Minkowski 3-forms and Axion Monodromy in String Theory

Irene Valenzuela

Max Planck Institute for Physics, Munich

S. Bielleman, L. Ibáñez, I.V., [arXiv:1507.06793 [hep-th]]
L. Ibáñez, M. Montero, A. Uranga, I.V., [arXiv:1512.00025 [hep-th]]
I.V., [arXiv:16xx…. [hep-th]]

DESY Theory Workshop, Hamburg 2016

Transplanckian field ranges

Large field inflation

Detectable tensor modes imply transplanckian field range

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

ϕ : axion (shift symmetry protects potential from higher dim operators)

Transplanckian field ranges

Large field inflation

Detectable tensor modes imply transplanckian field range

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

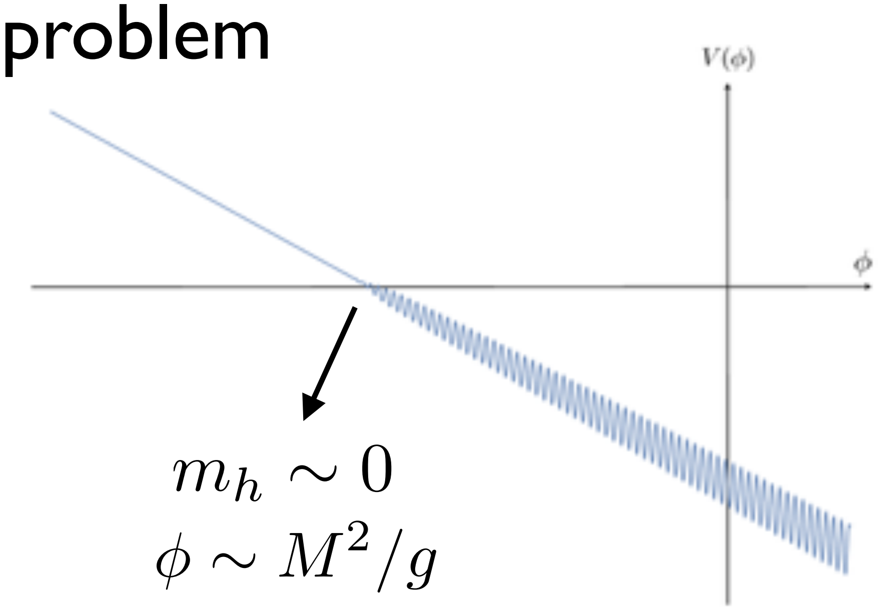
ϕ : axion (shift symmetry protects potential from higher dim operators)

Cosmological relaxation [Graham,Kaplan,Rajendran'15]

Dynamical solution to the EW hierarchy problem

Higgs-axion coupling: $g \sim 10^{-16} \frac{m_{EW}^2}{M^2}$ GeV

$$\Delta\phi \gtrsim \underbrace{M^2}_{\text{cut-off}}/g \gg M_p$$



Transplanckian field ranges

Natural inflation: Axion rolling down a potential

$V = A\,cos(\phi/f)$ with $\Delta\phi \sim f > M_p$

Technical difficulties in string theory [Banks et al.'03]

Transplanckian decay constant f ➡ strong coupling or small volume

No single (controlled) example so far…

Is this pointing to a fundamental problem?

Transplanckian field ranges

Natural inflation: Axion rolling down a potential

$V = A\ cos(\phi/f)$ with $\Delta\phi \sim f > M_p$

Technical difficulties in string theory [Banks et al.'03]

Transplanckian decay constant f ➡ strong coupling or small volume

No single (controlled) example so far…

Is this pointing to a fundamental problem?

Weak Gravity Conjecture [Arkani-Hamed et al.'06]

For each axion there should be an instanton with $S \leq \frac{M_p}{f} n$

$\delta V = Pe^{-S} cos(n\phi/f)$ ➡ higher harmonics reduce effective field range

Transplanckian field ranges!?

