Axions, Monodromy, and the 'Geometric Weak Gravity Conjecture'

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based on work with F. Rompineve/A. Westphal

and on work in progress with J. Jaeckel/F. Rompineve/L. Witkowski

and with P. Mangat/L. Witkowski/S. Theisen

Outline

- The WGC beyond particles
- Dualities vs. the geometric WGC
- Constraining monodromy by the WGC for domain walls
- Gravitational instantons and the axion potential
- Reheating and gravity waves from axion monodromy

The WGC is interesting as ...

Arkani-Hamed/Motl/Nicolis/Vafa '06

1) A possible fundamental feature of quantum gravity

- It quantifies the non-existence of global symmetries

  (If $g \to 0$ is impossible, we need to know g_{min}.
  The WGC states $g_{min} = m$.)

2) Since it may constrain large-field inflation / relaxation...

Cheung/Remmen; de la Fuente/Saraswat/Sundrum . . . '14
Rudelius; Ibanez/Montero/Uranga/Valenzuela; Brown/Cottrell/Shiu/Soler;
Bachlechner/Long/McAllister; AH/Mangat/Rompineve/Witkowski;
Junghans; Heidenreich/Reece/Rudelius; Kooner/Parameswaran/Zavala;
Harlow; AH/Rompineve/Westphal; . . . '15; Conlon/Krippendorf . . . '16

Ibanez/Montero/Uranga/Valenzuela '15

The (generalized) weak gravity conjecture

- The basic underlying lagrangian is
  (for p-dim. objects in d dims.; with $\overline{M}_P \equiv 1$)

$$S \;\sim\; \frac{1}{g^2}\int (F_{p+1})^2 \;+\; T\int_{p-dim.} dV \;+\; \int_{p-dim.} A_p$$

with

$$F_{p+1} = dA_p\,.$$

- To avoid stable extremal black branes, one requires charged objects with sub-extremal mass (tension):

$$q/T \geq \gamma_{p,d}^{1/2}\,, \quad \text{where} \quad \gamma_{p,d} = \frac{p(d-p-2)}{d-2}\,.$$

- As one clearly sees, this fails for instantons and objects with codimension 1 & 2 (domain walls and cosmic 'strings').

Heidenreich/Reece/Rudelius '15

Note:

- This failure outside the range $0 < p < d-2$
  is not unexpected:
- Indeed, the argument that
  'the WGC protects us from too many stable objects'
  fails also intuitively outside this range.

  (E.g., strings and domain walls induce no long-range gravitational force.) see e.g. Susskind '95

However:

- The arguments that
  'the WGC protects us from the global-symmetry limit'
  and
  'string theory always obeys the WGC'
  support the conjecture even outside the above range.

- Arguments supporting/quantifying the WGC outside the 'canonical range' of $0 < p < d-2$ include
  - string dualities

Brown/Cottrell/Shiu/Soler '15

  - consistency of generic KK-reductions
  - consideration of dilatonic black branes.

Heidenreich/Reece/Rudelius '15

('lattice WGC')

- Here, we will try develop the duality argument....

- The key is not in the dualities, but rather in the fact that different p-branes on the same CY give different 4d objects.
- Hence, there ought to be a

Geometric WGC

- Consider a IIA-CY X with D2-branes wrapped on 2-cycles.
- Let w_i be a basis of $H^2(X, \mathbb{Z})$.

  The metric on X induces a metric for 2-forms,

$$K_{ij} \equiv \int_X w_i \wedge \star w_j \, ,$$

  and on the (dual) space of 2-cycles, K^{ij} .

- We make the standard ansatz

$$C_3 \; = \; A_1^i(x) \wedge w_i(y) \, .$$

- Focus on 4d particles coming from D2s on a particular cycle Σ
- The relevant 4d action reads ($l_s = 1$)

$$S_4 \sim (V_X/g_s^2) \int \sqrt{g}\, R \;+\; \int K_{ij}\, F_2^i \wedge \star F_2^j \;+\; q_i^\Sigma \underbrace{\int}_{\text{world-line}} A_1^i$$

with the charges

$$q_i^\Sigma = \int_\Sigma w_i \,.$$

- Now, rewrite the WGC for particles in terms of compactification data:

$$\frac{e\overline{M}_P}{M_\Sigma} \geq \frac{1}{\sqrt{2}} \qquad \Rightarrow \qquad \frac{|q^\Sigma|\, V_X^{1/2}}{V_\Sigma} \geq \frac{1}{2}\,.$$

Thus a particular, purely geometric (rescaling- and g_s-independent) quantity characterizing X is constrained.

