I. New de Sitter Solutions

Work in progress with

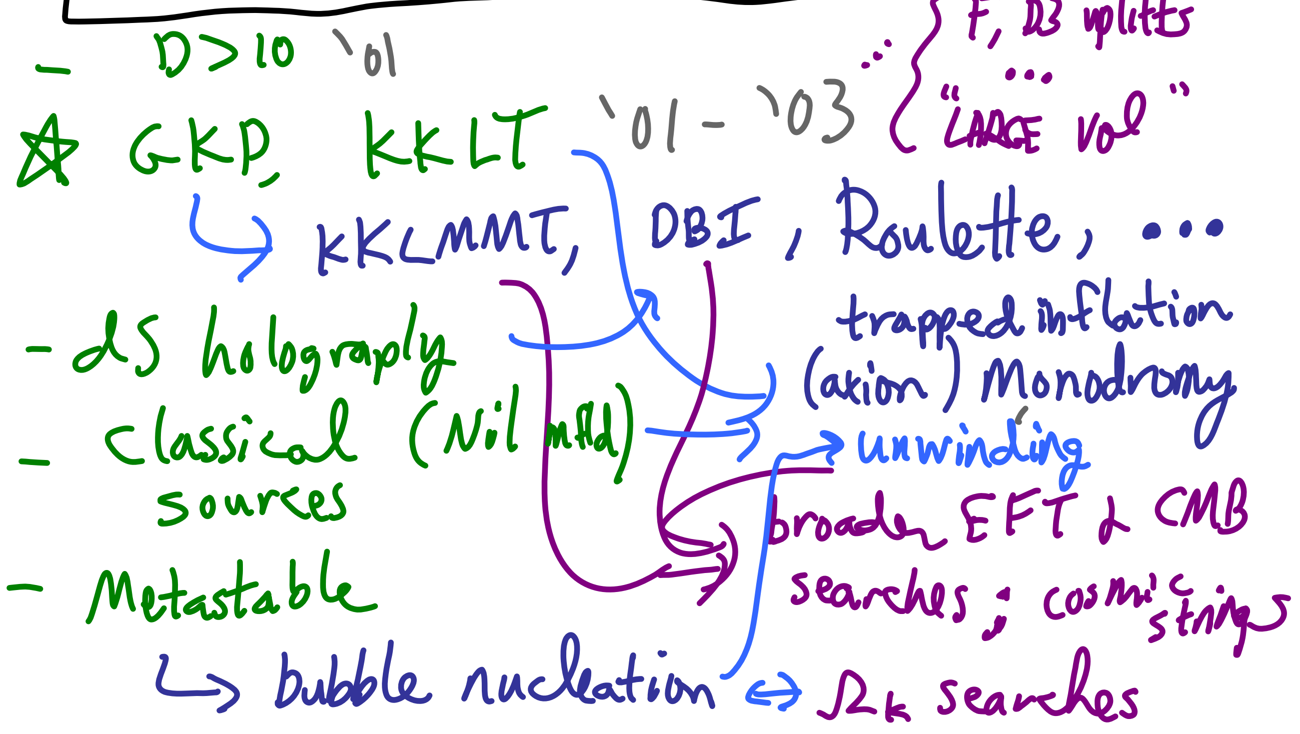
M. Dodelson, X. Dong, G. Torroba

II. Data Mining comments

Cosmological constant & inflation

- raises big questions about framework & initial conditions
- UV-sensitive (to quantum gravity) phenomenological observables

→ $\boxed{\text{Seek tractable String Theory Solutions for dS } (\rightarrow \text{inflation})}$



- D>10 '01

☆ GKP, KKLT '01-'03 ⋯ { F, $\overline{D3}$ uplifts … "LARGE Vol"

↳ KKLMMT, DBI, Roulette, …

trapped inflation

(axion) Monodromy

unwinding

broader EFT & CMB searches; cosmic strings

- dS holography
- classical (Nil mfd) sources
- Metastable

↳ bubble nucleation ↔ Ω_k searches

Simple backgrounds ("p-branes", "D-branes" "Freund-Rubin") led to rapid progress in black hole physics, string dualities, and the AdS/CFT correspondence.

The cosmological (dS, FRW) case has been slower in part because of the complication of the solutions (Simplest is in $d=3$, 10 sources Dong et al '10)

String theory →

potential with structure

$$V(\Phi, \sigma; \dots) \sim$$

dilaton size other sizes, axions, brane positions...

bulk localized defects

$$\sum_i \hat{V}_i e^{\beta_i \Phi + \gamma_i \sigma} + \sum_\ell \sigma_\ell e^{\gamma_i \Phi_i} \frac{\delta(w-w_\ell)}{\sqrt{g_{ww}}}$$

$$\gamma_i, \beta_i \sim \mathcal{O}(1/M_p)$$

+ warping effects (cf constraints)

+ quantum, non-perturbative

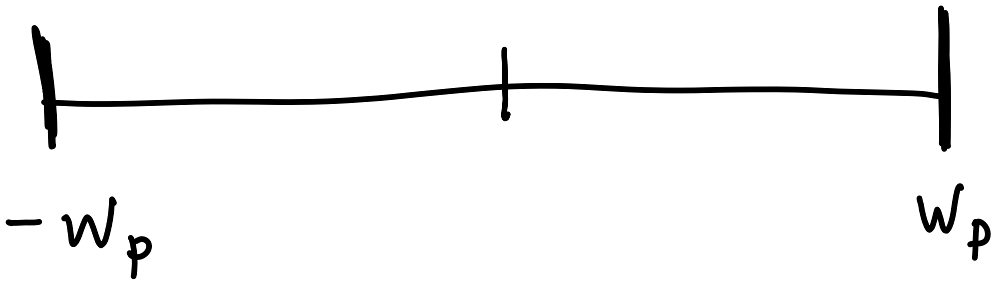
Consider 5d theory with potential that is simply

