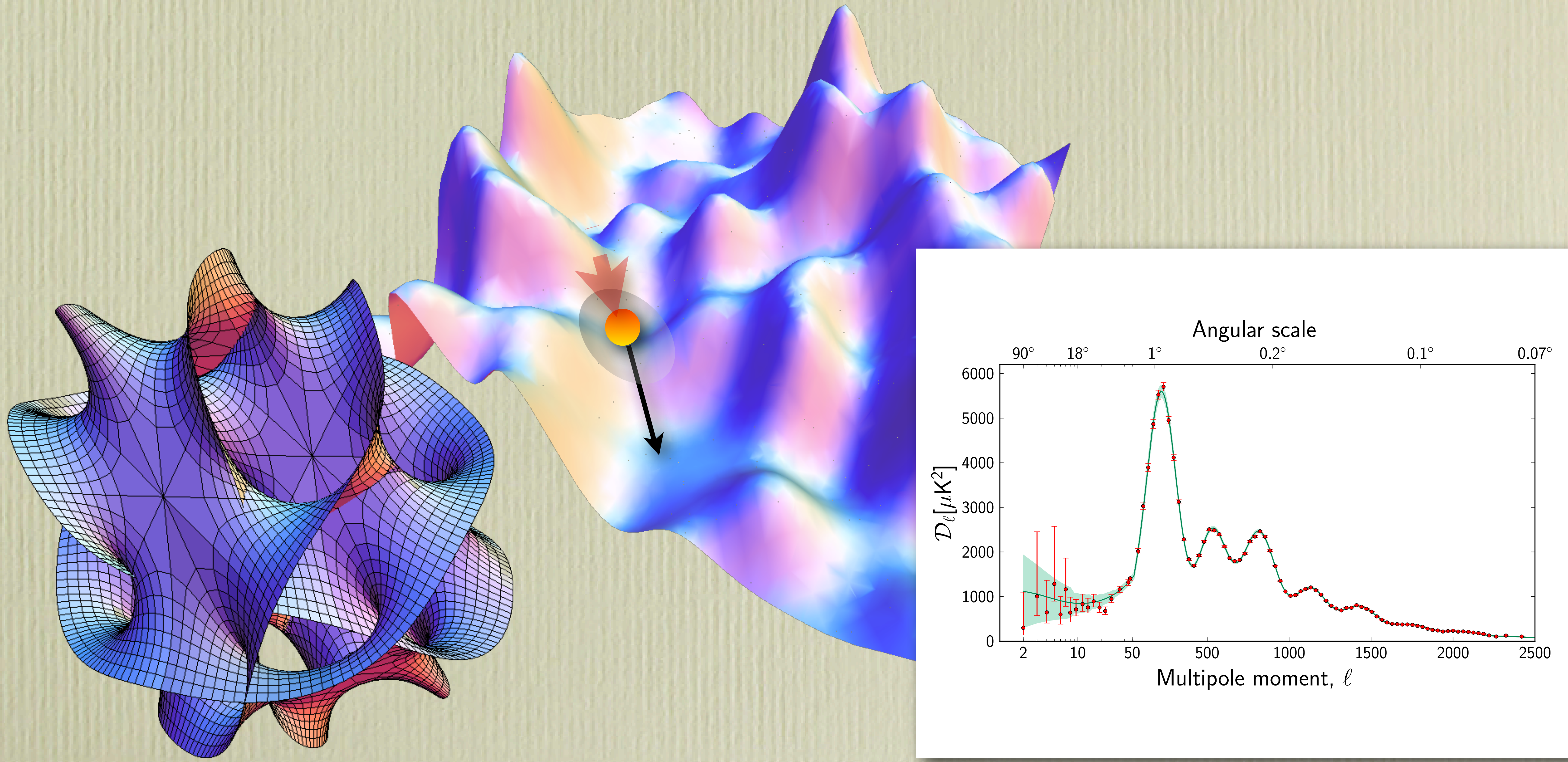
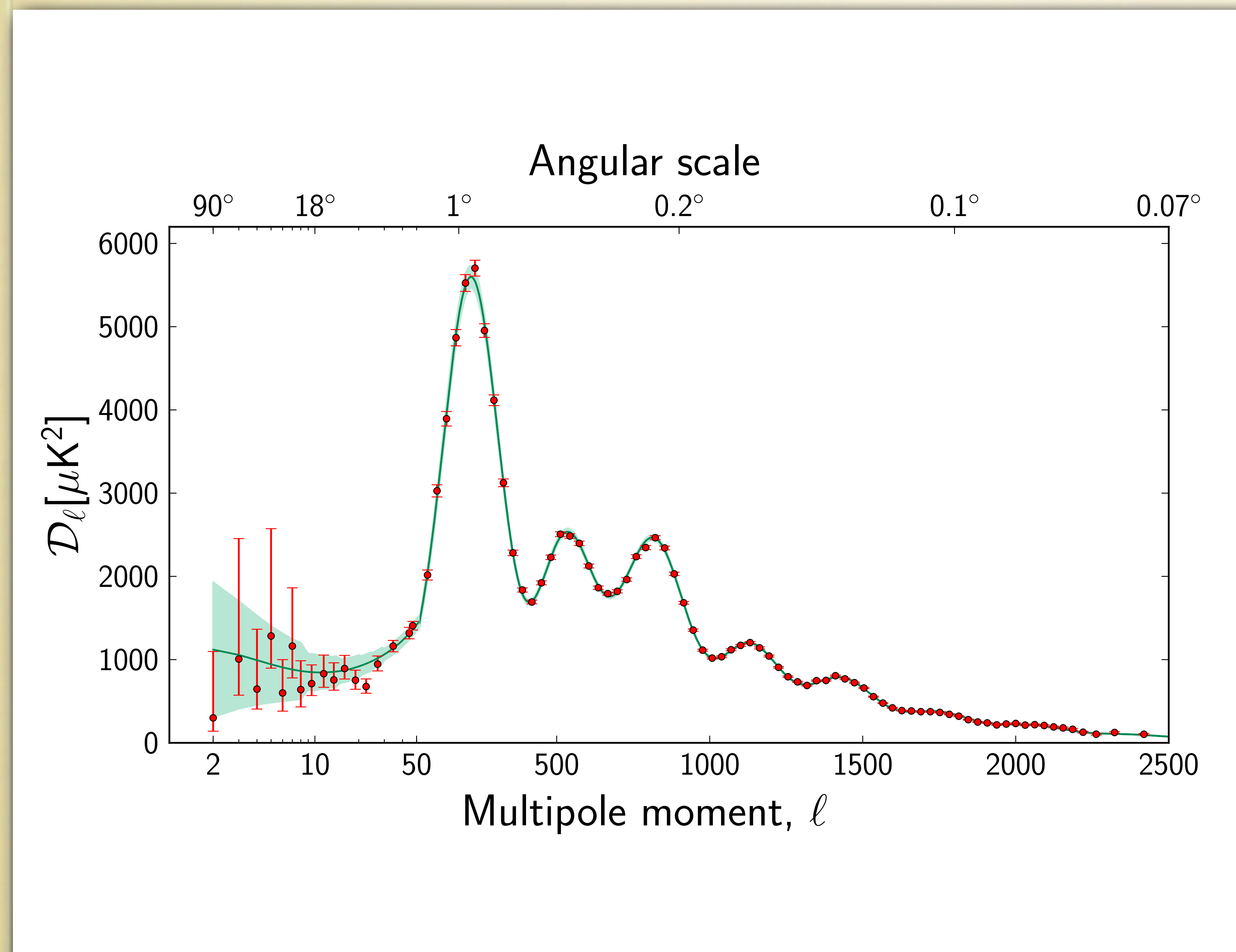
CMB power suppression at low-l from string inflation



