Status of dS space in string theory

Russell's teapot

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Paris 2021

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Hence I will focus on general principles and try to convey a few simple points of potential interest to a broader audience.

The talk will be slightly biased and I mention own work probably too much.

Why should you care about the status of dS vacua in string theory?

Dark energy is a quantum gravity problem.
Despite lowest energy scale, largest distances.
→ cc hierarchy problem.

Vacuum energy in quantum (effective field theory)= sum of loop diagrams cut off at scale of new physics.

$$\Lambda = \Lambda_{\text{New Physics}}$$

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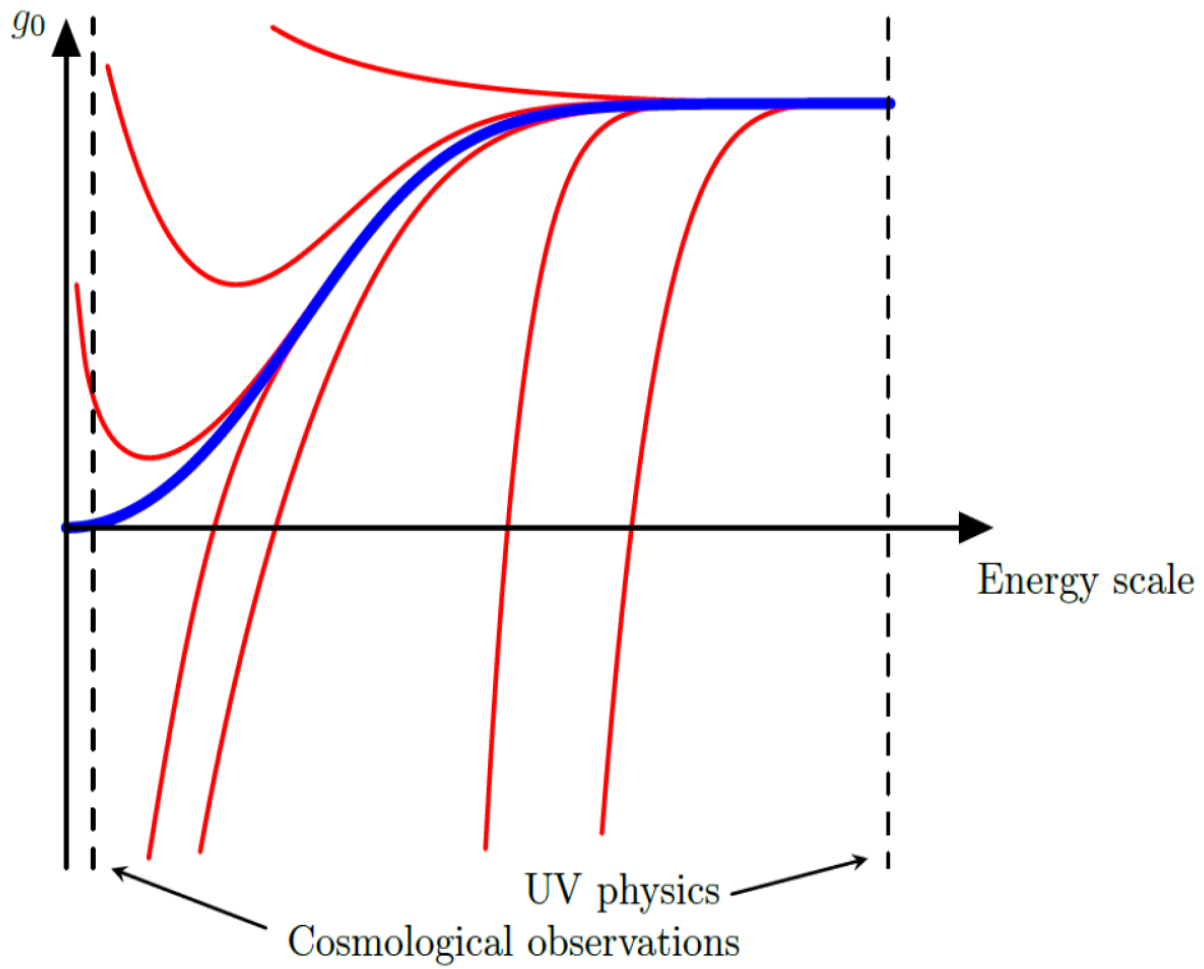

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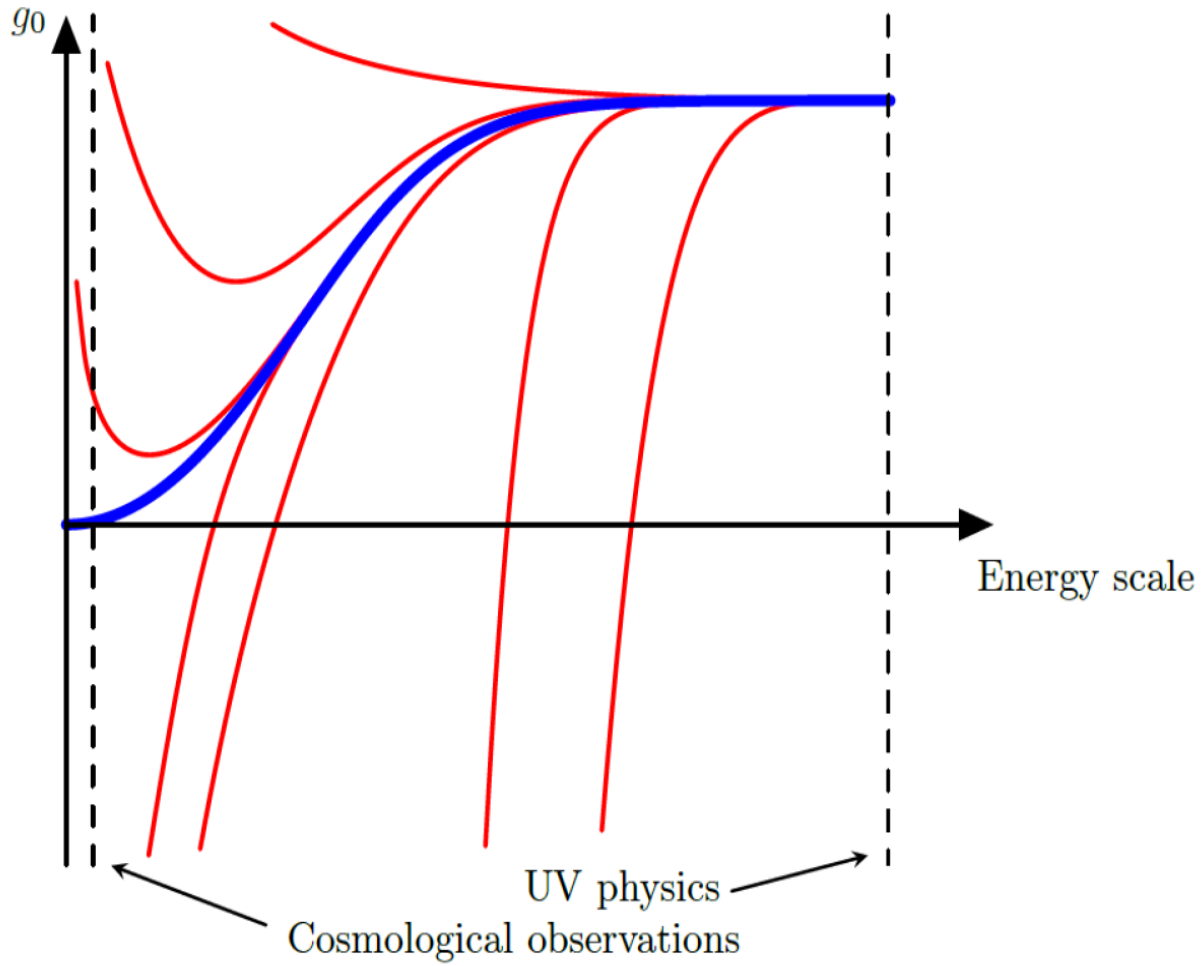

UV completeness of string theory implies we know in principle how to compute vacuum energy, no cut off needed. But how? Using the UV physics; *extra dimensions, branes, fluxes,….*

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.

