Flux vacua and the Swampland

Thomas Van Riet, Leuven (Belgium)

‘Eurostrings 2023’, Gijon, Spain

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(iii) Referencing is not at all complete! More correct referencing, see upcoming lecture notes with Gianluca Zoccarato on which talk is largely based

Beginners lectures on flux compactifications and related Swampland topics

Thomas Van Riet[1] and Gianluca Zoccarato[2]

References

[1] C. Vafa, "The String landscape and the swampland," arXiv:hep-th/0509212.

[2] T. D. Brennan, F. Carta, and C. Vafa, "The String Landscape, the Swampland, and the Missing Corner," *PoS* **TASI2017** (2017) 015, arXiv:1711.00864 [hep-th].

[3] E. Palti, "The Swampland: Introduction and Review," *Fortsch. Phys.* **67** no. 6, (2019) 1900037, arXiv:1903.06239 [hep-th].

[4] M. van Beest, J. Calderón-Infante, D. Mirfendereski, and I. Valenzuela, "Lectures on the Swampland Program in String Compactifications," *Phys. Rept.* **989** (2022) 1–50, arXiv:2102.01111 [hep-th].

[5] M. Graña and A. Herráez, "The Swampland Conjectures: A Bridge from Quantum Gravity to Particle Physics," *Universe* **7** no. 8, (2021) 273, arXiv:2107.00087 [hep-th].

[6] N. B. Agmon, A. Bedroya, M. J. Kang, and C. Vafa, "Lectures on the string landscape and the Swampland," arXiv:2212.06187 [hep-th].

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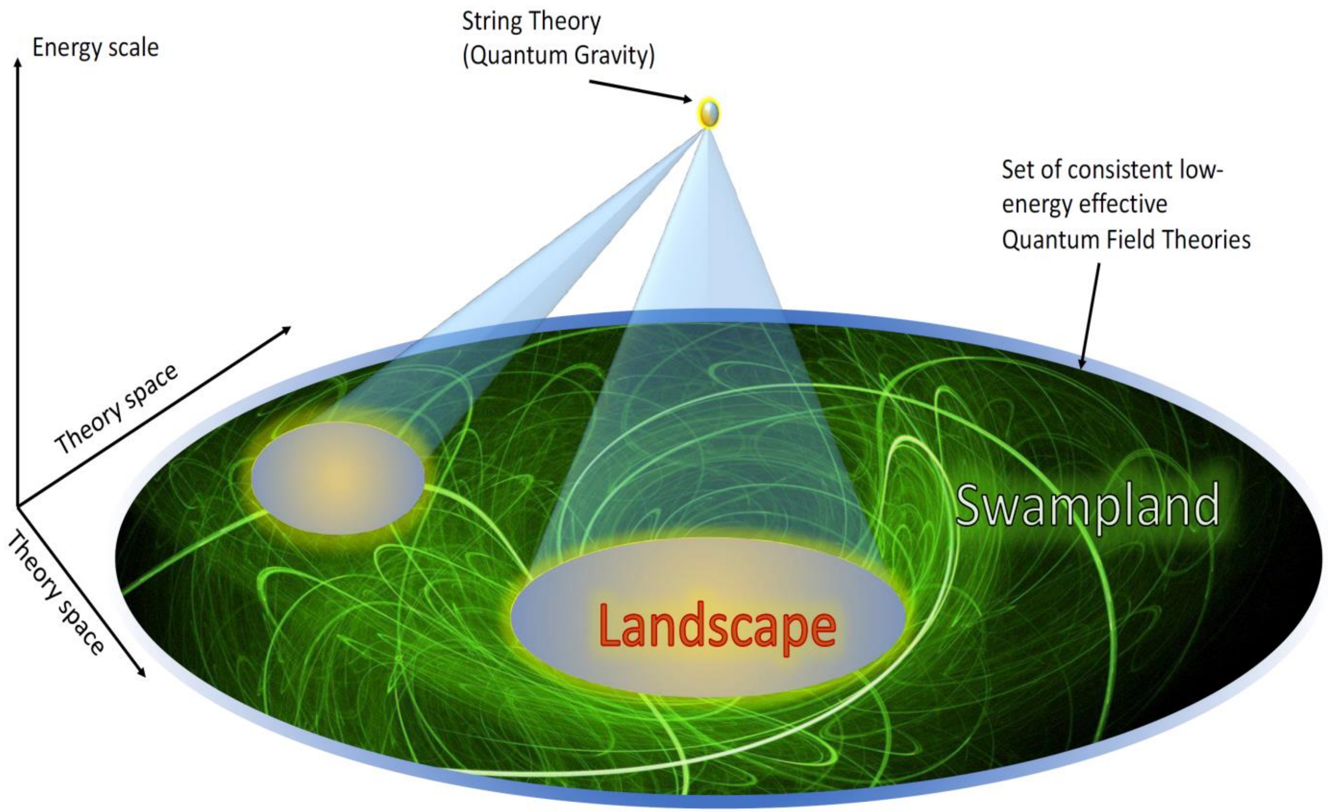
Swampland?



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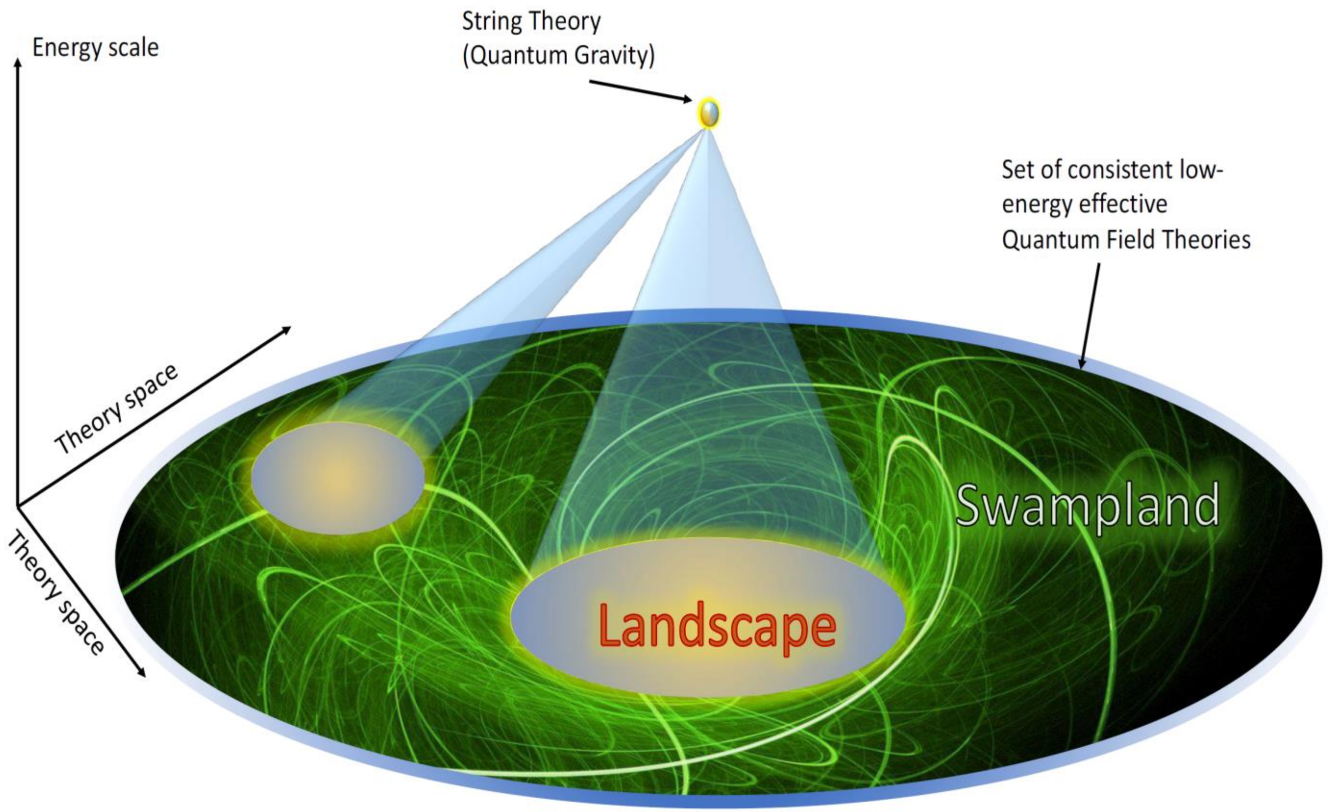
Approach entirely different: *inequalities instead of equalities.*

Swampland?



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- Keywords: **interdisciplinary** (pheno meets black hole physics, holography,…), **focusing on the 'why',** trying to find **patterns**.

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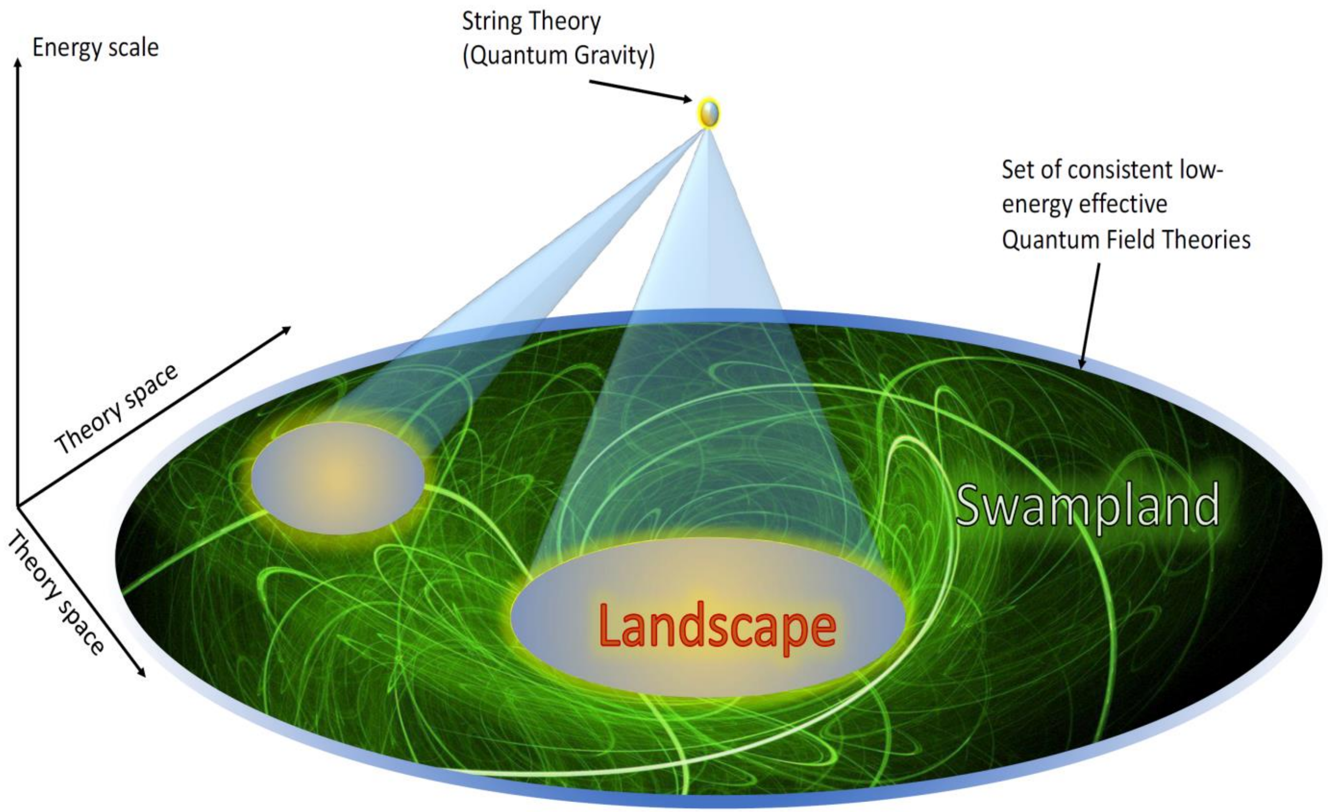

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- Keywords: **interdisciplinary** (pheno meets black hole physics, holography,…), **focusing on the 'why',** trying to find **patterns**.
- *Conjectures* instead of *statements*. Become theorems when proven. Usually conjectures come from 1) patterns in string compactifications + 2) heuristic reasoning with black holes.

Vacuum energy and swampland?

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Despite lowest energy scale, largest distances.
→ cc hierarchy problem.

