INSTITUT POLYTECHNIQUE DE PARIS

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

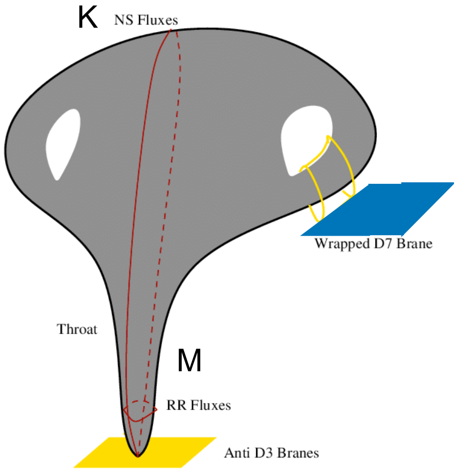
Why perturbative strings with broken SUSY ?

(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



Warping redshifts mass of a complex structure modulus, probably generically the case for any long thoat
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

Talks: Andriolo,Bonnefoy, Buratti, Gonzalo, Heidenreich,Heisteeg,Ibanez,Palti,Vafa…

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 $q \to 0$ 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 → 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:

Coord.	0	1	2	3	4	5	6	7	8	9
D6	x	0	0	0	x	x	x	x	x	x

$$\underbrace{\langle F_1 \rangle} \quad \underbrace{\langle F_2 \rangle} \quad \underbrace{\langle F_3 \rangle}$$

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: $F_i = \frac{k_i}{v_i} \ , k_i \in Z$

Defining $\tan \pi\epsilon_i = \pi q F_i \ , 0 \leq \epsilon_i \leq 1$, one finds

- large distances $r \gg \sqrt{\alpha'}$

$$V_{6_1 6_2} \sim \prod_{i=1}^{3}(qk_i) \int_0^\infty \frac{dl}{l^{3/2}} \frac{\sin\frac{\pi(\epsilon_1+\epsilon_2+\epsilon_3)}{2} \sin\frac{\pi(-\epsilon_1+\epsilon_2+\epsilon_3)}{2} \sin\frac{\pi(\epsilon_1-\epsilon_2+\epsilon_3)}{2} \sin\frac{\pi(\epsilon_1+\epsilon_2-\epsilon_3)}{2}}{\sin\pi\epsilon_1 \sin\pi\epsilon_2 \sin\pi\epsilon_3} e^{-\frac{r^2}{2\pi\alpha' l}}$$

which is $V_{6_1 6_2} \sim \prod_{i=1}^{3}(qk_i) \frac{\sin\frac{\pi(\epsilon_1+\epsilon_2+\epsilon_3)}{2} \sin\frac{\pi(-\epsilon_1+\epsilon_2+\epsilon_3)}{2} \sin\frac{\pi(\epsilon_1-\epsilon_2+\epsilon_3)}{2} \sin\frac{\pi(\epsilon_1+\epsilon_2-\epsilon_3)}{2}}{\sin\pi\epsilon_1 \sin\pi\epsilon_2 \sin\pi\epsilon_3} \frac{1}{r}$

- short distances $r \ll \sqrt{\alpha'}$

$$V_{6_1 6_2} \sim \prod_{i=1}^{3} (q k_i) \int_0^\infty \frac{d\tau_2}{\tau_2^{3/2}} \frac{\sinh \frac{\tau_2(\epsilon_1+\epsilon_2+\epsilon_3)}{4} \sinh \frac{\tau_2(-\epsilon_1+\epsilon_2+\epsilon_3)}{4} \sinh \frac{\tau_2(\epsilon_1-\epsilon_2+\epsilon_3)}{4} \sinh \frac{\tau_2(\epsilon_1+\epsilon_2-\epsilon_3)}{4}}{\sinh \frac{\tau_2 \epsilon_1}{2} \sinh \frac{\tau_2 \epsilon_2}{2} \sinh \frac{\tau_2 \epsilon_3}{2}} e^{-\frac{\tau_2 r^2}{4\pi\alpha'}}$$

- 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 :

$$\epsilon_1 + \epsilon_2 \geq \epsilon_3 \ , \ \epsilon_2 + \epsilon_3 \geq \epsilon_1$$

$$\epsilon_3 + \epsilon_1 \geq \epsilon_2 \ , \ \epsilon_1 + \epsilon_2 + \epsilon_3 \leq 2$$

