Title: The Weak Gravity Conjecture, Natural Inflation, and the Conformal Bootstrap

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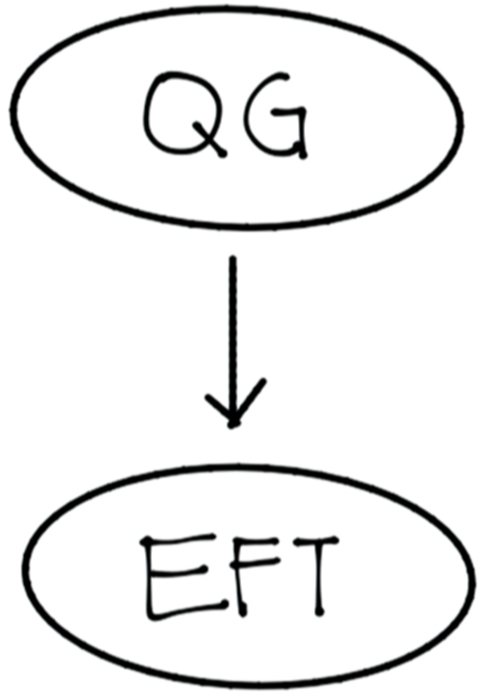
Abstract: <p>There have been recent claims that the weak gravity conjecture (WGC) rules out multi-field natural inflation. I review these claims and then show how 2-field natural inflation can be consistent with even the most stringent form of WGC. I also discuss my recent attempt at numerically proving the WGC via the conformal bootstrap.</p>

