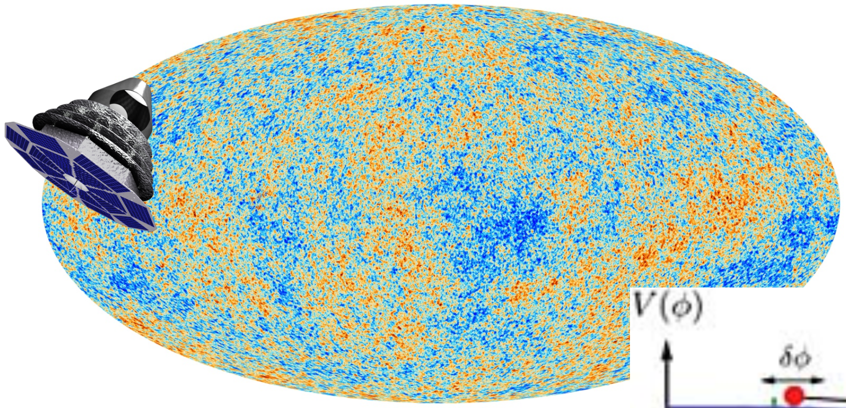
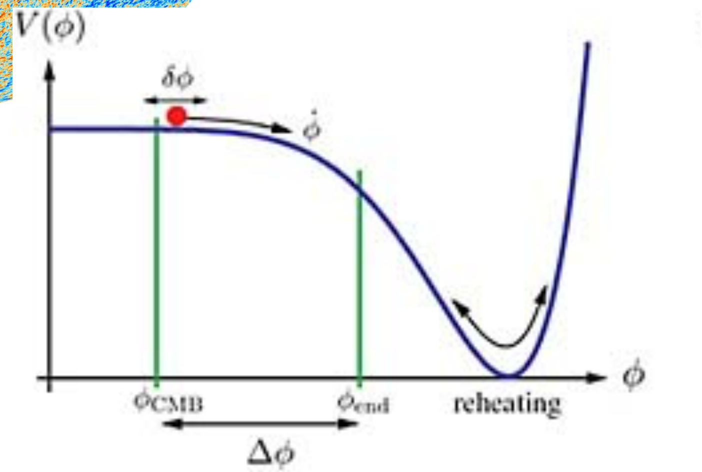
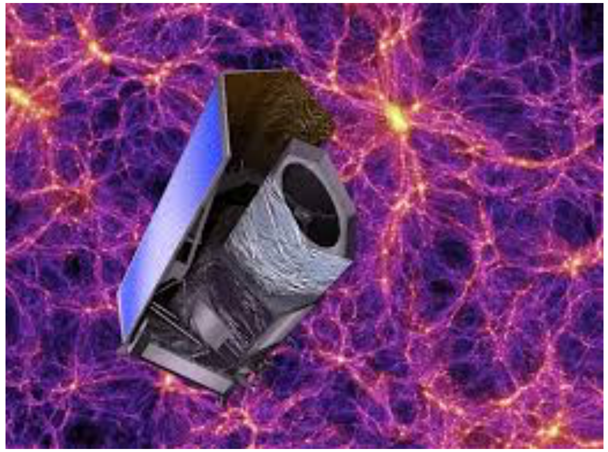
Status of Inflationary Models after Planck







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DSU 2018, LAPTh, Annecy, France

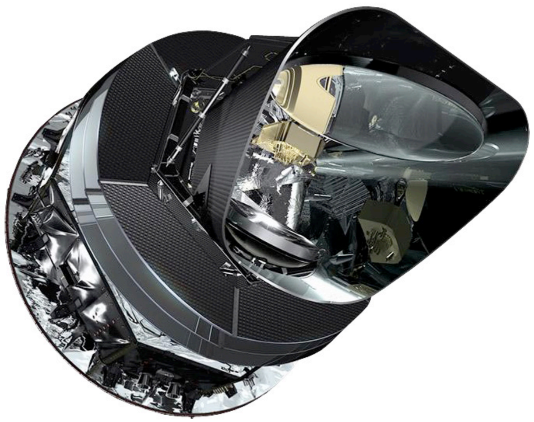
Outline

Introduction and highlights of the Planck 2015 results for inflation

Status for features in the primordial power spectrum and
outlook for the next galaxy surveys

Perspectives for the physics of inflation with future CMB experiments

The Planck satellite



Launched in May 2009, operated until October 2013.

1.5 m telescope, 2 instruments onboard, 9 frequency channels.

LFI (PI N. Mandolesi)

22 radiometers: 30, 44, 70 GHz

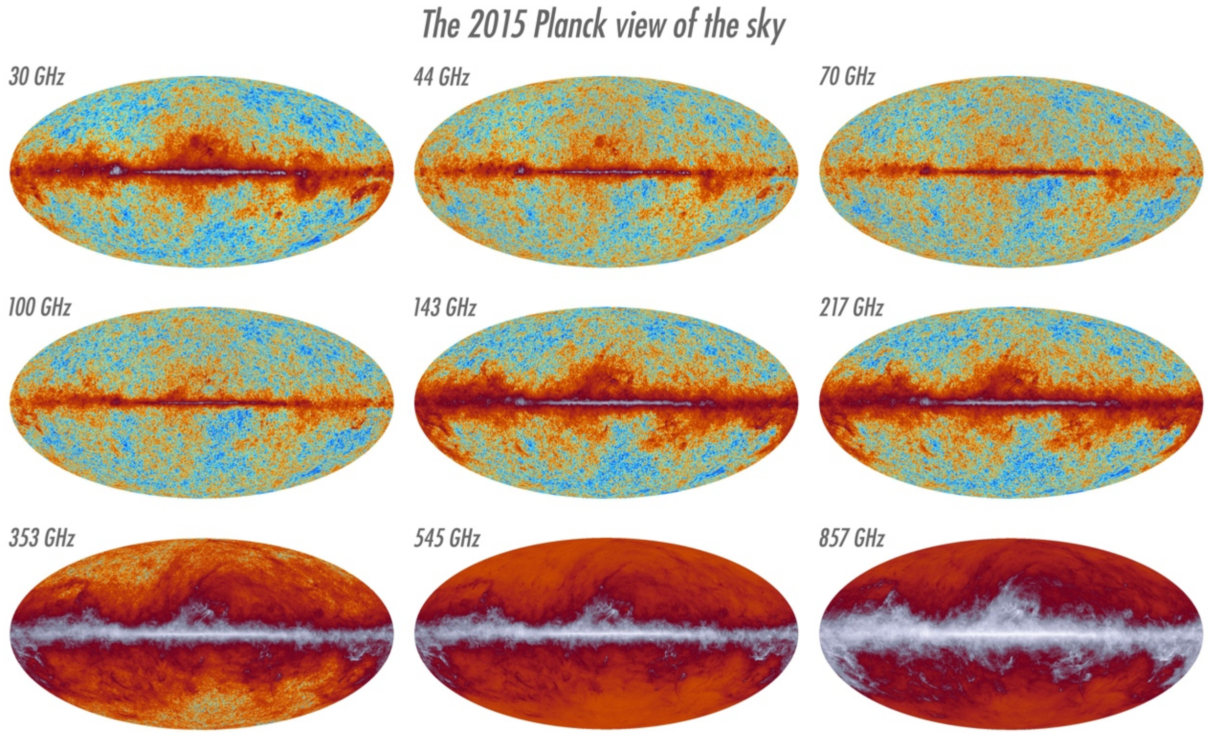
HFI (PI J.L. Puget)

50 bolometers (32 polarized): 100, 143, 217, 353, 535, 857 GHz

30-353 GHz range include polarization

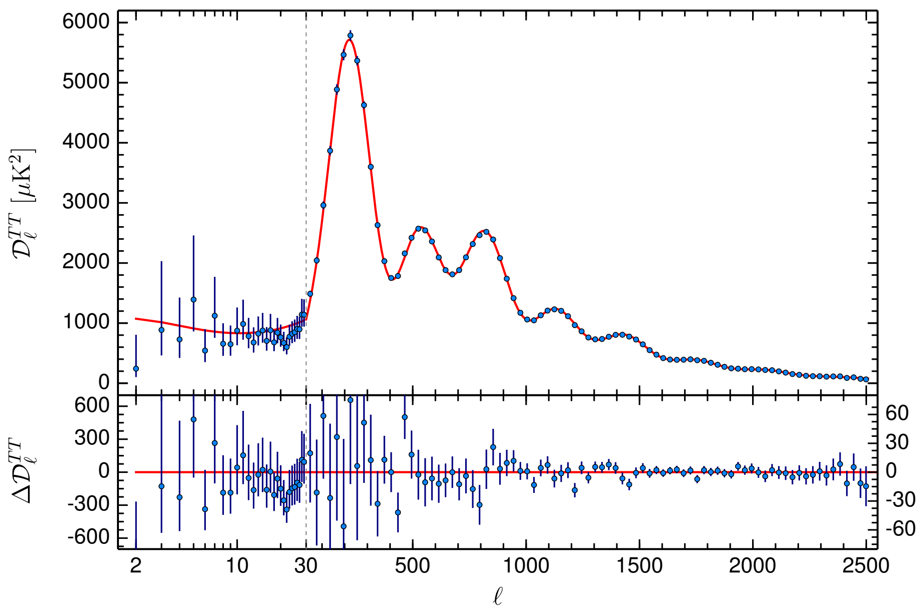
1st cosmological release in 2013.
Nominal mission, 15.5 months,
temperature data

2nd cosmological release in 2015.
Full mission, 29 months for HFI,
48 months for LFI, temperature and
a first release of polarization data



Planck & ΛCDM

Parameter	TT+lowP	TT+lowP+lensing	TT,TE,EE+lowP
$\Omega_b h^2$	0.02222 ± 0.00023	0.02226 ± 0.00023	0.02225 ± 0.00016
$\Omega_c h^2$	0.1197 ± 0.0022	0.1186 ± 0.0020	0.1198 ± 0.0015
$100\theta_{MC}$	1.04085 ± 0.00047	1.04103 ± 0.00046	1.04077 ± 0.00032
τ	0.078 ± 0.019	0.066 ± 0.016	0.079 ± 0.017
$\ln(10^{10} A_s)$	3.089 ± 0.036	3.062 ± 0.029	3.094 ± 0.034
n_s	0.9655 ± 0.0062	0.9677 ± 0.0060	0.9645 ± 0.0049
H_0	67.31 ± 0.96	67.81 ± 0.92	67.27 ± 0.66
Ω_m	0.315 ± 0.013	0.308 ± 0.012	0.3156 ± 0.0091



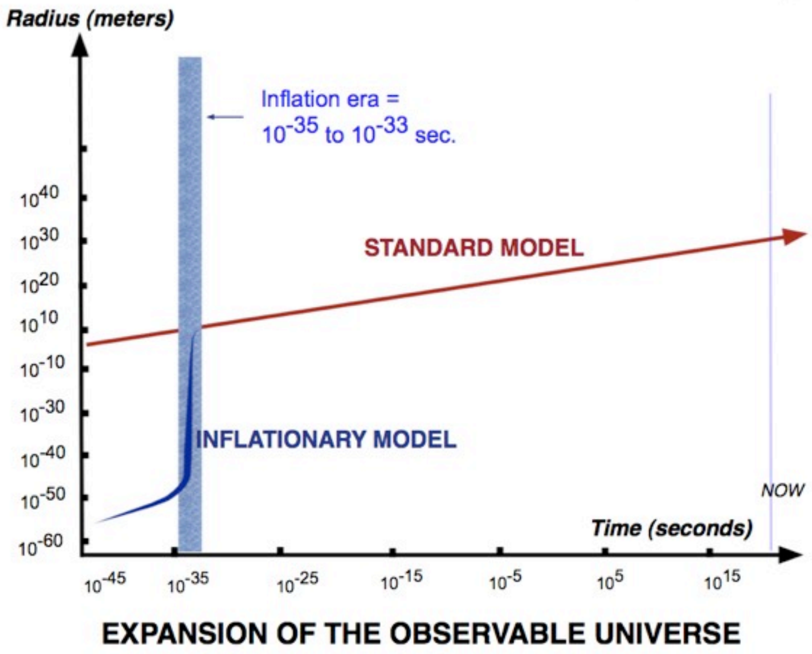
No statistically significant deviations from Λ CDM in the matter content

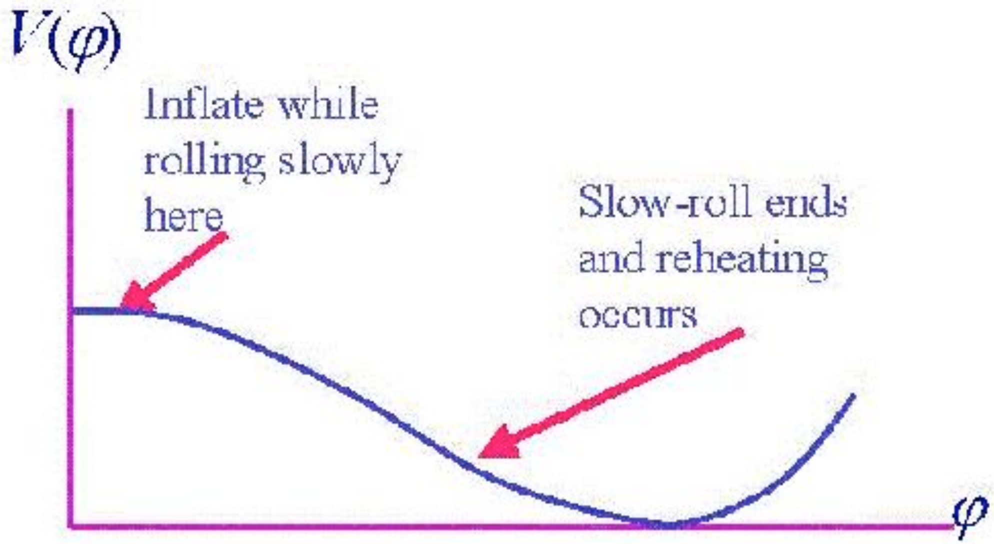
$$N_{\rm eff} = 3.13 \pm 0.32 \quad (68\,\%\ {\rm CL}\,, \textit{Planck}\ {\rm TT} + {\rm lowP})$$

$$\sum m_\nu < 0.68\,{\rm eV}\ (95\%\,{\rm CL}\,, \textit{Planck}\ {\rm TT} + {\rm lowP} + {\rm lensing})$$

$$Y_{\rm P}^{\rm BBN} = 0.253 \pm 0.041 \quad (68\,\%\ {\rm CL}\,, \textit{Planck}\ {\rm TT} + {\rm lowP})$$

Cosmic Inflation





Minimal early universe framework which solves puzzles of the Standard Big Bang model such as the flatness, horizon and monopole problems and at the same time provides a generation mechanism of primordial fluctuations.

A standard scalar field with a flat potential which supports slow-roll inflation before decaying in additional particles during the coherent oscillation stage is the simplest example.

Generation of fluctuations

Inflation solves the puzzles of the Standard Big Bang model and at the same time generates the primordial spectra of gravitational waves and of density perturbations by quantum fluctuations.

Tensor perturbations (gravitational waves)

$$\mathcal{P}_{\rm t}(k) = A_{\rm t}\left(\frac{k}{k_*}\right)^{n_{\rm t}+\frac{1}{2}\frac{dn_{\rm t}}{d\ln k}\ln\left(\frac{k}{k_*}\right)+\ldots}$$

$$A_{\rm t} \simeq \frac{2H^2}{\pi^2 M_{\rm pl}^2} \approx \frac{2V}{3\pi^2 M_{\rm pl}^4}$$

$$n_{\rm t} \simeq -2\epsilon_1 \approx -\frac{M_{\rm pl}^2 V_\phi^2}{V^2}$$

$$\epsilon_1 = -\frac{\dot{H}}{H^2} << 1$$

$$\frac{dn_{\rm t}}{d\ln k} \simeq -2\epsilon_1\epsilon_2$$

$$\epsilon_2 = -\frac{\dot{\epsilon}_1}{H\epsilon_1} << 1$$

Scalar perturbations

$$\mathcal{P}_{\mathcal{R}}(k) = A_{\rm s}\left(\frac{k}{k_*}\right)^{n_{\rm s}-1+\frac{1}{2}\frac{dn_{\rm s}}{d\ln k}\ln\left(\frac{k}{k_*}\right)+\ldots}$$

$$A_{\rm s} \approx \frac{V^3}{12\pi^2 M_{\rm pl}^6 V_\phi^2}$$

$$n_{\rm s} - 1 \simeq -2\epsilon_1 - \epsilon_2$$

$$\approx -3\frac{M_{\rm pl}^2 V_\phi^2}{V^2} + 2\frac{M_{\rm pl}^2 V_{\phi\phi}}{V}$$

$$\frac{dn_{\rm s}}{d\ln k} \simeq -2\epsilon_1\epsilon_2 - \epsilon_2\epsilon_3$$

$$r = \frac{\mathcal{P}_{\rm t}(k_*)}{\mathcal{P}_{\mathcal{R}}(k_*)} \simeq 16\epsilon_1 \simeq -8n_{\rm t}$$

Generation of fluctuations: 2

The generation of quantum fluctuation is not only characterized by the two-point correlation function

$$\langle \mathcal{R}(\mathbf{k}_1)\ \mathcal{R}(\mathbf{k}_2)\rangle = (2\pi)^3\ \frac{2\pi^2}{k^3}\mathcal{P}_{\mathcal{R}}(k)\ \delta^3(\mathbf{k_1}+\mathbf{k_2})$$

but also from higher order correlations due to non-linearity in the inflation potential and in EG

$$\langle \mathcal{R}(\mathbf{k_1})\ \mathcal{R}(\mathbf{k}_2)\ \mathcal{R}(\mathbf{k}_3)\rangle = (2\pi)^3 B_{\mathcal{R}}(k_1,k_2,k_3)\delta^3(\mathbf{k_1}+\mathbf{k_2}+\mathbf{k_3})$$

$$B_{\mathcal{R}}(k_1,k_2,k_3) \propto f_{\rm NL} F(k_1,k_2,k_3)$$

The non-Gaussianity parameter $f_{\rm NL}$ generated in single field slow-roll inflation with a kinetic term with vacuum initial conditions for fluctuations is $f_{\rm NL} \sim \mathcal{O}(\epsilon_1\ , \epsilon_2)$, i.e. at an undetectable level below the Planck sensitivity and smaller than other general relativistic contributions, such as the cross-correlation between the integrated Sachs-Wolfe effect and the gravitational lensing of the CMB.

