The Weak Gravity Conjecture

The Weak Gravity Conjecture

Arkani-Hamed et al. ‘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.

$$\frac{q}{m} M_P \geq \text{“1”}$$

$M_P \equiv 1$

The Weak Gravity Conjecture

- Take a U(1) and a single family with q < m (~~WGC~~)

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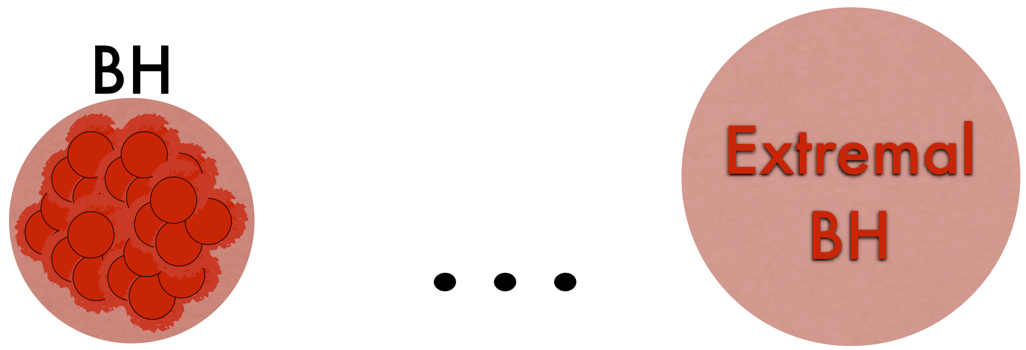
The Weak Gravity Conjecture

- Take a U(1) and a single family with q < m (~~WGC~~)

- Form bound states

$\cdots$



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

- All these (BH) states are stable. Trouble w/ remnants   Susskind '95

$M_P \equiv 1$

The Weak Gravity Conjecture

- Take a U(1) and a single family with q < m (~~WGC~~)

  - Form bound states

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  - All these (BH) states are stable. Trouble w/ remnants Susskind '95

- Need a light state into which they can decay

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

The Weak Gravity Conjecture

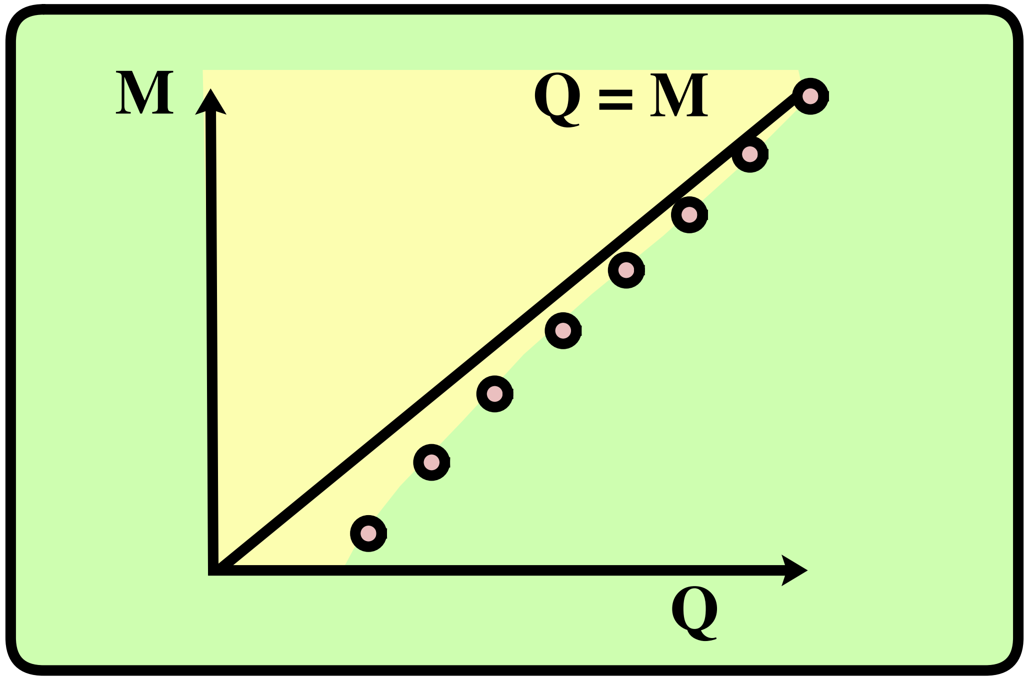
Arkani-Hamed et al. '06

- For bound states to decay, there must ∃ a particle w/

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

Strong-WGC: satisfied by *lightest* charged particle

Weak-WGC: satisfied by *any* charged particle



E.g. Heterotic spectrum:

$$M^2 \propto Q_L^2 + 2N_L - 2$$

The Weak Gravity Conjecture

- Suggested generalization to p-dimensional objects charged under (p+1)-forms:

$$\frac{Q}{T_p} \geq \text{``1''}$$

- p=-1 applies to instantons coupled to axions:

$$e^{-S_{inst}} = e^{-m+i\phi/f} \qquad \Longrightarrow \qquad fm \leq \text{``1''}$$

