Gravity Waves & the LHC:

Towards High-Scale Inflation with low-energy SUSY

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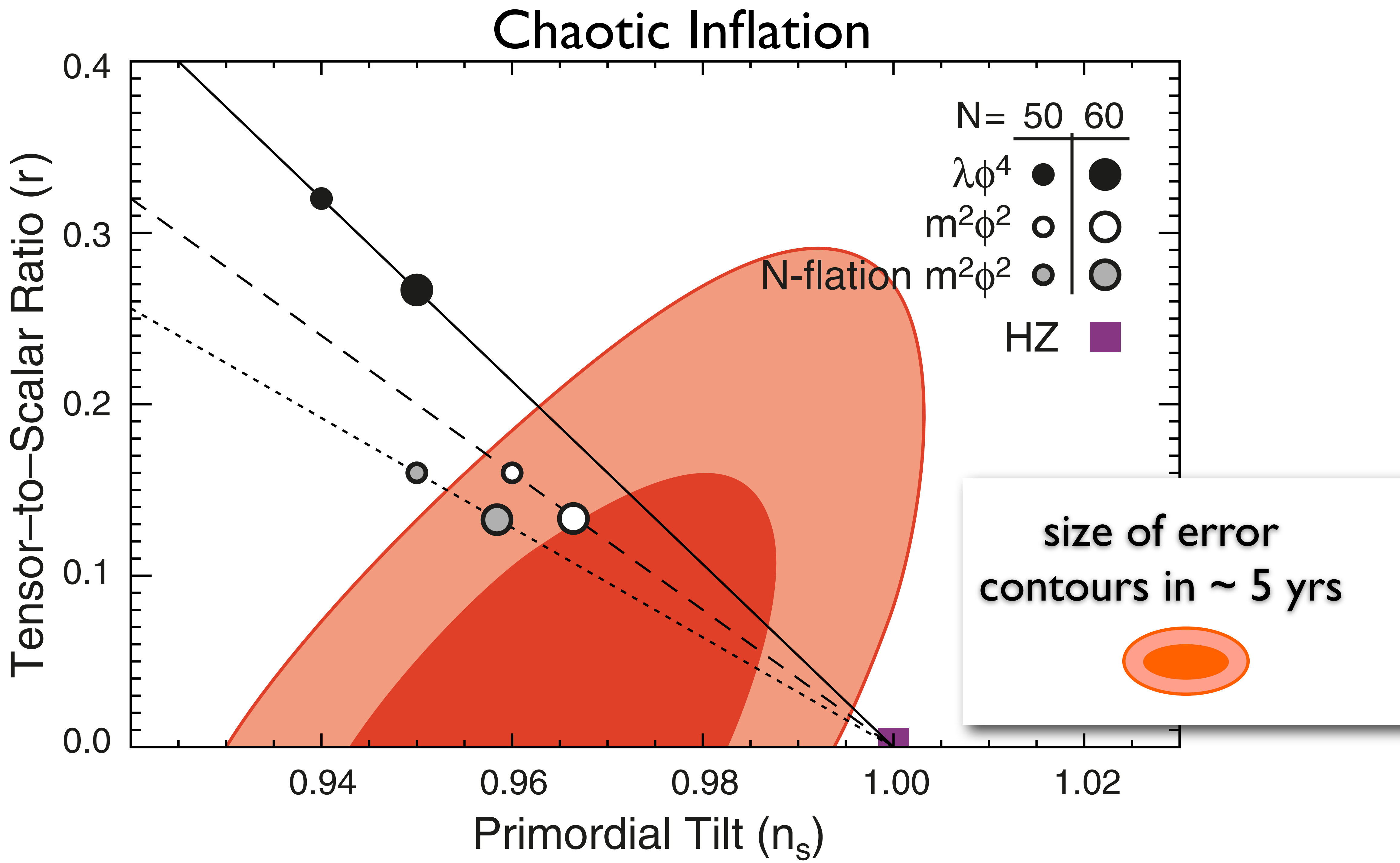
(arXiv: 1003.4265)

with: Temple He & Shamit Kachru

where I want to take you ...

- why:
  - large-field inflation (Φ moves more than M_P)?
  - strings?
- inflation & moduli stabilization - the Kallosh-Linde problem
- the demise of the problem - natural high-scale inflation @ the TeV
  - a natural setup for $H >> m_{3/2}$ in KKLT
  - dynamics of the volume modulus during inflation
  - hierarchies & scales - horse trading

present status: WMAP 7yr + BAO + H_0

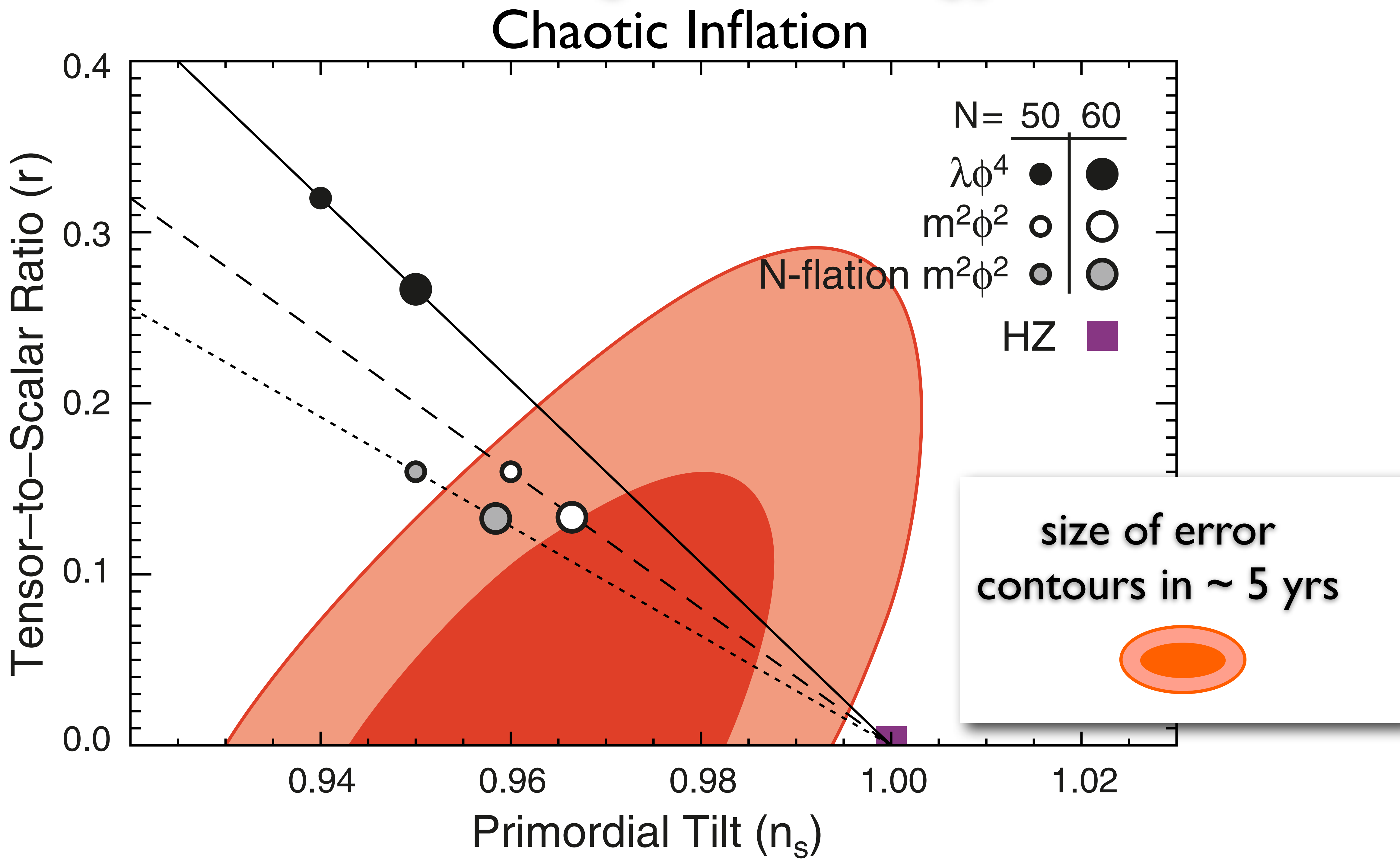


expect dramatic improvement in next 5 yrs:

Planck & **BICEP2** taking data, Keck Array ('10...)

