CMB power suppression at low-l from string inflation

Table 8. Constraints on the basic six-parameter ΛCDM model using *Planck* data. The top section contains constraints on the six

ln(1010*A*s) 3.098 3.103 ± 0.072 3.0980 3.089⁺0.⁰²⁴

−0.027

Michele Cicoli, Sean Downes, Bhaskar Dutta, Francisco Pedro, AW arXiv: 1309.3412, 1309.3413, and work in progress r ancicco Pedro A 1 0.0220 ± 0.02205 ± 1.00 100000 L_{III} progress ns 0.9624 0.9616 ± 0.0094 0.9616 ± 0.0094 0.0094 ± 0.0094 0.0094 ± 0.0094 ± 0.0094 ± 0.0094 ± 0.0073 ±

for *N* ∈ [50*,* 60].

\blacksquare \approx March 2013: BPA N M M M N N M \text

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

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

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

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

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

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

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

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

15.5 months of temperature data

Fig. 10.4 Polarization in the B-model E-model polarization yet! the two-dimensional constraints on *r* and *ns* as colored contours at the 68% and 95% confidence levels for three datasets: *WMAP*7 (grey contours), CMB (red contours), and CMB+*H*0+BAO (blue contours). Adding the SPT bandpowers partially breaks the degeneracy Fig. 4.— The SPT bandpowers (blue), *WMAP*7 bandpowers (orange), and the lensed ΛCDM+foregrounds theory spectrum that provides the best fit to the SPT+*WMAP*7 data shown for the CMB-only component (dashed line), and the CMB+foregrounds spectrum Table 8. Constraints on the basic six-parameter ΛCDM model using *Planck* data. The top section contains constraints on the six primary parameters included directly in the estimation process, and the bottom section contains constraints on derived parameters.

τ 0.0925 0.097 ± 0.038 0.0925 0.089⁺0.⁰¹²

Full release of polarization and all 30 months of temperature data in 2014 constraint constraint constraints for inflations for several models of inflation. We restrict our constraints to the simplest cases of inflations to the simplest cases of the simplest cases of the simplest cases of the sim of slow-roll inflation due to a single scalar field as reviewed in Baumann et al. (2009). **16π Ωροάσε στροπαι ικασιστιαι απο απο το τ** Black lines with colored circles: The predictions of chaotic inflation models (*^V* (φ) [∝] (φ*/µ*)*p*, *p >* 0) for five different values of *^p* lie on the corresponding line. The predictions in the *r* – *n^s* plane are a function of *N*, where *N* is expected to be in the range *N* ∈ [50*,* 60]. Purple region: The predictions of large-field hill-top inflation models (*^V* (φ) [∝] ¹ [−] (φ*/µ*)2) lie within the colored region, which is shown (solid line). As in Figure 3, the bandpower errors shown in this plot do not include beam or calibration uncertainties. **for a systematic error in one systematic error in one most significantly in one most significant significantly i** or more of the data sets, or simply a statistical fluctua t ome aratura dat <u>the datasets are combined and combine them to produce</u> many of the results presented here. the five free ΛCDM parameters, moving by 1*.*5 σ and $\frac{1}{2}$ **by a** $\frac{1}{2}$ from **M SPT bandpowers measure by virtue of the set o** *Planck Planck*+WP Parameter Best fit 68 $$ **erature gata in ZVT4**

by the SPT bandpowers. The SPT constraint on *n^s* is

−0.014 minutes

PLANCK+WP+highL+BAO vs WMAP7 + BAO + HO

Fig. 19. \sim 19. \sim

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

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

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

 $\left(\frac{P}{P}P\right) \sim H^2 \sim \left(\frac{H}{P}P\right)$ and $\left(\frac{P}{P}P\right) \sim H^2 \sim \left(V\right)$

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

 \int $\delta \rho$

 ρ

 \setminus^2

 \sim k^{n_S-1}

 H^2

 ϵ

 \sim

scalar spectral index:

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

window to GUT scale & direct measurement of inflation scale

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:

$$
{\cal O}_6 \sim V(\phi) \frac{\phi^2}{M_{\rm P}^2} \quad \Rightarrow \quad m_\phi^2 \sim H^2 \; , \; \eta \sim 1 \label{eq:O6}
$$

