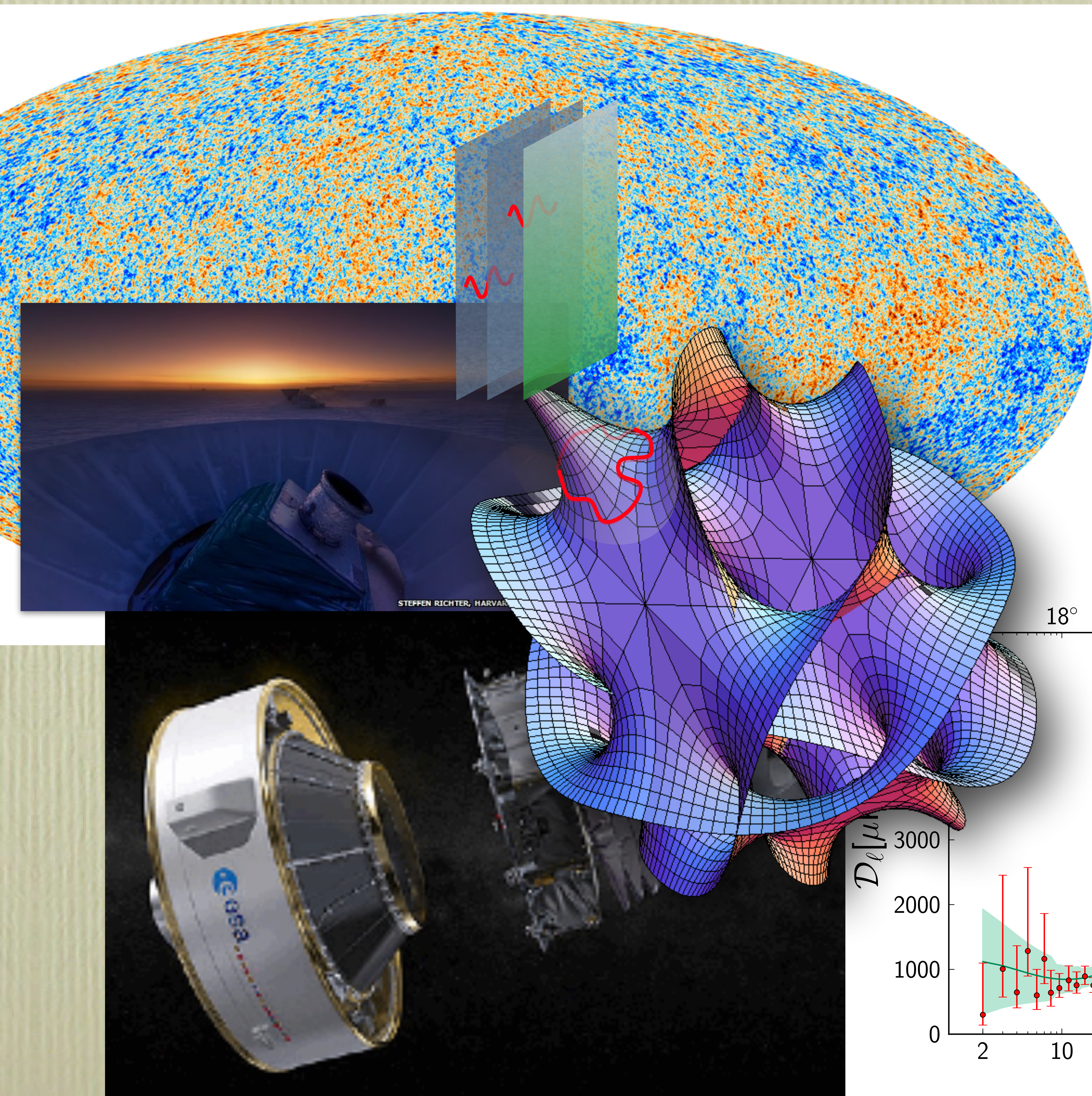
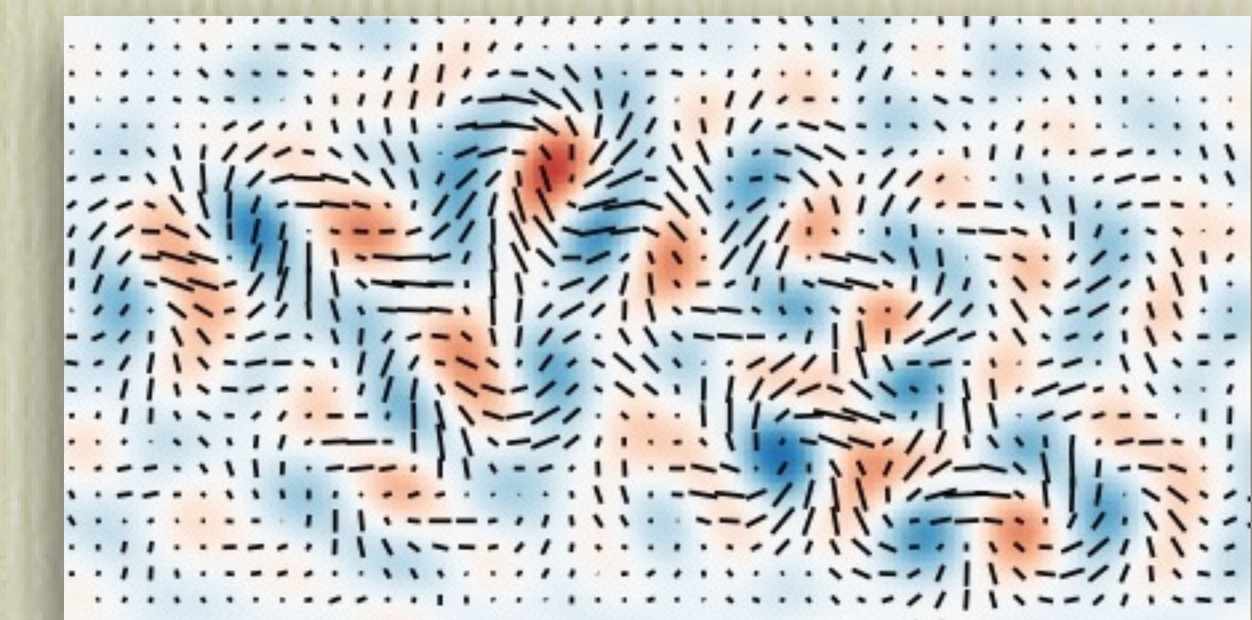
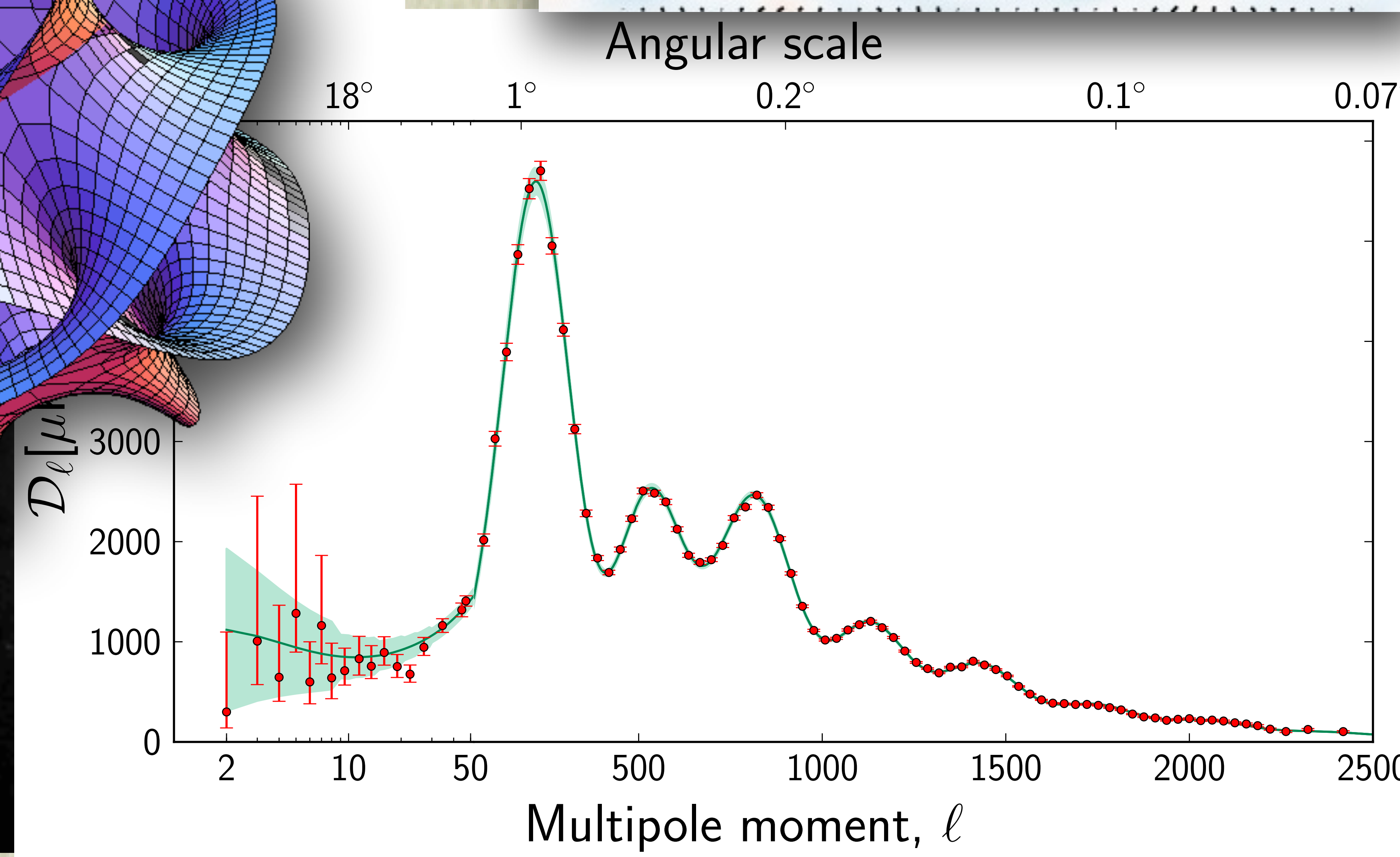
Large-field inflation - strings & pheno

Alexander Westphal
(DESY)