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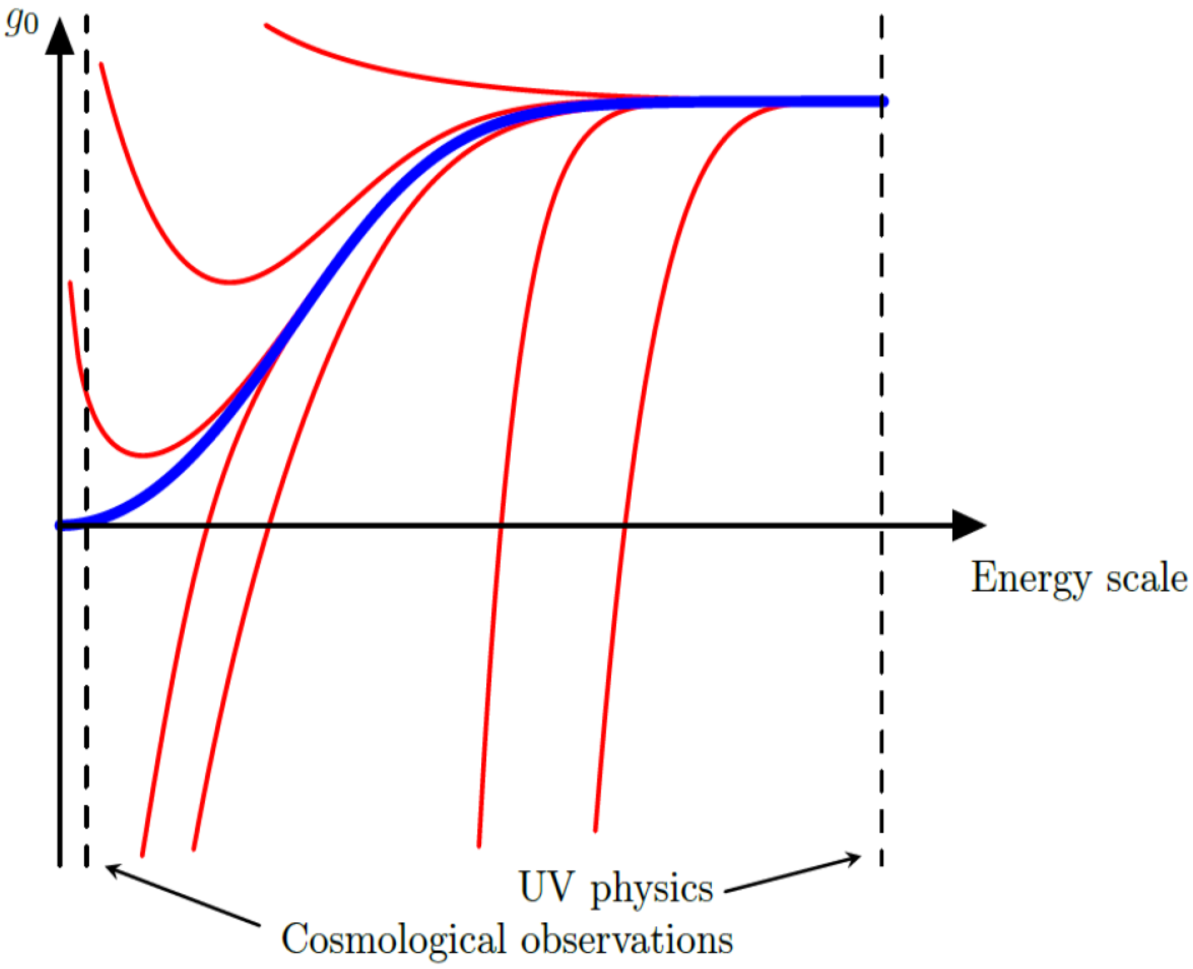

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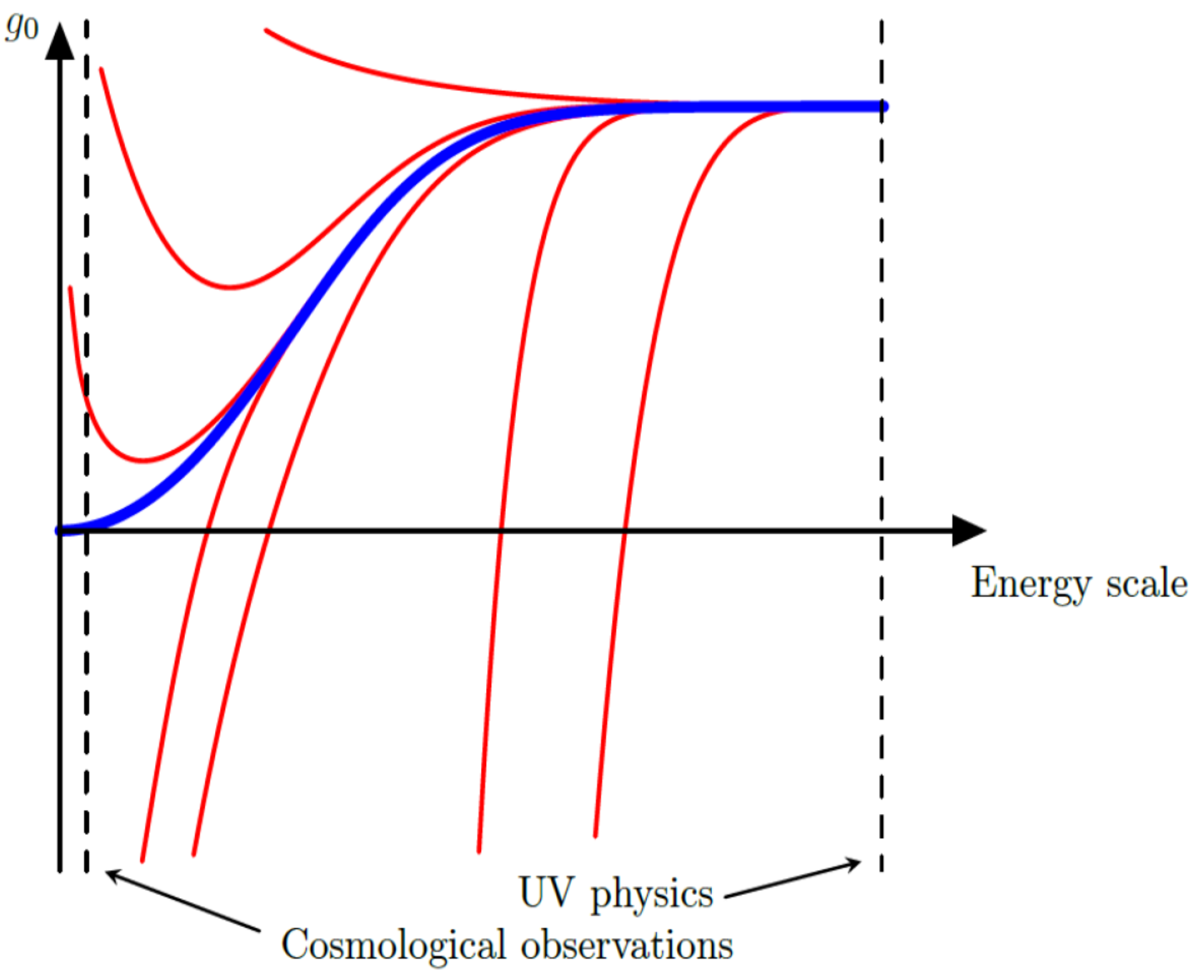

UV completeness of string theory implies we know in principle how to compute vacuum energy, no cut off needed. But how? → Using the UV dof; *extra dimensions, branes, fluxes,….*

How? construct vacuum at the ***boundary of string moduli space from compactification***

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Curvature gives 4D cc

$$ds^2_{10} = ds^2_4 + ds^2_6$$

Metric on compact space.

$$L_{KK} = \text{Volume}^{1/6} = \frac{1}{M_{KK}}$$

$$L_{\text{Hubble}} = \frac{1}{M_\Lambda}$$

Vacuum is perceived as 4D if

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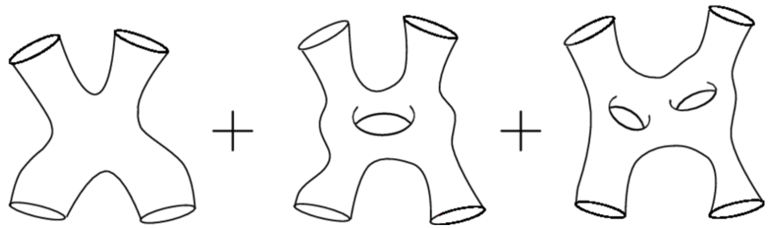
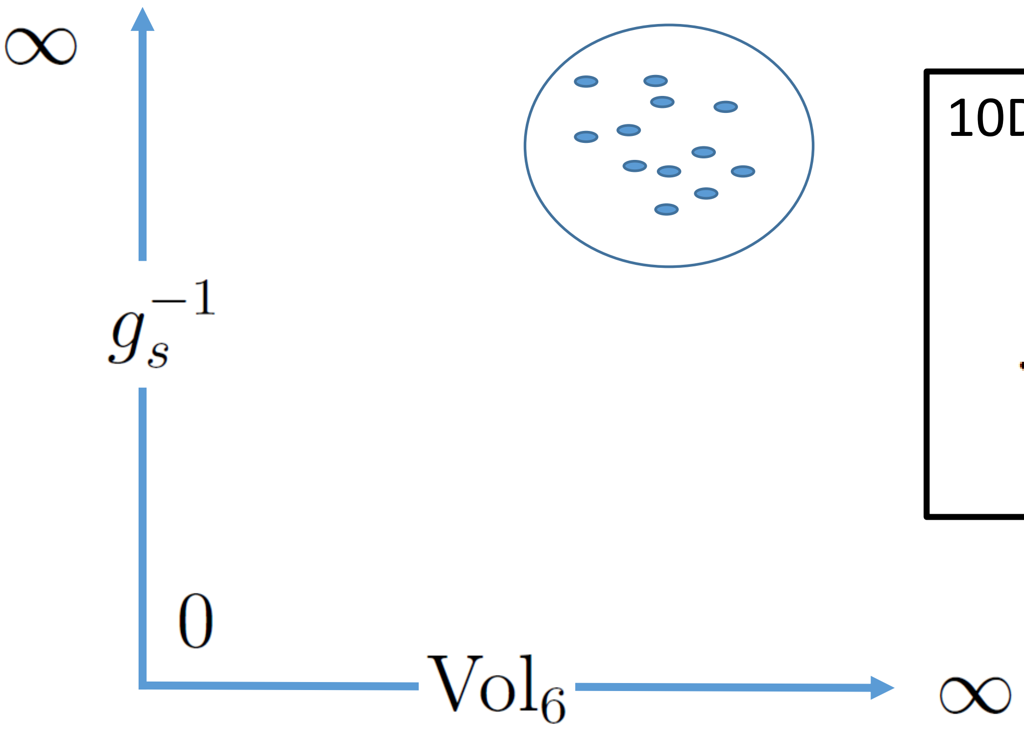
String theory reduces to classical 10D SUGRA if

1) g_s is small ($g_s << 1$):



2) All field gradients are small with respect to $1/l_s$ to control higher derivative expansion.

boundary of string moduli space:



10D sugra, possibly with some leading quantum corrections

$$\int \sqrt{g}\left\{R - \tfrac{1}{2}(\partial\phi)^2 - \sum_n \frac{1}{2\, n!} e^{a_n \phi} F_n^2 \right\} + S_{loc}\,,$$

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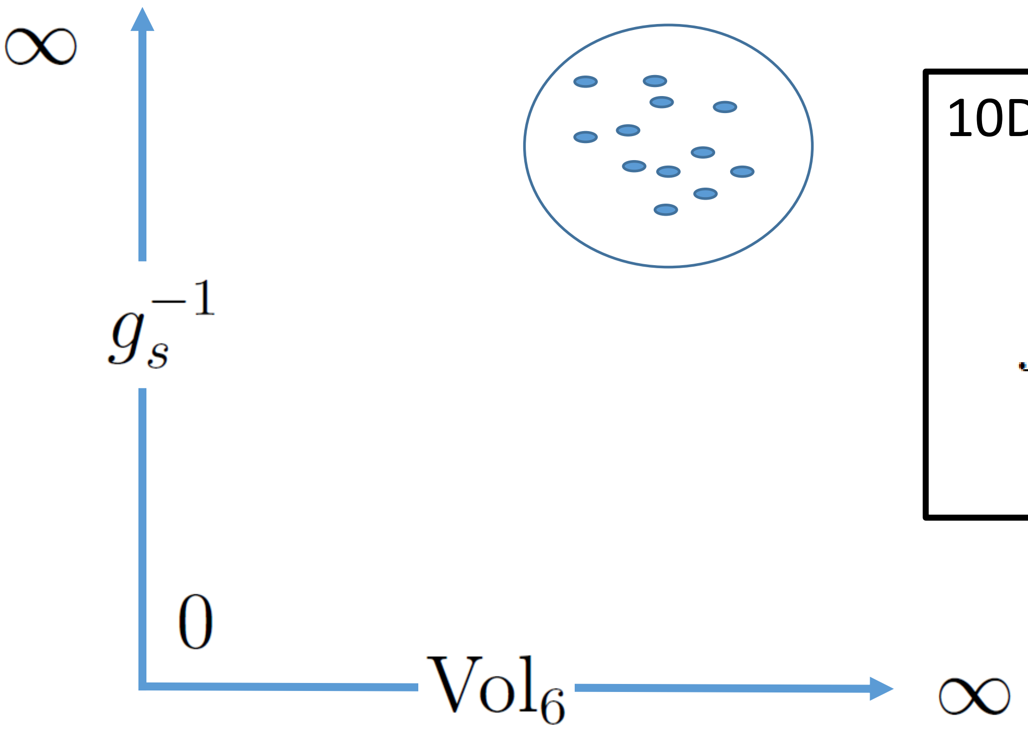

