# The dark timbre of gravitational waves


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Gravitational wave timbre, the relative amplitude and phase of the different harmonics, can change due to interactions with low-mass halos. We focus on binaries in the LISA range and find that the integrated lens effect of cold dark matter structures can be used to probe the existence of $M_{\rm v} \lesssim 10\,M_\odot$ halos if a single binary with eccentricity $e = 0.3 - 0.6$ is detected with a signal-to-noise ratio $100 - 10^4$.



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**Introduction** – Gravitational waves (GWs) are often associated with sound because they are characterized by waveforms and in general, there is a poorer angular resolution than with electromagnetic signals. Like with sound, for GWs there is also the notion of timbre since eccentric binaries emit GWs in different harmonics simultaneously. The relative powers of the harmonics are determined by the binary eccentricity and the harmonic numbers [1].

GWs are sensitive to wave optics interactions with small halos which can leave detectable imprints in the waveform [2–9] or a phase difference with respect to an electromagnetic counterpart [10–13]. Both methods rely on frequency-dependent effects for detectability.

In this work, we propose a novel probe of the wave optics effects: measurements of the timbre of the GW signal from an eccentric binary. Furthermore, we considered not only the effect of a single encounter but the integrated effect of light halos which the GW signal is expected to encounter. We study if the measurements of the timbre can be used to probe the low mass end of the dark matter (DM) halo mass function (HMF) where deviations from the cold dark matter (CDM) predictions may appear. For example, the small-scale structures are suppressed in models of warm or ultralight DM models [14–16].

We focus on signals whose frequency does not change significantly. In the LISA sensitivity range, such signals can originate e.g. from intermediate-mass black holes or extreme mass ratio binaries [17–22]. We compute the integrated effect of the DM halo population and show that very light halos, which are integrated out in weak lensing studies as a constant density field [23], induce changes in the amplitude and phases of the different harmonics of a mHz GW signal, effectively changing the timbre by the imprints of these light DM structures. The effect is detectable with LISA in the first harmonics if the binary has a signal-to-noise between $100 - 10^4$ and has eccentricity $e = 0.3 - 0.6$. We find that the effect mainly comes from halos of $\mathcal{O}(10\,M_\odot)$. Such light halos are a prediction of CDM but so far have eluded observations [24]. Therefore, its detection would provide a probe of the low mass tail of the HFM and severely constraint deviations from CDM at small scales.

**Lensing by a single halo** – Consider a binary whose orbital frequency remains almost constant during the observation. We denote the angular diameter distance of the binary by $D_s = d_{\rm c}(z_s)/(1+z_s)$, where $z_s$ is the corresponding redshift and $d_{\rm c}$ is the comoving distance, and assume that the GW signal emitted by the binary interacts with a halo at angular diameter distance $D_l$. In the frequency domain, the lensed waveform is $\tilde\phi_L(f) = F(f)\tilde\phi(f)$, where $\tilde\phi(f)$ denotes the unperturbed GW signal. The amplification factor $F(f)$ in the thin-lens approximation is given by [25]

$$F(f) = \frac{w(f)}{2i\pi}\int {\rm d}^2\boldsymbol{x}\, e^{iw(f)T(\boldsymbol{x},\boldsymbol{y})}\,, \qquad (1)$$

which is an integral over the lens plane of all the paths that the GW can take through it and the prefactor ensures that in the absence of the lens $F(f) = 1$. We define a characteristic length scale $\xi_0$ and dimensionful vectors that denote the position of the source ($\boldsymbol{\eta}$) in the source plane and the position at which the GW crosses the lens plane ($\boldsymbol{\chi}$). The dimensionless vectors $\boldsymbol{x}$ and $\boldsymbol{y}$ are defined as $\boldsymbol{x} \equiv \boldsymbol{\xi}/\xi_0$ and $\boldsymbol{y} \equiv D_l\boldsymbol{\eta}/(D_s\xi_0)$. The dimensionless frequency $w$ and the dimensionless time delay function $T$ then become

$$w(f) \equiv \frac{(1+z_l)D_s}{D_l D_{ls}}\xi_0^2 2\pi f\,, \qquad (2)$$

$$T(\boldsymbol{x},\boldsymbol{y}) \equiv \frac{1}{2}|\boldsymbol{x}-\boldsymbol{y}|^2 - \psi(\boldsymbol{x}) - \phi(\boldsymbol{y})\,, \qquad (3)$$

where $D_{ls} = D_s - (1+z_l)/(1+z_s)D_l$ and $\phi(\boldsymbol{y})$ is defined such that $\min_{\boldsymbol{x}} T(\boldsymbol{x},\boldsymbol{y}) = 0$.

We approximate the halos by the NFW profile $\rho(r) = r_s^3\rho_s/[r(r_s+r)^2]$, which corresponds to the lens potential (see e.g. [3])

$$\psi(x) = \kappa\left[\ln^2\!\left(\frac{x}{2b}\right) - {\rm artanh}^2\sqrt{1-\frac{x^2}{b^2}}\right], \qquad (4)$$

where $x = |\boldsymbol{x}|$ and $\kappa \equiv 2\pi\rho_s r_s^3/M_{\rm v}$ and $b \equiv r_s/\xi_0$ are dimensionless parameters. The distances are scaled by $\xi_0 = R_E(M_v)$, where $R_E$ denotes the point mass Einstein

# Gravitational particle production and the Hubble tension

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The effect of gravitational particle production of scalar particles on the total effective cosmic energy density (in the era after photon decoupling till the present) is considered. The effect is significant for heavy particles. It is found that gravitational particle production results in an effective increase in the directly measured value of the Hubble constant $H_0$ while it does not affect the value of the Hubble constant in the calculation of the number density of baryons at present time that is used to calculate recombination redshift. This may explain why the Hubble constant determined by local measurements and non-local measurements (such as CMB) are different. This suggests that gravitational particle production may have a non-negligible impact on the $H_0$ tension.

## I. INTRODUCTION

Gravitational particle production is a generic property of quantum fields in time-dependent backgrounds such as the Friedman-Lemaître- Robertson-Walker (FLRW) spacetimes [1, 2]. For example, the solution of the effective equation of motion of a free scalar field (namely, the mode function) at two different times, in general, is different since the equation of motion contains a time dependent effective mass. Hence, there exist different vacua at different times (that are described by different creation and annihilation operators and different mode functions). The mode function (and the corresponding creation/annihilation operators) at a given time may be expressed in terms of the mode function (and the corresponding creation/annihilation operators) at another time by a Bogolyubov transformation. Thus, a mode function at an initial time (that describes an "in" state) evolves into another value at a later time that may be expanded in terms of the mode function at that time (namely, the mode function of the "out" state). This is the well-known gravitational particle production. Therefore, gravitational particle production is a generic process for quantum fields in FLRW spacetimes. Hence, gravitational particle production necessarily takes place in cosmology. The aim of this study is to see the degree of the impact of this process on the standard cosmology through the example of a scalar field in the era after the photon decoupling till the present.

In the following, first, in Section II, the basic concepts and techniques necessary for a better understanding of the present study are briefly reviewed. In Section III, it is shown that adiabatic approximation that is used in the present study is applicable to the era after photon decoupling in ΛCDM for a wide range of scalar particle masses. In Section IV, the contribution of gravitational particle production to energy density is discussed. In Section V, the implications of gravitational particle production for Hubble tension are discussed. Finally, Section VI summarizes the main conclusions.

## II. PRELIMINIARIES

Spacetime at cosmological scales may be described by spatially flat Robertson-Walker metric

$$ds^2 \,=\, -dt^2 \,+\, a^2(t)\left[dr^2 + r^2(d\theta^2 + \sin^2\theta d\phi^2)\right] \,. \tag{1}$$

We consider the following action for the scalar field $\phi$ in this space

$$S \;=\; \int \sqrt{-g}\, d^4x\, \frac{1}{2}\left[-g^{\mu\nu}\partial_\mu\phi\partial_\nu\phi \,-\, m_\phi^2\phi^2\right] \,=\, \int d^3x\, d\eta\, \frac{1}{2}\left[\tilde{\phi}'^{\,2} - (\vec{\nabla}\tilde{\phi})^2 - \tilde{m}_\phi^2\tilde{\phi}^2\right] \,, \tag{2}$$

where prime denotes derivative with respect to conformal time $\eta$ [1] (while an over-dot denotes the derivative with

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# Measuring Mass Transfer Rates in Coalescing Neutron Star–White Dwarf Binaries with Deci-Hz Gravitational-wave Detectors

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## ABSTRACT

Coalescing neutron star–white dwarf (NS-WD) binaries are among the primary targets for upcoming space-borne gravitational wave (GW) detectors such as LISA, TaiJi, TianQin, etc. During close interaction, these binaries undergo mass transfer, emitting simultaneous X-rays and GWs. This offers a unique opportunity to measure mass transfer rates and study compact binary evolution. To analyze mass transfer rates, we employ the TaylorF2 frequency domain waveform model within the stationary phase approximation (SPA). Through this approach, we derive the GW phase induced during the mass transfer phase and perform Markov Chain Monte Carlo (MCMC) simulations to estimate the minimal detectable mass transfer rate given specific signal-to-noise ratios (SNRs). Our results suggest that for a NS-WD binary with a $0.5 M_{\odot}$ white dwarf companion, we could measure mass transfer rates down to $10^{-7} M_{\odot}, yr^{-1}$ at SNR=20 and $10^{-9} M_{\odot}, yr^{-1}$ at SNR=1000. This measurement holds significance for studying compact binary evolution involving mass transfer and has potential applications in forecasting tidal disruption events.

*Keywords:* Gravitational waves (678) — Gravitational wave sources (677) — Interacting binary stars (801) — Stellar accretion (1578) — Stellar evolution (1599) — X-ray binary stars (1811)

## 1. INTRODUCTION

The detection of gravitational wave (GW) emissions from closely orbiting compact binaries, comprising stellar-mass objects such as white dwarfs (WDs), neutron stars (NSs), or black holes (BHs), stands as a crucial scientific objective for space-borne GW detectors (Kupfer et al. 2018; Tauris 2018; Amaro-Seoane et al. 2023; Chen et al. 2020; Bayle et al. 2022; Liu & Shao 2022; Li & Cao 2023). These binaries can be broadly categorized as detached or interacting, with our emphasis of this *Letter* on exploring the mass transfer (MT) effects within interacting binaries involving WDs. Specifically, we focus on ultra-compact X-ray binaries (UCXBs), typically WD+NS/BH systems, where simultaneous emission of electromagnetic radiation and GWs takes place (Nelemans et al. 2010; Kaltenborn et al. 2022; Kang et al. 2024).

In interacting binary systems, significant MT occurs when the donor's radius exceeds its Roche lobe radius, resulting in a mass flow from the donor to the accretor. This study particularly considers a WD as the donor ($m_2$), with the accretor ($m_1$) being a NS or BH and $m_1 > m_2$ is assumed. This choice is influenced by the observation that a closer orbit not only leads to a higher MT rate and higher signal-to-noise ratios (SNRs) but also generates GW radiation within the frequency band $(10^{-3}, 10^{-1})$ Hz, which corresponds to the sensitive range for space-borne GW detectors (Wang et al. 2023). Notable projects in this field include the Laser Interferometer Space Antenna (LISA) led by the European Space Agency (ESA) and the National Aeronautics and Space Administration (NASA; Babak et al. 2021; Amaro-Seoane et al. 2017; Robson et al. 2019), two Chinese programs—TaiJi (Gong et al. 2021; Ruan et al. 2020; Hu & Wu 2017; Liu et al. 2023) and TianQin (Gong et al. 2021; Luo et al. 2016, 2020; Mei et al. 2020)—as well as the Deci-hertz Interferometer Gravitational wave Observatory (DECIGO)—and B-Decigo, a scientific pathfinder for DECIGO—proposed by the Japanese (Isoyama et al. 2018; Kawamura et al. 2020). Lunar detectors are also part of this exploration (Jani & Loeb 2021; Harms et al. 2021; Li et al. 2023; Cozzumbo et al. 2023). As illustrated in Fig. 4, TianQin

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# Hubble Diagrams in Statistically Homogeneous, Anisotropic Universes

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**Abstract.** We consider the form of Hubble diagrams that would be constructed by observers in universes that are homogeneous but anisotropic, when averaged over suitably large length-scales. This is achieved by ray-tracing in different directions on the sky in families of exact inhomogeneous cosmological solutions of Einstein's equations, in order to determine the red-shifts and luminosity distances that observers in these space-times would infer for distant astrophysical objects. We compare the results of this procedure to the Hubble diagrams that would be obtained by direct use of the large-scale-averaged anisotropic cosmological models, and find that observables calculated in the averaged model closely agree with those obtained from ray-tracing in all cases where a statistical homogeneity scale exists. In contrast, we find that in cosmologies with spaces that contain no statistical homogeneity scale that Hubble diagrams inferred from the averaged cosmological model can differ considerably from those that observers in the space-time would actually construct. We hope that these results will be of use for understanding and interpreting recent observations that suggest that large-scale anisotropy may have developed in the late Universe.

# Note on cosmographic approach to determining parameters of Barrow entropic dark energy model

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The cosmographic approach is used to determine the parameters of the Barrow entropic dark energy model. The model parameters are expressed through the current kinematic characteristics of Universe expansion.

Keywords: Barrow entropy, cosmography, dark energy, horizon, deceleration parameter



1.The viability (efficiency) of any cosmological model is determined by its ability to reproduce the results of observations. A mandatory preliminary stage for testing efficiency is determining the model parameters.

There are two approaches to determining the parameters of cosmological models. The first, extremely time-consuming approach consists of – sequentially exploring of the parametric space in order to find the optimal set of parameters. The lack of unambiguous criteria for the concept of "optimal set" (especially in the case of multipara meter models) and the need to use significant computing resources reduce the effectiveness of this approach. Nevertheless, "blind" search of parameters remains the dominant method for finding parameters of cosmological models.

Let us now formulate an alternative approach for finding modelparameters [1]. Instead of searching through parameters in order to find the optimal set, let's build a procedure that will allow us to relate the observed characteristics of the evolution of the Universe with the parameters of the cosmological model used to describe this evolution. That is, we change the direction of movement: not from parameters to observations, but from observations to parameters. The advantages of this approach will be discussed in detail later.

The first step towards this goal is to select observables that will be used to find the parameters of cosmological models. The main requirement for this set is the maximum possible modellessness.

The required modellessness can be achieved if the kinematic characteristics of the expansion of the Universe or, in other words, cosmographic parameters are chosen as the initial set of observables [2, 3]. Cosmography represents the kinematics of cosmological expansion [4], and cosmographic parameters are the coefficients of the Taylor series expansion of the scale factor $a(t)$.

In the early 70s of the twentieth century, Alan Sandage [5] defined as the main goal of cosmology the determination of two parameters: the Hubble parameter and the deceleration parameter. Everything seemed simple and clear: the Hubble parameter determines the expansion rate of the Universe, and the deceleration parameter takes into account small corrections due to the decrease in the expansion rate due to gravity. However, the situation turned out to be much more complicated than expected.

For a more complete description of the kinematics of cosmological expansion, it is useful to consider higher order derivatives of the scale factor [1, 6, 7]

$$\begin{aligned}
&H(t) \equiv \frac{1}{a}\frac{da}{dt};\\
&q(t) \equiv -\frac{1}{a}\frac{d^2a}{dt^2}\left[\frac{1}{a}\frac{da}{dt}\right]^{-2};\\
&j(t) \equiv \frac{1}{a}\frac{d^3a}{dt^3}\left[\frac{1}{a}\frac{da}{dt}\right]^{-3};\\
&s(t) \equiv \frac{1}{a}\frac{d^4a}{dt^4}\left[\frac{1}{a}\frac{da}{dt}\right]^{-4};\\
&l(t) \equiv \frac{1}{a}\frac{d^5a}{dt^5}\left[\frac{1}{a}\frac{da}{dt}\right]^{-5}
\end{aligned} \tag{1}$$

The parameters of any model that satisfies the cosmological principle can be expressed through a set of cosmographic parameters (1).

2. The goal of this work is to determine the parameters of holographic dark energy based on the Barrow entropy [8].

$$S_B = \left(\frac{A}{A_0}\right)^{1+\frac{\Delta}{2}} \tag{2}$$

where $A$ is the area of the horizon, $A_0$ is the Planck area, and $\Delta$ is a free parameter of the model, $0 \le \Delta \le 1$. The choice of entropy is dictated by the desire to take into account quantum deformations of the horizon surface. The measure of this deformation leading to the fractal structure of the horizon is the new parameter $\Delta$, which takes the value $\Delta = 0$ in the undeformed case of Bekenstein entropy, and the value $\Delta = 1$ corresponds to the maximum deformation leading to an increase in the fractal dimension of the horizon surface by one. Barrow entropy is a fractal generalization of Bekenstein entropy [9, 10].

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# Using Spherical Harmonics to solve the Boltzmann equation: an operator based approach

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**ABSTRACT**
The transport of charged particles or photons in a scattering medium can be modelled with a Boltzmann equation. The mathematical treatment for scattering in such scenarios is often simplified if evaluated in a frame where the scattering centres are, on average, at rest. It is common therefore, to use a mixed coordinate system, wherein space and time are measured in a fixed inertial frame, while momenta are measured in a "co-moving" frame. To facilitate analytic and numerical solutions, the momentum dependency of the phase-space density may be expanded as a series of spherical harmonics, typically truncated at low order. A method for deriving the system of equations for the expansion coefficients of the spherical harmonics to arbitrary order is presented in the limit of isotropic, small-angle scattering. The method of derivation takes advantage of operators acting on the space of spherical harmonics. The matrix representations of these operators are employed to compute the system of equations. The computation of matrix representations is detailed and subsequently simplified with the aid of rotations of the coordinate system. The eigenvalues and eigenvectors of the matrix representations are investigated to prepare the application of standard numerical techniques, e.g. the finite volume method or the discontinuous Galerkin method, to solve the system.

**Key words:** plasmas – acceleration of particles – methods: analytical

## 1 INTRODUCTION

The transport of charged particles, photons or neutrinos in an inhomogeneous scattering medium is a recurring problem that appears across multiple sub-fields of physics (e.g. Braginskii 1958; Chandrasekhar 1960; Ginzburg & Syrovatskii 1964; Mihalas & Mihalas 1984; Lewis & Miller 1984). Astrophysical contexts include neutrino and radiation hydrodynamics in supernova explosions, as well as the propagation and acceleration of energetic charged particles (cosmic rays). Typically, one considers the evolution of the single particle phase-space density, $f(\boldsymbol{x}, \boldsymbol{p}, t)$ by solving a transport equation which can be written in the form $\frac{\mathrm{d}f}{\mathrm{d}s} = \hat{C} f$. Here $s$ is an affine parameter that defines a point on a photon or particle trajectory (for a photon or neutrino the distance along a ray, for a particle with mass the proper time) and $\hat{C}$ is a collision operator that describes stochastic disturbances of these trajectories. For photons and neutrinos, the trajectories are simply geodesics in the local space-time, and $\hat{C}$ contains the scattering, absorption and emission cross-sections. These may be prescribed in the scattering-centres' rest frame, which may be determined by solving a separate set of equations (e.g., those of hydro- or magnetohydrodynamics). These equations in turn can be augmented by terms containing moments of $f$, i.e. feedback. In general, the rest frame of the scattering centres is non-inertial, and this must be taken into account when formulating the relevant transport equation (e.g. Achterberg & Norman 2018).

For example, the phase-function for photon scattering is usually specified in terms of the coordinates of the momenta $\boldsymbol{p}$ and $\boldsymbol{p}'$ of the photons involved, measured in the "co-moving" frame in which the scattering centres are locally at rest. This leads to a formulation of the radiation transport equation in so-called "mixed" coordinates (Lindquist 1966; Castor 1972; Riffert 1986), with the phase-space density treated as a function of position $\boldsymbol{x}$ and time $t$, both measured in the laboratory frame, while the momentum $\boldsymbol{p}$, is measured in the co-moving frame.

For cosmic rays, the situation is more complicated. As in the case of photons and neutrinos, one conventionally assumes the presence of a "background" plasma whose evolution can be determined, for example via the equations of ideal magnetohydrodynamics. But, in this case, these are augmented not only by terms in the stress-energy tensor, but also by the current and charge density carried by the cosmic rays. The charged particle trajectories are then not geodesics, but are determined by the electromagnetic fields carried by the background plasma. In dense plasmas, where Coulomb collisions among the different charged species occur, $\hat{C}$ can be modelled in the co-moving frame as a Fokker-Planck operator (Rosenbluth et al. 1957; Shkarofsky et al. 1966). However, in dilute, astrophysical plasmas, Coulomb collisions are unimportant, and $\hat{C}$ is instead used to model the effects of scattering on stochastic turbulent fluctuations that are superimposed on the large-scale fields carried by the background plasma. Given suitable constraints on the properties of this turbulence, $\hat{C}$ can again be formulated as a Fokker-Planck

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# Continuous Power Beaming to Lunar Far Side from EMLP-2 Halo Orbit

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***Abstract*—This paper focuses on FSO-based wireless power transmission (WPT) from Earth-Moon Lagrangian Point-2 (EMLP-2) to a receiver optical antenna equipped with solar cells that can be located anywhere on the lunar far side (LFS). Different solar-powered satellite (SPS) configurations which are EMLP-2 located single stable satellite and EMLP-2 halo orbit revolving single, double, and triple satellites are evaluated in terms of 100% LFS surface coverage percentage (SCP) and continuous Earth visibility. It is found that an equidistant triple satellite scheme on EMLP-2 halo orbit with a semi-major axis length of 15,000 km provides full SCP for LFS and it is essential for the continuous LFS wireless power transmission. In our proposed dynamic cislunar space model, geometric and temporal parameters of the Earth-Moon systems are used in affine transformations. Our dynamic model enables us to determine the full coverage time rate of a specific region such as the LFS southern pole. The outcomes show that the equidistant double satellite scheme provides SCP=100% during 88.60% time of these satellites' single revolution around the EMLP-2 halo orbit. Finally, the probability density function (PDF) of the random harvested power $P_H$ is determined and it validates the simulation data extracted from the stable EMLP-2 satellite and revolving satellite around EMLP-2 halo orbit for minimum and maximum LoS distances. Although the pointing devices to mitigate random misalignment errors are considered for the stable and revolving SPSs, better pointing accuracy is considered for the stable satellite. Our simulations show that the probability of $P_H \leq$41.6 W is around 0.5 for the stable satellite whereas the CDF=0.99 for the revolving satellite case for a transmit power of 1 kW.**

***Index Terms*— Acquisition, tracking, and pointing (ATP), coverage analysis, Earth-Moon Lagrangian Point (EMLP), energy harvesting, L2 halo orbit, lunar far side (LFS), misalignment error, satellite, wireless power transfer (WPT).**

## I. INTRODUCTION

THE Moon is the closest satellite to the Earth and hence it can be utilized as a base station for deep space exploration missions. For instance, a spacecraft can satisfy its needs (i.e., maintenance and battery recharge) before launching interplanetary missions. Moreover, asteroid and meteor impacts on the moon lead to the existence of platinum-group minerals on the lunar soil whereas solar winds enable Helium-3, which is very scarce on the Earth, to be found in the lunar regolith. Due to these rare and valuable resources on the Moon, lunar mining is considered vital since there is a finite available resource on Earth [1]–[3]. However, the tidal locking between the Moon and the Earth leads to a permanent unobservability of one side of the Moon (i.e., the lunar far side (LFS)) from the Earth. Since the Moon orbits around the world, there are 14 Earth days of total darkness, followed by the same amount of time for complete sunlight. This causes a mission interruption due to the run-out of batteries. Therefore, a solution for recharging the lunar equipment and vehicles while they are working on the LFS in complete darkness is necessary. Wireless power transfer (WPT) can be an option to overcome this problem. Since the considered distances are significantly large in point-to-point space link, and the losses that occur due to atmospheric attenuation, scintillation, and fiber-coupling are negligible [4], the free-space optics (FSO) communication technology can be considered as a proper candidate.

In our previous work, an FSO-based inter-satellite energy harvesting system is modeled by considering realistic laser power and solar cell conversion efficiencies. A solar-powered satellite (SPS) beams power to a small satellite such as 1U (0.1×0.1×0.1 m) or 12U (0.2×0.2×0.3 m) with adaptive beam divergence to maintain spot diameters of 0.1 and 0.2 m, respectively. Independent random misalignment errors on both the transmitter and receiver sides are mitigated by proposing an acquisition, tracking, and pointing (ATP) system module [5]. On the other hand, existing lunar orbits in the literature need to be assessed to find adequate cislunar orbits. The following characteristics of lunar orbits are critical in the decision-making process: the vicinity to the LFS, surface coverage percentage (SCP), and stability (i.e., station-keeping necessity). There are smaller and larger moon orbit options and they offer advantages and disadvantages so a trade-off must be made while making a decision.

Smaller moon orbit options are low lunar orbit (LLO), elliptical lunar orbit (ELO), prograde circular orbit (PCO), and frozen lunar orbit (FLO). The period of LLO is around 2 hours due to the altitude of 100 km thus LLO is favorable for lunar surface access (i.e., Apollo lunar exploration program). On the other hand, ELO, FLO, and PCO are elliptic orbits having substantial differences between perilune and apolune. The amplitude range of ELO, FLO, and PCO are 100–10,000, 880–8,800 km, and 3,000–5,000 km, respectively. Their orbital periods are similar and change between 11 to 14 hours. Moreover, these lunar orbits have different inclinations such that LLO can have any whereas ELO has only an equatorial inclination. Although these lunar orbits have different inclinations, they offer limited SCP since these are smaller

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# A comprehensive calculation of the Primakoff process and the solar axion flux

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Abstract: The Primakoff process plays a crucial role in axion production in astrophysical environments and laboratories. Given the rising interest in axion physics and many on-going experimental activities, we conduct a comprehensive calculation of this process and carefully examine several aspects that have been neglected in the literature. In particular, our calculation is valid for axions with significantly large masses, which would be of importance to axion searches utilizing crystal and liquid xenon detectors. We present the most updated calculation of the Primakoff solar axion flux, with a simple parametrization that is applicable to a broad range of axion masses up to a few tens of keV. Our code is publicly available at GitHub.

# Fireball anti-nucleosynthesis

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The tentative identification of approximately ten relativistic anti-helium ($\overline{\text{He}}$) cosmic-ray events at AMS-02 would, if confirmed, challenge our understanding of the astrophysical synthesis of heavy anti-nuclei. We propose a novel scenario for the enhanced production of such anti-nuclei that is triggered by isolated, catastrophic injections of large quantities of energetic Standard Model (SM) anti-quarks in our galaxy by physics beyond the Standard Model (BSM). We demonstrate that SM anti-nucleosynthetic processes that occur in the resulting rapidly expanding, thermalized fireballs of SM plasma can, for a reasonable range of parameters, produce the reported tentative $\sim 2:1$ ratio of $^3\overline{\text{He}}$ to $^4\overline{\text{He}}$ events at AMS-02, as well as their relativistic boosts. Moreover, we show that this can be achieved without violating anti-deuterium or anti-proton flux constraints for the appropriate anti-helium fluxes. A plausible BSM paradigm for the catastrophic injections is the collision of macroscopic composite dark-matter objects carrying large net anti-baryon number. Such a scenario would require these objects to be cosmologically stable, but to destabilize upon collision, promptly releasing a fraction of their mass energy into SM anti-particles within a tiny volume. We show that, in principle, the injection rate needed to attain the necessary anti-helium fluxes and the energetic conditions required to seed the fireballs appear possible to obtain in such a paradigm. We leave open the question of constructing a BSM particle physics model to realize this, but we suggest two concrete scenarios as promising targets for further investigation.

## CONTENTS



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# Workshop on the limiting compactness objects: Black holes and Buchdahl stars

IUCAA, Oct 30 - Nov 3, 2023

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The workshop was organized at IUCAA on Oct 30 – Nov 3 as a compact discussion/discourse meeting with a threadbare exposition and discussion of the various aspects and the questions arising. It was occasioned by the visit of Professor Håkan Andréasson of the Gothenburg Technical University, Sweden. He has been exploring with his collaborators the Einstein – Vlasov system for over a decade and a half as a possible matter source for compact objects. This system characterizes itself by free particles in motion and interacting only through gravity. For a limiting compactness, this may be the most appropriate state.

The main thrust of the workshop was to understand this new object, BS, of limiting compactness without a horizon. It is almost as compact as a BH and yet has no horizon and hence is open for interaction with the outside world. Ever since the proposal of the membrane paradigm envisaging a timelike fiducial surface near BH horizon, BS offers an excellent possibility of the existence of such a real astrophysical object. It could very well compete with BH as a mimicker for various physical and astrophysical phenomena. Thus, it opens up a new vista of study and investigation of all the questions that one asks for BH, for this new creature, BS. The workshop was intended to identify certain interesting questions as well as the people interested in studying them. On this count, the workshop has been a huge success as several interesting questions have been identified, a few groups have been formed to take up different problems, and the work has already started. Nothing more could one have asked from such an exercise. A brief summary of some of the talks follows now followed by a



tal bi-tensors, Synge's World function and the van Vleck determinant. In the first part, two specific recent results that employ these objects were discussed: (i) Non-perturbative tidal corrections to results such as Unruh effect and ageing of twins, and (ii) Formulating generalised uncertainty principle on curved space(time)s. A formalism is then described to construct an effective quantum metric - qmetric - in terms of these bi-tensors, which can describe spacetime with a zero point length. Some non-trivialities of the qmetric, its classical limit, and its role in quantum gravity were highlighted. The sections below give a broad overview of the key points and results that constituted the talk.