  - Seems to explain difficulties in finding $f > M_P$

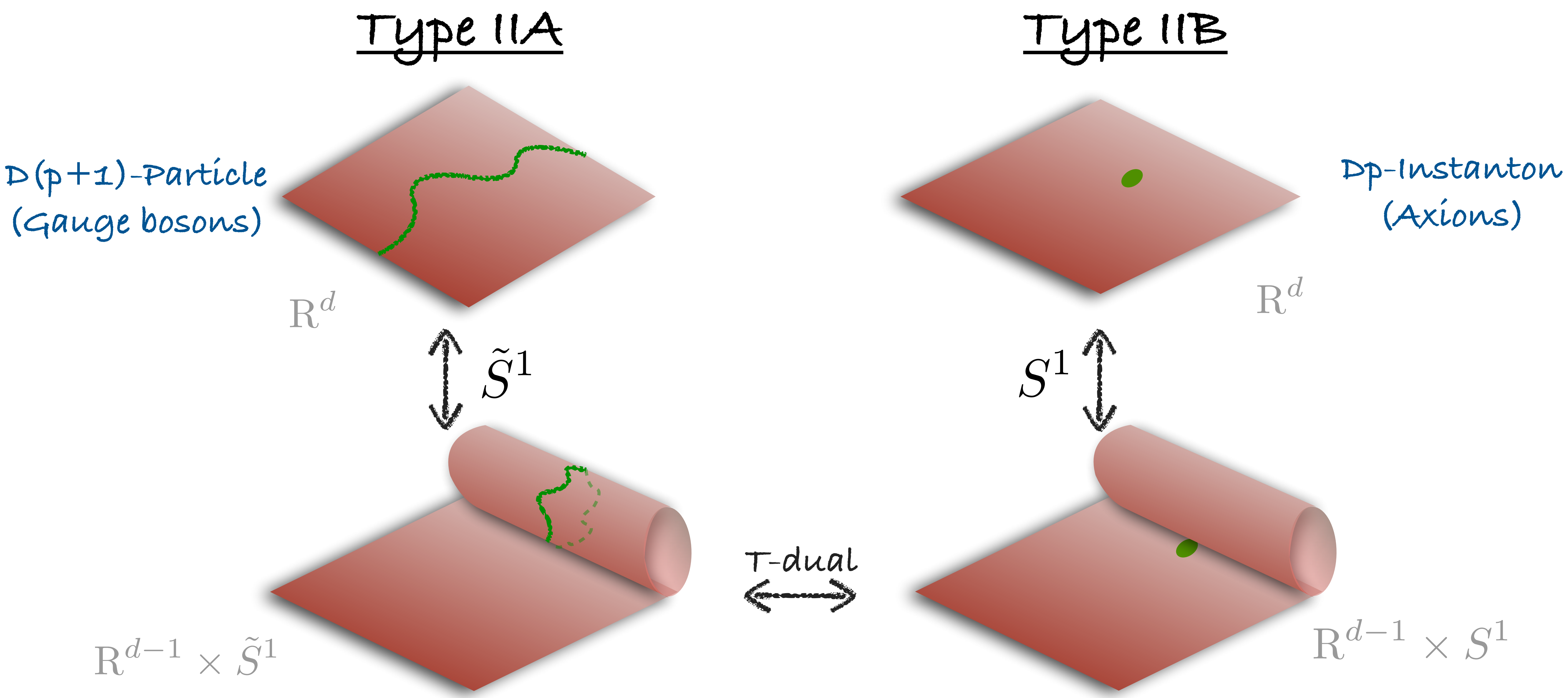
- Is there evidence for the p=-1 version of the WGC?

Brown, Cottrell, GS, Soler

WGC and Axions

Brown, Cottrell, GS, Soler

- T-duality provides a subtle connection between instantons and particles



WGC and Axions

Brown, Cottrell, GS, Soler

Type IIA	Type IIB
Gauge fields: $A_i \sim \int_{\Sigma_2^{(i)}} C_3$	**Axions:** $\phi_i \sim \int_{\Sigma_2^{(i)}} C_2$
Particles: D2 on $\Sigma_2^{(i)}$	**Instantons: D1 on** $\Sigma_2^{(i)}$
WGC $\tilde{m}_k = m_k \frac{\sqrt{g_{33}}}{2\pi\, l_s}$ $\tilde{q}_k^i = (f_k^i)^{-1} \frac{\sqrt{2}}{4\pi\, l_s}$	$S_{inst_k} \sim -m_k + i(f_k^i)^{-1}\phi_i$
"Couplings": $\tilde{g}_s = \frac{g_s}{\sqrt{g_{33}}}$ $\tilde{M}_P = M_P\sqrt{g_{33}}$	**"Couplings":** g_s M_P

WGC and Axions

Brown, Cottrell, GS, Soler

4d Type IIB D1-instantons	**4d Type IIA D2-particles**	**5d M-theory M2-particles**
m_i	$\tilde{m}_i \sim m_i$	$M_i^{(5d)} \sim m_i$
f_i	$\tilde{q}_i \sim f_i^{-1}$	$Q_i^{(5d)} \sim f_i^{-1}$
$g_s \ll 1$	$\tilde{g}_s \gg 1$	$R_M \to \infty$

- Apply the WGC to 5d particles:

$$\frac{Q^{(5d)}}{M_i^{(5d)}} M_P^{(5d)} = \frac{M_P^{(IIB)}}{\sqrt{2} f_i\, m_i} \geq \text{“}1\text{”} \equiv \left(\frac{Q}{M} M_P \right)_{\mathrm{Ext}_{5d}} = \sqrt{\frac{2}{3}}$$

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WGC and Axions

- For each axion (gauge U(1)) there must be an instanton (particle) with

$$e^{-S_{inst}} = e^{-m+i\phi/f}$$

$$\boxed{f \cdot m \leq \frac{\sqrt{3}}{2} M_P}$$

Brown, Cottrell, GS, Soler

For a RR 2-form in IIB string theory. Similar bounds for axions from other p-forms in other string theories have also been obtained.

