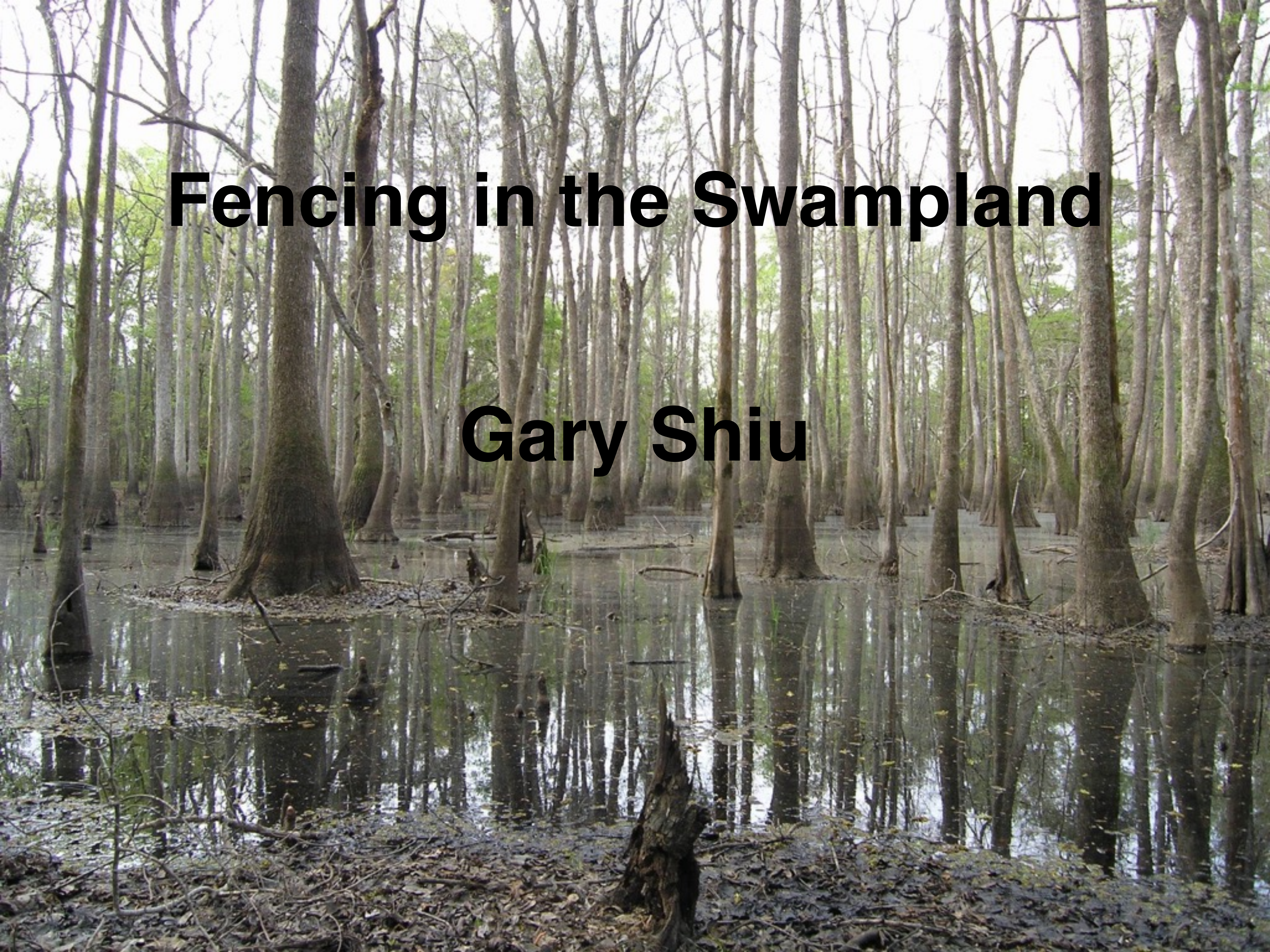
Fencing in the Swampland

Gary Shiu



The Fencing Team

Jon Brown

Billy Cottrell

Pablo Soler

J. Brown, W. Cottrell, GS and P. Soler,
arXiv:1503.04783 [hep-th],
arXiv:1504.00659 [hep-th].

Prologue

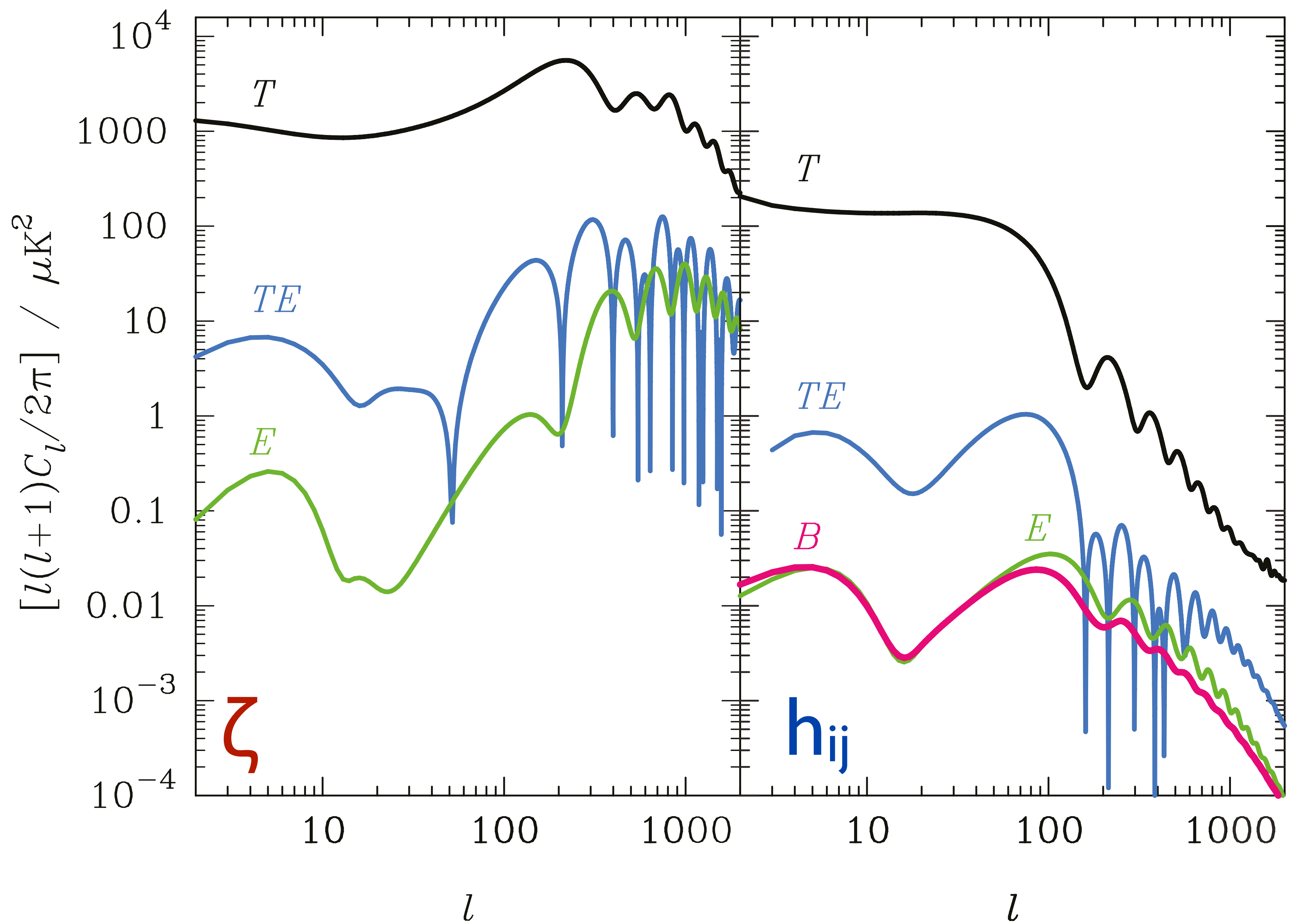
- String Pheno is 14-th and is going strong:
  - BSM scenarios of particle physics and cosmology have found their UV embedding in string theory.
  - Many new scenarios have been uncovered.
- The other side of the question is equally interesting:
  - Are there low energy theories that are ***not*** UV completable in quantum gravity?

