Lessons from the String Swampland

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For further reading, see the reviews/lectures:
Brennan, Carta & Vafa 1711.00864
Palti 1903.06239
van Beest, Calderón-Infante, Mirfendereski & Valenzuela 2102.01111

For a more general String Cosmology review see:
Cicoli, Conlon, Maharana, SLP, Quevedo & Zavala 2303.04819

Motivation

The SMs of Particle Physics and Cosmology are extremely successful EFTs, with no confirmed deviations between predictions and data and only a few mild tensions.

Yet they leave huge open questions, including:

- the why questions and hierarchy problems of the SM
- the microscopic nature of Dark Matter and Dark Energy
- the state of the pre-BBN early Universe, inflation(?) and baryogenesis
- the quantisation of gravity.

We may have to wait a long time for experimental insights into these questions... can theoretical insights from **fundamental principles** and **consistency criteria** from quantum gravity help us make progress?

Preview

Framework for the SMs is effective field theory - EFTs should be anomaly free with scattering amplitudes that respect unitarity, causality and analyticity.

String theory, our leading candidate for quantum gravity, is a unique theory from which one can derive a plethora – **but not all!** – EFTs.

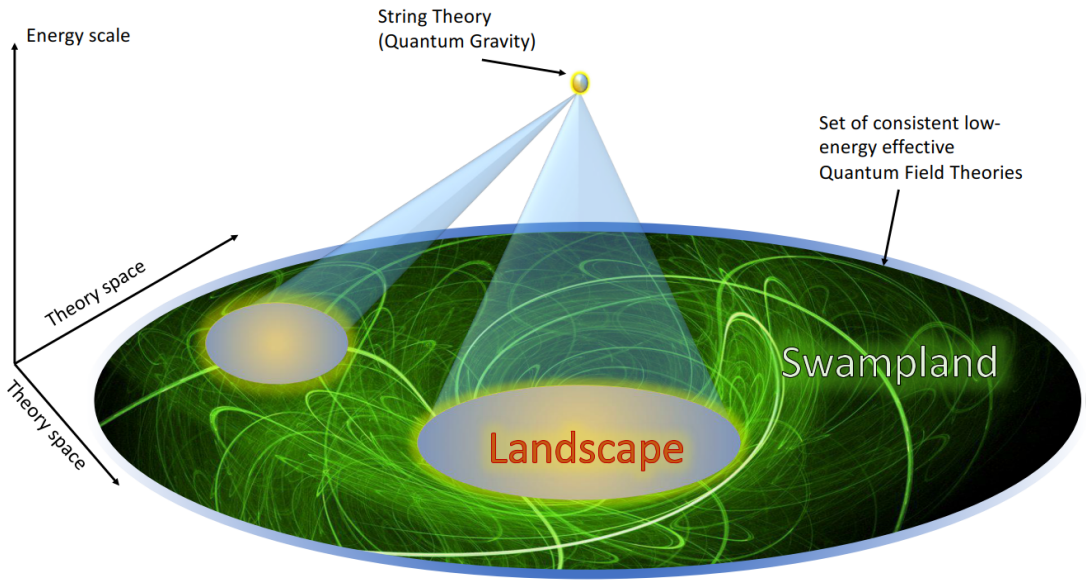

Figure from Palti '19

The Swampland = the set of **apparently** consistent EFTs that cannot be completed into quantum gravity in the ultraviolet.

No Global Symmetries in Quantum Gravity

Conjecture: A theory with a finite number of states, coupled to gravity, can have no exact global symmetries.

