The Swampland and Emergence

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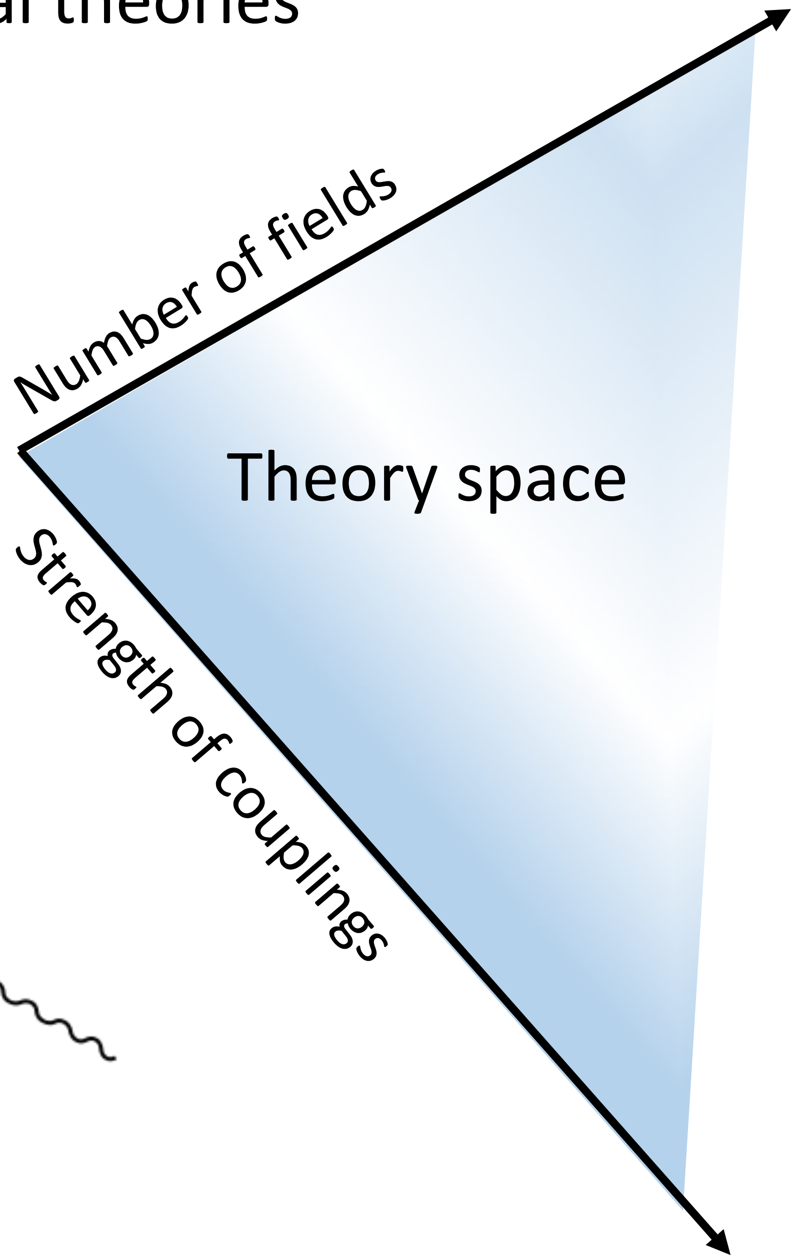
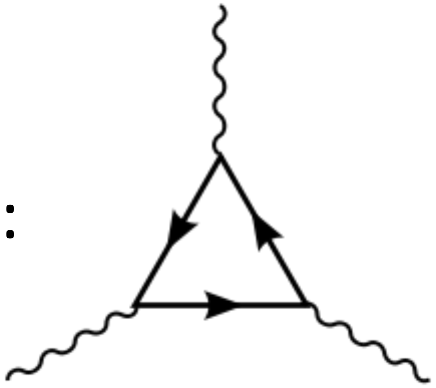
Quantum Field Theories are a rich set physical theories

$$\mathcal{L} = \sum_i \frac{1}{4g_i^2} Tr(F_i^2) + \sum_n \overline{\psi_n} D \psi_n + g_{\phi\phi}(\phi)(\partial\phi)^2 + Y_{nm}\phi\overline{\psi_m}\psi_n$$



QFTs have some self-consistency constraints, for example anomalies:



Effective QFTs valid up to cutoff scale Λ

Which Quantum Field Theories can be consistently coupled to gravity?

