



ИТЭФ, 19 сентября 2013

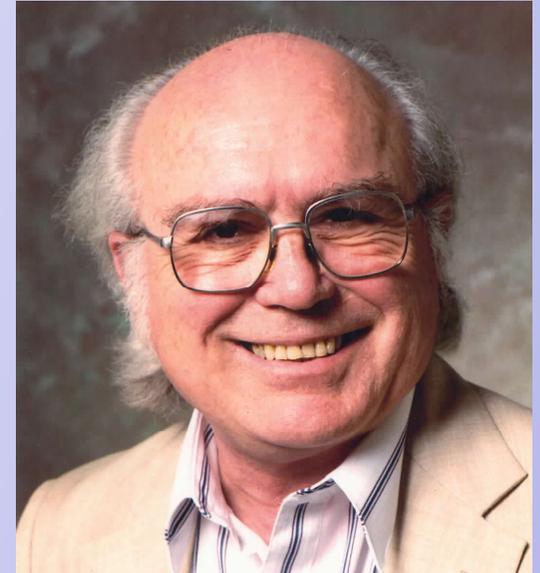
М. Шифман

*Суперсимметрия и Янг-Миллс:
куда мы пришли*



1985

1970's:

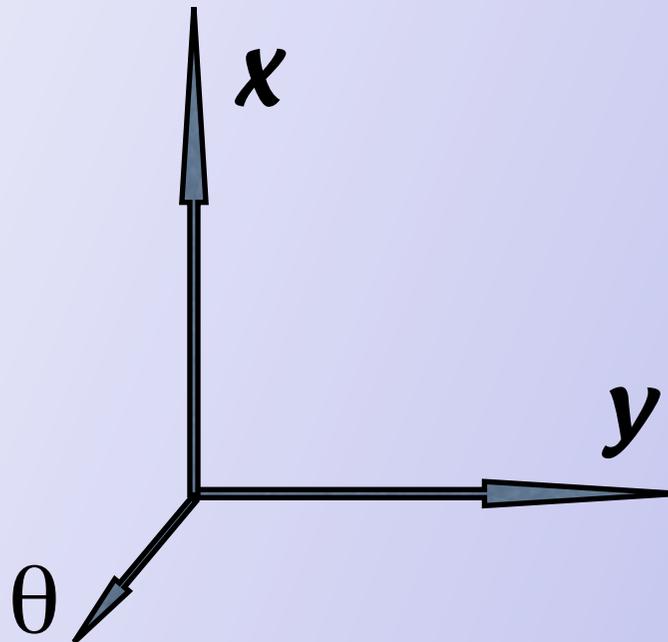


Golfand & Likhtman, 71

Wess & Zumino, 73

$$\theta^2 = 0$$

*“fermion” direction
of the superspace*



In 1+3 dimensions

$$\{t, x, y, z\} \longrightarrow \{t, x, y, z; \theta_{\alpha}^i\}$$

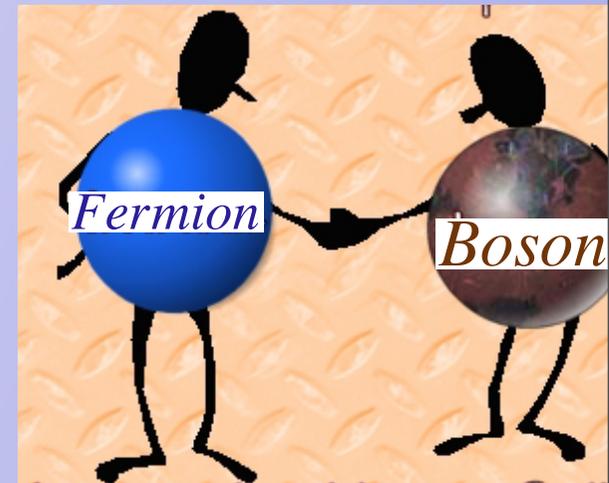
$$\{Q_{\dot{\alpha}}, Q_{\dot{\beta}}\} = 2\sigma^{\mu}_{\dot{\alpha}\dot{\beta}} P_{\mu}$$

- ☺ 40 лет суперсимметрии, ~ 40 тысяч работ опубликовано.

ЧАСТЬ 1

- ☺ Первое направление: феноменологическая суперсимметрия (для решение проблемы натуральности и стабилизации иерархии масс)
- ☺ MSSM с середины 1970х ✨ с 1982 (Witten, иерархия) доминирующая парадигма (+ к Виттену темная материя)!

Supersymmetry entails that for every particle that has been found there are mirror particles that are identical in all respects except for their spin: e.g. photon, W, Z, and gluon – photino, wino, and gluino.