These statements are correct, but enough to explain all difficulties?

Is there something deeper? There are 'conspiracy'-thinkers who suspect that string theory contains no dS vacua. They used to be a minority. Thanks to the surge of the Swampland program this line of thought has become acceptable.

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

de Sitter space from strings?

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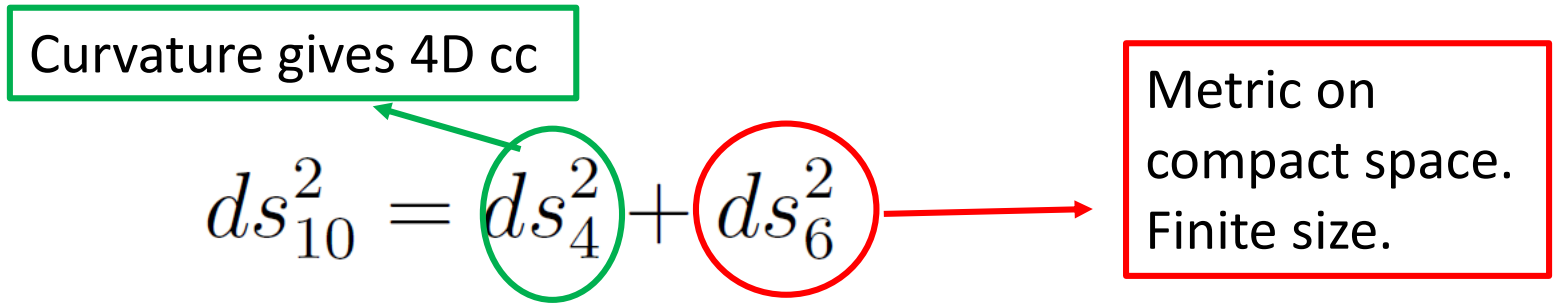
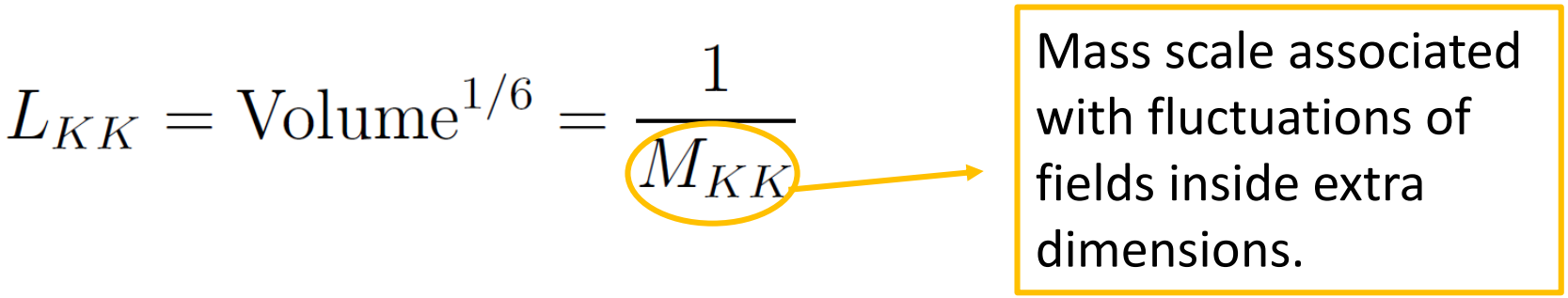
String theory in its usual form has 10 space-time dimensions & we "curl up" 6 of them:



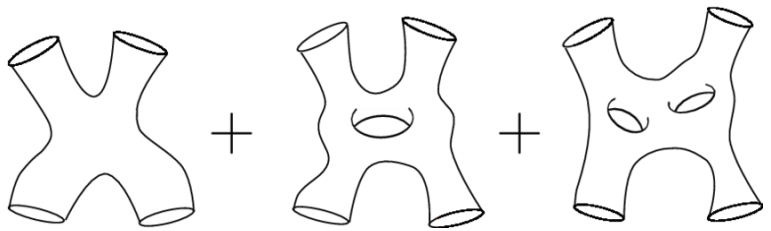
→ Associated length scale is called Kaluza-Klein scale (KK scale):



Most used approach to compute cc : construct a vacuum at the ***boundary of string moduli space.***

String theory reduces to classical 10D SUGRA if

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

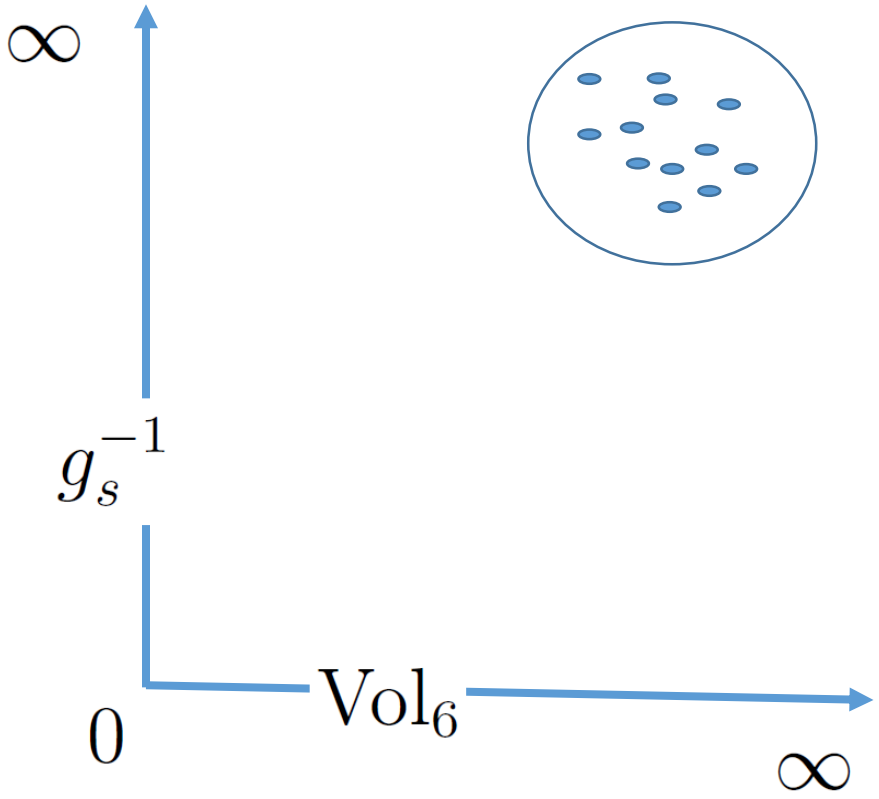


2) All field gradients are small with respect to $1/l_s$ to control higher derivative expansion. OK, if "curvature is small enough → volumes are large enough".

- Both g_s and volume *are fields in 4D* that should be stabilized in the vacuum!

- Note that : $$M_{pl} = \frac{Vol_6}{g_s^2}\frac{1}{l_s}\,.$$

boundary of string moduli space:



10D sugra, possibly with some leading quantum corrections

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

A flavor of the UV physics

Extra dimensions

$$\int_{10} \sqrt{|g_{10}|}\mathcal{R}_{10} = \int_4 \sqrt{g_4}\Big((\int_6 \sqrt{g_6})\mathcal{R}_4 + \int_6 \sqrt{g_6}\mathcal{R}_6 \Big)$$

Positively (negatively) curved internal dimensions want to dynamically contract (expand).