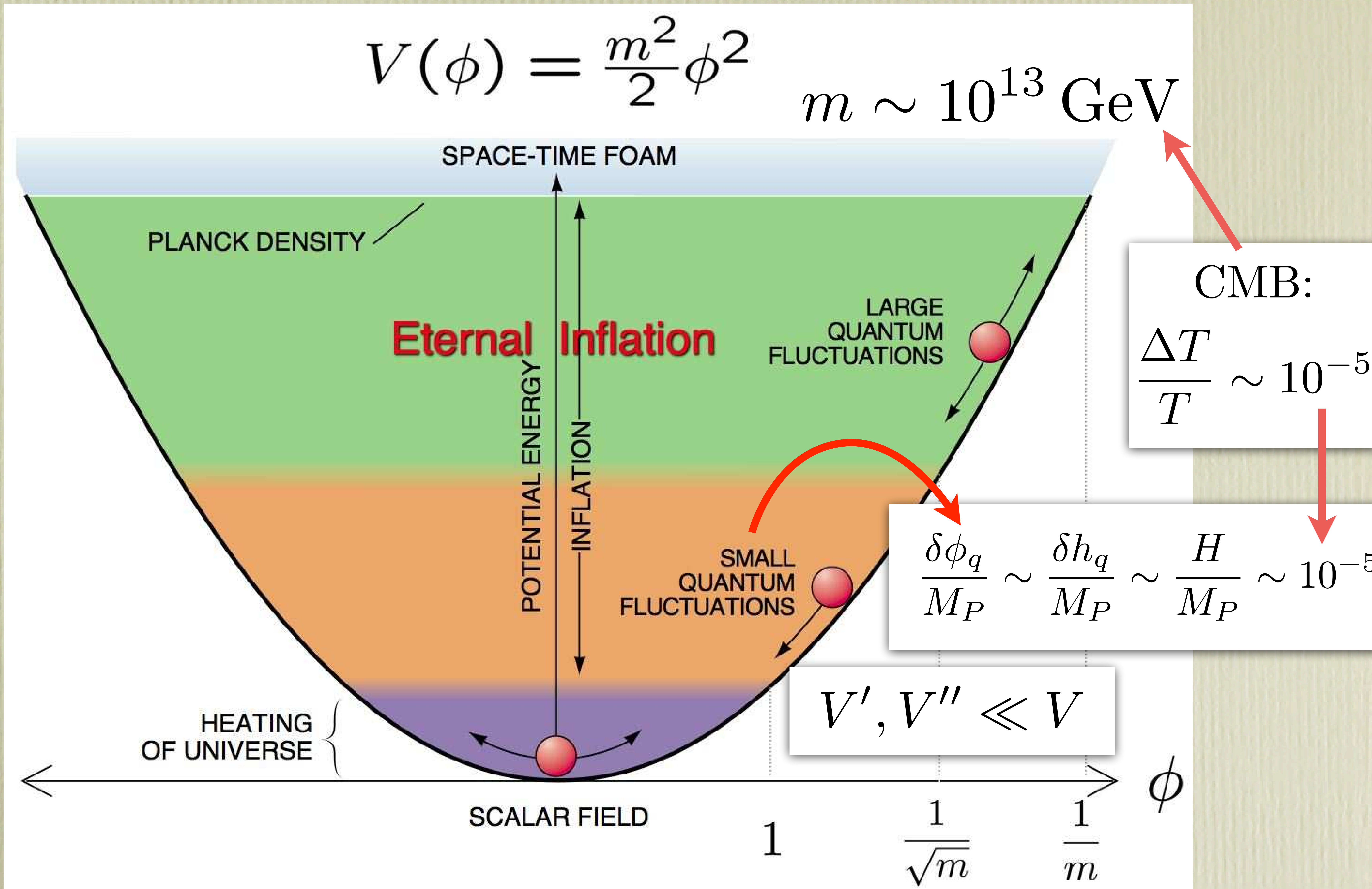






slow-roll inflation ...

[Guth, Linde, Albrecht, Steinhardt '80s]



[picture from lecture notes: Linde '07]

slow-roll inflation ...

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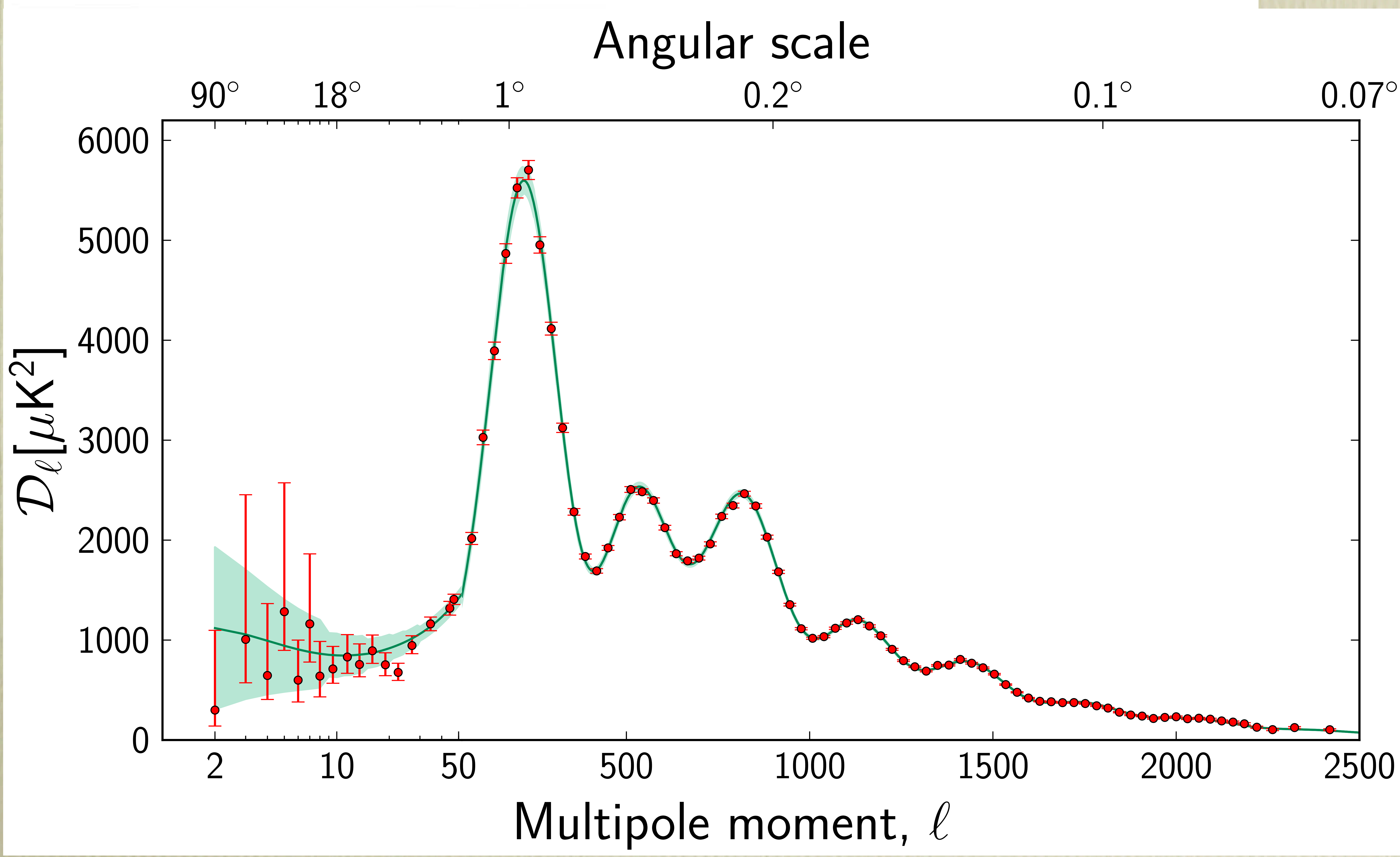
$$V(\phi) = \frac{m^2}{2}\phi^2$$



why strings?

- We need to understand generic dim ≥ 6 operators

$$\mathcal{O}_{p\geq 6} \quad \sim \quad V(\phi)\left(\frac{\phi}{M_{\rm P}}\right)^{p-4}$$

$$\Rightarrow \quad \Delta\eta \quad \sim \quad \left(\frac{\phi}{M_{\rm P}}\right)^{p-6} \gtrsim 1 \quad \forall p \geq 6 \quad \text{if} \quad \phi > M_{\rm P}$$

- requires **<u>UV-completion</u>**, e.g. string theory: need to know string and α'-corrections, backreaction effects, … if $\phi > M_P$ we need a **<u>shift symmetry</u>** !

- strings have extra dimensions — detailed information about **moduli stabilization necessary** !

varieties of string inflation ...

- tensor-to-scalar ratio linked to field range:

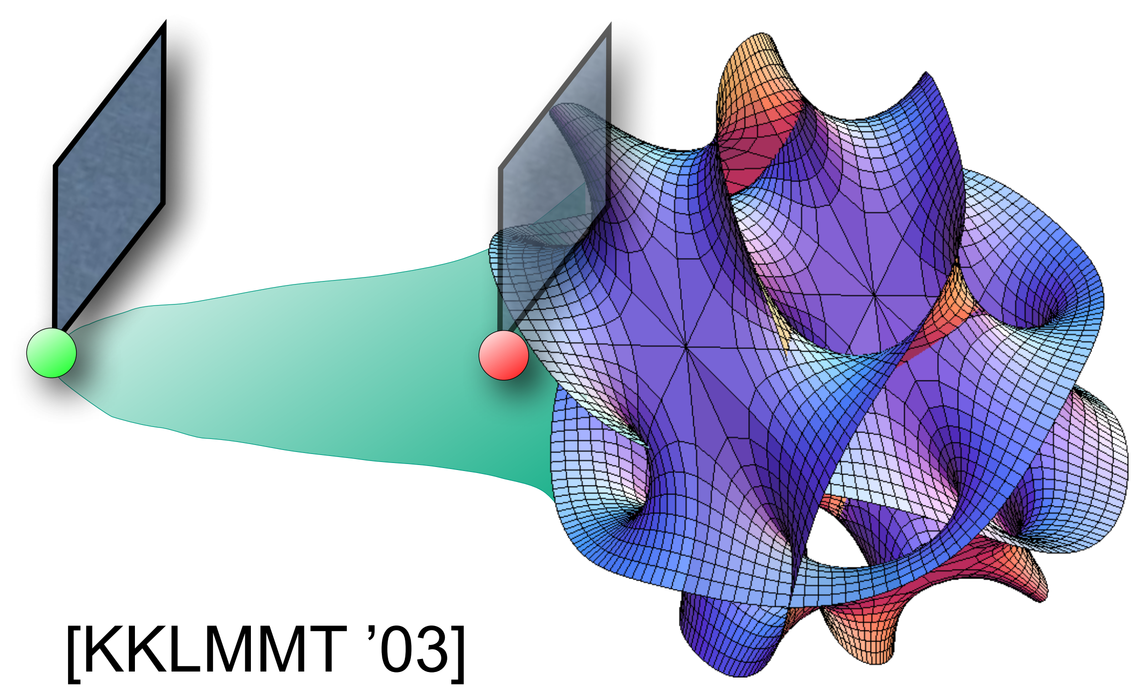
$$\frac{\Delta\phi(N_e)}{M_{\mathrm{P}}} \gtrsim \frac{N_e}{50}\sqrt{\frac{r}{0.01}} \quad , \quad r = \frac{\mathcal{P}_T}{\mathcal{P}_S}$$

