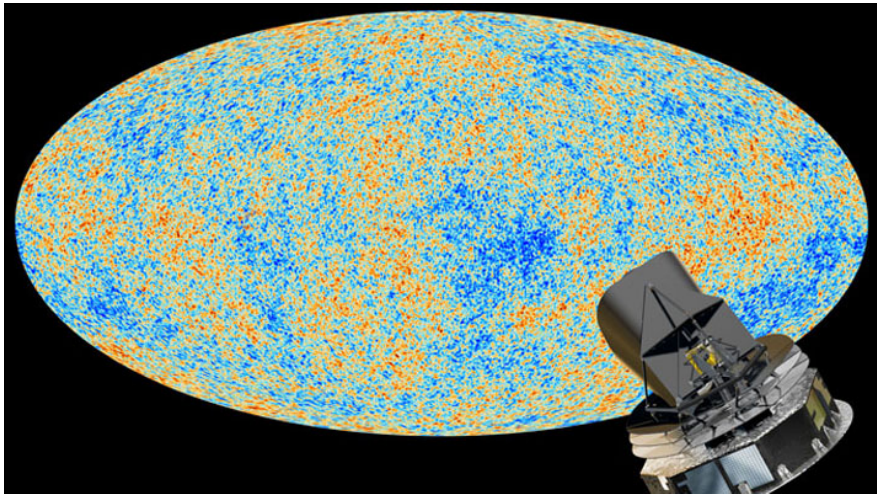
The *Planck* satellite: implications for Cosmology



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- INFN-Padova, INAF-OAPD

What are we going to learn?

- *Planck* main features
- Cosmic Microwave Background (CMB) basics
- (Some of the) 2015 *Planck results*

  Focus on early universe and inflation
- Future perspectives

The *Planck* mission

- The development of Planck has been supported by: ESA; CNES and CNRS/INSU-IN2P3-INP (France); ASI, CNR, and INAF (Italy); NASA and DoE (USA); STFC and UKSA (UK); CSIC, MICINN, JA and RES (Spain); Tekes, AoF and CSC (Finland); DLR and MPG (Germany); CSA (Canada); DTU Space (Denmark); SER/SSO (Switzerland); RCN (Norway); SFI (Ireland); FCT/MCTES (Portugal); and PRACE (EU)

http://www.sciops.esa.int/index.php?project=planck&page=Planck_Collaboration

esa

planck

cnes

asi agenzia spaziale italiana

HFI PLANCK

PLANCK LFI

NASA

CNRS

DTU Space
National Space Institute

INAF ISTITUTO NAZIONALE DI ASTROFISICA

Science & Technology Facilities Council

CSIC

National Research Council of Italy

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MINISTERIO DE CIENCIA E INNOVACIÓN

IAS orsay

IAP

INAF - IASF BO
ISTITUTO NAZIONALE DI ASTROFISICA
ISTITUTO DI ASTROFISICA SPAZIALE E FISICA COSMICA DI BOLOGNA

CSA ASC

DLR Deutsches Zentrum für Luft- und Raumfahrt e.V.

