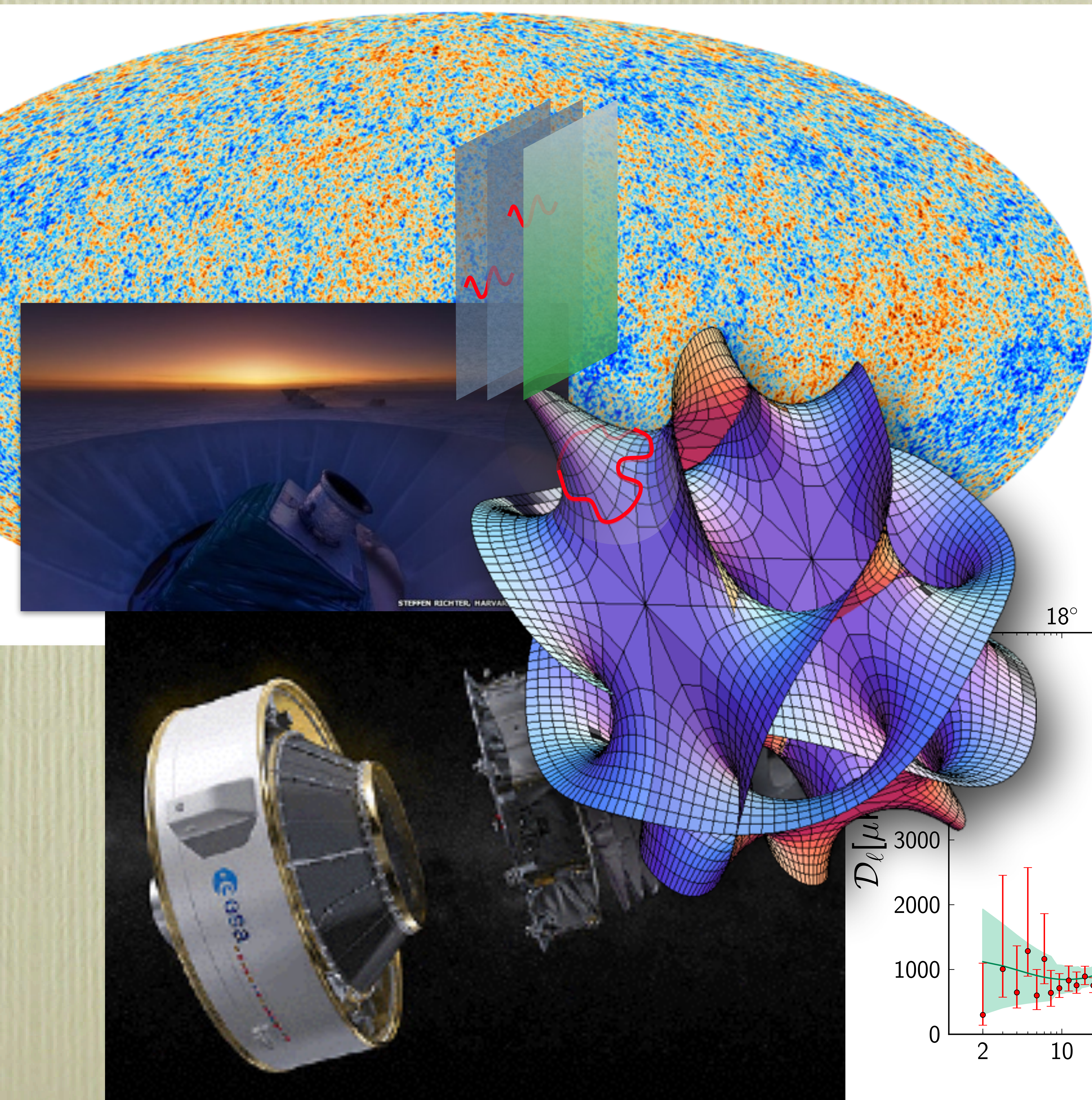
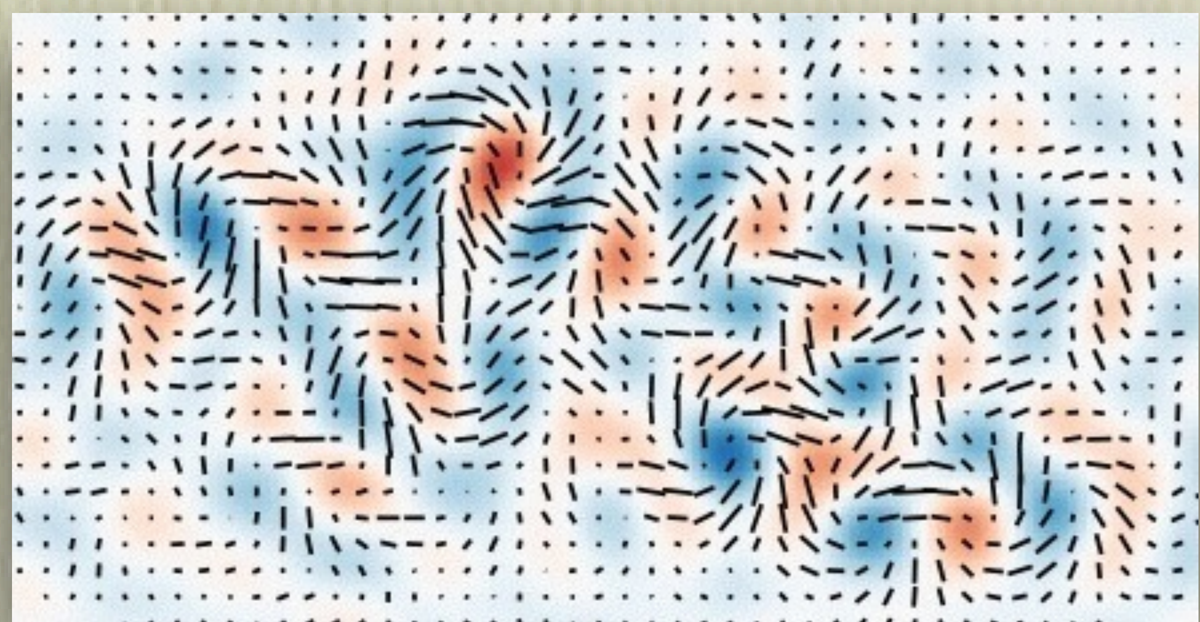
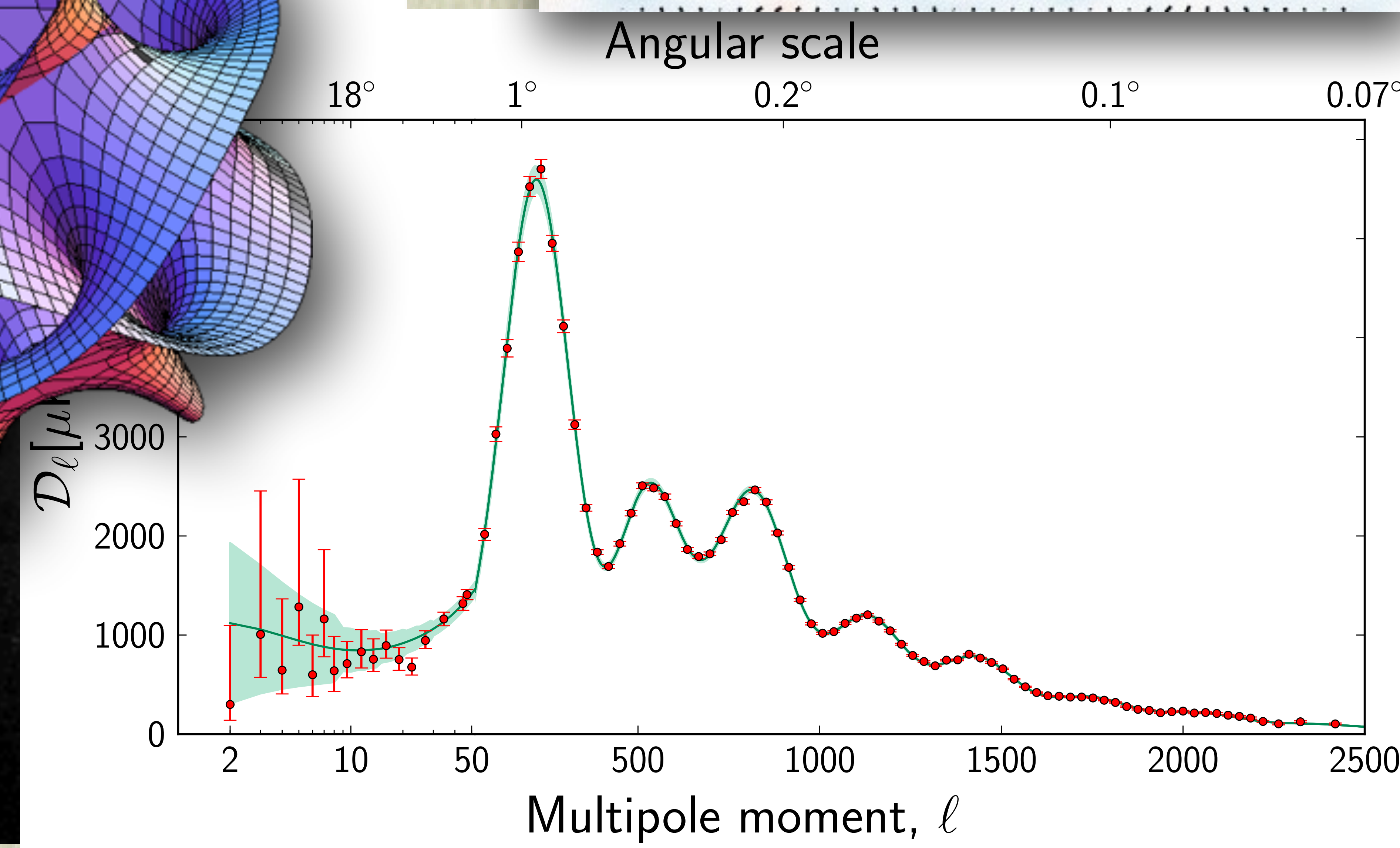
Large-field inflation - strings & pheno



Alexander Westphal
(DESY)



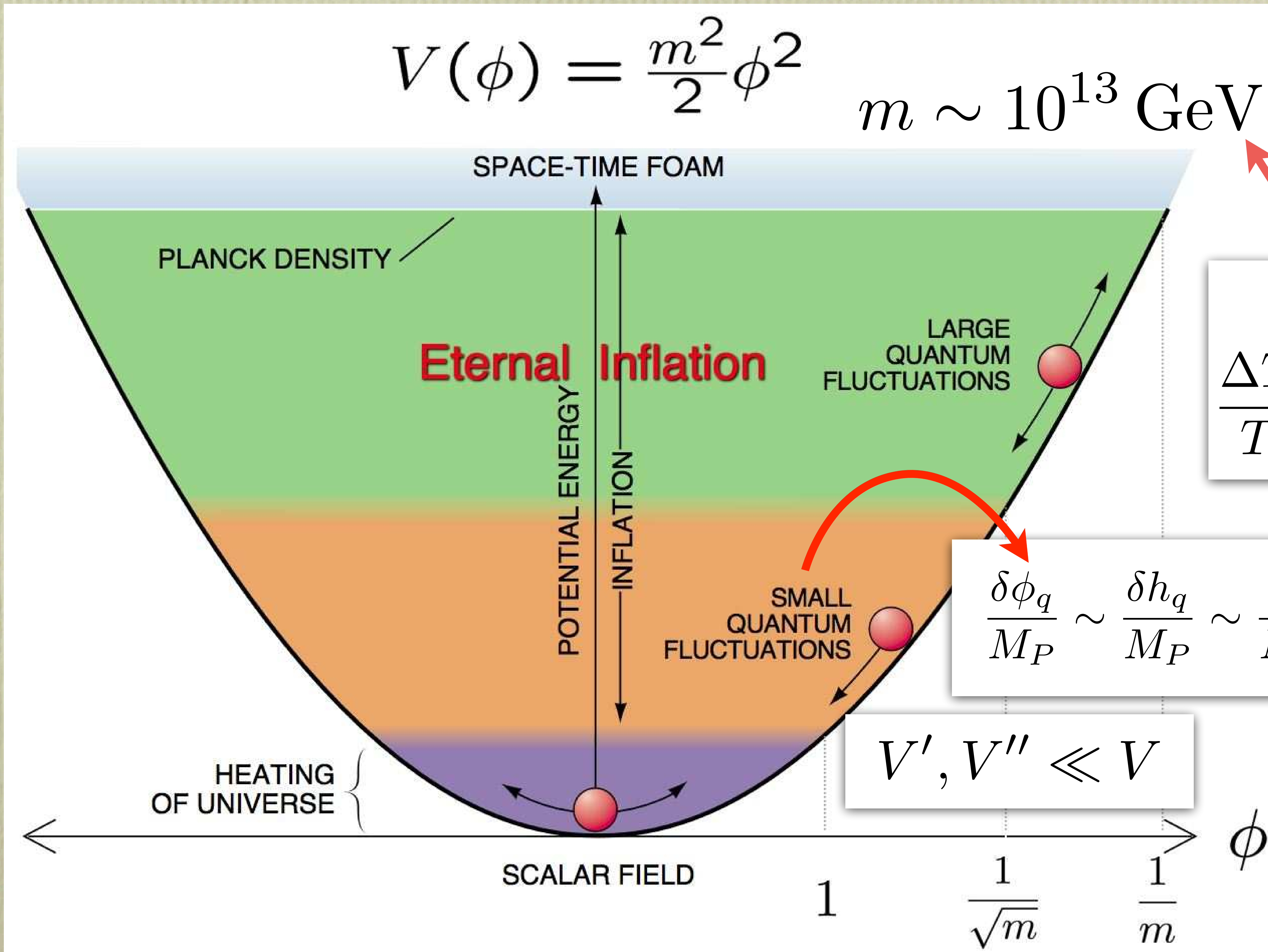


slow-roll inflation ...

