Relaxion Monodromy and the Weak Gravity Conjecture

Universiteit Utrecht

Irene Valenzuela

Max Planck Institute for
Physics, Munich

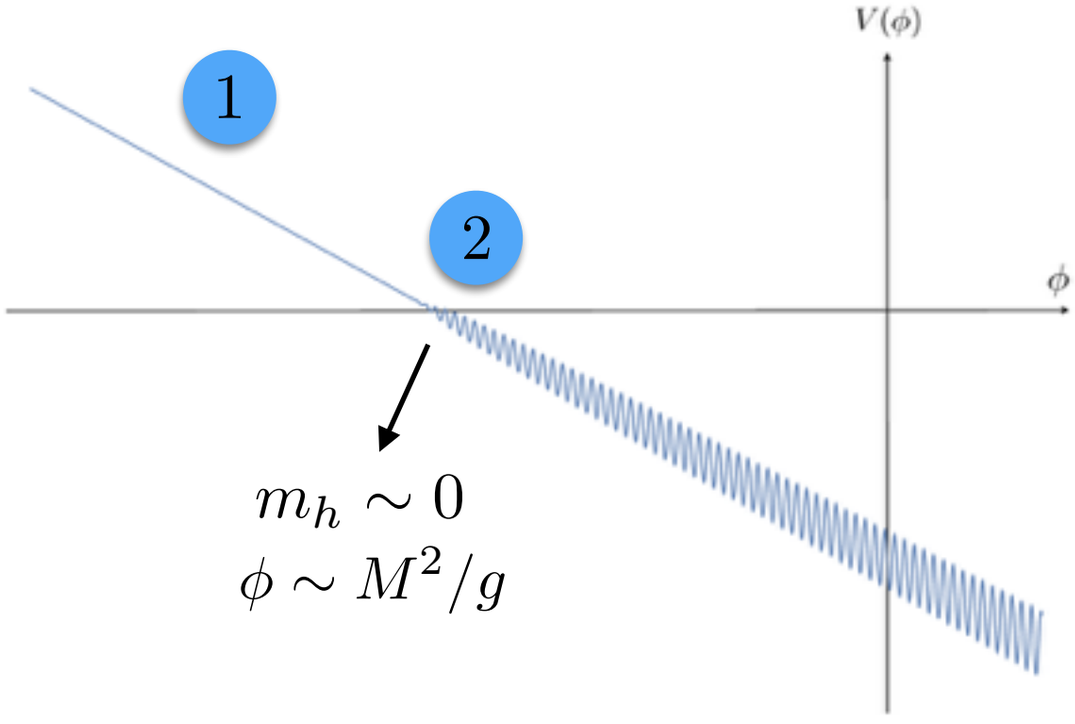
L. Ibáñez, M. Montero, A. Uranga, I.V., [arXiv:1512.00025 [hep-th]]

StringPheno 2016, Ioannina

Cosmological relaxation

Dynamical solution to the EW hierarchy problem:

$$V = V_0(g\phi) + (-M^2 + g\phi)|h|^2 + \Lambda^4(h)\cos\left(\frac{\phi}{f}\right)$$ [Graham,Kaplan,Rajendran'15]



1 Slow-roll controlled by $V_0(g\phi)$

2 At $m_h \sim 0 \longrightarrow$ EWSB $\longrightarrow$
$\Lambda(h) \neq 0 \longrightarrow$ stabilises ϕ
shortly after it