UK SPACE AGENCY

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Aalto University

APC

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ioa

Kavli Institute for Cosmology Cambridge KICC

Cavendish Astrophysics

UNIVERSITY OF CAMBRIDGE

CARDIFF UNIVERSITY PRIFYSGOL CAERDYDD

irfu cea saclay

cea

CESR

CITA–ICAT

CNRS IN2P3 Les deux infinis

ipac Infrared Processing and Analysis Center

HELSINKI INSTITUTE OF PHYSICS

Instituto de Astrofísica de Canarias

IFCA

Imperial College London

Università degli Studi di Milano

NÉEL institut

IPAG

ISDC

JPL

LAL Laboratoire de l'Accélérateur Linéaire

l'Observatoire de Paris LERMA

LPSC Grenoble

MilliLab

Max-Planck-Institut für Astrophysik

NUI MAYNOOTH

INAF Osservatorio Astronomico di Padova

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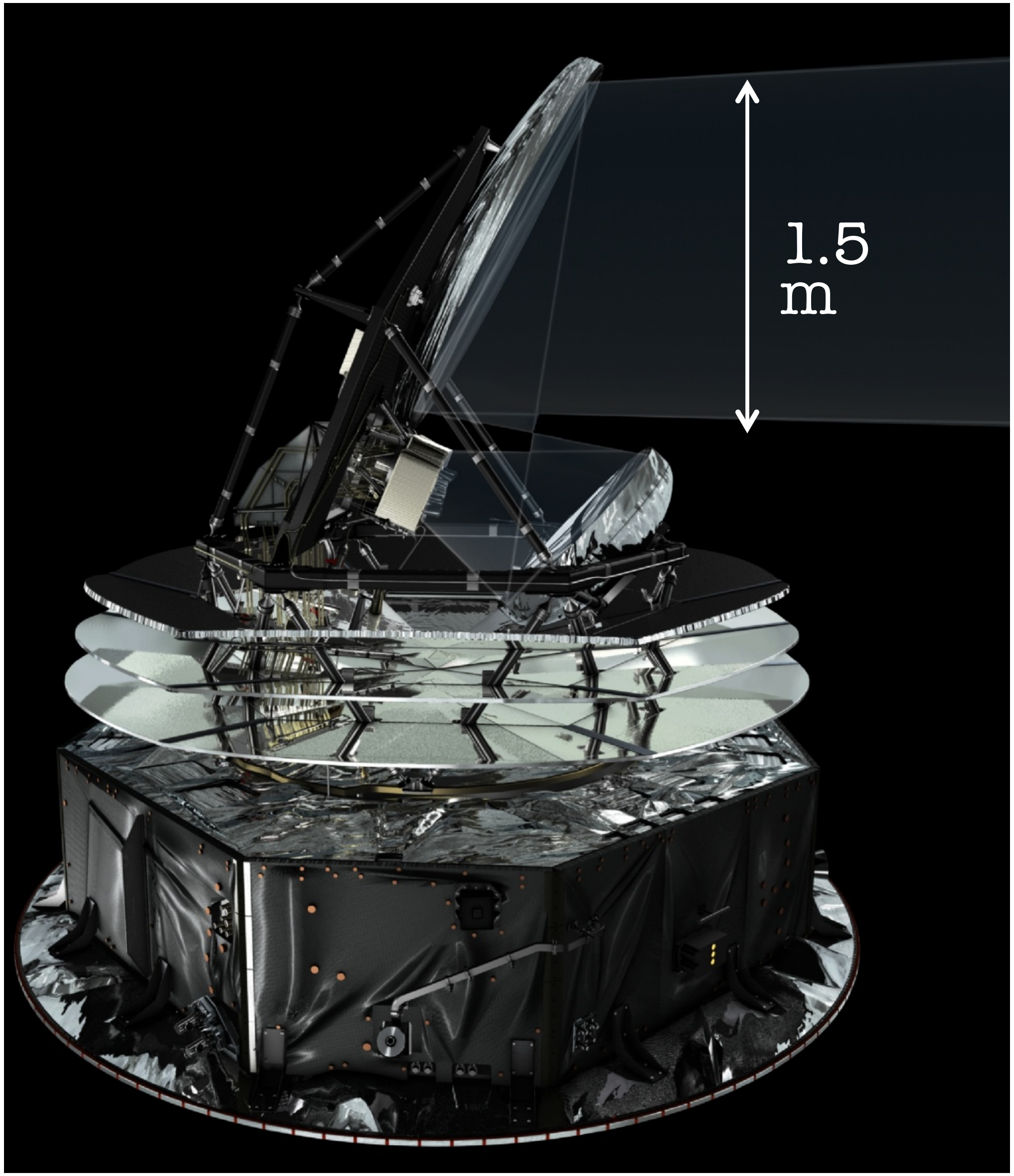
The Planck Mission



3rd CMB space mission - 1st ESA in collaboration with European, US and Canadian scientific community