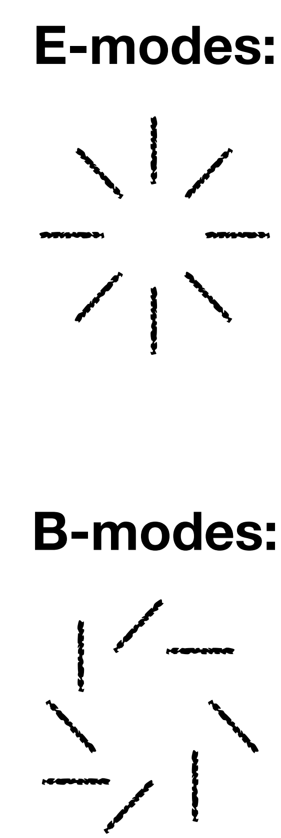
WTF with the Swampland?


Where are The Fences
within the Swampland?

Where are The Fences within the Swampland?

Gravity Waves and CMB Polarization





Many experiments including BICEP/KECK, PLANCK, ACT, PolarBeaR, SPT, SPIDER, QUEIT, Clover, EBEX, QUaD… can potentially detect such primordial B-mode if r≲10^{-2}.

LiteBIRD may even have the sensitivity to detect r ~ 10^{-3}.

Large Field Inflation

- Detectable r suggest super-Planckian field range $\Delta\Phi > M_P$

D. Lyth '96

- Chaotic $m^2\phi^2$ inflation **[Linde, '86]** & natural inflation **[Freese et al, '90]** are radiatively stable, but coupling to UV dofs:

- Large field inflation is highly sensitive to UV physics.

Axions & Large field inflation

- Axions seem ideal inflaton candidates: V protected by a perturbatively exact global symmetry:

$$\phi \sim \phi + c \quad \Longrightarrow \quad V^{(p)} = 0$$

Natural Inflation:
Freese et. al '90

- Non-perturbative potential:

$$V(\phi) = \sum_k c_k \, e^{-km} \left[1 - \cos\left(\frac{k\phi}{f} \right) \right]$$

  - Broken shift symmetry: $\phi \sim \phi + c \quad \longrightarrow \quad \phi + 2\pi f$

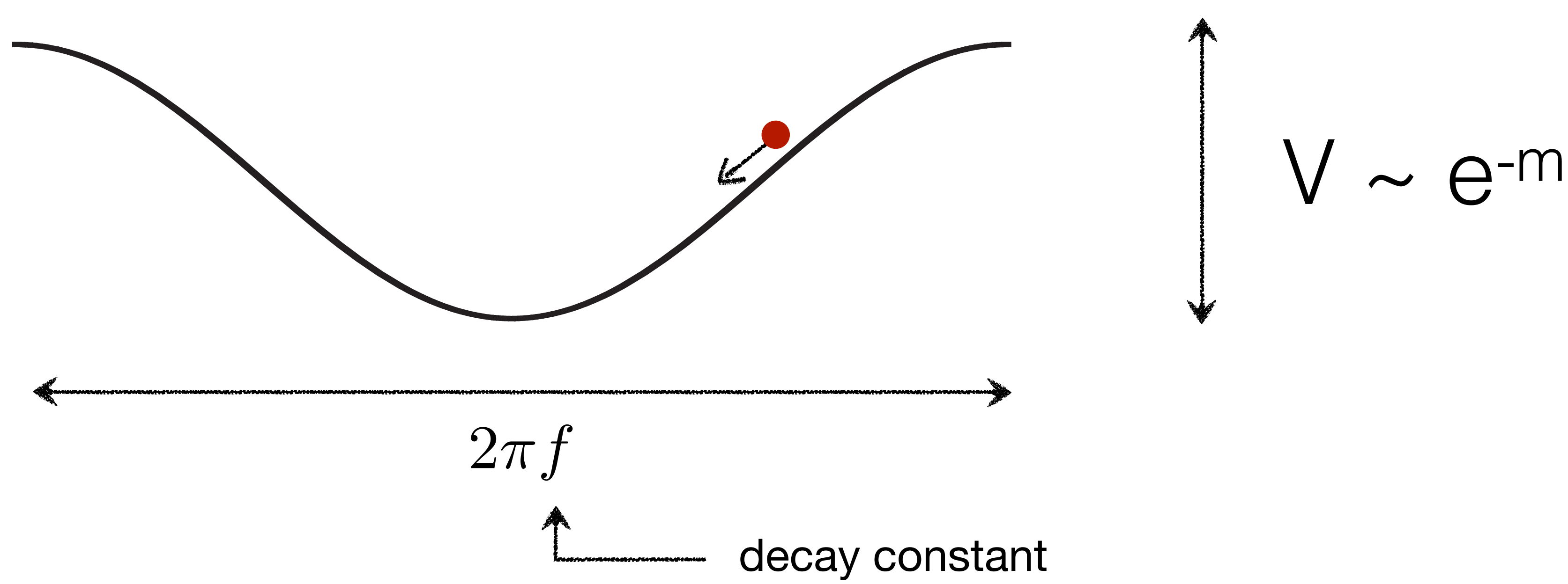
- Controlled, slow-roll potential: $e^{-m} \ll 1 \,, \quad f > M_p$

$$\boxed{f \cdot m > M_p}$$

Axions & Large field inflation

However…

- $f \cdot m \gg M_p$ the global symmetry becomes effectively exact.



- Quantum gravity dislikes and violates global symmetries

Kallosh et al. ‘95

Axions & Large field inflation

- Axions are abundant in string compactifications, e.g.

$$b^i = \int_{\Sigma_2^i} B_2 \ , \qquad c^i = \int_{\Sigma_p^i} C_p$$

- Large decay constants do not seem to arise

  - Either $f < M_P$

  - Or higher harmonics become important (and new light states appear)

$$e^{-m} \sim 1$$

Banks et al. '03
Svrcek, Witten '06

Multiple Axions

Can the collective effort of N axions evade the no-go?