- Crucially, the same function appears in WGC constraints on other objects obtained from other branes wrapped on 2-cycles.

- For example, D4s give domain walls with

$$\frac{e_{DW}\overline{M}_P}{T_{DW}} = \frac{(2V_X)^{1/2}|q^\Sigma|}{V_\Sigma}\,.$$

- Thus, using the 'particle-WGC', we constrain $V_X^{1/2}|q^\Sigma|/V_\Sigma$, obtaining a precise 'domain-wall-WGC':

$$\frac{e_{DW}\overline{M}_P}{T_{DW}} \geq \frac{1}{\sqrt{2}}\,.$$

- This goes through for any dimension of the cycle Σ and any dimension of the brane. Hence, any object in 4d is constrained by the imposition of the WGC for particles.

- Thus, allowing also for multiple gauge fields,

  Cheung/Remmen '14; Rudelius '14/'15,
  Brown/Cottrell/Shiu/Soler, Bachlechner/Long/McAllister '15

  we find in full generality:

  Geometric conjecture:

  The convex hull spanned by the vectors $(V_X^{1/2}/V_\Sigma)\, q^\Sigma$ (with $\Sigma \in H^p(X,\mathbb{Z})$) contains the ball of radius $1/2$.

- Note: At the structural level, this can be understood from the calibration condition on branes. Details remain to be worked out....

  Thanks to F. Marchesano for discussions on this point.

- Note: We did not use SUSY, the CY-condition, or the existence of a SUSY-brane on Σ. So this may be much stronger then the 'not too surprising' BPS-like result.

  see also work in progress by Heidenreich/Reece/Rudelius

Constraining axion monodromy with the WGC

Disclaimer:

Only brief summary; for deeper analysis and relation to earlier work...

Kaloper/Lawrence/Sorbo '08..'11 (see also Dvali '05)

Brown/Cottrell/Shiu/Soler; Ibanez/Montero/Uranga/Valenzuela '15

- Let's assume, based on the above, that all 4d objects, in particular DWs, are constrained.
- Note: the 'light' stringy objects fulfilling the WGC above are nevertheless always heavier than the KK-scale $M_{KK} = \Lambda$.
- Thus, one might conjecture that the magnetic WGC

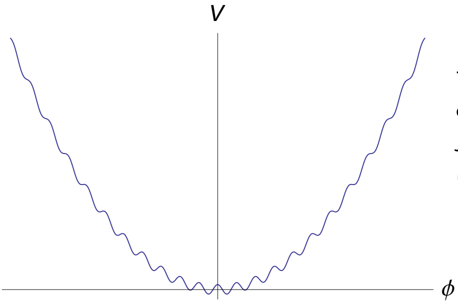
$$\Lambda^3 \lesssim e_2 \overline{M}_P$$

always holds.

- Start from the 'standard' monodromy potential (with 'instantonic wiggles')

AH/Rompineve/Westphal '15

$$\mathcal{L} = (\partial\varphi)^2 - \frac{1}{2}m^2\varphi^2 - \alpha\cos(\varphi/f)\,.$$



The low-energy effective theory of this model has no scalar but just a set of discrete vacua (as in the Bousso-Polchinski landscape).

(Effective) domain walls are automatically present, but are too light to give any useful WGC constraint.

(In fact, one may argue that they make the electric WGC useless.)

