Planck 2013 results: constraints on inflation

arXiv: 1303.5082

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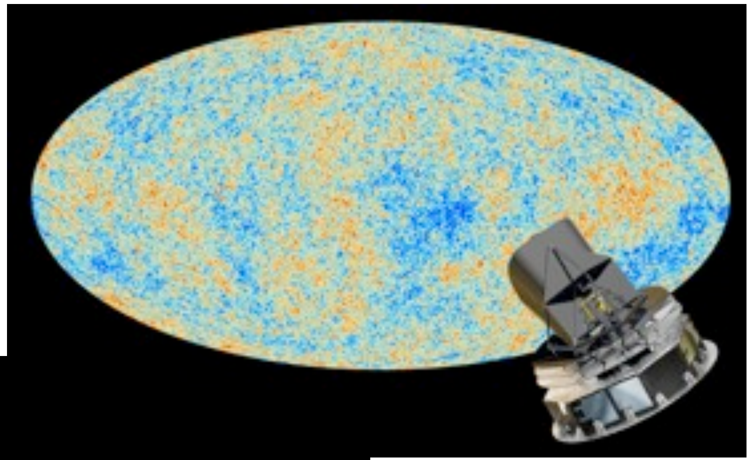
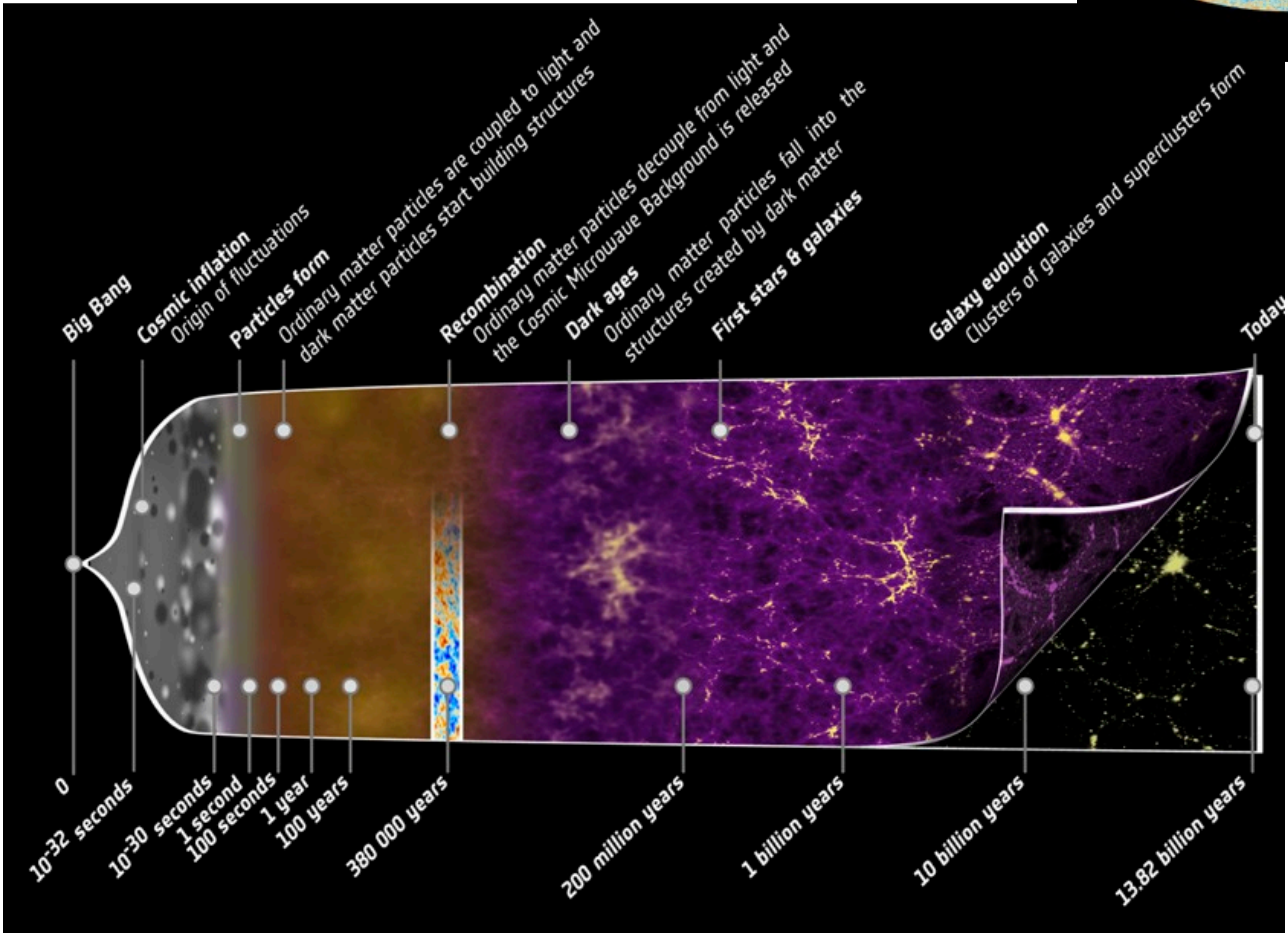
Golden Age of Cosmology





Planck Website

Facts and Goals

- Selected by ESA in 1996.

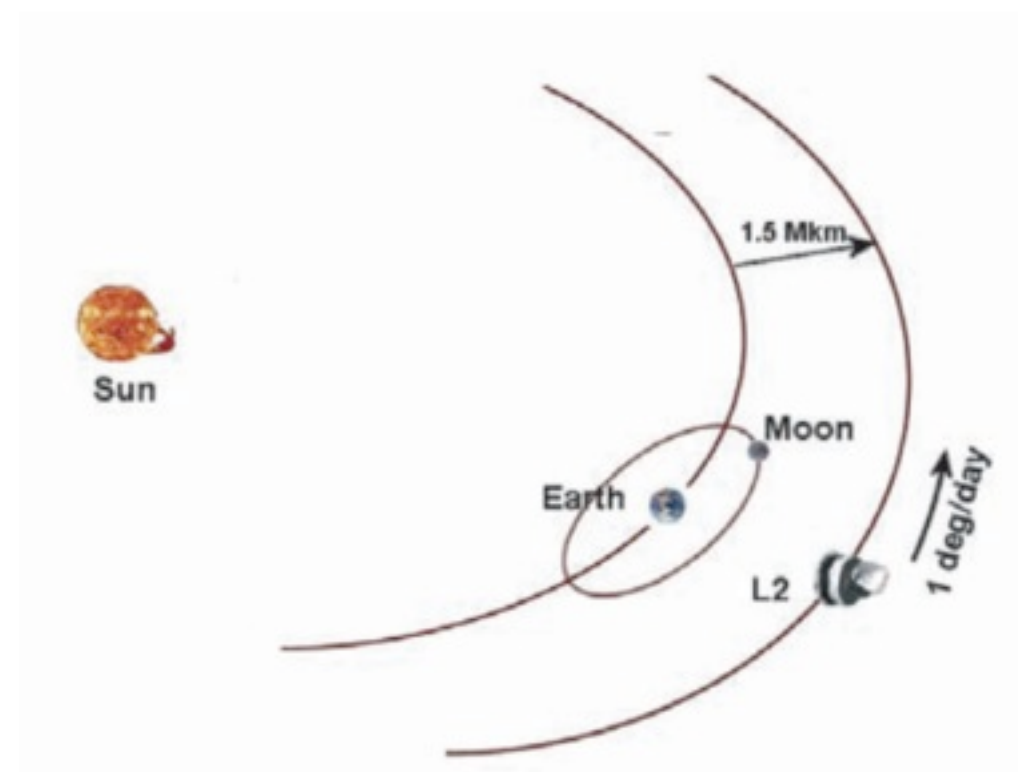
- To measure the CMB temperature anisotropy + polarizations of CMB to study the physics of early universe cosmology.

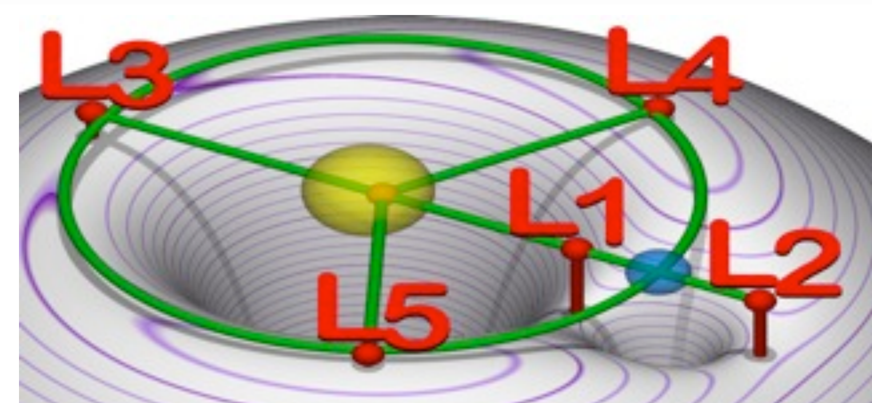
- Planck is launched on 14 May 2009 with Herschel and reached in L2 orbit after two months.

- Planck had full scan of sky survey every 6 months. Two full sky coverage completed by November 2010. Four full sky coverage by Jan 2012.

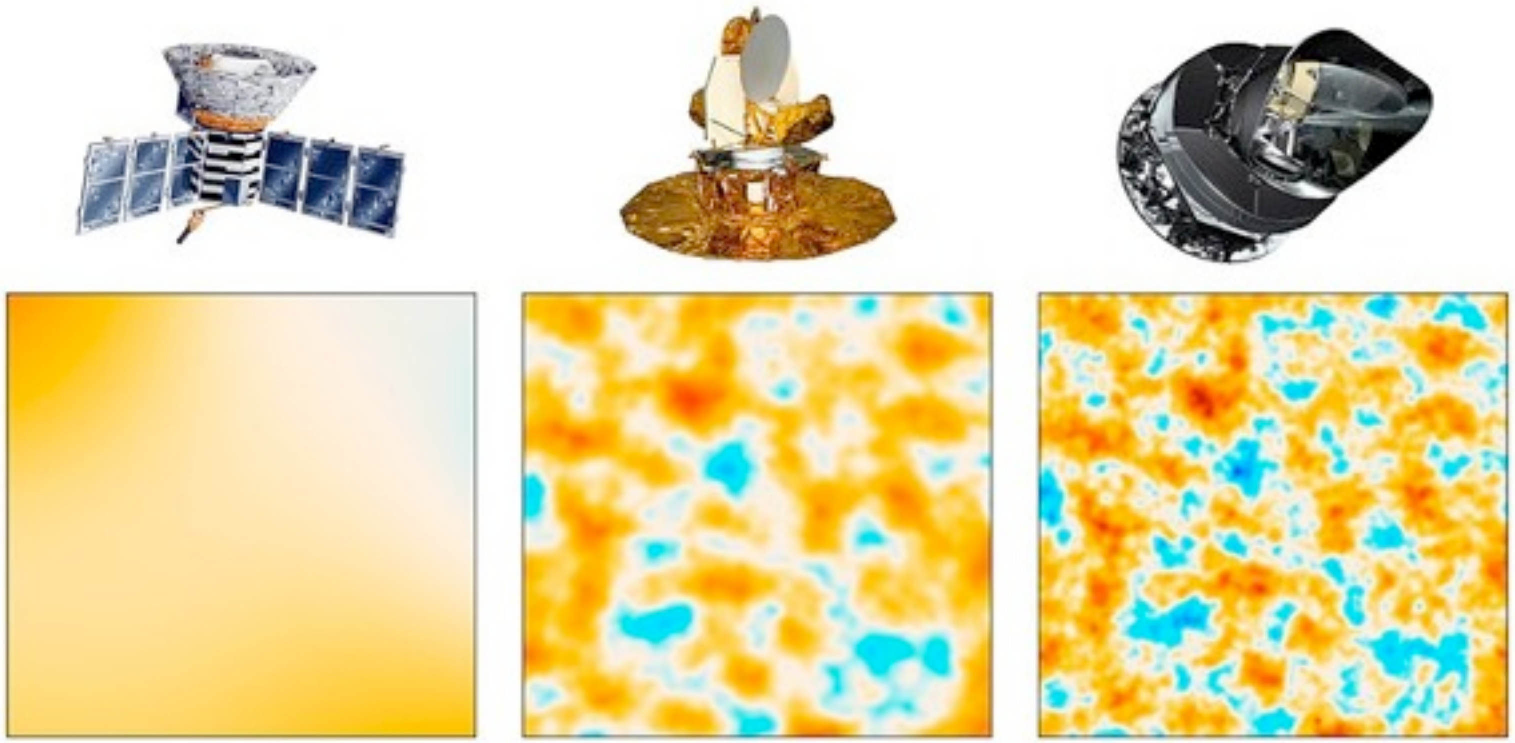
- First data released 2013.