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

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

$$m \sim 10^{13}\,\mathrm{GeV}$$



CMB:

$$\frac{\Delta T}{T} \sim 10^{-5}$$

$$\frac{\delta\phi_q}{M_P} \sim \frac{\delta h_q}{M_P} \sim \frac{H}{M_P} \sim 10^{-5}$$

$$V', V'' \ll V$$

[picture from lecture notes: Linde '07]

slow-roll inflation ...

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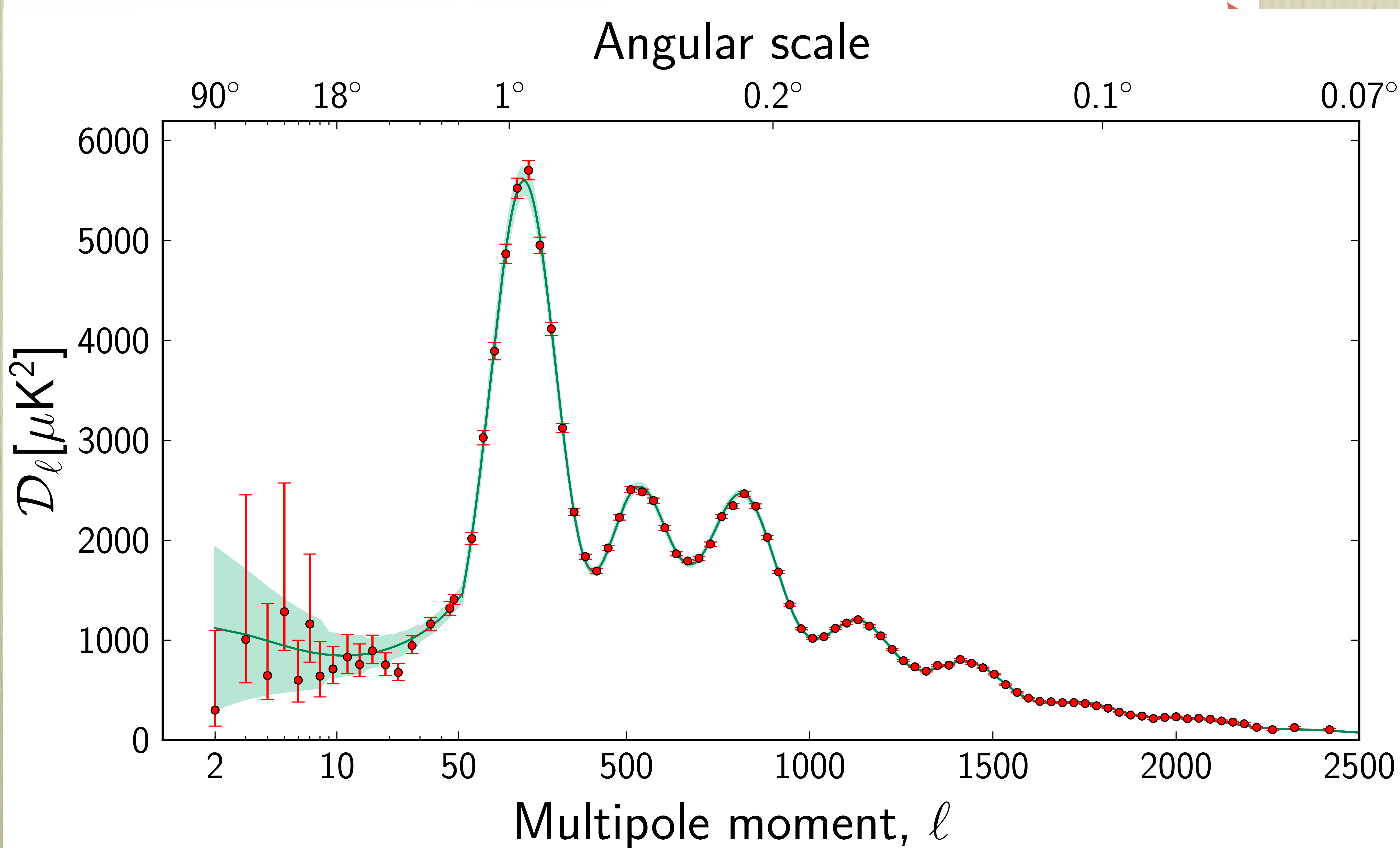


Inflation ...

- inflation: period quasi-exponential expansion of the very early universe

  (solves horizon, flatness problems of hot big bang ...)

  [Guth '80]

- driven by the vacuum energy of a slowly rolling light scalar field:

  e.o.m.: $\cancel{\ddot{\phi}} + 3H\dot{\phi} + V' = 0$

  [Linde; Albrecht & Steinhardt '82]

Inflation ...

- slow-roll inflation: [Linde; Albrecht & Steinhardt '82]

$$\text{scale factor grows exponentially} : a \sim e^{Ht} \quad \text{if} : \begin{cases} \dot{\phi}^2 \ll V \\ |\ddot{\phi}| \ll |3H\dot{\phi}| \end{cases}$$

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

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

e-folds N_e in $a \sim e^{N_e}$: $N_e = \int H \mathrm{d}t = \int_{\phi_E}^{\phi_E + \Delta\phi} \frac{\mathrm{d}\phi}{\sqrt{2\epsilon}}$

Inflation ...

- inflation generates metric perturbations: scalar (us) & tensor

$$\mathcal{P}_S \sim \frac{H^2}{\epsilon} \sim \left(\frac{\delta\rho}{\rho}\right)^2 \quad \text{and} \quad \mathcal{P}_T \sim H^2 \sim V$$

$$\sim k^{n_S - 1}$$

window to GUT scale & direct measurement of inflation scale

- scalar spectral index:

$$n_S = 1 - 6\epsilon + 2\eta$$

- tensor-to-scalar ratio:

$$r \equiv \frac{\mathcal{P}_T}{\mathcal{P}_S} = 16\epsilon$$

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

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

- string compactification produces **moduli -- stabilize them!!** :

  - spectrum of massive scalars - field range in string theory?

  i) first level question: *kinematical* field-range

  -> **large-volume** / **weak-coupling** limits:
  kinematic large field ranges arise straight forwardly
  however — extra states becoming light in parametric limit!

  -> **monodromy**:
  branes and fluxes *unwind* would-be
  periodic directions into kinematically unbounded fields

  ii) 2nd-level question: *dynamical* field-range

  -> effects of moduli stabilization and backreaction/flattening
  may limit the available field range

inflatons should be light ...

- **supersymmetry/warping**
  - D-brane positions — **no symmetry protection** — **bounded by volume**
- **no-scale structure**
  - 'cycle' radii — **no symmetry protection** — **bounded by volume**
  - overall volume modulus — **unbounded**

[Dodelson, Dong, Silverstein & Torroba '13]

- **gauge/shift symmetries**
  - axions — **good symmetry protection** — **periodically bounded** by non-pert. effects
  - *exclude* dilaton $S = 1/g_s$ -- *pervasive couplings to all sectors*

varieties of string inflation ...

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

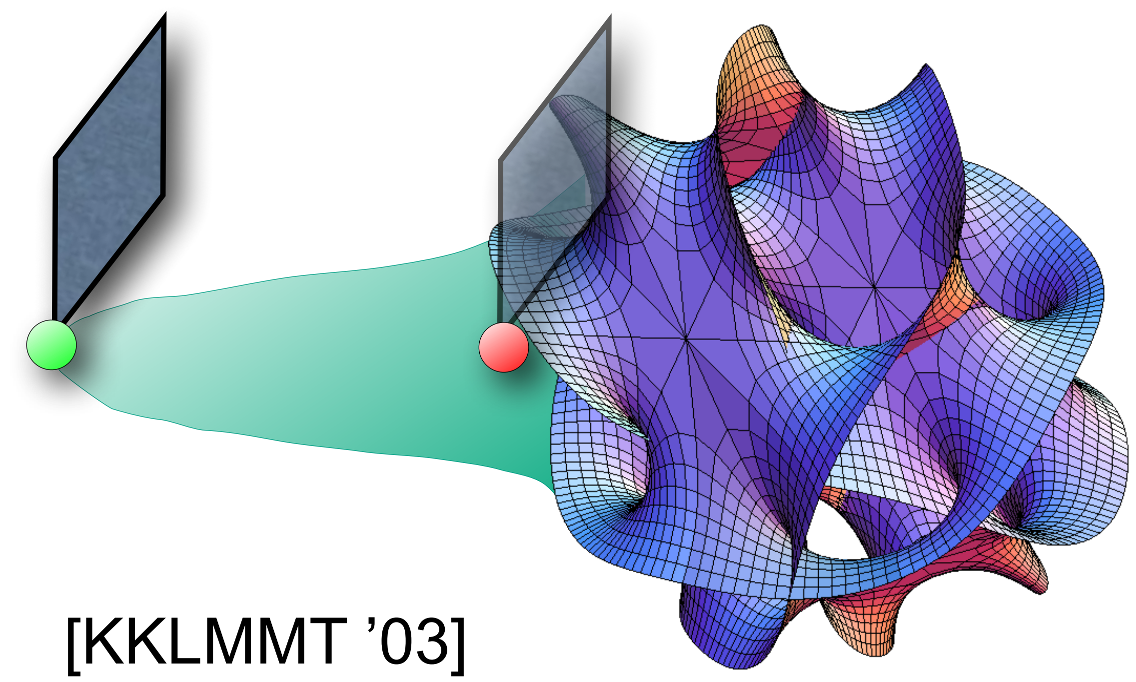
$$\frac{\Delta\phi(N_e)}{M_{\rm P}} \gtrsim \frac{N_e}{50}\sqrt{\frac{r}{0.01}} \quad , \quad r = \frac{\mathcal{P}_T}{\mathcal{P}_S}$$

[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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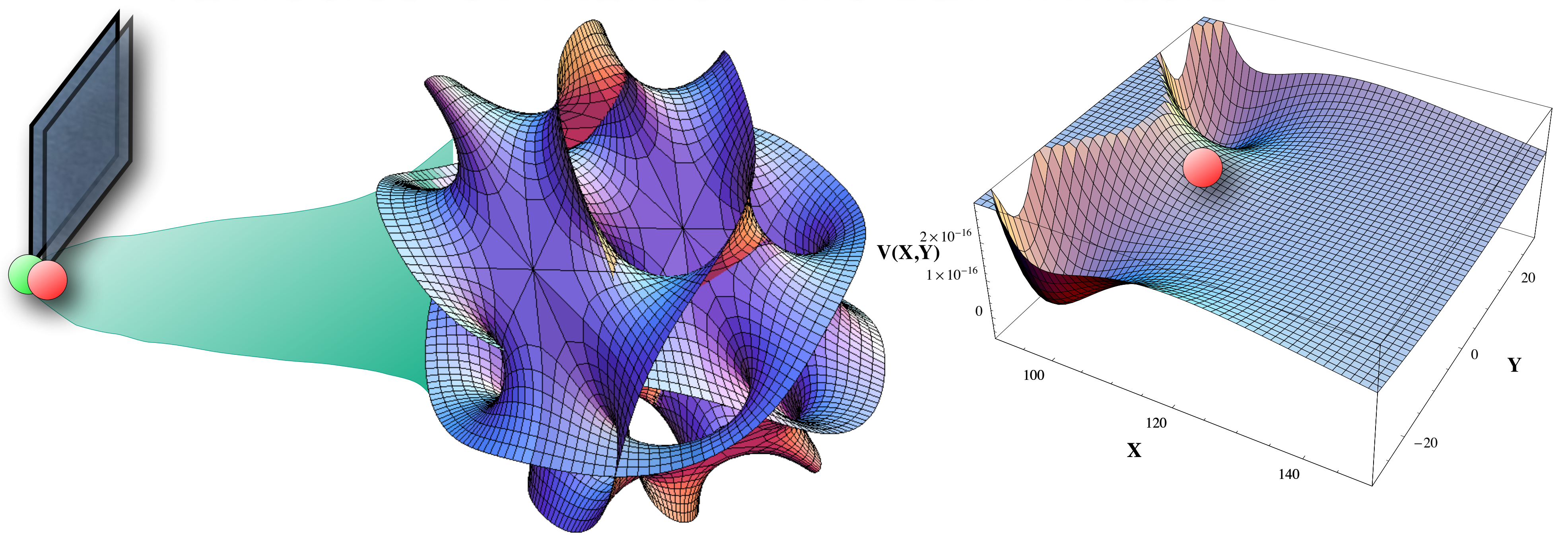