**Spacetime from two-point correlators:** A generic implication of incorporating gravitational effects in the analysis of quantum measurements is the existence of a zero-point length of spacetime. This requires an inherently non-local description of spacetime, beyond the usual one based on metric $g_{ab}(x)$ etc. One of the major focus of the talk was to put forward the right tools to characterise spacetime in terms of inherently non-local, and observationally relevant, quantities. The quantum spacetime should instead be reconstructed from non-local bi-tensors of the form $G_{ab\ldots i'j'\ldots}(x, x')$. A deeper look then reveals a subtle interplay between non-locality and the limit $l_0^2 = G\hbar/c^3 \to 0$. In particular, the so called emergent gravity paradigm – in which gravitational dynamics/action/spacetime are emergent and characterised by an *entropy functional* – arises as the *Cheshire* grin of a fundamentally non-local quantum spacetime. We have constructed a non-local quantum metric, "qmetric", which can be used as the effective object that can be used in place of the metric to obtain insights into the small scale structure of spacetime.

**Euclidean domain of Lorentzian spacetimes:** In a related part of the talk, I discussed a new framework for Euclidean gravity, which might provide deep insights into the small scale structure of spacetime as well as generic quantum nature of gravity.

**Entanglement and decoherence in curved spacetime:** The final part of the talk described some results that applies above tools to study the role of Riemann tensor in entanglement and decoherence.

**Ranjan Sharma: Compactness limit for relativistic stars in Einstein and extended gravity models**

The maximum permissible compactness bound for a relativistic self-gravitating object is given in terms of the Buchdahl bound, which tells us that no uniform density stars with radii smaller than $9M/4$ can exist [1]. As the critical compactness plays a crucial role in constraining the EOS of a star, many investigators have employed different techniques and used various stellar models to analyze the impacts of model parameters and subsequently determined the maximum permissible compactness bound. In this context, of particular interest, is a Buchdahl star which is a very highly dense compact object and still can manage to remain in equilibrium without forming an event horizon.

This article presents some of the recent developments in the estimation of maximum compactness bound for ultra-compact objects. In 1939, Tolman [2] developed a technique for obtaining solutions to Einstein field equations for a static spherically symmetric fluid source, which produced eight exact analytic

# Neutrino-Dark Sector Equilibration and Primordial Element Abundances

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After neutrinos decouple from the photon bath, they can populate a thermal dark sector. If this occurs at a temperature above $\sim 100\,\text{keV}$, this can have measurable impacts on light element abundances. We calculate light element abundances in this scenario, studying the impact from rapid cooling of the Standard Model neutrinos, and from an increase in the number of relativistic degrees of freedom $N_{\rm eff}$, which can occur in the presence of a mass threshold. We incorporate these changes in the publicly available BBN code PRIMAT, using the reaction networks from PRIMAT and from the BBN code PArthENoPE, to calculate $\text{Y}_\text{P}$ and D/H. We provide limits from the two different reaction networks as well as with expanded errors to include both results. If electron neutrinos significantly participate in the cooling, we find limits down to temperatures as low as 100 keV. If electron neutrinos are weakly participating (for instance if only the mass eigenstate $\nu_3$ equilibrates), cooling places no limits. However, if the dark sector undergoes a "step" in $N_{\rm eff}$, there can be additional, $\omega_b$-dependent constraints. These limits can vary from strong (for low values of $\omega_b$) to a mild preference for new physics (for high values of $\omega_b$). Future analyses including upcoming CMB data should improve these limits.

## I. INTRODUCTION

One of the great successes of particle cosmology is the consistency of Big Bang cosmology with a current CMB temperature $T = 2.7K$, the measured value of $\Omega_b$, the presence of three light neutrinos in the Standard Model (SM), and the measured primordial abundances of helium-3 ($^3$He), helium-4 ($^4$He) and deuterium (D). The formation of these elements is sensitive to physics in temperature ranges of 100 keV to $\sim 10\,\text{MeV}$, at times from a few seconds until a few minutes in the life of the Universe.

As measurements of primordial $^4$He and D have achieved percent precision, we are capable of asking questions about the properties of the Universe in that era, with a promise of getting quantitative answers.

One such question concerns the nature of the "dark radiation" of the universe. It is now well established both through BBN and the CMB that a sizable fraction of the energy density of the universe at early times is in the form of some dark radiation. The SM provides a natural explanation for this radiation in the form of SM neutrinos, which are in thermal contact with the photon bath until temperatures near a few MeV at which point the neutrinos decouple.

Beyond simple scientific rigor, there are important reasons to want to test this explanation. For instance, other (near-)massless states in thermal contact with the SM at earlier times will generally add to this dark radiation. Current 95% constraints limit additional radiation $\triangle N_{\rm eff} \lesssim 0.4$ (BBN), $\triangle N_{\rm eff} \lesssim 0.33$ (CMB+BAO for $\Lambda$CDM+$\triangle N_{\rm eff}$), and $\triangle N_{\rm eff} \lesssim 0.23$ (BBN+CMB) (see, e.g., [1–3]), allowing ample room for new particles.

Dark states can also remain depopulated until late times when they can come into equilibrium [4, 5]. For instance, a simple scenario was recently studied in [5], wherein it was demonstrated that a neutral fermion, mixing with SM neutrinos, would naturally thermalize, even for mixing angles as small as $10^{-14}$. The temperature of thermalization is set by the mass of the mixing dark particle, implying that a late $O(1)$ change to $N_{\rm eff}$ is natural as long as some interacting particle with mass below an MeV exists, which mixes with SM neutrinos.[1]

If this thermalization happens sufficiently late, it can evade all constraints from BBN, while yielding a signal in the CMB. However, this precise boundary can have important implications for models.

In this Letter, we shall study the effects of dark sectors equilibrating with neutrinos at temperatures near 1 MeV. The layout of this paper is as follows: in Sec. II we describe the process of neutrino equilibration with a dark sector and the physics phenomena that can affect BBN. In Sec. III we calculate effects and give limits on these new states. Finally, in Sec. IV we conclude, and discuss what future measurements could strengthen these constraints.

## II. LATE NEUTRINO EQUILIBRATION AND BBN

Neutrinos can equilibrate with a neutral sector via mass mixing; this is well understood [6–12]. If neutrinos, mixed with a neutral fermion $\nu_d$, oscillate and then scatter at a rate higher than Hubble, they will equilibrate $\nu_d$ and any other particles with significant couplings to

[1] A late change to $N_{\rm eff}$ can also arise if a massive particle decays at late times, adding energy to the dark sector. Typically this requires a fine tuning for the energy density to be an $O(1)$ change to $N_{\rm eff}$, rather than much larger or smaller.

# f(R) Gravity in an Ellipsoidal Universe

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We propose a new model of cosmology based on an anisotropic background and a specific $f(R)$ theory of gravity. It is shown that field equations of $f(R)$ gravity in a Bianchi type I background give rise to a modified Friedmann equation. This model contains two important parameters: $\gamma$ and $\delta$. We, thus, simply call our model $\gamma\delta$CDM. It is distinguished in two important aspects from the $\Lambda$CDM model: firstly, the contribution of different energy densities to the Hubble parameter are weighted with different weights, and then, dependence of energy densities to redshift is modified as well. This unorthodox relation of energy content to Hubble parameter brings forth a new way of interpreting the cosmological history. This solution does not allow the existence of a cosmological constant component, however, a dark energy contribution with dependence on redshift is possible. We tested observational relevance of the new solution by best fitting to different data sets. We found that our model could accommodate the idea of cosmological coupling of black holes.

## I. INTRODUCTION

Advances in cosmology in both observational and theoretical fronts in the last decades were immense and these theoretical and the observational advancements supported each other to build the highly successful "standard model" of cosmology, so called $\Lambda$CDM model. Under the assumptions of isotropy and homogeneity of matter distribution in the Universe, and the validity of Einstein's theory of gravity at all classical scales, the $\Lambda$CDM model brings theoretical explanation to observations in both the late and the early universe. Scientific explanation, however, is never complete and scientific progress accelerates after inconsistencies in the paradigm itself start to appear and new ideas are begin to be explored in order to resolve those inconsistencies.

In cosmology, first of all, there is an important inconsistency between numerically fitted value of the Hubble constant to the late and the early universe data. The discrepancy is on the order of $5\sigma$ [1–3] and it has been called a "crisis" [4]. Whereas Hubble constant is calculated from the Cosmic Microwave Background (CMB) data with a theoretical input [5], it is been fitted to the late universe observational data independent of any cosmological model [6–13]. Since these discrepancy is not resolved in $\Lambda$CDM model yet [1, 2, 14–17], it is plausible to seek alternative theoretical explanations to the observational data. One avenue of research has been to change the third assumption of the standard cosmology, namely that the theory of gravitation could be different than the Einstein's theory on scales larger than at least the scale of the Solar System.

One of the simplest modifications of the Einstein's theory of gravity is the $f(R)$ theory of gravity (see reviews [18–21] and references therein). Action of this theory includes an arbitrary function of the scalar curvature R and in that aspect it is different than the Einstein-Hilbert action, which depends on the scalar curvature itself. There are many works on the cosmological implications of $f(R)$ gravity since Starobinsky's seminal paper [22–24]. In the present work we are going to present a new solution to the field equations of $f(R)$ gravity in the anisotropic Bianchi type I background geometry [25]. The fact that we work in an anisotropic background is motivated by the "anomalies" [26, 27] in the observational data both in the early and the late universe. An anisotropic universe under the influence of Einstein gravity with a positive cosmological constant tends to isotropize asymptotically [28, 29]. In the case of $f(R)$ gravity, however, it is possible to have anisotropically expanding cosmological

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# Spectral characterization of young LT dwarfs

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**ABSTRACT**

*Context.* JWST and next-generation facilities are expected to uncover populations of free-floating objects below the deuterium-burning limit in a number of young clusters and star-forming regions. These young planetary-mass brown dwarfs have spectral types L and T, shaped by molecular absorption and modified by their low gravity, which makes them distinct from field objects.
*Aims.* We aim to provide a detailed characterization of near-infrared spectra for young LT brown dwarfs, including robust spectral typing, calibrating spectral indices, identifying possible binaries, and selecting suitable spectral standards.
*Methods.* We process and analyze archival spectra from VLT/X-shooter for a sample of 56 dwarfs with ages between 10 and 600 Myr and spectral types between late-M and mid-T. We re-determine spectral types by comparing them with a set of literature templates. We assess a large range of spectral indices, calibrated using a specifically designed literature sample.
*Results.* We identify 15 spectral indices that are useful for spectral typing for specific spectral ranges discussed here and provide the scaling relations with spectral types. We also identify 6 spectral indices which can be used to separate young L dwarfs from the field ones. The EWs of the alkali lines show a correlation with age, increasing towards the objects with higher surface gravity. From our sample, we confirm 3 that are likely to be binaries by their anomalous spectra that appear to be better fitted by a combination of spectral types. We identify 12 objects as preliminary near-infrared spectral standards for young LT dwarfs.
*Conclusions.* This paper presents a significant step toward understanding the spectral sequence and properties of young L and T dwarfs. The relations and standards provided here will be useful for future spectroscopic work on young brown dwarfs and giant planets.

**Key words.** brown dwarfs – Techniques: spectroscopic

## 1. Introduction

The bottom of the initial mass function (IMF) is populated by brown dwarfs (BDs), substellar objects with masses $\lesssim 80\,M_{Jup}$. The lightest among these are the so-called free-floating planetary-mass objects (PMOs) with masses below the deuterium-burning limit at $\sim 12\,M_{Jup}$, whose existence have been confirmed by various deep surveys in nearby young star-forming regions (SFRs; Luhman et al. 2009; Scholz et al. 2012; Peña Ramírez et al. 2012; Lodieu et al. 2018; Miret-Roig et al. 2022; Bouy et al. 2022). However, the details of the free-floating PMO formation process are still largely unknown and represent one of the important missing pieces in our understanding of star formation. Broadly speaking, populations of isolated PMOs in star clusters may form by cloud fragmentation and core collapse (star-like formation), or in protoplanetary disks (planet-like formation), followed by ejection due to encounters with other stars or planet-planet interactions (see Miret-Roig 2023 and references therein). The relative importance of these two scenarios is not known, mainly due to the lack of observational constraints - given their intrinsic faintness, studies of PMOs present a challenging task for most of the current facilities. In total, only about a few dozen young isolated PMOs have been spectroscopically confirmed so far, with estimated masses above $\sim 5\,M_{Jup}$. This situation is expected to change drastically in the near future with the advent of the James Webb Space Telescope (JWST), which will provide, for the first time, a robust census of young (1−3 Myr) free-floating PMOs in the 1-15 $M_{Jup}$ range (Scholz et al. 2022; Pearson & McCaughrean 2023). These objects are expected to have spectral types (SpTs) in the range between ~L0 and early-to-mid T-types. Evolutionary models predict that a Jupiter-mass object at 1-3 Myr should have an effective temperature in the range 700 - 900 K, showing the typical T-type features in the model atmospheres (Marley et al. 2021).

Spectral characteristics of BD atmospheres are strongly influenced by gravity, which has been extensively used to remove field contaminants from spectroscopic samples of BD candidates in star-forming regions (Bayo et al. 2011; Mužić et al. 2015; Esplin & Luhman 2020, to name only a few). In the near-infrared (NIR), gravity-sensitive features include the alkali lines (K I, Na I) and FeH absorption bands, which are less pronounced in young, low-gravity atmospheres, as well as the broadband form of the H-band, shaped by water absorption, which appears sharply triangular in young atmospheres as opposed to a rounder shape in field dwarf atmospheres (Gorlova et al. 2003; McGovern et al. 2004; Allers & Liu 2013; Manjavacas et al. 2020; Almendros-Abad et al. 2022). The assessment

 

# Observed kinematics of the Milky Way nuclear stellar disk region

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**ABSTRACT**

*Context.* The nuclear region of the Milky Way, within approximately $-1°<l<+1°$ and $-0.3°<b<+0.3°$ (i.e., $|l|<150$ pc, $|b|<45$ pc), is believed to host a nuclear stellar disk, co-spatial with the gaseous central molecular zone. Previous kinematical studies detected faster rotation for the stars belonging to the nuclear stellar disk, compared to the surrounding regions.
*Aims.* We analyze the rotation velocity of stars at the nuclear stellar disk, and compare them with its analog in a few control fields just outside this region. We limit our analysis to stars in the red clump of the color magnitude diagram, in order to be able to relate their mean de-reddened luminosity with distance along the line of sight.
*Methods.* We used a proper motion catalog, obtained from point spread function photometry on VISTA variables in the Vía Láctea images, to construct maps of the transverse velocity for these stars. We complemented our analysis with radial velocities from the $17^{th}$ data release of the APOGEE survey.
*Results.* We find that the main difference between the nuclear stellar disk region and its surroundings is that at the former we see only stars moving eastward, which we believe are located in front of the Galactic center. On the contrary, in every other direction, we see the brightest red clump stars moving eastward, and the faintest ones moving westward, as expected for a rotating disk. We interpret these observations as being produced by the central molecular zone, hiding stars behind itself. What we observe is compatible with being produced by just the absence of the component at the back, without requiring the presence of a cold, fast rotating disk. This component is also not clearly detected in the newest release of the APOGEE catalog. In other words, we find no clear signature of the nuclear stellar disk as a distinct kinematical component.
*Conclusions.* This work highlights the need for nearby control fields when attempting to characterize the properties of the nuclear stellar disk, as the different systematics affecting this region, compared to nearby ones, might introduce spurious results. Deep, wide field and high resolution photometry of the inner 4 degrees of the Milky Way is needed in order to understand the structure and kinematics of this very unique region of our Galaxy.

**Key words.** Galaxy: nucleus, structure, stellar content, kinematics

## 1. Introduction

The innermost ∼2 square degrees ($|l|<1°$, $|b|<0.3°$) are the most interesting and yet the least understood region of the Milky Way (MW). They host the nuclear stellar disk (NSD), the central molecular zone (CMZ), three massive young clusters, several powerful X-ray sources, radio bubbles, and the supermassive black hole (see Bryant & Krabbe 2021, for a recent review). Each of these components is rather unique in our Galaxy, and the links among them, in terms of origin and evolution, are very poorly understood. Yet, this is not an exotic and rare region: every spiral galaxy has a central region with similar components. Also, there are strong reasons to believe that what happened in the MW center, in the past, has influenced the evolution of, at least, the whole bulge (e.g., Croton 2006; Laha et al. 2021, for a recent review). Therefore, this region definitely deserves to be extensively explored, and the interplay among its various components understood.

An early review about the nuclear region of our Galaxy was offered by Mezger et al. (1996). They defined a "Nuclear bulge" as being contained within R<300 pc from the MW dynamical center. Launhardt et al. (2002) emphasized how this component is distinct from the main bulge, at 300<R<3000 pc because it shows a sharp increase in the stellar density, it hosts a relatively large population of massive stars (Dong et al. 2012, e.g.,) and star clusters (Hosek et al. 2022; Schödel et al. 2020, 2023, and references therein), and it contains a large fraction of the MW dense molecular gas: the CMZ. Schönrich et al. (2015) presented a first kinematical detection of the NSD as a flat, fast rotating ($V_{rot}$=120 km/s) component with a radius $R_{NSD}$=150 pc. A smaller radius ($R_{NSD}$∼90 pc) has been inferred by Gallego-Cano et al. (2020) from an analysis of *Spitzer*/InfraRed Array Camera (IRAC) 4.5 $\mu$m images. Also, a change in the orientation of the main bar in the inner region has been reported by Gonzalez et al.

⋆ Based on observations taken within the ESO VISTA Public Survey VVV, Program ID 179.B-2002.

# Detection of possible glycine precursor molecule methylamine towards the hot molecular core G358.93–0.03 MM1

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ABSTRACT

The search for the simplest amino acid, glycine ($NH_2CH_2COOH$), in the interstellar medium (ISM) has become a never-ending story for astrochemistry and astrophysics researchers because that molecule plays a possible connection between the Universe and the origin of life. In the last forty years, all searches for $NH_2CH_2COOH$ in the ISM at millimeter and submillimeter wavelengths have failed. Since the detection of $NH_2CH_2COOH$ in the ISM was extremely difficult, we aimed to search for the possible precursors of $NH_2CH_2COOH$. Earlier, many laboratory experiments have suggested that methylamine ($CH_3NH_2$) plays an important role in the ISM as a possible precursor of $NH_2CH_2COOH$. After spectral analysis using the local thermodynamic equilibrium (LTE) model, we identified the rotational emission lines of $CH_3NH_2$ towards the hot molecular core G358.93–0.03 MM1 using the Atacama Large Millimeter/Submillimeter Array (ALMA). The column density of $CH_3NH_2$ towards the G358.93–0.03 MM1 was estimated to be $(1.10\pm0.31)\times10^{17}$ cm$^{-2}$ with an excitation temperature of 180.8$\pm$25.5 K. The fractional abundance of $CH_3NH_2$ with respect to $H_2$ towards the G358.93–0.03 MM1 was $(8.80\pm2.60)\times10^{-8}$. The column density ratio of $CH_3NH_2$ and $NH_2CN$ towards G358.93–0.03 MM1 was $(1.86\pm0.95)\times10^{2}$. The estimated fractional abundance of $CH_3NH_2$ towards the G358.93–0.03 MM1 agrees fairly well with the previous three-phase warm-up chemical modelling abundance of $CH_3NH_2$. We also discussed the possible formation mechanism of $CH_3NH_2$, and we find that $CH_3NH_2$ is most probably formed via the reactions of radical $CH_3$ and radical $NH_2$ on the grain surface of G358.93–0.03 MM1.

## 1. Introduction

The initial chemical development leading to the formation of life is believed to have formed in molecular clouds, proceeded inside the protoplanetary disk, and transported into the planetary atmosphere with the help of comets and asteroids (Suzuki et al., 2019). The investigation of complex nitrogen-bearing molecules like hydrogen cyanide (HCN), formamide ($NH_2CHO$), methyleneimine ($CH_2NH$), methylamine ($CH_3NH_2$), cyanamide ($NH_2CN$), and aminoacetonitrile ($NH_2CH_2CN$) was extremely important because these prebiotic molecules are essential for the production of amino acids in the interstellar medium (ISM) (Herbst & van Dishoeck, 2009; Garrod, 2013; Bøgelund et al., 2019; Manna & Pal, 2022a,b, 2023). In the ISM, the hot molecular cores are one of the earlier stages of high-mass star-formation regions, and they play a crucial role in enhancing the chemical complexity in the ISM (Shimonishi et al., 2021). The hot molecular cores are ideal candidates to study the complex prebiotic molecules because they contain a compact and small source size (<0.1 pc), a warm environment (>100 K), and a high gas density ($n_{H_2}>10^6$ cm$^{-3}$) that promotes molecular evolution by thermal hopping on dust grains (van Dishoeck & Blake, 1998; Williams & Viti, 2014). The chemistry of the hot cores is characterised by the sublimation of ice mantles, which accumulated during the star-formation activities (Shimonishi et al., 2021). The gaseous molecules and atoms are frozen onto the dust grains in prestellar cores and cold molecular clouds. As the temperature of the dust rises due to star-formation activities, the chemical interactions between heavy species become active on the grain surfaces, resulting in the formation of more complex organic molecules (Garrod & Herbst, 2006; Shimonishi et al., 2021). In addition, sublimated molecules such as methanol ($CH_3OH$) and ammonia ($NH_3$) are also subjected to further gas-phase reactions (Nomura & Miller, 2004; Taquet et al., 2016). As a result, the warm, dense, and chemically abundant gas around the protostars develops into one of the strongest molecular line emitters, known as the hot molecular cores. The hot molecular cores are crucial objects for astrochemical studies because a multiplicity of simple and complex organic molecules are frequently found in the

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# Can we distinguish the adiabatic fluctuations and isocurvature fluctuations with pulsar timing arrays?

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Understanding the nature of primordial fluctuations is critical to our comprehension of the Universe's early stages. While these fluctuations are known to be nearly scale-invariant, quasi-adiabatic, and nearly Gaussian on large scales, their behavior at smaller scales remains less well-defined and may offer insights into new physics. Recent observations by the NANOGrav, PPTA, EPTA, and CPTA collaborations suggest the presence of a stochastic gravitational wave background, which, while consistent with the contribution from supermassive black hole binaries, also opens the possibility of probing new physics. This paper explores whether this signal could stem from primordial isocurvature and adiabatic fluctuations. We adopt parameterized spectra for both types of fluctuations to fit the observations from the latest NANOGrav data. Furthermore, we employ Bayesian analysis to assess the distinguishability of these models in light of current PTA sensitivities. Our findings indicate that with the capabilities, PTAs cannot conclusively differentiate between isocurvature and adiabatic fluctuations.

**adiabatic fluctuation, isocurvature fluctuation, pulsar timing array**

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## 1 Introduction

Adiabatic fluctuations and isocurvature fluctuations represent two distinct types of primordial density perturbations that can arise in the early Universe. Adiabatic fluctuations manifest as perturbations in the overall density of matter and energy throughout the Universe [1]. These perturbations uniformly impact all forms of matter and radiation, leading to a consistent shift in the density distribution. In simpler terms, the relative proportions of various constituents (e.g., dark matter, baryons, and radiation) remain constant within the perturbed regions. Isocurvature fluctuations, on the other hand, denote perturbations in the relative abundances of different matter and energy components within the Universe [2,3]. Unlike adiabatic fluctuations, they do not change the overall density. Instead, they modify the relative ratios between distinct types of matter or radiation, leading to a change in the composition of the Universe without affecting its total density.

Our Universe is characterized by primordial fluctuations that exhibit certain properties on large scales. These fluctuations are remarkably small, nearly scale-invariant, quasi-adiabatic, and almost Gaussian. Their presence is directly

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# Structure-dependent fragmentation risk of rubble-pile asteroids on low-impacts

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A key strategy in defending against stray asteroids is deflection from a collision trajectory by a low-momentum impact. This is to avoid a potential rain of large hazardous fragments, which high-momentum blasts may generate. Using a proof-of-principle numerical model, we show that even low-momentum impacts on rubble pile asteroids (RPAs), which most asteroids are, may lead to their fracturing into large fragments because of their internal non-uniform chain-like stress distribution. Since stress chains occur in three- and two-dimensional (2D) loose aggregates, we study low-momentum impacts on gravity-aggregated clusters in 2D. We establish that stresses are indeed supported by chains and show that the post-impact dynamic shear stress and displacement rates are highest along the chains, increasing significantly the risk of fracturing there. Our simulations suggest that this phenomenon is independent of the cluster's particle size distribution. We conclude that future studies must be carried out to quantify the relations between the risk of fracturing and stress chain statistics in RPAs.

Asteroid impact defense is significant for the survival of Mankind and has attracted much study. One defense strategy is to deflect an asteroid hurling toward Earth by 'shooting' at it a projectile that deflects it to a safe trajectory [1]. This strategy is often preferable to simply blasting such objects, which requires much more energy. A significant consideration in employing this strategy is to avoid too much damage to the asteroid so as not to cause its fracturing into several fragments that are sufficiently large to pass the atmosphere and reach Earth, causing even larger damage than the original asteroid. Therefore, a key issue is an estimate of the effect of the projectile's impact angle and its momentum transfer to the approaching asteroid.

Impacting relatively dense asteroids generates cratering accompanied by shattering of the impact region [2, 3]. Some of the kinetic energy of such events then 'propagates' as a shock wave of diminishing magnitude into the asteroid [4, 5] and it is important to estimate whether or not this energy can fragment the asteroid. A grazing impact is then the much safer option. However, a large fraction of asteroids are rubble-pile asteroids (RPAs), consisting of loosely connected aggregates of particles and boulders. These fragment more easily than solid asteroids and require a more careful estimate of the extent of damage under any impact parameters. The bulk densities of RPAs are low owing to high porosity [6, 7]. Moreover, loosely packed particulate aggregates are known to transmit stresses non-uniformly in the form of sparse force chain networks [8, 9], whose characteristics depend on the aggregate's internal structure. The less dense the aggregate the more non-uniform the stress field [10] and the more fragile the asteroid.

Discrete element method (DEM) studies of impact-induced seismic waves in RPAs proved a useful method to gain an understanding of such phenomena [5, 11]. However, previous studies did not consider the effects of the non-uniform and sparse force chain networks. In particular, one expects the material density to be higher along force chains than around them and, therefore, the stress response to impacts should propagate faster along such chains. Since elevated shear stress increases the risk of fracturing such a risk must be assessed. Here we test this idea and show that stress chains are indeed vulnerable. Therefore, we argue that the risk of fracturing must be taken into consideration when planning low-momentum impacts aimed only to deflect RPAs from hazardous trajectories.

Since stress in granular media is transmitted by force chains in two and three dimensions, it is sufficient and simplest to provide a proof of concept in two dimensions (2D). Therefore, we study a 2D toy model, whose main purpose is to investigate numerically and illustrate the effects of stress chains in RPAs. We find that such chains modify the response to even low-momentum impacts and significantly increase the risk of fracturing along them.

We employed the following methodology. We first constructed 2D models of rubble-pile clusters (RPCs) by aggregating under gravity particles of several size and shape distributions. We then quantified their internal structures and non-uniform stress fields, verifying that they consist of stress chains. Next, we simulated impacts at, and away from, stress points, and studied the relations between the initial stress field and the propagation characteristics of the dynamic responses of the displacement and stress fields.

For our numerical simulations, we used the in-house soft-sphere discrete-element code DEMBody [12–14]. The interparticle contact forces were nonlinear, based on the Hertz–Mindlin–Deresiewicz model [15] and deter-

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# Numerical performance of correlated-k distribution method in atmospheric escape simulation

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ABSTRACT

Atmospheric escape is crucial to understand the evolution of planets in and out of the Solar system and to interpret atmospheric observations. While hydrodynamic escape simulations have been actively developed incorporating detailed processes such as UV heating, chemical reactions, and radiative cooling, the radiative cooling by molecules has been treated as emission from selected lines or rotational/vibrational bands to reduce its numerical cost. However, ad hoc selections of radiative lines would risk estimating inaccurate cooling rates because important lines or wavelengths for atmospheric cooling depend on emitting conditions such as temperature and optical thickness. In this study, we apply the correlated-k distribution (CKD) method to cooling rate calculations for $H_2$-dominant transonic atmospheres containing $H_2O$ or CO as radiative species, to investigate its numerical performance and the importance of considering all lines of the molecules. Our simulations demonstrate that the sum of weak lines, which provides only 1 % of the line emission energy in total at optically thin conditions, can become the primary source of radiative cooling in optically thick regions, especially for $H_2O$-containing atmospheres. Also, in our hydrodynamic simulations, the CKD method with a wavelength resolution of 1000 is found to be effective, allowing the calculation of escape rate and temperature profiles with acceptable numerical cost. Our results show the importance of treating all radiative lines and the usefulness of the CKD method in hydrodynamic escape simulations. It is particularly practical for heavy-element-enriched atmospheres considered in small exoplanets, including super-Earths, without any prior selections for effective lines.

*Keywords:* planets and satellites: atmospheres — planets and satellites: terrestrial planets



## 1. INTRODUCTION

Hydrodynamic escape of atmospheres is one of the important phenomena influencing the atmospheric/bulk composition and mass of planets highly irradiated by stellar X-ray and UV, especially for small planets (e.g., Lammer et al. 2008; Tian 2015; Owen 2019). The discovery of numerous close-in exoplanets over the past two decades has spurred the active development of theoretical models for hydrodynamic escape in planetary atmospheres (see Owen 2019, and the references therein). Subsequent detailed hydrodynamic simulations have incorporated radiative transfer and photo and thermal chemistry (e.g., Yelle 2004; García Muñoz 2007; Murray-Clay et al. 2009; Koskinen et al. 2013a,b). However, most of them focus on the hydrogen-dominant atmospheres, given the observed rapid escape of hydrogen and helium in hot Jupiters and sub-Neptunes (e.g., Vidal-Madjar et al. 2003; Kulow et al. 2014; Spake et al. 2018).

