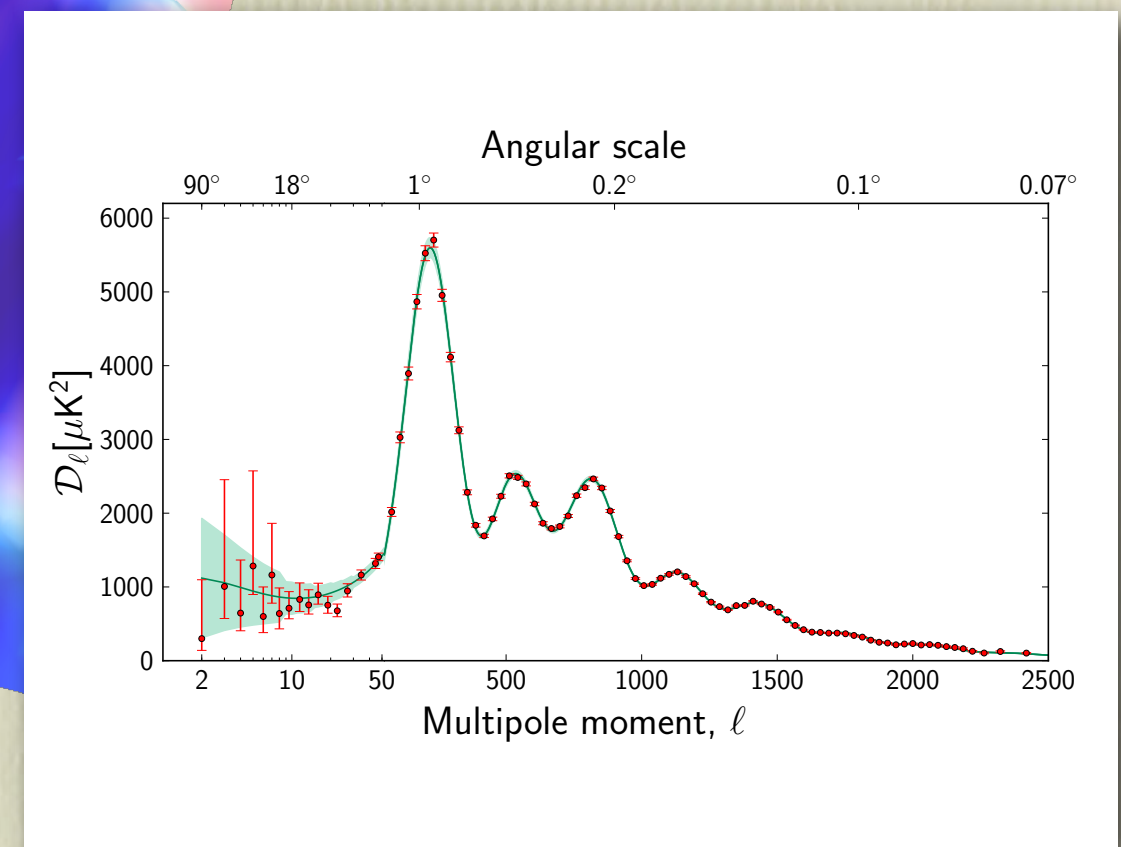
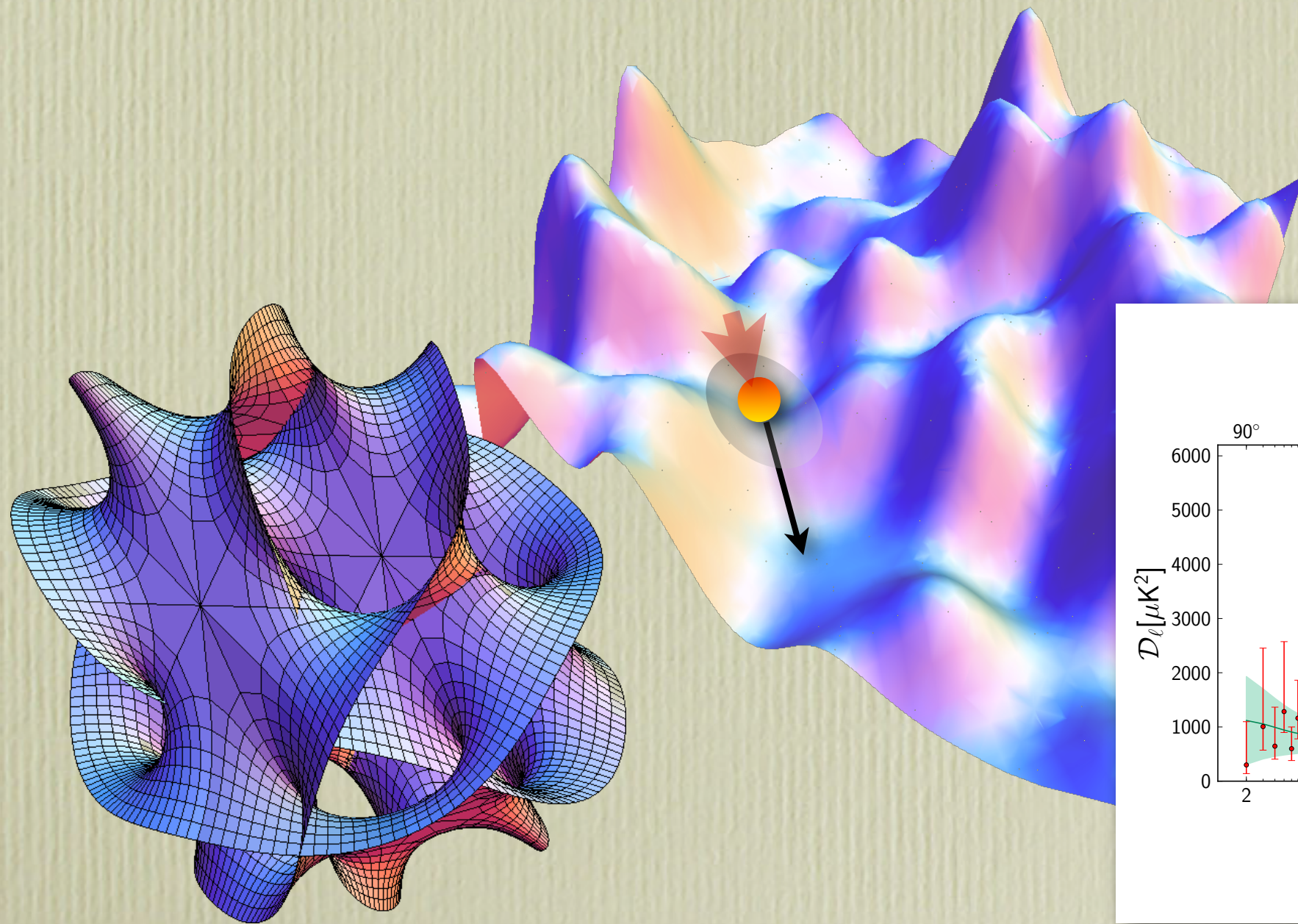


