SUPERSYMMETRY BREAKING AND THE SWAMPLAND

Based on collaboration with

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Outline

- Why perturbative strings with broken SUSY?
- The weak gravity conjecture (WGC)
- Brane interactions in string theory
- Supersymmetry breaking and WGC
- Perspectives
Why perturbative strings with broken SUSY?

(talks: perturbative Bonnefoy, Cribiori, Coudarchet, Faraggi, Roupec, Wrase...
nonperturbative (KKLT): Blumenhagen, Buratti, Grana, Hebecker, Klaewer, S. Lust, McAllister, Moritz, Sethi, Soler, Van Rlet...)

- Since consistency/conceptual issues are similar in both perturbative/nonperturbative cases

Ex: hierarchies from fluxes → long throats

Warped redshifts mass of a complex structure modulus, probably generically the case for any long throat
Affects steps I and III of KKLT (Bena, E.D., Grana, S. Lust, ‘18; Blumenhagen, Klaewer, Schechter, ‘19;
Talks: Blumenhagen, Grana, Klaewer, S. Lust)
- Since there a landscape of **perturbative strings** with broken SUSY and non-SUSY strings:

  - Strings broken SUSY: Scherk-Schwarz comp., brane SUSY breaking, internal magnetic fields/intersecting branes

  - non-SUSY: comp. of $SO(16) \times SO(16)$ heterotic strings, $O'B$ orientifolds

- Since scale of SUSY breaking **higher** than expected (LHC)

- Important to understand their role in the **swampland**
The weak gravity conjecture (WGC)

Arkani-Hamed, Motl, Nicolis, Vafa, 2006

Loose form: **GRAVITY IS THE WEakest FORCE.**

For a theory with a massless photon coupled to gravity, it implies that there should exist one charged particle with

\[ |q| M_P \geq m \]

Some arguments in favor of WGC:

a) Avoidance of stable charged black hole remnants
b) Absence of global symmetries in string theory/quantum gravity
a) A charged (RN) black hole has $|Q| < M$

It can evaporate by emitting particles with $|q| M_P \geq m$

b) In the limit $q \rightarrow 0$ gauge symmetry becomes global. This should be forbidden, at least in string theory.

There are potential intriguing connections between WGC and

- The hierarchy problem (Cheung-Remmen) : quadratically div. contributions to a charged scalar could violate WGC

- Cosmic censorship (Horowitz et al.) : bad singularities in geometries violating CC are forbidden by WGC
Brane interactions in string theory

- Charged BPS D-branes have mass/tension and in superstrings they do not interact, since \( T = |Q| \)

What about non-BPS charged ones?

A simple way to generate them is putting internal magnetic fluxes on DP branes \( \rightarrow \) generate lower-dim. charges, bound states of branes

\[
\int_{Dp} C \wedge e^F = \int_{Dp} (C_{p+1} + C_{p-1} \wedge F + \frac{1}{2} C_{p-3} \wedge F \wedge F + \cdots)
\]
Interesting example: D6 branes in type IIA, wrapping the whole internal space:

<table>
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<th>0</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
<th>9</th>
</tr>
</thead>
<tbody>
<tr>
<td>D6</td>
<td>x</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
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</tr>
</tbody>
</table>

\[ \langle F_1 \rangle \quad \langle F_2 \rangle \quad \langle F_3 \rangle \]

Such D6 branes behave as particles in spacetime. We compute the interaction potential of two such objects, separated by a distance \( r \) in space (string formulae). Then take the limits:

- Large distance \( r \gg \sqrt{\alpha'} \) : tree-level exchange of SUGRA modes
- Small distance \( r \ll \sqrt{\alpha'} \) : one-loop of charged states
- Magnetic fields are quantized: \[ F_i = \frac{k_i}{v_i}, \quad k_i \in \mathbb{Z} \]

Defining \( \tan \pi \epsilon_i = \pi qF_i, \quad 0 \leq \epsilon_i \leq 1 \), one finds

- large distances \( r \gg \sqrt{\alpha'} \)

\[
V_{6162} \sim \prod_{i=1}^{3} (qk_i) \int_0^\infty \frac{dl}{l^{3/2}} \sin \frac{\pi(\epsilon_1+\epsilon_2+\epsilon_3)}{2} \sin \frac{\pi(-\epsilon_1+\epsilon_2+\epsilon_3)}{2} \sin \frac{\pi(\epsilon_1-\epsilon_2+\epsilon_3)}{2} \sin \frac{\pi(\epsilon_1+\epsilon_2-\epsilon_3)}{2} \frac{1}{r^2} e^{-\frac{r^2}{2\alpha' l}}
\]

which is

\[
V_{6162} \sim \prod_{i=1}^{3} (qk_i) \sin \frac{\pi(\epsilon_1+\epsilon_2+\epsilon_3)}{2} \sin \frac{\pi(-\epsilon_1+\epsilon_2+\epsilon_3)}{2} \sin \frac{\pi(\epsilon_1-\epsilon_2+\epsilon_3)}{2} \sin \frac{\pi(\epsilon_1+\epsilon_2-\epsilon_3)}{2} \frac{1}{r}
\]