Multiple Axions

Aligned Axions

Kim Nilles, Peloso ‘04;
Choi et al. ’14;
Junghans ’15;…

N-flation

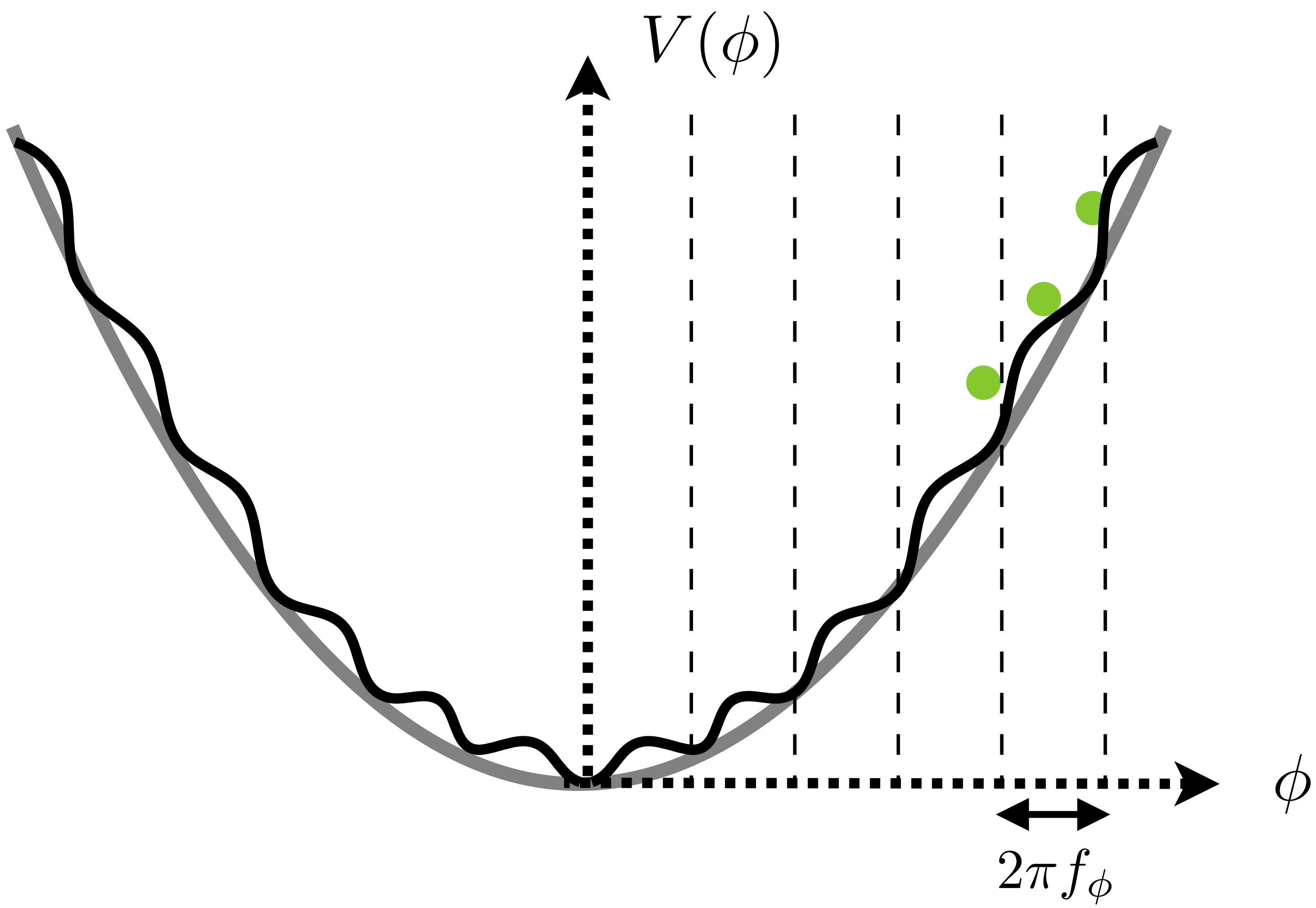
Dimopoulos et al ’05;
…

Kinetic Mixings

Bachlechner et. al ’14–’15
GS, Staessens, Ye, ’15;
…

Extend the effective _*kinematic*_ field range of axions

Axion Monodromy



via brane coupling [Silverstein, Westphal '08];[McAllister, Silverstein, Westphal '08]; …, or flux potential [Marchesano, GS, Uranga '14];[Blumenhagen, Plauschinn '14]; [Hebecker, Kraus, Witowski, '14];[McAllister, Silverstein, Westphal, Wrase '14]; …

A single axion with a *perturbative* mass

See talks of Blumenhagen, Hebecker, Silverstein,…

Multi-axion Inflation

- Recent efforts into evading such constraints with

Multiple Axions

- Aligned axions: $\phi\,,\ \rho$

KNP '04; ...

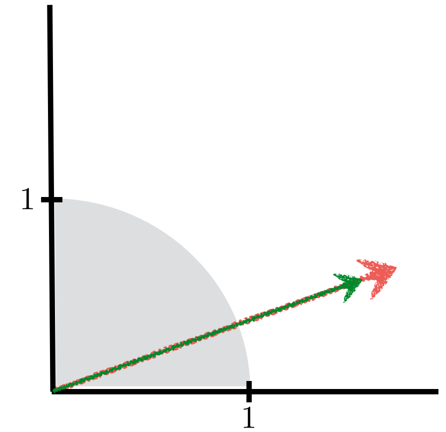
$$V(\phi,\rho)=\Lambda_1\left[1-\cos\left(\frac{\phi}{f_1}+\frac{\rho}{g_1}\right)\right]+\Lambda_2\left[1-\cos\left(\frac{\phi}{f_2}+\frac{\rho}{g_2}\right)\right]$$

$f_1/g_1=f_2/g_2$

$f_\perp\to\infty$

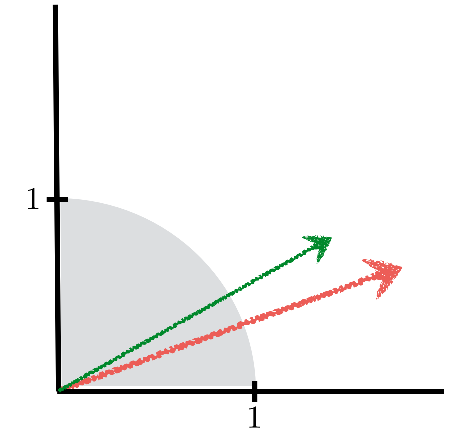
$f_1/g_1\approx f_2/g_2$

$f_\perp\gg M_P$



$$\vec{z}_1=\begin{pmatrix}1/f_1 & 1/g_1\end{pmatrix}$$

$$\vec{z}_2=\begin{pmatrix}1/f_2 & 1/g_2\end{pmatrix}$$



Multi-axion Inflation

- Recent efforts into evading such constraints with

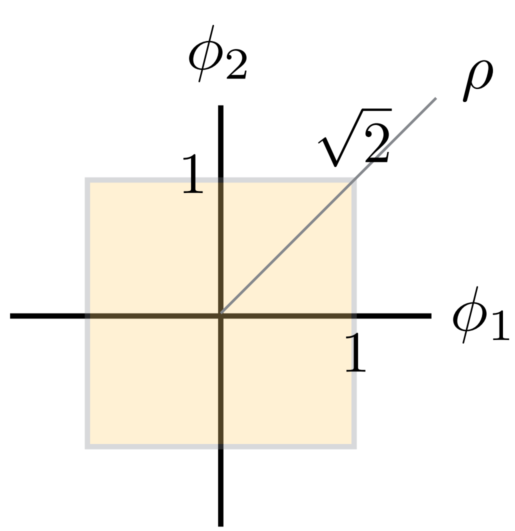
Multiple Axions

- N-flation: N axions ϕ_i Dimopoulos et al. '08

$$V(\phi_i) = \sum_i \Lambda_i \left[1 - \cos\left(\frac{\phi_i}{f}\right)\right]$$

- Large decay constant along the "radial" direction:

$$\rho^2 = \sum_i \phi_i^2 \qquad f_\rho^{(eff)} \sim \sqrt{N} f$$



Multi-axion Inflation

- Recent efforts into evading such constraints with

Multiple Axions

- Generically: large-N, KNP-alignment, kinetic mixing

$$(\Delta\rho)_{max} \sim \begin{cases} N^p f\,, & p \geq 1/2 \\ n^N f & \end{cases}$$

Choi et al. '14
Bachlechner et. al '14
Junghans '15

- Even if $f \ll M_p$, it seems possible that $(\Delta\rho)_{max} \gg M_p$

Axions & Large Field Inflation

- Is there a fundamental reason why models with a single axion have small decay constants?

$$m \cdot f < M_P$$

- If so, can multi-axion models (or axion monodromy) evade it?

- Input from quantum gravity & string theory needed

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

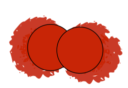
- Take a U(1) and a single family with q < m (~~WGC~~)

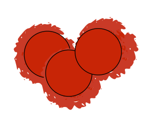
$M_P \equiv 1$

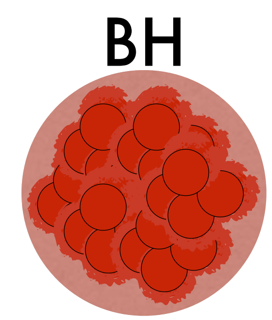
The Weak Gravity Conjecture

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

- Form bound states







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

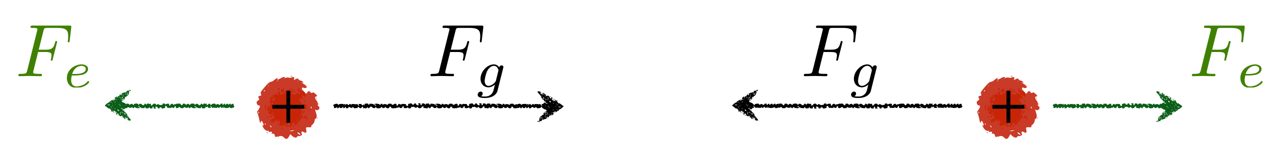
- All these (BH) states are stable. Trouble w/ remnants