Are they possible in a consistent theory of quantum gravity?

Transplanckian field ranges

Current proposals in string theory:

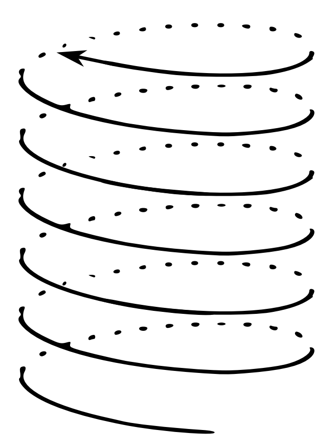
Natural inflation with multiple axions [Dimopoulos et al,Kim-Nills-Peloso,McAllister et al…]

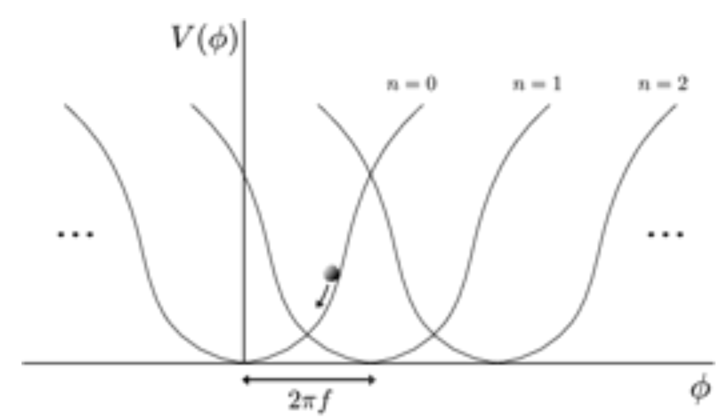
Engineer a transplanckian flat direction in the moduli space

Constraints from WGC [Rudelius,Heidenreich,Reece,Montero,Ibanez,Uranga,IV,Brown, Cottrell,Shiu,Soler,Bachlechner,Long,McAllister,Hebecker,Mangat, Rompineve,Witowski,Junghans,Palti,Saraswat…]

Axion monodromy [Silverstein et al., Flauger et al…]

Unfold the moduli space of the axion by inducing a multi-branched potential





WGC?

[Brown et al,Hebecker et al.]
[Ibanez,Montero,Uranga,IV]