  700 million euro for Planck



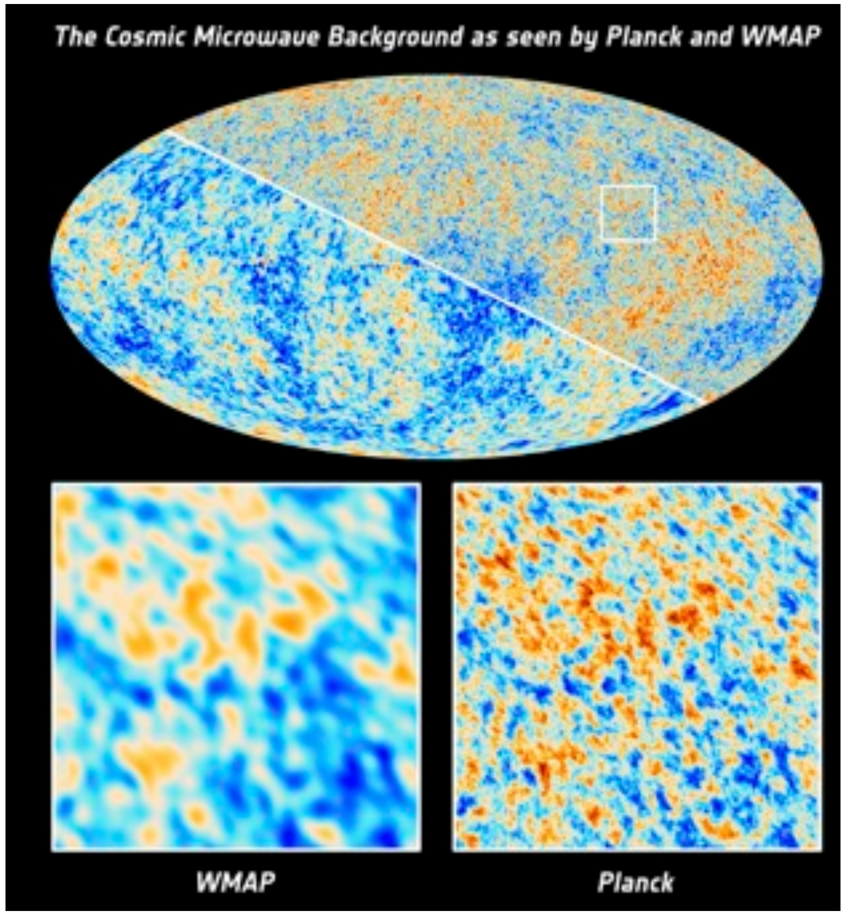


Planck is the third generation CMB space observations

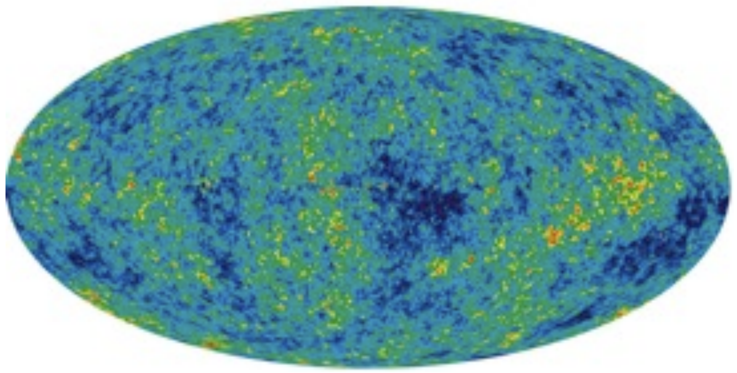


COBE WMAP Planck

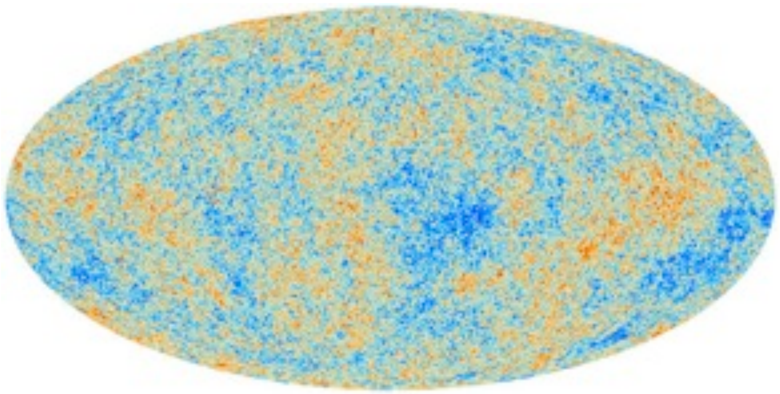
1992 2003 2013



- It has higher resolution ($\times 3$), 5-30 arc min.
- It has higher sensitivity ($\times 10$), micro Kelvin.
- It observes in 9 frequency bands rather than 5, with the goal of improving the astrophysical foreground models.