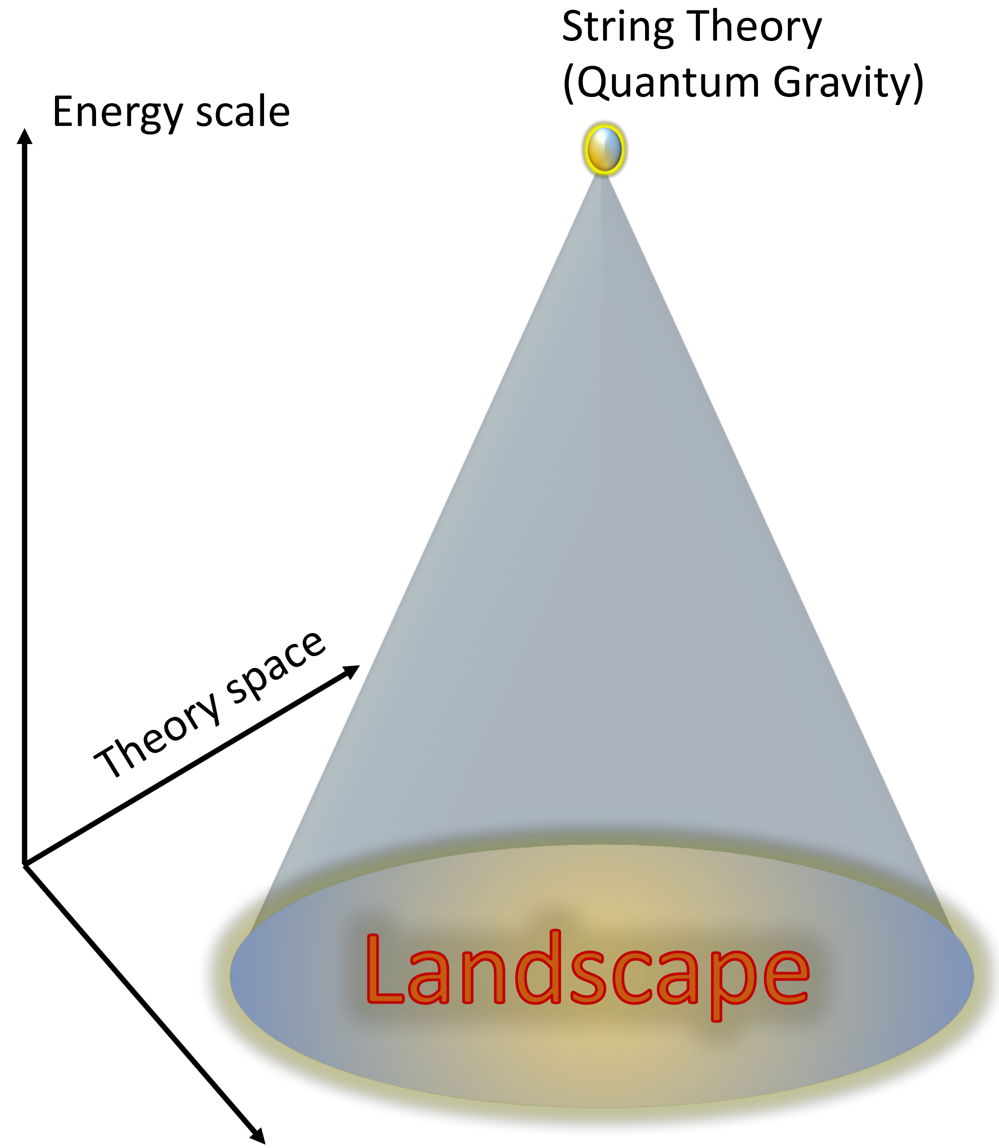
Coupled to Gravity: $M_P^2 R$

$$M_p \sim 10^{18} GeV$$

If $\Lambda \sim M_p$ then very difficult to do consistently – string theory?