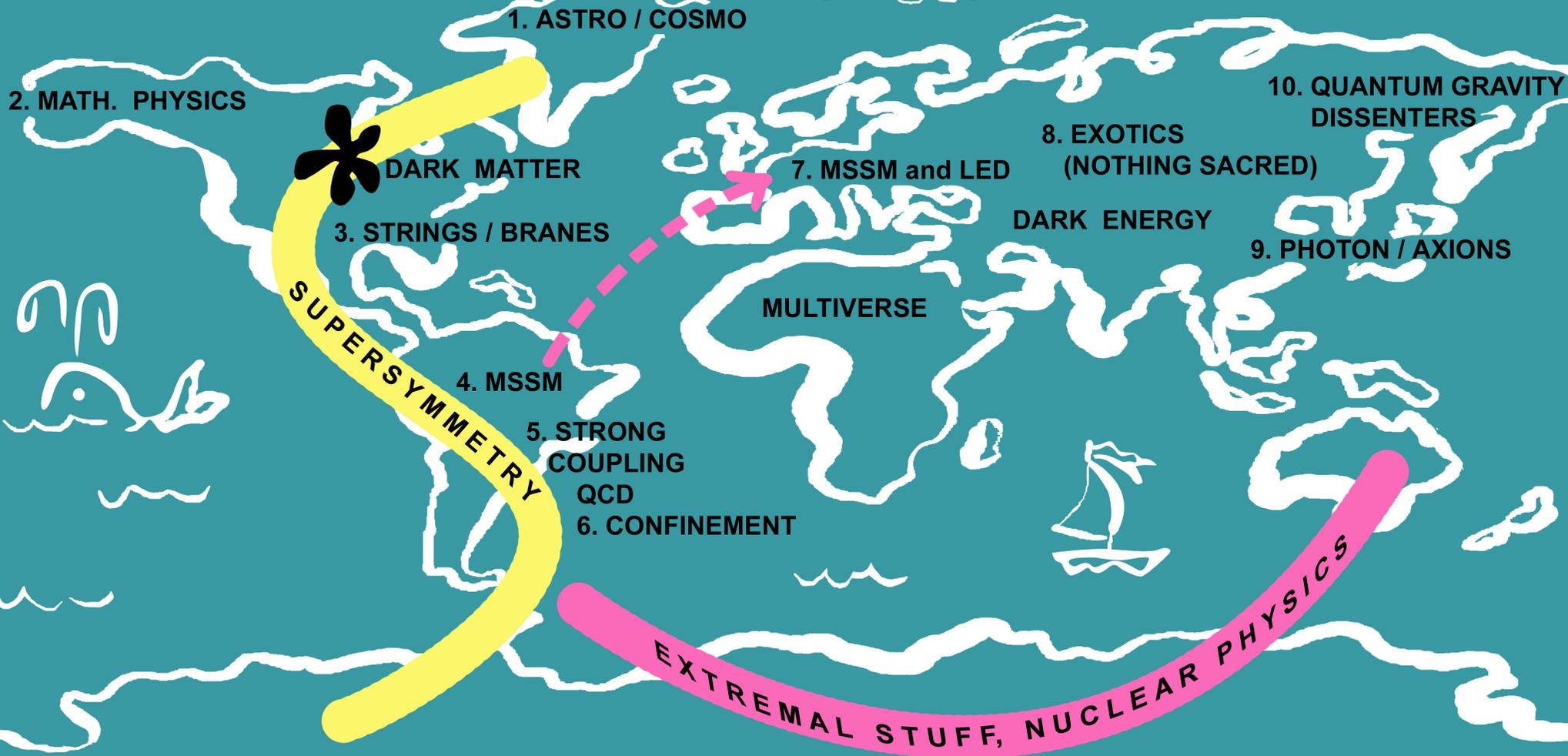


- ☺ *Хиггсовская частица в стандартной модели НЕОБХОДИМА*
- ☺ *Ее масса и вакуумное ожидание расходятся квадратично*
- ☺ *Если по дороге к M_{pl} нет новой физики, массы всех частиц “естественно” выталкиваются на M_{pl}*



- ☺ *Стандартная модель ненатуральна*

MAP OF HEP THEORY



- ☺ Открытие хиггсовской частицы с массой ≈ 125 ГэВ (и ничего более) стало ударом по MSSM-феноменологии. Относительно простая модель с единым масштабом нарушения SUSY близким к электрослабому масштабу умерла!
- ☺ Проблемы иерархии масс и натуральности вернулись, масса $\tilde{t} \geq 5-10$ ТэВ, finetuning \sim (неск) промилле!
- ☺ Split supersymmetry, spread supersymmetry, A-terms, you name it, still called “natural”
(например, в первом и втором поколении суперпартнеры чрезвычайно тяжелые и не проявятся, масса \tilde{t} подгоняется под 10 ТэВ, глюино и вино тяжелые и не будут видны на LHC)

Исходная парадигма потерпела фиаско ☹ ☹ ☹

Часть 2: Янг-Миллс в сильной связи / КХД

😊 Суперсимметрии - мощный (и почти единственный) аналитический инструмент в режиме конфайнмента

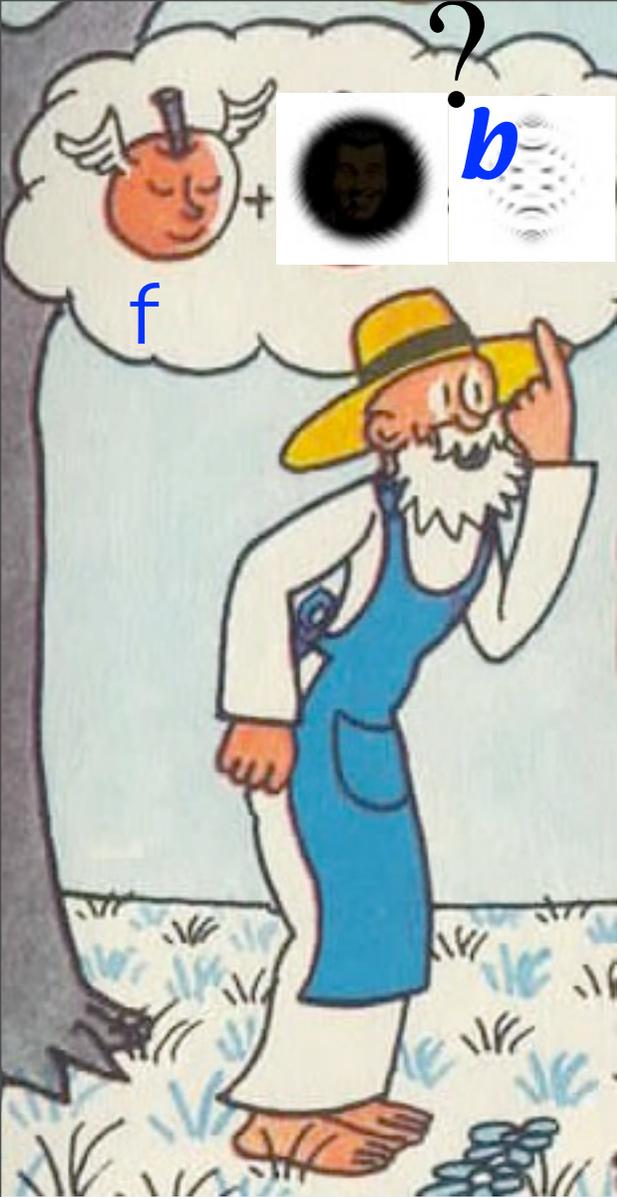
😊😊 Экскурсы в историю: Индекс Виттена (1982);