SPIDER, Clover, QUIET-II, EBEX, PolarBEAR ...

We live in the Golden Age of cosmology !



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$$\Rightarrow \quad \epsilon \equiv -\frac{\dot{H}}{H^2} \simeq \frac{1}{2}\left(\frac{V'}{V}\right)^2 \ll 1 \quad , \quad \eta \equiv \frac{\dot{\epsilon}}{\epsilon H} \simeq \frac{V''}{V} \ll 1$$

with the Hubble parameter $H^2 = \frac{\dot{a}^2}{a^2} \simeq const. \sim V$

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- *but:* if field excursion sub-Planckian, no measurable gravity waves: [Lyth '97]

$$r \equiv \frac{\mathcal{P}_T}{\mathcal{P}_S} = 16\epsilon \leq 0.003 \left(\frac{50}{N_e}\right)^2 \left(\frac{\Delta\phi}{M_{\mathrm{P}}}\right)^2$$

why strings?

- *large field* model of inflation, i.e. "chaotic inflation"

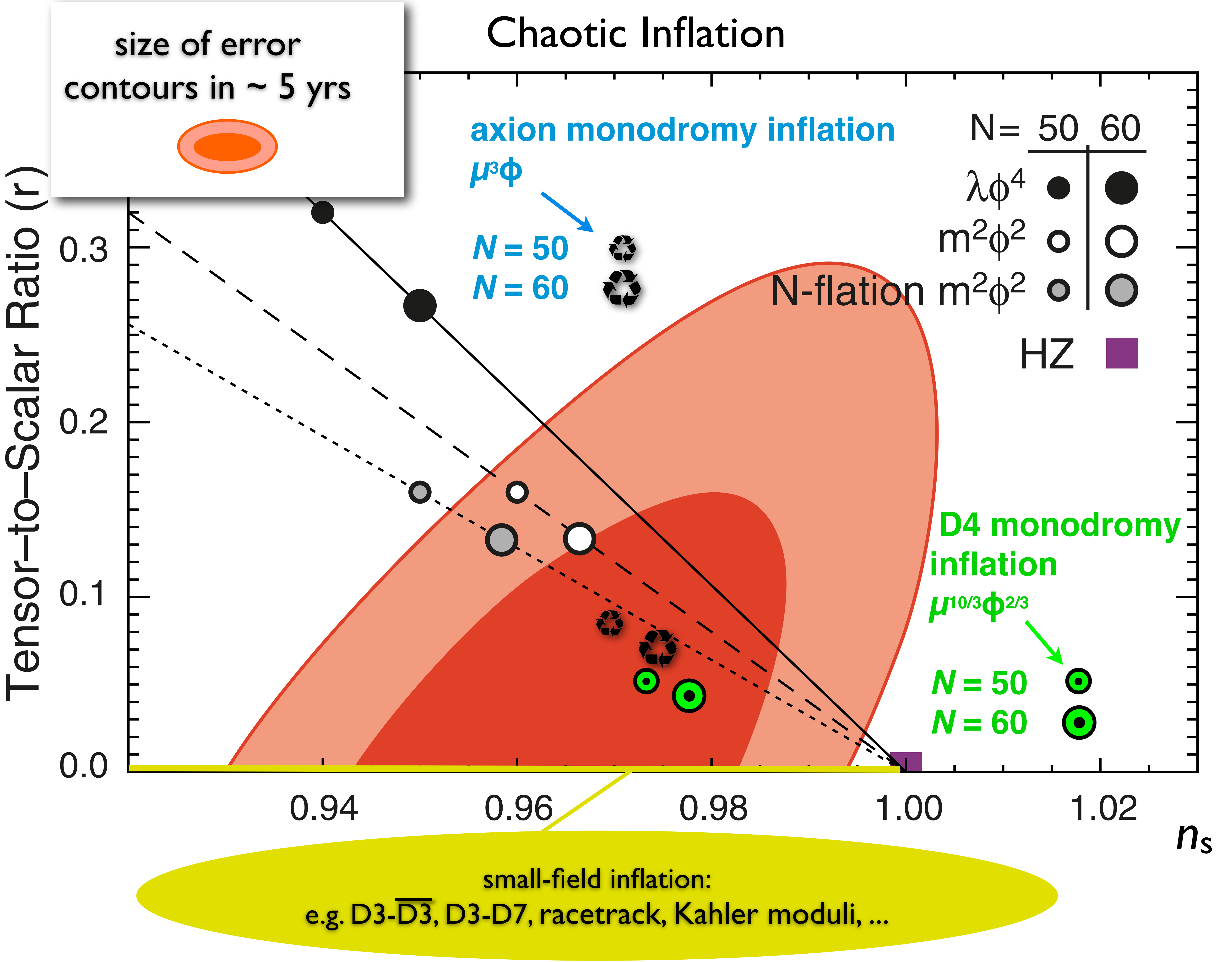
$$\Delta\phi > M_P \quad \Rightarrow \quad r > 0.01$$

- with control of ε & η over a super-Planckian field distance - avoid generic dim ≥ 6 operators:

$$\delta V \sim V(\phi)\frac{(\phi-\phi_0)^2}{M_{\rm P}^2}$$

need UV-complete theory: e.g. strings

- idea: arrange for approximate shift symmetry of ϕ , broken only by the inflaton potential itself
[Linde '83]