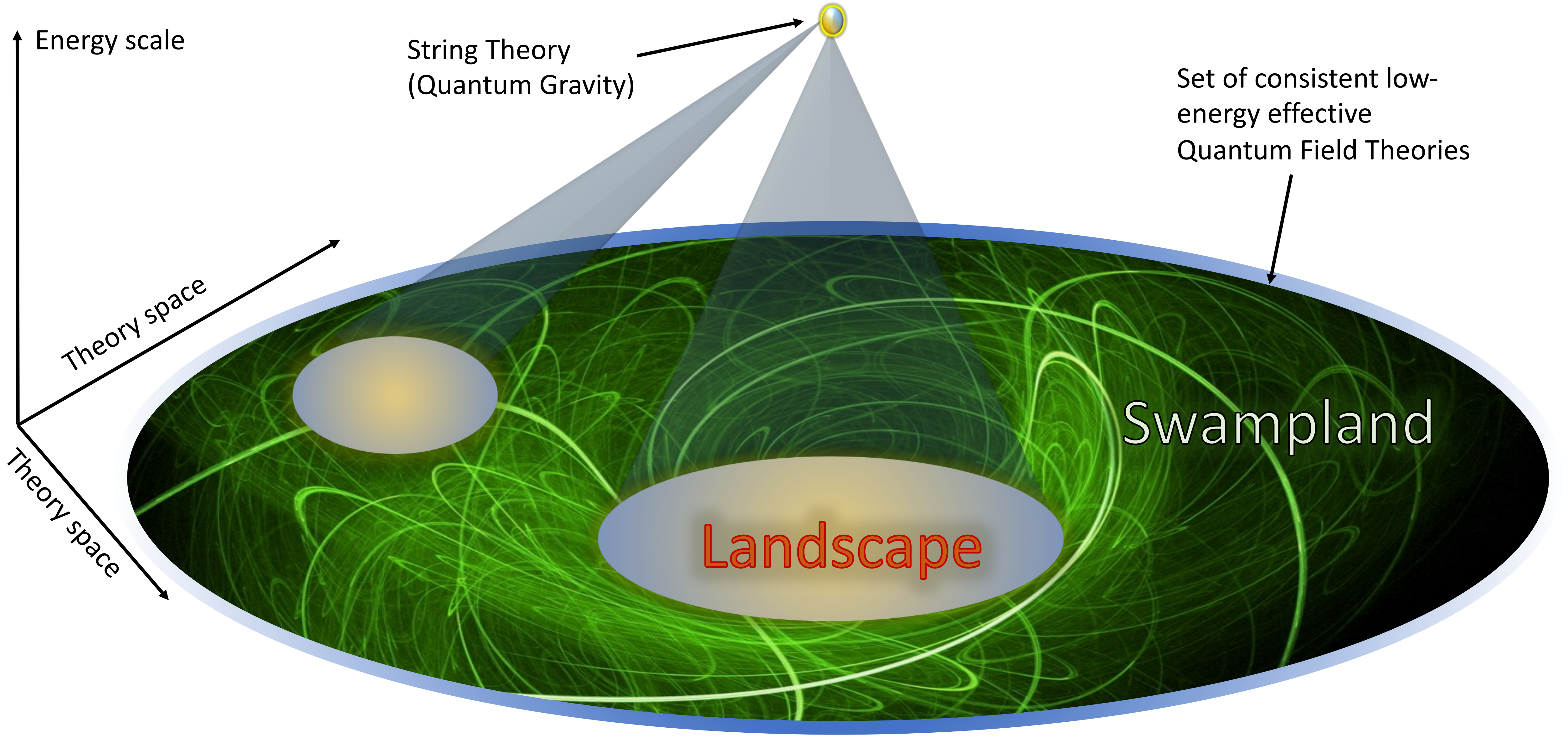
No constraints (up to anomalies) on the EQFT from gravity for $\Lambda \ll M_p$?

This (apparent) freedom manifests itself in string theory as the Landscape



But the Landscape is surrounded by an even vaster **Swampland** of inconsistent effective theories

[Vafa '05]



Prototypical example: Einstein-Maxwell theory

$$S = \int \sqrt{-G} \left(M_p^2 R + \frac{1}{4g^2} F^2 \right)$$

The **Weak Gravity Conjecture**

[Arkani-Hamed, Motl, Nicolis, Vafa ’06]