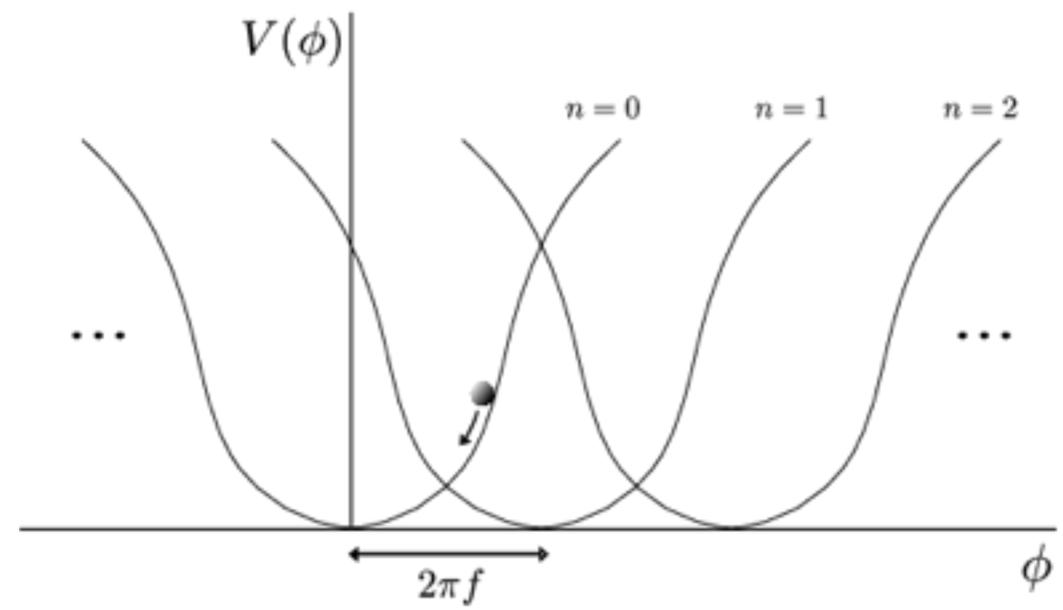
Axion Monodromy

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

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

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

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

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

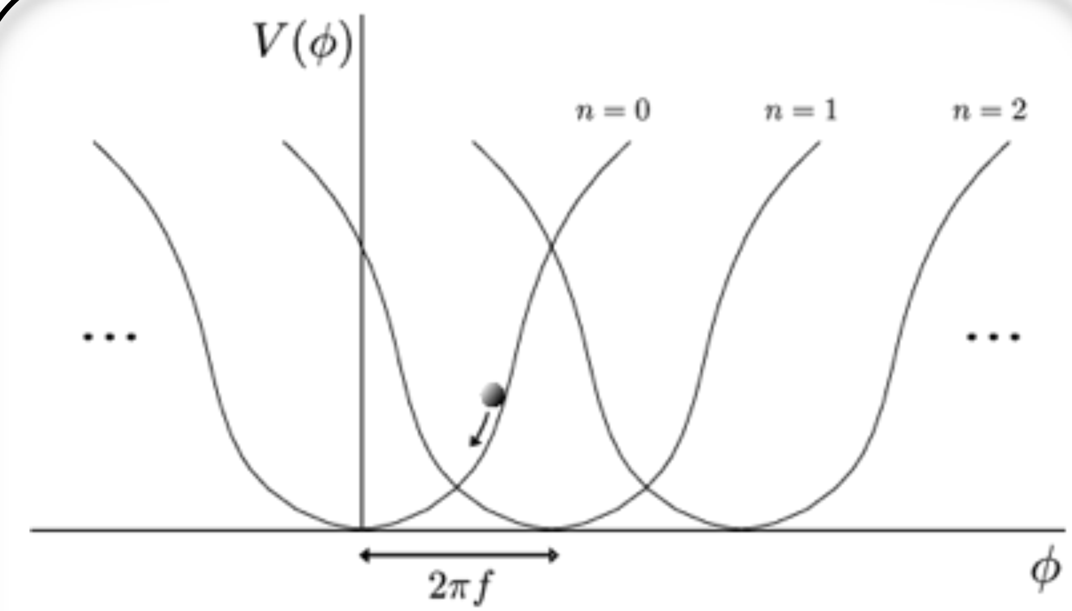
we get a multi-branched potential invariant under

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

Axion Monodromy

✓ Potential stable against higher dimensional operators (protected by gauge invariance of the 3-form field)

$$\delta V \sim \sum_n \left(\frac{F_4^2}{M_p^4} \right)^n \sim \sum_n \left(\frac{V_0}{M_p^4} \right)^n$$

