
Swampland Conjectures and their
Phenomenological Applications
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String Field Theory & String Phenomenology

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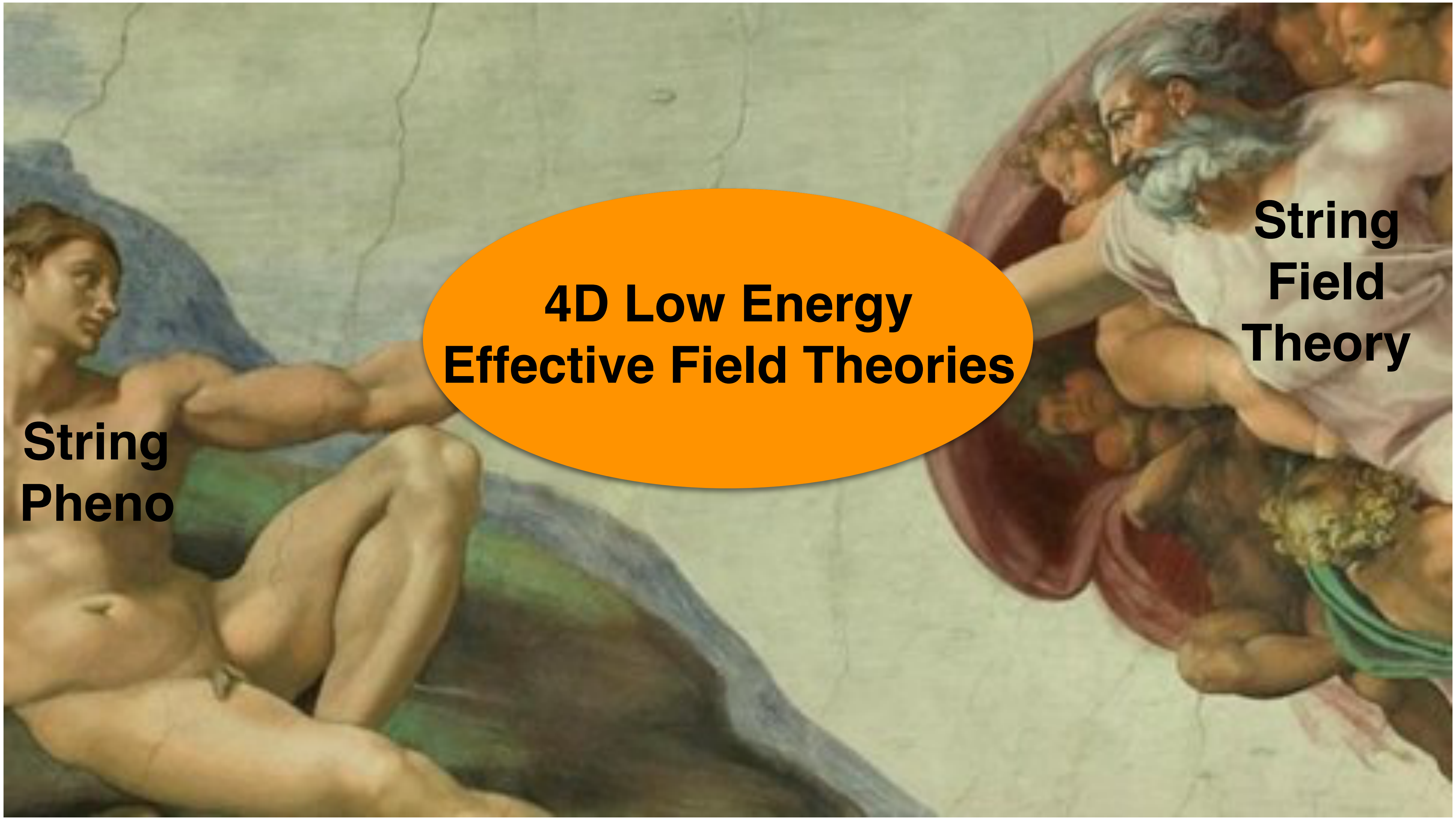

String Theory Landscape

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An even vaster Swampland?

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Landscape vs Swampland

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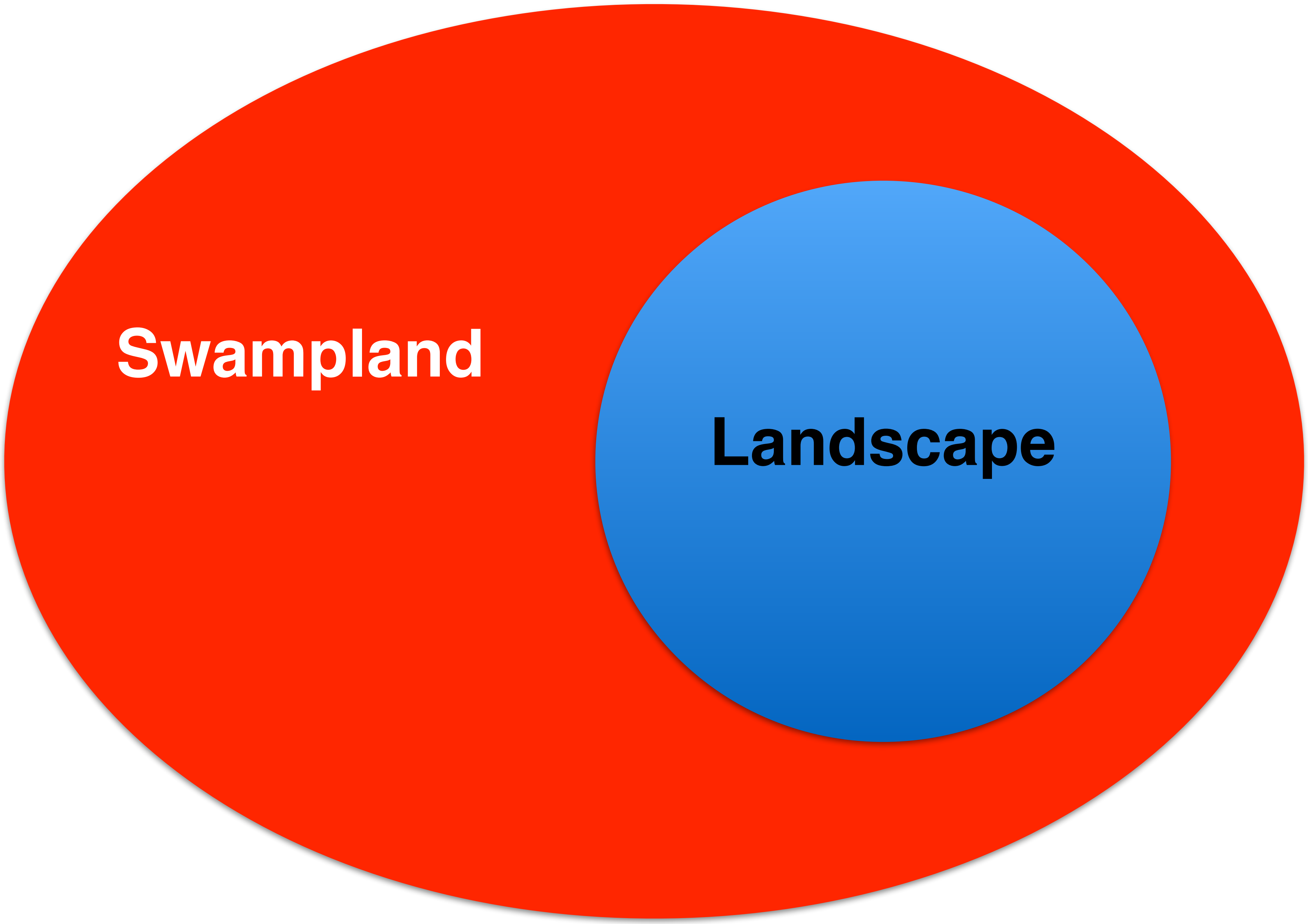
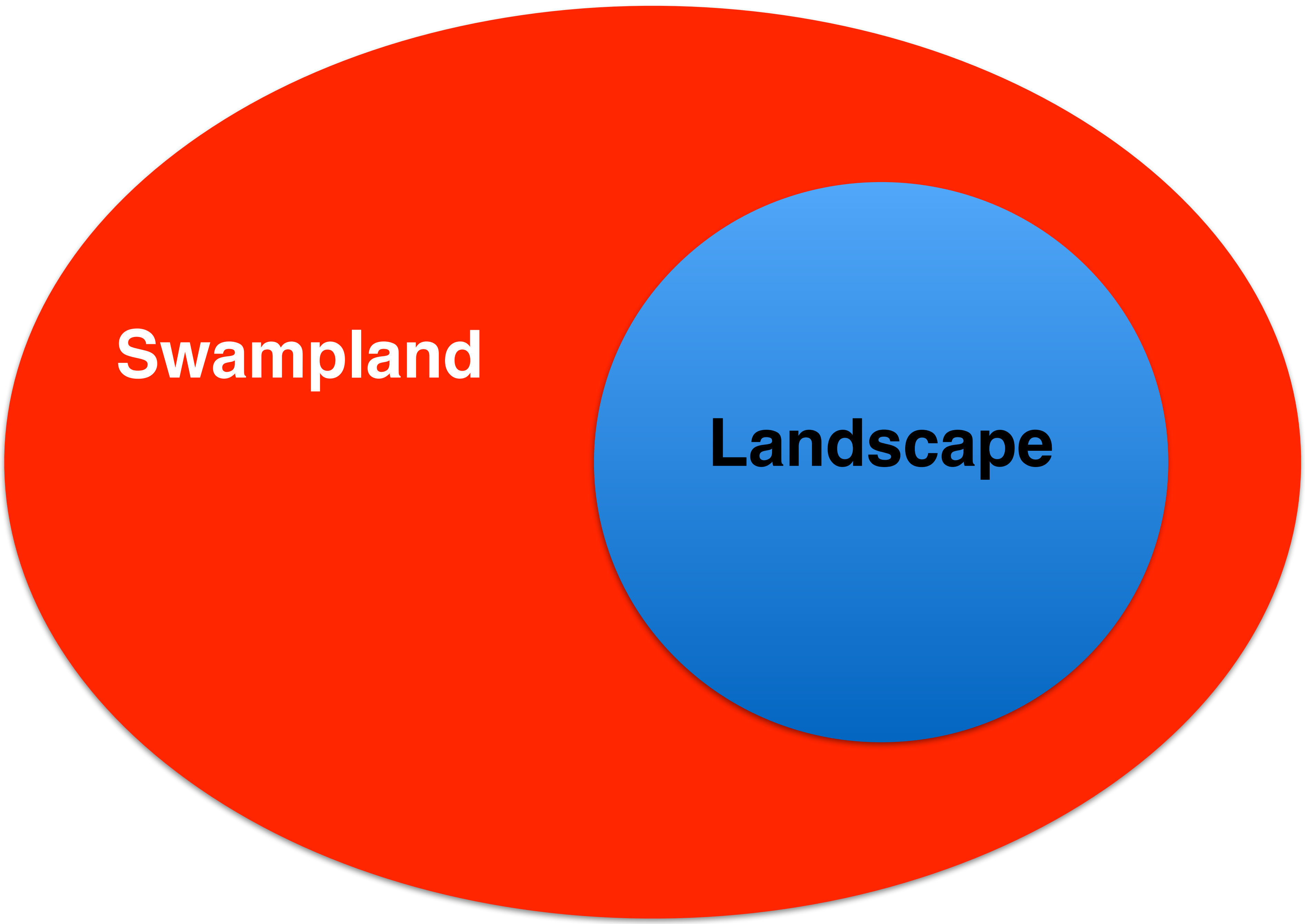


Landscape vs Swampland

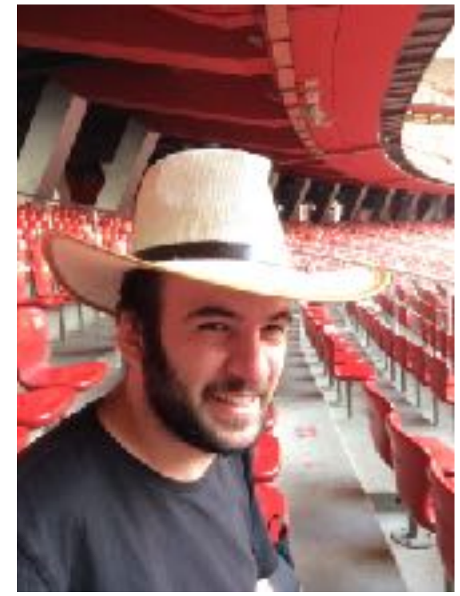


We refer to the space of quantum field theories which are incompatible with quantum gravity as the ***swampland***. [Vafa, '05]

Based on work with:

J. Brown

W. Cottrell



P. Soler

M. Montero

Y. Hamada

S. Andriolo

D.Junghans

T. Noumi

J. Brown, W. Cottrell, GS, P. Soler, JHEP **1510**, 023 (2015), JHEP **1604**, 017 (2016), JHEP **1610** 025 (2016).
M. Montero, GS and P. Soler, JHEP **1610** 159 (2016).
W. Cottrell, GS and P. Soler, arXiv:1611.06270 [hep-th].
Y. Hamada and GS, JHEP **1711**, 043 (2017).
S. Andriolo, D. Junghans, T. Noumi and GS, arXiv: 1802.04287 [hep-th].