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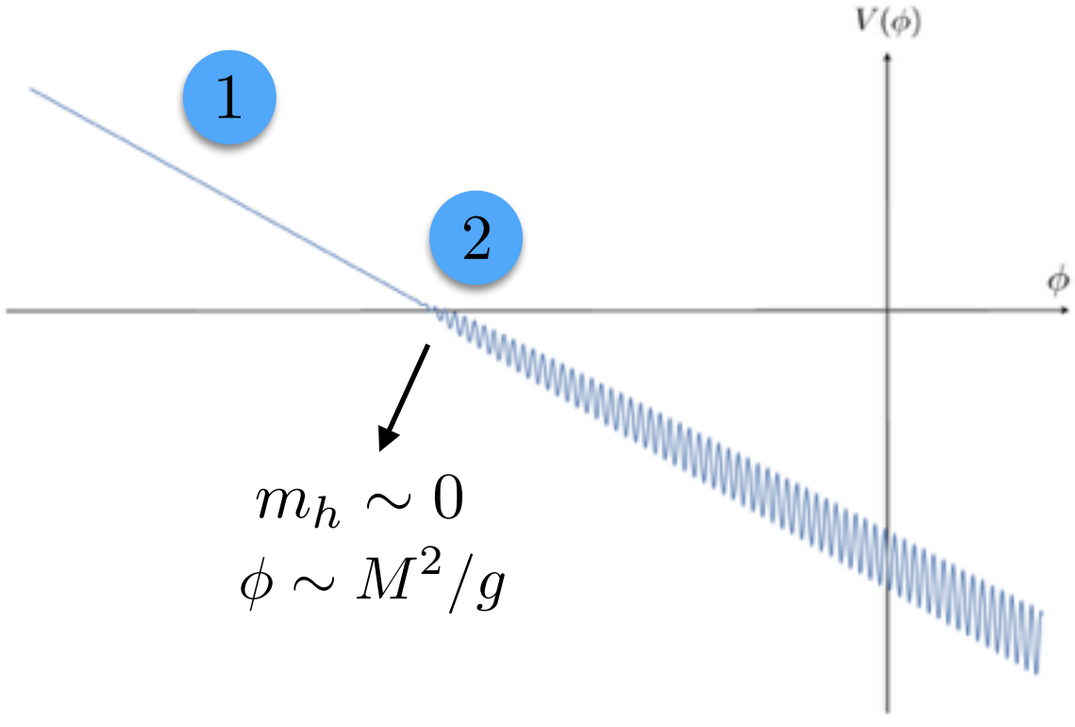

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Barriers form and stabilise the relaxion if:

$$gM^2 \sim \frac{\Lambda^4(h=v)}{f} \longrightarrow g \sim 10^{-16}\,\frac{m_{\rm EW}^2}{M^2}\ {\rm GeV}$$ Very small coupling!

$$\Delta\phi \gtrsim M^2/g \gg M_p$$ Transplanckian field range!

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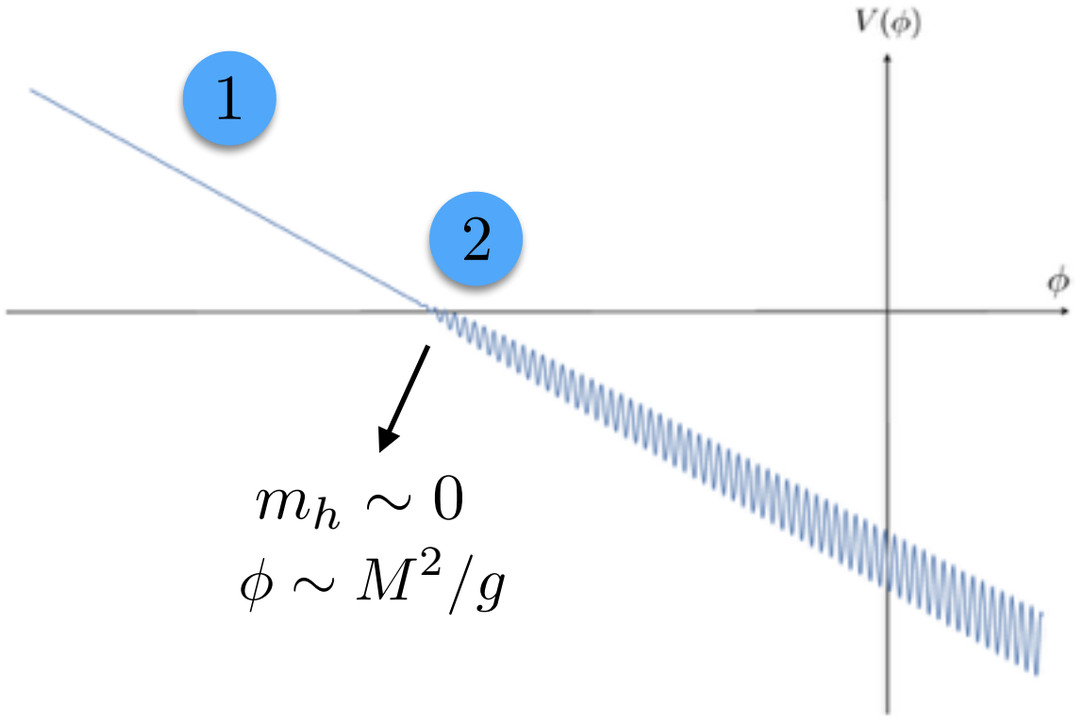