Multiple Axions/ Multiple U(1)'s

WGC and Axions

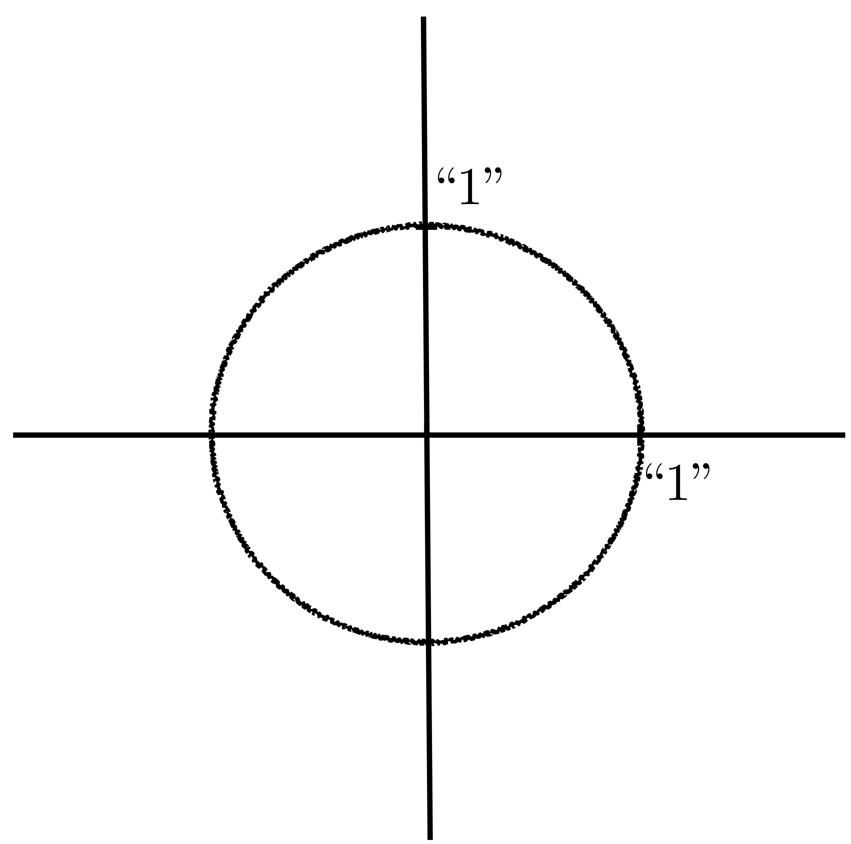
Multiple axions/U(1)s

Cheung, Remmen '14
Brown, Cottrell, GS, Soler '15
Rudelius '15

- Consider two U(1) bosons (axions): there must be 2 particles (instantons) i=1,2, so that BH's can decay.

$$\vec{z}_i \equiv \frac{M_P}{M_i}\left(Q_i^1 \quad Q_i^2 \right) \qquad \left(= \frac{M_P}{\sqrt{2}\, m_i}\left(1/f_i^1 \quad 1/f_i^2 \right) \right)$$

$$|\vec{z}_{EBH}| \equiv \text{“}1\text{”}$$



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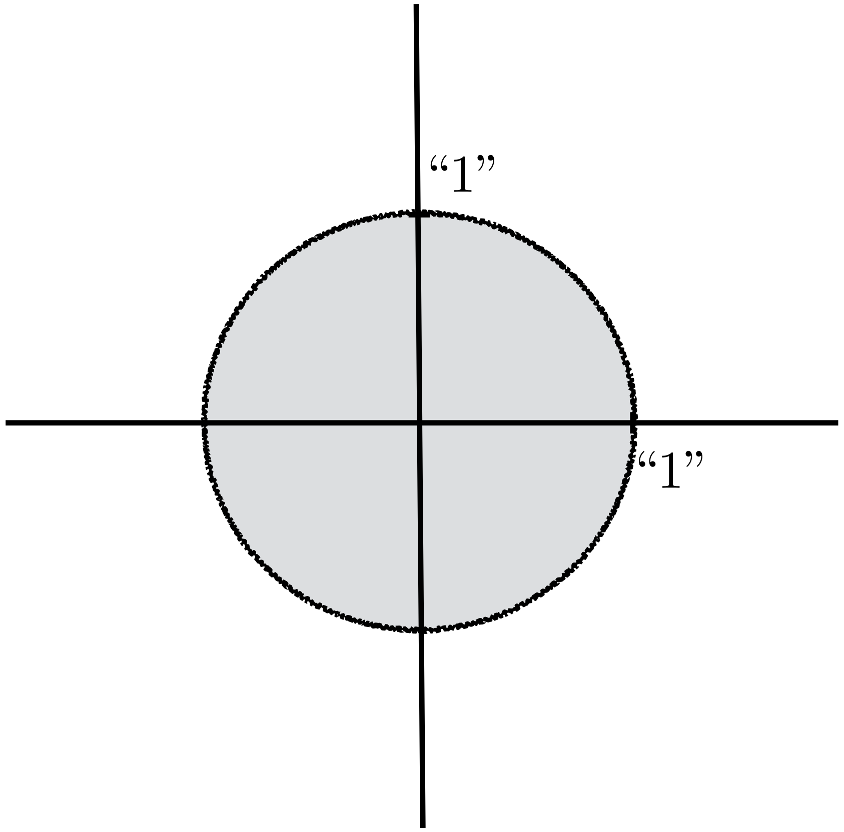

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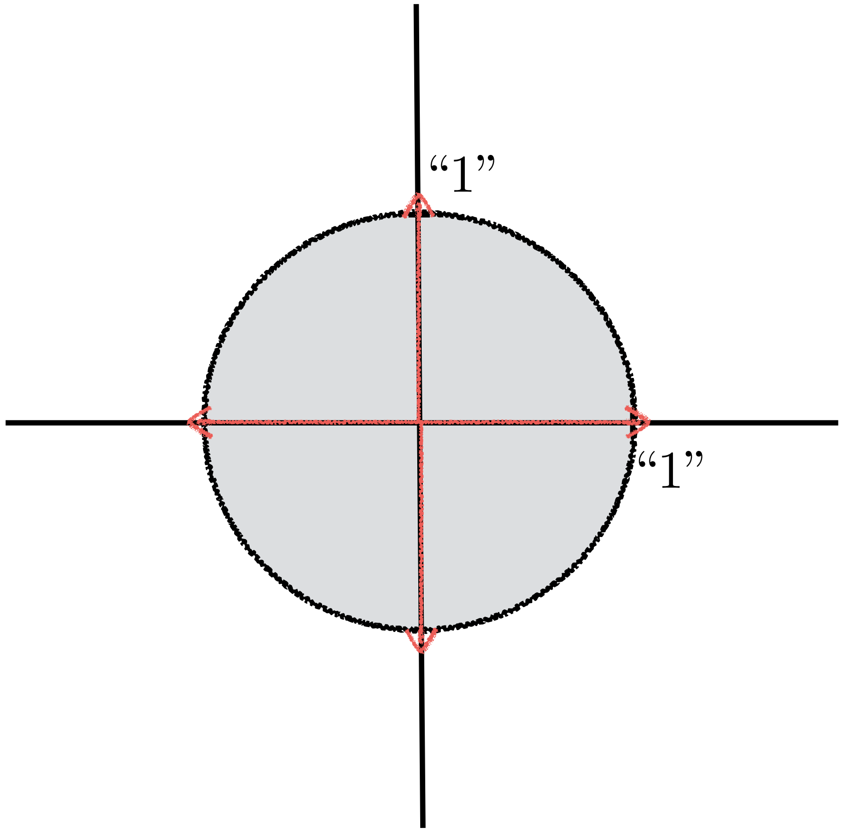