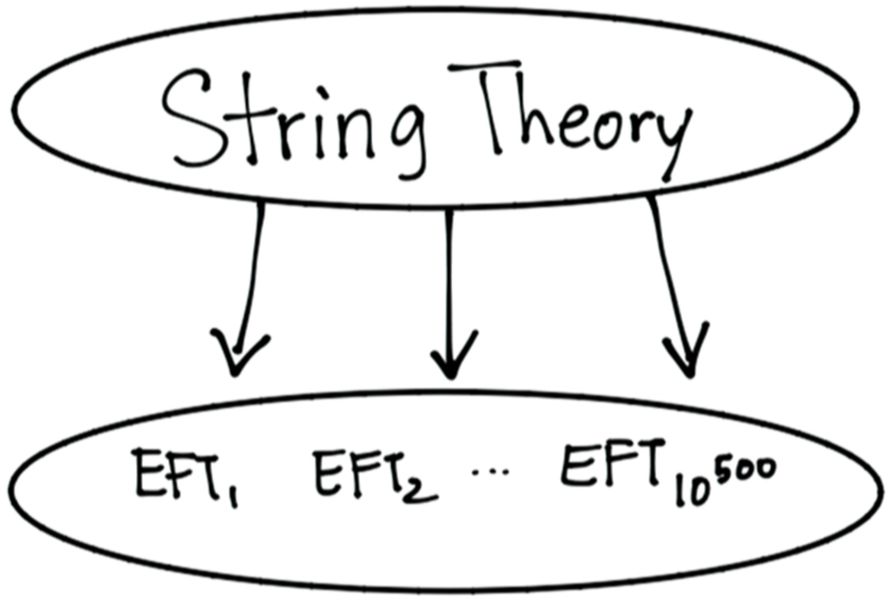
The WGC for Everyone

work with Raman Sundrum
and Prashant Saraswat

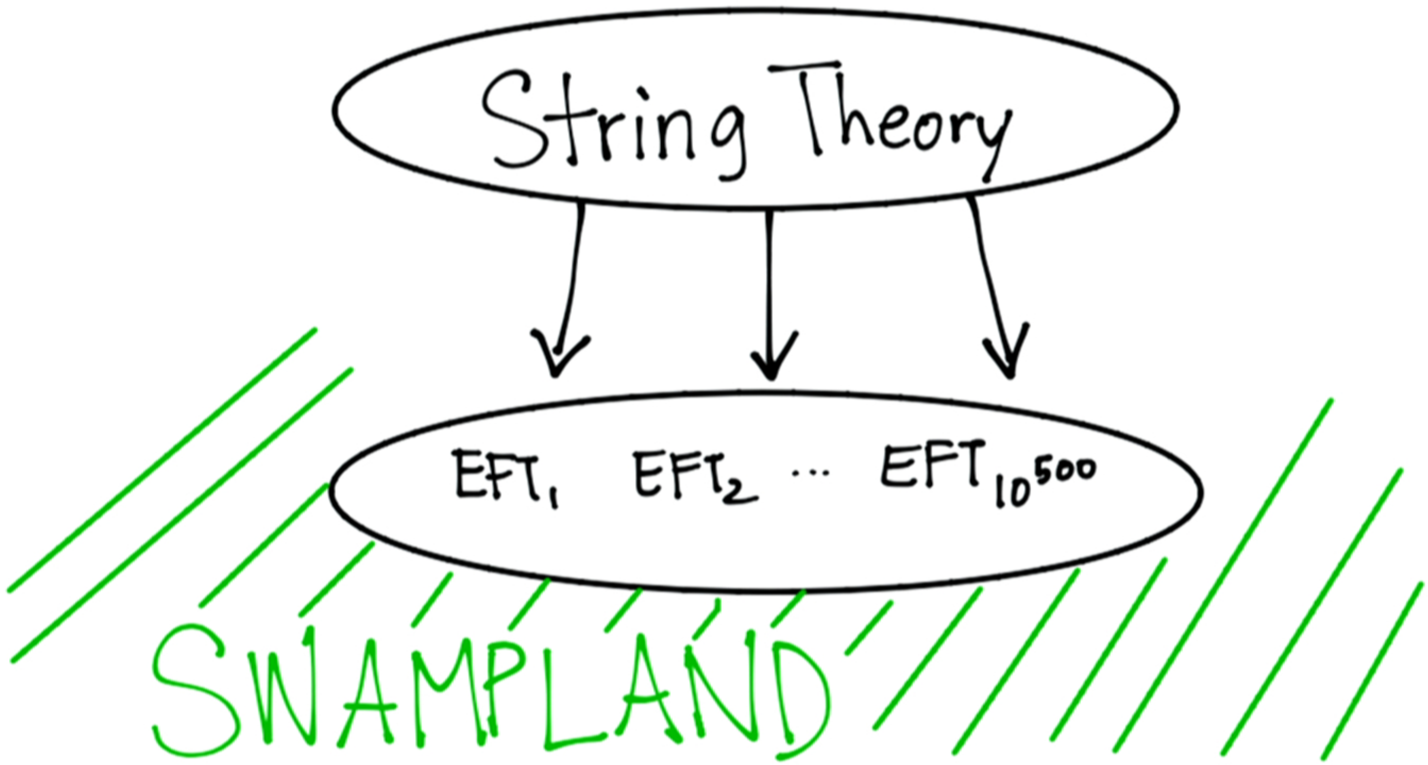
QG reduces to EFT at low energies.



String theory reduces to a vast landscape of EFTs.



The swampland consists of EFTs that are not in the landscape.