Fluxes

Maxwell theory with higher forms

$$S = -\frac{1}{2p!}\int_6 \sqrt{g_6} F_{\mu_1 \ldots \mu_{p+1}} F^{\mu_1 \ldots \mu_{p+1}}$$

For any hidden dimension filled with flux there is an associated *positive* energy density.
Its volume wants to expand to lower the energy density.

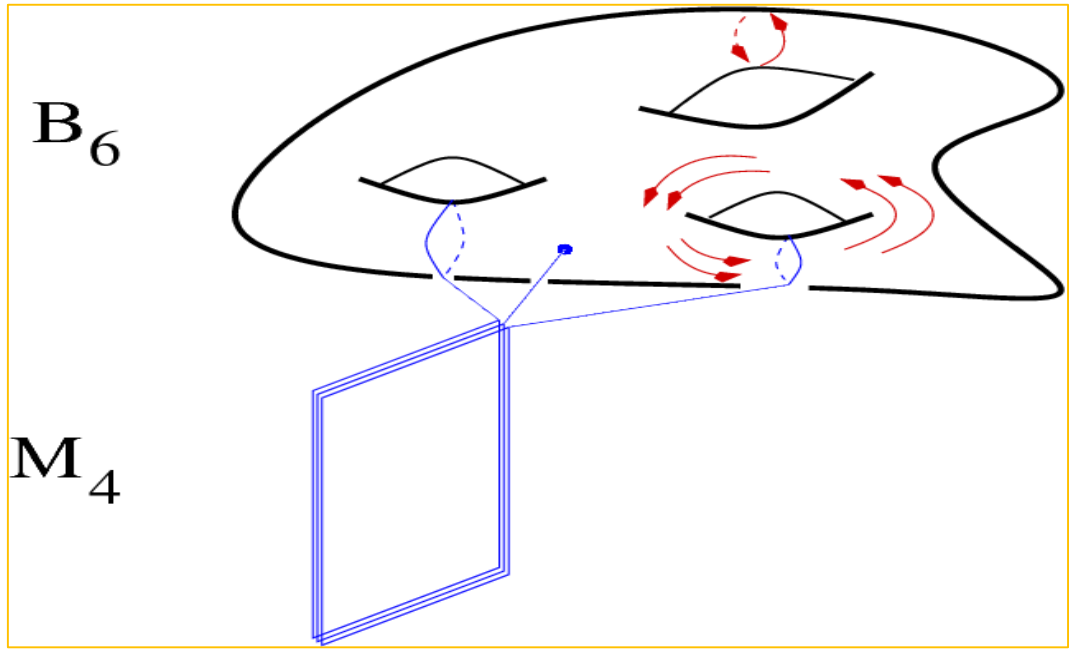
Branes

- Branes must fill our dimensions and wrap some hidden dimensions

- The dynamics of the brane is

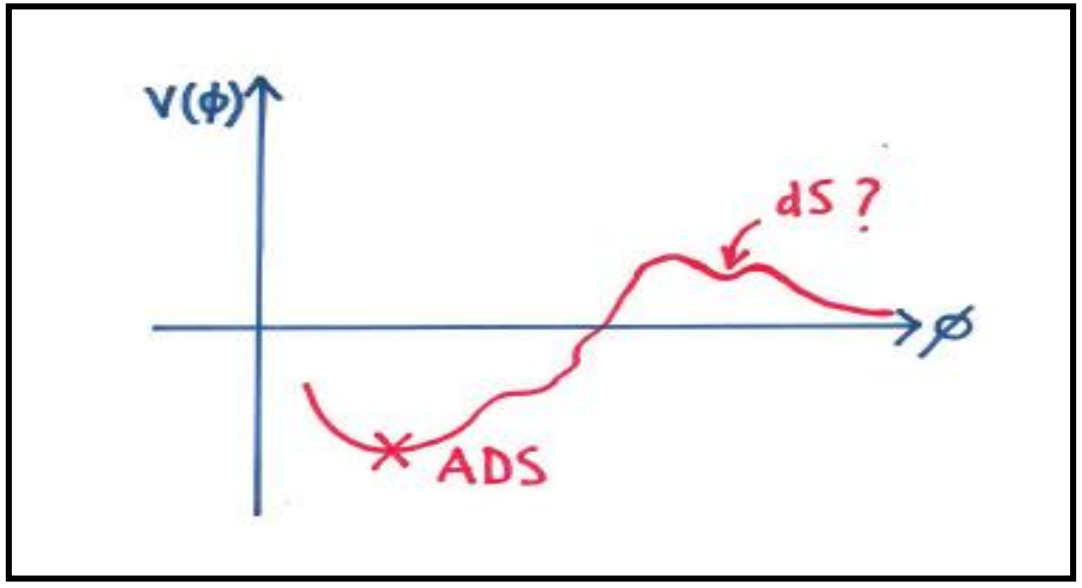
$$S = -T_{\text{brane}} \int_{\text{brane}} \sqrt{g_{\text{brane}}} = Vol(\text{Brane})$$

- If tension is positive (negative) the space wrapped by the brane wants to lower energy by shrinking (expanding).



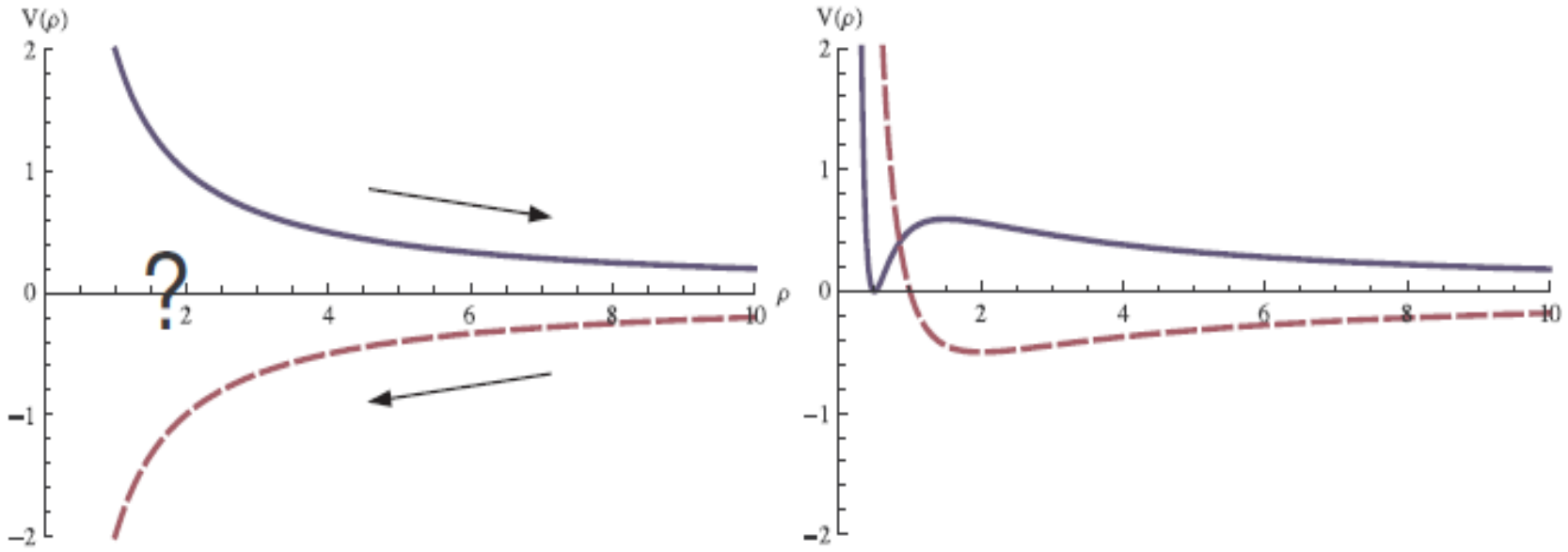
Vacuum energy:
E = Fluxes + Branes + Curvature

'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!