Outline

- What is the Weak Gravity Conjecture?
- Phenomenological applications of the WGC

  Axions, large field inflation, and CMB B-mode

  QCD axion

  Relating Neutrino masses and type with the CC.
- Evidences for the WGC
- Conclusions

Quantum Gravity and Global Symmetries

QG and Global Symmetries

- **Global symmetries** are expected to be violated by gravity:

  - **No hair theorem:** Hawking radiation is insensitive to Q.
    - ➡ <u>Infinite</u> number of states (remnants) with $m \lesssim M_p$
    - ➡ Violation of entropy bounds. At finite temperature (e.g. in Rindler space), the density of states blows up. Susskind '95
  - **Swampland conjecture**: theories with exact global symmetries are not UV-completable.
  - In (perturbative) string theory, all symmetries are gauged
  - Many phenomenological ramifications, e.g., mini-charged DM comes with a new massless gauge boson **[GS, Soler, Ye, '13]**.

The Weak Gravity Conjecture

The Weak Gravity Conjecture

- We have argued that global symmetries are in conflict with Quantum Gravity
- Global symmetry = gauge symmetry at g=0
    - It is not unreasonable to expect problems for gauge theories in the weak coupling limit: $g \to 0$
- When do things go wrong? How? …

The Weak Gravity Conjecture

Arkani-Hamed, Motl, Nicolis, Vafa '06

- The conjecture:

"Gravity is the Weakest Force"

- For every long range gauge field there exists a particle of charge q and mass m, s.t.

$$\frac{q}{m} M_P \geq \text{``1''}$$

- Seems to hold for all known string theory models.

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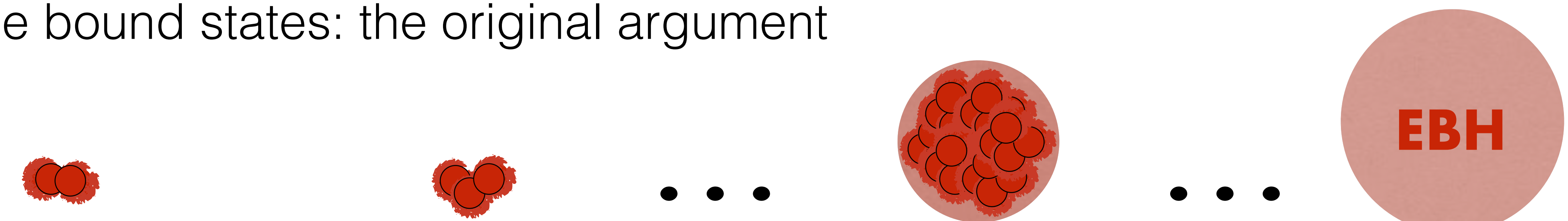
$$\frac{q}{m} M_P \geq \text{“}1\text{”} \equiv \frac{Q_{Ext}}{M_{Ext}} M_P$$

- Seems to hold for all known string theory models.

The Weak Gravity Conjecture

- Take U(1) gauge theory and a scalar with $m > q\, M_p$

- Stable bound states: the original argument



$2m > M_2 > 2q$ $3m > M_3 > 3q$ $Nm > M_N > Nq$ $M_\infty \to Q_\infty$

- All these BH states are **exactly stable**. In particular, large bound states (charged black holes) do not Hawking radiate once they reach the extremal limit M=Q, equiv. T=0.

> "...there should not exist a large number of exactly stable objects (extremal black holes) whose stability is not protected by any symmetries."

Arkani-Hamed et al. '06

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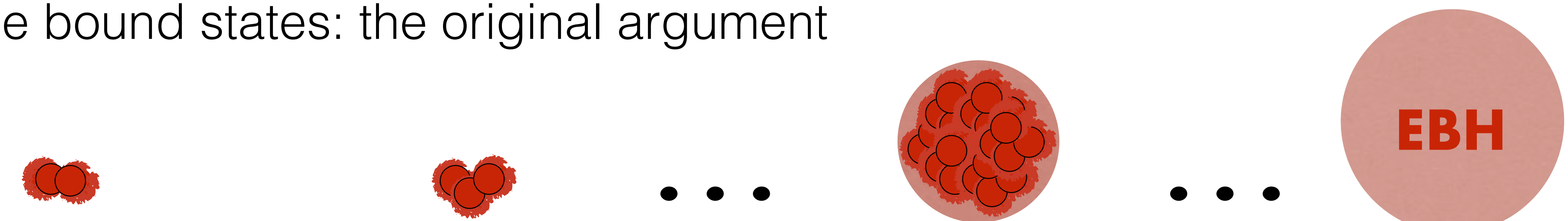

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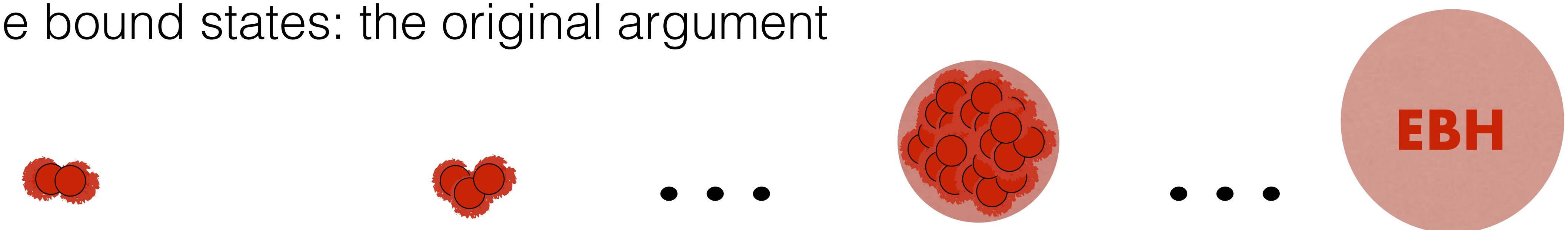

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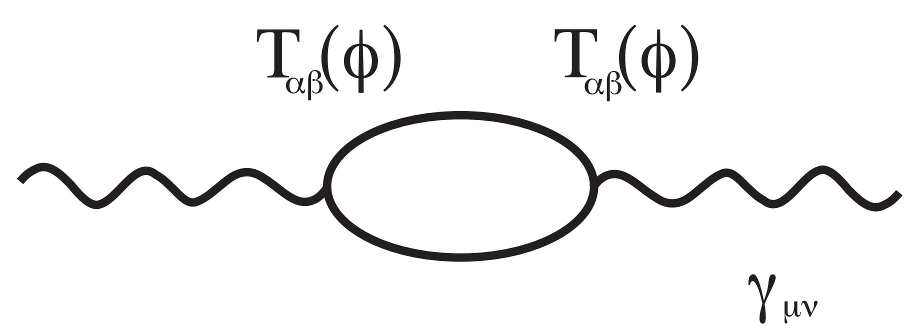
- All these BH states are **exactly stable**. In particular, large bound states (charged black holes) do not Hawking radiate once they reach the extremal limit M=Q, equiv. T=0.

- In order to avoid a large number of exactly stable states one must demand the existence of some particle with

$$\frac{q}{m} \geq \frac{Q_{ext}}{M_{ext}} = \frac{1}{M_p}$$

Why is this a conjecture?

- Heuristic argument suggests ∃ a state w/ $\frac{q}{m} \geq \text{"1"} \equiv \frac{Q_{Ext}}{M_{Ext}}$
- One often invokes the remnants argument [Susskind] for the WGC but the situations are different (finite vs infinite mass range).



- Perfectly OK for some extremal BHs to be stable [e.g., Strominger, Vafa] as q ∊ central charge of SUSY algebra.
  - No q>m states possible (∵ BPS bound).
  - More subtle for theories with some q ∉ central charge
- The WGC is a conjecture on the ***finiteness of the # of stable states that are <u>not</u> protected by a symmetry principle.***

WGC for Axions

Axions and ALPs

The QCD axion [Wilczek, '78]; [Weinberg, '78] was introduced in the context of the Pecci-Quinn mechanism and the strong CP problem.

An axion enjoys a **perturbative shift symmetry.**

String theory has many **higher-dimensional form-fields**:

e.g. $F = \mathrm{d}A$

3-form flux → F; A ← 2-form gauge potential:

gauge symmetry: $A \to A + \mathrm{d}\Lambda$

Integrating the 2-form over a 2-cycle gives an ***axion-like particle* (ALP)**:

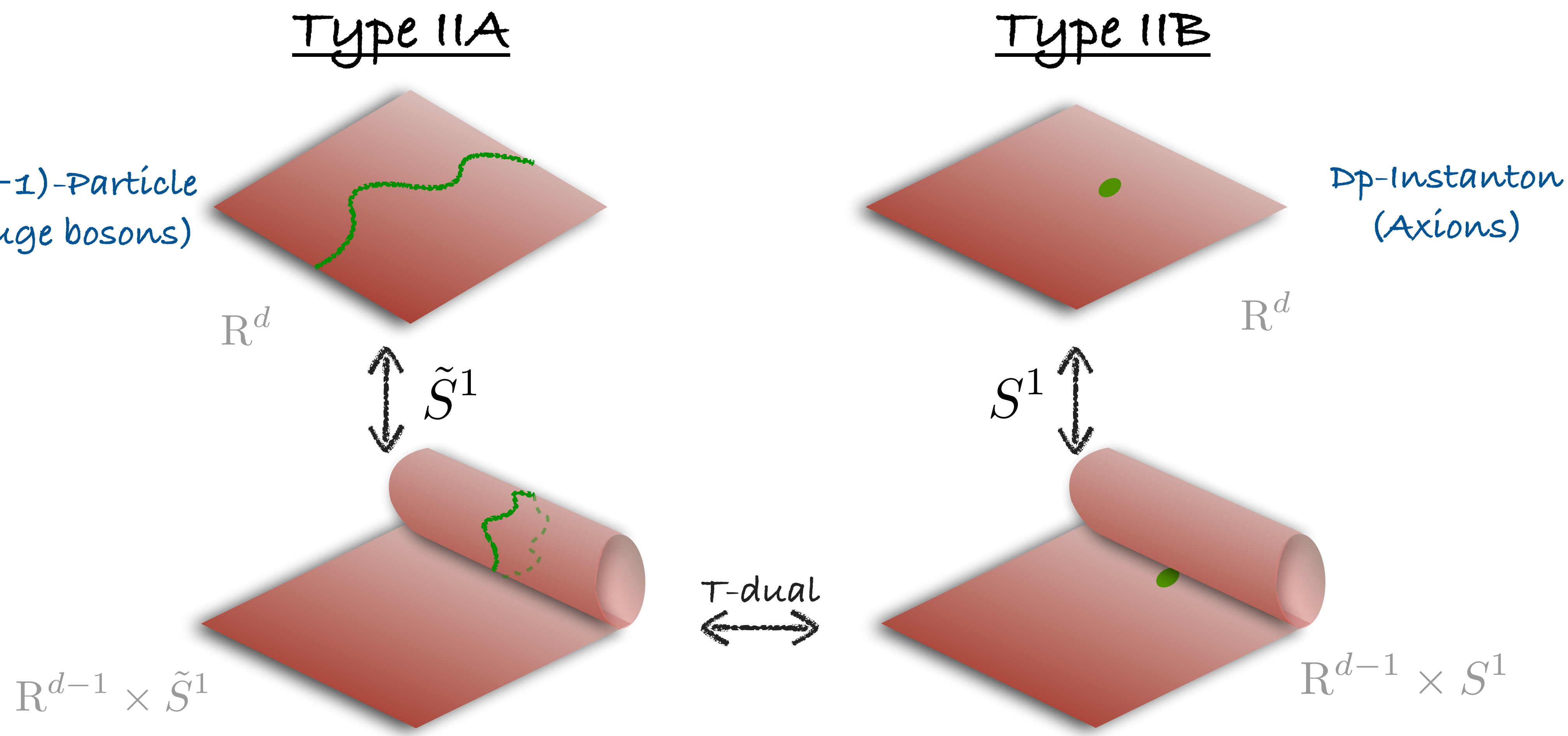
$$a(x) \equiv \int_{\Sigma_2} A$$

The gauge symmetry becomes a **shift symmetry,** that is broken by non-perturbative (instanton) effects**.**