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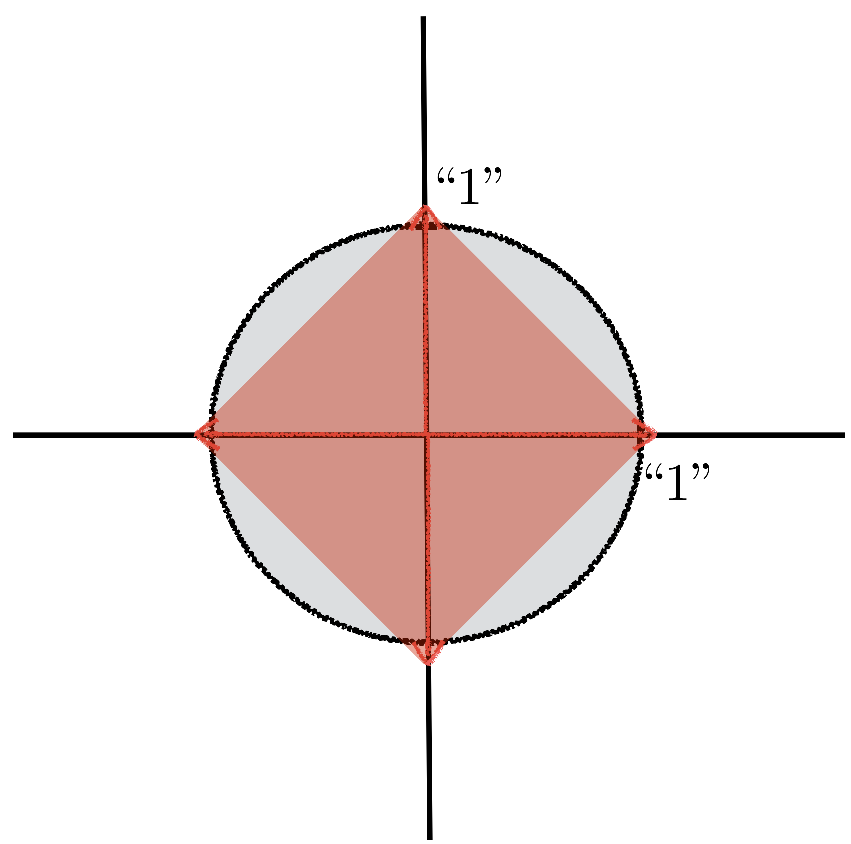

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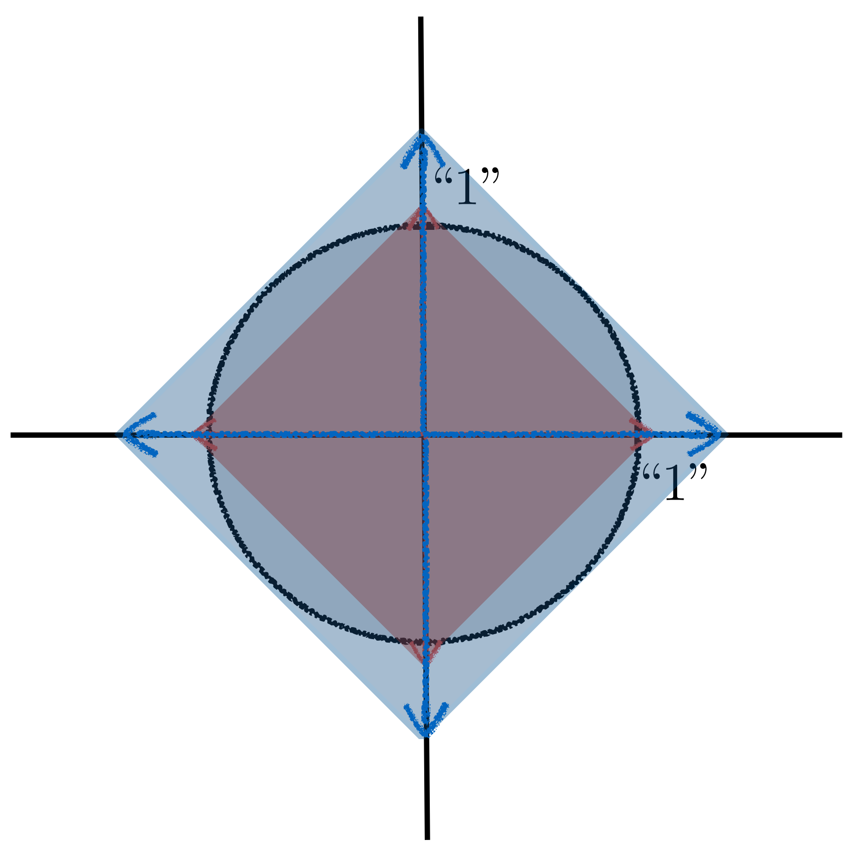