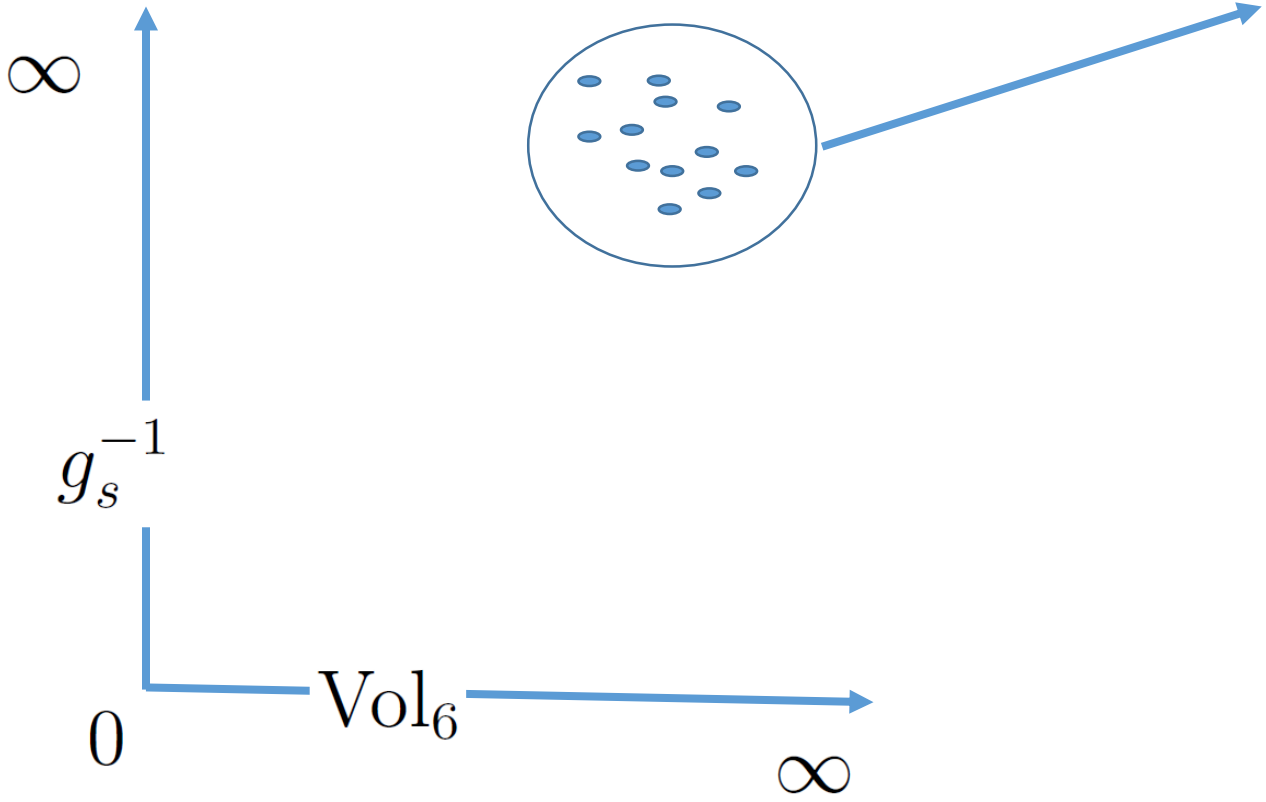
Fluxes are a way out of Dine-Seiberg problem: vacua are typically “non-calculable”



Aim of flux compactification program is to construct ***calculable vacua.*** Solutions “under control”. We can stabilize at the boundary of moduli space.

The last years more insights have crushed this hope

boundary of string moduli space:



Only anti-de Sitter space here.

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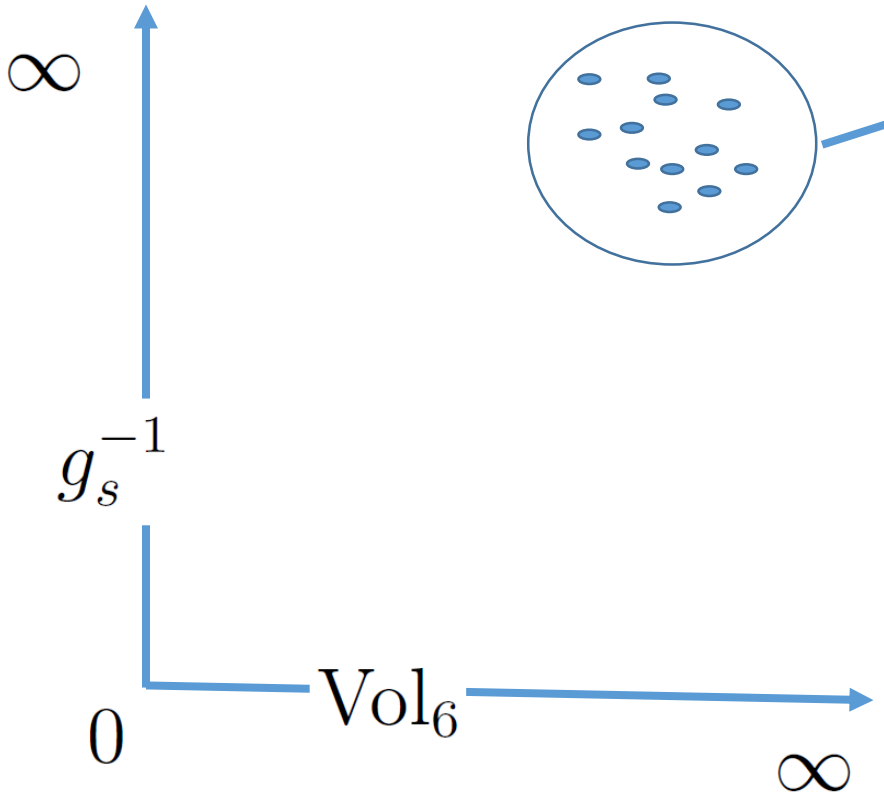

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- Example $AdS_5 \times S_5$. As you crank up flux to infinity all length scales go to infinity, coupling is free parameter and can be dialed small. We trust it.