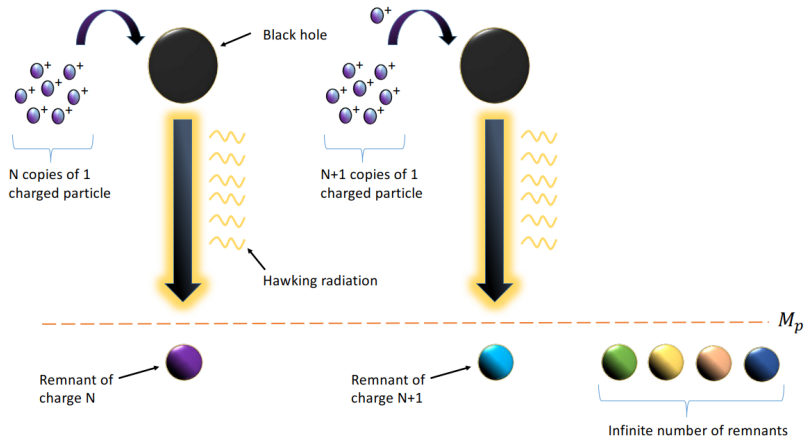

Figure from Palti '19

Heuristic argument:

- Suppose a semi-classical black hole charged under global symmetry.
- As it Hawking radiates it will lose mass but not global charge, ending up as a Planckian sized remnant.
- This occurs for any representation of the global symmetry.
- An infinite number of stable remnants below a finite energy scale - pathological!

Note that global symmetry can be broken at very high energies, so there are no phenomenological consequences.

Plan

- A lightening review of string theory, compactifications, and moduli
- The string landscape and swampland
- Some swampland conjectures
- A phenomenological application
- Summary and outlook

Lightening Review of String Theory

see van Riet's lectures

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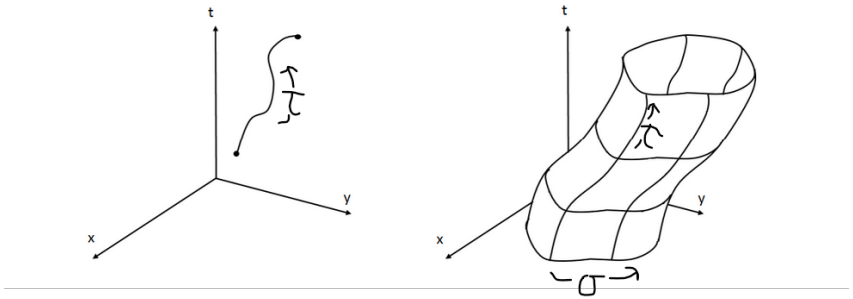

- We extend our notion of fundamental particle with worldline $x^\mu(\tau)$ ($\mu = 0, 1, 2, 3$) to fundamental (super)string with worldsheet $X^M(\tau, \sigma)$ ($M = 0, 1, \ldots, D-1$).

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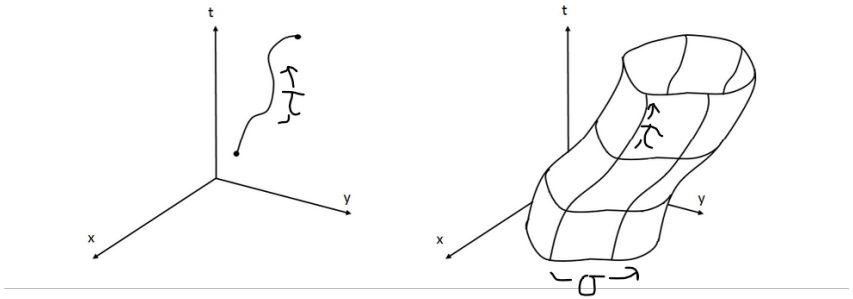

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- After quantisation, consistency imposes $D = 10$ for the superstring, and a spectrum of string states include:
  - the massless spin-2 graviton g_{MN} and the gravitino
  - the massless spin-0 'dilaton', Φ, related to the string coupling as $g_s = e^\Phi$
  - a number of massless 'higher-dimensional' gauge fields, like B_{MN}, C_0, C_{MN}, C_{MNPQ}, ...
  - towers of massive modes with masses $M_s \sim n/\ell_s$.

