# Inflation from flux cascades

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Based on arXiv:1611.07037 with Fridrik Freyr Gautason and Thomas Van Riet

# Inflation in string theory

- The CMB provides a laboratory at energies far beyond Earth-bound experiment.
- A high energy theory is needed to describe the very early universe.
- High-scale inflation falls under the purview of quantum gravity, or for the purpose of this talk, string theory. Non-detectable B-modes still leave 11 orders of magnitude between today's colliders and the largest possible scale of inflation.
- Conversely being able to accommodate an inflationary epoch and a range of possible CMB observables is an important test of string theory.
  - Weak gravity conjecture/Ooguri Vafa: does string theory predict small field inflation?

hep-th/0601001
hep-th/060526

# Do we need another model of inflation?

- Focusing only on string inflation models, there are already a host of variations on D-brane inflation, axion inflation, and axion monodromy.
- What does this model have to offer?
  - It showcases the first string theory embedding of the flux cascade.
  - It can accommodate a super-Planckian field range: observable B-modes.
  - It can be embedded in very a well-controlled geometry: the Klebanov-Strassler throat glued to a compact Calabi-Yau.

# Motivation: Unwinding Inflation

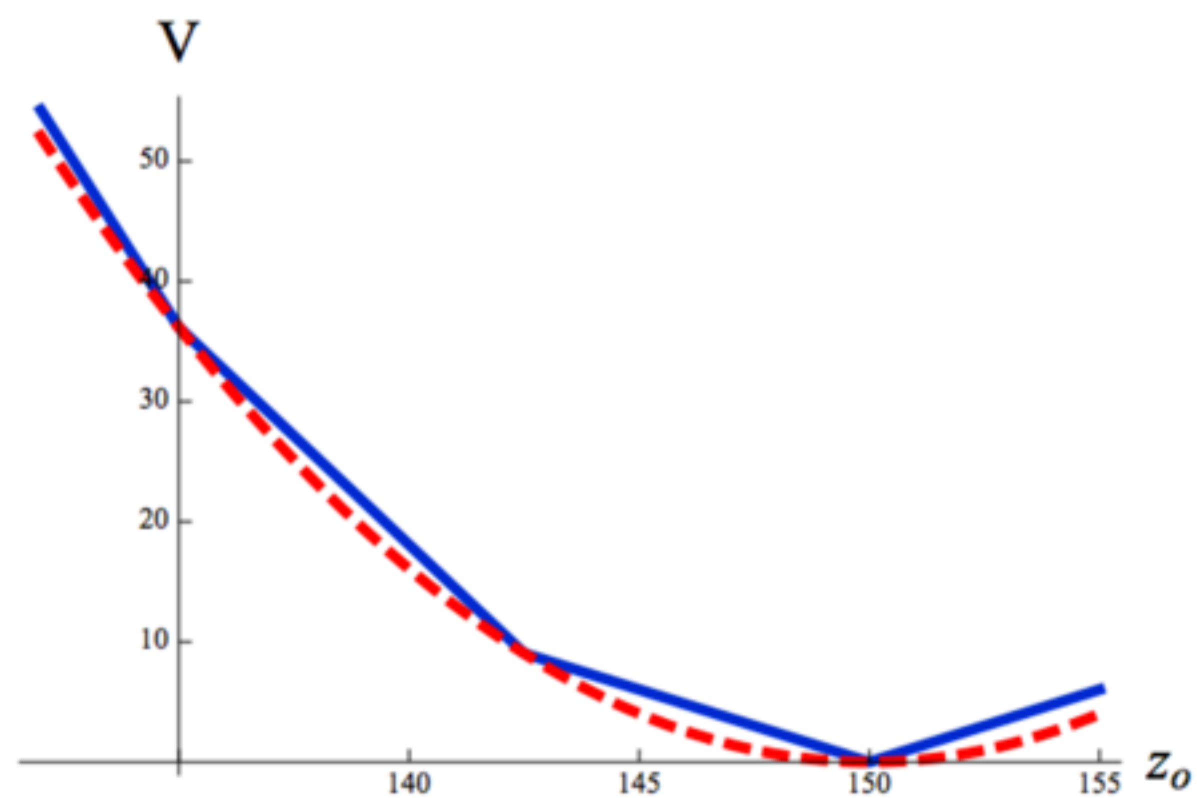
- Unwinding Inflation is a relatively recent addition to the set of stringy inflationary models.
  D'Amico, Gobbetti, Kleban, MS: 1211:4589

- It has many virtues:

  - Makes use of a novel mechanism — the flux cascade — to achieve large field (high scale) inflation.

  - Observable features in the power spectrum are linked to the details of the compactification manifold.

  - It is able to naturally post-dict the hemispherical anomaly and power asymmetry observed by Planck in the CMB, and predicts a related temperature gradient.
    D'Amico, Gobbetti, Kleban, MS: 1306:6872



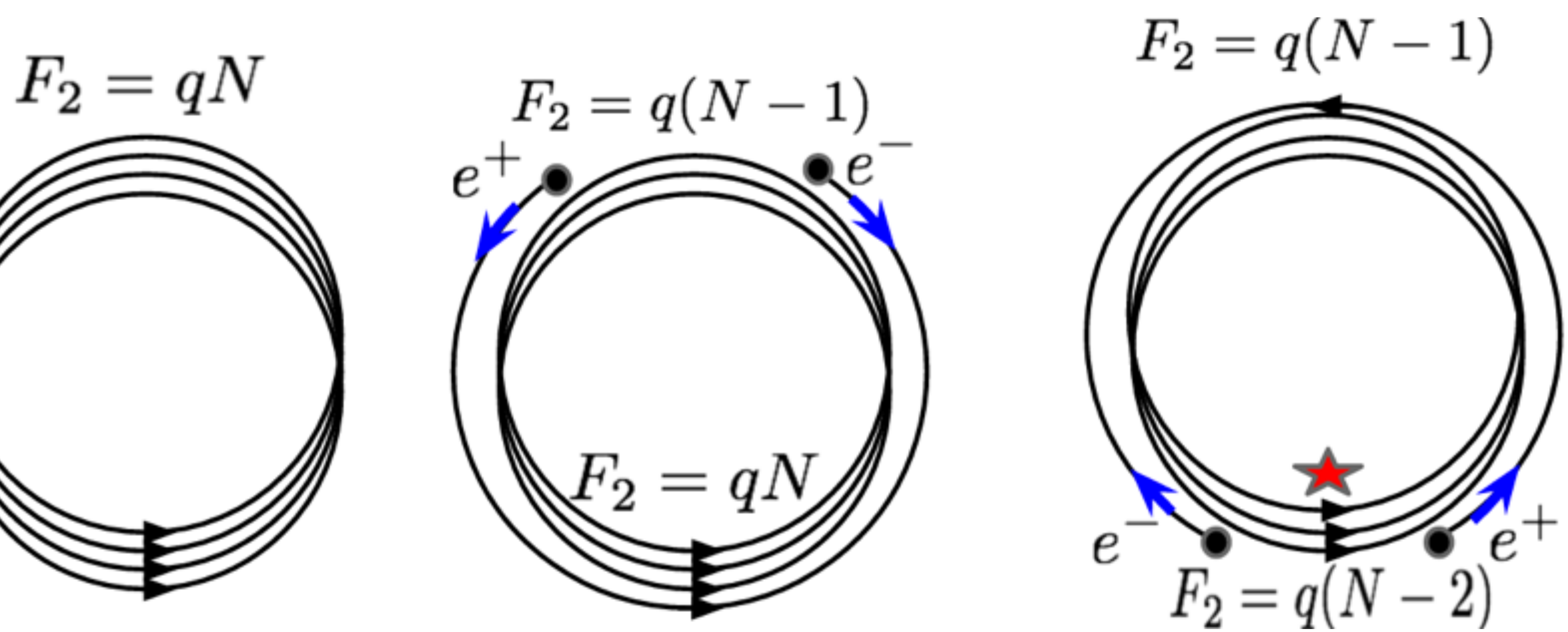
# Motivation: Unwinding Inflation

- Unwinding Inflation has one major shortcoming:
  - The model has only been studied using a toy, non-dynamical compactified geometry.
  - Extending this to a realistic flux compactification is the subject of this talk

# Mechanism: a flux cascade

Kleban, Krishnaiyengar, Porrati: 1108:6102

- A flux that fills at least 3+1 dimensions acts as a vacuum energy.
- Fluxes are unstable to nucleation of charged objects. (Brown, Teitelboim) These charged bubbles will then grow with constant proper acceleration due to electric forces. If they expand in a compact dimension, they can discharge multiple units of flux. Nucl.Phys. B297 (1988) 787-836
- Prototypical example: Electromagnetism in 1+1 dimensions:



# Higher dimensional flux cascade

Three-form flux, $F_3$, in 2 +1 dimensions

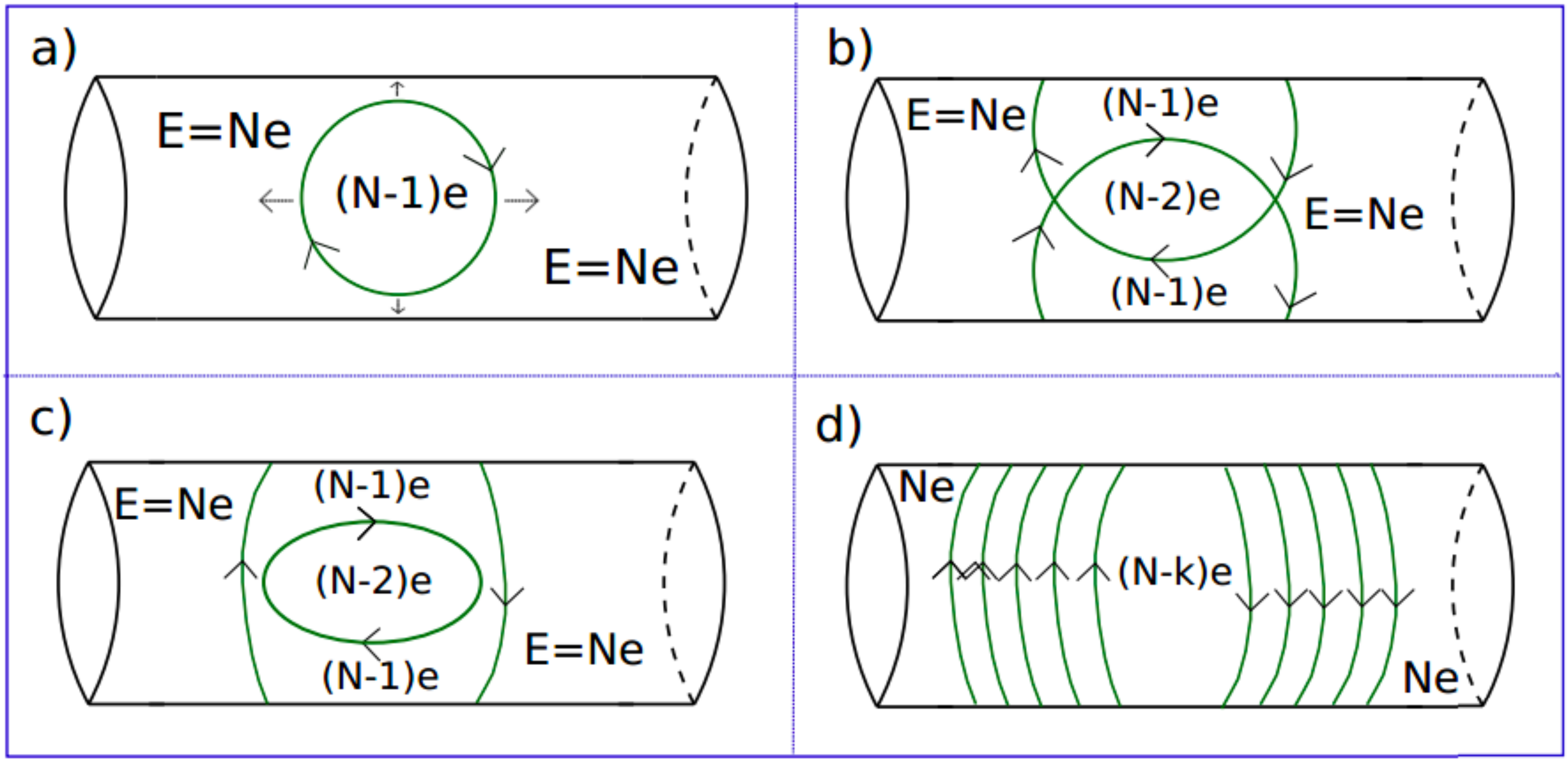



Figure taken from 1108:6102

# Going beyond the toy-model

- We need a background that solves the supergravity equations of motion, has flux, and exhibits a separation of scales, *i.e.* the low energy effective theory is 4D