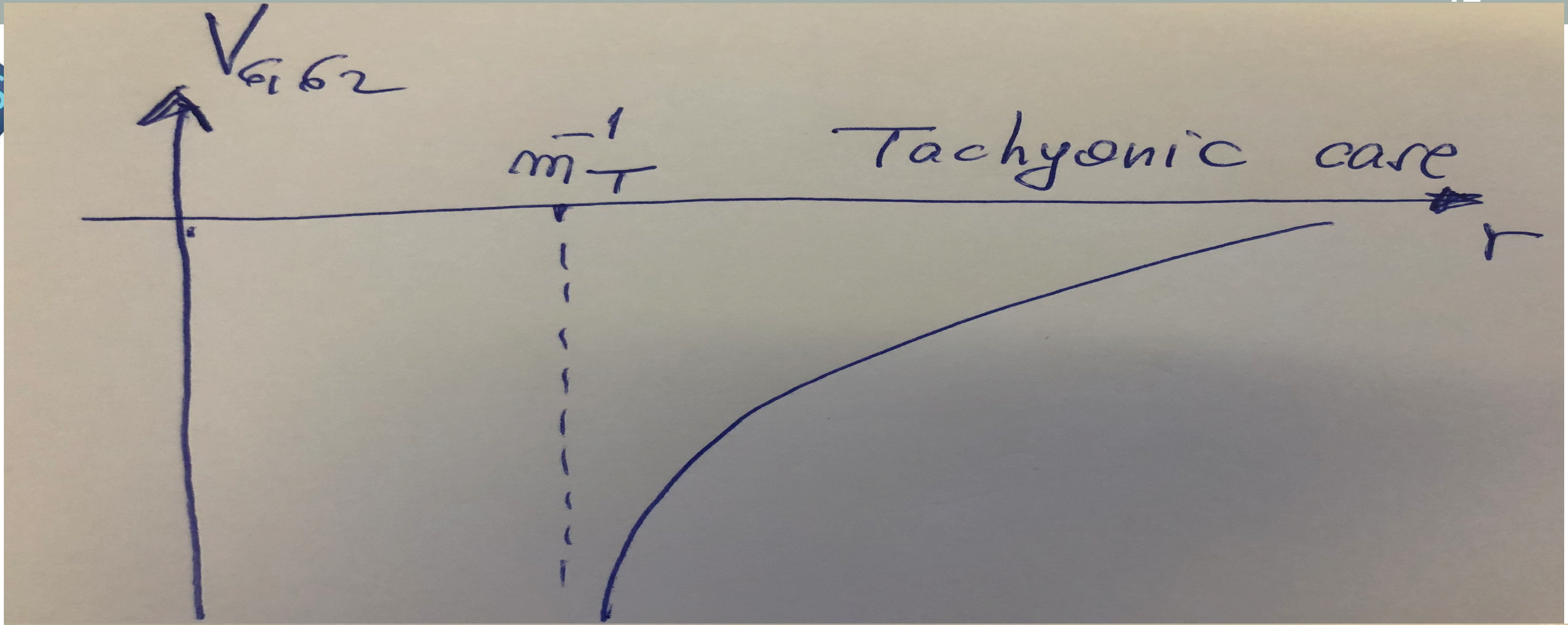
- Necessary condition: all $\epsilon_i \neq 0$