WGC and Axions

Brown, Cottrell, GS, Soler

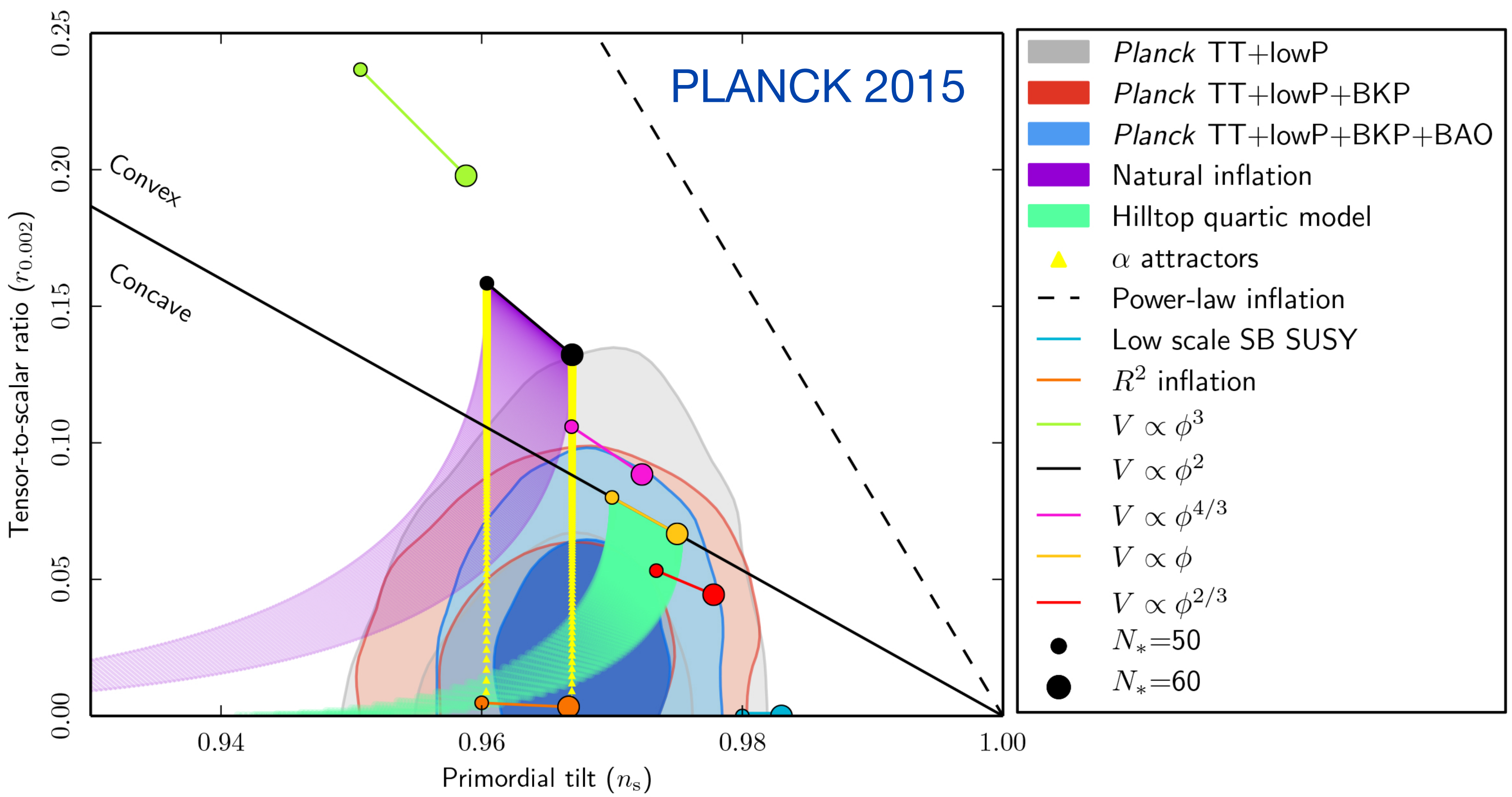
- Formulate the WGC in a duality frame where the axions and instantons turn into gauge fields and particles, e.g.

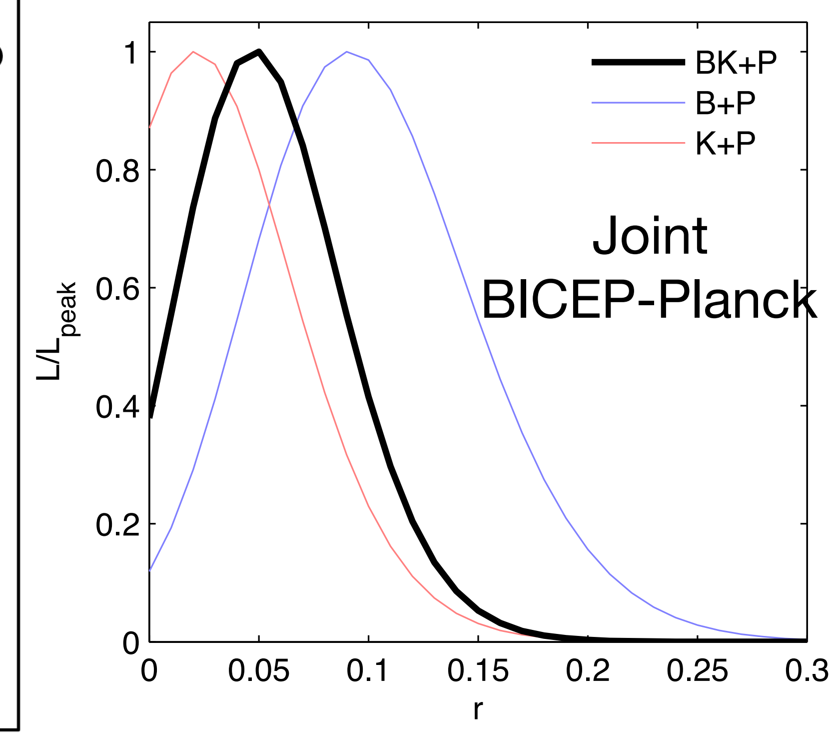


model–dependent, calculable

- The WGC takes the form $f \cdot S_{\text{instanton}} \leq \mathcal{O}(1) M_P$

Primordial Gravitational Waves





Many experiments including BICEP/KECK, PLANCK, ACT, PolarBeaR, SPT, SPIDER, QUEIT, Clover, EBEX, QUaD, … can potentially detect primordial B-mode at the sensitivity $r \sim 10^{-2}$.

Further experiments, such as CMB-S4, PIXIE, LiteBIRD, DECIGO, Ali, .. may improve further the sensitivity to eventually reach $r \sim 10^{-3}$.

B-mode and Inflation

If primordial B-mode is detected, natural interpretations:

- Inflation took place at an energy scale around the GUT scale

$$E_{\rm inf} \simeq 0.75 \times \left(\frac{r}{0.1}\right)^{1/4} \times 10^{-2} M_{\rm Pl}$$

- The inflaton field excursion was super-Planckian

$$\Delta\phi \gtrsim \left(\frac{r}{0.01}\right)^{1/2} M_{\rm Pl}$$

Lyth '96

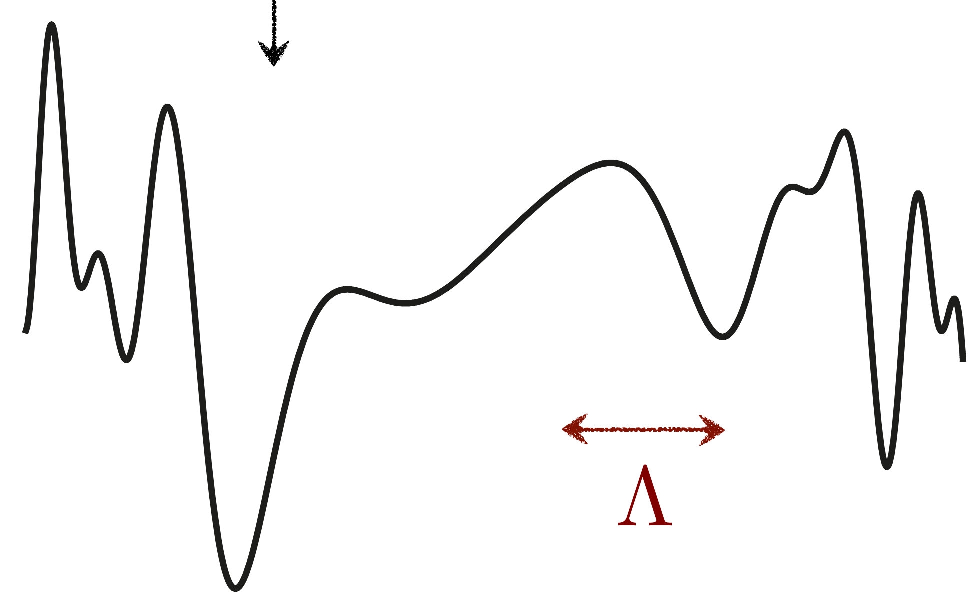
- Great news for string theory due to strong UV sensitivity!

Large field inflation and UV Sensitivity

UV sensitivity of large field inflation:

$$\mathcal{L}_{\text{eff}}[\phi] = \frac{1}{2}(\partial\phi)^2 - \frac{1}{2}m^2\phi^2\left(1 + \sum_{i=1}^{\infty} c_i \frac{\phi^{2i}}{\Lambda^{2i}} + \cdots\right)$$

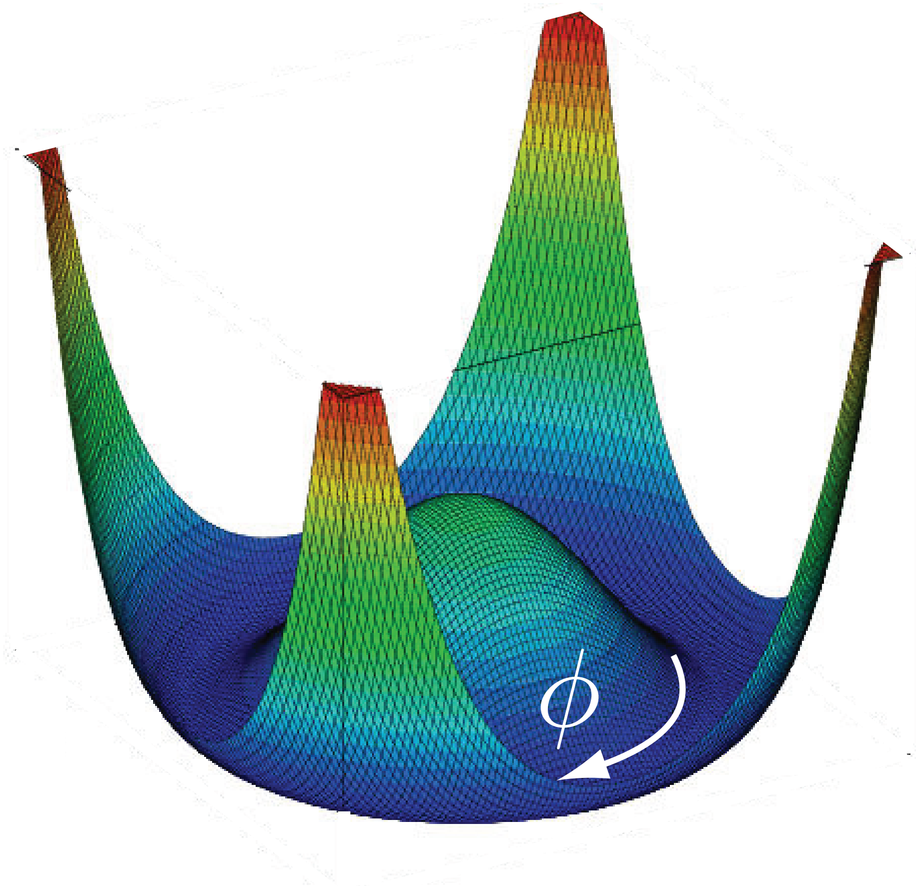
$c_i \sim \mathcal{O}(1)$



Axions & Large Field Inflation

Natural Inflation [Freese, Frieman, Olinto]

Pseudo-Nambu-Goldstone bosons are natural inflaton candidates.