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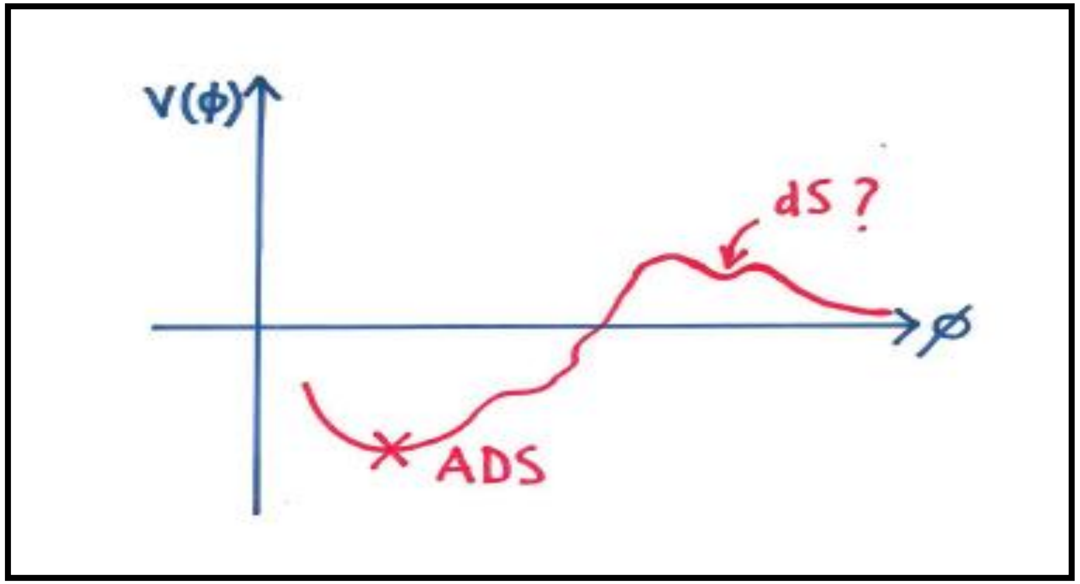

Vacuum energy:

E = Fluxes + Branes + Curvature

'Arrange' solutions such that quantum corrections are negligible or not.

Then the computed result is the full result (up to small corrections.) Nice virtue of string theory. We can compute vacuum energies in certain corners of the theory!

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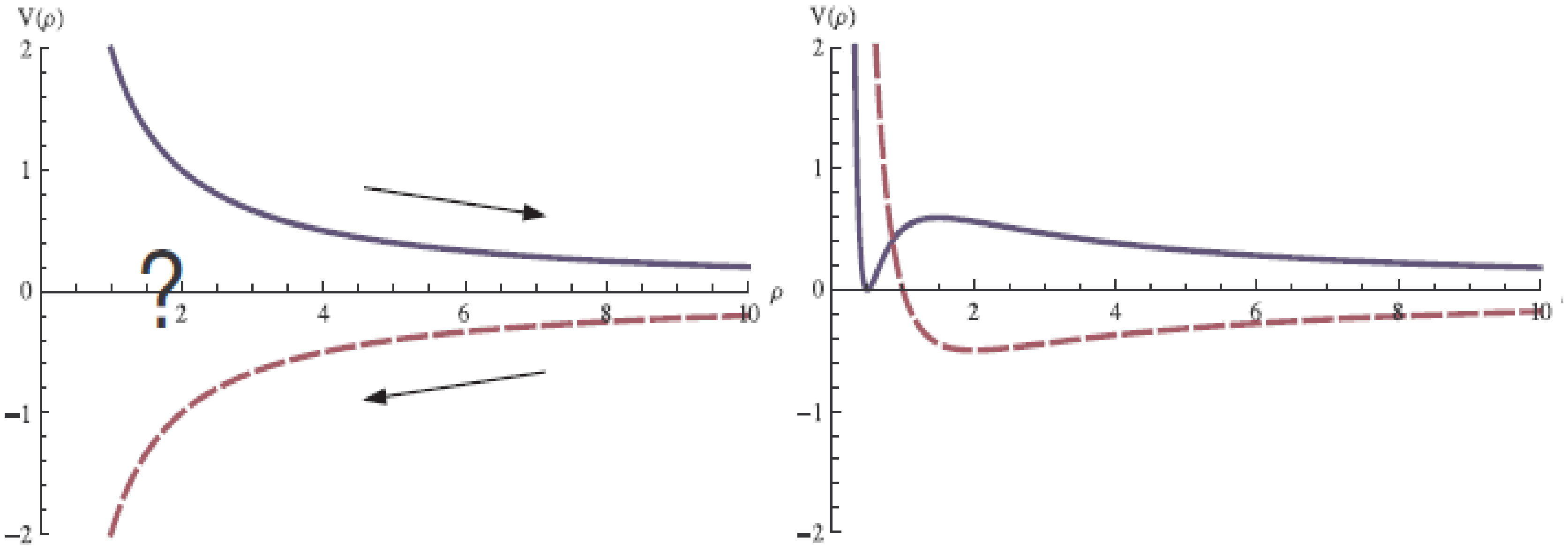
Fluxes are a way out of Dine-Seiberg problem: vacua are typically "non-calculable" [Denef review 2008]



Aim of flux compactification program is to construct ***calculable vacua.*** Solutions "under control".

If the critical superstring is useful for phenomenology then there is a laundry list of requirements on its vacuum structure. We need (many?) vacua where

1. Six extra dimensions are compact and “small enough”

2. All moduli are stabilized.

3. The 4D dimensions can be de Sitter like.

4. Chiral fermions, standard model gauge group.

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(Items 1–3: Cosmology ‘IR’)

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(1–3) Cosmology ‘IR’

(4–5) Particle physics ‘UV’

Connected? Hints from the Swampland.

Some basics of the Swampland Program

No global symmetries conjecture

Consider a field theory with a global symmetry that is not a gauge symmetry. This global symmetry will be broken when coupled to gravity. [Banks-Dixon 1988] [Harlow-Ooguri 2018])

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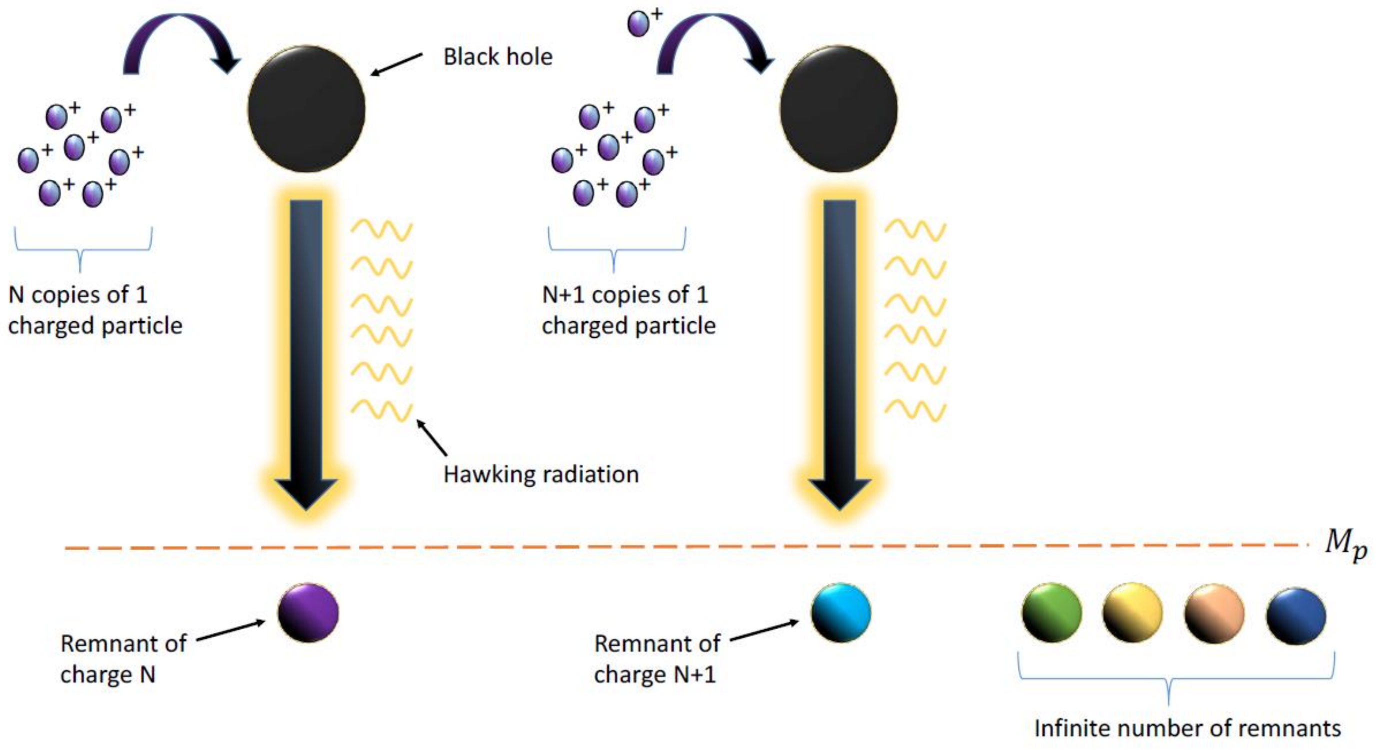

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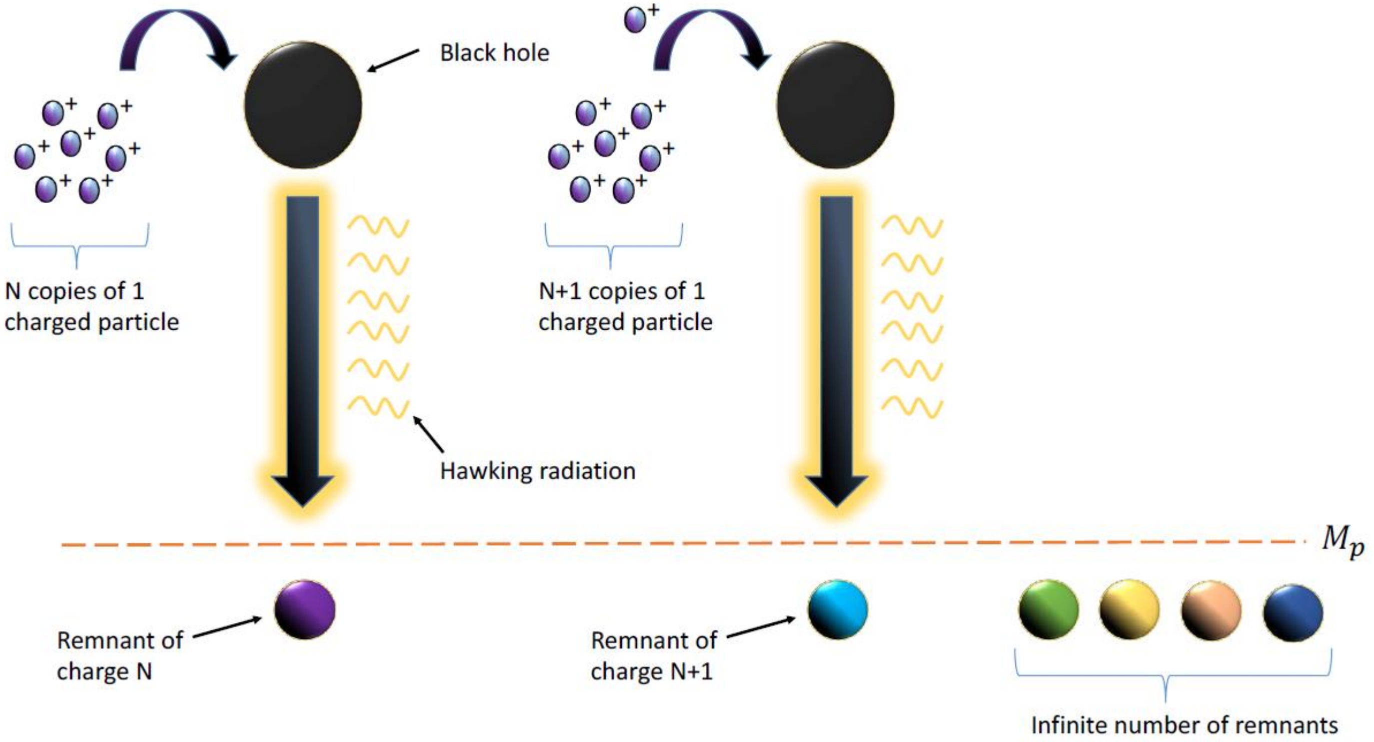

- Generalised by the Cobordism conjecture [McNamara,Vafa, 2019] (The cobordism class of any k-dimensional compact space on which a d-dimensional theory of quantum gravity can be compactified must be trivial)


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OK, but it perhaps implies that gauge coupling constant cannot be arbitrary small? Gravity as weakest force?

