Planck constraints on inflation I

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on behalf of the Planck Collaboration

Planck 2013...

The Planck 2013 Universe matched all the key predictions of the simplest models: gaussian, single power law power spectrum, no evidence for non-standard ....

2014...what's new?

-Change in the calibration pipeline : Planck and WMAP agree at less than 0.3% level, inside the statistical uncertainties

-Better understanding of systematics

-Using the full mission data the l=1800 feature discovered in 2013 which was due to the the 4K cooler line has no impact on the cosmological results.

-Likelihood which only uses Planck data in both temperature and polarization

Data combination used

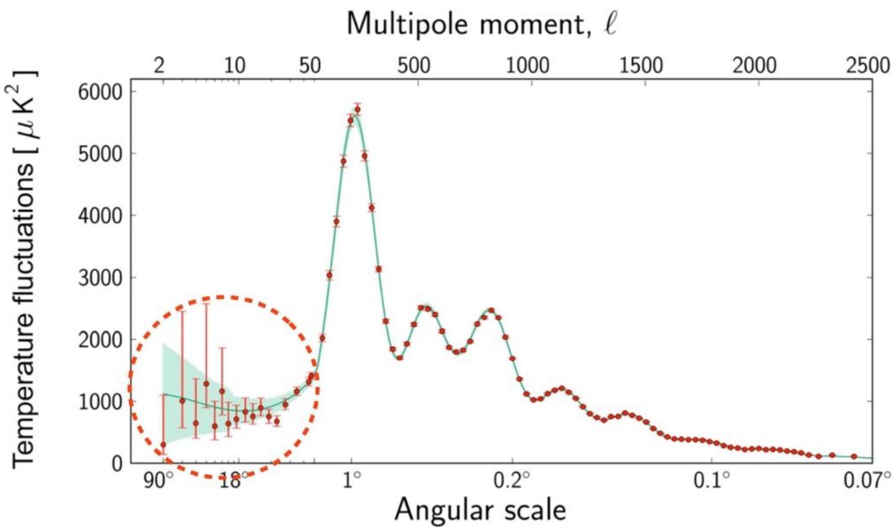
Low-ell likelihood: T,Q and U likelihood. T is provided by the Commander multiband CMB solution, Q and U by the 70GHz with template fitting for the cleaning of the dust polarization and synchrotron with the 30GH and the 353. **2<l<29**.

High-ell likelihood : cross spectra of 100, 143 and 217 GHz, with masks optimized for the frequency considered. **30<l<2000** for TT TE and EE, **2001<l<2500** TT only. See Elsner talk for likelihood details

Lensing likelihood: T and P derived lensing potential. We use a conservative cut **40<l<400.** See Challinor Talk

BAO: We use 6dFGRS *(Beutler et al., 2011)* data at z = 0.106, the SDSS-MGS data at *(Ross et al., 2014)* z = 0.15 and the SDSS-DR11 CMASS and LOWZ data *(Anderson et al., 2013)* at redshifts z = 0.32 and 0.57.

To slow-roll or not to slow-roll?



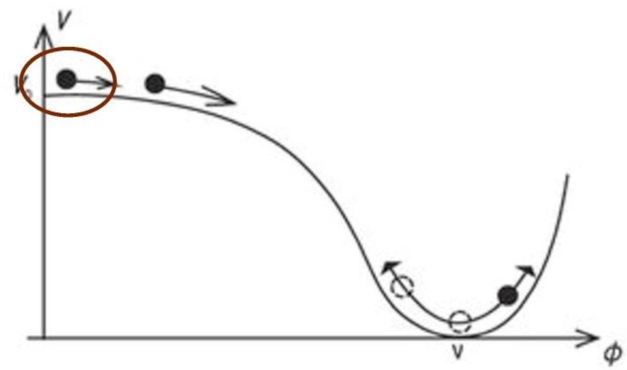
Planck 2013 results XV: CMB power spectra and likelihood

$$\ddot{\phi}(t) + 3H(t)\dot{\phi}(t) + V_\phi = 0,$$

$$H^2 = \frac{1}{3M_{\rm pl}{}^2}\left(\frac{1}{2}\dot{\phi}^2 + V(\phi)\right).$$

$$\dot{\phi}^2/2 << V$$

$$\ddot{\phi} << 3H\dot{\phi}\,, V_\phi$$



Constraints on the spectral index

With the different combinations of the datasets and likelihood we can constrain the spectral index as:

$$n_S = 0.9562 \pm 0.0062 \quad (65\%\ \mathrm{CL}, \mathit{Planck}\ \mathrm{TT} + \mathrm{lowP})$$

$$n_S = 0.9639 \pm 0.0047 \quad (65\%\ \mathrm{CL}, \mathit{Planck}\ \mathrm{TT, TE, EE} + \mathrm{lowP})$$

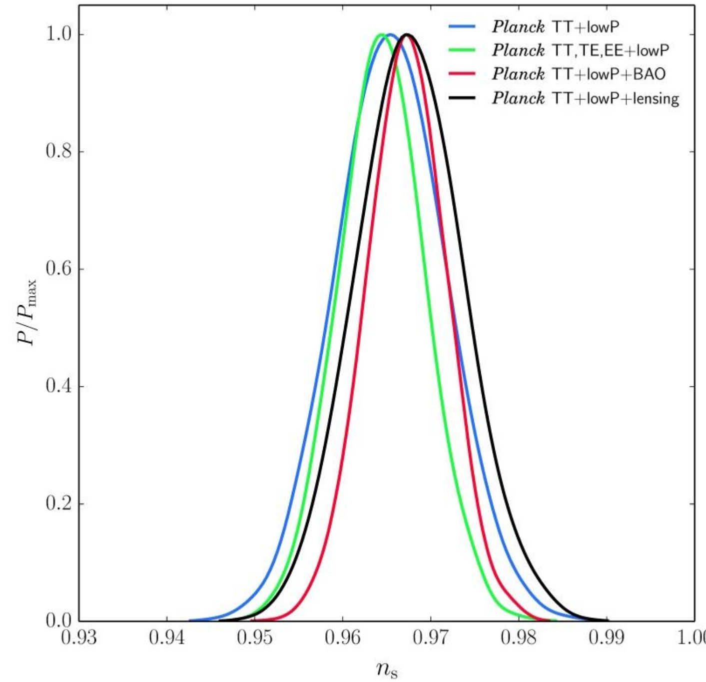
$$n_S = 0.9672 \pm 0.0045 \quad (65\%\ \mathrm{CL}, \mathit{Planck}\ \mathrm{TT} + \mathrm{lowP} + \mathrm{BAO})$$

$$n_S = 0.9675 \pm 0.0059 \quad (65\%\ \mathrm{CL}, \mathit{Planck}\ \mathrm{TT} + \mathrm{lowP} + \mathrm{lensing})$$