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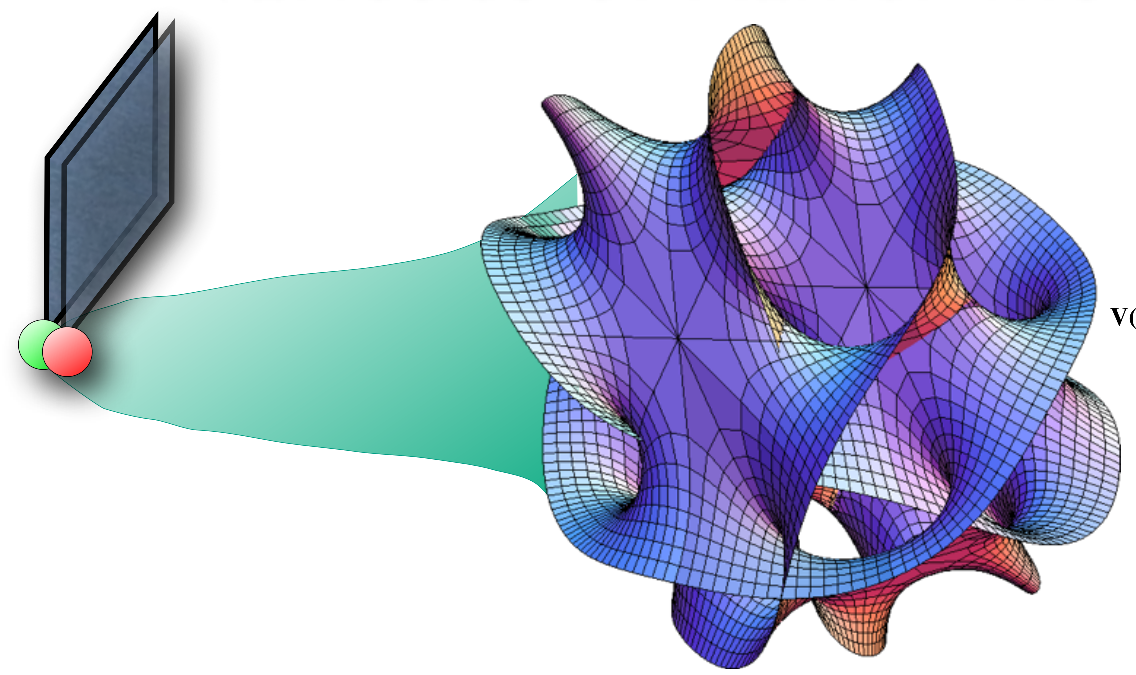

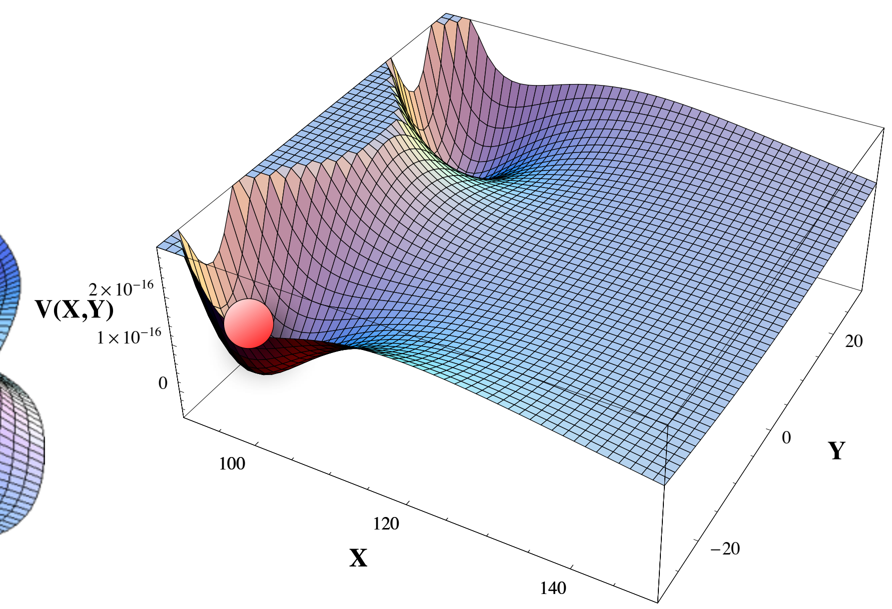

- r = $O(1/N_e^2)$ models:

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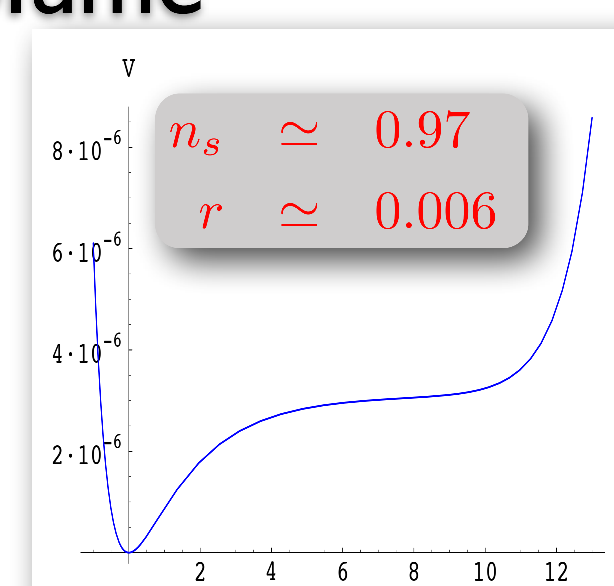
fibre inflation in LARGE volume scenarios (LVS)

[Cicoli, Burgess & Quevedo '08]



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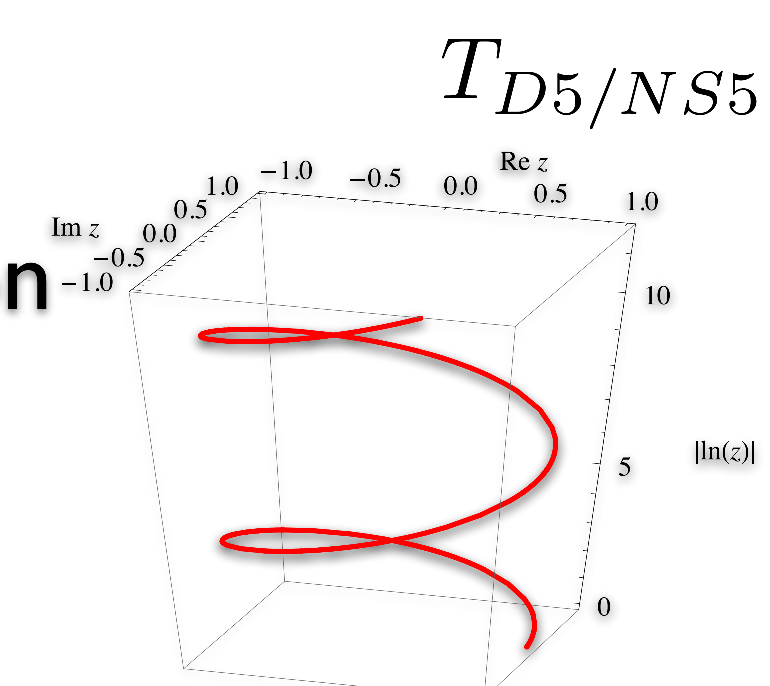
[Lyth '97]

observable tensors: $r > 0.01$

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

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

axion monodromy inflation
2-axion inflation
N-flation



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 $T_{\mu\nu}$:

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

shift symmetry

- while field fluctuation interactions:

$$\mu^{4-p}(\phi_\star + \delta\phi)^p \sim \mu^{4-p}\phi_\star^p \left(1 + \sum_n c_n \frac{\delta\phi^n}{\phi_\star^n}\right)$$

  die out with increasing field displacement …

- if the inflaton potential breaks the shift symmetry *weakly* & *smoothly* (means: with falling derivatives)

  —

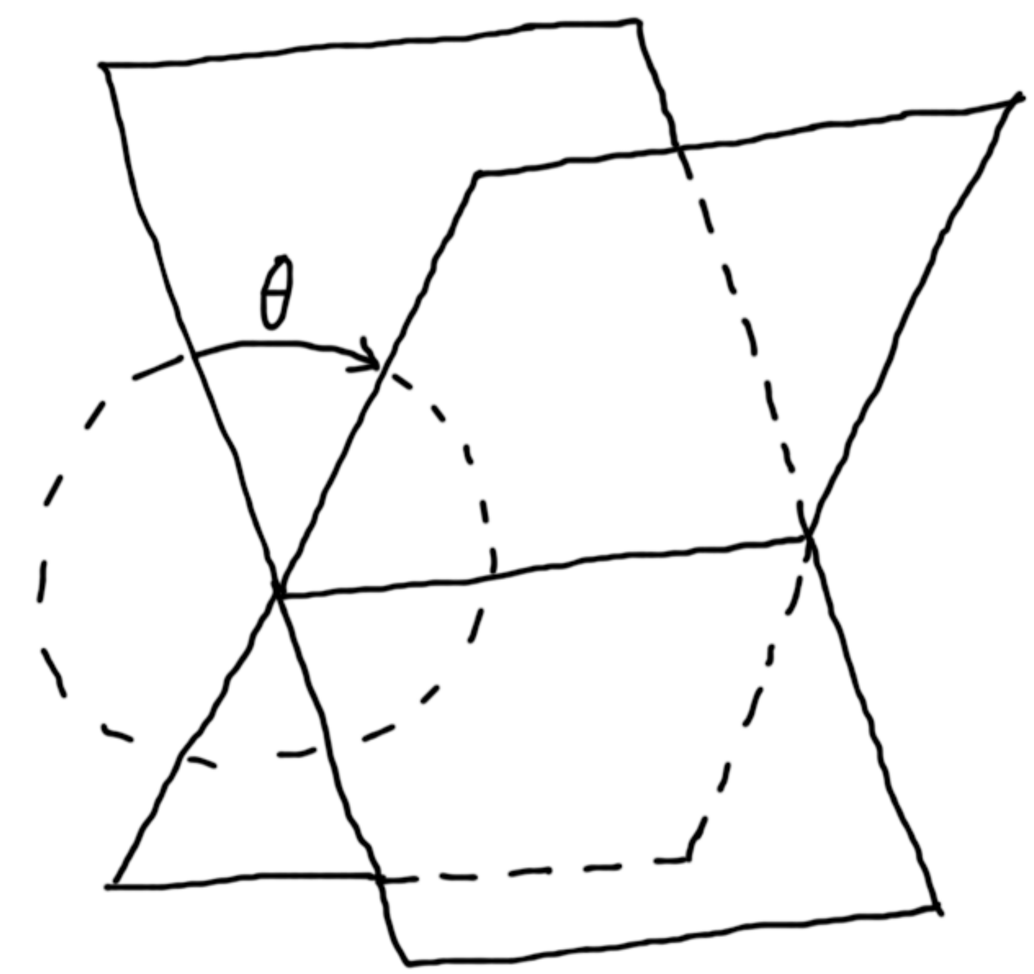
  it does *not* matter, if the shift symmetry is periodically broken, or secularly

- a shift symmetry itself does not guarantee *smoothness* of breaking — need UV theory as input, for all models!

axion monodromy

stringy large field inflation - why the worry ?