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size of error contours in ~ 5 yrs
axion monodromy inflation
μ³φ
N = 50
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N= 50 60
λφ⁴
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N-flation m²φ²
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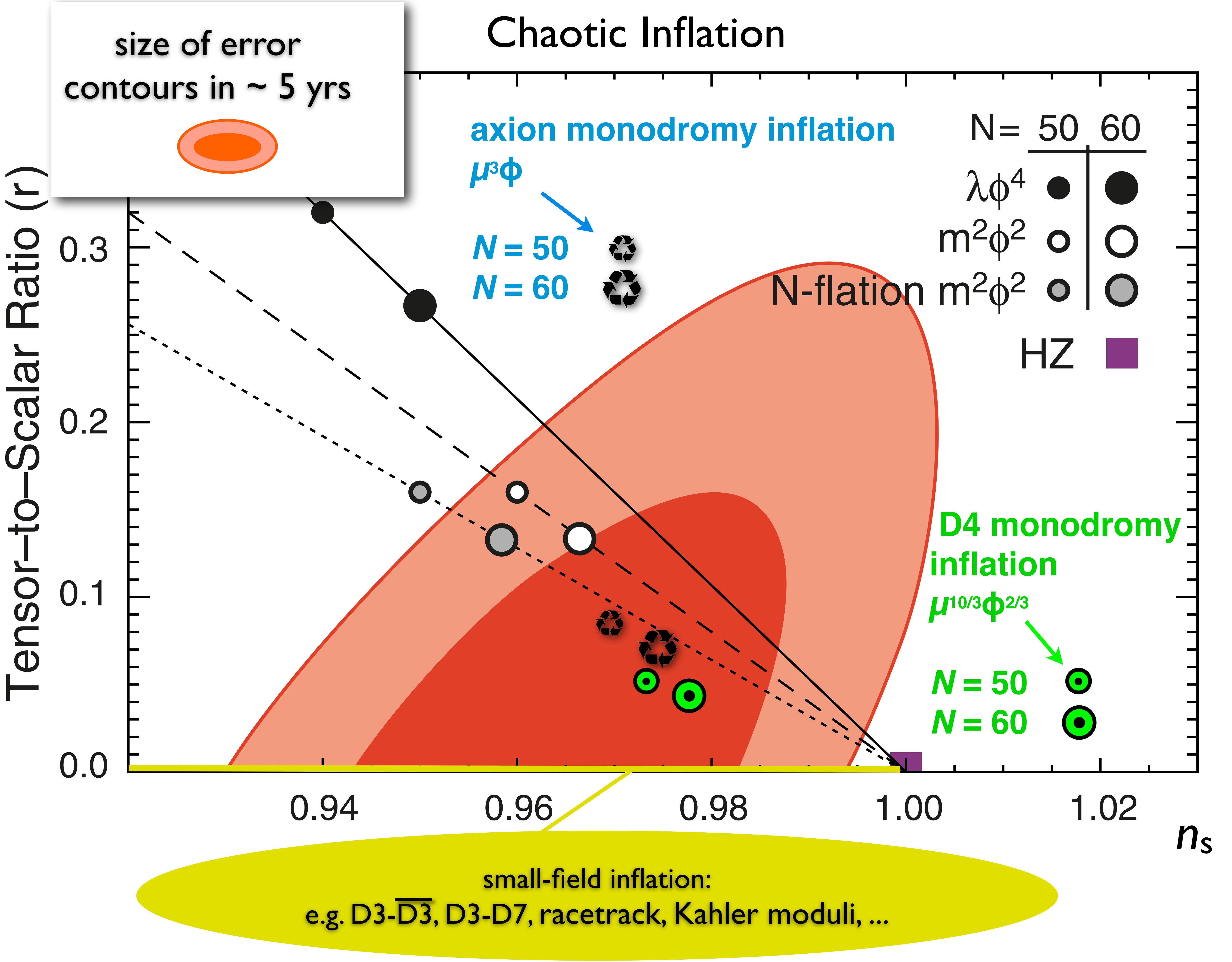

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the Kallosh-Linde problem ...

... all it needs are SUSY and extra dimensions
(NOT specific to string theory) ...

- A well-motivated extension of the standard model is TeV-scale broken supersymmetry - if this is local, we deal with 4D N=1 supergravity.

- the vacuum energy in supergravity is given by the scalar potential in terms of 2 functions - *K* and *W*

$$V(\phi_i) = e^K \left(\sum_i |F_i|^2 - 3|W|^2 \right)$$

- for (nearly) vanishing cosmological constant, this ties the VEV of the superpotential *W* to the size of the dominant F-term - and determines the order parameter of SUSY breaking in supergravity, the gravitino mass $m_{3/2}$

$$m_{3/2}^2 \simeq e^K \frac{|W|^2}{M_{\rm P}^4}$$

we are in 4D - string compactification ...

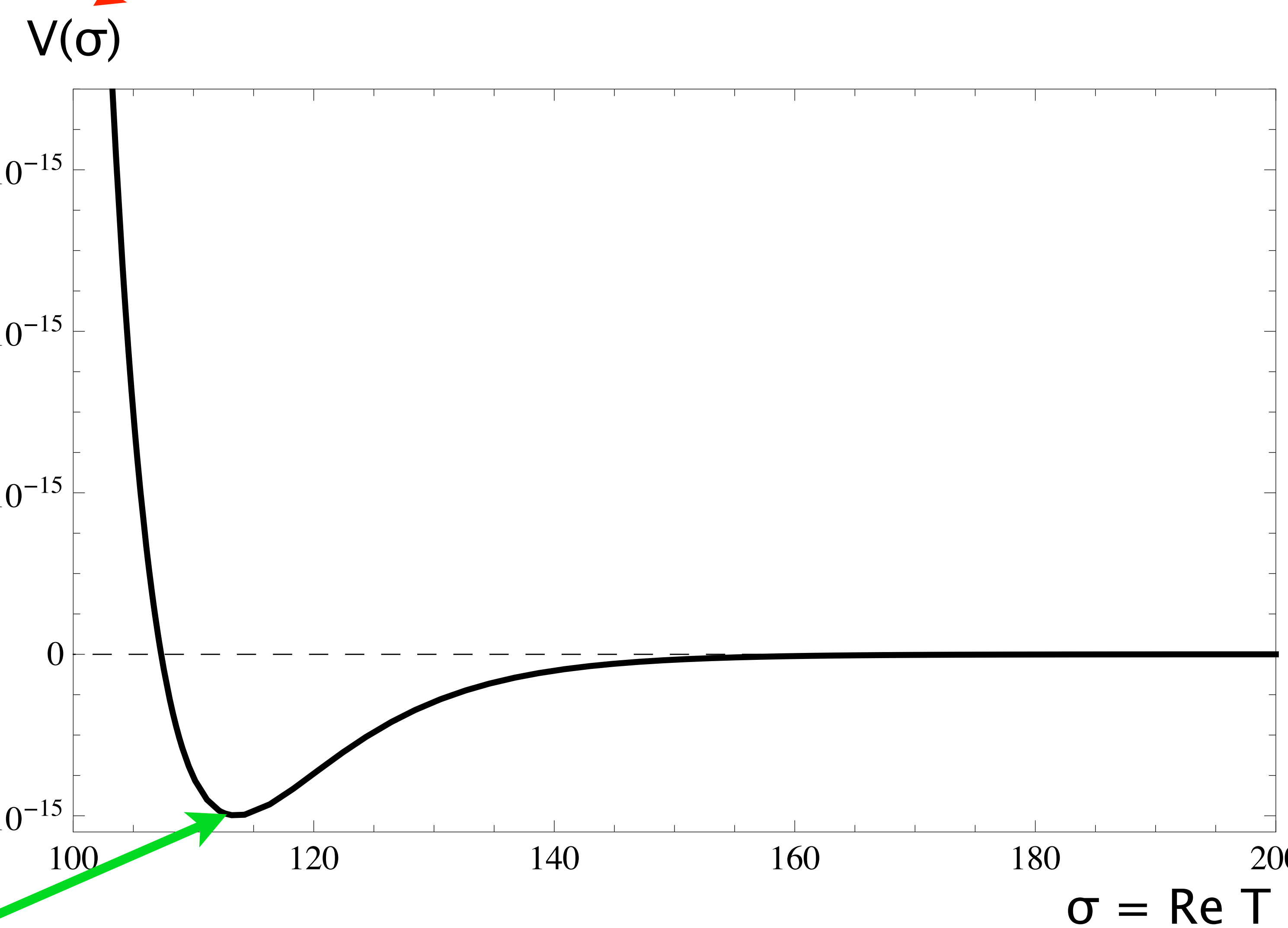
- we wish for 1 low-energy supersymmetry in 4D - need to compactify internal 6 dimension on a Calabi-Yau manifold

- $\Rightarrow$ moduli: massless scalar fields, determining size(s) and shape(s) of the CY

- $\Rightarrow$ one path to controlled compactification (KKLT) in IIB string theory:
  - fix the shapes with fluxes of p-form gauge fields
  - fix the sizes with 1 instanton per size modulus