Суперинстантон в 3D (слабая связь)
Аффлек и др. (1982) 

Супер-Янг-Миллс



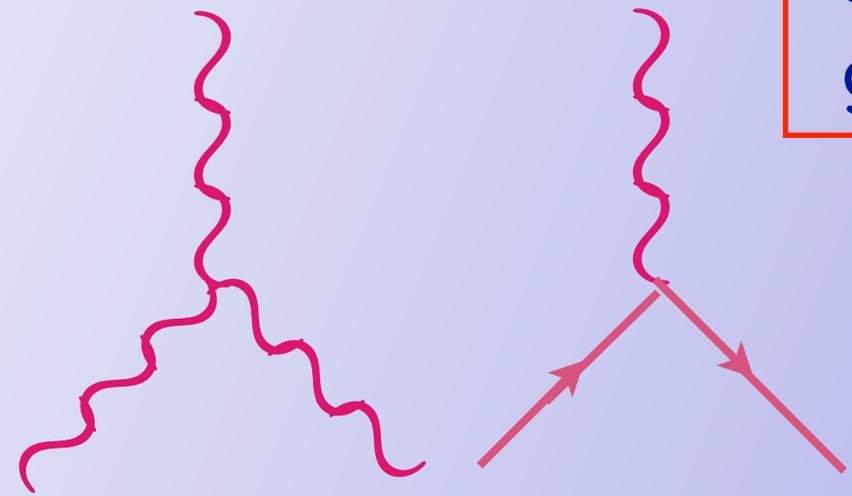
1982-83
(ИТЭФ)



$$\mathcal{L} = -\frac{1}{4g^2} G_{\mu\nu}^a G^{\mu\nu a} + \frac{i}{2} \lambda \not{D} \lambda$$

gluon

gluino



SUSY Yang-Mills

supersymmetric
gluodynamics

Superinstanton calculus

NSVZ β exact function, 1983, $T_G = N$ for $SU(N)$

$$\beta(\alpha) \equiv \frac{d\alpha(M_{PV})}{d\ln M_{PV}} = -\frac{3T_G \alpha^2}{2\pi} \left(1 - \frac{T_G \alpha}{2\pi}\right)^{-1}$$

Чуть позже с произвольной материей:

$$\beta(\alpha) \equiv \frac{d\alpha(M_{PV})}{d\ln M_{PV}} = -\frac{\alpha^2}{2\pi} \left[3T_G - \sum_i T(R_i)(1 - \gamma_i)\right] \left(1 - \frac{T_G \alpha}{2\pi}\right)^{-1}$$

γ_i ; аномальная размерность поля материи R_i



Элемент зайберговской дуальности (1994), конформ. окно

Конденсат глюино через аналитическое продолжение из слабой связи в сильную, Вайнштейн, МШ, 1987

SU(2) SQCD with one flavor:

$$\langle \text{Tr } \lambda^2 \rangle = 16\pi^2 m \langle \Phi^2 \rangle = \pm 16\pi^2 [m \Lambda_{\text{one-fl}}^5]^{1/2} = \pm 16\pi^2 \left[\frac{m e^{-8\pi^2/g^2}}{Z g^4} (M_{\text{PV}})^5 \right]^{1/2}$$