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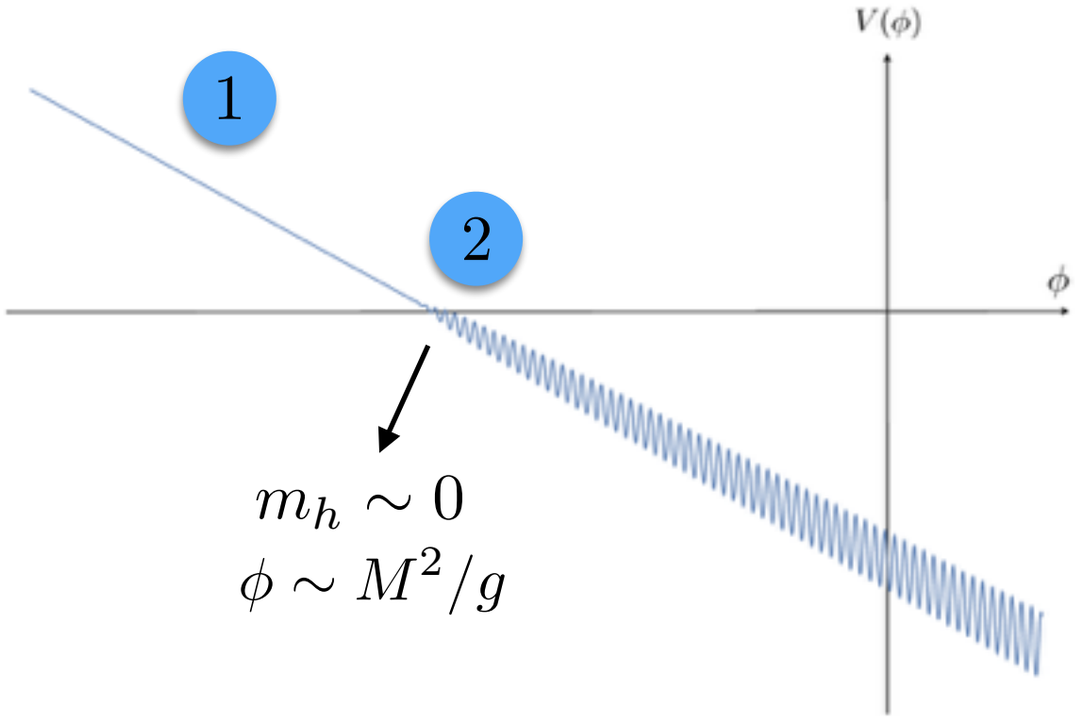

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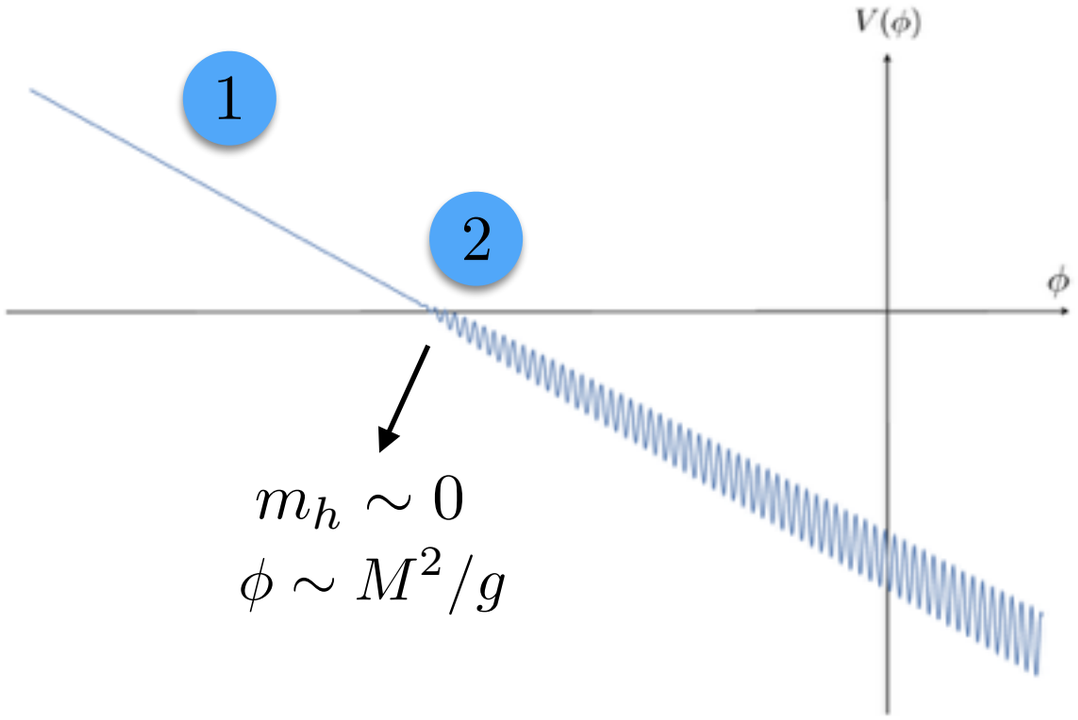