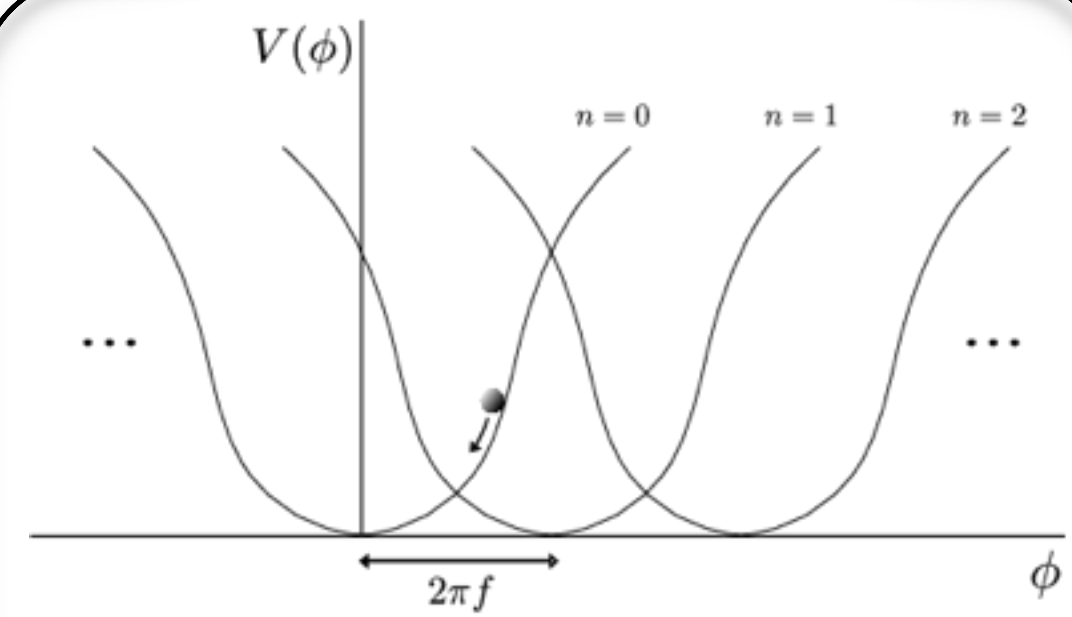


$$\phi \to \phi + 2\pi f \quad ; \quad f_0 \to f_0 - 2\pi g f$$

Axion Monodromy

✓ Potential stable against higher dimensional operators (protected by gauge invariance of the 3-form field)

$$\delta V \sim \sum_n \left(\frac{F_4^2}{M_p^4}\right)^n \sim \sum_n \left(\frac{V_0}{M_p^4}\right)^n$$



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

What are the problems then?

✦ Bottom-up: Tunneling between branches [Brown et al.] [Ibanez,Montero,Uranga,IV]

(constraints from WGC if applied to the 3-form field)

✦ Top-bottom: Backreaction problems from non-axionic moduli

[Blumenhagen et al] [Hebecker et al.] [Dudas,Wieck] [Baume,Palti]

Axion Monodromy

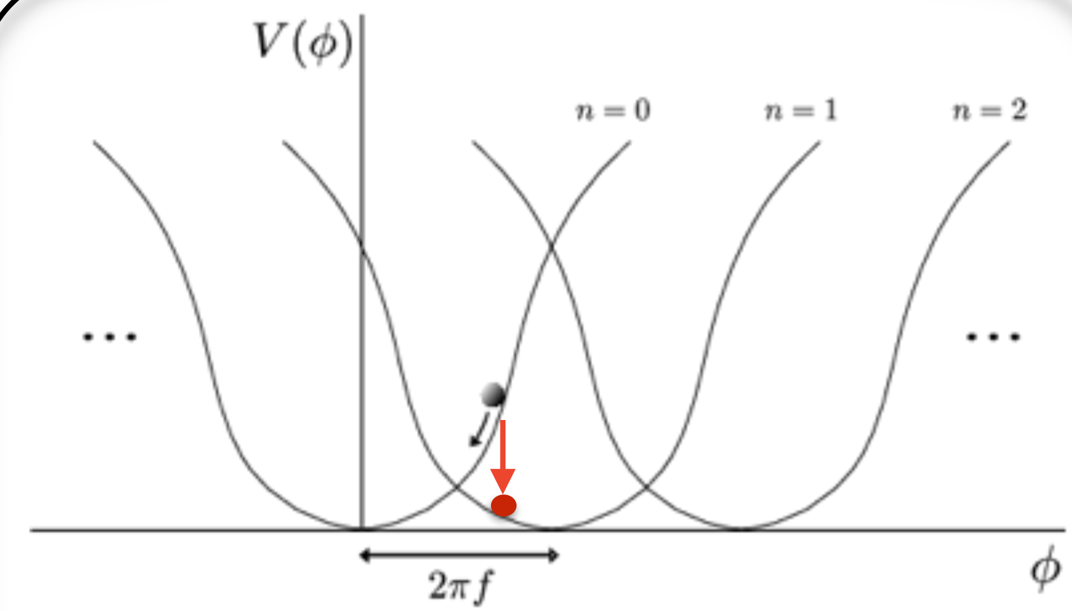
Tunneling between different branches

(field range can not be arbitrarily large)