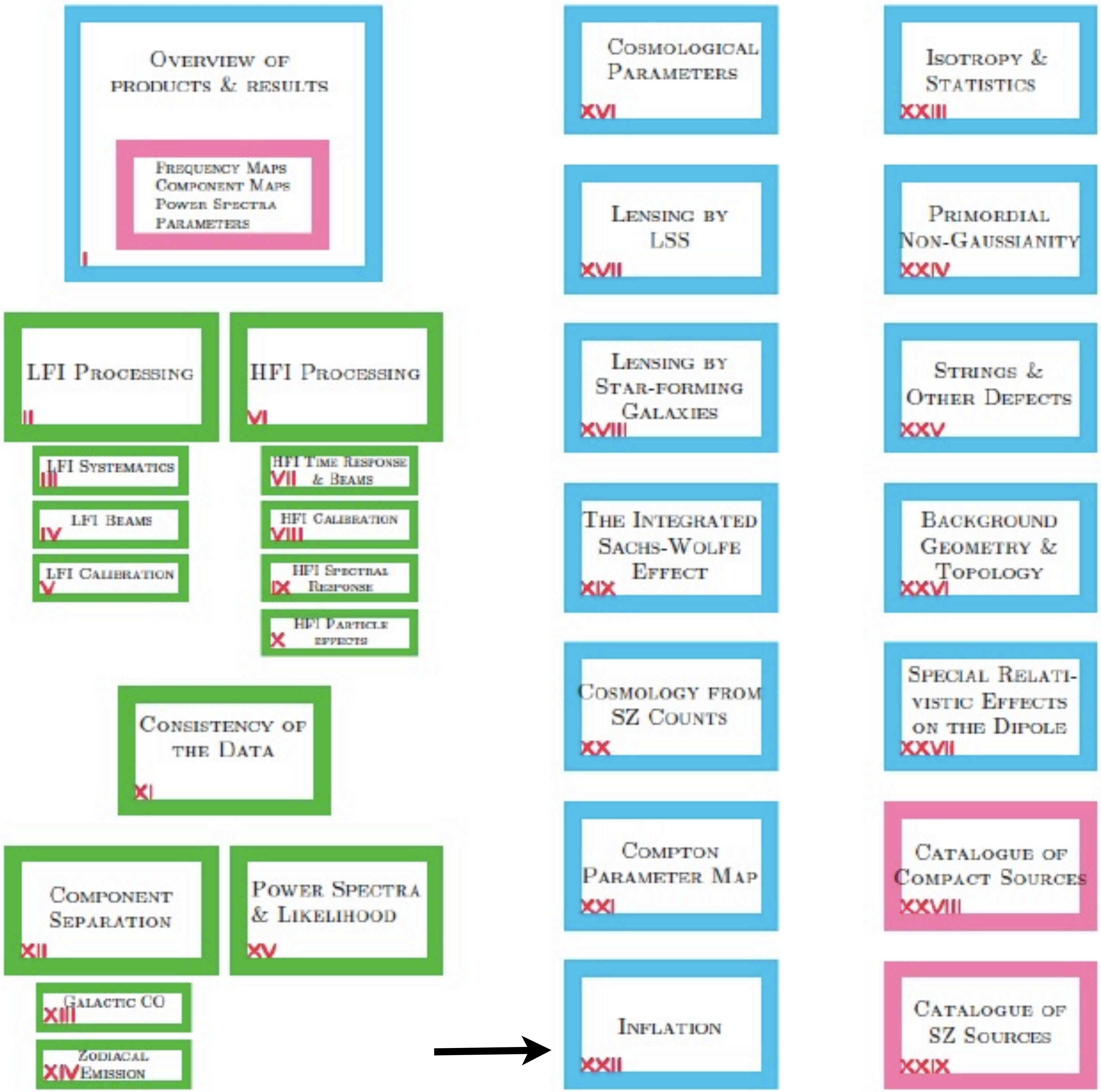


WMAP

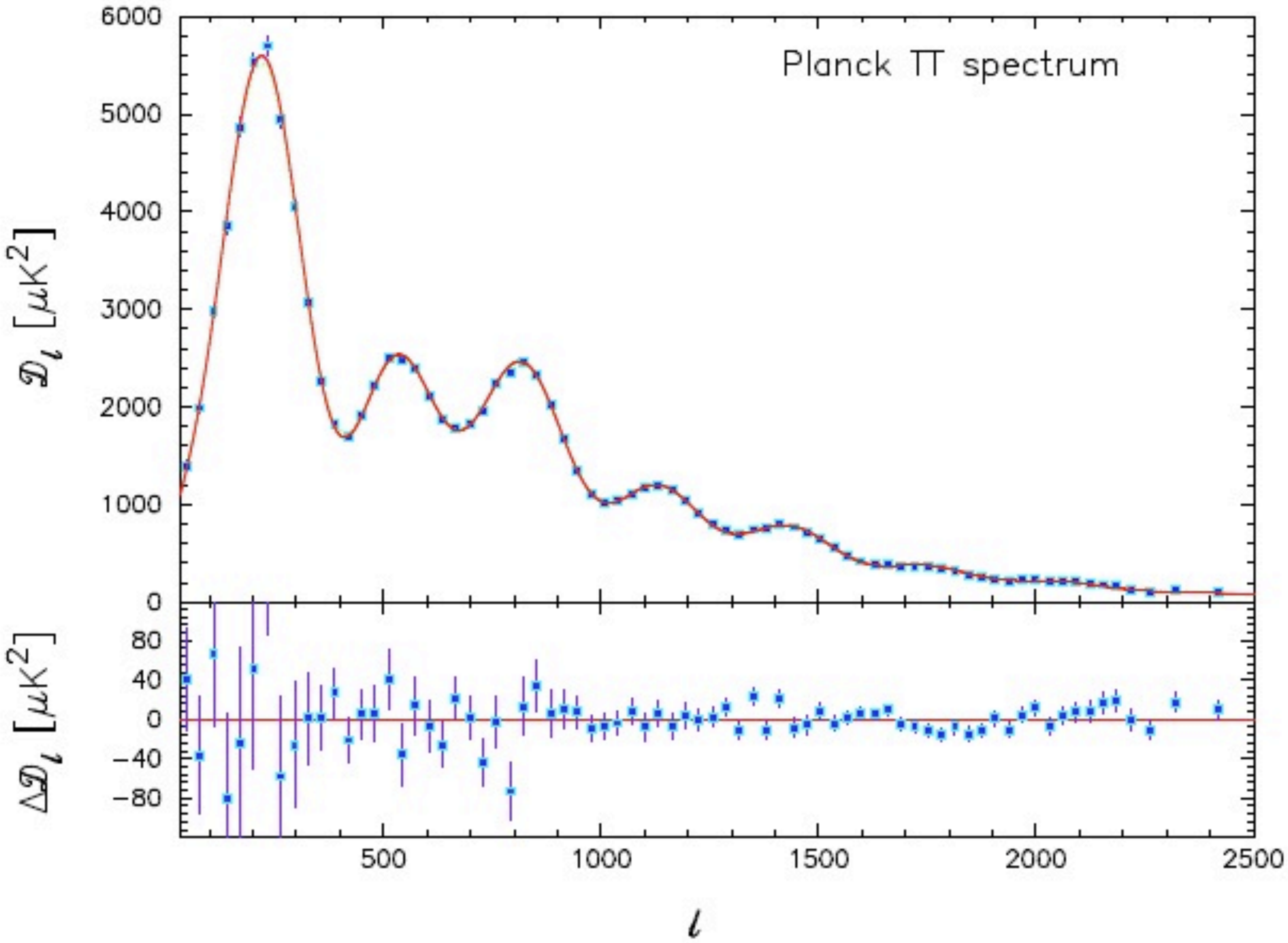


Planck

Planck publications



	Planck		*Planck*+lensing		*Planck*+WP	
Parameter	Best fit	68% limits	Best fit	68% limits	Best fit	68% limits
$\Omega_b h^2$	0.022068	0.02207 ± 0.00033	0.022242	0.02217 ± 0.00033	0.022032	0.02205 ± 0.00028
$\Omega_c h^2$	0.12029	0.1196 ± 0.0031	0.11805	0.1186 ± 0.0031	0.12038	0.1199 ± 0.0027
$100\theta_{MC}$	1.04122	1.04132 ± 0.00068	1.04150	1.04141 ± 0.00067	1.04119	1.04131 ± 0.00063
τ	0.0925	0.097 ± 0.038	0.0949	0.089 ± 0.032	0.0925	$0.089^{+0.012}_{-0.014}$
n_s	0.9624	0.9616 ± 0.0094	0.9675	0.9635 ± 0.0094	0.9619	0.9603 ± 0.0073
$\ln(10^{10} A_s)$	3.098	3.103 ± 0.072	3.098	3.085 ± 0.057	3.0980	$3.089^{+0.024}_{-0.027}$
Ω_Λ	0.6825	0.686 ± 0.020	0.6964	0.693 ± 0.019	0.6817	$0.685^{+0.018}_{-0.016}$
Ω_m	0.3175	0.314 ± 0.020	0.3036	0.307 ± 0.019	0.3183	$0.315^{+0.016}_{-0.018}$
σ_8	0.8344	0.834 ± 0.027	0.8285	0.823 ± 0.018	0.8347	0.829 ± 0.012
z_{re}	11.35	$11.4^{+4.0}_{-2.8}$	11.45	$10.8^{+3.1}_{-2.5}$	11.37	11.1 ± 1.1
H_0	67.11	67.4 ± 1.4	68.14	67.9 ± 1.5	67.04	67.3 ± 1.2
$10^9 A_s$	2.215	2.23 ± 0.16	2.215	$2.19^{+0.12}_{-0.14}$	2.215	$2.196^{+0.051}_{-0.060}$
$\Omega_m h^2$	0.14300	0.1423 ± 0.0029	0.14094	0.1414 ± 0.0029	0.14305	0.1426 ± 0.0025
$\Omega_m h^3$	0.09597	0.09590 ± 0.00059	0.09603	0.09593 ± 0.00058	0.09591	0.09589 ± 0.00057
Y_P	0.247710	0.24771 ± 0.00014	0.247785	0.24775 ± 0.00014	0.247695	0.24770 ± 0.00012
Age/Gyr	13.819	13.813 ± 0.058	13.784	13.796 ± 0.058	13.8242	13.817 ± 0.048
z_*	1090.43	1090.37 ± 0.65	1090.01	1090.16 ± 0.65	1090.48	1090.43 ± 0.54
r_*	144.58	144.75 ± 0.66	145.02	144.96 ± 0.66	144.58	144.71 ± 0.60
$100\theta_*$	1.04139	1.04148 ± 0.00066	1.04164	1.04156 ± 0.00066	1.04136	1.04147 ± 0.00062
z_{drag}	1059.32	1059.29 ± 0.65	1059.59	1059.43 ± 0.64	1059.25	1059.25 ± 0.58
r_{drag}	147.34	147.53 ± 0.64	147.74	147.70 ± 0.63	147.36	147.49 ± 0.59
k_D	0.14026	0.14007 ± 0.00064	0.13998	0.13996 ± 0.00062	0.14022	0.14009 ± 0.00063
$100\theta_D$	0.161332	0.16137 ± 0.00037	0.161196	0.16129 ± 0.00036	0.161375	0.16140 ± 0.00034
z_{eq}	3402	3386 ± 69	3352	3362 ± 69	3403	3391 ± 60
$100\theta_{eq}$	0.8128	0.816 ± 0.013	0.8224	0.821 ± 0.013	0.8125	0.815 ± 0.011
$r_{drag}/D_V(0.57)$	0.07130	0.0716 ± 0.0011	0.07207	0.0719 ± 0.0011	0.07126	0.07147 ± 0.00091



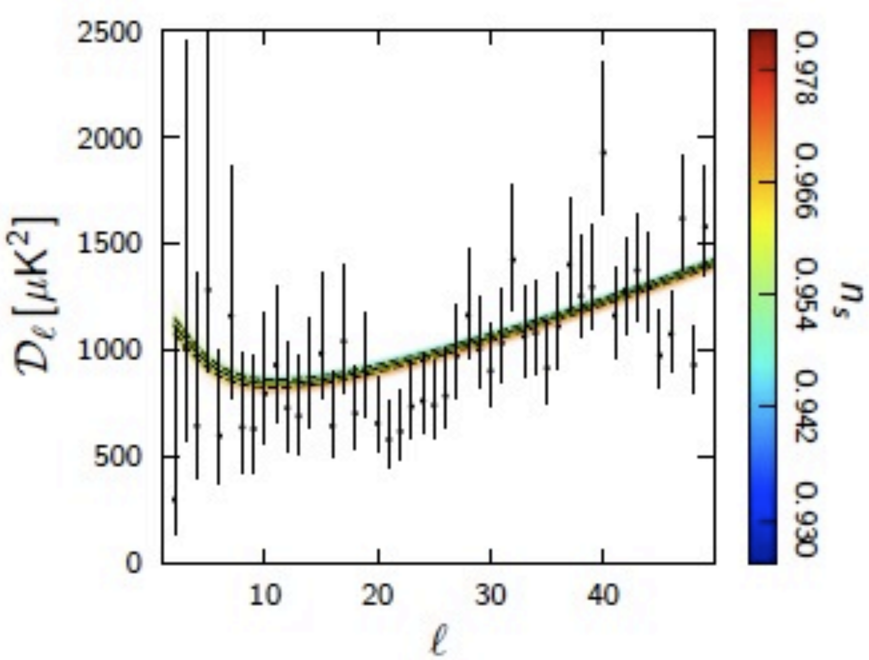
Temperature anisotropy power spectrum

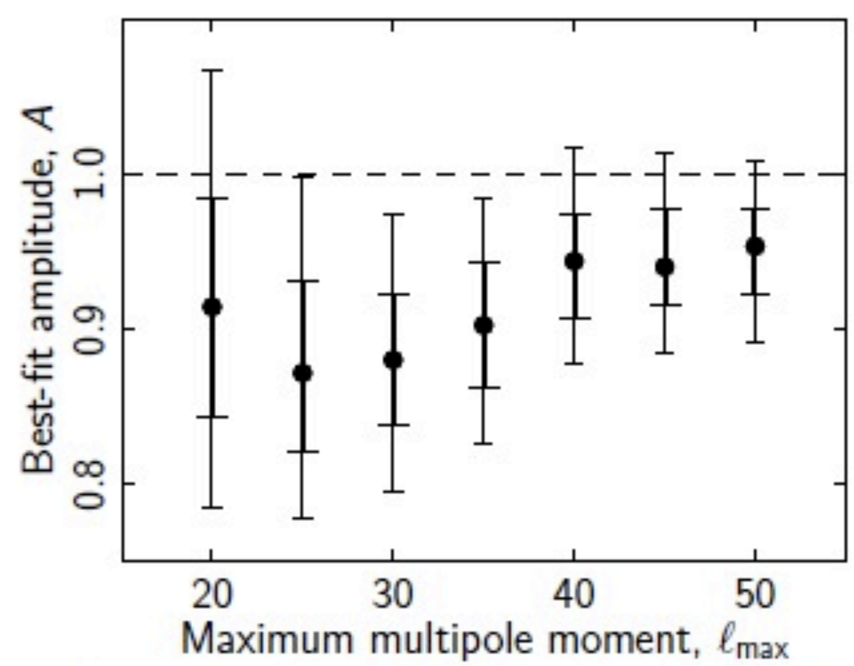
$$\langle \Delta T(\hat{n}) \Delta T(\hat{n}') \rangle$$

$$\Delta T(\hat{n}) \equiv T(\hat{n}) - T_0 = \sum_{\ell m} a_{\ell m} Y_\ell^m(\hat{n})$$

$$\langle a_{\ell m} a^*_{\ell' m'} \rangle = \delta_{\ell\ell'} \delta_{mm'} C_\ell$$

$$\langle \Delta T(\hat{n}) \Delta T(\hat{n}') \rangle = \sum_{\ell m} C_\ell \, Y_\ell^m(\hat{n}) \, Y_\ell^{-m}(\hat{n}')$$



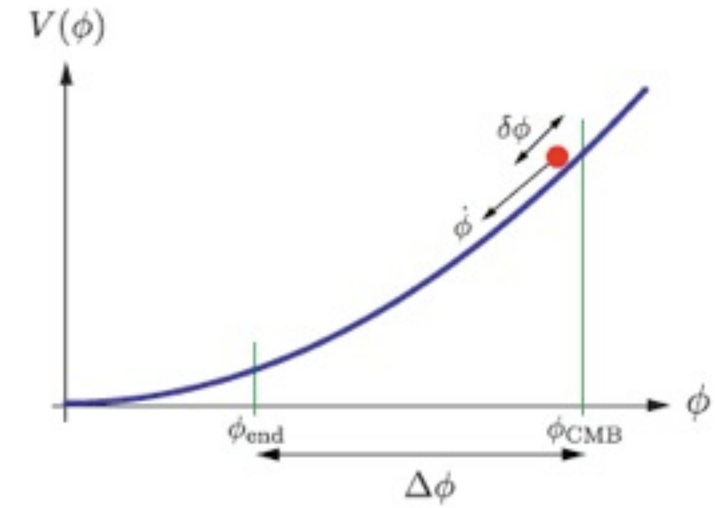


Andrei Linde

Alan Guth

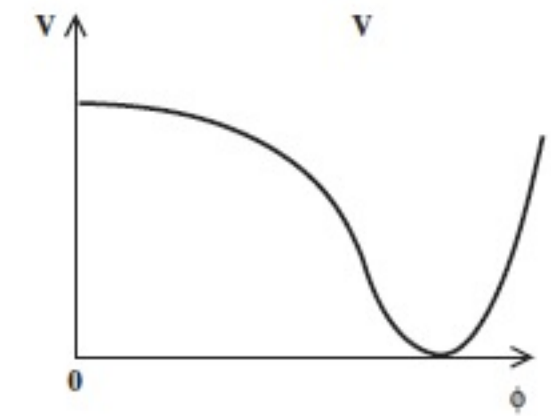
Winners of 2012 Milner Fundamental Physics Prize