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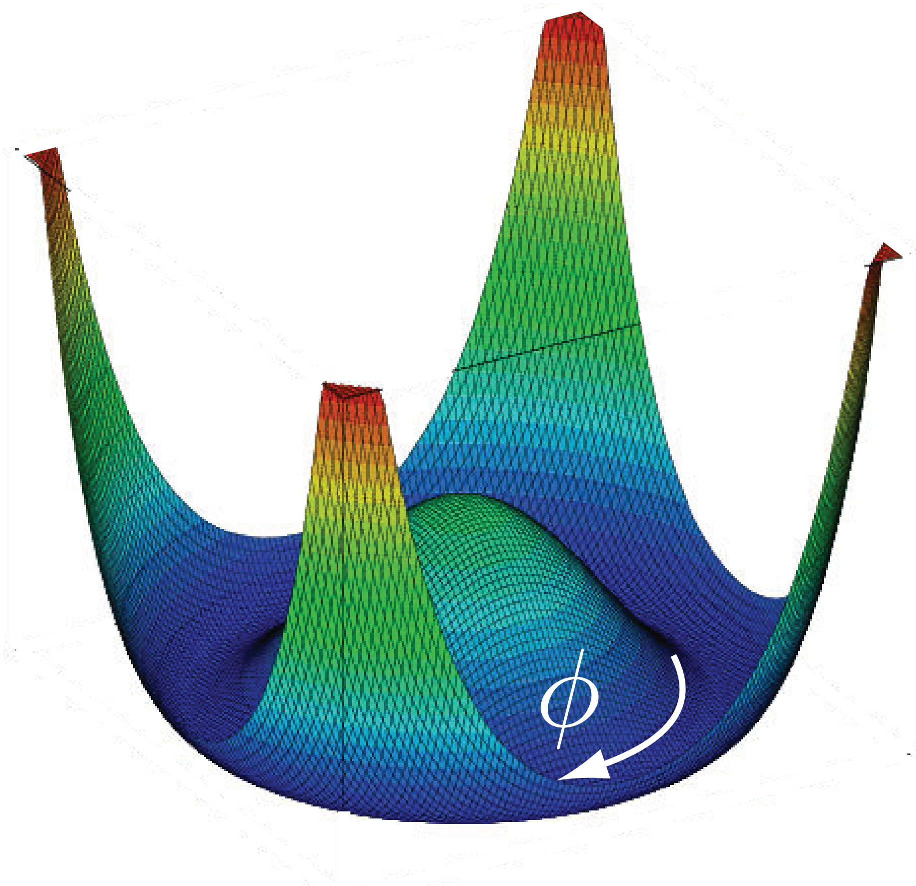
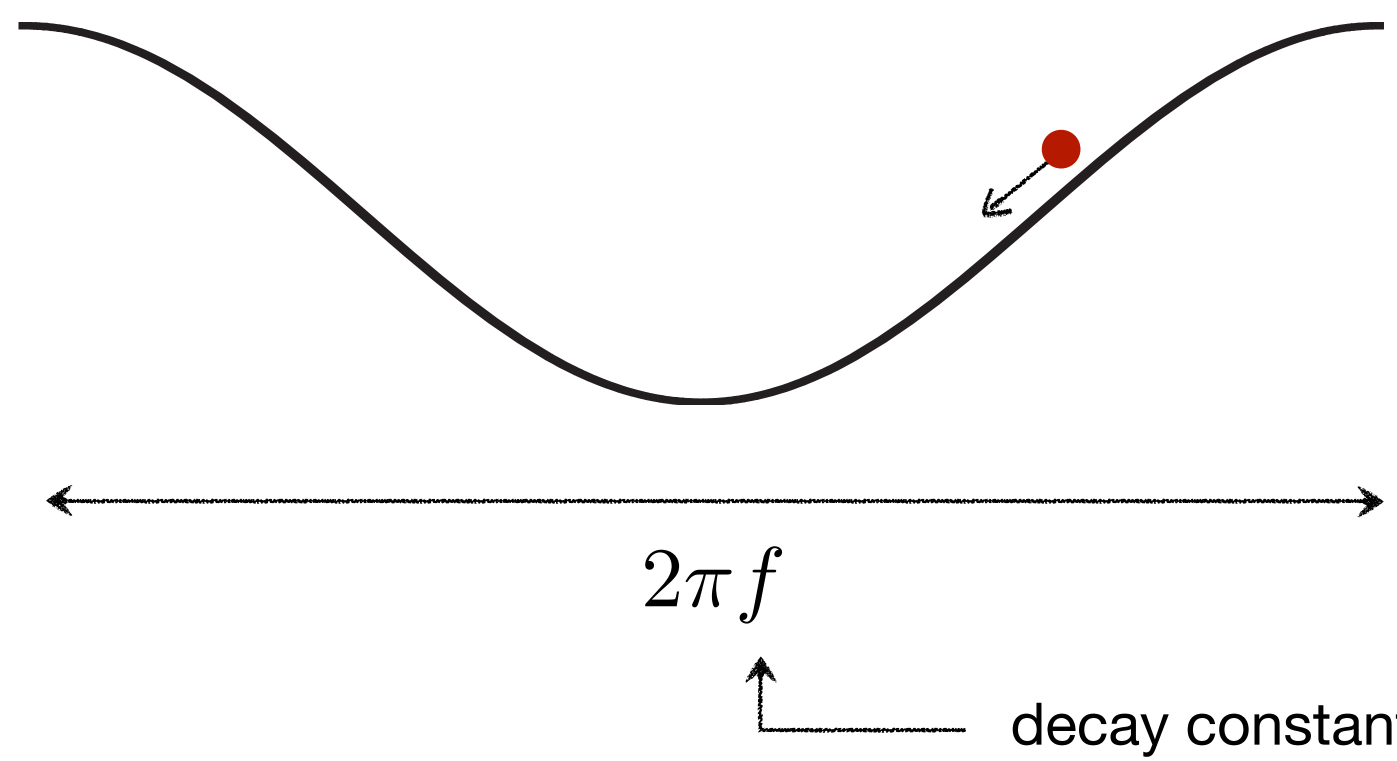


They satisfy a shift symmetry that is only broken by non-perturbative effects:



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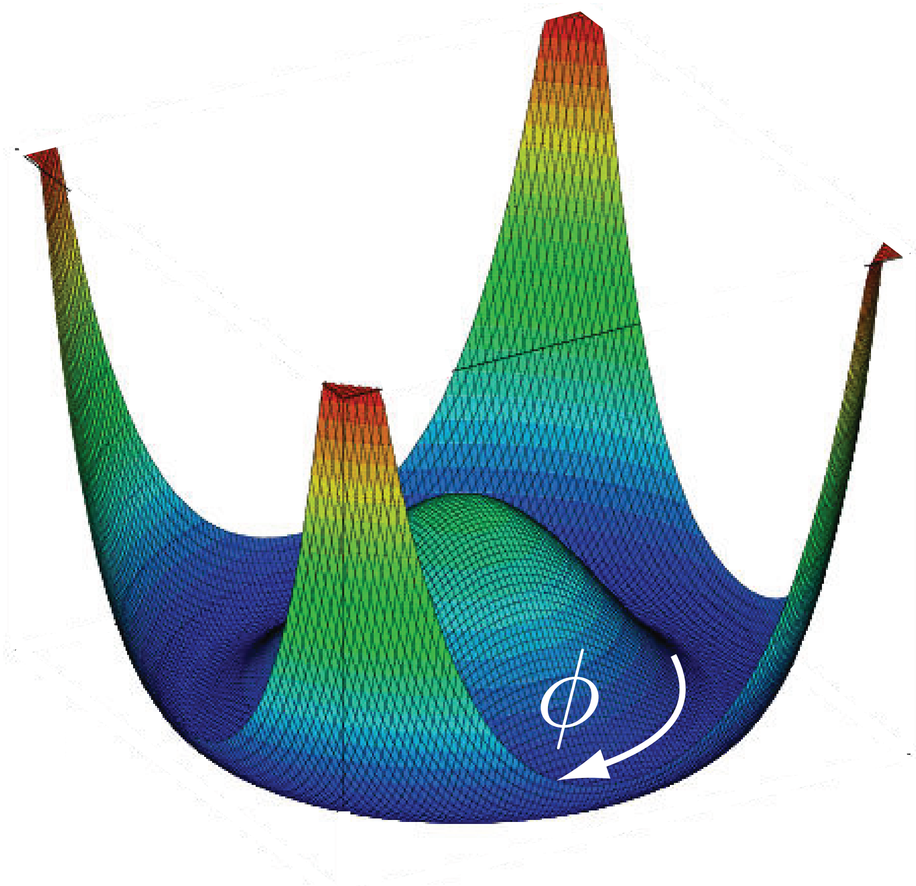

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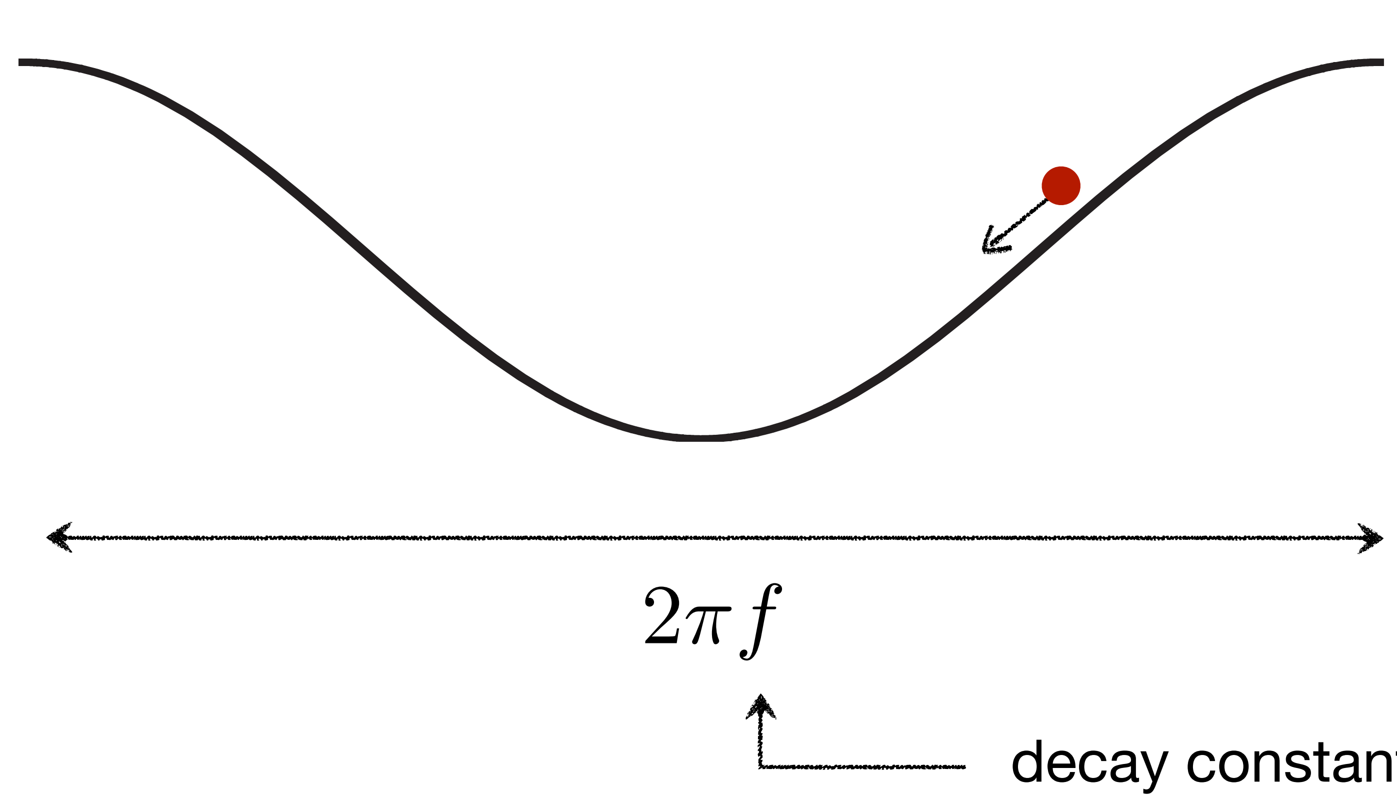

Slow roll: $f > M_P$

$$V(\phi) = 1 - \Lambda^{(1)} \cos\left(\frac{\phi}{f}\right) + \cancel{\sum_{k>1} \Lambda^{(k)} \left[1 - \cos\left(\frac{k\phi}{f}\right)\right]} \quad \text{if} \quad \frac{\Lambda^{(n+1)}}{\Lambda^{(n)}} \sim e^{-S_{\text{inst}}} << 1$$