$$m/Z = m_{\text{bare}}$$

$$\sqrt{m_{\text{bare}}}$$

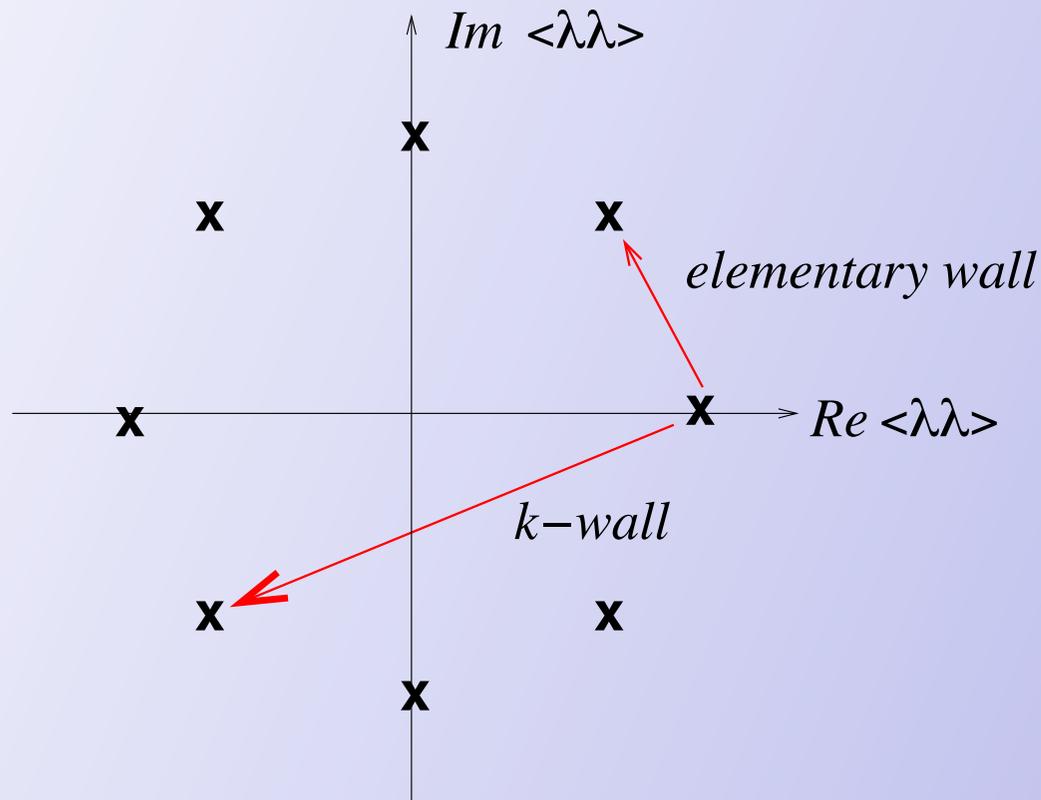
exact

Общая формула

$$\langle \lambda^a \lambda^a \rangle = -6 N \Lambda^3 \exp(2\pi i k/N)$$

Схожий метод (поднятый на невероятную высоту) в прорывном решении N=2 супер-Янг-Миллса Зайберга-Виттена (1994).

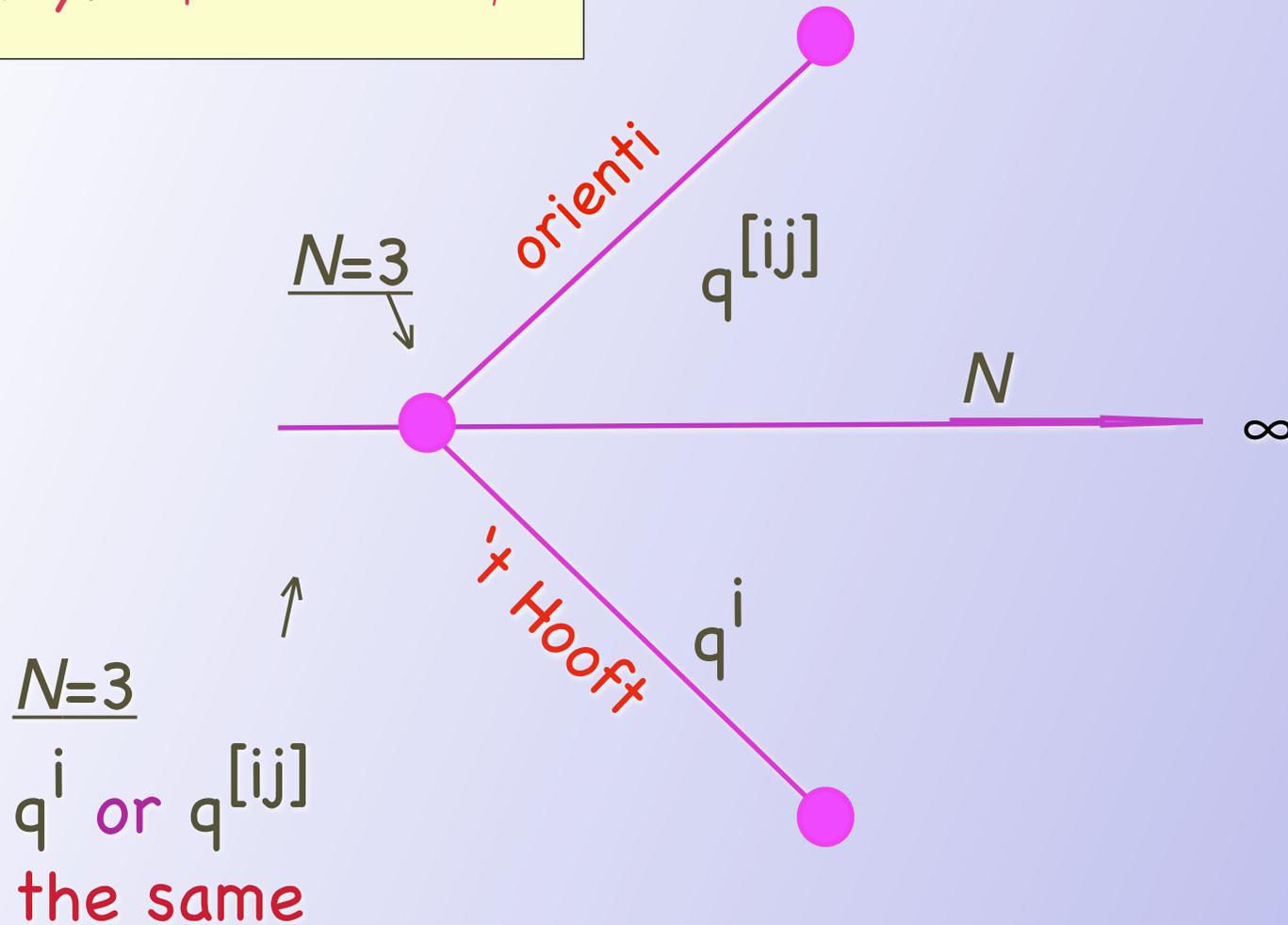
Натяжение доменных стенок в супер-глюодинамике,
Гия Двали, МШ, 1995-96 (BPS-protected!)



$$T = \frac{N}{8\pi^2} \left| \langle \text{Tr} \lambda^2 \rangle_{\text{vac } f} - \langle \text{Tr} \lambda^2 \rangle_{\text{vac } i} \right| \sim N \text{ если } i, f \text{ близки друг к другу}$$

Виттен, 1996, Доменная стенка = D brane, т.к. $N \sim 1/g_s$

Each Weyl $\lambda_i^j \rightarrow$ Dirac $\psi^{[ij]}$



Armoni-Shifman-Veneziano (2003): Planar equivalence between SUSY-Yang-Mills and orientifold daughter AND orientifold large N limit (replacing 't Hooft limit).

- **Summary:** SUSY gluodynamics at large N is equivalent to nonsupersymmetric orientifold daughter which at $N=3 \Rightarrow$ one-flavor QCD!