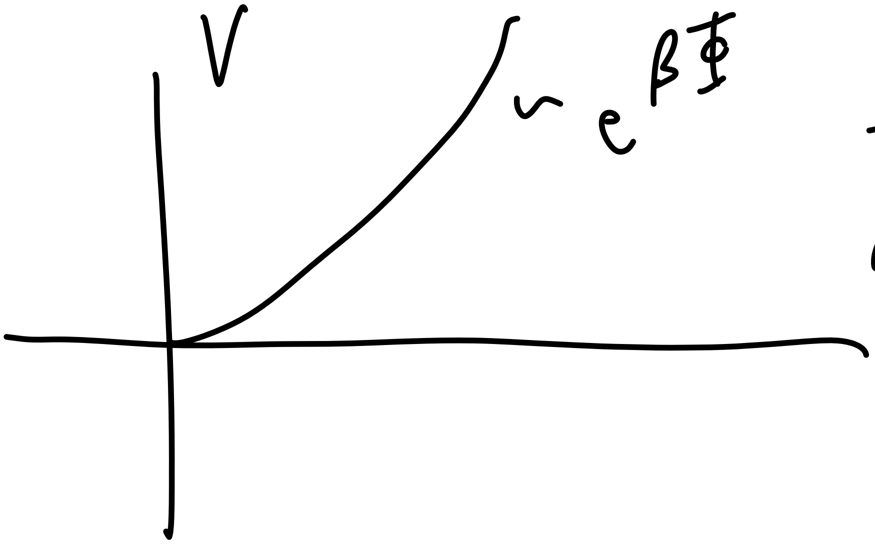
$$V = \hat{V} e^{\beta\phi}$$

plus a localized source (cf "orientifold plane")

$$\sigma = -\hat{\sigma} e^{\gamma\phi}\left[\delta(w-w_p) + \delta(w+w_p)\right]$$

$(\hat{\sigma} > 0)$





tadpole in $d=5$

Reduce to $d=4$ along one direction

$$ds^2 = a(w)^2 ds^2_{dS_4} + dw^2$$

cf RS Kaloper et al ...

$$\phi = \phi(w)$$

O-planes $T_{loc} \sim -\hat{\sigma} e^{\alpha\phi} [\delta(w-w_p) + \delta(w+w_p)]$

$\Rightarrow$ 2 (of 3) boundary conditions

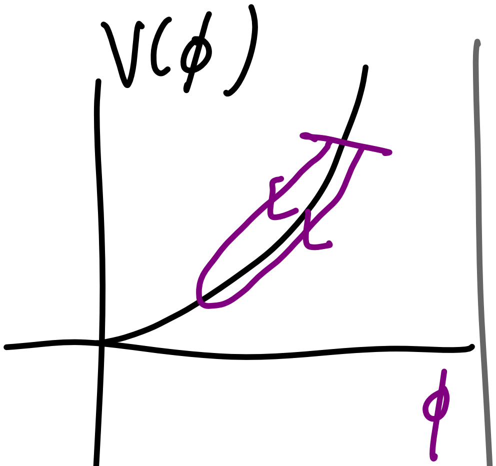
Equations (radial version of Friedmann eqn's) $(K_5 = 1$ here$)$

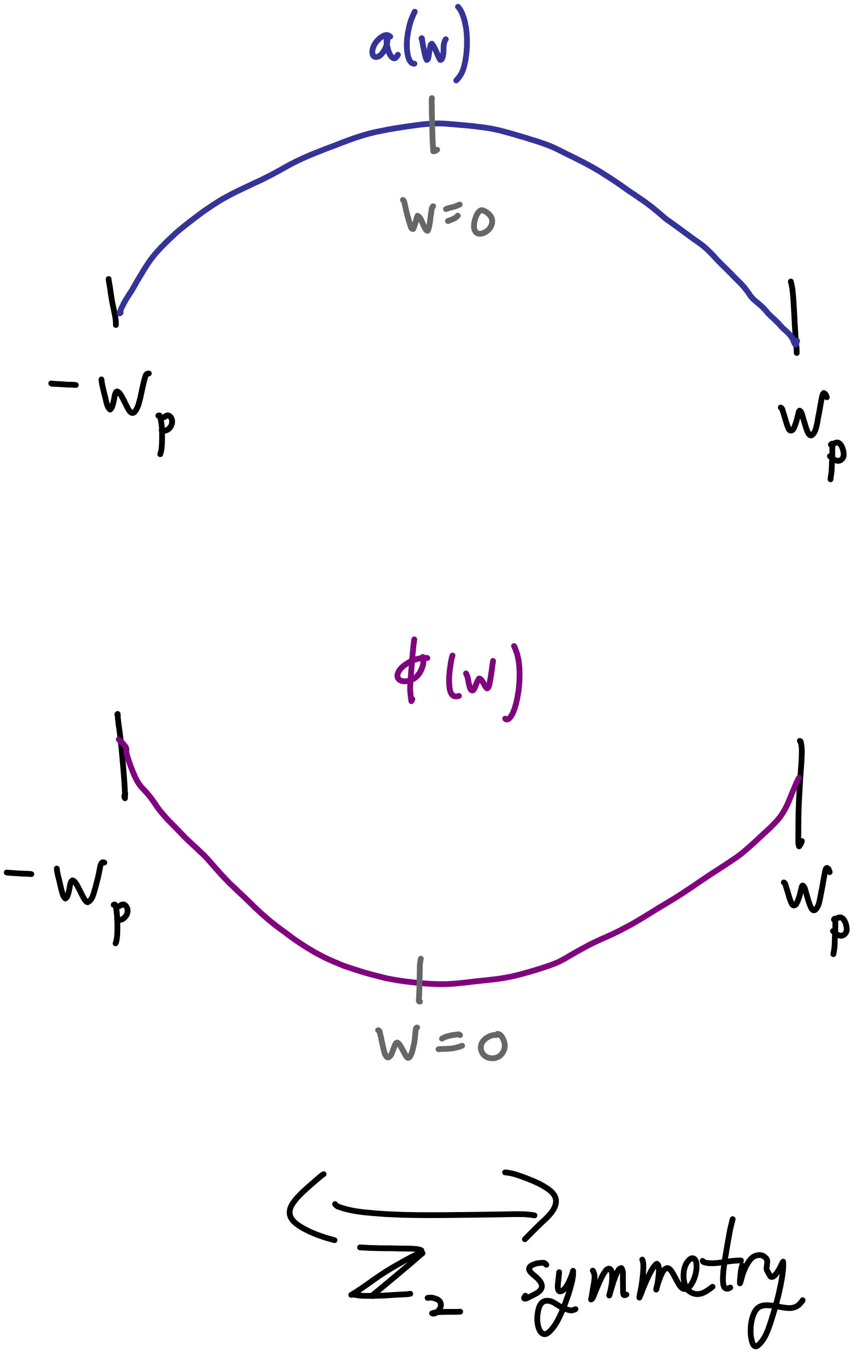
$$\frac{1}{2}(d-1)(d-2)\,\frac{a'^2-1}{a^2} = \frac{1}{2}\phi'^2 - V(\phi)$$