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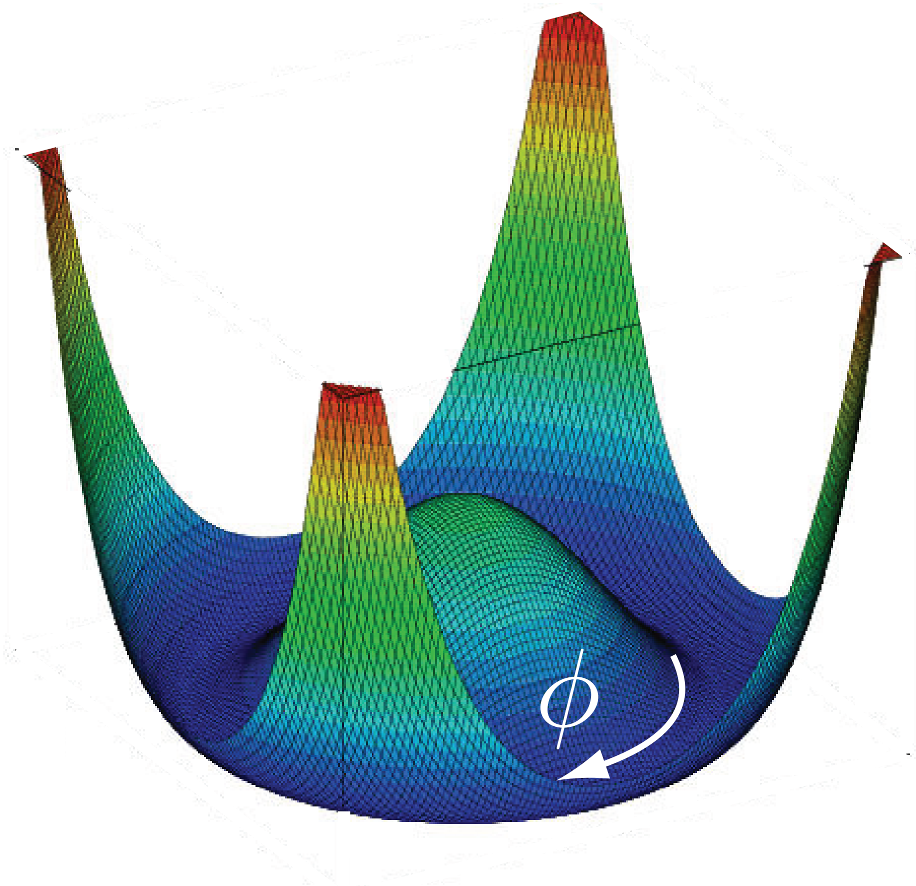

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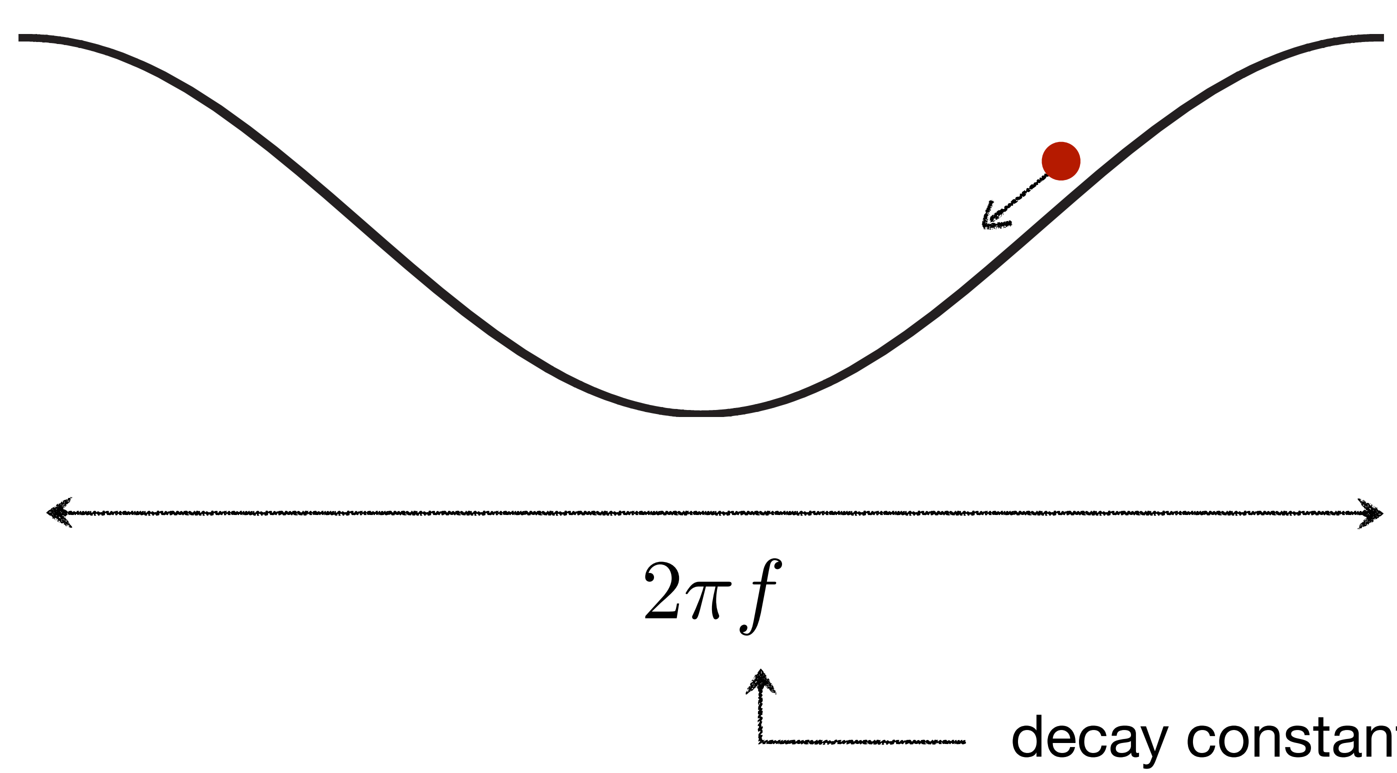

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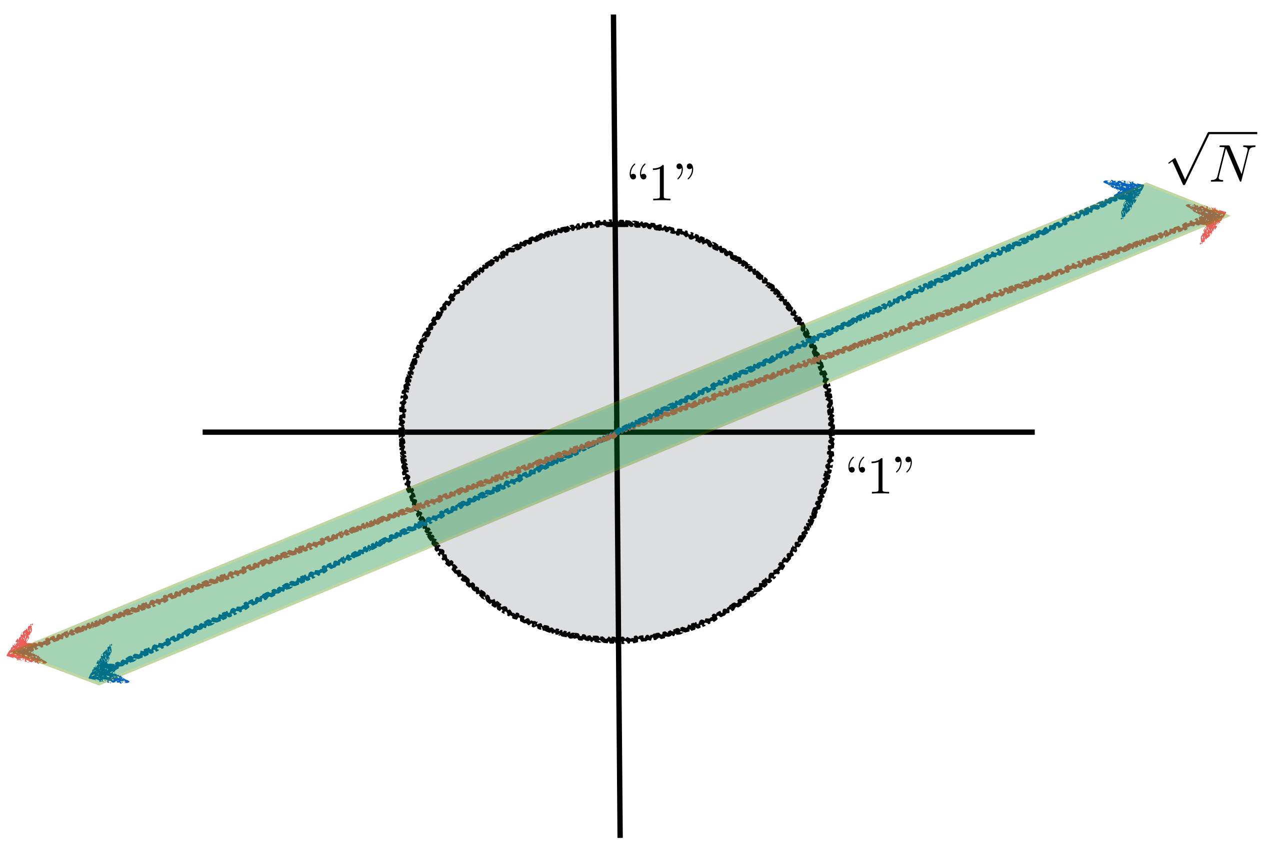
The WGC implies that these conditions cannot be *simultaneously* satisfied.

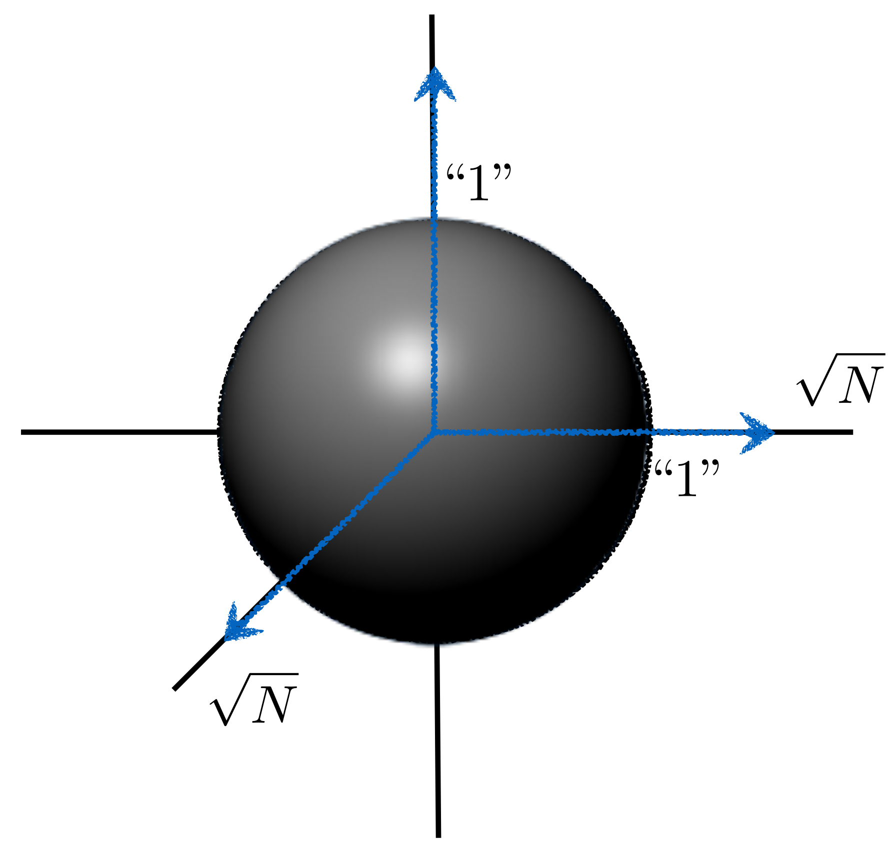
WGC and Multi-Axion Inflation

- Thorough searches for transplanckian axions in the string landscape have not been successful. Banks et al. ’03 …

- Models with multiple axions (e.g., N-flation, KNP-alignment) have been proposed but they do not satisfy the convex hull condition [Brown, Cottrell, GS, Soler];[Cheung, Remmen]