- quark condensate in one-fl QCD at $N = \infty$ calculable!

- ★ Infinite number of degeneracies: e.g. 0^+ & 0^- | 1^+ & 2^+ | ...;

* k flavors of $\psi^{[ij]}$'s

A new "orientifold" large N expansion

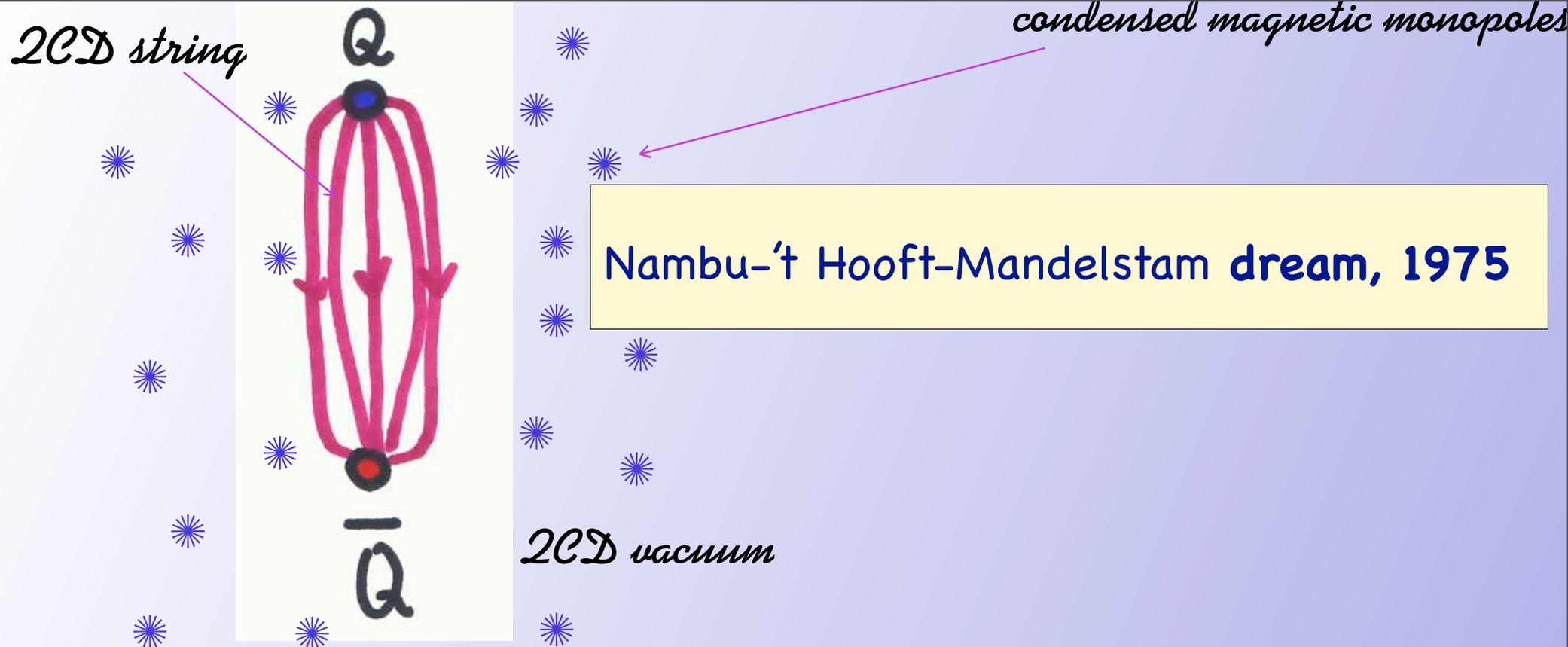
't Hooft: fundamental Dirac quarks at all N

$$\Gamma_{gl}/\Gamma_{qu} \sim N^{-1}$$

The same at $N=3$!
orientifold: Dirac $\psi^{[ij]}$ at all N

$$\Gamma_{gl}/\Gamma_{qu} \sim N^0$$

Обе феноменологии хороши ...