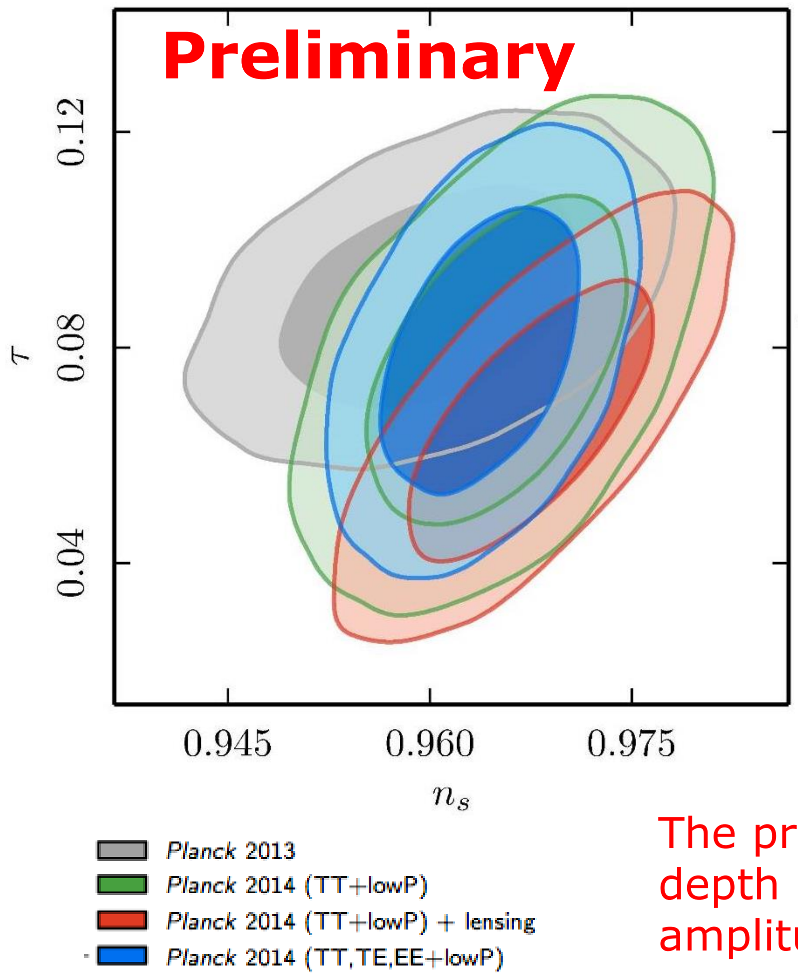
Preliminary

All datasets consistent with each other

HZ spectra excluded at more than 5 sigma (with the LCDM)



Spectral index versus the optical depth



$$\tau = 0.078 \pm 0.019 \quad (65\%\ \mathrm{CL}, \mathit{Planck}\ \mathrm{TT} + \mathrm{lowP})$$

$$\tau = 0.08 \pm 0.017 \quad (65\%\ \mathrm{CL}, \mathit{Planck}\ \mathrm{TT, TE, EE} + \mathrm{lowP})$$

$$\tau = 0.081 \pm 0.018 \quad (65\%\ \mathrm{CL}, \mathit{Planck}\ \mathrm{TT} + \mathrm{lowP} + \mathrm{BAO})$$

$$\tau = 0.066 \pm 0.017 \quad (65\%\ \mathrm{CL}, \mathit{Planck}\ \mathrm{TT} + \mathrm{lowP} + \mathrm{lensing})$$

With respect to the 2013 we observe a slight modification in the contours of the optical depth-spectral index plane . The main causes are the preference for lower optical depth of Planck and the higher precision on the spectral index.

The preference of the lensing for a smaller optical depth is driven by a preference for lower amplitudes of the primordial spectrum

Running of the spectral index

planck

If we introduce a dependence on the scale in the spectral index

$$\mathcal{P}_{\mathcal{R}}(k) = A_s \left(\frac{k}{k_*}\right)^{n_s - 1 + \frac{1}{2}\, dn_s/d\ln k\, \ln(k/k_*) + \frac{1}{6}\, d^2 n_s/d\ln k^2 (\ln(k/k_*))^2 + \ldots}$$

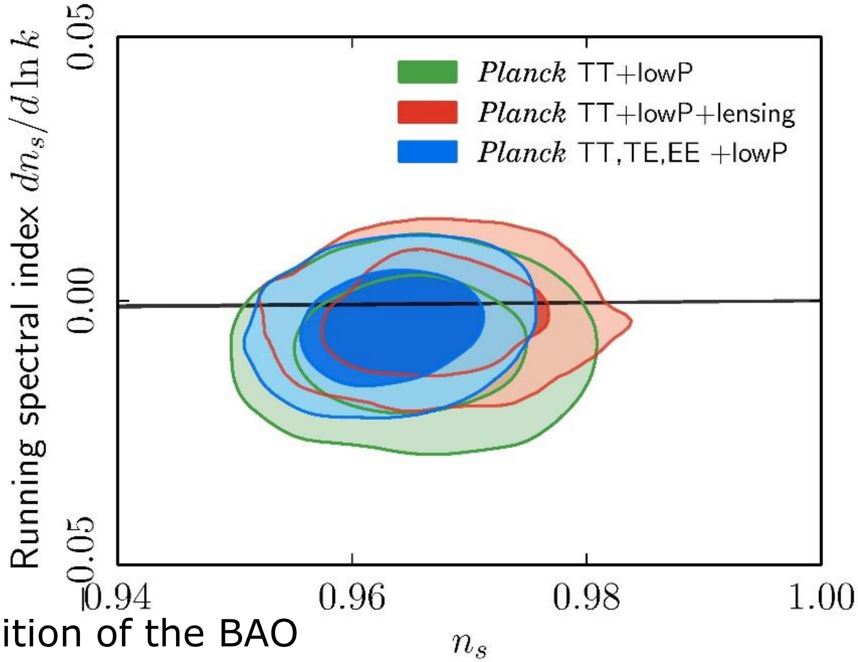
$$\frac{d\,n_s}{d\,\ln k} = \text{-}0.0087 \pm 0.0082 \quad (65\%\ \text{CL}, \mathit{Planck}\ \text{TT} + \text{lowP})$$

Preliminary

$$\frac{d\,n_s}{d\,\ln k} = \text{-}0.0049 \pm 0.0070 \quad (65\%\ \text{CL}, \mathit{Planck}\ \text{TT}, \text{TE}, \text{EE} + \text{lowP})$$

$$\frac{d\,n_s}{d\,\ln k} = \text{-}0.0031 \pm 0.0074 \quad (65\%\ \text{CL}, \mathit{Planck}\ \text{TT} + \text{lowP} + \text{lensing})$$

The low ell lack of power probably responsible for the slightly preference for negative running



Planck 2013

$$\frac{d\,n_s}{d\,\ln k} = \text{-}0.013 \pm 0.009$$

The decrease of the central value is caused mainy by the improvement with the 1800 feature with the full mission and the different calibration.