The classifications of inflation



1- Large fields $\Delta\phi > M_P$

$$V = \frac{m^2}{2}\phi^2 \quad , \quad V = \frac{\lambda}{4}\phi^4$$



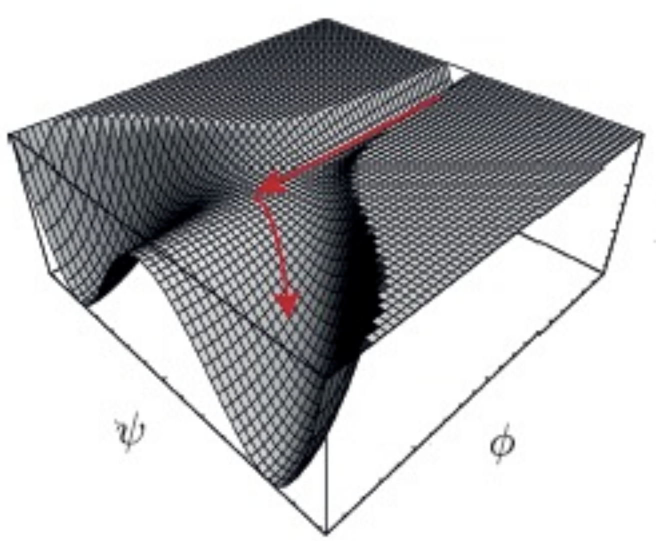
2- Small fields $\Delta\phi < M_P$

$$V = V_0 - \frac{m^2}{2}\phi^2$$

a)- Single field models

$$V = \frac{m^2}{2}\phi^2 \quad , \quad V = \frac{\lambda}{4}\phi^4$$

b)- Multiple fields models



$$V(\phi,\psi) = \frac{\lambda}{4}\left(\psi^2 - \frac{M^2}{\lambda}\right)^2 + \frac{1}{2}m^2\phi^2 + \frac{1}{2}g^2\phi^2\psi^2$$

Inflation in the context of ever changing fundamental theory

Lev Kofman

1980

R^2-inflation

Old Inflation

New Inflation

Chaotic inflation

SUGRA inflation

Double Inflation

Power-law inflation

Extended inflation

1990

Hybrid inflation

Assisted inflation

SUSY F-term inflation

SUSY D-term inflation

Brane inflation

2000

SUSY P-term inflation

Super-natural Inflation

K-flation

N-flation

DBI inflation

$D3 - D7$ inflation

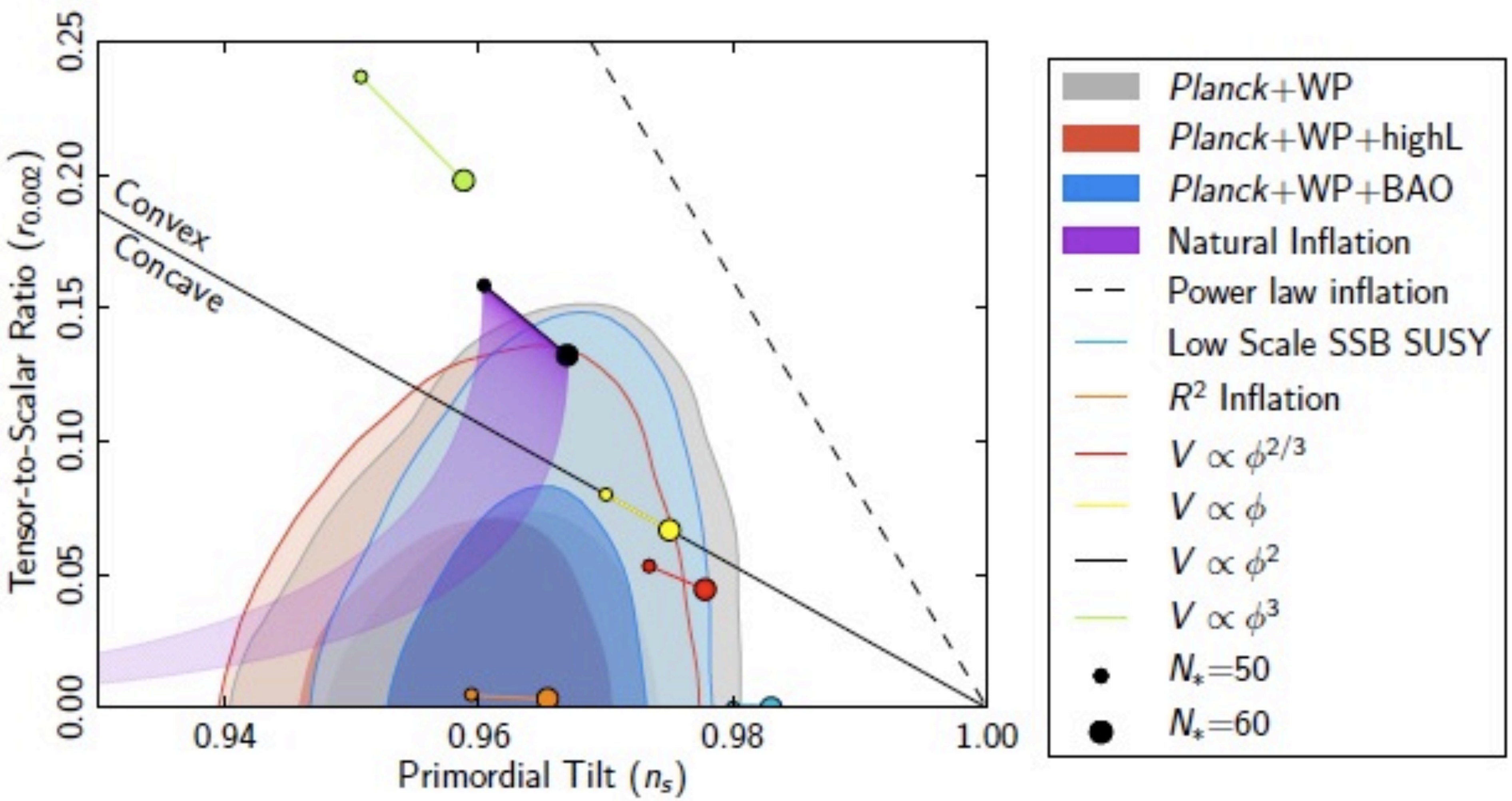
Warped Brane inflation

Tachyon inflation

Racetrack inflation

Constraints for inflation

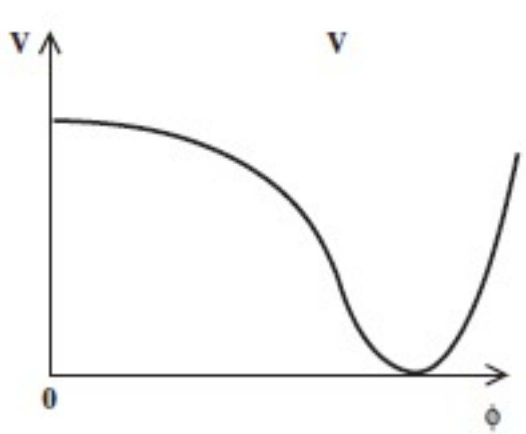
Two key parameters are r and the spectral index ns. From Planck and WP: $n_s = 0.9603 \pm 0.0073$

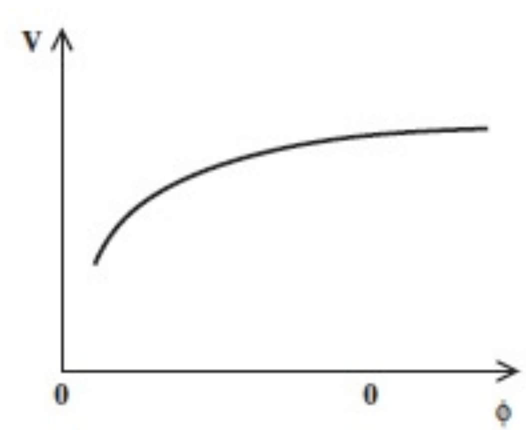


$$\mathcal{P}_{\mathcal{R}}(k) = A_s \left(\frac{k}{h_s}\right)^{n_s-1}$$

$$V_* = (1.94 \times 10^{16}\ \mathrm{GeV})^4 (r_{0.002}/0.12)$$

The Planck data prefers models with V" <0, concave potentials

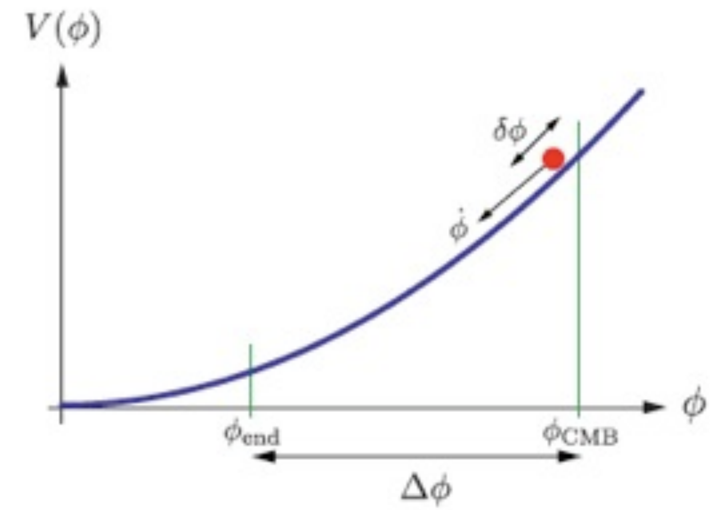




Predictions for power law potential

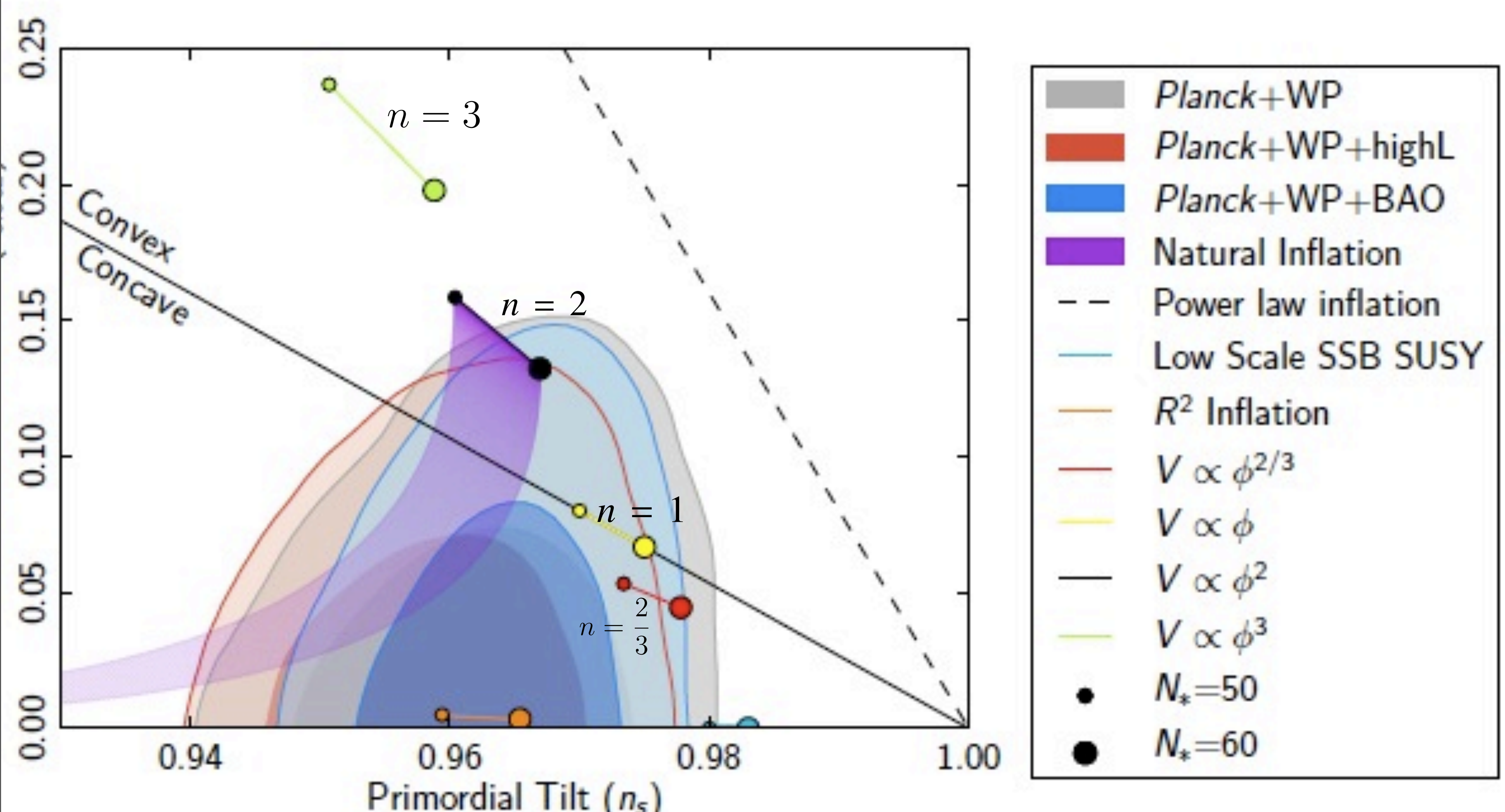
$$V(\phi) = \lambda M_{\rm pl}^4 \left(\frac{\phi}{M_{\rm pl}}\right)^n .$$