Alignment [Kim, Nilles, Peloso, ’04]



N–flation [Dimopoulos et al, ’05]

WGC for the QCD Axion

- **The QCD instanton action**

$$S_{\rm QCD} = 4 \ln M_*/\Lambda_{\rm QCD} \approx 160\,, \quad \text{where } M_* = \text{UV scale, e.g.,} M_{GUT}$$

- **The WGC implies a bound:** $f_{\rm QCD} \lesssim 10^{16}$ GeV

- While weaker than the commonly quoted **cosmological bound**:

$$f_{\rm QCD} < 10^{12} \text{ GeV}$$

scenarios that allow larger $f_{\rm QCD}$ have been proposed, e.g. [Wilczek, '04]

- QCD axion with decay constants above the GUT scale can be tested:
  - **laboratory searches** e.g., ABRACADABRA
  - **gravitational wave observatory** e.g., LIGO (via black hole super-radiance, [Arvanitaki, Dimopoulos, Dubovsky, Kaloper, March-Russell, '09])

WGC and Particle Physics

The Standard Model in the Deep IR

- The deep IR of the SM, below the electron mass scale, is simple:
  - **Bosonic dof:** photon (2) and graviton (2)
  - **Fermionic dof:** ν's (6 or 12 for **Majorana/Dirac** ν's)
- The **mass scale of neutrinos**:

$$m_\nu \simeq 10^{-1} - 10^{-2} eV$$

- The only other known IR scale is the **cosmological constant**:

$$\Lambda \simeq 3.25 \times 10^{-11} eV^4 = (0.24 \times 10^{-2} eV)^4$$

- This coincidence (?) has been a source of inspiration/speculations:

$$\Lambda \simeq m_\nu^4$$

WGC for Branes

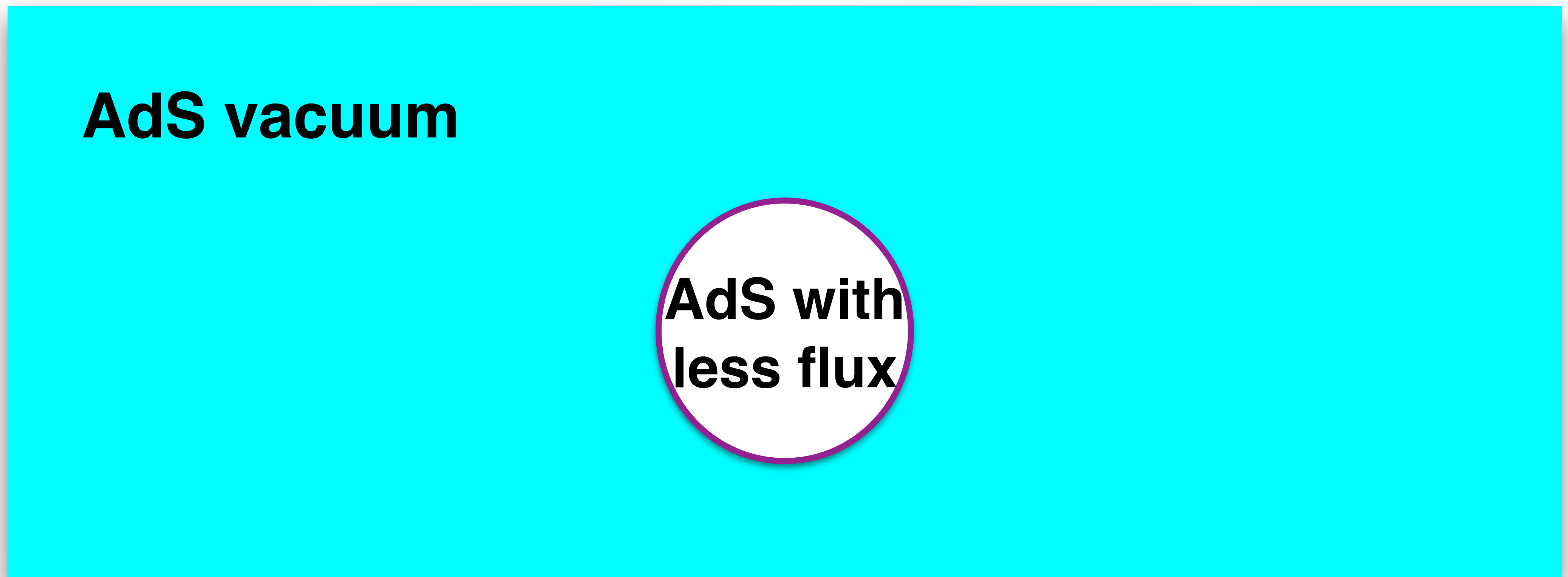
- We have seen the applications of the WGC to particles (and instantons). Analogously, the WGC for branes is:

$$\text{``}T_p \leq Q_p\text{''}$$

- A stronger form [Ooguri,Vafa, '16]: **this bound is saturated only for a BPS state in a SUSY theory.**
- A ***corollary*** of this strong form: **non-SUSY AdS vacua supported by fluxes are unstable.**
- In AdS space, a brane with T < Q leads to an instability (AdS fragmentation) [Maldacena, Michelson, Strominger, '99].
- This brane gets nucleated and expands. It reaches the boundary of AdS within a finite time and dilute the flux.

AdS Instability

- Instability if there exists a T<Q brane (bubble wall) in AdS:



- A stronger form of the Ooguri-Vafa conjecture:

  "all non-SUSY AdS (in theories whose low energy description is Einstein gravity coupled to a finite # of fields) **are unstable"**

- **How do we test this conjecture?**

AdS Instability

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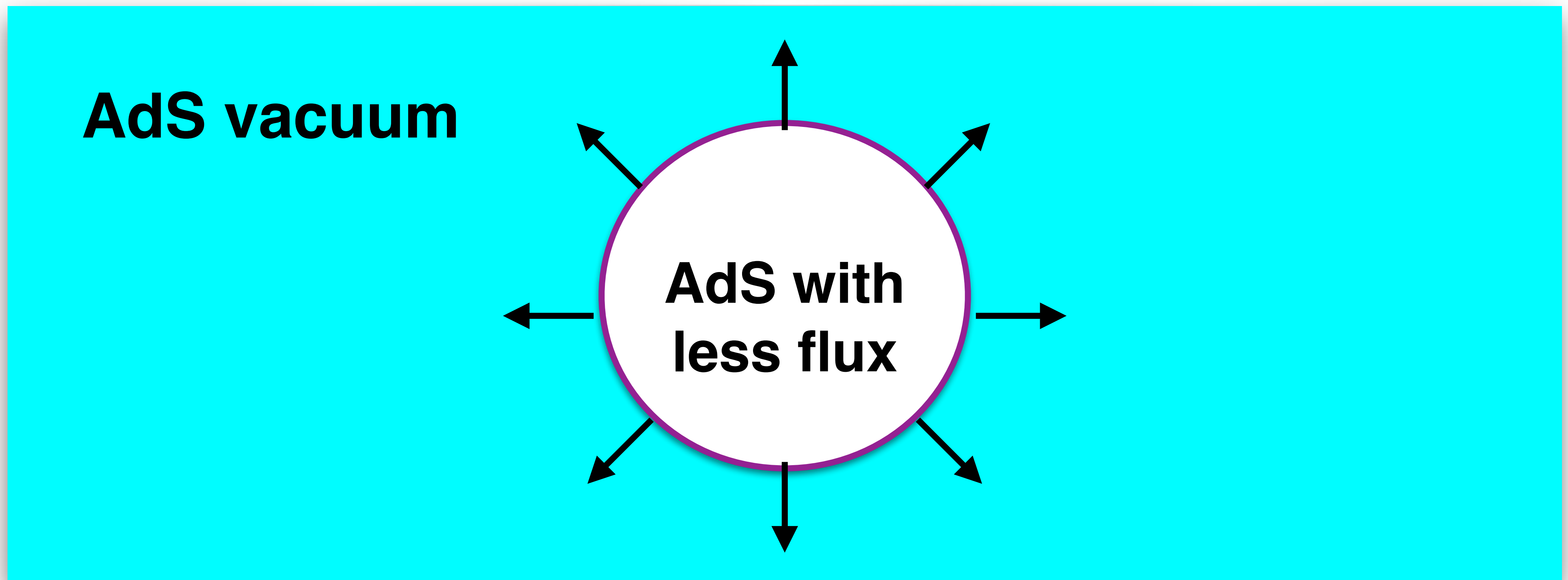

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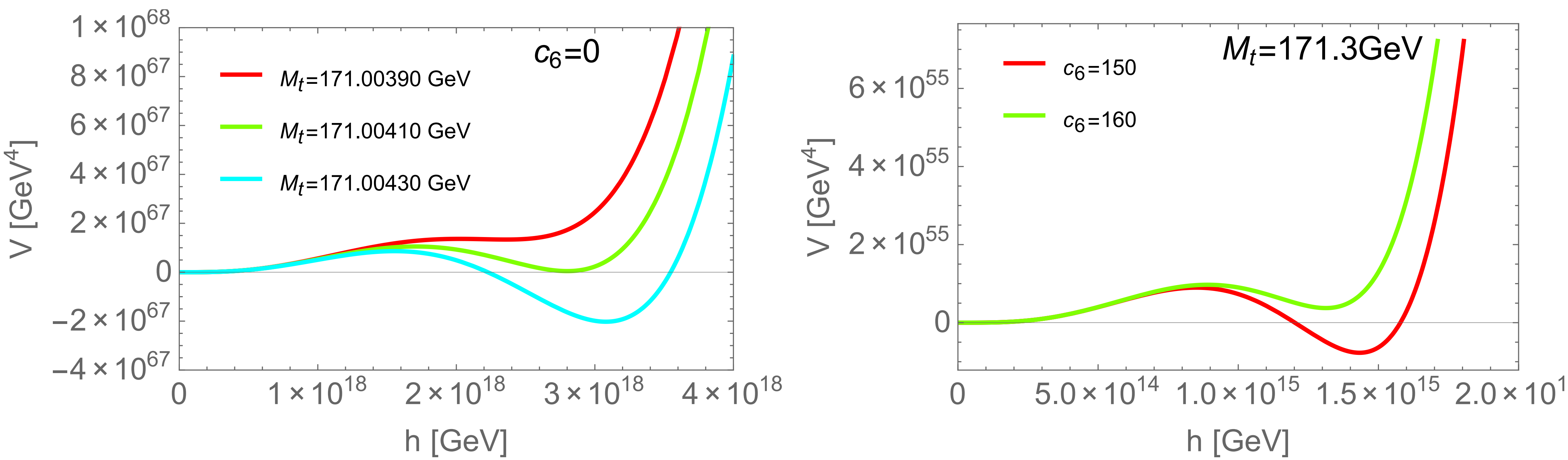
The Higgs Potential

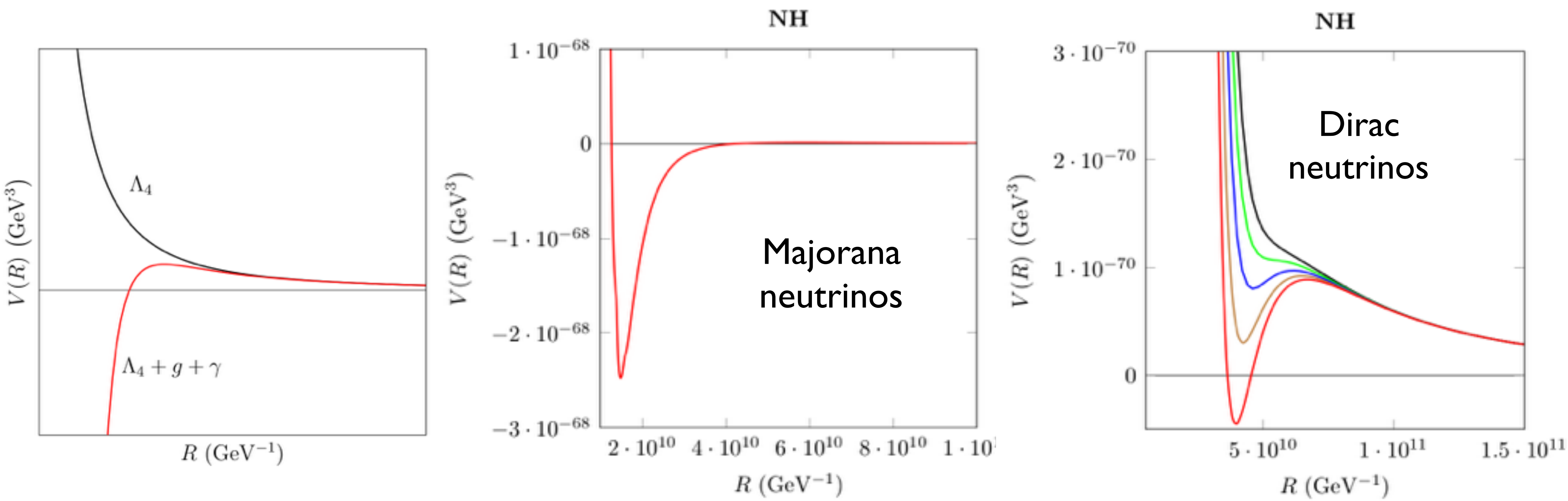
- After the Higgs discovery, we know that there is an additional Higgs vacuum at high scale, other than the EW vacuum:



- This high scale vacuum can be AdS_4, M_4, or dS_4 depending on the **top quark mass** and the **higher-dimensional operators**.
- Applying this conjecture to the SM landscape, we can constrain the **top mass, Higgs potential,** and **BSM physics**. [Hamada, GS].