Mass	2˙000 kg
Power	1˙600 W
Size	4.2 × 4.2 m
Cost	600×10^6 €

50˙000 Electronic components
36˙000 l ^{4}He
12˙000 l ^{3}He
11˙400 Documents

20 yrs between project & results

2 instruments & consortia
16 countries
400 researchers

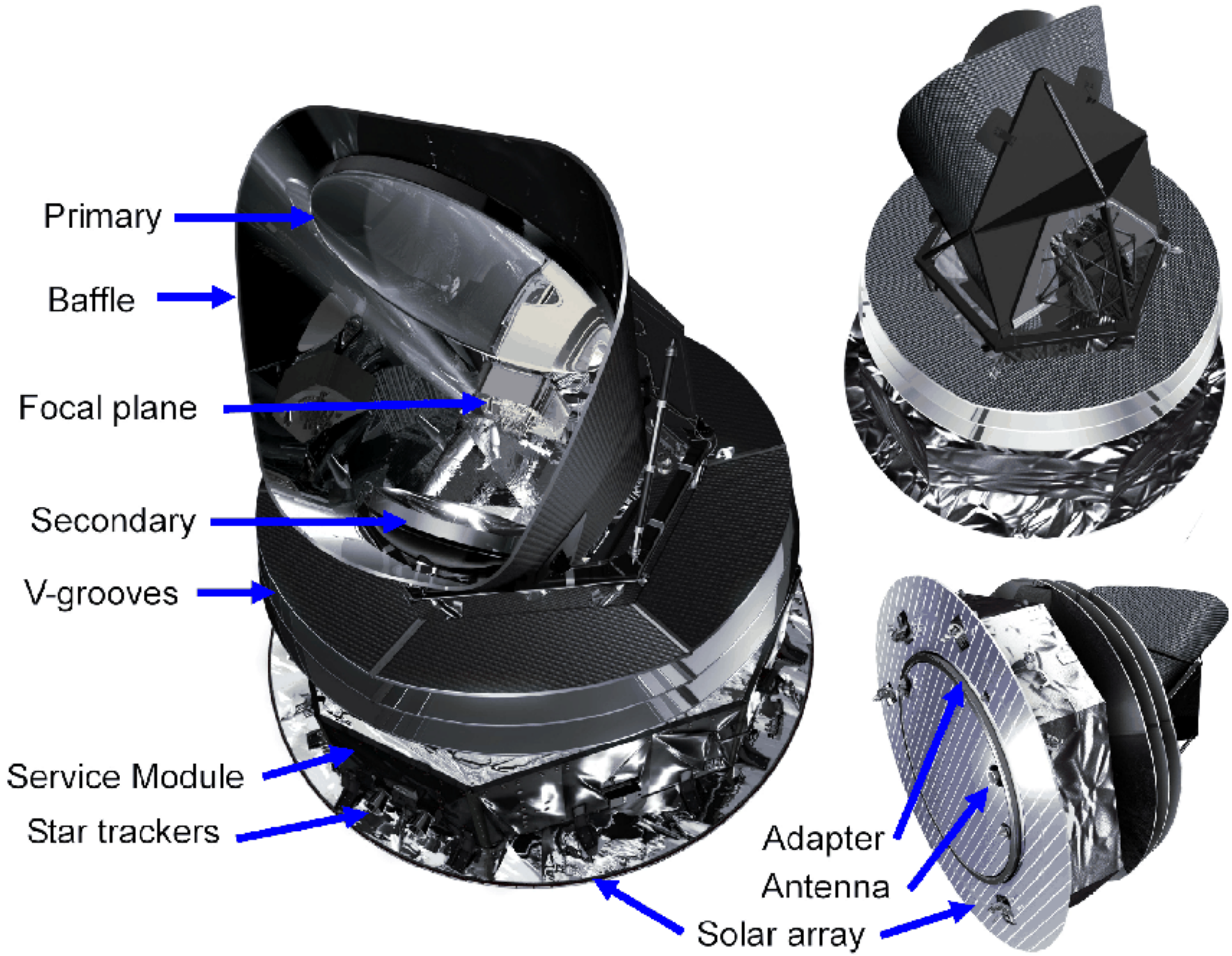

The launch of ESA Planck satellite on 14th May 2009
esa
ariane
Switched off on the 23rd October 2013

The *Planck* mission: a *very* short summary

- 3rd generation space mission after COBE and WMAP to measure CMB anisotropies
- Two instruments: Low Frequency Instrument (LFI) radiometers (30, 44, 70 GHz.) High Frequency Instrument (HFI) bolometers (100, 143, 217, 353, 545 and 857 GHz).
- *Planck* carries a scientific payload consisting of an array of 74 detectors sensitive to a range of frequencies between ~25 and ~1000 GHz, which scan the sky simultaneously and continuously with an angular resolution varying between ~30 arcminutes at the lowest frequencies and ~5' at the highest.

http://www.sciops.esa.int/index.php?project=planck&page=Planck_Collaboration

The *Planck* mission: a *very* short summary



The *Planck* mission: a *very* short summary

- Unprecedented combination of sensitivity, angular resolution, and frequency coverage. E.g. the *Planck* detector array at 143 GHz has instantaneous sensitivity and angular resolution 25 and 3 times better, respectively, than the WMAP V band (Bennett et al. 2003; Hinshaw et al. 2012a). Max. resolution of 5'.
- In addition, Planck has a large overlap in l with the high resolution ground-based experiments ACT (Sievers et al. 2013) and SPT (Keisler et al. 2011). The noise spectra of SPT and Planck cross at around l~2000, allowing an excellent check of the relative calibrations and transfer functions.

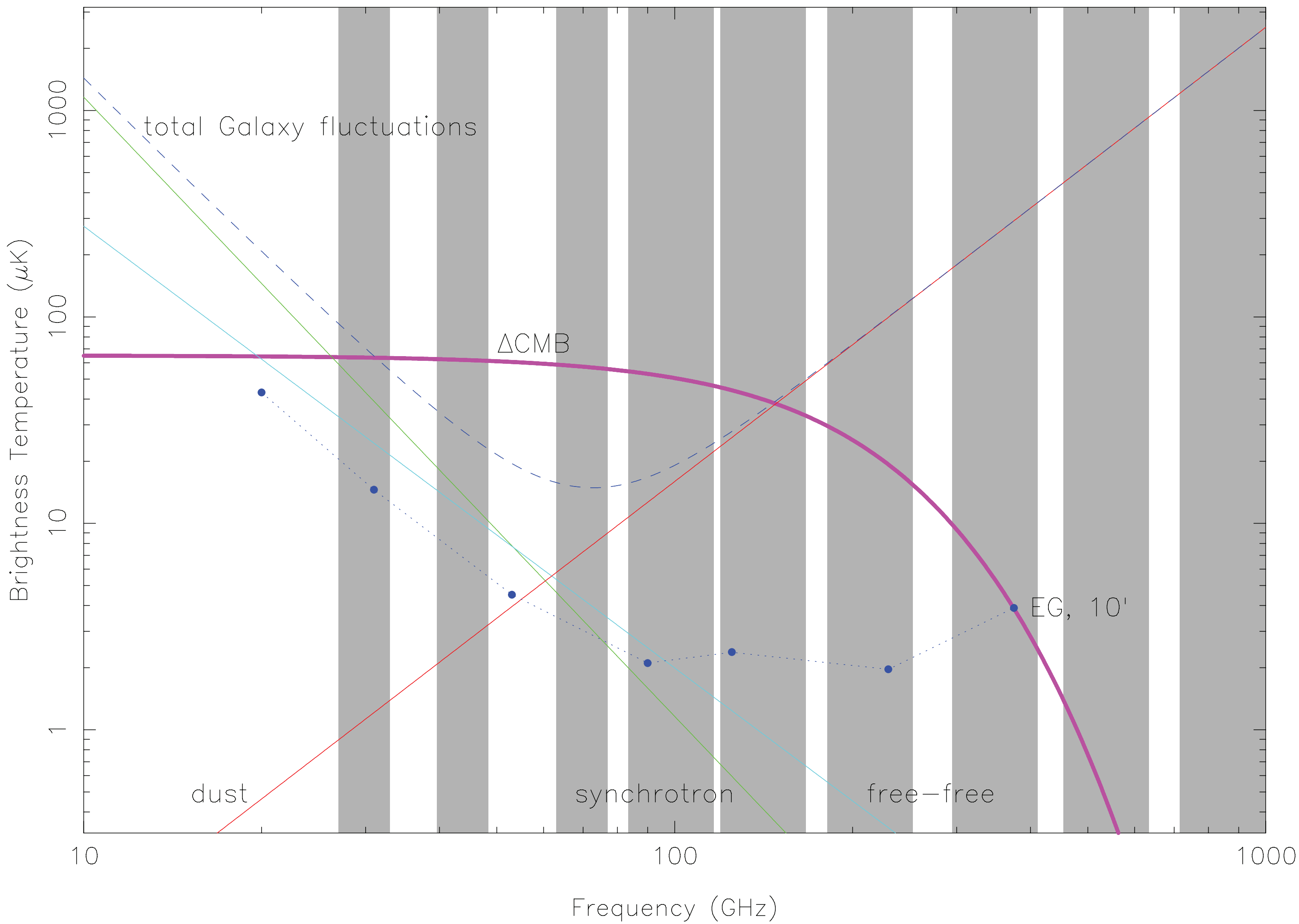
http://www.sciops.esa.int/index.php?project=planck&page=Planck_Collaboration