Stable with respect to the addition of the BAO

esa

HFI PLANCK

Low ell deficit fit

Together with the running and the running of running we tested other two models to fit the lack of power on large angular scales

Exponential cut-off

Short inflationary stage, in which the slow-roll phase coincides with the time when the largest observable scales exited the Hubble radius during inflation. This parametrization results as an average through the oscillations which remain imprinted in the power spectrum.

$$\mathcal{P}_{\mathcal{R}}(k) = \mathcal{P}_0(k)\left\{1 - \exp\left[-\left(\frac{k}{k_c}\right)^{\lambda_c}\right]\right\}.$$

$$\lambda_c \epsilon [0{,}10]$$

$$\ln\left(\frac{k_c}{Mpc^{-1}}\right)\epsilon[-12,-3]$$

Broken power-law

Phenomenological model to search for a better fit to the low ell behavior of the spectrum

$$\mathcal{P}_{\mathcal{R}}(k) = \begin{cases} A_{\mathrm{low}}\left(\frac{k}{k_*}\right)^{n_s-1+\delta}, & \text{if } k \le k_b \\ A_s\left(\frac{k}{k_*}\right)^{n_s-1} & \text{if } k \ge k_b \end{cases}$$

$$\delta \in [0{,}2]$$

$$\ln\left(\frac{k_b}{Mpc^{-1}}\right) \in [-12,-3]$$

$$A_{\mathrm{low}} = A_s(k_b/k_*)^{-\delta}$$

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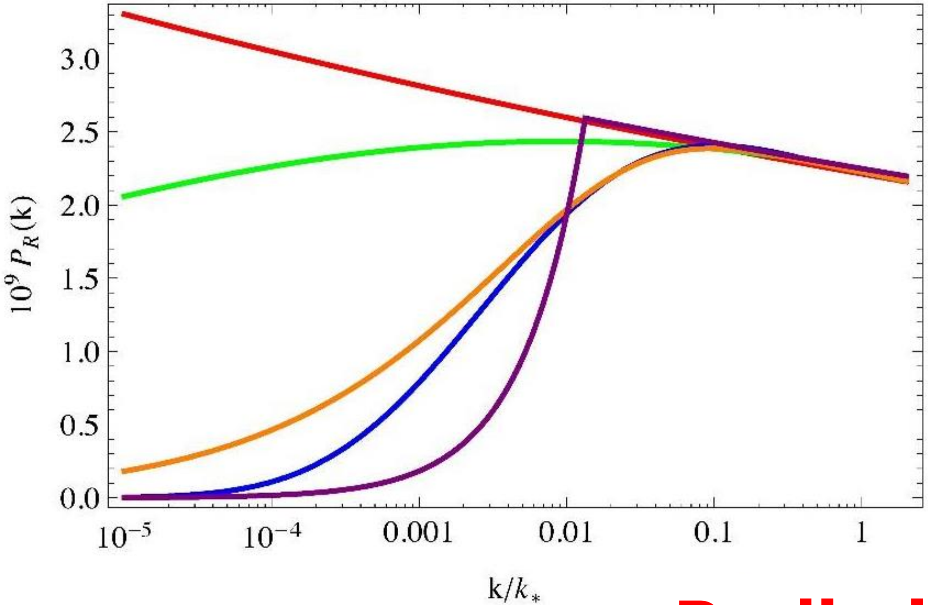

	$-2\Delta \ln \mathcal{L}_{max}$
Running (+1)	-0.9
Running of running (+2)	-4.9
Exponential cut-off (+2)	-3.0
Broken power-law (+2)	-1.0

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Exponential cut off and broken power-law (together with negative running and positive running of the running) represent good fits to the lack of power.

The single power law form is still preferred by data

TENSORS

We consider the inclusion of primordial tensor mode contribution

Preliminary

$$r_{0.002} < 0.10 \quad (95\%\ \mathrm{CL}, \mathit{Planck}\ \mathrm{TT} + \mathrm{lowP})$$

$$r_{0.002} < 0.10 \quad (95\%\ \mathrm{CL}, \mathit{Planck}\ \mathrm{TT,TE,EE} + \mathrm{lowP})$$

Inflationary consistency condition

$$r = \frac{\mathcal{P}_t(k_*)}{\mathcal{P}_\mathcal{R}(k_*)} \approx 16\epsilon_V \approx -8n_t$$

$$r_{0.002} < 0.11 \quad (95\%\ \mathrm{CL}, \mathit{Planck}\ \mathrm{TT} + \mathrm{lowP} + \mathrm{BAO})$$

$$r_{0.002} < 0.11 \quad (95\%\ \mathrm{CL}, \mathit{Planck}\ \mathrm{TT} + \mathrm{lowP} + \mathrm{lensing})$$

$$r_{0.002} < 0.09 \quad (95\%\ \mathrm{CL}, \mathit{Planck}\ \mathrm{TT} + \mathrm{lowP/WMAP})$$

WMAP cleaned with the 353 GHz

Constraints on the primordial gravitational waves are mostly driven by the temperature with no improvements with the addition of either high ell polarization data or lensing and BAO

And what about BICEP.....