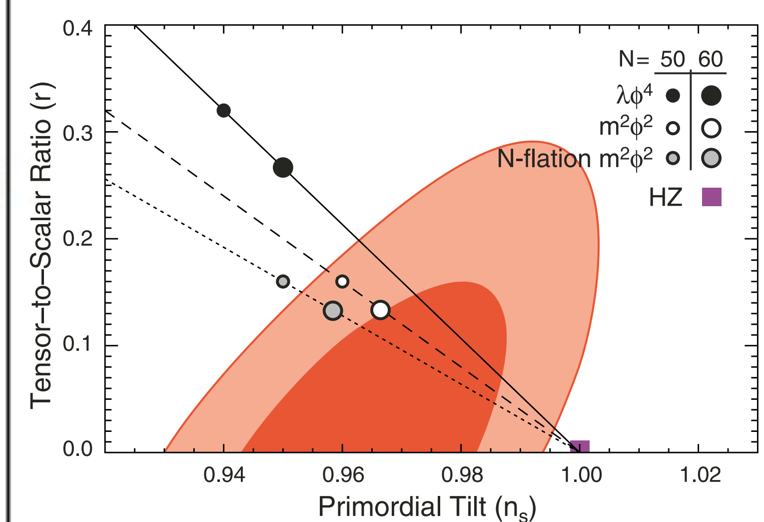
$$r = 8(1-n_s)\frac{n}{n+2} \qquad\qquad r = \frac{4n}{N}$$



The model with n=2 lies outside the joint Planck+WP+high L (95 % CL).

The model with n=4 lies well outside the joint 99.7 % CL.





WMAP

Hybrid Inflation

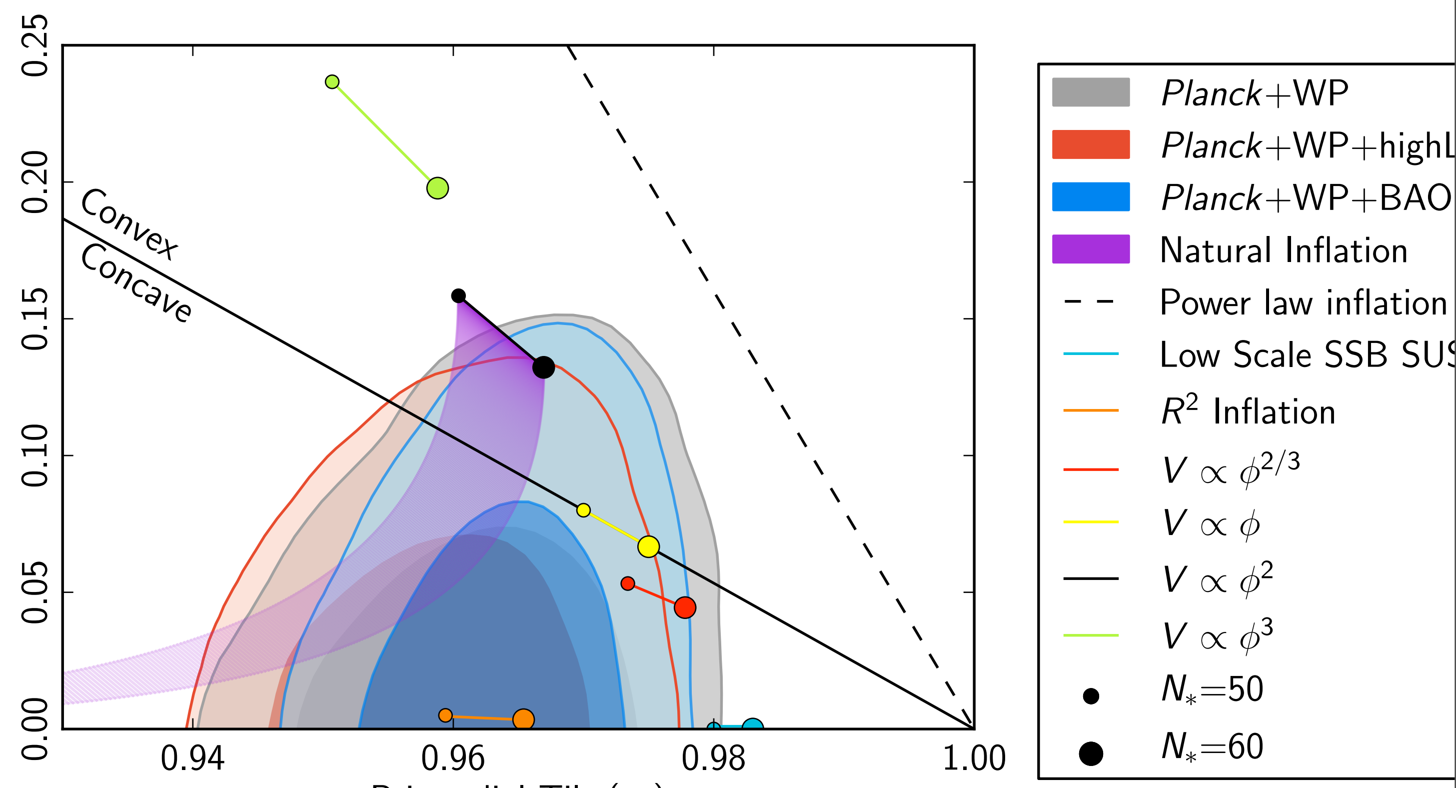
$$V(\phi,\psi) = \frac{\lambda}{4}\left(\psi^2 - \frac{M^2}{\lambda}\right)^2 + \frac{1}{2}m^2\phi^2 + \frac{1}{2}g^2\phi^2\psi^2$$

Generally predicts n_s >0 and r << 0.1. Not in good shape with data !

Natural inflation

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

This model agrees with Planck + WP for f > M_P .



R^2 inflation

$$S = \int d^4x\sqrt{-g}\frac{M_{\rm pl}^2}{2}\left(R + \frac{R^2}{6M^2}\right)$$

This model predicts a small value of r with n_s = 0.963

Power law inflation

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

This model can be solved exactly but is outside the joint 99.7% CL.

$$r = -8(n_s - 1)$$

Running of Spectral Index

Allowing for the running of ns has

$$\mathcal{P}_{\mathcal{R}}(k) = A_s \left(\frac{k}{k_0}\right)^{n_s - 1 + (1/2)(dn_s/d\ln k)\ln(k/k_0)}$$

$$dn_s/d\ln k = -0.013 \pm 0.009 \quad (68\%\ \mathrm{CL},\ Planck\mathrm{+WP})$$

A negative running at 1.5 sigma. However, many models of inflation predict running < 0.001.

$$\frac{dn_s}{d\ln k} \sim (n_s - 1)^2$$

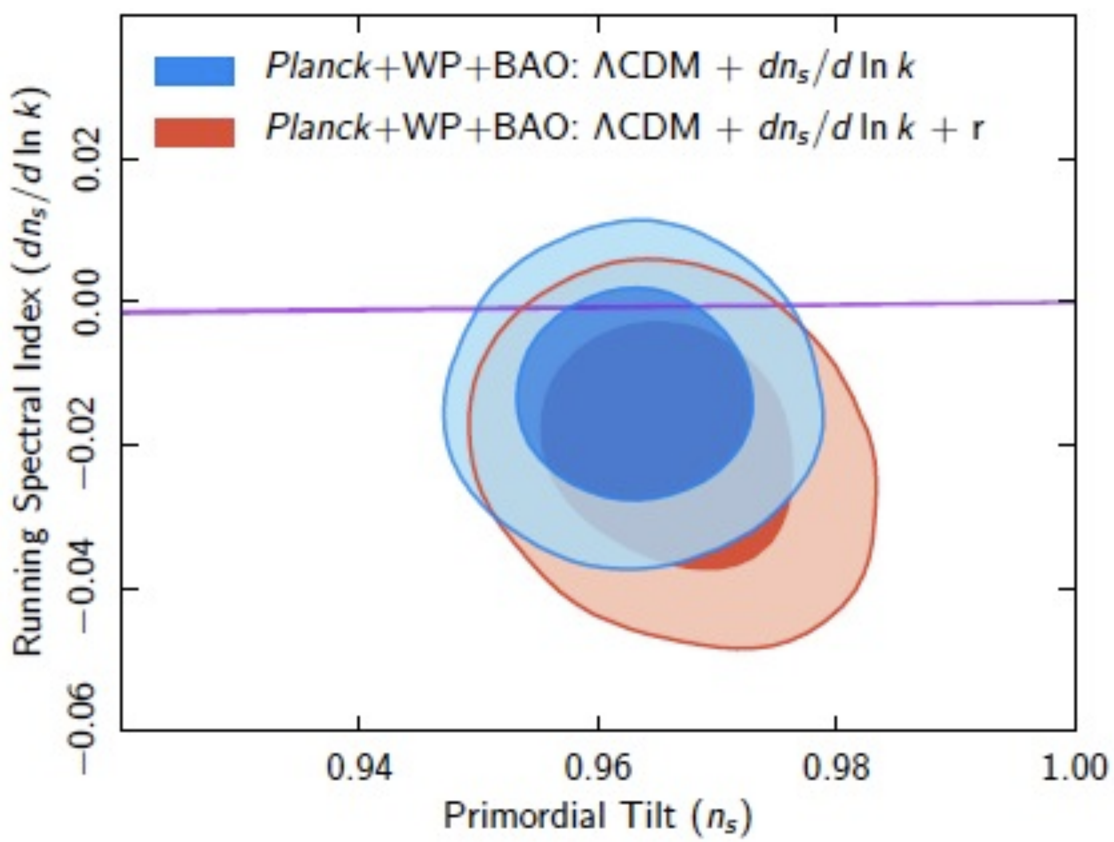
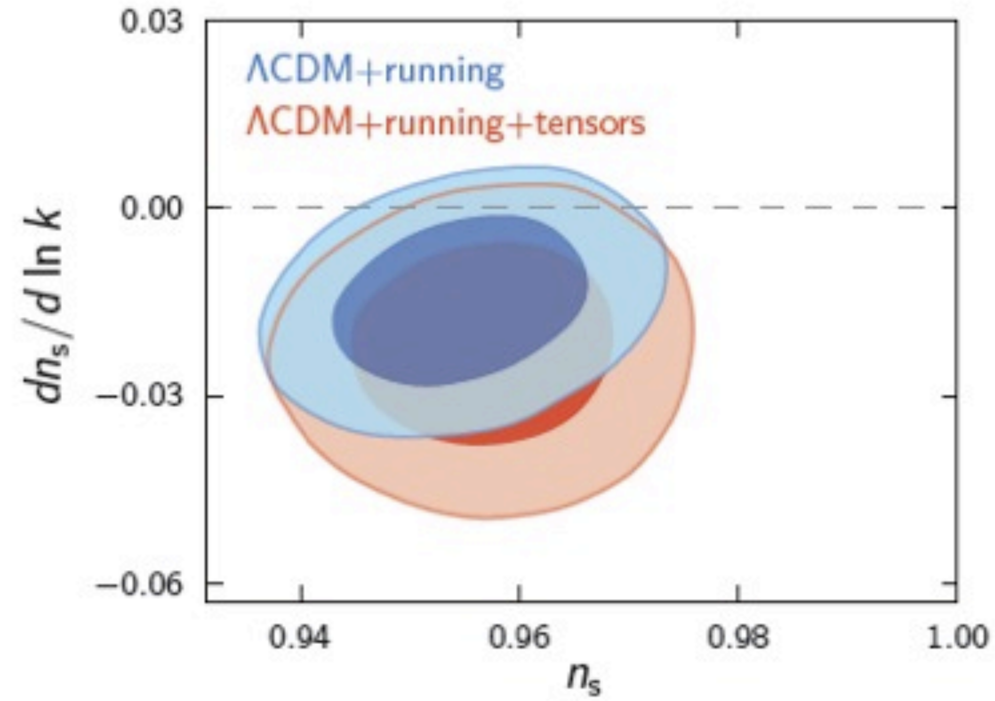
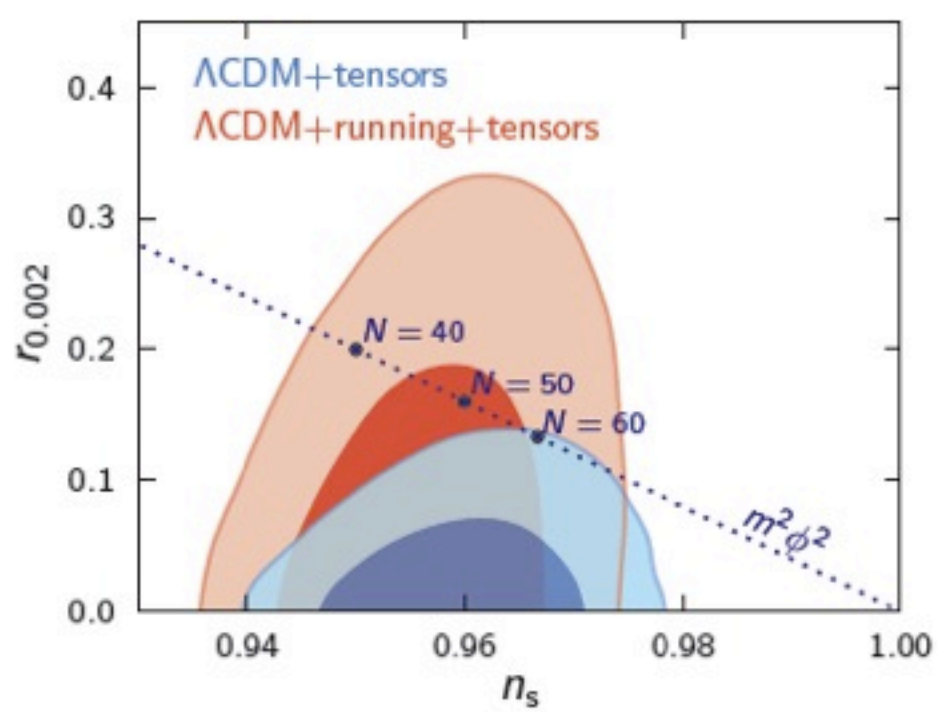