- single size modulus case - the whole volume: 1 instanton balances against the non-*T* sector W_0 (e.g. from fluxes)

$$V(T) = e^K (K^{T\bar{T}} |D_T W|^2 - 3|W|^2)$$



$$K = -3\ln(T + \bar{T})$$

$$W = W_0 + Ae^{-aT}$$

fixes shape moduli

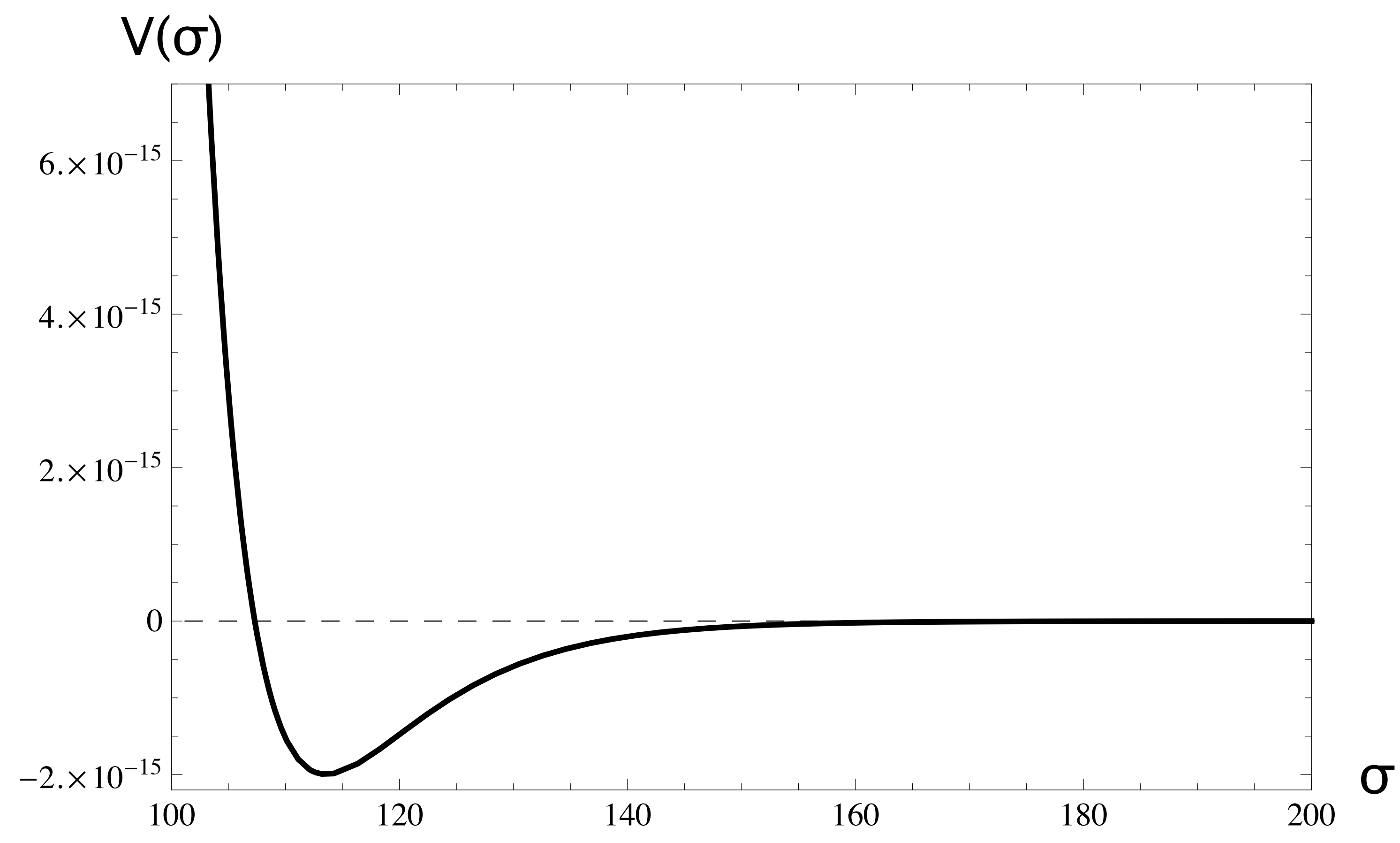
$$T_0 : \; D_T W(\varphi)|_{T_0} = 0$$

- inflationary sector generates a large positive vacuum energy
- by locality in the extra dimensions all energy forms can at most grow as fast as the volume
- Weyl rescaling into 4D Einstein frame - all energy forms scale as σ^{-3} = volume^{-2}
- $\Rightarrow$ all potentials vanish at infinite volume &

  all positive energy states are metastable to *de-compactification*

- Einstein frame rescaling - SUSY breaking scales as inverse power of the volume σ = Re *T*

$$|V_{AdS}| = 3e^{K}|\langle W \rangle_0|^2$$



[Kallosh & Linde ’04]

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$$V(\Phi) \sim e^K K^{\Phi\bar{\Phi}} |D_\Phi W|^2 \sim \frac{1}{\sigma^r}$$

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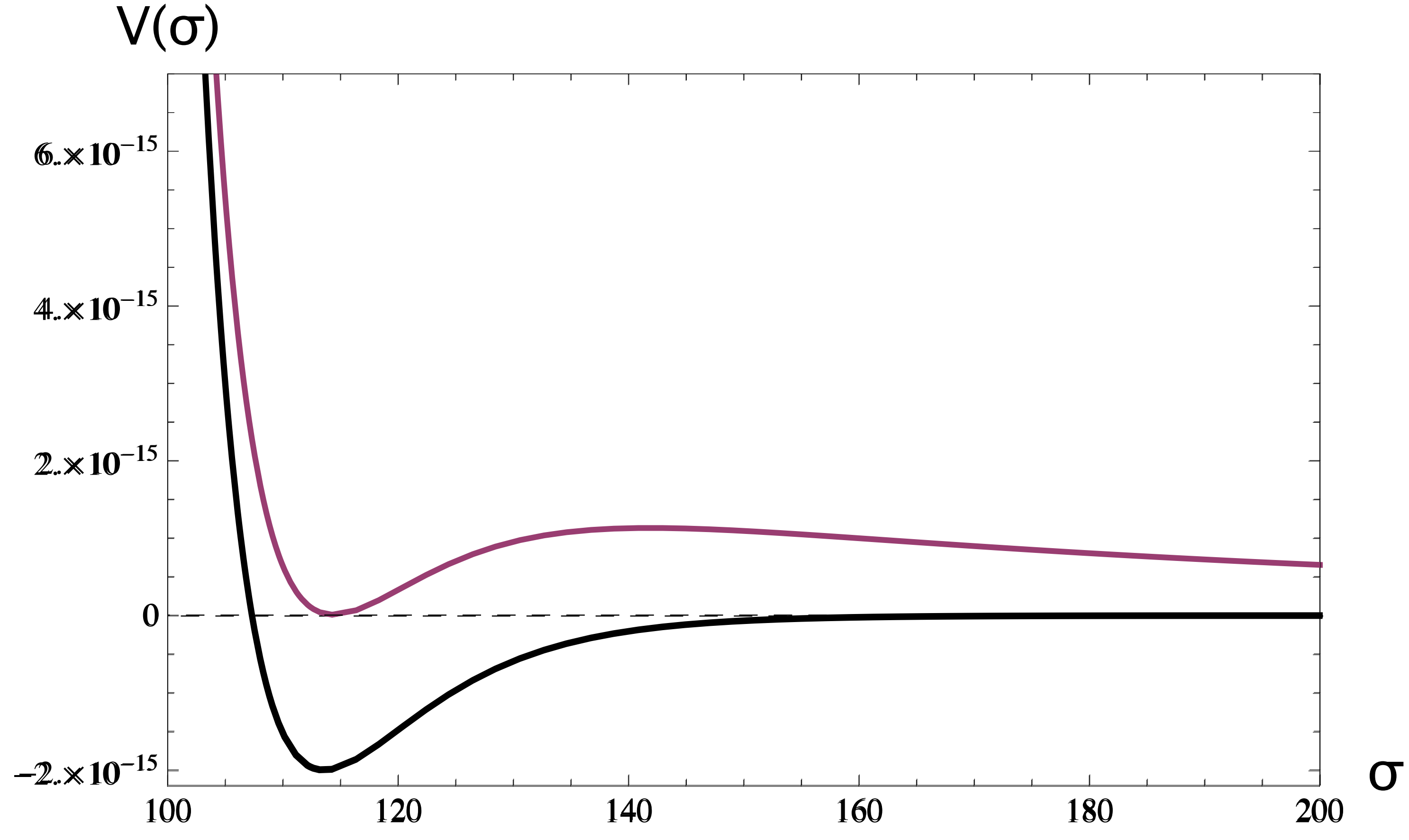