- many periodic inflaton candidates
  e.g. brane positions or
  angles θ_a between branes



$$a < (2\pi)^2 \quad \text{or} \quad a < L^q$$

- $E_{internal} \longrightarrow 0$ for L large,
  all internal sources die at large volume

$$\mathcal{L}_{kin} \sim \frac{M_{\mathrm{P}}^2}{L^p}(\partial_\mu a)^2 \quad , \quad p > q$$

- field range is limited to $< M_{\mathrm{P}}$

[Banks, Dine, Fox & Gorbatov '03; Srvcek & Witten '06]
[Baumann, McAllister '06]

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 $f < M_{\rm P}$:

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

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

[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]

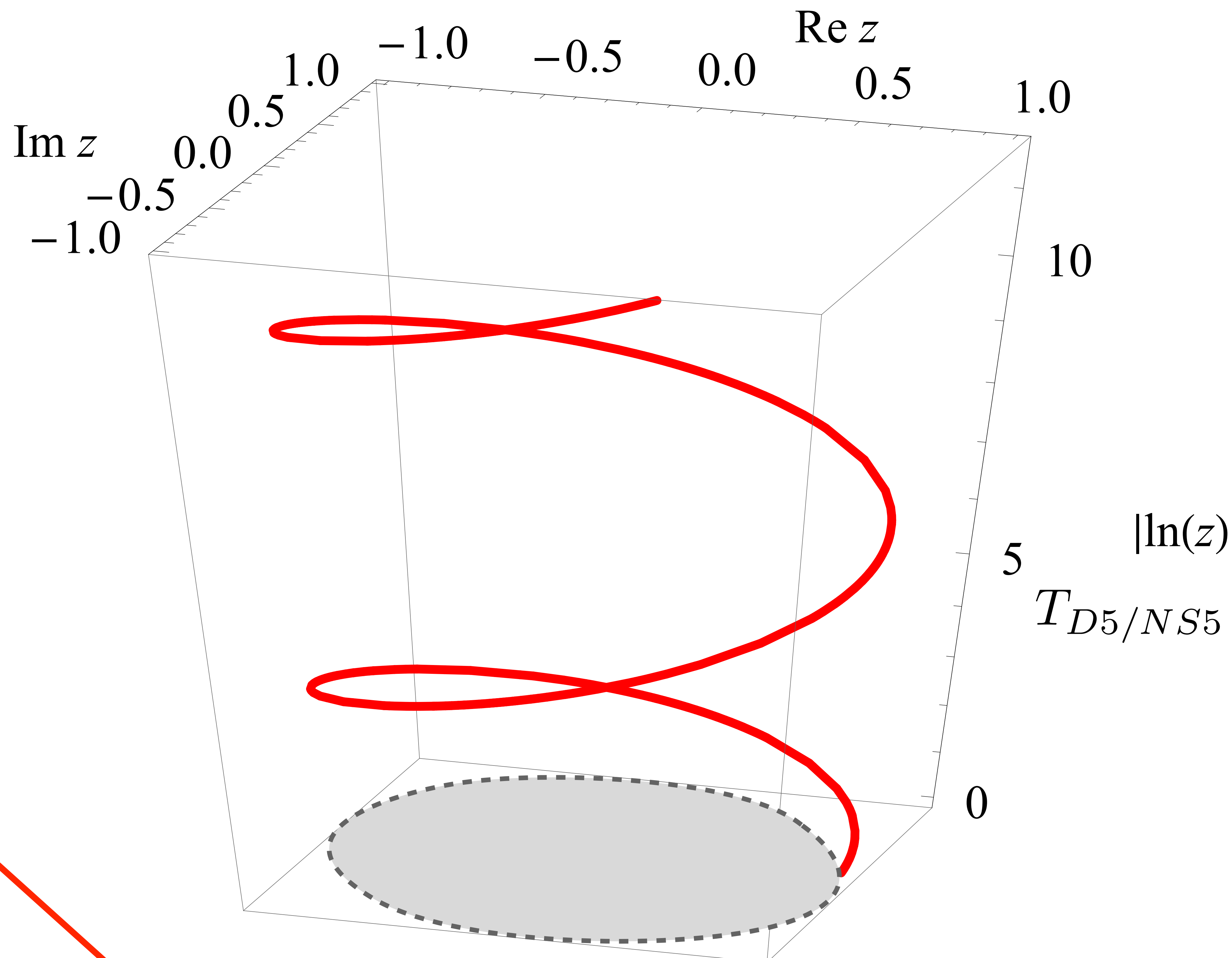
  - cos-potential for 2 axions can align/tune for large-field direction

    [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

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



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

[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:

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

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

- 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

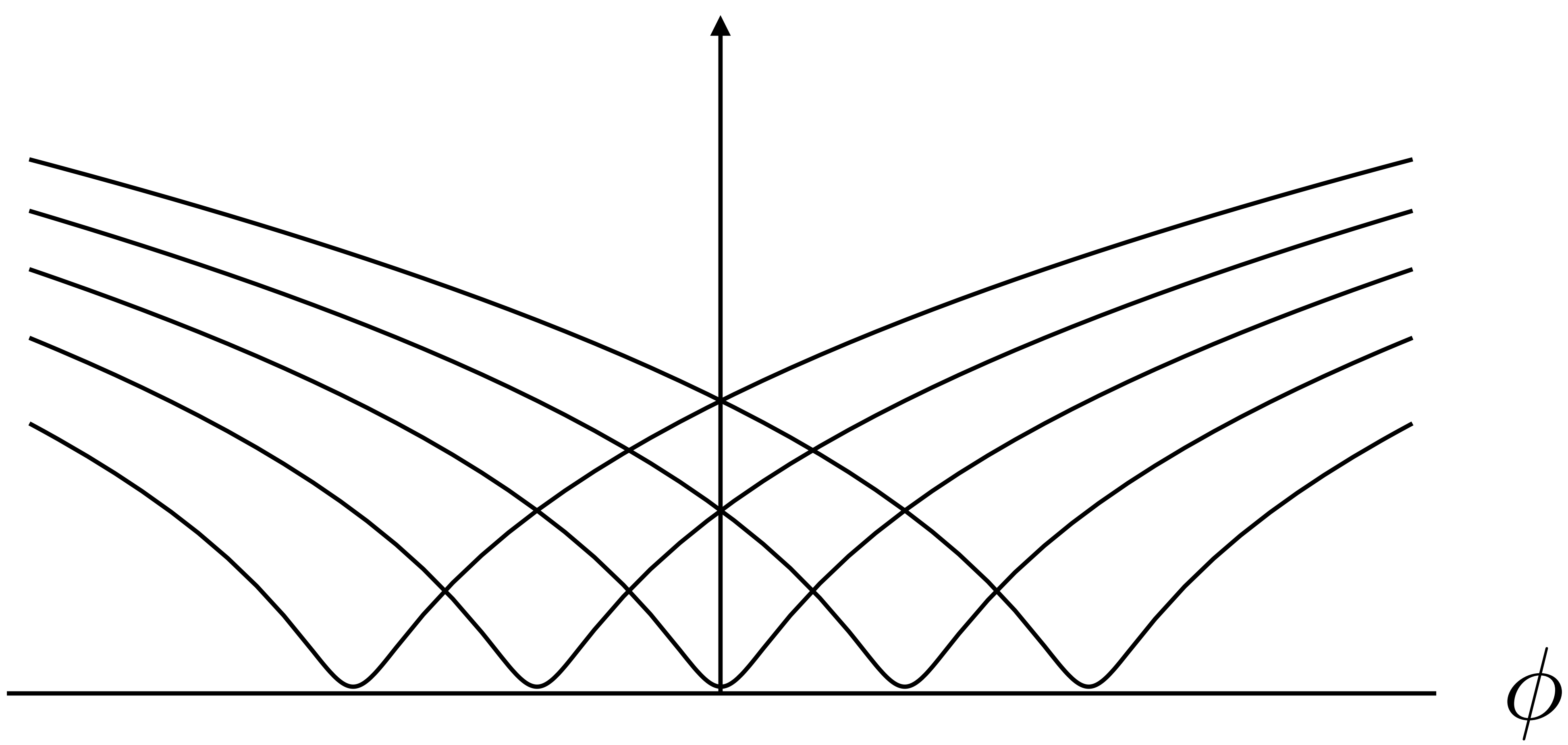
- p-form axions get **non-periodic** potentials from coupling to **branes** or **fluxes/field-strengths**

- 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 monodromy - 4D effective picture

[Kaloper & Sorbo '08] [Dubovsky, Lawrence & Roberts '11]
[Lawrence, Kaloper & Sorbo '11] [Kaloper & Lawrence '14]

- 4D effective action: F_4 field strength, axion ϕ :

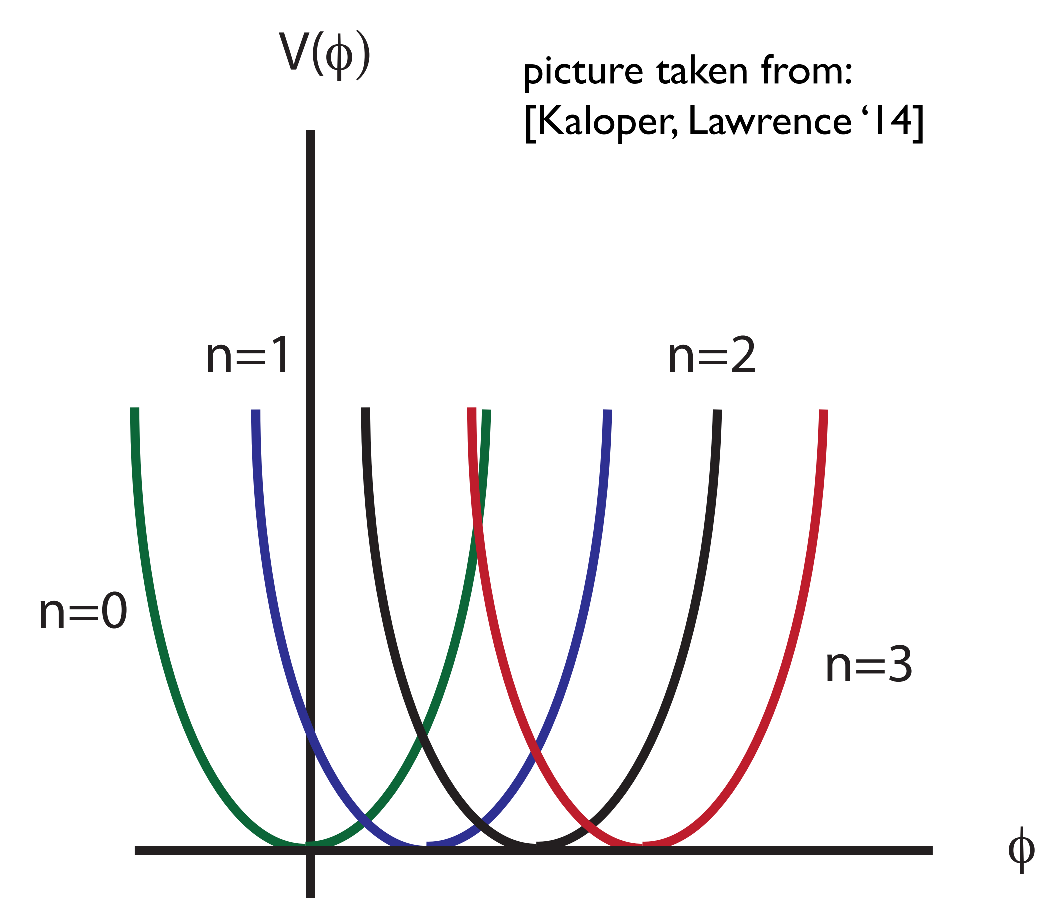
$$\mathcal{L} = \frac{1}{2} m_{pl}^2 R - \frac{1}{2}(\partial\phi)^2 - \frac{1}{48} F_{(4)}^2 + \frac{\mu}{24} \phi^* F_{(4)}$$

- 4D effective Hamiltonian:

$$H = \frac{1}{2}\left(p_\phi\right)^2 + \frac{1}{2}\left(\nabla\phi\right)^2 + \frac{1}{2}\left(ne^2 + \mu\phi\right)^2$$

$$\phi \;\rightarrow\; \phi + f \qquad\qquad \Rightarrow \quad \mu f = e^2 \;\;, \quad n \rightarrow n+1$$

- again:
  - axion *unwound into multiple branches*
  - *n jumps by flux tunneling*, e^{-S}*-suppressed*
  - periodicity by summing over branches



flux monodromy with F-term supergravity description

- flux-induced potentials for B_2- or C_2-axions & D7-brane position moduli, the T-duals of Wilson lines

[Marchesano, Shiu & Uranga '14]

IIA F-term axion monodromy of B_2- or C_2-axions or Wilson lines from flux

ϕ^2, ϕ^4 potentials

[Hebecker, Kraus & Witkowski '14]

IIB F-term D7-position axion monodromy from F-theory G_4 flux

ϕ^2 potential

[Ibanez, Marchesano & Valenzuela '14]
[Garcia-Etxebarria, Grimm & Valenzuela '14]

-beautiful F-term realizations — but open question: moduli stabilization!!