Susskind '95

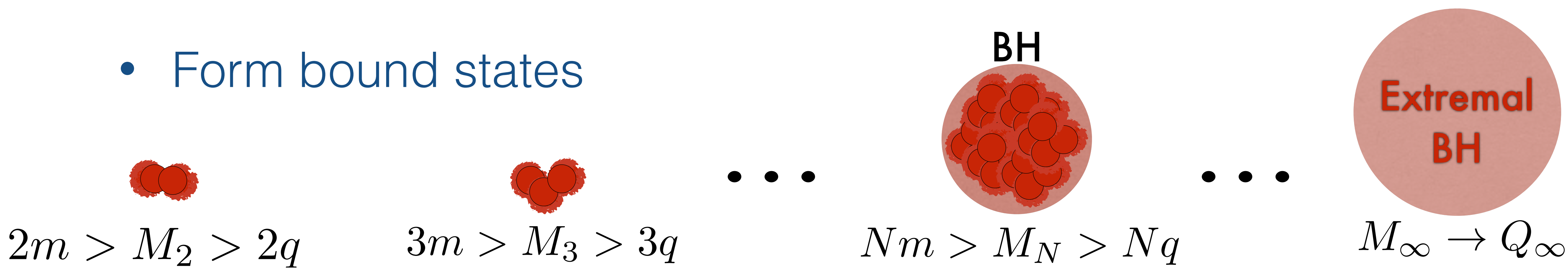
$M_P \equiv 1$

The Weak Gravity Conjecture

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



  - Form bound states



  - 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

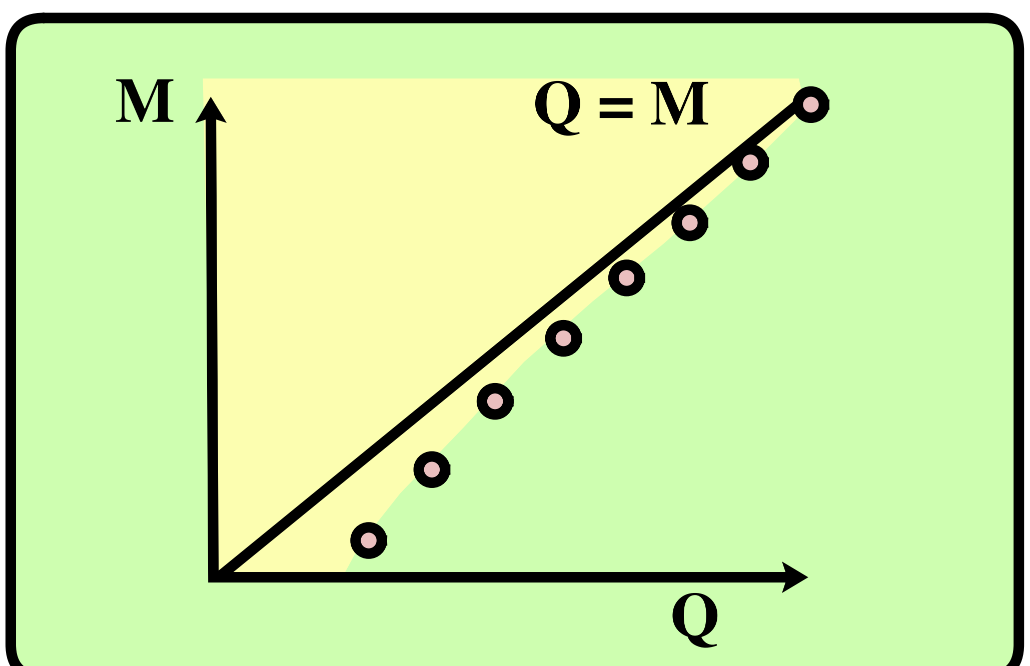
Arkani-Hamed et al. '06

- 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



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 $f > M_P$

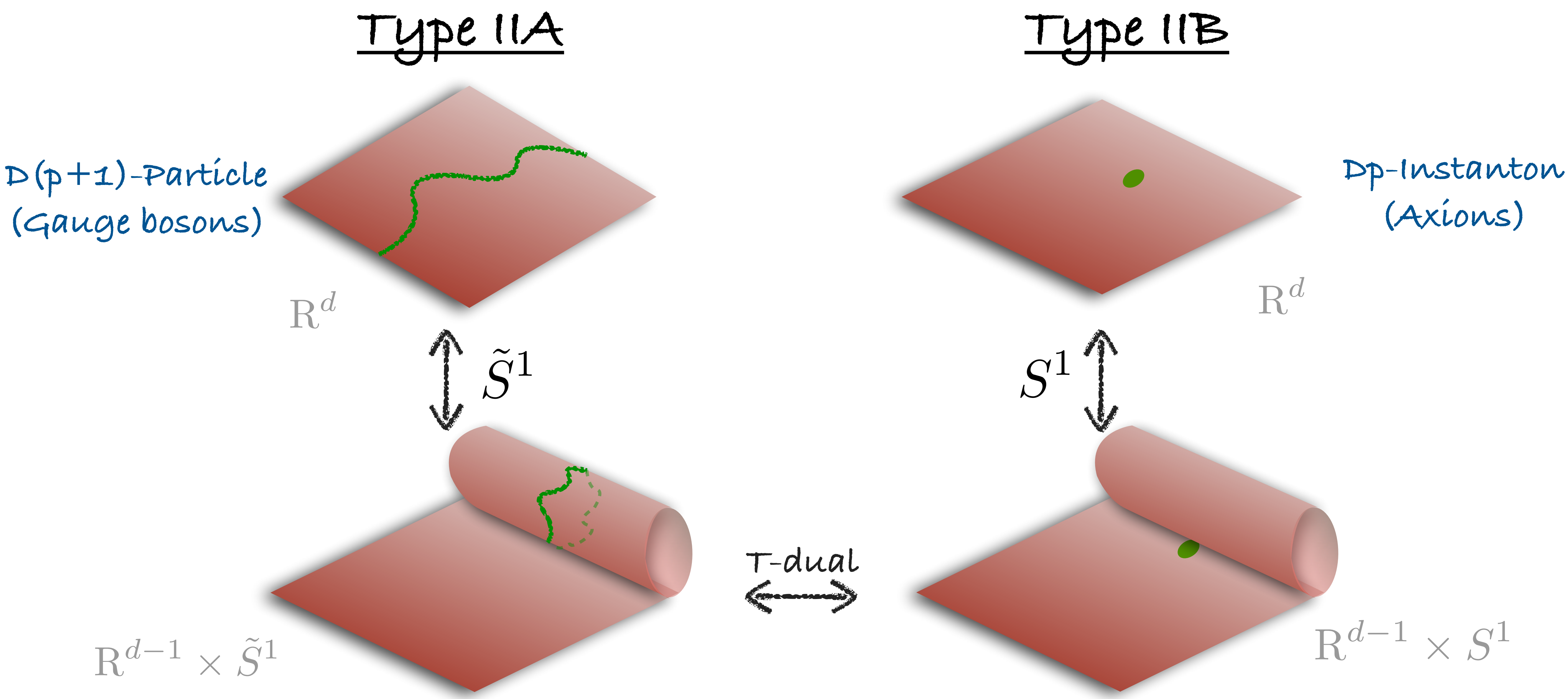
- Is there evidence for the p=-1 version of the WGC?

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

Gauge fields: $A_i \sim \int_{\Sigma_2^{(i)}} C_3$

Particles: D2 on $\Sigma_2^{(i)}$

WGC

$$\tilde{m}_k = m_k \frac{\sqrt{g_{33}}}{2\pi\, l_s}$$

$$\tilde{q}_k^i = (f_k^i)^{-1} \frac{\sqrt{2}}{4\pi\, l_s}$$

"Couplings":

$$\tilde{g}_s = \frac{g_s}{\sqrt{g_{33}}}$$

$$\tilde{M}_P = M_P \sqrt{g_{33}}$$

Type IIB

Axions: $\phi_i \sim \int_{\Sigma_2^{(i)}} C_2$

Instantons: D1 on $\Sigma_2^{(i)}$

$$S_{inst_k} \sim -m_k + i(f_k^i)^{-1}\phi_i$$

"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:

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

WGC and Axions

Brown, Cottrell, GS, Soler

4d Type IIB D1-instantons	**4d Type IIA D2-particles**	**5d M-theory M2-particles**
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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