For a general scalar field Lagrangian or for multi-field inflation, the non-Gaussian contribution can be large enough to be accessible to Planck.

Planck 2015 results and the basic predictions of inflation

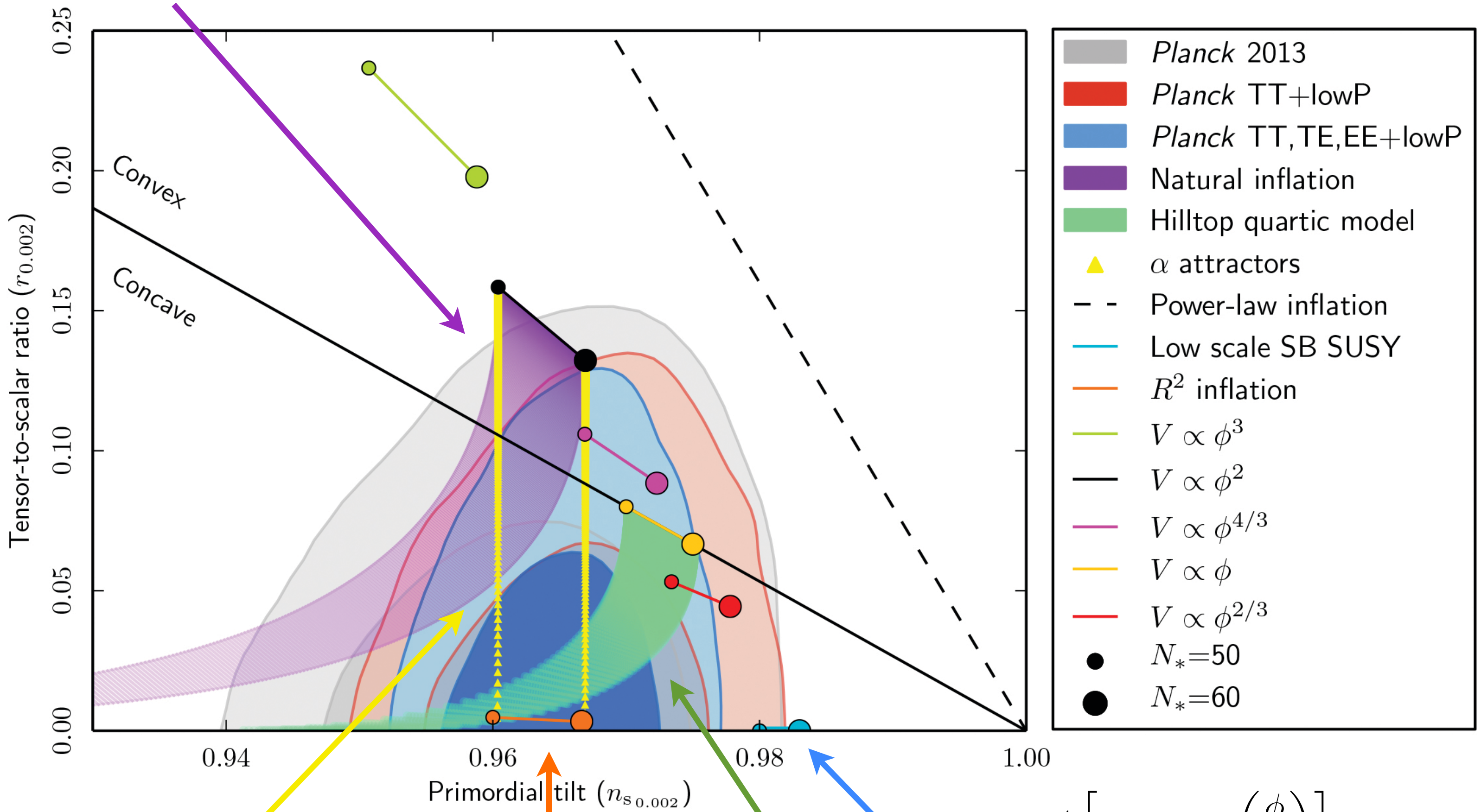
A nearly flat Universe (incl. Planck lensing)	$\Omega_K = -0.005^{+0.016}_{-0.017}$	95%CL
A tilted power-law spectrum for density perturbations	$n_\mathrm{s} = 0.9655 \pm 0.0062$	68%CL
No statistical evidence of scale dependence of ns	$dn_\mathrm{s}/d\ln k = -0.0084 \pm 0.0082$	68%CL
Small relative amount of gravitational waves	$r_{0.002} < 0.10$	95%CL
Nearly Gaussian perturbations (incl. polarization)	$f_\mathrm{NL}^\mathrm{local} = -0.8 \pm 5.0$ $f_\mathrm{NL}^\mathrm{equil} = -3.7 \pm 43$ $f_\mathrm{NL}^\mathrm{ortho} = -26 \pm 21$	68%CL
No need for additional fields: nearly adiabatic fluctuations	$\beta_\mathrm{iso} < 0.035$	95%CL
No evidence of cosmic strings	$f_{10} < 0.020$ $(G\mu < 1.8\, 10^{-7}$	95%CL 95% CL)

Inflationary models & Planck 2015

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

Freese et al. 1990

Planck 2015 results. XX. Constraints on inflation, Astron. Astrophysics 594 (2016) A20



$$V(\phi) = \Lambda^4 \left[1 + \alpha_h \ln\left(\frac{\phi}{\mu}\right)\right]$$

Dvali et al. 1994

$$V(\phi) = \Lambda^4 \tanh^2\left(\frac{\phi}{\sqrt{6\alpha}M_{pl}}\right)$$

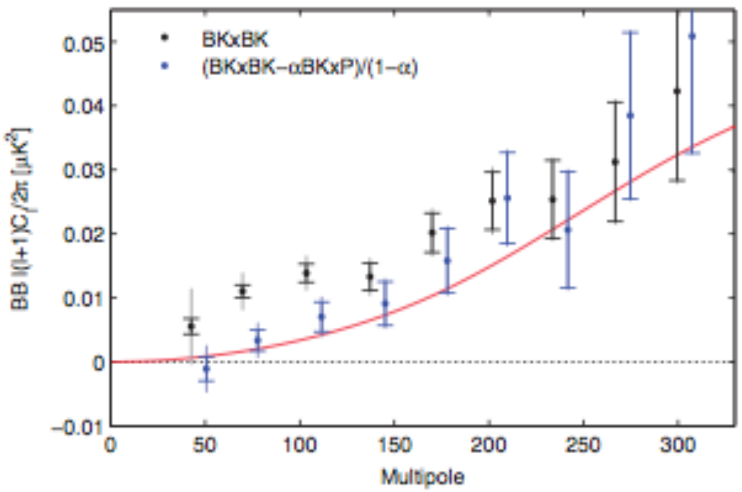
Kallosh & Linde 2013

$$V(\tilde{\phi}) = \frac{\Lambda^4}{4}\left(1 - e^{-2\tilde{\phi}/\sqrt{6}M_{pl}}\right)^2$$

Starobinsky 1980

$$V(\phi) = \Lambda^4 \left(1 - \frac{\phi^4}{\mu^4} + \ldots\right)$$

Inflationary models incl. BKP joint analysis



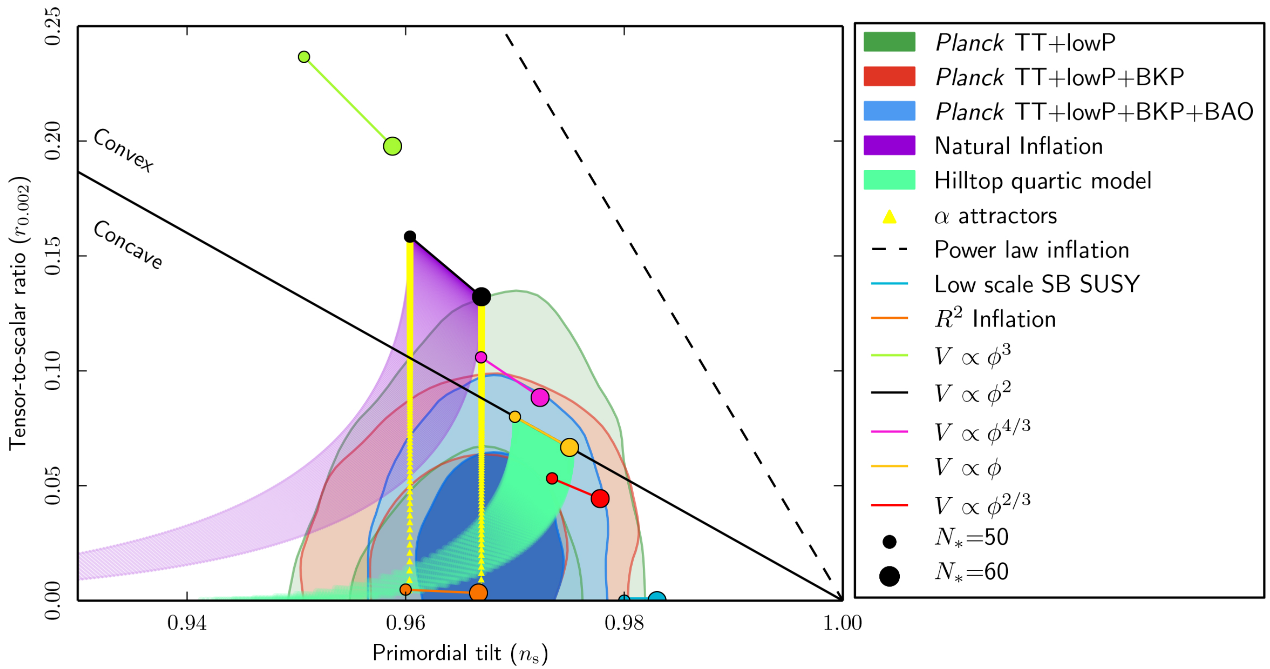
PRL 114 (2015) 101301

r < 0.12 at 95%CL

Same constraint as
Planck 2013 + high-l
but NOW from BB alone!

Planck TT + lowP + BKP

r < 0.08 at 95%CL



$$V^{1/4} \lesssim 1.8 \times 10^{16} \mathrm{GeV}\ (95\%\mathrm{CL})$$

The allowed relative region of concave potentials over convex ones is increased.

Inflationary models incl. BKP joint analysis (2)

Planck TT + lowP + BKP + BAO

Inflationary model	$\ln B_{0X}$ $w_{\rm int}=0$	$\ln B_{0X}$ $w_{\rm int}\neq 0$
$R+R^2/(6M^2)$	...	+0.3
$n=2/3$	−1.9	−1.2
$n=1$	−1.6	−1.8
$n=4/3$	−2.1	−2.5
$n=2$	−6.0	−5.6
$n=3$	−16.0	−15.6
$n=4$	−30.1	−29.9
Natural	−5.6	−5.0
Hilltop ($p=2$)	−0.7	−0.4
Hilltop ($p=4$)	−0.6	−0.9
Double well	−4.3	−4.2
Brane inflation ($p=2$)	+0.2	0.0
Brane inflation ($p=4$)	+0.1	−0.1
* Exponential tails	−0.1	0.0
SB SUSY	−1.8	−1.5
** Supersymmetric α-model	−1.1	+0.1
*** Superconformal ($m=1$)	−1.9	−1.4
Superconformal ($m\neq 1$)	−2.5	−2.2

R + R² inflation, a linear potential, fractional exponents (2/3, 4/3) for monomial potentials, brane inflation, SB SUSY, alpha attractors fit the data in a similar manner.

When including BKP quadratic potential and natural inflation also strongly disfavoured as were quartic potential, power-law inflation, hybrid inflation predicting ns > 1 and inverse power-law for 2013. Double well is moderately disfavoured.

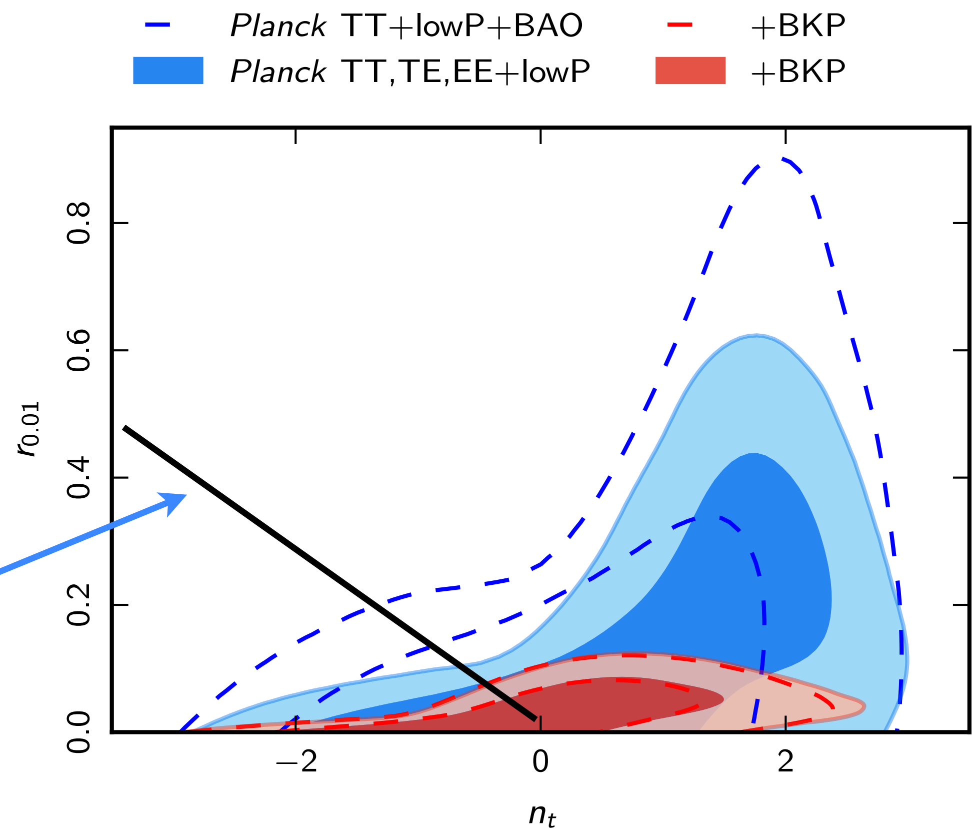
Allowing for $w_{\rm int}$ to vary does not alter these conclusions for this selection of models at Planck + BKP precision.