The *Planck* mission: a *very* short summary

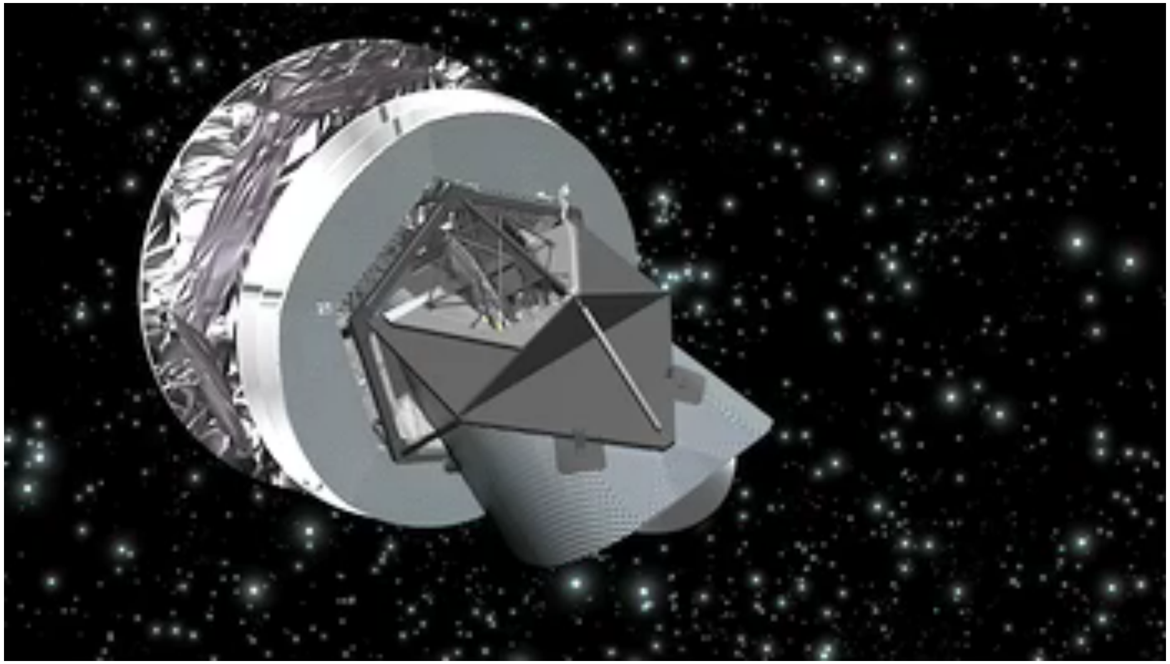
- *Planck*'s all-sky wide-frequency coverage becomes a key factor, allowing it to measure foregrounds and remove them to below intrinsic detector noise levels, but the contribution of higher resolution experiments to resolve foregrounds is also very important.
- Increased sensitivity places *Planck* in a new situation. Earlier satellite (COBE/DMR (Smoot et al. 1992), WMAP (Bennett et al. 2012)) experiments were limited by detector noise more than by systematic effects and foregrounds. Recent ground-based and balloon-borne experiments ongoing or under development (e.g., ACT (Kosowsky 2003), SPT (Ruhl et al. 2004), SPIDER (Fraisse et al. 2011), EBEX (Reichborn-Kjennerud et al. 2010)), have far larger numbers of detectors and higher angular resolution than *Planck* but can survey only a fraction of the sky over a limited frequency range. They are therefore sensitive to foregrounds or limited to analysing only the cleanest regions of the sky

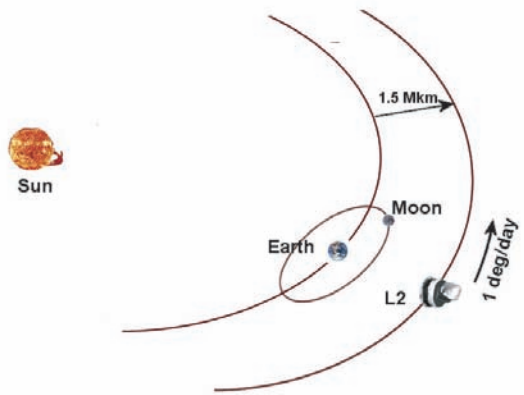
http://www.sciops.esa.int/index.php?project=planck&page=Planck_Collaboration

The *Planck* mission: a *very* short summary



Planck





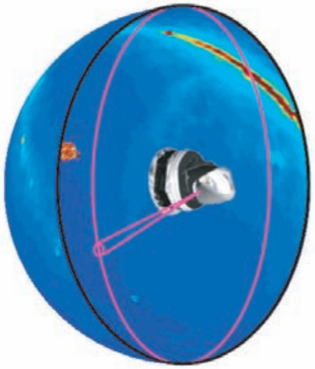


FIG 1.4.—*Planck* orbit at the 2nd Lagrangian point of the Earth-Sun system (L_2). The spin axis is pointed near the Sun, with the solar panel shading the payload, and the telescope sweeps the sky in large circles at 1 rpm.