$$\phi'' + (d-1)\frac{a'}{a}\phi' - V'(\phi) = 0$$

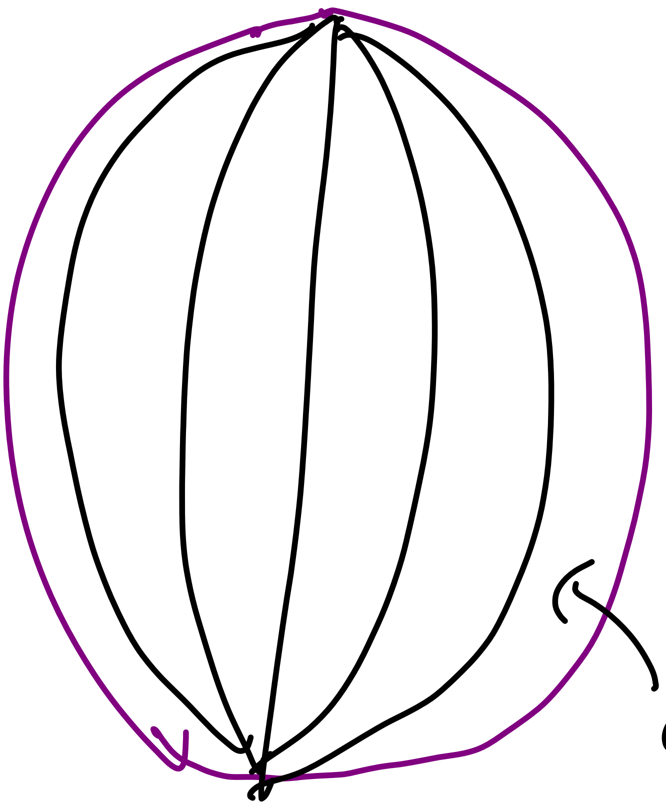
3 integration constants + w_p parameter

- $a'(-w_p) = -\dfrac{a\,\sigma(\phi)}{2(d-2)}$
- $\phi'(-w_p) = \frac{1}{2}\sigma'(\phi)$ $\quad w=-w_p$
- $a'(0) = 0 = \phi'(0)$





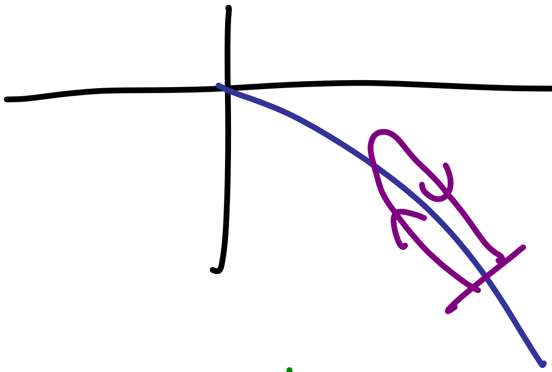
☆ Non singular dS_4 solution



dS_{d-1} slices

$$ds^2_{\underset{\underset{5}{\shortparallel}}{d}} = dw^2 + a(w)^2 ds^2_{dS_{\underset{\underset{4}{\shortparallel}}{d-1}}}$$

For intuition (if it helps), this is analogous to ($w \leftrightarrow$ time) to field rolling in time on $V < 0$ with negative spatial curvature



(This would have bang/crunch singularities, but in our case the Orientifolds cut off the interval at $\pm w_0$, excising singularities.)

- Explicit numerical solutions

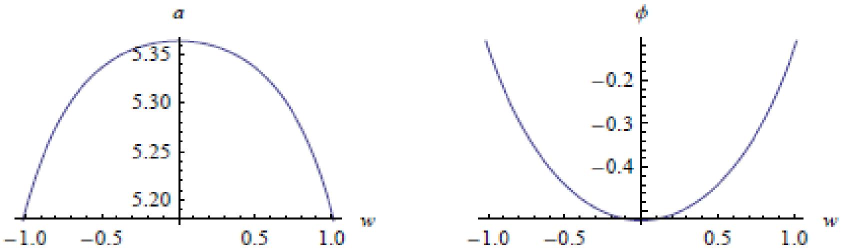


Figure 1: $V(\phi) = e^{3\phi}, \quad \sigma(\phi) = -e^{3\phi}$.

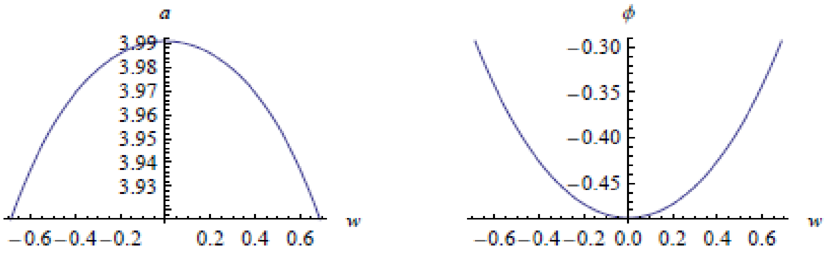


Figure 2: $V(\phi) = e^{2\phi}, \quad \sigma(\phi) = -e^{3\phi}$.

- Some no-go regions in α, β but easy to avoid

- Working on explicit $10d \to 5d \to 4d$ examples in string theory (multiple $\alpha_i, \beta_i \ldots$)

So far, took $V_{d=5}(\phi)$ with a tadpole, and used radial evolution $\phi(w)$ & strong warping $a(w)$ to obtain d=4 de Sitter solution.