- *Must have a charged particle with mass smaller than charge*

$$g\, M_p \geq m$$

Electric WGC

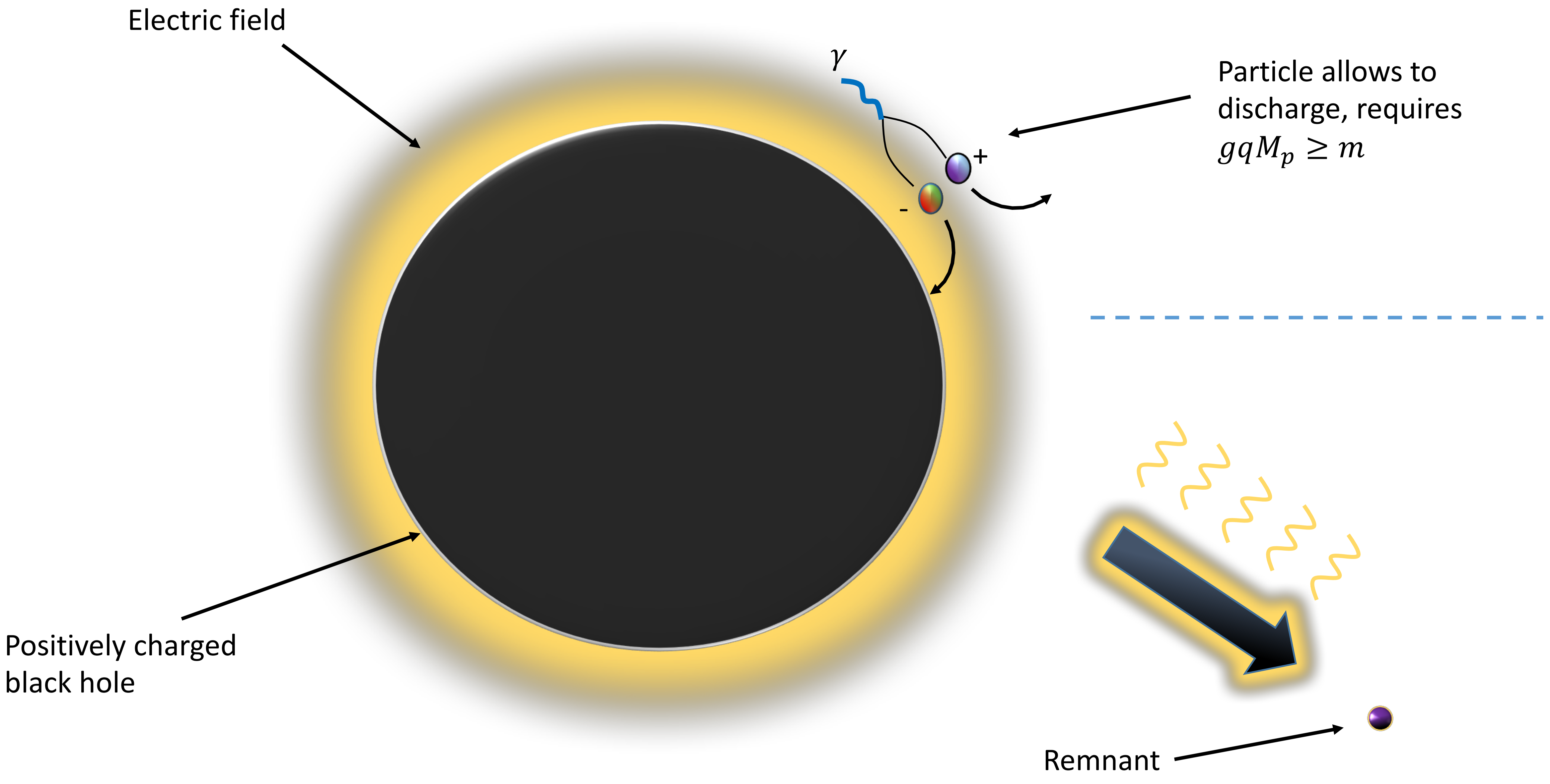
- *The cutoff scale of the theory (infinite tower of new states) is at*

$$\Lambda \sim g\, M_p$$

Magnetic WGC

(The electron has $g\, M_p$ = $4{\times}10^{18}$ GeV and m = $5{\times}10^{-4}$ GeV)

Weak Gravity Conjecture particle allows black holes to discharge



- The Weak Gravity Conjecture $\Lambda \sim g\, M_p$

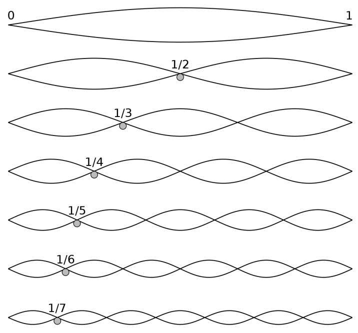
  [Arkani-Hamed, Motl, Nicolis, Vafa '06]

- The Distance Conjecture $\Lambda \sim e^{-\alpha \frac{\phi}{M_p}} M_p$

  [Ooguri, Vafa '06; Baume, EP '16; Klaewer, EP '16]

Example, String Coupling:

$M_s \sim g_s M_p, \;\; g_s = e^{-\frac{\phi}{M_p}}$



- The de Sitter Conjecture $|\partial_\phi V| \geq \frac{c}{M_p} V$ **or** $\partial_\phi^2 V \leq -\frac{c'}{M_p^2} V$

  [Obied, Ooguri, Spodyneiko, Vafa '18; Ooguri, Shiu, EP, Vafa '18]

- The Spin-2 Conjecture $\Lambda \sim \frac{m\, M_p}{M_w}$

  [Klaewer, Lüst, EP '18]

* Λ is mass scale of an infinite tower of states

[Review 1903.06239, EP '19]

Emergence Proposal: the Swampland conjectures are consequences of the emergent nature of dynamical fields in quantum gravity

[Grimm, EP, Valenzuela ’18; EP ‘19]

See also [Harlow ’15; Heidenreich, Reece, Rudelius ‘17+‘18]