The scientific target

- The main objective of Planck, defined in 1995, is to measure the spatial anisotropies of the temperature of the Cosmic Microwave Background (CMB), with an accuracy set by fundamental astrophysical limits. Its level of performance was designed to enable Planck to extract essentially all the cosmological information embedded in the CMB temperature anisotropies: ***Planck* can be considered the ultimate experiment as far as CMB temperature anisotropies are concerned.**

- Planck was also designed to measure, to high accuracy, the polarization of the CMB anisotropies, which encodes not only a wealth of cosmological information, but also provides a unique probe of the early history of the Universe during the time when the first stars and galaxies formed. Finally, the Planck sky surveys produce a wealth of information on the properties of extragalactic sources and on the dust and gas in our own galaxy

The scientific target

→ A major goal of the *Planck* experiment is to determine with great precision the key cosmological parameters describing our Universe. A combination of high sensitivity, high angular resolution, and wide frequency coverage makes Planck ideal for this task.

→ *Planck* is able to measure anisotropies on intermediate and small angular scales over the whole sky much more accurately than previous experiments (COBE, Boomerang, Maxima, WMAP, ...) → improved constraints on individual parameters, and the breaking of degeneracies between combinations of other parameters.

→ *Planck*'s sensitivity and angular resolution make the analysis less reliant on supplementary astrophysical data than previous CMB experiments.

