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Session E1: AdS/CFT Physics

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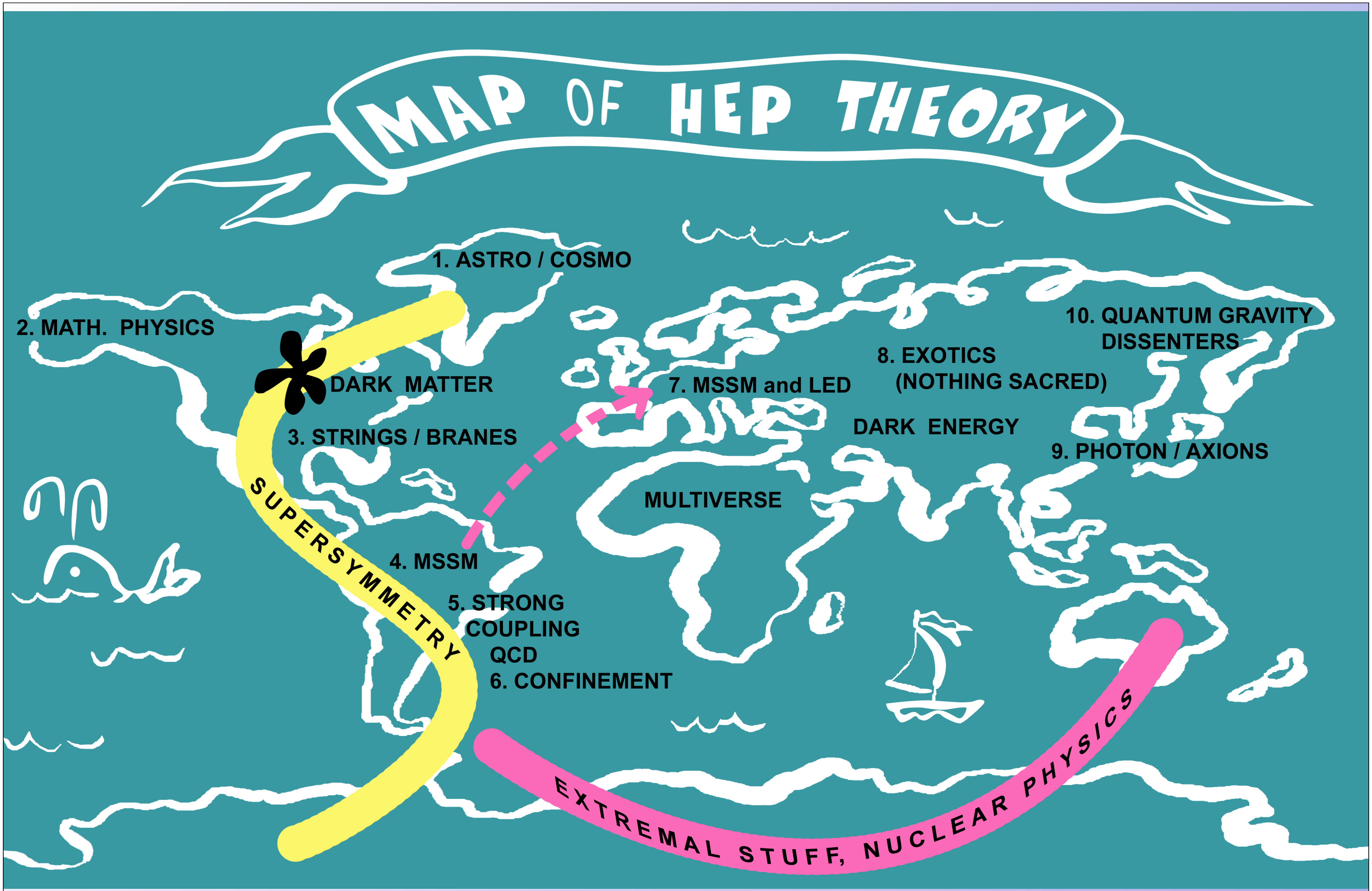
Developments in QCD from Holography and Supersymmetry


MAP OF HEP THEORY
1. ASTRO / COSMO
2. MATH. PHYSICS
DARK MATTER
3. STRINGS / BRANES
SUPERSYMMETRY
4. MSSM
5. STRONG
COUPLING
QCD
6. CONFINEMENT
7. MSSM and LED
MULTIVERSE
8. EXOTICS
(NOTHING SACRED)
DARK ENERGY
10. QUANTUM GRAVITY
DISSENTERS
9. PHOTON / AXIONS
EXTREMAL STUFF, NUCLEAR PHYSICS

Four Topics:

- Confined monopoles in dense QCD (GSY, & Eto, Nitta, Yamamoto)
- Transverse part of the triangle anomaly via holography (Son + Yamamoto)
- Developments in soft wall holographic QCD (Karch, Katz, Son, Stephanov)
- Deriving exact vector meson dominance via Seiberg's duality (Komargodsky)

6. CONFINEMENT

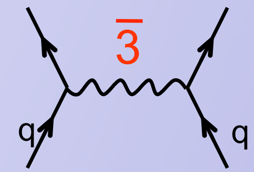
1) Confined monopoles in dense QCD

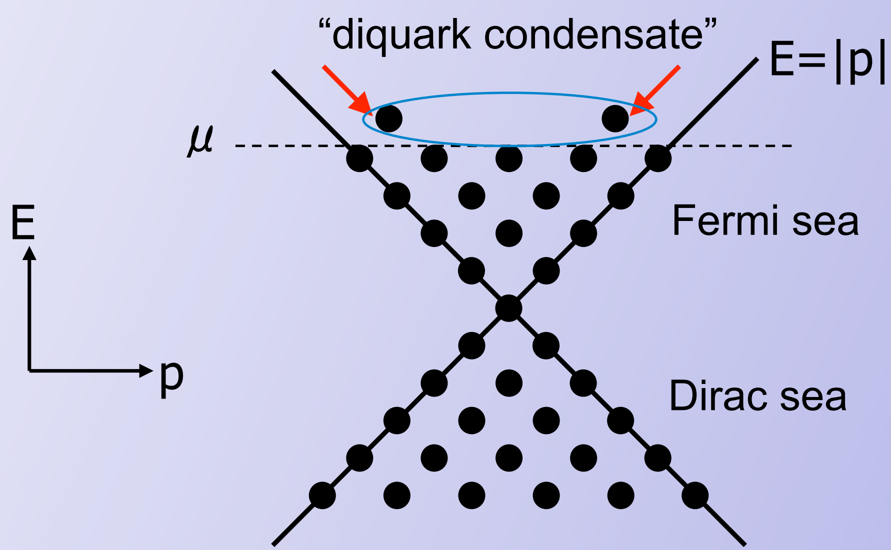
Color Superconductivity (CSC)