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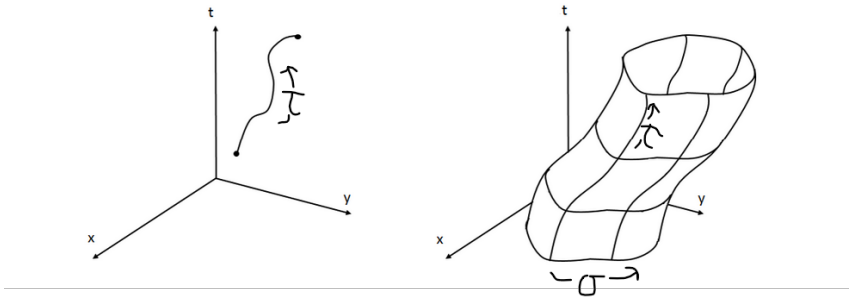

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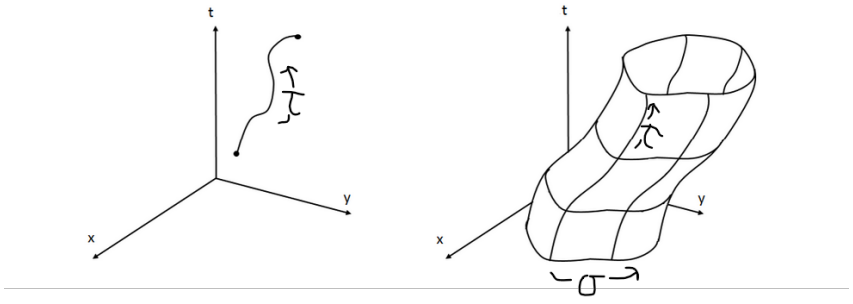

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  At energy scales below M_s, we truncate massive string states.
- At weak string coupling and weak 10D curvature, we obtain a 10D EFT:

$$S_{sugra} = M_s^8 \int d^{10}X \sqrt{-G} e^{-2\Phi} \left(R - \frac{1}{12} H_{MNP} H^{MNP} + 4\partial_M \Phi \partial^M \Phi + \ldots \right) .$$

Web of Dualities

String theory is a unique theory, with type IIA, type IIB, $SO(32)$ heterotic, $E_8 \times E_8$ heterotic, and type I theories all related by a web of dualities.

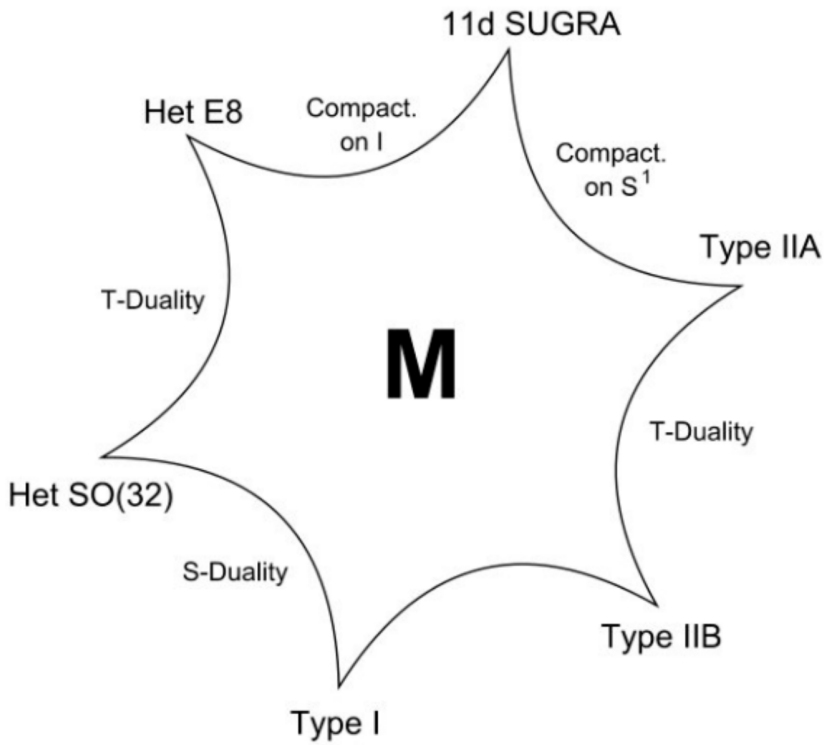

figure from Wiki

String Compactifications, Moduli, and Towers

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- Integrating out the compact dimension gives the contribution to 9D action:

$$\int d^{10}X \sqrt{-G} R_{(10)} = \int d^9X \sqrt{-g} \left(R_{(9)} - \frac{1}{2} \partial_\mu \phi \partial^\mu \phi \right) .$$

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- A 10D scalar field can be decomposed into harmonics on the circle:

$$\Psi(X^M) = \sum_{k=-\infty}^{k=+\infty} \psi_k(X^\mu) e^{2\pi i k X^9}$$

  with $\partial^M \partial_M \Psi = 0 \Rightarrow \left(\partial^\mu \partial_\mu - M_k^2\right) \psi_k = 0$ with $M_k^2 \sim (\frac{k}{R})^2$.

String Towers

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- towers of heavy string states from quantising the string:

$$M \sim \frac{n}{\ell_s}$$

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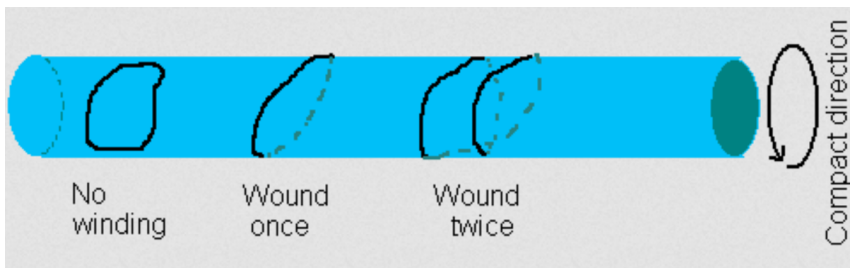

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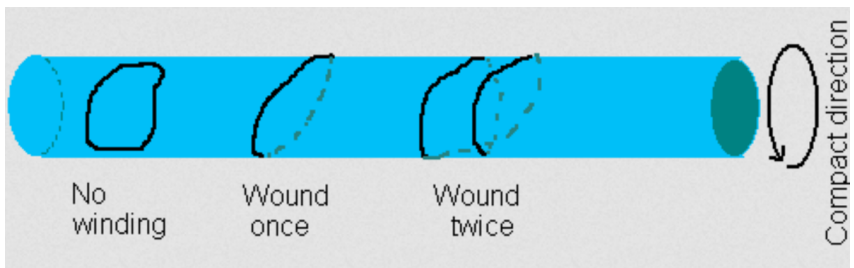

KK and winding modes imply T-duality: string theory compactified on circle of radius R is indistinguishable from that compactified on a radius $1/R$.

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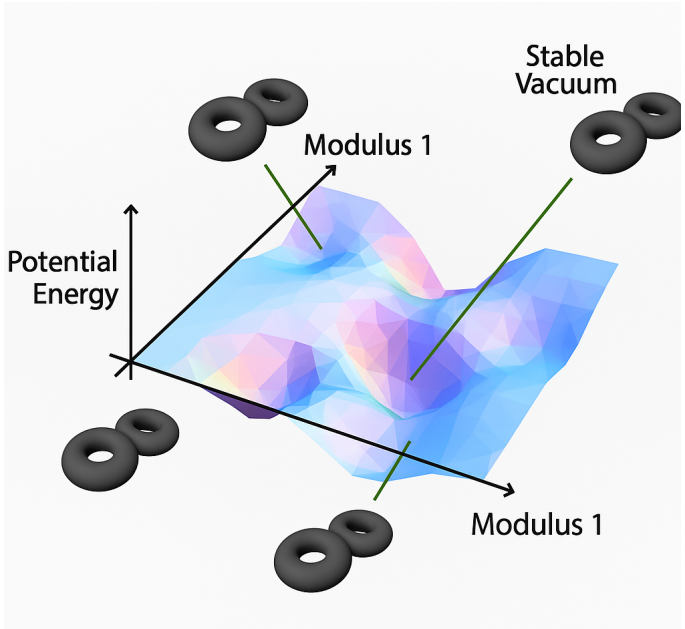
- But moduli also correspond to coupling and mass parameters in the EFT - unstabilised moduli lead to unobserved consequences like fifth forces and time-variation of fundamental constants.
- Ingredients like fluxes, and corrections to the weak coupling and weak curvature approximations, induce a scalar potential for the moduli that stabilises them.