Planck results

→ First major release in 2013

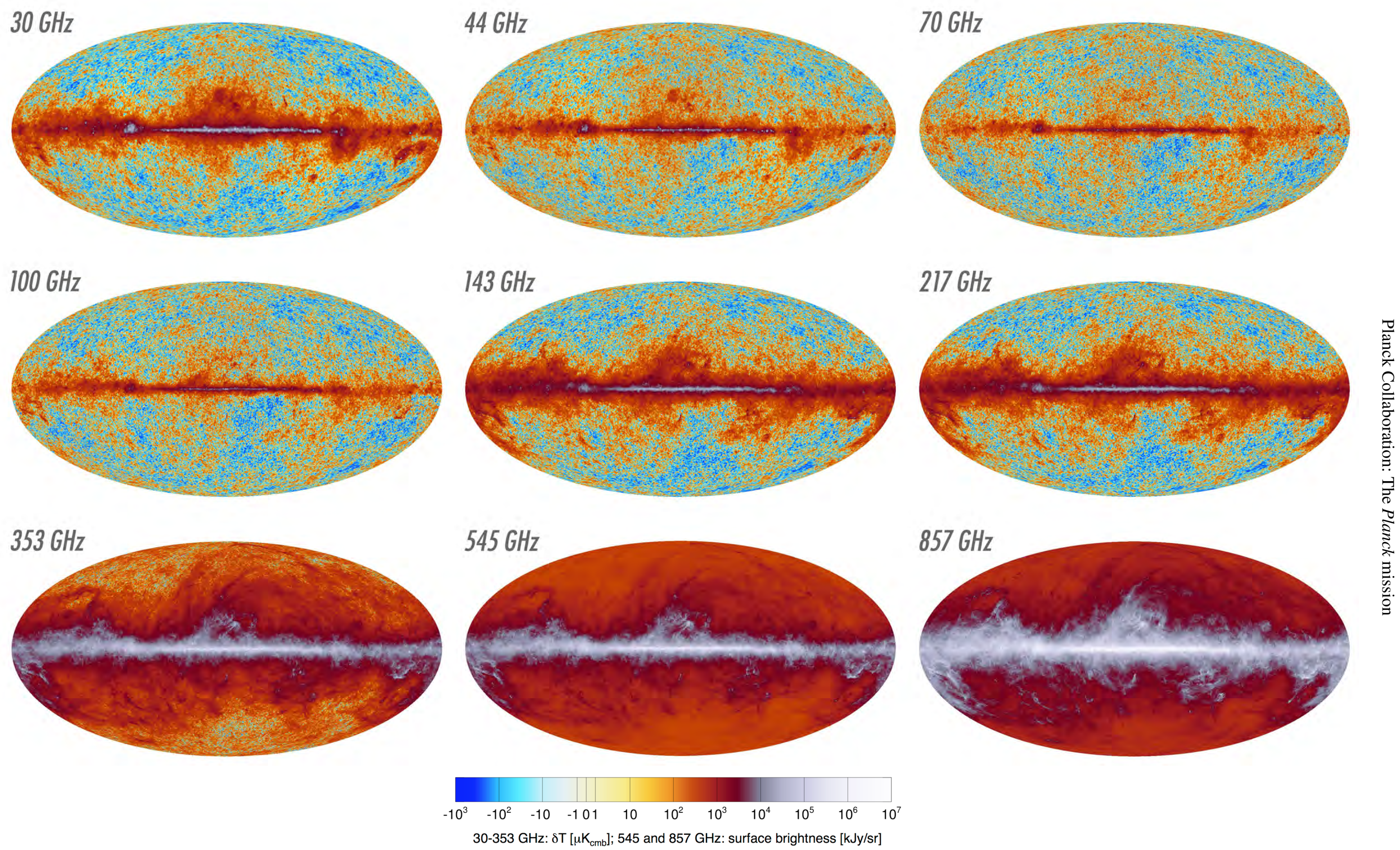
→ Second major release in 2015

→ in total >>100 papers from the Planck collaboration

→ I am doing a massive compression of information

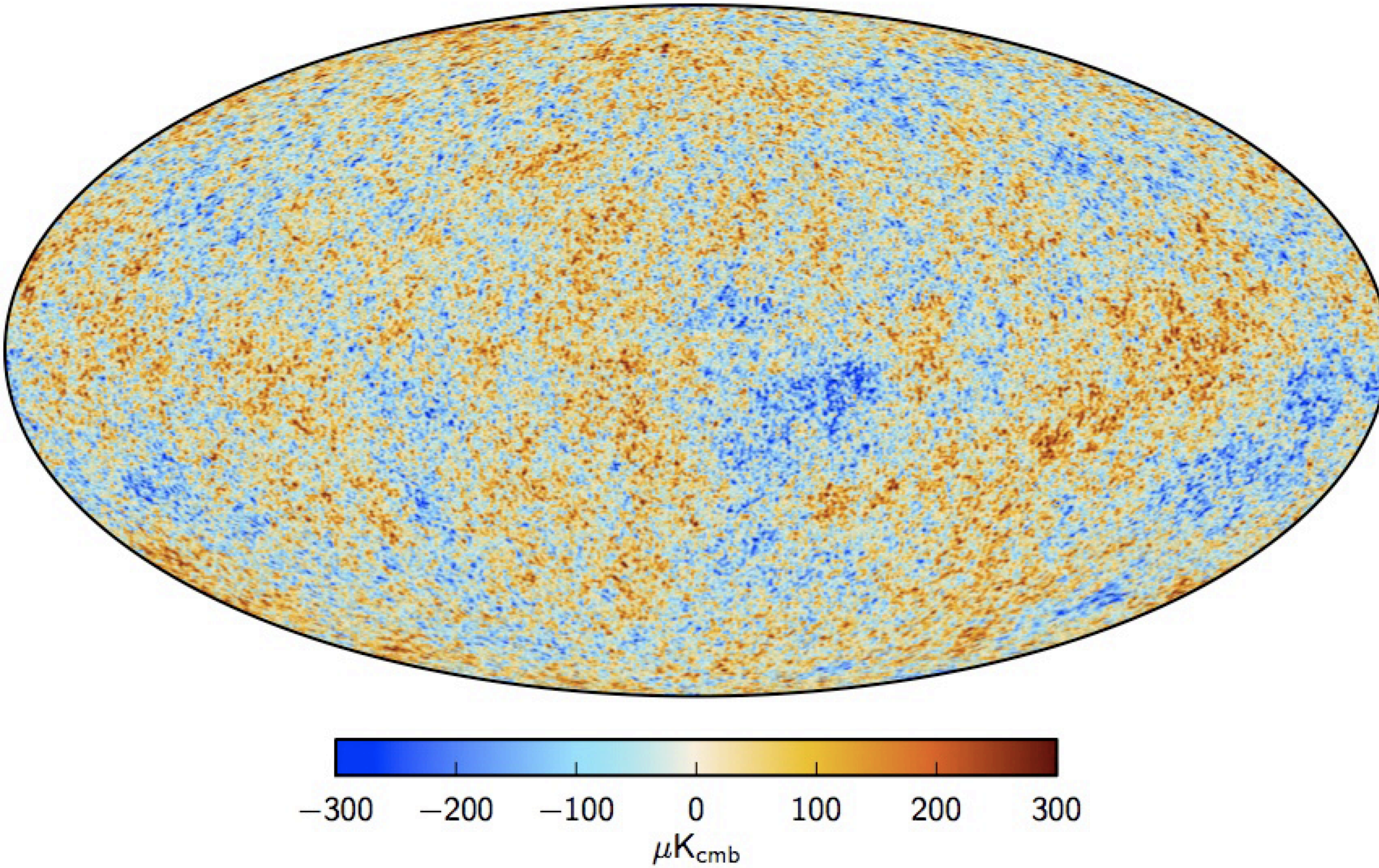
→ I might have a bias towards results on early universe and inflation physics.

→ At the moment we are working for the Legacy papers, to be delivered by the end of 2017.

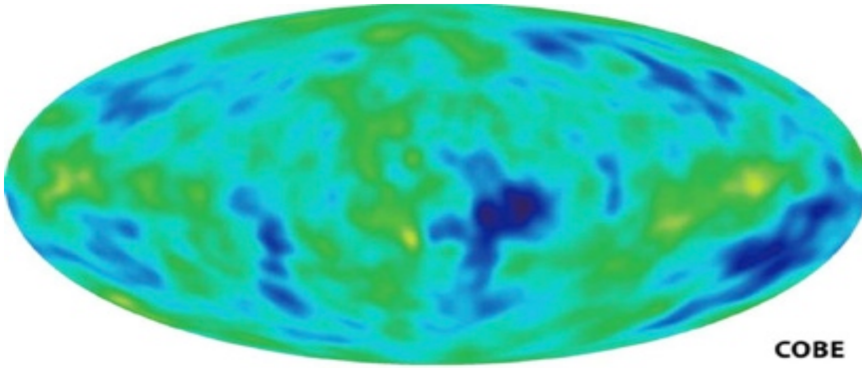


The nine Planck frequency maps show the broad frequency response of the individual channels. The color scale has been tailored to show the full dynamic range of the maps.