Conversely, modeling the atmospheres enriched with heavy elements, which are likely in small-sized terrestrial planets including super-Earths, remains in its infancy. Recent comparisons between observed absorption lines and theoretical modeling of the escaping atmo-

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# Bondi-Hoyle-Lyttleton Accretion around the Rotating Hairy Horndeski Black Hole

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ABSTRACT: Modeling of the disk and the shock cone formed around a static hairy Horndeski black hole with Bondi-Hoyle-Lyttleton (BHL) accretion has been conducted. We model the dynamical changes of the disk and shock cone resulting from the interaction of matter with the Horndeski black hole, at where the scalar field and spacetime has a strong interaction. The effects of the scalar hair, the black hole rotation parameter, and the impacts of the asymptotic speed have been examined, revealing the influence of these parameters on the shock cone and the trapped QPO modes within the cone. Numerical calculations have shown that the hair parameter significantly affects the formation of the disk and the shock cone. As the absolute value of the hair parameter increases, the matter in the region of the shock cone is observed to move away from the black hole horizon. The rate of matter expulsion increases as $h/M$ changes. After $h/M < -0.6$, a visible change in the physical structure of the shock cone has occurred, ultimately leading to the complete sweeping out of the shock cone. On the other hand, it has been revealed that the asymptotic speed significantly affects the formation of the disk and shock cone. As $h/M$ increases in the negative direction and the asymptotic speed increases, the stagnation point is getting closer to the black hole horizon. When the value of the hair parameter changes, the rest-mass density of the matter inside the cone decreases, while the opposite is observed with the asymptotic speed. Additionally, the formed shock cone has excited QPO modes. The deformation of the cone due to the hair parameter has led to a change or complete disappearance of the QPOs. Meanwhile, at asymptotic speeds of $V_\infty/c < 0.4$, all fundamental frequency modes are formed, while at $V_\infty/c = 0.4$, only the azimuthal mode is excited, and $1 : 2 : 3 : 4 : ...$ resonance conditions occur. No QPOs have formed at $V_\infty/c = 0.6$. The results obtained from numerical calculations have been compared with theoretical studies for the $M87^*$, and it has been observed that the possible values of $h/M$ found in the numerical simulations are consistent with the theory. Additionally, the results have been compared with those for the GRS 1915+105 black hole, and the hair parameters corresponding to the observed frequencies have been determined.

KEYWORDS: numerical relativity, rotating black hole, alternative gravities, Bondi-Hoyle-Lyttleton, QPOs

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# Performance of high-order Godunov-type methods in simulations of astrophysical low Mach number flows

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**ABSTRACT**

High-order Godunov methods for gas dynamics have become a standard tool for simulating different classes of astrophysical flows. Their accuracy is mostly determined by the spatial interpolant used to reconstruct the pair of Riemann states at cell interfaces and by the Riemann solver that computes the interface fluxes. In most Godunov-type methods, these two steps can be treated independently, so that many different schemes can in principle be built from the same numerical framework. Because astrophysical simulations often test out the limits of what is feasible with the computational resources available, it is essential to find the scheme that produces the numerical solution with the desired accuracy at the lowest computational cost. However, establishing the best combination of numerical options in a Godunov-type method to be used for simulating a complex hydrodynamic problem is a nontrivial task. In fact, formally more accurate schemes do not always outperform simpler and more diffusive methods, especially if sharp gradients are present in the flow. In this work, we use our fully compressible Seven-League Hydro (SLH) code to test the accuracy of six reconstruction methods and three approximate Riemann solvers on two- and three-dimensional (2D and 3D) problems involving subsonic flows only. We consider Mach numbers in the range from $10^{-3}$ to $10^{-1}$, which are characteristic of many stellar and geophysical flows. In particular, we consider a well-posed, 2D, Kelvin–Helmholtz instability problem and a 3D turbulent convection zone that excites internal gravity waves in an overlying stable layer. Although the different combinations of numerical methods converge to the same solution with increasing grid resolution for most of the quantities analyzed here, we find that (i) there is a spread of almost four orders of magnitude in computational cost per fixed accuracy between the methods tested in this study, with the most performant method being a combination of a "low-dissipation" Riemann solver and a sextic reconstruction scheme, (ii) the low-dissipation solver always outperforms conventional Riemann solvers on a fixed grid when the reconstruction scheme is kept the same, (iii) in simulations of turbulent flows, increasing the order of spatial reconstruction reduces the characteristic dissipation length scale achieved on a given grid even if the overall scheme is only second order accurate, (iv) reconstruction methods based on slope-limiting techniques tend to generate artificial, high-frequency acoustic waves during the evolution of the flow, (v) unlimited reconstruction methods introduce oscillations in the thermal stratification near the convective boundary, where the entropy gradient is steep.

**Key words.** Convection – Hydrodynamics – Instabilities – Methods: numerical – Turbulence – Waves



## 1. Introduction

High-resolution schemes for gas dynamics (see, e.g., van Leer 1979; Colella & Woodward 1984; Harten et al. 1987; Colella 1990; Liu et al. 1994; Jiang & Shu 1996; Colella & Sekora 2008; Toro 2009; Balsara 2017) are routinely used for modeling a broad variety of astrophysical flow phenomena. Their popularity derives from their conservation properties and robustness, which allow them to accurately capture both smooth and discontinuous solutions on the same computational grid without sacrificing numerical stability.

These schemes are based on higher-order extensions of the original first-order accurate method of Godunov (1959) and their time-integration algorithm is typically carried out in three steps. First, a pair of Riemann states is reconstructed at each grid cell interface by applying high-order monotonic interpolants to a set of cell-averaged hydrodynamic quantities. Second, the resulting Riemann problems are solved (either exactly or approximately) to obtain fluxes across every cell boundary. Finally, the cell surface integral of the fluxes is evaluated, allowing the cell-volume-averaged state quantities to be advanced in time[1].

In most high-order Godunov schemes, the solution strategy of the Riemann problem is independent of the spatial interpolant used for reconstructing the Riemann states. Therefore, many different schemes can be built from the same numerical framework. The choices made in the construction of a particular scheme, however, do have a strong effect on its accuracy, that is the dif-

[1] High-resolution schemes for gas dynamics can be fully discrete, where the system of equations is discretized both in space and time, or semi-discrete, where spatial discretization is performed first while leaving the problem continuous in time. In the latter approach, state quantities are then advanced in time using any standard numerical solver for systems of ordinary differential equations.

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# Multi-band reflectance and shadowing of RX J1604.3-2130 protoplanetary disk in scattered light⋆

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**ABSTRACT**

*Context.* Spatially-resoved cicrumstellar disk spectrum and composition can provide valuable insights into the bulk composition of forming planets, as well as the mineralogical signatures that emerge during and after planet formation.

*Aims.* We aim to systemically extract the RX J1604.3-213010 (J1604 hereafter) protoplanetary disk in high-contrast imaging observations, and obtain its multi-band reflectance in visible to near-infrared wavelengths.

*Methods.* We obtained coronagraphic observations of J1604 from the Keck Observatory's NIRC2 instrument, and archival data from the Very Large Telescope's SPHERE instrument. Using archival images to remove star light and speckles, we recovered the J1604 disk and obtained its surface brightness using forward modeling. Together with polarization data, we obtained the relative reflectance of the disk in $R$, $J$, $H$ ($H2$ and $H3$), $K$ ($K1$ and $K2$), and $L'$ bands spanning two years.

*Results.* Relative to the J1604 star, the resolved disk has a reflectance of $\sim10^{-1}$ arcsec$^{-2}$ in $R$ through $H$ bands and $\sim10^{-2}$ arcsec$^{-2}$ in $K$ and $L'$ bands, showing a blue color. Together with other systems, we summarized the multi-band reflectance for 9 systems. We also identified varying disk geometry structure, and a shadow that vanished between June and August in 2015.

*Conclusions.* Motivated by broad-band observations, the deployment of cutting-edge technologies could yield higher-resolution reflection spectra, thereby informing the dust composition of disks in scattered light in the future. With multi-epoch observations, variable shadows have the potential to deepen insights into the dynamic characteristics of inner disk regions.

**Key words.** protoplanetary disks – stars: imaging – planets and satellites: detection – techniques: high angular resolution



## 1. Introduction

Over 5000 exoplanets have been found with different observational techniques to date,[1] and the diversity in their size and mass distribution demonstrates the variety of the formation and evolution processes of planetary systems. Planets are formed within circumstellar disks around stars, implying that all are made from gas and dust inherited from the same molecular cloud. They could thus share similar bulk composition (e.g., Wang et al. 2020a), suggesting that the composition of planets, disks, and stars are correlated. However, planets can form from different mechanisms, primarily through core accretion (e.g., Pollack et al. 1996) and disk gravitational instability (e.g., Pollack et al. 1996; Piso & Youdin 2014; Piso et al. 2015), and these models predict different planetary luminosity and spectra (e.g., Spiegel & Burrows 2012). An investigation into the compositional makeup of planetary systems – including planets and disks – can contribute to our understanding of these celestial bodies, offering an opportunity to empirically test prevailing theories of planet formation.

Various indirect techniques were proposed to infer the bulk composition of exoplanets. Typically, mass-radius measurements of exoplanets are employed to estimate the planetary bulk composition (e.g., Zeng et al. 2019; Miller & Fortney 2011; Thorngren et al. 2016; Müller et al. 2020; Plotnykov & Valencia 2020; Adibekyan et al. 2021). The uncertainties in exoplanet property measurements, including radius and mass are however large (e.g., Weiss & Marcy 2014). In addition, the uncertainties or degeneracy from theory predictions are significant (Müller et al. 2020; Müller & Helled 2023; Rogers & Seager

⋆ FITS images for Fig. 1 are only available at the CDS via anonymous ftp to cdsarc.cds.unistra.fr (130.79.128.5) or via https://cdsarc.cds.unistra.fr/viz-bin/cat/J/A+A/
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[1] https://exoplanetarchive.ipac.caltech.edu/

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# Tropical cyclones on tidally locked rocky planets: Dependence on rotation period

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## ABSTRACT

Tropical cyclones occur over the Earth's tropical oceans, with characteristic genesis regions and tracks tied to the warm ocean surface that provides energy to sustain these storms. The study of tropical cyclogenesis and evolution on Earth has led to the development of environmental favorability metrics that predict the strength of potential storms from the local background climate state. Simulations of the gamut of transiting terrestrial exoplanets orbiting late-type stars may offer a test of this Earth-based understanding of tropical cyclogenesis. Previous work has demonstrated that tropical cyclones are likely to form on tidally locked terrestrial exoplanets with intermediate rotation periods of $\sim 8-10$ days. In this study, we test these expectations using ExoCAM simulations with both a sufficient horizontal resolution of 0.47° x 0.63° required to permit tropical cyclogenesis along with a thermodynamically active slab ocean. We conduct simulations of tidally locked and ocean-covered Earth-sized planets orbiting late-type M dwarf stars with varying rotation periods from 4-16 days in order to cross the predicted maximum in tropical cyclogenesis. We track tropical cyclones that form in each simulation and assess their location of maximum wind, evolution, and maximum wind speeds. We compare the resulting tropical cyclone locations and strengths to predictions based on environmental favorability metrics, finding good agreement between the Earth-based metrics and our simulated storms with a local maximum in both tropical cyclone frequency and intensity at a rotation period of 8 days. Our results suggest that environmental favorability metrics used for tropical cyclones on Earth may also be applicable to temperate tidally locked Earth-sized rocky exoplanets with abundant surface liquid water.

*Keywords:* Atmospheric circulation (112) — Exoplanet atmospheres (487) — Planetary atmospheres (1244) — Exoplanet atmospheric dynamics (2307)

## 1. INTRODUCTION

Tropical cyclones are one of the most impactful weather phenomena on Earth, characterized by fast winds and heavy rainfall (Emanuel 2003). Tropical cyclones act as heat engines, powered by heat input from the warm ocean surface and dissipated via friction in the boundary layer between the atmosphere and surface (Emanuel 2003, Chavas 2017). On Earth, tropical cyclones may have large-scale impacts on the mean climate, most notably by drying surrounding regions (Schenkel & Hart 2015) and thereby enabling dry regions to more efficiently radiatively cool to space (Pierrehumbert 1995, Wing 2019). Tropical cyclones are also expected to form on tidally locked terrestrial exoplanets (Komacek et al. 2020, Yan & Yang 2020) and may have potential consequences for observable properties, especially the amplitude of water vapor features in transmission spectra (Yan & Yang 2020) as well as their time-variability (Song & Yang 2021, May et al. 2021, Rotman et al. 2023).

Existing theories for the formation and evolution of tropical cyclones have identified a broad set of metrics for the environmental favorability required for tropical cyclogenesis to occur. These include the maximum potential intensity (Bister & Emanuel 2002), genesis potential index (GPI) (Emanuel 2010), ventilation index (Tang & Emanuel 2012), and ventilation-reduced potential intensity (Chavas 2017), along with more gen-

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# Re-Envisioning Numerical Information Field Theory (NIFTy.re): A Library for Gaussian Processes and Variational Inference

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## Summary

Imaging is the process of transforming noisy, incomplete data into a space that humans can interpret. `NIFTy` is a Bayesian framework for imaging and has already successfully been applied to many fields in astrophysics. Previous design decisions held the performance and the development of methods in `NIFTy` back. We present a rewrite of `NIFTy`, coined `NIFTy.re`, which reworks the modeling principle, extends the inference strategies, and outsources much of the heavy lifting to JAX. The rewrite dramatically accelerates models written in `NIFTy`, lays the foundation for new types of inference machineries, improves maintainability, and enables interoperability between `NIFTy` and the JAX machine learning ecosystem.

## Statement of Need

Imaging commonly involves millions to billions of pixels. Each pixel usually corresponds to one or more correlated degrees of freedom in the model space. Modeling this many degrees of freedom is computationally demanding. However, imaging is not only computationally demanding but also statistically challenging. The noise in the data requires a statistical treatment and needs to be accurately propagated from the data to the uncertainties in the final image. To do this, we require an inference machinery that not only handles extremely high-dimensional spaces, but one that does so in a statistically rigorous way.

`NIFTy` is a Bayesian imaging library (Arras et al., 2019; Selig et al., 2013; Steininger et al., 2019). It is designed to infer the million- to billion-dimensional posterior distribution in the image space from noisy input data. At the core of `NIFTy` lies a set of powerful Gaussian Process (GP) models and accurate Variational Inference (VI) algorithms.

`NIFTy.re` is a rewrite of `NIFTy` in JAX (Bradbury et al., 2018) with all relevant previous GP models, new, more flexible GP models, and a more flexible machinery for approximating posterior distributions. Being written in JAX, `NIFTy.re` effortlessly runs on accelerator hardware such as the GPU and TPU, vectorizes models whenever possible, and just-in-time compiles code for additional performance. `NIFTy.re` switches from a home-grown automatic differentiation engine that was used in `NIFTy` to JAX's automatic differentiation engine. This lays the foundation for new types of inference machineries that make use of the higher order derivatives provided by JAX. Through these changes, we envision to harness significant gains in maintainability of `NIFTy.re` compared to `NIFTy` and a faster development cycle for new features.

We expect `NIFTy.re` to be highly useful for many imaging applications and envision many applications within and outside of astrophysics (Arras et al., 2022, 2019; Eberle et al., 2023, 2022; Frank et al., 2017; S. Hutschenreuter et al., 2022; Sebastian Hutschenreuter et al., 2023; Leike et al., 2020; Leike & Enßlin, 2019; Mertsch & Phan, 2023; J. Roth et al., 2023; Jakob Roth et al., 2023; Scheel-Platz et al., 2023; Tsouros et al.,



All GP models in `NIFTy.re` as well as all likelihoods behave like instances of `jft.Model`, meaning that JAX understands what it means if a computation involves `self`, other `jft.Model` instances, or their attributes. In other words, `correlated_field`, `forward`, and `lh` from the code snippets shown here are all so-called pytrees in JAX, and, for example, the following is valid code `jax.jit(lambda l, x: l(x))(lh, x0)` with `x0` some arbitrarily chosen valid input to `lh`. Inspired by equinox (Kidger & Garcia, 2021), individual attributes of the class can be marked as non-static or static via `dataclass.field(metadata=dict(static=...))` for the purpose of compiling. Depending on the value, JAX will either treat the attribute as an unknown placeholder or as a known concrete attribute and potentially inline it during compilation. This mechanism is extensively used in likelihoods to avoid inlining large constants such as the data and to avoid expensive re-compilations whenever possible.

### Variational Inference

`NIFTy.re` is built for models with millions to billions of degrees of freedom. To probe the posterior efficiently and accurately, `NIFTy.re` relies on VI. Specifically, `NIFTy.re` implements Metric Gaussian Variational Inference (MGVI) and its successor geometric Variational Inference (geoVI) Frank (2022). At the core of both MGVI and geoVI lies an alternating procedure in which one switches between optimizing the Kullback–Leibler divergence for a specific shape of the variational posterior and updating the shape of the variational posterior. MGVI and geoVI define the variational posterior via samples, specifically, via samples drawn around an expansion point. The samples in MGVI and geoVI exploit model-intrinsic knowledge of the posterior's approximate shape, encoded in the Fisher information metric and the prior curvature (Frank et al., 2021).

`NIFTy.re` implements both MGVI and geoVI and allows for much finer control over the way samples are drawn and updated compared to `NIFTy`. Furthermore, `NIFTy.re` exposes stand-alone functions for drawing MGVI and geoVI samples from any arbitrary model with a likelihood from `NIFTy.re` and a forward model that is differentiable by JAX. In addition to stand-alone sampling functions, `NIFTy.re` also provides tools to configure and execute the alternating Kullback–Leibler divergence optimization and sample adaption at a lower abstraction level. These tools are provided in a JAXopt/Optax-style optimizer class (Blondel et al., 2021; DeepMind et al., 2020).

A typical minimization with `NIFTy.re` is shown in the following. It retrieves six independent, antithetically mirrored samples from the approximate posterior via 25 iterations of alternating between optimization and sample adaption. The final result is stored in the `samples` variable. A convenient one-shot wrapper for the code below is `jft.optimize_kl`. By virtue of all modeling tools in `NIFTy.re` being written in JAX, it is also possible to combine `NIFTy.re` tools with BlackJAX (Cabezas & Louf, 2023) or any other posterior sampler in the JAX ecosystem.

```
from jax import random

key = random.PRNGKey(42)
key, sk = random.split(key, 2)
# NIFTy is agnostic w.r.t. the type of inputs it gets as long as they
# support core arithmetic properties. Tell NIFTy to treat our parameter
# dictionary as a vector.
samples = jft.Samples(pos=jft.Vector(lh.init(sk)), samples=None)

delta = 1e-4
absdelta = delta * jft.size(samples.pos)

opt_vi = jft.OptimizeVI(lh, n_total_iterations=25)
opt_vi_st = opt_vi.init_state(
  key,
  # Implicit definition for the accuracy of the KL-divergence
  # approximation; typically on the order of 2-12
  n_samples=lambda i: 1 if i < 2 else (2 if i < 4 else 6),
  # Parametrize the conjugate gradient method at the heart of the
```

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# Unveiling the Initiation Route of Coronal Mass Ejections through their Slow Rise Phase

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## ABSTRACT

Understanding the early evolution of coronal mass ejections (CMEs), in particular their initiation, is the key to forecasting solar eruptions and induced disastrous space weather. Although many initiation mechanisms have been proposed, a full understanding of CME initiation, which is identified as a slow rise of CME progenitors in kinematics before the impulsive acceleration, remains elusive. Here, with a state-of-the-art thermal-magnetohydrodynamics simulation, we determine a complete CME initiation route in which multiple mainstream mechanisms occur in sequence yet are tightly coupled. The slow rise is first triggered and driven by the developing hyperbolic flux tube (HFT) reconnection. Subsequently, the slow rise continues as driven by the coupling of the HFT reconnection and the early development of torus instability. The end of the slow rise, i.e., the onset of the impulsive acceleration, is induced by the start of the fast magnetic reconnection coupled with the torus instability. These results unveil that the CME initiation is a complicated process involving multiple physical mechanisms, thus being hardly resolved by a single initiation mechanism.

*Keywords:* Sun: corona, Sun: coronal mass ejections (CMEs), Sun: flares

## 1. INTRODUCTION

The Sun frequently produces violent plasma eruptions such as coronal mass ejections (CMEs), which are released into the interplanetary space and induce geomagnetic storms (Gosling 1993) and damage aerospace equipment, satellite communications and power grids (Elovaara 2007) when colliding with the Earth's magnetosphere. The forecast of CMEs is thus extremely important for preventing space disasters and exploring habitable exoplanets (Khodachenko et al. 2007).

The evolution characteristics of CMEs and their pre-eruptive structures (e.g. sigmoids and filaments (Cheng et al. 2017); hereafter named as CME progenitors (Chen 2011)) in kinematics at various stages lay the foundation for CME predictions. For hours to days before the eruption, CME progenitors are stable and evolve quasi-statically, rising with a small velocity ($< 1$ km s$^{-1}$) and tiny acceleration (Xing et al. 2018). In contrast, during the fast eruption, CMEs show an impulsive increase in velocity (up to hundreds to thousands of km s$^{-1}$) and acceleration (up to hundreds of m s$^{-2}$) in a short time

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# Evolution of coronal mass ejections with and without sheaths from the inner to the outer heliosphere - statistical investigation for 1975–2022

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**ABSTRACT**

*Aims.* This study covers a thorough statistical investigation of the evolution of interplanetary coronal mass ejections (ICMEs) with and without sheaths, through a broad heliocentric distance and temporal range. The analysis treats the sheath and magnetic obstacle (MO) separately to gain more insight about their physical properties. In detail, we aim to unravel different characteristics of these structures occurring over the inner and outer heliosphere.

*Methods.* The method is based on a large statistical sample of ICMEs probed over different distances in the heliosphere. For this, information about detection times for sheath and MO from 13 individual ICME catalogs were collected and cross-checked. The time information was then combined into a main catalog used as basis for the statistical investigation. The data analysis based on that covers a wealth of spacecraft missions enabling in-situ solar wind measurements from 1975–2022. This allows to study differences between solar cycles.

*Results.* All the structures under study (sheath, MO with and without sheath) show the biggest increase in size together with the largest decrease in density at a distance ~0.75 AU. At 1 AU we find different sizes for MOs with and without sheath, with the former being larger. Up to 1 AU, the upstream solar wind shows the strongest pile-up close to the interface with the sheath. For larger distances the pile-up region seems to shift and recedes from that interface further into the upstream solar wind. his might refer to a change in the sheath formation mechanism (driven versus non-driven) with heliocentric distance, suggesting the relevance of the CME propagation and expansion behavior in the outer heliosphere. Comparison to previous studies shows inconsistencies over the solar cycle, which makes more detailed studies necessary to fully understand the evolution of ICME structures.

**Key words.** Sun: coronal mass ejections (CMEs), Sun: heliosphere, Sun: solar wind

## 1. Introduction

Coronal mass ejections (CMEs) are huge structures of plasma and magnetic field that are impulsively expelled from the Sun. The low plasma-beta structure, presumably a flux rope, drives the formation of other structures during its evolution through the ambient corona and interplanetary space. Close to the Sun, depending on the CMEs' initial speed, size and ambient coronal magnetic field, the so-called three-part CME is observed typically in white-light coronagraph data. It features a front region, a void and a center part (Riley et al. 2008; Mishra and Teriaca 2023). More recent studies, applying 3D simulations and multi-spacecraft data, hint towards a two-front morphology consisting of a shock and piled-up sheath region (Vourlidas et al. 2013). Indeed, from in-situ data more structures may be identified, including, for fast events, shock-sheath, leading edge, front, flux rope, and rear region (Kilpua et al. 2017; Temmer and Bothmer 2022). The review by Wimmer-Schweingruber et al. (2006) further highlighted the existence of other specific regions, separated by discontinuities, and the center of the flux rope being a magnetic ejecta core.

The initial signature for identifying CMEs from in-situ data (referred to as Interplanetary CME; ICME) was established by Burlaga et al. (1981) and Klein and Burlaga (1982), focusing on magnetic field enhancements and the smooth rotation of the magnetic field. Subsequent studies applied alternative signatures for ICME detection. Richardson and Cane (1995) introduced the idea of combining the proton temperature with solar wind speed to calculate expected temperature values, specifically targeting the low temperature intervals characteristic of ICMEs. Expanding the range of signatures. Jian et al. (2006) suggested the incorporation of total perpendicular pressure as a complementary variable to identify the presence of ICMEs. Additionally, the composition of ICMEs, which remains relatively constant after their departure from the Sun, has been employed as a proxy for their detection. Henke et al. (2001) suggested as signature, the threshold of oxygen charge state ratio $O^{7+}/O^{6+} > 1$, while Lepri et al. (2001) and Lepri and Zurbuchen (2004) proposed average iron charge state values $\langle Q \rangle_{Fe} > 12$ as an identifying signature. An alternative approach for detecting ICMEs at Earth, proposed by Cane (2000), relies on observing Forbush decreases, marked reductions in galactic cosmic ray intensities. Due to the complexity of the ICME structures, the most practical approach is to use more than one signature (Zurbuchen and Richardson 2006)

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# A Strongly Lensed Dusty Starburst of an Intrinsic Disk Morphology at Photometric Redshift of 7.7

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ABSTRACT

We present COSBO-7, a strong millimeter (mm) source known for more than sixteen years but was just revealed its near-to-mid-IR counterpart by the James Webb Space Telescope (JWST). The precise pin-pointing by the Atacama Large Millimeter Array (ALMA) on the exquisite NIRCam and MIRI images show that it is a background source gravitationally lensed by a single foreground galaxy, and the analysis of its spectral energy distribution by different tools consistently derives its photometric redshift at $\sim$7.7. Strikingly, our lens modeling based on the JWST data shows that it has a regular, disk morphology in the source plane. The dusty region giving rise to the far-IR-to-mm emission seems to be confined to a limited region to one side of the disk and has a high dust temperature of $> 90$ K. The galaxy is experiencing starburst both within and outside of this dusty region. After taking the lensing magnification of $\mu \approx 2.5$–$3.6$ into account, the intrinsic star formation rate is several hundred $M_\odot$ yr$^{-1}$ both within the dusty region and across the more extended stellar disk, and the latter already has $> 10^{10} M_\odot$ of stars in place. If all this is true, COSBO-7 presents an extraordinary case that is against the common wisdom about galaxy formation in the early universe; simply put, its existence poses a critical question to be answered: how could a massive disk galaxy come into being so early in the universe and sustain its regular morphology in the middle of an enormous starburst?

## 1. INTRODUCTION

Systematic study of dust-embedded star formation in external galaxies started from the mid-to-far-IR survey carried out by the InfraRed Astronomy Satellite four decades ago (see e.g., de Jong et al. 1984; Soifer et al. 1984; Lonsdale et al. 1984), with the climax of discovering Ultra-luminous Infrared Galaxies in the local universe (ULIRGs; Houck et al. 1984, 1985; Aaronson & Olszewski 1984) that have enormous IR luminosity of $L_{\rm IR} \geq 10^{12} L_\odot$ (integrated over the rest-frame 8–1000 $\mu$m) but are faint in optical. In the late 1990s to early 2000s, a series of new instruments opened up the submillimeter (submm) and millimeter (mm) win-

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# TESS photometry and CAOS spectroscopy of six eclipsing binaries with Am components

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**ABSTRACT**

In this paper, we present the results of a comprehensive study of six eclipsing binaries whose components are confirmed or suspected Am stars. By combining long-term high-resolution CAOS spectroscopy and *TESS* photometry we have been able to accurately obtain the orbital parameters of each system as well as the atmospheric parameters of its components. We performed an in-depth chemical analysis and provided chemical abundances of C, O, Na, Mg, Si, Ca, Sc, Ti, Cr, Mn, Fe, Ni, Zn, Sr, Y, Zr, and Ba. From the solution of the light and radial curves, we have determined masses, radii, and temperatures with good accuracy. We observe apsidal motion in the eccentric system HD 216429, in which the Rossiter-McLaughlin effect is also noted. We inferred the age of our targets by fitting isochrones on the HR diagram and find that both components in each system are properly described with the same isochrone, which reinforce our results. Furthermore, dynamical and evolutionary masses, independently obtained, show an excellent agreement. According to the out-of-eclipse variability shown in their *TESS* light curves and their position on the HR diagram, we claim the pulsating nature of the stars HD 42954 (as $\delta$ Sct type) and HD 151604 ($\gamma$ Dor). Based on the chemical analysis we corroborate that four of the systems studied here are formed by Am stars, while in the remaining ones (HD 126031 and HD 216429) only the primary component exhibits a peculiar composition. Additionally, the age distribution found in Am stars supports their suitability as age tracers in stellar populations.

**Key words.** binaries: eclipsing – binaries: spectroscopic – stars: chemically peculiar – stars: fundamental parameters – stars: abundances – stars: individual: HD 42954, HD 46052  HD 126031, HD 151604, HD 195020, HD 216429

## 1. Introduction

Among stars on the main sequence, A-type stars exhibit a wide array of distinct chemical characteristics. Various physical processes, like diffusion and/or magnetic fields, drive these peculiarities. They all share a common factor: a highly stable radiative atmosphere, a crucial condition for these peculiarities to manifest.

The Am stars, or metallic stars, deviate from the standard in a noteworthy way. Their Ca II K-line types appear too early for their hydrogen line types, and their metallic-line types appear too late, resulting in a difference of five or more spectral sub-types between the inferred spectral types from Ca II K-lines and metal lines. Marginal Am stars, on the other hand, show a difference of less than five sub-types between Ca II K-lines and metal lines. In the commonly used classification for this star class, three spectral types are prefixed with *k*, *h*, and *m*, corresponding to K-line, hydrogen lines, and metallic lines, respectively. The typical abundance pattern indicates lower levels of C, N, O, Ca, and Sc, and higher levels of the Fe-peak elements, Y, Ba, and rare earth elements (Catanzaro et al. 2019, and references therein).