Michele Cicoli, Sean Downes, Bhaskar Dutta, Francisco Pedro, AW

arXiv: 1309.3412 , 1309.3413, and work in progress

March 2013: PLANCK



$$n_s = 0.9608 \pm 0.0054 \ (68\%)$$

$$r < 0.11 \ (95\%)$$

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

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

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

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

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

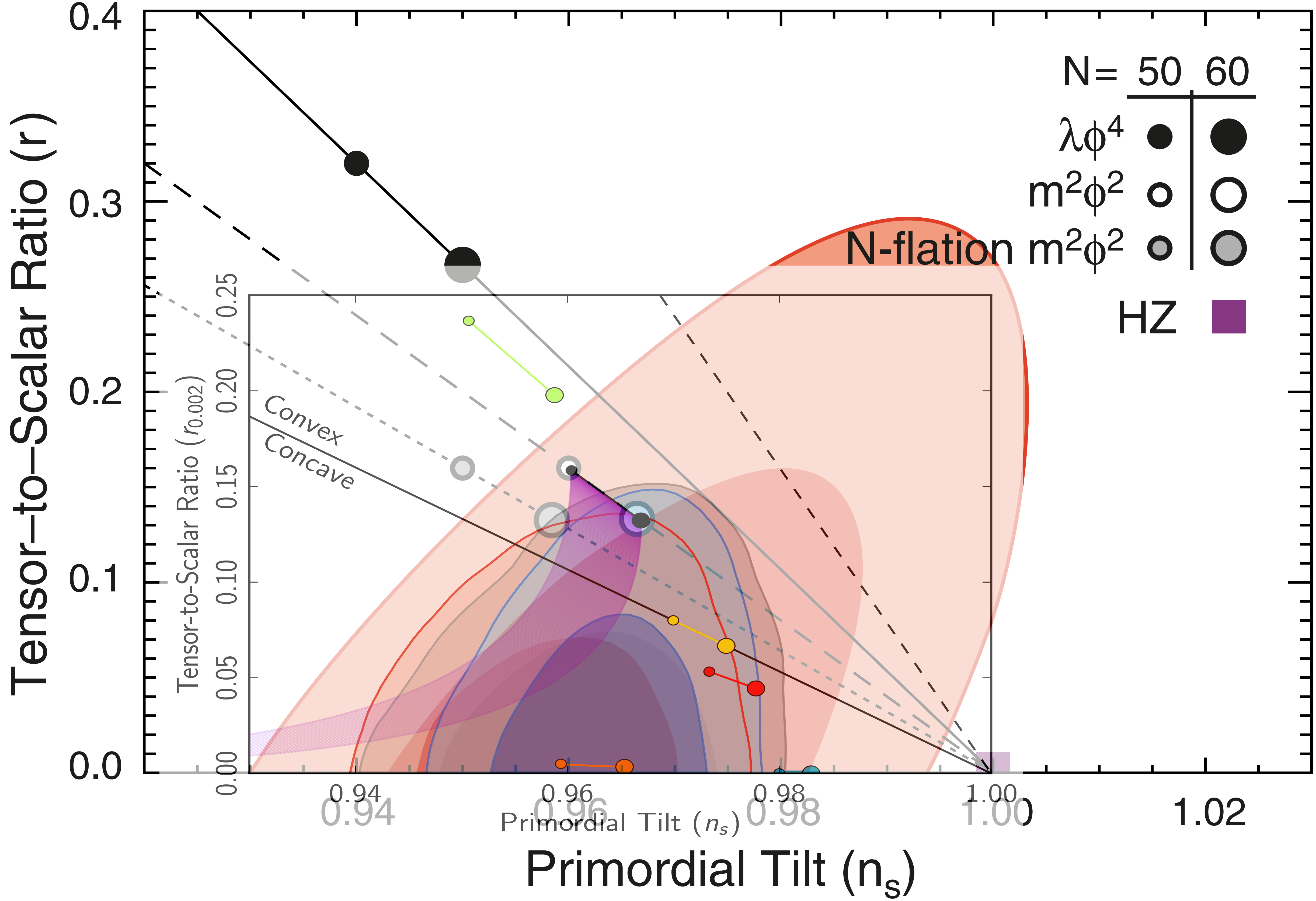
$$\sum m_\nu < 0.28 \, \mathrm{eV} \ (95\%)$$

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

Inflation ...

- slow-roll inflation:

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

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

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

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:

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

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

[Barnaby, Namba & Peloso '11; Senatore, Silverstein & Zaldarriaga '11]
[Barnaby, Moxon, Namba, Peloso, Shiu & Zhou '12]

large-field vs small-field inflation ...

- large-field inflation needs shift symmetry to control UV corrections:

$$\mathcal{O}_6 \sim V(\phi)\frac{\phi^2}{M_{\rm P}^2} \quad \Rightarrow \quad m_\phi^2 \sim H^2 \;,\; \eta \sim 1$$

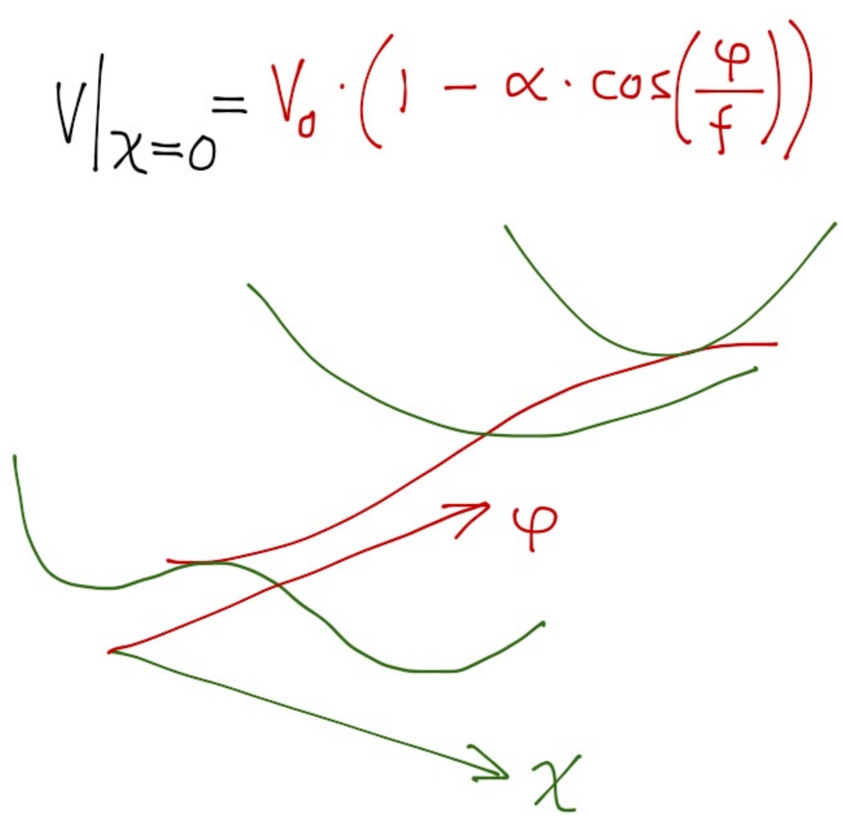
- small-field models need tuning of the dim-6 corrections

Inflation ...