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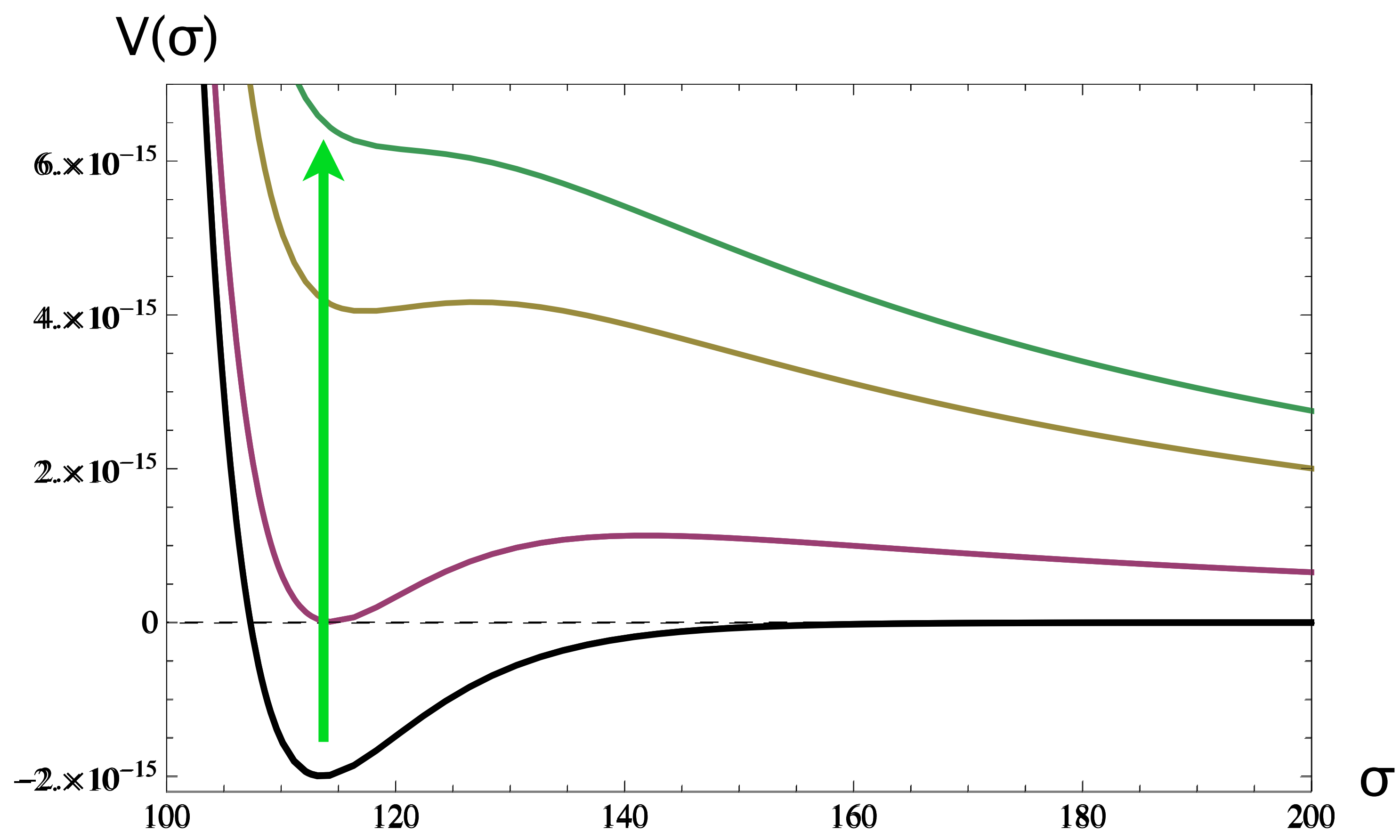


$$H^2 \lesssim \mathcal{O}(10) V_B \simeq \mathcal{O}(10)|V_{AdS}| \sim e^K |\langle W \rangle_0|^2 \sim m_{3/2}^2$$

[Kallosh & Linde '04]

- related to earlier studies noting, that reheating after inflation will lead to decompactification and/or run-away to weak coupling, if the reheat temperature exceeds the energy scale of the barriers ...

[Buchmüller, Hamaguchi, Lebedev & Ratz '04]

- $\Rightarrow$ reheat temperature problem in higher-dimensional models

overcoming the KL problem ...

[He, Kachru & AW '10]

What to do ?

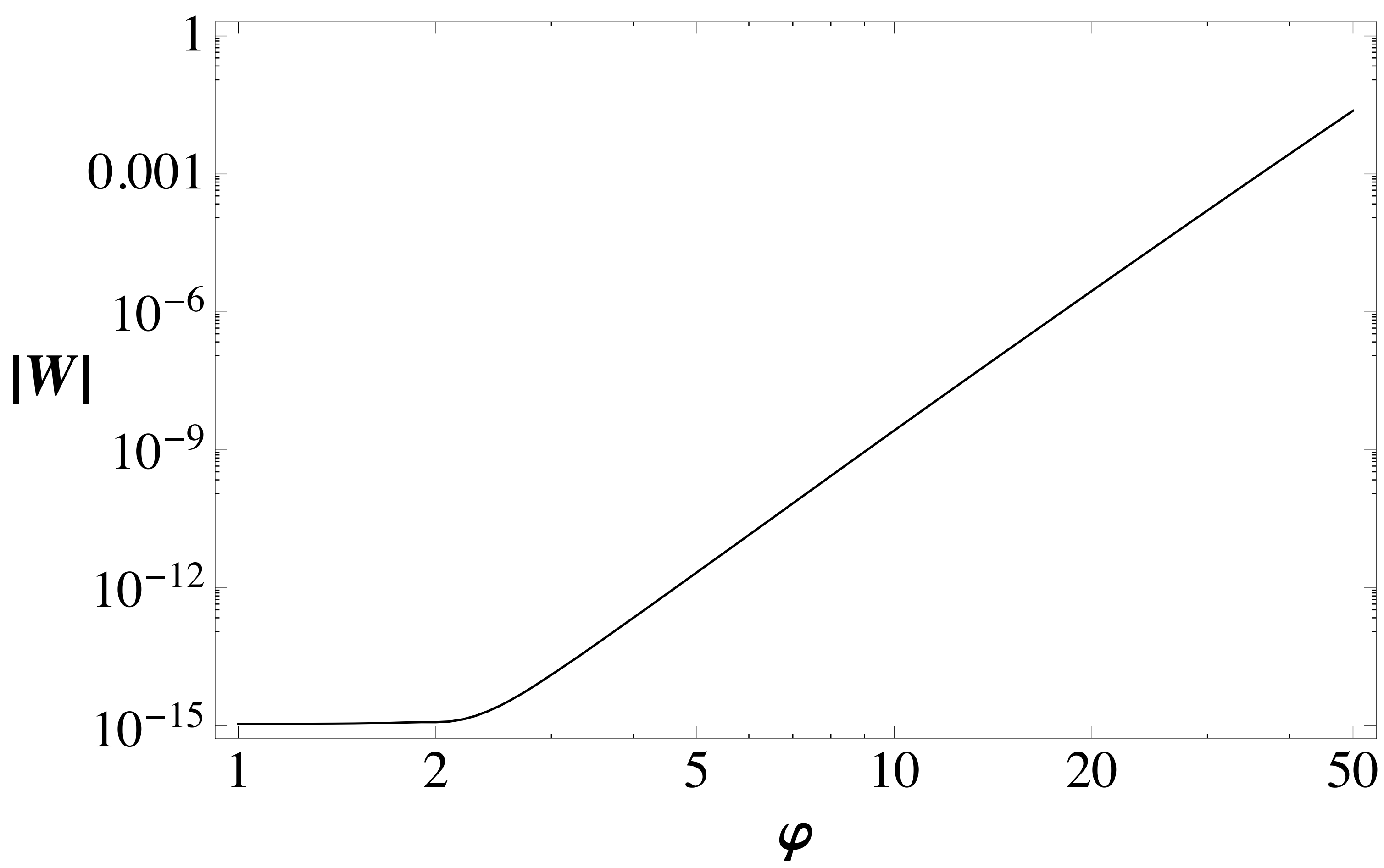
- decouple the barrier height from the (post-) inflationary uplifting: racetrack model of Kallosh & Linde, heavily fine-tuned at $O(m_{GUT}/m_W) \sim 10^{-13}$

- alternative: have the barrier height adjusting with the rolling inflaton!