* $V(\phi)=\Lambda^4\left(1-e^{-q\phi/M_{\rm pl}}+...\right)$ (*Goncharov & Linde 1984; Burgess et al. 2002; Cicoli et al. 2009*)

** E-model with n=1 $\quad V(\phi)=\Lambda^4\left(1-e^{-\sqrt{2}\phi/(\sqrt{3\alpha}M_{\rm pl})}\right)^{2n}$

*** T-model $\quad V(\phi)=\Lambda^4\tanh^{2m}\left(\frac{\phi}{\sqrt{6\alpha}M_{\rm pl}}\right)$

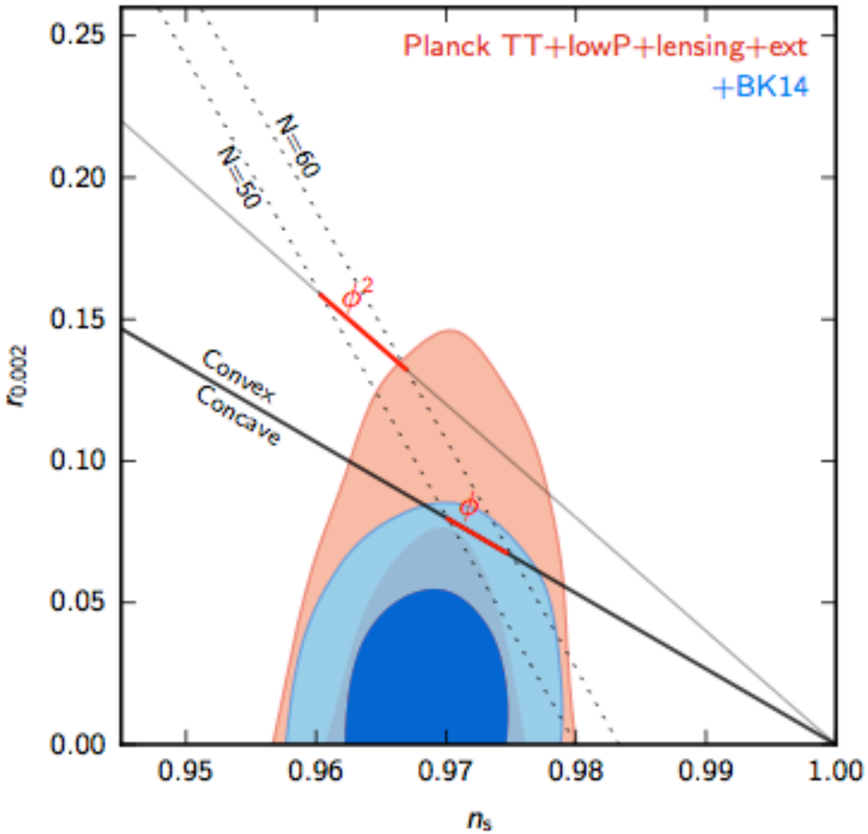
A test for the tensor tilt consistency relation



$n_{\rm t} = -r/8$

$$-0.38 < n_{\rm t} < 2.6\,(95\%\text{CL})$$

The constraint on r had been tightened by the latest release of Bicep 2/Keck Array including the Keck Array 95 GHz channel to $r_{005} < 0.07$ at 95 % CL (Ade et al., BICEP 2 and Keck Array collaborations, Phys.Rev.Lett. 116 (2016) 031302) and the previous conclusions are further strengthened.



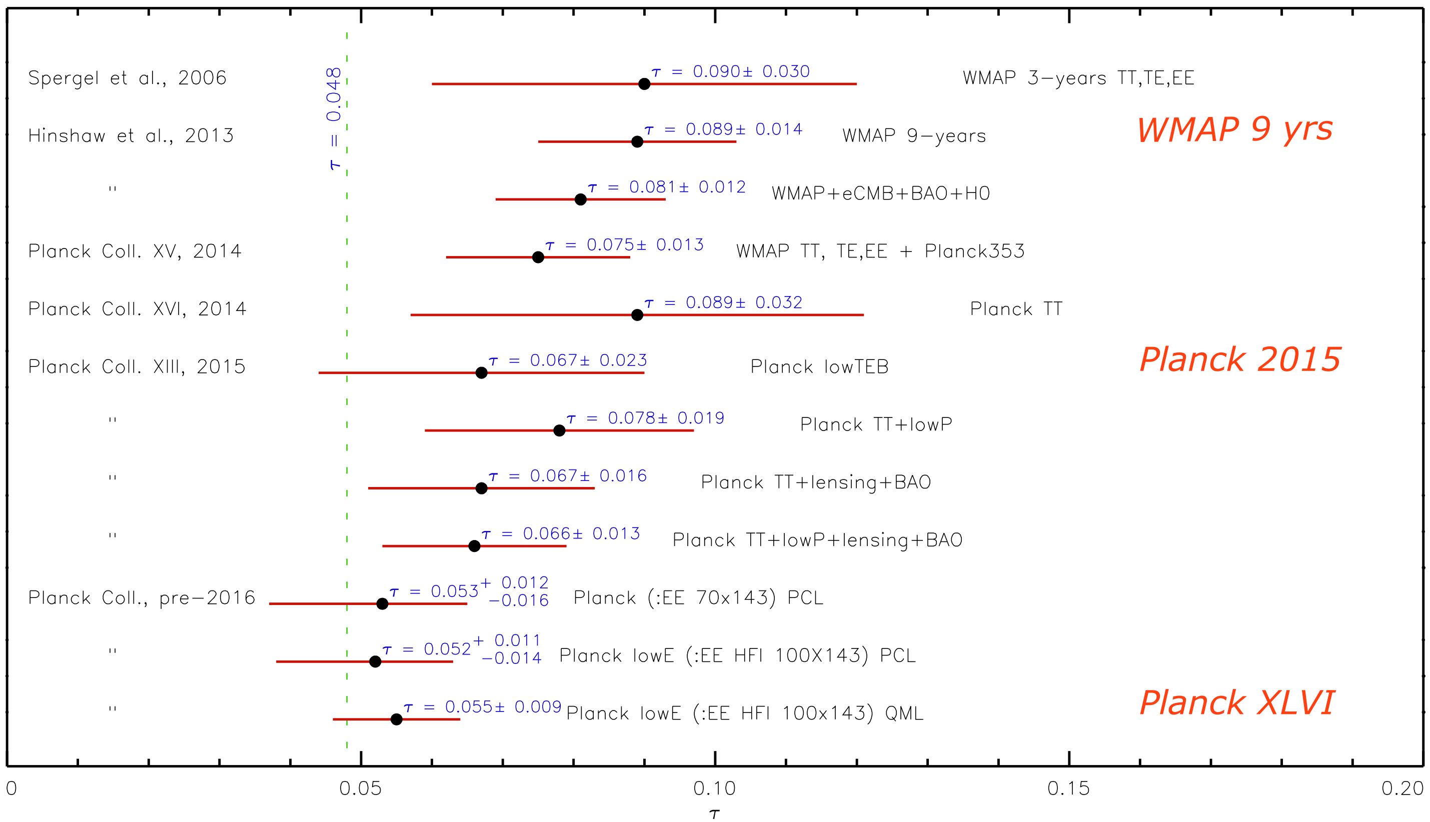
Beyond the Planck 2015 release

Planck 2015 results were based on a joint temperature-polarization low multipole likelihood, whose data on polarization are from LFI 70 GHz channel cleaned by the 30 GHz and 353 GHz channels for synchrotron and dust, respectively.

First results on the average optical depth from HFI data in 2016, obtained by a EE simulation based likelihood for 100x143 GHz channels foreground cleaned again by 30 GHz and 353 GHz

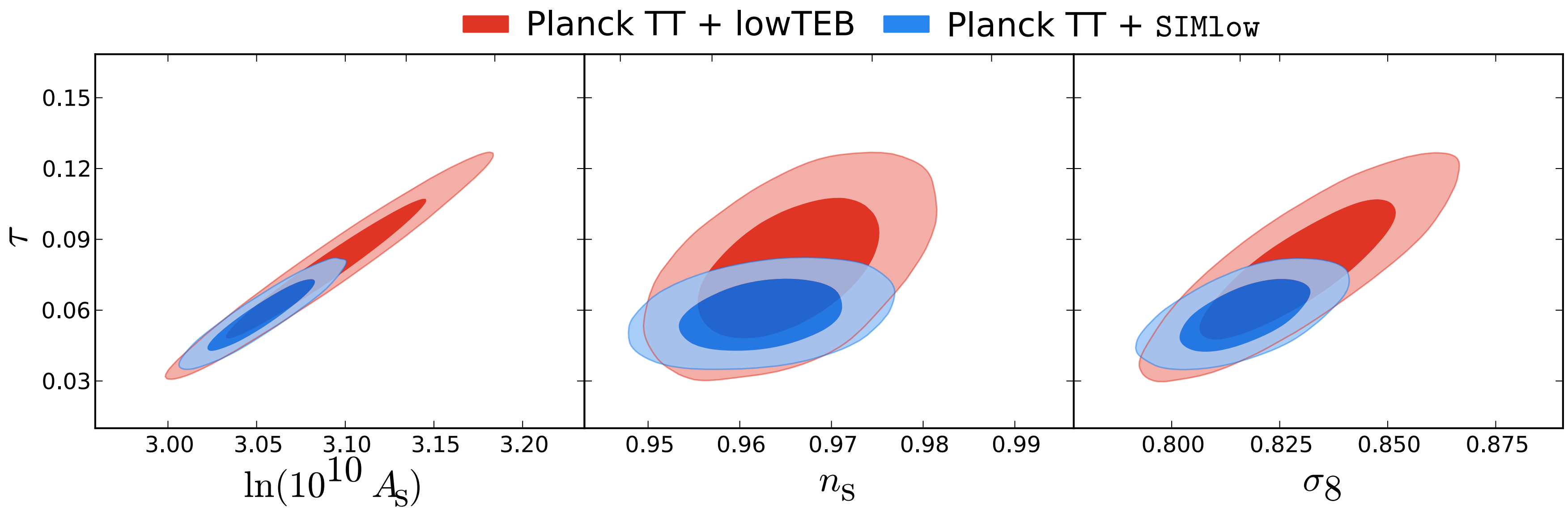
$$\tau = 0.055 \pm 0.009 \quad (68\,\%\mathrm{CL}\,,\mathrm{lowE})$$

Planck 2015 $$\tau = 0.067 \pm 0.023 \quad (68\,\%\mathrm{CL}\,,\mathrm{lowTEB})$$



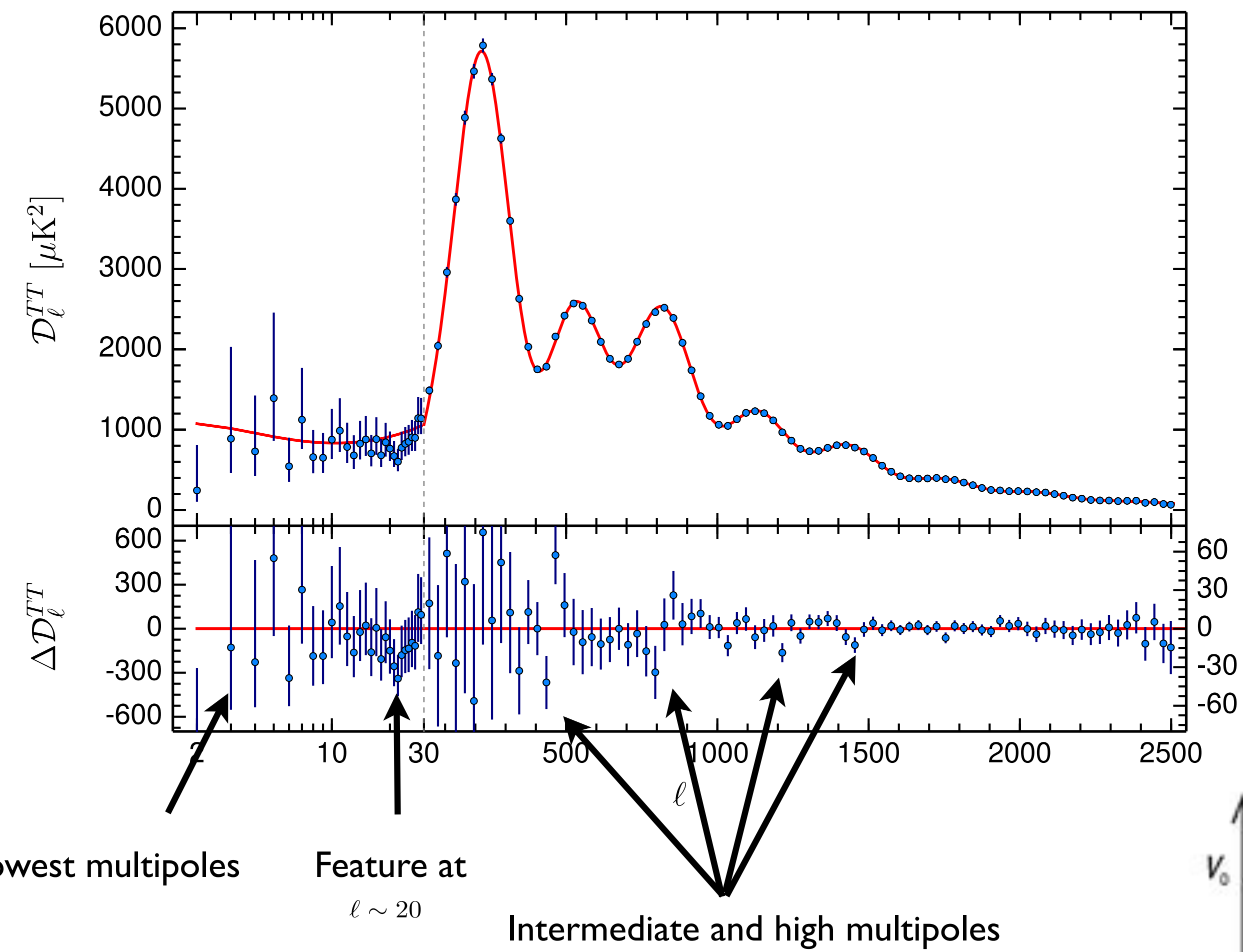
Planck intermediate results. XLVI. Reduction of large-scale systematic effects in HFI polarization maps and estimation of the reionization optical depth, Astron. Astrophysics 596 (2016) A107

Beyond the Planck 2015 release: 2

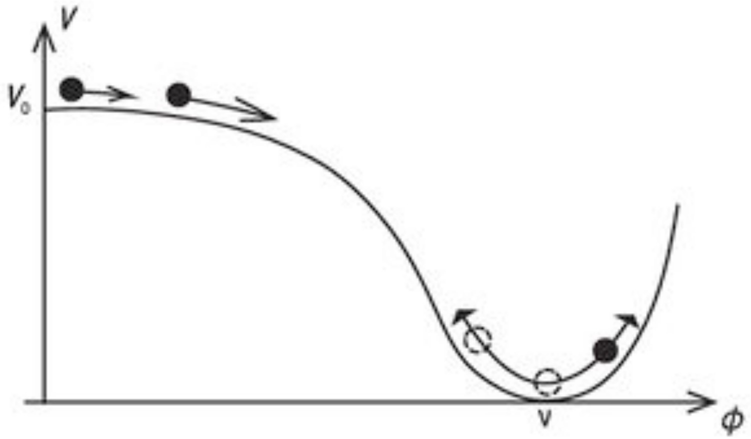


Forthcoming Planck final release PR3 will be dedicated to the improvement of the polarization data model at low and high multipoles

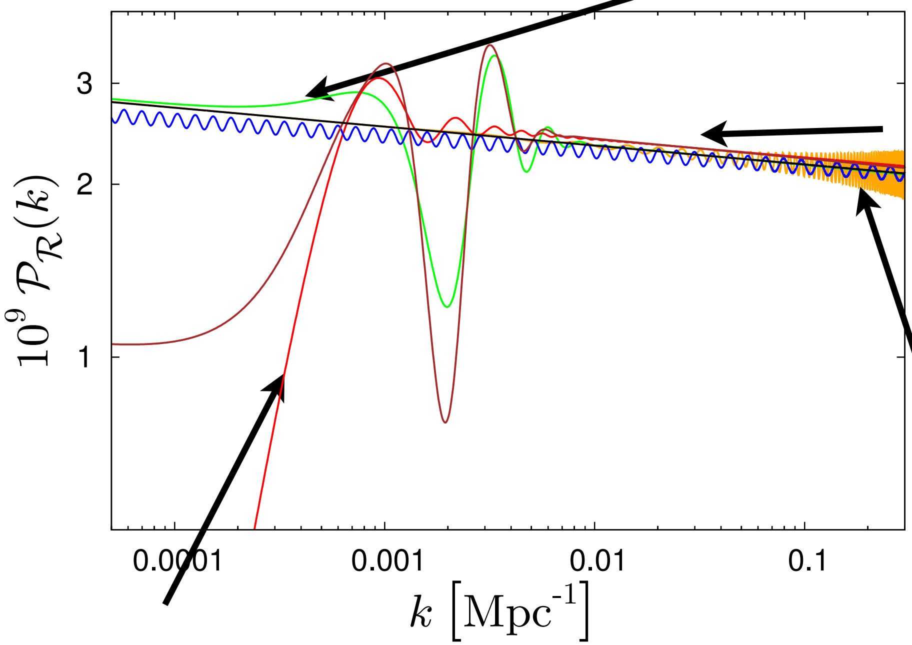
A smooth PPS?



Slow roll?