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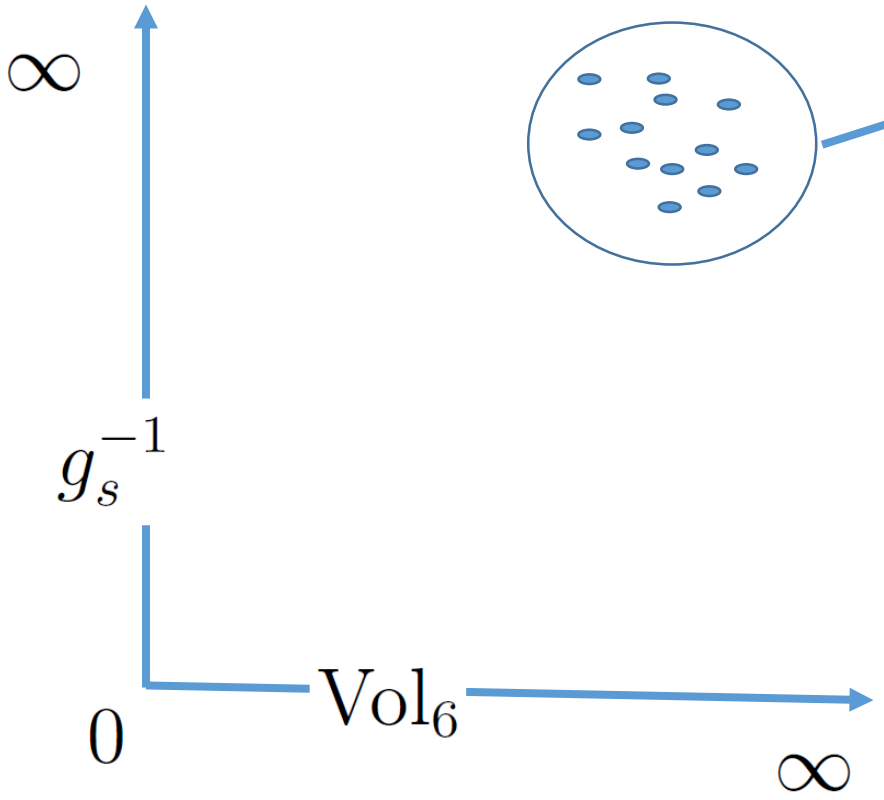

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- Such a ``cranking up" never gives dS solutions. So no number that can be dialed to favorite region. [Junghans 2018, Banlaki, Showdury, Roupec, Wrase, 2018]

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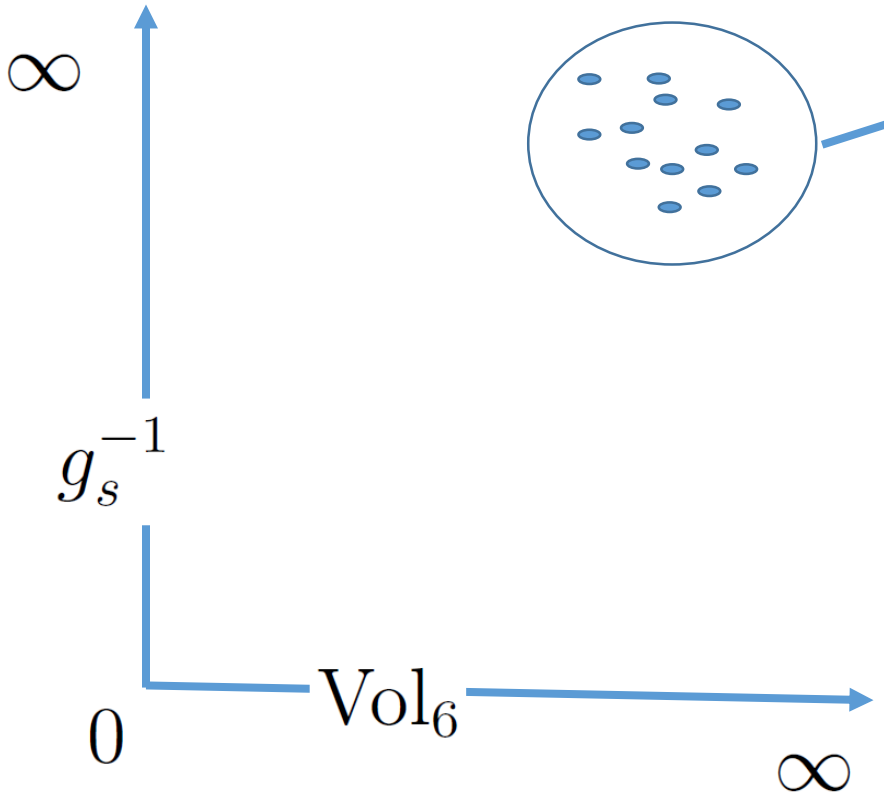

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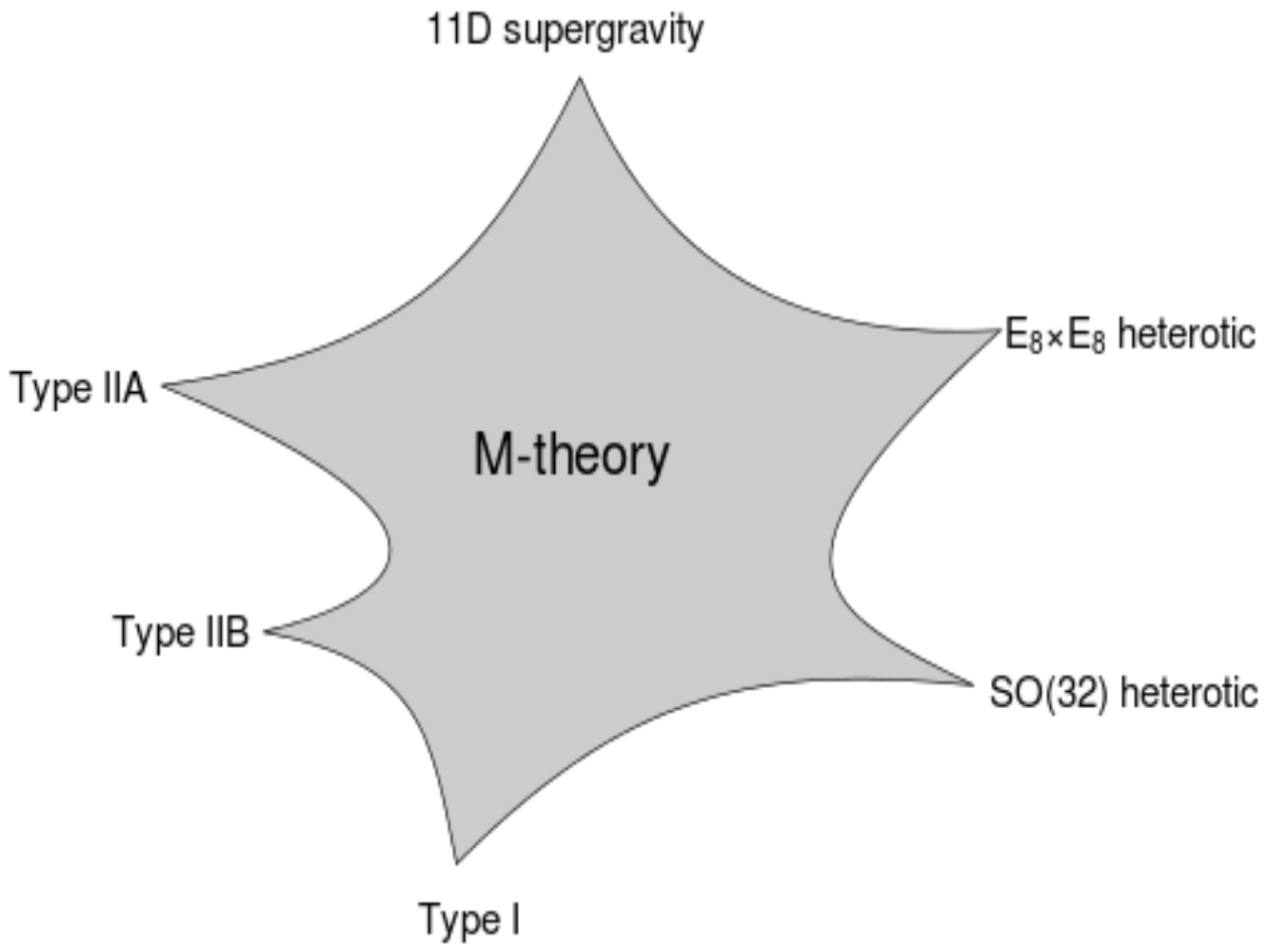
- Such a ``cranking up" never gives dS solutions. So no number that can be dialed to favorite region. [Junghans 2018, Banlaki, Showdury, Roupec, Wrase, 2018]
- Consistent with heuristic (and more general) Swampland arguments. [Ooguri, Palti, Shiu, Vafa 2018, Wrase, Hebecker 2018]

Note how non-obvious this result is: weak coupling for one string theory is strong for the other:



I would say that the main **technical** outcome of the Swampland program has been the realization that the Dine-Seiberg problem is really not evaded in a satisfactory way.