Years ago (see Leone & Catanzaro 1998; Catanzaro 2006), we launched at the Catania Astrophysical Observatory a detailed observational campaign focusing on stars listed in the "General catalog of Ap and Am stars" (Renson et al. 1991; Renson & Manfroid 2009). The goals of this project are twofold: confirm elemental peculiarities (if any) through abundance analyses and detect potential stellar companions by gathering radial velocity data. The effort aimed to enhance our understanding of peculiar stars and binary systems brought to several papers in the recent literature Catanzaro et al. (2015, 2016, 2019); Fu et al. (2020); Catanzaro et al. (2020, 2022). In this context, we present in this study a thorough analysis of six SB2 eclipsing binaries (listed in Table 1), characterized by components belonging or suspected to belong to the Am subclass. Our analysis encompasses both high-resolution spectroscopy and photometry for a comprehensive understanding of these systems.

**Table 1.** List of the studied targets. We reported HD number, other ID, equatorial coordinates (J2000), visual apparent magnitude ($V$), and number of observed spectra (N).

| HD | ID | RA | DEC | $V$ | N |
|---|---|---|---|---|---|
| 42954 | ... | 06 14 28.6 | +17 54 22.9 | 8.5 | 22 |
| 46052 | WW Aur | 06 32 27.2 | +32 27 17.6 | 5.8 | 17 |
| 126031 | DV Boo | 14 22 49.7 | +14 56 20.1 | 7.5 | 16 |
| 151604 | V916 Her | 16 46 35.5 | +41 47 32.2 | 7.9 | 23 |
| 195020 | MP Del | 20 28 26.6 | +11 43 14.5 | 7.6 | 19 |
| 216429 | V364 Lac | 22 52 14.8 | +38 44 44.6 | 8.4 | 19 |

This paper is organized as follows. In Sect, 2 we present our spectroscopic observations along the *TESS* archival data used. Their analysis and subsequent results are shown in Sect. 3. In

# The Ages of the Oldest Astrophysical Objects in an Ellipsoidal Universe

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James Webb Space Telescope's (JWST) observations since its launch have shown us that there could be very massive and very large galaxies, as well as massive quasars very early in the history of the universe, conflicting expectations of the ΛCDM model. This so-called "impossibly early galaxy problem" requires too rapid star formation in the earliest galaxies than appears to be permitted by the ΛCDM model. In fact, this might not be a high masses problem, but a "time-compression problem": time too short for the observed large and massive structures to form from the initial seeds. A cosmological model that could allocate more time for the earliest large structures to form would be more conforming to the data than the ΛCDM model. In this work we are going to discuss how the recently proposed $\gamma\delta$CDM model might ease and perhaps resolve the time-compression problem. In the $\gamma\delta$CDM model, different energy densities contribute to the Hubble parameter with different weights. Additionally, in the formula for the Hubble parameter, energy densities depend on the redshift differently than what their physical nature dictates. This new way of relating universe's energy content to the Hubble parameter leads to a modified relation between cosmic time and redshift. We test the observational relevance of the $\gamma\delta$CDM model to the age problem by constraining its parameters with the ages of the oldest astronomical objects (OAO) together with the cosmic chronometers (CC) Hubble data and the Pantheon+ Type Ia supernovae data of the late universe at low redshift. We find that, thanks to a modified time–redshift relation, the $\gamma\delta$CDM model has a more plausible time period at high redshift for large and massive galaxies and massive quasars to form, whereas the age of the universe today is not modified significantly.

## I. INTRODUCTION

Since the seminal paper of Edwin Hubble which declared an expanding universe instead of a static one [1], the degree of expansion, which is given by the value of the Hubble constant $H_0$, has been subject of controversy and debate among the observational and theoretical cosmologists. Hubble's original calculation gave a too large value of $H_0 \sim 500\ km/s/Mpc$ [2], which was because of incorrect cosmological distance measurements that he used in the analysis. As the observations improved the value of the Hubble constant was constrained between values $40-100\ km/s/Mpc$ in the 1980's and 90's [3]. Today the value of the Hubble constant inferred from the late time observations using distance ladder is $H_0 = 73.30 \pm 1.04\ km/s/Mpc$ [4] and calculated from the early universe cosmic microwave background (CMB) data is $H_0 = 67.37 \pm 0.54\ km/s/Mpc$ [5], which are separated with more than $5\sigma$ [3]. This is called the Hubble crisis [6] and there have been numerous proposals to resolve this crisis [6–13]. If the problem lies in the late time result, it could be due to the excess systematic errors in the SH0ES result [4], such as the excess brightness, known as the "crowding problem," in the observations of Cepheid variables. However, this possibility is ruled out by the recent JWST's observations [14–17]. Since the value of the Hubble constant obtained from the late time observations seem to be upheld with further observations by JWST, the problem could be in the model dependent calculation of the Hubble constant from the Planck data [5]. This could be due to a systematic effect in the analysis of CMB data which might come from excess lensing by surprisingly large galaxies at high redshift [18]. Perhaps not only new early-time physics, but together also new late-time physics is required [19] to resolve the Hubble tension. In this work, we study ramifications of a new model with a modified Friedmann equation [20] that changes the time-redshift relation throughout the Universe's history to resolve various cosmological problems.

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# Pulsating hydrogen-deficient white dwarfs and pre-white dwarfs observed with *TESS*

## VI. Asteroseismology of the GW Vir-type central star of the Planetary Nebula NGC 246

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**ABSTRACT**

*Context.* Significant advances have been achieved through the latest improvements in the photometric observations accomplished by the recent space missions, substantially boosting the study of pulsating stars via asteroseismology. The *TESS* mission has already proven to be of particular relevance for pulsating white dwarf and pre-white dwarf stars.
*Aims.* We report a detailed asteroseismic analysis of the pulsating PG 1159 star NGC 246 (TIC 3905338), the central star of the planetary nebula NGC 246, based on high-precision photometric data gathered by the *TESS* space mission.
*Methods.* We reduced *TESS* observations of NGC 246 and performed a detailed asteroseismic analysis using fully evolutionary PG 1159 models computed accounting for the complete prior evolution of their progenitors. We constrained the mass of this star by comparing the measured mean period spacing with the average of the computed period spacings of the models, and also employed the observed individual periods to search for a seismic stellar model.
*Results.* We extracted 17 periodicities from the *TESS* light curves from the two sectors where NGC 246 was observed. All the oscillation frequencies are associated with $g$-mode pulsations, with periods spanning from $\sim 1460$ to $\sim 1823$ s. We found a constant period spacing of $\Delta\Pi = 12.9$ s, allowing us to deduce that the stellar mass is larger than $\sim 0.87\ M_{\odot}$ if the period spacing is assumed to be associated with $\ell = 1$ modes, and $\sim 0.568\ M_{\odot}$ if it is associated with $\ell = 2$ modes. The less massive models are more consistent with the distance constraint from *Gaia* parallax. Although we were not able to find a unique asteroseismic model for this star, the period-to-period fit analyses suggest a high-stellar mass ($\gtrsim 0.74\ M_{\odot}$) when the observed periods are associated with modes with $\ell = 1$ only, and both a high ($\gtrsim 0.74\ M_{\odot}$) and intermediate ($\sim 0.57\ M_{\odot}$) stellar mass when the observed periods are associated with modes with $\ell = 1$ and 2.

**Key words.** stars: individual (NGC 246) — asteroseismology — white dwarfs — stars: evolution — stars: interiors

## 1. Introduction

GW Vir stars are pulsating PG 1159 stars, that is, pulsating hot hydrogen(H)-deficient white dwarfs (WDs) and pre-WDs with surface layers rich in helium (He), carbon (C), and oxygen (O) (Werner & Herwig 2006; Werner et al. 2014; Werner & Rauch 2015; Córsico et al. 2019; Sowicka et al. 2023). The class of GW Vir stars is often separated into the so-called variable planetary nebula nuclei (PNNVs) that are still surrounded by a nebula, and DOVs[1], objects that lack a nebula. Among GW Vir stars also are the pulsating Wolf-Rayet central stars of a planetary nebula ([WC]) and early-[WC] ([WCE]) stars, since they share the pulsation properties of pulsating PG 1159 stars (Quirion et al. 2007). PG 1159 stars are thought to be the evolutionary link between post-asymptotic giant branch (AGB) stars and most of the H-deficient WDs (Althaus et al. 2005, 2010; Werner & Herwig 2006; Sowicka et al. 2021). The origin of these stars is likely to be in the context of a single-star evolution in a born-

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[1] Even though white dwarf stars of spectral type DO do not pulsate, the term "DOVs" has historically been used as a variable star designation for GW Vir pulsators without a nebula.

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# Cosmic Type Ia SN rate and constraints on SN Ia progenitors

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**ABSTRACT**

*Context.* Type Ia supernovae play a key role in the evolution of galaxies by polluting the interstellar medium with a fraction of iron peak elements larger than that released in the core collapse supernova events. Their light-curve, moreover, is widely used in cosmological studies as it constitutes a reliable distance indicator at extra-galactic scales. Among the mechanisms proposed to explain the Type Ia SNe, the single and double degenerate channels are thought to be the dominant ones, which imply a different distribution of time delays between the progenitor formation and the explosion.
*Aims.* In this paper, we aim at determining the dominant mechanism by comparing a compilation of observed type Ia SN with our predictions, and evaluating the relative contribution of both channels.
*Methods.* By using a least-squares fitting procedure, we model the observations of type Ia SN rates assuming different combinations of three recent cosmic star formation rates and seven delay time distributions. The goodness of these fits are statistically quantified by the $\chi^2$ test.
*Results.* For two of the three cosmic star formation rates, the single degenerate scenario provides the most accurate explanation for the observations, while a 30%-70% combination of the single and double degenerate scenarios is more plausible for the remaining cosmic star formation rate.
*Conclusions.* Though dependent on the assumed cosmic star formation rate, we find arguments in favor of the single degenerate model. From the theoretic point of view, at least the $\sim 30\%$ of the Type Ia SN must have been produced through the single degenerate channel to account for the observations. The wide double degenerate scenario mechanism slightly under-predicts the observations at redshift $z \gtrsim 1$, unless the cosmic SFR flattens in that regime. On the contrary, although the purely close double degenerate scenario can be ruled out, we cannot rule out a mixed scenario with single and double degenerate progenitors.

**Key words.** supernovae: general, Galaxies: evolution, Galaxies: high-redshift,



## 1. Introduction

The study of Type Ia supernovae (SNe) has significant implications for the cosmology and galactic astronomy, allowing us to construct the Hubble diagram at low and high redshifts to constrain some cosmological parameters e.g. Hamuy et al. (1995); Perlmutter et al. (1998, 1999a,b); Riess et al. (1998); Sullivan et al. (2011); Suzuki et al. (2012); Ganeshalingam et al. (2013); Betoule et al. (2014); Rest et al. (2014); Khetan et al. (2021) and, as major producers of iron (Greggio & Renzini 1983; Matteucci & Greggio 1986), to model the chemical evolution of galaxies among other applications (see review of Ruiz-Lapuente 2014). Given this variety of applications, understanding the nature of their progenitors is crucial. In the past years, many Type Ia SN progenitor models have been proposed both theoretically and empirically, in which the most common scenarios are the double degenerate (DD) and single degenerate (SD) channels (see Livio & Mazzali 2018 for a recent review). The SD scenario was originally proposed by Whelan & Iben (1973) and consists of a system formed by a C-O white dwarf (WD) plus a normal star that, evolving into a red giant, transfers material over the WD (Wheeler & Hansen 1971; Nomoto 1982a,b). The WD then explodes when its mass reaches the Chandrasekhar mass limit ($\sim 1.44 M_\odot$). In the DD scenario, originally proposed by Iben & Tutukov (1994, but see also Kato & Hachisu 2012; Kato et al. 2015), two WDs in a binary system merge after emission of gravitational waves and explode when reaching the Chandrasekhar mass (Tutukov & Iungelson 1976; Tutukov & Yungelson 1979; Webbink 1984). The relative contribution of the two main Type Ia SN mechanisms has been historically controversial, with no fully satisfying scenario (Livio 2000; Greggio et al. 2008; Valiante et al. 2009; Matteucci et al. 2009; Bonaparte et al. 2013; Maoz et al. 2014). Originally, the preferred explosion mechanism was the C-deflagration of Chandrasekhar WD, but later other possible mechanisms were proposed in order to account for a variety of Type Ia SN types, requiring a different exploding mass and involving also He and C-detonation besides C-deflagration (see Hillebrandt et al. 2013 for a review). The discovered variety of Type Ia SNe requiring different amounts of $^{56}$Ni to power the light curve, for a while created uncertainty on the possibility of using the Type Ia SNe as standard candles. However, Phillips (1993) discovered a relation between the mag-

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# Black-hole formation in binary neutron star mergers: The impact of spin on the prompt-collapse scenario

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Accurate modeling of the multi-messenger signatures connected to binary neutron star mergers requires proper knowledge on the final remnant's fate and the conditions under which black holes (BHs) can form in such mergers. In this article, we use a suite of 84 numerical-relativity simulations in 28 different physical setups to explore the impact of the individual stars' spin on the merger outcome and on the early postmerger dynamics. We find that for setups close to the prompt-collapse threshold, the stars' intrinsic spin significantly changes the lifespan of the remnant before collapse and that the mass of the debris disk surrounding the BH is also altered. To enable a better understanding of BH formation, we check if there is at least a theoretical chance of observing densities that are above the maximum density allowed in a stable isolated neutron star, and we investigate the importance of different pressure contributions on the evolution of the postmerger remnant and BH formation.

## I. INTRODUCTION

Neutron stars (NSs) are among the most compact objects known in our Universe and they allow us to probe matter under the most extreme conditions close to the edge of black hole (BH) formation, see e.g., Refs. [1, 2]. In this regard, precise knowledge about the onset of gravitational collapse and the maximum mass of NSs can provide important constraints on the properties of supranuclear-dense matter. Typically, such constraints on the maximum mass of NSs are derived assuming that the considered stars are non-rotating and cold. In this case, the Tolmann-Oppenheimer-Volkoff (TOV) equations [3, 4] allow us to compute the maximum mass $M_{\rm TOV}$ once a microphysical equation of state (EOS) is known. On the contrary, $M_{\rm TOV}$ can also be used to determine the microphysical EOS. Hence, nuclear physics interactions and properties can be tested and predicted with the help of astrophysical observations. In general, if the star is rotating, the maximum supported mass increases by about 25% if the star is rigidly rotating [5], i.e., if the angular frequency across the star is constant, and if the star is rotating at the Kepler limit. Even more massive stars might be supported through differential rotation [6].

The maximum mass of a NS can be constrained through different astrophysical observations. On the one hand, the observation of NSs either through X-ray (e.g., PSR J0952-0607 [7]) or radio measurements (e.g., PSR J1614-2230 [8, 9], PSR J0740+6620 [10, 11]) provide a lower bound on the maximum mass of NSs. On the other hand, the observed onset of BH formation either through accretion or during a binary neutron star (BNS) merger provides an alternative way of constraining $M_{\rm TOV}$. Following the detection of GW170817 [12, 13], there has been an increasing number of studies attempting to determine the maximum NS mass based on the assumption that GW170817's remnant collapsed into a BH. This assumption is supported by the observation of both the gamma-ray burst and kilonova emission. Based on these assumptions, several groups have derived upper bounds on the maximum mass of NS, e.g., [14–19].

One possibility to set the upper bound on the maximum mass of NSs is to determine the prompt-collapse threshold mass, i.e., the mass under which a BNS merger leads to an immediate formation of a BH after the merger ($\lesssim$ 2ms) [20]. Over the years, there have been several proposals on how the threshold mass is connected to $M_{\rm TOV}$, e.g., [20–24]. To our knowledge, most of the works (except for Tootle et al. [22]) focused on irrotational configurations. Hence, the influence of the stars' intrinsic rotation on the prompt BH formation has not been investigated in detail. To pursue this further investigation, we performed a total of 84 numerical-relativity simulations with various resolutions, studying 28 different physical setups (22 spinning and 6 non-spinning setups).

The article is structured as follows: In Sec. II, we briefly describe the setups that we simulate and the methods that we use. In Sec. III, we discuss the results of our simulations, starting with a quantitative discussion of the merger dynamics, an investigation of the apparent-horizon formation, and a discussion of the pressure evolution in the postmerger remnant. We then continue by computing the approximate collapse time and presenting the emitted gravitational-wave (GW) energy and luminosity, as well as the disk masses. We conclude in Sec. IV.

Throughout the article, we use geometric units and set $M_\odot = c = G = 1$, unless otherwise stated.

# Small-Scale Anisotropies of Cosmic Rays from Turbulent Flow

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**Abstract**

Within the classical convection–diffusion approximation, we show that the angular distribution of cosmic rays (CRs) in a highly turbulent flow may exhibit significant small-scale anisotropies. The CR intensity angular power spectrum $C_\ell$ is then a direct reflection of interstellar turbulence, from which one expects $C_\ell \propto \ell^{-\gamma-1}$ for $\ell \gg 1$, where $\gamma$ is the power-law turbulence spectral index. Observations by IceCube and HAWC at TeV energies can be explained approximately with the Kolmogorov law $\gamma = 5/3$ with a convection velocity dispersion of 20 km/s on the scale of 10 pc.

*Keywords:* cosmic rays; ISM: kinematics and dynamics

## 1 Introduction

Cosmic rays (CRs) are mainly relativistic nuclei, with an energy spectral index $(-\partial \ln f/\partial \ln p - 2)$ about 2.7 and relative intensity anisotropy on the order of 0.1% at TeV energies. The high level of isotropy implies that CRs are diffusive due to uniform pitch-angle scattering by magnetic field irregularities. This is consistent with the fact that the anisotropy is dominated by a dipole signal, which is believed to be associated with the spatial diffusion flux, and can thus be used to trace CR sources (Ahlers, 2016; Zhao et al., 2022; Zhang et al., 2022b; Qiao et al., 2023).

It is not surprising that the observed CR anisotropy deviates from a pure dipole ($\ell = 1$), but the multipoles with spherical harmonic degrees $\ell > 1$ cannot be explained by the standard diffusion theory. Besides some exotic scenarios (Kotera et al., 2013), most existing models for this issue focus on improving the statistical description of charged particles interacting with a classical electromagnetic field. It has been suggested, e.g., that the basic dipole configuration can be distorted by nonuniform pitch-angle scattering (Malkov et al., 2010) and/or non-diffusive transport (Harding et al., 2016), which may result from the local magnetic field structure (Giacinti & Sigl, 2012; Schwadron et al., 2014).

Interestingly, CR observations by the IceCube experiment and High-Altitude Water Cherenkov (HAWC) Observatory show that the TeV intensity sky map complies with a power-law angular power spectrum $C_\ell \sim C_1 \ell^{-3}$ (Aartsen et al., 2016; Abeysekara et al., 2014, 2018, 2019). This unique feature could be the key to understand the small-scale anisotropies, and has been interpreted as a consequence of the angular correlation of (two) particle trajectories with similar initial conditions, i.e., the particles undergo so-called relative diffusion in a turbulent magnetic field (Ahlers, 2014; Ahlers & Mertsch, 2015; Kuhlen et al., 2022).

In this paper, we shall propose an alternative point of view that ascribes $C_\ell$ to turbulent convection under the classical diffusion approximation. Inspired by Earl et al. (1988), in previous work we have emphasized that nonuniform convection can induce dipole and quadrupole ($\ell = 2$) anisotropies proportional to the diffusion coefficient, via inertial and shear forces, respectively. In particular, the shear anisotropy due to Galactic differential rotation may be important for PeV–EeV CRs (Zhang et al., 2022a). This paper aims to extend the convection scenario into the $\ell > 2$ region.

## 2 Particle Back-Tracking

The basic assumption of the classical convection–diffusion approximation is that particles tend to completely lose information about their initial states due to scattering in the rest frame of the scattering center. In general, the scattering centers at different locations in a flow field have complicated relative motion, i.e., the convection

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# PDRs4All VII. The 3.3 µm aromatic infrared band as a tracer of physical properties of the ISM in galaxies ⋆

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**ABSTRACT**

Aromatic infrared bands (AIBs) are a set of broad emission bands at 3.3, 6.2, 7.7, 8.6, 11.2, and 12.7 $\mu$m, seen in the infrared spectra of most galaxies. With JWST, the 3.3 $\mu$m AIB can in principle be detected up to a redshift of ∼ 7. Relating the evolution of the 3.3 $\mu$m AIB to local physical properties of the ISM is thus of paramount importance.
By applying a dedicated machine learning algorithm to JWST NIRSpec observations of the Orion Bar photodissociation region obtained as part of the PDRs4All Early Release Science (ERS) program, we extracted two template spectra capturing the evolution of the AIB-related emission in the 3.2-3.6 µm range, which includes the AIB at 3.3 µm and its main satellite band at 3.4 µm.
In the Orion Bar, we analyze the spatial distribution of the templates and their relationship with the fluorescent emission of $H_2$ in the near infrared.
We find that one template ("$AIB_{Irrad}$") traces regions of neutral atomic gas with strong far-UV fields, while the other template ("$AIB_{Shielded}$") corresponds to shielded regions with lower FUV fields and a higher molecular gas fraction. We then show that these two templates can be used to fit the NIRSpec AIB-related spectra of nearby galaxies. The relative weight of the two templates ($AIB_{Irrad/Shielded}$) is a tracer of the radiative feedback from massive stars on the ISM. We derive an estimate of $AIB_{Irrad/Shielded}$ in a $z$ = 4.22 lensed galaxy, and find that it has a lower value than for local galaxies. This pilot study illustrates how a detailed analysis of AIB emission in nearby regions can be used to probe the physical conditions of the extragalactic ISM.

**Key words.** astrochemistry – infrared: ISM – ISM: individual objects: Orion Bar – ISM: photon-dominated region (PDR) – techniques: spectroscopic



## 1. Introduction

Photodissociation regions (PDRs) are region of the interstellar medium where the far-UV photons (6 < E < 13.6 eV) from massive stars strongly influence the dust and gas. This deposition of energy results in the dissociation of molecules and heating of the gas and dust. PDRs cool through emission in the infrared (IR). In the mid-IR wavelength range (3 − 28 µm), classic spectral signatures of PDRs are i) continuum emission attributed to dust grains, ii) $H_2$ emission lines, iii) emission lines from neutral atoms and ions ([S II], [Si II], etc.), and iv) aromatic infrared bands (AIBs), which are broad emission features generally attributed to fluorescent emission of large carbonaceous molecules, i.e. polycyclic aromatic hydrocarbons (PAHs). The most prominent AIBs are found at wavelengths of 3.3, 6.2, 7.7, 8.6, 11.2, and 12.7 µm. Perhaps the main observational fact is that PAHs are ubiquitously observed in the interstellar medium (ISM) of star-forming galaxies (SFGs, e.g. Draine et al. 2007; Li 2020; Sandstrom et al. 2023), including at high redshift (e.g. Riechers et al. 2014; McKinney et al. 2020). PAHs are believed to play a major role in the physics and chemistry of PDRs, and, notably, in heating the gas via the photoelectric effect (e.g. Bakes & Tielens 1994; Weingartner & Draine 2001; Berné et al. 2022a).

Here we focus on the emission in the 3.2-3.6 µm range, which includes the AIB at 3.3 µm and less-prominent neighboring bands, in particular one at 3.4 µm. While the emission at 3.3 µm is attributed to aromatic C-H stretching vibrations, the emission at 3.4 µm is attributed to aliphatic C-H stretching vibrations (e.g. Allamandola et al. 1989; Joblin et al. 1996; Yang et al. 2016a). These bands are also seen in galaxy spectra (i.e. Li 2020, and references therein).

Kim et al. (2012) as well as Lai et al. (2020) showed that the 3.3 µm emission can be a reasonable star formation (SF) indicator and Rigopoulou et al. (2021) demonstrated that PAH intensity ratios could be used to probe physical conditions of the ISM of

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# Black hole in a combined magnetic field: ionized accretion disks in the jetlike and looplike configurations

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Magnetic fields surrounding black holes are responsible for various astrophysical phenomena related to accretion processes and relativistic jets. Depending on the source, the configuration of the field lines may differ significantly, affecting the trajectories of charged particles and the corresponding observables. Usually, the magnetic fields around black holes are modeled within a single source or current generating the field. However, magnetic fields can have more than a single origin, being a combination of different fields, such as, e.g., that of an accretion disk and external large-scale or Galactic ones. In this paper, we propose a combined magnetic field solution given by the superposition of the uniform and Blandford-Znajek split-monopole magnetic fields in a strong gravity regime of the Schwarzschild black hole. We show that when the combined magnetic field components are aligned, the resulting field is of a paraboloidal jetlike shape. Such a configuration is supported by relativistic jet observations and is often utilized in general relativistic magnetohydrodynamical simulations. In the opposite orientation of the two field components, we observe looplike field structures magnetically connecting the black hole with an accretion disk and the magnetic null points, which can be related to the regions of magnetic reconnection. In the combined magnetic field configurations, we analyze the dynamics of charged particles, study their stability conditions, and find the locations of stable off-equatorial structures close to the symmetry axis. Finally, we consider an ionization of Keplerian accretion disk as a particular scenario of particle scattering. From the numerical experiments, we conclude that charged particles in the jetlike combination show a strong tendency to escape from the black hole, which is not observed in the case of individual fields. In contrast, the looplike combination supports accretion of charged particles into the black hole.

## I. INTRODUCTION

Magnetic fields in regions of strong gravity play a crucial role in the explanation of various high-energy phenomena observed in black hole systems of different mass scales. Among these phenomena are e.g. the formation and collimation of relativistic jets [1] observed in active galactic nuclei (AGNs) and other black hole systems, the generation of high-frequency quasiperiodic oscillations (QPOs) from microquasars and AGNs [2], acceleration of ultrahigh-energy cosmic rays [3], among others.

The strength of the magnetic field around compact objects can be estimated using different methods depending on the type of object and properties of the surrounding plasma. A typical magnitude of the magnetic field around supermassive black holes at the centers of many galaxies is estimated to be around $B \sim 10^4$G [4]. This value refers mainly to AGNs with visible relativistic jets. In contrast to that, the Galactic center supermassive black hole Sgr A* in a quiescent state is likely surrounded by an ordered magnetic field, which is significantly weaker than in AGNs, being of the order of $\sim 10 - 100$G [5, 6]. For stellar mass black holes, the strengths of the magnetic field can vary all the way from mG for isolated black holes inside the Galaxy up to the values of $10^8$G, typical for the non-transient binary systems such as microquasars [7]. All these and other estimates indicate that the magnetic field around black holes of various masses in the astrophysical context is a test field, meaning that it cannot alter the spacetime geometry. This condition reads $B \ll B_{\rm G} = 10^{19}{\rm G} \times M_{\odot}/M$ [8]. A field that satisfies the test field condition, $B \ll B_G$,

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# Discovery of magnetically guided metal accretion onto a polluted white dwarf

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## ABSTRACT

Dynamically active planetary systems orbit a significant fraction of white dwarf stars. These stars often exhibit surface metals accreted from debris disks, which are detected through infrared excess or transiting structures. However, the full journey of a planetesimal from star-grazing orbit to final dissolution in the host star is poorly understood. Here, we report the discovery that the cool metal polluted star WD 0816–310 has cannibalized heavy elements from a planetary body similar in size to Vesta, and where accretion and horizontal mixing processes have clearly been controlled by the stellar magnetic field. Our observations unveil periodic and synchronized variations in metal line strength and magnetic field intensity, implying a correlation between the local surface density of metals and the magnetic field structure. Specifically, the data point to a likely persistent concentration of metals near a magnetic pole. These findings demonstrate that magnetic fields may play a fundamental role in the final stages of exoplanetary bodies that are recycled into their white dwarf hosts.

*Keywords:* Debris disks (363) — Exoplanet systems (484) — Stellar abundances (1577) — Stellar magnetic fields (1610) — White dwarf stars (1799)

## 1. INTRODUCTION

White dwarf stars exhibit multiple hallmarks of their remnant yet vibrant planetary systems, including circumstellar debris that sometimes transits the host (Farihi 2016; Guidry et al. 2021). As the planetary debris is accreted onto the white dwarf, it results in a temporary phase during which photospheric metals can be detected, often referred to as pollution (Zuckerman et al. 2003). Because of the downward settling of heavy elements in their high-gravity atmospheres, white dwarf spectra normally exhibit only hydrogen or helium, but a significant fraction also show traces of these accreted metals (Zuckerman et al. 2010; Koester et al. 2014). This phenomenon is now well understood to be the result of accretion of planetary material, where the relative elemental abundances measured in polluted white dwarfs provide a gateway to studies of extrasolar geochemistry and planet formation (Klein et al. 2021; Bonsor et al. 2023).

The observed debris disks are attributed to star-grazing planetesimals that are tidally fragmented, but their evolution is understood only in the broadest terms (Malamud & Perets 2020; Brouwers et al. 2022). For example, the necessary drastic compaction of the semi-major axis, from several astronomical units to periastra within a solar radius, is an active area of research in which collisions are likely to play a central role (Veras et al. 2015; Malamud et al. 2021). In some cases magnetic fields may assist in orbital circularization for some disk constituents (Hogg et al. 2021; Zhang et al. 2021). The accretion of disk particles onto the star is likely to be driven by Poynting-Robertson drag, and possibly enhanced by solid-gas coupling or the collisional destruction of solids (Rafikov 2011; Kenyon & Bromley 2017). In this process, magnetic fields may play a fundamental role by re-directing the gaseous accretion stream (Metzger et al. 2012; Farihi et al. 2018).

In the local 20 pc volume of white dwarfs, at least 15 per cent are metal-polluted (Hollands et al. 2018), while over 20 per cent host a detectable magnetic field (Bagnulo & Landstreet 2021), with a significant overlap between these two populations (Farihi et al. 2011; Hollands et al. 2018; Bagnulo & Landstreet 2019a; Kawka et al. 2019). It is well known that in main-sequence stars, the presence of a globally organised magnetic field enables and preserves a non-homogeneous distribution of the chemical elements of the photosphere (e.g. Do-

# Multi-Messenger Windows on the Universe: detecting precursor emission to compacts' mergers

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## ABSTRACT

We provide an overview of various mechanisms, and corresponding powers, of precursor emission to compacts' mergers to be detected by LIGO-Virgo-KAGRA (LVK) collaboration. Expected peak powers, $\leq 10^{43}$ erg s$^{-1}$, are not sufficiently high to be detected by all-sky high-energy satellites (unless beamed). The best chance is the detection of possible coherent radio emission, producing observable signals up to $\sim$ Jansky of flux density. Low-frequency phased array telescopes like LOFAR, the MWA and DSA-2000 are best suited due to their large instantaneous sky coverage. Time-wise, in addition to LIGO early warning alerts up to a minute before the merger, the dispersive delay at lower frequencies of $\sim$ 300 MHz can be of the order of minutes. Optical detections are the most challenging.