Search for parametrized features in the power spectrum



Step in the potential:

$$V(\phi) = \frac{m^2}{2}\phi^2\left[1 + c\tanh\left(\frac{\phi-\phi_c}{d}\right)\right]$$

Non vacuum initial conditions/instanton effects in axion monodromy (log wiggles)

$$V(\phi) = \mu^3\phi + \Lambda^4\cos\left(\frac{\phi}{f}\right)$$

$$\mathcal{P}_{\mathcal{R}}^{\log}(k) = \mathcal{P}_{\mathcal{R}}^{0}(k)\left[1 + \mathcal{A}_{\log}\cos\left(\omega_{\log}\ln\left(\frac{k}{k_*}\right) + \varphi_{\log}\right)\right].$$

Linear oscillations as from Boundary EFT (linear wiggles)

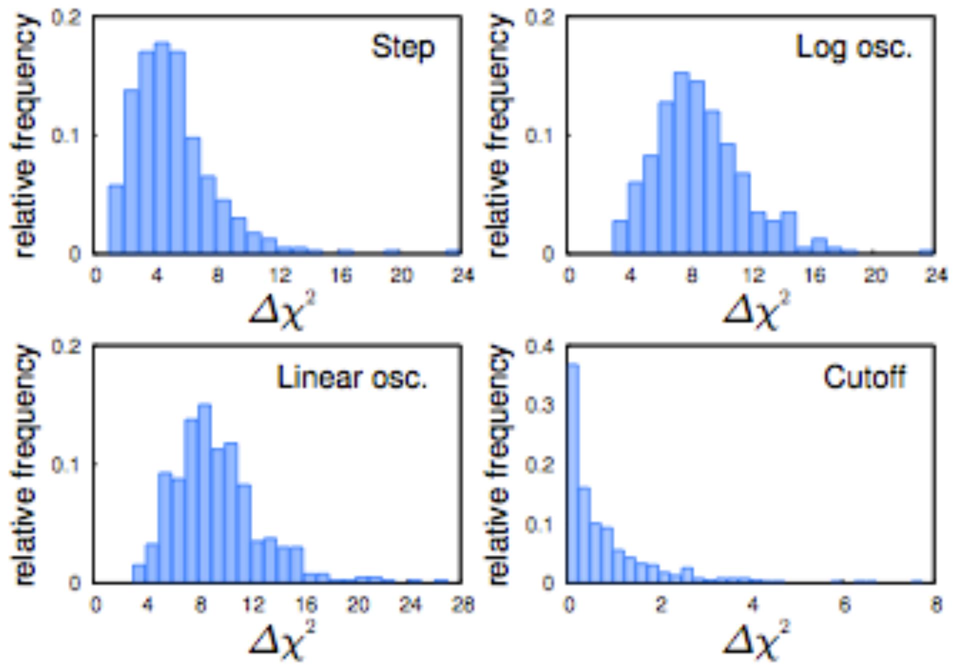
$$\mathcal{P}_{\mathcal{R}}^{\rm lin}(k) = \mathcal{P}_{\mathcal{R}}^{0}(k)\left[1 + \mathcal{A}_{\rm lin}\left(\frac{k}{k_*}\right)^{n_{\rm lin}}\cos\left(\omega_{\rm lin}\frac{k}{k_*} + \varphi_{\rm lin}\right)\right]$$

Short stage of inflation preceded by a kinetic stage

Bayesian & frequentist analysis

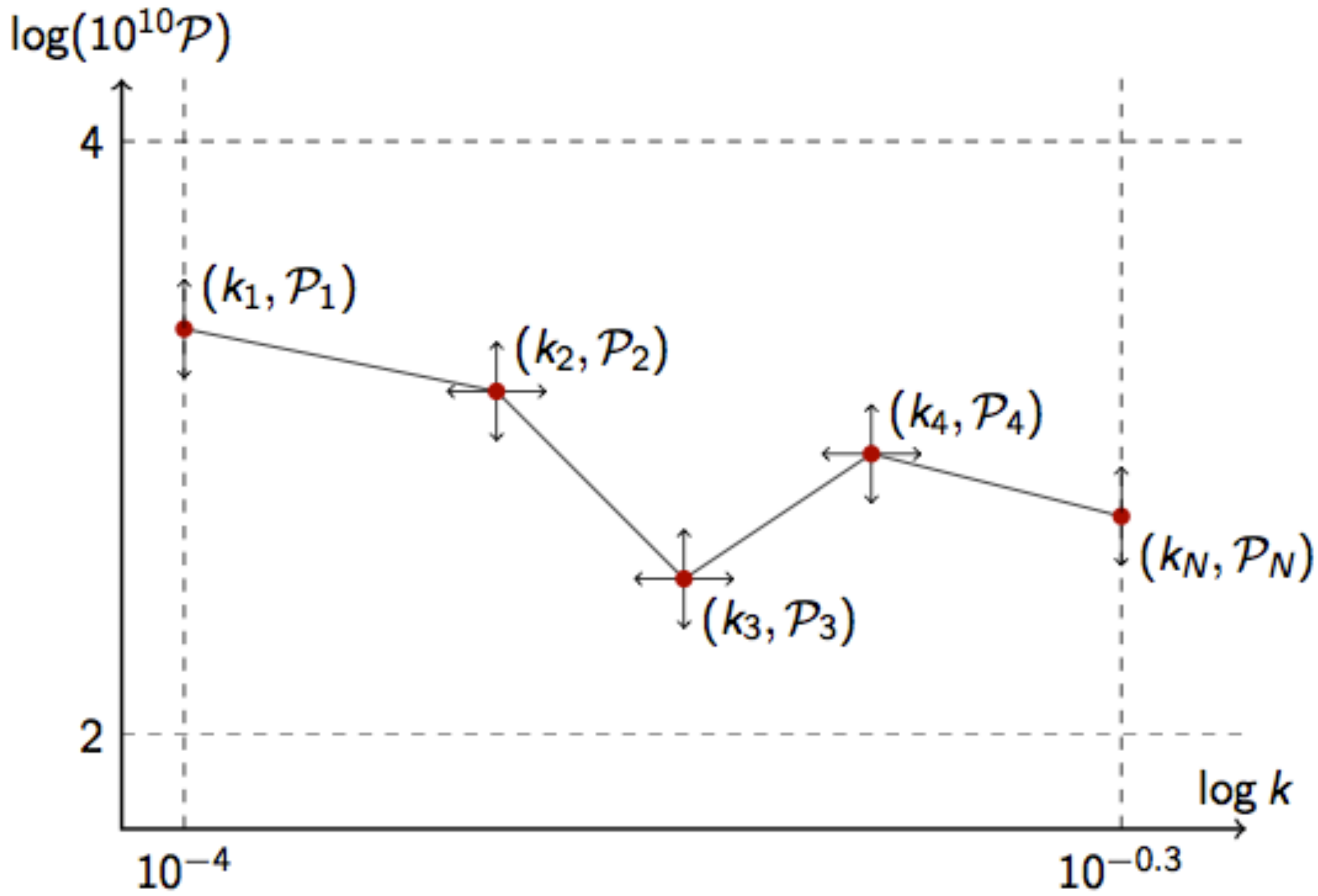
Model	*Planck* TT+lowP $\Delta\chi^2$	*Planck* TT+lowP $\ln B$	*Planck* TT,TE,EE+lowP $\Delta\chi^2$	*Planck* TT,TE,EE+lowP $\ln B$	PTE
Step	−8.6	−0.3	−7.3	−0.6	0.09
Log osc.	−10.6	−1.9	−10.1	−1.5	0.24
Linear osc.	−8.9	−1.9	−10.9	−1.3	0.50
Cutoff	−2.0	−0.4	−2.2	−0.6	0.12

Table 13. Improvement in fit and Bayes factors with respect to power-law base ΛCDM for *Planck* TT+lowP and *Planck* TT,TE,EE+lowP data, as well as approximate probability to exceed the observed $\Delta\chi^2$ (p-value), constructed from simulated *Planck* TT+lowP data. Negative Bayes factors indicate a preference for the power-law model.

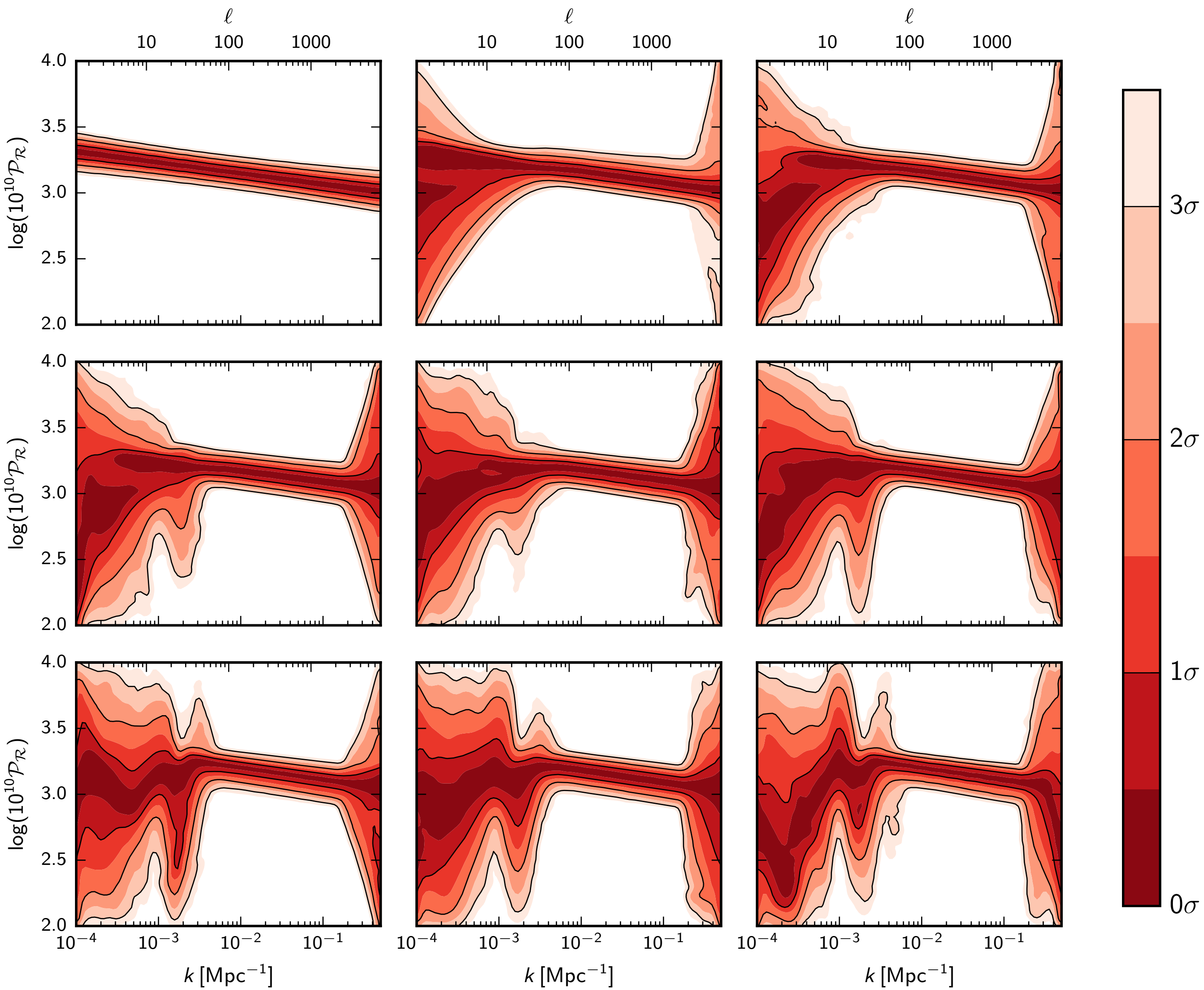


None of the models considered is preferred to the baseline model, and none of the corresponding improvement in fit seems statistically anomalous.

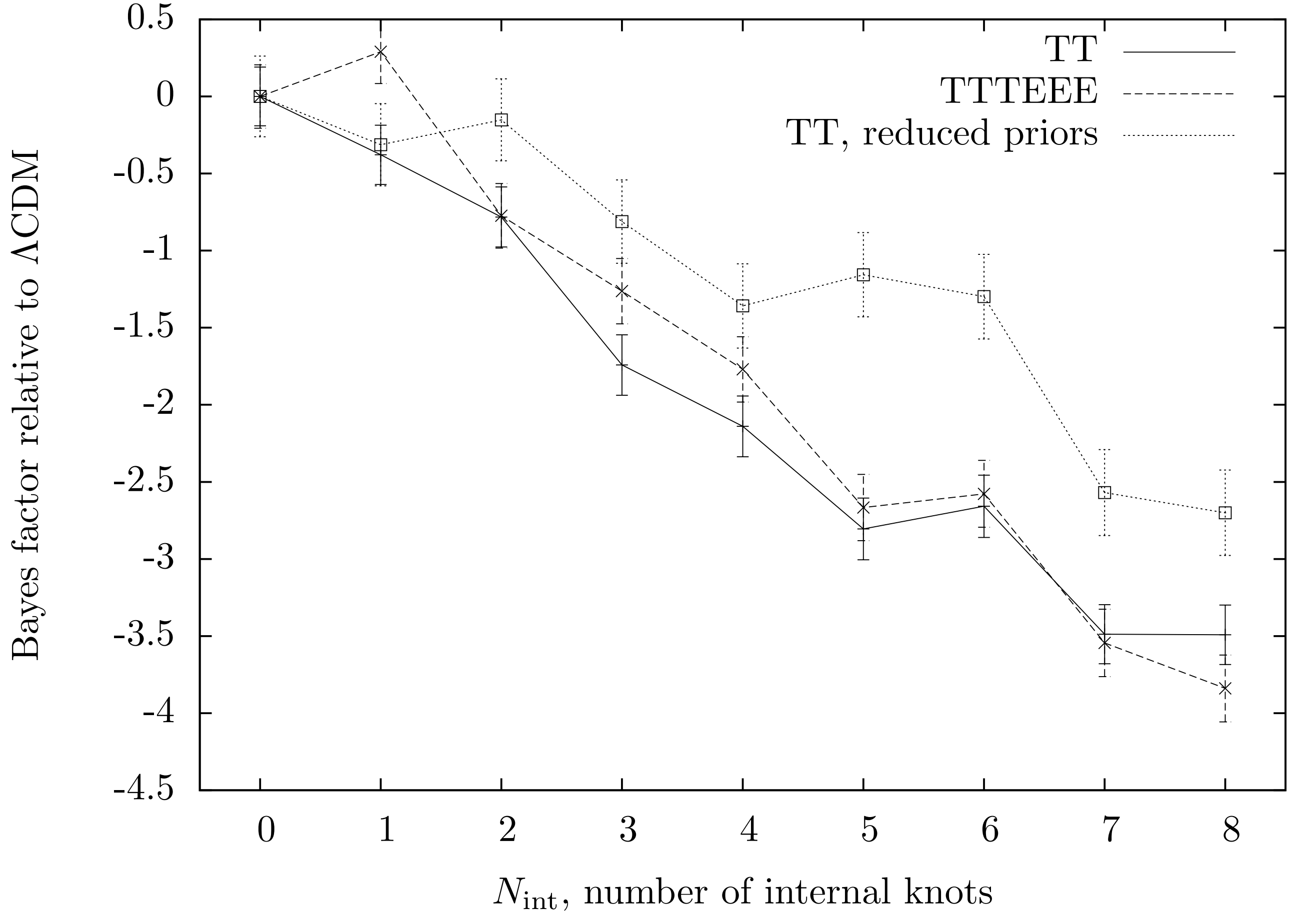
Reconstruction of the primordial power spectrum



Reconstruction of the primordial power spectrum (2)