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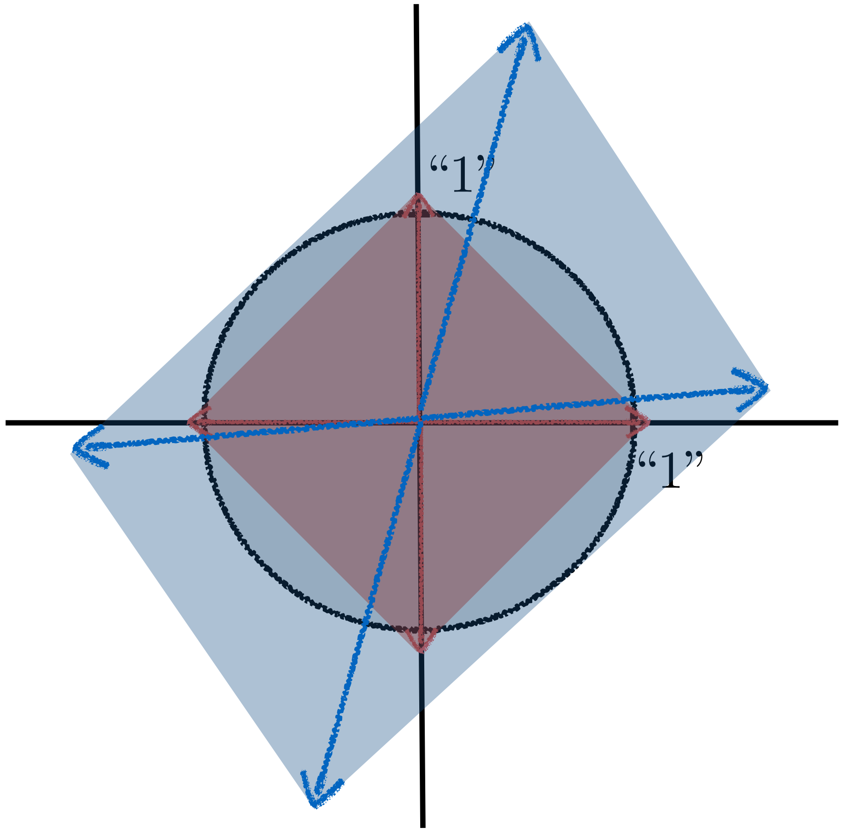

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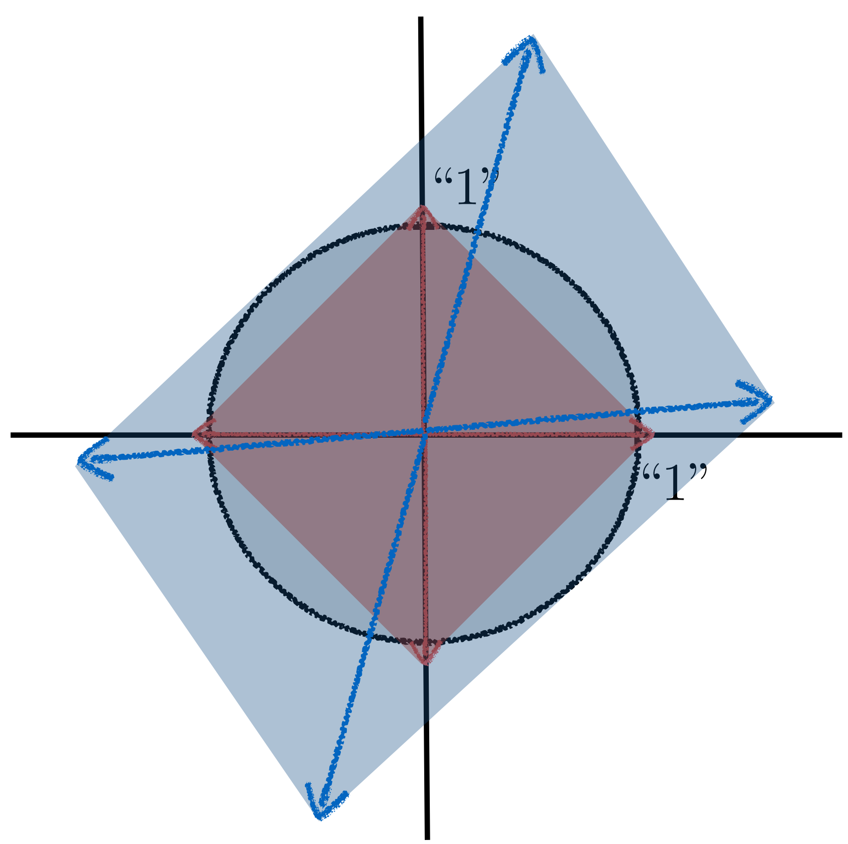