- Giddings, Kachru & Polchinski (GKP): *Hierarchies from fluxes in string compactifications*, *2002*

$$ds^2 = \mathrm{e}^{2A(y)} ds_4^2 + \mathrm{e}^{-2A(y)} g_{mn} dy^m dy^n$$

- Complex structure moduli — fields which parameterize the shapes and relative sizes of the cycles of the compact manifold — are stabilized by 3-form flux

- 3-form flux satisfies a quantization condition:

$$M \equiv \frac{1}{(2\pi\ell_s)^2} \int F_3 \in \mathbf{Z} \ , \quad K \equiv -\frac{1}{(2\pi\ell_s)^2} \int H \in \mathbf{Z} \ ,$$

# GKP background

- There is a five-form flux, $F_5$, on this background that determines the warping:

$$F_5 = d\alpha \wedge dV_4/g_s \quad \text{and} \quad \alpha = \mathrm{e}^{4A}$$

- The charge cancellation condition for $F_5$ gives rise to a tadpole condition

$$\int \mathrm{d}F_5 = N_{\mathrm{D3}} + \frac{1}{(2\pi\ell_s)^4}\int H \wedge F_3 = 0$$

$$KM + N_{\mathrm{D3}} = 0$$

- This presents complications for the instantons considered in Unwinding Inflation, where a spherical brane does not change the net number of brane charges, but does change the flux numbers.

- This was fine in Unwinding Inflation where $H$-flux was turned off. But now something more sophisticated is needed: brane-flux annihilation.

# $F_5$ Confines anti-D3

- The dynamics we will be interested result from adding anti-D3 branes as probes in this background

- The anti-D3s feel a force due to their coupling to the five-form flux:

$$C_4 = \frac{\alpha}{g_s} dV_4 \qquad\qquad F_{y_i}(\vec{y}) = -\frac{2\mu_3}{g_s}\partial_{y_i} \mathrm{e}^{4A(\vec{y})}$$

- This drives the anti-branes into the region of smallest warp factor.

- Since we are interested in the effects of adding anti-branes, we can restrict attention to highly warped “throat” regions. This is very important because we know a good deal about warped throats, whereas we know nothing about metrics on compact Calabi-Yau spaces.

# The warped deformed conifold in GKP

- The Klebanov-Strassler (KS) deformed conifold describes how typical conifold singularities in Calabi-Yau manifolds are resolved in the presence of three-form flux.

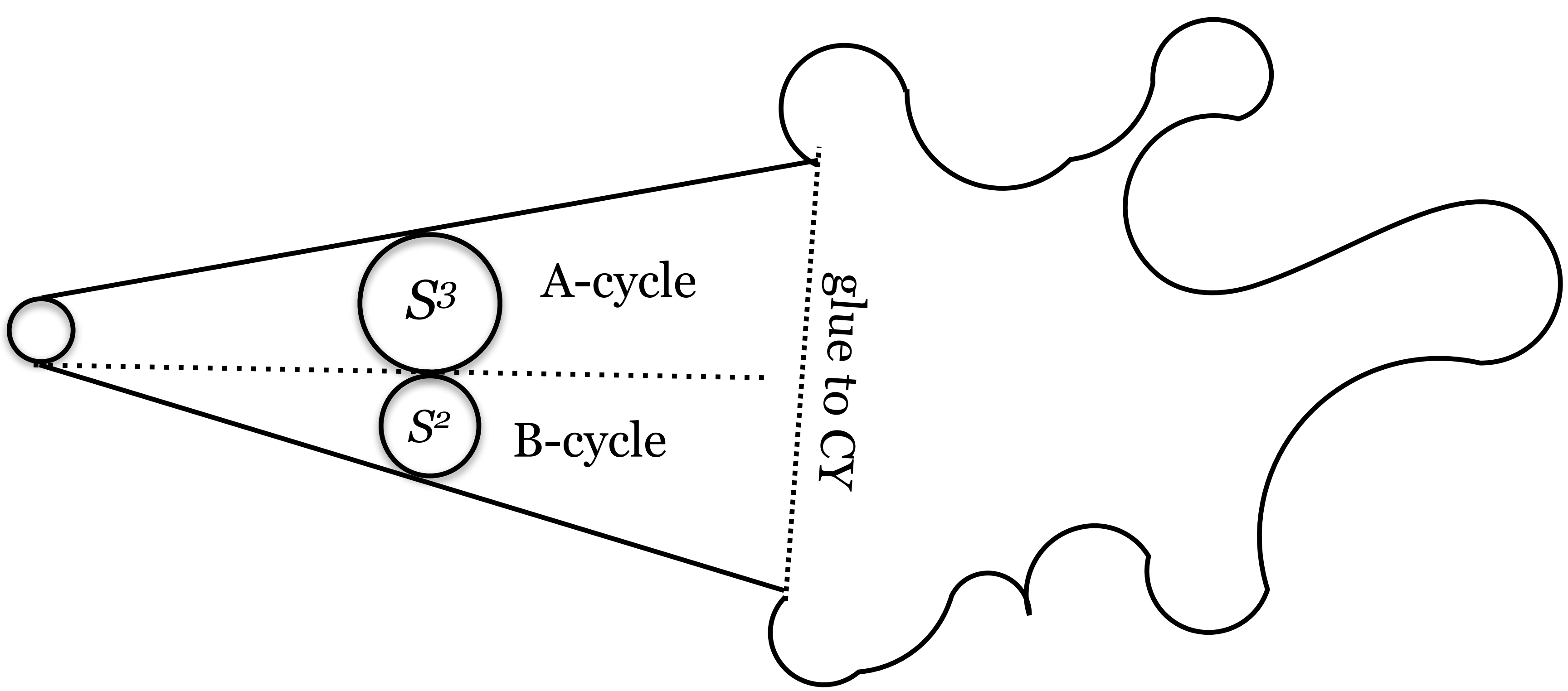
$$\text{cone: } ds_{10}^2 = \mathrm{e}^{2A} ds_4^2 + \mathrm{e}^{-2A}(dr^2 + r^2 ds_{T^{1,1}}^2)$$

⬇

$$(r \to 0) \quad \text{deformed: } ds_{10}^2 = a_0^2 ds_4^2 + g_s M \left( \frac{1}{2} dr^2 + r^2 d\Omega_2^2 + d\Omega_3^2 \right)$$

- We only need to focus on the small *r* region because of the confining potential due to $F_5$.

- The hierarchy of scales comes from the property of the GKP solution: $a_0 \propto \mathrm{e}^{\frac{-2\pi K}{3 g_s M}}$

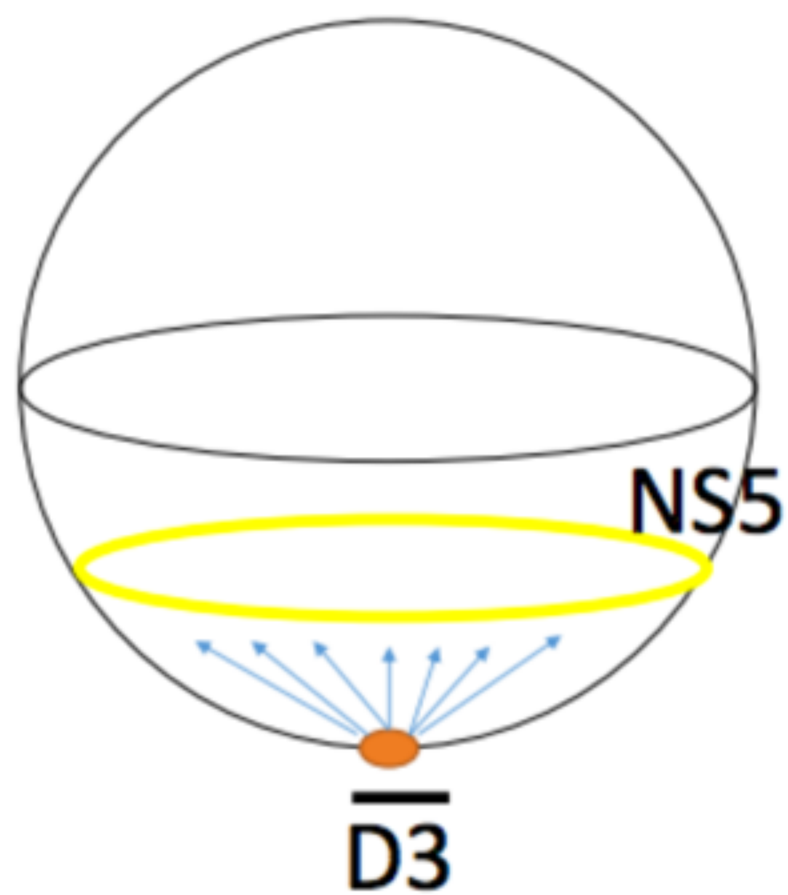


# Brane-flux annihilation

- Kachru, Pearson and Verlinde (KPV) first pointed out the phenomena of brane-flux annihilation by considering the effect of placing several anti-D3 branes in this background hep-th/0112197

- Once the branes have collected at the tip of the conifold, they undergo polarization into an NS5 brane via the Myers effect. hep-th/9910053

  - The Myers effect describes how a system of coincident branes in the presence of fluxes are polarized. They "blow up" into a fuzzy sphere which should be interpreted a spherical brane of larger dimension.