⇒ at least new saddle points,

next checking if $\delta\phi$, $\delta g_{\mu\nu}$ are stable at 2nd order

☆ Tool: $V_{eff}[\delta\phi, \delta g_{\mu\nu}]\Big|_{\text{sol'n of constraints}}$

with strong warping   Douglas '10, Giddings ..

$$V_{eff} G_N^2 = \frac{-\frac{3}{2}}{\sum_i \frac{1}{\lambda_i} \left| \int \sqrt{g}\, u_i \right|^2}$$

where λ_i are energy eigenvalues & u_i normalized wavefunctions for the analogue Schrodinger problem

$$\lambda_i u_i = -\partial_w^2 u_i + [\overbrace{-V[\phi(w)] - \phi'^2(w) - \sigma_{lox}}^{U_{Q.M.}(w)}] u_i$$

In our case, $U(w)$ is a double well potential. $\delta\phi$, $\delta g_{\mu\nu}$ affect $\{\lambda_i, u_i\}$ (low-lying levels dominate)

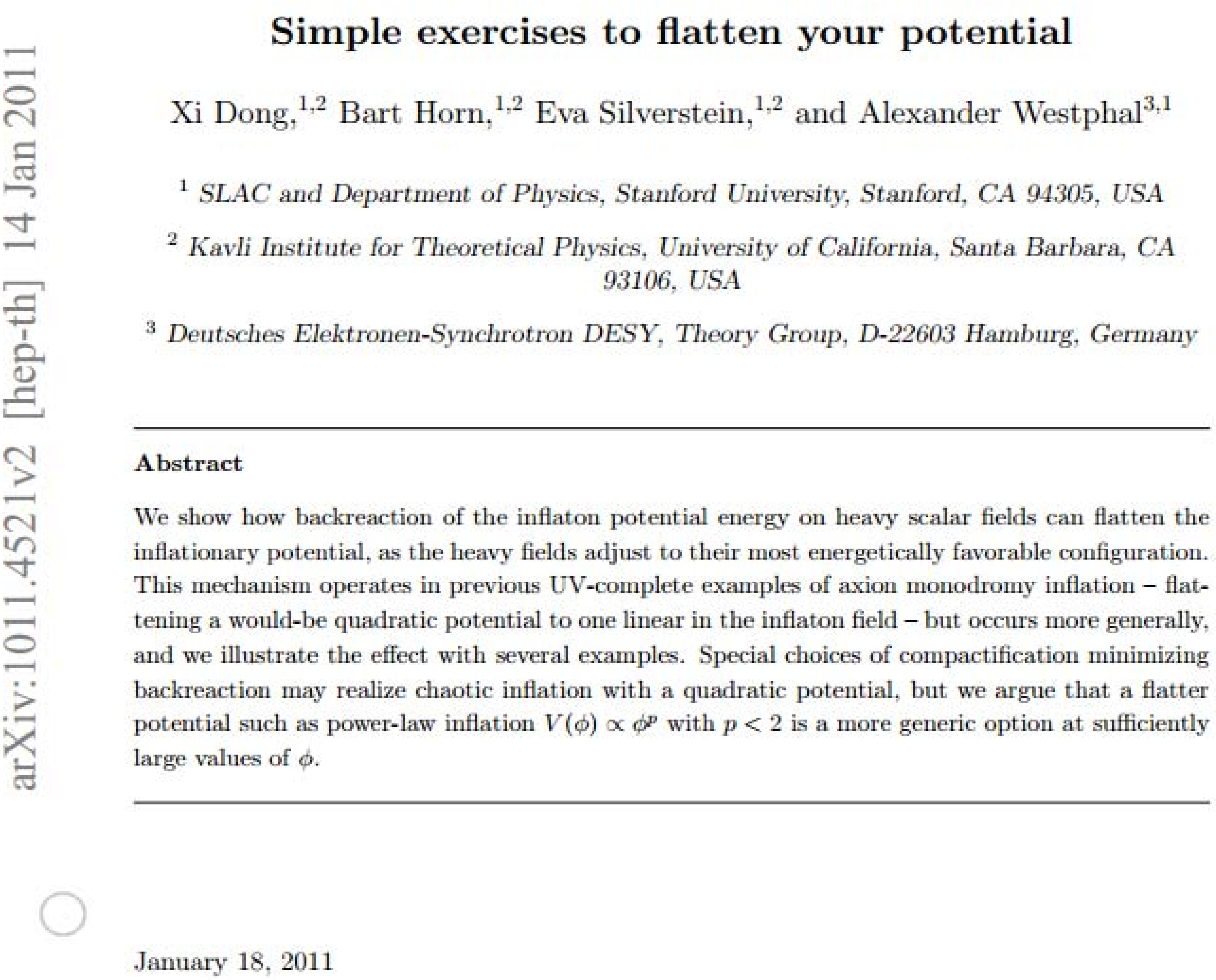
in progress

II. Data Mining Comments

Lots of interesting constraints and opportunities for further searches.

A few remarks on large-field inflation, e.g. axion monodromy

- potential flattening
- oscillations
- particle/string production
- reheating



arXiv:1011.4521v2 [hep-th] 14 Jan 2011

Simple exercises to flatten your potential

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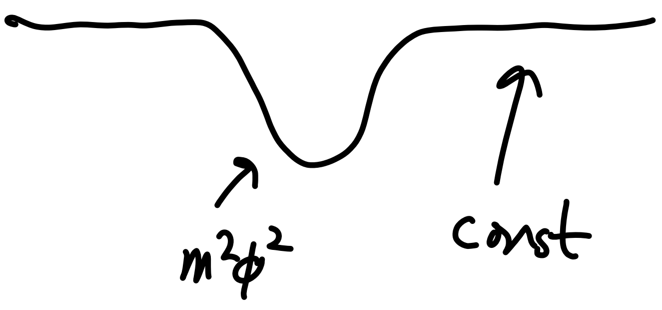
Abstract

We show how backreaction of the inflaton potential energy on heavy scalar fields can flatten the inflationary potential, as the heavy fields adjust to their most energetically favorable configuration. This mechanism operates in previous UV-complete examples of axion monodromy inflation – flattening a would-be quadratic potential to one linear in the inflaton field – but occurs more generally, and we illustrate the effect with several examples. Special choices of compactification minimizing backreaction may realize chaotic inflation with a quadratic potential, but we argue that a flatter potential such as power-law inflation $V(\phi) \propto \phi^p$ with $p < 2$ is a more generic option at sufficiently large values of ϕ.

