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- ✿ Heterotic strings from $N=1$ SUSY field theory;
- ✿ Worldsheet theory: $N=(0,2)$ extension of 2D $CP(N-1)$ sigma model.

With A. Yung

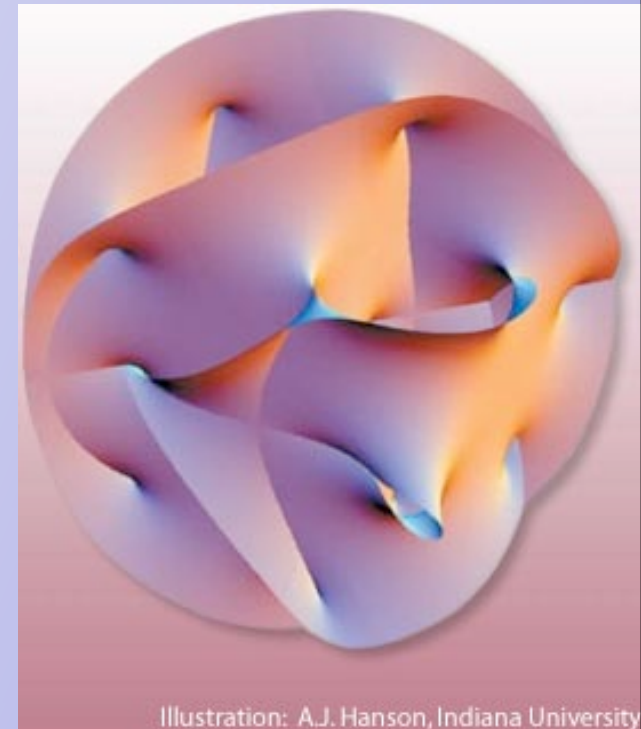


Illustration: A.J. Hanson, Indiana University

Non-Abelian flux tubes in N=2 super-Yang-Mills

✿ U(N) gauge group, N flavors

gluons + 2 gluinos + adjoint scalars

For U(2): 2 (s)quark flavors

q^{iA} & $\tilde{q}_{iA}$ ($i=1,2$, $A=1,2$)



color



flavor

+ U(1) Fayet-Iliopoulos term $\rightarrow$ “BPS-ness”

$$\mathcal{W} = \sum_{A=1}^2 \left(\tilde{q}_A \mathcal{A} q^A + \tilde{q}_A \mathcal{A}^a \tau^a q^A \right)$$

Vacuum:

$$q^{kA} = \sqrt{\xi} \begin{pmatrix} 1 & 0 \\ 0 & 1 \end{pmatrix}$$


FI

$$\tilde{q} \equiv 0, \quad a^a = a = 0$$

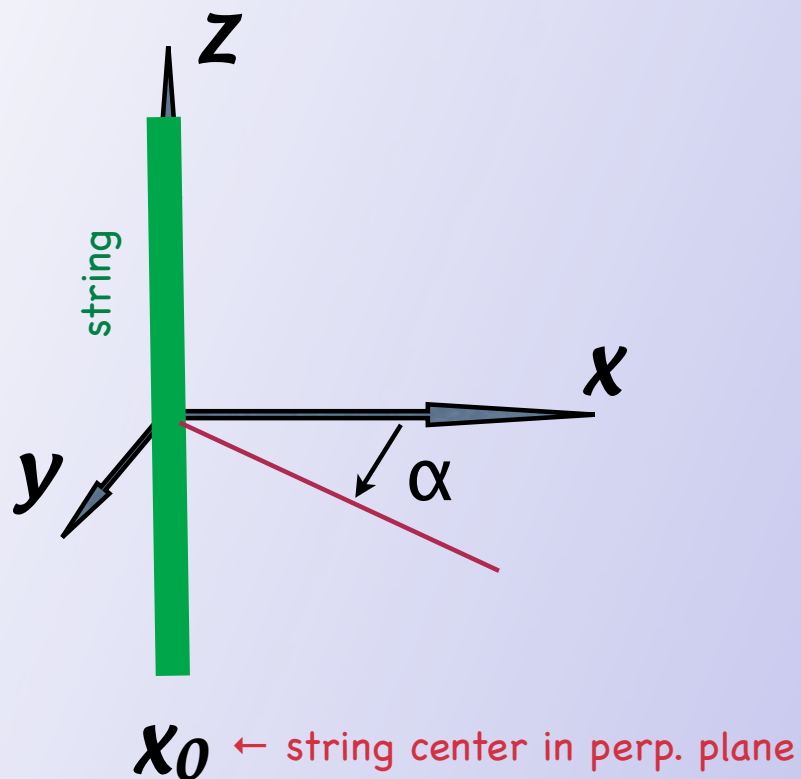
* Bulk theory is fully Higgsed

* Color+Flavor SU(2) survives!

$$\longrightarrow U_c \begin{pmatrix} 1 & 0 \\ 0 & 1 \end{pmatrix} U_F^\dagger = \begin{pmatrix} 1 & 0 \\ 0 & 1 \end{pmatrix}$$