# Brane-flux annihilation

- There is a force on the NS5 brane that causes it to move across the $S^3$, simultaneously decreasing the number of anti-D3 branes and the H flux in such a way that the tadpole remains satisfied.

$$p = MK + \text{const.} \qquad\qquad p - M = M(K-1) + \text{const.}$$

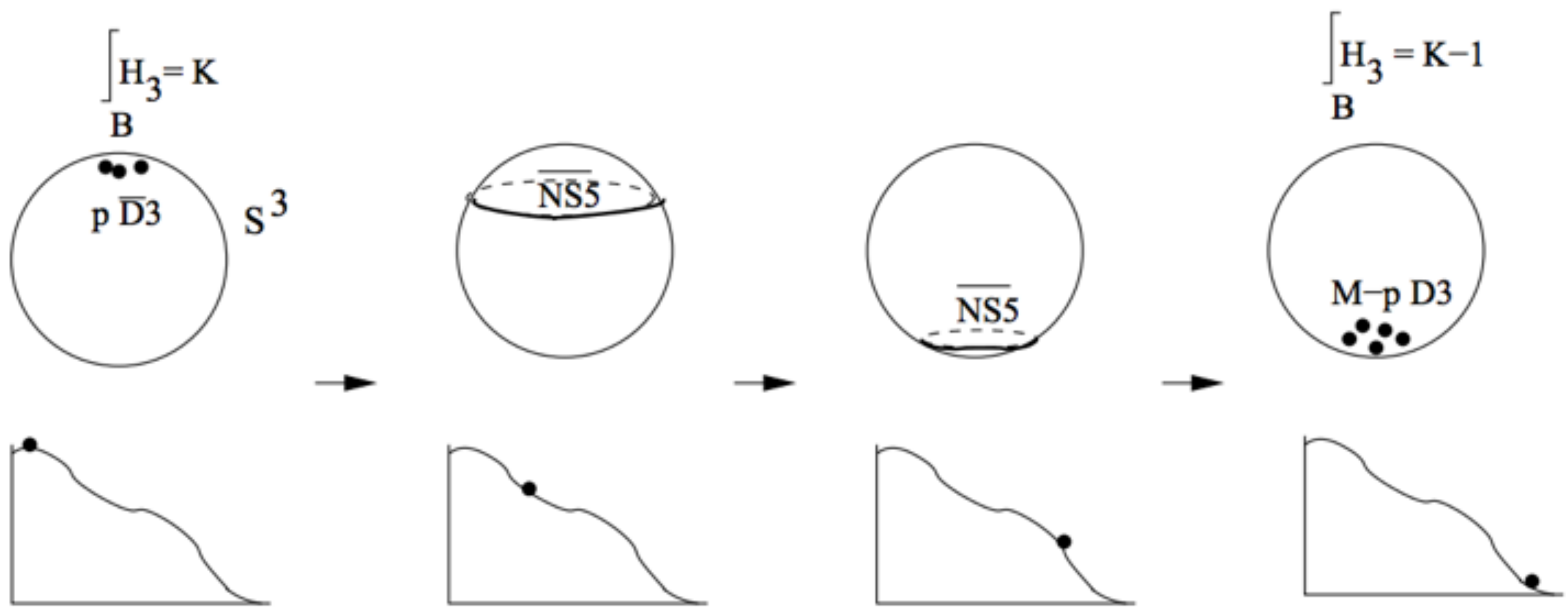



Figure taken from "The Giant Inflaton," DeWolfe, Kachru, Verlinde 2004

- We extend this process to the case where many anti-D3 branes are placed into the throat geometry, such that the brane will move over the sphere many times, discharging many units of flux in a flux cascade.

# Brane-flux annihilation in detail

- We will work in the S-dual of the Klebanov-Strassler throat, this simply switches the cycles that the $F_3$ and $H$ flux wrap, leading to the anti-D3 branes polarizing into a D5 as opposed to NS5 brane, and $F_3$ being discharged as opposed to H.

- The starting point is the action for the probe D5:

$$S = \frac{-\mu_{\rm D5}}{g_s} \int d^6\xi \left[-\det(G_{\|}) \det(G_{\perp} - \mathcal{F}_2)\right]^{1/2} - \mu_{\rm D5} \int \{C_6 + \mathcal{F}_2 \wedge C_4\}$$

$$ds_{10}^2 = \underbrace{a_0^2 ds_{\rm FLRW}^2 + K(d\psi^2}_{G_{\|}} + \underbrace{\sin^2(\psi) d\Omega_2^2}_{G_{\perp}} + ds_{\text{B-cycle}})$$

$$\mathcal{F}_2 = 2\pi \ell_s F_2 + B_2$$

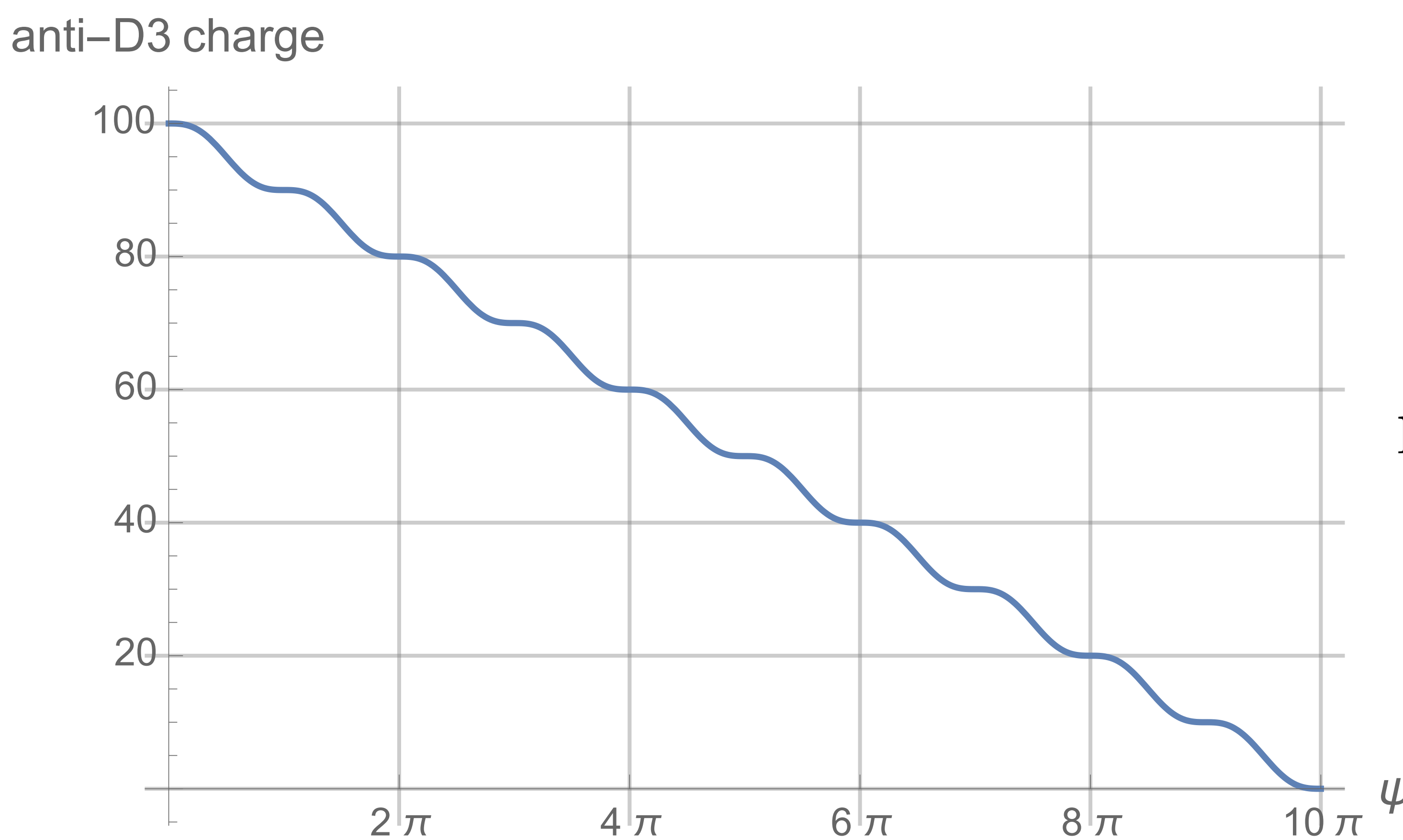
- The flux quantization conditions tells us that (choosing a gauge where $C_6 = 0$):

$$\mathcal{F}_2 = \pi \ell_s^2 \left(p - K\left(\frac{\psi}{\pi} - \frac{1}{2\pi}\sin(2\psi)\right)\right) \text{vol}_{S^2}$$

# How does the D5 discharge anti-D3s

- One can see the D3 charge carried by the D5 by looking at the Chern-Simons term

$$-\mu_{\rm D5}\int_{S^2}\mathcal{F}_2\int C_4 = -(2\pi\ell_s)^2\mu_{\rm D5}\left(p - K\left(\frac{\psi}{\pi}-\frac{1}{2\pi}\sin(2\psi)\right)\right)\int C_4$$




plot: $p = 100, \;\; K = 10$

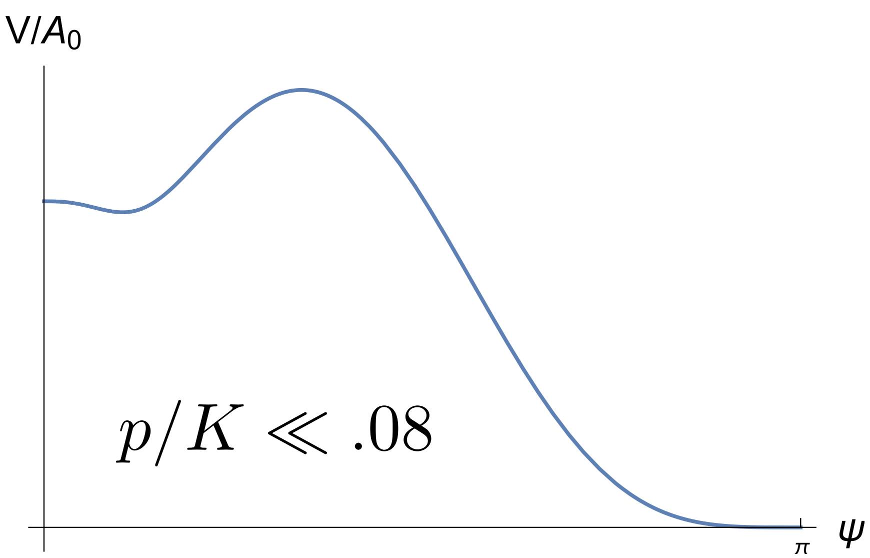
- In order to have a sustained cascade, we need to have many more antibranes than $H$-flux.