Multiple Axions/
Multiple U(1)'s

WGC and Axions

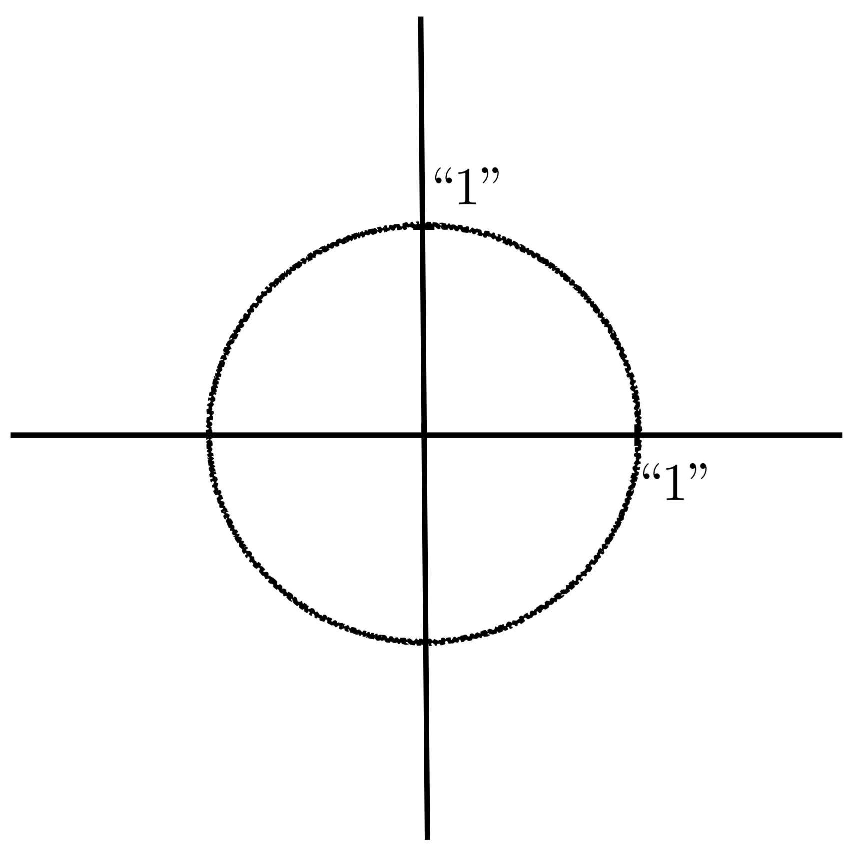
Brown, Cottrell, GS, Soler '15
Cheung, Remmen '14
Rudelius '15

Multiple axions/U(1)s

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

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

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



WGC

WGC and Axions

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

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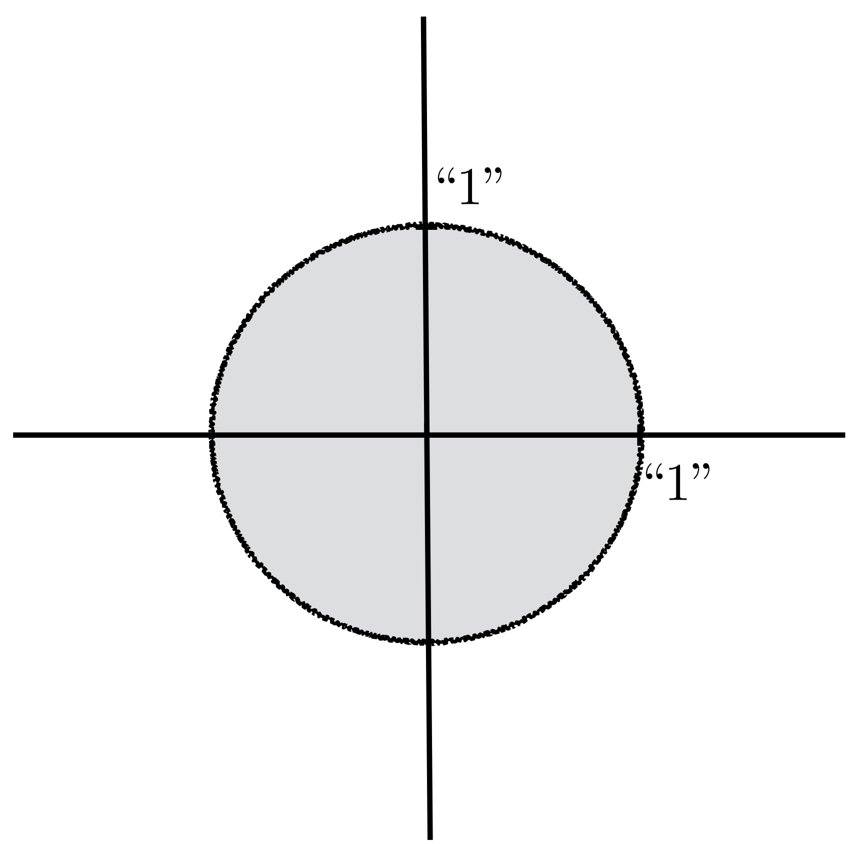

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$$|\vec{z}_{EBH}| \equiv \text{“1”}$$

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$$\vec{z}_{p1} \geq (\text{“1”} \;\; 0)$$

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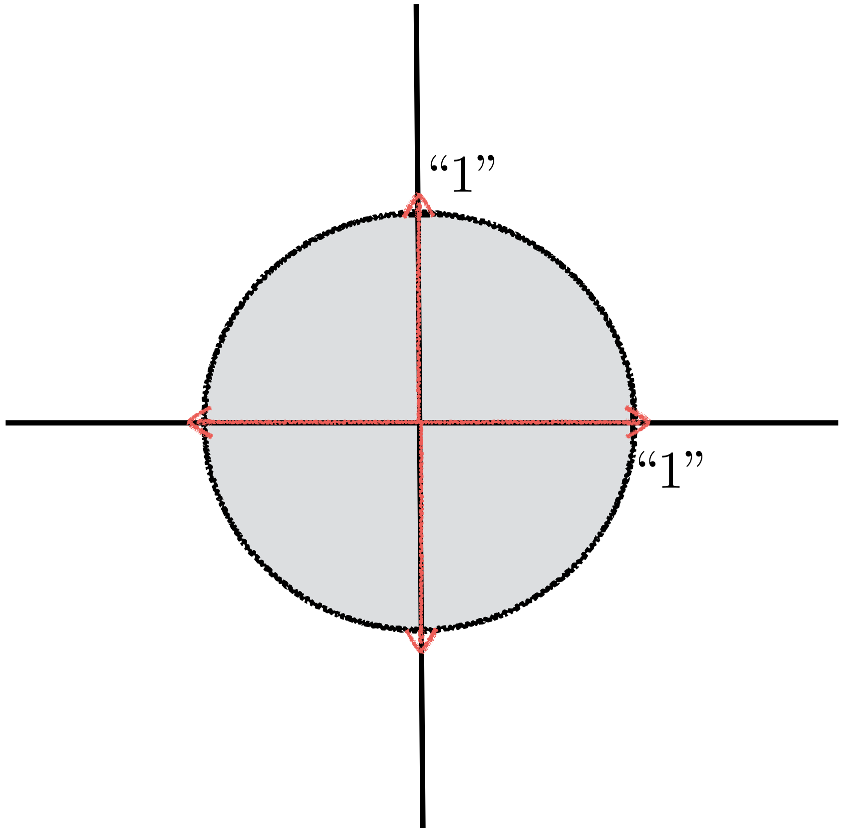