Weak Gravity Conjecture [Arkani-Hamed, Motl, Nicolis, Vafa 2006]

- *(Electric WGC) There exists a particle in the theory with mass m and charge q satisfying the inequality*

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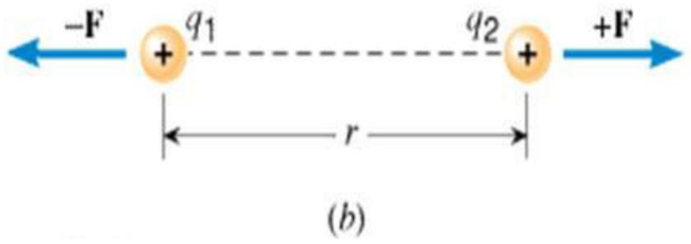
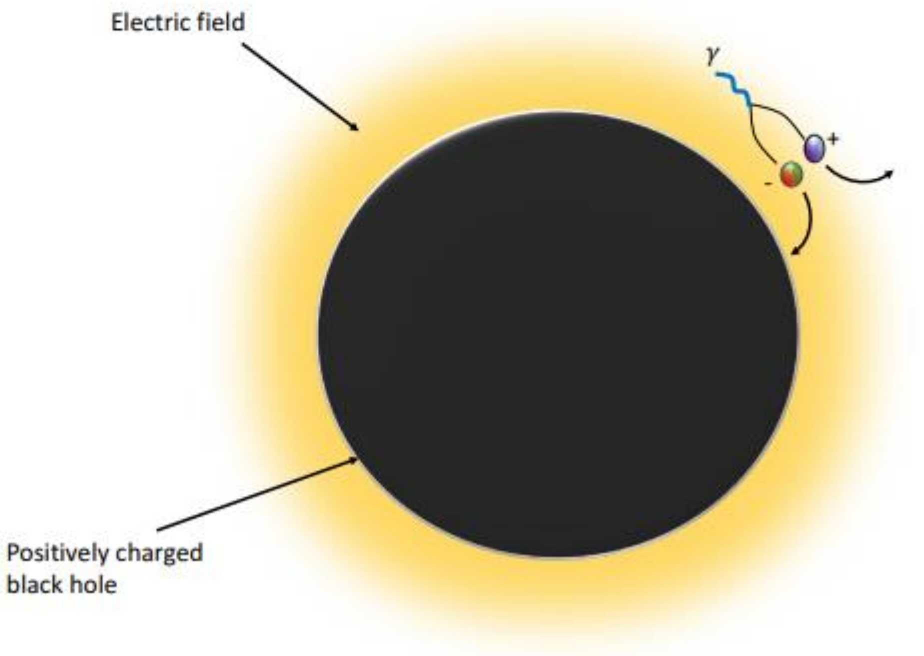
Constants in Nature not arbitrary, some parts of field theory space are empty when coupled to gravity, despite being "ok" (renormalisable, unitary…).

Electric WGC? Means particle is self repulsive





Why needed? Otherwise charged extremal black holes cannot decay. Absolutely stable.

Magnetic WGC? Similar reasoning for monopoles vs magnetic black holes in “magnetic regime” of the theory. (Mass monopole goes like Lambda/g^2)

Distance conjecture *[Ooguri, Vafa 2006]*:

At large geodesic distance Δ in field space from the original vacuum, the mass scale m of a tower of modes becomes lighter as

$$m \sim m_0 \, \mathrm{e}^{-\beta\Delta}$$

with β an order-one number.

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- Holographic version: 'CFT distance conjecture': [Perlmutter, Rastelli, Vafa, Valenzuela 2021]. Spectrum of operators vs distance on conformal manifold.

Current difficulty with Swampland program

Trustworthiness of Swampland statement

Usefulness of Swampland statement

Swampland and vacuum energy

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$\Lambda > 0$

de Sitter. Needed for late- and early-time cosmology

$\Lambda = 0$

Minkowski? With less than 8 supercharges unclear whether it exist (cc problem).
With 8 or more supercharges, always with moduli [Palti, Vafa, Weigand 2020].

$\Lambda < 0$

Anti-de Sitter space. Interesting as a steppingstone towards de Sitter after "uplift" or for holography.

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Swampland bounds on size extra dimensions

Extra dimensions "small enough?"

Two length scales $L_{KK} = \text{Volume}^{1/6} = \frac{1}{M_{KK}}$ and $L_{\text{Hubble}} = \frac{1}{M_\Lambda}$

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The EFT expectation is that the "typical" cc is order cut-off. The "typical" string flux solution **indeed** obeys:

$$\frac{m_\Lambda}{m_{KK}} = \mathcal{O}(1)$$

The failure of the solution to look 4D is the same as not having a cc hierarchy.

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4D QFT predicts "large cc", but 4D QFT is only valid whenever: $\frac{m_\Lambda}{m_{KK}} \to 0$

Danger of circular reasoning?

Holographic view

Vanilla top-down (understood) AdS/CFT pairs feature **AdS_d x X_n** With X a compact 11-d or 10-d dimensional space with same size radius as AdS. *Can we make X small as we want? If so, what is the dual CFT? In other words: how many large bulk dimensions does the CFT reconstruct?*

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- Scale separated AdS vacua would have dual CFTs with only few low lying single trace scalar operators, then a parametric gap!

$$\Delta = \frac{3}{2} + \frac{1}{2}\sqrt{9 + 4\kappa^2} \gg 1 \qquad mL_{AdS} = \kappa >> 1$$

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- Even more special: scale separated AdS vacua suited for uplifting have no tachyons, so no relevant deformations: **Dead-end CFTs with huge gap.**

Bizar CFTs. See [Polchinski&Silverstein 2009, Alday&Perlmutter 2019].

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Nogo-Example for 11d compactifications.

Assume no warping for simplicity, then one easily finds;

$$R_4 = -\frac{4}{3}|F_4|^2 - \frac{8}{3}|F_7|^2 \ ,$$
$$R_7 = \frac{5}{3}\,|F_4|^2 + \frac{7}{3}\,|F_7|^2 \ .$$

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Taking the integrated ratio we find:

$$\boxed{\left|\frac{\int R_7}{\int R_4}\right| = \frac{5\int |F_4|^2 + 7\int |F_7|^2}{4\int |F_4|^2 + 8\int |F_7|^2} \leq \frac{5}{4}}$$

Now define the curvature radius as $L_R^{-2} = \mathrm{vol}_d^{-1} \int \mathrm{d}^d y \sqrt{g_d}\, R_d \,,$

- For the external dimensions this defines the Hubble length, aka AdS radius L_{AdS}
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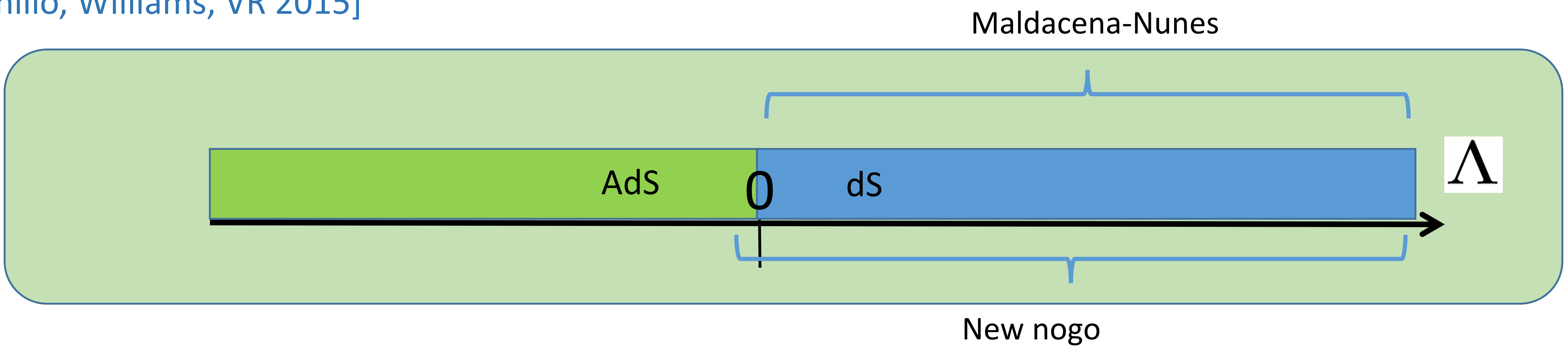
We arrive at an extension of the MN nogo to AdS vacua with scale separation [Gautason, Schillo, Williams, VR 2015]



Precise & complete treatment, see [De Luca, Tomasiello, 2104.12773]

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Despite certain beliefs intersecting brane solutions in SUGRA are **not known**, only upon partial smearing.

→ Less easy way out: find Einstein space for which one can shrink L_{KK} at fixed curvature.

[Collins, Jafferis, Vafa, Xu, Yau, 2201.03660]: Large set of holographic CFTs checked. There is universal upper bound for dimension of first non-trivial spin 2 operator. The internal space for the CFT dual has minimal diameter in AdS units.

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But the two ways out can be related! [arXiv 2107.00019, with N. Cribiori, D. Junghans, V. Van Hemelryck and T. Wrase]

→ There exist AdS vacua in IIA with O6 planes on generalized CY that can be scale separated at strong coupling, such that O6 backreaction is small. →lifts to weakly curved pure Freund-Rubin vacua in 11d: *a geometry contradicting conjecture Collins et al*?

→ Lift is not fully explicit since we only have first-order description of backreacted O6 planes. Work in progress. *But, a priori, seems controlled.*

Other way to generate scale separation is **Casimir energy**, see eg [De Luca, De Ponti, Mondino, Tomasiello, 2022]

Swampland Conjectures against scale separation

Strong AdS scale separation conjecture *of* [Lust, Palti, Vafa 2019] claiming ratio of lengthscales is order 1 for **SUSY** AdS vacua. However beautiful refinement by [Buratti et al 2020]: (k is from discrete Z_k 3-form symmetry)

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- **Counter example** to refined strong AdS distance conjecture by [Buratti et al 2020] ***AdS_3*** *vacua from massive IIA on G2 space with 06 planes* [Farakos, Tringas, VR, 2020] as pointed out in [Apers, Montero, VR, Wrase, 2022]

The weaker version allows still scale separation

Anti-de Sitter Distance Conjecture (ADC) [90]: In a d-dimensional theory of quantum gravity with cosmological constant Λ_d, there exist a tower of states that becomes light in the limit $\Lambda_d \to 0$ as

$$\frac{m_{\text{tower}}}{M_P} \sim \left| \frac{\Lambda_d}{M_P^d} \right|^{\gamma_d}, \tag{2.18}$$

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Alternative (related) version

Gravitino Distance Conjecture (GDC) [93,94]: In a supersymmetric theory with a non-vanishing gravitino mass $m_{3/2}$, a tower of states becomes light in the limit $m_{3/2} \to 0$ according to

$$\frac{m_{\text{tower}}}{M_{\text{P}}} \sim \left(\frac{m_{3/2}}{M_{\text{P}}} \right)^{\delta} \quad \text{with} \quad 0 < \delta \leq 1 . \tag{2.19}$$

[93] N. Cribiori, D. Lüst, and M. Scalisi, "The Gravitino and the Swampland," arXiv:2104.08288 [hep-th].

[94] A. Castellano, A. Font, A. Herraez, and L. E. Ibáñez, "A Gravitino Distance Conjecture," arXiv:2104.10181 [hep-th].

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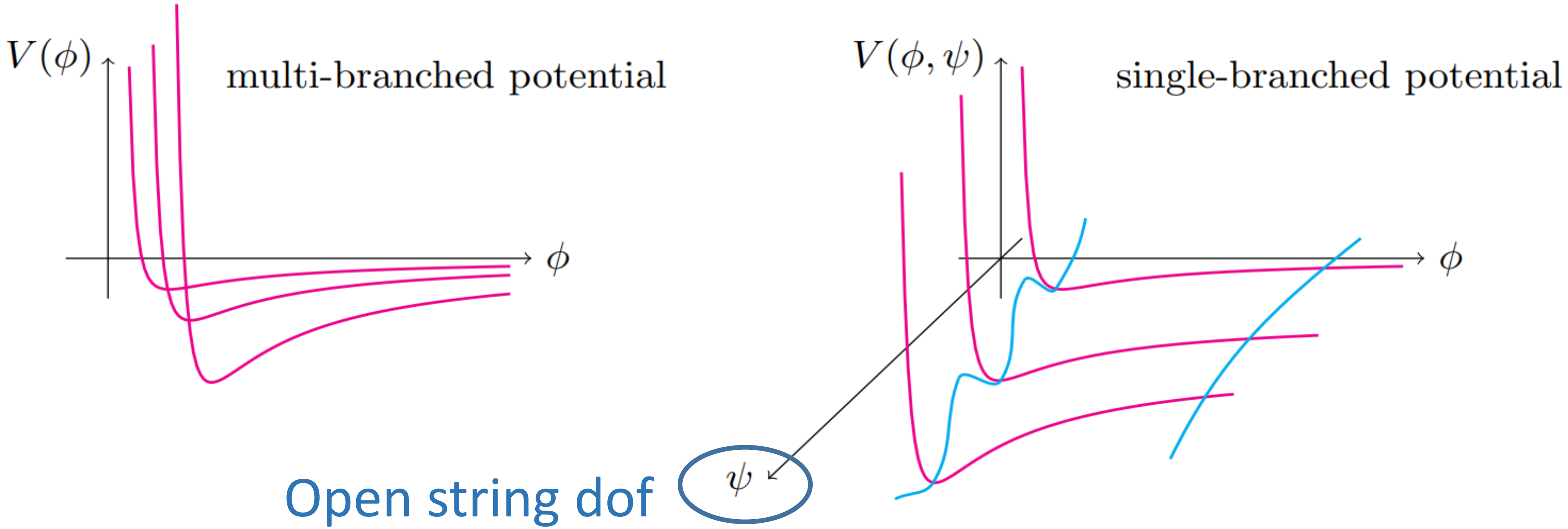
[Shiu, Tonioni, Van Hemelryck, VR 2022] found a **scalar** field that allows us to interpolate between the DGKT fluxes. This field is a brane position. This field makes DGKT vacua obey the distance conjecture



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1. Magnetic WGC [Cribiori, Dall' Agata 2022]: *For SUSY 4d AdS vacua preserving Q>4, no scale separation if magnetic WGC holds.*

→One way to understand this is from electric WGC: KK particles charged under isometries have to be light enough.
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2. **Extreme scale separation**, meaning X is vanishing small at fixed M_{planck}, can be ruled out for AdS vacua with gauged R-symmetry! The R-symmetry becomes a global, unbroken symmetry in that limit. [Martinec, Montero, Vafa 2022]

Curious holography of IIA vacua?