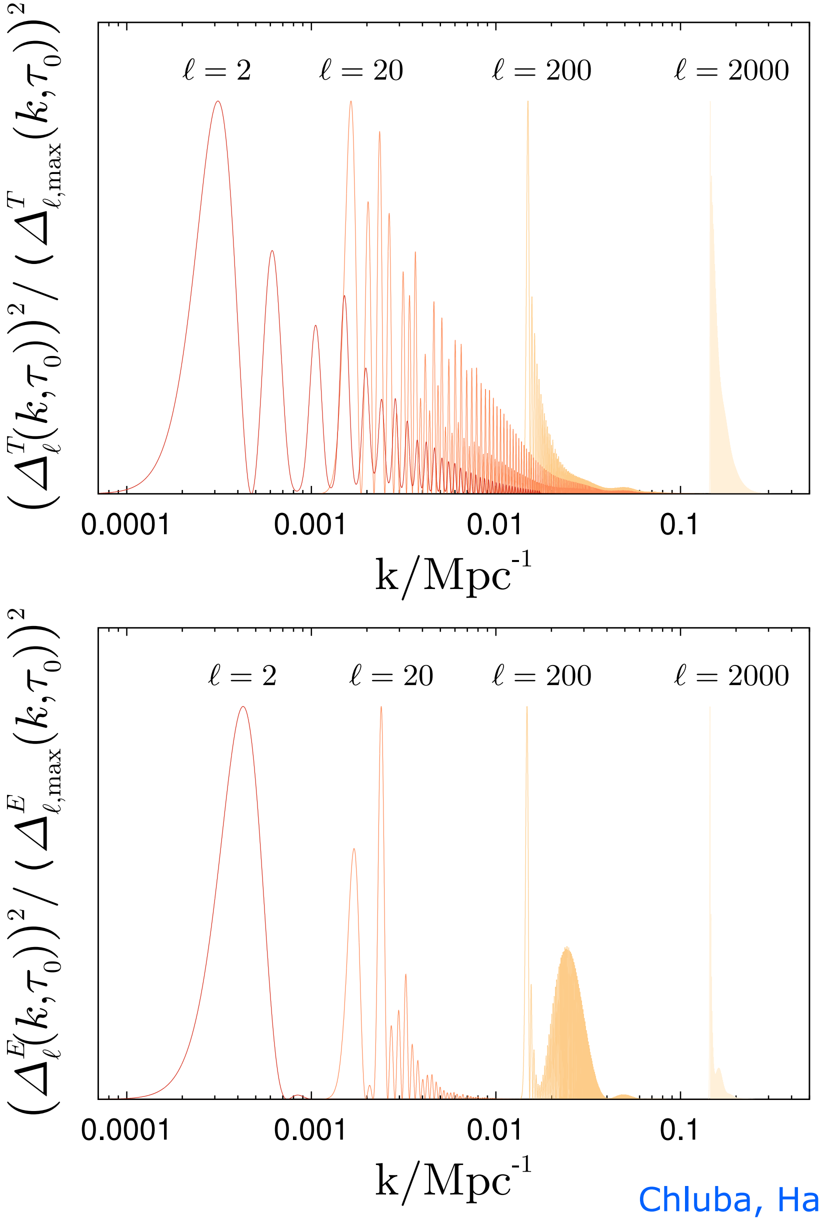


Reconstruction of the primordial power spectrum (3)



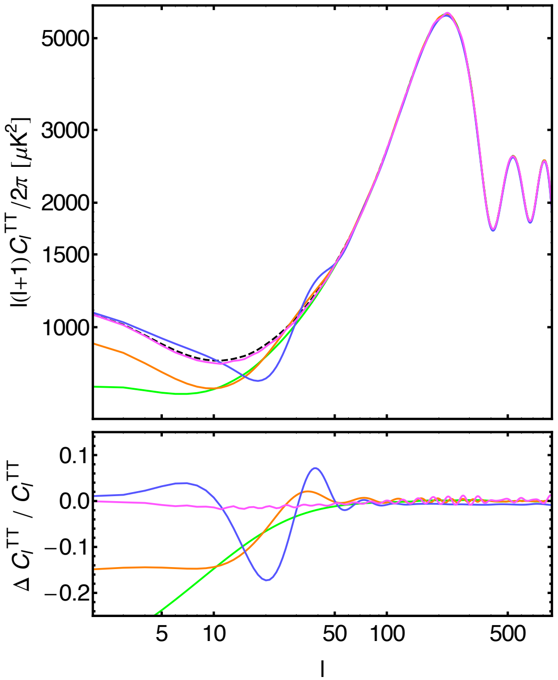
How do we move from here?

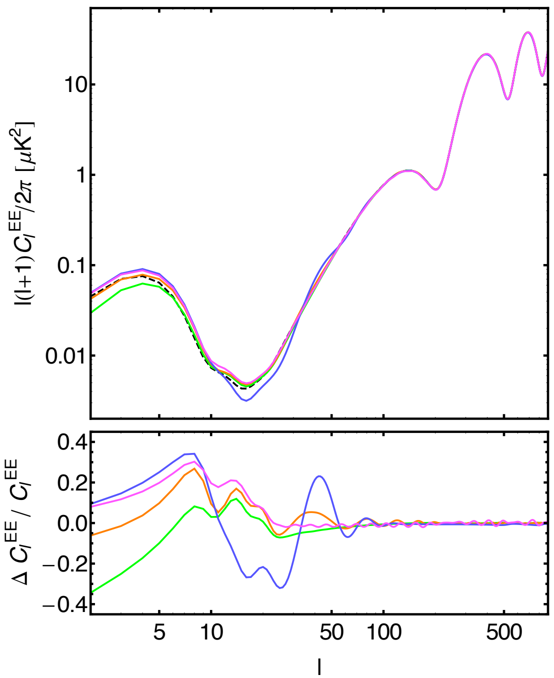
CMB Polarization

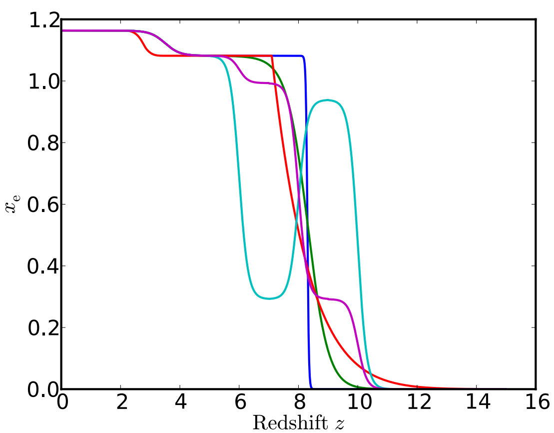


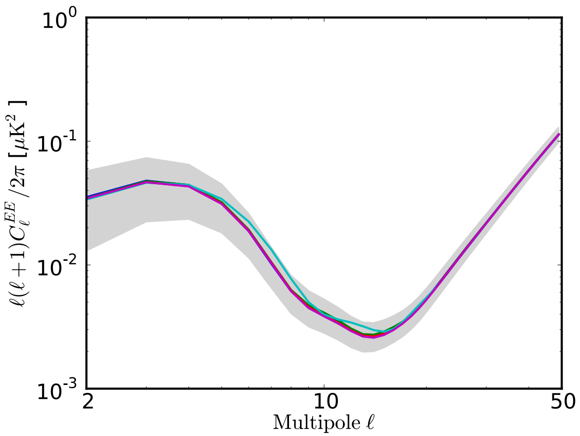
Chluba, Hamann, Patil, IJMPD 24 (2015) 1530023

CMB Polarization: confusion with reionization









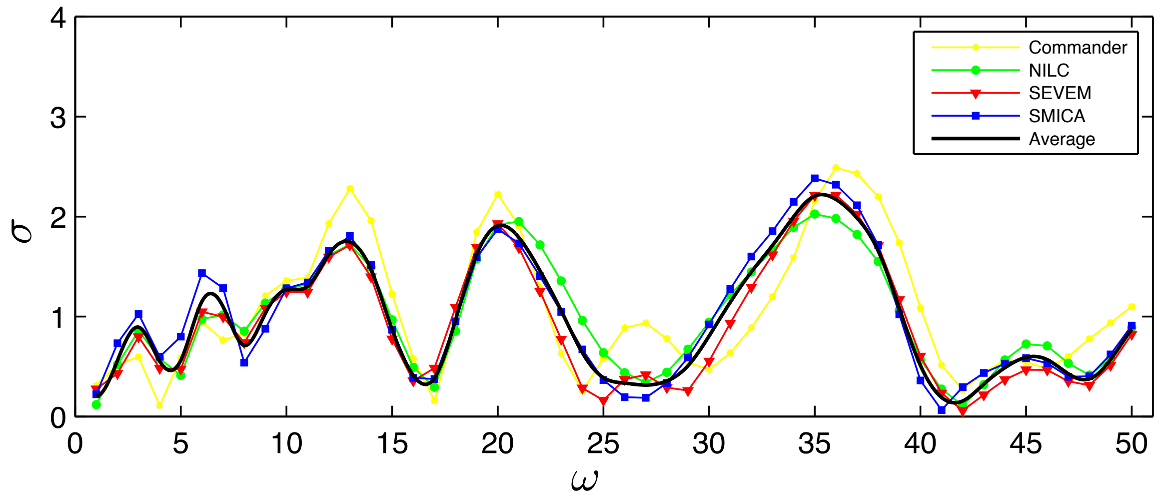
Planck intermediate results XLVII. Planck constraints on reionization history

Bispectrum

$$V(\phi) = \frac{1}{2} m^2 \phi^2 \left[1 + c \, \sin\left(\frac{\phi}{\Lambda}\right) \right]$$

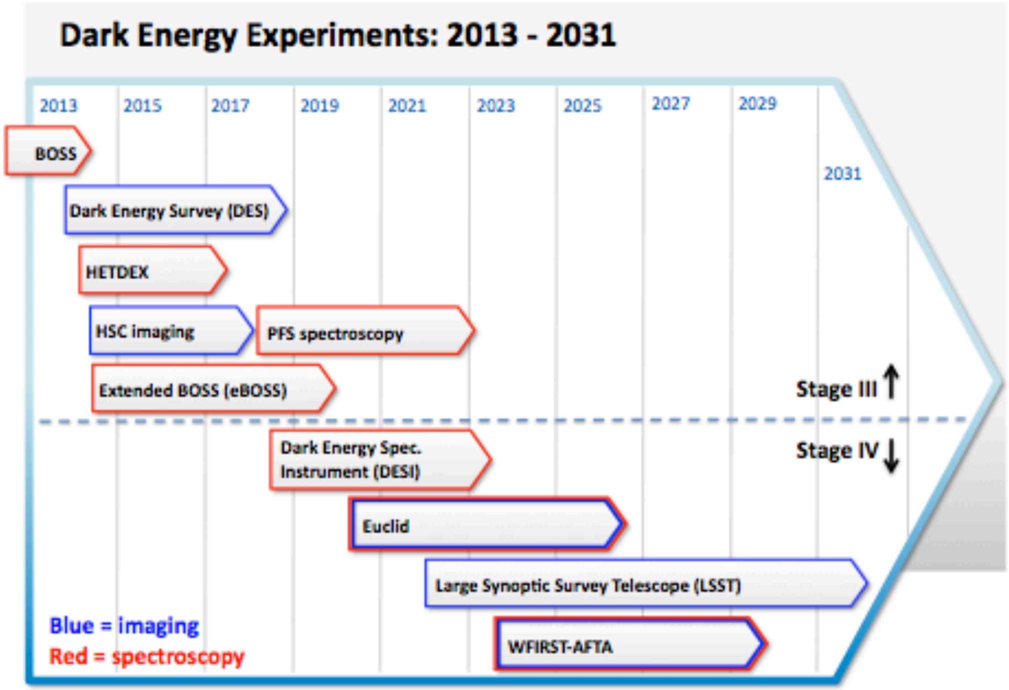
$$B^{\rm feat}(k_1, k_2, k_3) = \frac{6 A^2 f_{\rm NL}^{\rm feat}}{(k_1 k_2 k_3)^2} \sin\left[\omega(k_1 + k_2 + k_3) + \phi\right] \, ,$$

Chen, Easther, Lim, JCAP 0804 (2008)

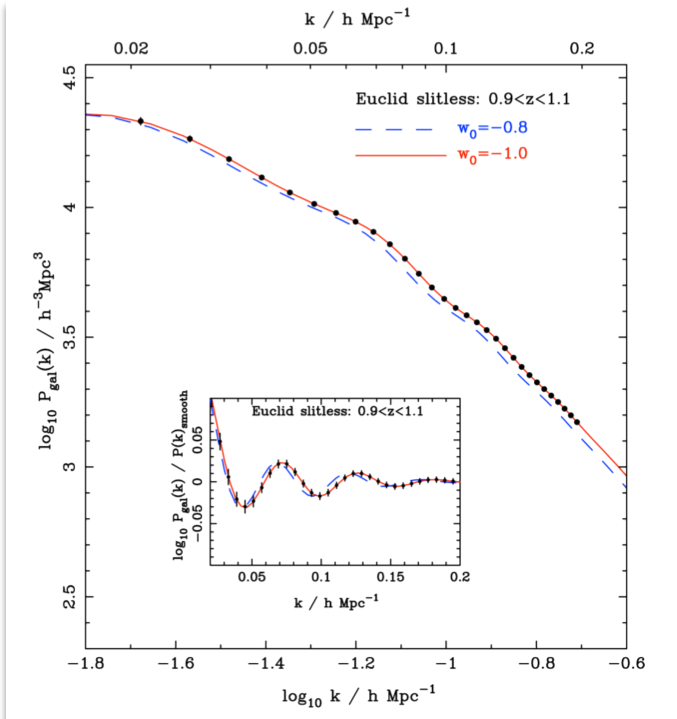


Planck 2015 results. XVII. Constraints on primordial non-Gaussianity, Astron. Astrophysics 594 (2016) A17, Fig. 24

Future Large Scale Structure Surveys



Dodelson et al., arXiv:1309.5386 (2013)



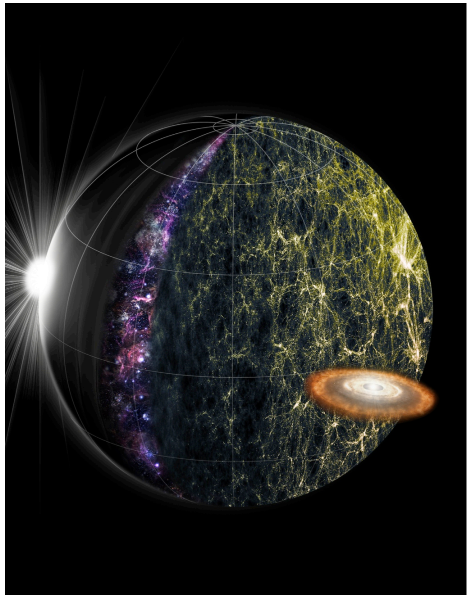
Probing primordial features with future galaxy surveys

Ballardini, FF, Fedeli, Moscardini, JCAP 1610 (2016) 041

We consider four current best-fits for models with parametrized features presented in Planck 2015. XX. Constraints on Inflation.

We use a combined Fisher approach for CMB and the expected clustering power spectrum (conservatively to linear scales, i.e. $k < 0.1\ \mathrm{Mpc}^{-1}$) from three future galaxy surveys as DESI, Euclid (spectroscopic survey) and SphereX to forecast the uncertainties on feature parameters and on the cosmological parameters.

http://sci.esa.int/euclid/



http://desi.lbl.gov/

http://spherex.caltech.edu/

Models

Exponential cut-off

$$\mathcal{P}_{\mathcal{R}}(k) = \mathcal{P}_{\mathcal{R},0}(k)\left\{1 - \exp\left[-\left(\frac{k}{k_{\rm c}}\right)^{\lambda_{\rm c}}\right]\right\}$$

(Contaldi, Peloso, Kofman & Linde, 2003)

Discontinuity in the first derivative of the potential

$$V(\phi) = \begin{cases} V_0 + A_+(\phi - \phi_0)\,, & \phi \gg \phi_0 \\ V_0 + A_-(\phi - \phi_0)\,, & \phi \ll \phi_0 \end{cases}.$$

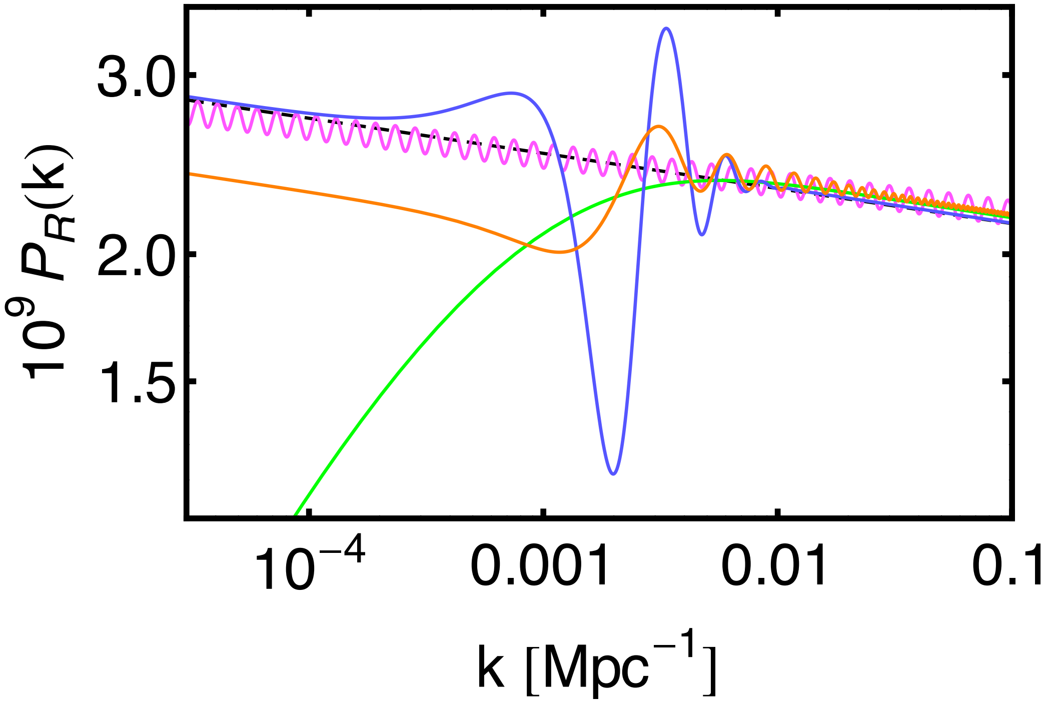
Analytic approximation for the power spectrum (Starobinsky, 1993).