January 18, 2011

$$V[\phi_L, \phi_H] = \frac{1}{2}(\phi_H - m)^2 M_H^2 + \frac{1}{2}\phi_H^2 \phi_L^2$$

$$V[\phi_L ; \phi_{H*}(\phi_L)]$$



$$M_H^2 \gg H^2$$

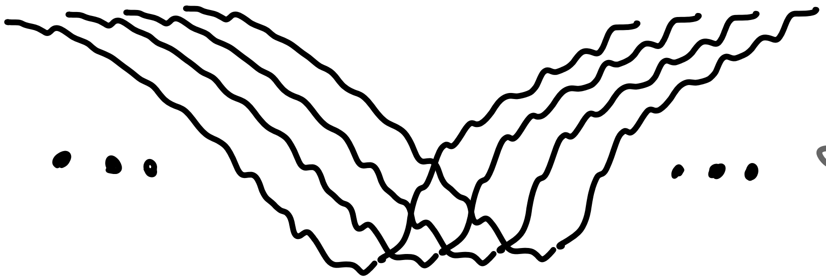
String theory comes with many quasiperiodic fields (ϕ_L) and heavy fields (ϕ_H) including Kaluza-Klein modes of metric & fluxes. Basic structure

$$\int \sqrt{g}\left\{ |dC_4 + C_2 \wedge H_3|^2 + |dC_2|^2 + R + \dots \right\}$$

w/ McAllister & Westphal + Flauger Pajer

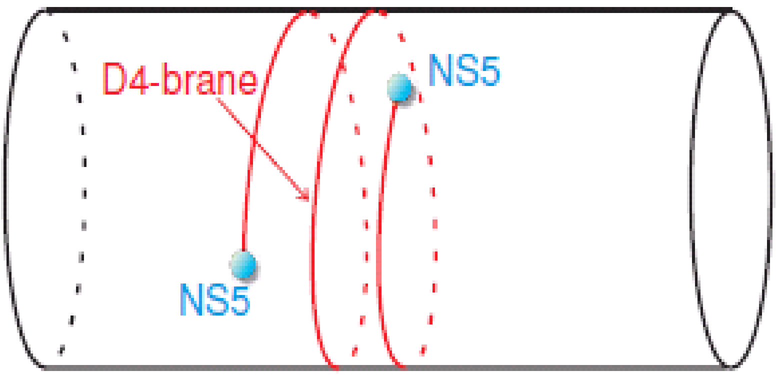
cf Kaloper Sorbo Lawrence et al

→



each branch : $\Delta\phi \gg M_p$.

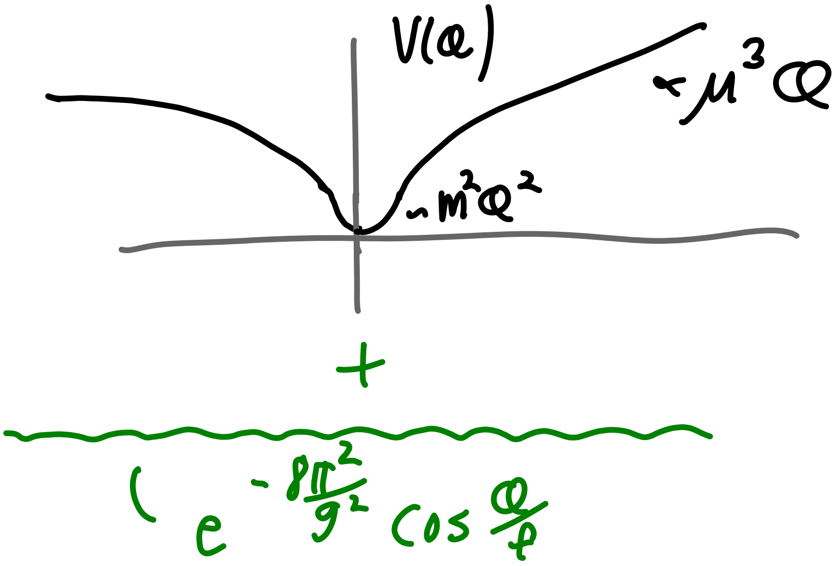
An illustrative example:



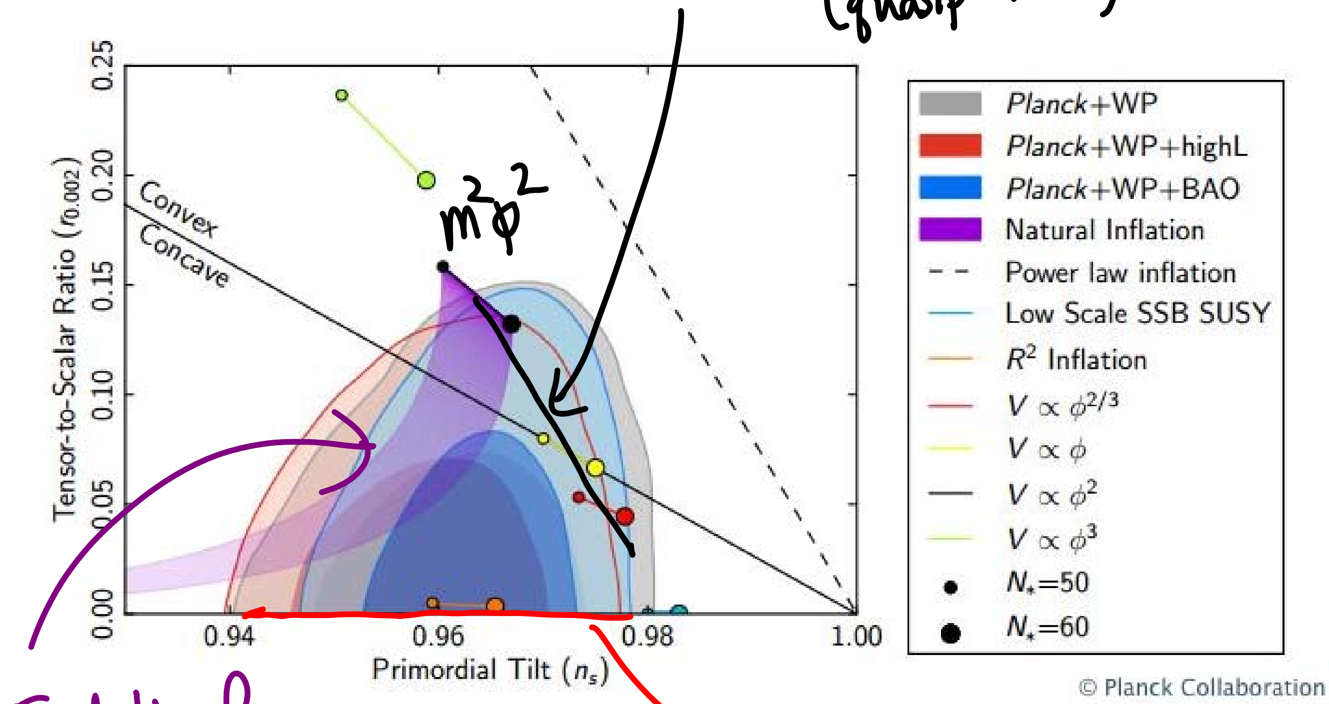
["T-dual" to axions]