The CMB @ Planck resolution



COBE, WMAP, Planck

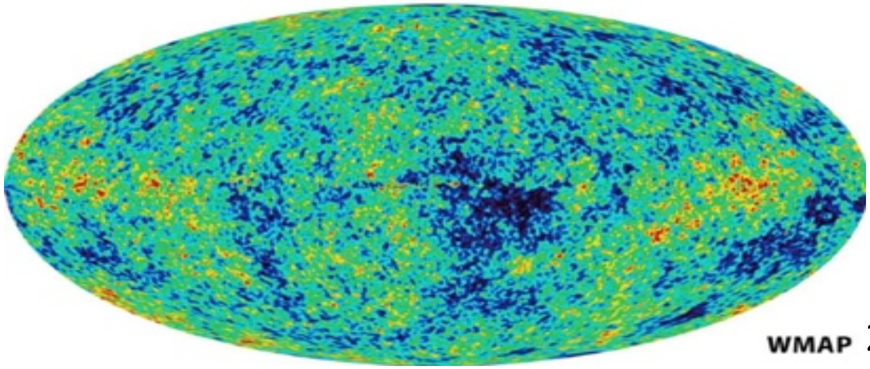


COBE 1992

N_{pix} ~ 10^4

FWHM ~ 7^o

l_{max} ~ 30

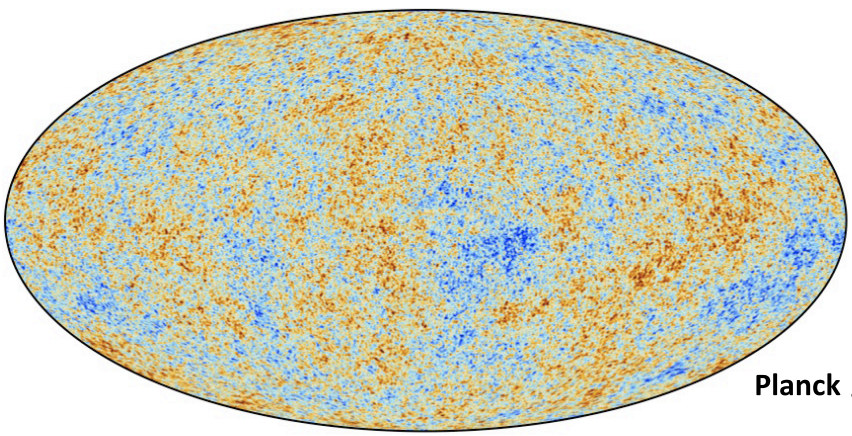


WMAP 2003

N_{pix} ~ 3×10^6

FWHM ~ 12 arcmin

l_{max} ~ 1000



Planck 2015

N_{pix} ~ 5×10^7

FWHM ~ 5 arcmin

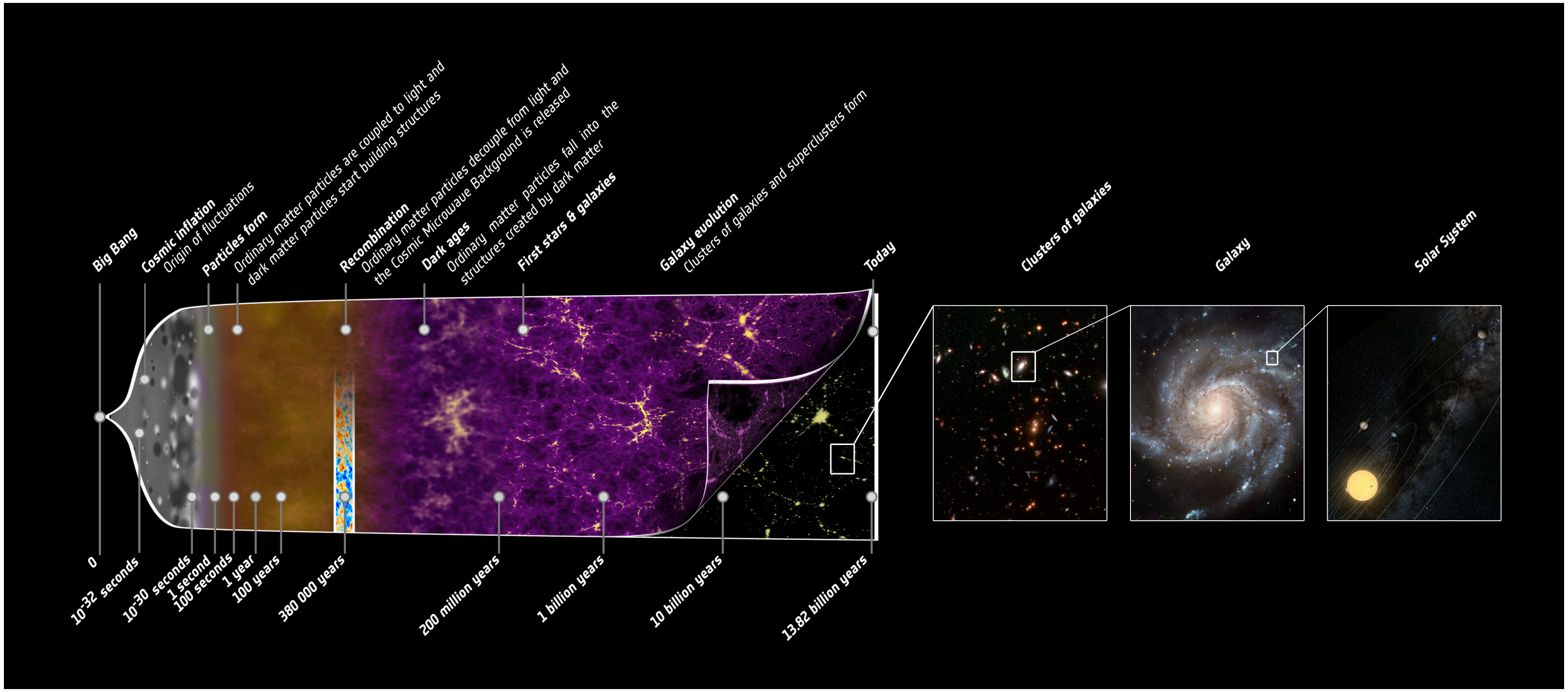
l_{max} ~ 3000

CMB basics

- (Afer inflation) the Universe is initially in a hot and dense state
- Free electrons and nuclei interact with photons via Compton scattering
- As the Universe cools down, electrons combine with protons to form Hydrogen atoms **(recombination) ➔ matter-radiation decoupling: last scattering surface.**

  Time of decoupling ~ 380000 yrs. Temperature at decoupling ~ 3000 K.