[Lyth '97]

- r << $O(1/N_e^2)$ models:

$$\Delta\phi \ll \mathcal{O}(M_P) \quad \Rightarrow$$

warped D-brane inflation & DBI;



[KKLMMT '03]
[Baumann, Dymarsky, Klebanov, McAllister & Steinhardt '07]

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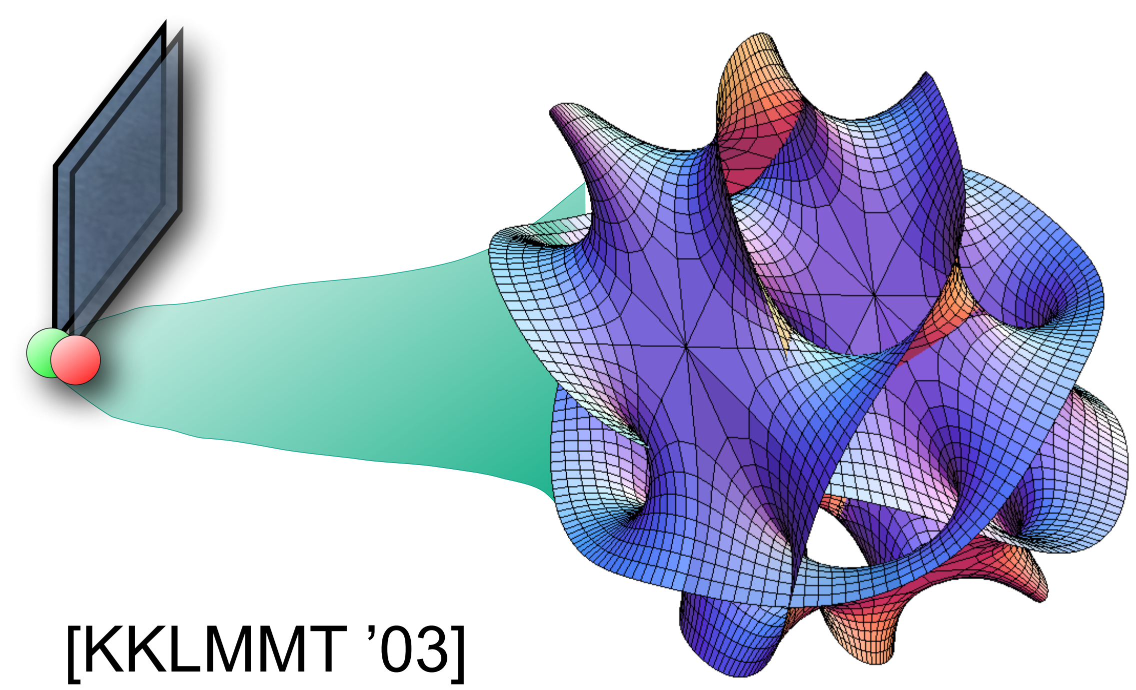

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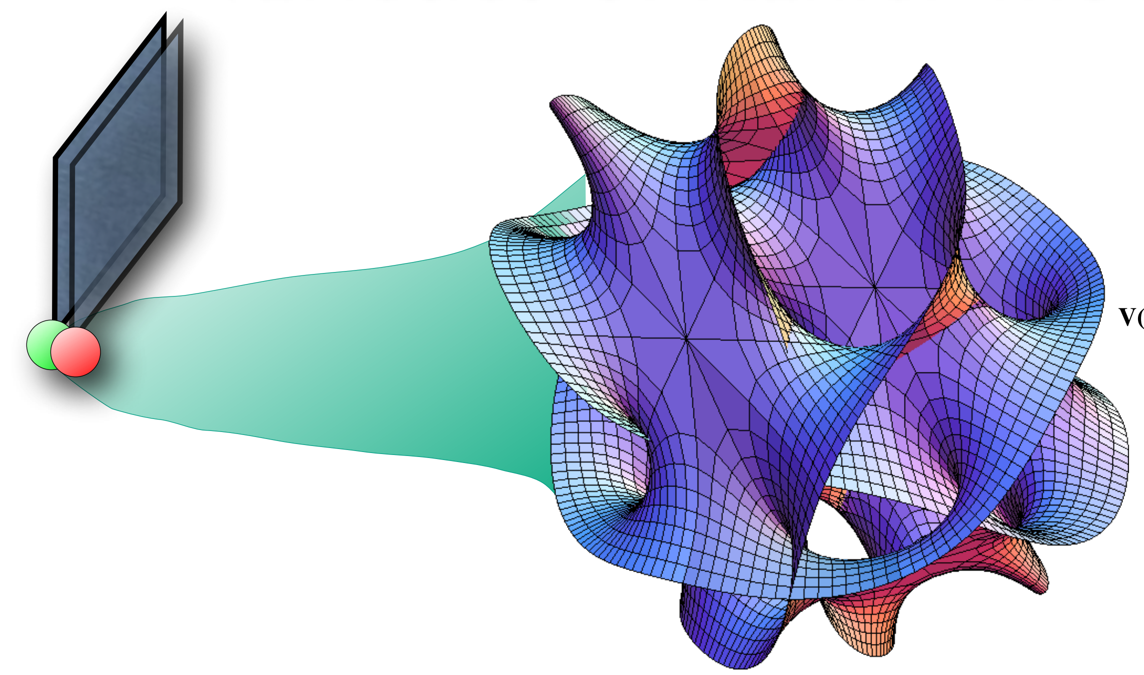
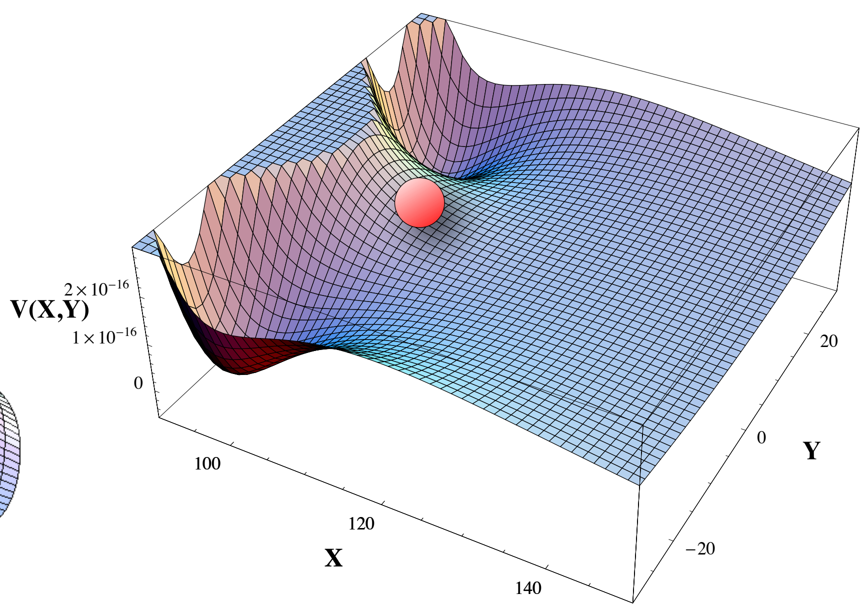
varieties of Kähler moduli inflation





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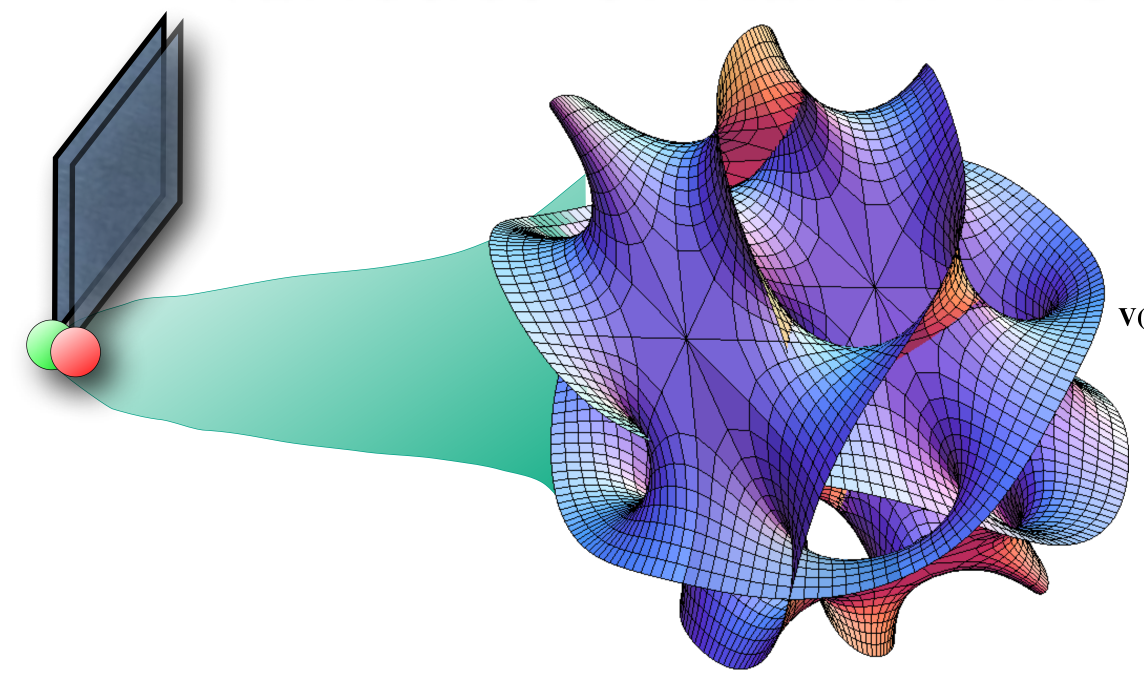

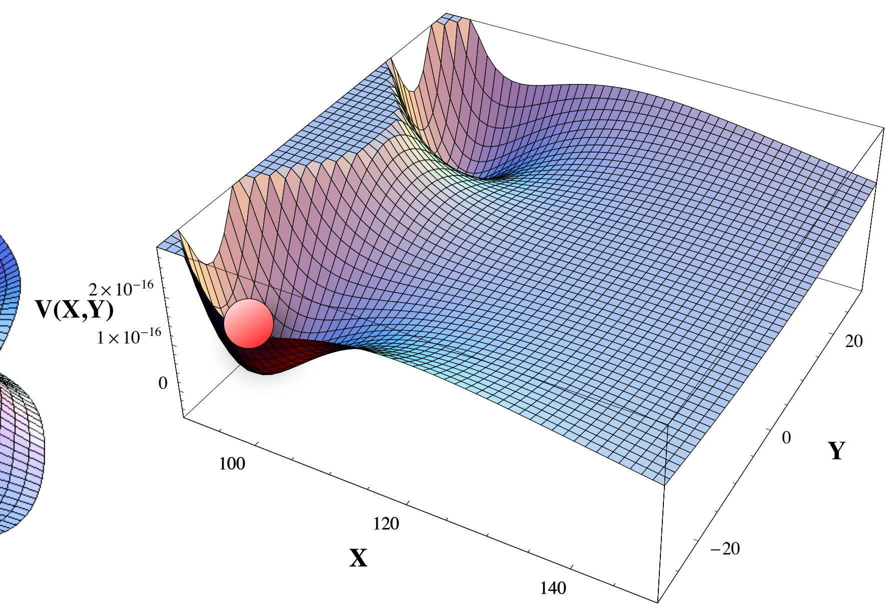

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$\Delta\phi \sim \mathcal{O}(M_P) \quad \Rightarrow$

fibre inflation in LARGE volume scenarios (LVS)
[Cicoli, Burgess & Quevedo '08]