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• short distances \( r \ll \sqrt{\alpha'} \)

\[
V_{6,1,6,2} \sim \prod_{i=1}^{3} (q k_i) \int_0^\infty \frac{d\tau_2}{\tau_2^{3/2}} \sinh \frac{\tau_2 (\epsilon_1 + \epsilon_2 + \epsilon_3)}{4} \sinh \frac{\tau_2 (-\epsilon_1 + \epsilon_2 + \epsilon_3)}{4} \sinh \frac{\tau_2 (\epsilon_1 - \epsilon_2 + \epsilon_3)}{4} \sinh \frac{\tau_2 (\epsilon_1 + \epsilon_2 - \epsilon_3)}{4} e^{-\frac{\tau_2 r^2}{4 \pi \alpha'}}
\]

• No interaction if \( \epsilon_1 \pm \epsilon_2 \pm \epsilon_3 = 0 \)

In this case there is some partial SUSY preserved by the branes. If SUSY broken, there are potential tachyons in the charged open string spectrum. They can be avoided (any \( r \) ) provided triangle inequalities are satisfied:

\[
\begin{align*}
\epsilon_1 + \epsilon_2 & \geq \epsilon_3 , \quad \epsilon_2 + \epsilon_3 \geq \epsilon_1 \\
\epsilon_3 + \epsilon_1 & \geq \epsilon_2 , \quad \epsilon_1 + \epsilon_2 + \epsilon_3 \leq 2
\end{align*}
\]
• Necessary condition: all $\epsilon_i \neq 0$

Easy to check that:

- Absence of tachyons any repulsive brane interactions

- Tachyons short distances attractive brane interactions

- Any connection with the existence of black holes in type IIA (WGC) ?
$V_{6.62}$

\[ m_T^{-1} \]

Tachyonic case

$V_{6.62}$

Non-tachyonic case

$\gamma \sim \frac{1}{m_{\text{light}}}$

Highest scalar mass
WGC and SUSY breaking in string theory

(more details: talk Q. Bonnefoy)

- Charged BPS D-branes have mass/tension and in superstrings they satisfy marginally WGC \( T = |Q| \)

- Our « particles » are D1 branes (in type I strings) wrapping a circle. They behave like particles after compactification.

- SUSY broken by compactification along the circle (Scherk-Schwarz), different boundary conditions fermions /bosons (heterotic strings: Rohm, Ferrara, Kounnas, Porrati: type I/II Blum, Dienes; Antoniadis, E.D., Sagnotti...)

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\[
\Phi(2\pi R) = e^{i q \int A} \Phi(0), \quad \Psi(2\pi R) = -e^{i q \int A} \Psi(0)
\]

mass splittings ( \( A = \frac{a}{R} \) = Wilson line )

\[
M_{k,\Phi} = \frac{(k + a)}{R} \quad M_{k,\Psi} = \frac{(k + a + 1/2)}{R}
\]

• SUSY breaking generates a runaway potential for the radius R

\[
\mathcal{L} = \left( \frac{\partial R}{R} \right)^2 - \frac{c}{R^9}
\]

similar to quintessence models, \( R = e^{\frac{\sigma}{2}} \).

• SUSY restored in the \( R \to \infty \) limit. Assume R is rolling slowly towards the runaway ( \( c > 0 \) with appropriate WL: stability subtle: Abel,E.D.,Lewis,Partouche)
We are interested in D1-D1 interactions, for branes separated by a distance \( r = |\vec{r}| \) in space (and \( 2\pi a R' \) on the circle).

- For superstrings, cancelation between NS-NS and RR exchanges, for \( T_1 = |Q_1| \)

- SUSY breaking generates quantum corrections to \( T_1 \) and \( Q_1 \):

\[
T_{1,eff} = T_1 + g_s T_1' + \cdots
\]

\[
Q_{1,eff} = Q_1 + g_s Q_1' + \cdots
\]

◆ Naive implementation of WGC: repulsive D1-D1 interaction long distances \( r \gg \sqrt{\alpha'} \) (repulsive force conjecture: Palti; talk Heidenreich)
One-loop brane-brane interactions can be expressed as tree-level exchange of closed-string modes (for $r^2 \gg \alpha'$)

The result is (one needs string methods)

$$V_{11} = -\frac{R \alpha'^2}{2 \pi^2} \sum_n \int d^8 k \ e^{i k r} \left[ (1 - 1) \frac{\cos[4\pi n a_i] \cos[4\pi n a_j]}{k^2 + \frac{4n^2 R^2}{\alpha'^2}} + \frac{1}{8} \frac{\cos[2\pi (2n + 1) a_i] \cos[2\pi (2n + 1) a_j]}{k^2 + \frac{(2n+1)^2 R^2}{\alpha'^2} - \frac{2}{\alpha'}} \right]$$

Massless exchange cancels: Yukawa attraction violation of WGC?