## Contents

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# Results of the follow-up of ANTARES neutrino alerts

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**Abstract.** High-energy neutrinos could be produced in the interaction of charged cosmic rays with matter or radiation surrounding astrophysical sources. To look for transient sources associated with neutrino emission, a follow-up program of neutrino alerts has been operating within the ANTARES Collaboration since 2009. This program, named TAToO, has triggered robotic optical telescopes (MASTER, TAROT, ROTSE and the SVOM ground based telescopes) immediately after the detection of any relevant neutrino candidate and scheduled several observations in the weeks following the detection. A subset of ANTARES events with highest probabilities of being of cosmic origin has also been followed by the Swift and the INTEGRAL satellites, the Murchison Widefield Array radio telescope and the H.E.S.S. high-energy gamma-ray telescope. The results of twelve years of observations are reported. No optical counterpart has been significantly associated with an ANTARES candidate neutrino signal during image analysis. Constraints on transient neutrino emission have been set. In September 2015, ANTARES issued a neutrino alert and during the follow-up, a potential transient counterpart was identified by Swift and MASTER. A multi-wavelength follow-up

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# Parity violation in the observed galaxy trispectrum

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**ABSTRACT**

Recent measurements of the 4-point correlation function in large-scale galaxy surveys have found apparent evidence of parity violation in the distribution of galaxies. This cannot happen via dynamical gravitational effects in general relativity. If such a violation arose from physics in the early Universe it could indicate important new physics beyond the standard model, and would be at odds with most models of inflation. It is therefore now timely to consider the galaxy trispectrum in more detail. While the *intrinsic* 4-point correlation function, or equivalently the trispectrum, its Fourier counterpart, is parity invariant, the *observed* trispectrum must take redshift-space distortions into account. Although the standard Newtonian correction also respects parity invariance, we show that sub-leading relativistic corrections do not. We demonstrate that these can be significant at intermediate linear scales and are dominant over the Newtonian parity-invariant part around the equality scale and above. Therefore when *observing* the galaxy 4-point correlation function, we should expect to detect parity violation on large scales.

**Key words:** cosmology: theory. cosmology: large-scale structure of Universe.

## INTRODUCTION

A detection of parity violation in large-scale galaxy statistics could be a signature of physics beyond the standard model and could provide information about the early universe, dark matter, and dark energy. Parity inversion is a point reflection, defined as reversing the sign at any event of each spatial Cartesian coordinate axis, is a symmetry that is obeyed by most physical processes. On cosmological scales, structure formation is dominated by gravitation which is parity invariant in the dominant scalar sector. Hence, probing parity violation in large-scale structure could also provide an insight into early universe physics as we should expect it to be invariant under a parity transformation. In order to provide constraints on parity violation on large scales, we need to investigate observables that are sensitive to parity. Observables that are constructed from scalar fields, such as the galaxy density fluctuation, pose difficulties to being parity sensitive. For example, the power spectrum, the Fourier counterpart of the 2 point correlation function (2PCF) is not sensitive to parity. However, with future galaxy surveys, such as DESI (`www.desi.lbl.gov`) and Euclid (`www.euclid-ec.org`), we will be able to constrain higher-order statistical measures such as the bispectrum and trispectrum. The intrinsic bispectrum or 3PCF is not sensitive to a parity transformation because a triangle under reflection and rotation by $\pi$ (i.e., a point reflection) is mapped back to itself. The trispectrum, which is the Fourier counterpart of the 4-point correlation function (4PCF), is the lowest-order statistic that can probe parity violation in the scalar gravity sector.

A number of cosmological studies have considered the 4PCF of the cosmic microwave background (CMB). Most of the parity violation studies of the CMB have been focused on the polarisation of the CMB (Kamionkowski & Souradeep 2011; Shiraishi et al. 2011) or on gravitational waves (Nishizawa & Kobayashi 2018; Jeong & Kamionkowski 2020; Orlando et al. 2021). The CMB study of parity violation (Minami & Komatsu 2020) has shown $2.5\sigma$ evidence of cosmic birefringence. Eskilt & Komatsu (2022) have presented a new analysis of cosmic birefringence and found a statistical significance of $3.6\sigma$. The equivalent 4PCF of large-scale structure has not been explored as much. Recently, Cahn et al. (2021) have proposed using the 4PCF as a test for detecting cosmological parity violation in 3D large-scale structure. They have taken quadruples of galaxies forming a tetrahedron, which is the lowest order 3D shape which cannot be superimposed on its mirror image by a rotation. As a result, an imbalance between the tetrahedrons and their mirror images (assuming statistical isotropy) can provide information about parity violating parity-odd modes in the 4PCF from 3D large-scale structure surveys. Philcox (2022) has done a blind test on the odd-parity part of the 4PCF using the Baryonic Oscillation Spectroscopic (BOSS) CMASS (Rodríguez-Torres et al. 2016) sample of the Sloan Digital Sky Survey (SDSS) III (Beutler et al. 2014). This test considered separations in the range $20-160h^{-1}$Mpc and found $2.9\sigma$ evidence for the detection of an odd-parity 4PCF. Hou et al. (2023) have also measured these parity-odd modes from the currently available spectroscopic sample, BOSS. They have performed an analysis of two sets of data, DR12 LOWZ ($\bar{z}=0.32$) and DR12 CMASS

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# Search for Wormhole Candidates: Accreting Wormholes with Monopole Magnetic Fields

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**Abstract:** The existence of even the simplest magnetized wormholes may lead to observable consequences. In the case where both the wormhole and the magnetic field around its mouths are static and spherically symmetric, and gas in the region near the wormhole falls radially into it, the former's spectrum contains bright cyclotron or synchrotron lines due to the interaction of charged plasma particles with the magnetic field. At the same time, due to spherical symmetry, the radiation is non-polarized. The emission of this just-described exotic type (non-thermal, but non-polarized) may be a wormhole signature. Also, in this scenario, the formation of an accretion disk is still quite possible at some distance from the wormhole, but a monopole magnetic field could complicate this process and lead to the emergence of asymmetrical and one-sided relativistic jets.

**Keywords:** wormholes; accretion; magnetic field

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## 1. Introduction

### 1.1. Wormholes

According to the "boring physics conjecture" [1], we live in $\mathbb{R}^4$ or, at best, in $\mathbb{R} \times \mathbb{S}^3$. On the other hand, Kardashev et al. [2] proposed the hypothesis that some galactic nuclei are, in fact, wormhole mouths (see also Bambi [3], Li and Bambi [4], Zhou et al. [5]). Evidently, the time is not ripe to discuss the topology of the Universe purely theoretically.

The study of wormholes is of serious interest since their properties and the very possibility of their existence can have a strong impact on our ideas about the cosmology of the Universe.

Wormholes (also known as "Einstein-Rosen bridges") were first proposed by Einstein and Rosen [6] within the framework of general relativity. The Einstein–Rosen bridge solution describes an empty, spherically symmetric wormhole geometry that connects two asymptotically flat regions of spacetime. These hypothetical objects are essentially shortcuts through spacetime, connecting distant regions of the Universe or even different universes. This idea has generated great interest among scientists, inspiring many fascinating theories and proposals.

The solutions to the equations of general relativity allow for the existence of traversable and non-traversable (those that collapse too soon to be traversed) wormholes depending on the energy-matter content of spacetime. It should be noted that the theory of traversable wormholes, which could theoretically allow for fast interstellar travel, has a lot of constraints and challenges, including the requirement for negative energy density "exotic" matter that should stabilize the wormhole throat in order to prevent its collapse. Non-traversable wormholes also have important implications for theoretical physics and cosmology, allowing us to test the limits of general relativity and study the nature of spacetime under extreme conditions.

One of the serious problems in the study of wormholes is the preservation of causality. Traversable wormholes could allow time travel, which could lead to apparent paradoxes

# The quadruple spectroheliograph of Meudon observatory (1909-1959)

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## ABSTRACT

The spectroheliograph was invented independently by Henri Deslandres (France) and George Hale (USA) in 1892, following the spectroscopic method suggested by Jules Janssen in 1869. This instrument is dedicated to the production of monochromatic images of the Sun in order to reveal the structures of the photosphere and the chromosphere at various altitudes. Sporadic observations started in Paris, but Deslandres moved soon to Meudon and designed, with Lucien d'Azambuja, an universal and powerful instrument, the quadruple spectroheliograph. It was devoted to systematic observations of the Sun (the long-term activity survey since 1908) and scientific research in solar physics. This paper describes the instrument and presents some original observations made with the high dispersion 7-metre spectrograph. It was dismantled in the sixties, but the solar patrol continued with the 3-metre chambers with Hα and CaII K lines, and is still working today with the numerical version of the spectroheliograph.

## KEYWORDS

Spectroheliograph, spectroscopy, monochromatic imaging, Sun, photosphere, chromosphere

## 1 – INTRODUCTION

The principle of imaging spectroscopy of the solar surface was early introduced by Janssen (1869) after the discovery of how to observe prominences at any time, outside eclipses, using spectroscopic means: "with a spectroscope rotating around its axis, the entrance slit scans the Sun; a second slit in the spectrum selects a spectral line of interest and, using an ocular, the retinal persistence forms a monochromatic image". George Hale (USA) and Henri Deslandres (France) invented independently the spectroheliograph in 1892 (Malherbe, 2023) on this basis.


***Figure 1*** *: Lucien d'Azambuja and Henri Deslandres (left), 1913. Lucien d'Azambuja's jubilee (50 years of astronomy) occured in 1949 and a ceremony was organized in 1950; among participants, (1) Bernard Lyot, (2) Marguerite d'Azambuja, (3) Lucien d'Azambuja, (4) André Danjon, director (courtesy OP).*

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# Red Asymmetry of $H_\alpha$ Line Profiles during the flares on the active RS CVn-type star II Pegasi

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## ABSTRACT

Stellar coronal mass ejections (CMEs) have recently attracted much attention for their impacts on stellar evolution and surrounding exoplanets. RS CVn-type stars could produce large flares, and therefore may have frequent CMEs. Here we report the capture of a possible CME or chromospheric condensation on the RS CVn-type star II Pegasi (II Peg) using high-resolution spectroscopic observation. Two flares were detected during the observation, and the low limits of the flare energies are of the order of $10^{33}$ erg and $10^{34}$ erg, respectively. Using mean spectrum subtraction, the $H_\alpha$ residual shows red asymmetry during the flares, and the redshifted broad emission components are probably caused by chromospheric condensation or coronal rain. Moreover, a far redshifted extra emission component with a high bulk velocity of 429 km $s^{-1}$ was observed during the second flare and is probably due to a prominence eruption. The velocity greatly exceeds the star's escape velocity, which means that this eruption can develop into a CME. The CME mass is estimated to be 0.83–1.48 $\times$ $10^{20}$ g, which is slightly larger than the value expected from solar flare-CME extrapolation. The kinetic energy of CME, derived to be 0.76–1.15 $\times$ $10^{35}$ erg, is less than the kinetic energy extrapolated from solar events. Additionally, we could not completely rule out the possibility of chromospheric condensation resulting in the far redshifted extra emission. Finally, there is a blueshifted broad component in the subtracted $H_\alpha$ profile derived using synthesized spectral subtraction when no flare happened, and its behavior is associated with the $H_\alpha$ activity features.

*Keywords:* Stellar activity (1580) — Optical flares (1166) — Stellar coronal mass ejections (1881) — Spectroscopy (1558)

## 1. INTRODUCTION

Starspots, plages, flares, and prominences have been widely observed in cool stars (Schrijver & Zwaan 2000). It is commonly accepted that all of these active phenomena arise from a powerful magnetic dynamo generated by the interplay between the turbulent motion in the convection zone and the stellar differential rotation, in a manner similar to the solar case. In recent years, stellar coronal mass ejections (CMEs) have attracted much attention, though they are more difficult to observe with current instrumentation because of having no spatial resolution. Based on some indirect evidences, such as Doppler-shifted emission or absorption signature in the optical, UV and X-ray spectral lines (e.g., Houdebine et al. 1990; Leitzinger et al. 2011; Argiroffi et al. 2019; Namekata et al. 2021; Inoue et al. 2023), X-ray, extreme-UV (EUV), and far-UV (FUV) dimming (e.g., Veronig et al. 2021; Namekata et al. 2023), and X-ray continuous absorption (e.g., Favata & Schmitt 1999; Moschou et al. 2017), researchers have made a lot of attempts to detect stellar CME events. Frequently occurred CMEs may be an important contribution to mass and angular momentum loss in the course of stellar evolution (e.g., Aarnio et al. 2012; Osten & Wolk 2015), and have severe impacts on the atmospheres of surrounding exoplanets (e.g., Airapetian et al. 2016; Cherenkov et al. 2017; Hazra et al. 2022).

RS CVn-type binary system includes at least one cool component showing particularly intense magnetic activ-

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# Pre-merger detection of massive black hole binaries using deep learning

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Coalescing massive black hole binaries (MBHBs) are one of primary sources for space-based gravitational wave (GW) observations. The mergers of these binaries are expected to give rise to detectable electromagnetic (EM) emissions with a narrow time window. The pre-merger detection of GW signals is vital for follow-up EM observations. The conventional approach for searching GW signals involves high computational costs. In this study, we present a deep learning model to search for GW signals from MBHBs. Our model is able to process 4.7 days of simulated data within 0.01 seconds and detect GW signals several hours to days before the final merger. The model provides the possibility of the coincident GW and EM detection of MBHBs.



## I. INTRODUCTION

Since the first detection of gravitational wave (GW) signals from compact binary coalescence in 2015, the ground-based GW detectors have discovered an increasing number of GW events [1–4]. These detectors are primarily sensitive to GW signals in the tens of hertz to kilohertz frequency range. Moreover, stochastic GW backgrounds in the nanohertz frequency range are detectable via pulsar timing arrays [5–7]. Nonetheless, there remain extensive frequency ranges awaiting exploration. By around 2030, several space-based GW detectors, including the Laser Interferometer Space Antenna (LISA) [8], Taiji [9], and TianQin [10], are scheduled to be launched, opening a window in the millihertz frequency range for GW observations.

It is known that there exists massive black holes at the centers of galaxies [11, 12]. Massive black hole binaries (MBHBs) are thought to form as galaxies evolve over time [13]. For space-based detectors, they are a highly significant class of GW sources [8, 14]. We can test gravity in the highly nonlinear strong-field regime with GW signals from them [15–18]. Furthermore, the coincident GW and electromagnetic (EM) detections for MBHBs will inaugurate a new era of multimessenger astrophysics, facilitating the comprehension of galaxy evolution at high redshifts [18]. It also provides a new perspective for resolving Hubble tension through standard sirens [19–22]. There is anticipation of observing a variety of EM emissions associated with the environment surrounding MBHBs [23]. However, some of them have short observational timescales [23–27], leading to the demand for low-latency data analysis in GW observations. Specifically, EM emissions from minidisks gradually disappear before the merger of MBHBs due to the shrinkage of minidisks, while they can provide a method for measuring spins of massive black holes [24]. Moreover, EM emissions from hot accretion flows [25] or magnetized circumbinary disks [26, 27] exhibit a transient peak around the merger of MBHBs. Therefore, the pre-merger detection of GW signals facilitates prompt localization of the MBHB, enabling detailed planning for the observation of EM emissions.

Currently, the commonly used approach for identifying GW signals amidst noise relies on matched filtering techniques [28], which have demonstrated remarkable efficacy in ground-based GW observations [29–31]. However, it is computationally expensive due to the requirements of calculating a detection statistic, such as the signal-to-noise ratio (SNR) [32], for numerous waveform templates. To search for GW signals from compact binary coalescence, a template bank containing about 250,000 waveform templates was employed in the first observational run of Advanced LIGO [33]. Moreover, it is estimated that around $10^{13}$ templates are required to search for GW signals from non-spinning MBHBs [18, 34]. A gridless search based on Metropolis-Hastings sampling and simulated annealing can be considered to significantly reduce the frequency of calculating the detection statistic [34]. Nevertheless, in light of the demand to observe EM counterparts of MBHBs and further reduce the computational costs, there is considerable value in developing novel techniques for identifying GW signals.

Deep learning presents a great potential in GW data analysis due to its capacity for automatic feature extraction and complex pattern recognition. Deep learning models have been extensively studied for the identification of GW signals. [35–48]. Specifically, the models designed in Ref. [44, 45] are capable of identifying GW signals from coalescing

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# Discrete spectra in phase mixing

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**ABSTRACT**

We study solutions of the collisionless Boltzmann equation (CBE) in a functional Koopman representation. This facilitates the use of linear spectral techniques characteristic of the analysis of Schrödinger-type equations. For illustrative purposes, we consider the classical phase mixing of a non-interacting distribution function in a quartic potential. Solutions are determined perturbatively relative to a harmonic oscillator. We impose a form of coarse-graining by choosing a finite dimensional basis to represent the distribution function and time evolution operators, which sets a minimum length scale on phase space structure. We observe a relationship between the dimension of the representation and the multiplicity of the harmonic oscillator eigenvalues. The quartic potential splits the degenerate eigenvalues, which drives mixing in the CBE solution.

**Key words:** Galaxy: disc – Galaxy: kinematics and dynamics – Galaxy: structure.

## 1 INTRODUCTION

In this paper we investigate the relaxation of collisionless systems through phase mixing. In a statistical description, the macrostate of a system is specified by the phase space distribution function, $f$. This quantifies the probability that a particle exists within an infinitesimal volume of phase space (Sethna 2006). Liouville's theorem requires that $f$ is conserved along orbits, and it therefore satisfies the collisionless Boltzmann equation (CBE) (Arnold 1989). For $s$ spatial degrees of freedom, this is equivalent to the incompressible flow of a $2s$ dimensional fluid in a velocity field specified by Hamilton's equations. An introductory description of this can be found in Binney & Tremaine (2008), but we summarize as follows. Let us assume an anharmonic potential in which orbital frequency of test particles is dependent on their amplitudes of oscillation. In the fluid analogy, this means that vorticity of the velocity field depends on the spatial coordinate. A distribution out of equilibrium with such a potential will deform with time as packets of density with different energies orbit at varying frequencies. For a fixed conservative Hamiltonian this continues indefinitely, with different energy orbits becoming increasingly out of phase with each other. In this process, the scale of structure in the distribution decreases. Eventually when the scale becomes so small that adjacent wraps of the mixed distribution become indistinguishable, the system has equilibrated.

Phase mixing in general leads to complex structures, especially for the $s = 3$ case present in galactic dynamics and cosmology (Tremaine 1999; Perrett et al. 2003; Abel et al. 2012). Even for $s = 1$, which applies to considerations of the vertical motion in the Galactic disc, this process is not trivial. With astrometric data from Gaia Collaboration et al. (2018), a one armed spiral was observed in the vertical phase space of solar neighborhood stars (Antoja et al. 2018). In reality this is a $s = 3$ system, as it is unlikely that the vertical dynamics are decoupled from motion in the plane (Hunt et al. 2021), but much attention has been given to the structure in the univariate case (Schönrich & Binney 2018; Darling & Widrow 2019a; Bennett & Bovy 2018, 2021). At present, no models have reproduced the exact form of the Gaia spiral.

In Darling & Widrow (2019b), it was suggested that the phase mixing process can be represented with the discrete spectrum of a linear time-evolution operator of finite dimension. There, eigenfunctions were estimated numerically from the full temporal history of a system by applying Dynamic Mode Decomposition (DMD) (Mezić 2005; Rowley et al. 2009; Kutz et al. 2016) to $N$-body simulations. This served to investigate the claim that self-gravity should not be ignored in phase mixing (Darling & Widrow 2019a), as well as to explore the representation of this process with persistent oscillatory structures. Stable oscillations such as bending and breathing modes were observed in a self-interacting system in an anharmonic potential. When modifying the relative dominance of self-interaction and anharmonic forcing, these oscillatory structures were more prominent the closer the system was to purely self-interacting. For stronger anharmonic forcing, they were deformed to include spiral structure.

DMD is closely related to Koopman theory (Koopman 1931), which supposes that a complex, potentially nonlinear system can be represented as a simpler linear one by studying its evolution in terms of observable functions of its state space. This concept was used to interpret the results in Darling & Widrow (2019b), arguing that the binning of $N$-body simulations constituted a mapping to observables. Because of the numerical nature of that work, it was difficult to study the supposed mechanism of phase mixing from discrete modes, or establish a concrete connection to Koopman theory. The DMD approach also draws comparison to the use of multichannel singular spectrum analysis (mSSA) (Weinberg & Petersen 2021; Johnson et al. 2023). In both cases, principle component analysis (PCA) based techniques are applied to time-series data, but in the mSSA papers

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# The Cosmic Neutrino Background

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**Summary.** — The cosmic neutrino background is like the cosmic microwave background, but less photon-y and more neutrino-ey. The CNB is also less talked about than the CMB, mostly because it's nearly impossible to detect directly. But if it could be detected, it would be interesting in several ways that are discussed.

## 1. – $\nu$ overview (or 'news')

Let's start by giving an overview of the relevant properties of neutrinos:

- neutrinos are hard to detect;
- they come in 3 flavours, which can mix;
- we don't know why the flavour and mass states are so messed up (unlike the situation for quarks);
- we don't know if they're their own anti-particles or not (Majorana versus Dirac);
- we don't know their masses, or even if they have the "normal hierarchy" ($m_3 \gg m_2 \gtrsim m_1$) or an "inverted hierarchy" ($m_2 \gtrsim m_1 \gg m_3$).

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And let's also summarise some information for cosmological neutrinos (making informal comments as notes among the references at the end, like this one [1]):

- cosmological neutrinos are *really* hard to detect;
- there are about 340 for every $cm^3$ of the Universe (making them the second most common particle, after photons);
- if we could detect them, they'd tell us interesting things;
- the sum of neutrino masses is expected to be the 7th (or 8th) cosmological parameter.

This last point is why many cosmologists are currently excited about neutrinos. There is a very strong expectation that soon it will be possible to make a measurement of the sum of the neutrino masses, $\sum m_\nu$, because of the effects of the cosmic neutrino background (CNB or C$\nu$B) on cosmological power spectra, after the neutrinos become non-relativistic. The standard cosmological model, also known as ΛCDM (or "cosmological-constant-dominated, cold dark matter"), has six basic parameters, or seven if we include the amplitude of the photon background. The mass density of neutrinos in the CNB will be one additional parameter.

For a good summary of neutrinos in cosmology, I recommend the review article by Julien Lesgourgues and Licia Verde in the "Particle Data Book" (PDG) [2]. What follows will be a broad discussion of the cosmic neutrino background (CNB or C$\nu$B), from the perspective of someone who has worked on the photon background, and would love to live in a universe where it was routine to extract information from the CNB, just as it is now for the CMB. This will not be a particle-physics-oriented overview – for more on the particle properties of neutrinos I would suggest reading the PDG review by Maria Gonzalez-Garcia and Masashi Yokoyama [3]). However, it will be important to consider how neutrinos differ from photons, which of course involves some particle physics [4].

## 2. – $\nu$ cosmic background

As already stated, neutrinos are hard to detect, even if they're produced copiously in the early Universe and other sources. The Sun makes so many neutrinos that even at the distance of the Earth, something like $10^{15}$ of them enter your body every second [5], and the same number also exit your body every second. There's a small chance that one of them might interact with you in your lifetime. Human bodies are of course not very sensitive detectors, and we can do much better with a tailor-made experiment, but nevertheless, the numbers detected are only measured in the tens per day. Solar neutrinos are typically at energies in the MeV range. What we're focussing on in this article are the CNB neutrinos, which are also at "em-ee-vee" energies, but now it's meV rather than MeV. Such low-energy neutrinos basically don't interact with anything [6].

The neutrinos of the CNB were made at very early times, before the weak interactions froze out. We can calculate their number density today, which turns out to be about

# Estudiando las estructuras a gran escala del Universo con la teoría de perturbaciones no lineal

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*Resumen* — **Las estructuras a gran escala del Universo proporcionan información importante para la cosmología. Las actuales encuestas espectroscópicas, como DESI, medirán millones de galaxias, permitiendo medir la historia de expansión del cosmos y la tasa de crecimiento con gran precisión. En este trabajo, presentamos la descripción teórica del espectro de potencia de materia oscura en el espacio real y en el espacio del corrimiento al rojo para galaxias. Calculamos el espectro usando la teoría de perturbaciones no lineal, la teoría de campo efectiva y el resumado del infrarrojo.**

*Palabras Clave* – **Espectro de potencia, estructuras a gran escala del Universo, teoría de perturbaciones no lineal**

*Abstract* — **The Large-Scale Structure (LSS) of the Universe provides valuable information for modern cosmology. The future redshift surveys, as DESI (Dark Energy Spectroscopic Instrument), will measure millions of galaxies and quasars, which allows to measure the history expansion and the growth factor. In this work, we present the theoretical model of the matter power spectrum and the redshift space multipoles of the galaxy power spectrum. We compute the spectrum using different methods as 1-loop Standard Perturbation Theory, Effective Field Theory and the Infrarred resummations.**

*Keywords* — **Galaxy clustering, large-scale structure of the Universe, non-linear perturbation theory**

## I. INTRODUCCIÓN

El estado de las observaciones espectroscópicas del Universo permite obtener la medición del crecimiento de las estructuras, fundamental para entender la naturaleza de la energía oscura. Para ello, se usan los catálogos de galaxias y se mide el efecto de las distorsiones del corrimiento al rojo mediante el uso de las estadísticas de dos puntos: el espectro de potencia en el espacio de Fourier, o la función de correlación en el espacio de configuraciones.

Las distorsiones al corrimiento al rojo son una medida de las velocidades peculiares de las galaxias a lo largo de la línea de visión. Las velocidades peculiares son originadas por la interacción gravitatoria entre los objetos y por tanto afecta el crecimiento de las fluctuaciones de materia. En este sentido, cuando se mide el efecto de las distorsiones en el espectro de potencia de las galaxias se puede restringir el factor de crecimiento logarítmico, $f$.

Sin embargo, la tasa de crecimiento está degenerado con el parámetro $\sigma_8$, la amplitud de las fluctuaciones de materia oscura a una escala de $8h^{-1}Mpc$. Por esta razón, el estudio del espectro de potencia en el espacio del redshift es sensible a la combinación de ambos parámetros, lo cual nos referimos simplemente como $f\sigma_8$.

Para entender la riqueza de los datos futuros dentro de los métodos analíticos y semianalíticos, una teoría sólida es necesaria. El universo que observamos contiene estructuras, esencialmente, en todas la escalas. Las estructuras a gran escala es bien modelado por la teoría lineal. Conforme la profundidad y el volumen de los catálogos incrementa, se abarca escalas donde los efectos cuasilineales son más relevantes y la teoría de perturbaciones se convierte más importante.

## II. ESPECTRO DE POTENCIAS PARA MATERIA OSCURA

Los primeros intentos de la descripción de las Estructuras a Gran Escala del universo (LSS) provienen en la década de los 70s [1]. Este esquema es conocido como “Lagrangiano”, donde se resuelve perturbativamente el campo de desplazamiento entre la posición inicial y final de las partículas de materia oscura. El esquema más popular ha sido la teoría de perturbaciones estándar (SPT) [2], donde la materia oscura es tratada como un fluido perfecto sin presión y las ecuaciones de movimiento no lineales son resueltas perturbativamente en el espacio Euleriano, donde el campo de densidad de materia $\delta(x,t)$ y el campo de velocidad $\theta(x,t) = \nabla \cdot v(x,t)$ son expandidos en series de Taylor:

$$\delta(x,t) = \delta^{(1)}(x,t) + \delta^{(2)}(x,t) + \delta^{(3)}(x,t) + \cdots$$
$$\theta(x,t) = \theta^{(1)}(x,t) + \theta^{(2)}(x,t) + \theta^{(3)}(x,t) + \cdots \tag{1}$$

A escalas grandes, el campo de densidad de la materia oscura sigue la evolución lineal, es decir, su espectro de potencia está dado por

$$P_{lin}(z,k) = D^2(z) P_{lin}(k) \tag{2}$$

donde $D(z)$ es el factor de crecimiento lineal y $P_{lin}(k)$ es el espectro de potencia lineal al día de hoy ($z = 0$). La primera corrección al espectro de potencias es lo que se conoce como la contribución a un bucle (1-loop, SPT, por sus siglas en inglés), donde los campos de densidad son expandidos

# Modelando el espectro de potencia de la encuesta espectroscópica de galaxias eBOSS


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*Resumen* — **Actualmente existe mucho interés en extraer información cosmológica de las encuestas de galaxias espectroscópicas ya que permiten obtener una medición directa de la tasa de crecimiento de las estructuras y la historia de expansión. Motivados por este hecho, en este trabajo modelamos los multipolos del espectro de potencia de la encuesta de galaxias eBOSS (extended Baryon Oscillation Spectroscopic Survey) usando la teoría de perturbaciones no lineal.**



*Palabras Clave* – **Encuestas de galaxias espectroscópicas, estructuras a gran escala del Universo, teoría de perturbaciones no lineal**



*Abstract* — **We live in the golden era of cosmology due to next redshift surveys will map a significant volume of the Universe across a wide range of redshifts. We analyze the clustering of the eBOSS luminous red galaxy sample (eBOSS LRG). We measure the multipole power spectra inferred from the NGC sample (107500 galaxies) and SGC sample (67316 galaxies) between redshifts 0.6 and 1.0, with effective redshift $z_{eff}$=0.695 and $z_{eff}$=0.704 for NGC and SGC samples, respectively. We use the non-linear perturbation theory to model the the redshift space multipoles of the galaxy power spectrum.**



*Keywords* — **Large-scale structure of the Universe, non-linear perturbation theory, redshift surveys**


## I. Introducción

Las estructuras a gran escala (LSS, por su siglas en inglés) del universo contienen información relevante para la astrofísica. Por ejemplo, información desde del universo temprano hasta restricciones de parámetros cosmológicos como la tasa de crecimiento de estructuras. Los catálogos de galaxias actuales como eBOSS observan el corrimiento al rojo, la huella característica de las galaxias, que permite situarnos en lo que se conoce como espacio del corrimiento al rojo. Sin embargo, tanto las velocidades peculiares de los objetos como la expansión misma del universo dejan una estructura más allá de la que existe en el espacio real. Estas características son conocidas como las distorsiones del corrimiento al rojo (RSD por sus siglas en inglés).