Collective excitations of many-particle systems can be viewed themselves as particles, but with properties very different from the constituents

[Grimm, Li, EP ’18; Lee, Lerche, Weigand ’18-’19; Marchesano, Wiesner ‘19; Font, Herraez, Ibanez ’19]

Emergent gauge field **toy model** CP^N [..., Witten ’79, ... Harlow ‘15 (4D)]

$$\mathcal{L} = \partial z_i^* \partial z^i + (z_i^* \partial z^i)(z_j^* \partial z^j) \qquad z_i^* z^i = \frac{N}{c^2}$$

Contains a gauge symmetry $z_i \to e^{i\alpha(x)} z_i$, with a gauge field ‘variable’

$$A \equiv \frac{c^2}{2iN}\left(z_i^* \partial z^i - z^i \partial z_i^*\right)$$

The charged scalars develop a mass m_z, can integrate them out, and in the IR find an emergent gauge field

$$\mathcal{L}_{IR} = \frac{1}{4 g_{IR}^2} F^2$$

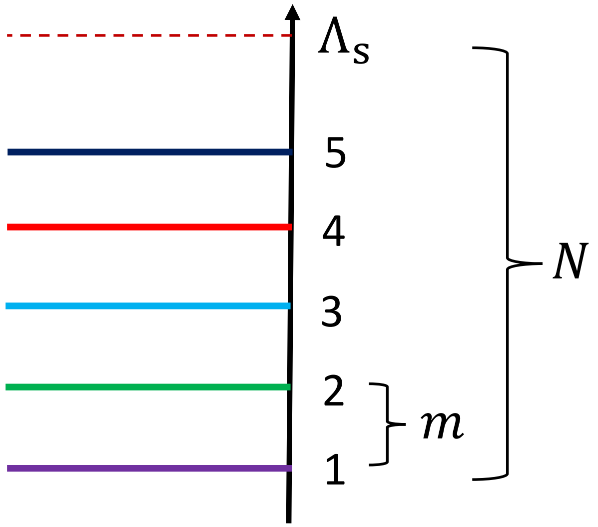
The gauge coupling behaves as if it comes purely from 1-loop effects

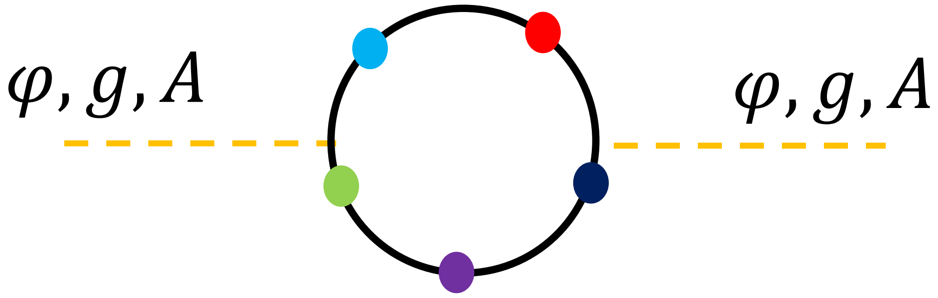
$$\frac{1}{g_{IR}^2} = \cancel{\frac{1}{g_{UV}^2}} + \frac{N}{12\pi^2} \log \frac{\Lambda_s}{m_z}$$

(Like QED + N massive fields)

Emergent behavior: IR coupling given by integrating down from scale Λ_s

Integrating out a tower could generate dynamics for gravity/gauge/scalar





$$M_p^2 R$$

$$\frac{1}{4g^2} F^2$$

$$g_{\varphi\varphi}(\varphi)(\partial\varphi)^2$$

Integrate down from a UV scale Λ

$$M_p^2\Big|_{IR} = M_p^2\Big|_{UV} + N\,\Lambda_s^2$$

Fixes the UV cut-off scale as the Species scale

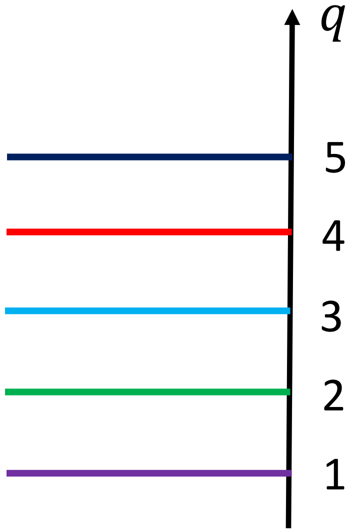
$$\Lambda_s = \frac{M_p}{\sqrt{N}}$$

[…; Dvali ’07]