Non-Abelian flux tubes

$\pi_1(U(1) \times SU(2))$ 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

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

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

$$T = 2\pi\xi$$

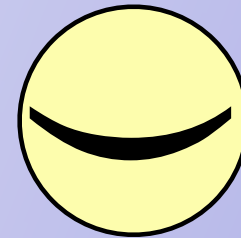
SU(2)/U(1) orientational moduli emerge

8 supercharges in the bulk $\rightarrow$ 1/2 BPS flux tube $\rightarrow$
 4 supercharges on world sheet $\rightarrow$

MODULI:

(super)Translational

x_{0i} ($i=1,2$) & $\zeta_R, \zeta_R^\dagger, \zeta_L, \zeta_L^\dagger \Leftarrow \text{decouple}$



SU(2)/U(1) moduli

2 orientational + 4 superorientational $\rightarrow$ CP(1) model
 with N= (2,2) SUSY

$$\mathcal{L} = \int d^4\theta K, \quad K = \frac{1}{g_0^2} \ln(1 + \bar{\Phi}\Phi)$$

✿ Non-Abelian strings have:

✿ Dynamical IR scale Λ generated on worldsheet;

$$\Lambda \ll m_W \ll \sqrt{\xi}$$

String thickness $\sim 1/m_W$

String tension $\sim \xi$

✿ Lüscher coefficient different

Bulk theory weakly coupled; world-sheet theory strongly coupled!

From N=2 to N=1 in the bulk → Eliminating adjoint fields

$$\mathcal{W} = \frac{1}{2} \mu \mathcal{A}^2$$

If $\mu \gg m_W$ adjoint fields are GONE!

The classical string solution remains the same, and so does the number of moduli;

N=2 is broken down to N=1 in the bulk;

Expect 4 supercharges in the bulk & 2 supercharges on the worldsheet;

BUT: CP(1) with N=1 is automatically elevated to N=2 ✓✓✓

Accidental SUSY enhancement?

Edalati-Tong suggestion:

assume x_0 and ζ_L decouple BUT ζ_R gets mixed with ψ from $CP(1)$

supertranslational

superorintational



Then the $N(0,2)$ generalization of bosonic $CP(1)$ IS possible!

Our task was to derive it directly from the bulk;
explicit expressions for all fermion zero modes needed

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

$$= G \left\{ \partial_\mu \phi^\dagger \partial^\mu \phi + \frac{i}{2} (\psi_L^\dagger \overset{\leftrightarrow}{\partial}_R \psi_L + \psi_R^\dagger \overset{\leftrightarrow}{\partial}_L \psi_R) \right. \\ \left. - \frac{i}{\chi} [\psi_L^\dagger \psi_L (\phi^\dagger \overset{\leftrightarrow}{\partial}_R \phi) + \psi_R^\dagger \psi_R (\phi^\dagger \overset{\leftrightarrow}{\partial}_L \phi)] - \frac{2(1 - g_0^2 |\gamma|^2)}{\chi^2} \psi_L^\dagger \psi_L \psi_R^\dagger \psi_R \right\}$$

$$g_0^2 |\gamma|^2 = \alpha^2 / (1 + \alpha^2), \quad \alpha = 2\sqrt{2} \mu / m_W \text{ if } \mu \ll m_W \\ = 1 \quad \text{if } \mu \gg m_W$$

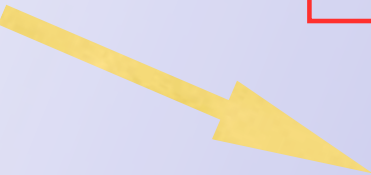
← saturation

At small γ /small μ


$$\gamma \zeta_R R (i \partial_L \phi^\dagger) \psi_R$$


$$\Delta J_{sc,R} = \gamma \langle R \psi_R^\dagger \psi_L \rangle \zeta_R^\dagger$$


Goldstino


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

SUSY vacua are LIFTED!

SUSY is broken, and so is Z_{2N}

$Z_{2N} \rightarrow Z_2$,
as in conventional $N=(2,2)$ CP(N-1)

Large-N solution for all μ 's $\Rightarrow \Rightarrow \Rightarrow$

At $m_W \ll \mu < \infty$:

$$\mathcal{E}_{vac} = \Lambda^2$$

Goldstino is a mixture of ζ_R and $R\psi_R^\dagger \partial_L \phi_R$

The chiral condensate $\langle R\psi_R^\dagger \psi_L \rangle$ becomes small $\rightarrow$
 $Z_{2N} \rightarrow Z_2$ breaking is weak!

What happens in the limit $\mu \rightarrow \infty$?

Bulk theory becomes gapless in IR $\rightarrow$ derivation
of heterotic $CP(N-1)$ fails (at $\mu \sim \xi/\Lambda$).

N vacua coalesce? Conformal? Perhaps, M model?.....

Conclusions:

- ☀ Heterotic non-Abelian flux tube in $N=1$ SUSY YM constructed;
- ☀ Heterotic generalization of $CP(N-1)$ on worldsheet derived from the bulk;
- ☀ Heterotic $CP(N-1)$ solved at large N ; patterns of SUSY breaking and Z_{2N} breaking established.