The String Landscape

String theory is a unique theory, and yet it has a plethora of solutions or vacua, each corresponding to a distinct EFT.



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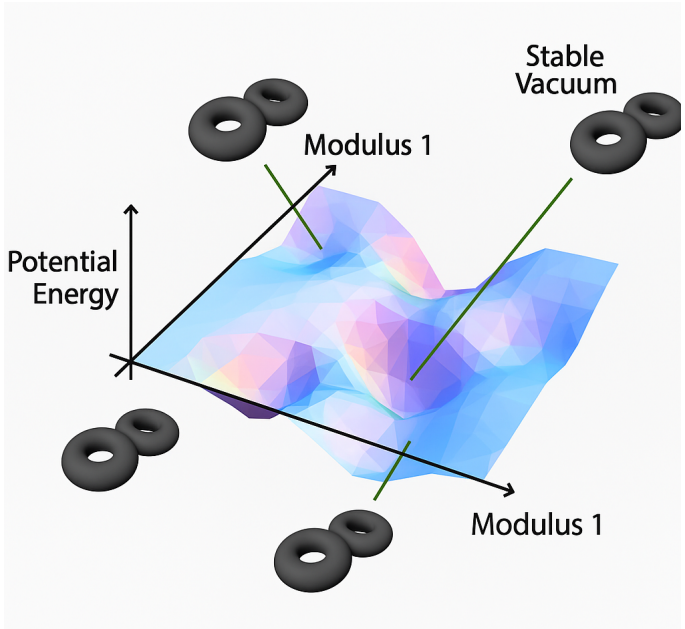

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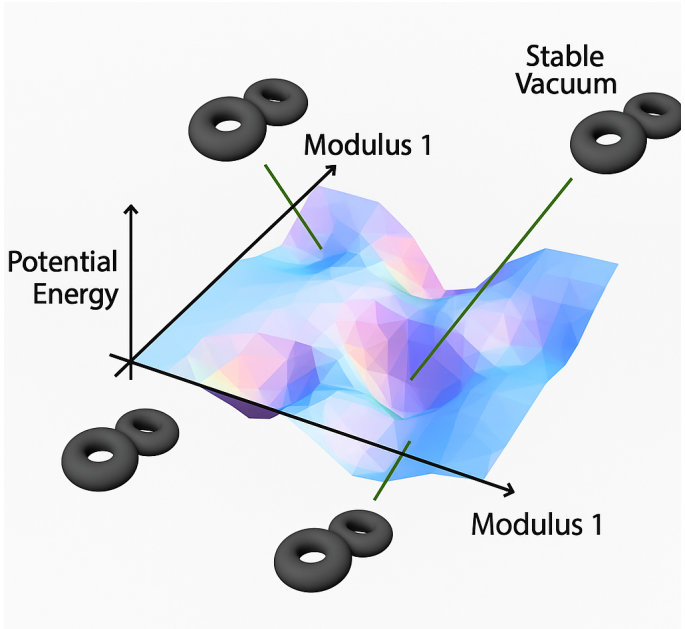

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What conditions does an EFT have to satisfy in order for it to be derivable from QG?