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

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

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

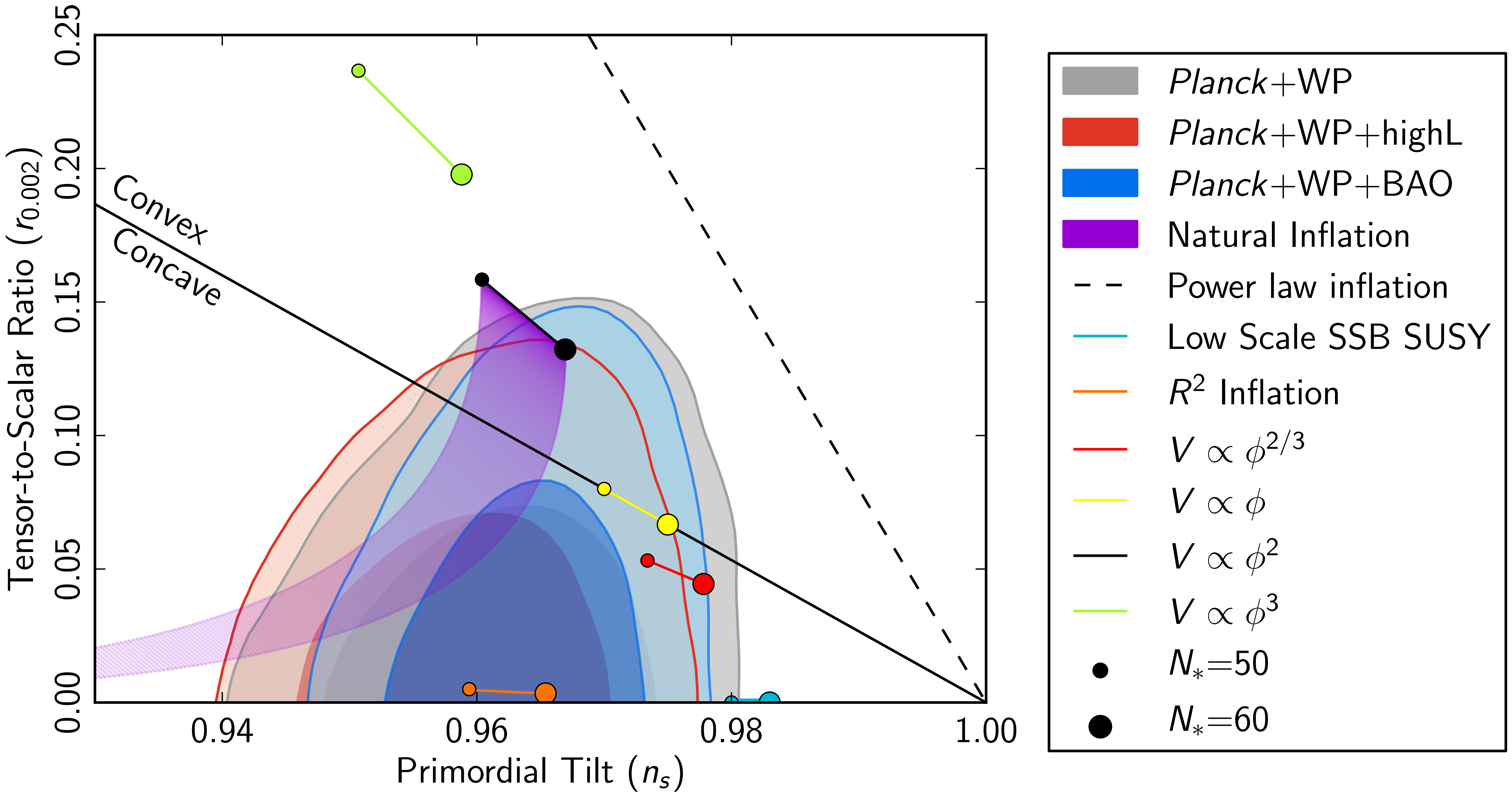


- have ε *decreasing* during inflation ...

- 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 ...



Tensor-to-Scalar Ratio ($r_{0.002}$)
0.25
0.20
0.15
0.10
0.05
0.00
0.94
0.96
0.98
1.00
Primordial Tilt (n_s)
Convex
Concave
Planck+WP
Planck+WP+highL
Planck+WP+BAO
Natural Inflation
Power law inflation
Low Scale SSB SUSY
R^2 Inflation
$V \propto \phi^{2/3}$
$V \propto \phi$
$V \propto \phi^2$
$V \propto \phi^3$
$N_*=50$
$N_*=60$

single field models ...

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

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

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

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

shades of difficulty ...

- observable tensors link levels of difficulty:

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

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

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

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

➡ enumeration & fine-tuning reasonable

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

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

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

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

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

Large-Field inflation ... needs suppression of all-order corrections

➡ symmetry is essential!

shades of difficulty ...

- observable tensors link levels of difficulty:

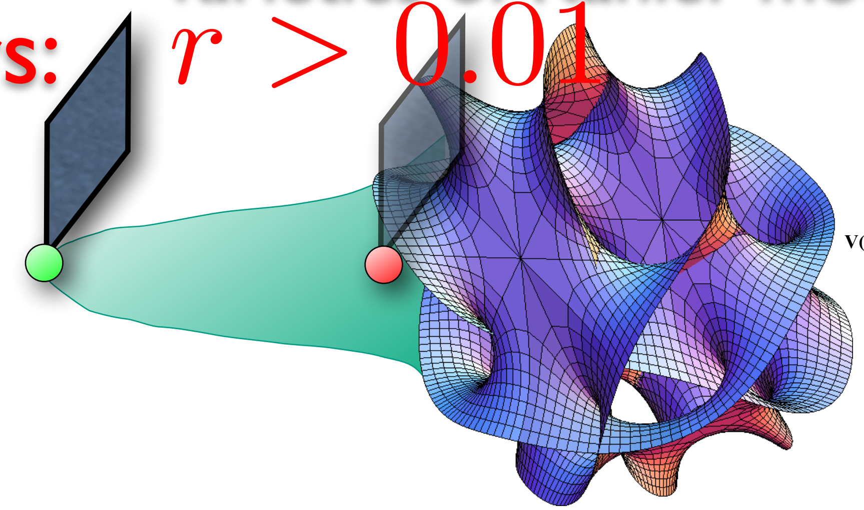
$$r \equiv \frac{\mathcal{P}_T}{\mathcal{P}_R} = 16\epsilon \leq 0.003 \left(\frac{50}{N_e}\right)^2 \left(\frac{\Delta\phi}{M_{\rm P}}\right)^2$$ [Lyth '97]

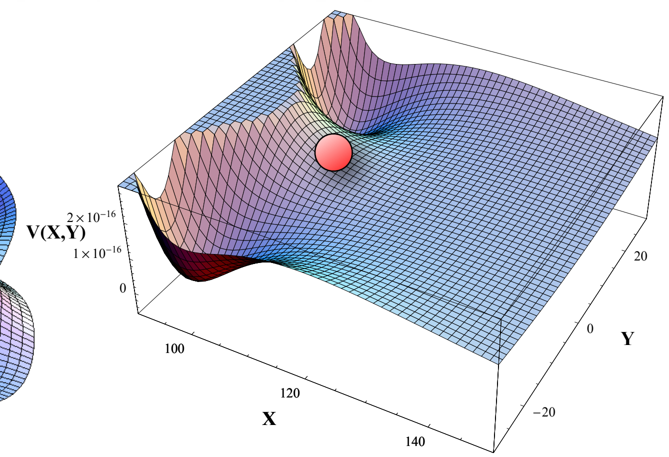
- $r \ll O(1/N_e^2)$ models:

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

observable tensors: $r > 0.01$

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





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

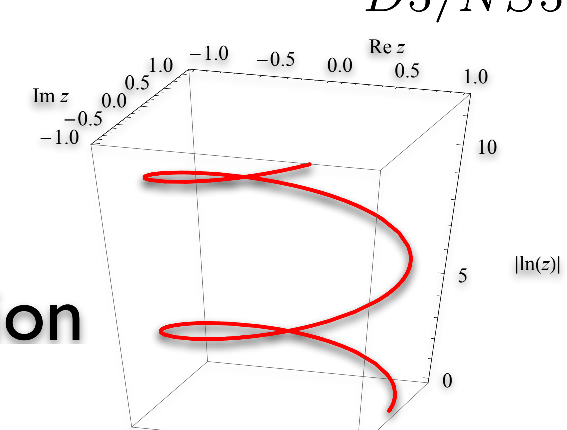
$\Delta\phi \sim \mathcal{O}(M_P) \quad \Rightarrow$

fibre inflation in LARGE volume scenarios (LVS)

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

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

axion monodromy inflation



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

- hemispheric asymmetry of mean power and temperature ~ 3 σ

- quadrupole - octopole alignment

- cold spot ~ 3 σ

- 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, ~ 2.5 σ

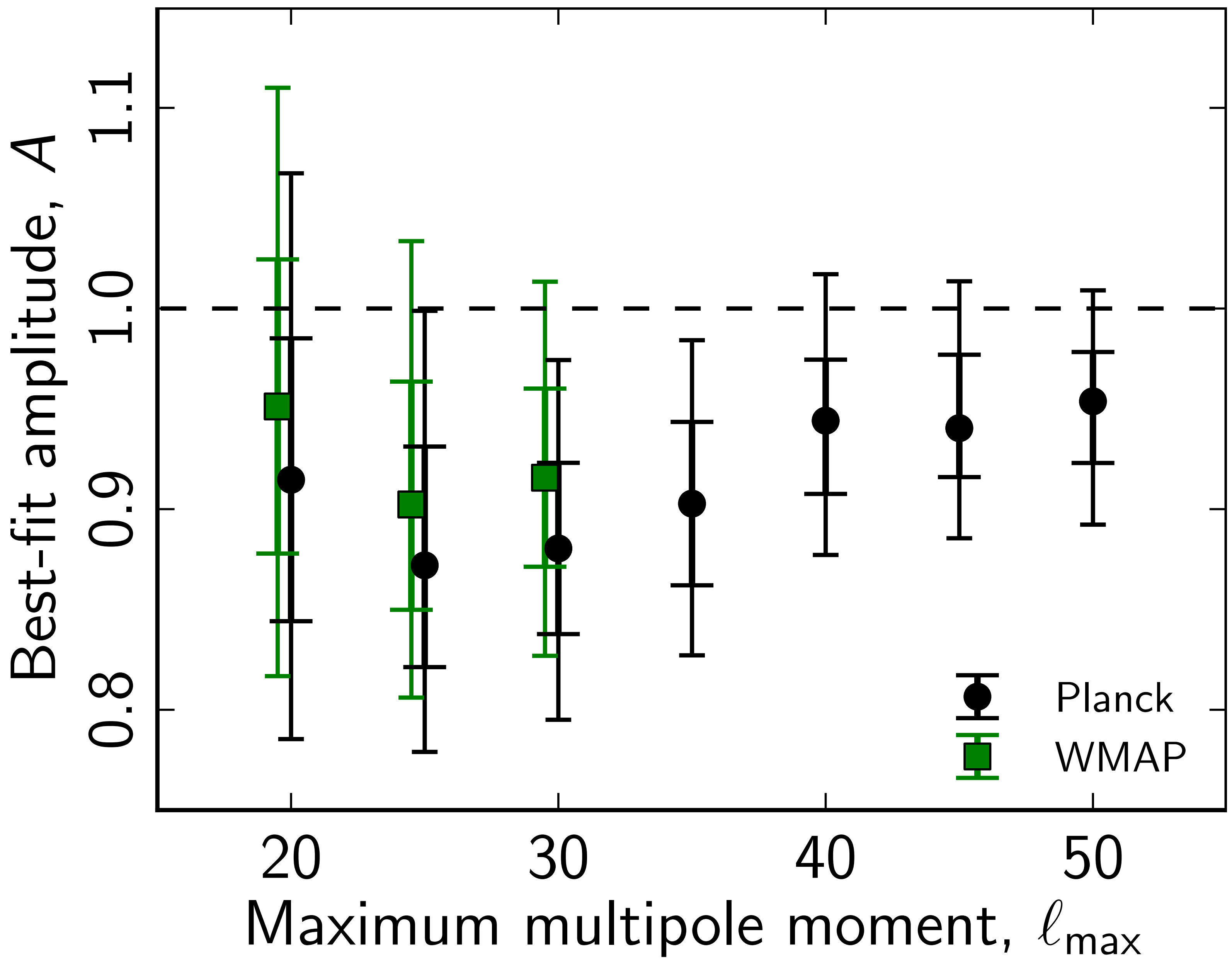
theory task: explain!

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

[PLANCK Coll. XV '13]

$$q = \frac{C_\ell^{\ell=2\ldots50}}{C_\ell^{\ell>50}}$$

$$q = 0.9 \quad \text{at} \quad 2.5 - 3\sigma$$



[Bousso, Harlow, Senatore '13]

- significance of the power suppression -- now:

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

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

$$\Rightarrow \quad \text{significance of suppression measurement:}$$

$$2 \ldots 3\,\sigma \qquad \text{CMB + a bit of LSS}$$

- the future:

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

$$\Rightarrow \quad \text{significance of suppression measurement:}$$

$$3 \ldots 4\,\sigma \qquad \text{CMB + LSS from EUCLID}$$

$$5 \ldots 6\,\sigma \qquad \text{CMB + LSS from EUCLID + 21cm data}$$

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 $\Delta\phi$

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

$$\text{while} \qquad \phi \to \phi + \Delta\phi$$

$$\text{then} \qquad \Delta^2_{\mathcal{R}} \sim \frac{H^4}{\dot\phi^2} \sim \frac{V}{\epsilon} \to \frac{1}{\beta}\Delta^2_{\mathcal{R}} < \Delta^2_{\mathcal{R}}$$

- 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 ...

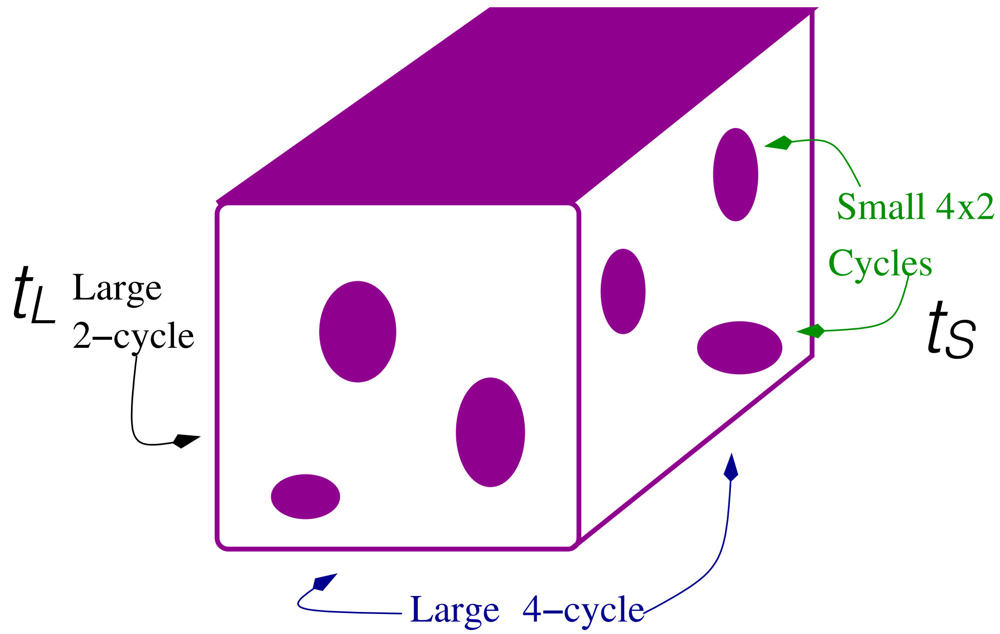
[Cicoli, Burgess & Quevedo '08]

- setup

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

3-form flux superpotential

ED3-brane instanton



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

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

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

fibre inflation in type IIB string theory ...