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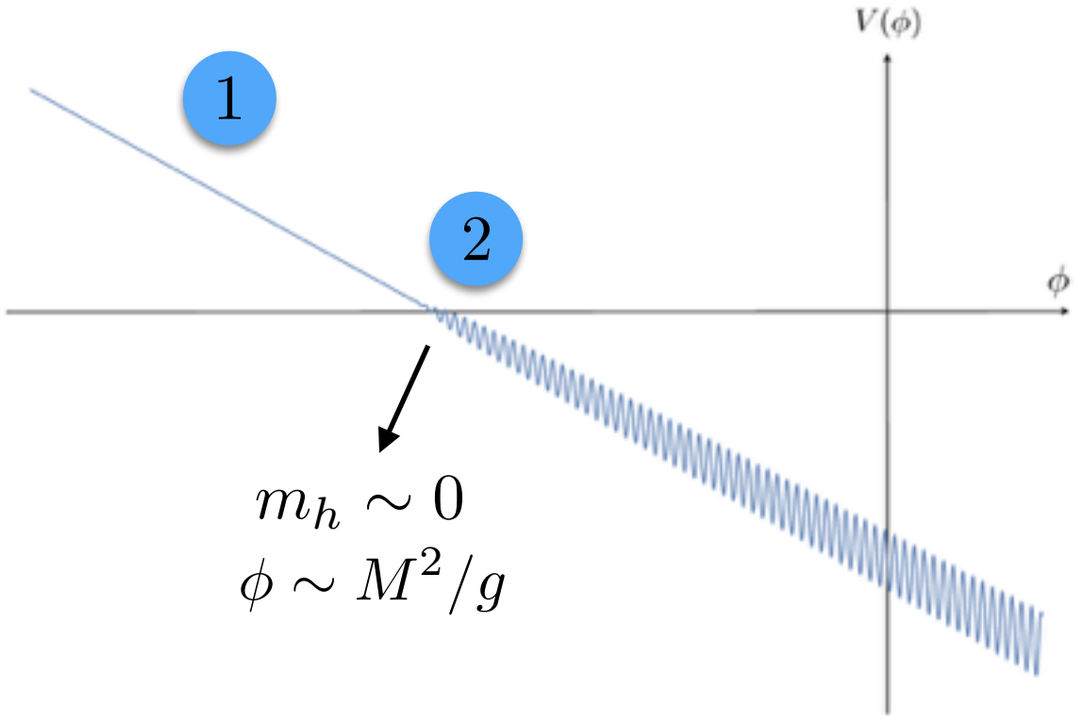

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Very similar to axion monodromy inflation

Goal: UV completion of cosmological relaxion using monodromy

Axion Monodromy

How can we induce potential terms for an axion while preserving the discrete shift symmetry?