-addressed in supergravity model:

> the D7-position proposal

[Hebecker, Kraus & Witkowski '14]

-and non-supergravity model:

> IIB on Riemann surfaces: $\phi^{4/3}$, ϕ^2, ϕ^3

[McAllister, Silverstein, AW & Wrase '14]

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
$$F_3 = Q_{31} dy_1^{(1)} \wedge dy_1^{(2)} \wedge dy_1^{(3)} + Q_{32} dy_2^{(1)} \wedge dy_2^{(2)} \wedge dy_2^{(3)}$$
$$F_1 = \frac{Q_1}{L_1} \sum_{i=1}^{3} dy_1^{(i)}$$

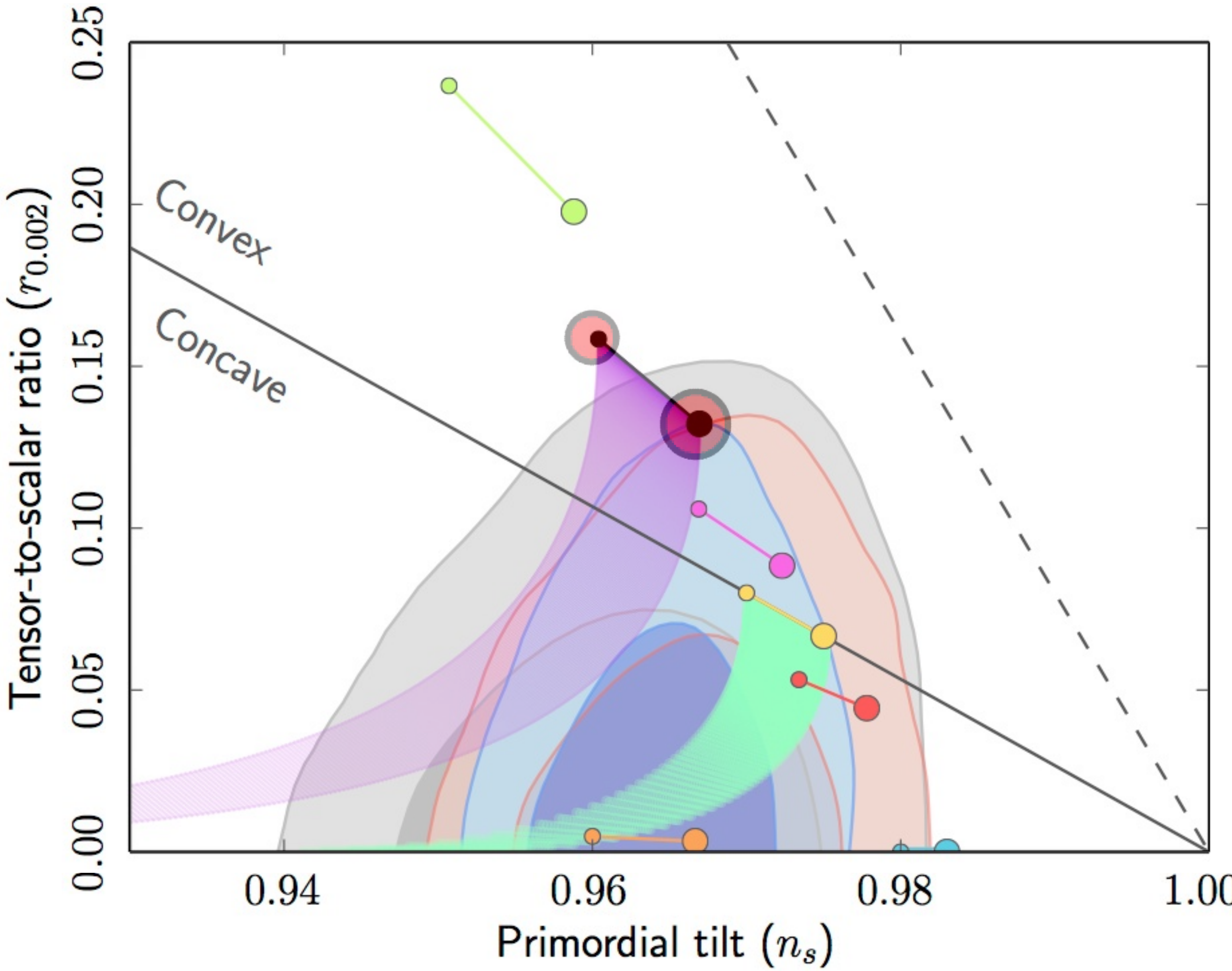
- effective 4d action gives ϕ^3-potential: $$u = \frac{L_2}{L_1} \quad , \quad \frac{\phi}{M_{\rm P}} = \frac{b}{L^2}$$

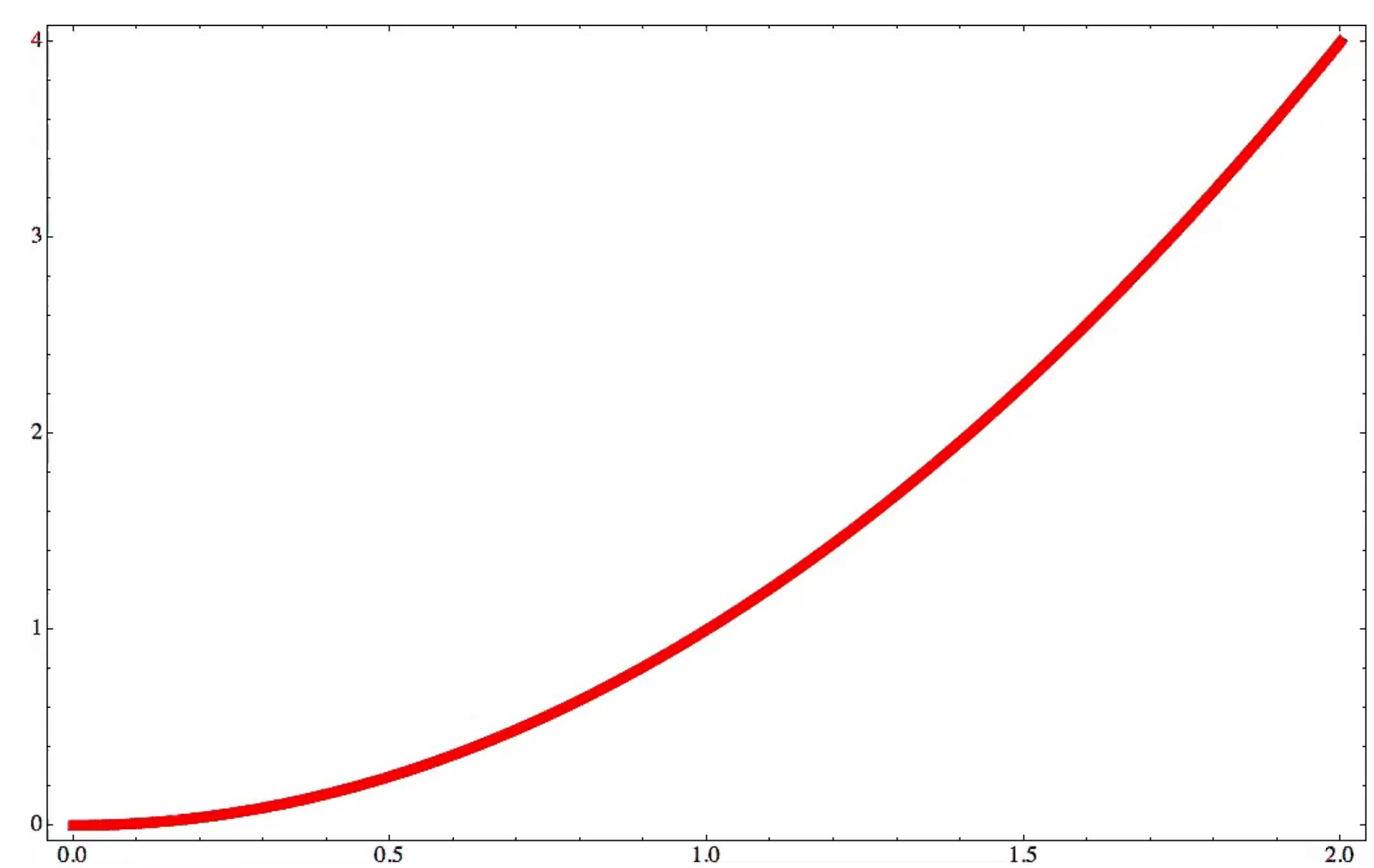
$$\mathcal{L} \sim M_{\rm P}^2 \frac{\dot{b}^2}{L^4} + M_{\rm P}^4 \frac{g_s^4}{L^12} \left[Q_1^2 L^4 \left(\frac{b}{L^2} \right)^4 u + Q_{31}^2 u^3 + \frac{Q_{32}^2}{u^3} \right] \sim \dot{\phi}^2 + \mu \, \phi^3$$

- 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!!]

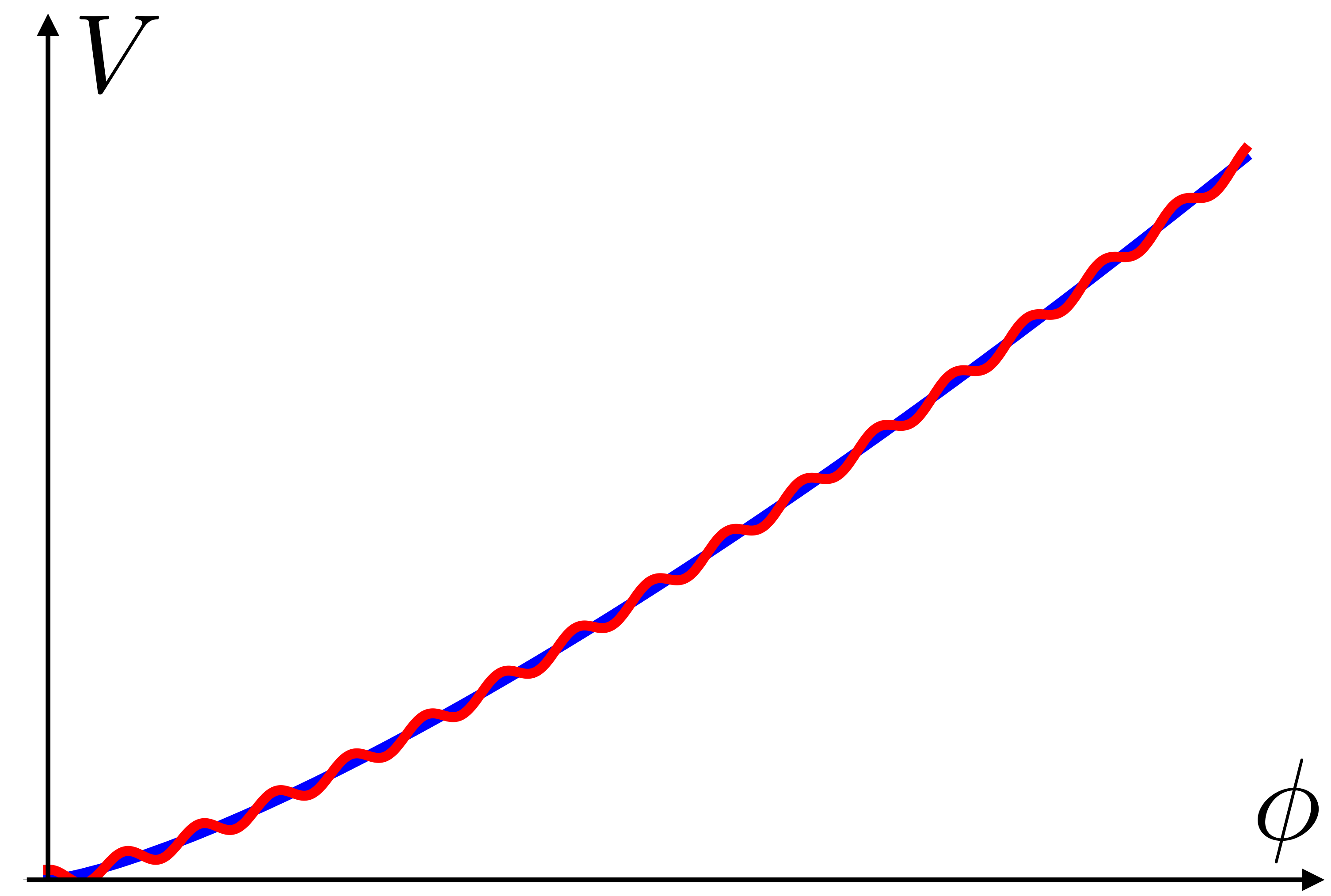




phenomenology ... drifting CMB oscillations !