The Swampland Distance Conjecture

Ooguri & Vafa '06

- Consider string theory compactified on a circle with 9D EFT given by:

$$\int d^9X\sqrt{-g}\left(R_{(9)}-\frac{1}{2}(\partial\phi)^2\right)$$

plus the KK and winding towers:

$$M_{kk}\sim\frac{k}{R}\sim k\,e^{\beta\phi}\quad\text{and}\quad M_{\text{winding}}\sim w\,R\sim w\,e^{-\beta\phi}$$

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The Weak Gravity Conjecture

Arkani-Hamed, Motl, Nicolis & Vafa '06

- Compactification may give rise to new KK gauge fields, e.g. for circle

$$ds^2 = e^{2\alpha\phi} g_{\mu\nu} dX^\mu dX^\nu + e^{2\beta\phi} (dX^9 + A_\mu dX^\mu)^2$$

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  Note that the gauge coupling g_A is related to the modulus ϕ as $g_A^2 = e^{\gamma\phi}$.
- A 10D scalar $\Psi(X^M)$'s KK tower $\Psi(X^M) = \sum \psi_n(X^\mu) e^{2\pi i n X^9}$ is charged under $U(1)_{kk}$ with charges $q_n = 2\pi n$ related to masses as $g_A q_n = M_n$.

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  the $U(1)$ isometry of the circle gives rise to a $U(1)_{kk}$ gauge symmetry.
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  Note that the gauge coupling g_A is related to the modulus ϕ as $g_A^2 = e^{\gamma\phi}$.
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  and moverover the cutoff scale of the EFT is bounded from above by:

$$\Lambda \lesssim g_A M_{Pl} .$$

The Weak Gravity Conjecture

Arkani-Hamed, Motl, Nicolis & Vafa '06

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- Breakdown of EFT due to SDC tower; WGC also follows from avoiding an infinite number of stable black hole remnants.

Charting the Swampland

- Using evidence from string compactifications, black hole physics and holography several ‘Swampland Constraints” have been proposed:

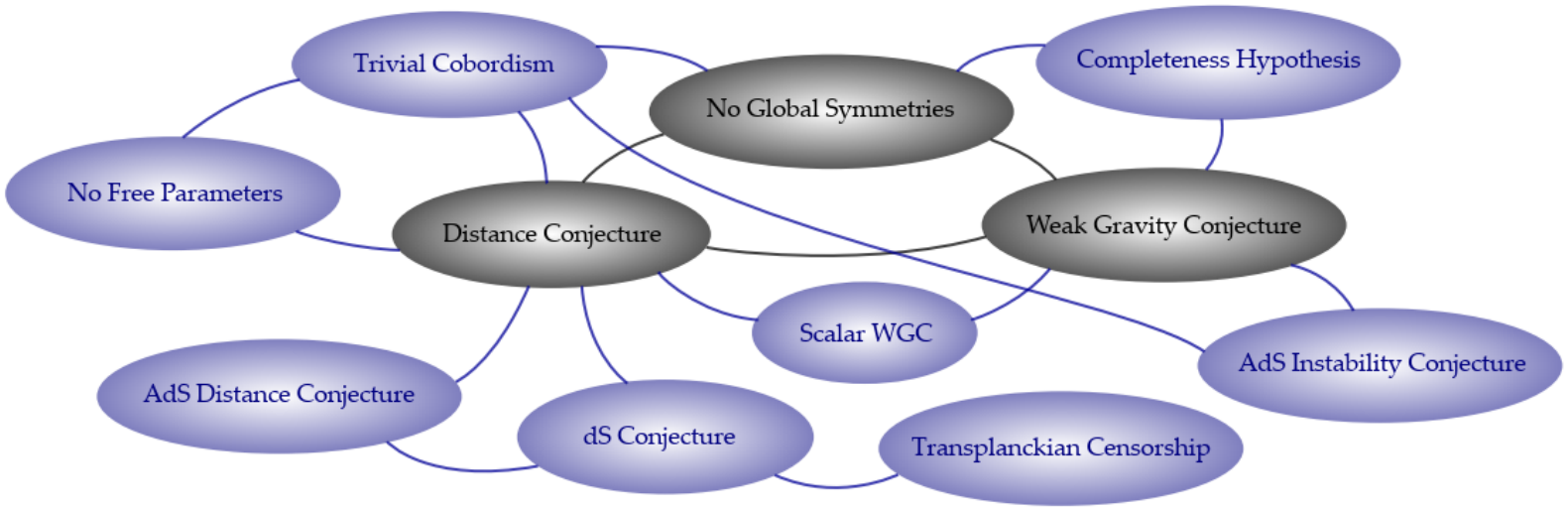

Figure from Valenzuela et al ’21

Several connections have been found amongst them, perhaps suggesting some underlying, unifying principle(s)?

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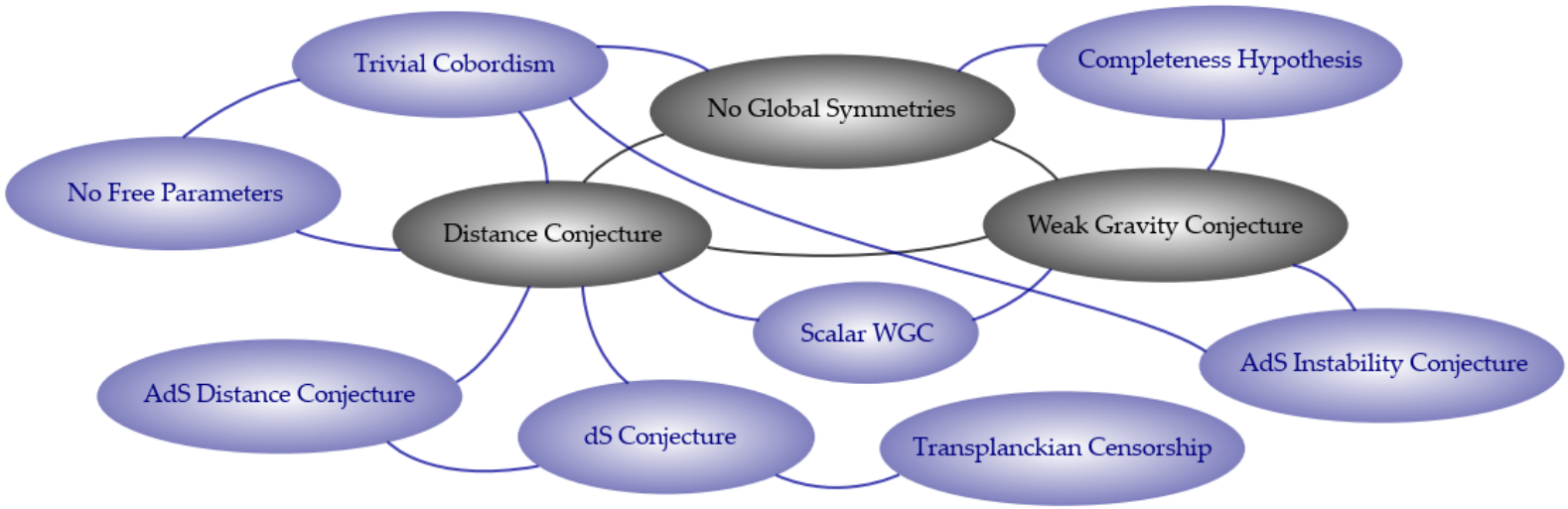

Figure from Valenzuela et al ’21

Several connections have been found amongst them, perhaps suggesting some underlying, unifying principle(s)?