- QCD at high density → Fermi surface, weak-coupling
- Attractive channel → Cooper instability

  $[3]_C \times [3]_C = [6]_S + [\overline{3}]_A$

$$(\tau_a)_{ij}(\tau_a)_{kl} = \frac{2}{3}(\tau_S)_{ik}(\tau_S)_{lj} - \frac{4}{3}(\tau_A)_{ik}(\tau_A)_{lj}$$





2 Ginsburg–Landau effective description

At large μ QCD is in the CFL phase. Diquark condensate

$$\Phi^{kC} \sim \varepsilon_{ijk}\,\varepsilon_{ABC}\left(\psi^{iA}_{\alpha}\,\psi^{jB\,\alpha} + \bar{\tilde{\psi}}^{iA\,\dot\alpha}\,\bar{\tilde{\psi}}^{jB}_{\dot\alpha}\right)$$

At $T \to T_c$ gap fluctuations become important.

Chiral fluctuations (π-mesons) are considered less important

$$S = \int d^4x \left\{ \frac{1}{4g^2}\left(F^a_{\mu\nu}\right)^2 + 3\,\mathrm{Tr}\,(\mathcal{D}_0\Phi)^\dagger\,(\mathcal{D}_0\Phi) \right.$$

$$\left. + \quad \mathrm{Tr}\,(\mathcal{D}_i\Phi)^\dagger\,(\mathcal{D}_i\Phi) + V(\Phi) \right\}$$

with the potential

$$V(\Phi) = -m_0^2\,\mathrm{Tr}\,\left(\Phi^\dagger\Phi\right) + \lambda\left(\left[\mathrm{Tr}\,\left(\Phi^\dagger\Phi\right)\right]^2 + \mathrm{Tr}\,\left[\left(\Phi^\dagger\Phi\right)^2\right]\right)$$

Vacuum

$$\Phi_{\text{vac}} = v\,\text{diag}\,\{1,1,1\}$$

where

$$v^2 = \frac{m_0^2}{8\lambda} = \frac{4\pi^2}{3}\,\frac{T_c - T}{T_c}\,\mu^2$$

The symmetry breaking pattern

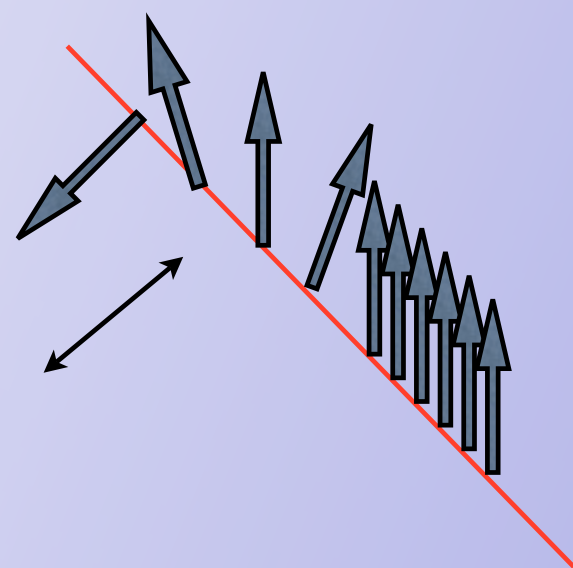
$$\text{SU}(3)_C \times \text{SU}(3)_F \times \text{U}(1)_B \to \text{SU}(3)_{C+F}$$

9 symmetries are broken.

8 are eaten by Higgs mechanism.

One Goldstone boson associated with broken $\text{U}(1)_B$.

"Non-Abelian" string is formed if all non-Abelian degrees of freedom participate in dynamics at the scale of string formation



2003: Hanany, Tong
Auzzi et al.
Yung + M.S.

$T = T_{ANO}/N$

classically gapless excitation

SU(3)/U(1) = CP(2) sigma model

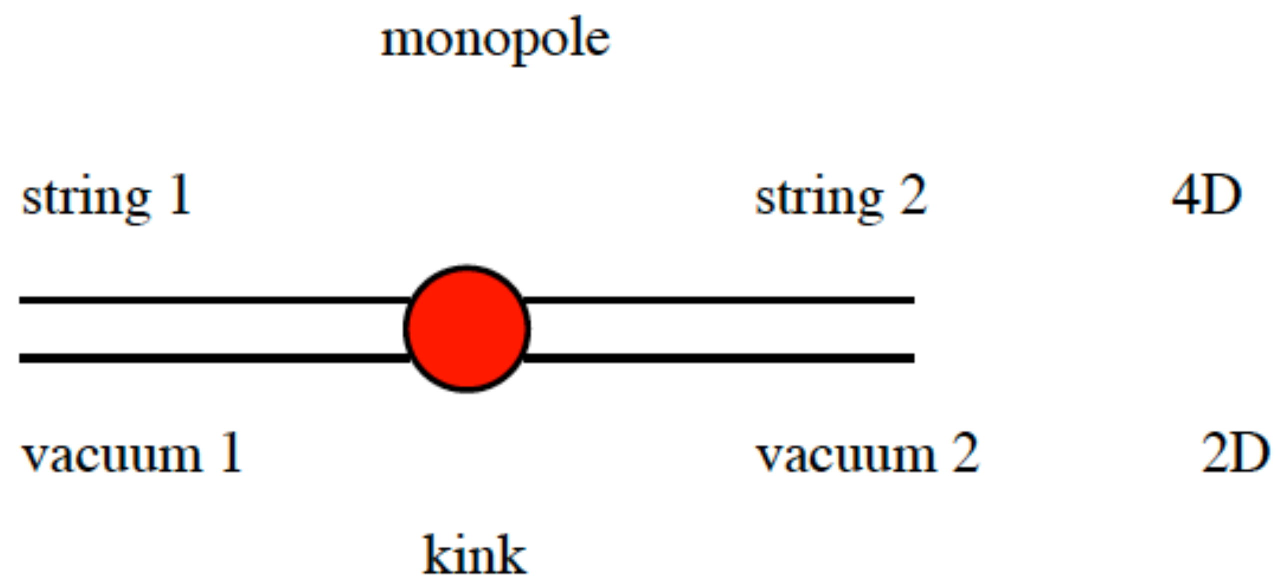
☺ In fact, mass gap Λ is developed; N vacua