CMB power suppression at low- ℓ from string inflation



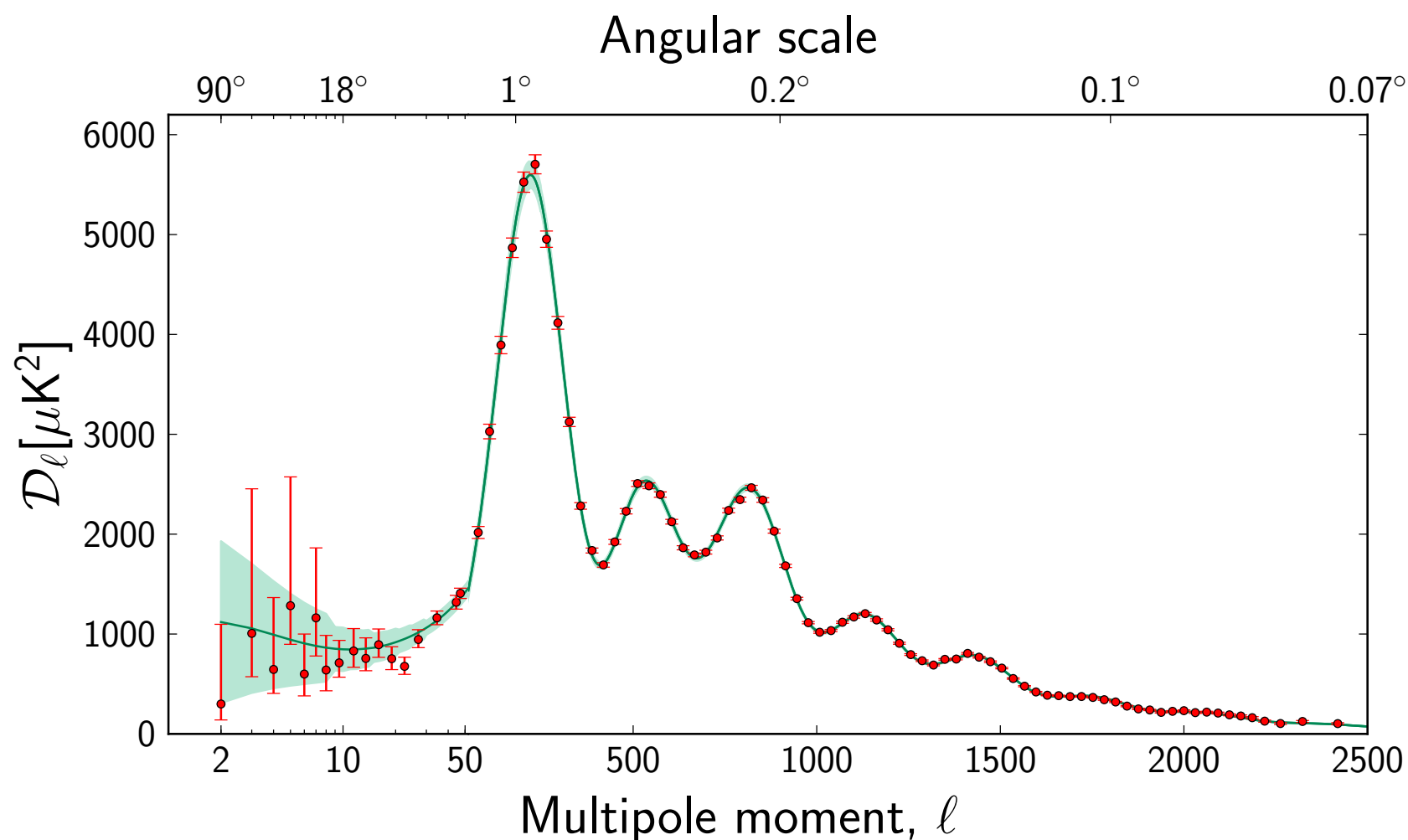
arXiv: 1309.3413 (1309.3412: Cicoli, Downes, Dutta)

Francisco Pedro & AW

DESY Hamburg

✖ March 2013:

PLANCK MAP 7yr + high- ℓ BO



$$n_s = 0.9608 \pm 0.0054 \text{ (68\%)}$$

$$r < 0.11 \text{ (95\%)}$$

$$\Omega_k = -0.0004 \pm 0.00036 \text{ (68\%)}$$

$$f_{NL}^{local} = 2.7 \pm 5.8 \text{ (68\%)}$$

$$f_{NL}^{equil} = -42 \pm 75 \text{ (68\%)}$$

$$f_{NL}^{orth} = -25 \pm 39 \text{ (68\%)}$$

$$N_{eff} = 3.32^{+0.54}_{-0.52} \text{ (95\%)}$$

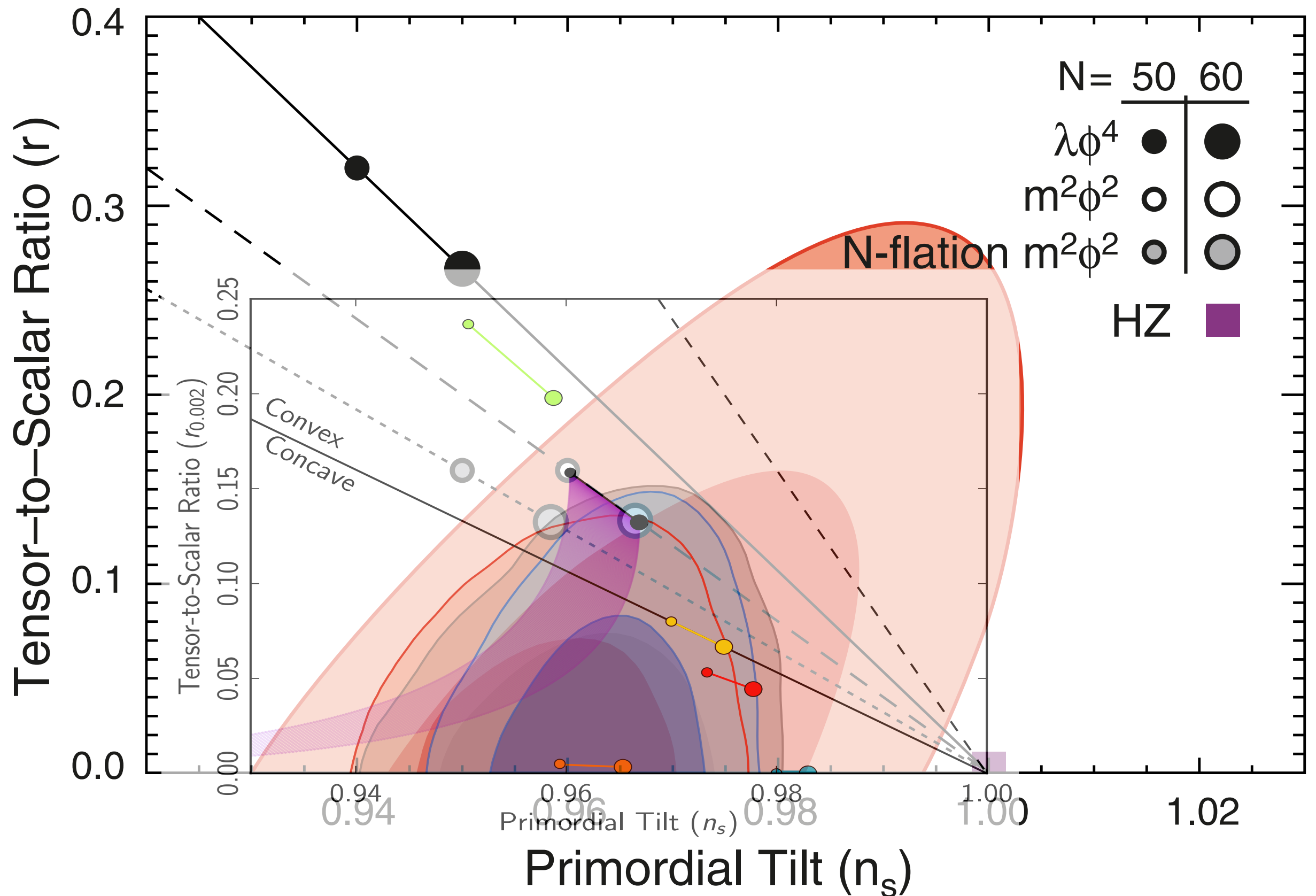
$$\sum m_\nu < 0.28 \text{ eV (95\%)}$$

15.5 months of
temperature data

no B-mode/E-mode polarization yet!