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WGC and Axions

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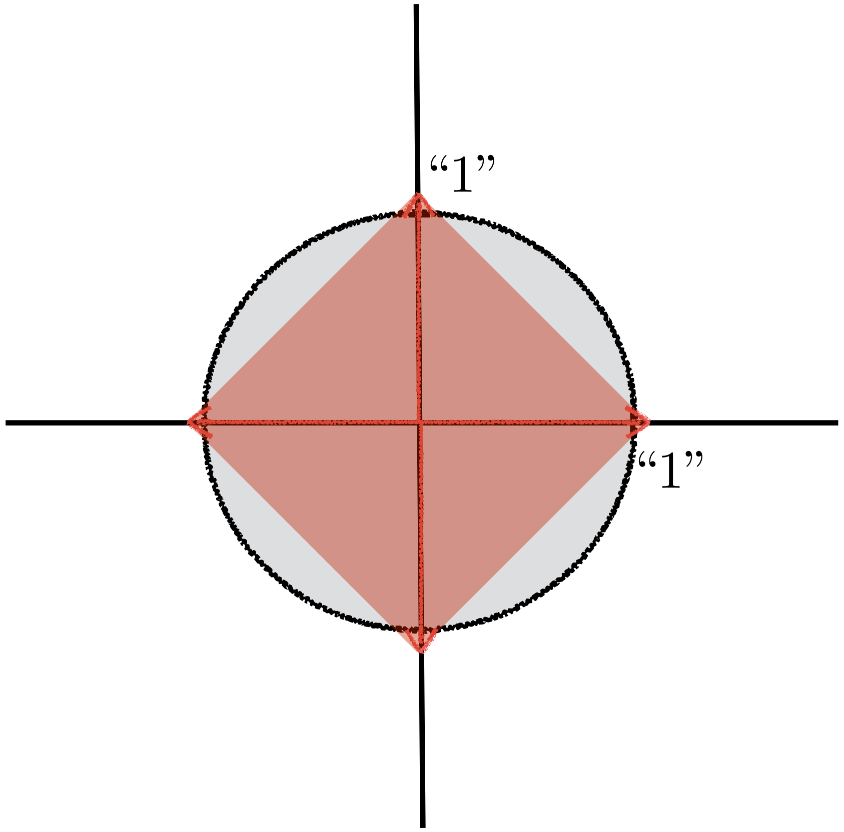

WGC

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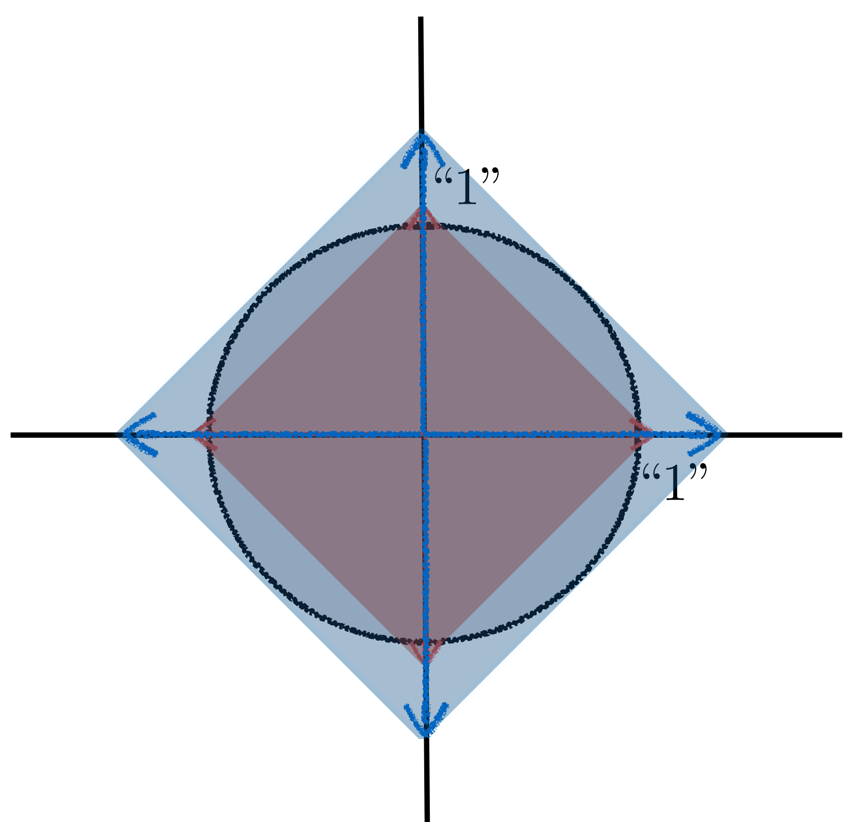

WGC

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WGC and Axions

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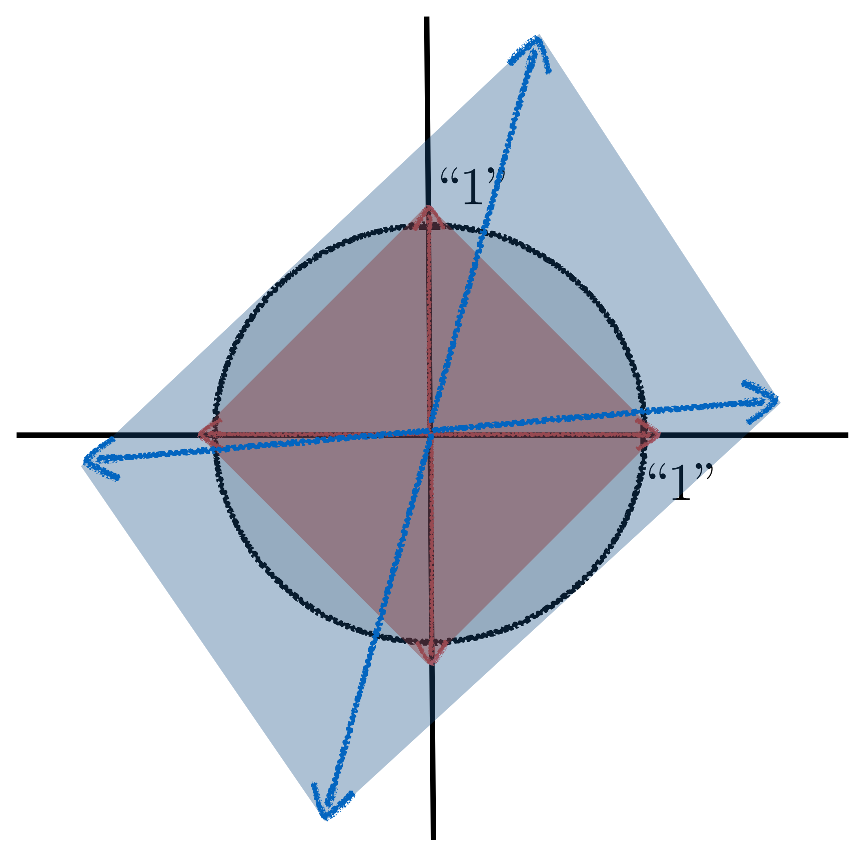

WGC

$$\vec{z}_{p1} \geq \begin{pmatrix} \text{“1”}\sqrt{2} & 0 \end{pmatrix}$$

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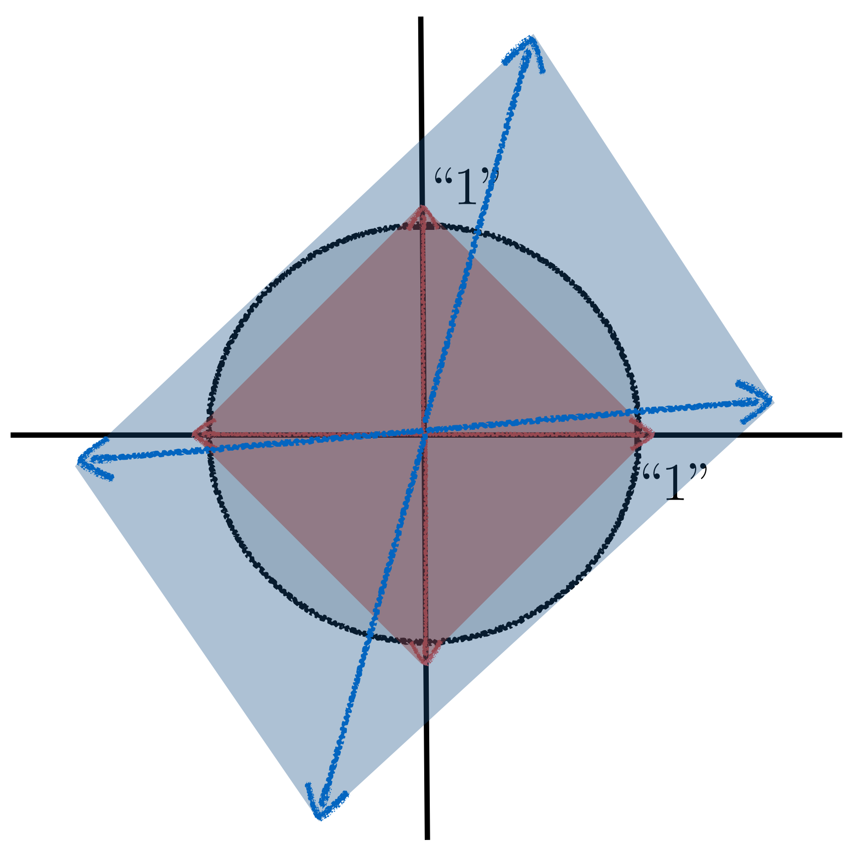