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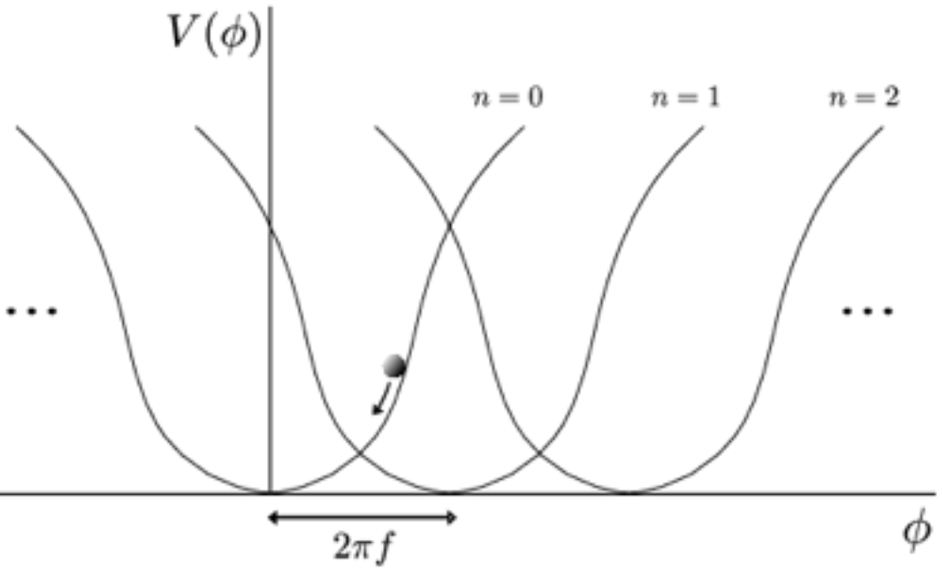
ϕ is an axion with multi-branched (monodromic) potential

By coupling the axion to a 3-form gauge field: $F_4 = dC_3$



$$L = -\frac{1}{2}(\partial_\mu \phi)^2 - \frac{1}{2}|F_4|^2 + g\phi F_4$$

Integrating out C_3

$$*F_4 = f_0 + g\phi \longrightarrow V_{KS} = \frac{1}{2}(f_0 + g\phi)^2$$

[Dvali'05]
[Kaloper,Sorbo'09]

we get a multi-branched potential invariant under

$$\phi \to \phi + 2\pi f \quad , \quad f_0 \to f_0 - 2\pi g f$$

Axion Monodromy

- Potential stable against higher dimensional operators (protected by gauge invariance)

$$\delta V \sim \sum_n V_0 (V_0/M^4)^n$$

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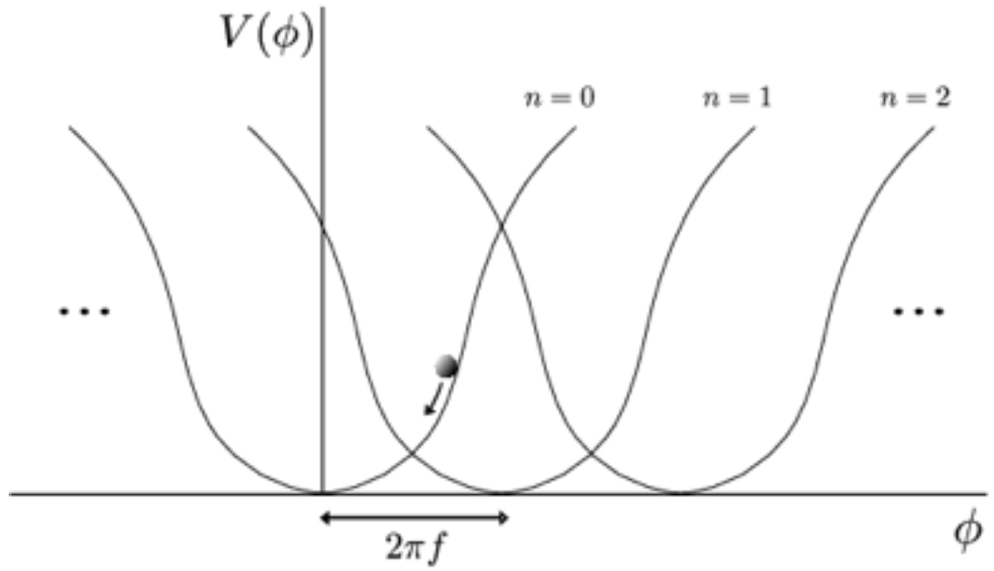