[Flauger, McAllister, Silverstein & AW '14]

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



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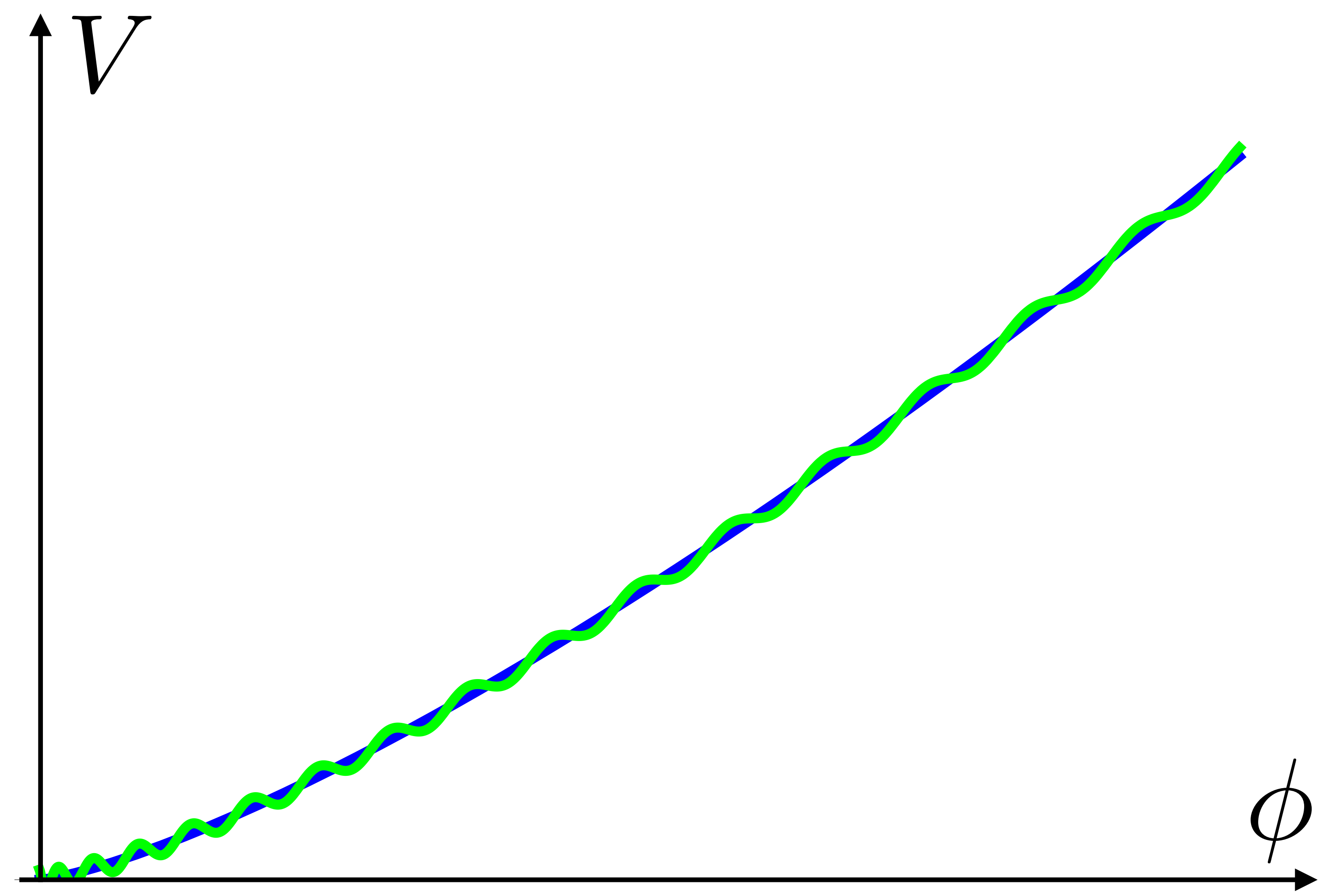

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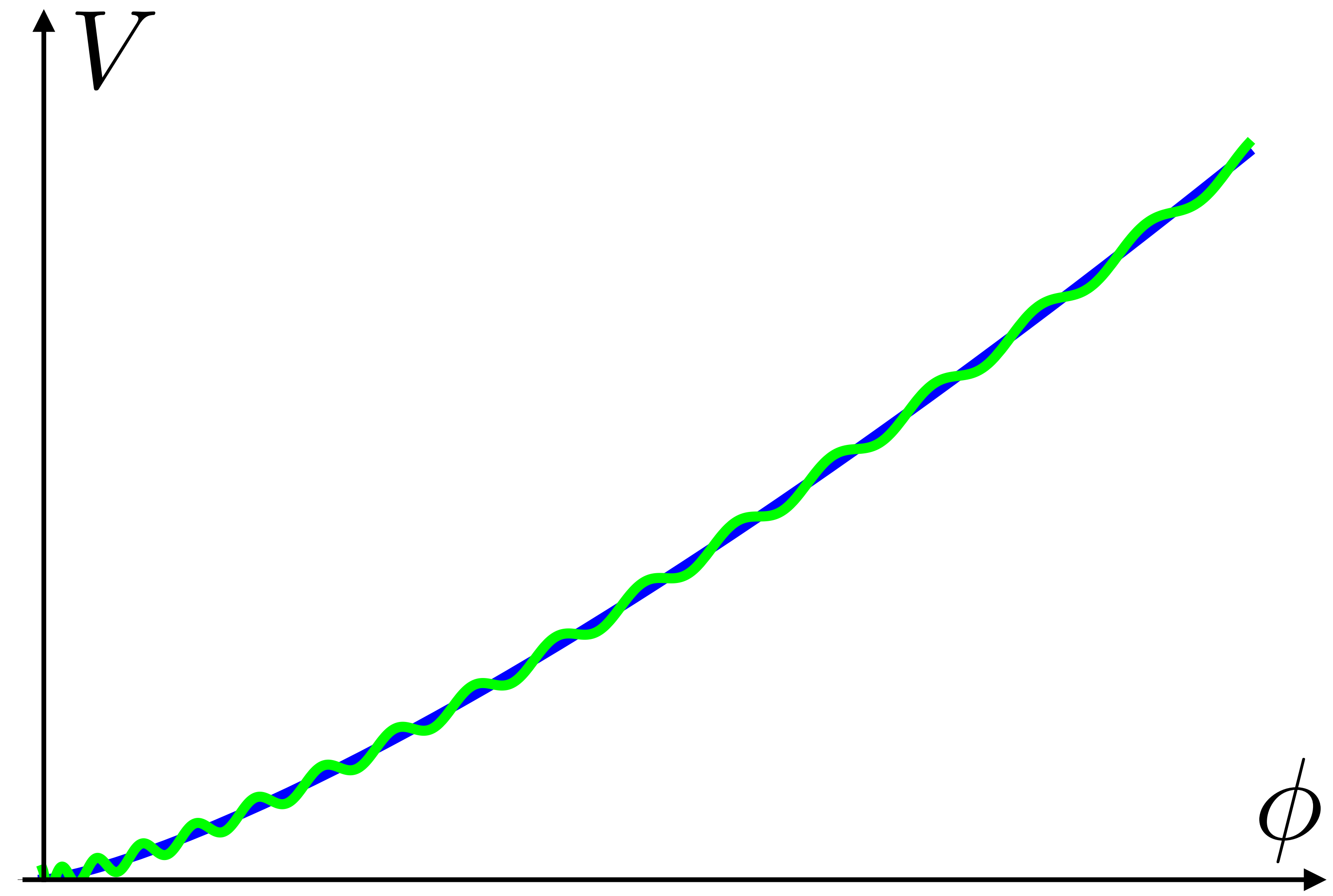