$$p \gg K$$

# The full action

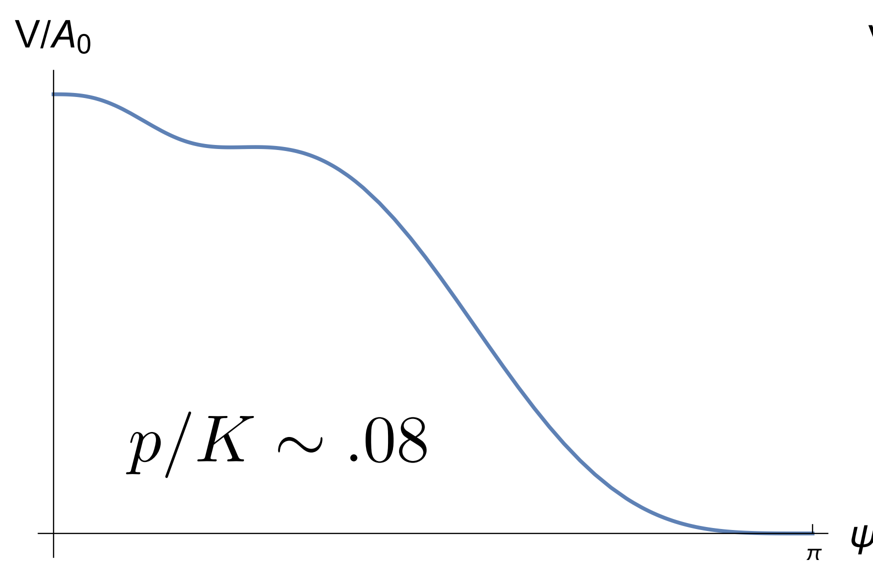
$$\text{“}S\text{”} \sim \int d^4x a^3(t)\,(\text{DBI} \;\; \text{kineticterm} + V_{\text{D5}}(\psi) + \Lambda)$$

$$V_{\text{D5}}(\psi) = A_0 \left[ \sqrt{\sin^4(\psi) + \left(\frac{\pi p}{K} - \psi + \frac{1}{2}\sin(2\psi)\right)^2} + \frac{\pi p}{K} - \psi + \frac{1}{2}\sin(2\psi) \right] .$$



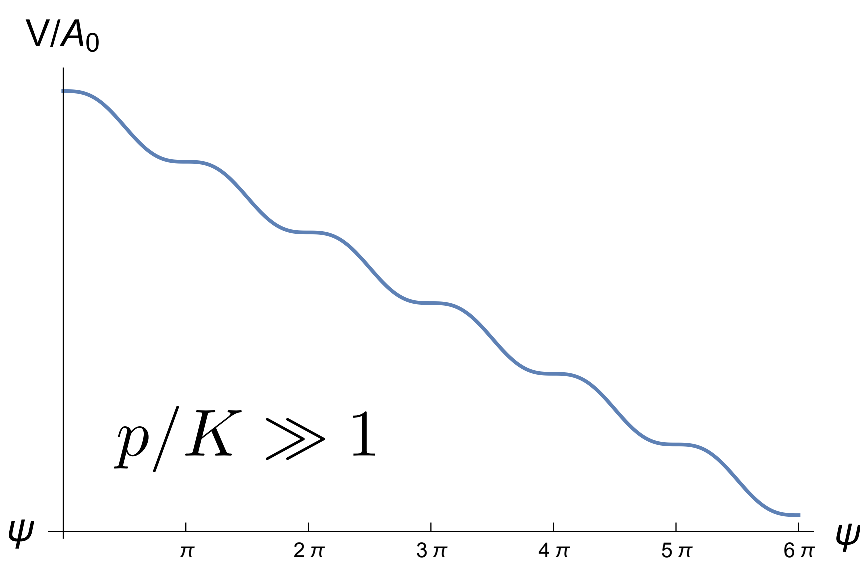

KKLT/KKLMMT / D-brane inflation

*e.g.* Baumann, McAllister, Dymarsky, Klebanov: arXiv:0706.0360




Giant Inflaton

DeWolfe, Kachru, Verlinde: hep-th/0403123




Unwinding

# At this point one should ask: “what about moduli stabilization?”

- We are throwing a large numbers of anti-D3 branes into a KS throat, we don’t want them to back-react strongly enough to destroy the geometry:

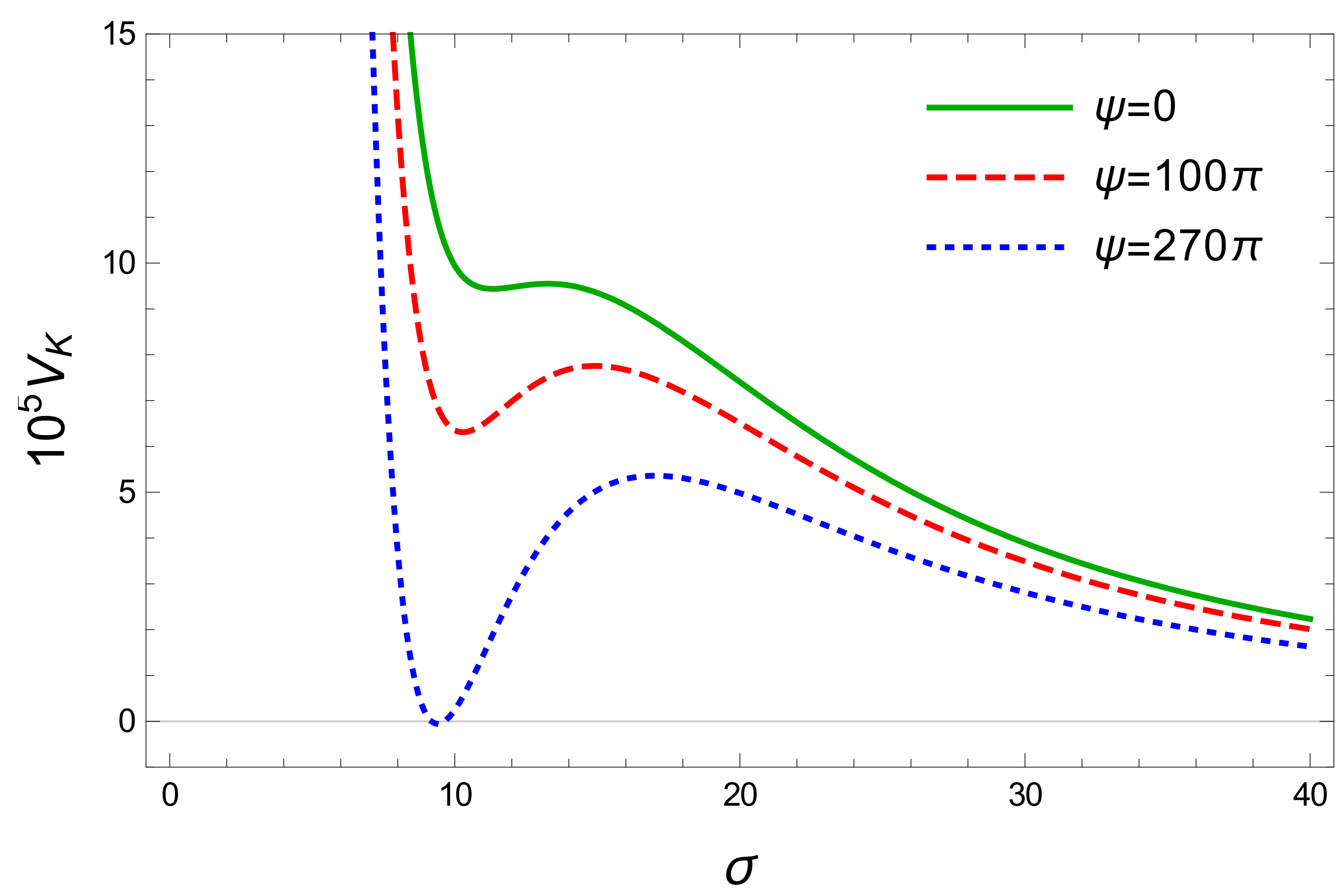
$$L^4_{\bar{\mathrm{D}}_3} = g_s p \ll K^2 = R^4_{S^3}$$

- We are discharging the flux that stabilizes a complex modulus, we should only discharge a small fraction of it:

$$1 \ll p/K \ll M$$

- The Kähler moduli can be fixed via the non-perturbative effects such as in the construction of KKLT. hep-th/0301240

- These concerns translate into constraints on the parameter space for available inflation potentials



# Parameter space has yet to be explored

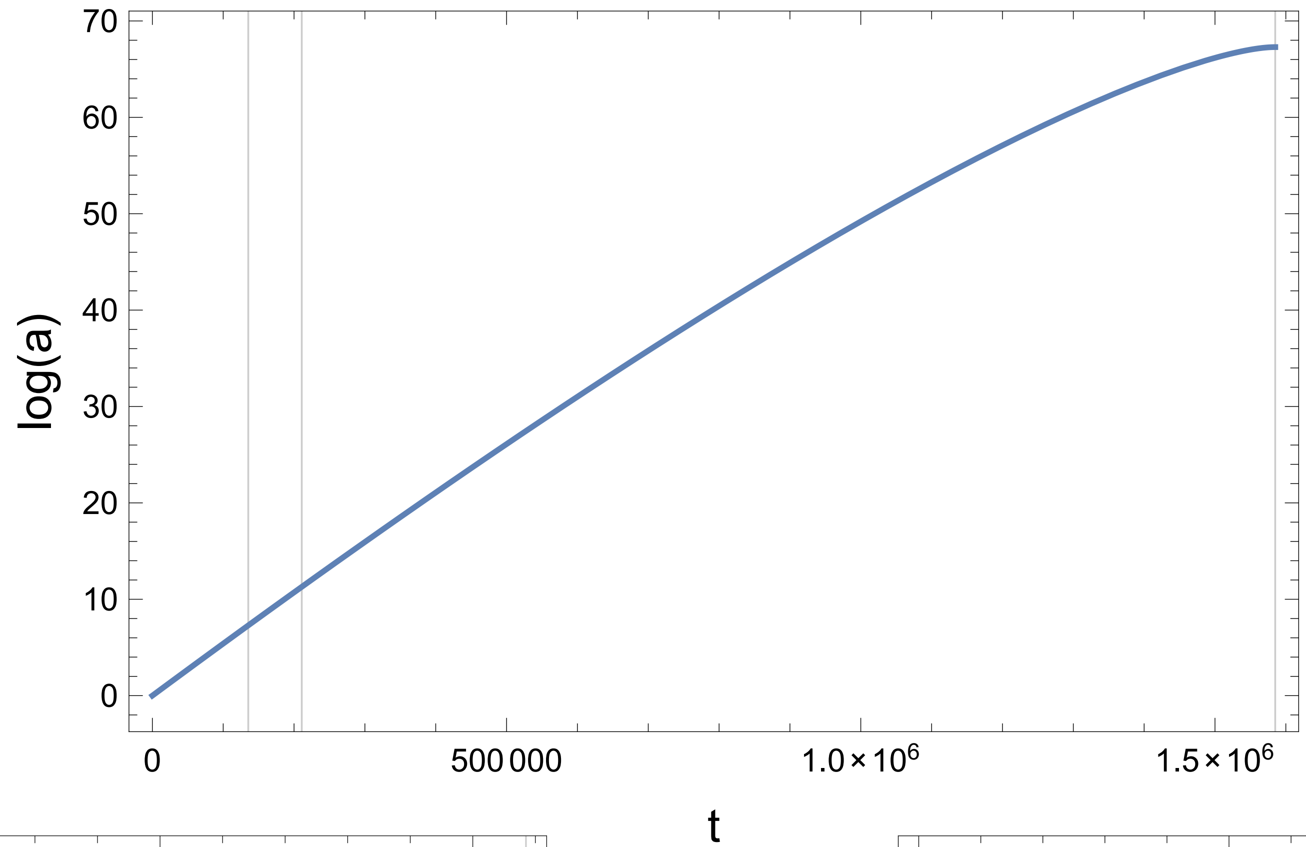
- The parameter space is spanned by: 3 parameters from Kahler modulus potential and