full release of polarization and all 30 months of
temperature data in 2014

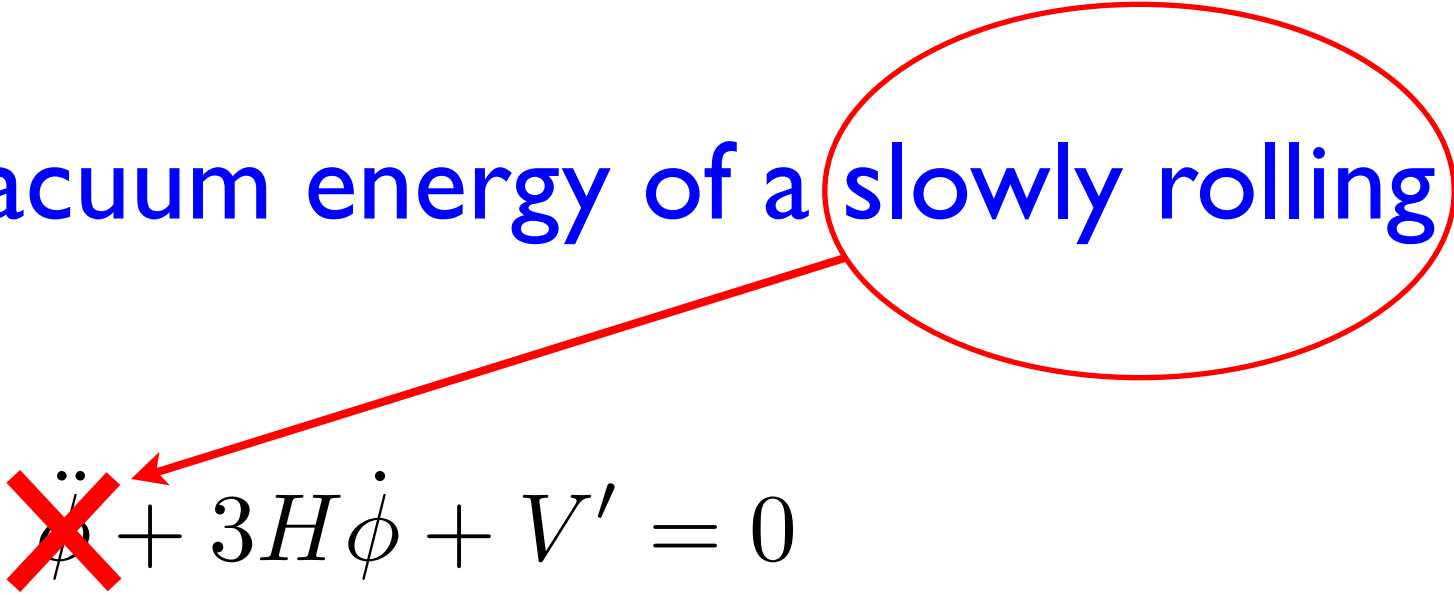
PLANCK+WP+highL+BAO vs WMAP7 + BAO + H0



Inflation ...

- inflation: period quasi-exponential expansion of the very early universe
(solves horizon, flatness problems of hot big bang ...)
- driven by the vacuum energy of a slowly rolling light scalar field:

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



Inflation ...

- **slow-roll** inflation:

scale factor grows exponentially : $a \sim e^{Ht}$ if : $\ddot{\phi} \ll \dot{\phi}$

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

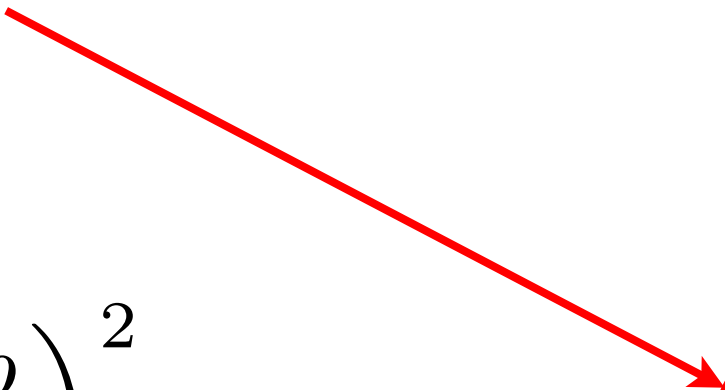
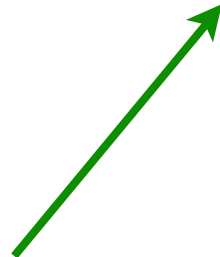
with the Hubble parameter $H^2 = \frac{\dot{a}^2}{a^2} \simeq const. \sim V$

Inflation ...

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


$$\mathcal{P}_S \sim \frac{H^2}{\epsilon} \sim \left(\frac{\delta\rho}{\rho} \right)^2$$
$$\sim k^{n_S-1}$$

and


$$\mathcal{P}_T \sim H^2 \sim V$$


window to GUT scale &
direct measurement of inflation scale

- scalar spectral index:

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

but caveat: inflaton w/ pseudo-scalar
couplings to light vector fields can
source additional B-modes

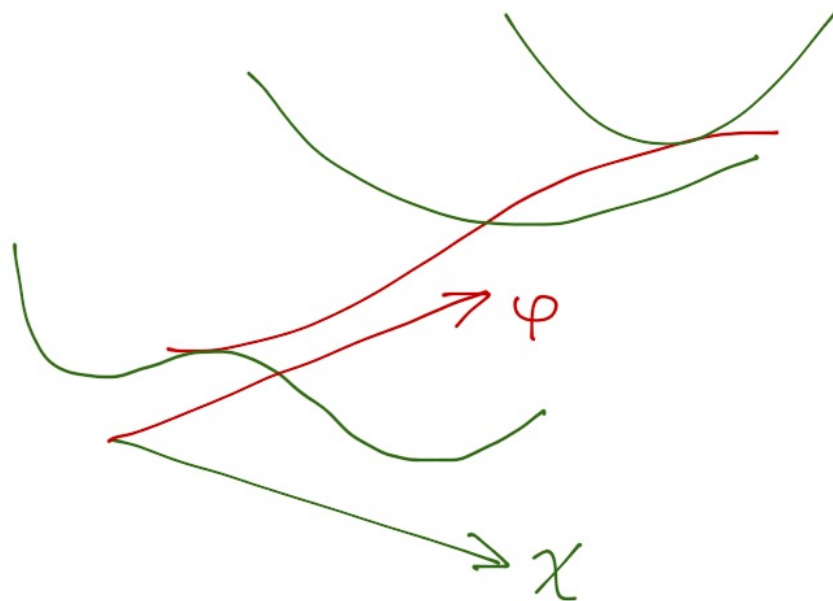
Inflation ...

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

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

- alternative: [Hebecker, Kraus & AW '13] also: [Ben-Dayana & Brustein '09]
[Hotchkiss, Mazumdar & Nadathur '11]

$$V|_{\chi=0} = V_0 \cdot \left(1 - \alpha \cdot \cos\left(\frac{\varphi}{f}\right) \right)$$