Fig. 2. Marginalized joint 68% and 95% CL for ($dn_s/d\ln k$, n_s) using *Planck*+WP+BAO, either marginalizing over r or fixing $r = 0$ at $k_* = 0.038\ \mathrm{Mpc}^{-1}$. The purple strip shows the prediction for single monomial chaotic inflationary models with $50 < N_* < 60$ for comparison.



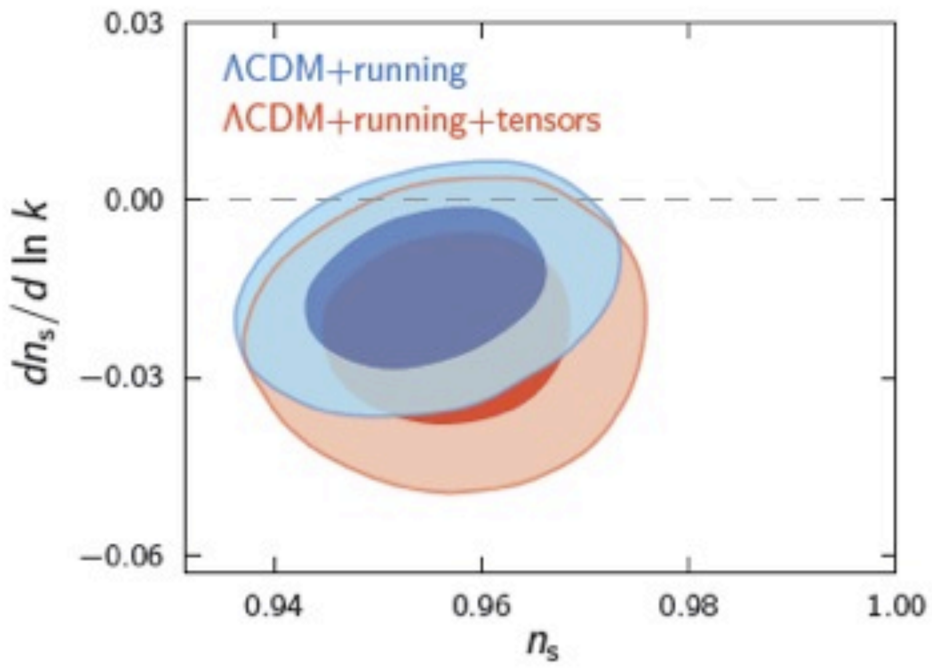


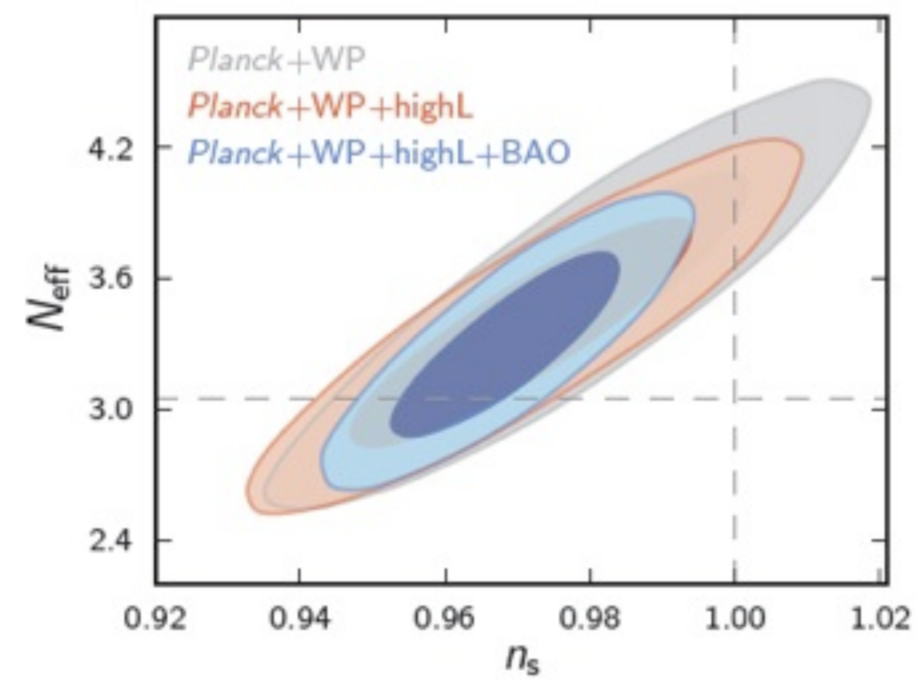
Deviations from Scale Invariance:

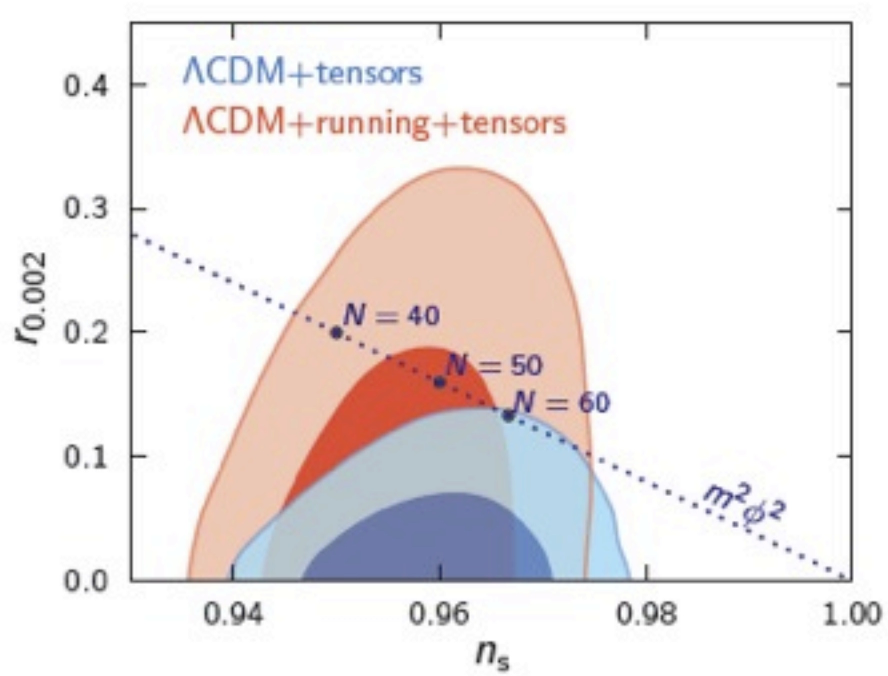
Scale-invariance is ruled out near 6 sigma CL.

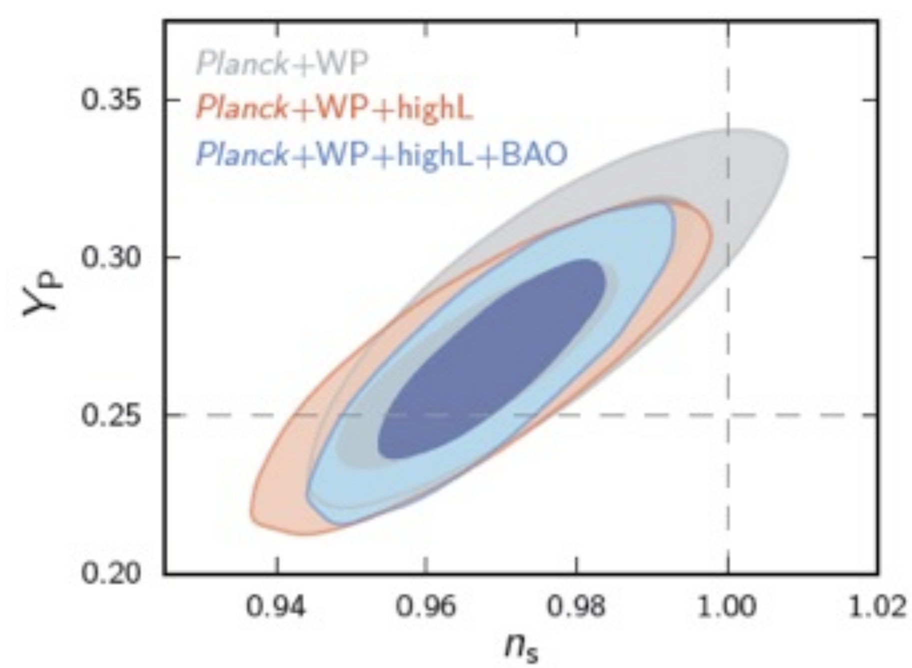
The degeneracy between ns and Y_P and N_{eff}:

Both these parameters affect the damping tail of the power spectrum. However if we set ns=1, we obtain too much baryon density and a large value of Y_P which is in contradiction with other observations.