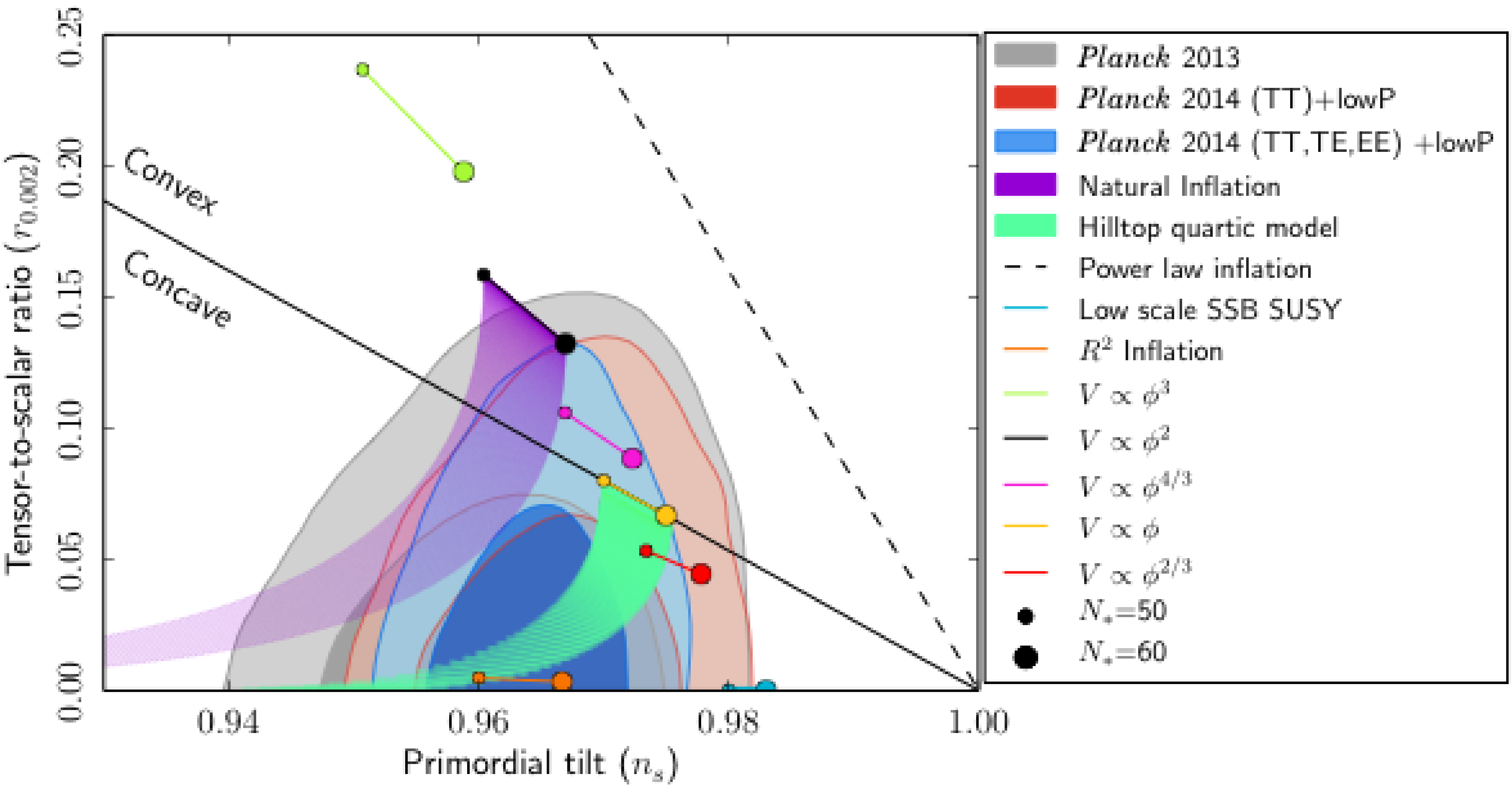
From the results on the dust contribution at high latitudes shown in *Planck intermediate results. XXX. The angular power spectrum of polarized dust emission at intermediate and high Galactic latitudes* and the previous talk by J. Aumont , it seems that the detection of tensor modes with r=0.2/0.16 was affected by an underestimation of the dust contribution to polarization

An agreement for a common effort between the two teams BICEP and Planck for a joint analysis is ongoing so…

quoting George Efstathiou…

what you have to do is just WAIT!

The ns-r constraints vs the inflationary world



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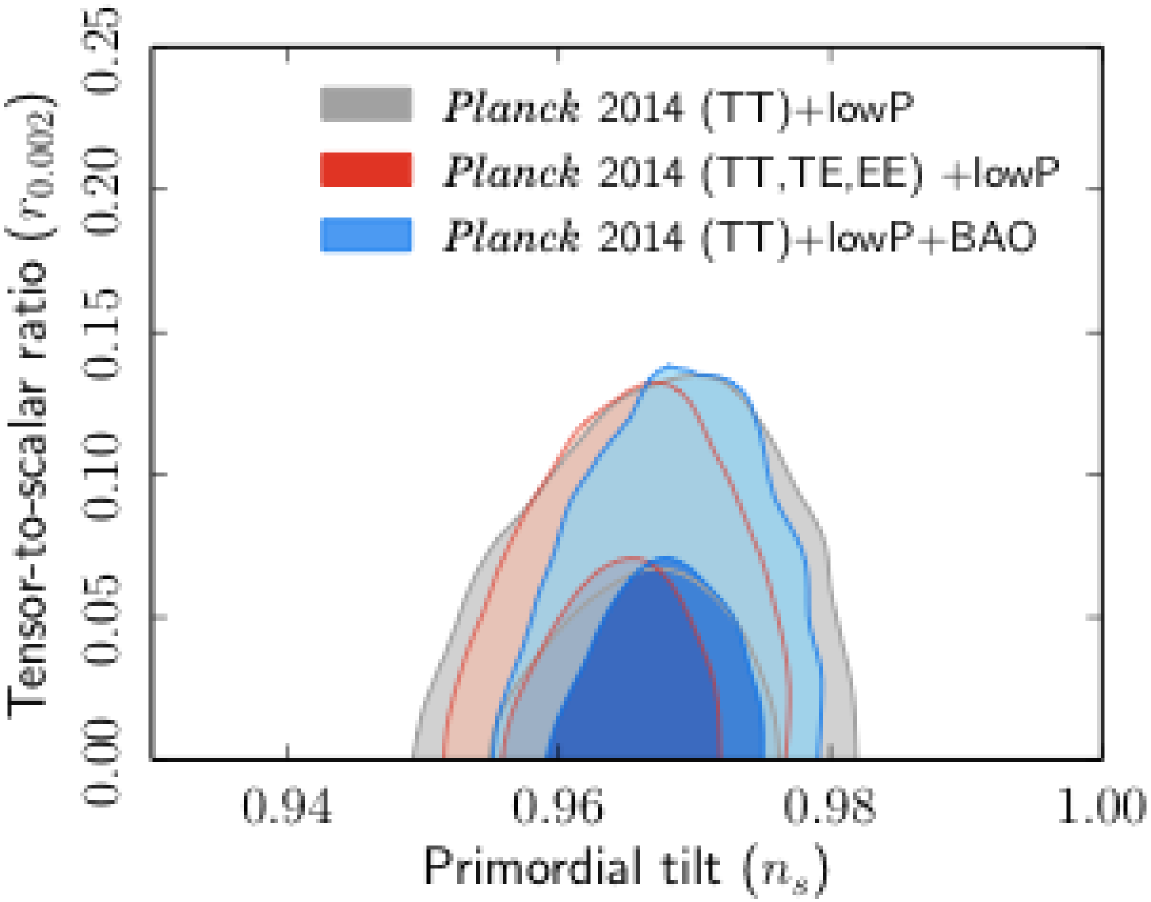
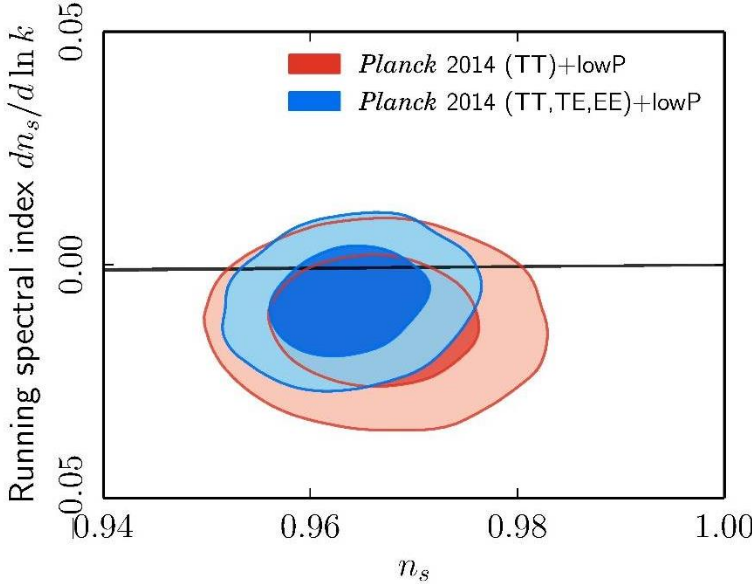
Adding the BAO