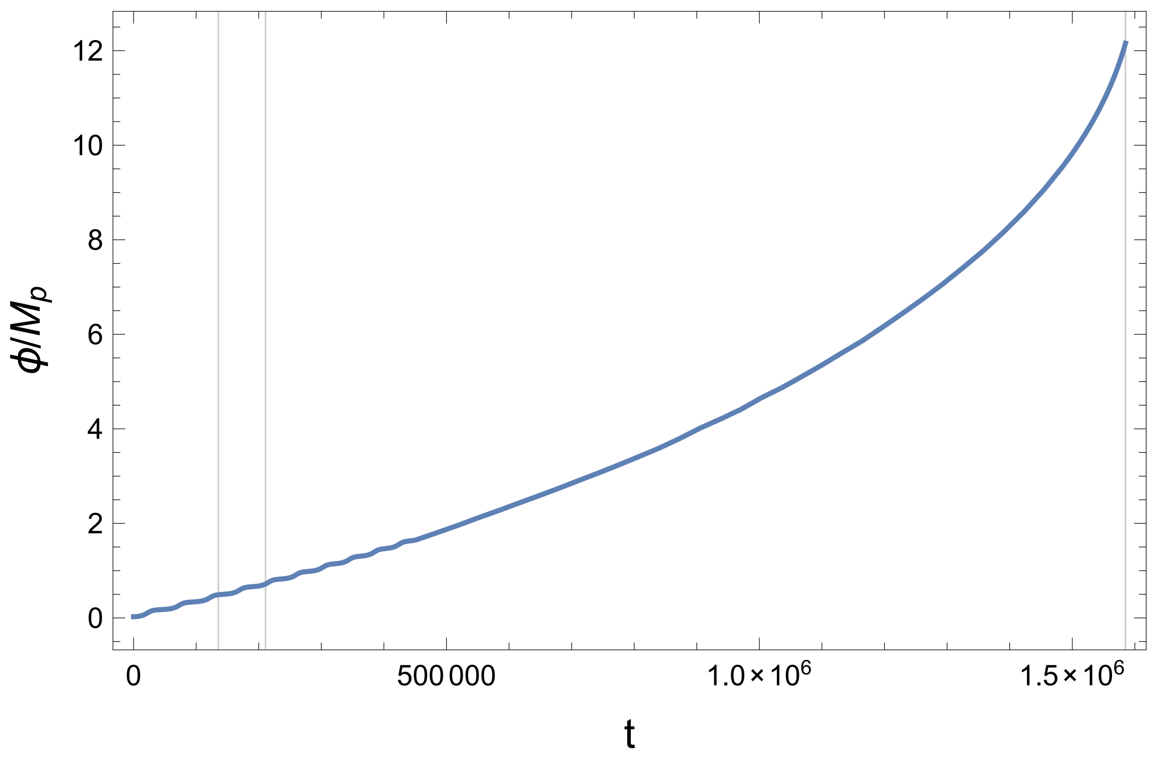
$$p\,,\quad K\,,\quad M\,,\quad g_s\,,\quad V_6. \qquad \text{with: } M_{pl}^2 = 2\frac{V_6}{(2\pi)^7 \ell_s^2 g_s^2}$$

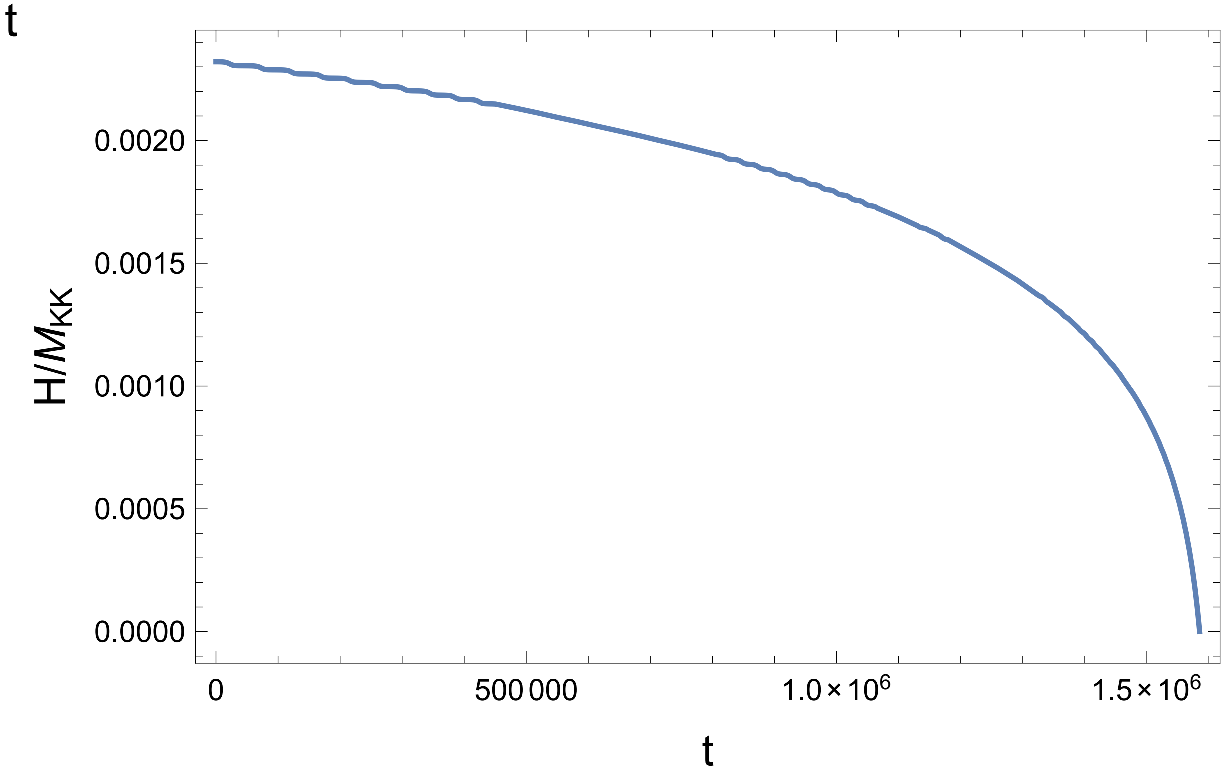
- The constraints are
  - Moduli stabilisation: $p \ll MK$
  - Sustained cascade: $p/K \gg 1$
  - 60 efolds of inflation: $\int H dt \gtrsim 60$
  - Volume of C.Y. is larger than volume of throat region: $V_6 > \int \sqrt{g_{\rm KS}}\, d^6 y$
  - Kaluza-Klein masses do not interfere with inflation: $V_6^{-1/6} \sim M_{KK} \gg H$

# We can get 60 efolds

- Despite extremely non-trivial constraints on a 8 dimensional parameter space, we can find inflationary epochs lasting at least 60 folds