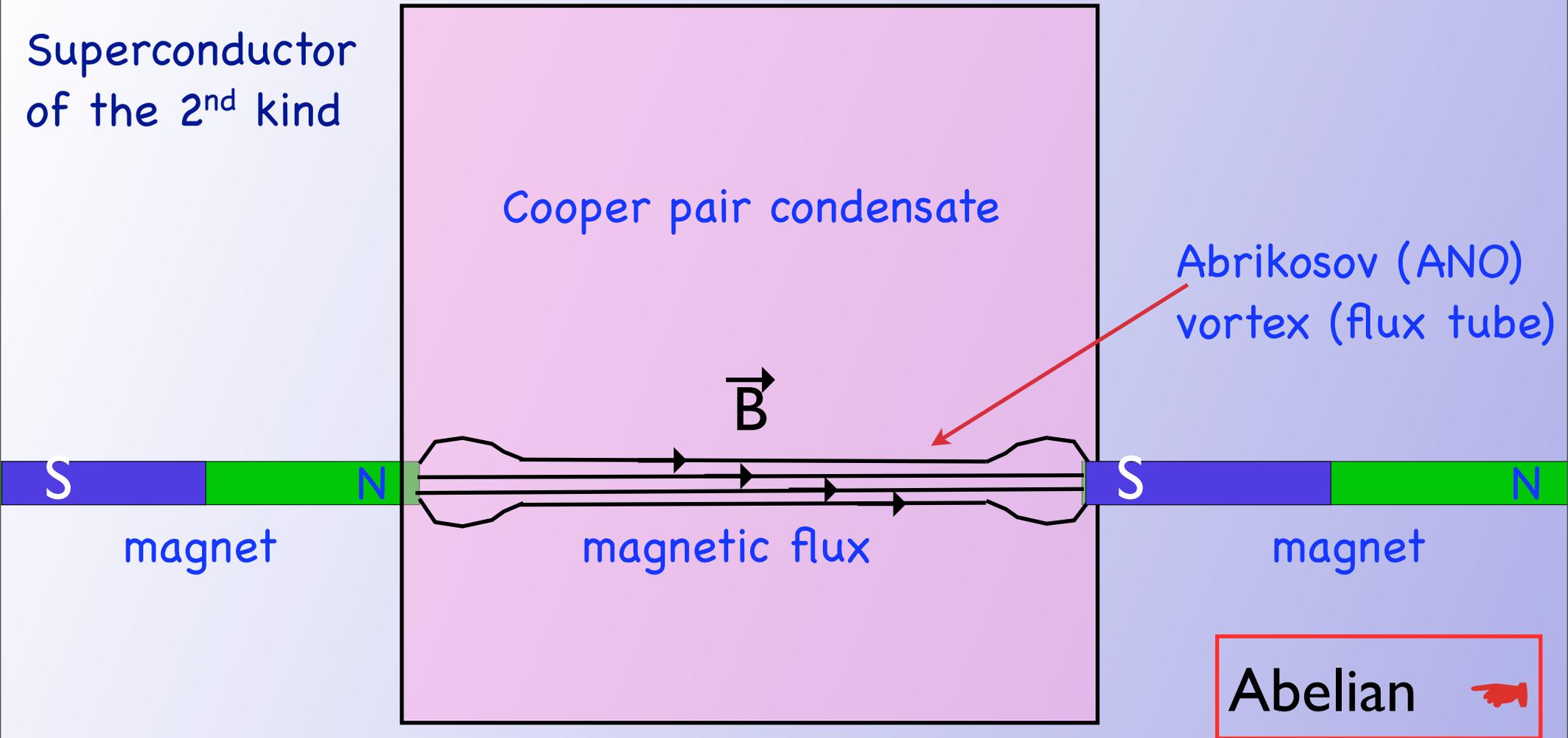


"...[monopoles] turn to develop a non-zero vacuum expectation value. Since they carry color-magnetic charges, the vacuum will behave like a superconductor for color-magnetic charges. What does that mean? Remember that in ordinary electric superconductors, magnetic charges are connected by magnetic vortex lines ... We now have the opposite: it is the color charges that are connected by color-electric flux tubes."

G. 't Hooft (1976)

👉 The Meissner effect: 1930s, 1960s

Superconductor
of the 2nd kind



DUAL MEISSNER EFFECT (Nambu-'t Hooft-Mandelstam, ~1975)

☺ First demonstration of the dual Meissner effect: Seiberg & Witten, 1994 ☺



- gluons+complex scalar superpartner
- two gluinos
- Georgi-Glashow model built in

$SU(2) \rightarrow U(1)$, monopoles \rightarrow

Monopoles become light if $|\phi^3| \simeq \Lambda \rightarrow$ At two points,

massless!

$N=1$ deform. forces M condensatition \rightarrow

$U(1)$ broken, electric flux tube formed \rightarrow

☞ Dynamical Abelianization ... dual Abrikosov string

$\xrightarrow{\hspace{10em}}$ analytic continuation

But...

★ Non-Abelian theory, but

Abelian flux tube 

Hanany, Strassler, Zaffaroni '97  SW=Abelian strings, "wrong" confinement...

☞ Non-Abelian Strings, 2003 → Now

Hanany-Tong

Auzzi et al.

Shifman-Yung

☞ Non-Abelian nature → to come as close to **Nature** as possible

Bulk $G \times G \rightarrow CF$ locking $\rightarrow (G_{\text{diag}} \rightarrow H) \rightarrow G/H$ coset model

on the world sheet \rightarrow (susy in bulk \rightarrow susy on ws)



$N=2 \rightarrow N=(2,2)$

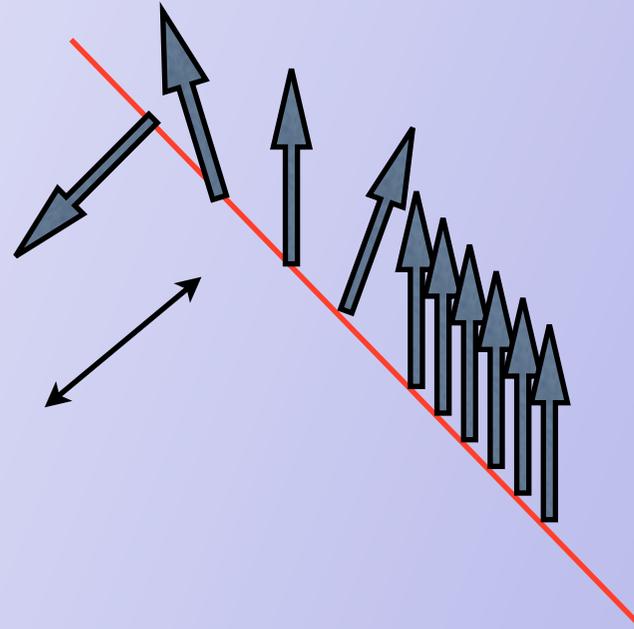
$N=1 \rightarrow N=(2,0)$ nonminimal;



$N=0 \rightarrow N=0$

❖ Gaiotto, 2012 & Gaiotto, Gukov, Seiberg, 2013 "surface defects"...