For an attempt to classify (pedagogically & critically) all existing dS constructions until 2018 see: [Danielsson & VR: 1804.01120]

For a complementary take + discussion on quintessence, see [Cicoli, De Alwis, Maharana, Muia, Quevedo 1808.08967]

The last couple of years we have seen 4 approaches

1. Some of us carry on as in the old days and try to find more dS constructions along old methods, even ignoring paradigm shift.

2. *Some try to understand beyond the technical battles of the last 20 years and follow a heuristic approach mixed with technical work to see patterns and links with other branches of physics [Swampland program]*

3. *Some try to find more dS constructions involving less used ingredients, move away from lamppost*

4. *Some try to scrutinize existing dS constructions through detailed technical computation [Motivation Swampland program]*

Rest of the talk: give examples of approach 2, 3.

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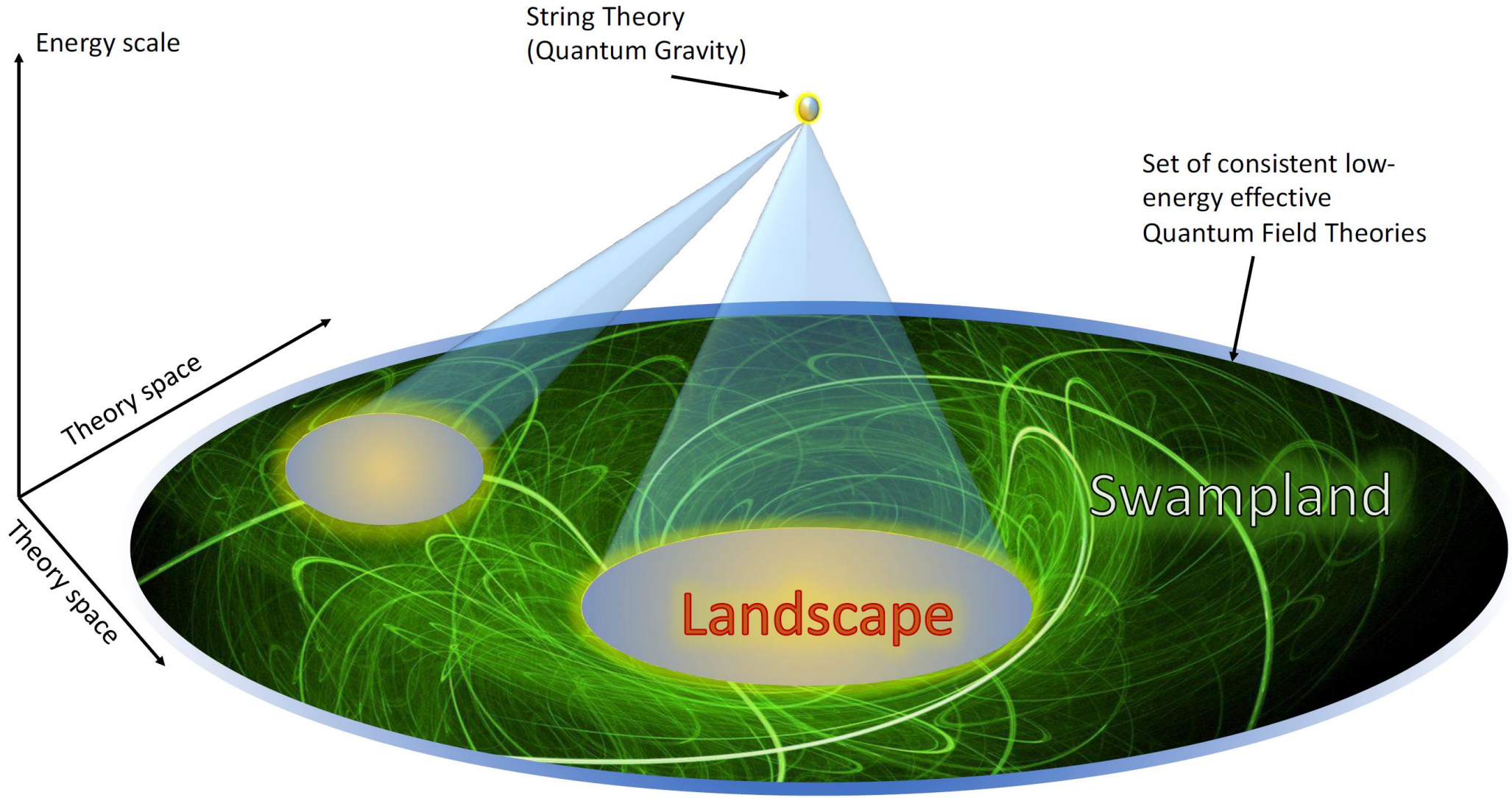
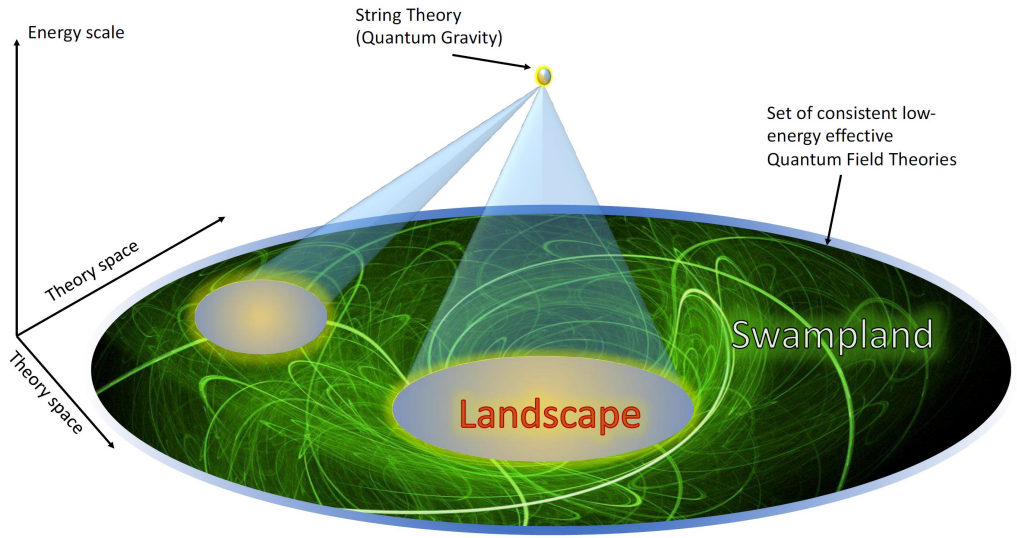
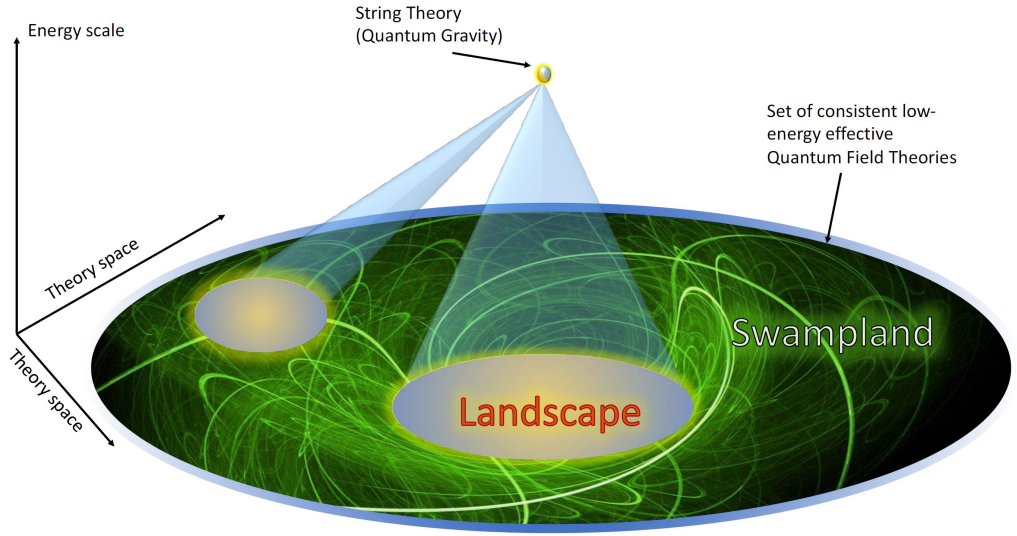