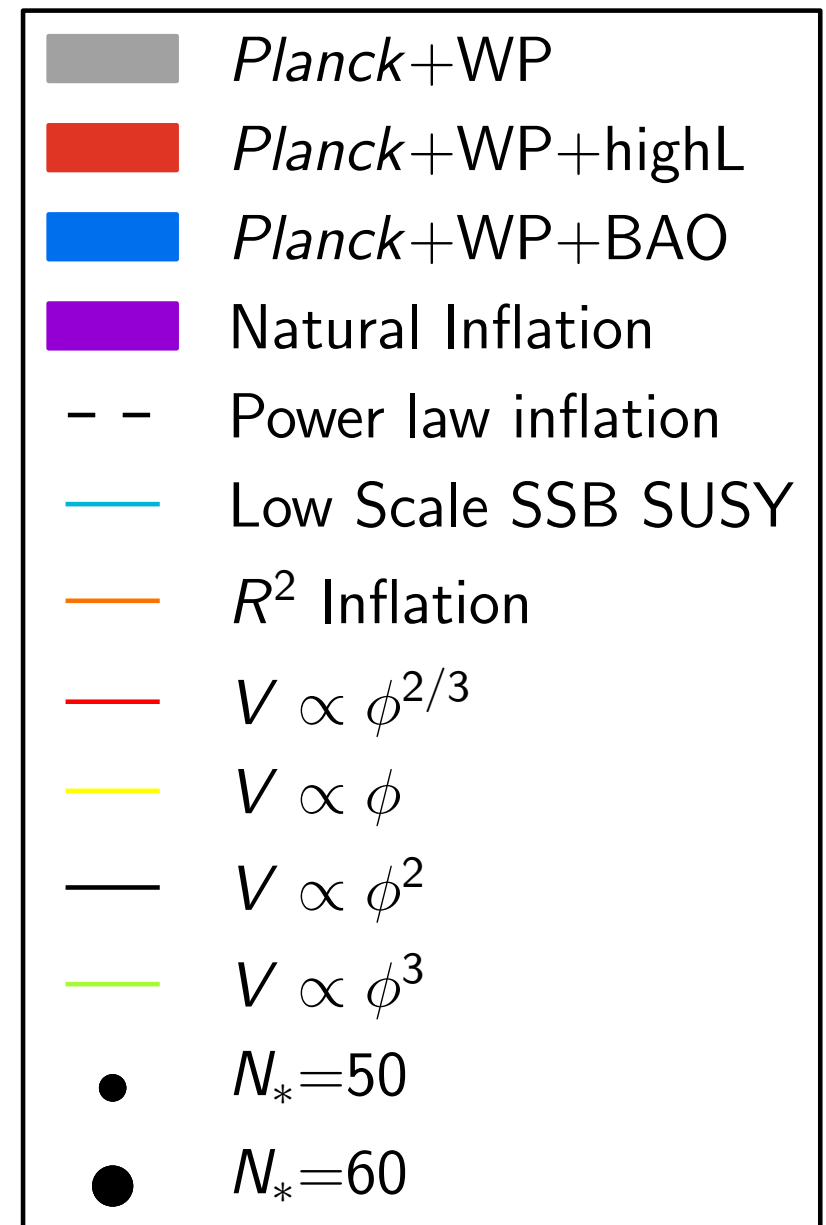
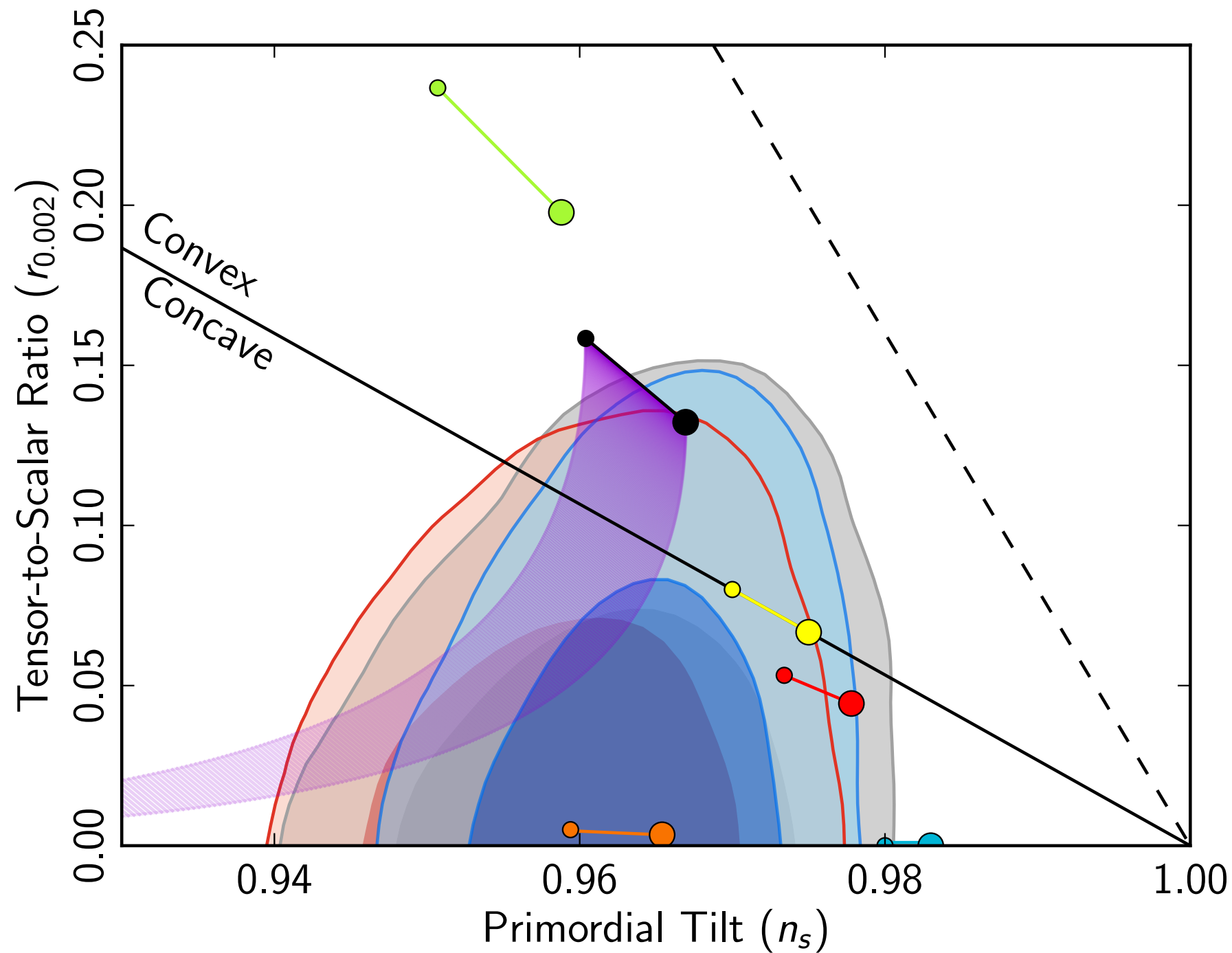


- have ϵ decreasing during inflation ...

- then r can be ~ 10 x larger at 60 e-fold point than for typical small-field model

- automatic in "hybrid natural inflation" from an axion

PLANCK ...



single field models ...

- $R+R^2$ / Higgs inflation / fibre inflation in LVS string scenarios:

$$S = \int d^4x \sqrt{-g} \frac{M_{\text{pl}}^2}{2} \left(R + \frac{R^2}{6M^2} \right) \quad \Rightarrow \quad V(\phi) = \frac{3M^2}{4} \left(1 - e^{-\sqrt{\frac{2}{3}}\phi} \right)^2$$

or fibre inflation : $V(\phi) \sim \left(1 - \frac{4}{3} e^{-\sqrt{\frac{1}{3}}\phi} \right)$

$$n_s = 1 - 8 \frac{4N_e + 9}{(4N_e + 3)^2} \quad , \quad r = \frac{192}{(4N_e + 3)^2}$$

shades of difficulty ...

- observable tensors link levels of difficulty:

$$r \equiv \frac{\mathcal{P}_T}{\mathcal{P}_R} = 16\epsilon \leq 0.003 \left(\frac{50}{N_e} \right)^2 \left(\frac{\Delta\phi}{M_P} \right)^2 \text{ [Lyth '97]}$$

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

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

Small-Field inflation ... needs control of leading **dim-6** operators

⇒ enumeration & fine-tuning reasonable

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

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

needs severe fine-tuning of **all dim-6** operators, or accidental cancellations

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

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

Large-Field inflation ... needs suppression of **all-order** corrections
⇒ symmetry is essential!

shades of difficulty ...

- observable tensors link levels of difficulty:

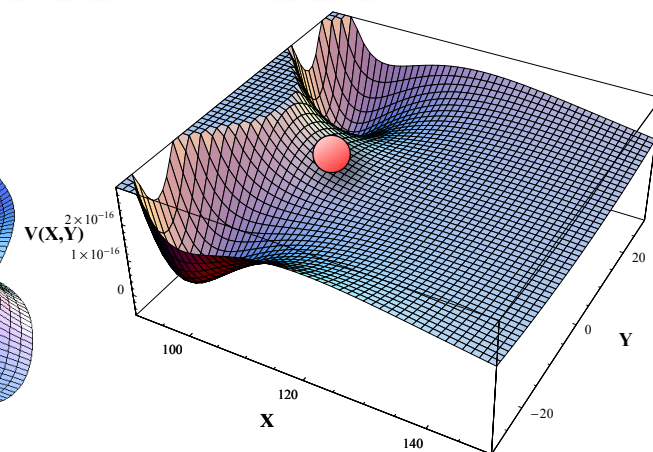
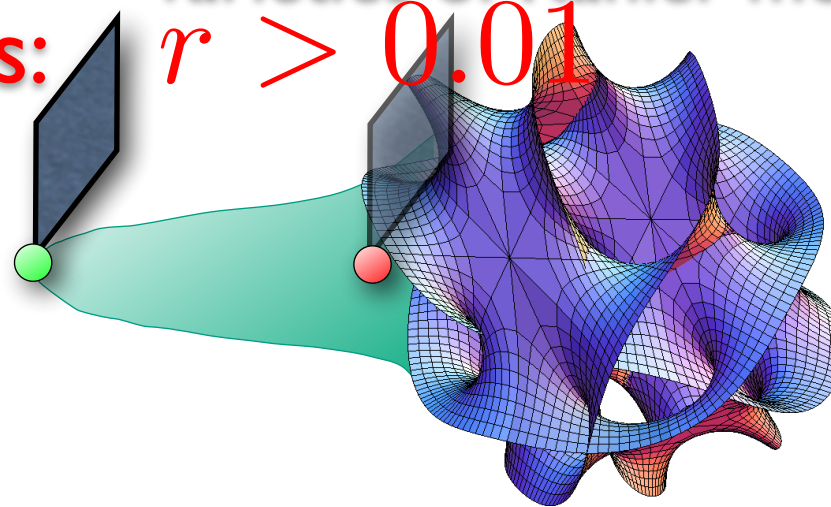
$$r \equiv \frac{\mathcal{P}_T}{\mathcal{P}_R} = 16\epsilon \leq 0.003 \left(\frac{50}{N_e} \right)^2 \left(\frac{\Delta\phi}{M_P} \right)^2 \text{ [Lyth '97]}$$