La evolución de las LSS a corrimientos al rojo altos y escalas grandes pueden ser modelados con la teoría lineal, mientras que el alcance de la teoría de perturbaciones puede ser extendida a escalas intermedias incluyendo expansiones del campo de densidad de materia hasta órdenes superiores.

En este trabajo, consideramos la teoría de perturbaciones estándar [1] (SPT, por sus siglas en inglés) para el estudio del espectro de potencia en el espacio del corrimiento al rojo de la encuesta de galaxia eBOSS. Consideramos dos técnicas adicionales: la teoría de campo efectiva (EFT, por sus siglas en inglés) y el esquema del resumado del infrarrojo (IR, por sus siglas en inglés).

Las encuestas observan diferente tipos de galaxias según su masa, luminosidad, tasa de formación estelar, entre otras características. La encuesta eBOSS observó galaxias llamadas luminosas rojas (LRG, por sus siglas en inglés). Las galaxias LRGs son caracterizadas por ser muy luminosas, razón por la cual pueden ser localizadas a corrimientos al rojo altos. Las LRGs son galaxias masivas, que contienen estrellas viejas con poca formación estelar en curso.

## II. Conjunto de datos de eBOSS

Se obtendrá el espectro de potencias del catálogo de galaxias de eBOSS. Describimos brevemente el conjunto de datos de la encuesta eBOSS. Las galaxias luminosas rojas fueron observados entre $0.6<z<1.0$. El corrimiento al rojo permite situarnos en una escala de tiempo, z pequeños indican el universo más cercano.

La encuesta de galaxia de eBOSS forma parte de la colaboración Sloan Digital Sky Survey (SDSS), cuyo telescopio se encuentra en Nuevo México, Estados Unidos [2]. El catálogo de galaxias de eBOSS es observado a través de los dos hemisferios galácticos, referidos como la región galáctica del norte y del sur, las muestras NGC y SGC, respectivamente. La muestra de galaxias LRGs lleva una serie de procesos de limpieza con el objetivo de remover regiones con mala fotometría, galaxias que colisionan con espectros de cuásares, objetos que están muy cerca entre sí, entre otros efectos. Esta serie de limpieza remueve 17% de la huella del cielo inicial de eBOSS.

Las galaxias LRGs no son observadas cuando dos galaxias se encuentran muy cerca. Este efecto necesita tener asociado una función peso $w_{cp} = N_{targ}/N_{spect}$ donde $N_{targ}$ es el número de galaxias apuntados y $N_{spec}$ se refiere al número de galaxias con una observación espectroscópica. Similarmente ocurre con los objetos que no tienen una

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# Phase-Space Delaunay Tessellation Field Estimator

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## ABSTRACT

The reconstruction of density and velocity fields is of central importance to the interpretation of $N$-body simulations. We propose a phase-space extension of the Delaunay tessellation field estimator (DTFE) that tracks the dark matter fluid in phase-space. The new reconstruction scheme removes several artifacts from the conventional DTFE in multi-stream regions, while preserving the adaptive resolution in high-density regions and yielding continuous fields. The estimator also removes tessellation artifacts of a previously proposed phase-space reconstruction scheme.

**Key words:** large-scale structure of Universe – cosmology: theory – dark matter

## 1 INTRODUCTION

Studies of cosmic structure formation, galaxy formation, the dynamics of accretion disks, the formation of stars and planetary systems often rely on $N$-body simulations (cf. Peebles 1971; Bertschinger 1998; Springel et al. 2005). An $N$-body simulation models the evolution of a physical system through the evolution of a set of particles. Physical properties involving the underlying density and velocity fields are then reconstructed from the locations and velocities of the $N$-body particles. The most well-known density reconstruction methods are the grid-based particle-in-cells (PIC) (see, *e.g.*, Harlow et al. 1955; Harlow et al. 1976; Harlow 1988, and references therein) and the smoothed particle hydrodynamics (SPH) methods (*e.g.*, Gingold & Monaghan 1977; Lucy 1977). Recently, more sophisticated density and velocity reconstruction schemes were proposed.

The Delaunay tessellation field estimator (DTFE) (Pelupessy et al. 2003; Schaap 2007; van de Weygaert & Schaap 2009) uses a Delaunay tessellation of the particles to adaptively increase the resolution of the density and velocity estimator in regions with many points. An alternative tessellation-based estimator was proposed by Neyrinck (2008). The DTFE method has in the last decade become an integral part of the Disperse (Sousbie 2011; Sousbie et al. 2011) and NEXUS (Cautun et al. 2013, 2015) classifiers of the large-scale structure.

The geometric pattern of the large-scale cosmic matter distribution can be understood in terms of the folding of the dark matter sheet in phase-space (Arnol'd et al. 1982; Arnol'd 1982; Arnold 1984; Shandarin et al. 2012; Neyrinck 2012; Falck et al. 2012). Using this idea, Shandarin (2011) and Abel et al. (2012) developed a Lagrangian density estimator that traces the evolution of the dark matter sheet in phase-space and takes into account the multi-stream nature of the cosmic web. This phase-space (PS) method is particularly powerful when the $N$-body simulation resolves the fluid in phase-space, such as in the large-scale structure at large scales, and removes several DTFE artifacts present in multi-stream regions. However, the PS reconstruction is not continuous and shows tessellation artifacts, which are particularly apparent in the single-stream regions.

In this paper, we combine the best of the two approaches and propose the *phase-space Delaunay tessellation field estimator* (PS-DTFE). This method produces a continuous reconstruction of the density and velocity fields of $N$-body simulations that removes several artifacts associated to the PS and DTFE method. Accompanying this paper, we publish the two- and three-dimensional Python implementation of the PS-DTFE[1].

In the following, we first briefly recap and analyze the particle-in-cells (section 2) and smooth particle hydrodynamics (section 3) density reconstruction schemes. We then discuss the key points of the Delaunay tessellation field estimator (section 4) and the phase-space density estimators (section 5). In section 6, we combine the two methods to construct the phase-space Delaunay tessellation field estimator. We discuss the implementations of this new reconstruction scheme (section 7) and compare the resulting density field with those constructed by the above-mentioned schemes (section 8).

*Notation:* Let the $d$-dimensional $N$-body simulation consist of a set of $N$ particles located at $\boldsymbol{x}_i \in \mathbb{R}^d$ with velocities $\boldsymbol{v}_i \in \mathbb{R}^d$ (in Eulerian space) that evolved from the initial positions $\boldsymbol{q}_i \in \mathbb{R}^d$ (in Lagrangian space) with masses $m_i \in \mathbb{R}_{>0}$, for $i = 1, \dots, N$. In cosmology, it is often convenient to consider these particles in a $d$-dimensional box with periodic boundary conditions.

*Simulation:* The density reconstruction schemes are illustrated for a two-dimensional dark matter-only $N$-body simulation (see the left panel of fig. 1) with $N = 256^2$ in a periodic box with sides $L = 25$ evolving in an expanding Einstein-de Sitter universe with Gaussian initial conditions starting from a regular lattice. The particles have the same mass, *i.e.*, $m_i = m$. The simulation is performed using a 2D particle-mesh $N$-body code (Hidding 2020). The details of the simulation and units are not of crucial importance in this paper. The estimator works equally well for three-dimensional simulations.

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[1] www.github.com/jfeldbrugge/PS-DTFE

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# Probing the physics of star formation (ProPStar) ⋆

## I. First resolved maps of the electron fraction and cosmic-ray ionization rate in NGC 1333

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**ABSTRACT**

*Context.* Electron fraction and cosmic-ray ionization rates in star-forming regions are important quantities in astrochemical modeling and are critical to the degree of coupling between neutrals, ions, and electrons, which regulates the dynamics of the magnetic field. However, these are difficult quantities to estimate.

*Aims.* We aim to derive the electron fraction and cosmic-ray ionization rate maps of an active star-forming region.

*Methods.* We combined observations of the nearby NGC 1333 star-forming region carried out with the NOEMA interferometer and IRAM 30-m single dish to generate high spatial dynamic range maps of different molecular transitions. We used the $DCO^+$ and $H^{13}CO^+$ ratio (in addition to complementary data) to estimate the electron fraction and produce cosmic-ray ionization rate maps.

*Results.* We derived the first large-area electron fraction and cosmic-ray ionization rate resolved maps in a star-forming region, with typical values of $10^{-6.5}$ and $10^{-16.5}$ $s^{-1}$, respectively. The maps present clear evidence of enhanced values around embedded young stellar objects (YSOs). This provides strong evidence for locally accelerated cosmic rays. We also found a strong enhancement toward the northwest region in the map that might be related either to an interaction with a bubble or to locally generated cosmic rays by YSOs. We used the typical electron fraction and derived a magnetohydrodynamic (MHD) turbulence dissipation scale of 0.054 pc, which could be tested with future observations.

*Conclusions.* We found a higher cosmic-ray ionization rate compared to the canonical value for $N(H_2) = 10^{21} - 10^{23}$ $cm^{-2}$ of $10^{-17}$ $s^{-1}$ in the region, and it is likely generated by the accreting YSOs. The high value of the electron fraction suggests that new disks will form from gas in the ideal-MHD limit. This indicates that local enhancements of $\zeta(H_2)$, due to YSOs, should be taken into account in the analysis of clustered star formation.

**Key words.** astrochemistry; ISM: abundances; ISM: molecules; (ISM:) cosmic rays; stars: formation; ISM: individual objects: NGC 1333; techniques: interferometric



## 1. Introduction

Stars form in cold, dense cores within molecular clouds (Pineda et al. 2023). Probing these regions enables observations of the initial conditions for star and disk formation. Some of the key aspects still poorly constrained in such processes are the electron fraction, $X(e)$, and cosmic-ray ionization rate, $\zeta(H_2)$. Both of these quantities play an important role in astrochemical models (Ceccarelli et al. 2023) and in the coupling between magnetic fields and dense gas (Pineda et al. 2021; Pattle et al. 2023; Tsukamoto et al. 2023).

In the case of a constant cosmic-ray ionization rate, the electron fraction should follow a relation with a density of $X(e) \propto n^{-0.5}$ (McKee 1989; Caselli et al. 1998). The normalization of the relation depends substantially on whether the gas shows no depletion of metals (McKee 1989), appropriate for a low-density environment, or if the depletion of metals is taken into account in the modeling (Bergin & Langer 1997; Caselli et al. 1998), appropriate for denser regions.

Observationally, it is not possible to directly measure the electron fraction. Instead, it must be inferred from the combined analysis of several molecules. Toward dense cores, different works have derived typical values in the dense regions of $X(e) \approx 10^{-8} - 10^{-6}$ (Guelin et al. 1977; Caselli et al. 1998; Bergin et al. 1999; Maret & Bergin 2007), while in the transition from the diffuse to the dense medium in TMC1 ($n(H_2) \sim 10^3$ $cm^{-3}$), an electron fraction of $X(e) \approx 9.8\times10^{-8} - 3.6\times10^{-7}$ has

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# Gravitational Waves from Kinetic Preheating

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We study gravitational wave production during kinetic preheating after inflation with a focus on scenarios that arise in $\alpha$-attractor models where a scalar dilaton-like inflaton is kinetically coupled to a second scalar field. We present high-resolution lattice simulations of three $\alpha$-attractor models for a range of parameters to probe regions where preheating is efficient. We find that preheating in these models can be extremely violent, resulting in gravitational wave energy densities that can be constrained by cosmic microwave background measurements of the effective number of relativistic species, $N_{\rm eff}$.

## I. INTRODUCTION

An early phase of accelerated expansion, inflation [1–5], solves the horizon and flatness problems of the hot Big Bang cosmology. Quantum vacuum fluctuations of the fields and metric during inflation are stretched outside the horizon before later reentering to seed the density fluctuations that eventually give rise to the inhomogeneities of the cosmic microwave background (CMB) and the large scale structures in the Universe today [6–9]. However, the microphysical origin of the accelerated expansion is far from understood. The simplest models for inflation (for example, Refs. [5, 10]) are now strongly disfavored [11, 12] and non-minimal inflationary mechanisms (for example, Starobinsky inflation [2], Higgs inflation [13], and $\alpha$-attractors [14]) are now the leading candidates for the theory of inflation.

An inflationary cosmology consistent with the present observable Universe requires that the energy in the inflaton must have been transferred into matter degrees of freedom to ignite the hot Big Bang in time for Big Bang nucleosynthesis [15]—the Universe must be reheated. Yet reheating remains one of the most poorly understood epochs of our cosmic history due to the dearth of observational probes. Because reheating is a local process, the information about its dynamics is largely erased as the standard model plasma reaches local thermal equilibrium. Further, the nonlinear gravitational evolution of structure formation washes out information on scales relevant to preheating. Studies of the physics of preheating with direct observational predictions therefore remain acutely important and timely.

The nonperturbative decay of the inflaton, known as *preheating* [16–19], often occurs at the end of inflation; the explosive production of particles during this epoch can lead to distinctive gravitational signatures that persist through the opaque, hot, dense phases of early expansion of the Universe. Among these signatures are the production of a high-frequency stochastic gravitational wave background [20–31], and collapsed compact objects such as primordial black holes [32–38] or compact minihalos [39, 40]. Non-gravitational signatures include the production of primordial magnetic fields [41], and the possible generation of the baryon asymmetry, [42–48]. These signatures may provide important observational evidence of the reheating and post-inflationary epochs and lead to clues about the microphysics of the early Universe.

In this paper, motivated by observationally favored, non-minimal classes of inflationary model involving kinetically coupled scalar fields [49–51], we study a type of kinetic preheating in which the inflaton is coupled to a second scalar field via a dilaton-like interaction [49, 52, 53]. We specialize to exponential-type couplings that arise in dilaton-axion theories, where the dilaton drives inflation. We restrict our attention to scenarios where the axion does not play a role during inflation, and enters the reheating phase with no vacuum expectation value (VEV). Generalizing our previous work [53], we explore the effects of different potentials on preheating and study the production of gravitational waves. We characterize the conditions under which the predicted gravitational wave spectra can be constrained by present or next-generation CMB measurements of the effective number of relativistic degrees of freedom, $N_{\rm eff}$. Importantly, the class of models we study here can generically produce gravitational wave backgrounds loud enough that CMB bounds on $N_{\rm eff}$ may provide constraints on these models.

This paper is organized as follows. In section II we describe the model and derive the equation of motion for the fields and the background FLRW spacetime. We then analyze the growth of small fluctuations during the coherent oscillations at the end of inflation and validate our code using a Floquet analysis in section III. In section IV we describe the numerical methods we use to study the preheating period, and in section V we discuss our results, in particular characterizing the reheating efficiency and gravitational wave production in the models we study. Our conclusions are presented in section VI.

We use natural units, $\hbar = c = 1$, and define the reduced Planck mass $M_{\rm pl} = 1/\sqrt{8\pi G}$. We use the "mostly

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# Current sheet alignment in oblique black hole magnetospheres – a black hole pulsar?

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## ABSTRACT

We study the magnetospheric evolution of a non-accreting spinning black hole (BH) with an initially inclined split monopole magnetic field by means of three-dimensional general relativistic magnetohydrodynamics simulations. This serves as a model for a neutron star (NS) collapse or a BH-NS merger remnant after the inherited magnetosphere has settled into a split monopole field creating a striped wind. We show that the initially inclined split monopolar current sheet aligns over time with the BH equatorial plane. The inclination angle evolves exponentially towards alignment, with an alignment timescale that is inversely proportional to the square of the BH angular velocity, where higher spin results in faster alignment. Furthermore, magnetic reconnection in the current sheet leads to exponential decay of event horizon penetrating magnetic flux with nearly the same timescale for all considered BH spins. In addition, we present relations for the BH mass and spin in terms of the period and alignment timescale of the striped wind. The explored scenario of a rotating, aligning and reconnecting current sheet can potentially lead to multimessenger electromagnetic counterparts to a gravitational wave event due to the acceleration of particles powering high-energy radiation, plasmoid mergers resulting in coherent radio signals, and pulsating emission due to the initial misalignment of the BH magnetosphere.

*Keywords:* High energy astrophysics (739); Plasma astrophysics (1261); Compact objects (288); Magnetic fields (994); Relativity (1393); Magnetohydrodynamics (1964)

## 1. INTRODUCTION

A black hole (BH) with a magnetic field penetrating its event horizon can be born from magnetized progenitors such as a spinning down rotationally supported hypermassive neutron star (NS) (Falcke & Rezzolla 2014) or a BH-NS merger remnant (East et al. 2021).

According to the no-hair theorem (Misner et al. 1973) the magnetic flux on a BH event horizon in vacuum will inevitably decay over time (Price 1972). However, BHs born from magnetized progenitors will, very likely, not be isolated in a vacuum but be surrounded by a (conductive) plasma, thereby changing the magnetospheric dynamics. In a stationary axisymmetric magnetosphere, poloidal magnetic field loops with their ends penetrating the event horizon can only exist if supported by non-force-free currents (MacDonald & Thorne 1982; Gralla & Jacobson 2014). It follows that in a force-free magnetosphere, an inherited closed magnetic field geometry, e.g., typically assumed to be a dipole, will inevitably evolve into a split monopole geometry (Komissarov 2004; Lyutikov & McKinney 2011; Bransgrove et al. 2021) in which the current sheet extends all the way to the event horizon. In the limit of infinite conductivity the magnetic field would be prevented from decaying. However in nature, although typically extremely high, a finite conductivity allows for magnetic reconnection leading to magnetic field decay (Lyutikov & McKinney 2011; Bransgrove et al. 2021). This is in contrast to the case of a neutron star (NS), where reconnection occurs past the light-cylinder and the flux through the assumed perfectly conducting NS surface remains unchanged (Goldreich & Julian 1969; Bogovalov 1999; Philippov et al. 2019).

A strikingly similar situation of a BH shedding its event horizon magnetic flux through magnetic reconnection could occur in accreting BHs in the magnetically arrested disk (MAD) state and may result in observable powerful X-ray and gamma-ray flares (Ripperda et al. 2020; Chashkina et al. 2021; Ripperda et al. 2022; Hakobyan et al. 2022).

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# Flares hunting in hot subdwarf and white dwarf stars from Cycles 1-5 of TESS photometry

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## ABSTRACT

Stellar flares are critical phenomena on stellar surfaces, which are closely tied to stellar magnetism. While extensively studied in main-sequence (MS) stars, their occurrence in evolved compact stars, specifically hot subdwarfs and white dwarfs (WDs), remains scarcely explored. Based on Cycles 1-5 of TESS photometry, we conducted a pioneering survey of flare events in ∼12 000 compact stars, corresponding to ∼38 000 light curves with 2-minute cadence. Through dedicated techniques for detrending light curves, identifying preliminary flare candidates, and validating them via machine learning, we established a catalog of 1016 flares from 193 compact stars, including 182 from 58 sdB/sdO stars and 834 from 135 WDs, respectively. However, all flaring compact stars showed signs of contamination from nearby objects or companion stars, preventing sole attribution of the detected flares. For WDs, it is highly probable that the flares originated from their cool MS companions. In contrast, the higher luminosities of sdB/sdO stars diminish companion contributions, suggesting that detected flares originated from sdB/sdO stars themselves or through close magnetic interactions with companions. Focusing on a refined sample of 23 flares from 13 sdB/sdO stars, we found their flare frequency distributions were slightly divergent from those of cool MS stars; instead, they resemble those of hot B/A-type MS stars having radiative envelopes. This similarity implies the flares on sdB/sdO stars, if these flares did originate from them, may share underlying mechanisms with hot MS stars, which warrants further investigation.

*Keywords:* Compact star — Photometry — Stellar Flare — Machine Learning — Random Forest

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## 1. INTRODUCTION

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# Pulsation in TESS Objects of Interest

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ABSTRACT

We report the discovery of three Transiting Exoplanet Survey Satellite Objects of Interest (TOI) with signatures of pulsation, observed in more than one sector. Our main goal is to explore how large is the variety of classical pulsators such as $\delta$ Sct, $\gamma$ Dor, RR Lyrae and Cepheid among TOI pulsators. The analysis reveals two stars with signatures of $\delta$ Sct and one of $\gamma$ Dor, out of a sample of 3901 TOIs with available light curves (LCs). To date, there is a very scarce number of known pulsating stars hosting planets. The present finding also emerges as an exciting laboratory for studying different astrophysical phenomena, including the effects of star-planet interaction on pulsation and timing detection of planetary companions. We have also identified 16 TOI stars with periodicities and LCs morphology compatible with different classical pulsating classes, but for most of them, the dominant frequency signals originate from contaminating sources.

*Keywords:* Transit photometry; Substellar companion stars; Star-planet interactions; Stellar pulsations

## 1. INTRODUCTION

Stellar pulsation represents a unique laboratory to test a variety of crucial questions concerning star evolution, including the distribution of material between core and envelope, stellar size determination, radial surface velocities, mass-loss dynamics in AGB variables, and mass-transfer in close binary systems (e.g., Chaplin & Miglio 2013; Aerts 2021). Pulsation and stellar rotation can act on the atmospheres to create other mixing effects, affecting atmospheric observables (Anderson et al. 2016). Stellar pulsation can also affect the efficiency of nucleosynthesis products measured in the atmosphere or during mass-loss (e.g., Karakas et al. 2012; Stancliffe et al. 2013). Stars with pulsation also represent interesting laboratories for planet detection, using light travel time variations, a phenomenon resulting from mutual gravitational interaction between a pulsating star and an orbital companion (Wolszczan & Frail 1992; Sigurdsson et al. 2003; Suleymanova & Rodin 2014; Starovoit & Rodin 2017; Hey et al. 2020), or from the identification of orbital modulation of planets in very tight orbits, caused by the reflected light from the illuminated side of the planetary companion (e.g.: Charpinet et al. 2011; Silvotti et al. 2014).

A study by von Essen et al. (2020) has identified non-radial pulsations in TIC 129979528, a star hosting a known planet ultra-hot Jupiter (WASP-33b), with periods comparable to the period of the primary transit, from observations collected by the Transiting Exoplanet

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# The statistics of Rayleigh-Levy flight extrema

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**ABSTRACT**

Rayleigh-Levy flights have played a significant role in cosmology as simplified models for understanding how matter distributes itself under gravitational influence. These models also exhibit numerous remarkable properties that enable the prediction of a wide range of characteristics. Here, we derive the one and two point statistics of extreme points within Rayleigh-Levy flights spanning one to three dimensions, stemming directly from fundamental principles. In the context of the mean field limit, we provide straightforward closed-form expressions for Euler counts and their correlations, particularly in relation to their clustering behaviour over long distances. Additionally, quadratures allow for the computation of extreme value number densities. A comparison between theoretical predictions in 1D and Monte Carlo measurements shows remarkable agreement. Given the widespread use of Rayleigh-Levy processes, these comprehensive findings offer significant promise not only in astrophysics but also in broader applications beyond the field.

**Key words.** Cosmology – Clustering – large scale structures – Method: Analytical, numerical.



## 1. Introduction

The geometry and structure of cosmic fields form a complex physical system that develops from homogeneity through the interplay of expansion and long-range forces. Its statistical properties should emulate those of such a class of systems. From the perspective of observational cosmology, its evolution mirrors both the history of the universe's expansion rate and the dynamic growth of embedded substructures (see for instance Bardeen et al. 1986; Bernardeau et al. 2002, for an account of the emergence of structure due to gravitational instability). While the small scale – galaxy size – structures are determined by the interaction of gravitational effects and complex baryonic physics, the large-scale structure is shaped solely by the development of the gravitational instabilities.

The most standard approach to describe the outcome of this evolution is to consider the matter correlation functions, or equivalently in Fourier space, the spectra (e.g. Peebles & Groth 1975; Fry 1985; Bernardeau 1994; Scoccimarro et al. 1998; Cappi et al. 2015). Those quantities capture however only partially the outcome of the gravitational processes. In particular gravitational instabilities leads to the formation of large scale structures, such as self gravitating massive haloes embedded in an intricate cosmic web made of voids, walls and filaments that are woven together under the influence of gravity (Bond et al. 1996). Inspired by such emerging features, a related alternative to quantify the properties of the field is to explore the topology of the excursion of the cosmic web. It can be done both in real space (e.g. Matsubara 1994; Gay et al. 2012) and redshift space (e.g. Matsubara 1996; Codis et al. 2013), using tools such as the void probability function (VPD, e.g. White 1979; Sheth & van de Weygaert 2004), the Euler-Poincaré characteristic (e.g. Gott et al. 1986; Park & Gott 1991; Appleby et al. 2018), or more generally Minkowski functionals (e.g. Mecke et al. 1994; Schmalzing & Buchert 1997), persistent homology (e.g. Sousbie et al. 2011; Pranav et al. 2017), and Betti numbers (e.g. Park et al. 2013; Feldbrugge et al. 2019). Given the duality established by Morse-Smale theory (Forman 2002) between the geometry or topology of excursion, and the loci of null gradients of the underlying density field, a summary statistics is given by the point process of these critical points (e.g. Bardeen et al. 1986; Bond et al. 1996; Gay et al. 2012; Cadiou et al. 2020). For instance, there has recently been some interest in also using the clustering of such points as cosmological probes (Baldauf et al. 2020; Shim et al. 2021), e.g., extracted from Lyman-$\alpha$ tomography (Kraljic et al. 2022). Unfortunately, the theory for capturing their statistics has been limited to the quasi Gaussian limit (e.g. Pogosyan et al. 2009), or slightly beyond (Bernardeau et al. 2015), while relying on the large deviation principle. This puts limitation on its realm of application to larger scales only (or involves relying on calibration over N-body simulations).

A notable cosmologically relevant counterexample is provided by Rayleigh-Levy flights[1] (Mandelbrot 1975; Peebles 1980; Szapudi & Colombi 1996; Zimbardo & Perri 2013; Uchaikin 2019), which are simply defined as a Markov chain point process whose jump probability depends on some power law of the length of the jump alone. In 3D, it acts as a coarse proxy to describing the motion of dark halos (Sefusatti & Scoccimarro 2005; Trotta & Zimbardo 2015), but its definition can be extended to arbitrary dimensions. Rayleigh-Levy flights were first introduced in astrophysics by Holtsmark (1919) in the context of fluctuations in gravitational systems (Litovchenko 2021). They have some connection first passage theory (Metzler 2019), underlying Press Schechter theory for halo formation (Press & Schechter 1974), and subsequent mass accretion (Musso et al. 2018). Rayleigh-Levy flights have also attracted lots of attention beyond cosmology, (from anomalous cosmic rays diffusion Wilk & Włodarczyk 1999; Boldyrev & Gwinn 2003, to ISM scintillation) or indeed beyond astronomy (from turbulence, Shlesinger et al. 1987; Sotolongo-Costa et al. 2000, to earthquakes), and

[1] See Klages et al. (2008) for a fairly recent review.

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# Evaluating Classification Algorithms: Exoplanet Detection using Kepler Time Series Data

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## ABSTRACT

This study presents a comprehensive evaluation of various classification algorithms used for the detection of exoplanets using labeled time series data from the Kepler mission. The study investigates the performance of six commonly employed algorithms, namely Random Forest, Support Vector Machine, Logistic Regression, K-Nearest Neighbors, Naive Bayes, and Decision Tree. The evaluation process involves analyzing a dataset that consists of time series measurements of star brightness, accompanied by labels indicating the presence or absence of exoplanets. To assess the effectiveness of each algorithm in accurately identifying exoplanets, performance metrics such as accuracy, precision, recall, and F1 score are employed. The results demonstrate that the Random Forest algorithm achieves the highest accuracy of 94.2%, followed closely by the Support Vector Machine with 93.8 percent accuracy. The Logistic Regression algorithm achieves an accuracy of 91.5 percent, while the K-Nearest Neighbors, Naive Bayes, and Decision Tree algorithms achieve accuracies of 89.6%, 87.3%, and 85.9% respectively. Furthermore, the precision, recall, and F1 score metrics provide insights into the strengths and weaknesses of each classifier. The Random Forest algorithm exhibits a precision of 0.92, recall of 0.95, and F1 score of 0.93, indicating a balanced performance in correctly identifying both positive and negative instances. The Support Vector Machine also demonstrates strong performance with precision, recall, and F1 score values of 0.91, 0.94, and 0.92 respectively. The evaluation demonstrates that Random Forest and Support Vector Machine algorithms are well-suited for exoplanet detection using Kepler time series data. These findings enhance our understanding of the detection process and assist in selecting suitable algorithms for future studies.

**Keywords:** Exoplanet detection, Support Vector Machine, data analysis, Accuracy, precision, recall, F1 score.

## 1. INTRODUCTION

Detecting exoplanets, planets that orbit stars outside our solar system, is a fascinating and rapidly evolving field of research that has revolutionized our understanding of the universe and the potential for extraterrestrial life [1]. Over the years, various methods have been employed to identify exoplanets, such as the radial velocity

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# NEW STAIRWAYS TO THE STARS. BIRTH AND EVOLUTION OF TWO PIONEERING USENET NEWSGROUPS IN ASTROPHYSICS (1983-1994)

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List of abbreviations:
GG: Google Groups
Cmc: computer-mediated communication

**Abstract:** The foundation of two pioneering Usenet newsgroups in astrophysics - still existent today - and some of the main milestones in their history have been tracked from the origins at Princeton University in 1983 to 1994. To this aim, in line with authoritative recommendations from the discipline of web history, different kinds of sources have been retrieved and combined: mainly, online archives of Usenet newsgroups and human sources. The latter have included on one side the kind contribution provided by four astrophysicists, two of which had a role in the maintaining of these newsgroups, through individual interviews; on the other side that from the sixty-seven researchers who answered a purpose-built questionnaire submitted within the Italian National Institute for Astrophysics in May 2023.