Taken from the excellent review by E. Palti 1903.06239



- Swampland program is highly needed paradigm shift in the field of string-pheno/cosmo.

- Instead of trying to “reverse engineer” effective field theories and arrive at a handwaving “almost anything goes” picture (landscape), we ask: “what is not allowed”. Logically, same question, approach entirely different: Loosely: *inequalities instead of equalities.*



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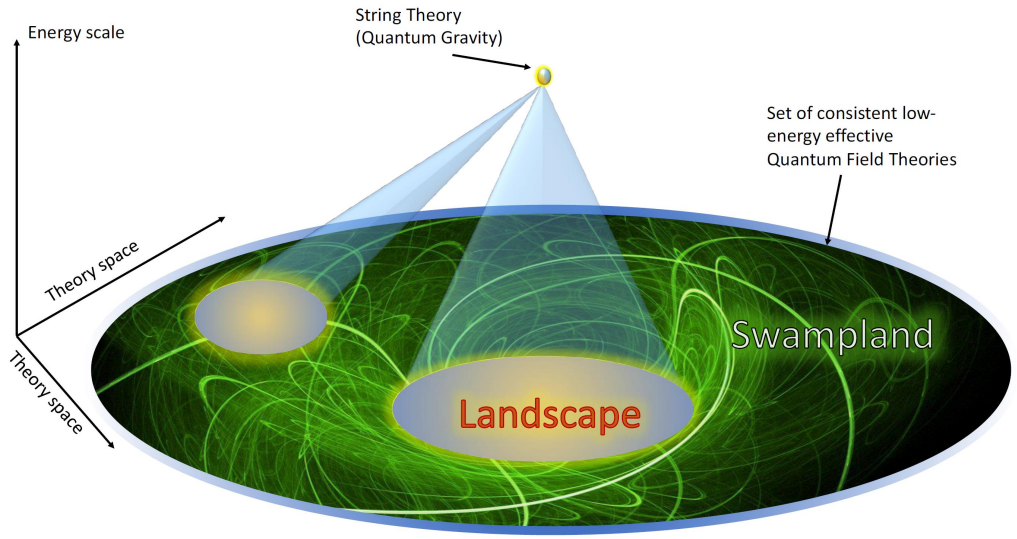

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- Keywords: interdisciplinary (pheno meets black hole physics, holography,…), focusing on the "why", trying to find patterns.
- No, it is not all heuristics. In fact it is an attempt to be more precise. But, current problem Swampland program

Trustworthiness of Swampland statement

Usefulness of Swampland statement

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

$$|\nabla V| \geq \frac{c}{M_p} \cdot V$$

Excluding all dS. The Higgs potential seems counterexample [Denef, Hebecker, Wrase, 2018]? Also``classical dS" solutions were known [Danielsson, Haque, Shiu, VR 2008] [Flauger, Paban, Robbins, Wrase 2008] [Caviezel, Koerber, Kors, Lust, Wrase, 2008]. However all with tachyons. (And when looking closely, at strong coupling after all.)

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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].

Away from parametric weakly coupled regime there is the more general TCC *conjecture* [Bedroya, Vafa 1909.11063] & [Bedroya, Brandenberger, Loverde, Vafa 1909.11106]: sub Planckian quantum fluctuations should not become super Hubble→ would-be dS universe is at best short lived.

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Other (motivated) conjectures constraining the matter content of a dS universe in any theory of quantum gravity :

- **Weak Gravity Conjecture** [Arkani-Hamed, Motl, Nicolos, Vafa, 2006] (should be like in flat space). Not so much predictive power, but good consistency test for model builders

$$m < \sqrt{2} q g M_p \qquad \text{(for some charged state in the theory)}$$

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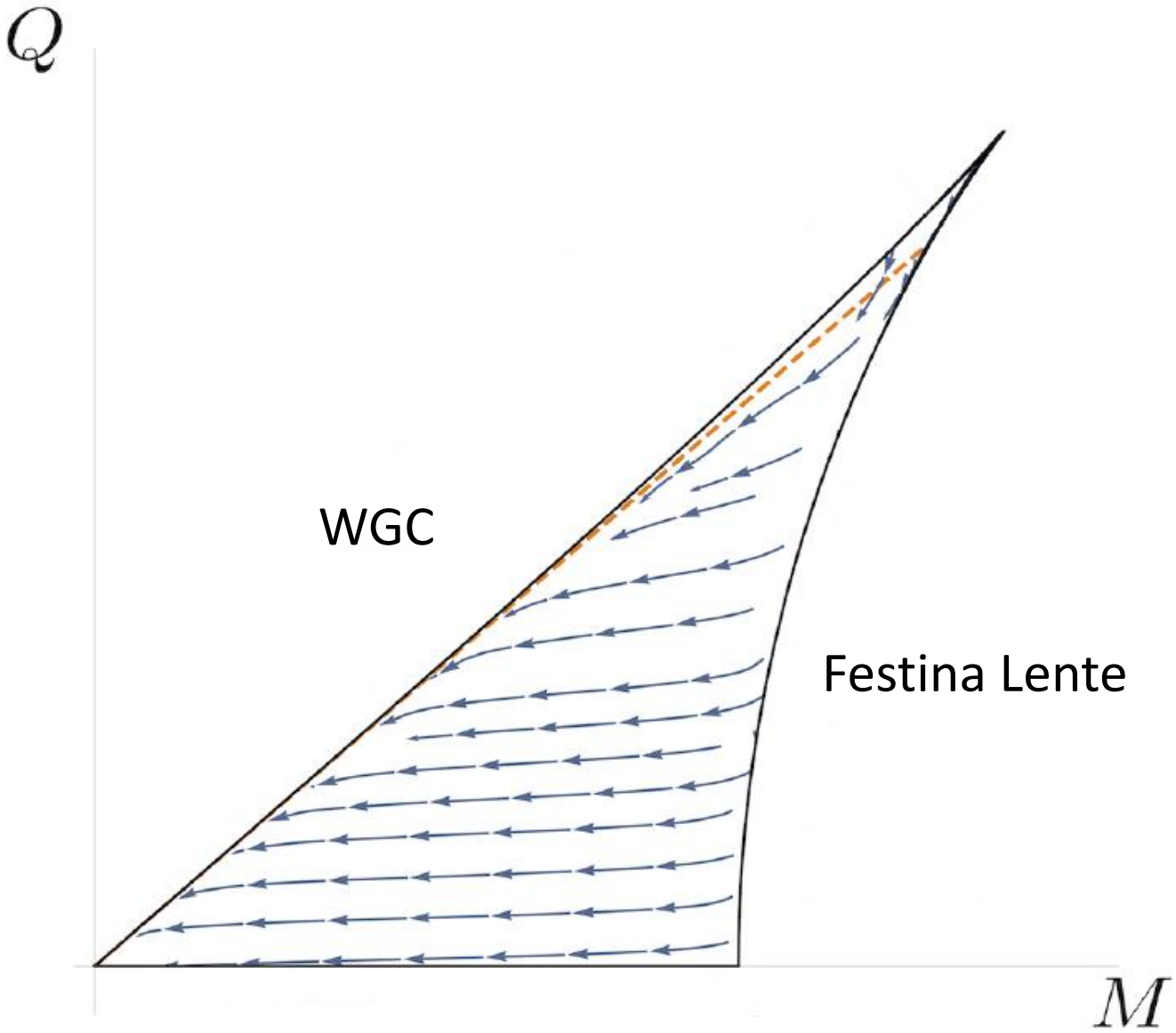
- **Festina Lente** [Montero, Venken, VR 2019], [Montero, Venken, Vafa, VR to appear]