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

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

warped D-brane inflation & DBI;
varieties of Kahler moduli inflation

$$r > 0.01$$



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

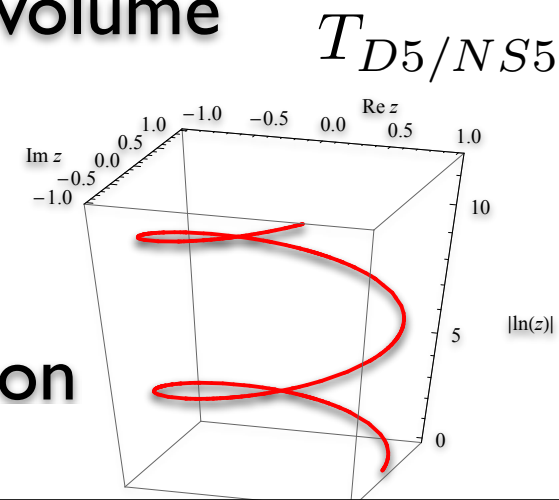
$$\Delta\phi \sim \mathcal{O}(M_P) \Rightarrow$$

fibre inflation in LARGE volume
scenarios (LVS)

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

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

axion monodromy inflation



PLANCK beyond vanilla ... large-scale anomalies !!

- hemispheric asymmetry of mean power and temperature $\sim 3 \sigma$
- quadrupole - octopole alignment
- cold spot $\sim 3 \sigma$
- fit Planck data from high-precision data at $l > 50$, then predict from that power at $l < 30$:
too low power at low- l , 10% deficit, $\sim 2.5 \sigma$

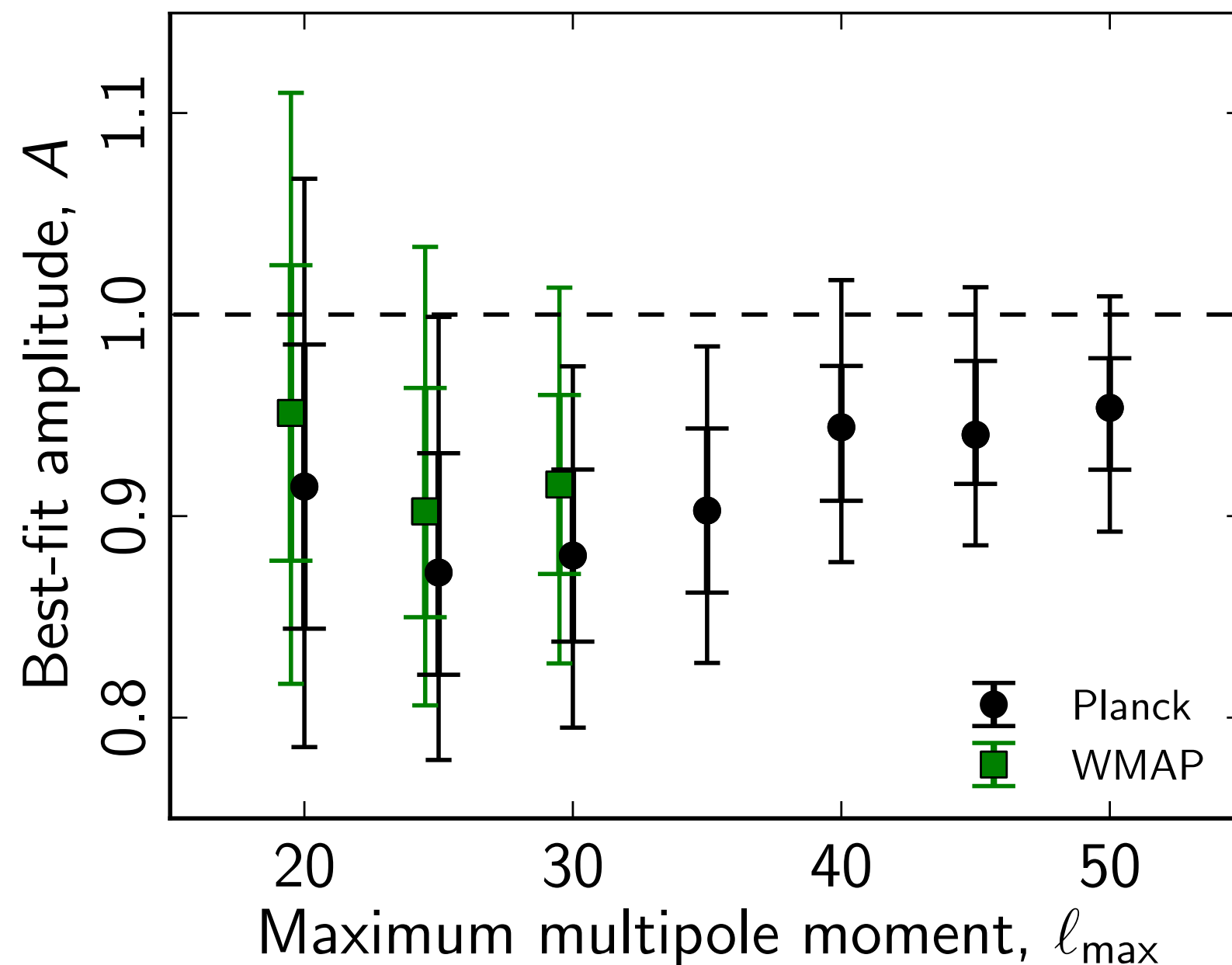
theory task: explain!

PLANCK anomaly - a lack of power at large scales !!

[PLANCK Coll. XV '13]

$$q = \frac{C_{\ell}^{\ell=2\dots 50}}{C_{\ell}^{\ell>50}}$$

$$q = 0.9 \quad \text{at} \quad 2 - 2.5\sigma$$



- significance of the power suppression -- now:

$$\frac{\sigma_\ell^2}{C_\ell^2} = \frac{2}{N_\ell}$$

$$N_\ell^{(\text{CMB})} = 2\ell + 1$$

$\Rightarrow$ significance of suppression measurement:

$2 \dots 3 \sigma$ CMB + a bit of LSS

- the future:

$$N_\ell^{(\text{CMB}+\text{LSS}+21\text{cm})} = 2\ell + 1 + 4\pi \frac{\ell^2}{\ell_z^3}$$

$\Rightarrow$ significance of suppression measurement:

$3 \dots 4 \sigma$ CMB + LSS from EUCLID

$5 \dots 6 \sigma$ CMB + LSS from EUCLID + 21cm data

an idea: rapid steeping potential can suppress power ...

[Contaldi, Peloso, Kofman, Linde '03]

- rapidly growing V' such that ϵ grows much faster than V in a narrow interval $\Delta\phi$

$$\text{if} \quad V \rightarrow \alpha V \quad , \quad \epsilon \rightarrow \beta \epsilon \quad , \quad \beta > \alpha \simeq 1$$

$$\text{while} \quad \phi \rightarrow \phi + \Delta\phi$$

$$\text{then} \quad \Delta_{\mathcal{R}}^2 \sim \frac{H^4}{\dot{\phi}^2} \sim \frac{V}{\epsilon} \rightarrow \frac{1}{\beta} \Delta_{\mathcal{R}}^2 < \Delta_{\mathcal{R}}^2$$

- our claim: there is a model of string inflation - fibre inflation - which can do this!