- "NS5" branes position periodic on this circle, until add stretched "D4" brane

→ Novel prediction for inflaton potential



String theory axions $\phi^{p<2}$ (quasiperiodic)



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Traditional QFT axions

Small-field inflation

distinguishing $m^2\phi^2$ from flattened potentials, and distinguishing axion scenarios, is an interesting direction

Oscillation analysis

Power Spectrum & Bispectrum

└ Flauger et al

Easther Flauger Pieris

Jackson Wandelt

Planck

Chen Easther Lim

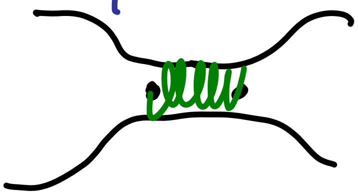
$$V_0(\phi) + \Lambda^4 \cos\frac{\phi}{f}$$

↑ model-dependent

heavy field adjustments

→ Flattening of V → $\phi^{p<2}$

→ f also adjusts

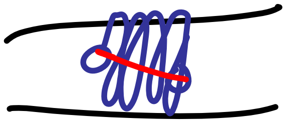


(Need care in parameterizing: e.g.

100 cycles × (1% mistake) ⇒ $\mathcal{O}(1)$ mistake)

Defect production (model-dependent)

w/ Green, Horn, Senatore, Zaldarriaga,



string tension ϕ-dependent

$\to$ NG   cf Porto et al

Beginning & Exit

- Explicit example of tunneling initiation

  D'Amico, Kleban talks

- Reheating: fix N_e uncertainty?

  - preheating dynamics & imprints

    cf Bond et al

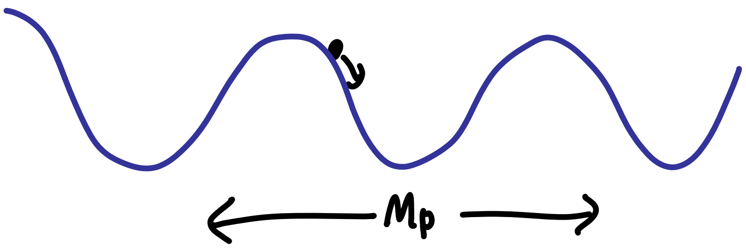
  - oscillons   Amin, Easther et al

Freese, Frieman, Olinto '90 ; +Adams, Bond '93

Axions naturally respect an (approximate) shift symmetry $\phi \to \phi + \alpha$

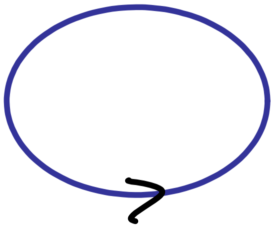
(couple via their derivatives)

→ "Natural Inflation"



$\Lambda^4 \sim e^{-\frac{const}{g^2}}$

Naturally small



$a \cong a + (2\pi)^2$

$\boxed{\phi_a = f_a a}$ — canonical scalar field

→ Does $\frac{\Delta\phi}{M_p} \gtrsim 1$, protected by shift symmetry, arise in string theory?

* Basic period small compared to M_p

Banks et al ...

In string theory, the basic period $f_\theta (2\pi)^2$ a priori turns out $\ll M_p$ at weak curvature + coupling

Banks/Dine/Fox/Gorbatov
Svrcek/Witten

cf Arkani-Hamed et al

e.g. <u>Axions</u>

$$a = \int_{\underbrace{\Sigma_p}_{\text{p-dim'l closed submanifold}}} \underbrace{A_{i_1\cdots i_p}}_{\text{potential field (higher-dim'l analogue of Maxwell } A_\mu)} dx^{i_1}\wedge\cdots\wedge dx^{i_p}$$

f_a comes from kinetic term:

$$\int d^D x \sqrt{G_{(D)}}\, F_{i_1\cdots i_{p+1}}\, G_{(D)}^{i_1 i_1'} \cdots G_{(D)}^{i_p i_p'}\, F_{i_1'\cdots i_{p+1}'}$$

$$= \int d^4x \sqrt{g_4}\, f_a^2 (\partial a)^2 = \int d^4 x \sqrt{g_4}\, (\partial \theta_a)^2$$