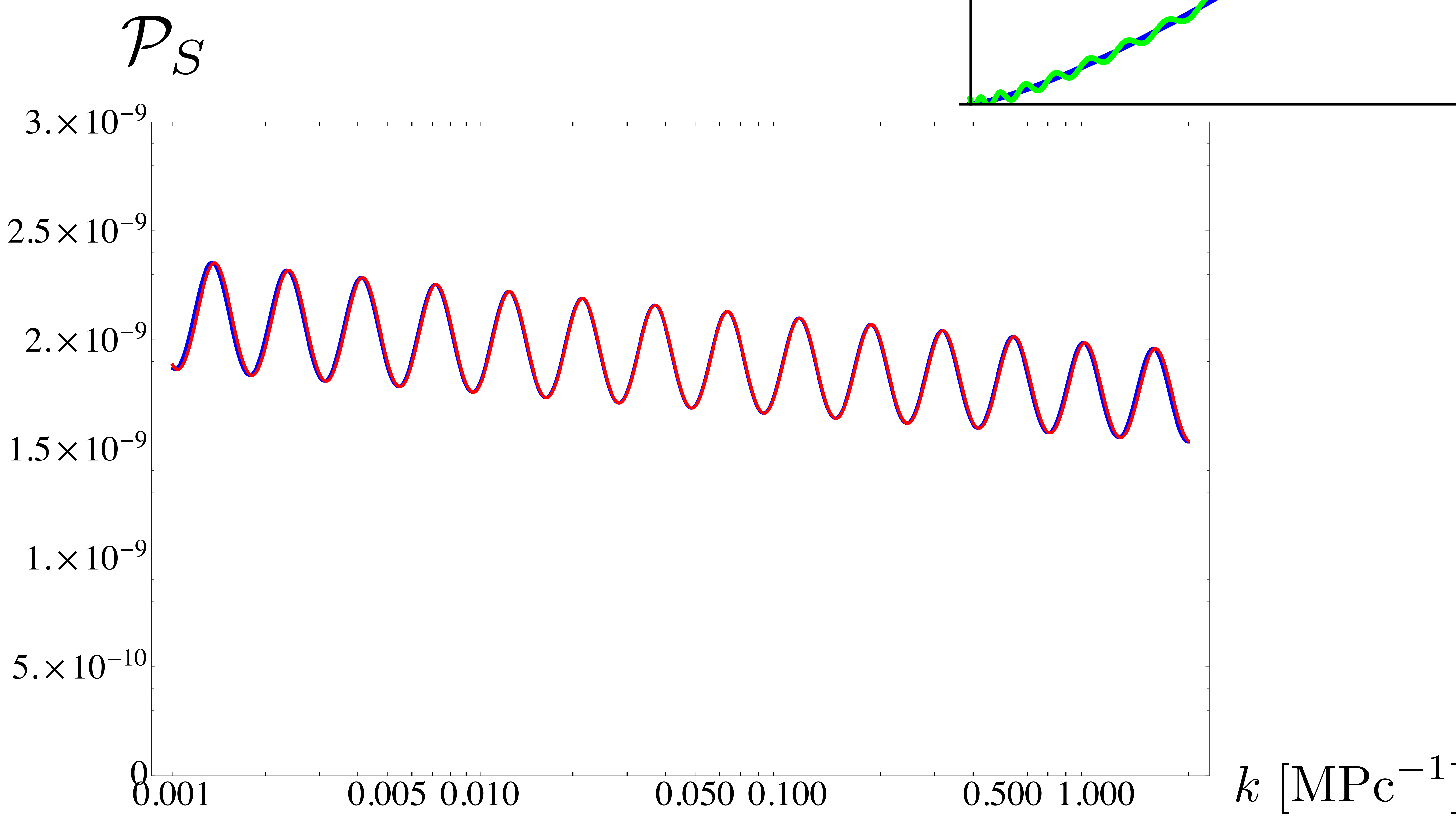

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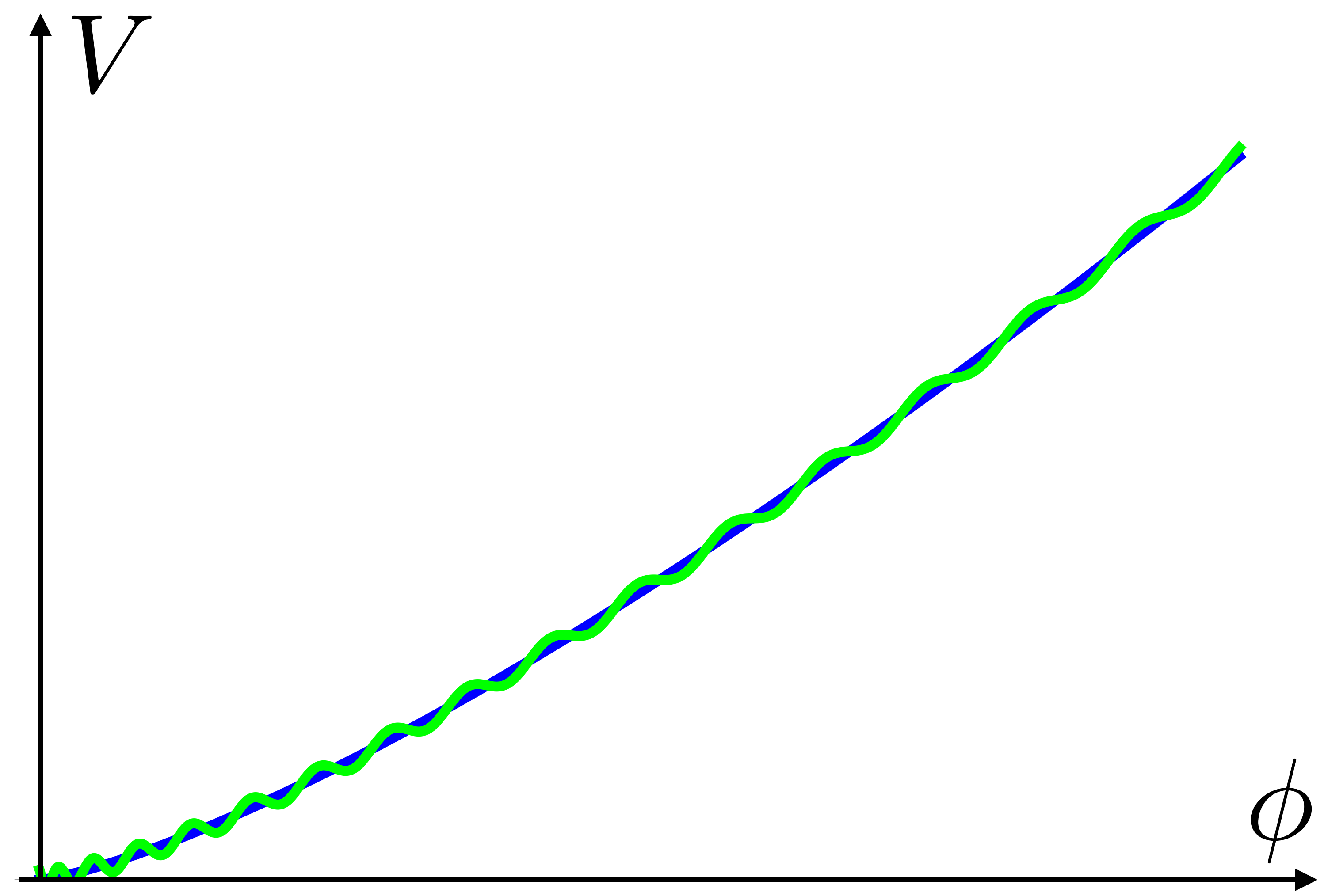
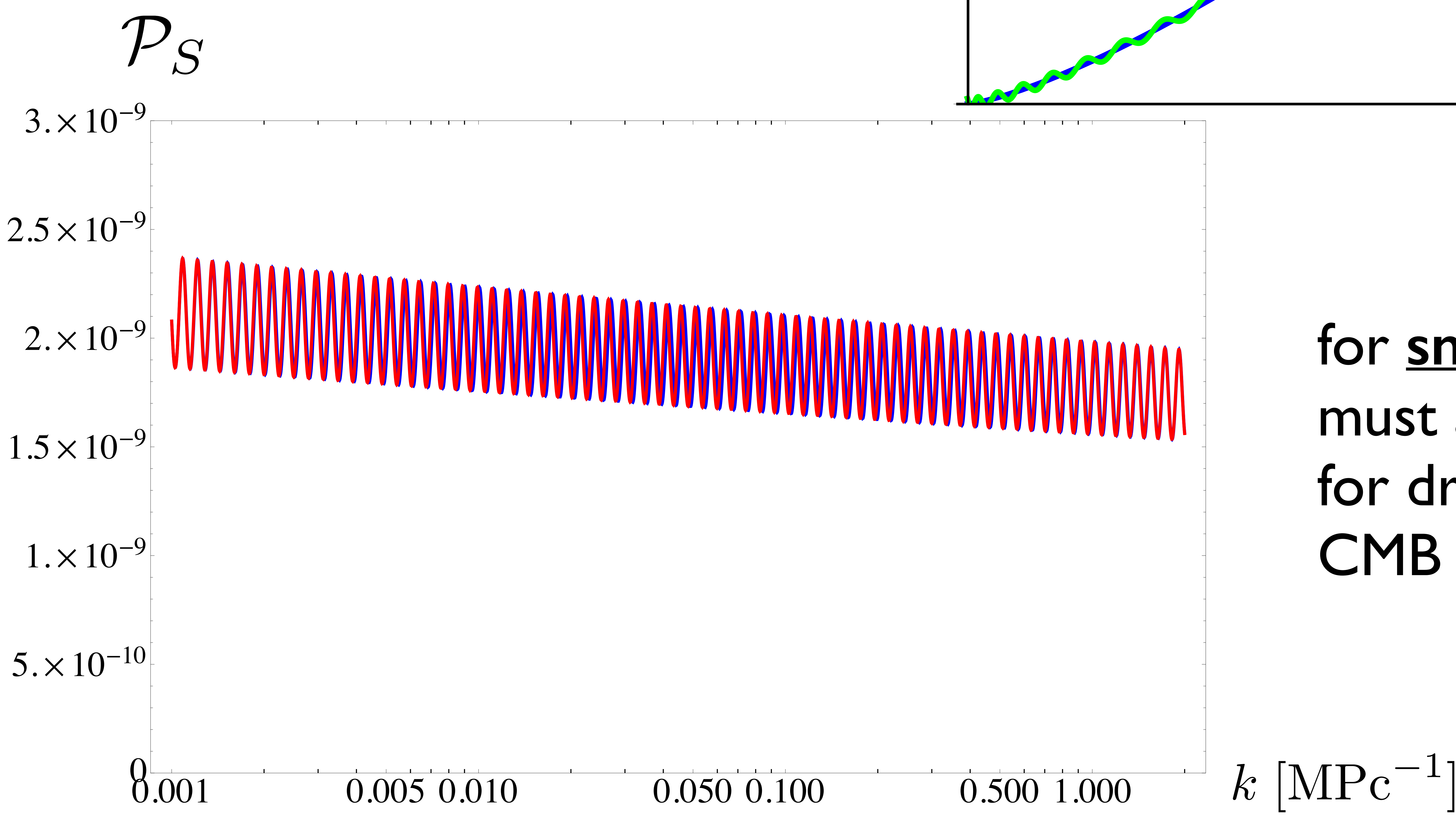




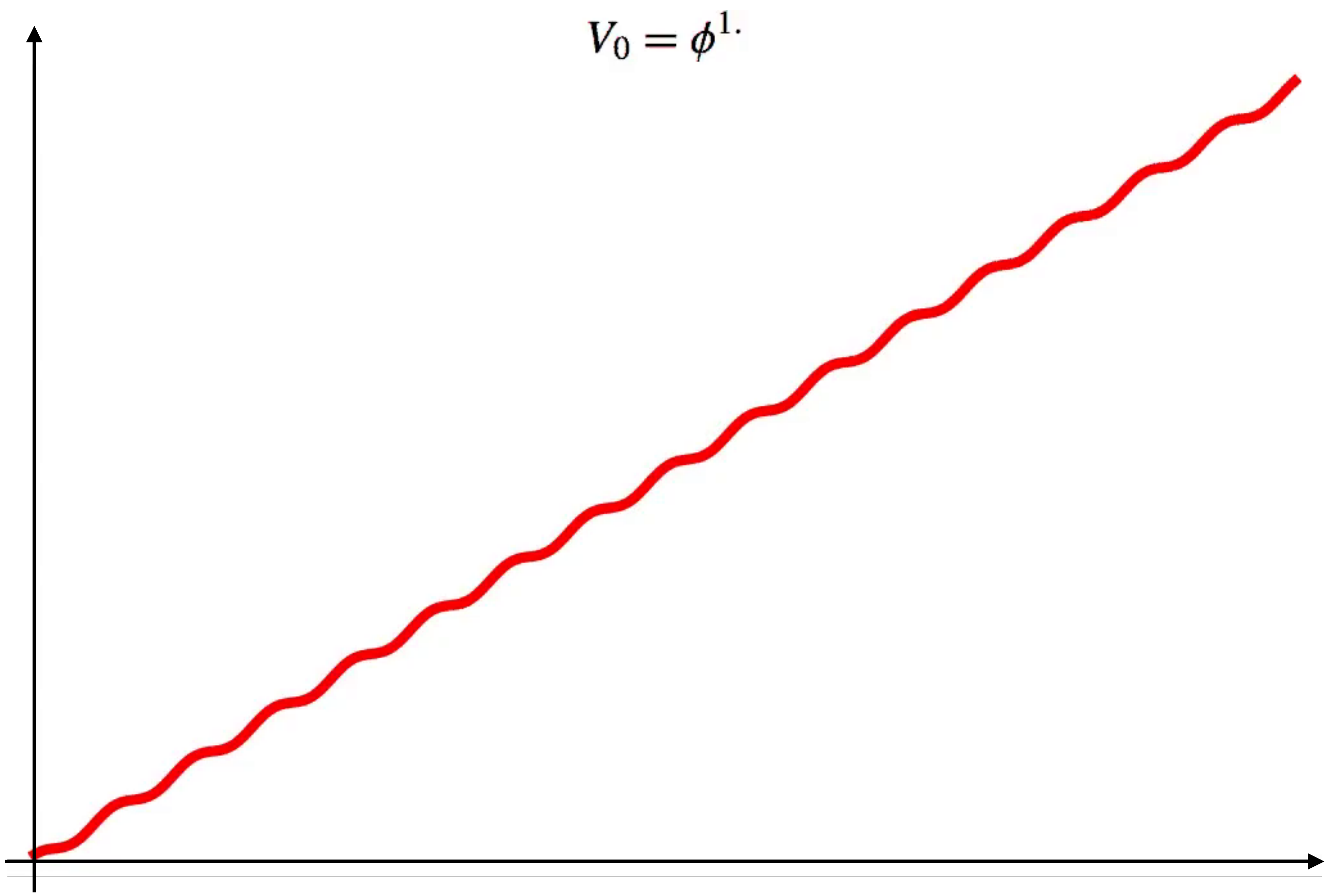
for **small *f*** must account for drift in CMB search !

… A Myth of Creation …

[Flauger, McAllister, Silverstein & AW '14]

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):