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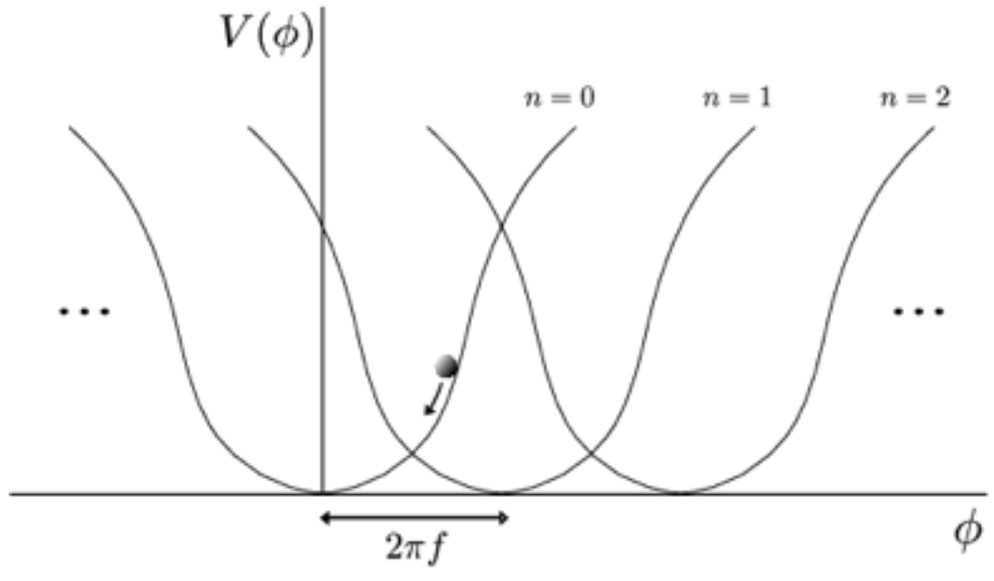

- Field range can not be arbitrarily large:

Tunneling between different branches mediated by membrane nucleation

In the presence of membranes: $\mathcal{L} \supset \Lambda_k^2 \int_{M_3} C_3$

- $\Delta f_0 = q\Lambda_k^2$ shifts when crossing a membrane of charge q
- Consistency condition: $2\pi f g = \Lambda_k^2$ [Kaloper,Sorbo,Lawrence'11]

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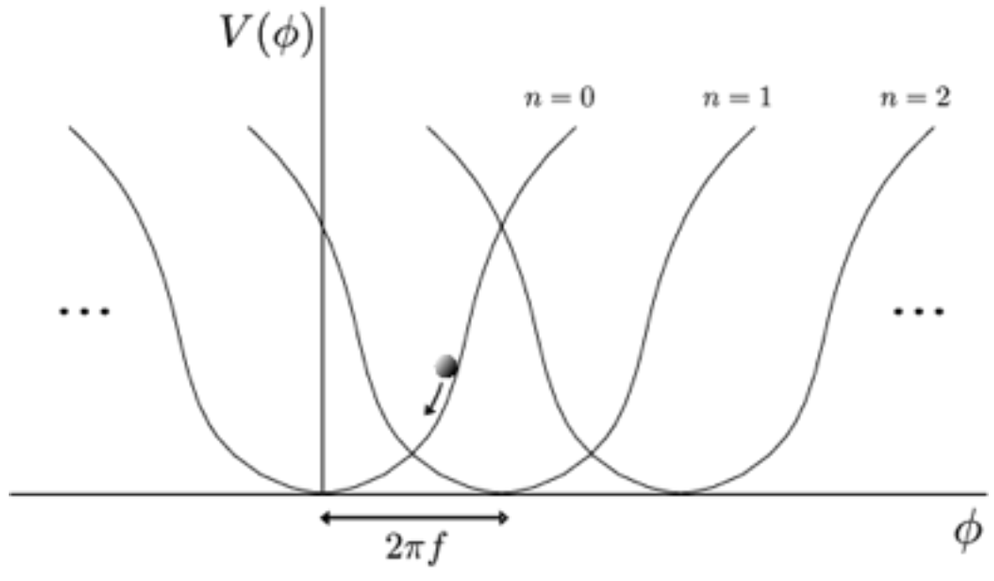

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Tunneling rate: $P \sim \exp(-B)$ with $B = \dfrac{27\pi^2 T^4}{2(\Delta V)^3}$ [Coleman'78] [Coleman,DeLuccia'80]

- Gravitational effects are important for relaxion.
- Additional correction due to the axion kinetic energy. [see Shiu's talk]