WGC

$$|\vec{z}| = \text{“1”}$$

$$\cap$$

$$\text{Convex Hull}\,\{\vec{z}_{p1}, \vec{z}_{p2}\}$$

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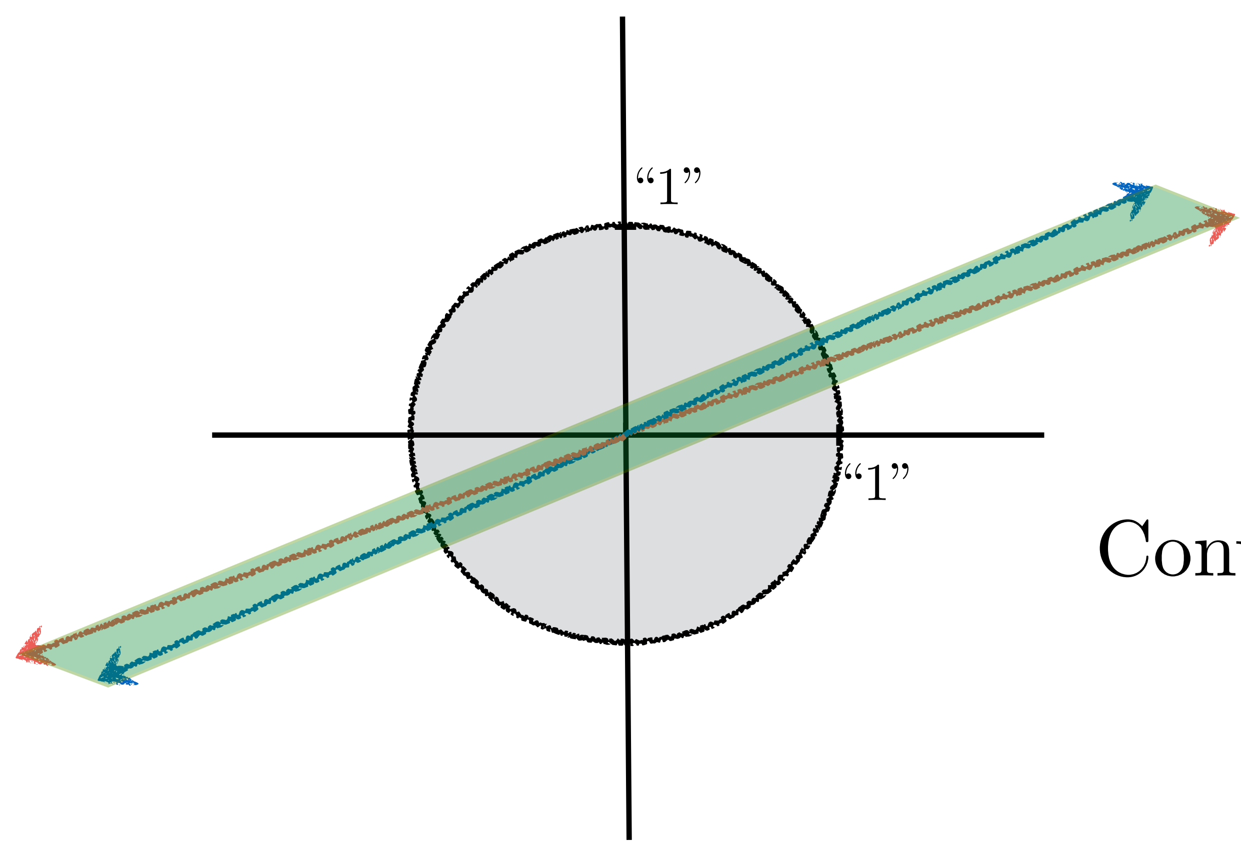
KNP

WGC



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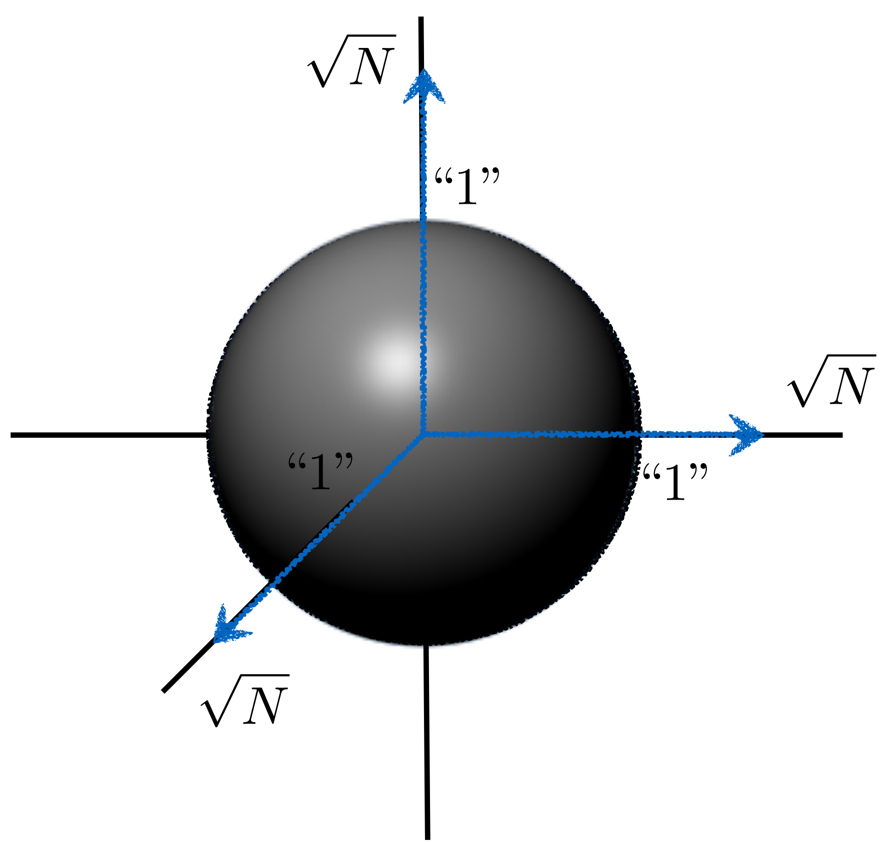
N-flation

$$z_i^k \geq \sqrt{N}\delta_i^k$$



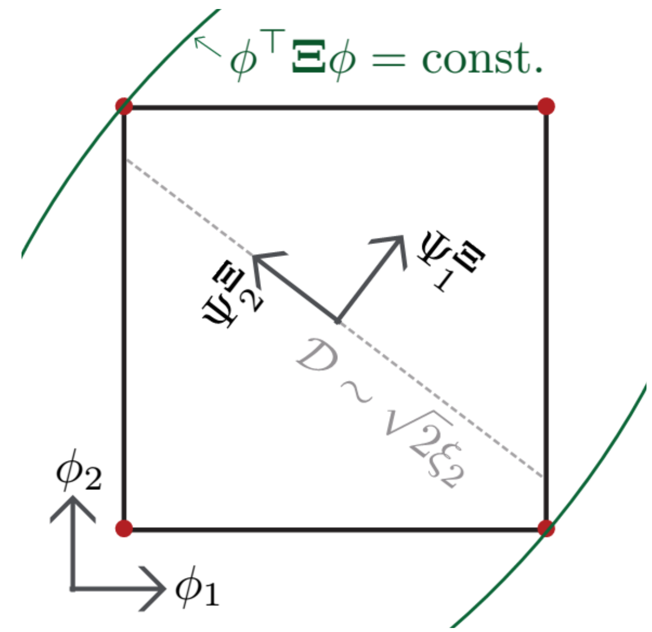
WGC

$$|\vec{z}| = \text{"1"}$$
$$\cap$$
$$\text{Convex Hull}\,\{\vec{z}_{p1}, \vec{z}_{p2}\}$$