Standard Model Landscape

- Upon compactification, the SM gives rise to a rich landscape of 3d vacua [Arkani-Hamed, Dubovsky, Nicolis, Villadoro].
- A competition between **Λ_4** and **Casimir energies** (depends on mass, spin, b.c., and #dof; negligible unless mL << 1):



- The more massive the neutrinos, the deeper the AdS minimum. Barring the potential instability of the AdS vacuum [Hamada, GS], the WGC puts a bound on the **neutrino mass and type**.

Summary of Results

[Hamada, GS]

- Compactify the SM on S^1 and T^2 , starting from both the electroweak vacuum and the high scale vacuum, with general b.c. and WL.

	model	AdS	flat	dS
S^1	$U(1)$, neutral	$\Lambda_4 \lesssim 10^{-2.8} M_e^4$	$\Lambda_4 \simeq 10^{-2.8} M_e^4$	$10^{-2.8} M_e^4 \lesssim \Lambda_4 \lesssim 10^{-2.6} M_e^4$
	$U(1)$, charged	–	–	–
	SM, ν_M	always	–	–
	SM, ν_D, NH	$8.4\,\text{meV} \lesssim m_{\nu,\text{lightest}}$	$m_{\nu,\text{lightest}} \simeq 8.4\,\text{meV}$	$7.3\,\text{meV} \lesssim m_{\nu,\text{lightest}} \lesssim 8.4\,\text{meV}$
	SM, ν_D, IH	$3.1\,\text{meV} \lesssim m_{\nu,\text{lightest}}$	$m_{\nu,\text{lightest}} \simeq 3.1\,\text{meV}$	$2.5\,\text{meV} \lesssim m_{\nu,\text{lightest}} \lesssim 3.1\,\text{meV}$
	SM, ν_M, high scale	–	–	–
	SM, ν_D, high scale	$\Lambda_4 \ll (\text{neutrino mass})^4$	–	–
	axion	$\Lambda_4 < 0$	–	–
T^2	$U(1)$, neutral	$\Lambda_4 \lesssim 10^{-2.1} M_e^4$	$\Lambda_4 \simeq 10^{-2.1} M_e^4$	$10^{-2.5} M_e^4 \lesssim \Lambda_4 \lesssim 10^{-2.1} M_e^4$
	$U(1)$, charged	–	–	–
	SM, ν_M	always	–	–
	SM, ν_D, NH	$4.5\,\text{meV} \lesssim m_{\nu,\text{lightest}}$	$m_{\nu,\text{lightest}} \simeq 4.5\,\text{meV}$	$4.5\,\text{meV} \lesssim m_{\nu,\text{lightest}} \lesssim 6.5\,\text{meV}$
	SM, ν_D, IH	$1.1\,\text{meV} \lesssim m_{\nu,\text{lightest}}$	$m_{\nu,\text{lightest}} \simeq 1.1\,\text{meV}$	$1.1\,\text{meV} \lesssim m_{\nu,\text{lightest}} \lesssim 1.55\,\text{meV}$
	axion	$\Lambda_4 < 0$	–	–

- Can avoid AdS vacua if neutrinos are Dirac w/ the lightest neutrino mass $\lesssim \mathcal{O}$ (1-10) meV. (also [Ibanez, Martin-Lozano, Valenzuela]).

Evidences for the WGC

Evidences for the Weak Gravity Conjecture

Several lines of argument have been taken (so far):

- Holography [Nakayama, Nomura, '15];[Harlow, '15];[Benjamin, Dyer, Fitzpatrick, Kachru, '16];[Montero, GS, Soler, '16]
- Cosmic Censorship [Horowitz, Santos, Way, '16];[Cottrell, GS, Soler, '16];[Crisford, Horowitz, Santos, '17]
- Entropy considerations [Cottrell, GS, Soler, '16] (note however unjustified claims in [Fisher, Mogni, '17]; [Cheung, Liu, Remmen, '18]).
- IR Consistencies (unitarity & causality) [Cheung, Remmen, '14] [Andriolo, Junghans, Noumi, GS,'18].

Evidences for *stronger* versions of the WGC:

- Consistencies with T-duality [Brown, Cottrell, GS, Soler, '15] and dimensional reduction [Heidenreich, Reece, Rudelius '15].
- Modular invariance + charge quantization suggest a **sub-lattice WGC** [Montero, GS, Soler, '16] (see also [Heidenreich, Reece, Rudelius '16])

WGC and Blackhole Entropy

Entropy Corrections

- We computed loop corrections to the entropy of extremal blackholes using Sen's entropy functional formalism **[Cottrell, GS, Soler, '16]**.
- While corrections from neutral particles have been well studied (loops of massless particles give log (A) corrections to BH entropy), we found new features when charged particles are integrated out.
- Fermion spectral density in $AdS_2 \times S_2$ is divergent for:

$$\text{Energy} \sim \frac{\lambda}{a} = \sqrt{2} q M_P$$

Magnetic WGC!

- The entropy corrections formulae used in **[Fisher, Mogni, '17]** cannot be applied to macroscopic black holes, nor away from extremality, which is where conflicts with the WGC were argued to arise.
- **[Cheung, Liu, Remmen, '18]** made a connection between the WGC and the positivity of entropy corrections. It is not known, however, if the latter follows from some fundamental consistency conditions.

WGC and Positivity Bounds

Einstein-Maxwell + massive charged particles

↓ integrate out matters

IR effective theory of photon & graviton

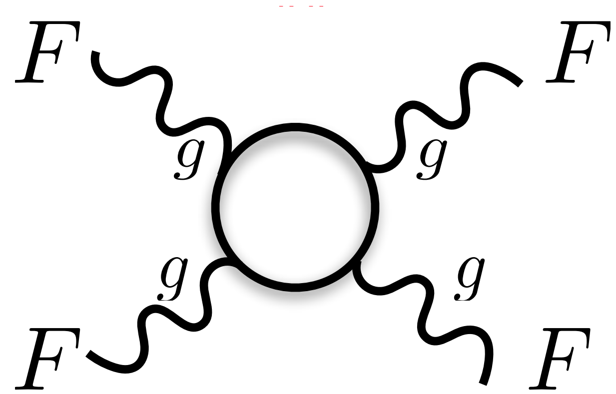
Positivity of EFT coefficients follow from unitary, causality, and analyticity of scattering amplitudes.

Q. What does the positivity of this EFT imply?

1-loop effective action for photon & graviton

$$\mathcal{L}_{\text{eff}} = \frac{M_{\text{Pl}}^2}{2} R - \frac{1}{4} F_{\mu\nu}^2$$
$$+ \alpha_1 (F_{\mu\nu} F^{\mu\nu})^2 + \alpha_2 (F_{\mu\nu} \tilde{F}^{\mu\nu})^2 + \alpha_3 F_{\mu\nu} F_{\rho\sigma} W^{\mu\nu\rho\sigma} + \ldots$$

- positivity implies $\alpha_1 + \alpha_2 \geq 0$
- α_i depends on mass and charge of particles integrated out

$\alpha_i =$ 

$+ \underbrace{\mathcal{O}(g^2) + \mathcal{O}(g^0)}_{\text{gravitational effects}}$

- Cheung-Remmen found positivity implies $z^4 - z^2 + \gamma \geq 0$

※ $z = \dfrac{qg}{m/M_{\text{Pl}}}$, γ is a UV sensitive $\mathcal{O}(z^0)$ coefficient
(free parameter in the EFT framework)

Positivity of photon-graviton EFT implies $z^4 - z^2 + \gamma \geq 0$

$\rightarrow$ at lest one of the following two should be satisfied

1) WGC type lower bound on charge-to-mass ratio

in particular when $\gamma = 0$, WGC $z^2 \geq 1$ is reproduced!

2) not so small value of UV sensitive parameter $\gamma > 0$

In [Andriolo, Junghans, Noumi, GS], we discussed

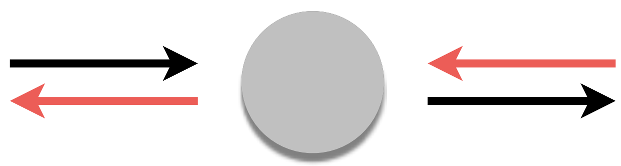
- multiple U(1)'s
- implications for KK reduction

and found qualitatively new features.

Multiple U(1)'s

for example, let us consider $U(1)_1 \times U(1)_2$

a new ingredient is positivity of $\gamma_1 + \gamma_2 \to \gamma_1 + \gamma_2$

Im  ≥ 0 implies $z_1^2 z_2^2 - z_1^2 - z_2^2 \geq 0$

- $z_i = q_i/m$ is the charge-to-mass ratio for each U(1)

- we set $\mathcal{O}(z^0) = 0$ for illustration (same as γ = 0 before)

the punchline here:

positivity bound cannot be satisfied unless $z_1^2 z_2^2 \neq 0$

$\to$ requires existence of a bifundamental particle!

Implications for KK reduction

S^1 compactify d+1 dim Einstein-Maxwell with single U(1)

into d dim Einstein-Maxwell with $U(1) \times U(1)_{\mathrm{KK}}$

d+1 dim charged particle (q,m)

$\rightarrow$ KK tower with the charged-to-mass ratios

$$(z, z_{\mathrm{KK}}) = \left(\frac{q}{\sqrt{m^2 + n^2 m_{\mathrm{KK}}^2}}, \frac{n}{\sqrt{(m/m_{\mathrm{KK}})^2 + n^2}} \right)$$