WGC

$$|\vec{z}| = \text{“1”}$$

$$\cap$$

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

WGC and Axions

Multiple axions/U(1)s

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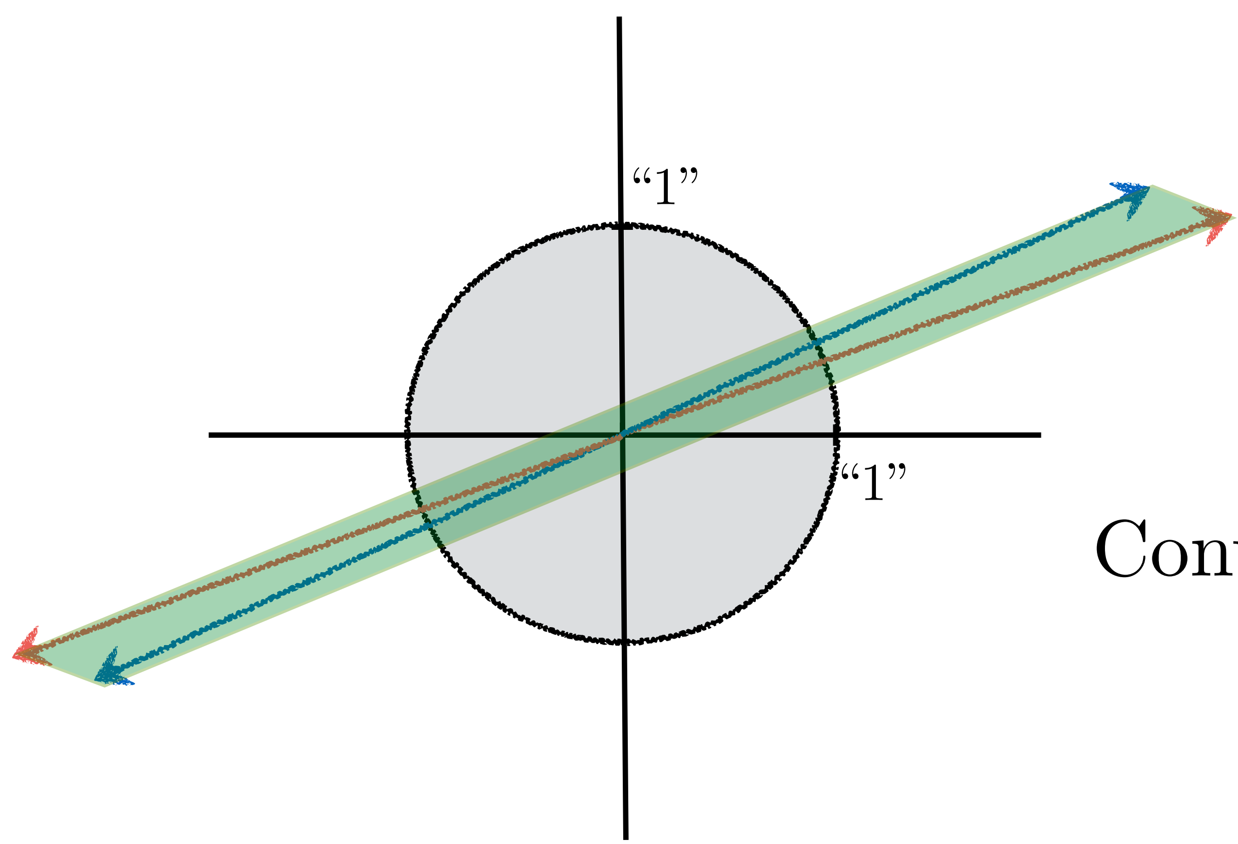
KNP



WGC

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

WGC and Axions

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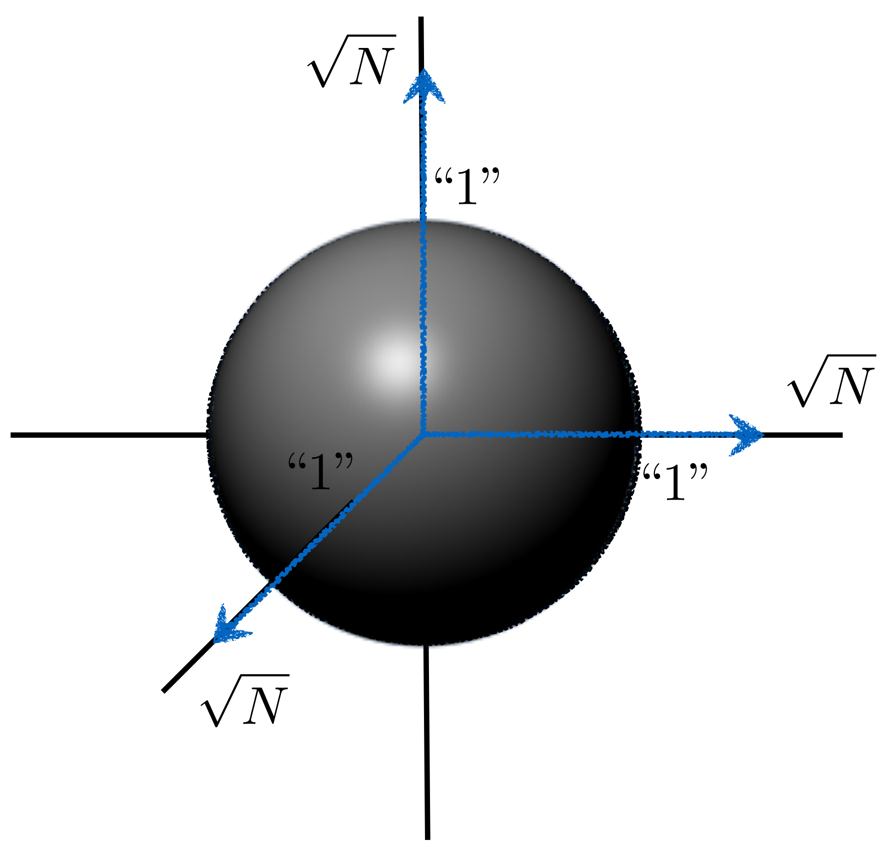
N-flation