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

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

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

• *alternative:* [Hebecker, Kraus & AW '13] also: [Ben-Dayan & Brustein '09]

[Hotchkiss, Mazumdar & Nadathur '11]

 $V|_{\chi=\Omega} = V_{\sigma} \cdot (1 - \alpha \cdot \cos(\frac{\varphi}{f}))$ $\geq \chi$

- 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

−2∆ ln Lmax 0 0 0 -0.31

Fig. 1. Marginalized joint 68% and 95% CL regions for *n*^s and *r*0.⁰⁰² from *Planck* in combination with other data sets compared to

single field models ... this conformal transformation, we can use the same methodol-

original (Jordan) frame or in the conformally-related Einstein $\mathcal{L}_\mathcal{A}$ related Einstein $\mathcal{L}_\mathcal{A}$

frame with a Klein-Gordon scalar field. Due to the invariance of

with the motivation to include semi-classical quantum effects.

model predicts a tiny amount of gravitational waves. This model

 A non-minimal coupling of the inflaton to gravity with the inflaton to gravity with the action to gravity with the action

ogy described earlier.

Planck constraints.

Non-minimally coupled inflaton

• *R*+*R*2 / Higgs inflation / fibre inflation in LVS string scenarios: \bullet R+R² / Higgs inflation / fibre inflation $\overline{}$ and based on higher order gravitational terms in the action of action $\overline{}$ $\begin{bmatrix} 1 & 1 \\ 1 & 1 \end{bmatrix}$

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

The predictions for *R*² inflation were first studied in Mukhanov or fibre inflation: $V(\phi) \sim 1$ as: *n*s−1 ≈ −8(4*N*∗+9)/(4*N*∗+3) and *r* ≈ 192/(4*N*∗+3)2. Since *r* is suppressed by another 1/N∗ with respect to the scalar tilt, this suppressed by another tilt, this suppressed
This suppressed by another time to the scalar time time to the scalar time to the scalar time to the scalar t or fibre inflation : $V(\phi) \sim$ $\left(1-\frac{4}{3}\right)$ 3 *e*[−] $\sqrt{1}$ $\frac{1}{3}\phi$ "

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

shades of difficulty ...

• observable tensors link levels of difficulty:

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

- *r* << *O*(1/*Ne ²*) models: $\Delta \phi \ll \mathcal{O}(M_P) \quad \Rightarrow \quad$
- $r = O(1/N_e^2)$ models:

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

• $r = O(1/N_e)$ models:

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

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

 \rightarrow enumeration & fine-tuning reasonable

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

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

 \rightarrow symmetry is essential!

shades of difficulty ...

• observable tensors link levels of difficulty:

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

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

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

theory task: explain!

 \tilde{c}

relative to the ΛCDM model at the 99% confidence level.

nominally decreases to 93%. This is consistent with the find-

significance of the power suppression -- now:

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

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

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

\n
$$
2...3 \sigma \qquad \text{CMB} + \text{a bit of LSS}
$$

the future:

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

 \Rightarrow significance of suppression measurement:

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

 $5...6\,\sigma$ 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 Δφ

if
$$
V \to \alpha V
$$
, $\epsilon \to \beta \epsilon$, $\beta > \alpha \simeq 1$

while
$$
\phi \to \phi + \Delta \phi
$$

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

• 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]

tibre intiation in type IIB string theory ... long left the horizon and are therefore unobservable in the CMB spectrum. we therefore argue that since symmetric influence symmetric influence symmetric influence of ~ 2001 long left the horizon and are therefore unobservable in the CMB spectrum. **EIDE CITTERING AND ALL YOU MUCH EXPANSION, THE KING OF A** fibre inflation in type IIB string theory ...

We therefore argue that since symmetric influence symmetric influence α much expansion, α

the large volume scenario (LVS).