- Those with most compelling evidence have limited conceptual/phenomenological implications... others are more powerful...

de Sitter Conjecture

Ooguri, Palti, Shiu & Vafa '18; Garg & Krishnan '18

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$$M_{Pl}\frac{|\nabla V|}{V} \geq c \quad or \quad min\left(\nabla_i \nabla_j V\right) \leq \frac{-cV}{M_{Pl}^2} \,,$$

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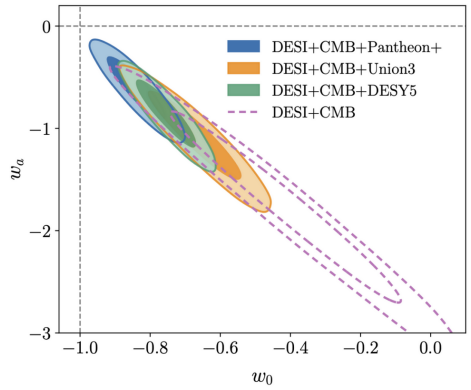
but there exist several candidate counter-examples inside moduli space, where we have less control of the weak coupling, weak curvature expansions, e.g. KKLT and LVS...

Dark Energy and the Swampland

- Intriguing hints towards Dynamical Dark Energy $w = w_0 + w_a(1 - a)$:



DESI Collaboration '25

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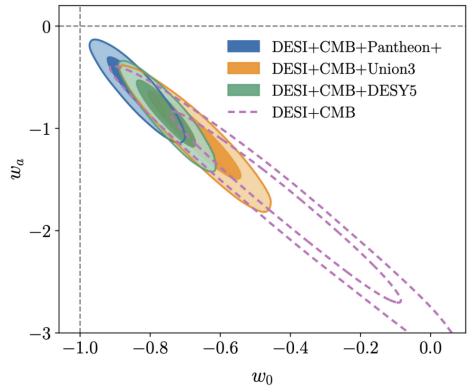
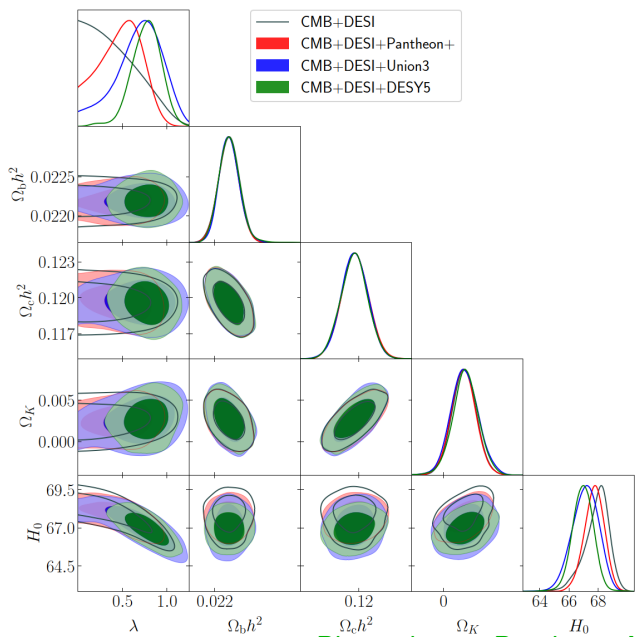


DESI Collaboration '25

- Cosmological fit to the runaway quintessence model $V = V_0 e^{-\lambda\phi}$:



Bhattacharya, Borghetto, Malhotra, SLP, Tasinato & Zavala '24, '25

is in tension with swampland constraint $\lambda \geq \sqrt{2}$.

Summary and Outlook

- String theory is a unique theory, but with a plethora of solutions, each giving rise to a distinct low energy Effective Field Theory.
- It is generally believed that not every EFT can be derived from string theory or be embedded consistently into Quantum Gravity.
- The Swampland Program aims to determine which EFTs are consistent with Quantum Gravity and thus might potentially be viable theories of Nature.
- There is mounting ‘empirical’ evidence for a web of inter-related Swampland Constraints, which potentially leave an imprint of UV QG physics in the IR EFT.
- Swampland constraints can be synergetic with observational ones - helping to rule out models of particle physics and cosmology and to stimulate new model building ideas to test experimentally.
- Ultimately we want to understand which Swampland Conjectures are correct, prove them and identify the fundamental QG principle(s) underlying them.
- We are sure to learn many interesting things along the way!