The weak gravity conjecture

- There exists some particle such that

$$G_N \frac{m^2}{r^2} < \frac{q^2}{r^2}$$

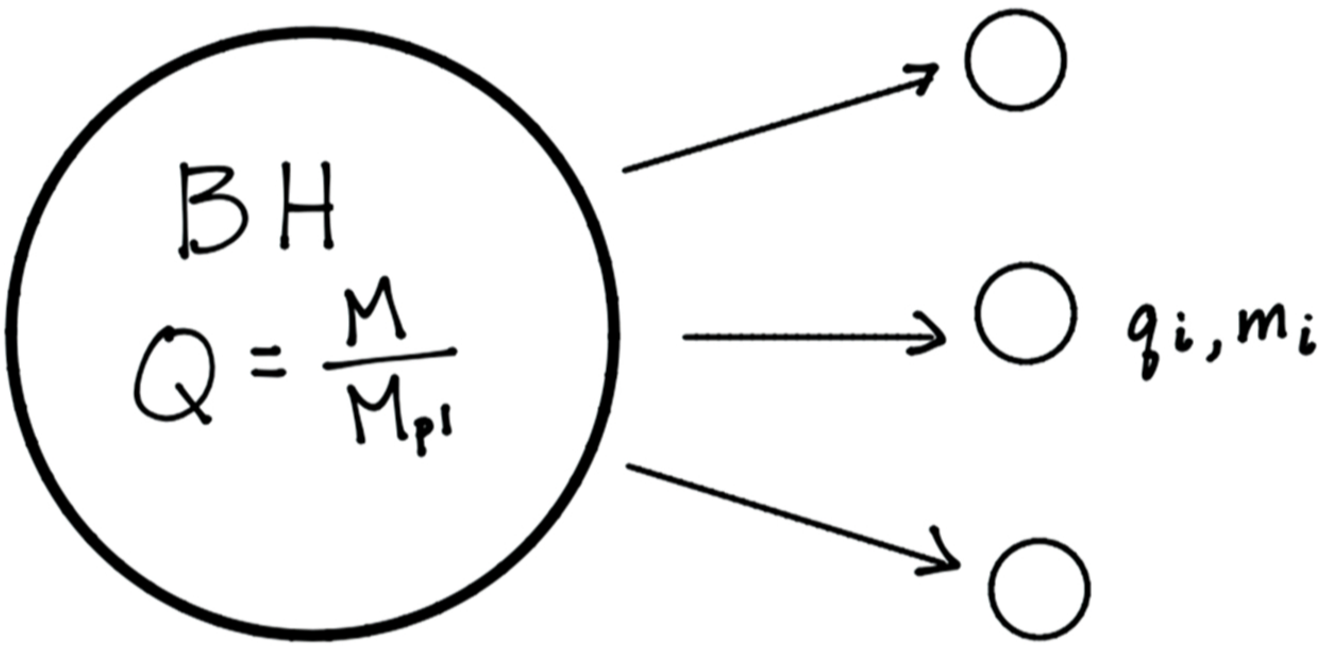
$$\frac{m}{m_{\rm pl}} < q$$

$$m < q$$

Messages

- The WGC is the CFT version of Noether's theorem.
- The WGC requires model builders to include particles and cutoffs that ensure all black holes can decay.
- Despite recent claims, two-axion models can achieve transplanckian field transits while remaining consistent with the WGC.

Why should the WGC be true?



To avoid an infinite number of exactly stable states

$$Q = \sum q_i \qquad M > \sum m_i$$

$$\sum q_i > \sum m_i$$

$$q_j > m_j$$

What prevents us from maximally violating it?

- The WGC imposes a lower bound on the strength of the gauge force

$$e \to 0 \qquad q = Ze$$

$m_{\rm pl}$ Fixed

We would be left with matter charged under a global symmetry and a decoupled photon.

QG violates all global symmetries.

- Form a black hole with area *A*
- Hawking radiation is ignorant of baryon number
- Feed it baryons to keep its area unchanged

We lose the statistical intepretation of black hole entropy.

$$S = \frac{\text{Area}}{4G_N} = \log(\#\text{ of states})$$

$$\left\{|B = 0\rangle, |B = 1\rangle, \cdots |B = e^s\rangle, \cdots\right\}$$

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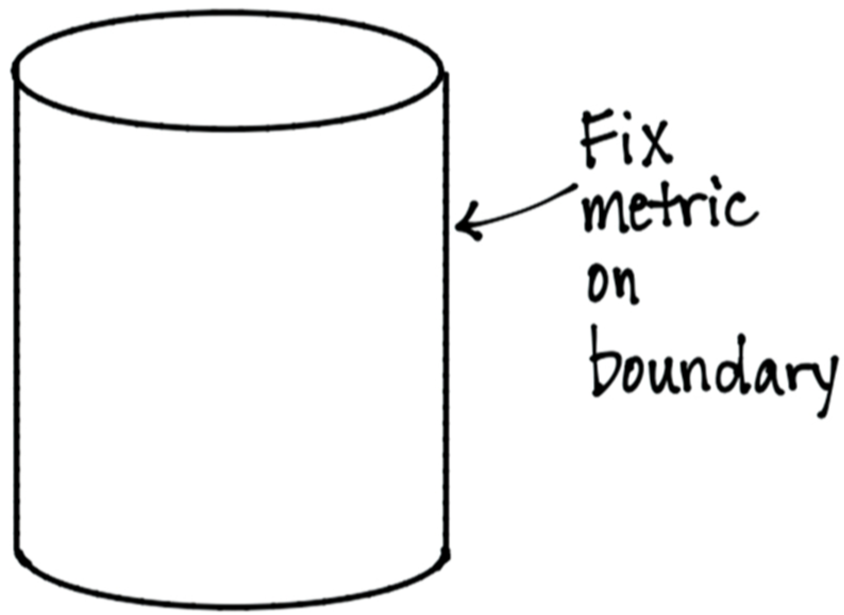
A direct proof could determine a lower bound on the gauge coupling.

QG involves a path integral over spacetime geometries.

$$Z = \int \mathcal{D}g_{\mu\nu} \cdots e^{i \int d^4x \sqrt{-g} R + \cdots}$$

Restrict to geometries that asymptotically approach AdS



That path integral is equal to a completely different one

$$Z_{\rm AdS} = Z_{\rm CFT}$$

- Same quantum theory described by two different sets of variables.