- Nevertheless, the effective action

$$S \sim \int \frac{1}{2(e_2)^2} F_4^2 + \int_{DW} A_3$$

is there and, using the quantization $F_4 = n\, e_2^2$, allows for matching the discrete effective potential

$$V(F_4)_{eff} = \frac{1}{2}(e_2)^2 n^2$$

to the previous effective potential

$$V(\varphi)_{eff} = \frac{1}{2} m^2 (2\pi n f)^2 \,.$$

- This implies $e_2 = 2\pi m f$ and hence

$$\Lambda^3 \lesssim e_2 \overline{M}_P = 2\pi m f \,\overline{M}_P \,.$$

- In the context of inflation, one has

$$H \sim m\,\varphi_{max} \lesssim \Lambda$$

and hence

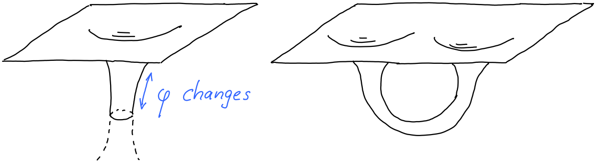
$$\Lambda^3 \sim m\,f\,\overline{M}_P \qquad \Rightarrow \qquad \frac{\varphi_{max}}{\overline{M}_P} \lesssim \left(\frac{\overline{M}_P}{m}\right)^{2/3} \left(\frac{2\pi f}{\overline{M}_P}\right)^{1/3} .$$

- There is still lots of parameter room for large-field inflation....

Gravitational Instantons and Moduli Stabilization

- In Euclidean Einstein gravity, supplemented with an axionic scalar φ , instantonic solutions exist:

Giddings/Strominger '88
...



- The 'throat' is supported by the gradient energy of φ or, equivalently, by flux of the dual 3-form H_3.

- The relevance for inflation arises through the induced instanton-potential for the originally shift-symmetric field φ.

Montero/Uranga/Valenzuela '15
Heidenreich/Reece/Rudelius '15

- The instanton action is

$$S \sim n/f \qquad \text{(with } n \text{ the instanton or flux number).}$$

- Their maximal curvature scale is $\sqrt{f/n}$, which should not exceed the UV cutoff:

$$f/n < \Lambda^2 \,.$$

- This fixes the lowest n that we can trust and hence the minimal size of the instanton correction to the potential $V(\varphi)$:

$$\boxed{\delta V \;\sim\; e^{-S} \;\sim\; e^{-n/f} \;\sim\; e^{-1/\Lambda^2}}$$

- For gravitational instantons not to prevent inflation, the relative correction must remain small:

$$\frac{\delta V}{V} \sim \frac{e^{-1/\Lambda^2}}{H^2} \ll 1$$

- For a Planck-scale cutoff, $\Lambda \sim 1$, this is never possible
- However, the UV cutoff can in principle be as low as H
- Then, if also $H \ll 1$, everything might be fine....

$$\frac{\delta V}{V} \sim \frac{e^{-1/H^2}}{H^2}$$

AH, Mangat, Rompineve, Witkowski '15

Results to appear soon:

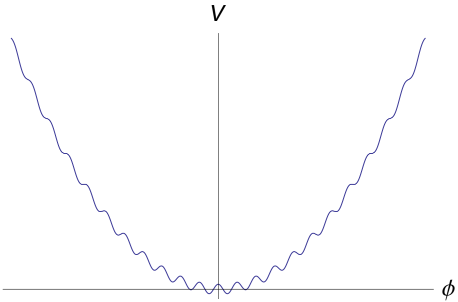
work with Mangat/Theisen/Witkowski

- Coleman's calculation of the potential remains valid even though one always encounters instanton / anti-instanton pairs.
- The size of the effect does not get suppressed by $\exp(-1/\Lambda^2)$, with Λ the moduli scale.
  (Light moduli do not disturb the solution significantly.)
- Hence, we expect $\Lambda \sim m_{KK}$.
- Let us see what the strongest, model-independent bound is:
  (Taking $\Lambda = 1/R_{throat} = 1/R_{self-dual}$.)
- Maximal effect: $\exp(-S) = \exp(-3\pi^2) \sim 10^{-13}$.