[Cicoli, Burgess & Quevedo '08]

- N = 1 eff. supergravity - F-term scalar potential

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

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

SUSY breaking LVS
(large volume) minimum

- string loop corrections from KK- & winding modes

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

- correct moduli potential

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

- stabilizes fibre modulus τ_1

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

- fibre modulus kinetic term - canonically normalize

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

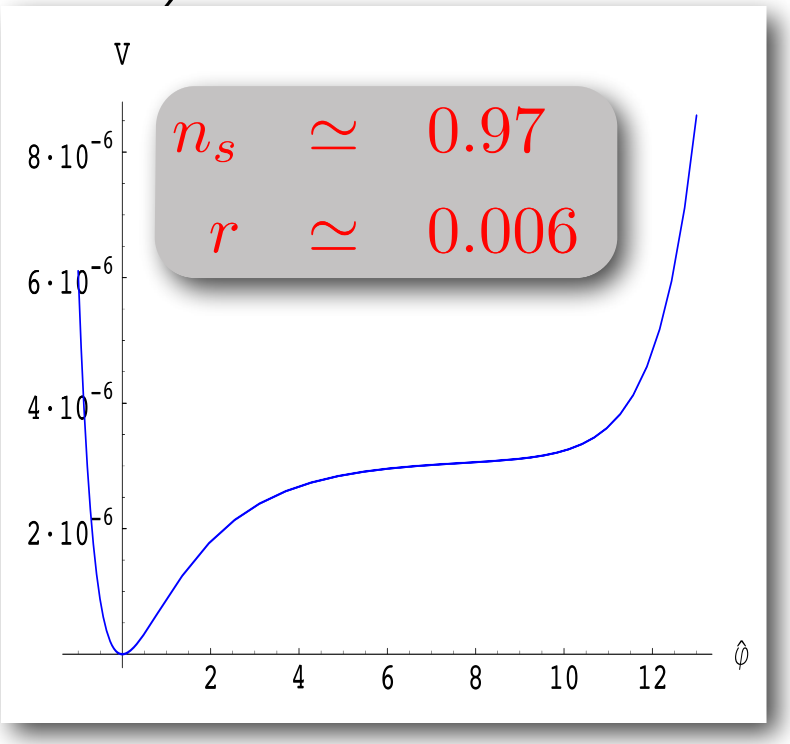
$$\phi \equiv \frac{\sqrt{3}}{2}\ln \tau_1 \qquad \text{or} \qquad \tau_1 \equiv e^{\kappa\phi} \qquad \text{with} \qquad \kappa = \frac{2}{\sqrt{3}}$$

- fibre modulus scalar potential from string loops

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

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_l at zero VEV:

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

$C_1 \sim g_S^{\#}, \# > 0$ with $C_1 \lesssim 10^{-5}$ 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:

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

- field range of steepening:

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

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

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

- for moderate power suppression (δ =10...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:

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

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

while

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

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

- Assume modified string loop corrections:

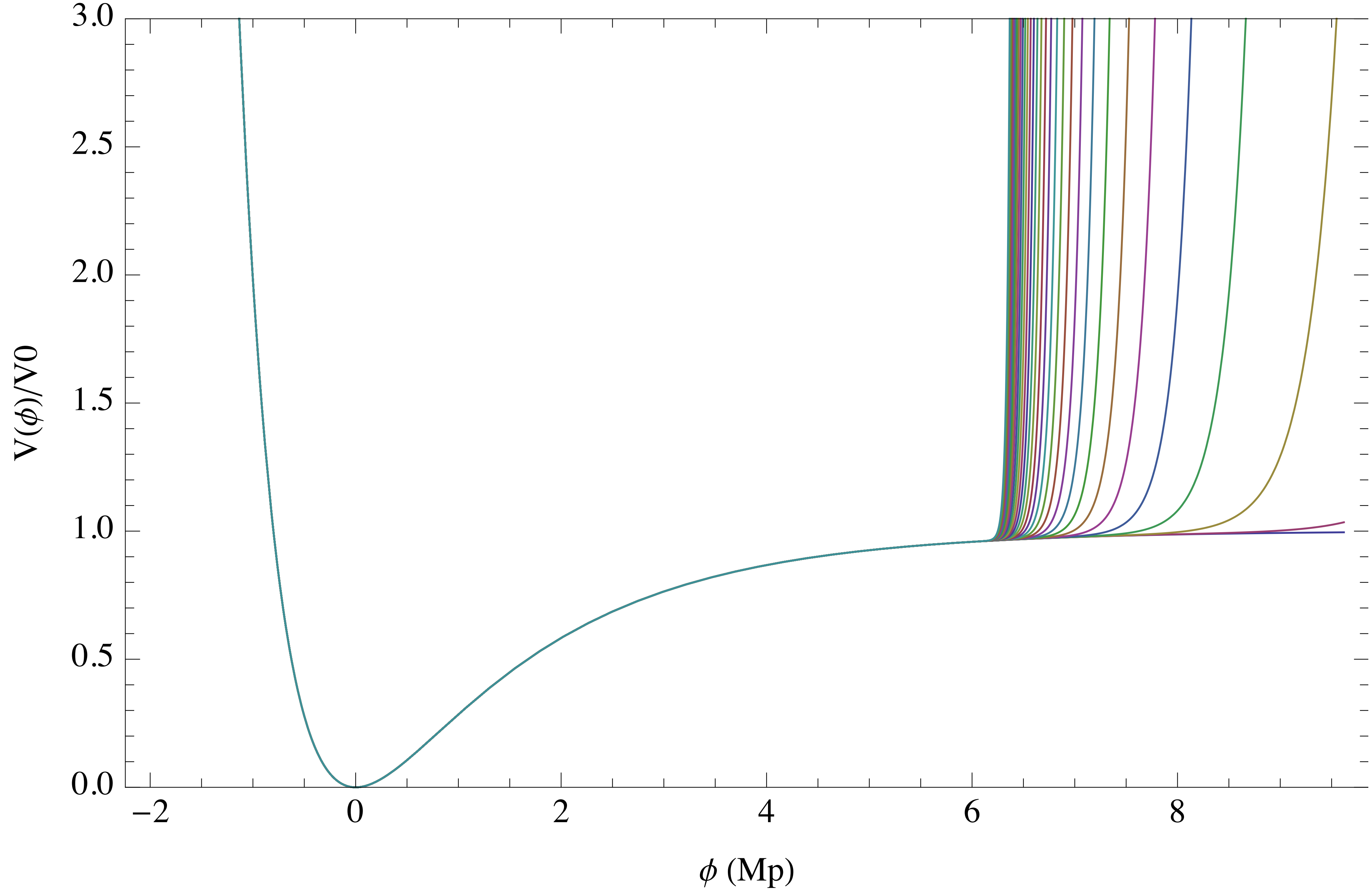
replace $\delta V \sim \frac{\tau_1}{\mathcal{V}^4}$