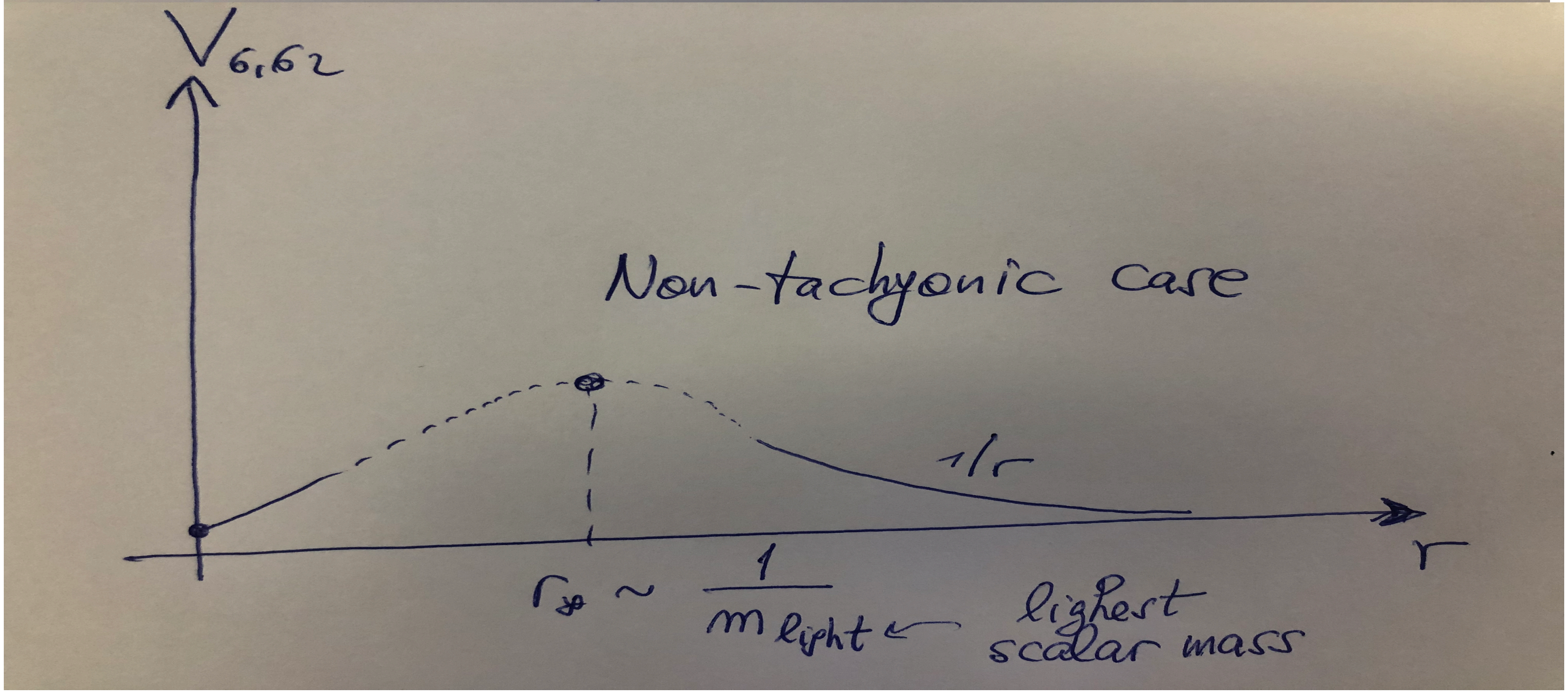
Easy to check that :

- Absence of tachyons any r ⟷ repulsive brane interactions

- Tachyons short distances ⟷ attractive brane interactions

- Any connection with the existence of black holes in type IIA (WGC) ?


$V_{\sigma_1\sigma_2}$
m_T^{-1}
Tachyonic case
r


$V_{\sigma_1\sigma_2}$
Non-tachyonic case
$1/r$
r
$r_* \sim \frac{1}{m_{light}}$ ← lightest 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…)

$$\Phi(2\pi R) = e^{iq\int A}\ \Phi(0) \quad , \quad \Psi(2\pi R) = -e^{iq\int A}\ \Psi(0)$$

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

$$M_{k,\Phi} = (k+a)/R \qquad M_{k,\Psi} = (k+a+1/2)/R$$

- SUSY breaking generates a runaway potential for the radius R

$$\mathcal{L} = (\frac{\partial R}{R})^2 - \frac{c}{R^9}$$

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)

field-theory gravity (closed string) states

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

windings closed strings

momenta perp. to D1 branes

masses closed string states (would-be tachyon, wrong GSO projection)

Massless exchange cancels: Yukawa attraction

$$V \sim -\frac{1}{r}e^{-mr}$$

violation of WGC ?

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 = brane self-energy

$$T_1' = V_{11}(r=0) < 0$$

One finds

$$T_{1,\mathrm{eff}} = T_1 - \frac{2}{\pi^3 R^2} \sum_n \frac{1}{(2n+1)^2} \;=\; T_1 - \frac{1}{2\pi R^2} \quad , \quad M_0 = 2\pi R T_{1,\mathrm{eff}}$$

There is no charge renormalization at that order $Q_1' = 0.$ (gauge invariance) . We obtain therefore $T_{1,eff} < Q_{1,eff}$

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

RR exchange dilaton graviton

$$V_{11}^{(0)} = \sum_{\mathbf{p}} \frac{16\kappa_{10}^2 \pi R}{(2\pi)^8 V_5} \int d^3k \ e^{i\mathbf{kr}} \left[\frac{Q_{1,\text{eff}}^2}{k^2 + m_{\mathbf{p}}^2} - \frac{T_{1,\text{eff}}^2}{4} \left(\frac{1}{k^2 + m_{\mathbf{p}}^2 + m_0^2} + \frac{3}{k^2 + m_{\mathbf{p}}^2} \right) \right]$$

$$V_{11}^{(n)} = -\frac{R\alpha'^2}{16\pi^2 V_5} \sum_{\mathbf{p}} \int d^3k \ e^{i\mathbf{kr}} \ \frac{\cos[2\pi a_i] \cos[2\pi a_j]}{k^2 + m_{\mathbf{p}}^2 + \frac{R^2}{\alpha'^2} - \frac{2}{\alpha'}} \ , \qquad (3$$

$V_{11}^{(0)} = 0$ at one-loop. Our arguments imply $V_{11}^{(0)} > 0$ at next order (genus 3/2).