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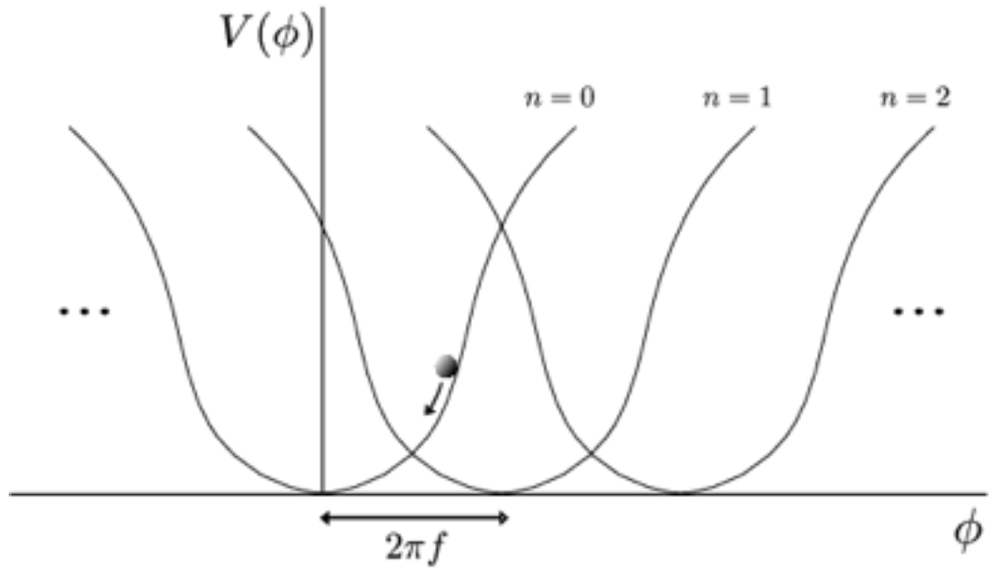

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How can we estimate the tension of the membranes?

- Concrete UV (stringy) examples [Brown,Cottrell,Shiu,Soler'15] [Franco,Galloni,Retolaza,Uranga'14]

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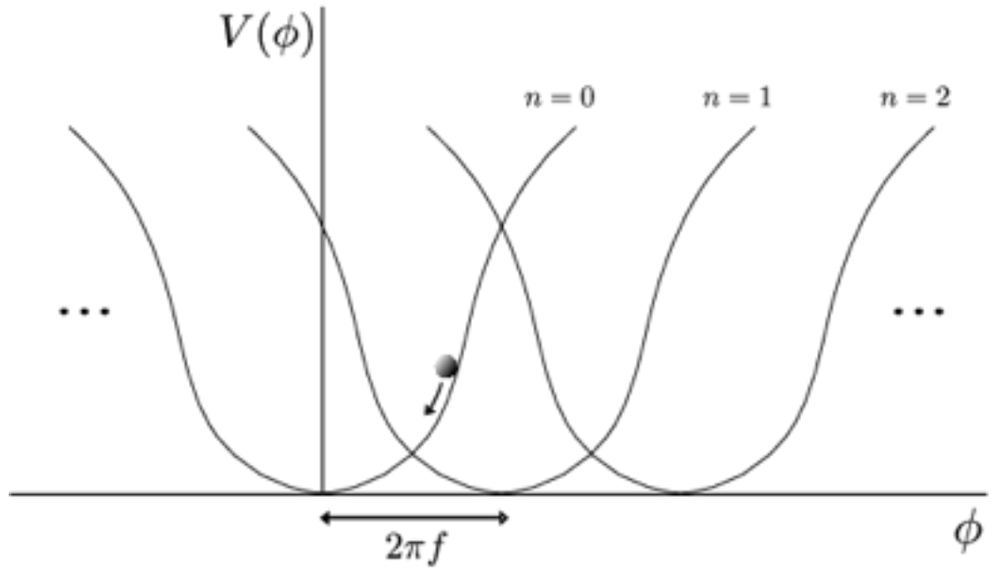

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- Weak Gravity Conjecture!

Weak Gravity Conjecture

For an abelian p-form gauge field there must exist a (p-1)-dimensional charged object which is superextremal, ie.

$$T \lesssim \frac{g_p Q}{\sqrt{G_N}}$$

[Arkani-Hamed et al.'06]

[Rudelius, Bachlechner, Long, McAllister, Ibanez, Montero, I.V., Uranga, Brown, Soler, Cottrell, Shiu, Hebecker, Mangat, Rompineve, Witkowski, Westphal, Junghans, Heidenreich, Reece, Palti, Kooner, Parameswaran, Zavala…]

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- Applied to a 3-form gauge field: $g_p = \Lambda_k^2 = 2\pi f g$

There must exist a membrane with tension lower than

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- Subtleties:

[Hebecker,Rompineve,Westphal.'16]

✦ No smooth solution within effective theory corresponding to a black membrane.