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]



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

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

Weak Gravity Conjecture gives a bound on the tension of the membranes!

$$\boxed{T \leq \Lambda_k^2 M_p \sim 2\pi f g M_p}$$

Axion Monodromy

Constraints from WGC:

Bound on the tension → Estimate the tunneling rate → Constraint on the field range

Inflation

$$m \sim 10^{-6} M_p \ll \sqrt{f M_p}$$

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

Not a problem…

Relaxion

Constraint on $\Delta\phi$ → Constraint on the cut-off M

$$B \sim 4\pi^3 \omega(q) q^3 \frac{\Lambda_v^4 M_p}{M^2} > 1 \rightarrow M \lesssim \tilde{\omega}(q)\sqrt{\Lambda_v M_p} \sim \tilde{\omega}(q) \cdot 10^9 \text{ GeV}$$

Relaxion = QCD axion: $M \lesssim \hat{\omega}(q) \cdot 10 \text{ TeV}$

[Ibanez,Montero,Uranga,IV'15]

Axion Monodromy

What are the problems then?

✦ Bottom-up: No strong obstruction for large field inflation, not even from the WGC

✦ Top-bottom: Difficulties related to backreaction

What is missing in the Kaloper-Sorbo description?

Let us derive the structure in terms of 3-form fields coming from string theory…

Minkowski 4-forms in IIA/B

RR and NSNS p-forms: $F_p = F_4 \wedge \omega_{p-4} + \langle F \rangle\ \omega_p$ [Bielleman,Ibanez,IV'15]

Minkowski 4-form internal flux

Flux-induced 4d scalar potential of Type IIA/B Calabi-Yau orientifolds:

$$V = \sum_i Z_{ij}(s^a) F_4^i F_4^j + \sum_i F_4^i \rho_i(\phi^a) + V_{loc}(s^a)$$

saxions axions

- All axion dependence comes from couplings to 4-forms, through shift invariant functions $\rho_i(\phi^a)$
- All 4-forms couple to some axions (no pure Bousso-Polchinski 4-form contributing to the cosmological constant)

Difference with Kaloper-Sorbo

$$V = \sum_i Z_{ij}(s^a) F_4^i F_4^j + \sum_i F_4^i \rho_i(\phi^a)$$

$$*F_4^i = Z^{ij}(s^a)\rho_j(\phi^a) \to \; V = Z^{ij}(s^a)\rho_i(\phi^a)\rho_j(\phi^a)$$

Non-linear couplings ➡ Generic scalar potentials (mass and interaction terms)

Multiple 4-forms ➡ Higher order corrections $\delta V = \sum_n (\prod_i (F_4^2)^i)^n$

(not as powers of V, but of the different $\rho_i(\phi^a)$)

Field-dependent metrics ➡ Backreaction

Minima of the saxions: $\langle s \rangle \propto \rho(\phi)$

$$\Delta\phi = \int \sqrt{K_{\phi\phi}} d\phi \sim \int \frac{1}{s} d\phi \sim \int \frac{1}{\rho(\phi)} d\phi \longrightarrow$$ Reduce field range

Summary

- ✦ Axion monodromy is better described in terms of an axion coupled to a Minkowski 4-form.

- ✦ Weak Gravity Conjecture implies the presence of membranes mediating the transitions between different branches and constraining the field range.

- ✦ The full flux-induced scalar potential for axions in Type IIA/B can be written in terms of 4-forms coming from NSNS and RR fields which have field-dependent metrics.