WGC and Multi-axion Inflation

- Generally, given a set of instantons that gives a super-Planckian ``diameter” in axion field space

$$\mathcal{L} = \frac{1}{2}\partial\phi^{\top}\Xi\,\partial\phi - \sum_{i=1}^{N}\Lambda_i^4\left[1-\cos\left(\phi_i\right)\right]$$



Bachlechner et al ‘15

we showed that the convex hull generated by these instantons ***does not*** contain the extremal ball, to have parametric control.

- Our conclusions agree with the gravitational instanton diagnostics of [Montero, Uranga, Valenzuela ’15] in some instances but go beyond theirs in other cases.

Is there a way around this?

Loophole suggested in Brown, Cottrell, GS, Soler,
"Fencing in the Swampland", arXiv:1503.04783 [hep-th]

A possible loophole

- The WGC requires f·m<1 for ONE instanton, but not ALL

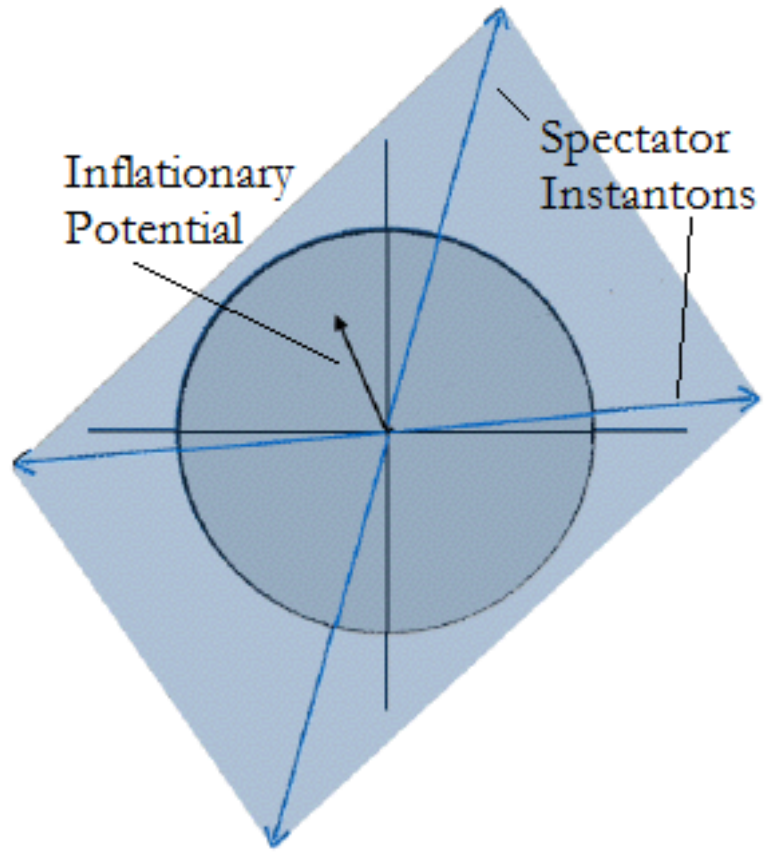
$$V = e^{-m}\left[1-\cos\left(\frac{\Phi}{F}\right)\right] + e^{-M}\left[1-\cos\left(\frac{\Phi}{f}\right)\right]$$

With $1 < m \ll M, \qquad F \gg M_P > f, \qquad M \times f \ll 1$

- The second instanton fulfills the WGC, but is negligible, an “spectator”. Inflation is governed by the first term.

A possible loophole

- In the presence of "spectator" (negligible) instantons that fulfill the WGC, dominant instantons can generate an inflationary potential



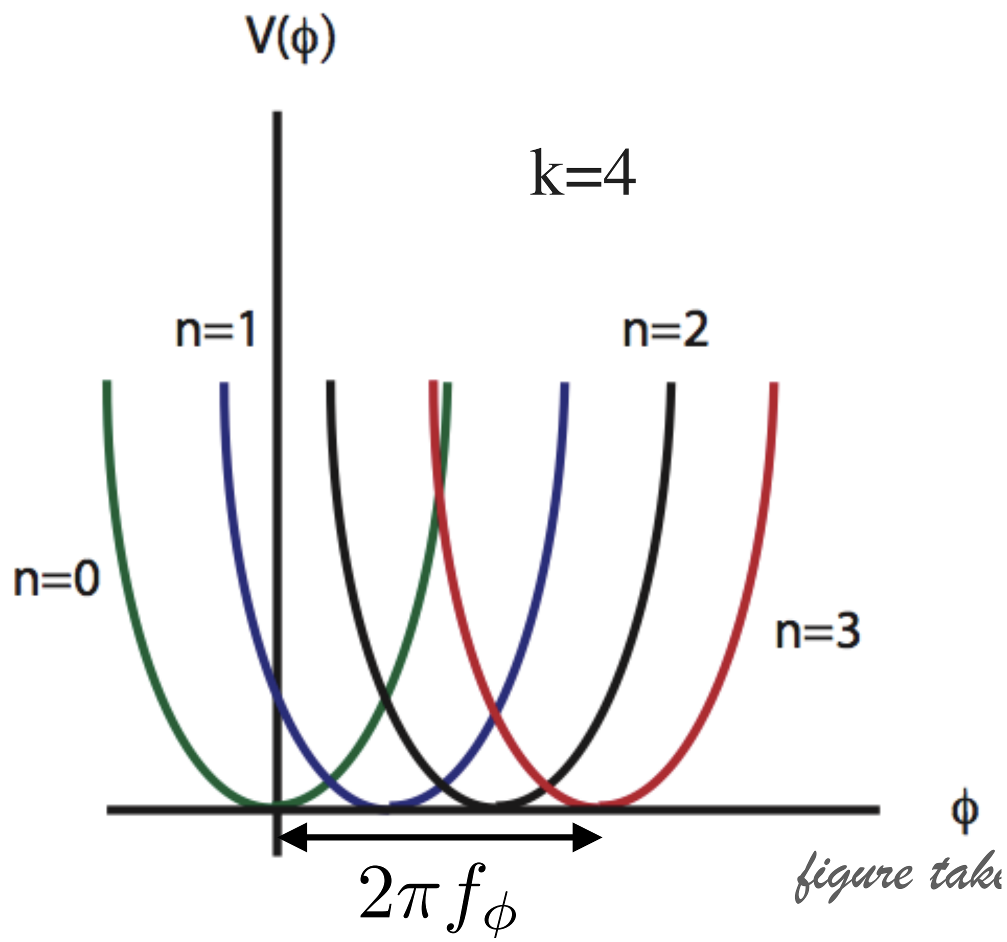
- These scenarios generically violate the Strong-WGC: "The LIGHTEST charged states satisfy $Q/M > 1$"
- Oscillations in power spectrum [Choi, Kim];[Kappl, Nilles,Winkler]