[Cicoli, Burgess & Quevedo '08]

the inflationary potential and phenomenology associated with this model in the context of

inflation that yields observable primordial gravitational waves. Here we will briefly describe

the inflationary potential and phenomenology associated with this model in the context of

 t_i denote 2-cycle volumes, $\tau_i = \frac{\partial \mathcal{V}}{\partial t_i}$ 4-cycle volumes t_i denote 2-cycle volumes, $\tau_i = \partial \mathcal{V}/\partial t_i$ 4-cycle volumes \mathbf{v}_i denote 2-cycle volumes, \mathbf{v}_i and \mathbf{v}_i are triple intersection. $\tilde{f}(t) = \tilde{f}(t) - \tilde{f}(t)$ in terms of $\tilde{f}(t)$ in terms of $\tilde{f}(t)$ in terms of $\tilde{f}(t)$ enote 2-cycle volumes, $\tau_i \,=\, \partial{\cal V}/\partial t_i$ 4-cycle v \mathcal{C} in (4.41); each expression contains higher input signs. There is another important important important in

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

the inflationary potential and phenomenology associated with this model in the context of

others (ts, i) are small. The volume of the volume of the cheese can be written be written be written be written be written be written by α

fibre inflation in type IIB string theory ...

[Cicoli, Burgess & Quevedo '08]

one can show that a F-term scalar potential gets generated for the K¨ahler moduli: • N = 1 eff. supergravity - F-term scalar potential

one can show that a F-term scalar potential gets generated for the K¨ahler moduli:

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

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

interesting consequence of allowing for the creation of a mass hierarchy in the moduli sector

interesting consequence of allowing for the creation of a mass hierarchy in the moduli sector

of the compactification, which sets the foundation, which sets the foundations for an inflation $\mathcal{L}^{\mathcal{L}}$

moduli sector that is effectively a single field. For a more detailed discussion of the mass

of the compactification, which sets the foundation, which sets the foundations for an inflation $\mathcal{L}^{\mathcal{L}}$

moduli sector that is effectively a single field. For a more detailed discussion of the mass of the m

SUSY breaking LVS compact space in the (targe volume) minimum (targe volume) minimum

originates from the exchange of closed strings carrying \mathbf{r} and \mathbf{r} and \mathbf{r} and \mathbf{r} and \mathbf{r} branes and *h* δ*K^g^s* = δ*KKK gs* + δ*K^W ^g^s* (3.5) *h* • string loop corrections from KK- & winding modes

δ*KKK*

!!

CKK

ⁱ ailt

Re(*S*)*^V* (3.6)

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

arises from exchange of winding strings between D7 branes. Note that in both *C^W* are functions of the complex structure moduli. Since complex structure moduli. Since α • correct moduli potential

aij in eqs. (3.6) and (3.7)) is such that the scalar potential is given by

computation of such terms on Calabi-Yau backgrounds is missing, they are conjectured to

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

In what follows we assume a scenario in which the brane setup (which determines the matrices the matrices the ma

modulus τ ^K level by fluxes, it is reasonable to assume that these subleading terms in their potential will This potential has the double virtue of stabilising the fibre modulus at not significantly perturb their vacua. • stabilizes fibre modulus τ_ι

and of having a flat plateau suitable for inflation.

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

In order to study the inflationary dynamics it is constructed inflationary dynamics it is constructed in \mathcal{I}_max

the blow-up cycle as finite as finite as finite as finite modulus interference term for the fibre modulus term $\frac{1}{2}$ the blow-up cycle as fixed during inflation, simplifying the term for the fibre modulus term for the fibre modulu • fibre modulus kinetic term - canonically normalize

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

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

hierarchy in the K¨ahler moduli sector moduli sector explained above allows one to consider the volume and volume

hierarchy in the K¨ahler moduli sector explained above allows one to consider the volume and

the blow-up cycle as fixed during inflation, simplifying the kinetic term for the kinetic term for the fibre modulus μ

where we kept only the leading order term in the volume expansion for each expansion for each entry. The mass α

hierarchy in the K¨ahler moduli sector explained above allows one to consider the volume and

 \mathbf{Q}

√3

 $\overline{}$

 \overline{a} \bullet fibre modulus scalar potential from string The scalar potential from String and the canonical modulus is the canonical modulus is the model of \sim r $\frac{1}{2}$ • fibre modulus scalar potential from string loops Cup 219.3 1200.8 29840.2 29840.