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# CDM and SIDM Interpretations of the Strong Gravitational Lensing Object JWST-ER1

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## ABSTRACT

van Dokkum et al. (2023) reported the discovery of JWST-ER1, a strong lensing object at redshift $z \approx 2$, using data from the James Webb Space Telescope. The lens mass within the Einstein ring is 5.9 times higher than the expected stellar mass from a Chabrier initial mass function, indicating a high dark matter density. In this work, we show that a cold dark matter halo, influenced by gas-driven adiabatic contraction, can account for the observed lens mass. We also derive constraints on dark matter self-interacting cross section per particle mass $\sigma/m$. For $\sigma/m \gtrsim 0.3$ cm$^2$/g within a $10^{13}$ $M_\odot$ halo, the density profile is too shallow to be consistent with the measured lens mass of JWST-ER1, while $\sigma/m \approx 0.1$ cm$^2$/g is well allowed. Intriguingly, self-interacting dark matter with $\sigma/m \approx 0.1$ cm$^2$/g can simultaneously explain the dark matter density profile of early-type galaxies at redshift $z \approx 0.2$, where adiabatic contraction is not observed overall.

*Keywords:* Dark matter (353); Strong gravitational lensing (261); Early-type galaxies (429); Galaxy dark matter halos (1880)

## 1. INTRODUCTION

Recently, van Dokkum et al. (2023) used data from the James Webb Space Telescope COSMOS-Web survey and found a strong lensing object JWST-ER1 at redshift $z \approx 2$. The object consists of a complete Einstein ring with a radius of 6.6 kpc and a compact early-type galaxy (JWST-ER1g) with an effective radius of 1.9 kpc. Within the ring, the total mass is $6.5\times10^{11}$ $M_\odot$, while the stellar mass mass is $1.1 \times 10^{11}$ $M_\odot$ assuming a Chabrier initial mass function (Chabrier 2003). The mass gap is large, indicating that JWST-ER1g has a dense halo. However, for a typical Navarro-Frenk-White (NFW) halo (Navarro et al. 1997), the dark matter density is not high enough to fully account for the mass gap, unless the halo mass is $10^{14}$ $M_\odot$ (van Dokkum et al. 2023), which would be rare at $z \sim 2$, significantly higher than expected in the stellar mass-halo mass relation (Behroozi et al. 2013).

Mercier et al. (2023) also analyzed the JWST-ER1 system and found the total mass is $3.7\times10^{11}$ $M_\odot$ within the Einstein ring, a factor of 2 smaller than that in van Dokkum et al. (2023), and a $10^{13}$ $M_\odot$ halo is favored for JWST-ER1g. The main reason is that their redshift measurements of the background source are different: $z \approx 2.98$ in van Dokkum et al. (2023), whereas $z \approx 5.48$ in Mercier et al. (2023); their other measurements are well consistent.

Another complication is that the population of low-mass stars could be higher than expected. For example, Salpeter-like initial mass functions can give rise to a good fit (van Dokkum et al. 2023), though the bottom-light Chabrier form is overall favored for quiescent galaxies at $z \gtrsim 2$ (Esdaile et al. 2021; Belli et al. 2014). While more work is needed to further improve our understanding of the JWST-ER1 system, we explore its rich implications for probing dark matter physics.

In this work, we interpret the observations of JWST-ER1 in collisionless cold dark matter (CDM) and self-interacting dark matter (SIDM) scenarios. In CDM, the halo can become denser due to adiabatic contraction induced by the infall and condensation of baryons (Blumenthal et al. 1986; Gnedin et al. 2004). We will show that the contraction effect on the halo is beyond the stellar effective radius and it is important for the interpretation of JWST-ER1. After including adiabatic contraction in modeling the halo of JWST-ER1g, the favored halo mass is reduced to $3 \times 10^{13}$ $M_\odot$, to be consistent with the measurement in van Dokkum et al. (2023); or $6 \times 10^{12}$ $M_\odot$ in Mercier et al. (2023).

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# Comparing transit spectroscopy pipelines at the catalogue level: evidence for systematic differences

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**ABSTRACT**

The challenge of inconsistent results from different data pipelines, even when starting from identical data, is a recognized concern in exoplanetary science. As we transition into the James Webb Space Telescope (JWST) era and prepare for the ARIEL space mission, addressing this issue becomes paramount because of its implications on our understanding of exoplanets. Although comparing pipeline results for individual exoplanets has become more common, this study is the first to compare pipeline results at the catalogue level. We present a comprehensive framework to statistically compare the outcomes of data analysis reduction on a population of exoplanets and we leverage the large number of observations conducted using the same instrument configured with HST-WFC3. We employ three independent pipelines: Iraclis, EXCALIBUR, and CASCADe. Our combined findings reveal that these pipelines, despite starting from the same data and planet system parameters, yield substantially different spectra in some cases. However, the most significant manifestations of pipeline differences are observed in the compositional trends of the resulting exoplanet catalogues. We conclude that pipeline-induced differences lead to biases in the retrieved information, which are not reflected in the retrieved uncertainties. Our findings underscore the critical need to confront these pipeline differences to ensure the reproducibility, accuracy, and reliability of results in exoplanetary research. Our results demonstrate the need to understand the potential for population-level bias that pipelines may inject, which could compromise our understanding of exoplanets as a class of objects.

**Key words:** exoplanets – techniques: spectroscopic – software: data analysis

## 1 INTRODUCTION

A successful methodology for detecting atomic and molecular species and unveiling the atmospheric chemistry of exoplanets involves the use of multi-band transit photometry and spectroscopy (e.g. Charbonneau et al. 2002; Tinetti et al. 2007; Swain et al. 2008, 2009; Tsiaras et al. 2016a; Chachan et al. 2019; Mugnai et al. 2021a; Swain et al. 2021). Current space instrumentation, such as the Spitzer and Hubble Space Telescopes, have facilitated the atmospheric characterization of approximately sixty exoplanets over a limited wavelength range (e.g. Sing et al. 2016; Iyer et al. 2016; Barstow et al. 2017; Tsiaras et al. 2018; Edwards et al. 2022; Estrela et al. 2022). However, these instruments were not specifically designed for exoplanetary science, necessitating specialized data reduction pipelines to remove instrument systematics that are similar in amplitude to the astrophysical signal (Deming et al. 2013; Tsiaras et al. 2016b).

To interpret the observed spectra, spectral retrieval techniques are commonly used to estimate astrophysical parameters (e.g. Irwin et al. 2008; Madhusudhan & Seager 2009; Line et al. 2013; Lee et al. 2013; Waldmann et al. 2015; Gandhi & Madhusudhan 2017; Lavie et al. 2017; Al-Refaie et al. 2021a). Studies have been conducted to compare and validate different retrieval models, demonstrating their robustness and consistency (Barstow et al. 2020, 2022). However, a similar in-depth large-scale validation has not been performed for data reduction pipelines, which estimate the spectra from raw data. Uncharacterized biases introduced at this stage of data analysis can potentially undermine the correct interpretation of observations using retrieval techniques. While the recent literature does chronicle multiple validation endeavours, these comparisons are undertaken on a singular-planet basis. A remarkable example of this trend is offered by the Early Release Science of James Webb Telescope: Alderson et al. (2023); Rustamkulov et al. (2023); Ahrer et al. (2023); Feinstein et al. (2023); Holmberg & Madhusudhan (2023). Thus, there is a compelling need for holistic, population-centric validation, which is the cornerstone of our proposed study.

The data reduction process for exoplanet transit spectroscopy has a number of steps where differences in methods have the potential to produce differences in final outcomes. A nonexhaustive list of specific areas where method differences might influence the final outcome includes; spectral extraction and background subtraction, interpolation errors associated with placing spectra on a common wavelength grid, system parameter values, astrophysical models such as the detailed

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# Tracing the Galactic disk from the kinematics of Gaia Cepheids

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## ABSTRACT

Classical Cepheids (CCs) are excellent tracers for understanding the structure of the Milky Way disk. The latest Gaia Data Release 3 provides a large number of line-of-sight velocity information for Galactic CCs, offering an opportunity for studying the kinematics of the Milky Way. We determine the three-dimensional velocities of 2057 CCs relative to the Galactic center. From the projections of the 3D velocities onto the XY plane of the Galactic disk, we find that $V_R$ and $V_\phi$ velocities of the northern and southern warp (directions with highest amplitude) are different. This phenomenon may be related to the warp precession or the asymmetry of the warp structure. By investigating the kinematic warp model, we find that the vertical velocity of CCs is more suitable for constraining the warp precession rate than the line of nodes angles. Our results suggest that CCs at $12-14$ kpc are the best sample for determining the Galactic warp precession rate. Based on the spatial structure parameters of Cepheid warp from Chen et al. (2019), we determine a warp precession rate of $\omega = 4.9 \pm 1.6$ km s$^{-1}$ kpc$^{-1}$ at 13 kpc, which supports a low precession rate in the warp model. In the future, more kinematic information on CCs will help to better constrain the structure and evolution of the Milky Way.

*Keywords:* Galaxy structure (622); Milky Way disk (1050); Galaxy rotation curves (619); Stellar kinematics (1608); Cepheid variable stars (218)

## 1. INTRODUCTION

Exploring the structure and evolution history of the Milky Way is one of the most important topics in astronomy. Constructing geometric and kinematic models of the Milky Way is limited by our location in the Galaxy and the effects of interstellar extinction, so a complete picture cannot be constructed as easily as for other galaxies. The research on the structure of the Galactic disk has been broadly divided into radial and vertical directions. In the radial direction, since the 1950s, we have known that the Milky Way has a spiral arm structure through the distribution of local OB associations (Morgan et al. 1953). Since then, many works have been devoted to studying the spiral arms of the Milky Way's disk (Reid et al. 2014, 2016; Xu et al. 2016). Reid et al. (2019) updated the logarithmic model of the spiral arms, and identified the main spiral arms as Norma-Outer arm, Sagittarius-Carina arm, Scutum-Centaurus arm, and Perseus arm, as well as an isolated segment, the Local arm. In addition, the Galactic disk has strong asymmetry and rich structures in velocity space. In particular, the structure of arches and ridges can be seen in Galactocentric azimuthal velocity and radius space (Antoja et al. 2018; Ramos et al. 2018; Fragkoudi et al. 2019; Khanna et al. 2019; Wang et al. 2020a). However, the dynamical nature of these phenomena and their formation mechanism remain unclear. Existing explanations include resonances with the bar (Trick et al. 2019; Monari et al. 2019; Laporte et al. 2020; Trick et al. 2021) and/or processes with spiral arms (Monari et al. 2019; Barros et al. 2020) and/or external perturbations such as the Sagittarius dwarf galaxy perturbation (Binney & Schönrich 2018; Bland-Hawthorn et al. 2019; Khanna et al. 2019).

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# Anomaly Detection for GONG Doppler Imagery Using a Binary Classification Neural Network

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**Abstract**

One of the products of the National Solar Observatory's Integrated Synoptic Program (NISP) is the farside seismic map which shows the magnetic activity on the unobserved side of the Sun. The production of these rudimentary maps began in 2006, and they have since proven to be a valuable tool in tracking solar activity which cannot be directly observed from the earth's surface. The continuous tracking of solar active regions allows space weather forecasters to monitor critical solar events which may have larger economic and societal impacts here on Earth. In an effort to improve these maps, several steps are underway through the Windows on the Universe project (WoU) funded by the NSF. One of these steps is to improve the quality assurance measures for the images collected at individual sites throughout the GONG network and is used to develop the farside maps. To this end, we have designed a binary classification neural network to determine which of these site images should and should not be included in the farside pipeline that produces the end product maps. This convolutional neural network is a highly effective and computationally efficient method of significantly improving the quality of the farside maps currently produced by the NISP program.

# Cosmological imprints in the filament with DisPerSE

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**ABSTRACT**
In the regime of cosmology and large-scale structure formation, filaments are vital components of the cosmic web. This study employs statistical methods to examine the formation, evolution, and cosmological constraints of filaments identified by DisPerSe. We run large-sample of N-body simulations to study the filament length and mass functions and their evolution. In general, the filament length function can be fitted by a power law with both the normalization and power index dependent on redshift and cosmological parameters. It is discovered that filament properties are influenced by various cosmological parameters, with $\sigma_8$ and $n_s$ exhibiting slightly stronger dependence than $\Omega_m$. We also uncover a three-stage filament formation process from $z \sim 3$ to $z \sim 1$: rapid formation of long and short filaments from $z \sim 3$ to $z \sim 2$, persistence of long filaments from $z \sim 2$ to $z \sim 1$, followed by fragmentation and increased prevalence of shorter filaments below $z \sim 1$. Additionally, both large and small-scale perturbations in power spectrum influence filament growth, with a characteristic scale around $k \sim 0.265$, wherein changes in matter fluctuations larger than this scale result in the formation of long filaments, while changes smaller than this scale have the opposite effect. These insights enhance our understanding of filament evolution and their cosmological relevance and also highlight their potential cosmological applications in observations.

**Key words:** Cosmology: cosmological parameters – large-scale structure of universe; Methods: statistical

**CONTENTS**



## 1 INTRODUCTION

The structure of the Universe on a large scale is in a web-like pattern referred to as the cosmic web (Bond et al. 1996) composed of clusters, filaments, walls, and voids. It is a colossal system of dark matter and baryon that emerged due to gravity's influence from the anisotropic collapse of initial density field fluctuations(Zel'dovich 1970). One of the principal challenges in observational and theoretical cosmology is to comprehend the physical properties and evolution of the different structures of the cosmic web.

Numerical simulations demonstrate that the cosmic web is characterized by the formation of nodes in dense regions, interconnected by filaments and sheets, while most regions are dominated by voids with incredibly low density. Filament plays an import role in large scale structures. Although galaxy clusters are easily detected and characterised in the large-scale structure and galaxy formation, it is predicted that filamentary structures contain the largest fraction of baryon (Aragón-Calvo et al. 2010a; Cen & Ostriker 2006; Cautun et al. 2014). With the advent of wide-area spectroscopic redshift surveys, filaments can be detected by surveys such as the Two-Degree Field Galaxy Redshift Survey (2dFGRS, Colless et al. (2003)), the Sloan Digital Sky Survey (SDSS, Gunn et al. (2006)), the Galaxy And Mass Assembly survey (GAMA, Driver et al. (2011)), the Vimos Public Extragalactic Redshift Survey (VIPERS, Scodeggio et al. (2018)), two micron all sky survey (2MASS, Gunn et al. (2006)) , and the COSMOS survey (Laigle et al. 2018). Therefore, filaments

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# Flows of Local Sheet Dwarfs in Relation to the Council of Giants

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**ABSTRACT**
The kinematics of isolated dwarf galaxies in the Local Sheet have been studied to ascertain how the Council of Giants has affected flows. Peculiar velocities parallel to the Sheet in the frame of reference of the Council ascend steeply from negative to positive values on the near side of the Council at a heliocentric radius of $2.4 \pm 0.2$ Mpc. They descend to preponderantly negative values at a radius of $3.9^{+0.4}_{-0.5}$ Mpc, which is near the middle of the Council realm. Such behaviour is evidence for a flow field set up by the combined gravitational effects of the Local Group and Council, the ascending node being where their gravitational forces balance. Receding dwarfs on the near side of the Council are predominantly located in the direction of M94, although this may be a manifestation of the limitations of sampling. If M94 were entirely responsible for the placement of the ascending node, then the galaxy's total mass relative to the Local Group would have to be $0.8^{+0.4}_{-0.3}$, the same as indicated by the orbits of satellite galaxies. Rather, if the placement of the ascending node were set by matter distributed evenly in azimuth at the Council's radius, then the required total mass relative to the Local Group would have to be $4^{+3}_{-2}$, which is 30% to 40% lower than implied by satellite motions but still consistent within errors. The mere existence of the ascending node confirms that the Council of Giants limits the gravitational reach of the Local Group.

**Key words:** galaxies: distances and redshifts – galaxies: kinematics and dynamics – galaxies: evolution – galaxies: dwarf – Local Group – large-scale structure of Universe

## 1 INTRODUCTION

The Local Group is encircled by giants in the Local Sheet ($M_{Ks} \leq -22.5$) concentrated around a mean radius of 3.75 Mpc from a centre which is offset from the Sun by 0.8 Mpc (see Figure 1). The collection is dynamically distinct from the Local Supercluster because angular momentum vectors are organized very differently from those of galaxies beyond. The configuration has been called the "Council of Giants" (McCall 2014). Although the Council may have arisen by chance, it nevertheless represents a proximate concentration of bright galaxies with an unusually high density relative to the field and simulated analogues of the Local Volume (Neuzil et al. 2020). As such, it may have influenced the development of the Local Group, because the gravitation of the Council limits the region of space from which the Local Group is able to pull matter.

If indeed the Council of Giants has influenced local evolution, then evidence may be found today in the peculiar motions of galaxies in the Local Sheet on either side of a boundary nearer than the Council where the gravitational forces of the Local Group and the Council balance. Galaxies on the near side of the boundary (i.e., closer to the Local Group) should be drawn towards the Local Group and consequently should be moving towards it. Galaxies on the far side of the boundary but still on the near side of the Council ought to be drawn towards the Council and consequently should be moving away from the Local Group. Galaxies on the far side of the Council should be drawn towards the Council also, but should be moving towards the Local Group. This paper focuses on the motions of isolated dwarf galaxies in the frame of reference of the Council to determine if there are any flows that fit this pattern. Karachentsev and collaborators have conducted many studies of the motions of galaxies in groups located in the Local Sheet (Karachentsev et al. 2002a,b,c, 2003a,c,b; Karachentsev 2005), but as far as is known no investigation of motions more globally has been conducted in relation to the Council of Giants.

In §2, the sample of dwarfs used to probe local flows is constructed. Positions and peculiar velocities are established in §3. In §4, the spatial distribution of peculiar velocities is examined and evidence for organized motions is presented. Implications are discussed in §5, and conclusions are presented in §6.

## 2 SAMPLE OF GALAXIES

Many dwarf galaxies are suitable to use as test particles for studying flows within constituents of the cosmic web. Motions that deviate from the Hubble flow incorporate responses to the gravitational field of the environment, yet the dwarfs themselves have little effect on the organization of the massive bodies establishing that field. Fur-

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# Water-Ice Dominated Spectra of Saturn's Rings and Small Moons from JWST

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**Key Points:**

- Near-IR spectra of Saturn's small moons and rings obtained by JWST's NIRSpec show water ice bands with different degrees of crystallinity.
- Near-IR spectra of Saturn's A ring confirm the existence of an O-D absorption band and may contain a weak aliphatic hydrocarbon band.
- Mid-IR spectra of Saturn's rings obtained by JWST's MIRI reveal a reflectance peak at 9.3 microns due to highly crystalline water ice.

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**Abstract**

JWST measured the infrared spectra of Saturn's rings and several of its small moons (Epimetheus, Pandora, Telesto and Pallene) as part of Guaranteed Time Observation program 1247. The NIRSpec instrument obtained near-infrared spectra of the small moons between 0.6 and 5.3 microns, which are all dominated by water-ice absorption bands. The shapes of the water-ice bands for these moons suggests that their surfaces contain variable mixes of crystalline and amorphous ice or variable amounts of contaminants and/or sub-micron ice grains. The near-infrared spectrum of Saturn's A ring has exceptionally high signal-to-noise between 2.7 and 5 microns and is dominated by features due to highly crystalline water ice. The ring spectrum also confirms that the rings possess a 2-3% deep absorption at 4.13 microns due to deuterated water ice previously seen by the Visual and Infrared Mapping Spectrometer onboard the Cassini spacecraft. This spectrum also constrains the fundamental absorption bands of carbon dioxide and carbon monoxide and may contain evidence for a weak aliphatic hydrocarbon band. Meanwhile, the MIRI instrument obtained mid-infrared spectra of the rings between 4.9 and 27.9 microns, where the observed signal is a combination of reflected sunlight and thermal emission. This region shows a strong reflectance peak centered around 9.3 microns that can be attributed to crystalline water ice. Since both the near and mid-infrared spectra are dominated by highly crystalline water ice, they should provide a useful baseline for interpreting the spectra of other objects in the outer solar system with more complex compositions.

## Plain Language Summary

Saturn's rings and small moons are all composed primarily of very pure water ice, making them useful targets for characterizing the performance of the various instruments onboard JWST. Observations of multiple small moons at near-infrared wavelengths demonstrate the ability of JWST to detect faint objects in the outer solar system, and reveal that the water ice on these bodies is not always organized into large, pure crystals. Observations of Saturn's rings, by contrast, confirm that they are composed of very pure and highly crystalline water ice. These data also provide new constraints on the amounts of carbon-containing compounds that could be present in the rings.

## 1 Introduction

The infrared spectra of Saturn's rings and small moons have been well characterized thanks to extensive observations obtained by the Visual and Infrared Mapping Spectrometer (VIMS) and Composite Infrared Spectrometer (CIRS) onboard the Cassini spacecraft (R. H. Brown et al., 2004; Flasar et al., 2004). Observations of these objects with the instruments onboard JWST therefore provide opportunities not only to obtain new information about the rings and small moons themselves, but also to evaluate the performance of JWST's instruments, particularly the Integral Field Unit (IFU) components of NIRSpec and MIRI (Gardner et al., 2023; Jakobsen et al., 2022; Böker et al., 2022, 2023; Wright et al., 2023).

A wide range of spectroscopic observations demonstrate that Saturn's main rings are composed of very pure and highly crystalline water ice. While there is evidence that the rings do contain variable amounts of non-icy materials that influence both the overall brightness of the rings and the shape of their spectra at visible and ultraviolet wavelengths (Clark et al., 2008, 2019; Cuzzi et al., 2009, 2018; Filacchione et al., 2012, 2014; Hedman et al., 2013; Nicholson et al., 2008), detailed modeling of infrared and radio data indicate that most of the rings are over 99% water ice (Ciarniello et al., 2019; Zhang et al., 2019). Indeed, while some observations by Cassini-VIMS have indicated that there could be weak ($\sim 3\%$) hydrocarbon features between 3.4 $\mu$m and 3.6 $\mu$m throughout the rings (Filacchione et al., 2014), extremely high signal-to-noise spectra of the B ring contained no non-water-ice spectral features between 1 and 5 $\mu$m at the $\sim$1% level, but did exhibit a 2-3% brightness dip

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# Multiwavelength Catalog of 10,000 4XMM-DR13 Sources with Known Classifications.

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## ABSTRACT

We present a collection of $\sim 10,000$ X-ray sources from the 4th XMM-Newton Serendipitous Source Catalog (4XMM-DR13) with literature-verified classifications and multi-wavelength (MW) counterparts. We describe the process by which MW properties are obtained and an interactive online visualization tool we developed.

## INTRODUCTION

Collections of reliably classified X-ray sources can be used for training supervised machine learning algorithms which can then quickly classify large numbers of X-ray sources (see e.g., McGlynn et al. 2004; Yang et al. 2022; Tranin et al. 2022). While bright X-ray sources can often be classified solely from X-ray properties, the classification of fainter but much more numerous sources can greatly benefit from including properties of their multiwavelength (MW) counterparts. We created such dataset[1] from 4XMM-DR13 (Webb et al. 2020).

## METHODS

We searched the literature described in Yang et al. (2021, 2022), with the addition of the following class-specific catalogs Jackim et al. (2020); Oh et al. (2018); Liu et al. (2019); Fortin et al. (2023); Neumann et al. (2023); Avakyan et al. (2023); Szkody et al. (2011); Drake et al. (2009); Inight et al. (2023); Luo et al. (2015) , for reliably classified sources. These sources were sorted into 9 broad astrophysical classes: active galactic nuclei (AGN), pulsars and isolated neutron stars (NS), non-accreting X-ray binaries (NS BIN)[2], cataclysmic variables (CV), high-mass X-ray binaries (HMXB), low-mass X-ray binaries (LMXB), high-mass stars (HM-STAR)[3], low-mass stars (LM-STAR) and young stellar objects (YSO). We then cross-matched these sources with 4XMM-DR13 within $r = 10''$, avoiding some particularly crowded environments (e.g., globular clusters, galaxies, the Galactic center), regions with complex diffuse X-ray emission (e.g., bright pulsar wind nebulae, supernova remnants) or infrared (IR)-bright fields (e.g., central parts of star-forming regions). Sources of populous classes (AGN, HM-STAR, LM-STAR, CV, and YSO) were omitted if the separations of their 4XMM-DR13 counterparts were larger than the combined positional uncertainties (PUs) from the literature and 4XMM-DR13 (at 95% confidence) or $> 3''$. For rare-type sources, we manually checked the counterparts by reviewing the publications on individual sources and inspecting the X-ray and MW images. Furthermore, all selected sources were matched to SIMBAD (Wenger et al. 2000), and sources with classifications conflicting with the main SIMBAD class were omitted from the dataset (unless a mistake in the SIMBAD class was identified from looking at the original publications). For 8.5% of our 4XMM-DR13 matches we were able to find matches in the Chandra Source Catalog version 2.1 (Evans et al. 2020) which provides more accurate positional information that we then adopted for these sources.

As a next step, within $r = 30''$ from each selected X-ray source, we combined sources from five all-sky lower-frequency catalogs[4] into a single merged MW catalog. In this process, the sources from (near-)IR catalogs were first matched to

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[1] https://yichaolin-astro.github.io/4XMM-DR13-XCLASS/
[2] Non-accreting binaries, including wide-orbit binaries with millisecond pulsars, red-back, and black widow systems (Strader et al. 2019).
[3] Includes Wolf-Rayet, O, B stars.
[4] *Gaia* DR3 (Gaia Collaboration et al. 2023), *Gaia* EDR3 Distances (Bailer-Jones et al. 2021), Two Micron All-Sky Survey (2MASS; Skrutskie et al. 2006), AllWISE (Cutri et al. 2021), and CatWISE2020 (Marocco et al. 2021)

# Chaotic tides as a solution to the Hyperion problem

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ABSTRACT

The dynamics of the outer regular satellites of Saturn are driven primarily by the outward migration of Titan, but several independent constraints on Titan's migration are difficult to reconcile with the current resonant orbit of the small satellite Hyperion. We argue that Hyperion's rapid irregular tumbling greatly increases tidal dissipation with a steep dependence on orbital eccentricity. Resonant excitation from a migrating Titan is then balanced by damping in a feedback mechanism that maintains Hyperion's eccentricity without fine-tuning. The inferred tidal parameters of Hyperion are most consistent with rapid Titan migration enabled by a resonance lock with an internal mode of Saturn, but a scenario with only equilibrium dissipation in Saturn is also possible.

## 1. Introduction

Much like miniature planetary systems, the regular satellites of Saturn are expected to have originated on nearly coplanar and circular orbits within the circumplanetary disk or the planet's rings. Since their formation, tidal dissipation within Saturn has caused the moons to migrate outwards and encounter mean motion resonances with each other. In some cases, pairs of moons captured into these mean motion resonances and remain there today, while in others there is indirect evidence of the excitation caused by resonant encounters. As such, resonant dynamics offer a unique window into the system's evolutionary past. In the tightly packed inner saturnian system (i.e. interior to Titan), a complex web of resonances sets strict constraints on the relative migration of each moon (Ćuk et al., 2016a; Ćuk and El Moutamid, 2023). In contrast with the well-understood dynamical history of the inner moons, the Titan–Hyperion system is strikingly enigmatic and one of the most remarkable mysteries of Solar System dynamics.

Hyperion, the only satellite in the large gap between Titan and Iapetus, is trapped in an exterior 4:3 mean-motion resonance with Titan. The origins of this orbital configuration have historically been attributed to an outwardly evolving Titan capturing Hyperion into commensurability (Colombo et al., 1974). This scenario is accompanied by specific consequences: preservation of the adiabatic invariant (Henrard, 1982) implies that, assuming no dissipation within Hyperion, Titan must migrate 4% in semi-major axis post-capture (Ćuk et al., 2013) and thus the tidal $Q$ of Saturn must be $Q_♄ < 1500$.[1]

There are, however, contradicting constraints on Titan's migration from Iapetus, the outermost regular satellite of Saturn. Iapetus lies just 0.4% inside the 5:1 mean-motion resonance with Titan, implying a recent but significant dynamical interaction between the moons. During the 5:1 resonant encounter, the eccentricity and inclination of Iapetus evolve chaotically and Titan's migration must be rapid enough to avoid ejecting Iapetus (Ćuk et al., 2013; Polycarpe et al., 2018). Evidently, the preservation of Iapetus necessitates rapid migration of Titan, while Hyperion's resonance demands slow, short-range migration.

Hyperion's rotational properties are equally remarkable, and constitute a unique example of stochastic rotation in the Solar System. Wisdom et al. (1984) predicted that it would be in a chaotically tumbling state before its rotation was directly observed. They argued that given its moderate eccentricity ($e \approx 0.1$) and highly elongated shape (seen in Voyager 2 images), regular rotation in the synchronous (1:1) or 3:2 spin-orbit state is impossible. Instead, a chaotic zone surrounds the 1:1 and 2:1 spin-orbit resonances and Hyperion's spin vector evolves over timescales of a few orbital periods. In addition, Wisdom et al. (1984) demonstrated that much of the parameter space is attitude unstable, so that an initial small obliquity is quickly amplified and rotation inevitably occurs on all three axes. Early ground-based light curve observations by Klavetter (1989) confirmed non-periodic rotation and suggested rotation at roughly the synchronous rate.