Curvature

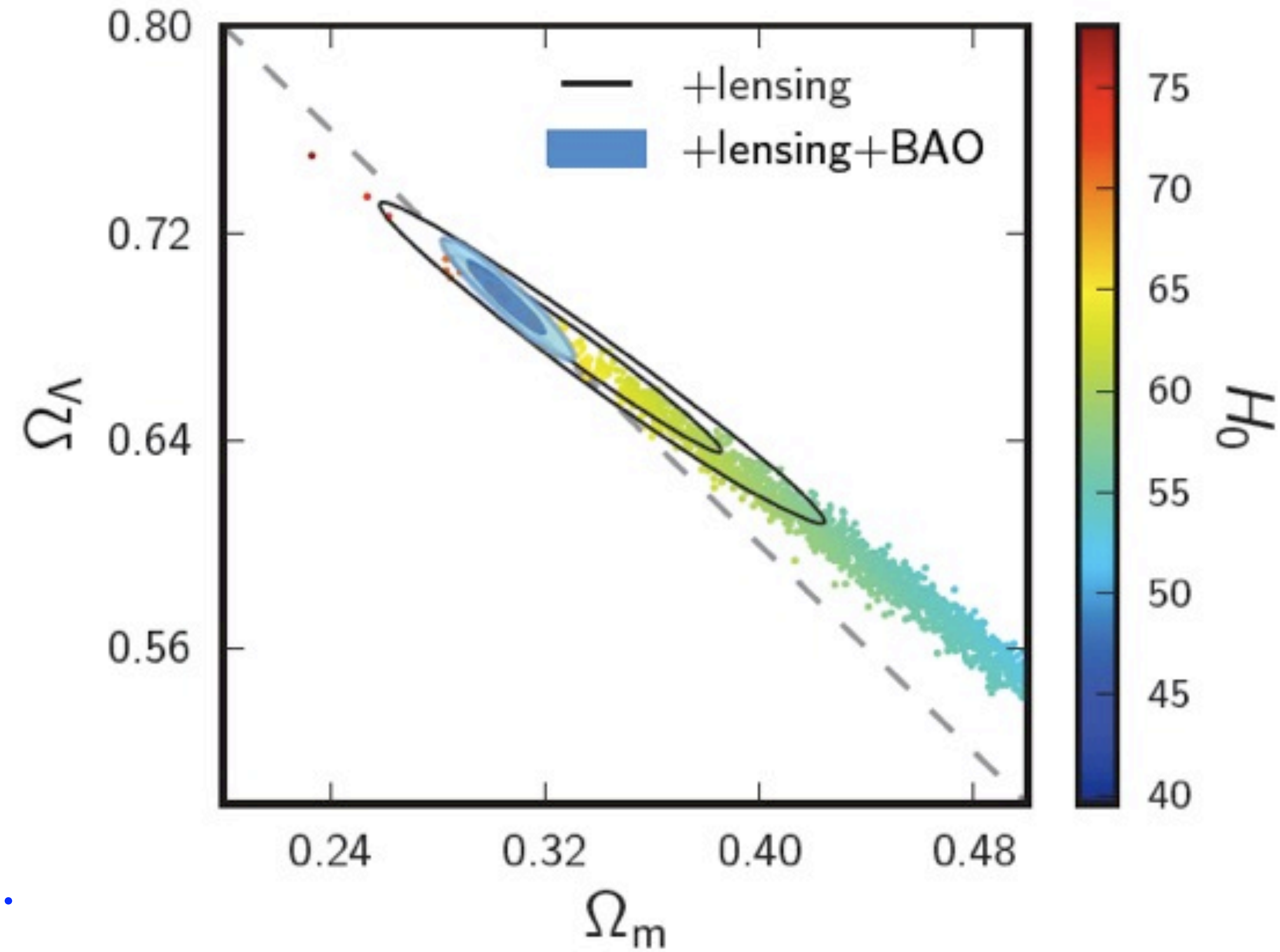
CMB alone (Planck+WP+HighL), despite geometrical degeneracy:

$100\Omega_k = -4.2 \pm 4.5$ (95%CL)

With lensing and BAO:

$100\Omega_k = -0.10 \pm 0.63$ (95%CL)

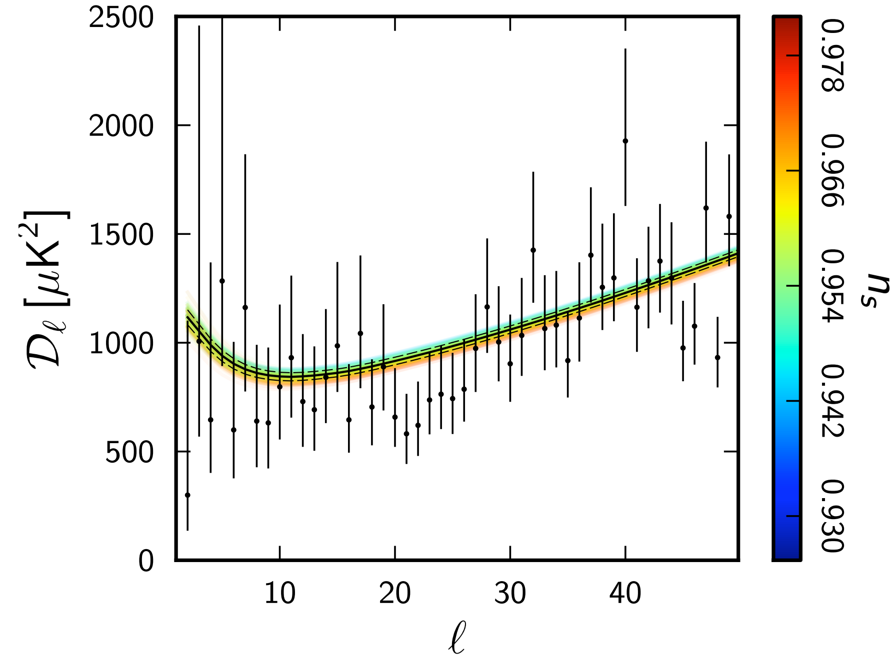
The Universe is flat better than 1%.



This is consistent with basic predictions of inflation in which $|\Omega_K| \sim 10^{-5}$.

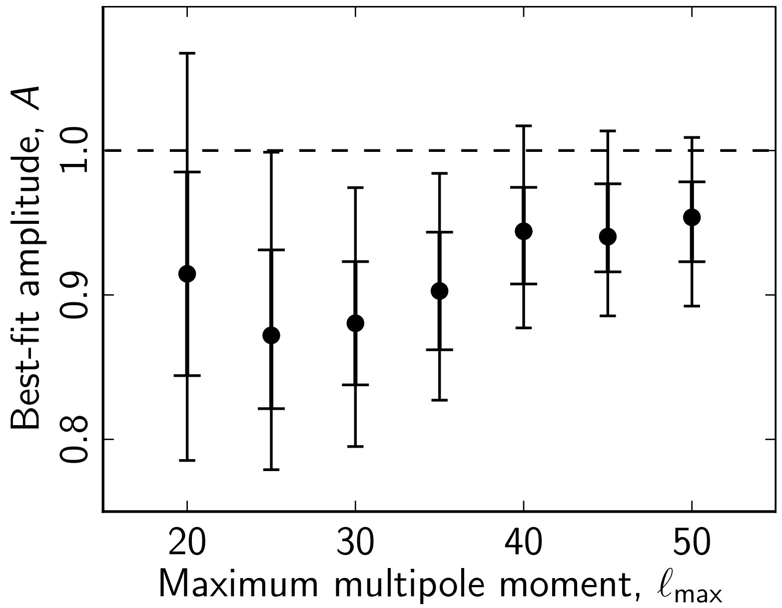
Search for feature during inflation

Inflation dynamics may have localized features. Examples: phase transition, particle production, tachyonic instability ,...



On the other hand Planck and WMAP have detected shortage of power on l =20 - 30

This motivate to construct models of inflation with local features in potential or power spectrum



Planck team has considered three phenomenological potentials with features

1- Wiggles models

This feature can happens when the initial state in not vacuum or in models where there are periodically recurring events such as in axion Monodromy inflation

$$\mathcal{P}_\mathcal{R}(k) = \mathcal{P}_0(k)\left\{1 + \alpha_\mathrm{w}\sin\left[\omega\ln\left(\frac{k}{k_*}\right) + \varphi\right]\right\}$$

$$\mathcal{P}_0(k) = A_\mathrm{s}\left(\frac{k}{k_*}\right)^{n_\mathrm{s}-1}$$

2- Step inflation models

This happens when there is a sudden change in potential or a sharp turn in field space or fro phase transition and particle creations

3- Cut off model

$$\mathcal{P}_\mathcal{R}(k) = \mathcal{P}_0(k)\left\{1 - \exp\left[-\left(\frac{k}{k_\mathrm{c}}\right)^{\lambda_\mathrm{c}}\right]\right\}$$

Results for Features

For all three models, including the local features improves the quality of the fit with respect to a pure power law spectrum.

For Wiggles model the oscillation around the first acoustic peak and in 700 < l < 900 improve the fit.

For the Step inflation model the fit is improved between the Sachs-Wolf plateau and the first acoustic peak.

The cut off model improves the fit moderately

Statistical significance?

“Whether or not these findings can be considered statistically significant or arise simply from over-fitting noisy data is not a trivial question.”

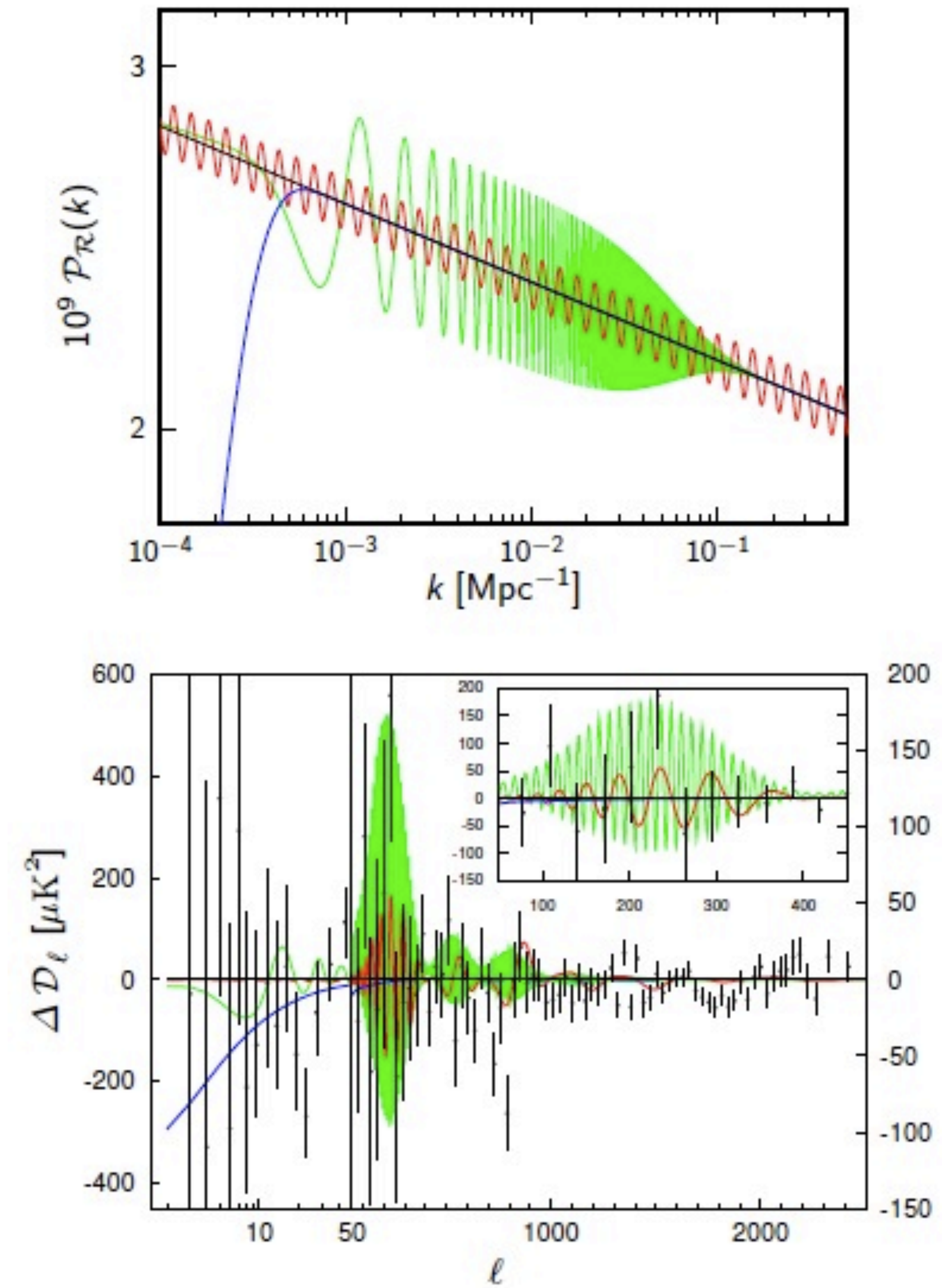
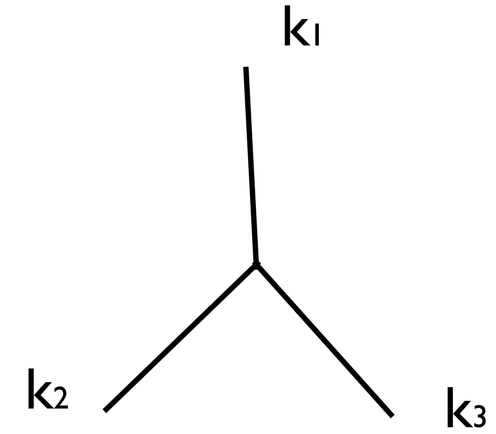


Fig. 18. *Top*: Best fit primordial spectrum of curvature perturbations for the power law (*black*), wiggles (*red*), step-inflation (*green*), and cutoff (*blue*) models. *Bottom*: Residuals of the temperature angular power spectrum. Note that the scale of the vertical axis changes at $\ell = 50$. *Inset*: Zoom on the region of the first acoustic peak.