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

$\overline{}$ slow-roll flat & asymmetric plateau $\begin{vmatrix} n_s & \simeq & 0.97 \\ \simeq & 0.98 \end{vmatrix}$ - and sudden steep wall !!

to give rise to a sufficiently long period of exponential exponential exponential expansion. The resulting per

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

 F itrary units) versus \mathcal{N} , with V and their minimals \mathcal{N} fixed at the plot assumes \mathcal{N}

the parameters used in the text (for which ≧→ip and R ≡ C μ ip μ) μ in the text (μ

u • tune a Minkowski minimum for τι at zero VEV: • tune a Minkowski minimum for τ_ι at zero VEV: \bullet *cune a Minkowski minimum for τ_ι at z* ¹ [−] *^C*1*/*2*e*−κφ*/*² ⁺ *^C*2*e*−2κφ ⁺ *^C*1*e*κφ" *.* (4.1) a Minkowski minimum for τ_ι at zero VEV:

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

V = *V*⁰

 \mathbf{b}

The best hope for steepening beyond the 60 e-fold point φ⁶⁰ is by having φ⁶⁰ = φ*ip* since for

For φ *>* φ*ip* consequently the *e*κφ-term dominates the scalar potential, so we have

 $E_{\rm eff}$ around the minimum, the scalar potential of fibre inflation reads $[28]$

 $C_1 \sim g_S^{\#}, \# > 0$ with $C_1 \lesssim 10^{-5}$ tunes plateau $C_1 \sim a^{\#}_{\infty}$, $\# > 0$ with $C_1 \leq 10^{-5}$ t $C_1 \sim g_S^{\#}, \# > 0$ with $C_1 \lesssim 10^{-5}$ tunes plateau $C_1 \sim g_S^{\#}$

^S , # *>* 0

1 + *C*1*e*κφ" *.* (4.3)

Requiring the post-inflationary minimum to sit at φ = 0 and *V* (φ = 0) = 0 fixes *C*1*/*² = 4*/*3

9

¹ [−] *^C*1*/*2*e*−κφ*/*² ⁺ *^C*2*e*−2κφ ⁺ *^C*1*e*κφ" *.* (4.1)

by there's always small via choosing *gS*. Accommodating the observed 60 e-folds at *n^s <* 1 requires *C*¹ ! 10−⁵. We see that the point always contains an asymmetric inflection point at φip determined point at φip determined
Determined point at φip determined point at φip determined point at φip determined point at φip determined poi o thare's always an inflaction point on t ■ there's always an inflection point on the plateau:

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

1 + *C*1*e*κφ" *.* (4.3)

^V # *^Vip* !

 $\alpha \psi > \varphi_{ip}$ we have a monotonically mercasing *e*−κφ*ip/*² = 3*C*1*e*κφ*ip .* (4.2) *e*−κφ*ip/*² = 3*C*1*e*κφ*ip .* (4.2) at $\phi > \phi_{ip}$ we have ϵ monotonically increasing.

• best chance $\frac{1}{\sqrt{2}}$ best chance to set rapid increase in ε at la • best chance to get rapid increase in ε at large scales:

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

1 + *C*₁ +

P above the inflection point we have: • above the inflection point we have: \mathbf{I} **e** 8 $\frac{1}{2}$ for point we have:

κ²*C*²

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

• field range of steepening: reasons of comparison with CMB data (observations say *ns*(φ60) *<* 1 at more than 5σ) we **d** $\overline{}$ the $\frac{1}{2}$ $\frac{1}{2}$ We now determine the point φ^δ *>* φ*ip* where !^δ *>* !*ip* has a value such that ∆²

increase in ! above φ*ip*.

φ *>* φ*ip* we have " monotonically increasing.