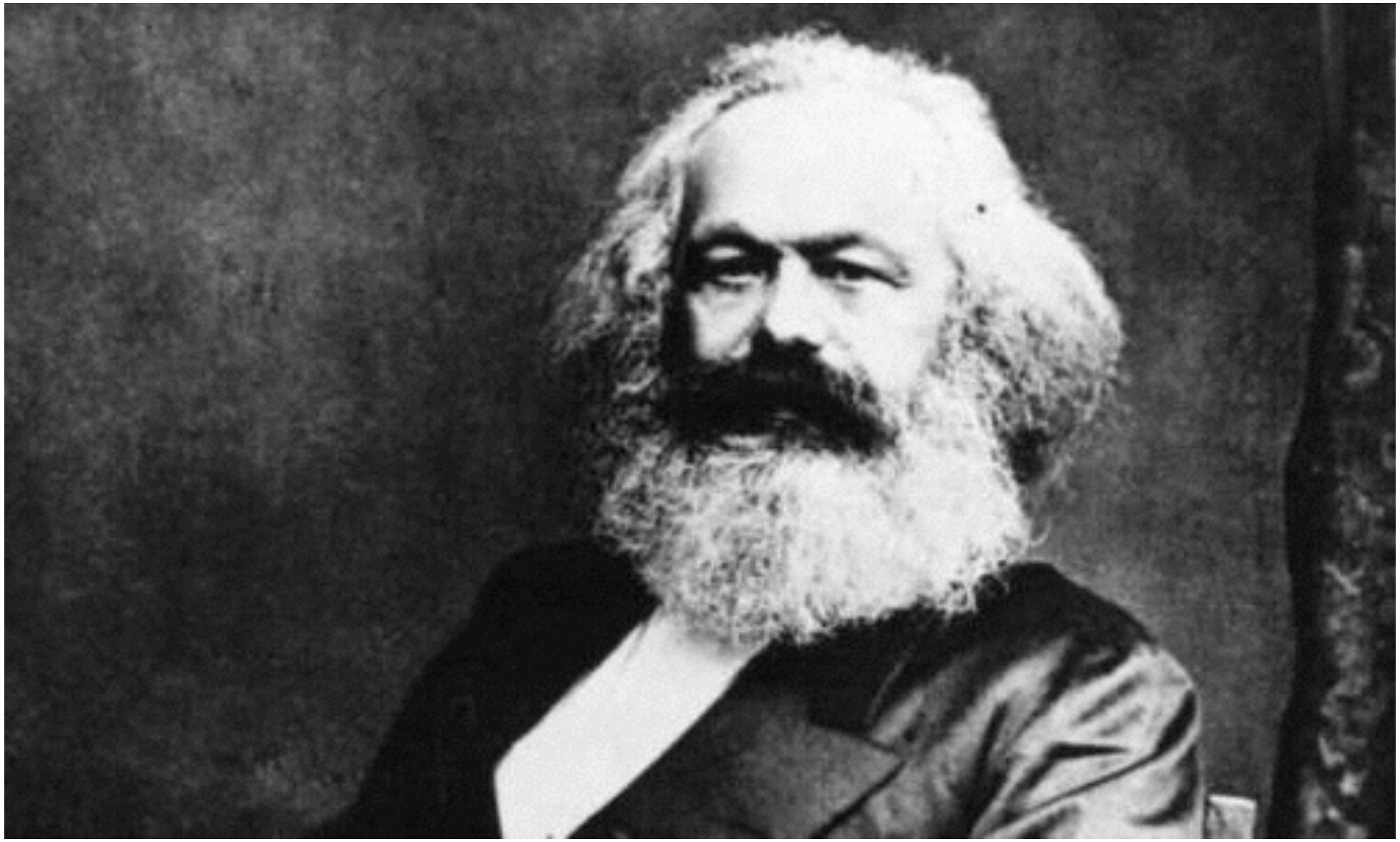
$$z_i^k \geq \sqrt{N}\delta_i^k$$



WGC

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

WGC and Multi-axion Inflation



While collective effort can achieve greatness,
it is prompt to corrective action.

Our conclusions agree with gravitational instanton diagnostics of
[Montero, Uranga, Valenzuela '15]

Is there a way around this?

Loophole suggested in Brown, Cottrell, GS, Soler

A possible loophole

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

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

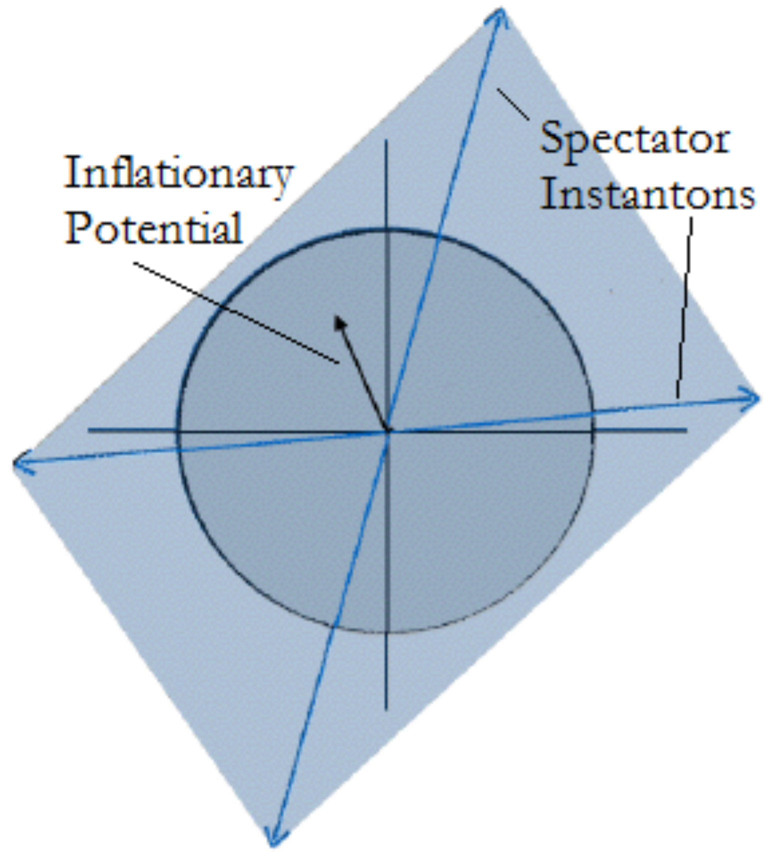
With $1 < m \ll M, \qquad F \gg M_P > f, \qquad M \times f \ll 1$

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

Possible implementation in Hebecker et al ‘15, see talks of Hebecker, Witkowski

A possible loophole

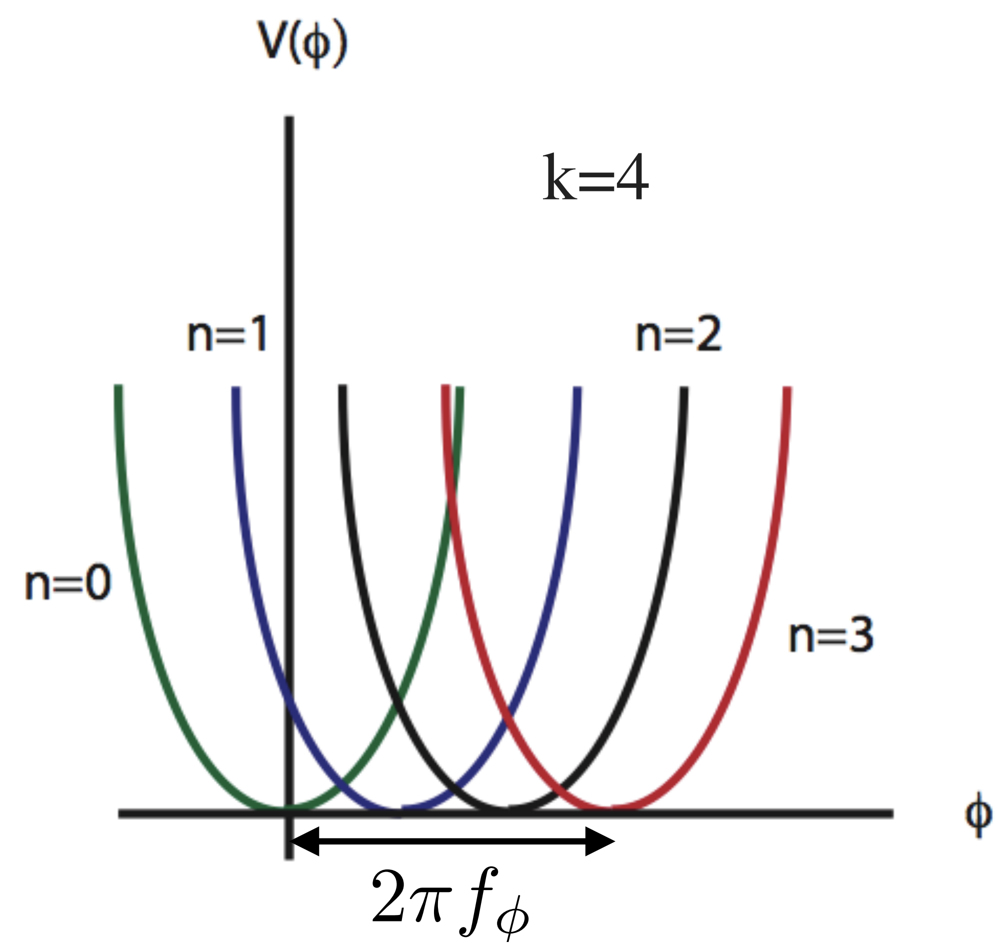
- In the presence of “spectator” (negligible) instantons that fulfill the WGC, dominant instantons can generate an inflationary potential



- These scenarios generically violate the Strong-WGC: “The LIGHTEST charged states satisfy $Q/M > 1$“

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

Conclusions

- Weak Gravity Conjecture applies to (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 “diameter” as used by **[Bachlehner et al]**):
    - KNP, N-flation, kinetic mixing,…

- Strong vs. Mild-WGC
    - The strong-WGC forbids certain large field models.
    - If the strong-WGC is violated, a loophole allows relatively large field ranges

More in Soler’s talk

Gracias!