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[Lyth '97]

observable tensors: $r > 0.01$

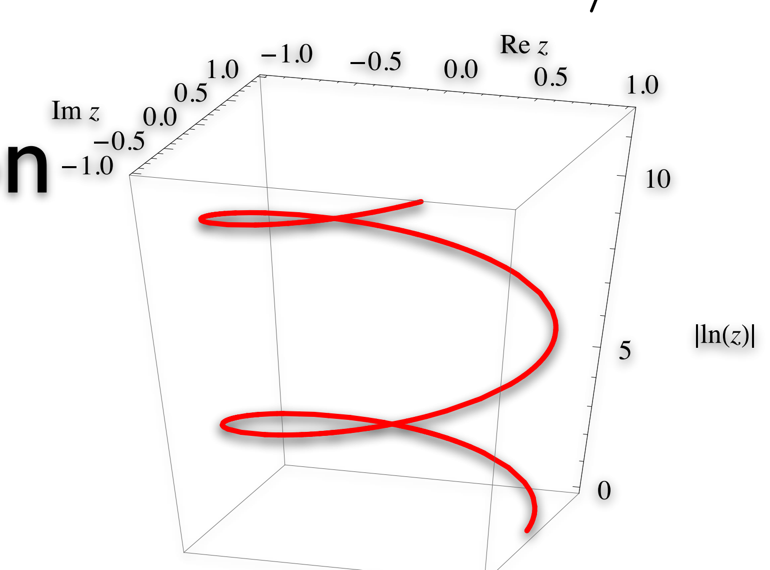
$\downarrow$

- $r = O(1/N_e)$ models:

$$\boxed{\Delta\phi \sim \sqrt{N_e} M_P \gg M_P \quad \Rightarrow}$$

axion monodromy inflation
2-axion inflation
N-flation

$T_{D5/NS5}$



large fields ...

shift symmetry

- effective theory of large-field inflation:

$$\mathcal{L} = \frac{1}{2}R + \frac{1}{2}(\partial_\mu \phi)^2 - \mu^{4-p}\phi^p$$

- the last term — the potential — spoils the shift symmetry …

- However, if: $$V_0 = \mu^{4-p}\phi^p \ll M_{\rm P}^4$$

- quantum GR only couples to $T_{\mu\nu}$:

$$\delta V^{(n)} \sim V_0 \left(\frac{V_0}{M_{\rm P}^4}\right)^n, \; V_0 \left(\frac{V_0''}{M_{\rm P}^2}\right)^n \ll V_0 \quad \textbf{\underline{not}} \quad \delta V^{(n)} \sim c_n \frac{\phi^n}{M_{\rm P}^n}$$

axion monodromy

axion inflation in string theory ...

- shift symmetry dictates use of string theory axions for large-field inflation

  - periodic, e.g.

$$b = \int_{\Sigma_2} B_2 \quad , \quad b \to b + (2\pi)^2 \quad \text{since} \quad S_{string} \supset \frac{1}{2\pi\alpha'} \int B_2$$

  - field range from kinetic terms $f < M_{\mathrm{P}}$:

$$S \sim \int d^{10}x \sqrt{-g} |H_3|^2 \supset \int d^4x \sqrt{-g_4} \frac{1}{L^4} (\partial_\mu b)^2$$

$$B_2 = b\omega_2 \quad \Rightarrow \quad \phi = fb \quad , \quad f = \frac{M_{\mathrm{P}}}{L^2} < M_{\mathrm{P}}$$

[Banks, Dine, Fox & Gorbatov ’03]

however, maybe not strict: [Grimm; Blumenhagen & Plauschinn; Kenton & Thomas ’14]

axion inflation in string theory ...

- large field-range from assistance effects of many fields
  - N-flation ...

[Dimopoulos, Kachru, McGreevy & Wacker ’05]
[Easther & McAllister ’05]
[Grimm ‘07]
[Cicoli, Dutta & Maharana ’14]
[Bachlechner, Long & McAllister ‘14]
[Bachlechner, Dias, Frazer & McAllister ‘14]

- or *monodromy*
  - *generic presence* from branes & fluxes !

[Silverstein & AW ’08]
[McAllister, Silverstein & AW ’08]
[Kaloper & Sorbo ’08]
[Dong, Horn, Silverstein & AW ’10]
[Lawrence, Kaloper & Sorbo ’11]

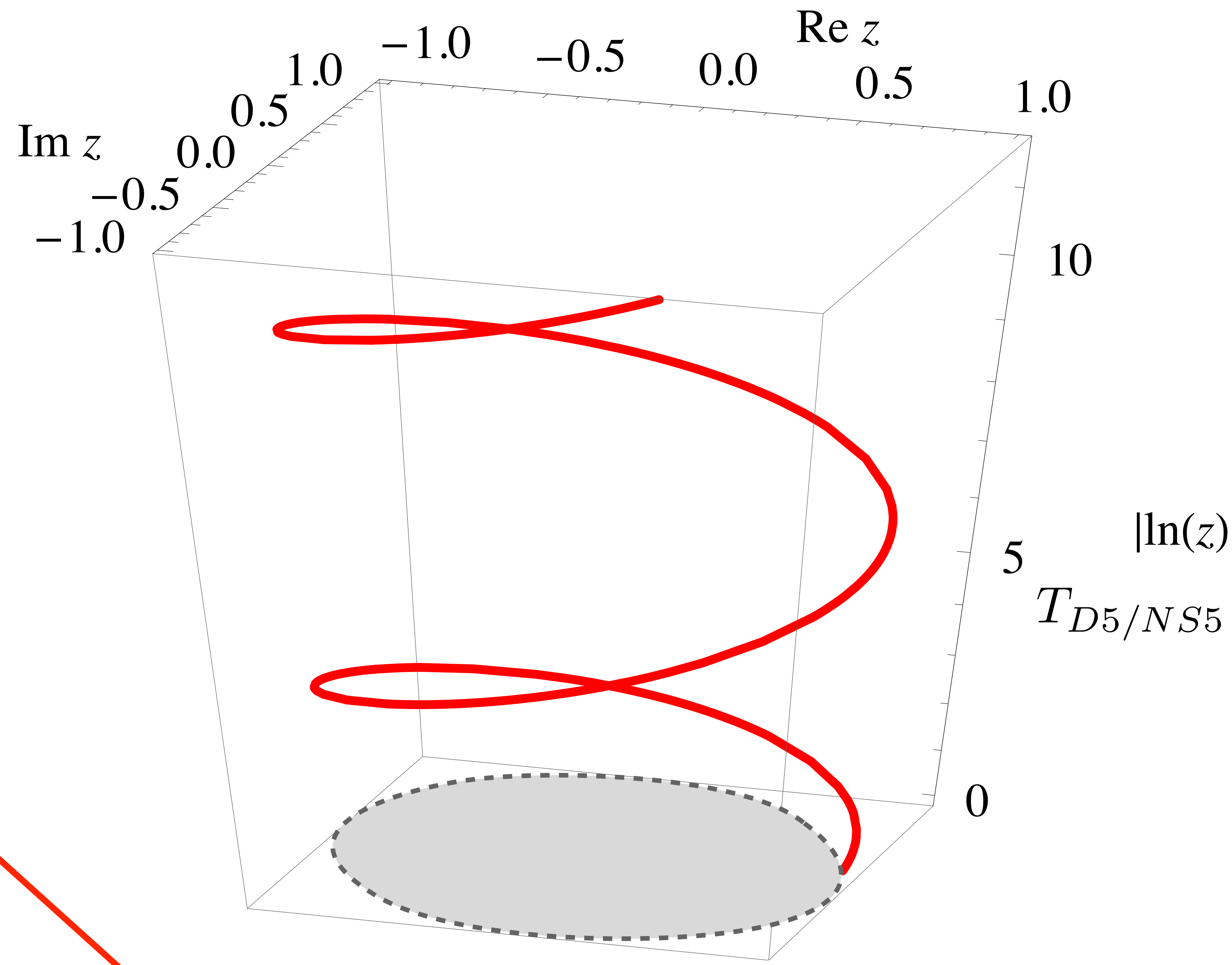
  - cos-potential for 2 axions can align/tune for large-field direction

[Kim, Nilles & Peloso ’04]
[Berg, Pajer & Sjörs ’09]
[Ben-Dayan, Pedro & AW ‘14]
[Tye & Wong; Long, McAllister & McGuirk ‘14]
[Gao, Li & Shukla; Higaki & Takahashi '14]

axion monodromy — the 5-brane example

- we have seen this: think of

$$\int B_2 \;\; , \int C_2$$



$$S_{5-\mathrm{brane}} \sim \int d^4x\sqrt{-g}\sqrt{v^2+\phi^2} \sim \phi$$

[McAllister, Silverstein & AW ’08]

embedding into a type IIB picture:

- e.g. CY with KKLT moduli stabilization — consistency constraints

axion monodromy — the general story

- EM Stueckelberg gauge symmetry:

$$S_{EM} = \int d^4x\sqrt{-g}\,\{F_{MN}F^{MN} - \rho^2(A_M + \partial_M C)^2 + \ldots\}$$

$$A_M \;\rightarrow\; A + \partial_M \Lambda_0 \qquad \Rightarrow \qquad C \rightarrow C - \Lambda_0$$

- string theory contains analogous gauge symmetries for NSNS and RR axions - e.g. IIA:

$$\begin{aligned} H &= dB\,, \\ F_0 &= Q_0\,, \\ \tilde{F}_2 &= dC_1 + F_0 B\,, \\ \tilde{F}_4 &= dC_3 + C_1 \wedge H_3 + \frac{1}{2}F_0 B \wedge B \end{aligned} \qquad \Rightarrow \qquad \begin{aligned} \delta B &= d\Lambda_1\,, \\ \delta C_1 &= -F_0\Lambda_1\,, \\ \delta C_3 &= -F_0\Lambda_1 \wedge B \end{aligned}$$

- type IIB similar

flux monodromy

[Marchesano, Shiu & Uranga '14]
[Blumenhagen & Plauschinn '14]
[Hebecker, Kraus & Witkowski '14]
[McAllister, Silverstein, AW & Wrase '14]

- fluxes generate a potential for the axions:

$$-\frac{1}{\alpha'^4}\int d^{10}x\sqrt{-G}\left\{\frac{1}{g_s^2}|H|^2+|Q_0B|^2+|Q_0B\wedge B|^2+\gamma_4 g_s^2|Q_0B\wedge B|^4+\dots\right\}$$

tune small ...