Hence, we have *n^s >* 1, at least for a large range of field values φ *>* φ*ip*. Therefore, for

Computing the slow-roll parameters in this region we find

eq. (4.4) we get that

^R(φ*ip*)

 $\sum_{n=0}^{\infty}$ $\sum_{n=0}^{\infty}$ $\sum_{n=0}^{\infty}$ ω value such that $\Delta_{\mathcal{R}}(\varphi_0) = \frac{1}{100} \Delta_{\mathcal{R}}(\varphi_{ip})$ find the point $\phi_{\delta} > \phi_{ip}$ where $\epsilon_{\delta} > \epsilon_{ip}$ has a value such that $\Delta^2_{\mathcal{R}}(\phi_{\delta}) = \frac{\delta}{100} \Delta^2_{\mathcal{R}}(\phi_{ip})$ ϵ_{ip} $R^2(\phi_{ip})$ *R*(*R*), i.e. the point $\varphi_{\delta} > \varphi_{ip}$ where $\epsilon_{\delta} > \epsilon_{ip}$

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

e−κ(φδ−φ*ip*) = !!*ip* " **R**
R
2008 *R* m∣ **μ** *e*−κ(φδ−φ*ip*) = **SE** *Pressi* $\delta = 10...90$ implies: *^R*(φδ) √ • for moderate power suppression (δ =10...90) implies: ¹⁰ *.* (4.5) *e*−κ(φδ−φ*ip*) =

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

rolling phase must take place close to horizon exit. It is therefore crucial not only to ensure

essentially constant between φ*ip* and φ^δ with the decrease in power completely driven by the

¹⁰ *.* (4.5)

To render this effect visible in this effect visible in the low-' region of the C MB power spectrum, the fast

!!*ip*

^R(φδ) =

^R(φδ) =

*e*²κφ =

reasons of comparison with CMB data (observations say *ns*(φ60) *<* 1 at more than 5σ) we

 C computing the slow-roll parameters in this region we find σ and σ roll parameters in this region we find σ

η² for φ *>* φ*ip .* (4.4)

• V essentially unchanged while ε increasing ... increase in ! above φ*ip*. essentially constant between φ*ip* and φ^δ with the decrease in power completely driven by the essentially constant between φ*ip* and φ^δ with the decrease in power completely driven by the **increasement of this effect with the computation of the computation of the fast of the fast of the fast of the f**
The fast of the fast of increase in ! above φ*ip*. • V essentially unchanged while *ε* increasing ...

To render this effect visible in the low-' region of the CMB power spectrum, the fast

 $\ddot{=}$ |
|
| **pute e-
pression and CMB** suppression: ls δ s fo *.* (4.6) then estimate the number of e-folds elapsing between the regime of suppressed power at φ^δ φ*ip* φ*ip* = 1 % ¹ [−] *^e*−κ(φδ−φ*ip*) • compute e-folds for field range of given power

&

∆*N*(δ) *e*

 $=$

[√]2!

Using *n^s* ! 0*.*94 from the CMB data, limits !*ip* " 0*.*01. Using this conservative value

 $=$

dequentes de la contrata de la contrata.
La contrata de la co

. (4.6)

. (4.7)

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

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

=

inflection point *ns*(φ*ip*)=1 − 6!*ip*)

1

%

this region is immediately followed by the 60 e-foldings region of the potential. One should

1 **e**−k
1 **e**−k(φδ−φip)
1 e−k(φδ−φip)

.
115 while while \blacksquare while

$$
\Delta N_e(\ell=2\ldots30)=\ln\frac{\ell=30}{\ell=2}<3
$$

1
100 - 100
100 - 100 - 100 - 100 - 100 - 100 - 100 - 100 - 100 - 100 - 100 - 100 - 100 - 100 - 100 - 100 - 100

ive expon ! 0*.*06 1 − *n^s* **•** positive exponential from loop term not steep enough but close ...

potentials beginning modi **Potentials and Assume modif** • Assume modified string loop corrections:

explanation of this apparent feature of the CMB spectrum requires considerably steeper

explanation of this apparent feature of the CMB spectrum requires considerably steeper

within the first single observable e-fold corresponding to 2 ≤ ! ! 40. Recalling the discussion

example is just not steep enough to provide the necessary rapid power loss of low-!. The

 H^s and \tilde{X} will generate a sufficient amount of \tilde{X} will generate a suppression amount of C