The addition of the BAO slightly shifts the spectral index towards higher values but their contribution to the r-ns plane is basically equivalent to the addition of high-ell polarization

Preliminary

Tensor + running

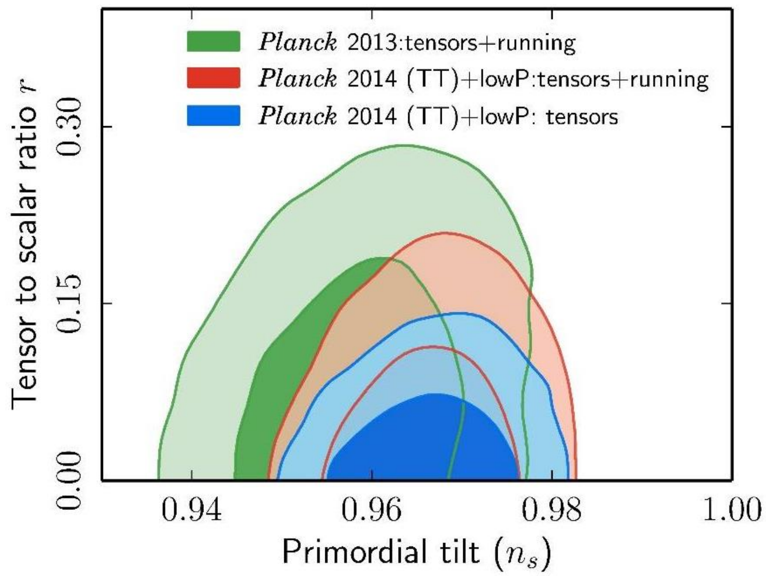


$$r < 0.165 \ \ (95\%\ \mathrm{CL}, \mathit{Planck}\ \mathrm{TT} + \mathrm{lowP})$$

$$(< 0.25 \quad 95\,\%\mathrm{CL}\,, \mathit{Planck}\, 2013)$$

$$\frac{dn_{\rm s}}{d\ln k} = -0.0124^{+0.0097}_{-0.0085} \quad (68\,\%\mathrm{CL}\,, \mathit{Planck}\,\mathrm{TT} + \mathrm{lowP})$$

$$(= -0.021 \pm 0.012 \quad 68\,\%\mathrm{CL}\,, \mathit{Planck}\, 2013)$$



The presence of the running enlarges the constraint on r and the presence of tensors prefers more negative running.

Strong improvement with respect ot the 2013

Preliminary

: 2014

Slow Roll parameters I

We can constrain directly the slow-roll parameters

Slow-roll parameters

$$\epsilon_V = \frac{M_{\rm pl}^2 V_\phi^2}{2V^2}\,,$$
$$\eta_V = \frac{M_{\rm pl}^2 V_{\phi\phi}}{V}\,.$$

Hubble Flow Function slow-roll parameters:
measure the departure frm perfect exponential expansion

$$\epsilon_1 = -\frac{\dot H}{H^2}$$
$$\epsilon_{i+1} = -\frac{\dot\epsilon_i}{H\epsilon_i}$$

Connection with the usual parameters

$$\epsilon_V = \frac{V_\phi^2 M_{\rm pl}^2}{2V^2} = \epsilon_1 \frac{\left(1 - \frac{\epsilon_1}{3} + \frac{\epsilon_2}{6}\right)^2}{\left(1 - \frac{\epsilon_1}{3}\right)^2}$$

$$\eta_V = \frac{V_{\phi\phi} M_{\rm pl}^2}{V} = \frac{2\epsilon_1 - \frac{\epsilon_2}{2} - \frac{2\epsilon_1^2}{3} + \frac{5\epsilon_1\epsilon_2}{6} - \frac{\epsilon_2^2}{12} - \frac{\epsilon_2\epsilon_3}{6}}{1 - \frac{\epsilon_1}{3}}\,,$$

$$\xi_V^2 = \frac{V_{\phi\phi\phi} V_\phi M_{\rm pl}^4}{V^2} = \frac{1 - \frac{\epsilon_1}{3} + \frac{\epsilon_2}{6}}{\left(1 - \frac{\epsilon_1}{3}\right)^2}\left(4\epsilon_1^2 - 3\epsilon_1\epsilon_2 + \frac{\epsilon_2\epsilon_3}{2} - \epsilon_1\epsilon_2^2 + \epsilon_1^2\epsilon_2 - \frac{4}{3}\epsilon_1^3 - \frac{7}{6}\epsilon_1\epsilon_2\epsilon_3 + \frac{\epsilon_2^2\epsilon_3}{6} + \frac{\epsilon_2\epsilon_3^2}{6} + \frac{\epsilon_2\epsilon_3\epsilon_4}{6}\right).$$