$V \sim -\frac{1}{r} e^{-m r}$
We believe NO : large-distance interactions governed by

Quantum corrections to brane tension

massless exchange generated at the next perturbative order

Quantum correction to D1-brane tension = \text{brane self-energy}

\[ T'_1 = V_{11}(r = 0) < 0 \]

One finds

\[ T_{1,\text{eff}} = T_1 - \frac{2}{\pi^3 R^2} \sum_n \frac{1}{(2n + 1)^2} = T_1 - \frac{1}{2\pi R^2} , \quad M_0 = 2\pi R T_{1,\text{eff}} \]
There is no charge renormalization at that order \( Q'_1 = 0 \). (gauge invariance). We obtain therefore \( T_{1,\text{eff}} < Q_{1,\text{eff}} \).

At large distances and after compactification, we can write brane-brane interactions as

\[
\begin{align*}
V_{11}^{(0)} &= \sum_{p} \frac{16k_{10}^{2}
\pi R}{(2\pi)^{8}V_{5}} \int d^{3}k \ e^{ikr} \left[ \frac{Q_{1,\text{eff}}}{k^{2} + m_{p}^{2}} - \frac{T_{1,\text{eff}}^{2}}{4} \left( \frac{1}{k^{2} + m_{p}^{2} + m_{0}^{2}} + \frac{3}{k^{2} + m_{p}^{2}} \right) \right] \\
V_{11}^{(n)} &= -\frac{R\alpha'^{2}}{16\pi^{2}V_{5}} \sum_{p} \int d^{3}k \ e^{ikr} \frac{\cos[2\pi a_{i}]}{k^{2} + m_{p}^{2} + \frac{R_{i}^{2}}{\alpha'^{2}} - \frac{2}{\alpha'}} \cos[2\pi a_{j}] \,
\end{align*}
\]

\( V_{11}^{(0)} = 0 \) at one-loop. Our arguments imply \( V_{11}^{(0)} > 0 \) at next order (genus 3/2).
We can define the « particle » mass and charge

\[ M_0 = 2\pi R T_{1,\text{eff}}, \quad Q_0 = 2\pi R Q_{1,\text{eff}} \]

We can then write the approximate long-distance potential as

\[
V_{11} \sim \frac{1}{M_P^2} \left[ \frac{4}{3} Q_0^2 - M_0^2 - \frac{1}{3} M_0^2 e^{-m_0 r}}{r} - \frac{Q_0^2}{6} e^{-r \sqrt{\frac{R^2}{\alpha'} - \frac{2}{\alpha}}} \right]
\]

massless exchange

massive exchange
Figure 1: The D1-D1 potential as a function of the distance in the transverse space (the potentials and distances are expressed in units of $\alpha'$, we fixed $R = 8$, $g_S = 0.2$, $V_5 \sim 1.5^5$ and introduced no Wilson lines for the D1 branes)
The **dangerous case** (for WGC) is when the maximum is reliable in the field-theory limit

\[ r_0 \gg \sqrt{\alpha'} \quad \quad \quad \quad g_s \ll \frac{R^3}{\alpha'^{3/2}} e^{-\frac{R}{\sqrt{\alpha'}}} \quad \quad \quad (*) \]

In this case, WGC is violated for \( r < r_0 \) and small black holes (for ex. D1 bound states) could be **stable remnants**.

Unclear if really problematic, in any case (*) is a **safe condition**.
Perspectives

- Swampland: stringy constraints on BSM and cosmological models. Important to test conjecture in perturbative strings with broken SUSY and effective field theory models.

- In superstrings, we checked interactions between non-BPS branes with several charges. There is a relation:
  - Repulsion $\iff$ absence of open string (charged) tachyons
  - Attraction $\iff$ tachyons at short brane separation
  - Interesting to understand the connexion brane repulsion/interaction and black holes
• We started to investigate WGC in strings with broken SUSY. We find short-range attraction, but long-range repulsion, since

\[ T_{1,\text{eff}} < Q_{1,\text{eff}} \]

Interesting further possible checks.

Thank You!