- produces periodically spaced set of multiple branches of large-field potentials:

$$f(\chi,\dots)\,\frac{(Q^{(n)}a^n+Q^{(n-1)}a^{n-1}+\cdots+Q^{(0)})^2}{L^{2n'}}+\cdots\sim\tilde{f}(\chi,\dots)\;a^{p_0}\quad\text{for } a\gg 1$$

- for given flux quanta $Q^{(i)}$ potential is non-periodic – we roll on a given branch

- $Q^{(i)}$ change by brane-flux tunneling –$Q^{(i)}$ shift absorbed by axion-shift – many branches:

  - brane spectrum on axion cycle has full periodicity

  - bulk moduli sector not periodic, account for back reaction: **flattening**

  - on each branch: weakly broken effective shift symmetry

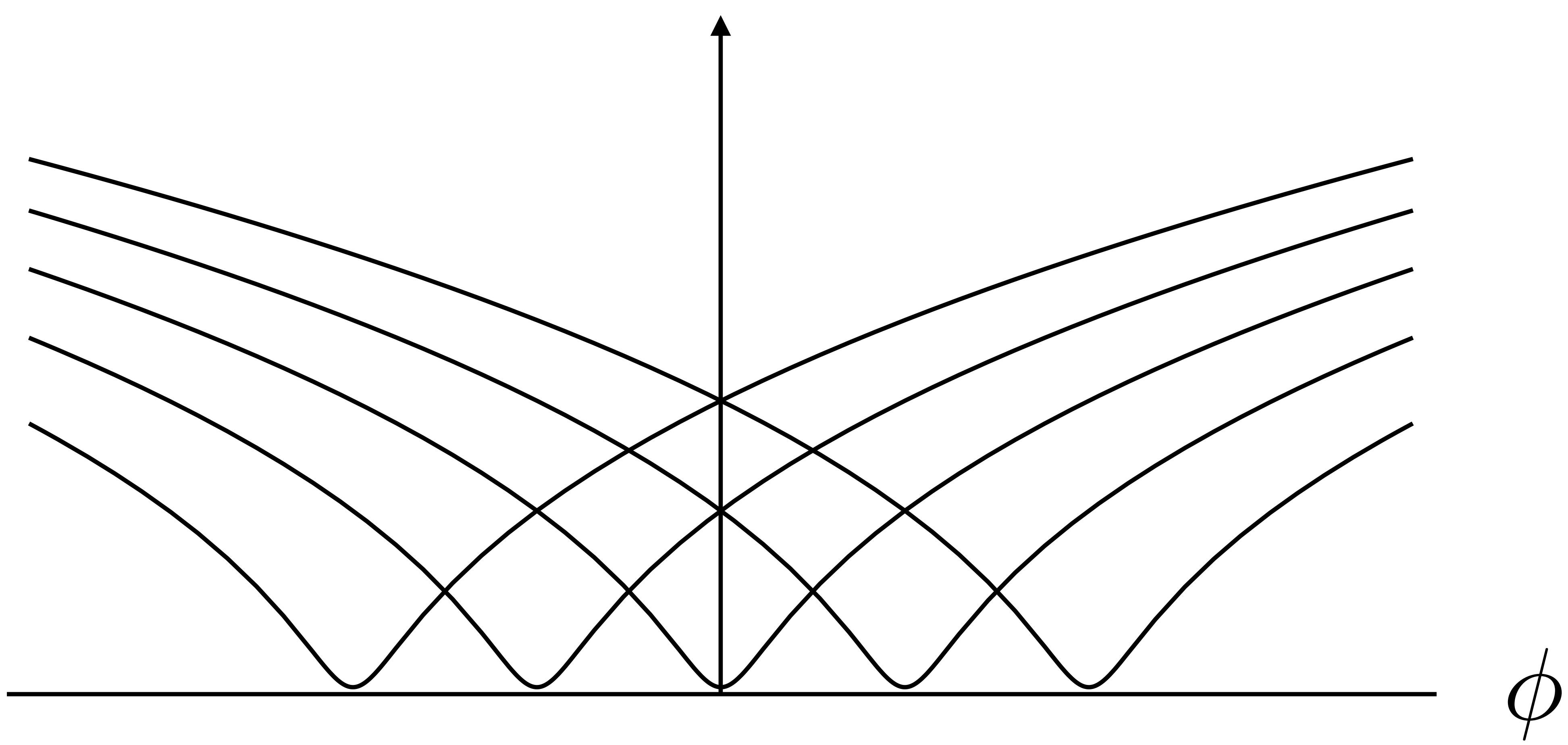
- p-form axions get **non-periodic** potentials from coupling to **branes** or **fluxes/field-strengths**

- produces periodically spaced set of multiple branches of large-field potentials:

$$V(\phi) \sim \mu^{4-p}\phi^p + \Lambda^4 \cos(\phi/f)$$

f = f(ϕ)

leads to oscillations
in the power spectrum
& resonant *non-Gauss.*



flux axion monodromy with moduli stabilization

[McAllister, Silverstein, AW & Wrase '14]

- type IIB string theory:

$$\int \mathrm{d}^{10}x \left(\frac{|dB|^2}{g_s^2} + |F_1|^2 + |F_3|^2 + \left|\tilde{F}_5\right|^2 \right)$$

$$\text{with:} \quad \tilde{F}_5 = dC_4 - B_2 \wedge F_3 + C_2 \wedge H_3 + F_1 \wedge B_2 \wedge B_2$$

- ϕ^2, ϕ^3, ϕ^4 terms …

  - generically flattening of the potential from adjusting moduli and/or flux rearranging its distribution on its cycle - 'sloshing', while preserving flux quantization [Dong, Horn, Silverstein & AW '10]

flux axion monodromy with moduli stabilization

[McAllister, Silverstein, AW & Wrase '14]

- simple torus example: $$ds^2 = \sum_{i=1}^{3} L_1^2 (dy_1^{(i)})^2 + L_2^2 (dy_2^{(i)})^2$$

axion $$B = \sum_{i=1}^{3} \frac{b}{L^2} dy_1^{(i)} \wedge dy_2^{(i)}$$

fluxes $$F_3 = Q_{31} dy_1^{(1)} \wedge dy_1^{(2)} \wedge dy_1^{(3)} + Q_{32} dy_2^{(1)} \wedge dy_2^{(2)} \wedge dy_2^{(3)}$$

$$F_1 = \frac{Q_1}{L_1} \sum_{i=1}^{3} dy_1^{(i)}$$

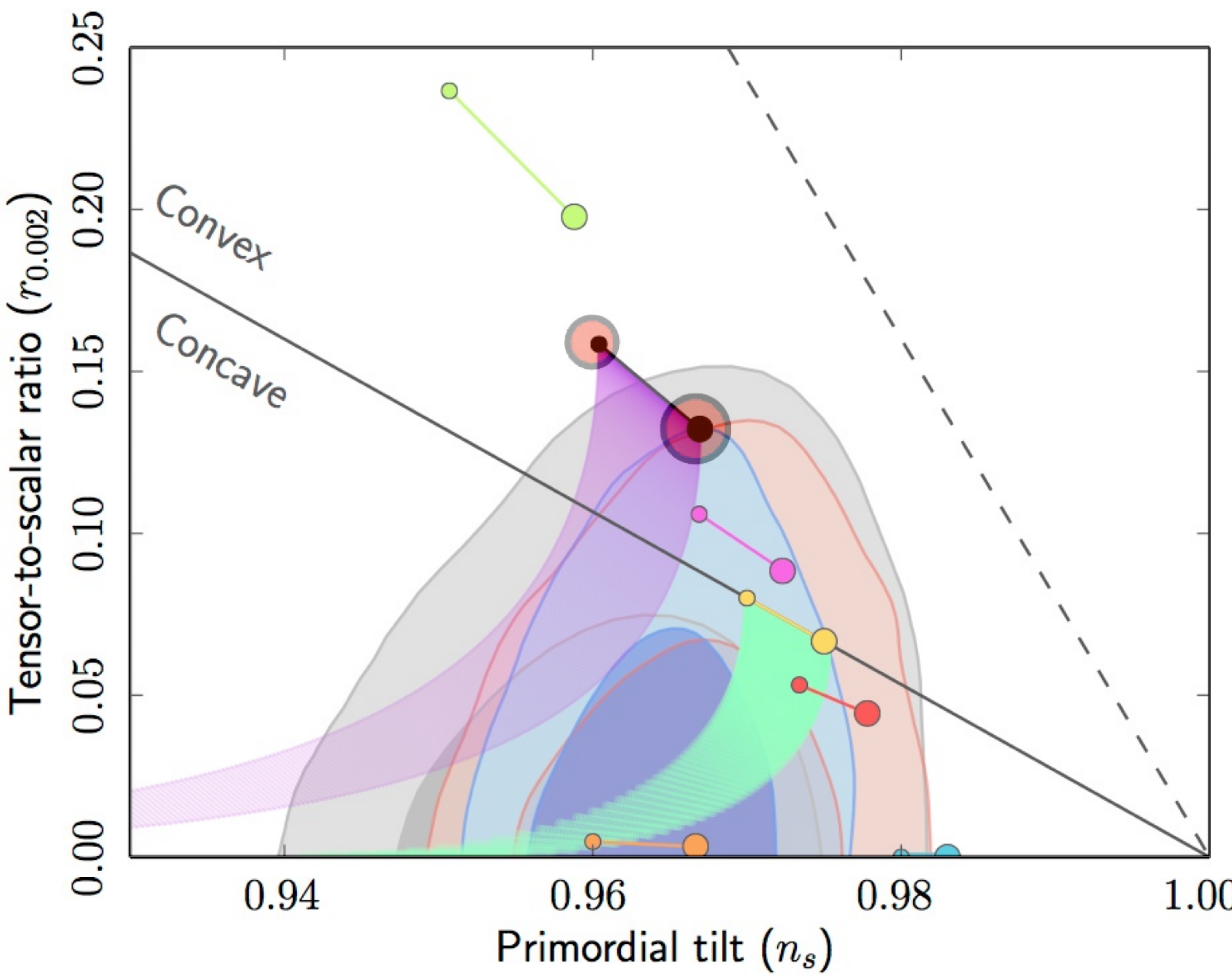
- effective 4d action gives ϕ^3-potential: $$u = \frac{L_2}{L_1} \quad , \quad \frac{\phi}{M_{\rm P}} = \frac{b}{L^2}$$