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

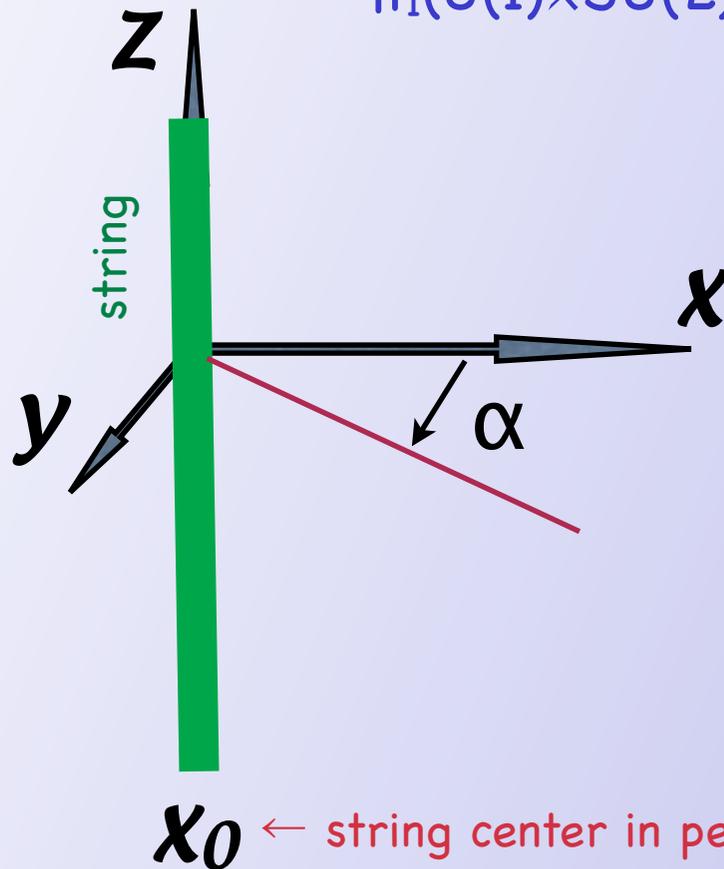


classically gapless excitation

$SU(2)/U(1) = CP(1) \sim O(3)$ sigma model

- ★ ANO strings are there because of U(1)!
- ★ New strings:

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



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

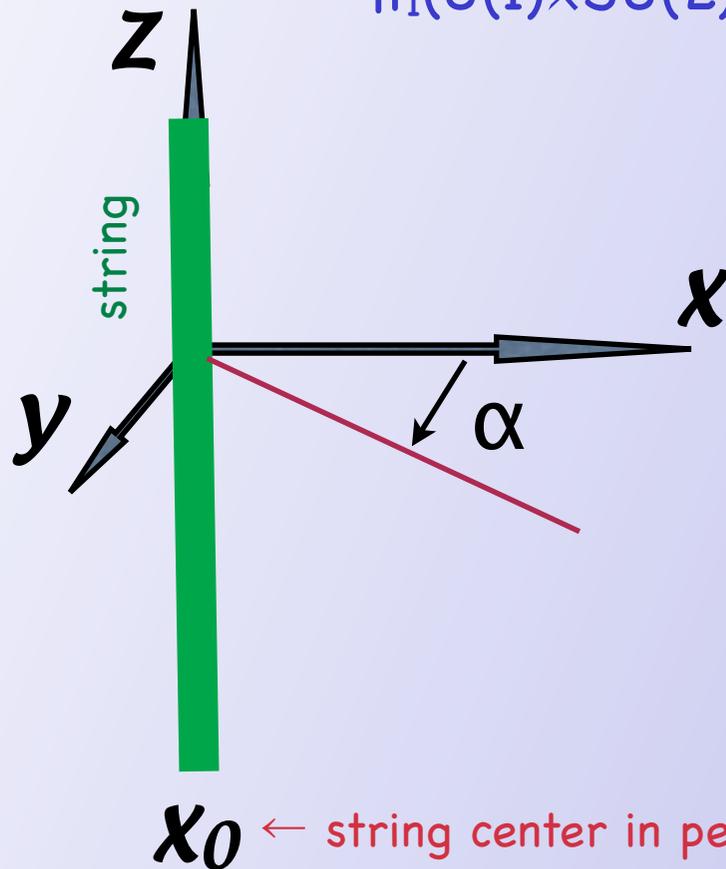
★ ANO strings are there because of U(1)!

★ 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)



ANO

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

$$T = 4\pi \xi$$

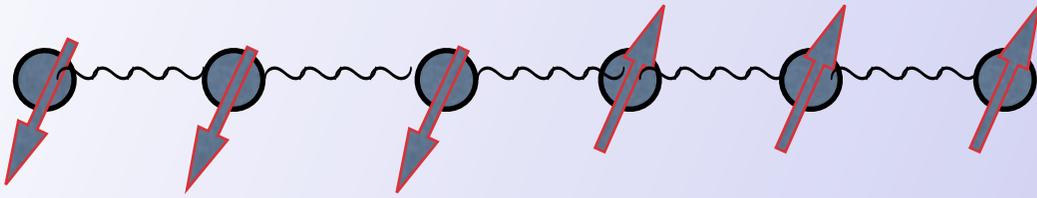
Non-Abelian

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

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

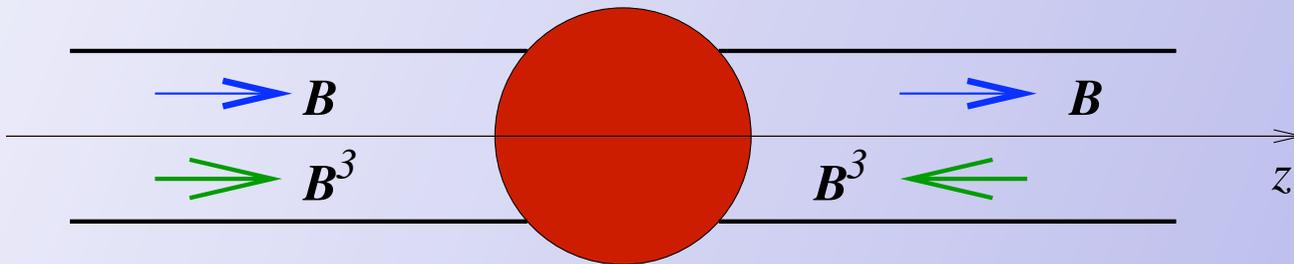
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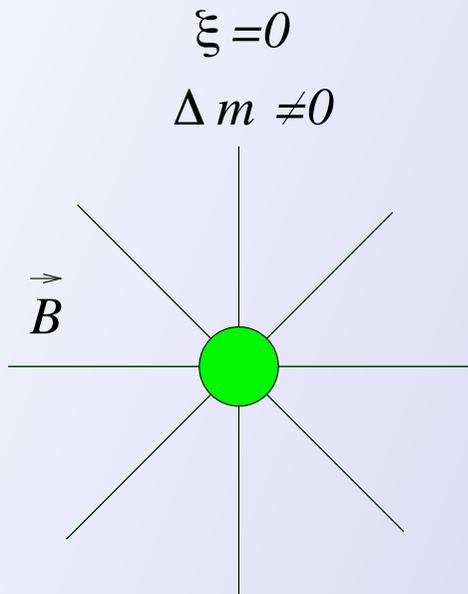