$\Rightarrow$ in W we have to adjust W_0 to adjust the barrier height

- Who says, we cannot have W_0 being an adiabatic function of the inflaton?

$$W = W_{0,eff.}(\Phi) + Ae^{-aT}$$



- Let's try find simple models doing that ... However, in supergravity we cannot just rely on the inflaton alone:

$$\mathrm{if}: \; W_{0,eff.}(\Phi) = W_0 + \alpha\Phi^n$$

$$\Rightarrow \quad \frac{|F_\Phi|}{|W|} \approx \frac{n\alpha\Phi^{n-1}}{\alpha\Phi^n + W_0} \sim \frac{1}{\Phi}$$

- for a polynomial superpotential suitable for large-field inflation the potential slopes downward and goes *negative* ... So we probably have to use the F-term $F_X = F_X(\phi)$ of a spectator field X

[Kawasaki,Yamaguchi & Yanagida '00]

- a simple setup which adjusts the barrier dynamically

$$\begin{aligned} K &= \frac{1}{2}(\Phi+\bar{\Phi})^2 + X\bar{X} - \gamma(X\bar{X})^2 - 3\log(T+\bar{T}) \\ W &= W_0\, g(X) + \alpha\, f(X)\, \Phi^n + e^{-aT} \end{aligned}$$

$$\text{with}: \; g(X) = 1 + \mathcal{O}(X) \quad \text{and} \quad f(X) = b + X + \mathcal{O}(X^2)$$

- this is t'Hooft natural, given that ϕ has R-charge 2/n and a shift symmetry in the Kähler potential:

$$\Phi = \eta + i\varphi \quad , \quad \varphi \to \varphi + C$$

- why do we need the 1st few terms in f and g, which are otherwise arbitrary?

- the $O(1)$ constant in g ensures the known KKLT-like post-inflation vacuum

- the $O(1)$ constant b in f has W scaling adiabatically with ϕ

- the linear term in f in X enforces $F_X \sim W$, so that the potential slopes upwards ...

- in the regime $\phi >> M_P$ and $X < M_P$ there is an attractor behaviour satisfying

$$F_X \sim W \sim \alpha\Phi^n \quad , \quad F_\Phi \sim \frac{F_X}{\Phi} \quad , \quad F_T \sim \frac{F_X}{T}$$

- this gives the inflaton potential to be

$$V_{inf.}(\varphi) \sim |F_X|^2 \sim \alpha^2\varphi^{2n}$$

- because there's a mass term for X (if $\gamma > 0$) via

$$K^{X\bar{X}} = (1 - 4\gamma X\bar{X})^{-1} \simeq 1 + 4\gamma X\bar{X} \qquad \Rightarrow X \lesssim M_{\rm P}$$

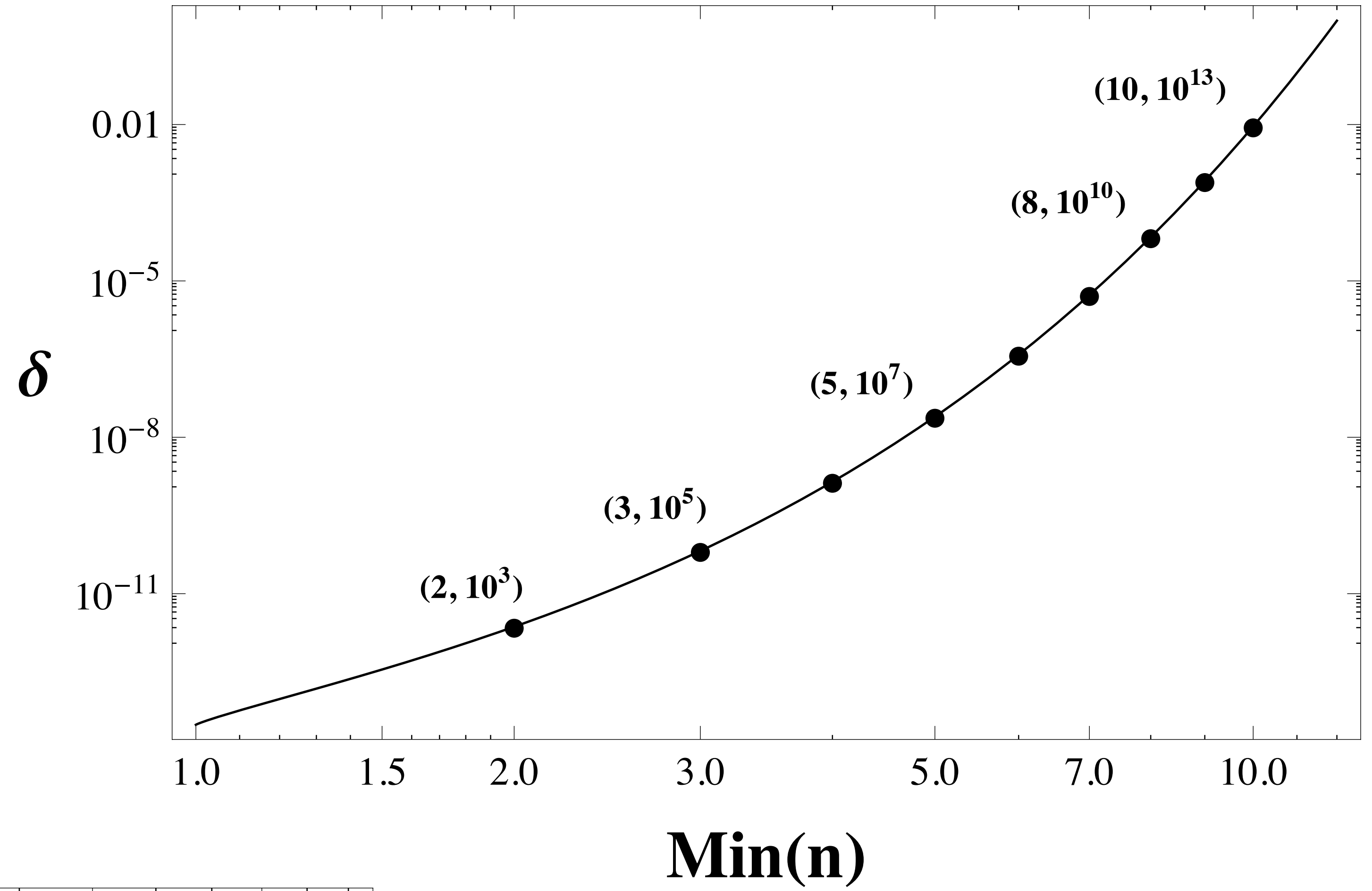
- Thus, we get a generalized KL-like constraint for the adiabatically adjusting VEV of *W*