[Pedro, AW '13; Cicoli, Downs, Dutta '13]

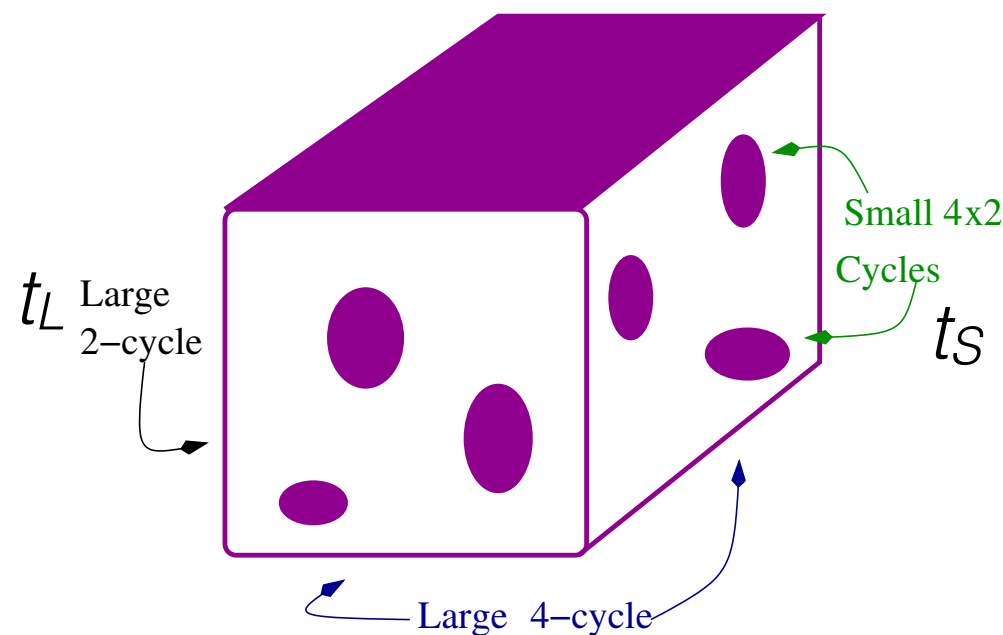
also: [Bousso, Harlow, Senatore '13]

fibre inflation in type IIB string theory ...

[Cicoli, Burgess & Quevedo '08]

- **setup**

$$K = -2 \log \left(\mathcal{V} + \frac{\hat{\xi}}{2} \right) \quad \text{and} \quad W = W_0 + A e^{-a\tau_3}$$



**3-form flux
superpotential**

**ED3-brane
instanton**

$$\mathcal{V} = \lambda_1 t_1 t_2^2 + \lambda_2 t_3^3 = \alpha (\sqrt{\tau_1 \tau_2} - \gamma \tau_3^{3/2})$$

t_i denote 2-cycle volumes, $\tau_i = \partial \mathcal{V} / \partial t_i$ 4-cycle volumes

$$\alpha = 1/(2\sqrt{\lambda_1}) \quad \text{and} \quad \gamma = \frac{2}{3} \sqrt{\lambda_1 / (3\lambda_2)}$$

fibre inflation in type IIB string theory ...

[Cicoli, Burgess & Quevedo '08]

- $\mathcal{N} = 1$ eff. supergravity - F-term scalar potential

$$V_{LVS} = \frac{8\sqrt{\tau_3}A^2a^2e^{-2a\tau_3}}{\mathcal{V}} - \frac{4W_0\tau_3Aae^{-a\tau_3}}{\mathcal{V}^2} + \frac{3\xi}{4g_s^{3/2}\mathcal{V}^3}$$

$$\langle \mathcal{V} \rangle \sim e^{1/g_s} \quad \text{and} \quad \langle \tau_3 \rangle \sim \frac{1}{g_s}$$

SUSY breaking LVS
(large volume) minimum

- string loop corrections from KK- & winding modes

$$\delta K_{g_s}^{KK} = \sum_{l=1}^{h(1,1)} \frac{C_i^{KK} a_{il} t^l}{\text{Re}(S) \mathcal{V}} \quad \delta K_{g_s}^W = \sum_{l=1}^{h(1,1)} \frac{C_i^W}{a_{il} t^l \mathcal{V}}$$

- correct moduli potential

$$\delta V_{g_s} = \left(\frac{(g_s C_1^{KK})^2}{\tau_1^2} - 2 \frac{C_{12}^W}{\mathcal{V} \sqrt{\tau_1}} + 2 \frac{(\alpha g_s C_2^{KK})^2 \tau_1}{\mathcal{V}^2} \right) \frac{W_0^2}{\mathcal{V}^2}$$

- stabilizes fibre modulus τ_i

$$\frac{1}{\langle \tau_1 \rangle^{3/2}} = \frac{4\alpha C_{12}^W}{(g_s C_1^{KK})^2 \mathcal{V}} \left(1 + \text{sign}(C_{12}^W) \sqrt{1 + 4g_s^4 \left(\frac{C_1^{KK} C_2^{KK}}{C_{12}^W} \right)^2} \right)$$

- fibre modulus kinetic term - canonically normalize

$$\mathcal{L}_{\text{kin}} = \frac{3}{8\tau_1^2} \partial_\mu \tau_1 \partial^\mu \tau_1$$

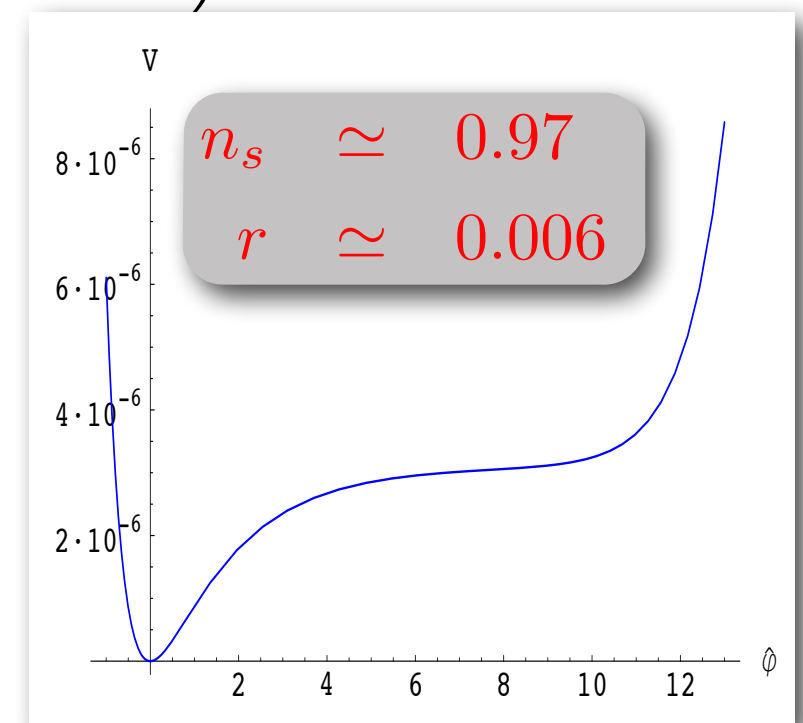
$$\phi \equiv \frac{\sqrt{3}}{2} \ln \tau_1 \quad \text{or} \quad \tau_1 \equiv e^{\kappa\phi} \quad \text{with} \quad \kappa = \frac{2}{\sqrt{3}}$$

- fibre modulus scalar potential

$$\delta V_{gs} = \frac{W_0^2}{\mathcal{V}^2} \left((g_s C_1^{KK})^2 e^{-2\kappa\phi} - 2 \frac{C_{12}^W}{\mathcal{V}} e^{-\frac{1}{2}\kappa\phi} + 2 \frac{(\alpha g_s C_2^{KK})^2}{\mathcal{V}^2} e^{\kappa\phi} \right)$$

**slow-roll flat & asymmetric plateau
- and sudden steep wall !!**

$$V = V_0 \left(1 - C_{1/2} e^{-\kappa\phi/2} + C_2 e^{-2\kappa\phi} + C_1 e^{\kappa\phi} \right)$$



- tune a Minkowski minimum for τ_I at zero VEV:

$$C_{1/2} = \frac{4}{3} \quad , \quad C_2 = \frac{1}{3}$$

$$C_1 \sim g_S^\# , \# > 0 \quad \text{with} \quad C_1 \lesssim 10^{-5} \quad \text{tunes plateau}$$

- there's always an inflection point on the plateau:

$$e^{-\kappa\phi_{ip}/2} = 3C_1 e^{\kappa\phi_{ip}}$$

at $\phi > \phi_{ip}$ we have ϵ monotonically increasing

- best chance to get rapid increase in ϵ at large scales:

$$\phi_{60} = \phi_{ip}$$

- above the inflection point we have:

$$V \simeq V_{ip} (1 + C_1 e^{\kappa\phi}) \quad \epsilon = \frac{\kappa^2 C_1^2}{2} e^{2\kappa\phi} = \frac{3}{8} \eta^2 \quad \text{for } \phi > \phi_{ip}$$

- field range of steepening:

find the point $\phi_\delta > \phi_{ip}$ where $\epsilon_\delta > \epsilon_{ip}$

has a value such that $\Delta_{\mathcal{R}}^2(\phi_\delta) = \frac{\delta}{100} \Delta_{\mathcal{R}}^2(\phi_{ip})$

$$\Rightarrow e^{-\kappa(\phi_\delta - \phi_{ip})} = \sqrt{\frac{\epsilon_{ip}}{\epsilon_\delta}} = \sqrt{\frac{\Delta_{\mathcal{R}}^2(\phi_\delta)}{\Delta_{\mathcal{R}}^2(\phi_{ip})}} = \frac{\sqrt{\delta}}{10}$$

- for moderate power suppression ($\delta = 10 \dots 90$) implies:

$$C_1 e^{\kappa(\phi_\delta - \phi_{ip})} \ll 1$$

- V essentially unchanged while ϵ increasing ...