Dictionary

$$\text{fields } \phi \longleftrightarrow \text{composite operators } \mathcal{O}$$

$$\text{gauge} \longleftrightarrow \text{global}$$

$$A_\mu \longleftrightarrow J_\mu$$

$$m_{\text{pl}} \longleftrightarrow \text{central charge } c$$

$$1/e \longleftrightarrow \text{flavor central charge } \kappa$$

Violation of CFT Noether theorem

$e \to 0$ at fixed $m_{\rm pl}$ $\qquad$ $\kappa \to \infty$ at fixed c

- At infinite flavor central charge, the conserved current decouples
- Intuitively, the central charge should be tied to flavor central charge

The conformal bootstrap

- The conformal bootstrap equations are a set of consistency conditions that all CFTs must satisfy.
- Try to show that for large enough flavor central charge, a “CFT” cannot satisfy the conformal bootstrap equations.

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Model building rules to satisfy WGC

- Do not impose exact global symmetries.
- Make sure all electric and magnetic black holes can decay.
- Take into account cutoffs due to magnetic monopoles.

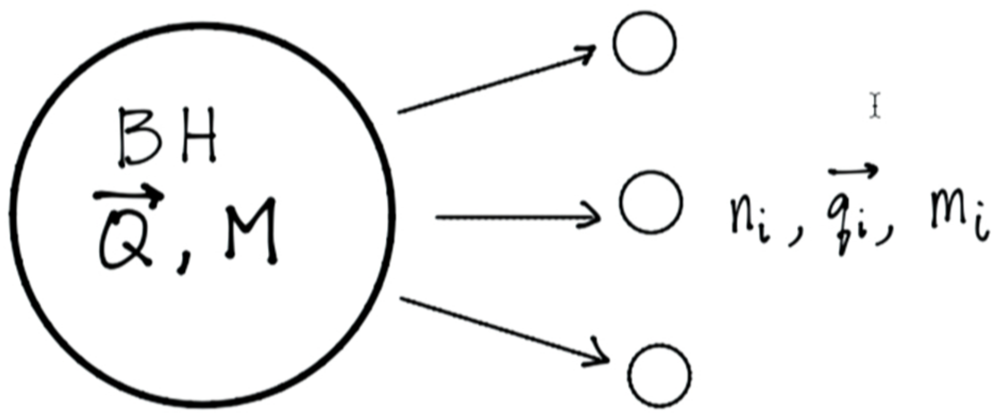
Do not impose exact global symmetries.

- Don't tune an infinite number of higher dimension operators to zero
- All global symmetries are just accidental

Make sure all electric and magnetic black holes can decay.

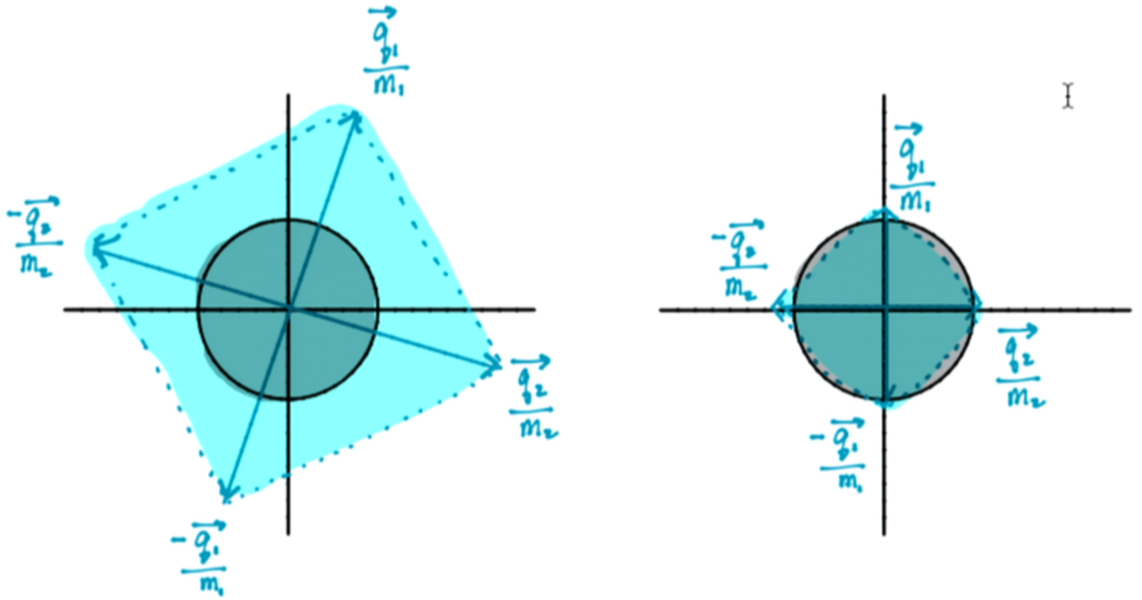
- Generalize the WGC to multiple U(1)'s.
- For each U(1), assume there exists both magnetically and electrically charged black holes.