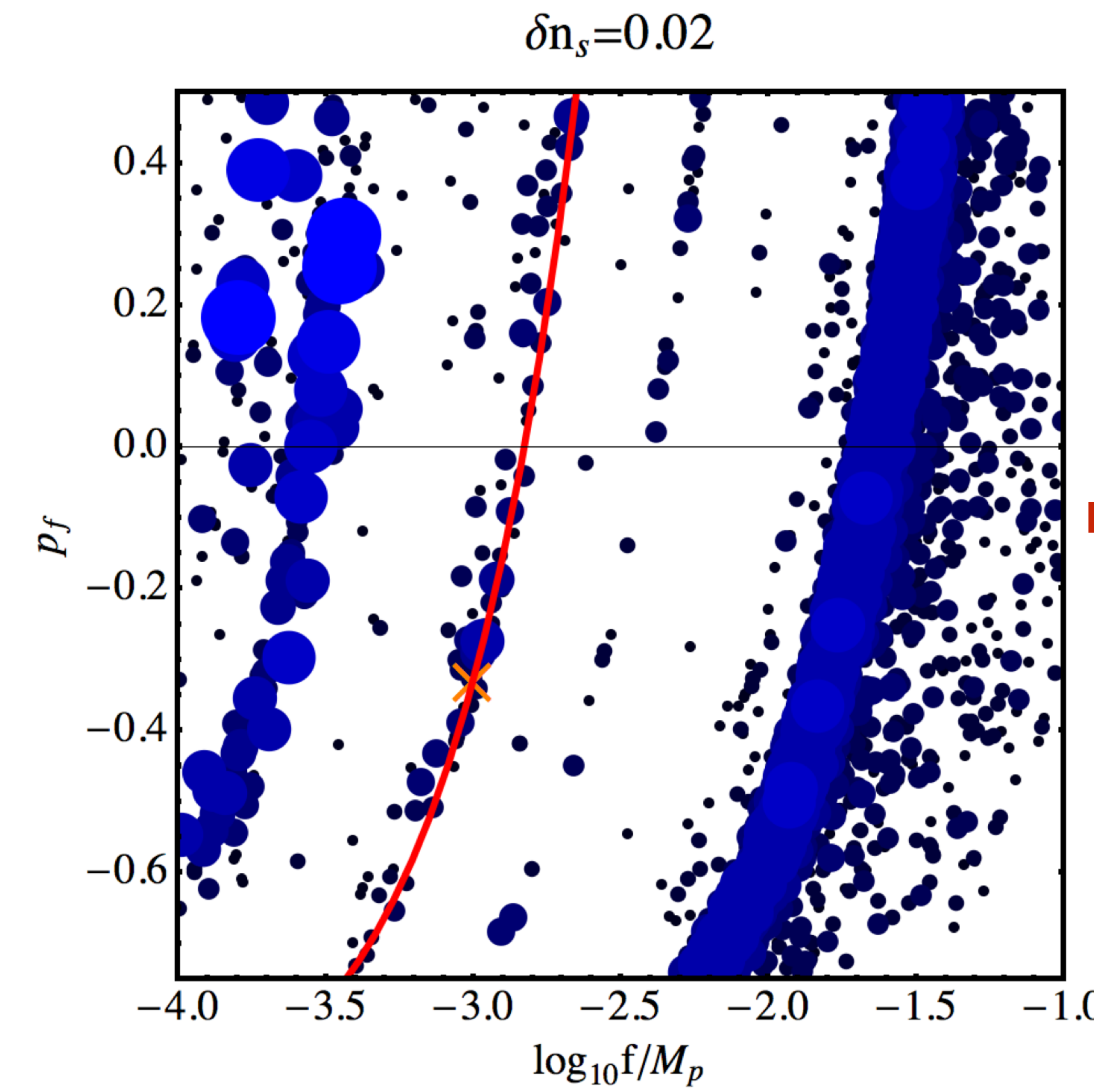
→ **upper bound** on ***p***

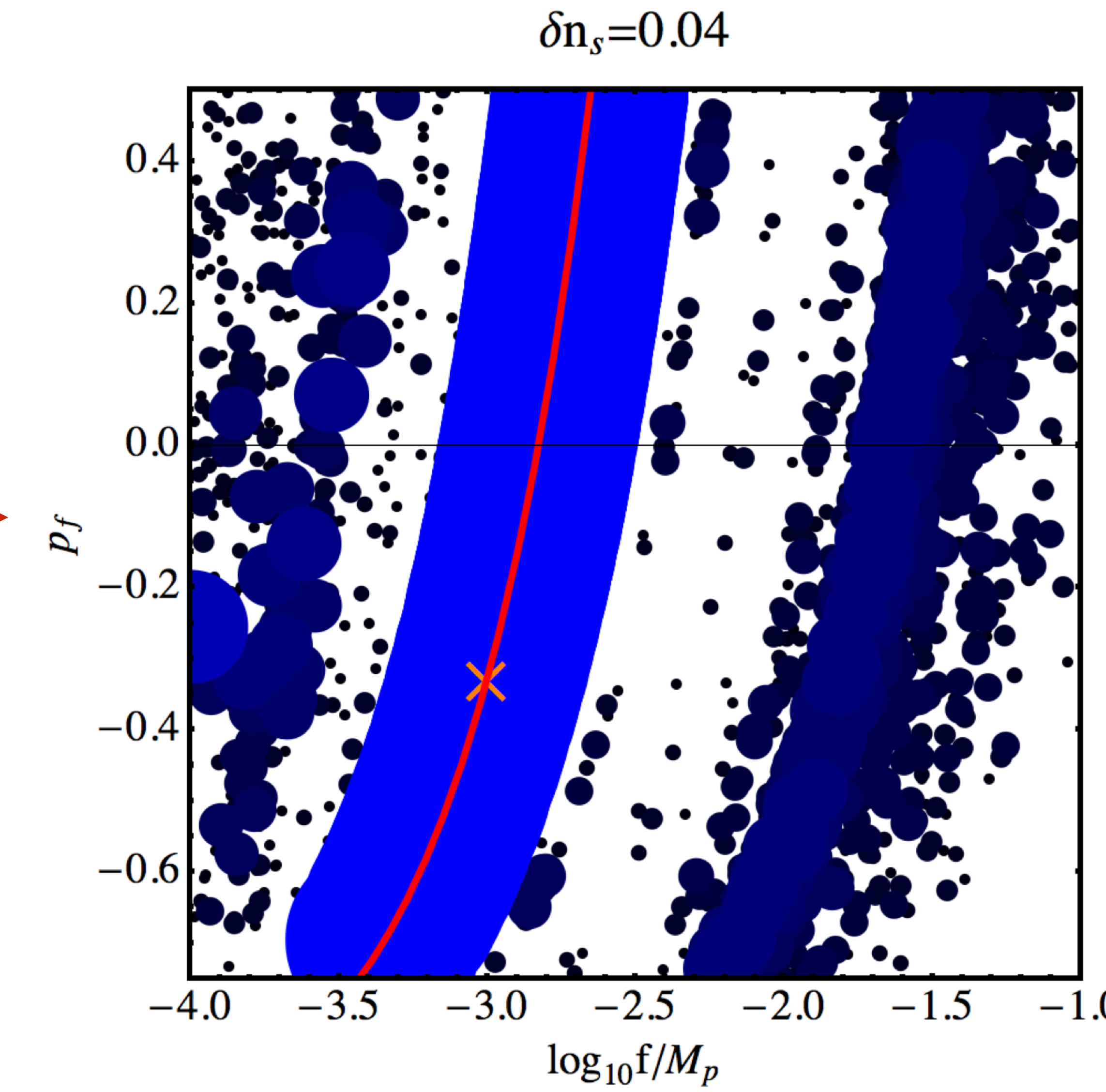
and on ***r*** (!!):

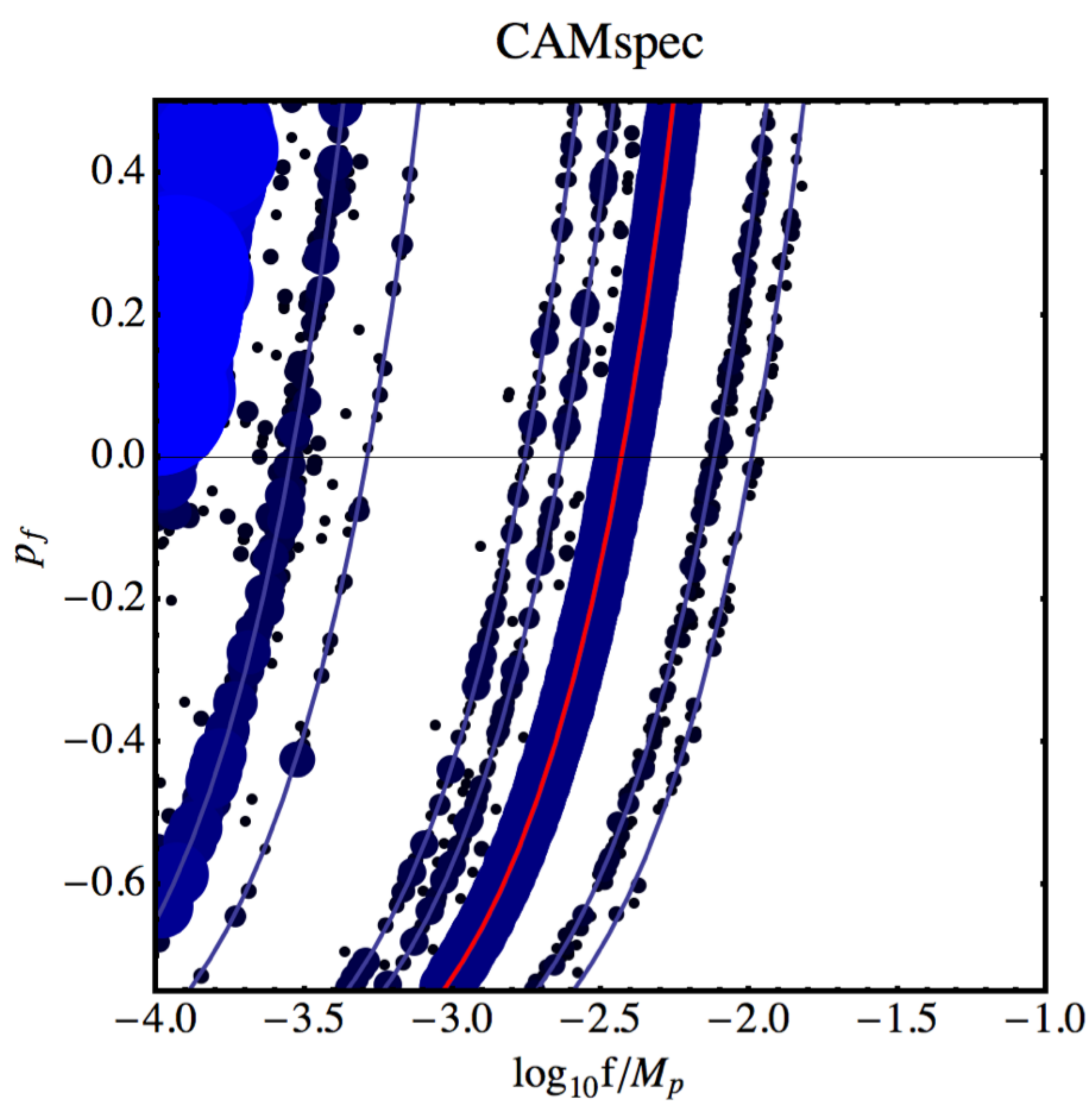
$$r \lesssim 0.04 \quad , \quad f = const.$$

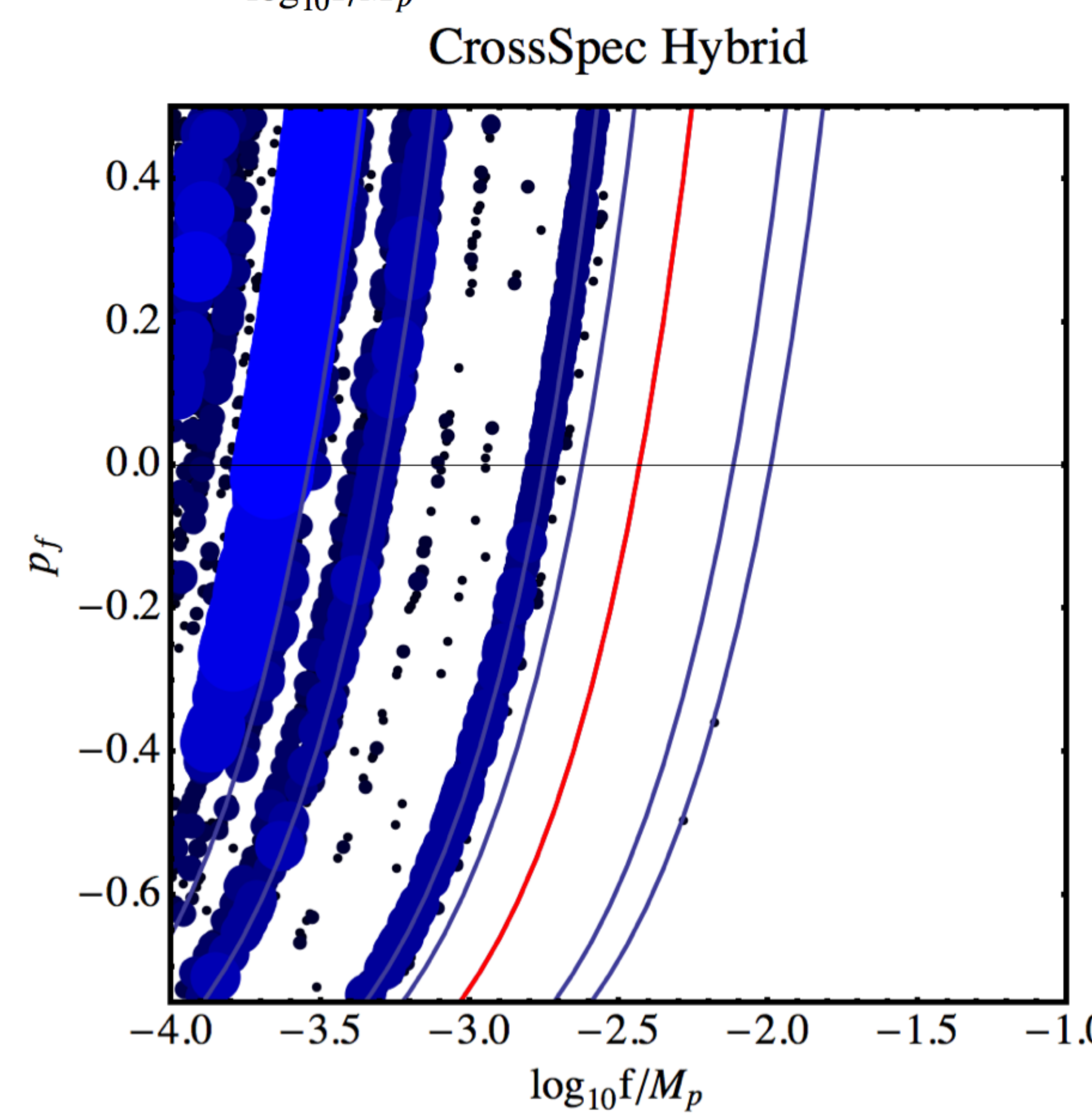
$$\Delta^2_{\mathcal{R}}(k) = \Delta^2_{\mathcal{R}} \left(\frac{k}{k_\star}\right)^{n_s-1}\left(1+\delta n_s \cos\left[\frac{\phi_0}{\tilde{f}}\left(\frac{\phi_k}{\phi_0}\right)^{p_f+1}+\Delta\varphi\right]\right)$$

<u>simulated data</u>









<u>Planck 2013 data</u>

[Flauger, McAllister, Silverstein & AW '14]

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!

⇒ if BICEP2 validated with r ~ 0.1 — need large-field