In 2D $CP(N-1)$ model on the string we have

N vacua $=$ N Z_N strings

and kinks interpolating between these vacua

Kinks = confined monopoles



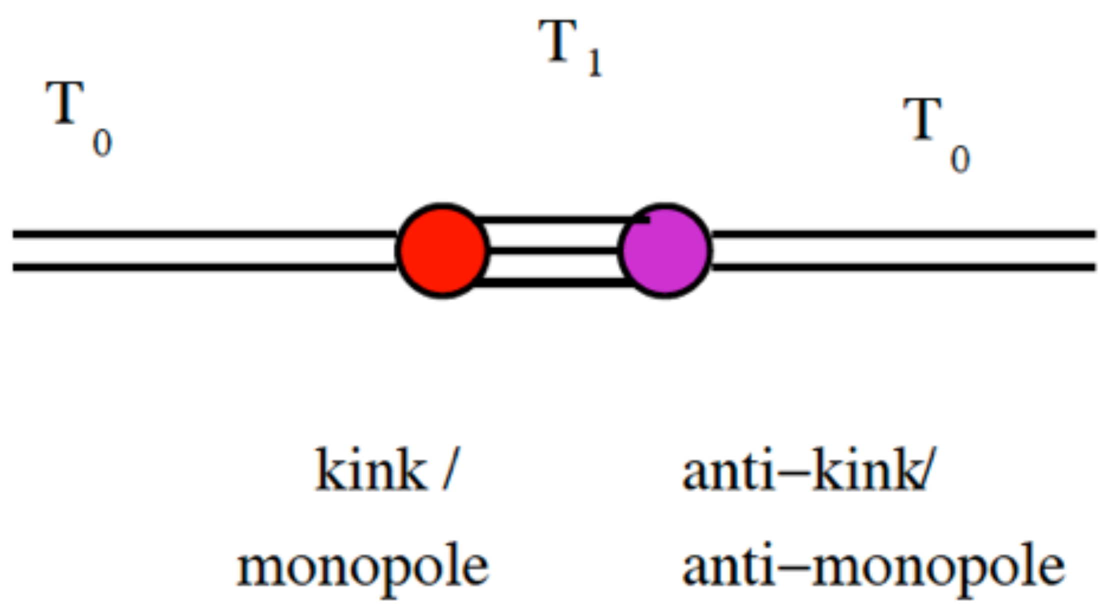
We might think that there is a certain deformation of the GL model which includes adjoint scalar fields. If these fields develop VEVs, the conventional 't Hooft-Polyakov monopoles are formed.

These confined monopoles in CFL phase are seen as kinks in the CP($N-1$) model on the string.

Now we give a mass to the adjoint scalars and decouple them.

Still there are confined monopoles = kinks of CP($N-1$) model on the string

Quantum splitting of the string tensions:



2) Transverse part of the triangle anomaly via holography

☞ Longitudinal part of fermion triangle graph exactly fixed by chiral anomaly

$$\downarrow$$

$$\pi^0 \to \gamma\gamma$$

Vainshtein: is the transverse part is constrained?

$$\langle j_\mu j^5_\nu \rangle_{\hat{F}} = -\frac{1}{4\pi^2}\Big[w_T(q^2)\Big(-q^2\tilde{F}_{\mu\nu} + q_\mu q^\sigma \tilde{F}_{\sigma\nu} - q_\nu q^\sigma \tilde{F}_{\sigma\mu}\Big) + w_L(q^2)\, q_\nu q^\sigma \tilde{F}_{\sigma\mu}\Big]$$

Vainshtein: NO perturbative corrections! $\chi = -\dfrac{N_c}{4\pi^2 f_\pi^2}\,. \qquad -9.0\ \mathrm{GeV}^{-2}$

$$\chi_{\mathrm{QCD\ SR}} = -3.15 \pm 0.3\ \mathrm{GeV}^{-2}$$

SY: In broad class of Yang-Mills-Chern-Simons dual theories, with chiral symmetry broken by b.c.'s in IR, independently of gravity metric:

$$w_T(Q^2) = \frac{N_c}{Q^2} - \frac{N_c}{f_\pi^2}\left[\Pi_A(Q^2) - \Pi_V(Q^2)\right]_F$$

vanishes in perturbation theory. A nonperturbative correction found through holography but independent of particulars of 5D metric! + Factorization

$\downarrow$

¿¿¿ Vainshtein formula ???

3) Soft wall holographic QCD, K^2S^2

$$S=-(1/4)\int d^5x\, g^{1/2}\, e^{-\Phi}\, V^{MN}V_{MN}$$

infinite tower of vector mesons

$$ds^2=z^{-2}[dt^2-(dx_i)^2-dz^2], \qquad \Phi=az^2$$

a positive or negative? ⟶ K^2S^2 vs. de Teramond, Brodsky

Zuo

Nicotri

Andreev, Zakharov

K^2S^2

a negative ⟶ unavoidable massless scalar boson, spont. breaking of the vector current. Forbidden by Witten

a negative ⟶ "better" confinement

4) Deriving exact vector meson dominance via Seiberg's duality

Basic concept: a hidden "flavor"gauge symmetry in QCD (ρ mesons → back to Yang-Mills) which is Higgsed. [Kawarabayashi, Suzuki, Fayyazzuddin, Riazuddin (1966); Bando et al. 1985-88.]

Consequences: (a) universality of the coupling, (b) vector meson dominance.

In QCD per se we cannot derive ☹☹☹ No obvious prarameter to dial to make ρ's massless or parametrically light ☹☹☹

BUT!

Consider supersymmetric QCD with N_f flavors, $N_{c+1}<N_f<(3/2)N_c$

↓

Seiberg's dual: $SU(N_f$-$N_c)$, N_f "magnetic" (s)quaks, plus c.singl. M_f^g

"Magnetic gluons" are "ρ mesons" ☺ ☺ ☺ Can be made massless at the origin of moduli space!!! VMD + Universality guaranteed ☺ ☺ ☺.