Despite the remarkable predictive power of Wisdom et al. (1984)'s calculations, images and light curves taken during the Voyager 2 and Cassini visits to the saturnian system demonstrated that Hyperion was rotating much faster than expected: roughly 4.2 times the synchronous rate (Thomas et al., 1995; Harbison et al., 2011). Rotation mostly occurs around the longest axis and is quasi-regular. Nevertheless, the wobble and precession are indeed clearly chaotic, with typical Lyapunov times of several orbital periods, as measured by Black et al. (1995) and Harbison et al. (2011). Using numerical simulations, Black et al. (1995) showed that this state was not an unexpected outcome—initialized near the synchronous state, Hyperion would irregularly alternate

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[1]However, too much migration of Titan is problematic: if Saturn has especially strong dissipation ($Q_♄ < 500$), Titan and Hyperion would have started wide of the 3:2 resonance and captured into the wrong resonance.

# A simple model of globally magnetized accretion discs

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## ABSTRACT

We present an analytic, quasi-local dynamo model for accretion discs threaded by net, vertical magnetic flux. In a simple slab geometry and ignoring stochastic mean-field dynamo effects, we calculate the large-scale field resulting from the balance between kinematic field amplification and turbulent resistive diffusion. The ability of the disc to accumulate magnetic flux is sensitive to a single parameter dependent on the ratio of the vertical resistive diffusion time to the Alfvén crossing time, and we show how the saturation levels of magnetorotational and other instabilities can govern disc structure and evolution. Under wide-ranging conditions, inflow is governed by large-scale magnetic stresses rather than internal viscous stress. We present models of such "magnetically boosted" discs and show that they lack a radiation pressure-dominated zone. Our model can account for "magnetically elevated" discs as well as instances of midplane outflow and field reversals with height that have been seen in some global simulations. Using the time-dependent features of our model, we find that the incorporation of dynamo effects into disc structure can lead to steady or episodic "magnetically arrested discs" (MADs) that maximize the concentration of magnetic flux in their central regions.


**Key words:** accretion, accretion discs – dynamo – instabilities – MHD – turbulence

## 1 INTRODUCTION

Magnetohydrodynamic (MHD) simulations of accretion discs, in both local (shearing-box) and global setups, yield drastically different outcomes depending on the presence or absence of a large-scale magnetic field, and its strength. An organized vertical magnetic field ($B_z$) of sufficient strength, carrying a net magnetic flux that threads the disc, can have dramatic effects on the inflow speed and vertical disc structure. Even for thin, gas pressure-supported discs, the $B_z B_\phi$ stress can dominate the extraction of angular momentum (Blandford & Payne 1982; Ferreira & Pelletier 1993, 1995), leading to much higher inflow speeds than produced by internal viscous stresses as in the model of Shakura & Sunyaev (1973). Moreover, such discs can become "magnetically elevated" at sufficiently strong $B_z$, with a combination of turbulent and laminar magnetic pressure taking over from gas or radiation pressure as the main source of support. This effect thickens the disc and increases its inflow speed further (Bai & Stone 2013; Salvesen et al. 2016; Zhu & Stone 2018; Lančová et al. 2019; Mishra et al. 2020). For a given accretion rate the disc density is correspondingly reduced, which can significantly affect the disc's thermodynamics and radiative transport.

Magnetic boosting of the inflow speed as well as magnetic elevation can be critical for understanding the dynamics, spectra and stability of accretion discs in a variety of astrophysical systems. Even before these computational trends had been established, the existence of magnetically supported discs had been proposed for phenomenological reasons (Begelman & Pringle 2007; Gaburov et al. 2012; Sądowski 2016; Begelman & Silk 2017; Dexter & Begelman 2019). Yet while magnetic elevation seems to be a robust feature of simulated flows, there is to date no clear explanation of how large-scale, organized magnetic field structures are created, and what factors determine their properties.

Even more extreme are so-called magnetically arrested discs (MADs) (Narayan et al. 2003; Igumenshchev 2008), which have been studied intensively as a type of accretion flow that maximizes the magnetic flux threading a black hole, thus maximizing the potential to extract energy from the black hole's spin (Tchekhovskoy et al. 2011). While the scaling between the accretion rate and trapped magnetic flux in a MAD was initially derived by equating the ram-pressure of free-fall accretion to the magnetic pressure of the trapped flux (Bisnovatyi-Kogan & Ruzmaikin 1974, 1976; Narayan et al. 2003), arguing that the magnetic flux would "arrest" the flow, it has been since recognized MAD models permit continuous accretion and that the accumulation of magnetic flux in a MAD can extend to much larger radii than the black hole horizon, in effect creating a large-scale magnetosphere (McKinney et al. 2012) co-existent with the accretion flow.

Despite the potential for magnetically elevated and arrested discs to explain a wide range of accretion phenomena, there remains deep uncertainty about how to establish and maintain them in the first place. A large body of work, begin-

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# Helioseismic Properties of Dynamo Waves in the Variation of Solar Differential Rotation

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## ABSTRACT

Solar differential rotation exhibits a prominent feature: its cyclic variations over the solar cycle, referred to as zonal flows or torsional oscillations, are observed throughout the convection zone. Given the challenge of measuring magnetic fields in subsurface layers, understanding deep torsional oscillations becomes pivotal in deciphering the underlying solar dynamo mechanism. In this study, we address the critical question of identifying specific signatures within helioseismic frequency-splitting data associated with the torsional oscillations. To achieve this, a comprehensive forward modeling approach is employed to simulate the helioseismic data for a dynamo model that, to some extent, reproduces solar-cycle variations of magnetic fields and flows. We provide a comprehensive derivation of the forward modeling process utilizing generalized spherical harmonics, as it involves intricate algebraic computations. All estimated frequency-splitting coefficients from the model display an 11-year periodicity. Using the simulated splitting coefficients and realistic noise, we show that it is possible to identify the dynamo wave signal present in the solar zonal flow from the tachocline to the solar surface. By analyzing observed data, we find similar dynamo wave patterns in the observational data from MDI, HMI, and GONG. This validates the earlier detection of dynamo waves and holds potential implications for the solar dynamo theory models.

*Keywords:* Sun: waves – Sun: oscillations – solar interior – solar convection zone – solar differential rotation

## 1. INTRODUCTION

Parker (1955) showed that dynamo action involves cyclic transformations of the poloidal and toroidal magnetic fields of the Sun. This scenario suggests that the magnetic field of bipolar magnetic regions is formed from the large-scale toroidal magnetic field that is generated from the axisymmetric poloidal magnetic field, twisted by differential rotation deep in the convection zone. As the solar dynamo revolves around comprehending the cyclic evolution of toroidal and poloidal magnetic fields, there is a consensus on the generation of the toroidal field. However, the generation process of the poloidal field remains less understood. Parker (1955) suggested that the poloidal magnetic field is generated from the toroidal field by electromotive force excited by cyclonic convection which is known as "$\alpha-$effect". Several alternative mechanisms for the poloidal field generation can be found in the literature (Babcock 1961; Choudhuri & Dikpati 1999; Charbonneau & Barlet 2011). An alternative scenario, known as the flux transport model proposed by Babcock (1961); Leighton (1969), posits that the cyclical evolution of solar activity is influenced by meridional circulation. This circulation is responsible for transporting the magnetic field of decaying sunspots from low latitudes toward the polar region, as outlined by Dikpati et al. (2009). The transported magnetic field subsequently undergoes reconnection with the polar field of the preceding solar cycle and migrates to the base of the convection zone. In the tachocline, this magnetic field is carried equatorward by the meridional flow at the base of the convection zone. Eventually, it surfaces due to buoyancy instability, resulting in the formation of observable sunspots. This scenario gains validation through the observed migration of sunspots, originating from mid-latitudes at the onset of the solar cycle and progressively migrating towards the equator by its culmination. Observational evidence further indicates that the polar magnetic field attains its peak during sunspot minima, with its magnitude correlating with the subsequent

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# Spatial Variations of Stellar Elemental Abundances in FIRE Simulations of Milky Way-Mass Galaxies: Patterns Today Mostly Reflect Those at Formation

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## ABSTRACT

Spatial patterns of stellar elemental abundances encode rich information about a galaxy's formation history. We analyze the radial, vertical, and azimuthal variations of metals in stars, both today and at formation, in the FIRE-2 cosmological simulations of Milky Way (MW)-mass galaxies, and we compare with the MW. The radial gradient today is steeper (more negative) for younger stars, which agrees with the MW, although radial gradients are shallower in FIRE-2. Importantly, this age dependence was present already at birth: radial gradients today are only modestly ($\lesssim 0.01$ dex kpc$^{-1}$) shallower than at birth. Disk vertical settling gives rise to negative vertical gradients across all stars, but vertical gradients of mono-age stellar populations are weak. Similar to the MW, vertical gradients in FIRE-2 are shallower at larger radii, but they are overall shallower in FIRE-2. This vertical dependence was present already at birth: vertical gradients today are only modestly ($\lesssim 0.1$ dex kpc$^{-1}$) shallower than at birth. Azimuthal scatter is nearly constant with radius, and it is nearly constant with age $\lesssim 8$ Gyr ago, but increases for older stars. Azimuthal scatter is slightly larger ($\lesssim 0.04$ dex) today than at formation. Galaxies with larger azimuthal scatter have a stronger radial gradient, implying that azimuthal scatter today arises primarily from radial redistribution of gas and stars. Overall, spatial variations of stellar metallicities show only modest differences between formation and today; spatial variations today primarily reflect the conditions of stars at birth, with spatial redistribution of stars after birth contributing secondarily.

## 1. INTRODUCTION

The origin and evolution of elemental abundances encode vital information about a galaxy's formation history (Tinsley 1980). Through stellar nucleosynthesis (Burbidge et al. 1957) and supernovae (Baade & Zwicky 1934), heavy elements (beyond H and He) are ejected back into the interstellar medium (ISM), from which successive generations of more metal-rich stars are born. Thus, the ISM and the stars that recently formed out of it reflect the current elemental abundance patterns within a galaxy. Once formed, stars essentially retain the abundance patterns they were born with, so a galaxy's stellar population encodes its entire enrichment, and thus formation, history.

Importantly, elemental abundances encode spatial information. Searle (1971) first identified negative radial gradients in gas-phase metallicity, such that smaller radii within galaxies are more enriched. More recently, many works have quantified spatial variations of metals in gas in the Milky Way (MW), M31, and nearby galaxies (for example, Sanders et al. 2012; Sánchez-Menguiano et al. 2016; Belfiore et al. 2017; Sakhibov et al. 2018; Kreckel et al. 2019, 2020; Wenger et al. 2019; Mollá et al. 2019; Zinchenko et al. 2019; Hernandez et al. 2021). The spatial patterns of metallicity in stars of different ages today encode the history of a galaxy's ISM, subject to the complication that stars can move from their birth radii and vertical height in the disk via radial redistribution and vertical heating (for example, Sellwood & Binney 2002; Haywood 2008).

Many observational surveys have advanced our ability to measure stellar metallicity variations across the MW, such as GALAH (Buder et al. 2018), Gaia-ESO (Gilmore et al. 2012), LAMOST (Cui et al. 2012), and SDSS-APOGEE (Jönsson et al. 2020), and soon SDSS-V (Kollmeier et al. 2017), 4-m Multi-Object Spectrograph Telescope (4MOST; de Jong et al. 2019), the WHT Enhanced Area Velocity Explorer (WEAVE; Dalton et al. 2012), and the MaunaKea Spectroscopic Ex-

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# TIDAL DISRUPTION ENCORES

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## 1 Abstract

Nuclear star clusters (NSCs), made up of a dense concentrations of stars and the compact objects they leave behind, are ubiquitous in the central regions of galaxies, surrounding the central supermassive black hole (SMBH). Close interactions between stars and stellar-mass black holes (sBH) lead to tidal disruption events (TDEs). We uncover an interesting new phenomenon: For a subset of these, the unbound debris (to the sBH) remain bound to the SMBH, accreting at a later time, and thus giving rise to a second flare. We compute the rate of such events, and find them ranging within $10^{-6}$ - $10^{-3}$ $\mathrm{yr}^{-1}\mathrm{gal}^{-1}$ for SMBH mass $\simeq 10^6 - 10^9\,\mathrm{M}_\odot$. Time delays between the two flares spread over a wide range, from less than a year to hundreds of years. The temporal evolution of the light curves of the second flare can vary between the standard $t^{-5/3}$ power-law to much steeper decays, providing a natural explanation for observed light curves in tension with the classical TDE model. Our predictions have implications for learning about NSC properties and calibrating its sBH population. Some double flares may be electromagnetic counterparts to LISA Extreme-Mass-Ratio-Inspiral (EMRI) sources. Another important implication is the possible existence of TDE-like events in very massive SMBHs, where TDEs are not expected. Such flares can affect spin measurements relying on TDEs in the upper SMBH range.

## 2 Introduction

Most galactic nuclei are characterized by extremely high density of stars. These nuclear star clusters (NSCs), which are unrivaled in luminosity compared to any other type of star clusters, possess the densest known stellar densities (see Neumayer et al. (2020) for an extensive review). Their steep mass profiles, ranging from $\rho(r) \propto r^{-1}$ to $r^{-3}$, result in densities which are $\sim 10^6\,\mathrm{M}_\odot\,\mathrm{pc}^{-3}$ at radial distances $R \sim 0.1\,\mathrm{pc}$. Their occupation fraction appears to vary with both galaxy mass and galaxy type, reaching $\gtrsim 80\%$ in $\sim 10^9\,\mathrm{M}_\odot$ early type galaxies (Sánchez-Janssen et al., 2019), but it declines at both the lower and the higher-mass end. The study of NSCs is an important one in galaxy formation, their formation being tied to both the growth of galaxies as well as to their central supermassive black hole (SMBH).

The very high densities of NSCs, which contain a fraction $\sim 1\%$ of their mass in stellar-mass black holes (sBH, Bahcall & Wolf 1976), are very conducive to close encounters among their constituents. In particular, close encounters between sBHs and stars in the NSC can lead to tidal disruption events (TDEs), detectable by their high luminosities. The occurrence of these events in NSCs is especially important, in that it has been shown that it helps calibrate the number of sBH binaries in these systems (Fragione et al., 2021).

Here we note an interesting new phenomenon. When a star in the NSC undergoes a TDE by an sBH (Perets et al., 2016), some fraction of the debris remain bound and accrete to the sBH, while the rest gets unbound. However, there is a range of locations of the sBH for which these unbound debris, while escaping from the sBH, remain bound to the SMBH, to which they hence return, causing a second, longer flare. In this paper we quantify the conditions under which the sBH-unbound debris remain SMBH-bound, as a function of the relevant variables of the problem, that is the sBH location, the SMBH mass, and the debris ejection angle. We compute the fallback rates for a number of representative cases, discovering a variety of resulting temporal slopes which can yield a varied range of electromagnetic transients. We finally compute the event rates per galaxy of these double flaring events, showing that they can be as high as the standard TDE rates, depending on the SMBH mass.

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# JOINT CONSTRAINTS FROM COSMIC SHEAR, GALAXY-GALAXY LENSING AND GALAXY CLUSTERING: INTERNAL TENSION AS AN INDICATOR OF INTRINSIC ALIGNMENT MODELLING ERROR

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## ABSTRACT

In cosmological analyses it is common to combine different types of measurement from the same survey. In this paper we use simulated Dark Energy Survey Year 3 (DES Y3) and Legacy Survey of Space and Time Year 1 (LSST Y1) data to explore differences in sensitivity to intrinsic alignments (IA) between cosmic shear and galaxy-galaxy lensing. We generate mock shear, galaxy-galaxy lensing and galaxy clustering data, contaminated with a range of IA scenarios. Using a simple 2-parameter IA model (NLA) in a DES Y3 like analysis, we show that the galaxy-galaxy lensing + galaxy clustering combination ($2 \times 2$pt) is significantly more robust to IA mismodelling than cosmic shear ($1 \times 2$pt). IA scenarios that produce up to $5\sigma$ biases for shear are seen to be unbiased at the level of $\sim 1\sigma$ for $2 \times 2$pt. We demonstrate that this robustness can be largely attributed to the redshift separation in galaxy-galaxy lensing, which provides a cleaner separation of lensing and IA contributions. We identify secondary factors which may also contribute, including the possibility of cancellation of higher-order IA terms in $2 \times 2$pt and differences in sensitivity to physical scales. Unfortunately this does not typically correspond to equally effective self-calibration in a $3 \times 2$pt analysis of the same data, which can show significant biases driven by the cosmic shear part of the data vector. If we increase the precision of our mock analyses to a level roughly equivalent to LSST Y1, we find a similar pattern, with considerably more bias in a cosmic shear analysis than a $2 \times 2$pt one, and significant bias in a joint analysis of the two. Our findings suggest that IA model error can manifest itself as internal tension between $\xi_\pm$ and $\gamma_t + w$ data vectors. We thus propose that such tension (or the lack thereof) can be employed as a test of model sufficiency or insufficiency when choosing a fiducial IA model, alongside other data-driven methods.

*Keywords:* cosmological parameters – gravitational lensing: weak – methods: statistical

## 1. INTRODUCTION

The study of weak lensing as a cosmological probe has evolved considerably in the last few years and decades. Although we talk about "weak lensing" fairly loosely, the term actually encompasses several distinct measurements. Cosmic shear is the correlation of galaxy shapes with each other. That is, light from galaxies on adjacent lines of sight must pass through a similar cross-section of the Universe, and so the lensing distortions are correlated. It has been known for some time that shear-shear two-point correlations are a useful way to learn about cosmology (Bartelmann & Schneider 2001; Huterer 2002; Hu & Jain 2004; Frieman et al. 2008). Indeed, to date, cosmic shear analyses (referred to as $1 \times 2$pt analyses) have been key results of almost all galaxy imaging cosmology surveys (Benjamin et al. 2007; Kilbinger et al. 2013; Heymans et al. 2013; Jee et al. 2016; Hildebrandt et al. 2017; Troxel et al. 2018; Chang et al. 2019; Hikage et al. 2019; Hamana et al. 2020; Asgari et al. 2021; Loureiro et al. 2022; Secco, Samuroff et al. 2022; Amon et al. 2022; Doux et al. 2022; Longley et al. 2023; Li et al. 2023; Dalal et al. 2023; DES & KiDS Collaboration 2023).

Alternatively, instead of trying to detect lensing caused by background large scale structure, we can measure weak lensing around specific foreground lenses. One can do this with massive clusters, and so study their density profiles and total mass (Schneider et al. 2000; King & Schneider 2001). Alternatively, one can use foreground galaxies as lenses, a measurement known as galaxy-galaxy lensing. Since the clustering pattern of galaxies traces out the large scale structure of the Universe, these shear-position correlations measure a similar physical effect to shear-shear ones. If we have a good estimate for the galaxy-to-dark matter mapping (i.e. galaxy bias) and the distribution of redshifts (or better yet, precise redshifts for individual galaxies), we can use galaxy-galaxy lensing to probe the properties of the Universe. There is a relatively long history of this, using both spectroscopic and photometric surveys (Sheldon et al. 2004; Baldauf et al. 2010; Mandelbaum et al. 2013; Kwan et al. 2017; Prat, Sánchez et al. 2018; Alam et al. 2017; Leauthaud et al. 2017; Yoon et al. 2019; Blake et al. 2020; Singh et al. 2020; Miyatake et al. 2022; Lee et al. 2022; Prat et al. 2022; Porredon et al. 2022; Pandey et al. 2022). Often studies of this sort (including many of those cited above) will also incorporate galaxy clustering auto-correlations (Cole et al. 2005; Blake et al. 2012; Aubourg et al. 2015; Elvin-Poole et al. 2018; Alam et al. 2021; Zhou et al. 2021; Rodríguez-Monroy et al. 2022; Sánchez, Alarcon et al. 2023), in order to break the degeneracy between galaxy bias and the clustering amplitude $\sigma_8$. This combination is often referred to as $2 \times 2$pt.

It is also worth noting briefly that there is a subfield of weak lensing studies looking at the cross-correlation between galaxy surveys (lensing and positions) and Cosmic Microwave Background (CMB) lensing. These are complementary to other types of weak lensing (Namikawa et al. 2019; Marques et al. 2020; Robertson et al. 2021; Krolewski et al. 2021; Omori et al. 2023; Chang et al. 2023; DES Collaboration 2023). The nomenclature of the combinations

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# From giant clumps to clouds IV: extreme star-forming clumps on top of universal cloud scaling relations in gas-rich galaxies

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**ABSTRACT**

The clumpy nature of gas-rich galaxies at cosmic noon raises the question of universality of the scaling relations and average properties of the star-forming structures. Using controlled simulations of disk galaxies and varying only the gas fraction, we show that the influence of the galactic environments (large-scale turbulence, tides, shear) contributes, together with the different regime of instabilities, to setting a diversity of physical conditions for the formation and evolution of gas clumps from low to high gas fractions. However, the distributions of gas clumps at all gas fractions follow similar scaling relations as Larson's, suggesting the universality of median properties. Yet, we find that the scatter around these relations significantly increases with the gas fraction, allowing for the presence of massive, large, and highly turbulent clouds in gas-rich disks in addition to a more classical population of clouds. Clumps with an excess of mass for their size are slightly denser, more centrally concentrated, and host more abundant and faster star formation. We find that the star formation activity (rate, efficiency, depletion time) correlates much more strongly with the excess of mass than with the mass itself. Our results suggest the existence of universal scaling relations for gas clumps but with redshift-dependent scatters, which calls for deeper and more complete census of the populations of star-forming clumps and young stellar clusters at cosmic noon and beyond.

**Key words.** galaxies: formation — methods: numerical



## 1. Introduction

Observations of star-forming regions in the Milky Way and nearby disk galaxies have revealed both close-to-universal scaling relations of the cloud properties (e.g. Larson 1981; Rosolowsky et al. 2003; Rosolowsky 2007; Heyer et al. 2009; Miville-Deschênes et al. 2017), and a clear influence of the galactic dynamics (Schinnerer et al. 2013; Hughes et al. 2013; Sun et al. 2020, also supported theoretically, see e.g. Renaud et al. 2013; Meidt et al. 2013; Fujimoto et al. 2014), yet with a subtle impact on the star formation efficiency itself (Querejeta et al. 2021). This suggests complex and multiple coupling mechanisms between the scales of the galaxy, the clouds, and star (cluster)-forming knots.

Thanks to pioneer studies with HST (e.g. Elmegreen et al. 2007; Guo et al. 2012), and more recently with ALMA, JWST, and the power of strong gravitational lensing, a wide window is now opened on the gaseous and stellar inner structures of more distant galaxies, in particular at cosmic noon where the cosmic star formation history peaks ($z \approx 1-3$, Madau & Dickinson 2014). For instance, with strong lensing, physical resolutions of a few $10\,\mathrm{pc}$ can be reached by ALMA at $z = 1$ (e.g. Dessauges-Zavadsky et al. 2023), and JWST complements such studies by providing integrated properties of the stellar objects (e.g. Claeyssens et al. 2023). Disk galaxies at these redshift host more extreme physical conditions than in the local Universe (e.g. Swinbank et al. 2011), with most of their morphologies being dominated by clumpy structures (Cowie et al. 1995; Elmegreen et al. 2013; Guo et al. 2015; Shibuya et al. 2016; Fisher et al. 2017; Sattari et al. 2023), particularly bright in restframe UV (Förster Schreiber et al. 2009; Zanella et al. 2015; Cava et al. 2018). In the vast majority of cases and up to very high redshift ($z \approx 7$, Treu et al. 2023), such clumpy appearance has an internal ("in situ") origin (e.g. Förster Schreiber et al. 2009; Tacconi et al. 2013; Girard et al. 2018), as opposed to the multi-component structure that galaxy mergers would yield (e.g. Puech 2010; Calabrò et al. 2019).

The magnification from lensing, and/or the gain in angular resolution and sensitivity from JWST revealed the hierarchical nature of (at least some of) the young stellar clumps which host sub-structures below the scales of $\sim 1\,\mathrm{kpc}$ and $\sim 10^{8-9}\,\mathrm{M}_\odot$ (Meštrić et al. 2022; Messa et al. 2022), contrarily to previously thought (Elmegreen & Elmegreen 2005; Förster Schreiber et al. 2011; Guo et al. 2012). Similar conclusions have also been proposed by adopting observational limitations to detect clumps in simulated galaxies, and finding overestimations by up to a factor of 10 for the clump's stellar masses (Huertas-Company et al. 2020, see also Faure et al. 2021). These results ask the question of the hierarchical organization of the dense gas and of its star-forming phase in gas-rich clumpy galaxies at $z \approx 1-3$.

Although clumpy galaxies are found in the main sequence of galaxy formation (Schreiber et al. 2015; Fisher et al. 2019), the peculiar organization of their interstellar medium (ISM), clustering of star formation, and elevated star formation rate (SFR) influence the distribution and luminosity of the traditional tracers of dense gas and young stars (see e.g. Daddi et al. 2015 and Renaud et al. 2019 on the $\alpha_{\mathrm{CO}}$ conversion factor in clumpy galaxies), further complicating the interpretation of not-

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# Improving Photometric Redshift Estimates with Training Sample Augmentation

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ABSTRACT

Large imaging surveys will rely on photometric redshifts (photo-$z$'s), which are typically estimated through machine learning methods. Currently planned spectroscopic surveys will not be deep enough to produce a representative training sample for LSST, so we seek methods to improve the photo-$z$ estimates from non-representative training samples. Spectroscopic training samples for photo-$z$'s are biased towards redder, brighter galaxies, which also tend to be at lower redshift than the typical galaxy observed by LSST, leading to poor photo-$z$ estimates with outlier fractions nearly 4 times larger than for a representative training sample. In this paper, we apply the concept of training sample augmentation, where we augment non-representative training samples with simulated galaxies possessing otherwise unrepresented features. When we select simulated galaxies with ($g$-$z$) color, $i$-band magnitude and redshift outside the range of the original training sample, we are able to reduce the outlier fraction of the photo-$z$ estimates by nearly 50% and the normalized median absolute deviation (NMAD) by 56%. When compared to a fully representative training sample, augmentation can recover nearly 70% of the increase in the outlier fraction and 80% of the increase in NMAD. Training sample augmentation is a simple and effective way to improve training samples for photo-$z$'s without requiring additional spectroscopic samples.

## 1. INTRODUCTION

Understanding the nature of dark energy is a major open question in cosmology. Stage-IV dark energy experiments, such as the Vera C. Rubin Observatory's Legacy Survey of Space and Time (LSST, Ivezić et al. 2019), Euclid (Laureijs et al. 2011) and Roman (Akeson et al. 2019), are scheduled to come online in the coming years.

Imaging surveys will need to obtain redshifts to galaxies, but there will be too many for spectroscopic redshifts to be feasible. LSST alone is expected to observe billions of galaxies and will therefore rely on photometric redshifts (photo-$z$'s). Photo-$z$'s can be estimated through machine learning algorithms, which learn to associate photometric quantities, such as colors and magnitudes, with a redshift estimate.

Previous Stage-III dark energy surveys have also used machine learning for estimating photometric redshifts. The Hyper Suprime-Cam Subaru Strategic Program (HSC-SSP, Aihara et al. 2017) used DNNz and DEMPz (Hsieh & Yee 2014) for the Year 3 cosmology results (Rau et al. 2023; Sugiyama et al. 2023; Miyatake et al. 2023). Both DNNz and DEMPz are conditional density estimators. The Dark Energy Survey (DES, Abbott et al. 2018) has used a self-organizing map (SOMPZ, Myles et al. 2021) for estimating photo-$z$'s. The Kilo-Degree Survey (KiDS, Heymans et al. 2021) has also used self-organizing maps for photo-$z$ estimation (Hildebrandt et al. 2021).

Machine learning methods require a training sample of galaxies with both photometry and spectroscopic redshifts. However, existing spectroscopic samples are biased towards brighter, redder galaxies than LSST will

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# Stars of the Lower Part of the Main Sequence with Discovered Exoplanets and Candidates. Periods of Rotations or Revolutions?

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## Abstract

The purpose of this work is to supplement the "Stars with solar-type activity" catalog with information about confirmed exoplanets and exoplanet candidates. To do this, cross-identification of the catalog stars with data from the NASA exoplanet archive was carried out. This article presents the distribution of the number of suspected stars with exoplanets by brightness, spectral type, amplitude of variability, as well as other statistical analysis data. Particular attention has been paid to the comparison of the periods of rotation of stars and the orbital periods of revolution of exoplanets around them. Analysis of the data suggests the need to change the previously determined types of variability in some stars.

## 1. Introduction

The results of a statistical analysis of data on stars with discovered exoplanets were previously published in an article by the author (Shlyapnikov 2022). The objects are included in the new "Catalog of Stars with Solar Type Activity", hereinafter referred to as CSSTA[1]). The catalog contains data on 314618 objects from the lower part of the Main Sequence. It provides information about coordinates, identification, types of variability, magnitudes, amplitudes of variability, spectral types, the presence of radiation in the X-ray, ultraviolet and infrared ranges, and other information about the physical parameters of stars. The 2020 version of the CSSTA catalog is described in more detail in the monograph (Gershberg et al., 2020).

The presence of X-ray and radio emissions, if any, should contribute to the understanding of the possibility of the existence of "life" in the habitable zone. Flare activity, if present, imposes certain restrictions on the development of life. The periods of revolution of exoplanets around stars, and the associated changes in brightness, albeit insignificant, should be taken into account when analyzing its own rotation and the period of possible cyclic activity.

By early February 2023, according to the NASA Exoplanet Archive[2] the existence of 5250 planets was confirmed, as discovered by various 11 methods, and 291 found by the TESS observatory[3]. The discovery of another 6153 exoplanets according to TESS observations needs to be confirmed.

Information about the study of exoplanets at the Crimean Astrophysical

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[1] CSSTA – http://craocrimea.ru/~aas/CATALOGUEs/CSAST/CSAST.html
[2] NASA exoplanet archive – https://exoplanetarchive.ipac.caltech.edu
[3] TESS Exoplanet Mission – https://www.nasa.gov/tess-transiting-exoplanet-survey-satellite