Z_2 string junction = kink

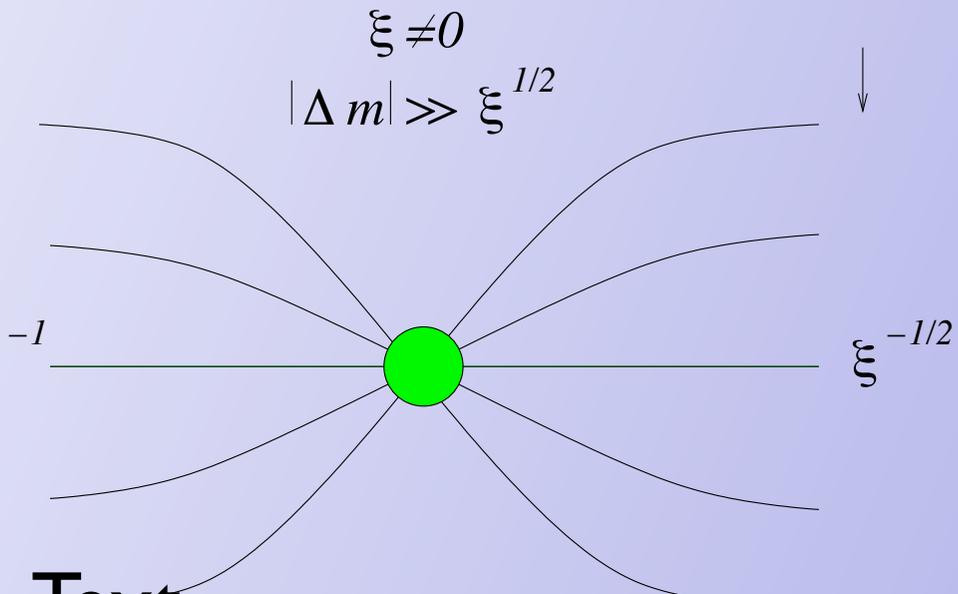
Yung + M.S.
Hanany, Tong



Evolution in dimensionless parameter m^2 / ξ

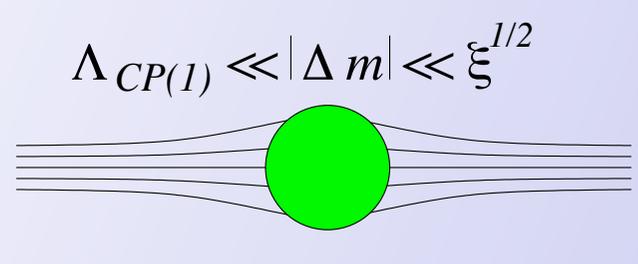


The 't Hooft-Polyakov monopole

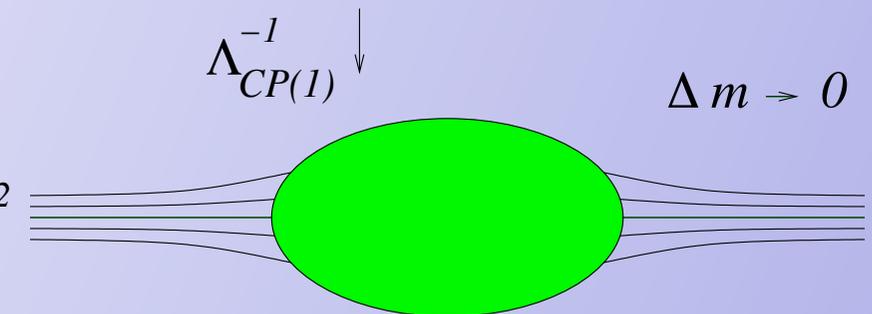


Text

Almost free monopole



Confined monopole, quasiclassical regime



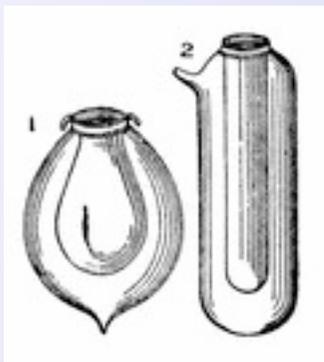
Confined monopole, highly quantum regime

- * Kinks are confined in 4D (attached to strings).
- * * Kinks are confined in 2D:

Kink = Confined Monopole

4D \leftrightarrow 2D Correspondence

☞ World-sheet theory \leftrightarrow strongly coupled bulk theory inside



Dewar flask

Break $\mathcal{N} = 2$ down to $\mathcal{N} = 1$ in the bulk

Deformation of the bulk: ADD $W = \mu (A^a)^2 + \mu' A^2$

Heterotic deformation the of the World-sheet theory:

(2,2) supersymmetry is broken down to (0,2)

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

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!

Instead of conclusions

- ➡ Heterotic models on string world-sheet under intense discussion!!!

A treasure trove of novel 2D models with intriguing dynamics

Спасибо!