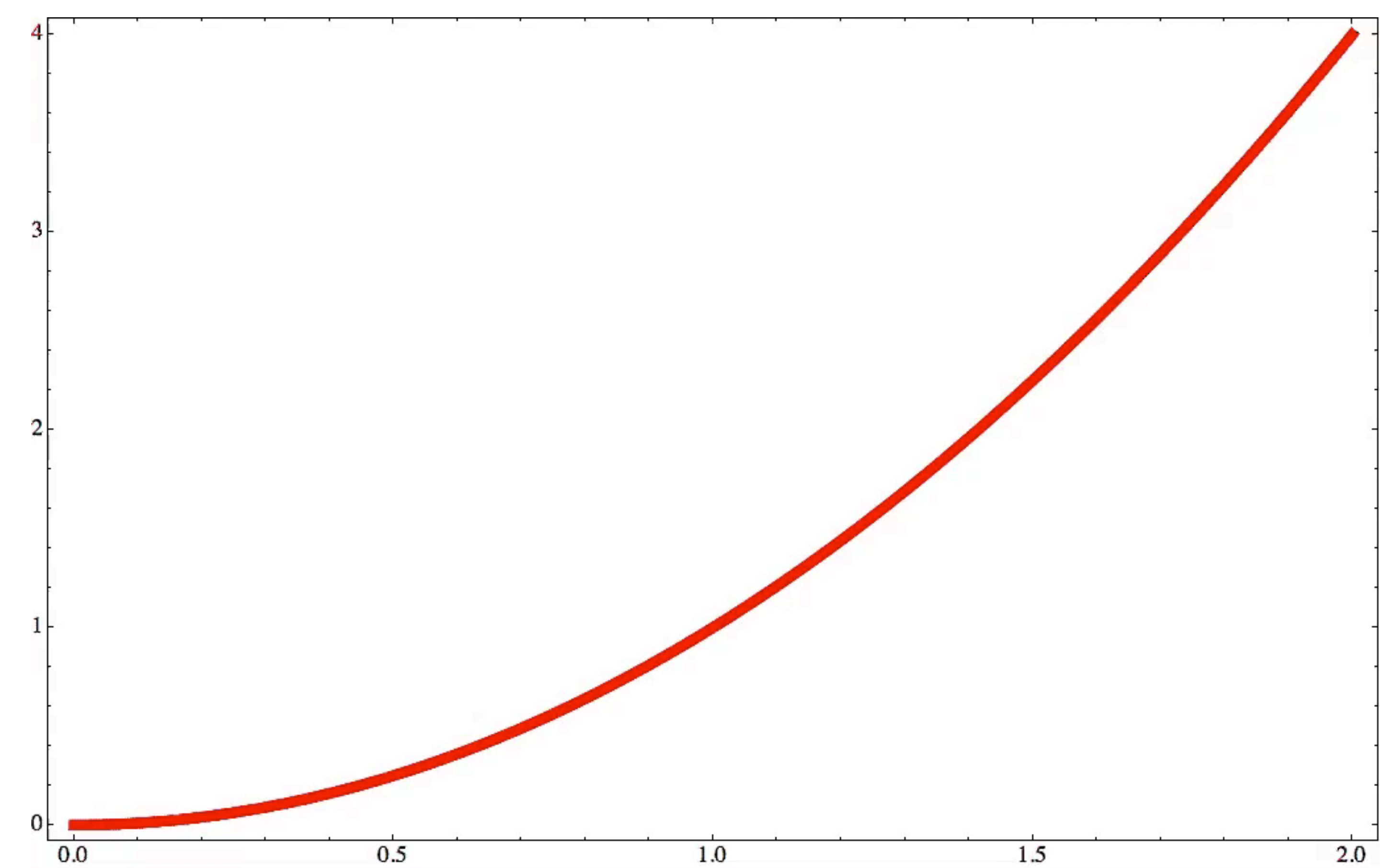
$$\mathcal{L} \sim M_{\rm P}^2 \frac{\dot{b}^2}{L^4} + M_{\rm P}^4 \frac{g_s^4}{L^12} \left[Q_1^2 L^4 \left(\frac{b}{L^2}\right)^4 u + Q_{31}^2 u^3 + \frac{Q_{32}^2}{u^3} \right] \sim \dot{\phi}^2 + \mu\, \phi^3$$

- use Riemann surfaces: can fix $Vol = L^6$ as well & get $\phi^{2/3}$, $\phi^{4/3}$, ϕ^2

phenomenology ... flattening !

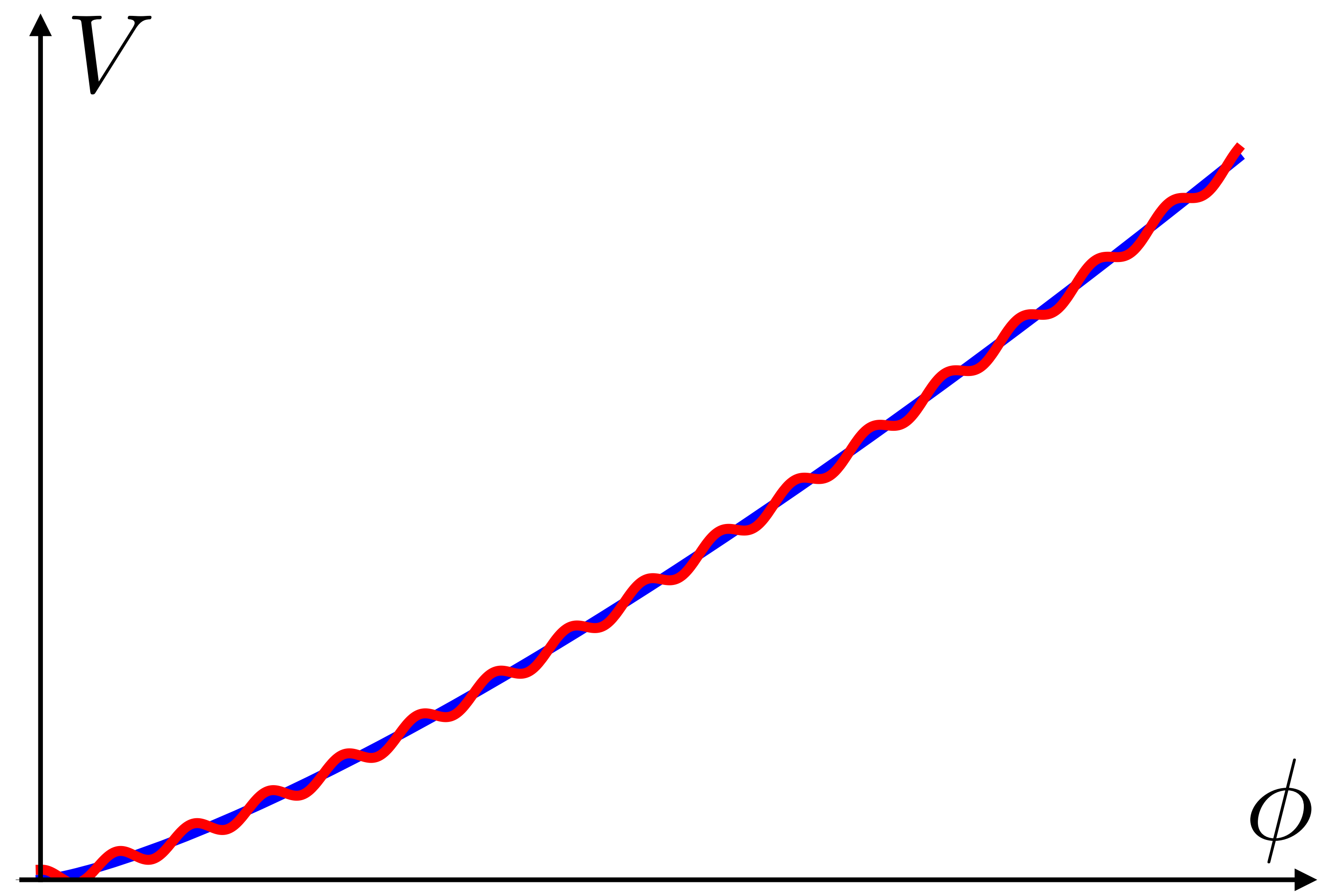
[n_s-r limits Planck 2014 (Ferrara), **preliminary!!**]





phenomenology ... drifting CMB oscillations !

$$V(\phi) \sim \mu^{4-p}\phi^{p} + \Lambda^{4}\,\cos\left(\frac{\phi}{f}\right)$$



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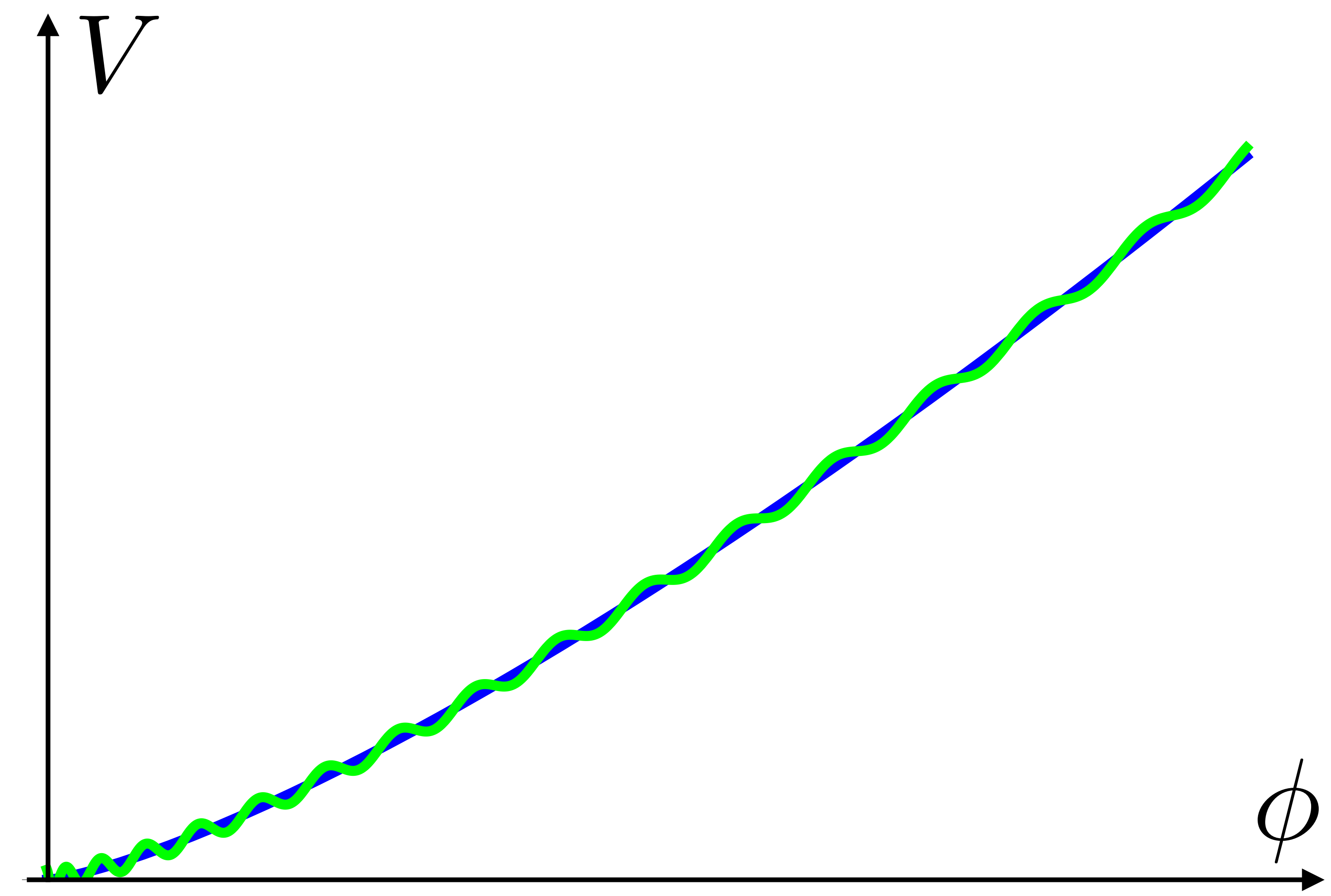