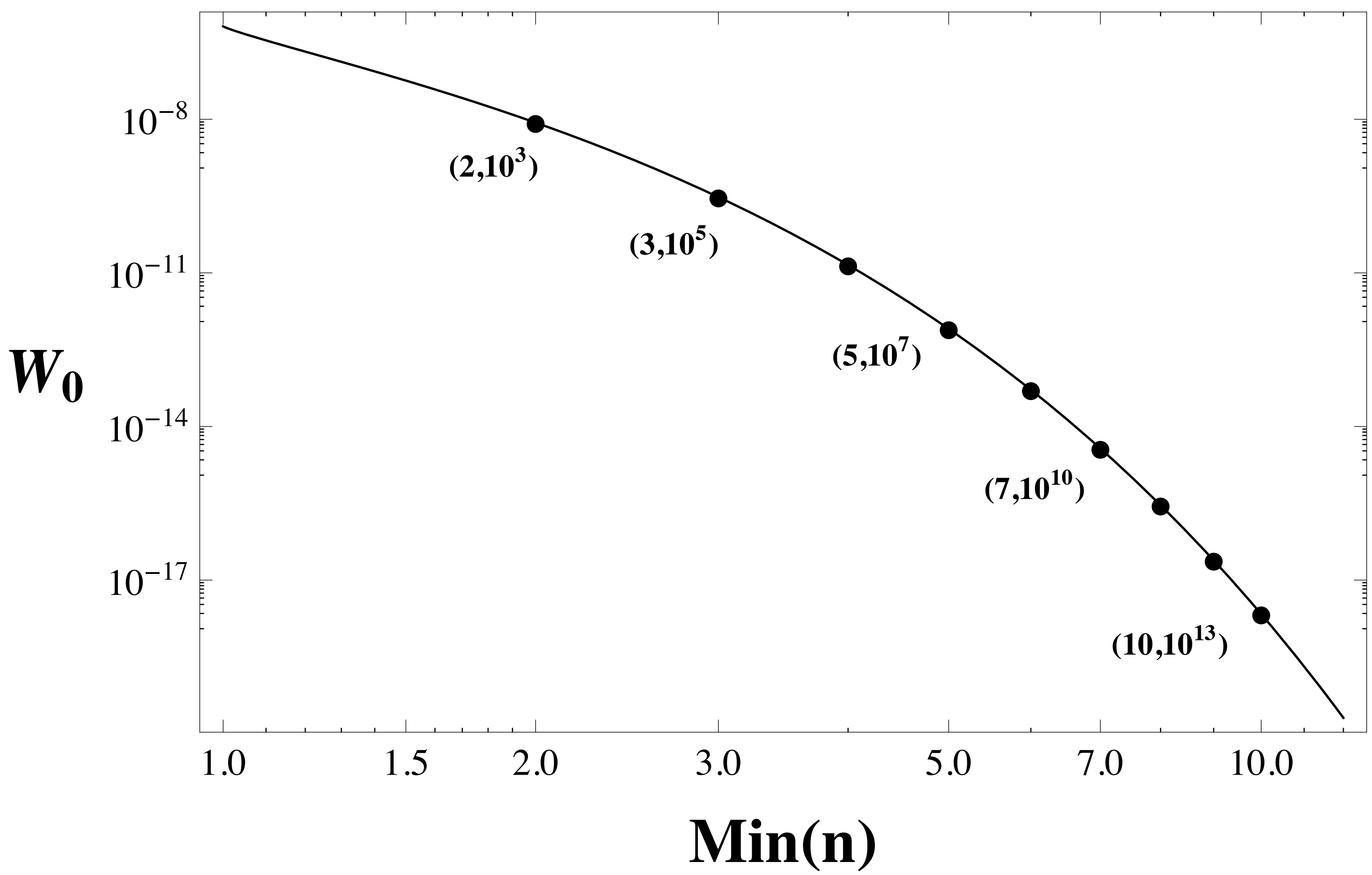
$$\frac{\sqrt{|F_\Phi^2| + |F_X^2|}}{|W|} \to \begin{cases} \frac{F_X}{|W|} \sim const. \lesssim \mathcal{O}(10) & \text{for } \frac{\varphi}{M_P} > 1 \\ & \Rightarrow V \sim |F_X|^2 \sim \alpha^2 \varphi^{2n} \\ \frac{F_\Phi}{|W|} \sim \frac{1}{\varphi} < \left(\frac{\alpha}{W_0}\right)^{1/n} \lesssim \mathcal{O}(10) & \text{for } \left(\frac{W_0}{\alpha}\right)^{1/n} < \frac{\varphi}{M_P} < 1 \\ 0 & \text{for } \frac{\varphi}{M_P} < \frac{W_0}{\alpha} \end{cases}$$

if this constraint can be maintained at all times, *T* never goes into run-away ...

now express α in terms of the density contrast δ (2×10^{-5}) and ϕ_{60}, the inflaton at 60 e-folds ...

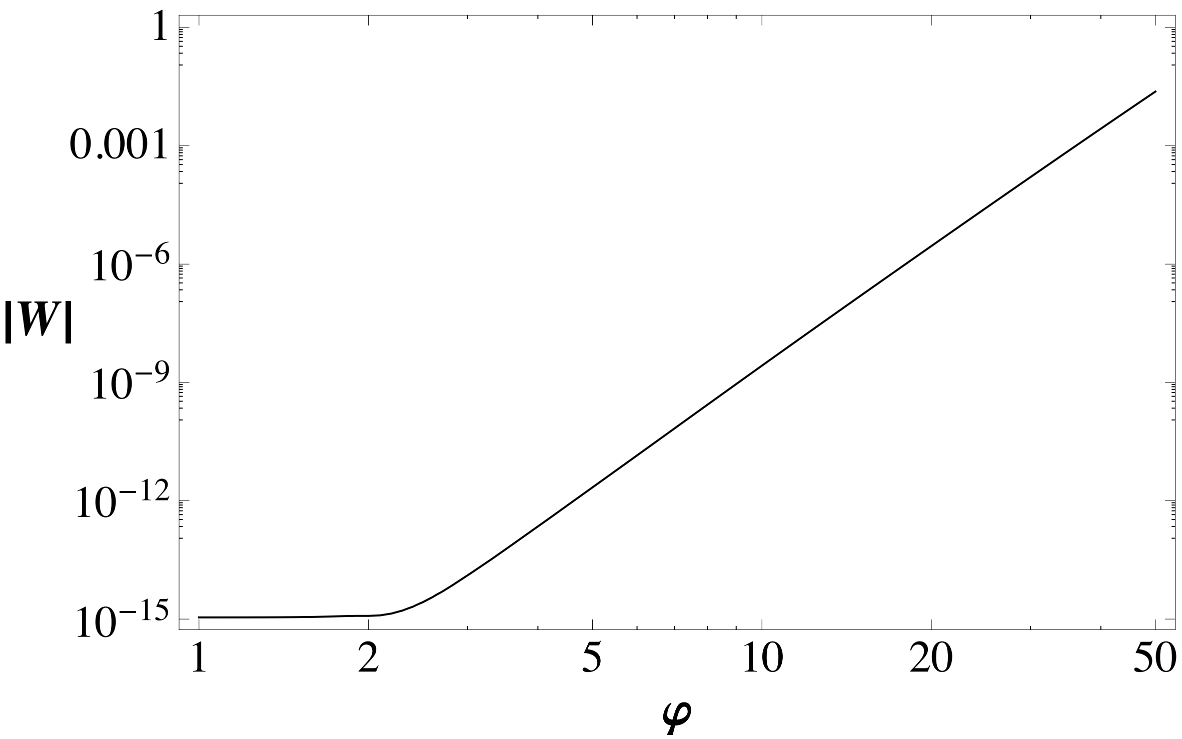
- then we *horse trade*: if we wish to attain a given W_0 (TeV...) at the end of inflation, we can exchange n for δ