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

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

5 Suppressing low-! power in fibre inflation

with the first single observable e-fold corresponding to 2 \leq 2

in Section 2, one sees that the relevant term in the scalar potential arose from a string loop

 P ∴ and a setup for find a setup for find a setup for find a setup for P set **V** valifies so $\overline{\text{ca}}$ **• Modifies scalar potential:**

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

φ*ip*

κ˜

\$2\$*ip*

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

φ*ip*

¹ [−] *^e*−κ˜(φδ−φ*ip*)

. (5.1)

" 3 *.* (5.4)

¹ [−] *^e*−κ˜(φδ−φ*ip*)

dφ*e*−κφ˜

. (5.2)

increase the value of κ in the *C*1*e*κφ-term in the scalar potential by a factor of a few, then

Hence, choosing ˜^κ " ³^κ = 2√3 will generate a sufficient amount of CMB power suppression

^R computed on the numerical solution φ(*Ne*). Left: The original

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

numerically and compute the slow-roll parameters α , α and α

Figure 4: Power spectrum ∆²

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

grows the potential becomes steps steeper to the inflationary region and the inflationary region and the infla

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

of the curvature perturbation evaluated on the numerical solution φ(*Ne*) within the region

an extra constraint on inflationary model building, to be added to the usual discriminants:

the spectral index and the tensor-to-scalar ratio.

Figure 4: Power spectrum ∆² $\tilde{\kappa} = \kappa = 2/\sqrt{2}$ and $\tilde{C} = 10^{-5}$ Right: The modified sotup with $\frac{1}{2}$ = $\frac{1}{2}$ = $\frac{2}{3}$ = $\frac{2}{3}$ = $\frac{2}{3}$ fibre inflation setup with $\tilde{\kappa} = \kappa = 2/\sqrt{3}$ and $C_1 = 10^{-5}$. Right: The modified setup with $\tilde{\kappa} = 10^{-3}$ $κ = 10k$ and $C_1 = 7 × 10−33$. The extra steepening leads to a clear suppression of curvature
nerturbation nower at low *l* Figure 4: Power spectrum $\Delta_{\mathcal{R}}^2$ computed on the numerical solution $\phi(N_e)$. Left: The original $\tilde{\kappa} = 10\kappa$ and $\tilde{C}_1 = 7 \times 10^{-33}$. The extra steepening leads to a clear suppression of curvature perturbation power at low ℓ . fibre inflation setup with $\tilde{\kappa} = \kappa = 2/\sqrt{3}$ and $C_1 = 10^{-5}$. Right: The modified setup with inflation and ϵ_1 in the significance significance with significance, the significance, the features can be can be computed with significance, the significance, the significance, the can be considered with significance

first is the original scalar potential of fibre inflation (˜κ = κ) with *C*¹ # 10−⁵. This choice

• 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

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

and
$$
|A_k|^2 - |B_k|^2 = 1
$$
, $B_k \to k^{-2}$
 $|k\eta| \gg 1$

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

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

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

for k with $|k\eta| < 1$ at $\eta > \eta_0 \wedge \eta < \eta_0$

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

- modes with $k \sim a_0 H_0$ map suddenly from the preinflation vacuum modes to the dS modes: "sudden approximation" - expect interference & "ringing"
- can do this analytically for radiation dominated preinflation: $w = 1/3$, $v = 1/2$

$$
v_k|_{\eta < \eta_0} \sim H_{1/2}^{(1)} \left(k(\eta - \eta_i) \right) \sim \frac{e^{-ik(\eta - \eta_i)}}{\sqrt{k}}
$$
\n
$$
v_k|_{\eta > \eta_0} \sim A_k H_{3/2}^{(1)}(k\eta) + B_k H_{3/2}^{(2)}(k\eta)
$$

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

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

\n
$$
B_k = \frac{1}{2\eta_0^2 k^2} e^{-2ik\eta_0}
$$

• 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 v :

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:

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

discussion ...

- fibre inflation in type IIB string theory provides an asymmetric inflationary plateau with steep wall, which can explain the low-I 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]