Since the UV scale is fixed we have a relation

$$N\Delta m \sim Nm \sim \Lambda_s \sim \frac{M_p}{\sqrt{N}} \qquad N \sim \left(\frac{M_p}{m}\right)^{\frac{2}{3}}$$

$$\frac{1}{g_{IR}^2} = \frac{1}{g_{UV}^2} + \sum_i^N \frac{q_i^2}{6\pi^2} log \frac{\Lambda}{m_i}$$

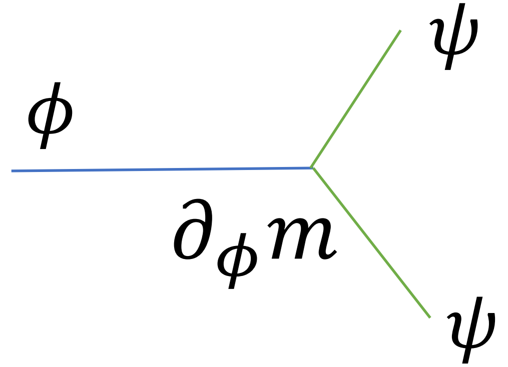


$$\frac{1}{g_{IR}^2} \sim N^3 \sim \frac{M_p^2}{\mathrm{m}^2}$$

The mass scale of the tower $m \sim g_{IR} M_p$ Weak Gravity Conjecture

For scalar field, the 1-loop wavefunction renormalization is

$$g^{IR}_{\varphi\varphi} = g^{UV}_{\varphi\varphi} + \sum_{i}^{N} \frac{\left(\partial_\varphi m_i\right)^2}{4\pi^2} \log\frac{\Lambda}{m_i}$$



$$g^{IR}_{\varphi\varphi} \sim N^3 \left(\partial_\varphi m\right)^2 \sim \left(\frac{M_p\, \partial_\varphi m}{m}\right)^2$$

$$\mathcal{L} \supset Y\phi\, \psi\bar{\psi}$$

Proper distance in field space

$$\Delta\phi = \int \sqrt{g^{IR}_{\varphi\varphi}}\, d\varphi \sim M_p \int \frac{\partial_\varphi m}{m} d\varphi \sim M_p \int \partial_\phi \log m\, d\varphi \sim -M_p \log m$$

$$m \sim e^{-\frac{\Delta\phi}{M_p}}$$

Distance Conjecture

Is Emergence why we are seeing the Swampland behavior in String Theory?

It is an infrared aspect of duality

$$A \equiv \frac{c^2}{2iN}\left(z_i^* \partial z^i - z^i \partial z_i^*\right)$$

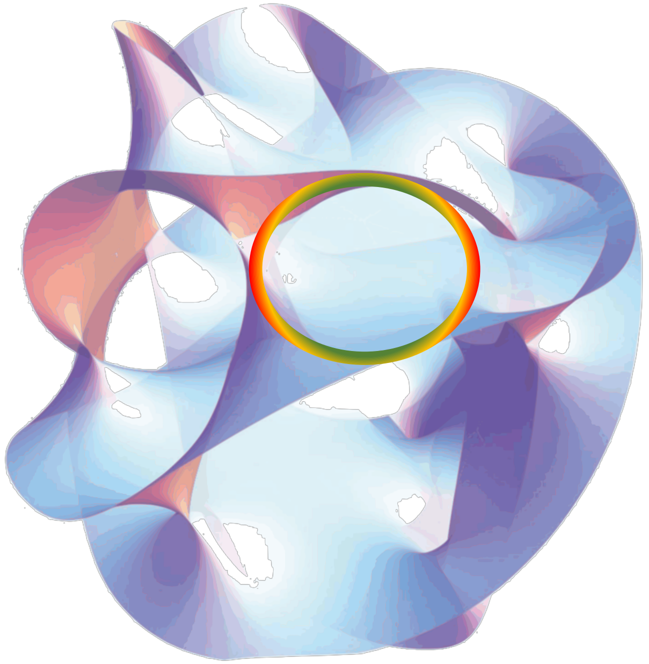
Evidence from *N*=2 Calabi-Yau complex-structure moduli space in type IIB

[Grimm, EP, Valenzuela '18]

Complex-structure moduli vector multiplets $\{\phi, A_\mu\}$

Tower of wrapped D3 branes on 3-cycles (integrated out)

[Strominger '95]