→ parallel talks by L. Witkowski and P. Mangat

Gravity Waves from Monodromy

(work in progress with Jaeckel/Rompineve/Witkowski)

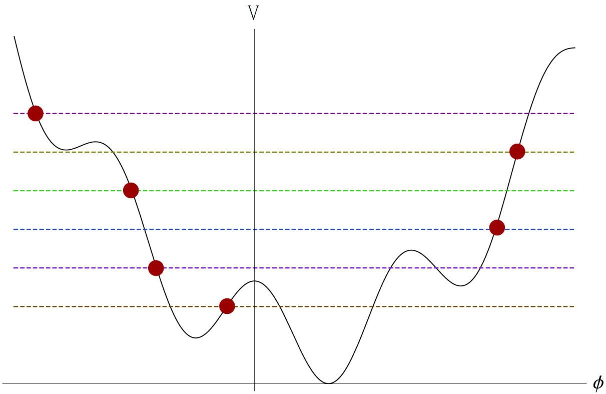


How does Rehating in this potential work?

for (somewhat) related considerations see papers by
T. Higaki and F. Takahashi (with different collaborators);
Kaloper/Padilla '16; Jaeckel/Metha/Witkowski '16

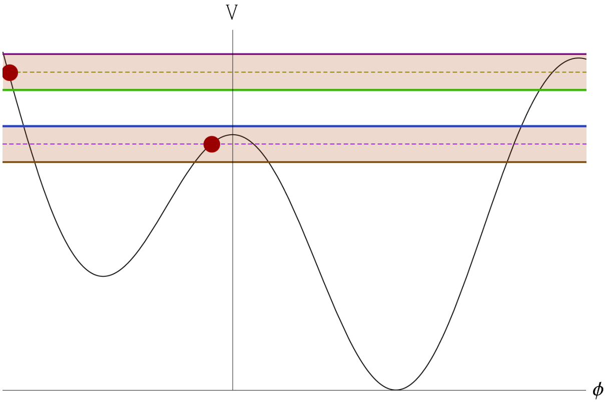
- The field oscillates and eventually 'gets stuck' in one of the local minima

- It then continues to oscillate in that minimum (where it later decays to light particles, i.e. reheats)

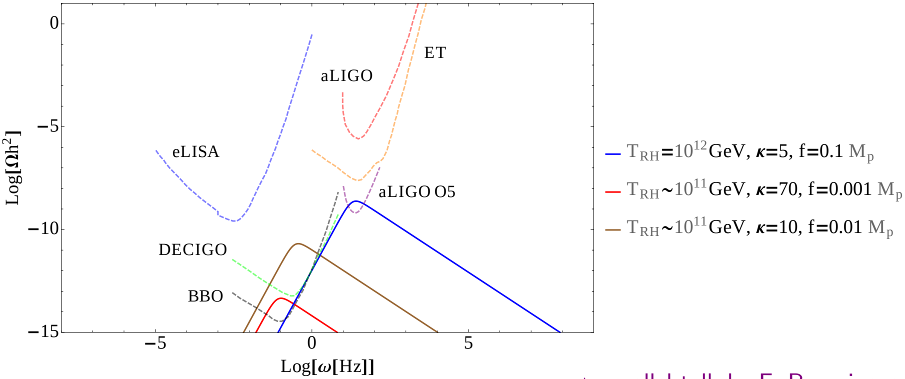


- At each ‘turning point’, an uncertainty due to field fluctuations exists

- Hence, with a certain probability, two different minima are populated inside one Hubble patch



- Evententually, bubbles of the lowest populated minmum expand and collide
- Gravity waves are produced in analogy to the case of a thermal first-order phase transition



→ parallel talk by F. Rompineve

Summary (1)

- Let's assume that string compactifications with form-fields / wrapped objects always obey the particle WGC.
- Then a geometric WGC follows.
- From this, one obtains a generalized WGC including axions, cosmic strings and DWs etc.
- The KK scale is always so low that also the generalized magnetic WGC is holds.
  Let's accept this latter form also more generally.
- The magnetic WGC for DWs provides for a very direct way of constraining axion-monodromy-type scalar potentials.

Summary (2)

- Independently of the WGC, Giddings-Strominger wormholes constrain large-field inflation
- This effect persists above the moduli stabilization scale; Calculational control is only lost at the KK scale
- However, due to a surprisingly large '$3\pi^2$' prefactor, bounds are weak even for the highest possible KK scale

Summary (3)

- Reheating after axion monodromy or 'winding' inflation can lead to a 'dynamical phase decomposition'
- This can induce a rather significant gravity wave signal