Step in the potential

$$V(\phi) = \frac{m^2}{2}\phi^2\left[1 + c\tanh\left(\frac{\phi - \phi_c}{d}\right)\right]$$

(Adams, Cresswell & Easther, 2003)

Second-order analytic approximation for the power spectrum (Miranda & Hu, 2014)

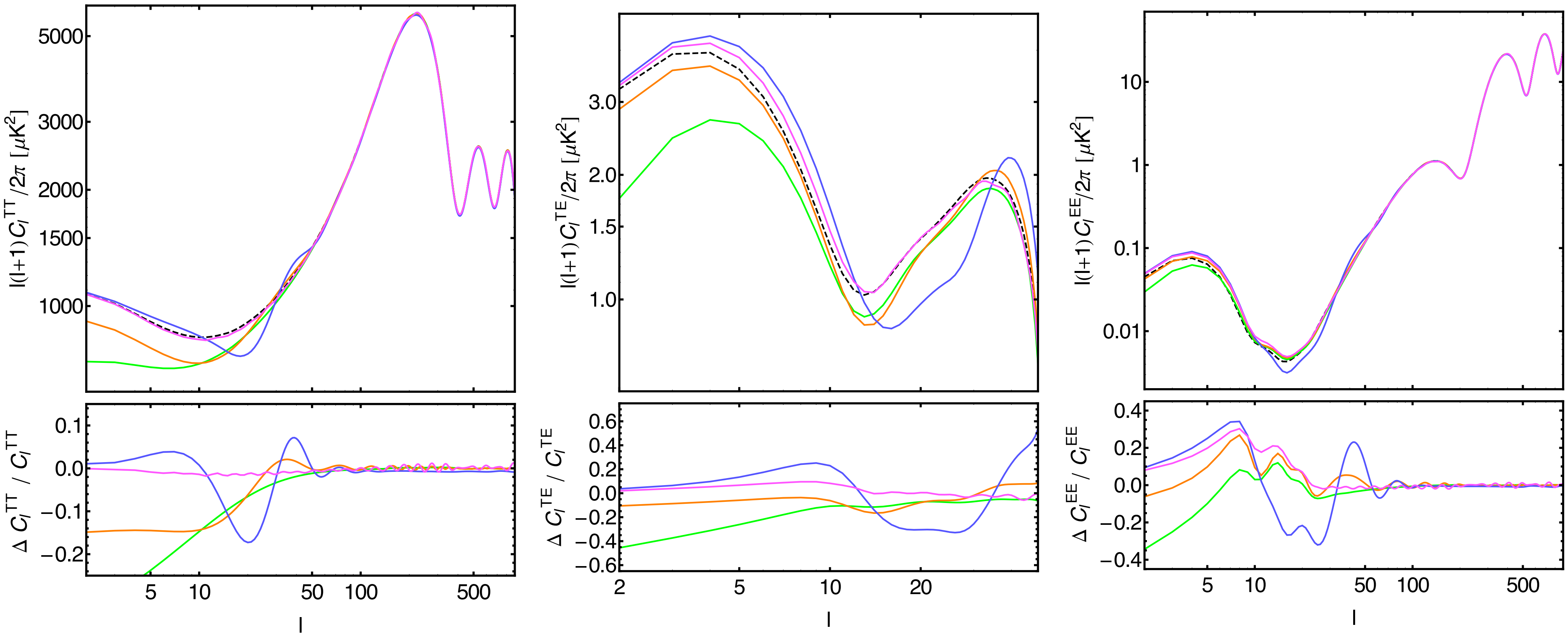


Logarithmic wiggles

$$\mathcal{P}_{\mathcal{R}}^{\rm log}(k) = \mathcal{P}_{\mathcal{R}}^{0}(k)\left\{1 + \mathcal{A}_{\rm log}\cos\left[\omega_{\rm log}\ln\left(\frac{k}{k_*}\right) + \varphi_{\rm log}\right]\right\}$$

(Chen, Easther & Lim, 2008; Flauger, McAllister, Pajer, Westphal, Xu, 2009)

Imprints in the CMB

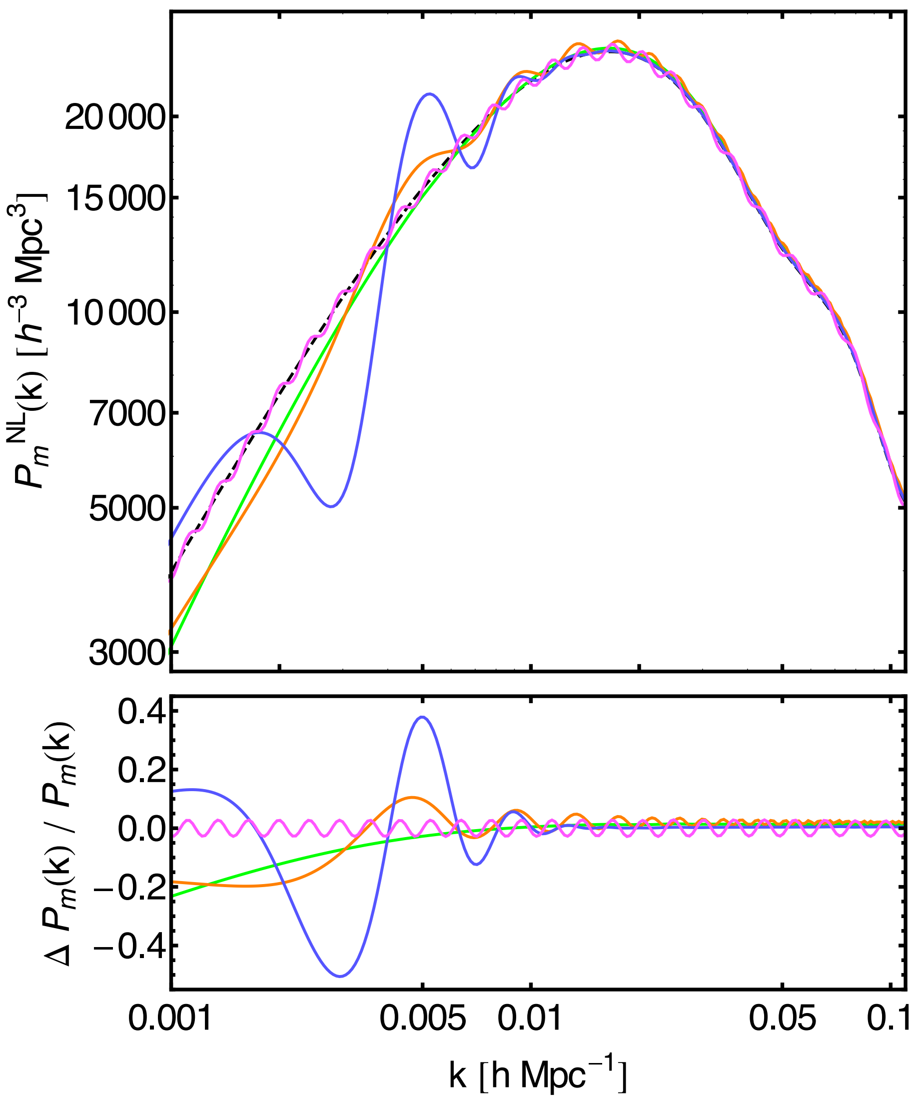


$-2\Delta \ln \mathcal{L}_{\max}$	
Exponential cut-off	-3.4
Discontinuity in V'	-4.5
Step in the potential	-8.6
Logarithmic wiggles	-10.6

Planck TT + lowP

Planck 2015 results. XX. Constraints on inflation

Imprints in the Matter Power Spectrum



Baseline

Exponential cut-off

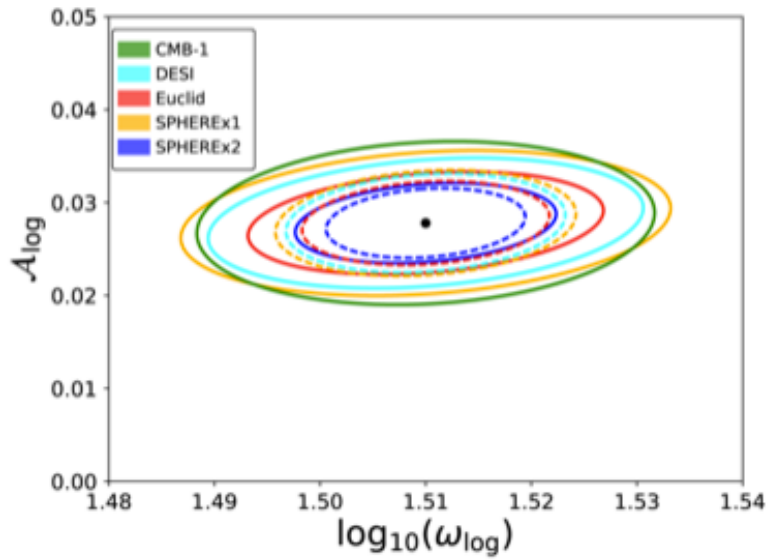
Discontinuity in the first derivative of the potential

Step in the potential

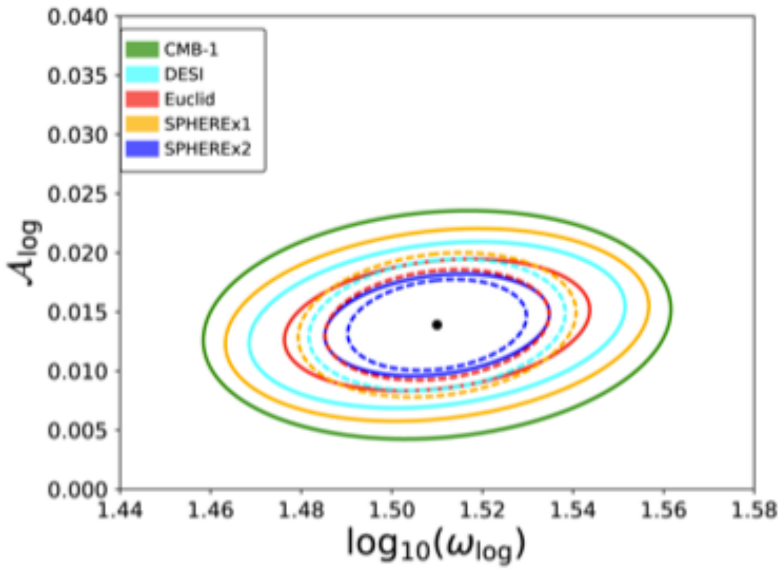
Logarithmic wiggles

Few analysis pre-Planck (Huang, Verde and Vernizzi, 2009; Gibelyou, Huterer & Fang, 2010) and post-Bicep 2 (Hazra, Shafieloo, Smoot and Starobinsky, 2014) with different parameters producing very large features, which would be ruled out by Planck 2015 data. Analysis more similar to Chen, Dvorkin, Huang, Namjoo, Verde, JCAP 1611 (2016) 014.

Logarithmic wiggles



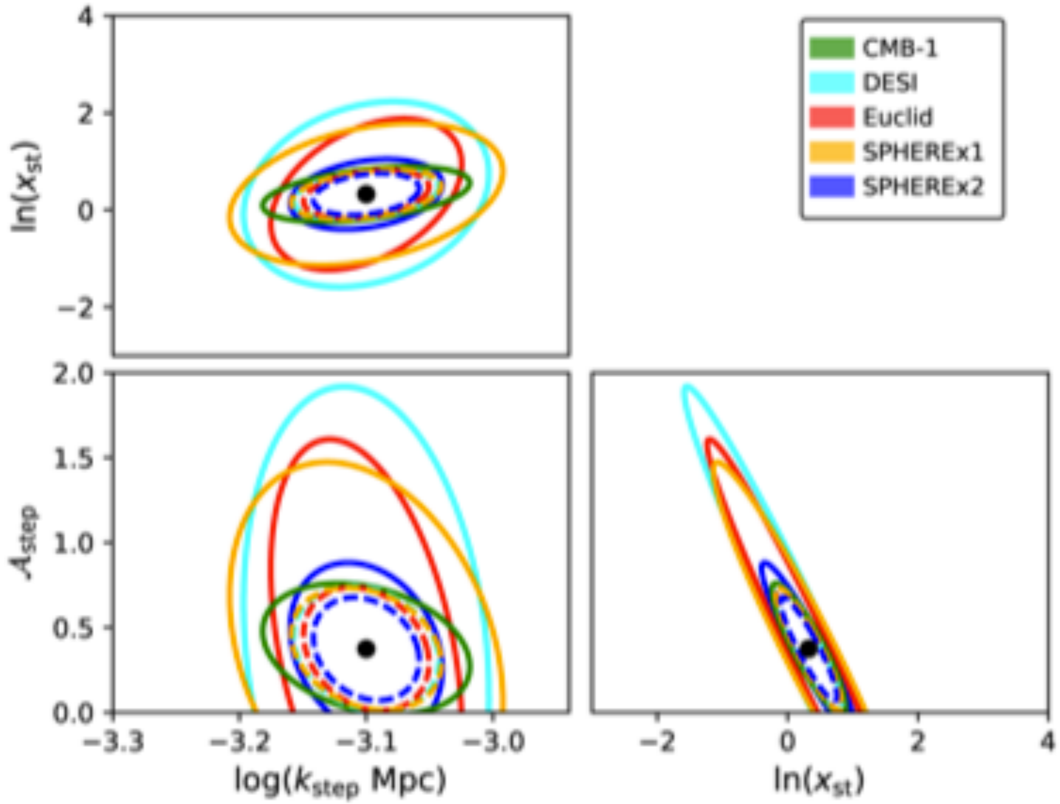
Constraints from LSS surveys alone are comparalble or tighter than those from CMB for these type of features appearing on all scales (global features).



Combined constraints from CMB and LSS could detect wiggles with amplitude smaller than the current Planck best-fits.

Dashed: combined with CMB

Step in the potential



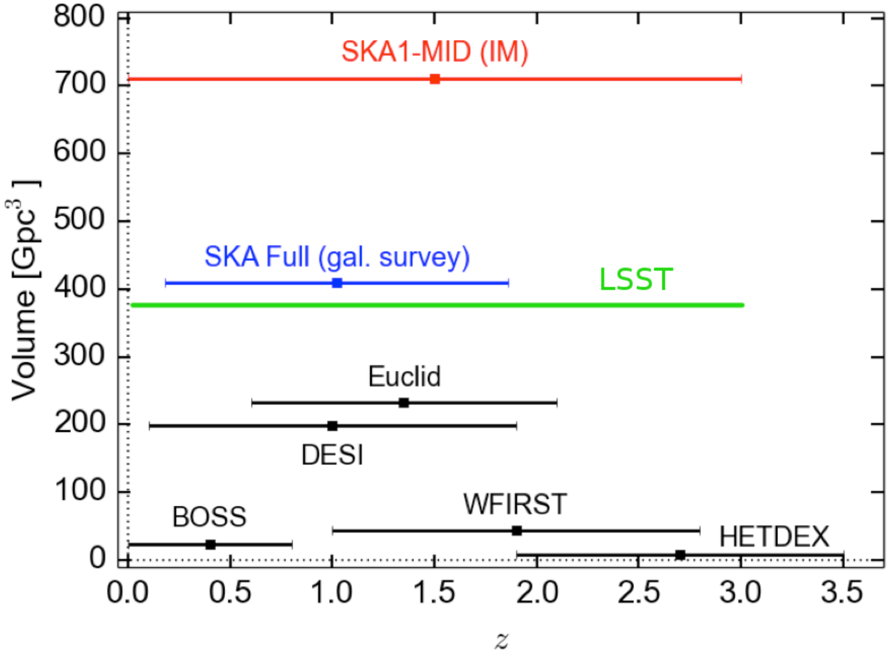
Future galaxy surveys will be of key importance also for this type of features on large scales, i.e. k approximately few in 10^{-3} Mpc^{-1}. However, these large scales are at the boundary of the redshift volume probed by the spectroscopic surveys considered.