Prototype model

$$S = \int d^4x \left\{ \frac{1}{4g_2^2}\left(F^a_{\mu\nu}\right)^2 + \frac{1}{4g_1^2}\left(F_{\mu\nu}\right)^2 + \frac{1}{g_2^2}|D_\mu a^a|^2 \right.$$

$$+ \quad \mathrm{Tr}\,(\nabla_\mu\Phi)^\dagger\,(\nabla^\mu\Phi) + \frac{g_2^2}{2}\left[\mathrm{Tr}\,\left(\Phi^\dagger T^a \Phi\right)\right]^2 + \frac{g_1^2}{8}\left[\mathrm{Tr}\,\left(\Phi^\dagger\Phi\right) - N\xi\right]^2$$

$$+ \quad \boxed{\frac{1}{2}\mathrm{Tr}\,\left|a^a T^a\,\Phi + \Phi\,\sqrt{2}M\right|^2} + \frac{i\,\theta}{32\,\pi^2}\,F^a_{\mu\nu}\tilde{F}^{a\,\mu\nu} \left. \right\},$$

$$\Phi = \begin{pmatrix} \varphi^{11}\varphi^{12} \\ \varphi^{21}\varphi^{22} \end{pmatrix}$$

$$M = \begin{pmatrix} m & 0 \\ 0 & -m \end{pmatrix}$$

U(2) gauge group, 2 flavors of (scalar) quarks

SU(2) Gluons A^a_μ + U(1) photon + gluinos+ photino

$\Phi = \sqrt{\xi} \times I$

Basic idea:

- Color-flavor locking in the bulk → Global symmetry G;
- G is broken down to H on the given string;
- G/H coset; G/H sigma model on the world sheet.

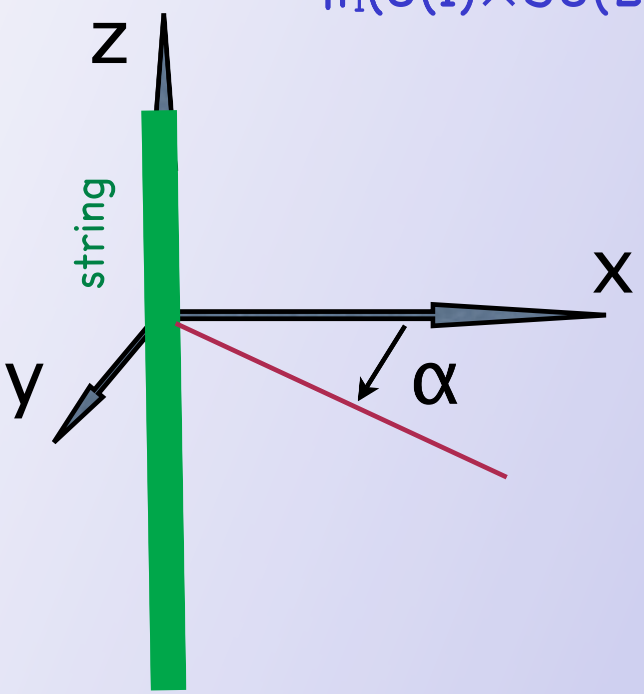
☆ ANO strings are there because of U(1)!

☆ New strings:

$\pi_1(SU(2)\times U(1)) = Z_2$: **rotate by π around 3-d axis in SU(2)**

→ -1; another -1 rotate by π in U(1)

$\pi_1(U(1)\times SU(2))$ nontrivial due to Z_2 center of SU(2)



x_0 ← string center in perp. plane

ANO $\sqrt{\xi}\, e^{i\alpha} \begin{pmatrix} 1 & 0 \\ 0 & 1 \end{pmatrix}$

$T=4\pi\xi$

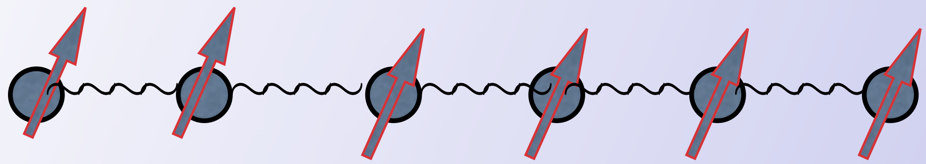
Non-Abelian $\sqrt{\xi} \begin{pmatrix} e^{i\alpha} & 0 \\ 0 & 1 \end{pmatrix}$