Consider a BH be charged under multiple *U(1)*'s



$$\vec{Q} = \sum n_i \vec{q}_i \qquad M > \sum n_i m_i$$

The convex hull in charge-to-mass ratio space must contain the unit ball.



Consistent with WGC

inconsistent with WGC

Take into account cutoffs due to magnetic monopoles.

UV Theory → U(1) with monopoles

UV Theory:
- Lattice Gauge Theory
- Extra Dimensions
- Grand Unified Theories

$$R_{\mathrm{mon}} \sim \frac{1}{\Lambda} \qquad m_{\mathrm{mon}} \sim \frac{\Lambda}{e^2}$$

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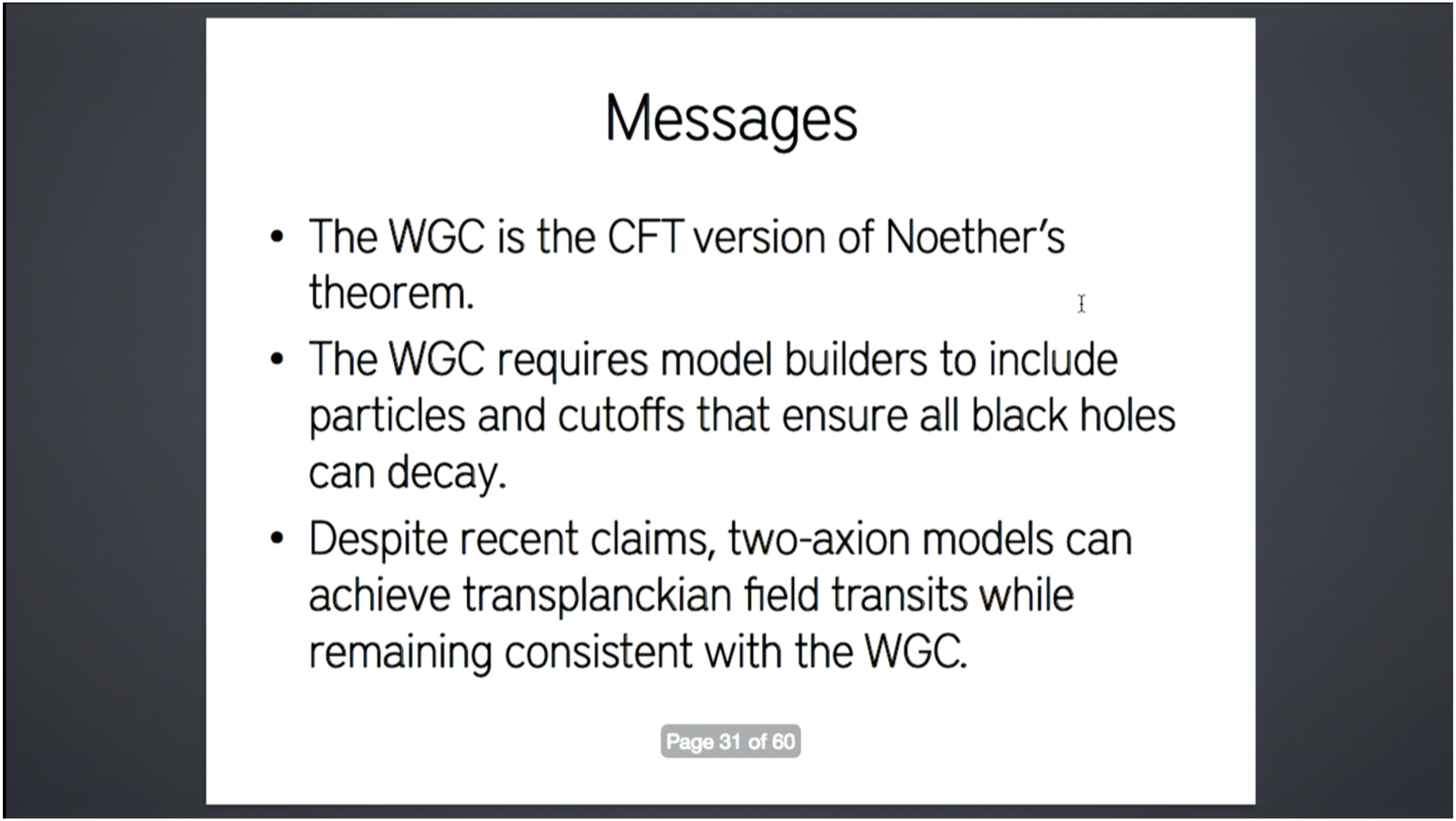
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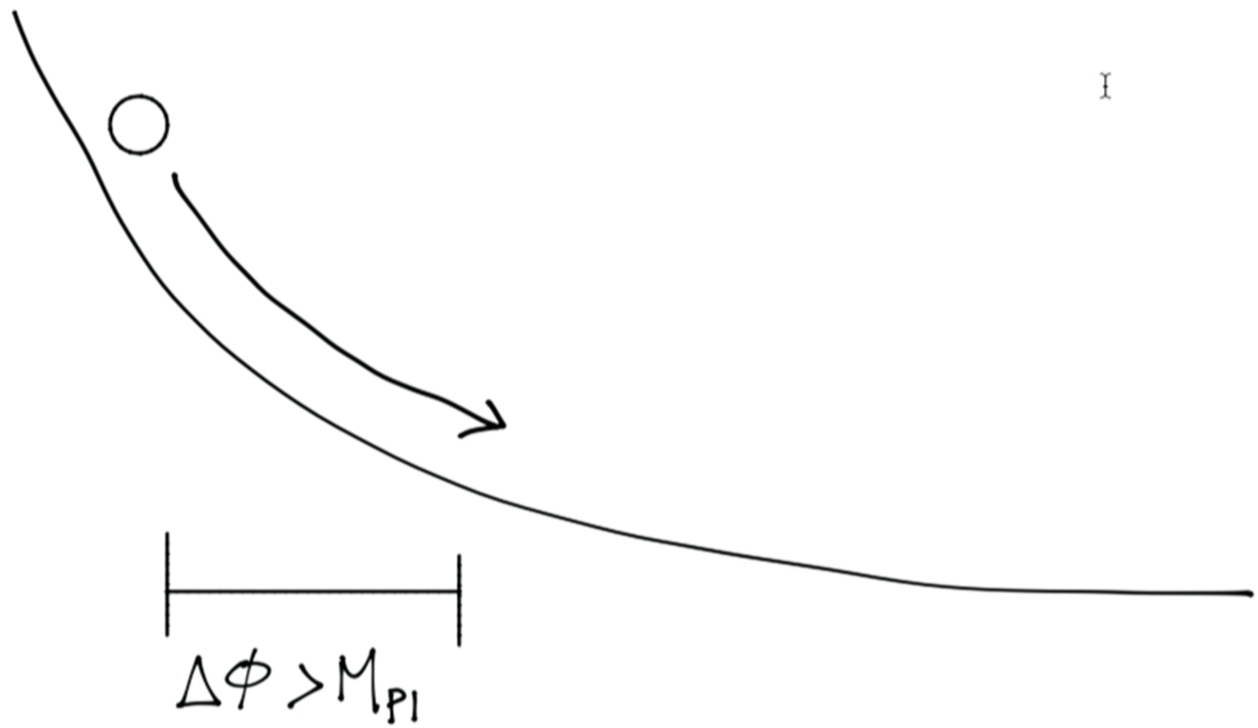
Page 31 of 60