- compute e-folds for field range of given power suppression:

$$\Delta N_e^{(\delta)} = \int_{\phi_{ip}}^{\phi_\delta} \frac{d\phi}{\sqrt{2\epsilon}} = \frac{1}{\kappa C_1} \int_{\phi_{ip}}^{\phi_\delta} d\phi e^{-\kappa\phi} = \frac{1}{\kappa \sqrt{2\epsilon_{ip}}} \left(1 - \frac{\sqrt{\delta}}{10} \right)$$

$$\Delta N_e^{(50\%)} \gtrsim 3 \sqrt{\frac{0.06}{1 - n_s}}$$

while

$$\Delta N_e(\ell = 2 \dots 30) = \ln \frac{\ell = 30}{\ell = 2} < 3$$

- positive exponential from loop term not steep enough but close ...

- Assume modified string loop corrections:

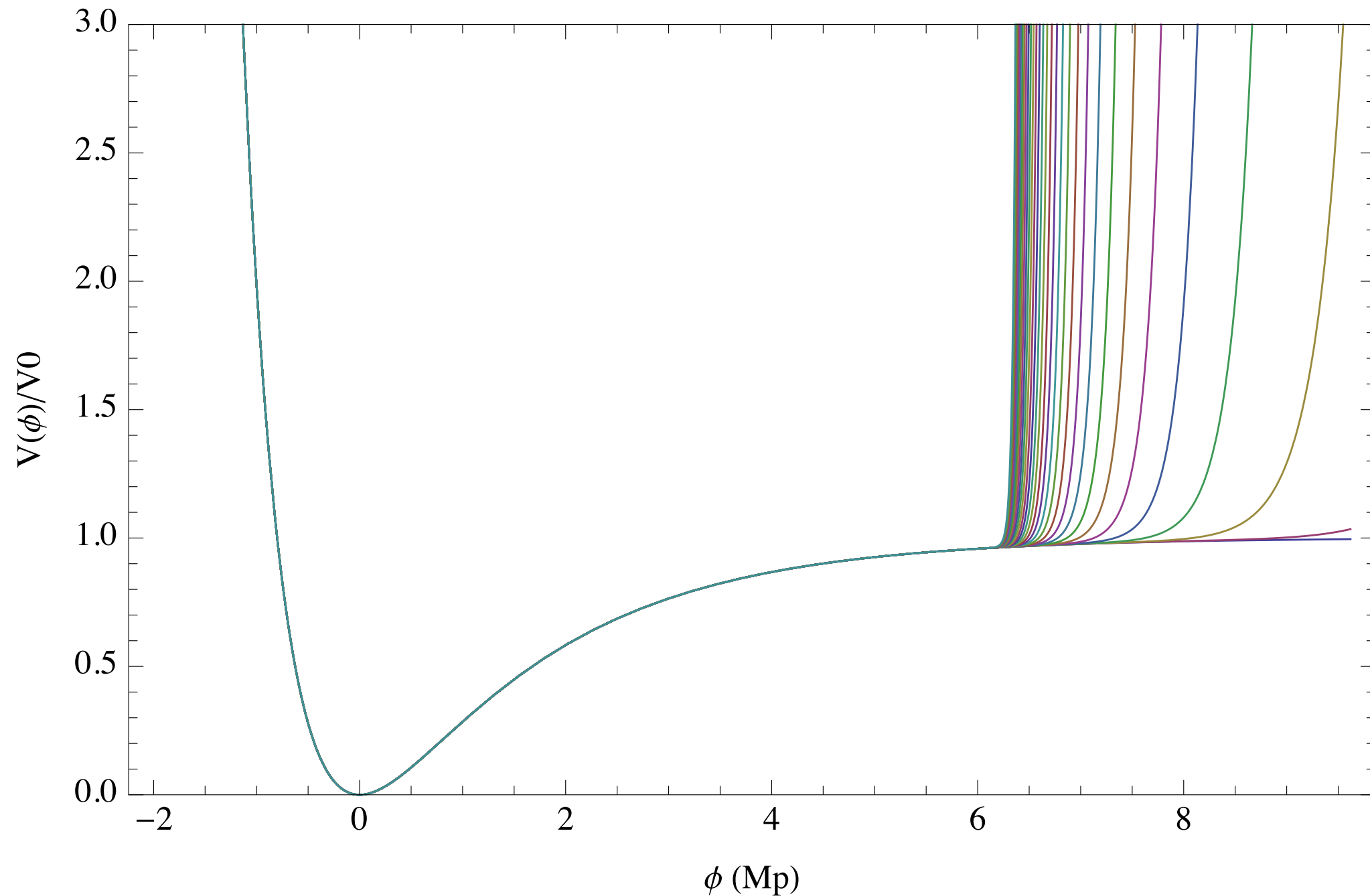
replace $\delta V \sim \frac{\tau_1}{\mathcal{V}^4}$

with $\delta V \sim \frac{\tau_1^{\tilde{\kappa}/\kappa}}{\mathcal{V}^p}$ with $p > 4$, $\frac{\tilde{\kappa}}{\kappa} \gtrsim 3$

- Modifies scalar potential:

$$V = V_0 \left(1 - C_{1/2} e^{-\kappa\phi/2} - C_2 e^{-2\kappa\phi} + \tilde{C}_1 e^{\tilde{\kappa}\phi} \right)$$

$$\Rightarrow \Delta N_e^{(\delta)} = \int_{\phi_{ip}}^{\phi_\delta} \frac{d\phi}{\sqrt{2\epsilon}} = \frac{1}{\tilde{\kappa}\tilde{C}_1} \int_{\phi_{ip}}^{\phi_\delta} d\phi e^{-\tilde{\kappa}\phi} = \frac{1}{\tilde{\kappa}\sqrt{2\epsilon_{ip}}} \left(1 - \frac{\sqrt{\delta}}{10} \right)$$



- numerical check - solve e.o.m. for scalar field:

$$\phi'' + 3 \left(1 - \frac{1}{6} \phi'^2 \right) \left(\phi' + \frac{1}{V} \frac{\partial V}{\partial \phi} \right) = 0 \quad \text{with} \quad ()' \equiv \frac{d}{dN_e}()$$

- **compute** $\Delta_{\mathcal{R}}^2 = \frac{1}{4\pi^2} \frac{H^4}{\dot{\phi}^2}$ **on the solution**