WGC applied to 3-forms can be justified by using string dualities.

[Brown,Cottrell,Shiu,Soler '15]

✦ Strong version of WGC (Lattice WGC) ⟶ We require presence of membrane of unit charge. [Heidenreich,Reece,Rudelius '15]

Not known counterexample in string theory.

Axion monodromy inflation: [Hebecker,Rompineve,Westphal.'16]

$$m \sim 10^{-6} M_p \ll \sqrt{f M_p}$$ Tunneling rate exponentially suppressed

$$B \sim \frac{M_p f}{m^2} \frac{M_p^3}{\phi_0^3} > 1 \;\rightarrow\; \phi_0 < 10^4 (M_p^2 f)^{1/3}$$

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Cosmological relaxation: $V = V_{SM} - \underbrace{\frac{1}{2}|F_4|^2 - g\phi F_4 - \eta F_4 |H|^2}_{(g\phi + \eta|H|^2)^2} + V_{cos}$

- Stability of the potential ✓
- See-saw mechanism: $g \sim \frac{\Lambda_k^2}{2\pi f}$ ✓

For $g \sim 10^{-34}$ GeV $\rightarrow \Lambda_k \sim 10^{-3}$ eV Cosmological constant?

- Tunneling rate: $B \approx w(q)\frac{2\pi^2 T}{H^3}$

Gravitational effects are important $q \equiv \frac{1}{rH} \sim \frac{\Delta V}{TH} < 1$

$r =$ bubble radius

Constraints on relaxion

Nucleation rate: $P \sim e^{-B}$ with $B \approx 4\pi^3 w(q) q^3 \frac{\Lambda_v^4 M_P}{M^2}$ and $q = (rH)^{-1}$

$B > 1 \rightarrow \; M \lesssim \tilde{w}(q)\sqrt{\Lambda_v M_P} \sim \tilde{w}(q) \cdot 10^9 \; GeV$

➡ **If relaxion is QCD axion**, it must also solve Strong CP problem, but….

$$\theta_{QCD} \sim \langle \phi \rangle \sim \mathcal{O}(f) \gg 10^{-10}$$

Possible solution: couple relaxion to inflaton [Graham,Kaplan,Rajendran'15]

$$M \lesssim \hat{\omega}(q)\sqrt{\Lambda_v M_p} \sim \hat{\omega}(q) \cdot 10 \text{ TeV}$$

➡ Inflation lasts an enormous amount of time!! $N \gtrsim \frac{H^2}{g^2} \gtrsim 10^{37} - 10^{67}$

Bubble nucleation can be an issue!

Relaxion in string theory

Toy model: D5-branes wrapping a 2-cycle in Type IIB orientifold comp.
leading to $SU(2) \times U(1)$

- Position modulus $\longrightarrow h$ (higgs) NS 2-form $\longrightarrow B_2 = \phi\omega_2$ (relaxion)

  Minkowski 4-form dual to magnetic brane flux $\longrightarrow F_2 = q\omega_2$

- Potential from DBI action: $M^4 = \mu_5 V_{\Sigma_2} g_s^{-1}$

$$V = \left(-\frac{\mu^2}{1+(q-\tilde{g}\phi)^2} + 4M^4\sigma^2 m^2\right)|\tilde{h}|^2 + M^4(q - \tilde{g}\phi)^2$$

- WGC membrane: monopole on D5 worldvolume (D3 ending on D5)

Problems:

- Mass scales: $\Lambda_k^4 \sim \frac{M_s^2}{g_s V_{\Sigma_2}} \gg 10^{-3}\ \text{eV}$ Warped throats? [see also Stout's talk]

- Global embedding and backreaction.

Summary

UV completion of cosmological relaxion by using monodromy.

- Dual description in terms of an axion coupled to a 3-form field.
- Naturally small g by a see-saw mechanism, stable under corrections.

Constraints from Weak Gravity Conjecture:

- WGC gives a lower bound on the tension of membranes

  $\longrightarrow$ tunneling between branches $\longrightarrow$ reduce field range

- Not big constraints for axion monodromy inflation.
- Too fast membrane nucleation rules out the simplest models with the QCD axion as the relaxion.

Thank you!