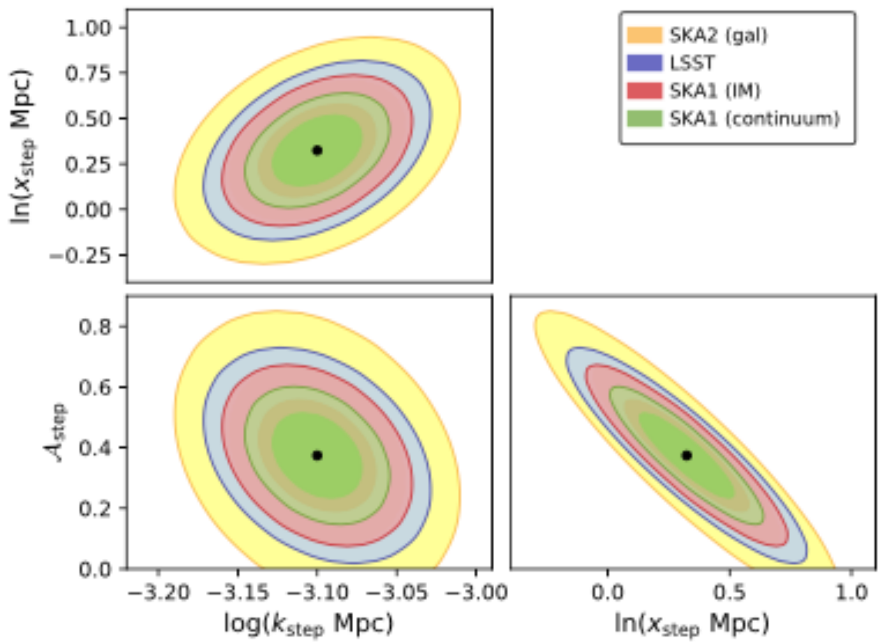
Dashed: combined with CMB

A_{step} corresponds to the amplitude of the feature
k_{step} corresponds to the scale
x_{st} is connected to the width of the feature

Outlook for next photometric and radio surveys

Next-generation photometric or radio surveys will probe even larger redshift volumes and will be more relevant for the primordial features on very large scales.





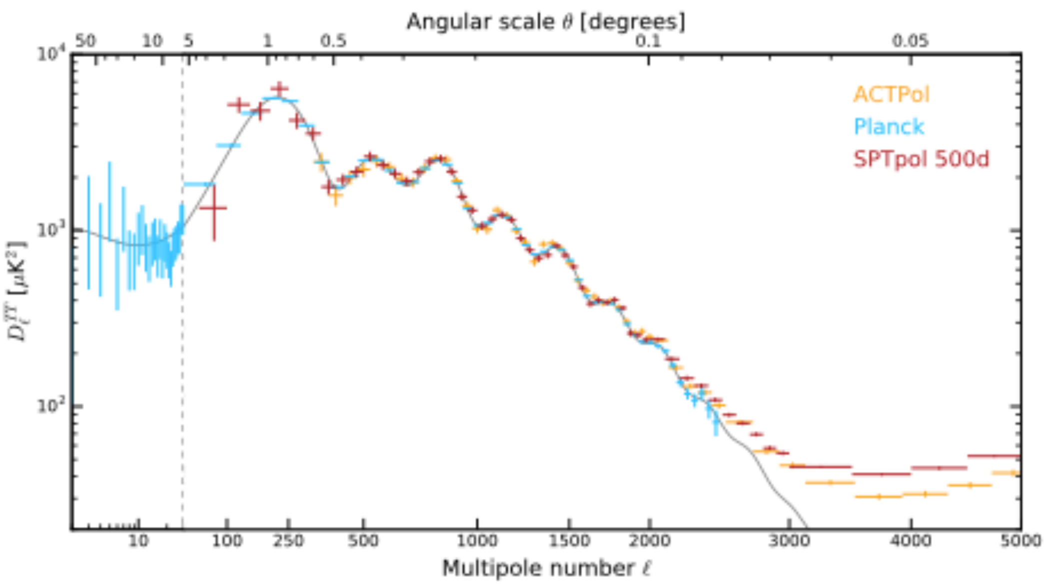
A_{step} corresponds to the amplitude of the feature
k_{step} corresponds to the scale
x_{step} is connected to the width of the feature

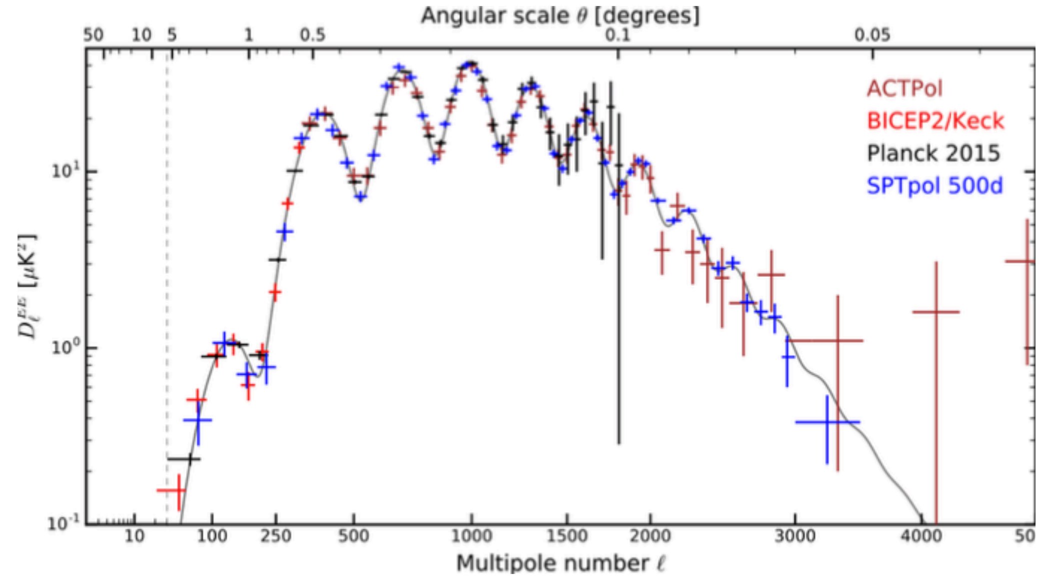
Ballardini, FF, Maartens, Moscardini, JCAP 1802 (2018)

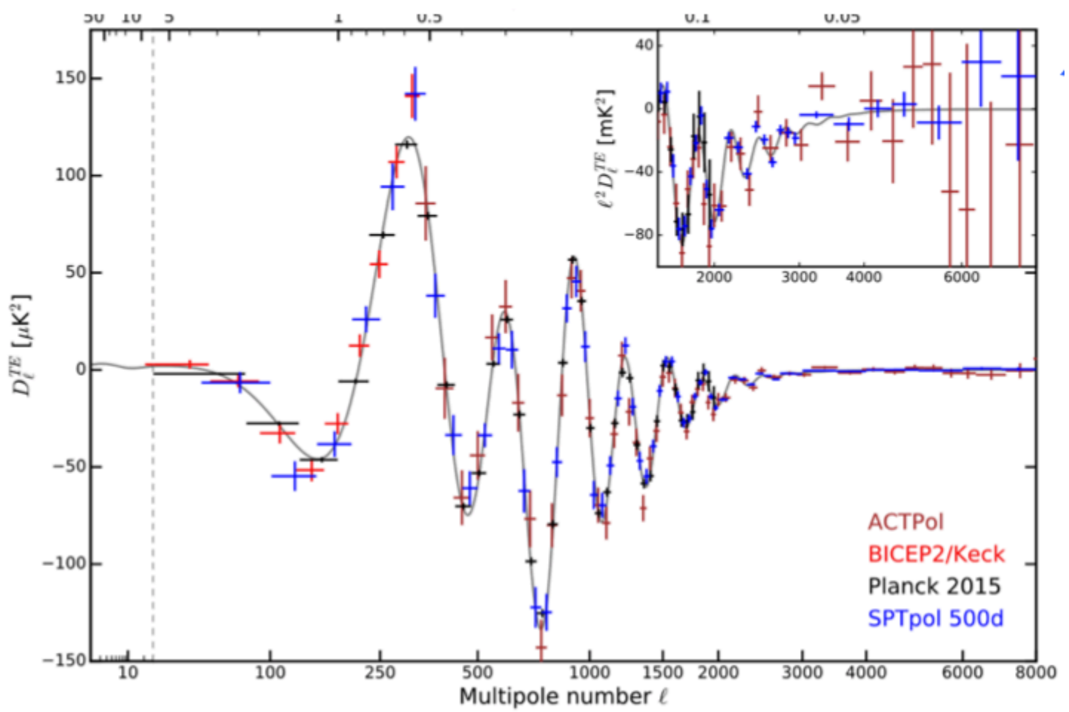
See also Xu, Hamann, Chen, PRD (2016) for a combined PS/BS forecast for SKA and its precursors.

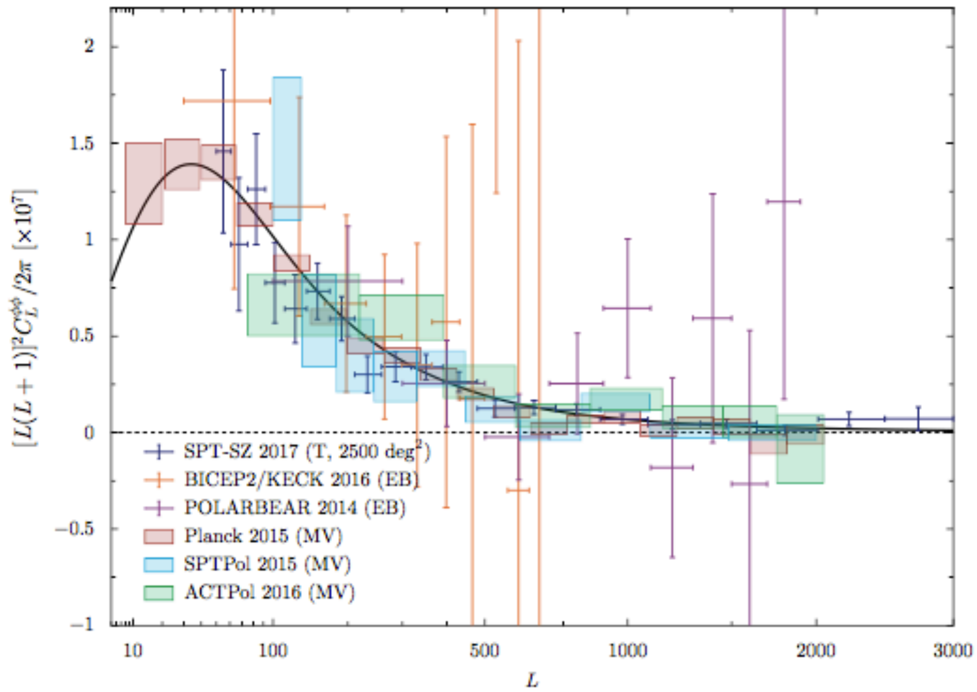
Ongoing and future CMB experiments

- Ground: BICEP 3, QUIJOTE, Polarbear/Simons Array, ACTPol, SPT-3G, ABS, CLASS, Simons Observatory, S4
- Balloon: EBEX, Spider, LSPE
- Space: LiteBird (phase A), Pixie, CORE, Pico, Bharat



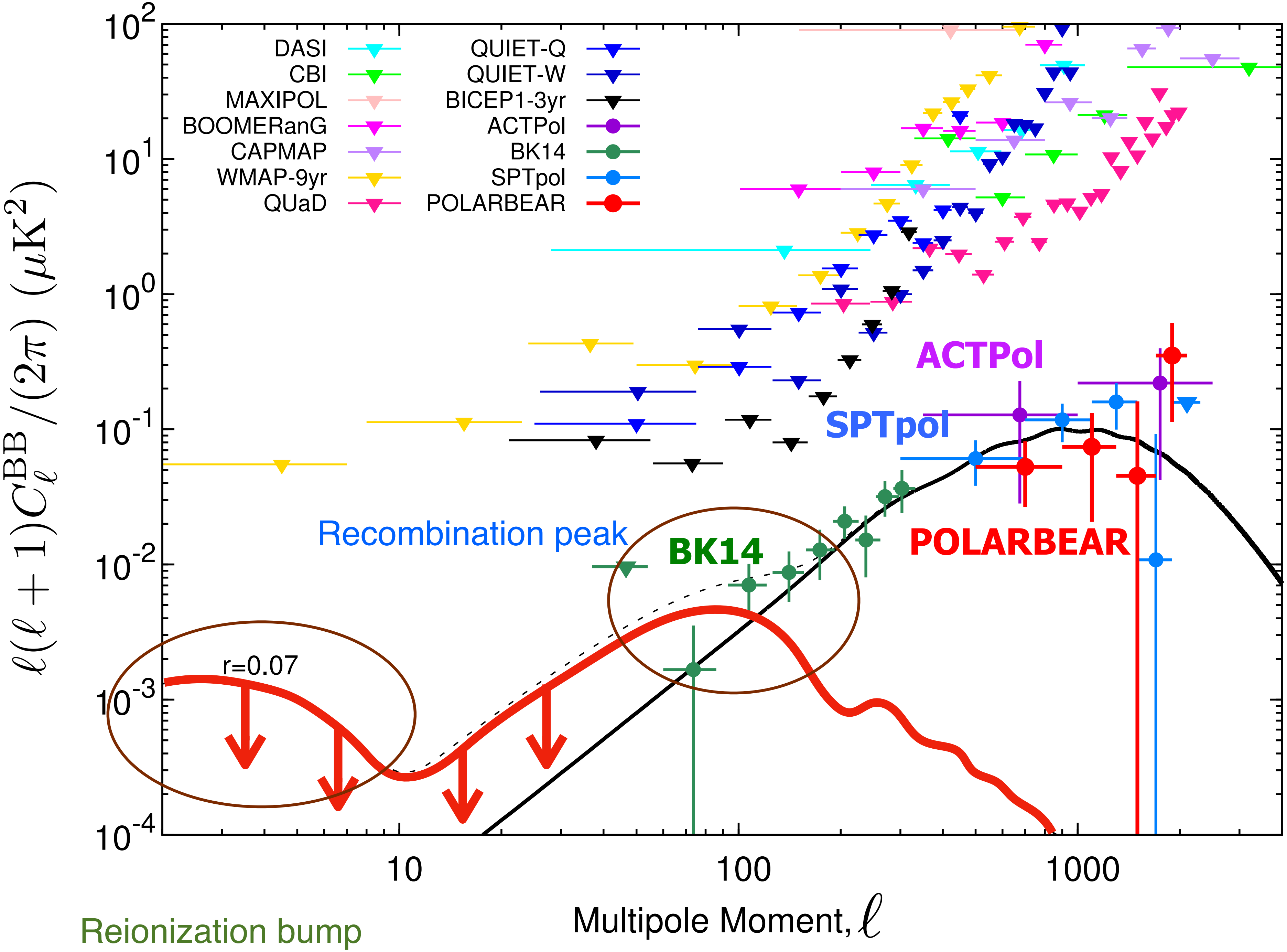






SPTpol Collaboration: Henning et al. , arXiv:1707.09353

CORE Collaboration: A. Challinor et al. arXiv:1707.02259



Reionization bump

Courtesy J. Errard

Cosmology with future CMB experiments

The next generation “Stage-4” ground-based CMB experiments consisting of dedicated telescopes in South Pole, Atacama plateau and possibly northern hemisphere. CMB-S4 aims at a sensitivity of 1 muK per arcmin in intensity, with a resolution of 3 arcmin over 40 % of the sky, capable of measuring the CMB lensing with a high S/N up to l=1000.

Targets B-modes at the recombination peak down to the level of a tensor-to-scalar ratio around 0.001 with efficient internal delensing.

It needs to be complemented with a measurement of the EE power spectrum at multipoles l < 30, as from Planck or CLASS or a next generation space mission.