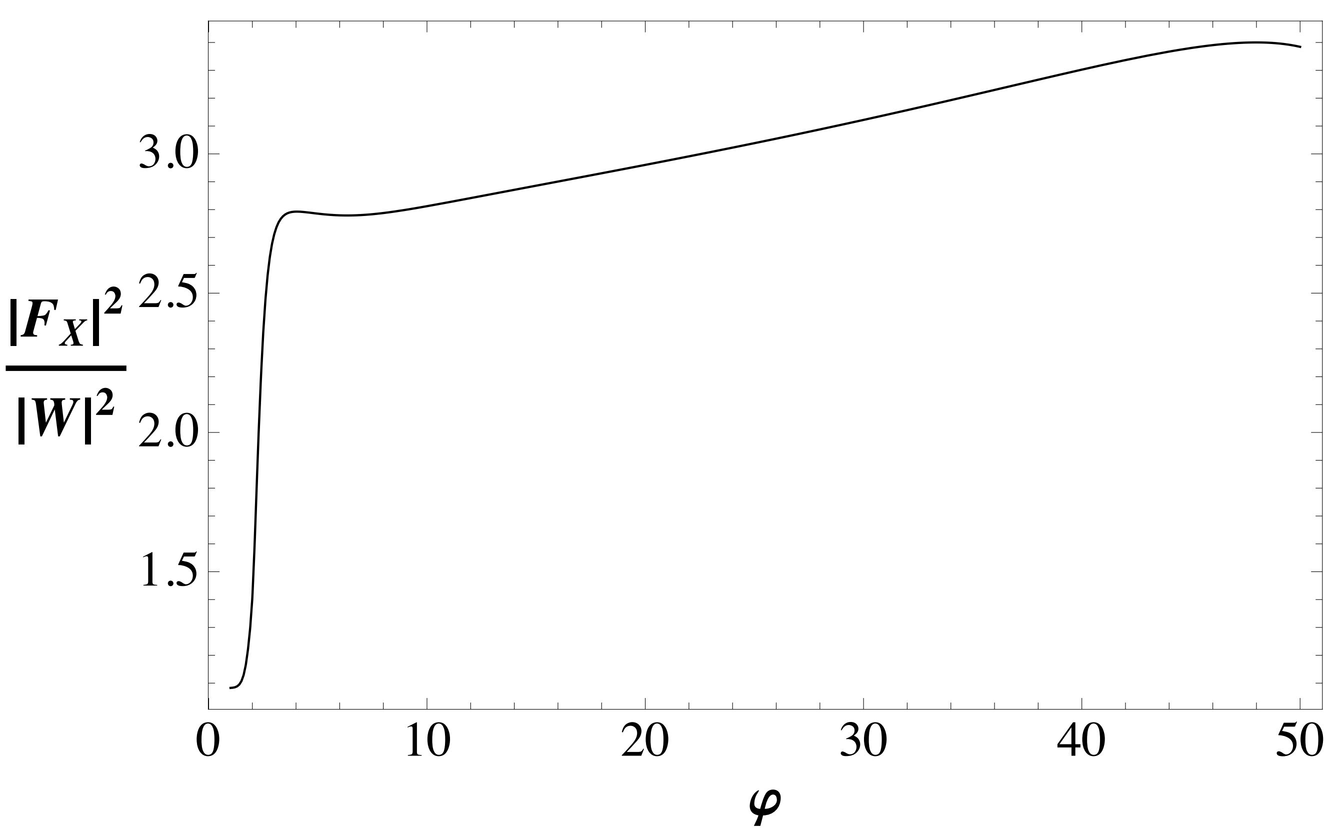
- *or*: if we wish to attain a given δ (2×10^{-5}) at ϕ_{60}, we can trade n for W_0 - and thus for the SUSY breaking scale after inflation

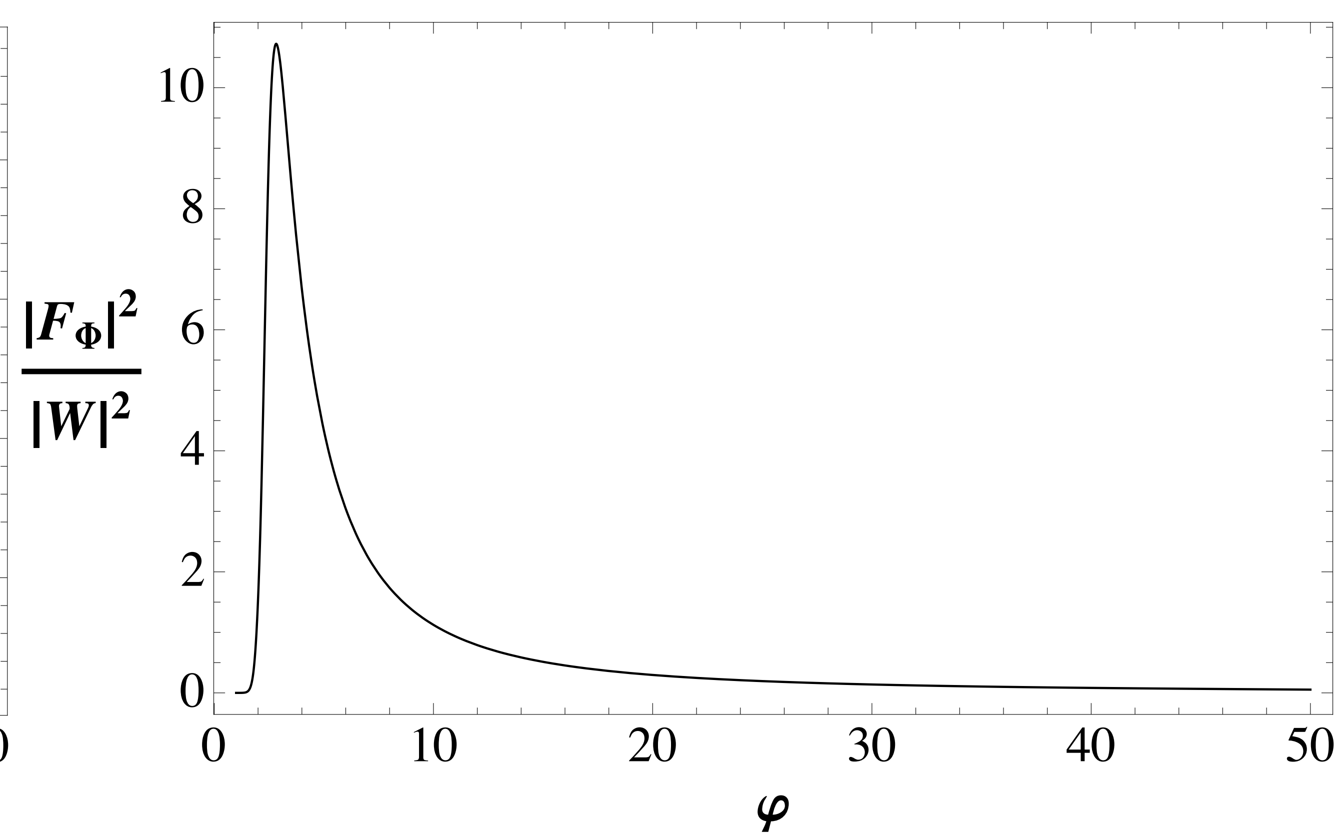
- a numerical example: $A = 1,\ a = \frac{2\pi}{10},\ W_0 = -10^{-15},$



$\alpha = 5 \times 10^{-19},\ b = \sqrt{2/5},\ n = 10,$

and $\gamma = 2$





open questions ...

- how to get large-field inflation with large-ish powers in string theory?
  ... we know of (axion) monodromy inflation, which gives so far at most *linear* potentials ... [McAllister, Silverstein & AW '08/'09]

- the horse trading could be presumably loosened by modifying the exit similar to hybrid inflation ...

- small field models using the same basic mechanism?