$T_{U(1)} \pm T^3_{SU(2)}$

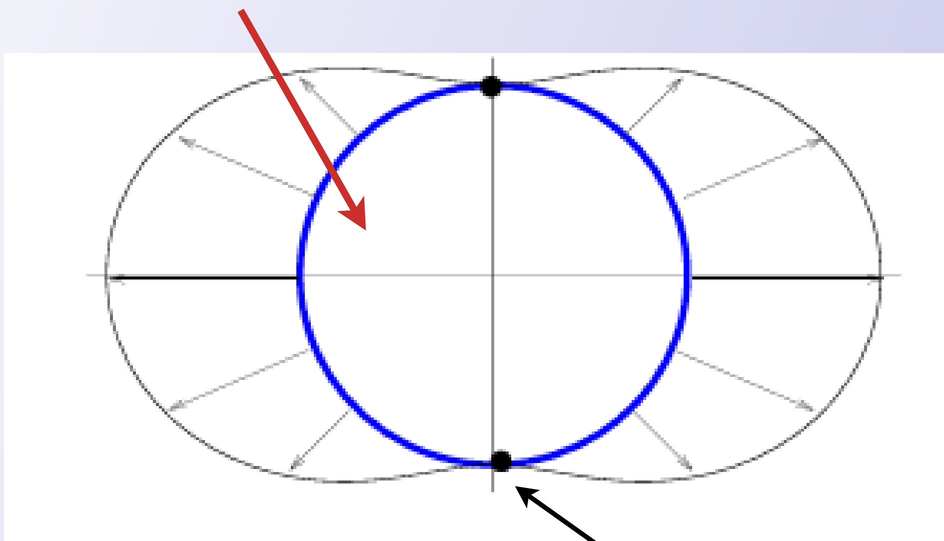
$T=2\pi\xi$

SU(2)/U(1) ←orientational moduli; O(3) σ model

Worldsheet theory



S_2

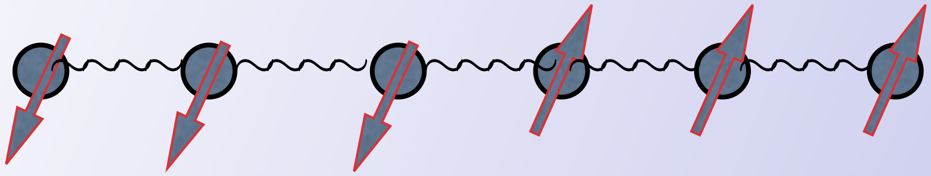


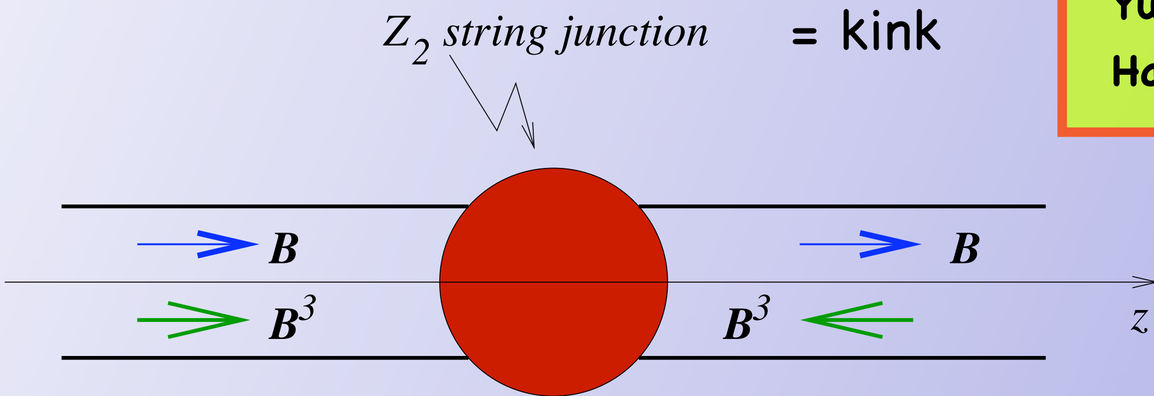
Global SU(2) is gone!
U(1) remains intact

Two vacua= 2 degenerate strings

CP(1) model with twisted mass

$$S = \int d^2x \left\{ \frac{2}{g^2} \frac{\partial_\mu \bar{\phi}\, \partial^\mu \phi - (\Delta m)^2 \bar{\phi}\phi}{(1+\bar{\phi}\phi)^2} + fermions \right\}$$





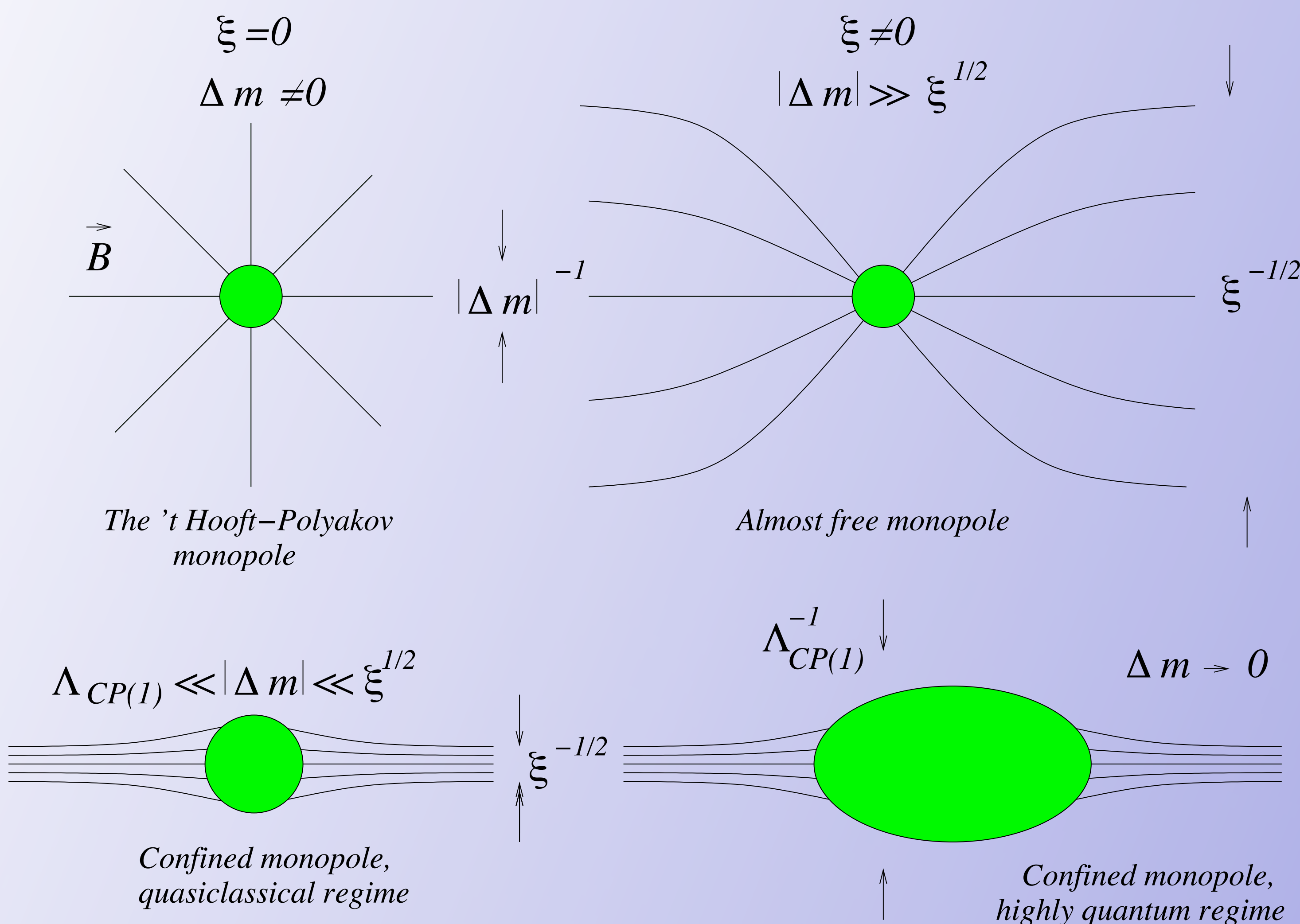
= kink

Yung + M.S.
Hanany, Tong

Evolution in dimensionless parameter m^2/ξ

Kink = Confined Monopole

Why?