Background: transplanckian field transits and axions



The transplanckian problem

$$\mathcal{L} = \frac{1}{2}(\partial\phi)^2 - m_{\rm pl}^4 \sum c_n \left(\frac{\phi}{m_{\rm pl}}\right)^n$$

Want a weakly broken shift symmetry

$$\phi \equiv \phi + c$$

An angular variable seems like a good starting point

$$\Sigma = \sigma e^{i\phi/f}$$

Corrections are periodic.

$$V = V_0 \left[e^{-S} \cos \frac{\phi}{f} + e^{-2S} \cos \frac{2\phi}{f} + \cdots \right]$$

$$S > 1$$

$$f > m_{\text{pl}}$$

Axions in string theory

- p-form gauge fields $\quad A_\mu,\ B_{\mu\nu},\ C_{\mu\nu\sigma}$

$$A_\mu \to A_\mu + \partial_\mu \Lambda$$
$$B_{\mu\nu} \to B_{\mu\nu} + \partial_\mu \Lambda_\nu - \partial_\nu \Lambda_\mu$$

Axions are the extra-dimensional components of gauge fields

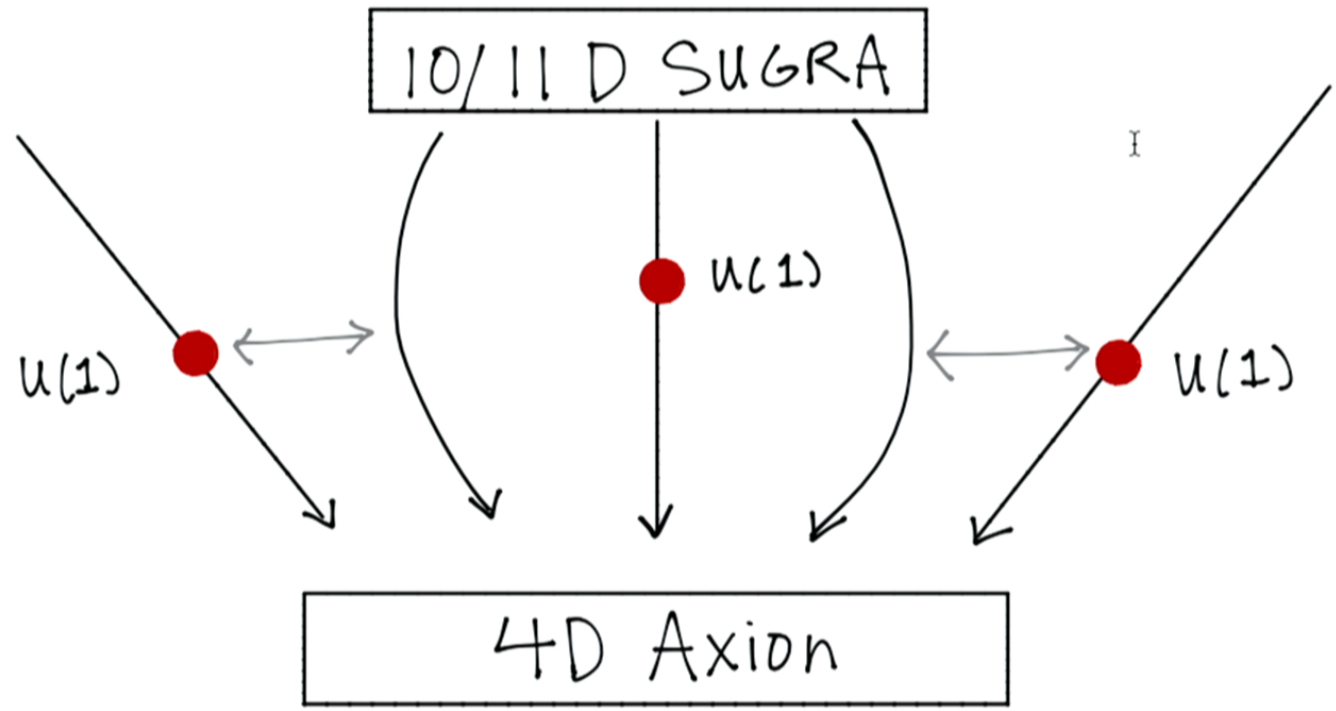
$$a = \int_0^{2\pi r} dx^5 \, A_5, \quad \int dx^5 dx^6 B_{56}, \quad \cdots$$

Field space is periodic due to invariance under large gauge transformations.

$$a \to a + \Lambda(2\pi r) - \Lambda(0)$$
$$\psi \to e^{i\Lambda}\psi$$

$$\Lambda(2\pi r) - \Lambda(0) = 2\pi n$$

Use various dualities to relate axions to U(1)'s. Then apply WGC.