$$n_{\rm s} - 1 \approx 2\eta_V - 6\epsilon_V,$$
$$n_{\rm t} \approx -2\epsilon_V,$$
$$dn_{\rm s}/d\ln k \approx +16\epsilon_V\eta_V - 24\epsilon_V^2 - 2\xi_V^2,$$
$$dn_{\rm t}/d\ln k \approx +4\epsilon_V\eta_V - 8\epsilon_V^2,$$
$$d^2n_{\rm s}/d\ln k^2 \approx -192\epsilon_V^3 + 192\epsilon_V^2\eta_V - 32\epsilon_V\eta_V^2 - 24\epsilon_V\xi_V^2 + 2\eta_V\xi_V^2 + 2\varpi_V^3,$$

$$\xi_V^2 = \frac{M_{\rm pl}^4 V_\phi V_{\phi\phi\phi}}{V^2} \qquad \varpi_V^3 = \frac{M_{\rm pl}^6 V_\phi^2 V_{\phi\phi\phi\phi}}{V^3}.$$

Constraints on the slow roll I

First order

$$\mathcal{P}_\mathrm{t}(k_*) = f(\mathcal{P}_\mathcal{R}(k_*), \epsilon_1)$$

$$n_\mathrm{s} - 1 = -2\epsilon_1 - \epsilon_2$$

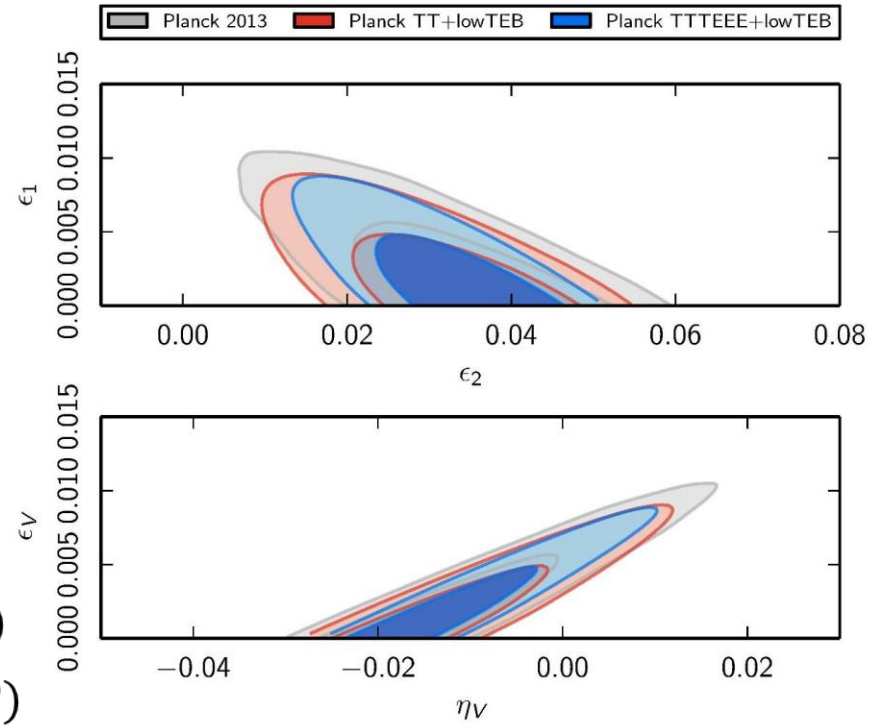
$$n_\mathrm{t} = -2\epsilon_1$$

$\epsilon_1 < 0.0067$ (95% CL, *Planck* TT + lowP)

$\epsilon_1 < 0.0067$ (95% CL, *Planck* TT, TE, EE + lowP)

$\epsilon_2 = 0.030 \pm 0.015$ (95% CL, *Planck* TT + lowP)

$\epsilon_2 = 0.032 \pm 0.014$ (95% CL, *Planck* TT, TE, EE + lowP)



Preliminary

Constraints on the slow roll II

$$\mathcal{P}_{\rm t}(k_*) = f_2(\mathcal{P}_{\mathcal{R}}(k_*), \epsilon_1, \epsilon_2)$$

$$n_{\rm t} = -2\epsilon_1 + \mathcal{O}(\epsilon_i^2)$$

$$n_{\rm s} - 1 = -2\epsilon_1 - \epsilon_2 + \mathcal{O}(\epsilon_i^2)$$

$$\xi_V^2 = \frac{M_{\rm pl}^4 V_\phi V_{\phi\phi\phi}}{V^2}$$

$\epsilon_1 < 0.012$ (95% CL, *Planck* TT + lowP)

$\epsilon_1 < 0.010$ (95% CL, *Planck* TT, TE, EE + lowP)

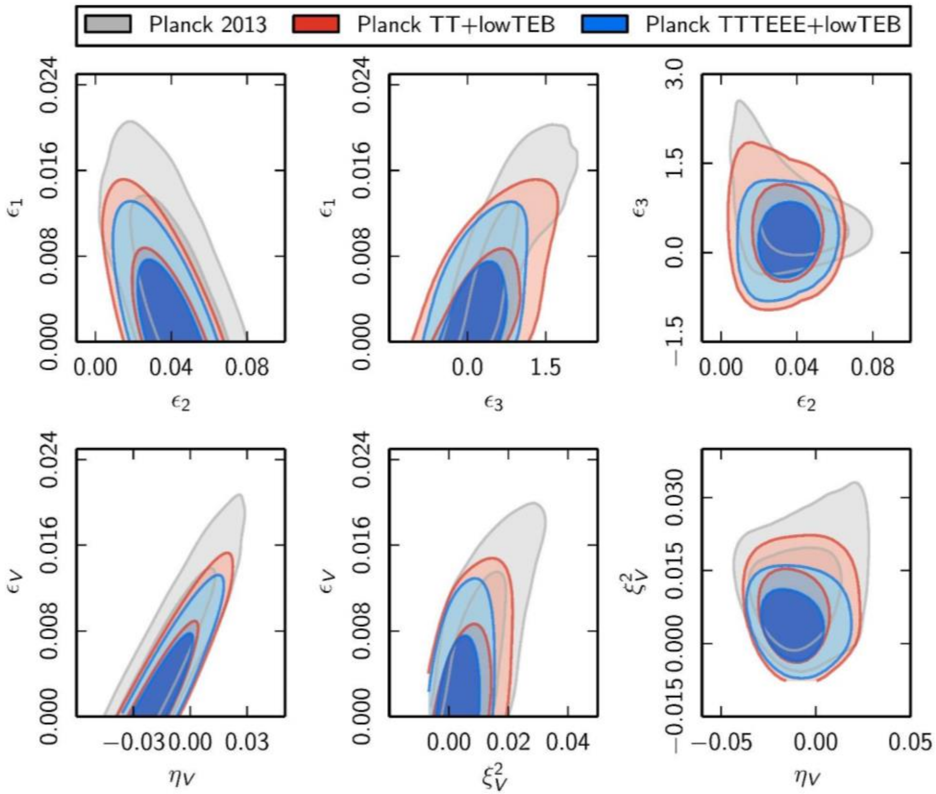
$\epsilon_2 = 0.033 \pm 0.021$ (95% CL, *Planck* TT + lowP)