in the small radius limit $m_{\mathrm{KK}} \to \infty$,

the lowest mode (n = 0): $(z, z_{\mathrm{KK}}) = (q/m, 0)$

KK modes (n ≠ 0): $(z, z_{\mathrm{KK}}) \simeq (0, 1)$

※ no bifundamentals → ~~positivity bound~~ generically

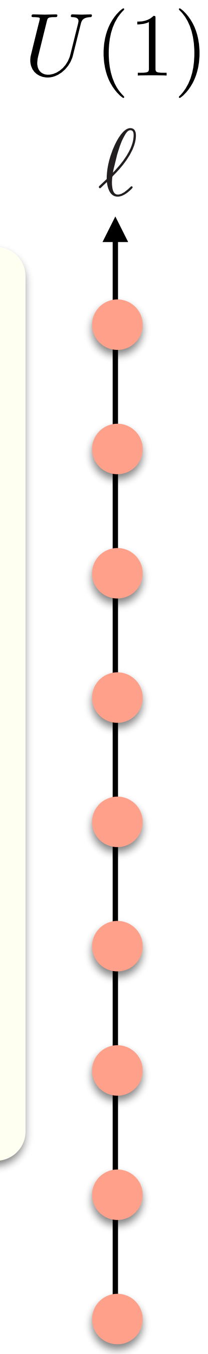
<u>d+1 dim</u>

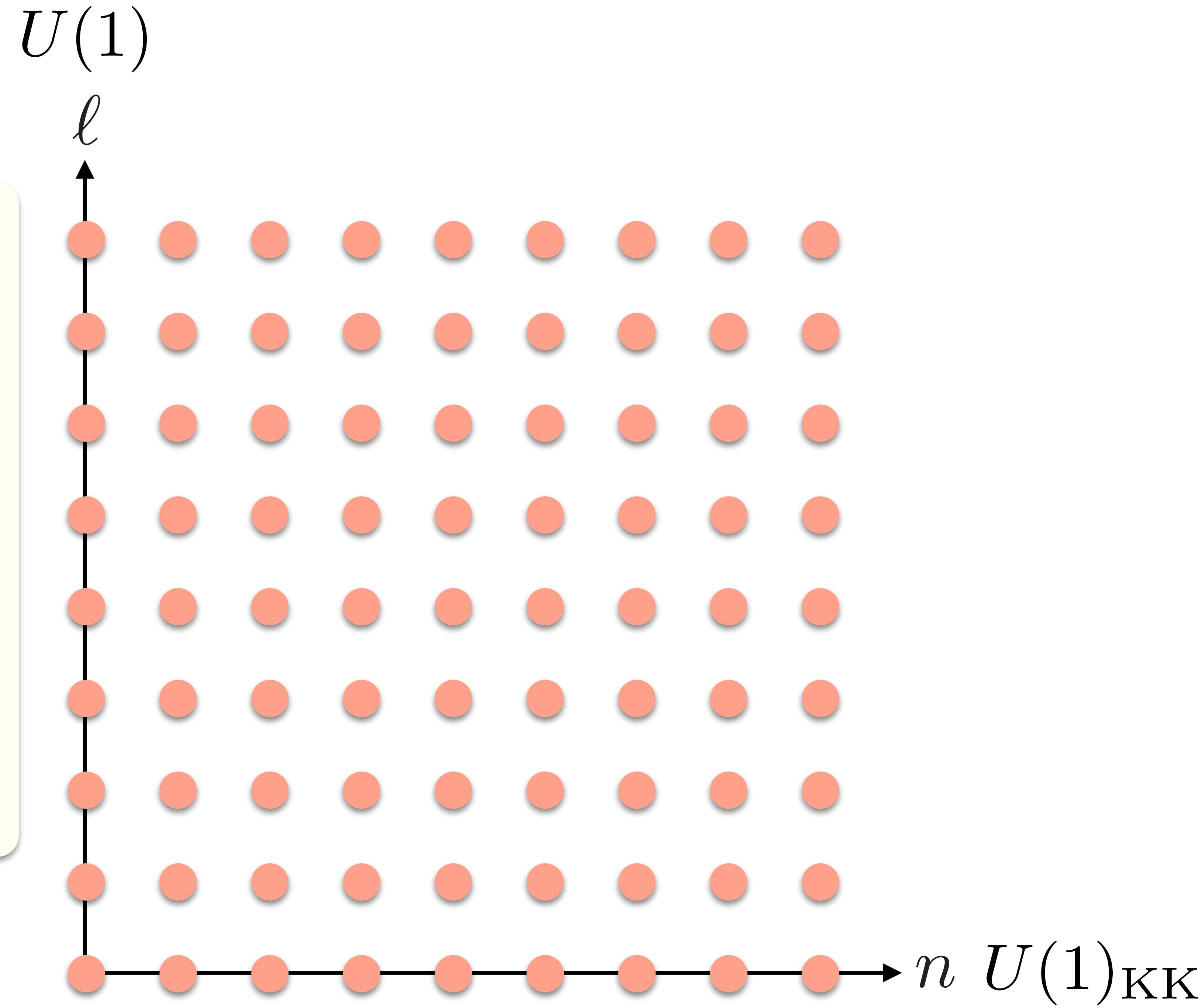
charged particles

labeled by $\ell = 1, 2, \ldots$

$$(q, m) = (\ell\, q_*, \ell\, m_*)$$

s.t. $z_* = \dfrac{q_*}{m_*} = \mathcal{O}(1)$





<u>d+1 dim</u>

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s.t. $z_* = \dfrac{q_*}{m_*} = \mathcal{O}(1)$

d dim charged particles

$$(z, z_{\mathrm{KK}}) = \left(\frac{\ell\, z_*}{\sqrt{\ell^2 (m_*/m_{\mathrm{KK}})^2 + n^2}},\ \frac{n}{\sqrt{\ell^2 (m_*/m_{\mathrm{KK}})^2 + n^2}} \right)$$

d+1 dim

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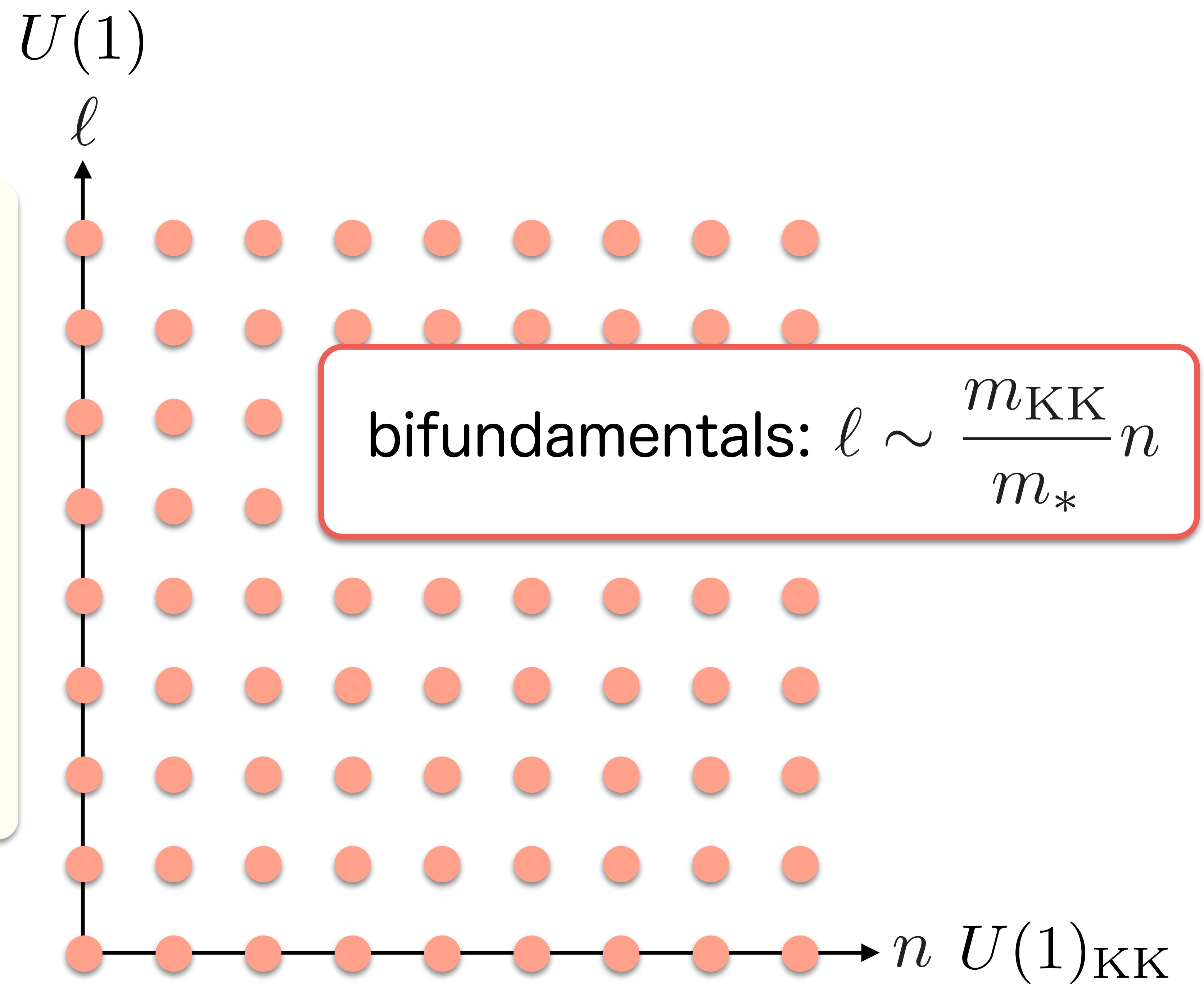

d dim charged particles

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<u>d+1 dim</u>

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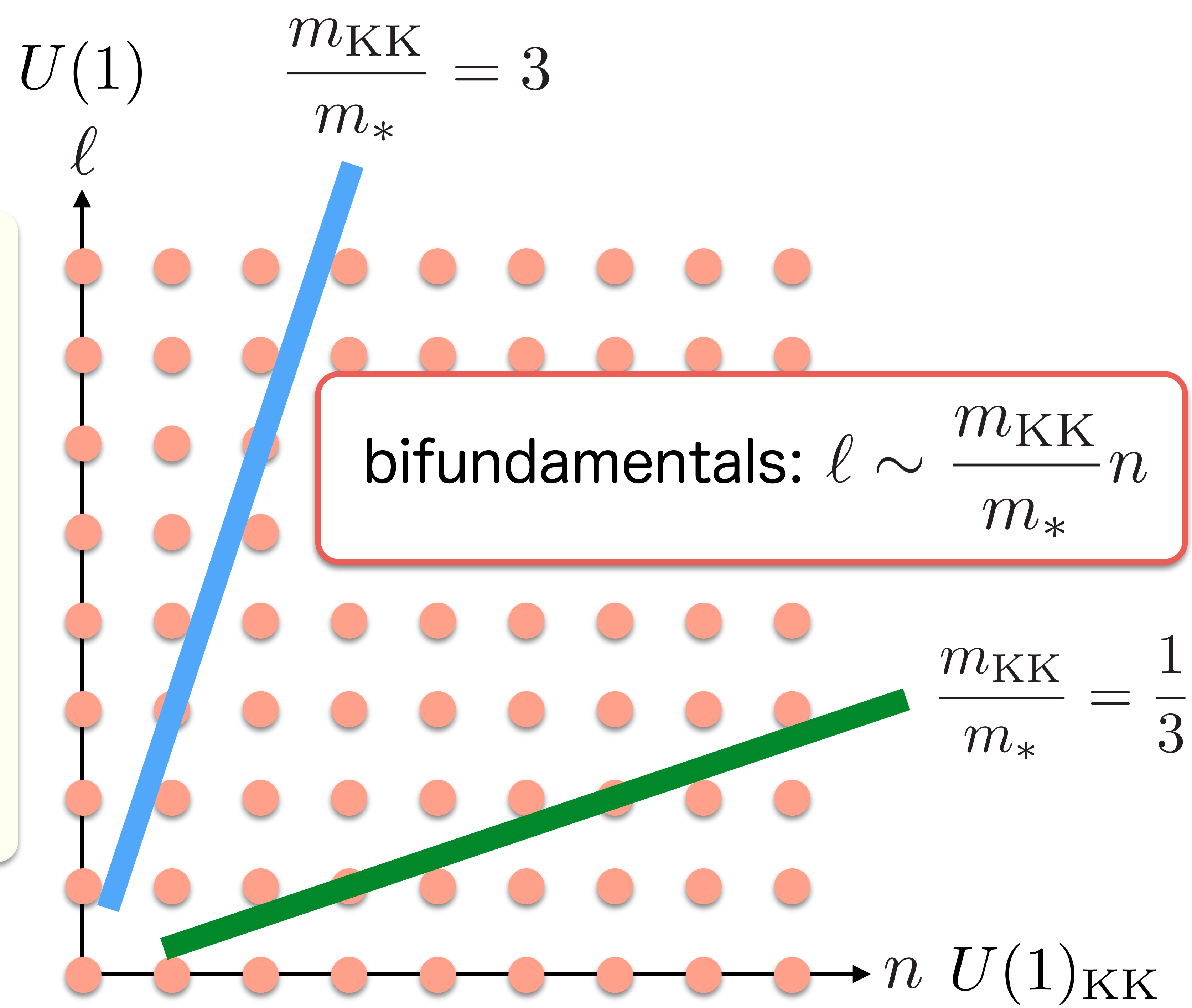

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$$(z, z_{\rm KK}) = \left(\frac{\ell\, z_*}{\sqrt{\ell^2 (m_*/m_{\rm KK})^2 + n^2}},\ \frac{n}{\sqrt{\ell^2 (m_*/m_{\rm KK})^2 + n^2}} \right)$$

Tower WGC

[Andriolo, Junghans, Noumi, GS]

Consistency with KK reduction seems to imply a tower of d+1 dim U(1) charged particles

→ Tower Weak Gravity Conjecture!

※ a similar "(sub)lattice WGC" was proposed based on modular invariance or holography

[Montero, GS, Soler, '16];[Heidenreich, Reece, Rudelius, '16]

Conclusions

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- Swampland conjectures have a variety of interesting applications in cosmology and particle physics.
- The WGC when applied to ALPs constrains **inflationary B-modes**; when applied to the **QCD axion** implies $f_{\rm QCD} \lesssim 10^{16}\ {\rm GeV}$ which can be falsified by **laboratory axion searches** or **GW detectors**.
- The WGC offers interesting perspectives on how **Λ and the neutrino masses are linked.**
- Further evidences for the WGC based on **entropy considerations** and **IR consistencies**.

Conclusions

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