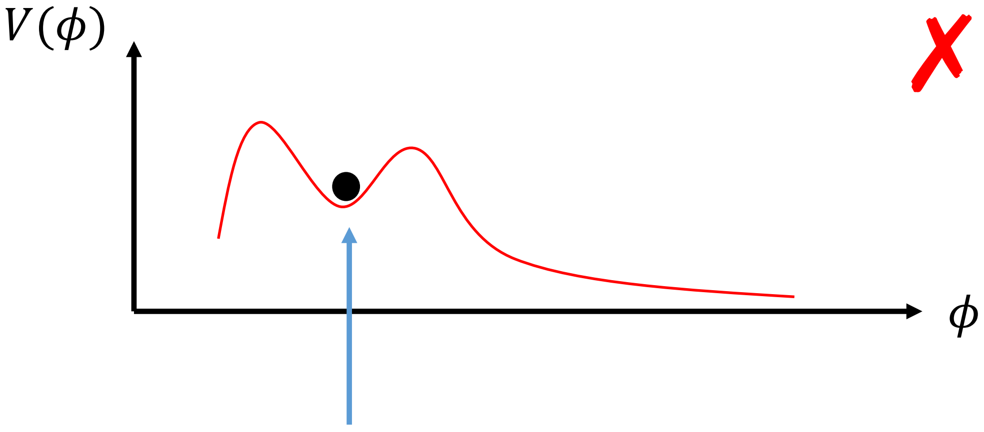


Recently proposed a Swampland conjecture on the the nature of scalar field potentials $V(\phi)$: de Sitter conjecture

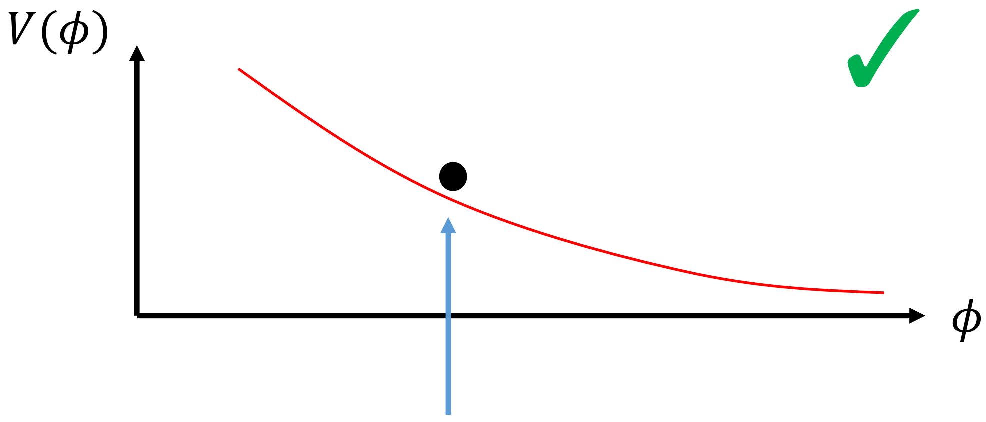
$$|\partial_\phi V| \geq \frac{c}{M_p} V \quad \textbf{or} \quad \partial_\phi^2 V \leq -\frac{c'}{M_p^2} V$$

[Obied, Ooguri, Spodyneiko, Vafa ‘18]
[Ooguri, Shiu, EP, Vafa ‘18]

Evidence is weaker than for the other conjectures – more tentative

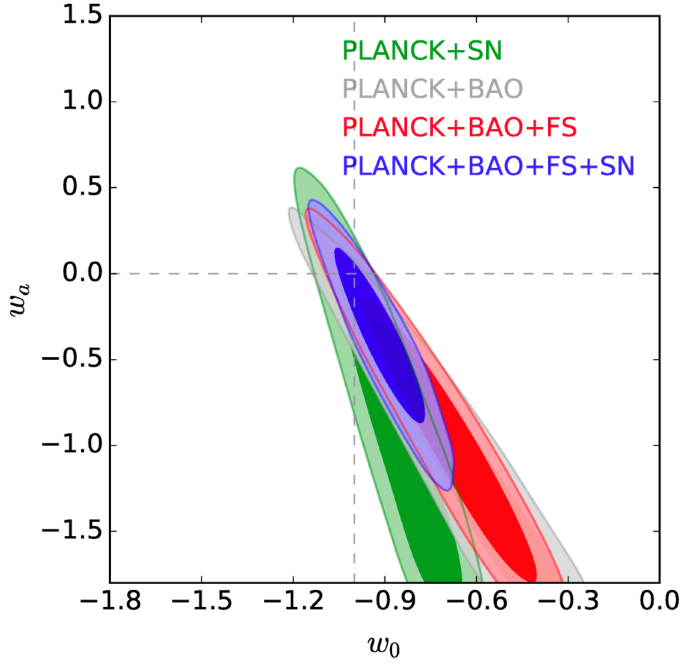


Cosmological Constant



Dynamical Dark Energy

Time variation of dark energy equation of state, potentially measurable



$$w(a) = w_0 + w_{\mathrm{a}}(1-a)$$

Already constrain $\left|\partial_\phi V\right| < \frac{0.6}{M_p}\ V$

[Agrawal, Obied, Steinhardt, Vafa ‘18]