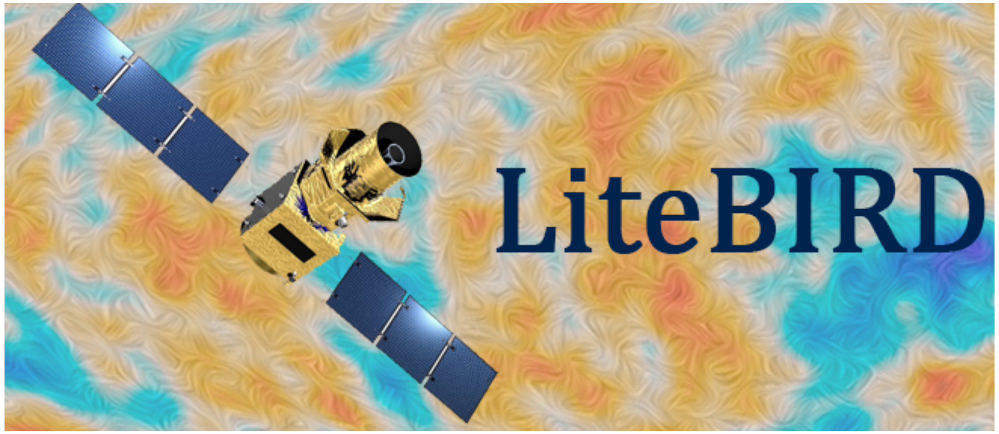
Table 8-1. *Forecasted LCDM parameters*

	fiducial	*Planck*	S4+*Planck*	Improvement factor
$100\Omega_b h^2$	2.22	±0.017	±0.003	5.7
$\Omega_c h^2$	0.120	±0.0014	±0.0006	2.3
H_0	69.0	±0.7	±0.24	2.9
$10^9 A_s$	2.2	±0.039	±0.021	1.9
n_s	0.966	±0.004	±0.002	2
τ	0.06	±0.01	±0.006	1.7

CMB-S4
Next Generation CMB Experiment

CMB-S4 Collaboration (K. N. Abazajian et al.):CMB-S4 Science Book, First Edition, arXiv:1610.02743

Cosmology with future CMB experiments (2)



LiteBIRD, a JAXA mission targeting inflationary B-modes at the degree scale with a sensitivity in r below the 10^{-3} level, will map the CMB sky in the 40-400 GHz frequency range in 15 frequency bands.

Parameter	Results from *Planck* 2015 release	LiteBIRD expected uncertainties	Improvement factor
ΛCDM model			
A_s	$A_s = (2.130 \pm 0.053) \times 10^{-9}$ (68 % CL)	$\sigma(A_s) = 0.0137$	3.9
n_s	$n_s = 0.9653 \pm 0.0048$ (68 % CL)	$\sigma(n_s) = 0.0034$	1.4
$\Omega_b h^2$	$\Omega_b h^2 = 0.02226 \pm 0.00016$ (68 % CL)	$\sigma(\Omega_b h^2) = 0.00013$	1.2
$\Omega_c h^2$	$\Omega_c h^2 = 0.1193 \pm 0.0014$ (68 % CL)	$\sigma(\Omega_c h^2) = 0.00099$	1.4
τ	$\tau = 0.063 \pm 0.014$ (68 % CL)	$\sigma(\tau) = 0.0021$	6.7
H_0 [km/s/Mpc]	$H_0 = 67.51 \pm 0.64$ (68 % CL)	$\sigma(H_0) = 0.47$	1.4

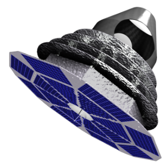
Table 2: Summary of the current results based on the latest *Planck* 2015 release and LiteBIRD forecasts presented in this paper. In the third column we quote the figure of merit of the improvement expected with LiteBIRD.

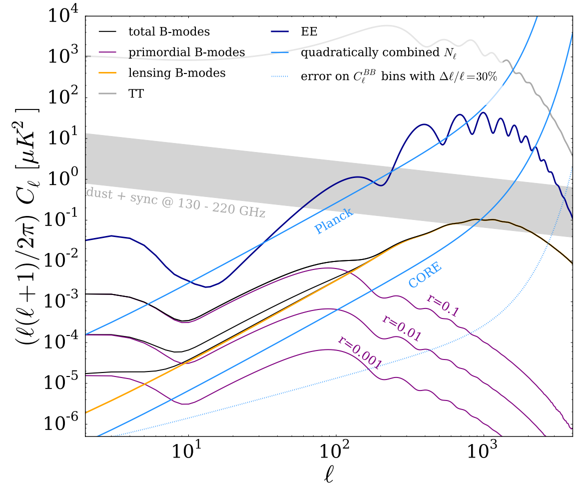
Results taken from Exploring cosmic origins with CORE: Inflation, arXiv:1610.02743

Cosmology with future CMB experiments (3)

CORE, the Cosmic Origins Explorer (Lead proposer J. Delabrouille, Co-leaders P. de Bernardis, F. Bouchet), was proposed as an ESA M5 medium mission to map the CMB sky in temperature and polarization in the 60-600 GHz frequency range in 19 frequency bands, with an aggregated sensitivity of 1.7 muK and an angular resolution of 5' at 200 GHz.

With a noise sensitivity smaller than Planck by approximatively a factor 25, it will provide a cosmic variance limited measurement of the EE (TT) spectrum up to multipoles of the order of 2000 (2500). CORE will also extract all the CMB lensing information up to scales where linear theory is reliable and allow an efficient internal delensing for B-modes.





Parameter	Results from *Planck* 2015 release	CORE expected uncertainties	Improvement factor
ΛCDM model			
A_s	$A_s = (2.130 \pm 0.053) \times 10^{-9}$ (68 % CL)	$\sigma(A_s) = 0.0073$	7.3
n_s	$n_s = 0.9653 \pm 0.0048$ (68 % CL)	$\sigma(n_s) = 0.0014$	3.4
$\Omega_b h^2$	$\Omega_b h^2 = 0.02226 \pm 0.00016$ (68 % CL)	$\sigma(\Omega_b h^2) = 0.000037$	4.3
$\Omega_c h^2$	$\Omega_c h^2 = 0.1193 \pm 0.0014$ (68 % CL)	$\sigma(\Omega_c h^2) = 0.00026$	5.4
τ	$\tau = 0.063 \pm 0.014$ (68 % CL)	$\sigma(\tau) = 0.002$	7.0
H_0 [km/s/Mpc]	$H_0 = 67.51 \pm 0.64$ (68 % CL)	$\sigma(H_0) = 0.11$	5.8

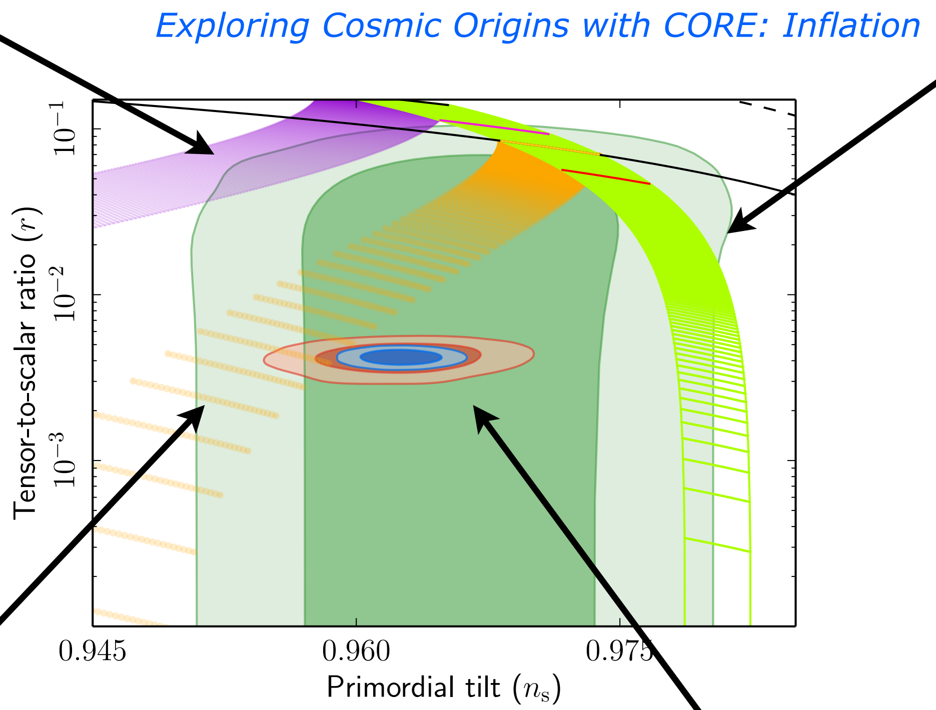
Table 3: Summary of the current results based on the latest *Planck* 2015 release and CORE forecasts presented in this paper. In the third column we quote the figure of merit of the improvement expected with CORE.

CORE Collaboration (F. Finelli et al.): Exploring cosmic origins with CORE: Inflation, arXiv:1610.02743

Inflationary Models with CORE

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

$$V(\phi) = \Lambda^{4-p}\frac{\phi^p}{M_{\rm pl}^p}$$



Planck 2015 + BKP

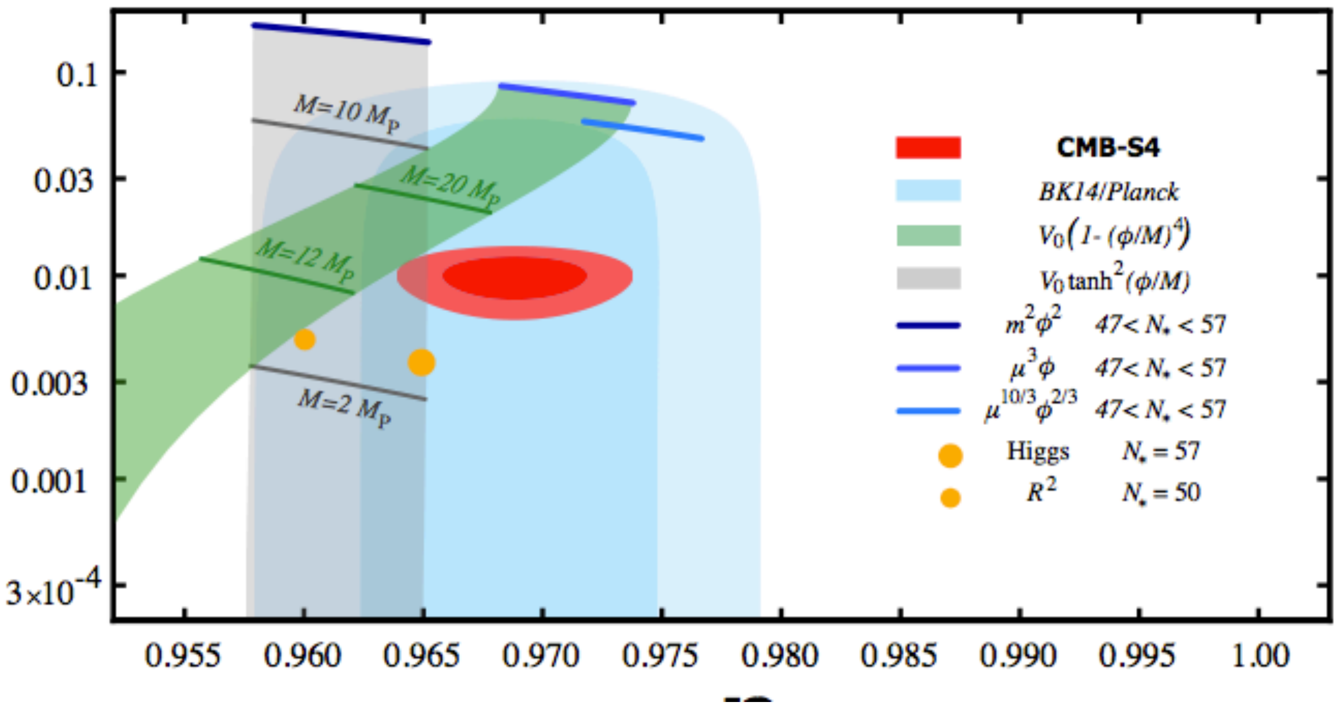
LiteBIRD

CORE (incl. delensing)

$$V(\phi) = \Lambda^4 \left(1 - \frac{\phi^4}{\mu^4} + \ldots\right)$$

$$V(\tilde{\phi}) = \frac{\Lambda^4}{4}\left(1 - e^{-2\tilde{\phi}/\sqrt{6}M_{\rm pl}}\right)^2$$

CMB-S4
Next Generation CMB Experiment



CMB-S4 Coll. (K. N. Abazajian et al.):CMB-S4 Science Book, First Edition, arXiv:1610.02743

Parameter	Results from *Planck* 2015 release	CORE expected uncertainties	Improvement factor
ΛCDM model			
A_s	$A_s = (2.130 \pm 0.053) \times 10^{-9}$ (68 % CL) [4]	$\sigma(A_s) = 0.0073$	7.3
n_s	$n_s = 0.9653 \pm 0.0048$ (68 % CL) [4]	$\sigma(n_s) = 0.0014$	3.4
$\Omega_b h^2$	$\Omega_b h^2 = 0.02226 \pm 0.00016$ (68 % CL) [4]	$\sigma(\Omega_b h^2) = 0.000037$	4.3
$\Omega_c h^2$	$\Omega_c h^2 = 0.1193 \pm 0.0014$ (68 % CL) [4]	$\sigma(\Omega_c h^2) = 0.00026$	5.4
τ	$\tau = 0.063 \pm 0.014$ (68 % CL) [4]	$\sigma(\tau) = 0.002$	7.0
H_0 [km/s/Mpc]	$H_0 = 67.51 \pm 0.64$ (68 % CL) [4]	$\sigma(H_0) = 0.11$	5.8
$dn_s/d\ln k$	$dn_s/d\ln k = -0.0023 \pm 0.0067$ (68 % CL) [4, 5]	$\sigma(dn_s/d\ln k) = 0.0023$	2.9
$d^2n_s/d\ln k^2$	$d^2n_s/d\ln k^2 = 0.025 \pm 0.013$ (68 % CL) [5]	$\sigma(d^2n_s/d\ln k^2) = 0.0046$	2.8
Ω_k	$\Omega_k = -0.0037^{+0.0083}_{-0.0069}$ (68 % CL) [4]	$\sigma(\Omega_k) = 0.0019$	4
r	$r < 0.08$ (95 % CL) [5, 48]	$\sigma(r) = 4 \cdot 10^{-4}$ ($r_{fid} = 0.01$)	10^2
n_t	$-0.38 < n_t < 2.6$ (95 % CL) [5]	$\sigma(n_t) = 0.08$ ($r_{fid} = 0.01$, $n_{fid\,t} = -r_{fid}/8$)	10
β_{iso}	$\beta_{iso}^{curvaton} < 0.0013$ (95 % CL) [5]	$\beta_{iso}^{curvaton} < 0.00026$ (95 % CL)	5.0
	$\beta_{iso}^{axion} < 0.038$ (95 % CL) [5]	$\beta_{iso}^{axion} < 0.018$ (95 % CL)	2.1
f_{NL}	$f_{NL}^{local} = 0.8 \pm 5.0$ (68 % CL) [46]	$\sigma(f_{NL}^{local}) = 2.1$	2.4
	$f_{NL}^{equil} = -4 \pm 43$ (68 % CL) [46]	$\sigma(f_{NL}^{equil}) = 21$	2.0
	$f_{NL}^{ortho} = -26 \pm 21$ (68 % CL) [46]	$\sigma\left(f_{NL}^{ortho}\right) = 9.6$	2.2
	$f_{NL}^{ISW-lens} = 0.79 \pm 0.28$ (68 % CL) [46]	$\sigma\left(f_{NL}^{ISW-lens}\right) = 0.045$	6.2
c_s	$c_s > 0.023$ (95 % CL) [46]	$c_s > 0.045$ (95 % CL)	2.0
$G\mu$	$G\mu < 2.0 \times 10^{-7}$ (95 % CL) [333]	$G\mu < 2.1 \times 10^{-8}$ (95 % CL)	9.5

Table 27: Summary of the current results based on the latest *Planck* 2015 release and CORE forecasts presented in this paper. In the third column we quote the figure of merit of the improvement expected with CORE.

CORE collaboration; Exploring Cosmic Origins with CORE: Inflation, F. Finelli et al., arXiv:1612.08270, JCAP (2017)

Summary

At present cosmological observations are statistically consistent with the predictions of the simplest slow-roll inflationary models, i.e. we have measured at high statistically significance only two numbers, the amplitude and tilt of the primordial power spectrum of scalar perturbations.

From the observational point of view, Planck has decreased the room for deviations from a simple power-law for the PPS or non-Gaussianities or isocurvature perturbations, i.e. for models beyond standard single field slow-roll inflation.

Concerning features in the PPS, the outliers in the Planck temperature power spectrum suggest deviations from a simple power law although not a statistical significant level yet. Future data, as the next galaxy surveys, will help in understanding if these outliers have a primordial explanation.

A detection of gravitational waves from inflation, and therefore of the scale of inflation, would be the first experimental signature of quantum gravity and of the physics of the Planck scale, since detectable levels of r would correspond to those large field inflationary models in which the inflaton excursion in the observable range would exceed the Planck scale. Even if a non-detection of r cannot rule out completely the class of large field inflationary models, there are several important theoretical targets in the $r=10^{-2}$ - 10^{-3} range.

The search of primordial B-mode polarization is undergoing and further planned with ground and balloon experiments; different concepts for the next CMB space mission are under study. Rather than detectors noise sensitivity, foregrounds and potential polarization systematics are at present the main obstacle to reach r at the level of few 10^{-3}. Within the current estimates including foreground contamination, the predictions of R^2 seem a feasible target.

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.