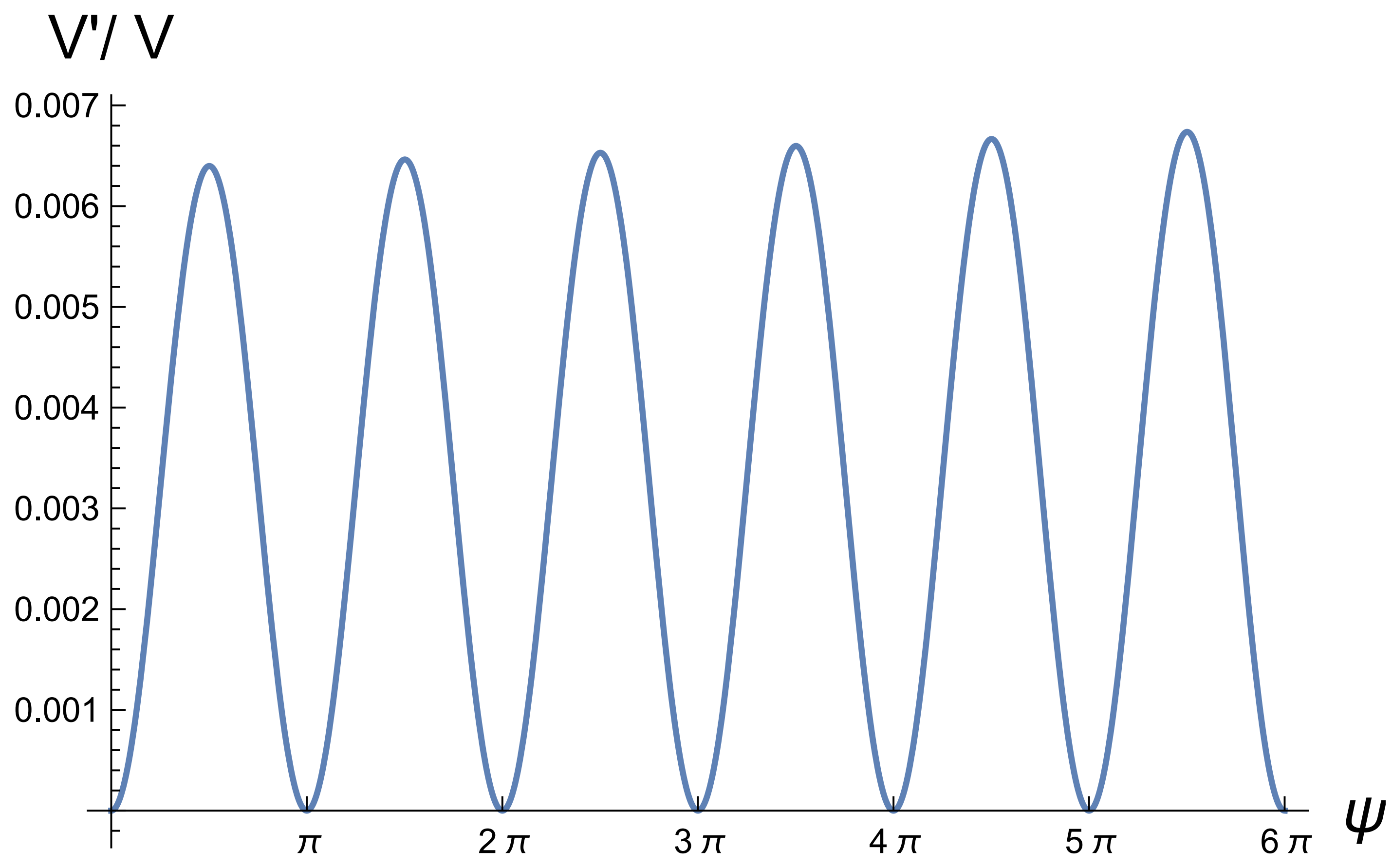


# What do we observe?

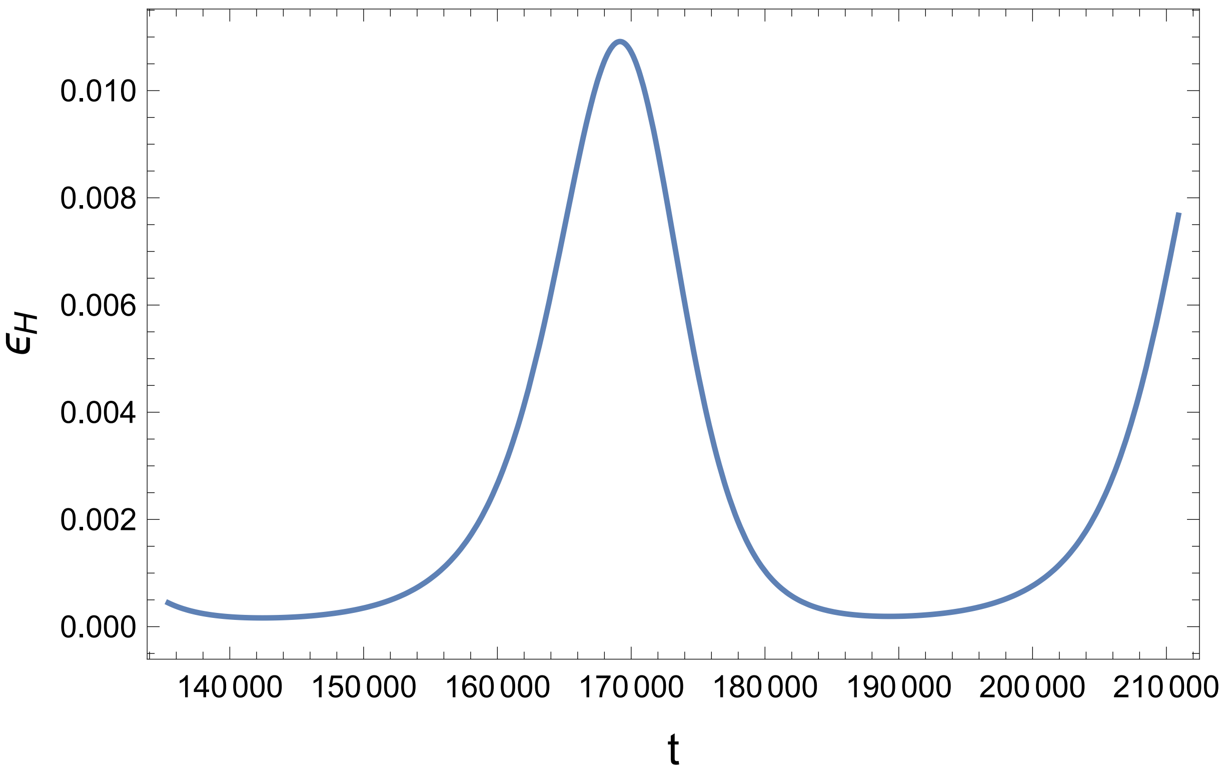
- Large oscillations in the power spectrum that must be fast (~10 per Hubble time) in order to be consistent with observations

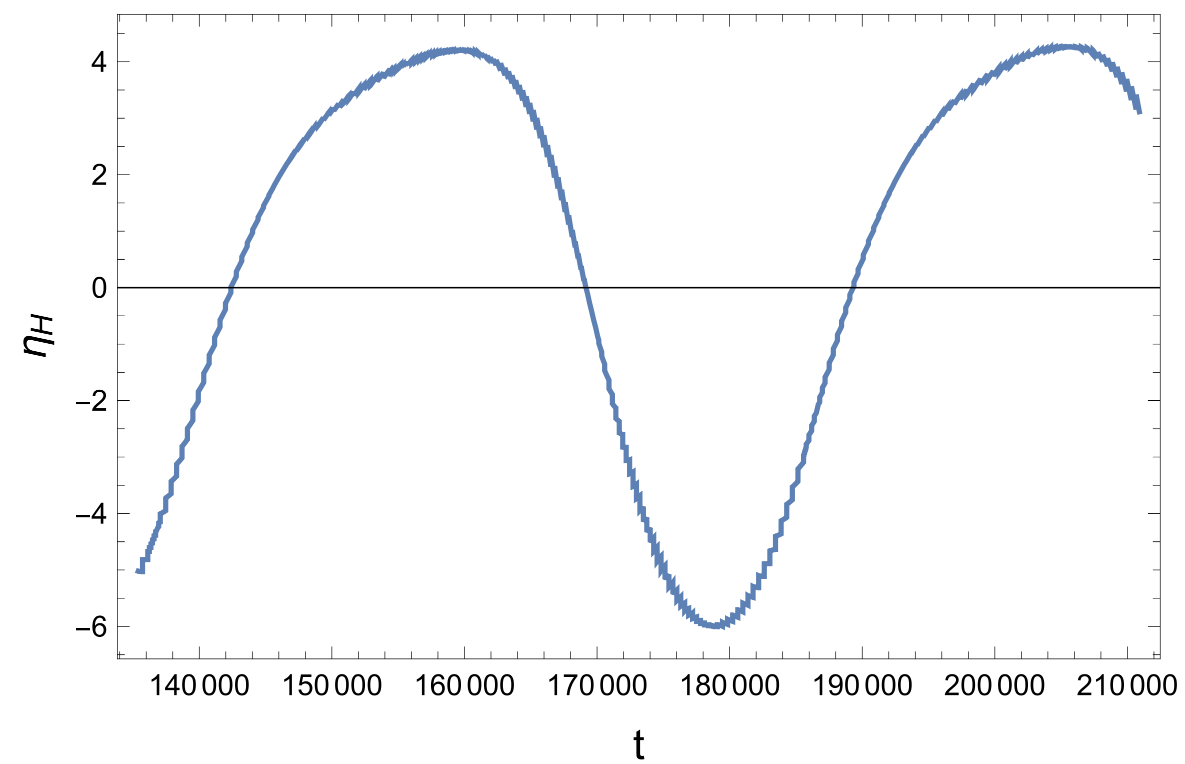



- Because the potential is perfectly flat at the poles, the second slow roll parameter must be large. We may not be in standard slow roll regime

# Oscillating slow roll parameters

$$\mathcal{P}_\zeta \sim \frac{H^2}{8\pi^2 M_{pl}^2 \epsilon}$$



# What do we observe?

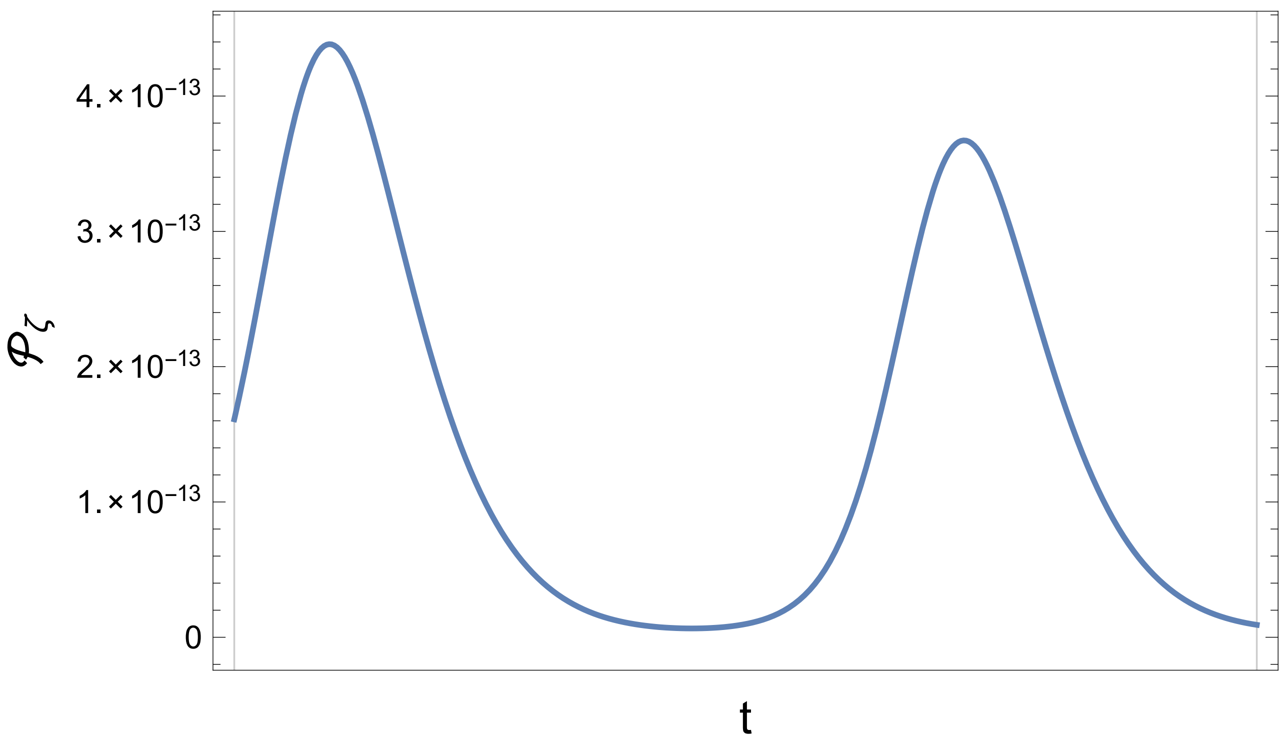
- A very tiny power spectrum

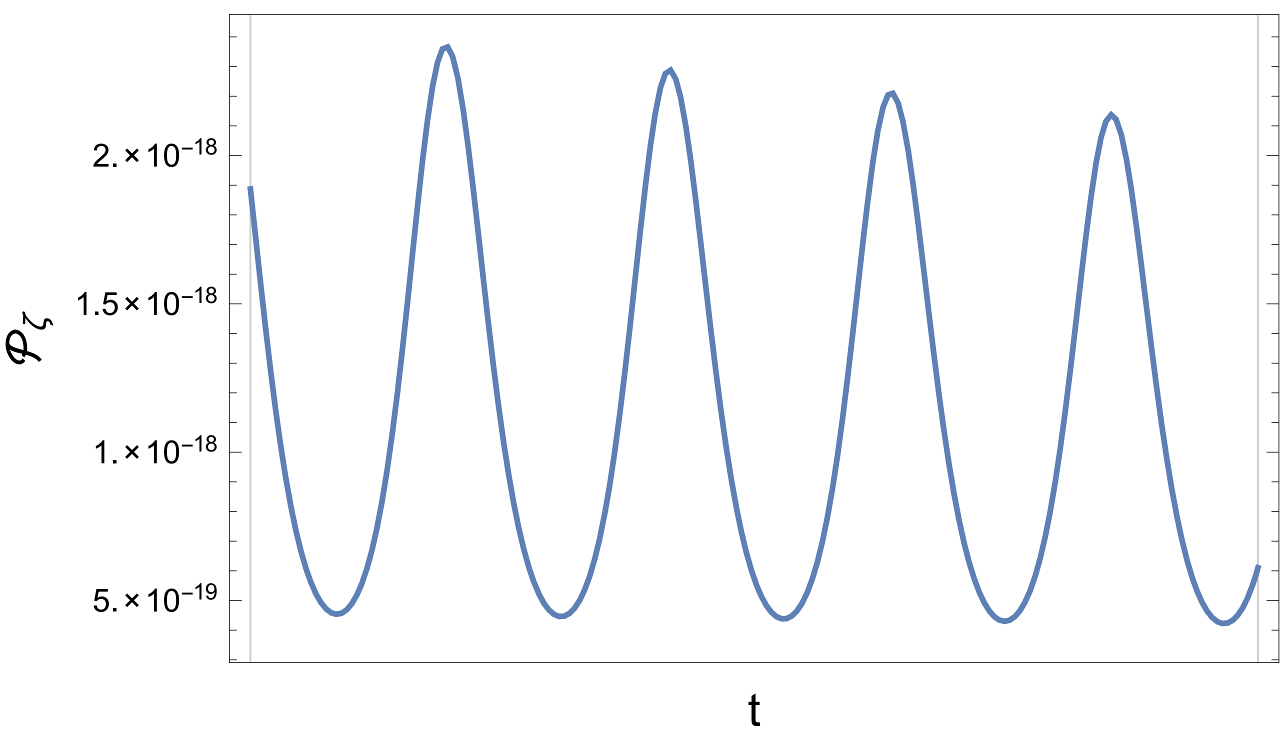
- Initial scans of parameter space indicate a tension between the observed scalar amplitude and:

    1. a Calabi-Yau volume large enough to fit the large warped throat

    2. a large second SR parameter so that we do not get stuck and oscillations are fast

- This is expected to change with different Kahler stabilization mechanisms (i.e. LVS) that don't require the such a deep throat



# Observables

- Equilateral non-gaussianity from DBI kinetic term - non-trivial speed of sound
- Potentially observable primordial tensors
- Reheating:
  - Pessimistic: we discharge all the anti-brane charge and end in supersymmetric AdS
  - Optimistic: we reheat through open string production when the acceleration spikes as approach Minkowski - we solved the CC problem by providing a way to move through the Bousso-Polchinski landscape in addition to a stopping mechanism!