$\epsilon_2 = 0.034 \pm 0.020$ (95% CL, *Planck* TT, TE, EE + lowP)

$-0.276 < \epsilon_3 < 0.126$ (95% CL, *Planck* TT + lowP)

$-0.308 < \epsilon_3 < 0.763$ (95% CL, *Planck* TT, TE, EE + lowP)

Second order



Preliminary

Reheating uncertainties in predicting the perturbations power spectrum

In this analysis we focus on the impact of the uncertainties of the post inflationary stages on the predictions of the perturbation power spectrum

In particular we can connect the pivot scale k_* today with the energy scale at which that scale exited the Hubble radius during inflation. To do this we need to match the equation for the number of e-folds before the end of the inflation at which the scale exited the Hubble radius with the quantification of how the scale changed between the end of inflation an its re-entering in the Hubble radius

$$N_* = \int_{t_*}^{t_e} \mathrm{d}t\, H \approx \frac{1}{M_{\mathrm{pl}}^2} \int_{\phi_*}^{\phi_e} \mathrm{d}\phi\, \frac{V}{V_\phi},$$

This connection depends both on the inflationary potential and the detail of the post inflation phase.

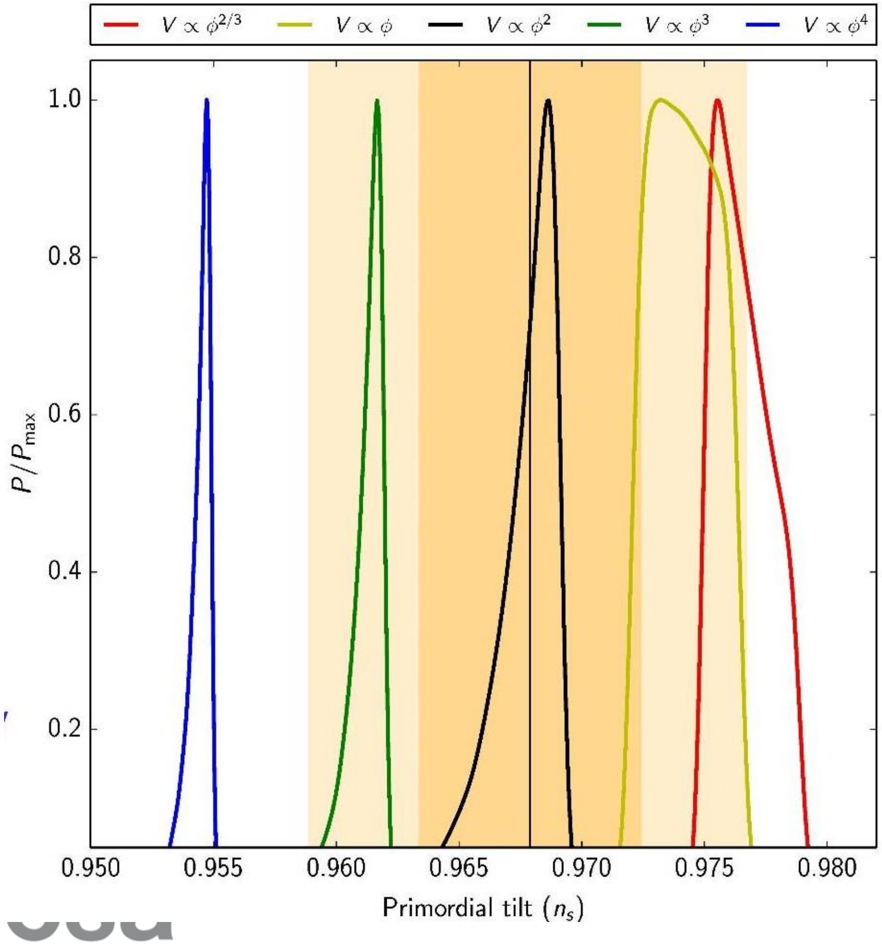
$$N_* \approx 67 - \ln\left(\frac{k_*}{a_0 H_0}\right) + \frac{1}{4}\ln\left(\frac{V_*^2}{M_{\mathrm{pl}}^4 \rho_{\mathrm{end}}}\right) + \frac{1-3w_{\mathrm{int}}}{12(1+w_{\mathrm{int}})}\ln\left(\frac{\rho_{\mathrm{reh}}}{\rho_{\mathrm{end}}}\right) - \frac{1}{12}\ln(g_{\mathrm{th}})$$

Number of bosonic degrees of freedom

Average equation of state parameter during thermalized epoch

Slow roll and reheating uncertainties

We can then vary the reheating density in a range between the end of the inflation and $(10^3\ \mathrm{GeV})^4$ an look at the predicted perturbation spectrum with the spectral index



Power law potential:

$$n_s - 1 \approx -2(n+2)/(4N_* + n)$$

$$r \approx 16n/(4N_* + n)$$

$w_{int} = 0$

$\rho_{\mathrm{end}} < \rho_{\mathrm{reh}} < (10^3 \mathrm{GeV})^4$

$k^* = 0.002\ \mathrm{Mpc}^{-1}$

$g_{th} = 10^3$

ρ_{end} is determined by assuming $\epsilon_1 = 1$ at the end of the inflation. The predictions considers to second order the expansion in slow roll

In yellow the contours for Planck TT +lowP +BAO

Preliminary

Comparison of Inflationary models: few examples

Power-law

$$V(\phi) = \lambda M_{\rm pl}^4 \left(\frac{\phi}{M_{\rm pl}}\right)^n$$

First order slow roll predictions

$$n_s - 1 \approx -2(n+2)/(4N_* + n)$$
$$r \approx 16n/(4N_* + n),$$

Hilltop

$$V(\phi) \approx \Lambda^4 \left(1 - \frac{\phi^p}{\mu^p} + ...\right)$$

First order slow roll predictions

$$n_s - 1 \approx 2p(p-1)(M_{\rm pl}/\mu)^2 x^{p-2}/(1-x^p) - 3r/8,$$
$$r \approx 8p^2(M_{\rm pl}/\mu)^2 x^{2p-2}/(1-x^p)^2$$
$$x = \phi_*/\mu.$$