WGC translated to decay constants and instanton actions

$$m \leftrightarrow S$$

$$e \leftrightarrow \frac{1}{f}$$

$$m < e\, m_{\rm pl} \longleftrightarrow S < \frac{m_{\rm pl}}{f} < 1$$

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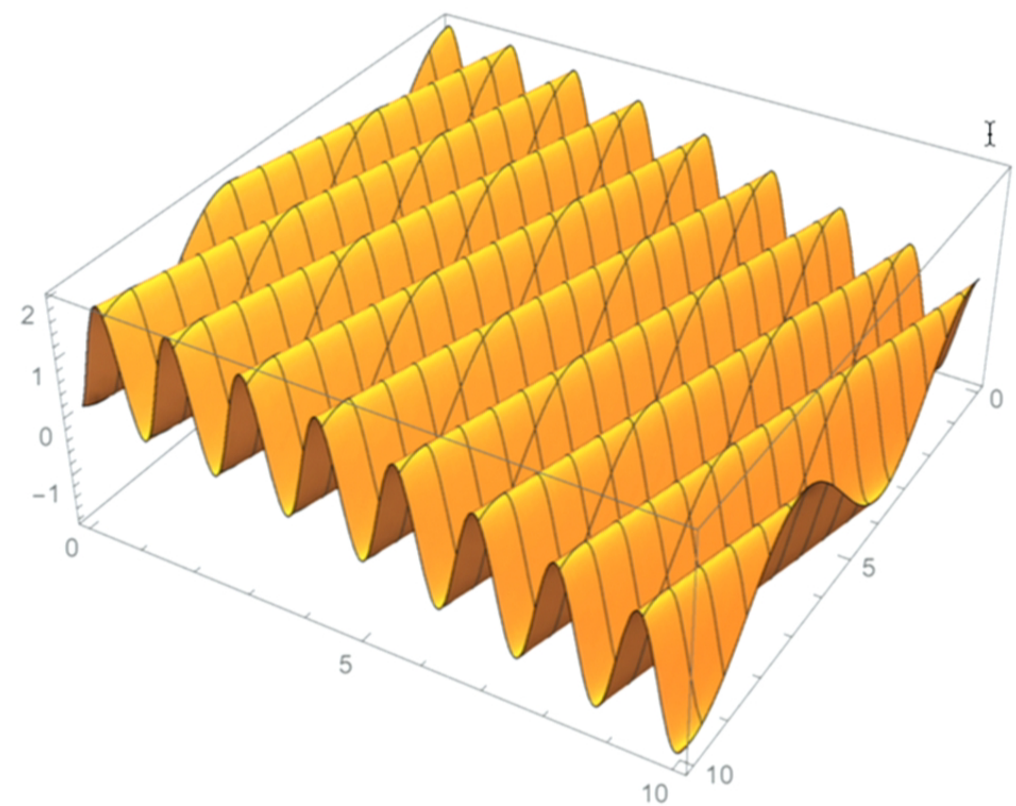
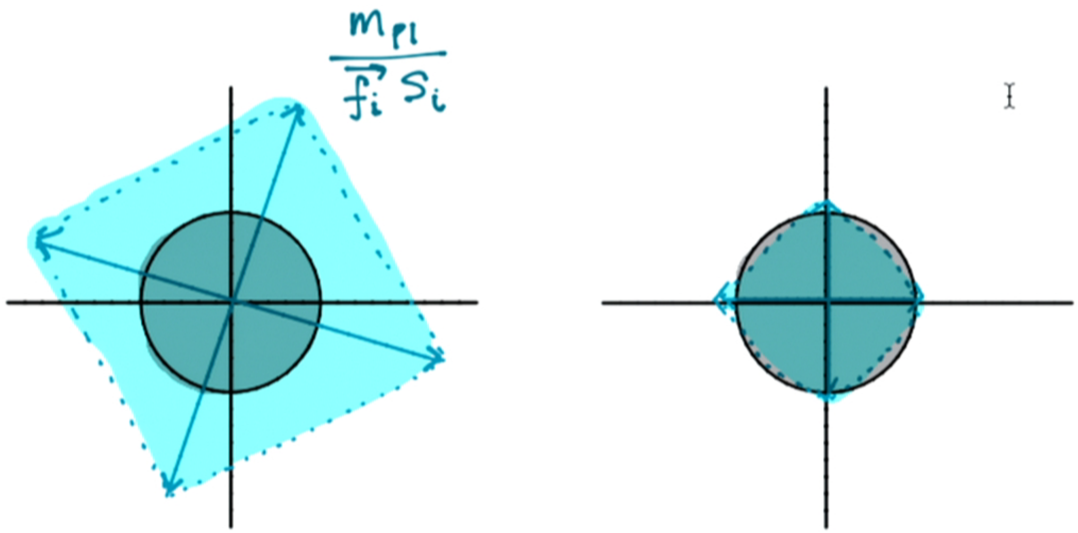
Multi-axion winding models



Convex hull



No-go "theorem"

- Cannot have an effective f greater than m_{pl} and have all $S_i > 1$
- Therefore, transplanckian field transits via multiple axions is "impossible."
- Really, it just explains why explicit constructions from string theory are extra hard

Our model

2 Gauge fields A and B
1 massless particle of charge (1,N)
1 massless particle of charge (0,1)

Further reduces to a single axion potential with transplanckian *f*.

$$V = V_0 \cos \frac{2\pi Re_A A}{N}$$

$$f = \frac{N}{2\pi Re_A}$$

Evades theorem because $S = 0$.

- Convex hull condition trivially satisfied.
- From gauge field perspective, we have massless charged particles.

The higher harmonics have been explicitly calculated.

$$V = \frac{1}{R^4} \sum \frac{1}{n^5} \cos \frac{n\phi}{f}$$

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- From the bottom up, we can specify the spectrum and then calculate
- From the top down, perhaps just moving the problem elsewhere
- From the bottom up, exactly!

The WGC for everyone

- For formal field / string theorists
  - Rephrasing in terms of CFT Noether theorem

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- For formal field / string theorists
  - Rephrasing in terms of CFT Noether theorem
- For model builders
  - Requires extra particles and cutoffs
- The WGC for string phenomenologists
  - Would explain why some potentials are hard to realize