We can define the « particle » mass and charge

$$M_0 = 2\pi R T_{1,\text{eff}} \qquad , \qquad Q_0 = 2\pi R Q_{1,\text{eff}}$$

We can then write the approximate long-distance potential as

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

massless exchange

massive exchange

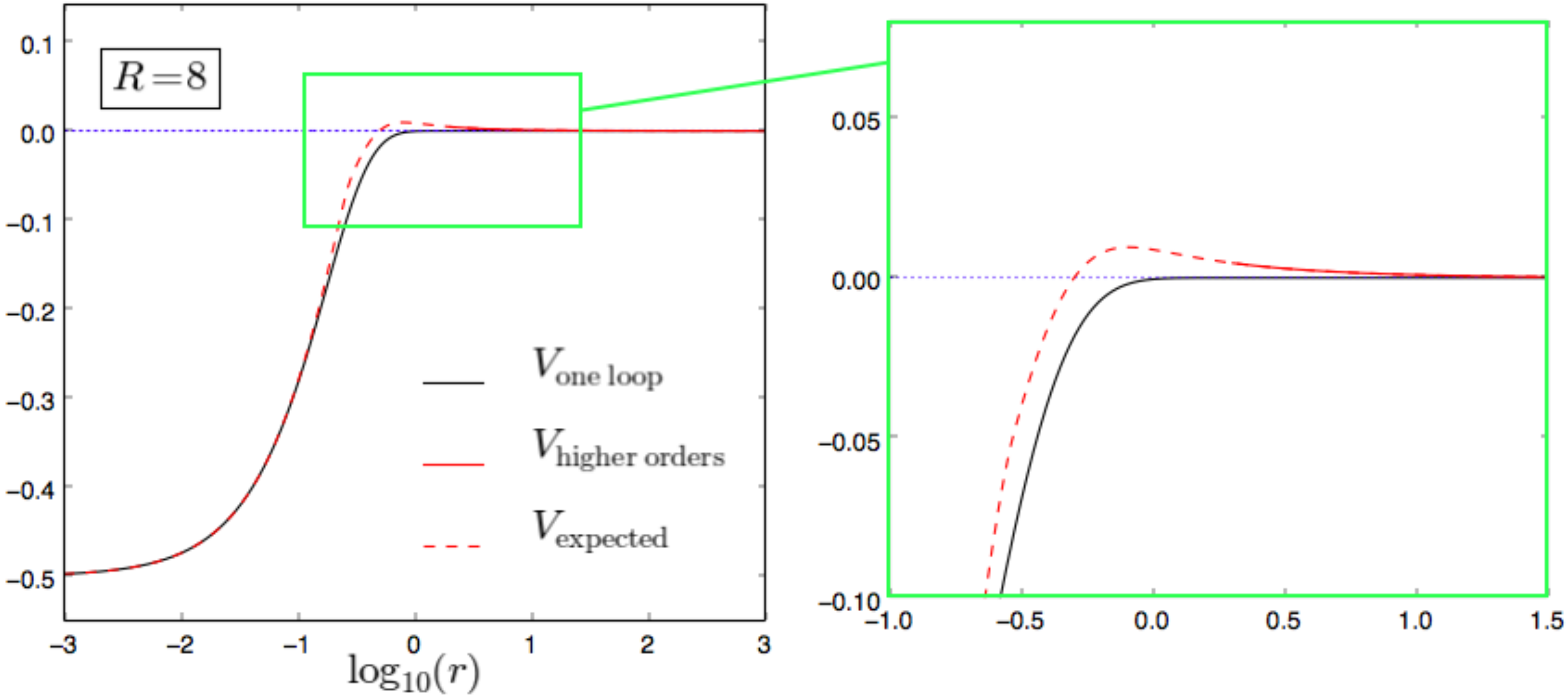


Figure 1: The D1-D1 potential as a function of the distance in the transverse space (the potentials and distances are expressed in units of α', we fixed $R = 8$, $g_S = 0.2$, $V_5 \sim 1.5^5$ and introduced no Wilson lines for the D1 branes)

The dangerous case (for WGC) is when the maximum is reliable in the field-theory limit

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

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 ↔ absence of open string (charged) tachyons
- Attraction ↔ 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

$$T_{1,eff} < Q_{1,eff}$$

Interesting further possible checks.

Thank You !