ξ =0
Δ m ≠0
B
|Δ m| −1
ξ ≠0
|Δ m| ≫ ξ 1/2
ξ −1/2
The 't Hooft−Polyakov
monopole
Almost free monopole
Λ CP(1) ≪ |Δ m| ≪ ξ 1/2
ξ −1/2
Λ −1 CP(1)
Δ m → 0
Confined monopole,
quasiclassical regime
Confined monopole,
highly quantum regime

What remains to be done?

- Dualize!
- Decrease Supersymmetry to N=1, or better to 0!

In both directions the current progress is inspiring

Tong

Yung + M.S.

N = 2→ **N** = 1 in the bulk

Heterotic deformation of CP(N−1)

$$L_{heterotic} = \zeta_R^\dagger i\partial_L \zeta_R + \left[\gamma \zeta_R R \left(i\partial_L \phi^\dagger\right) \psi_R + H.c.\right] - g_0^2 |\gamma|^2 \left(\zeta_R^\dagger \zeta_R\right) \left(R \psi_L^\dagger \psi_L\right)$$

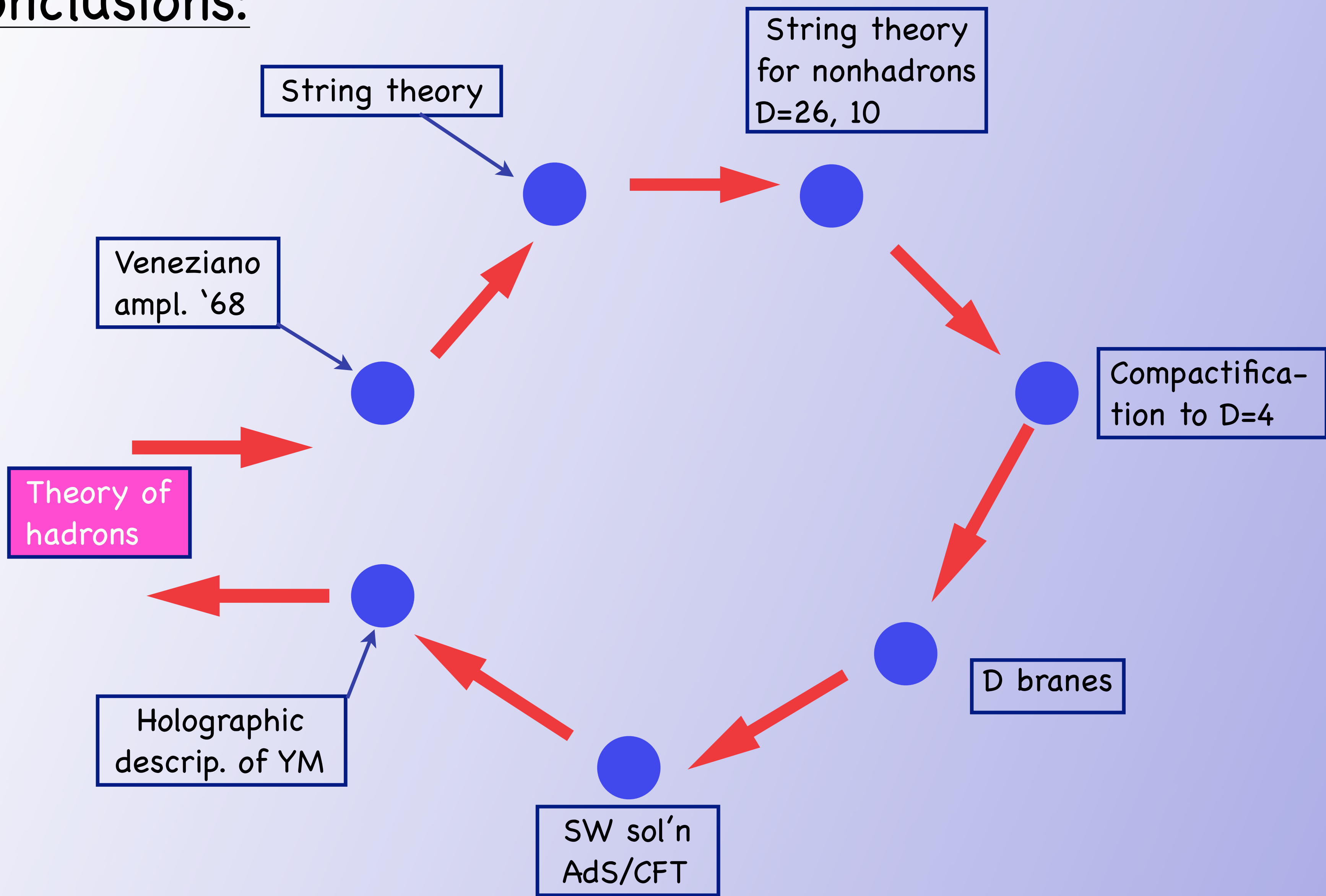
at small γ

ζ_R is Goldstino

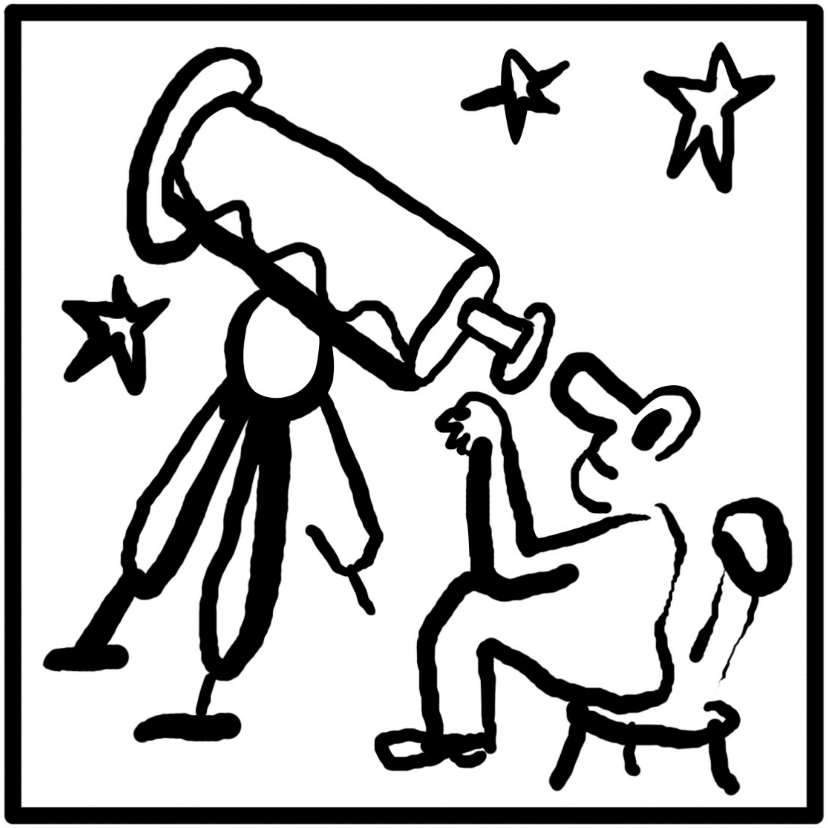
$$\mathcal{E}_{vac} = |\gamma|^2 \left|\langle R \psi_R^\dagger \psi_L \rangle\right|^2$$