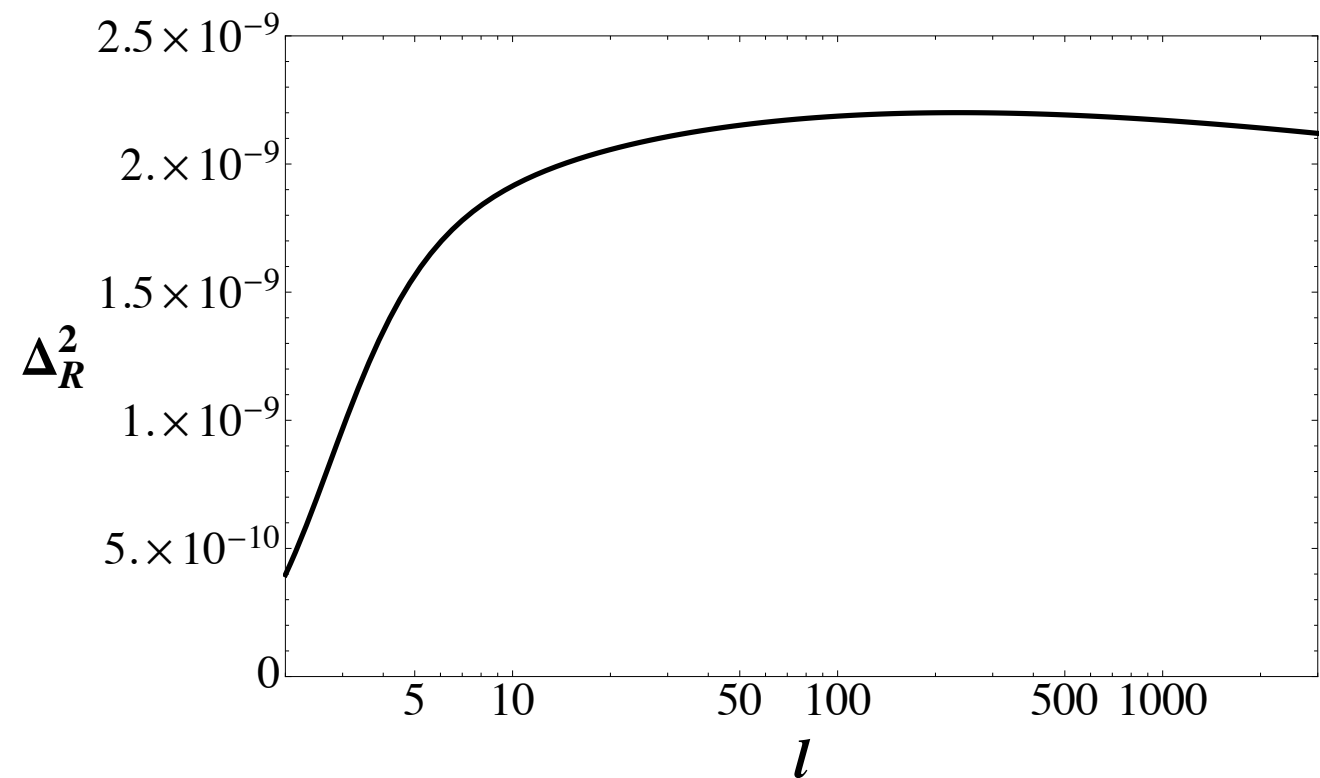
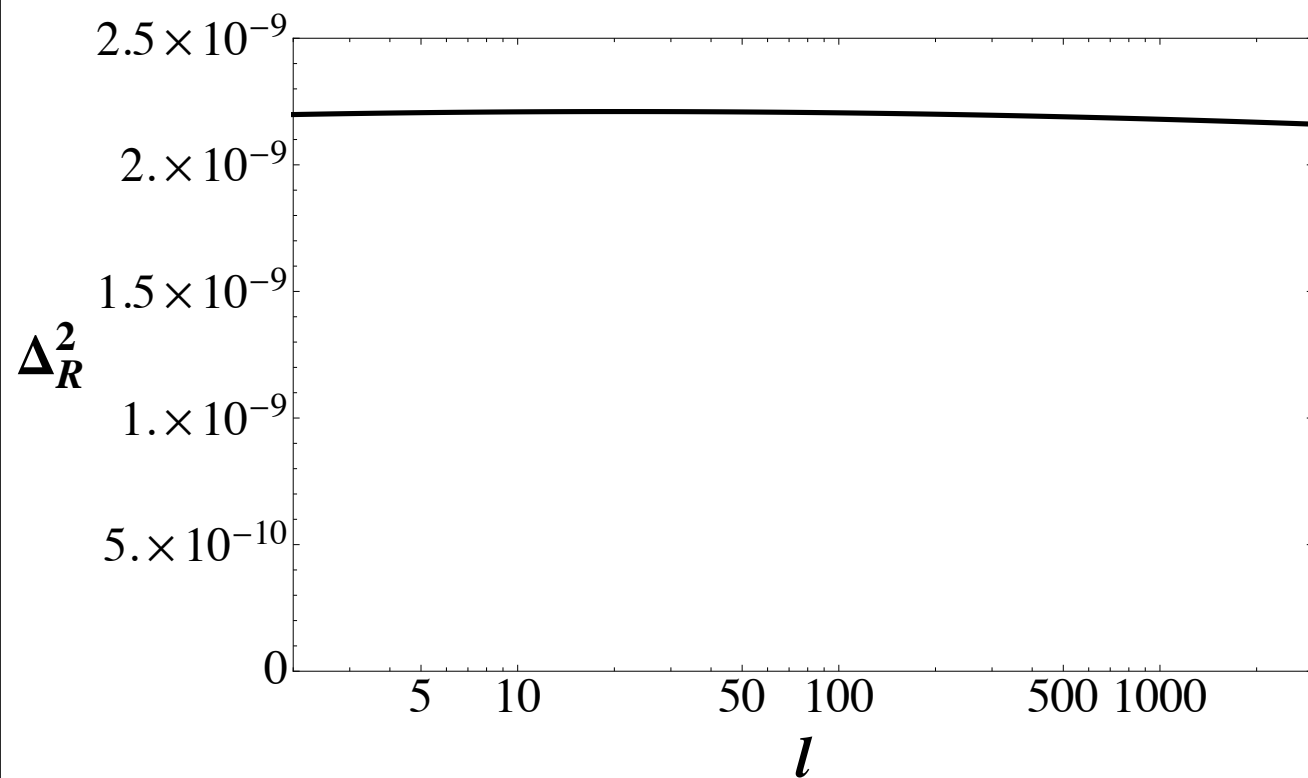


Figure 4: Power spectrum $\Delta_{\mathcal{R}}^2$ computed on the numerical solution $\phi(N_e)$. Left: The original fibre inflation setup with $\tilde{\kappa} = \kappa = 2/\sqrt{3}$ and $C_1 = 10^{-5}$. Right: The modified setup with $\tilde{\kappa} = 10\kappa$ and $\tilde{C}_1 = 7 \times 10^{-33}$. The extra steepening leads to a clear suppression of curvature perturbation power at low ℓ .

open questions ...

- fibre inflation in type IIB string theory provides an asymmetric inflationary plateau with steep wall, which can explain the low- l power suppression hinted at by PLANCK
- here: conservative analysis, power suppression arises entirely within slow-roll -- if using fast-roll further up the steep wall, can use less steepness for the loop correction [Cicoli, Downs, Dutta '13]
- how rare in the string model landscape? / change of the quantum vacuum between steep wall & plateau? / inflaton quanta or particle production? ... work in progress ... [Cicoli, Downs, Dutta, Pedro, AW]

$$\mathcal{L}_{\text{kin}} = K_{i\bar{j}} \partial_\mu T_i \partial^\mu \bar{T}_j = \frac{1}{4} \frac{\partial^2 K}{\partial \tau_i \partial \tau_j} (\partial_\mu \tau_i \partial^\mu \tau_j + \partial_\mu b_i \partial^\mu b_j)$$

$$K_{i\bar{j}}^0 = \begin{pmatrix} \frac{1}{4\tau_1^2} & \frac{\tau_3^{3/2}}{4\tau_1^{3/2}\tau_2^2} & -\frac{3\sqrt{\tau_3}}{8\tau_1^{3/2}\tau_2} \\ \frac{\tau_3^{3/2}}{4\tau_1^{3/2}\tau_2^2} & \frac{1}{2\tau_2^2} & -\frac{3\sqrt{\tau_3}}{4\sqrt{\tau_1}\tau_2^2} \\ -\frac{3\sqrt{\tau_3}}{8\tau_1^{3/2}\tau_2} & -\frac{3\sqrt{\tau_3}}{4\sqrt{\tau_1}\tau_2^2} & \frac{3}{8\sqrt{\tau_1}\tau_2\sqrt{\tau_3}} \end{pmatrix}$$

$$\mathcal{L}_{\text{kin}} = \frac{3}{8\tau_1^2} \partial_\mu \tau_1 \partial^\mu \tau_1 \qquad \phi \equiv \frac{\sqrt{3}}{2} \ln \tau_1 \qquad \text{or} \qquad \tau_1 \equiv e^{\kappa\phi} \qquad \text{with} \qquad \kappa = \frac{2}{\sqrt{3}}$$

$$\delta V_{gs} = \frac{W_0^2}{\mathcal{V}^2} \left((g_s C_1^{KK})^2 e^{-2\kappa\phi} - 2 \frac{C_{12}^W}{\mathcal{V}} e^{-\frac{1}{2}\kappa\phi} + 2 \frac{(\alpha g_s C_2^{KK})^2}{\mathcal{V}^2} e^{\kappa\phi} \right)$$

$$V = V_0 \left(1 - C_{1/2} e^{-\kappa\phi/2} + C_2 e^{-2\kappa\phi} + C_1 e^{\kappa\phi} \right)$$

[Contaldi, Peloso, Kofman, Linde '03]