$\Rightarrow$ for all sizes $\sim R$, this yields

$$f_a \sim M_p \left(\frac{\sqrt{\alpha'}}{R}\right)^p \ll M_p$$

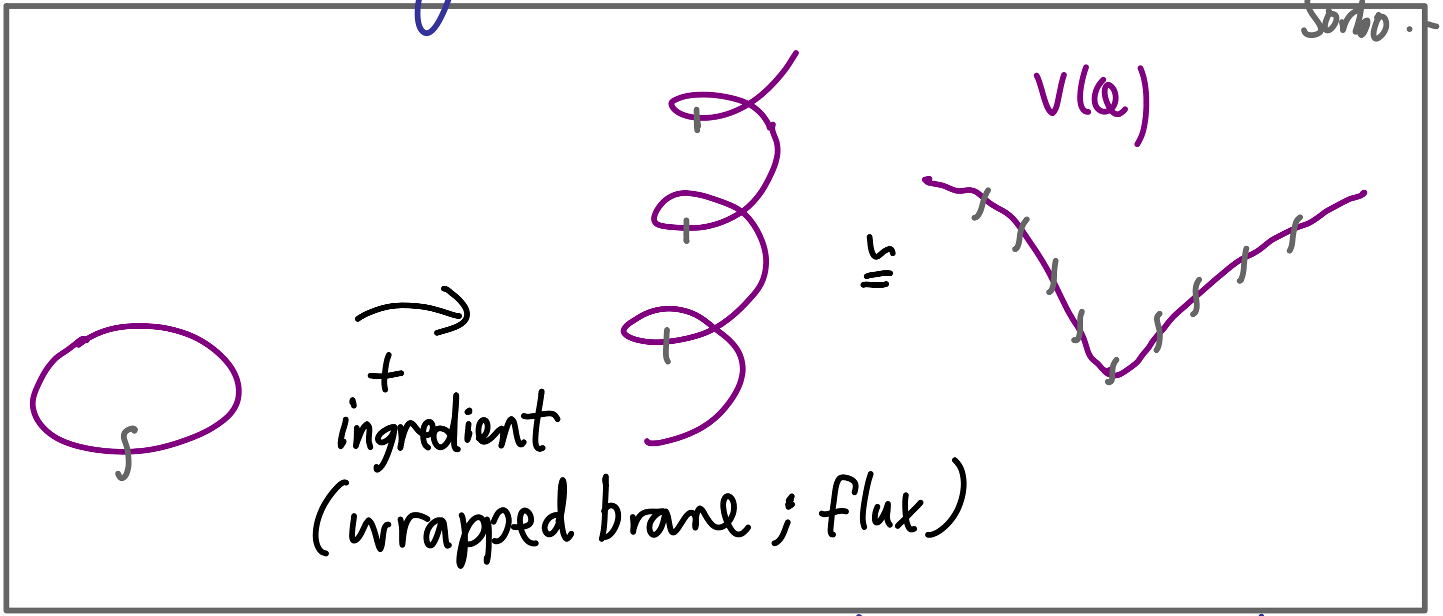
$\sqrt{\alpha'}$ = string length

Note: this is an example of the fact that not "anything goes" in the landscape. (In same regime $L \gg \sqrt{\alpha'}$, $g_s \ll 1$ where we control moduli stabilization & see multiple vacua, $f_{axion} \ll 1$.)

... But must take into account

"Monodromy" in string compactifications

ES, Westphal '08
McAllister, ES, AW '08
Kaloper Lawrence Sorbo ...



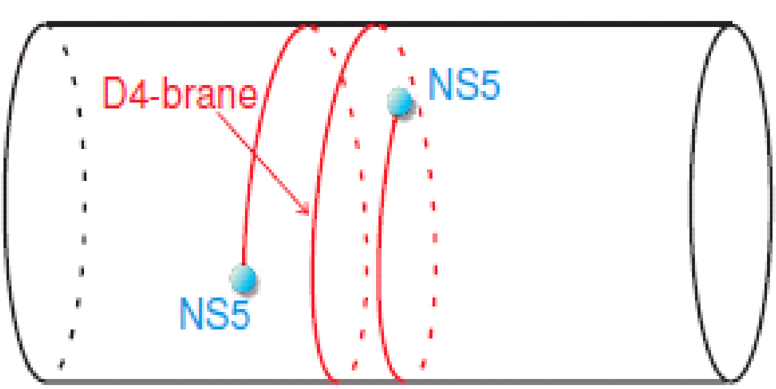
unwraps the would-be periodic direction. → Large field range with distinctive potential, with

$$V(\phi > M_p) \sim \begin{cases} \phi^{2/3} & \text{twisted torus} \\ \phi & \text{axions} \end{cases}$$

ES, AW '08
LMcA, ES, AW '08

the so far worked out examples.

The basic mechanism is very simple :