# The end of inflation

- At each pole of the $S^3$, the correct picture is not really that of the D5, but rather one should consider the anti-commuting system of anti-D3 branes.

- As long as anti-D3 charge remains, the brains will continue to polarise making the D5 picture relevant again.

- However, once all of the anti-brane charge has annihilated against flux, leaving only D3 charge, there is no force left on the brane(s).

- There are non-perturbative dissipative effects, such as open string production or closed string bremsstrahlung provide an outlet for the brane kinetic energy - may stop the brane before all anti-D3 charge is gone.

  McAllister, Mitra hep-th/0408085
  McAllister, Bachlechner arXiv:1306.0003

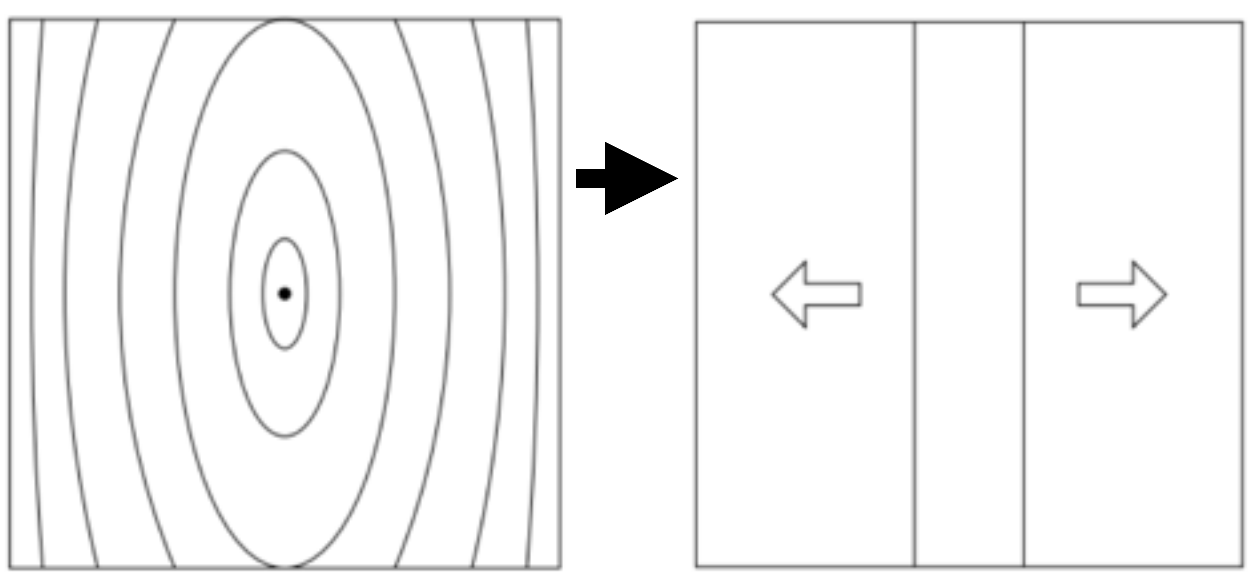
  - These effects were estimated and used in Unwinding Inflation to facilitate reheating

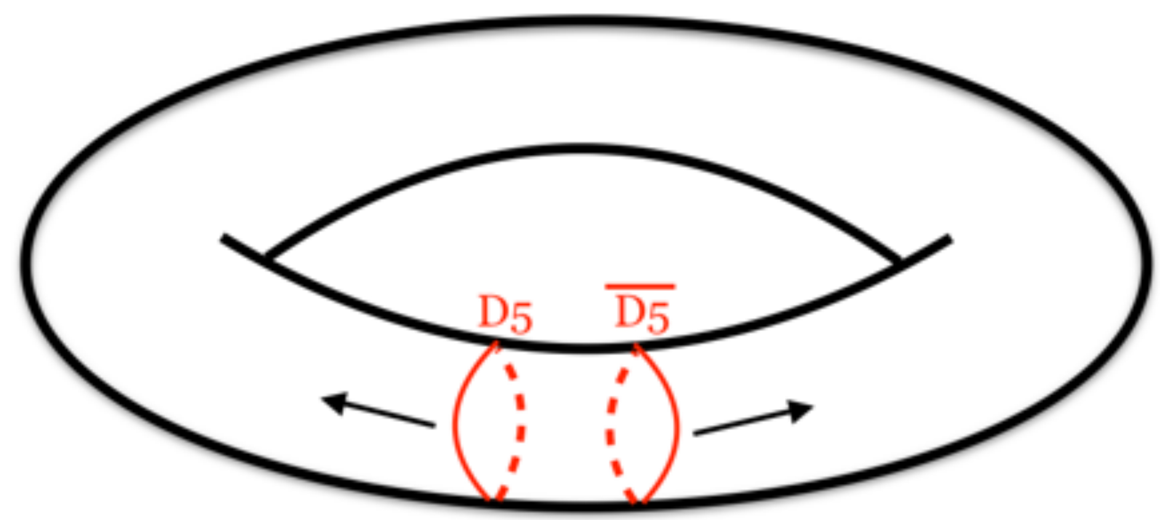
    D'Amico, Gobbetti, Kleban, MS: hep-th/1408.2540

  - These estimates are dubious in flux backgrounds

# Go to the torus where all your problems disappear

- The unwinding mechanism need not take place on a sphere: in the case of an anisotropic 3-torus:
    - The anti-D3s polarize into a D5 anti-D5 pair that is localized on one cycle, and wraps a two-cycle of the torus





# Cascading on the torus

- How does this help?
  - The large oscillations due to curvature disappear.
  - New wiggles arise because of the mutual interaction of the brane, anti-brane pair, but these are tunably small.

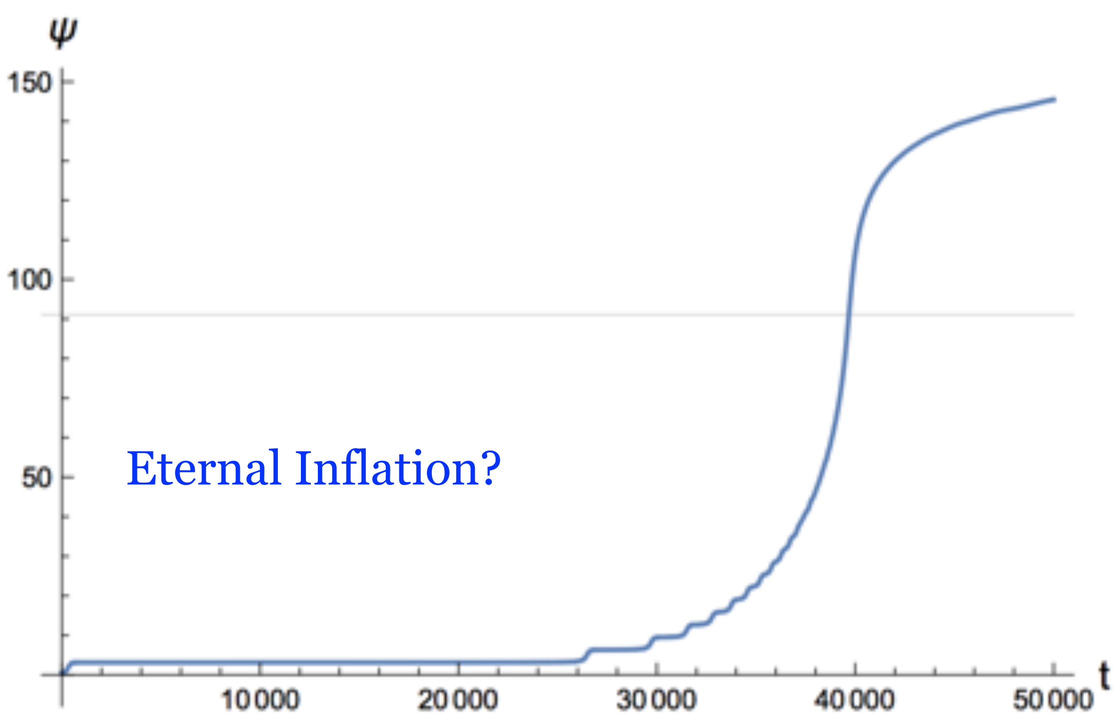
- This solves all of our problems with obtaining an observationally valid power spectrum, but we are no longer in a known-to-exist region of a Calabi-Yau. Uncertainty about the specifics of the geometry relaxes some constraints.
  - Toric special Lagrangian sub-manifolds are known to exist. This is a sub-manifold that is locally a torus, even though the full Calabi-Yau has no 1-cycles.
  - We must assume that we find such a toric sub-manifold at the bottom of a throat.

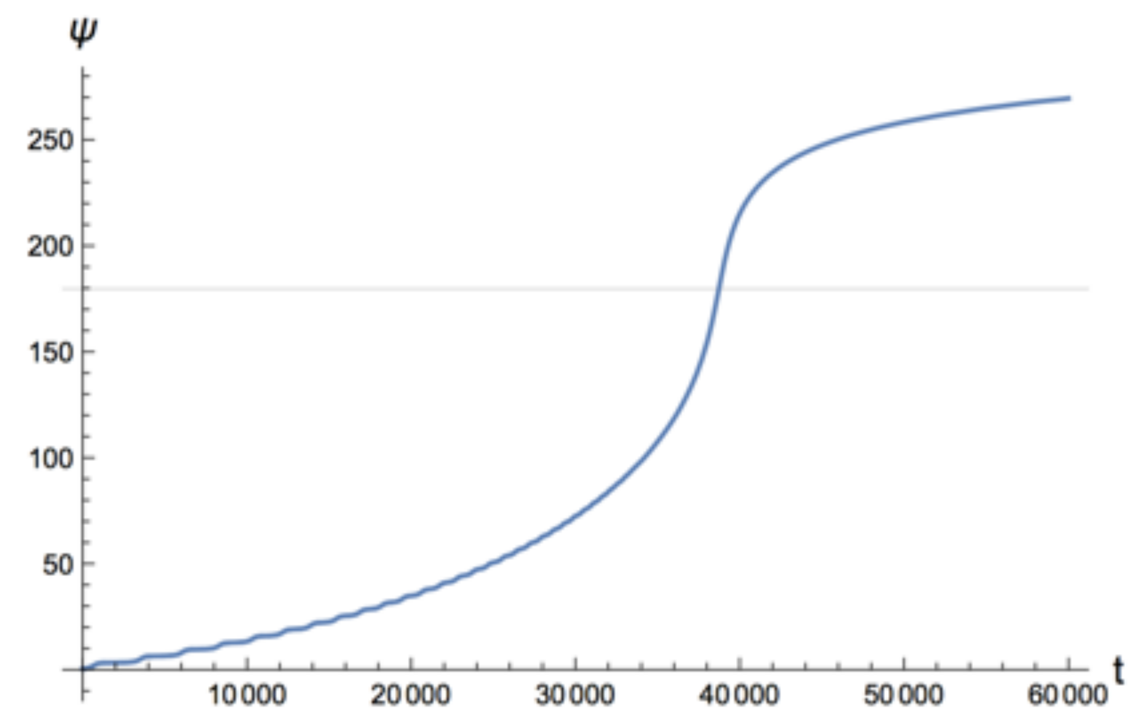
# On-going and future work

- Take into account back reaction on geometry - decreasing fluxes causes the throat to shrink; preliminary results indicate that this prolongs inflation and makes finding an acceptable power spectrum better.