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:

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

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



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

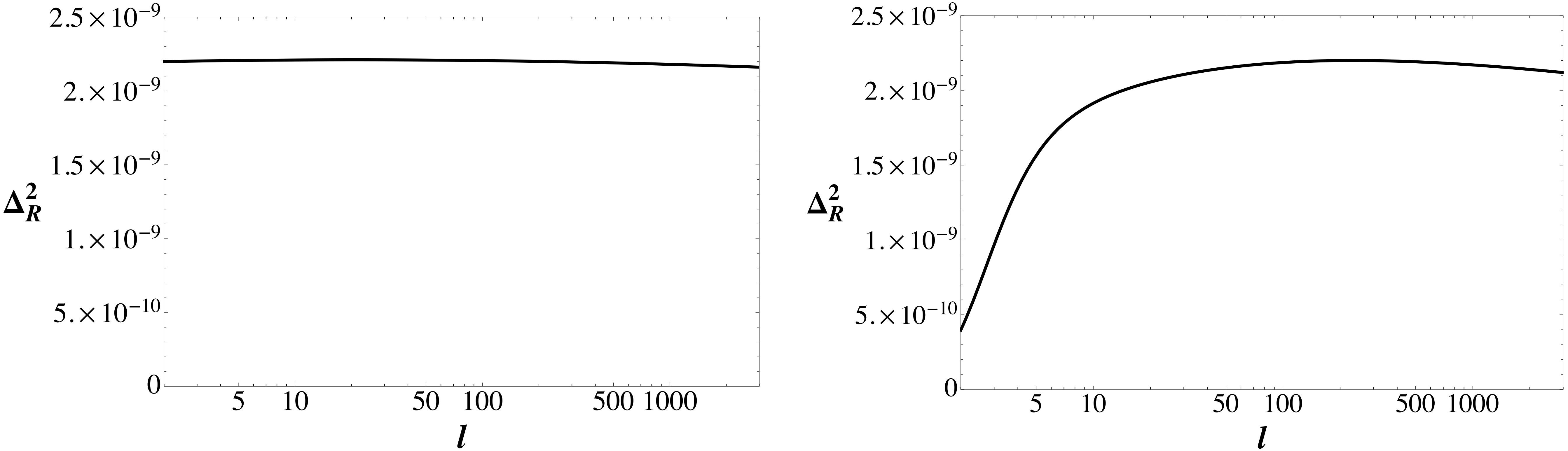


Figure 4: Power spectrum $\Delta^2_{\mathcal{R}}$ computed on the numerical solution $\phi(N_e)$. Left: The original fibre inflation setup with $\tilde{\kappa} = \kappa = 2/\sqrt{3}$ and $C_1 = 10^{-5}$. Right: The modified setup with $\tilde{\kappa} = 10\kappa$ and $\tilde{C}_1 = 7 \times 10^{-33}$.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

- generic case:

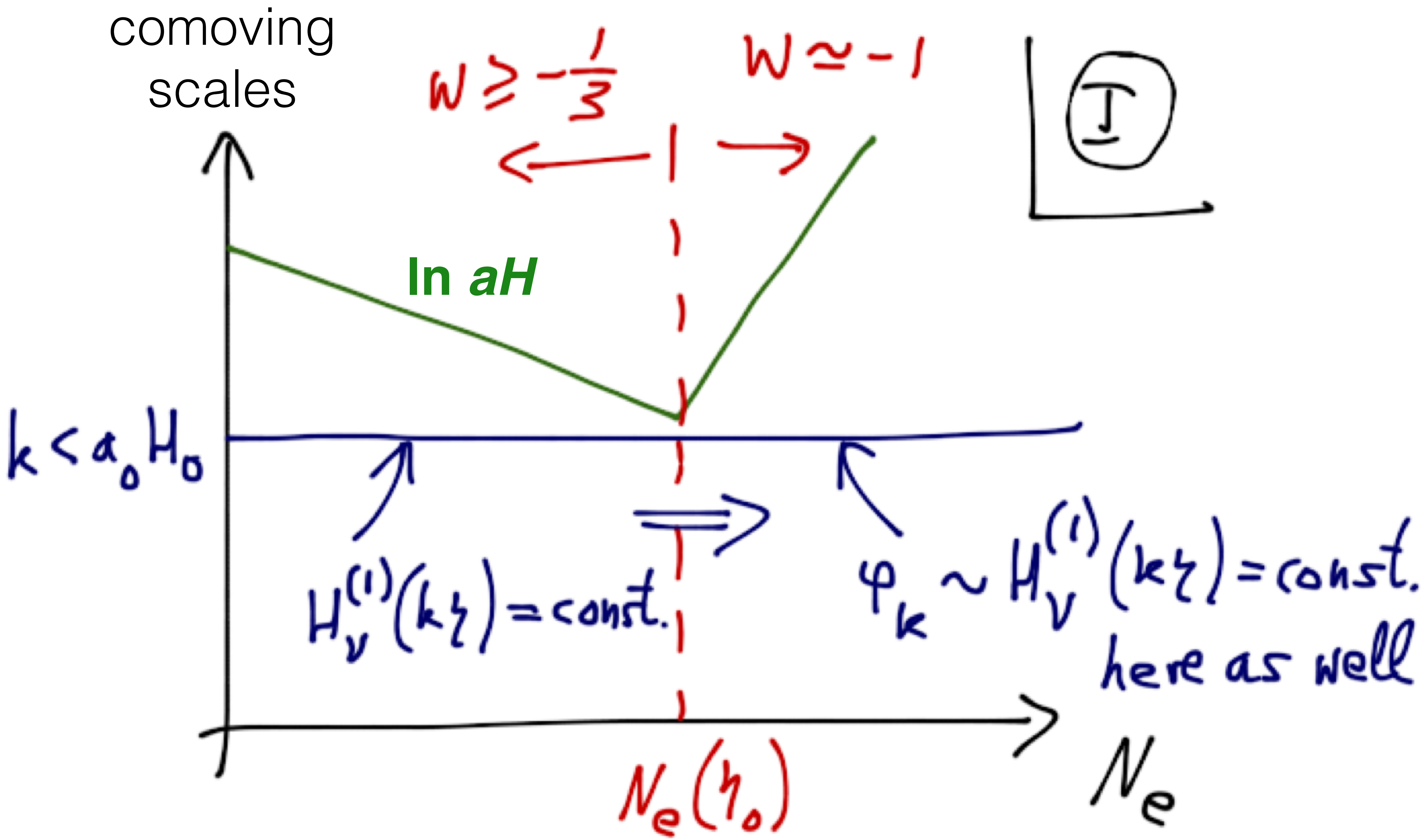
  if the potential shows sudden steepening in slow-roll regime -- generically gets MUCH steeper above slow-roll regime

- leads to a ***Fast-Roll*** phase before slow-roll

  if light fields are present, admixture of radiation possible

- we will now assume some non-accelerating phase transitioning suddenly into slow-roll

- Fast-Roll to Slow-Roll transition:
  comoving fluctuation scales & comoving horizon



- impose UV-normalizable vacuum during pre-inflation

$$v_k = A_k H_\nu^{(1)}(k(\eta-\eta_i)) + B_k H_\nu^{(2)}(k(\eta-\eta_i)) \quad \text{with} \quad \eta_i < \eta_0 < 0$$

$$\text{and} \quad |A_k|^2 - |B_k|^2 = 1 \;\;, \quad B_k \xrightarrow[|k\eta|\gg 1]{} k^{-2}$$

$$\text{background evol.:} \quad \nu^2 = 2\,\frac{1-3w}{(1+3w)^2} + \frac{1}{4}$$