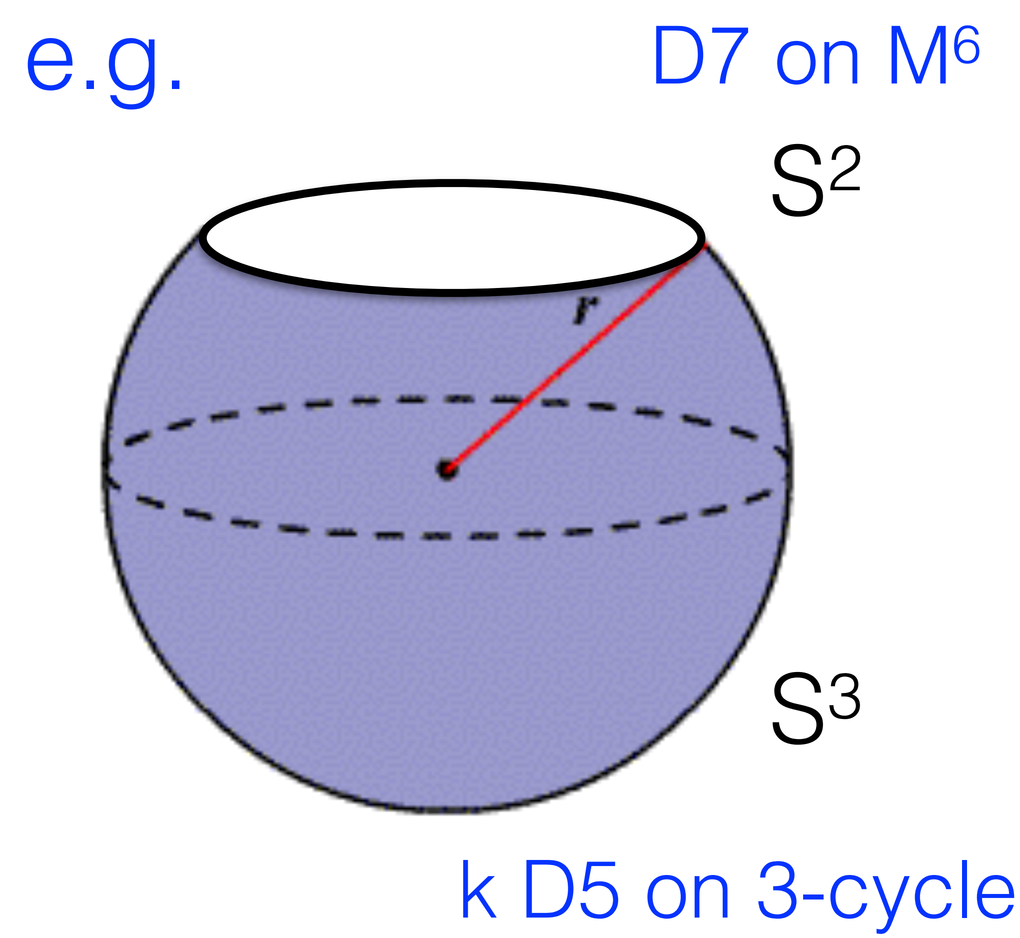
Further Evidences for the WGC

- ∞ manly stable remnants in a finite mass range lead to pathologies [Susskind]; WGC is a *stronger* requirement but
  - It is suggestive based on analyticity, unitarity of scattering amplitudes [Cheung, Remmen]
  - It seems compatible with holography [Nakayama, Nomura]
- For WGC to be compatible w/ dim. reduction, an *even stronger form* (lattice WGC) [Heidenreich, Reece, Rudelius], than our original strong form, was proposed.
- Attempts to evade the WGC (including our loophole) amount to hiding our ignorance about the UV.
- Realizing large field inflation in string theory to tame UV sensitivity; burden of proof on claim of counterexamples.

Axion Monodromy

- Axion is mapped to a ***massive*** gauge field.
- Possible tunneling to different branches of the potential:





- Suppressing this tunneling can lead to a bound on field range (hence r)

Brown, Garcia-Etxebarria, Marchesano, GS, in progress

Conclusions

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- Inflation is sensitive to UV physics. Large field inflation requires *even more input* from quantum gravity.
- F-term axion monodromy inflation
- We have made the WGC precise for (a large class of) axions which can be dualized to U(1) gauge fields.
- Constraints on multiple axions in terms of convex hull (bound on the “diameter” of axion space):
  - KNP, N-flation, kinetic mixing,…

Conclusions

- Exciting interface between BH in quantum gravity and inflation.

- Profound connections to quantum gravity promise to illuminate black holes, inflation, and string theory.

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THANKS