(0,2) supersymmetry is spontaneously broken!

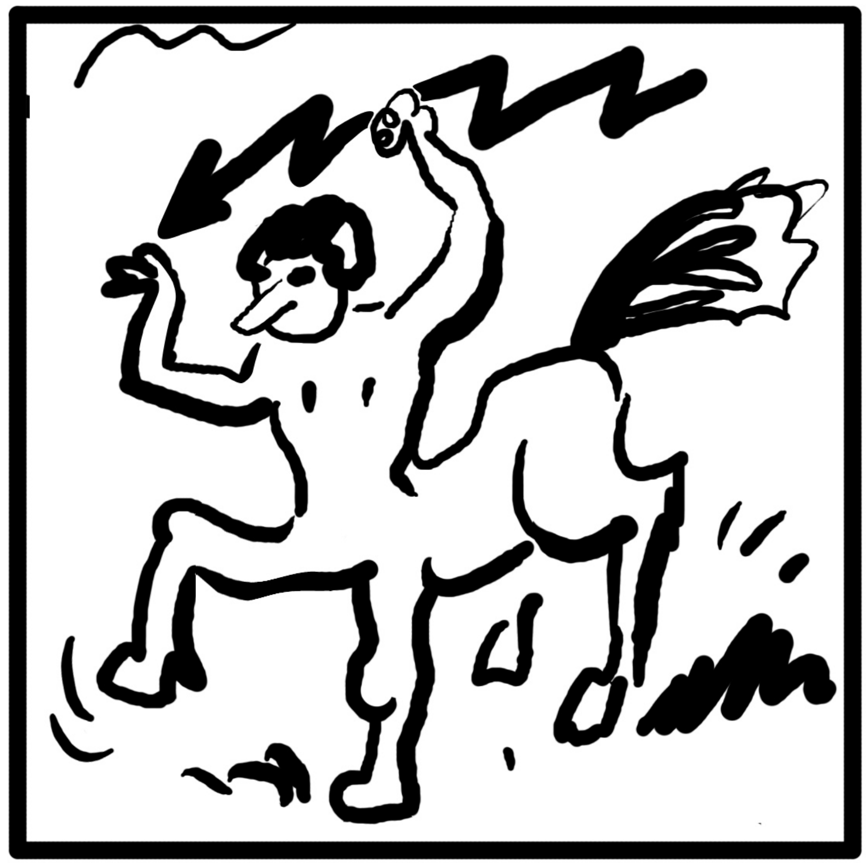
Conclusions:



After 1998: Back-to-roots stage

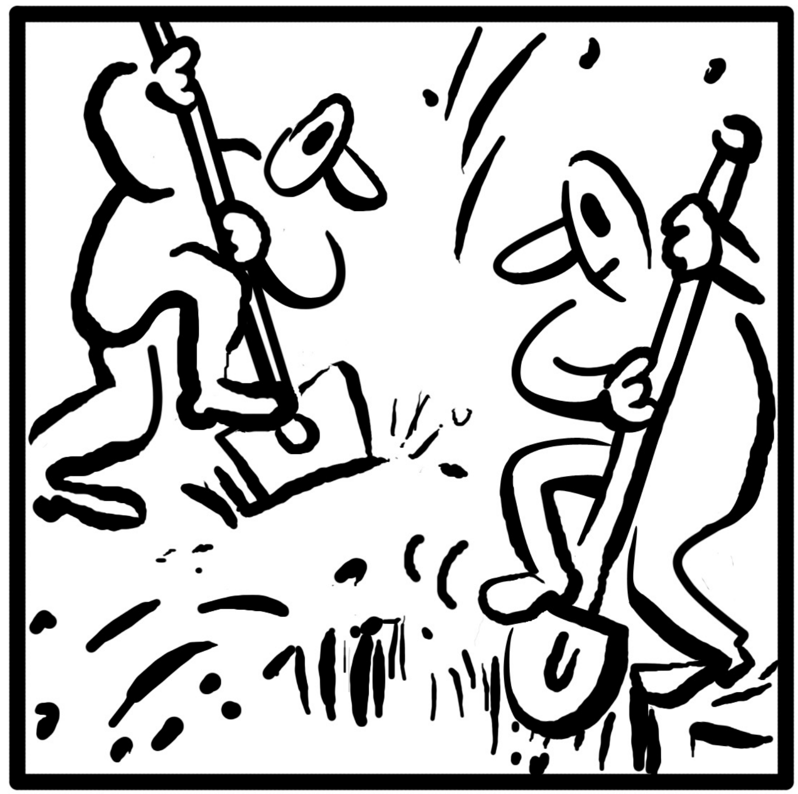


1. ASTRO / COSMO



8. EXOTICS (NOTHING SACRED)

2. MATH. PHYSICS

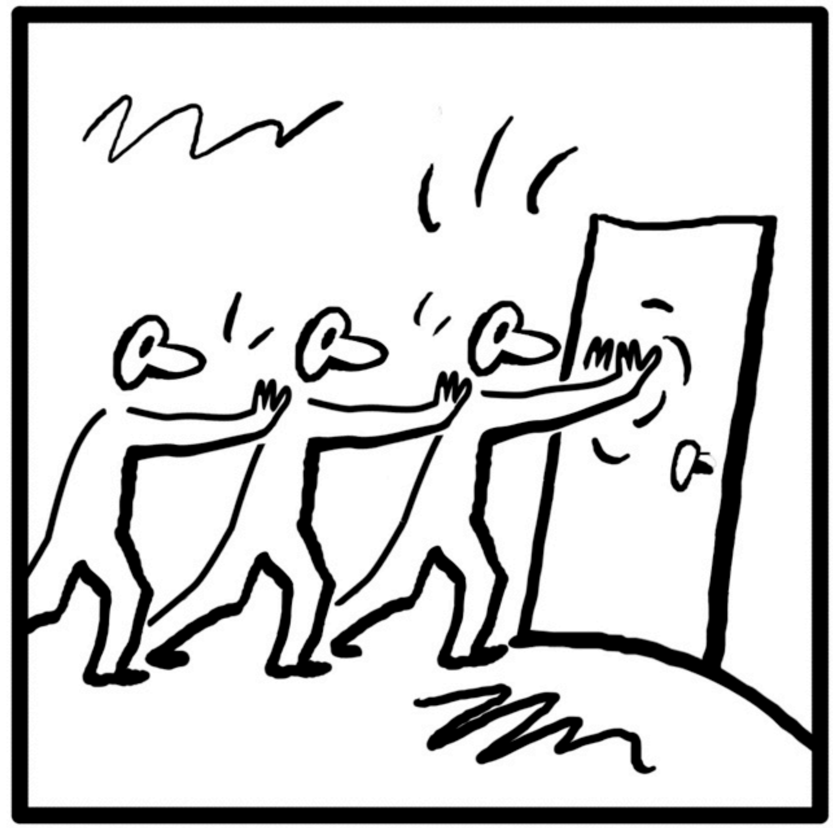


3. STRINGS / BRANES

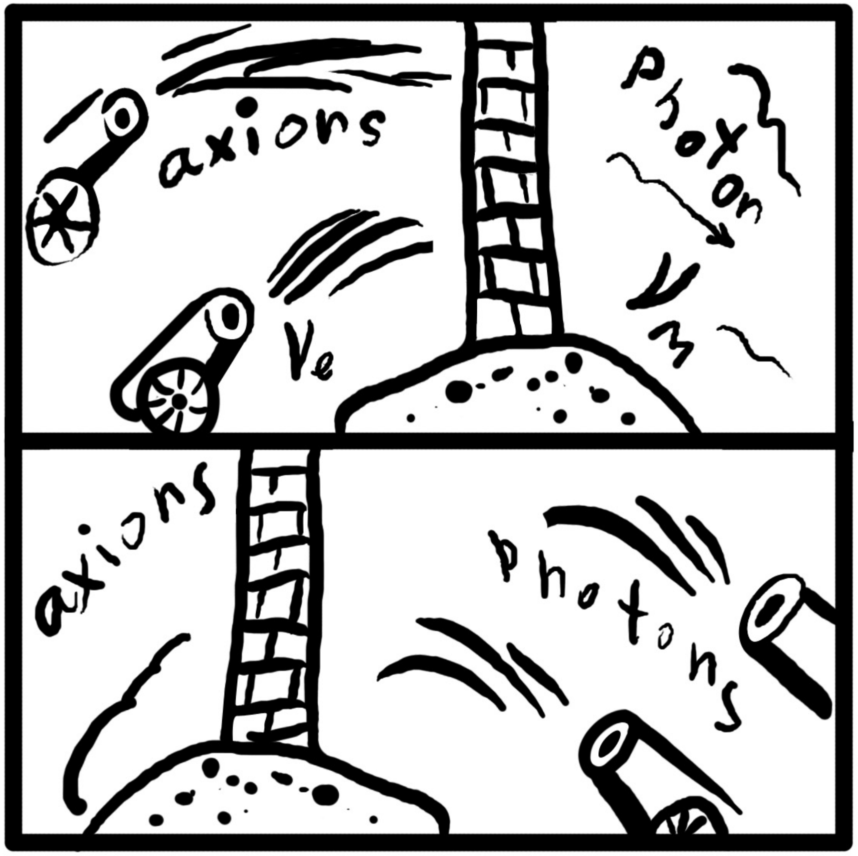
5. STRONG COUPLING

6. CONFINEMENT

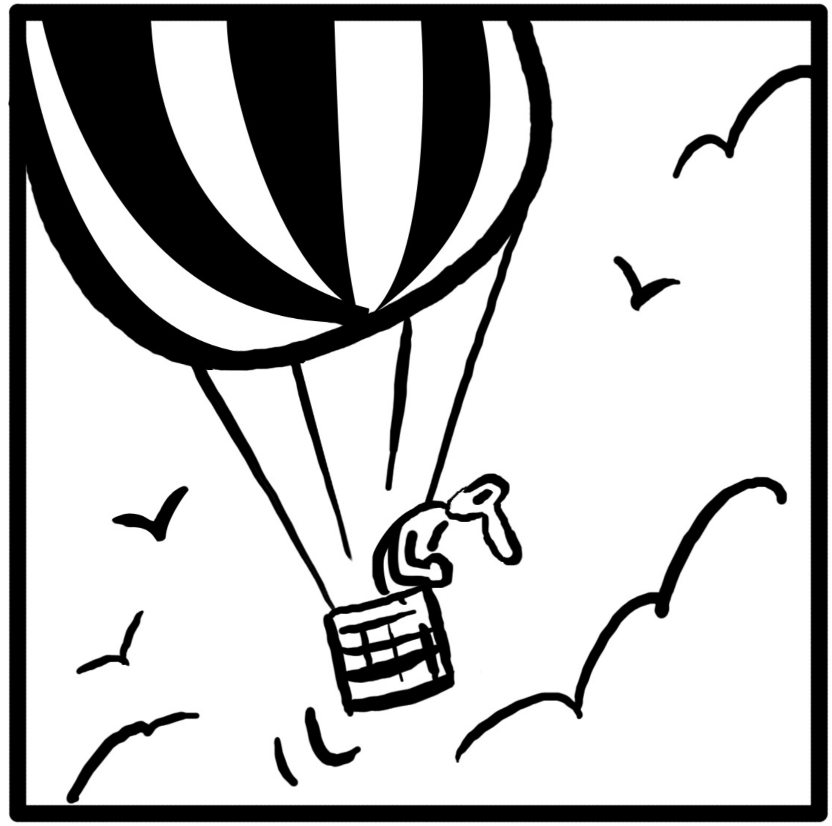
4



7. MSSM and LED



9. PHOTON / AXIONS



10. QUANTUM GRAVITY DISSENTERS