- modes with k < $a_0 H_0$ are frozen (never enter the horizon - preserve pre-inflation power spectrum!

$$H_\nu^{(1,2)}(k\eta) \xrightarrow[k\to 0]{} k^{-\nu}$$

$$\text{for} \quad k \;\; \text{with} \;\; |k\eta| < 1 \;\; \text{at} \;\; \eta > \eta_0 \;\wedge\; \eta < \eta_0$$

$$\Rightarrow \quad P(k) \sim k^3 \left| \left| \frac{v_k}{a} \right|^2 \right|_{k < a_0 H_0} \sim k^{3-2\nu} \left| A_k - B_k \right|^2$$

- modes with k ~ $a_0 H_0$ map suddenly from the pre-inflation vacuum modes to the dS modes: "sudden approximation" - expect interference & "ringing"

- can do this analytically for radiation dominated pre-inflation: w = 1/3 , ν = 1/2

$$v_k|_{\eta<\eta_0} \sim H^{(1)}_{1/2}\left(k(\eta - \eta_i)\right) \sim \frac{e^{-ik(\eta-\eta_i)}}{\sqrt{k}}$$

$$v_k|_{\eta>\eta_0} \sim A_k H^{(1)}_{3/2}(k\eta) + B_k H^{(2)}_{3/2}(k\eta)$$

$$v_k|_{\eta<\eta_0}(\eta_0) = v_k|_{\eta>\eta_0}(\eta_0)$$
$$v'_k|_{\eta<\eta_0}(\eta_0) = v'_k|_{\eta>\eta_0}(\eta_0)$$

$$\Rightarrow$$

$$A_k = 1 + \frac{i}{\eta_0 k} - \frac{1}{2\eta_0^2 k^2}$$
$$B_k = \frac{1}{2\eta_0^2 k^2}\, e^{-2ik\eta_0}$$

- power spectrum:

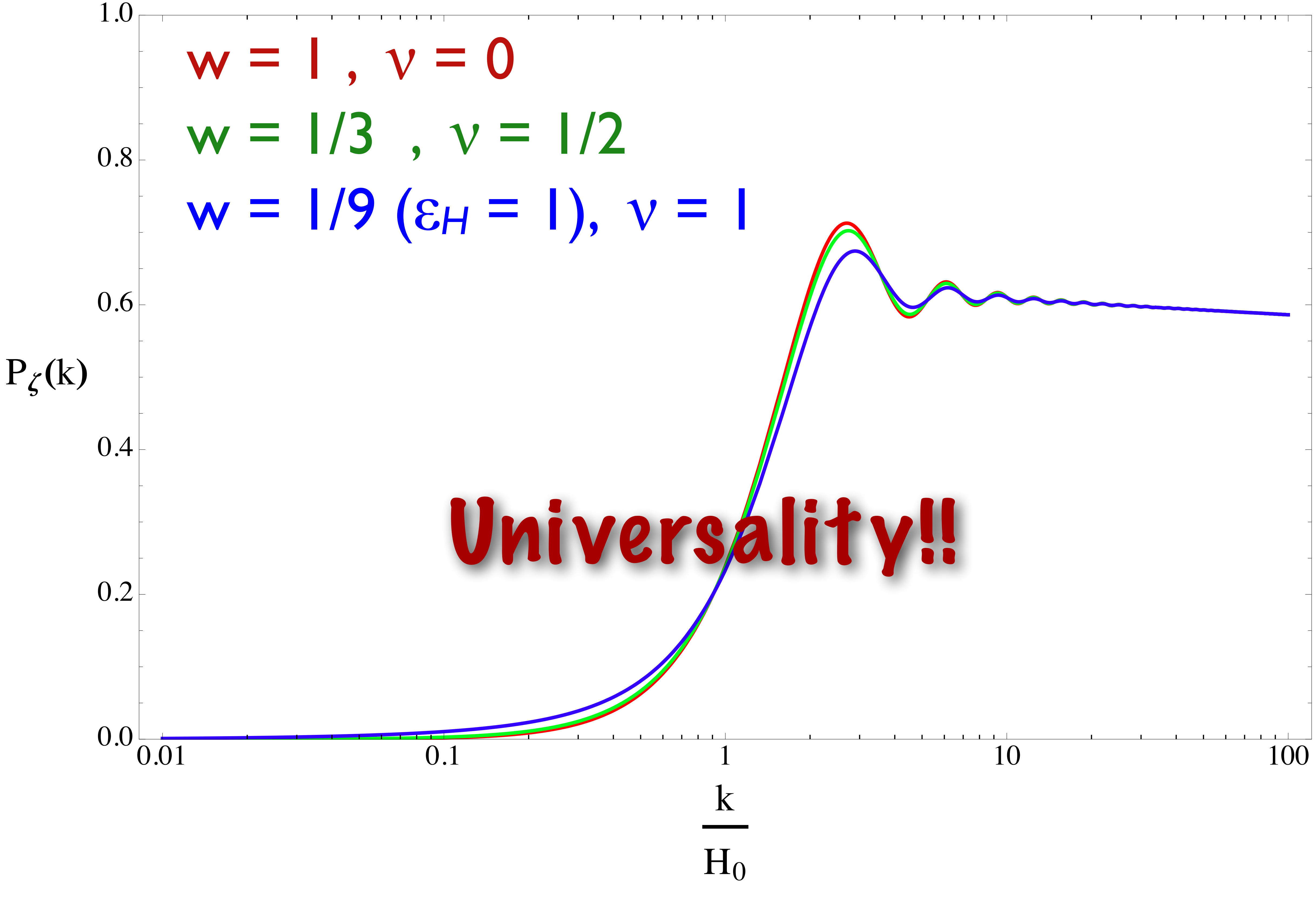
$$P_{\nu=1/2}(k) \sim \frac{1}{2} + \frac{1}{4\eta_0^4 k^4} + \frac{\cos(2k\eta_0)}{2\eta_0^2 k^2}\left(1 - \frac{1}{2\eta_0^2 k^2}\right) - \frac{\sin(2k\eta_0)}{2\eta_0^3 k^3}$$

- for general ν :
  initiate slow-roll in the pre-inflation BD vacuum & run the Mukhanov-Sasaki equation