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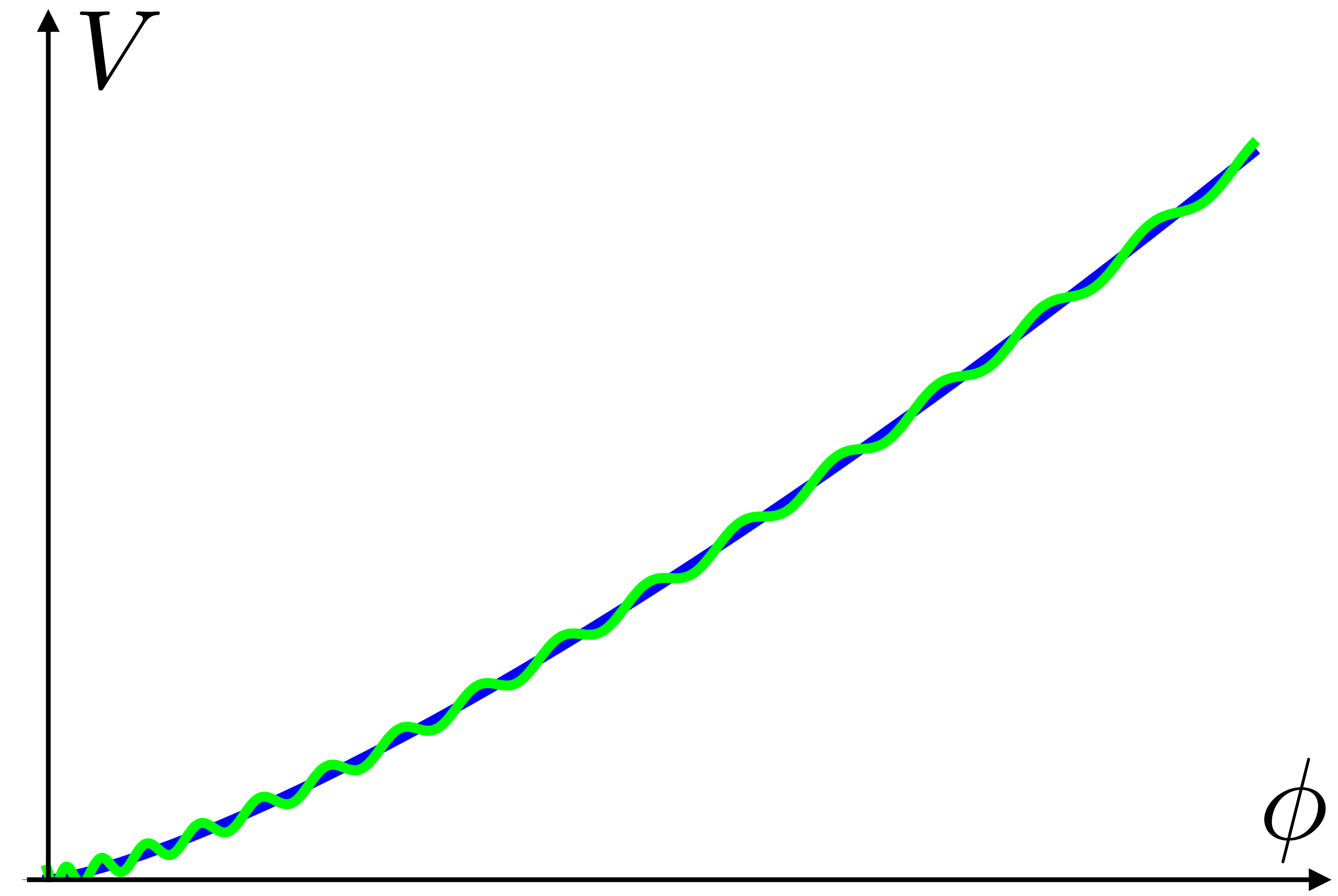