- ✦ Parametrically large field ranges are ruled out due to vacua transitions and backreaction, but…

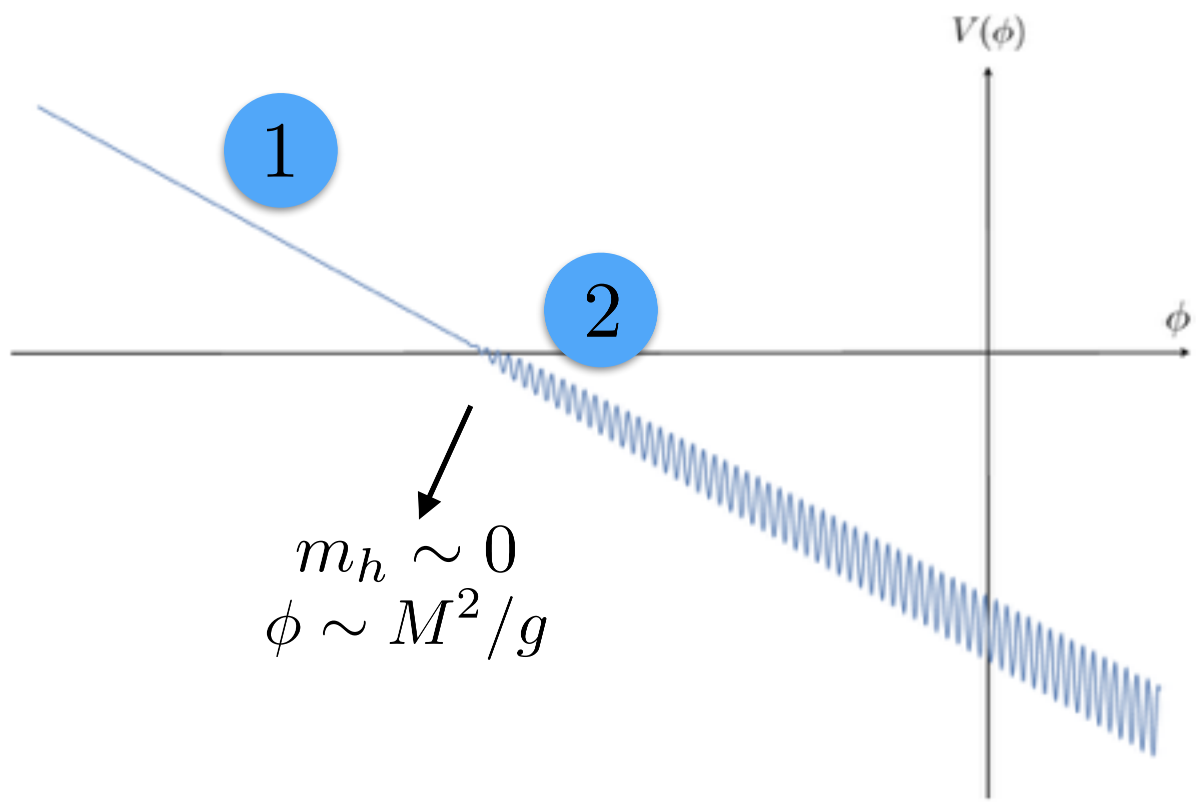
Anything special if $\Delta\phi > M_p$?

Thank you!

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

Barriers form and stabilise the relaxion if:

$$gM^2 \sim \frac{\Lambda^4(h=v)}{f} \quad \longrightarrow \quad g \sim 10^{-16}\frac{m_{\mathrm{EW}}^2}{M^2}\ \mathrm{GeV}$$

Very small coupling!

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]

- 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

$$\boxed{T \sim 2\pi f g M_p}$$

- 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) $\longrightarrow$ We require presence of membrane of unit charge. [Heidenreich,Reece,Rudelius '15]

Not known counterexample in string theory.

Transplanckian field ranges!?

Are they possible in a consistent theory of quantum gravity?