- Scan parameter space so that this mechanism in the KS throat can either be ruled "in" or "out."

- There are qualitatively different behaviors that we have seen so far. Are there others?




- This model should fall under the umbrella of F-term "axion" monodromy - make the relationship between mobile branes, world-volume wilson lines and axions precise.

- Understand reheating, corrections, and dissipation…

# Summary

- The mechanism of brane-flux annihilation can be extended to the case where there are many more anti-branes than units of flux.
- This gives rise to the first known embedding of a flux cascade in string theory.
- The flux cascade gives rise to an inflationary epoch
- The phenomenology of observables and predictions is difficult but not out of reach

Thank you for your attention!

# Ingredients: Higer form flux, branes and extra dimensions

- String theory contains higher dimensional analogs of the Faraday tensor:

$$F_n = F_{\mu_1 \ldots \mu_n} = \mathrm{d}A_{\mu_1 \ldots \mu_{n-1}}$$

- An n-form flux has (n-2)-dimensional charged objects: branes, which satisfy a higher dimensional analog of Gauss's Law:

$$d * F = 4\pi * J$$

- These fluxes source an energy density ~ $\rho_{\rm flux} \sim F^2$

- A d-form flux in d dimensions is called a top form. Gauss's Law in the absence of sources tells us that a top form is constant and therefore acts as a cosmological constant

$$F_{\mu_1 \ldots \mu_d} = c\epsilon_{\mu_1 \ldots \mu_d}, \qquad \rho_{\rm flux} = c^2$$

# Brane-flux annihilation in detail

- We will work in the S-dual of the Klebanov-Strassler throat, this simply switches the cycles that the $F_3$ and $H$ flux wrap, leading to the anti-D3 branes polarizing into a D5 as opposed to NS5 brane, and $F_3$ being discharged as opposed to H.

- The starting point is the action for the probe D5:

$$S = \frac{-\mu_{\rm D5}}{g_s} \int d^6\xi \left[ -\det(G_{||}) \det(G_{\perp} - \mathcal{F}_2) \right]^{1/2} - \mu_{\rm D5} \int \{ C_6 + \mathcal{F}_2 \wedge C_4 \}$$

$$ds^2_{10} = \underbrace{a_0^2 ds^2_{\rm FLRW} + K(d\psi^2}_{G_{||}} + \underbrace{\sin^2(\psi) d\Omega_2^2}_{G_{\perp}} + ds_{\text{B-cycle}})$$

$$\mathcal{F}_2 = 2\pi \ell_s F_2 + B_2$$

- The flux quantization conditions tells us that (choosing a gauge where $C_6 = 0$):

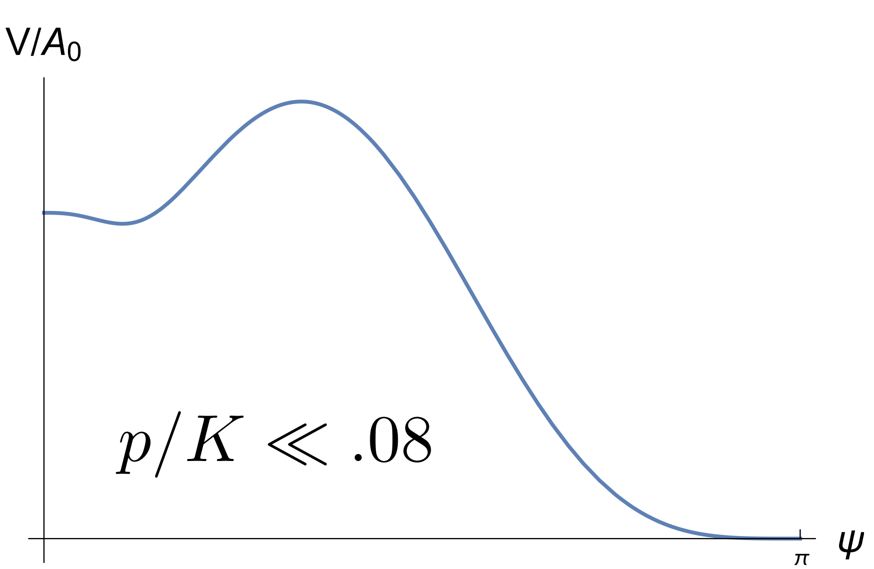
$$\mathcal{F}_2 = \pi \ell_s^2 \left( p - K \left( \frac{\psi}{\pi} - \frac{1}{2\pi} \sin(2\psi) \right) \right) \mathrm{vol}_{S^2}$$

# The full action

$$S = -\int d^4 x a^3(t) \left[ A_0 \left( V_2(\psi)\sqrt{1 - \ell_s K^2 \dot{\psi}^2} + U(\psi) \right) + \Lambda \right]$$

$$V_2(\psi) = \sqrt{\sin^4(\psi) + U(\psi)^2}, \qquad U(\psi) = \frac{\pi p}{K} - \psi + \frac{1}{2}\sin(2\psi), \qquad A_0 = \frac{\mu_{D3}}{g_s \pi K}$$

$$V_{\mathrm{D5}}(\psi) = A_0 \left[ \sqrt{\sin^4(\psi) + \left( \frac{\pi p}{K} - \psi + \frac{1}{2}\sin(2\psi) \right)^2} + \frac{\pi p}{K} - \psi + \frac{1}{2}\sin(2\psi) \right] .$$




KKLT/KKLMMT / D-brane inflation

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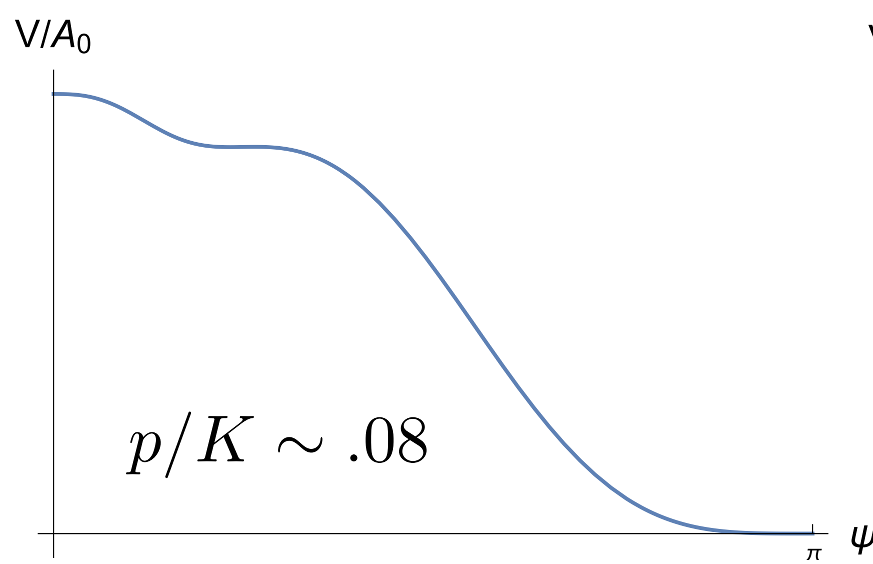
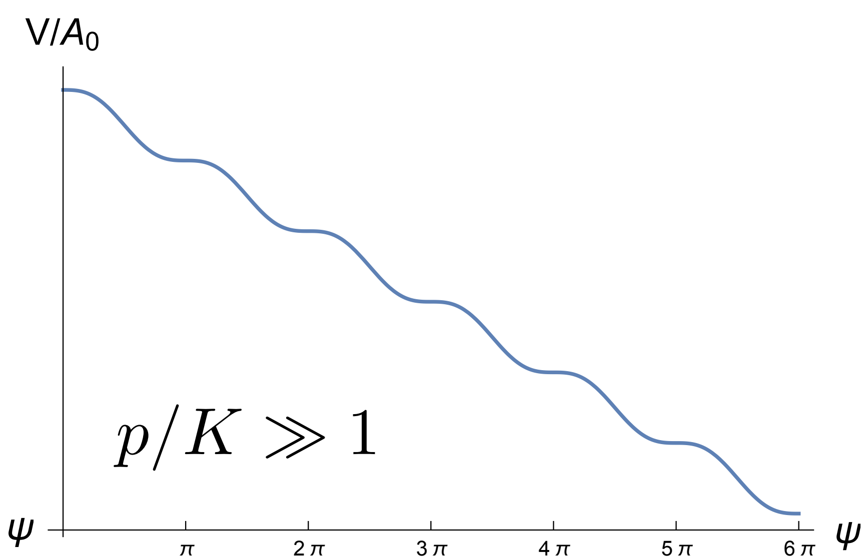



Giant Inflaton

DeWolfe, Kachru, Verlinde: hep-th/0403123




Unwinding

$$p = 81440, \qquad K = 509, \qquad M = 200, \qquad gs = 1/4$$

| | | | |
|---|---|---|---|
| $\Delta\phi/M_{pl} = 12.1$ | $H/M_{pl} = 6.5 \times 10^{-11}$ | $H/M_{KK} = 1.7 \times 10^{-4}$ | $\mathcal{V} = 5.3 \times 10^{12} \ell_s^6$ |
| $z^{1/3} = .012$ | $\mathcal{V}/\mathcal{V}_{\rm throat} = 1.1$ | $g_s p/K^2 = .06$ | $p/KM = .54$ |
| $p = 4.5 \times 10^6$ | $K = 4500$ | $M = 1852$ | $g_s = .27$ |
| $A_K = 3$ | $a_K = 2\pi/31$ | $\mathcal{W}_0 = 1.31$ | $\sigma_* = 10.4$ |

# Relation to axion monodromy

- Notice that a monodromy arises in the $B_2$ field with $\psi$ appearing outside of a trigonometric function. This pseudo-scalar:

$$b(\psi) = \int B_2 = 4\pi \ell_s^2 K \left( \psi - \frac{1}{2} \sin(2\psi) \right)$$

is of they  type used in axion monodromy inflation.

- However, there are several key difference:
  - Our $B_2$ wraps a topologically trivial 2-cycle.
  - The angle $\psi$ measures the position of a dynamical probe brane.
  - We don't need a "mirror" bifid throat
  - We don't use axions!