Early investigation on CFT dual to IIA vacua [Aharony et al 2008], but new investigation [Conlon, Ning Revello, 2021] shows **all such operator dimensions in DGKT are integer,** [Apers, Conlon, Ning, Revello, 2022] ([Apers, Montero, VR, Wrase 2022]) based on formalism of [Marchesano, Quirant 2019].

Modulus	Operator dimension Δ
1. $h_-^{1,1}$ saxionic Kähler moduli from J	6
1. $h_-^{1,1}$ axionic Kähler moduli from B_2	5
2. The dilaton direction	10
2. The C_3-axion appearing in W	11
3. $h^{2,1}$ saxionic complex structure moduli from $Re(\Omega)$	1 or 2
3. $h^{2,1}$ massless C_3-axions	3

Table 2: Summary of integer operator dimension of a putative CFT_3 dual for generic supersymmetric DGKT type AdS_4 vacua.

Why? See [Apers 2022] for comments: polynomial shift symmetries in large N limit on AdS side

Swampland bound on stability AdS

[Ooguri, Vafa, 2016] extension of WGC; any-non-SUSY AdS vacuum supported by fluxes must be able to decay.

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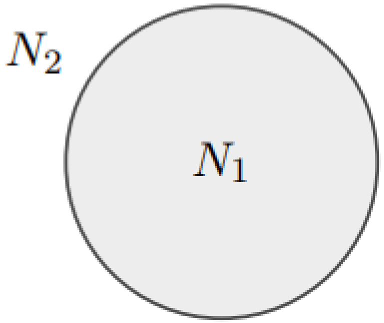

So if an AdS vacuum is build from flux then a Dp brane can change the flux numbers and thus the vacuum energy. Whether this happens depends on the tension. **If the tension is small enough** then quantum mechanically bubble nucleation will occur; WGC extended to higher form fields implies decay.

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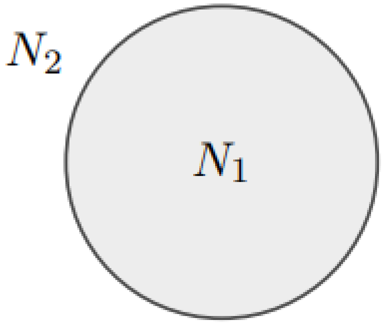

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Eg Coleman-de Luccia thin wall formula in 5d: $\Lambda_- < \Lambda_+ < 0. \quad \Lambda_\pm = -6k_\pm^2$

Decay if $\dfrac{3\,(k_- - k_+)}{\kappa_5} - \sigma > 0$

But conjecture more general than BT or CDL decay. Eg bubbles of nothing, see eg [Garcia-Etxebarria, Montero, Sousa, Valenzuela, 2020].

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Challenges for the conjecture:

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- Prime example [Guarino, Malek, Sambtleben, 2020]: massive IIA on S^6. See talk today by Sambtleben.

Swampland and vacuum energy

$$\Lambda > 0$$

de Sitter. Needed for late- and early-time cosmology

Why is it so hard to get de Sitter space? -a first glimpse

1. Because you necessarily break supersymmetry.
2. Because of the many fields. Statistical argument.
3. Anti-de Sitter can have tachyons. De Sitter cannot.

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But is this really a string theory issue? *Does dS space “exist” for sure in effective field theory*? [Danielsson, Markanen, Polyakov, Dvali, Gomez, Woodard, Tsamis, Mottola,…]

Status of dS space 2018, [see Danielsson, VR 2018]

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Status of dS space -Developments last 5 years?

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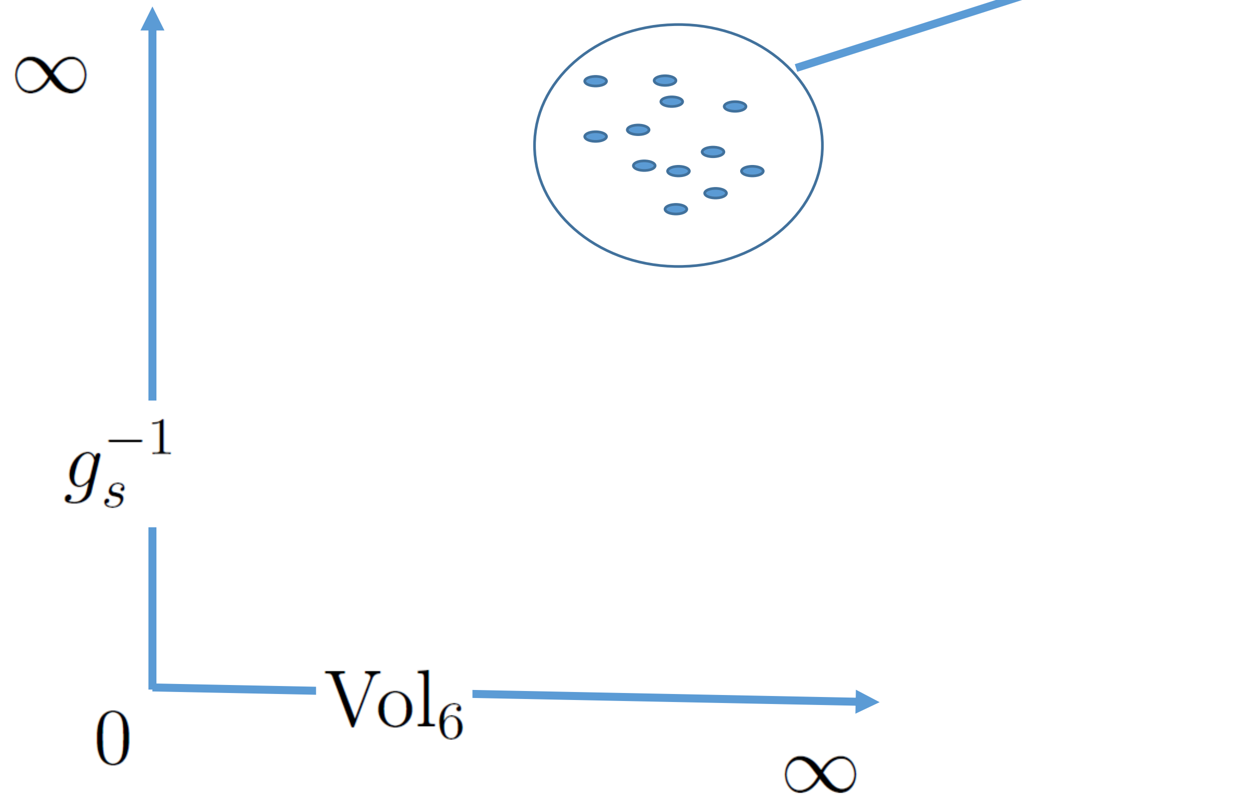
- New models; eg [De Luca, Silverstein, Torroba 2021]: hyperboloids with Casimir energy
- Sort of consensus on at least the (Swampland) arguments that parametrically controlled dS is impossible?

Only anti-de Sitter space here?

boundary of string moduli space:



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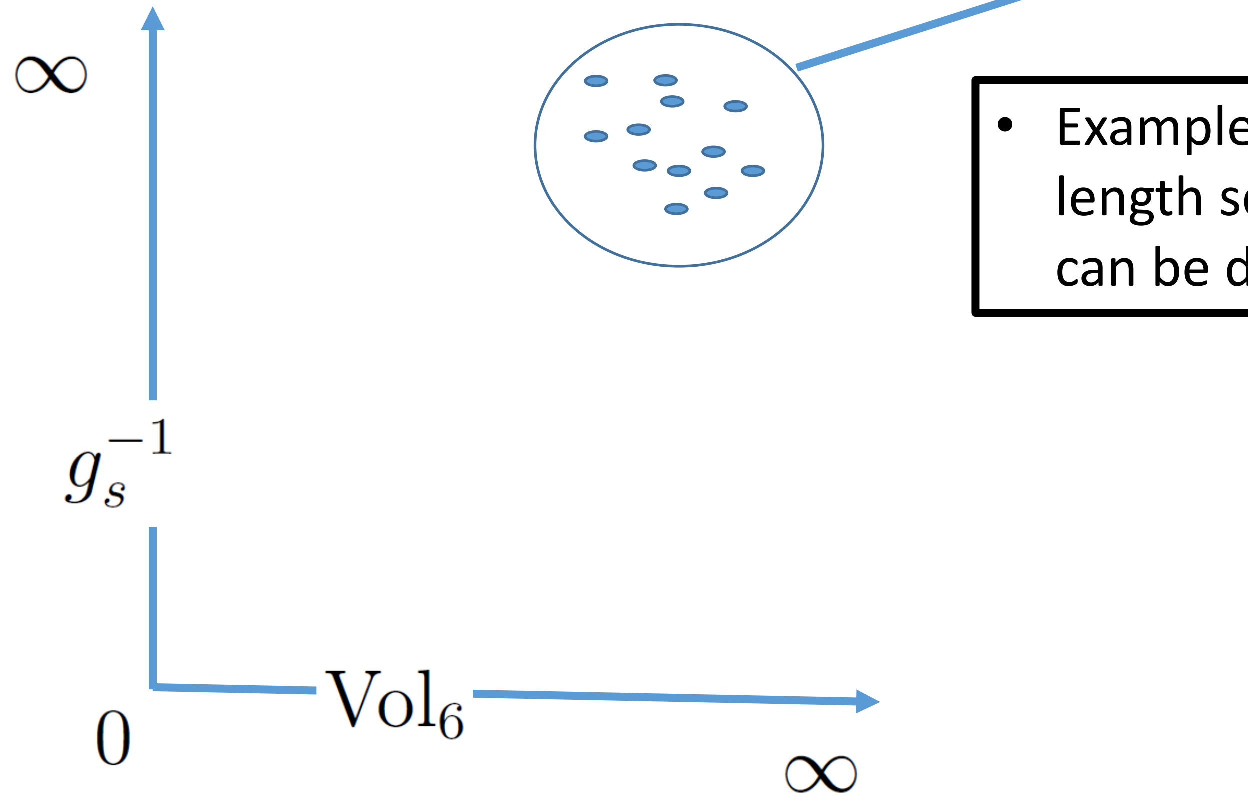

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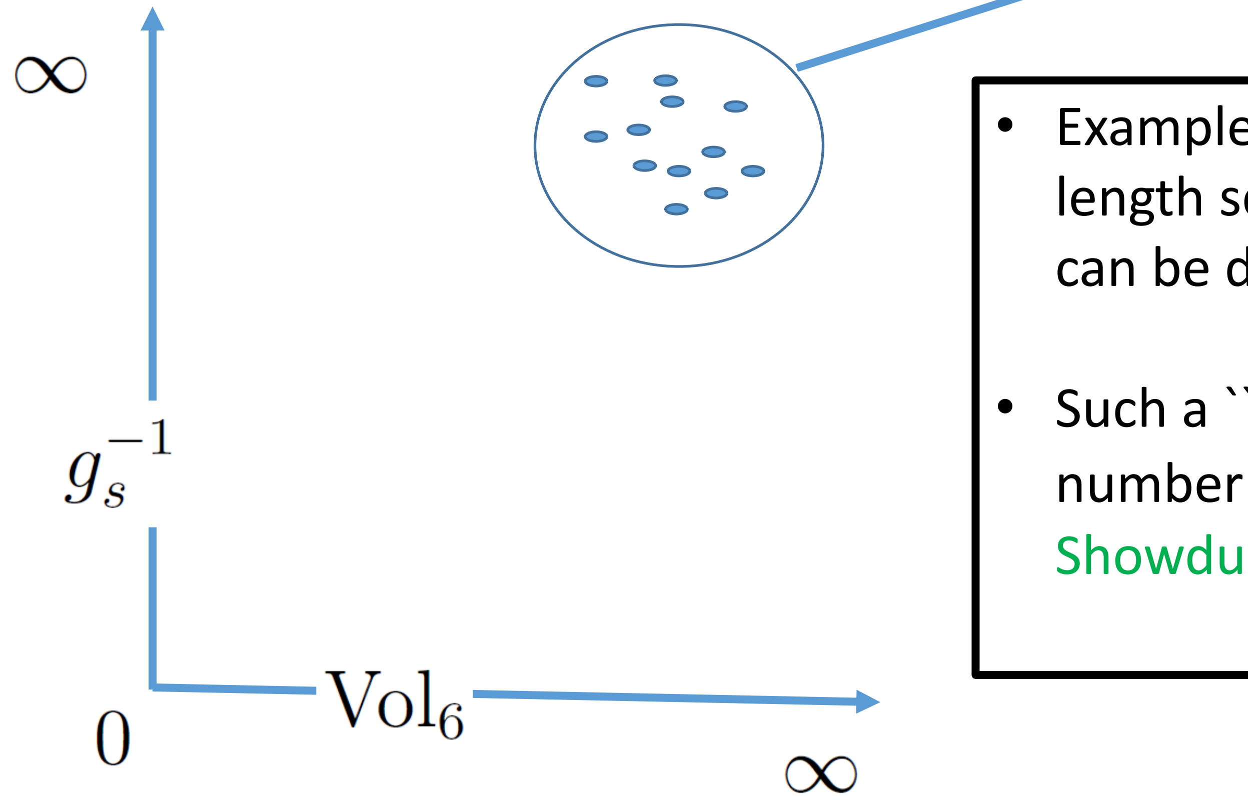