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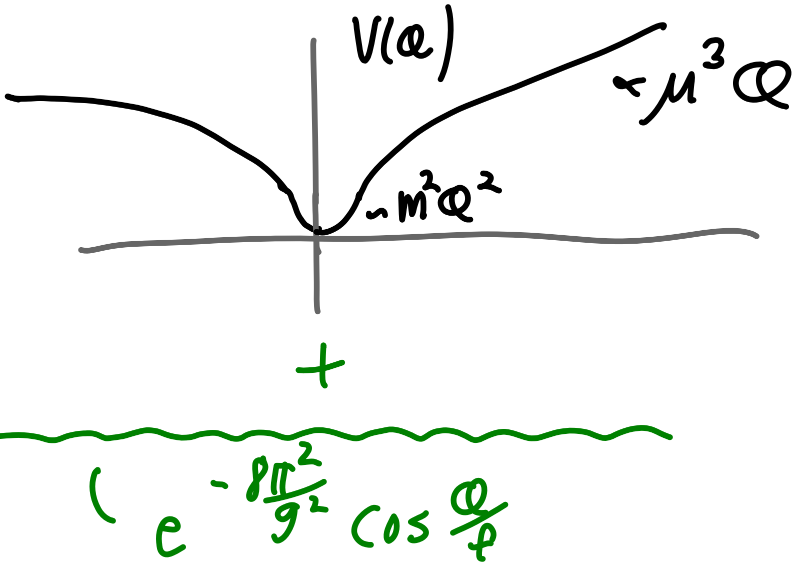
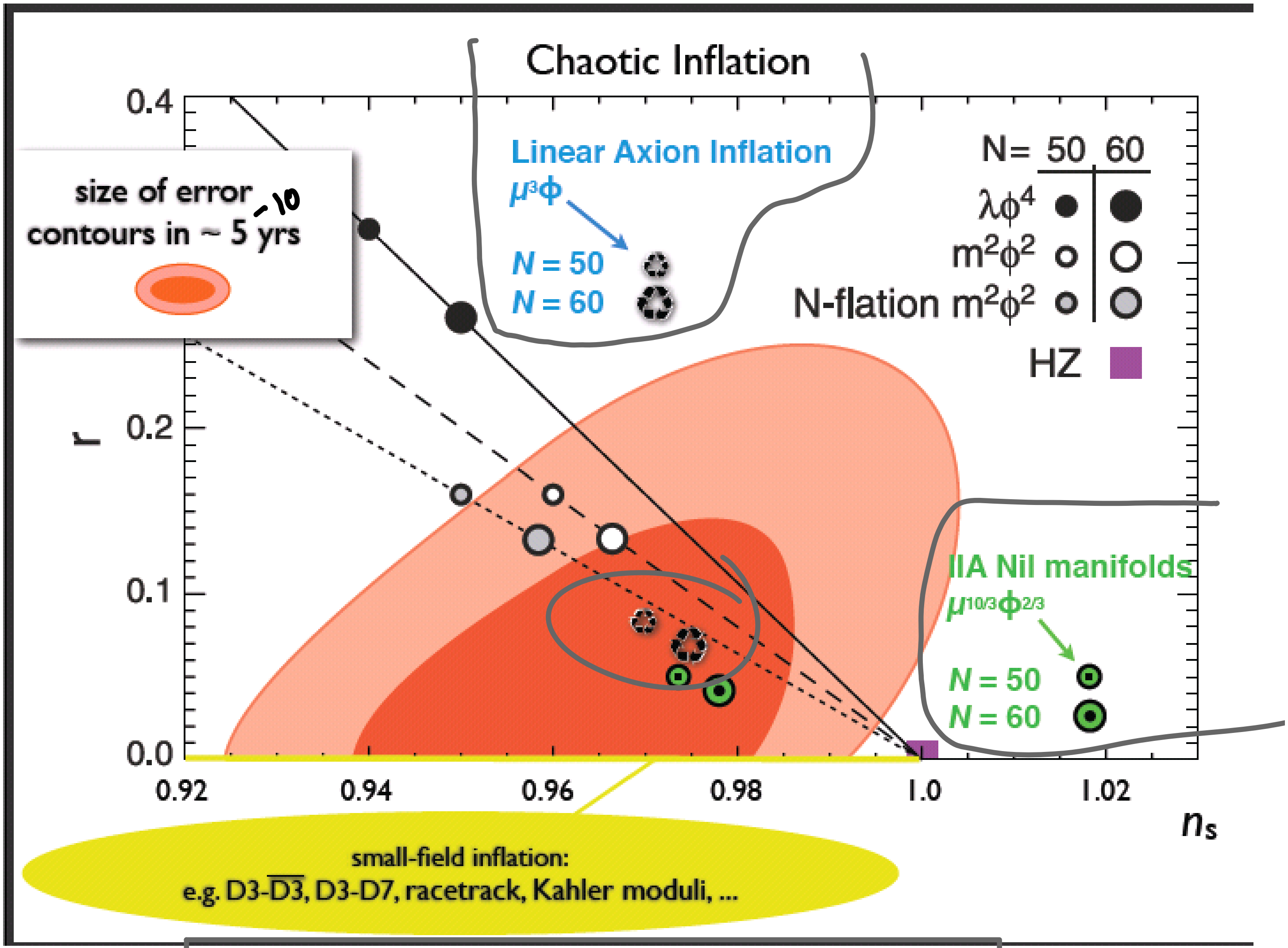


Result:

WMAP + (L. Page, D. Spergel, ...
cf Komatsu talk)



$$\boxed{\begin{array}{ll} r = 0.07 & V(\varphi) \simeq \mu^3\varphi + \Lambda^4 \cos\left(\frac{\varphi}{2\pi f}\right) \\ n_s \simeq 0.98 & \end{array}}$$

Because of the symmetry, and oscillating nature of the (instanton-suppressed) corrections, these predictions are robust ⇒ falsifiable

Encouraging … can we understand this effect more systematically?

Yes, a simple potential-flattening effect arises from adjustments of heavy fields:

Dong Horn ES Westphal

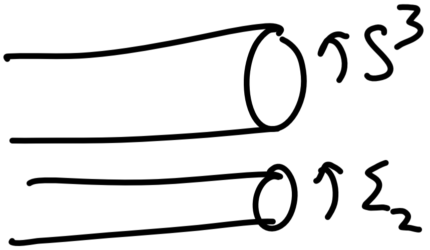
$$S_{\text{string theory}} \supset \int d^{10}x\sqrt{-G}\left\{|dB|^2 + |\overbrace{dC_2\wedge B}^{\text{Looks like } m^2\phi^2\dots} + \cancelto{0}{dC_4}|^2 + \dots\right\}$$

$$\text{axion} \quad b = \int_{\text{submanifold } \Sigma_2} B_{ij}\, dx^i \wedge dx^j$$

… but the potential energy contained in $|dC_2 \wedge B|^2$ term backreacts on geometry and fluxes:

Backreaction on geometry:

$$g_s \tilde{N}_{\text{eff}} = b \int F_3 \sim \underbrace{\frac{R^4}{l_s^4}}_{\substack{\text{Size of}\\ \text{geometry}\\ \text{in units of}\\ \text{string tension}}}$$



Plugging this back into $S_{\substack{\text{string}\\ \text{theory}}}$

$$\to S_{\substack{\text{str}\\ \text{theory}}} \sim \text{Vol}_{4d} \frac{\tilde{N}^2}{R^{10}} \times R^6 \sim \underbrace{\frac{\tilde{N}}{g_s}}_{\text{Linear in axion}} \times \text{Vol}_{4d}$$

In general, when slow-roll inflation applies, any heavy ($m > H$) fields will adjust in an energetically favorable way: can naturally flatten V relative to $m^2\phi^2$.

Another example:

$$V = \dots + |C_2 \wedge H_3|^2 + |F_3|^2 + |H_3|^2$$

flux H_3 sloshes around to $\downarrow |C_2 \wedge H|^2$ at cost of $\uparrow |H_3|^2 \rightarrow$ new equilibrium with $V(\phi) \propto \phi^{p<2}$.