$$m^2 > g q M_p H \qquad \text{(for all charged particles in the theory)}$$

Constraints come from demanding that black holes evolve within the "sharkfin":



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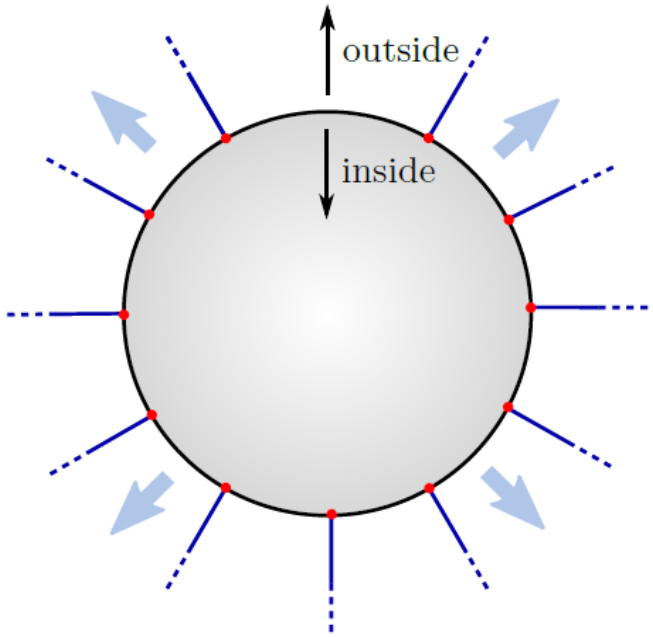
[Banerjee, Danielsson, Dibitetto, Schillo, Giri, 1807. 01570]



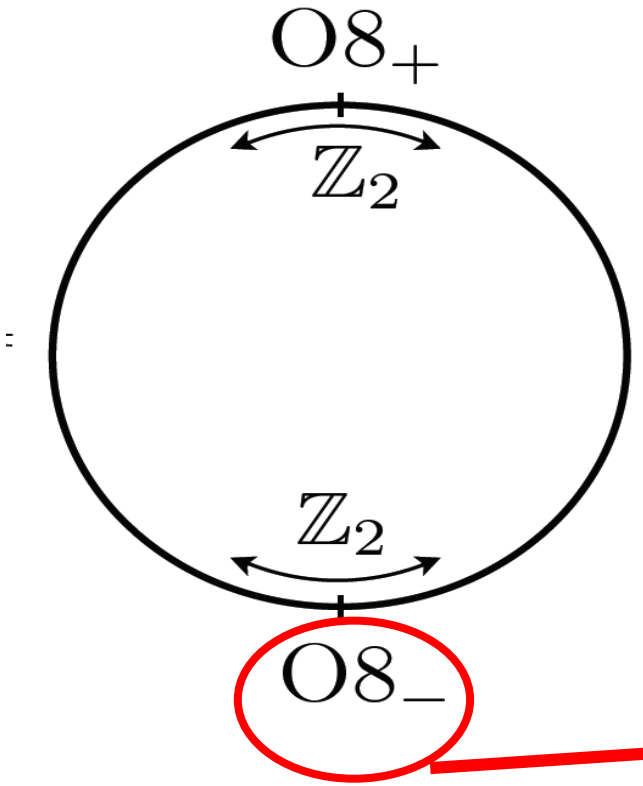
→ *Go back to non-compactifications & brane worlds. Really the problem is having to have control small extra dimensions as well. All we need is a 5-dimensional AdS vacuum that decays via a Coleman-De Luccia bubble! The wall describes 4D de Sitter space.*

Surprisingly natural and (easy?) to embed in string theory in contrast to Karch-Randall scenarios. Yet details can be hard; are all unstable AdS vacua also PERTURBATIVELY unstable? Maybe not [eg Basile , Lanza 2020]

Really nice toy model for deeper lying issues in quantum cosmology: Hartle Hawking vs Vilenkin [Danielsson, Tielemans, Panizo, VR 2021]

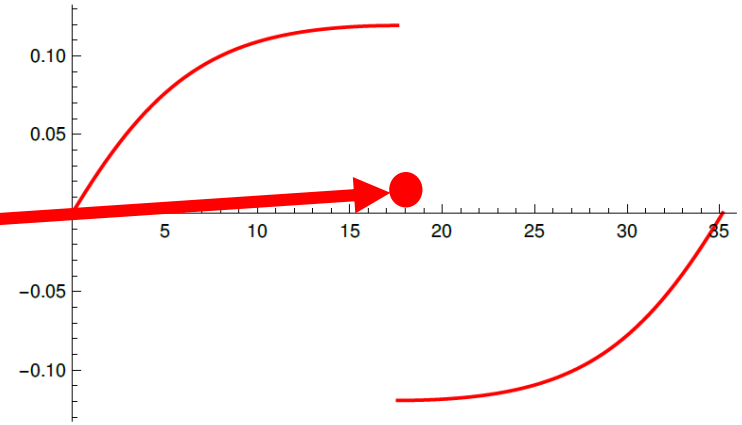
[Cordova, De Luca, Tomasiello, 1812.04147]

→ Incredible simple "classical" dS solution, which somehow all of us missed?! Standard "EFT" approach of constructing a scalar potential must change, because excludes this option [Danielsson et al 2009, VR 2011, Andriot 2018].



[Cribiori, Junghans, 1902.04147] understood why! The source singularities (O8) differ from the usual ones beyond leading order → standard EFT approach & tricks fail

$$\left(\int \mathrm{d}^{10-d}y\sqrt{g_{10-d}}\,\mathrm{e}^{(d-2)A}\right)\tilde{R}^{(d)} \leq 0.$$



→ Nice illustration of Dine-Seiberg problem entering again: to settle debate, we need to compute stringy corrections in highly curved, strongly coupled regime.

[De Luca,Silverstein, Torroba [2104.13380]

Slogan: negative tension singularities (orientifolds) are difficult to understand. But we can evade them and "replace" them with Casimir energies of supergravity fields inside the extra dimensions.

→ Really nice observation, but seems very tough to get control over computation (future will tell?)

conclusions

FAQ

Are there dS vacua in string theory?

→ We are still arguing about it. The answer is either: none at all, or a landscape.

Is there anything you people agree upon?

→ Yes: there are no dS solutions in the weakly coupled (ie controllable) regimes.

Has there been any progress?

→ Depends on what you call progress. I would say: yes! We have learned a great deal about SUSY breaking in string theory. We agree on more things than before.

Will you settle any time soon on this discussion?

→ Do not tell the funding agencies, but I think this could still take a while…

De Sitter space is