Non-Gaussianities on CMB

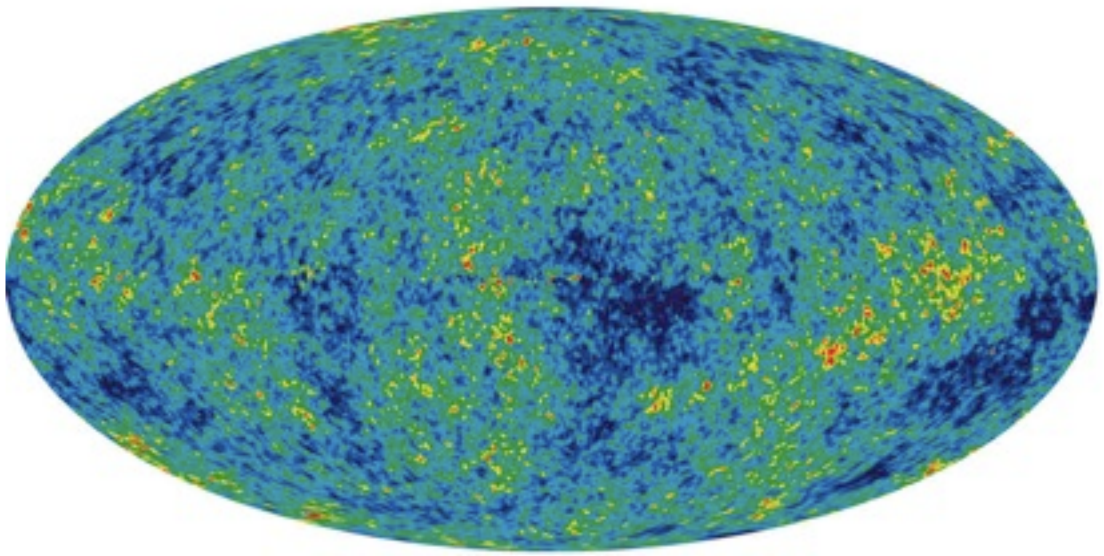
Simple models of slow-roll inflation predicts almost Gaussian perturbations

However, models like DBI inflation predicts large non-Gaussian perturbations



What is non-Gaussianity?

$$\langle\zeta(t,\mathbf{k}_1)\zeta(t,\mathbf{k}_2)\zeta(t,\mathbf{k}_3)\rangle = -i\int_{t_0}^{t} dt'\langle[\zeta(t,\mathbf{k}_1)\zeta(t,\mathbf{k}_2)\zeta(t,\mathbf{k}_3), H_{int}(t')]\rangle$$



In slow-roll inflation there is not much interaction,
$H_{int} \sim 0$, so there is no significant non-Gaussinities

Defining non-Gaussianity parameter f_{NL} via

$$\zeta = \zeta_L - \frac{3}{5} f_{NL}\zeta_L^2$$

Simple models of slow roll inflation predict

$$f_{NL} \sim n_s - 1 \sim 0.01$$

Maldacena, 2002

Non-Gaussianities in DBI Inflation

Alishahiha, Silverstein, Tong , hep-th/0404084

The action is

$$S=\frac{M_{pl}^2}{2}\int d^4x\sqrt{-g}R-\int d^4x\sqrt{-g}\,[f(\phi)^{-1}\sqrt{1+f(\phi)g^{\mu\nu}\partial_\mu\phi\partial_\nu\phi}-f(\phi)^{-1}+V(\phi)]$$

where $f(\phi)\simeq\frac{\lambda}{\phi^4}$ from the throat geometry and AdS/CFT considerations

The level of non-Gaussianity predicted in this model is

$$f_{NL}\sim\frac{1}{c_s^2}$$

in which c_s is the sound speed of cosmological perturbations

$$\gamma=\frac{1}{\sqrt{1-f\dot{\phi}^2}}=\frac{1}{c_s^2}$$

One can obtain f_{NL} as big as 100, which is easily observable by PLANCK.

This should be compared to slow-roll calculation in which

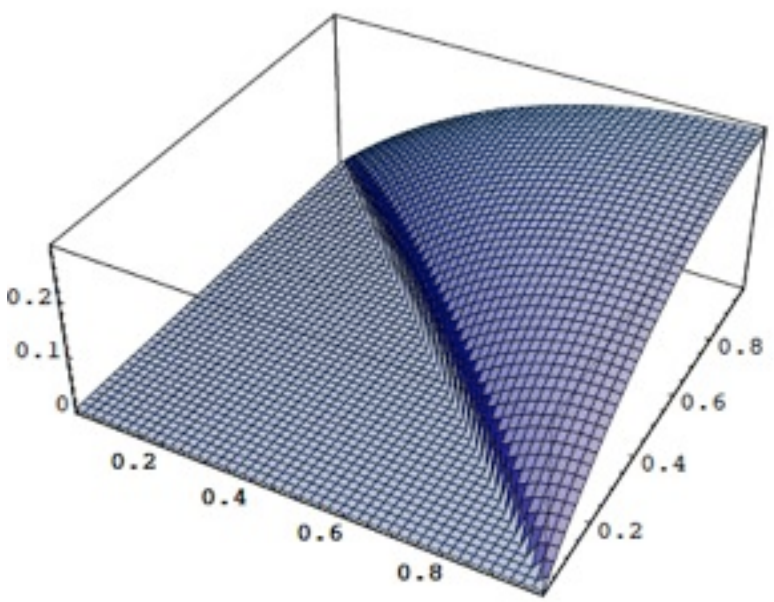
$$f_{NL}\sim n_s-1\sim 0.01$$ Maldacena, 2002

The Shapes of Non-Gaussianities

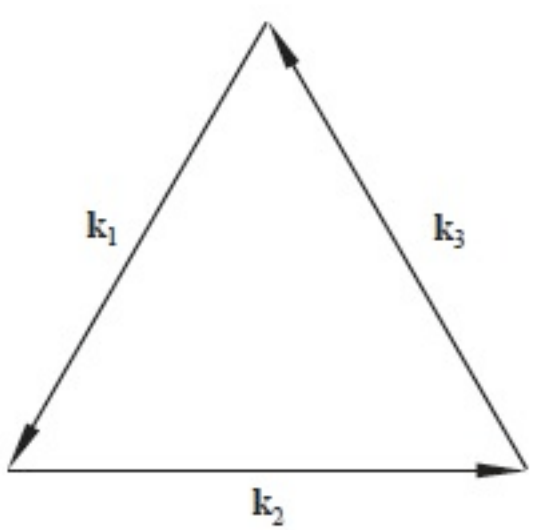
Consider the three-point function as

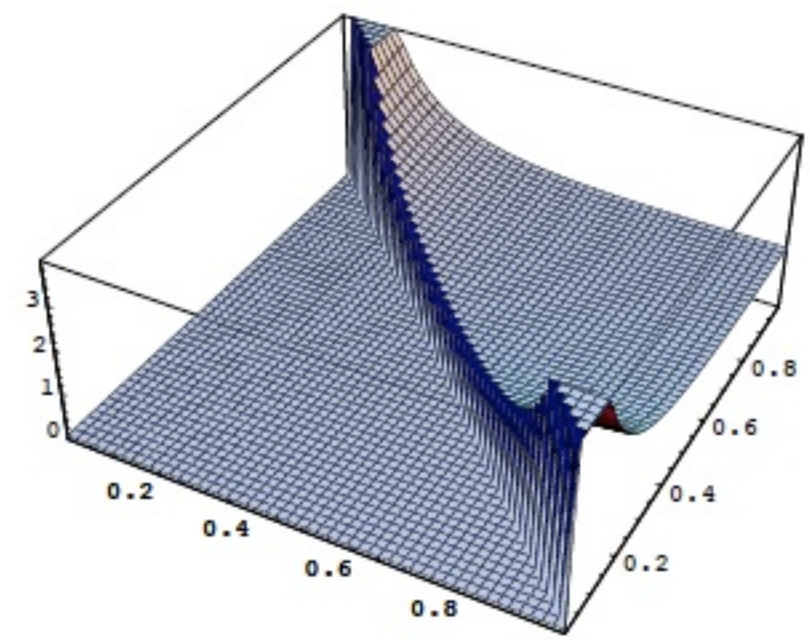
$$\langle \zeta(\mathbf{k}_1)\zeta(\mathbf{k}_2)\zeta(\mathbf{k}_3)\rangle = (2\pi)^7\delta^3(\mathbf{k}_1+\mathbf{k}_2+\mathbf{k}_3)(P_k^\zeta)^2\frac{1}{\prod_i k_i^3}\,\mathcal{A}$$

so A determines the shapes of the non-Gaussianity

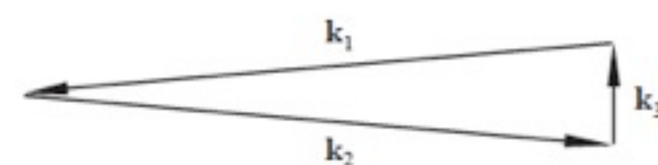


Shape in DBI inflation





Shape in multiple-field models



Planck Results for non-Gaussianity

Table 8. Results for the f_{NL} parameters of the primordial local, equilateral, and orthogonal shapes, determined by the KSW estimator from the SMICA foreground-cleaned map. Both independent single-shape results and results marginalized over the point source bispectrum and with the ISW-lensing bias subtracted are reported; error bars are 68% CL.

	Independent KSW	ISW-lensing subtracted KSW
SMICA		
Local	9.8 ± 5.8	2.7 ± 5.8
Equilateral	-37 ± 75	-42 ± 75
Orthogonal	-46 ± 39	-25 ± 39

$$f_{NL}^{DBI} = 11 \pm 69$$
$$f_{NL}^{EFT1} = 8 \pm 73$$
$$f_{NL}^{EFT2} = 19 \pm 57$$
$$f_{NL}^{Ghost} = -23 \pm 88$$

Implications for particular models

UV DBI inflation $\quad c_s^{DBI} \geq 0.07 \quad$ 95% CL.

IR DBI inflation $\quad V = V_0 - \frac{\beta}{2} H^2 \phi^2 \quad$ $\beta \leq 0.7 \quad$ 95% CL

Curvaton model $\quad f_{NL}^{local} = \frac{5}{4r_D} - \frac{5r_D}{6} - \frac{5}{3} \quad$ $r_D \geq 0.15 \quad$ 95% CL

No detection of non-Gaussianity.

"The paradigm of standard single field slow-roll inflation has survived its stringent test to date"

The end for Planck

- On 13 January 2012, it was reported that the on-board supply of helium-3 used in Planck's dilution refrigerator had been exhausted, and that the HFI would become unusable within a few days. By this date, Planck had completed five full scans of the CMB, exceeding its target of two. The LFI (cooled by helium-4) was expected to remain operational for another six to nine months

Planck and Inflation

- We are in the golden age of cosmology.
- Exact scale invariance is ruled out with 6 sigma CL.
- Simple single field models of inflation are well consistent with data.
- There was no detection of local type non-Gaussianity. This will have important implications for multiple fields scenarios .
- There is shortage of power on large scales, l =20-30. Does this imply a local feature in power spectrum?
- Detection of hemispherical asymmetry in Sky. Does it hint towards statistical anisotropy from models beyond scalar fields, such as vector or U(1) gauge fields? Does it indicate that our universe is located inside a big “Mega Universe”?

Papers from IPM cited in Planck reports:

Alishahiha et al : DBI inflation

Chen, H.F., Namjoo, Sasaki: 2012