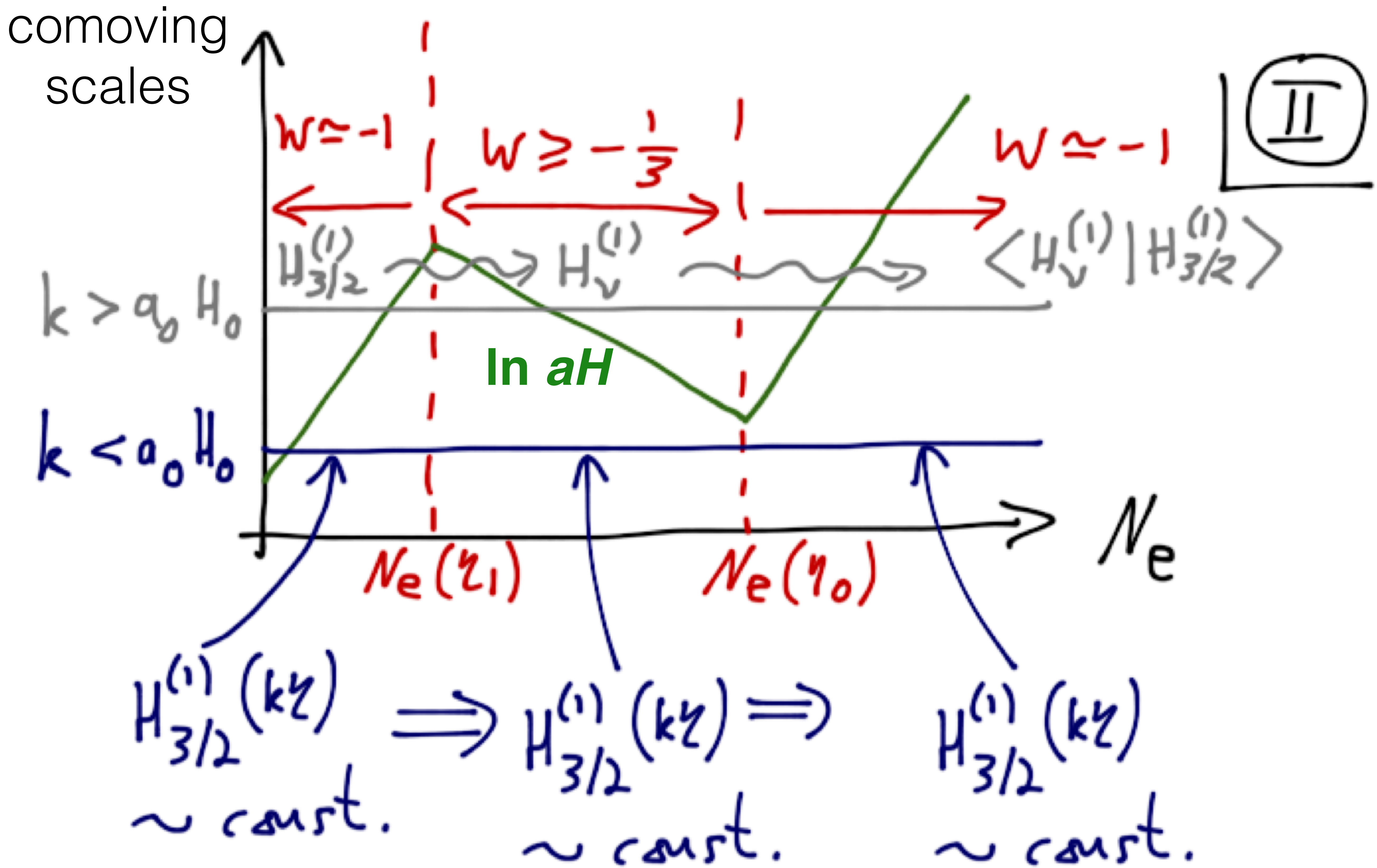
$$v_k|_{\eta<\eta_0}(\eta_0) = v_k|_{\eta>\eta_0}(\eta_0)$$
$$v'_k|_{\eta<\eta_0}(\eta_0) = v'_k|_{\eta>\eta_0}(\eta_0)$$

$$v''_k + \left(k^2 - \frac{z''}{z}\right)v_k = 0 \quad \text{with} \quad z = a\sqrt{2\epsilon}$$

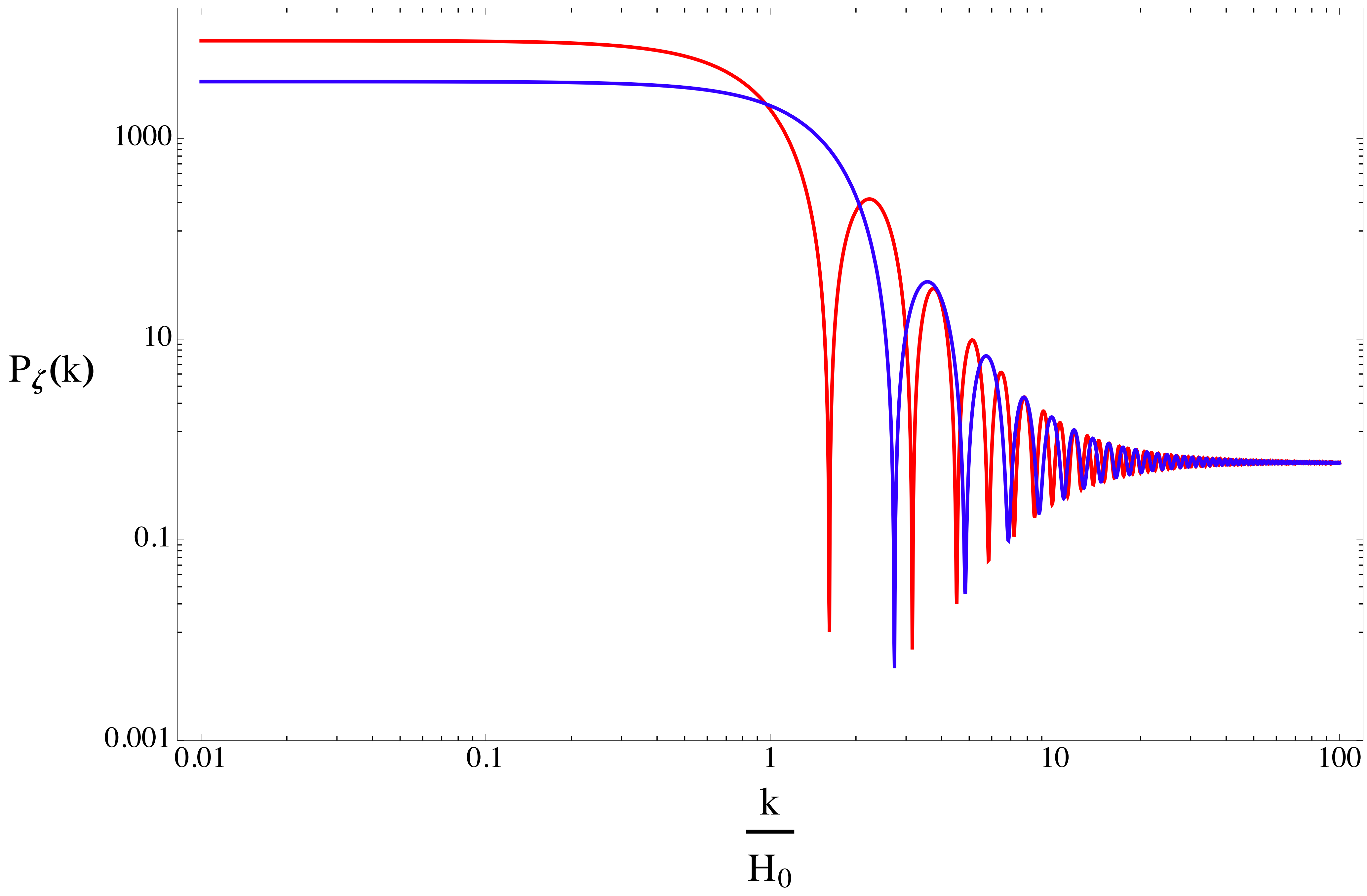
- power spectra for:



- dS to Fast-Roll to Slow-Roll transition: comoving fluctuation scales & comoving horizon



- expect ***no*** pronounced suppression, if prior inflation was there!!
- power spectra for: *dS to Fast-Roll to Slow-Roll* , 2 different initial H_{dS}



discussion ...

- 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

- universal signature!
  - if no prior inflation: universal power suppression spectral template with moderate wiggles
  - if prior inflation: *no* suppression & very strong wiggles

- caveats/open questions: false vacuum prior inflation with CDL tunneling - effects of bubble wall & negative spatial bubble curvature ?

[Yamauchi, Linde, Naruko, Sasaki, Tanaka '11]