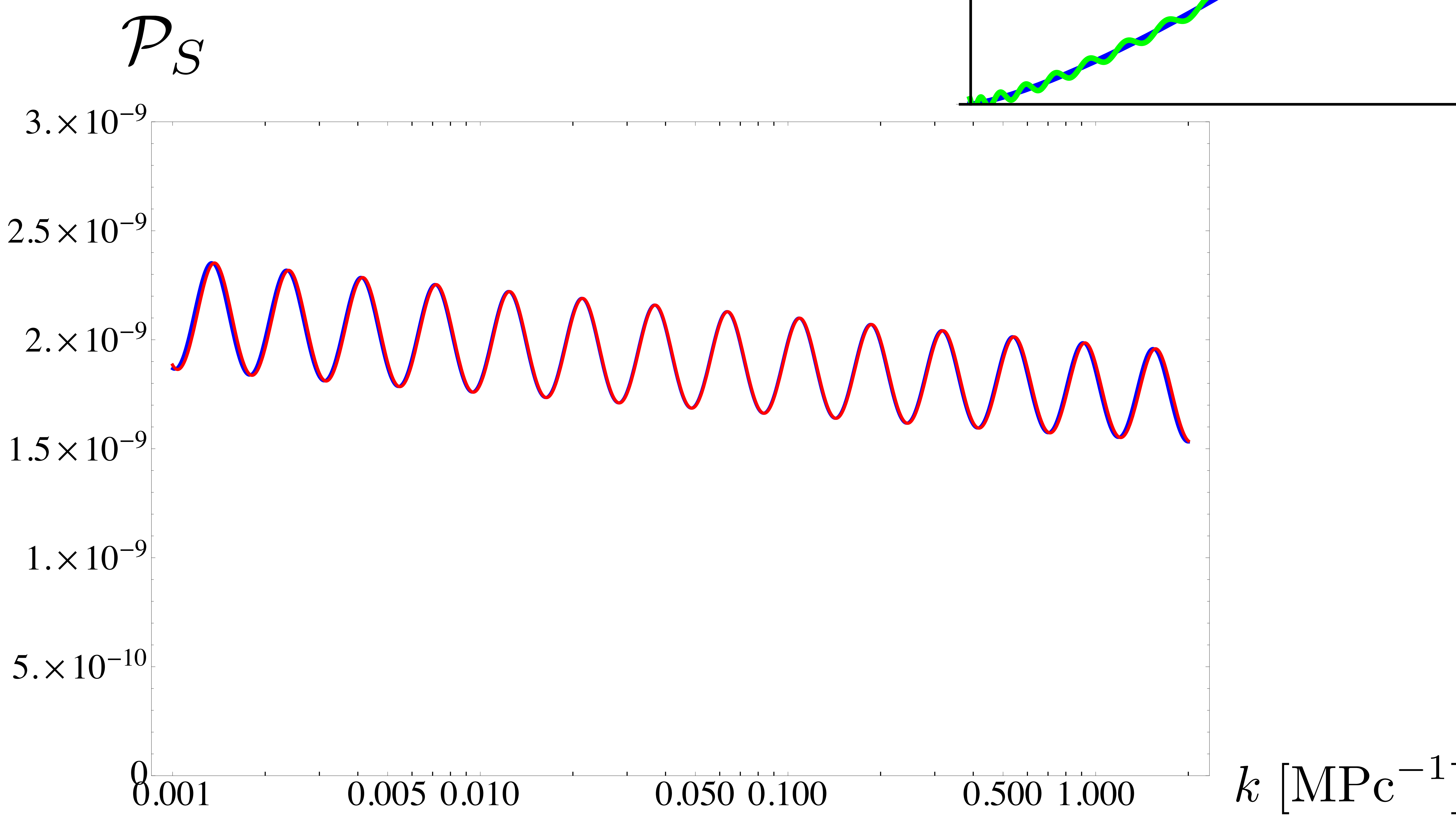

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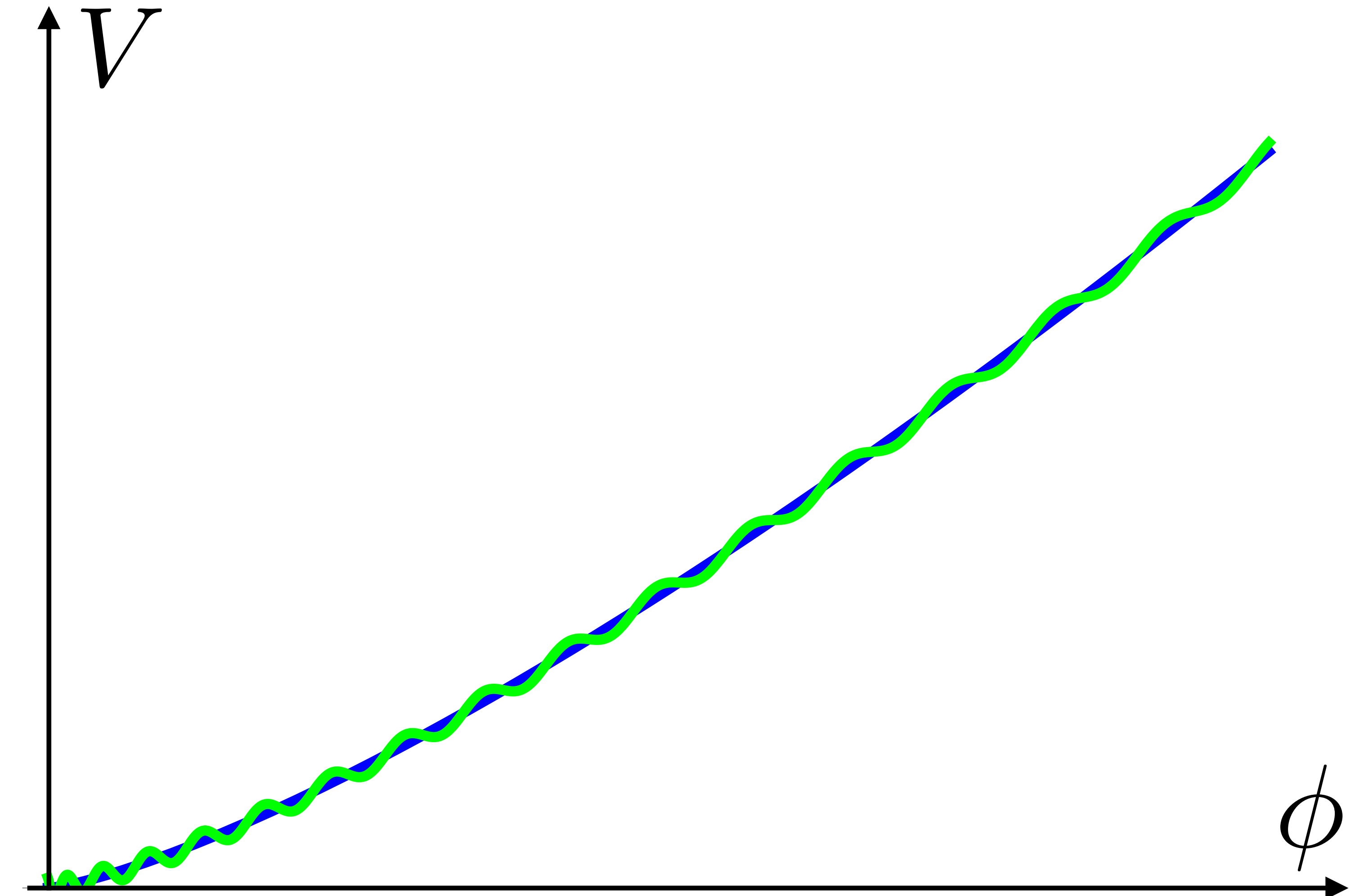
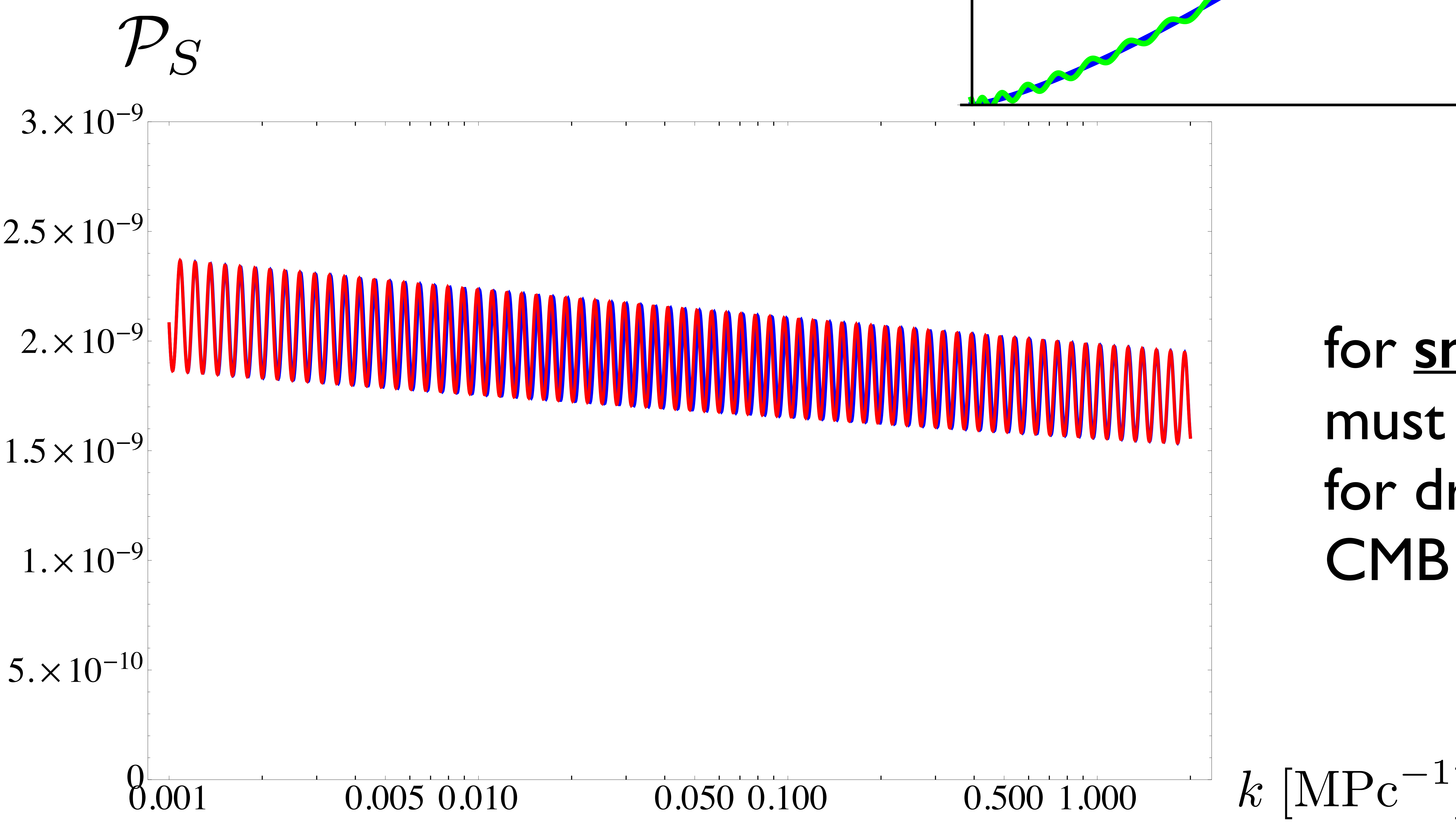


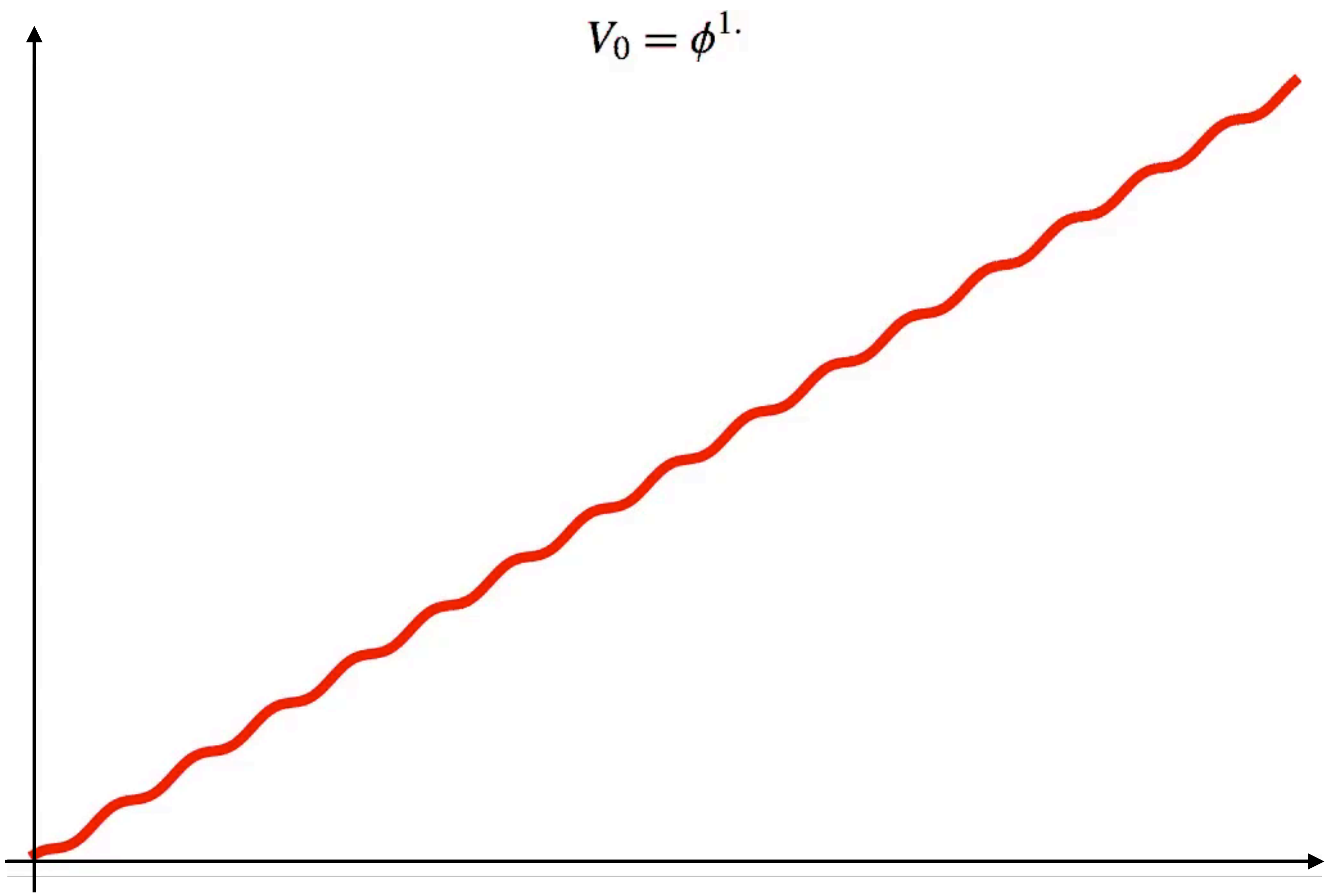


for **small *f***
must account
for drift in
CMB search !

... A Myth of Creation ...

for p < 1: ➔ dS **minima** beyond critical field value !

➔ false-vacuum eternal inflation + tunneling solves initial condition problem !



maximum field value due to control issues (backreaction/ decompactification):

➔ **upper bound** on ***p***

and on ***r*** (!!):

$$r \lesssim 0.04 \quad , \quad f = const.$$

summary ...

- moduli stabilization essential for string inflation! There is no meaningful way to talk about string inflation in presence of massless moduli ...

- first constructions: many <u>*small-field*</u> models, $r = 0$

- field-range bounds, overcome by *monodromy* - many primary power-law <u>*large-field*</u> potentials $\phi^{2/3}$ … ϕ^4

- *flattened* powers from moduli stabilization, so again crucial! *drifting oscillations* from NP effects!

$\Rightarrow$ if BICEP2 validated with r ~ 0.1 — need large-field