Substantial cosmological applications…

Relation to distance conjecture / emergence

[Ooguri, Shiu, EP, Vafa '18]

de Sitter space has a finite horizon for an observer, of radius R

[Gibbons, Hawking '77]

$$S_{ds} = Log\ dim\ \mathcal{H} = R^2$$

Can be interpreted as the number of states in the Hilbert space

[Banks '00; Witten '01]

In de Sitter space the potential can be associated an entropy

$$S_{ds}(\phi) = \frac{1}{V(\phi)}$$

At large distances in field space, a tower of N states becomes exponentially light

$$N(\phi) \sim e^{b\phi} \qquad b \sim \mathcal{O}(1)$$

We can assign an entropy to the tower below a cut-off scale

$$S_{tower}(\phi) \sim N(\phi)^{\gamma} R(\phi)^{\delta}$$

If the tower dominates the Hilbert space, then we can equate the two notions of entropy

$$\frac{1}{V(\phi)} \sim R(\phi)^2 \sim N(\phi)^{\gamma} R(\phi)^{\delta} \qquad V(\phi) \sim N(\phi)^{-\frac{2\gamma}{2-\delta}}$$

Utilizing the expression for $N(\phi)$ from the distance conjecture gives

$$\frac{\partial V}{\partial \phi} = \frac{\partial V}{\partial N}\frac{\partial N}{\partial \phi} \sim b\left(\frac{2\gamma}{2-\delta}\right)V$$

This is the de Sitter conjecture

$$\left|\frac{\partial V}{\partial \phi}\right| > c\, V \qquad\qquad \mathrm{c} \sim \frac{2b\gamma}{2-\delta}$$

Determining the exponents γ and δ is a difficult problem (Free fields have $\gamma = \frac{1}{4}$ and $\delta = \frac{3}{2}$)

Can also see directly: potentials dual to light domain walls [EP '19]

An apparent horizon exists if the universe is accelerating

$$\left|\frac{\partial V}{\partial \phi}\right| \leq \sqrt{2}\, V$$

The theory is stable on horizon scales (and over a Hubble time) if

$$\frac{\partial^2 V}{\partial \phi^2} \geq -\mathcal{O}(1)\, V$$

Finite temperature lifting of mass $m_\phi^2 = \frac{\partial^2 V}{\partial \phi^2} + H^2 = \frac{\partial^2 V}{\partial \phi^2} + V$

Any Weak Coupling $g \to 0$ ⇔ Large distance $\phi \to \infty$

$$\left|\partial_\phi V\right| \geq \frac{c}{M_p} V$$

or

$$\partial_\phi^2 V \leq -\frac{c'}{M_p^2} V$$

For parametrically controlled setups in string theory [Ooguri, Shiu, EP, Vafa '18]

Perhaps general? Difficult to determine…

Implications of the Weak Gravity Conjecture to massive spin-2 fields

[Klaewer, Lüst, Palti '18]

A massive spin-2 particle has 5 propagating degrees of freedom

$$w_{\mu\nu} = h_{\mu\nu} + \partial_{(\mu}\chi_{\nu)} + \Pi^{L}_{\mu\nu}\pi$$

helicity 2 helicity 1 helicity 0

The Fierz-Pauli mass term gives the kinetic term for the helicity-1 mode

$$m^2\left(w_{\mu\nu}w^{\mu\nu} - w^2\right) \sim m^2\left(\partial_{[\mu}\chi_{\nu]}\right)^2$$

There is another mass scale which sets interactions strength $\frac{1}{M_w} w_{\mu\nu} T^{\mu\nu}$

The gauge coupling strength is $g_m \sim \frac{m}{M_w}$ [Klaewer, Lüst, Palti '18]

Apply the Weak Gravity Conjecture to the helicity-1 mode $\Lambda \sim g_m M_p$

Spin-2 Conjecture: $\Lambda \sim \frac{m\, M_p}{M_w}$

Strong Spin-2 Conjecture: $\Lambda \sim m_{graviton}$

$m_{graviton} < 10^{-22}\ eV$ [Abbot et al. '16]

The spin-2 conjecture predicts $m_{graviton} = 0$ exactly

Summary

- There are a number of existing conjectures about the Swampland, and they form a coherent interlinked framework
- Discussed a proposal for the underlying microscopic physics behind the conjectures: emergence of dynamical fields in quantum gravity
- The de Sitter conjecture can be tied to the distance conjecture in any parametrically controlled regime of string theory
- The WGC applied to Stückelberg fields can be used to constrain theories with massive spin-2 fields

Thank You