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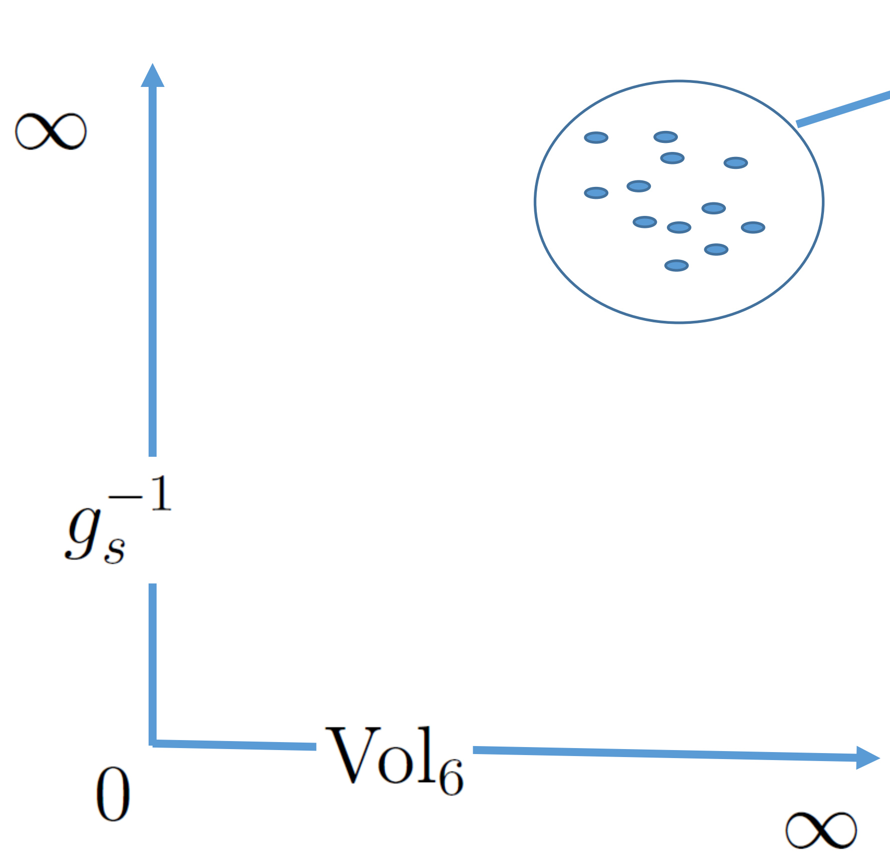

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- Consistent with heuristic (and more general) Swampland arguments. [Ooguri-Palti-Shiu-Vafa 2018, Wrase-Hebecker 2018]

- From looking at behavior of scalar potentials **near boundary of moduli space** [Obied-Ooguri-Spodyneiko-Vafa, 1806.08463] *conjectured*:

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- So [Garg-Krishnan 1807.05193] concluded there should be an extra condition, if a conjecture like that is to hold. In the end it got known as the *refined dS conjecture*

$$|\nabla V| \geq \frac{c}{M_p} \cdot V \quad \text{or} \quad \min\left(\nabla_i \nabla_j V\right) \leq -\frac{c'}{M_p^2} \cdot V$$

and heuristic derivations appeared in [Ooguri-Shiu-Palti-Vafa 1810.05506] and [Hebecker-Wrase 1810.08182] and [Danielsson 1809.04512]. Let us follow Hebecker&Wrase (easiest to explain)

Hebecker&Wrase

Consider some direction Φ in field space and go to its limits. *The distance conjecture* tells us there will appear a tower of states with masses going as multiples of

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On the other hand the *species bound [Dvali]* implies

$$\Lambda \approx M_P/\sqrt{N}.$$

Eliminate N :

$$\Lambda \approx (M_P^2 m)^{\frac{1}{3}} \approx M_P e^{-\frac{b\phi}{3}}$$

Consider a positive scalar potential, then:

$$3H^2 M_P^2 = V$$

Now demand that

$$\Lambda \gtrsim H \quad \Rightarrow \quad \boxed{M_P^2 e^{-2b\phi/3} \gtrsim V(\phi)/M_P^2 .}$$

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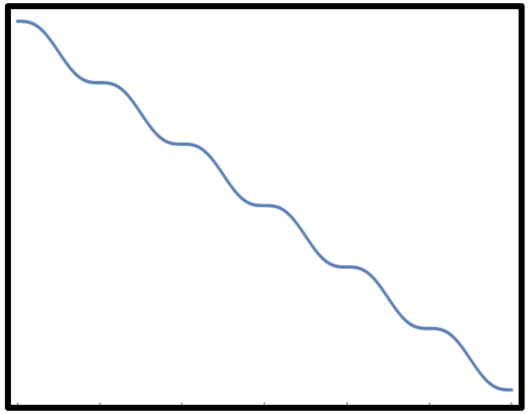
→ *Although loopholes sometimes suggest itself*
(local oscillations in the exponential decaying behavior.



Away from parametric weakly coupled regime there is a more universal proposal:

TCC *conjecture* [Bedroya-Vafa 1909.11063] & [Bedroya-Brandenberger-Loverde-Vafa 1909.11106]:
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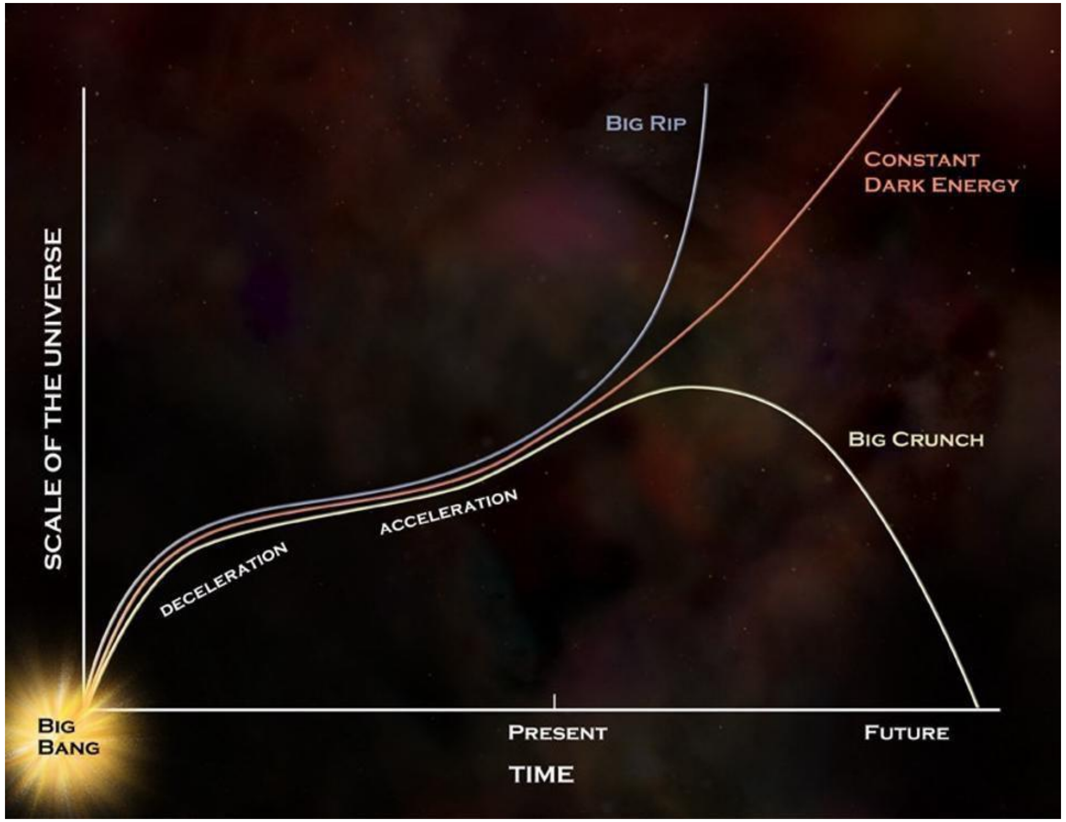
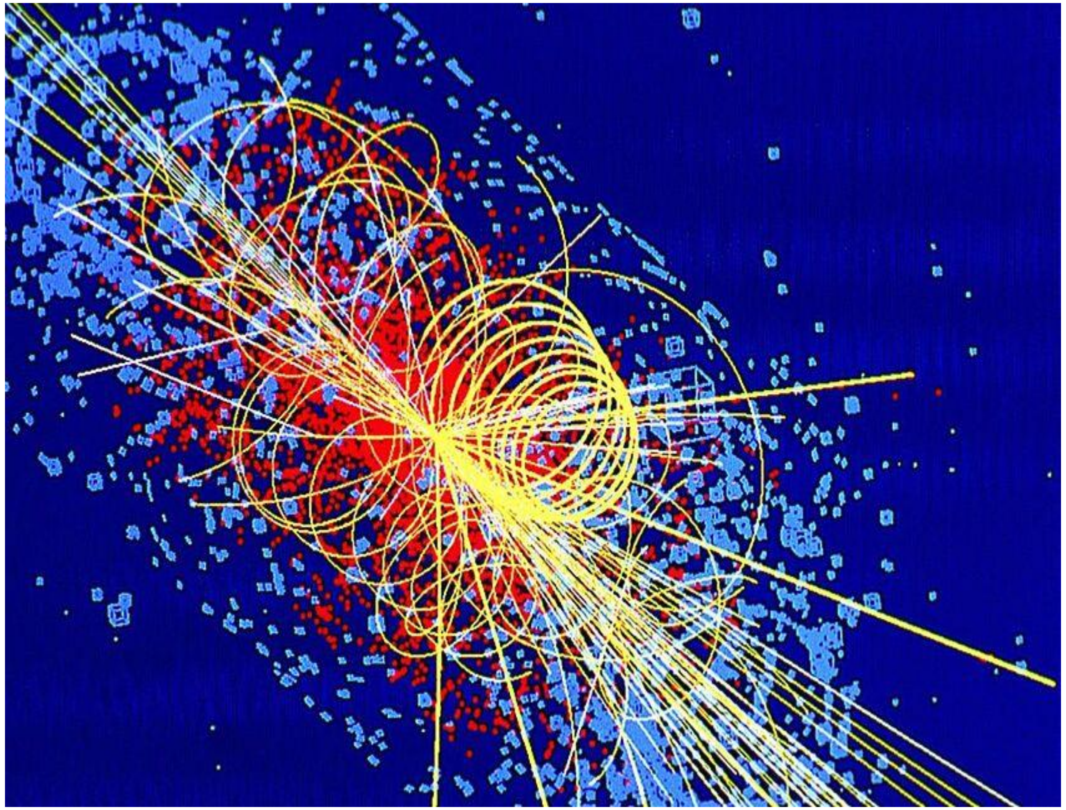
→ Away from boundary, dS is possible but

$$T \leq \frac{1}{H} \log \frac{M_p}{H}$$

Consistent with our own universe.

Swampland bounds from vacuum energy to particle physics





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- Neutrino mass scale

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- Cc scale

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[Ibanez , Martin-Lozano, Valenzuela, 2017] The AdS3 vacua will be stable unless the parent dS_4 is unstable and bubble size R is smaller than dS_4 length, so it does not lie in the range $l_3 < R < l_4$.