Natural

$$V(\phi) = \Lambda^4 \left[1 + \cos\left(\frac{\phi}{f}\right)\right],$$

$f \gtrsim 1.5\, M_{\rm pl}$ $\quad n_s \approx 1 - 2/N,\ r \approx 8/N$

$f \lesssim 1.5\, M_{\rm p}$ $\quad n_s \approx 1 - M_{\rm pl}^2/f^2$

R^2

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

First order slow roll predictions

$$n_s - 1 \approx -2/N$$
$$r \approx 12/N^2$$

Comparison of Inflationary models II

Model	$\Delta\chi^2$
$R + \frac{R^2}{6M^2}$	3.7
$n = 4$	46.9
$n = 3$	22.9
$n = 2$	9.7
$n = 4/3$	7.2
$n = 1$	6.2
$n = 2/3$	4.9
Natural	8.6
Hilltop ($p = 2$)	4.4
Hilltop ($p = 4$)	6.0
Double well	6.9
Exponential	4.0

For each model we have studied the $\Delta\chi^2$ with respect to the LCDM model (no tensors)

$$\Delta\chi^2 = -2\left(\ln \mathcal{L}_{\max}(\mathrm{M1}) - \ln \mathcal{L}_{\max}(\mathrm{M2})\right)$$

Quartic and quadratic exponential are strongly and moderately disfavoured whereas smaller values seem more compatible with Planck data

The slightly higher spectral index gives stronger constraints on natural, hilltop models etc.

Planck TT + lowP + BAO

$w_{int} = 0$ for all the models

The R^2 *(Starobinsky 1980)* is still among the preferred models (even if it favours N*>54 which is the value expected from theoretical analyses) The quadratic to be compatible with data needs higher N*. These are example of the impact of the uncertainties on post inflationary phases in the prediction of the perturbation spectrum

Preliminary

Reconstruction of the inflationary potential

We have just shown the constraints on selected potentials assuming a slow-roll approximation with one single inflationary stage from the time the fluctuations are generated in the observational window until the end of inflation.

But we can go the other way round.

We can reconstruct the inflationary potential **without any approximation on slow roll or the end of inflation** in the ϕ range which corresponds to the current scales of the CMB which means phi range which corresponds to the exit from the Hubble radius during inflation (few e-folds before and after) of the scales observable today in the CMB.

We can use two methods, either expanding V(ϕ) or H(ϕ) in Taylor series with powers n=2,3,4

H(ϕ)

$$V(\phi) = 3M_P^2 H^2(\phi) - 2M_P^4 \left[H'(\phi)\right]^2 ,$$

$$\dot{\phi} = -2M_P^2 H'(\phi)$$

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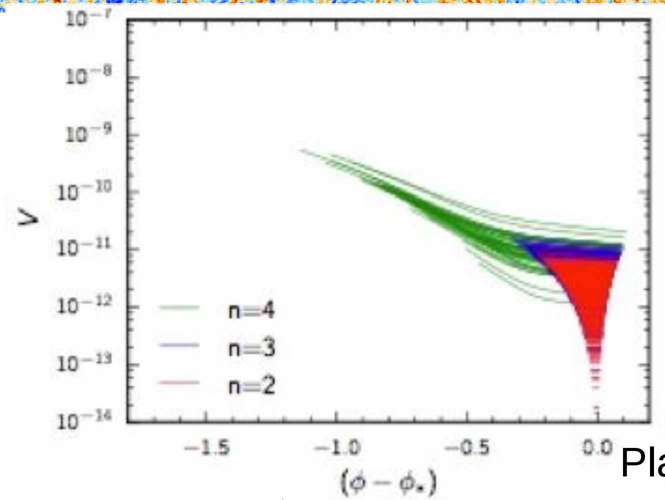
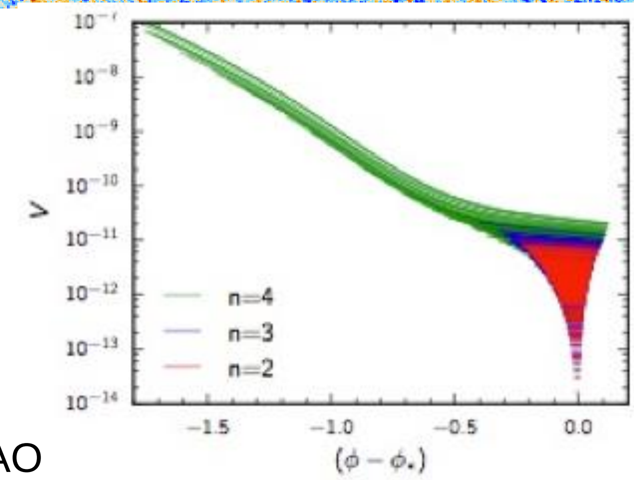
V(ϕ)



Reconstructed from the H(ϕ) expansion



Planck TT + lowP + BAO

Natural units: φ in M_p, V in M_P^4 (with reduced Planck mass)

The two reconstructions of the potential V by the two methods are different as expected (Liddle 2003).

None of the two reconstructions lead to a model preferred over ΛCDM with no tensors.

Both reconstructions allow a short stage of inflation, with a stage of fast roll which precedes it (longer for the H(ϕ) reconstruction).

Preliminary

Conclusions

planck

- The spectral index has shifted toward slightly higher values but the scale invariant spectrum is excluded at more than 5 sigma.
- There is still no evidence for running but with respect to 2013 the central values has shifted towards less negative running dur to improvement in calibration and the l=1800 feature removal.
- The temperature drives the tensor to scalar ratio constraints r<0.10 at the 95% confidence level
- All the results are consistent with each other with respect to the addition of high-ell polarization or lensing likelihood or BAO
- Low-l deficit in temperature possibly fit by violation of slow-roll at the largest scales, but not preferred at a statistical significant level
- **See the talk by Jan Hamann for other interesting methods to constrain inflation with Planck**

The scientific results that we present today are a product of the Planck Collaboration, including individuals from more than 100 scientific institutes in Europe, the USA and Canada.

Planck is a project of the European Space Agency, with instruments provided by two scientific Consortia funded by ESA member states (in particular the lead countries: France and Italy) with contributions from NASA (USA), and telescope reflectors provided in a collaboration between ESA and a scientific Consortium led and funded by Denmark.


Thank you