Classical piece of 3d action has runaway potential

$$S_{SM+GR} = \int d^3x \sqrt{-g_3}(2\pi r)\left[\frac{1}{2}M_p^2 \mathcal{R}_{(3)} - \frac{1}{4}\frac{R^4}{r^4}W_{\mu\nu}W^{\mu\nu} - M_p^2\left(\frac{\partial R}{R}\right)^2 - \frac{r^2\Lambda_4}{R^2}\right]$$

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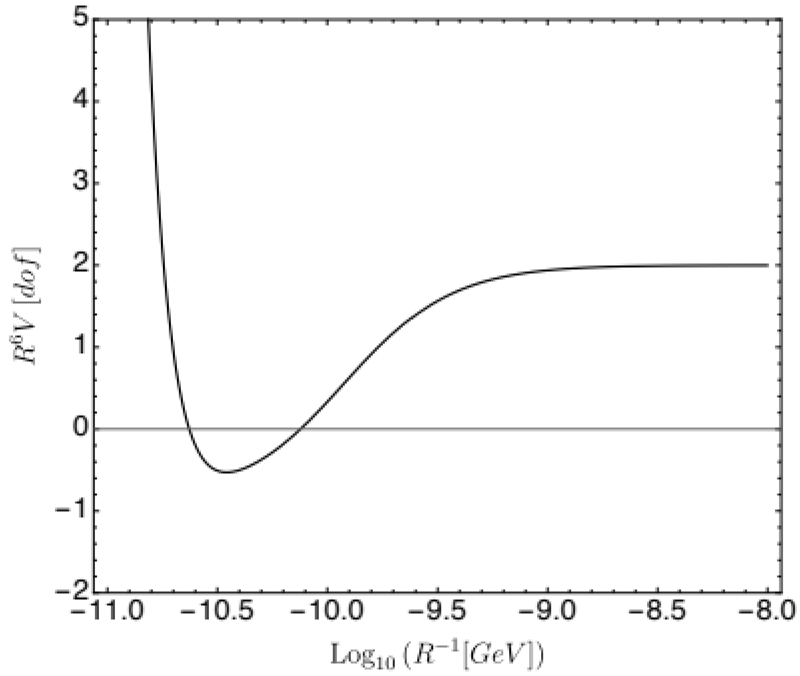

Heavy neutrino majorana mass

Particles with masses below 1/R contribute significantly to 1 loop correction aka Casimir energies. The existence of stable AdS3 now implies various constraints on nature neutrinos and mass scales. The two are linked indeed. Details omitted.

2) The Festina Lente bound.

Montero & Venken & VR 2019 ,
Montero & Venken & Vafa & VR 2021

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Montero & Venken & VR 2019 ,
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Consider Einstein-Maxwell theory with dark energy density in the form of a positive cosmological constant

$$3H^2 M_p^2 = V$$

The Festina Lente bound is: $m^4 \gtrsim (gq)^2 V \quad \text{for every charged state}$

2) The Festina Lente bound.

Montero & Venken & VR 2019 ,
Montero & Venken & Vafa & VR 2021

Consider Einstein-Maxwell theory with dark energy density in the form of a positive cosmological constant

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In 4D, in terms of fine structure constant, we have a window:

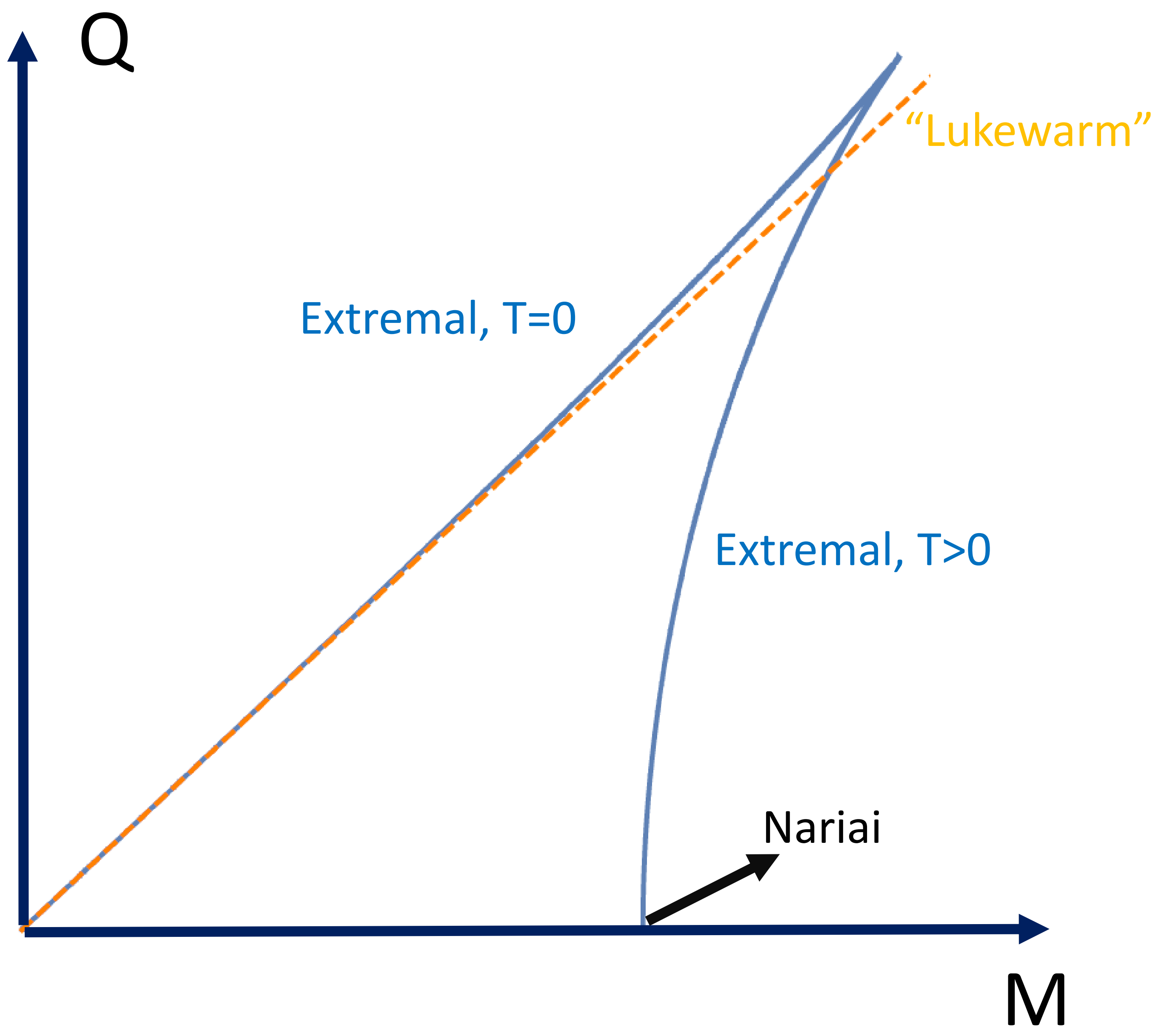
$$(8\pi\alpha V)^{1/4} < m < (8\pi\alpha)^{1/2} M_{\rm P}$$

$$\alpha = \frac{g^2}{4\pi}$$

Quantum dynamics of charged black holes in de Sitter space

$$ds^2 = -U(r)dt^2 + \frac{dr^2}{U(r)} + r^2 d\Omega,$$

$$U(r) \equiv 1 - \frac{2M}{r} + \frac{Q^2}{r^2} - r^2$$



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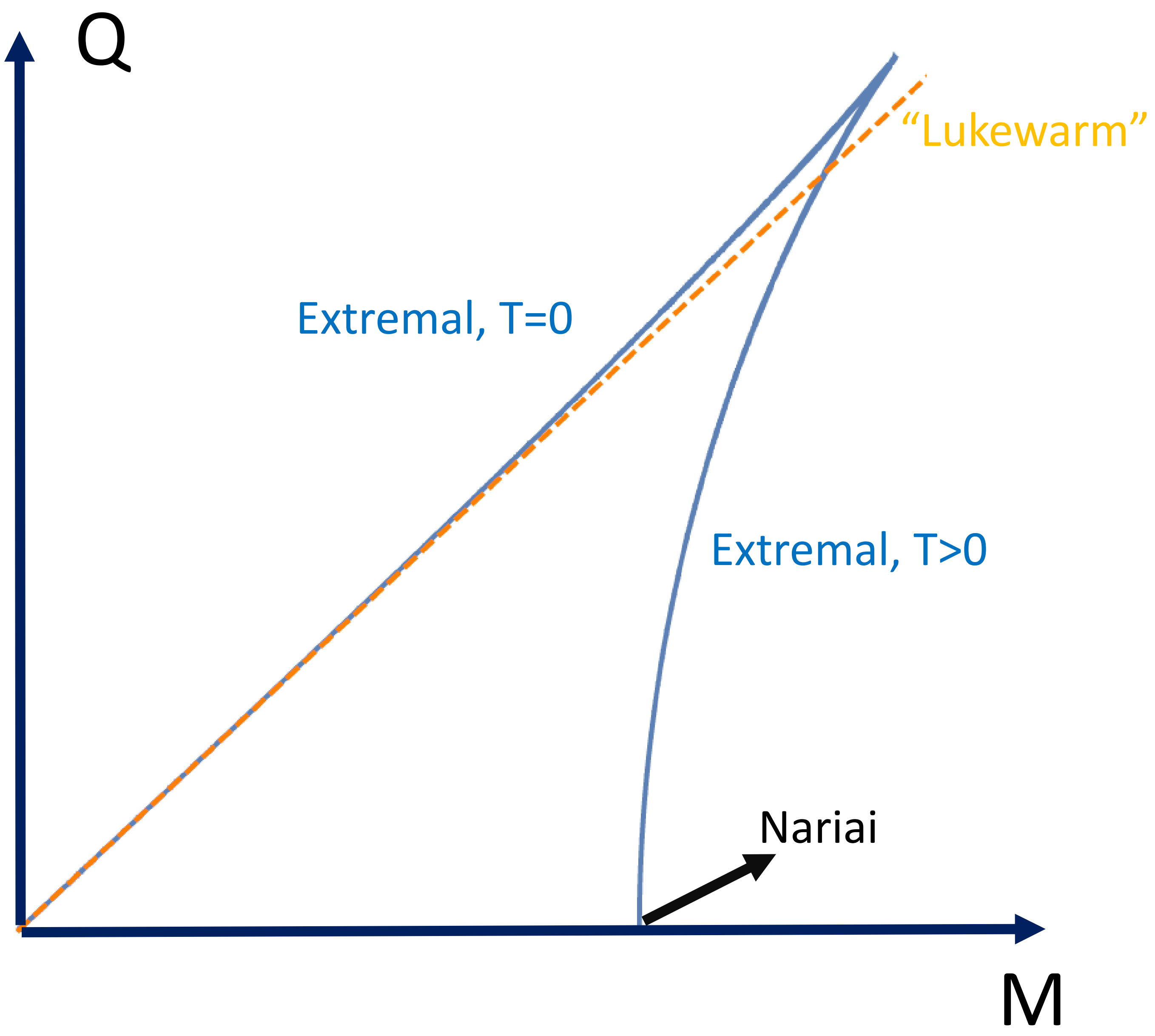
Weak gravity principles?

Left extremal branch. Almost like in flat space. But now black holes unstable without even requiring weak gravity conjecture.

Right extremal branch: Charged Nariai. Gigantic black holes probing cosmic horizon.



Guiding principle: constrain microscopic theory such that black holes *do not decay to region outside "shark fin"*.

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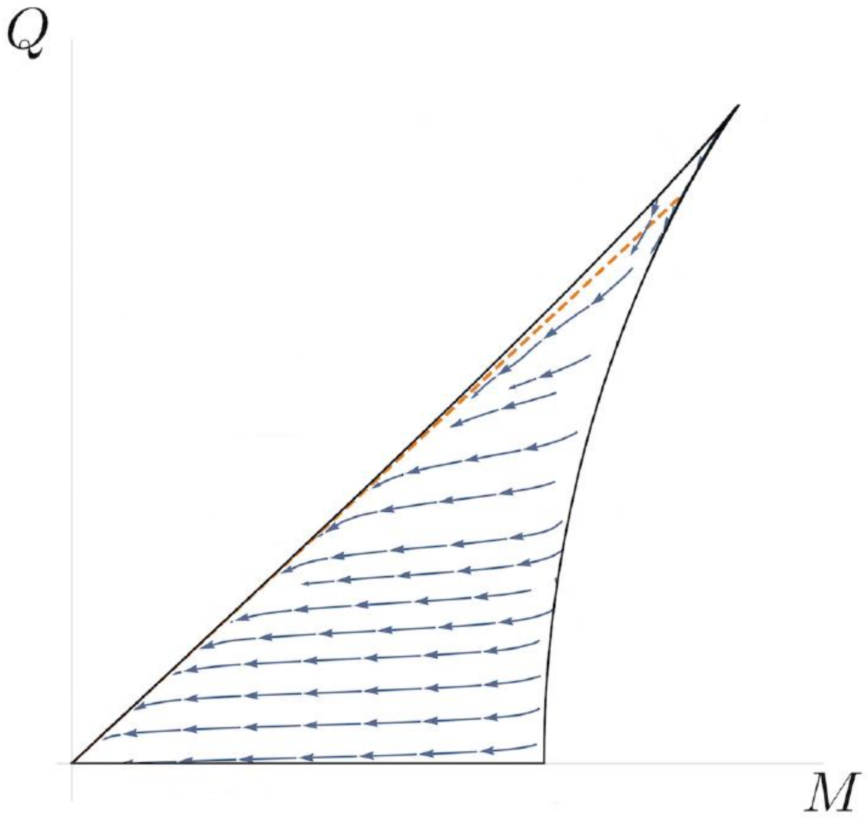

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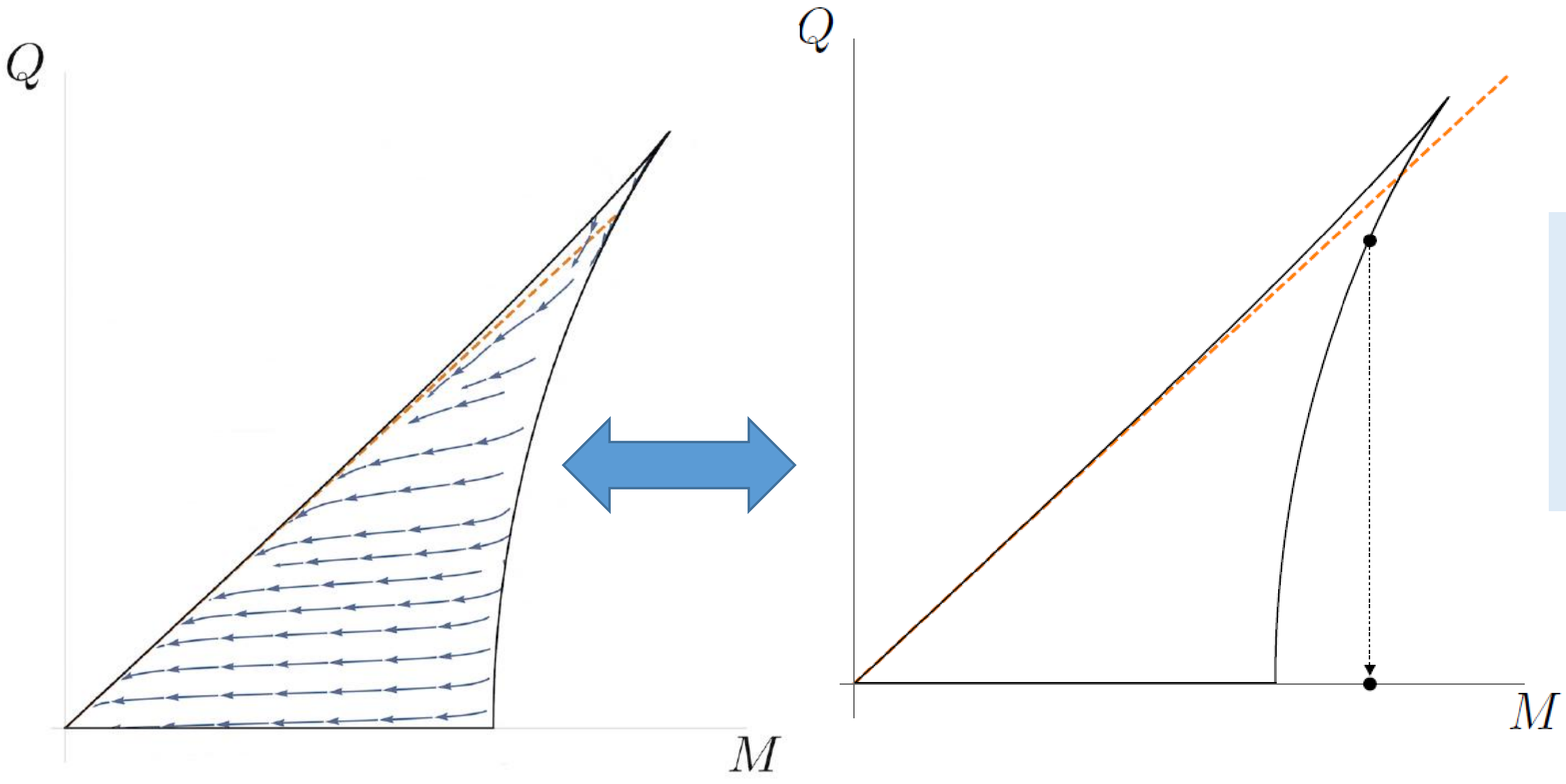


Details are such that evolution brings you to super-extremal branch unless you obey FL bound.

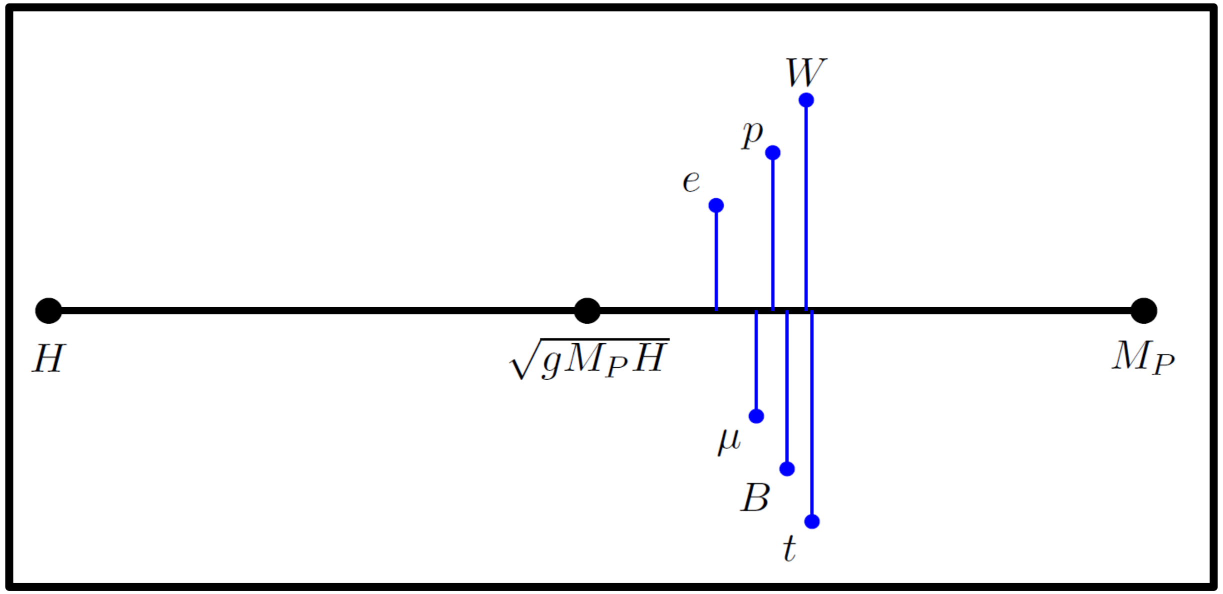
- All charged fields in the SM obey FL ☺

$$\sqrt{gM_P H} \sim 10^{-3}\, eV$$

- Can FL help with explaining hierarchy problems?

→ CC hierarchy (Planck units):

$$\Lambda \lesssim \frac{m^4}{4\pi\alpha}\,;\quad \xrightarrow{\text{Electron}} \quad \Lambda \lesssim 3 \cdot 10^{-89}\,;$$



Logarithmic scale

So massless non-abelian gauge fields are in contradiction with FL. FL predicts that in a de Sitter background non-abelian gauge fields must confine or be spontaneously broken, at a scale above H.

$$m_{\text{Gauge field}} \gtrsim H, \quad \text{or} \quad \Lambda_{\text{Confinement}} \gtrsim H$$

There cannot be a phase of the Standard Model where the weak interaction is long range → no local minimum at Phi = 0 for the Higgs potential. See also [Mook Lee et al 2111.04010]

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Constraints on charged dark matter [Montero, Munoz, Obied, 2207.09448]

Very constraining for inflationary models.

Summary

The Swampland is a very rich program. It can be applied to almost all corners of string theory, holography, phenomenology, black hole physics,…. It mostly inspires certain questions. There is more focus on ‘the why’ and interesting patterns arise.

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No. It is not just the art of conjecturing.

I presented a biased set of examples relating to the cosmological constant:

- its size (how small is vacuum energy with respect to KK scale)
- Its sign (what about dS?)
- Its stability (decays)
- And the non-trivial UV-IR connections! (Cosmo vs particle physics)

Extra slides

fluxes

$$H_3 = 2m\,\mathrm{Re}\,\Omega,$$
$$g_s F_0 = 5m,$$
$$g_s F_2 = \frac{\tilde{m}}{3} J + \mathrm{i}\mathcal{W}_2,$$
$$g_s F_4 = \frac{3}{2} m J \wedge J,$$
$$g_s F_6 = 3\tilde{m}\,\mathrm{dvol}_6.$$

geometry

$$\mathrm{d}J = 2\tilde{m}\,\mathrm{Re}\,\Omega\,,$$
$$\mathrm{d}\Omega = -\frac{4}{3}\mathrm{i}\,\tilde{m} J \wedge J + \mathcal{W}_2 \wedge J\,,$$
$$\frac{1}{L_H^2} = m^2 + \tilde{m}^2\,.$$

Sources

$$g_s j_3 = \mathrm{i}\,\mathrm{d}\mathcal{W}_2 + \left(\frac{2}{3}\tilde{m}^2 - 10m^2\right)\mathrm{Re}\,\Omega.$$

This source term represents the O6: $dF_2 = F_0 H_3 + j_3$

Inflation?

Consider the SM U(1) gauge field. If Higgs is still in the standard electroweak vacuum, we violate FL bound. But Higgs potential is changed in the UV. Many options. Strongly depends on scenario, whether we can obey FL bound [Lee, Cheong, Hyun, Park, Seo 2021]

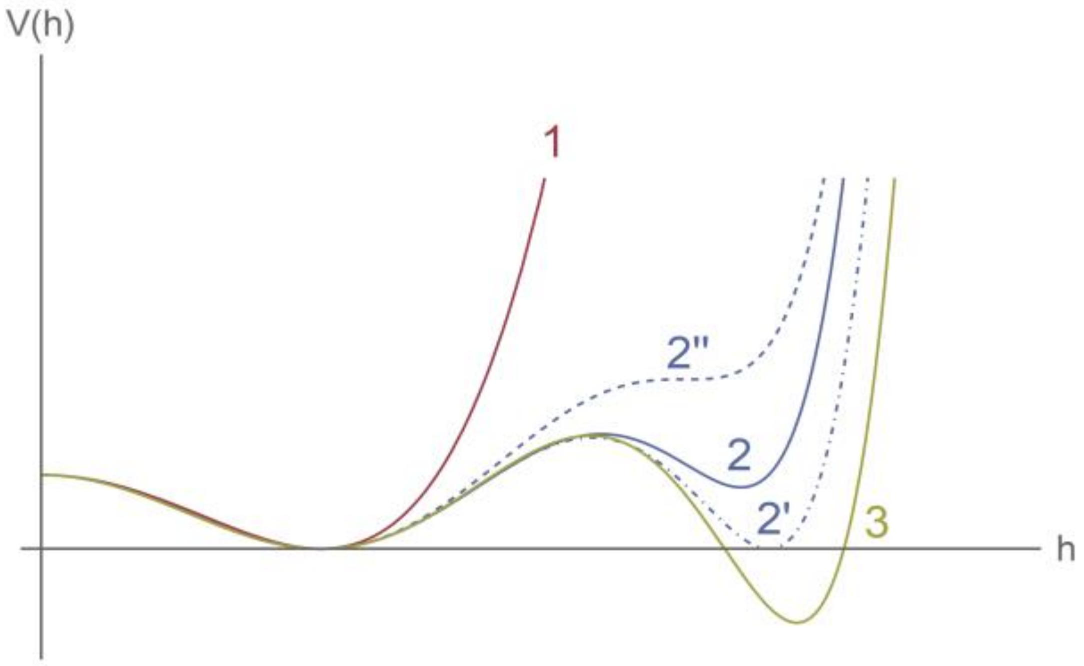

Figure 1: Schematic shape of the Higgs potential.

$$\sum_i U_i(\varphi_i) + V(h) = 3M_P^2 H_I^2,$$

FL: $$h \geq \left(\frac{96\pi\alpha_{\rm EM}}{y_e^4}\right)^{1/4} \sqrt{M_P H_I}.$$

If: $h < M_P,$ ⇒ $H_I \lesssim 10^7$ GeV, Refresh gauge theory formulas (U(1)):

$$\phi \to e^{iq\theta}\phi \qquad q \in Z$$

$$\mathcal{D}_\mu \equiv \partial\phi - iqgA_\mu\phi$$

$$\mathcal{L} = -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} - \frac{1}{2}\mathcal{D}_\mu\phi(\mathcal{D}^\mu\phi)^*$$

$$gA_\mu = A_\mu$$

$$\mathcal{L} = -\frac{1}{4g^2}F_{\mu\nu}F^{\mu\nu} - \frac{1}{2}\mathcal{D}_\mu\phi(\mathcal{D}^\mu\phi)^*$$

$$\mathcal{D}_\mu \equiv \partial\phi - iqA_\mu\phi$$

Limit g→0 means no gauging procedure. Global symmetry, no coupling charge to vector.

Coupling to gravity?

$$S = \int d^4x\sqrt{-g}\left[\frac{1}{16\pi G}\left(-R + \frac{6}{\ell^2}\right) + \frac{1}{4g^2}F_{\mu\nu}F^{\mu\nu}\right].$$