  After decoupling CMB photons travel feely to us.
- Due to Universe expansion the CMB has today a blackbody spectrum with color temperature T ~ 2.7 K



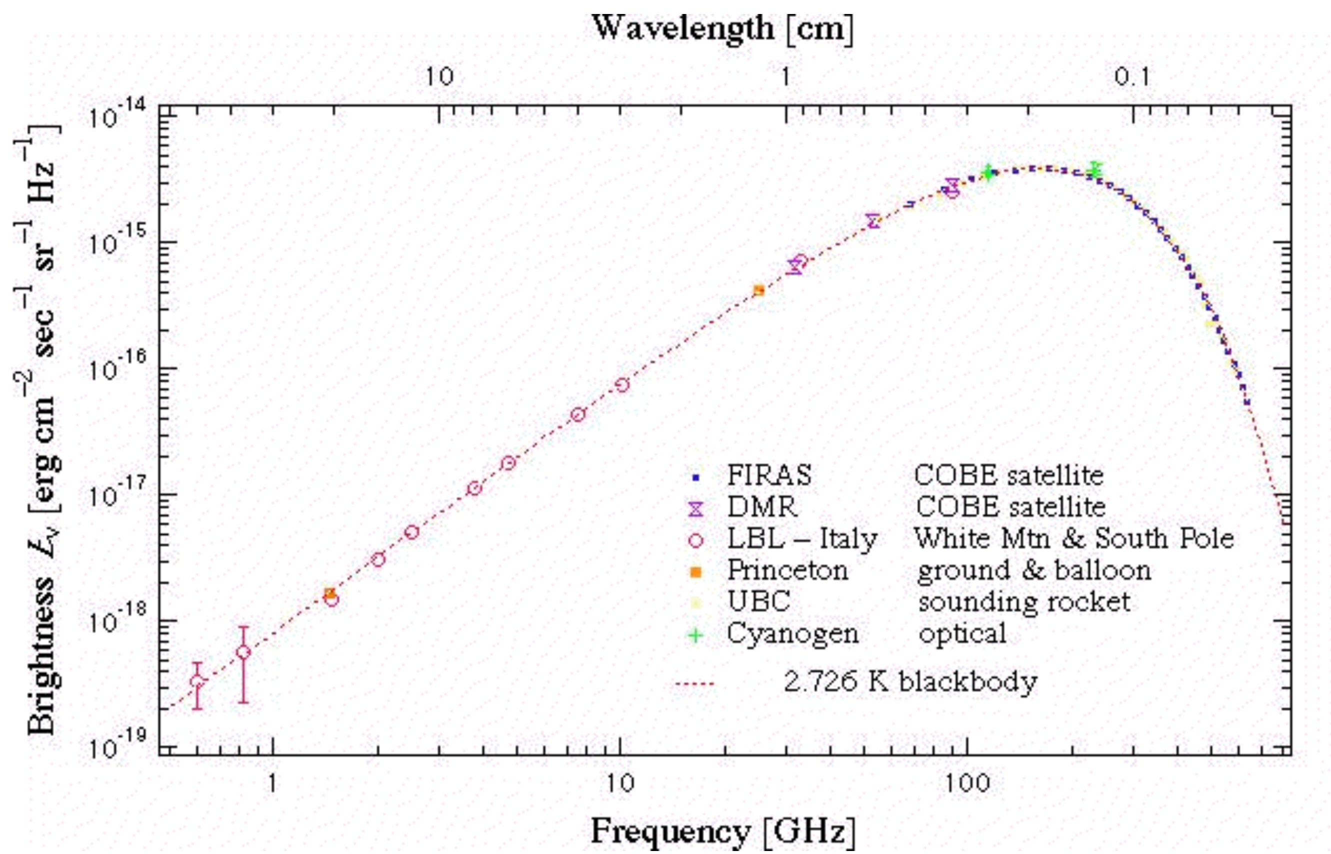
The ``smooth'' isotropic universe: CMB as a blackbody

THE CMB INTENSITY SPECTRUM

Best fit T_0=2.725 ± 0.002K (95% CL)
No distortions detected
(apart y-distortions from Sunyaev-Zel'dovich effect)

A ``perfect'' blackbody spectrum

$$I_\nu = \frac{2h\nu^3}{c^2}\frac{1}{e^{\frac{h\nu}{kT}}-1}$$



The Background Cosmology

$$ds^2 = -c^2 dt^2 + a^2(t) d\ell^2$$

Robertson-Walker metric

Friedmann equations

$$\begin{cases} \dfrac{\ddot{a}}{a} = -\dfrac{4\pi G}{3}\left(\rho + \dfrac{3p}{c^2}\right) + \dfrac{\Lambda c^2}{3} \\[2ex] \left(\dfrac{\dot{a}}{a}\right)^2 = \dfrac{8\pi G}{3}\rho + \dfrac{\Lambda c^2}{3} - \dfrac{\kappa c^2}{a^2} \\[2ex] \dot{\rho} = -3\dfrac{\dot{a}}{a}\left(\rho + \dfrac{p}{c^2}\right) \end{cases}$$

a(t) = scale-factor

ρ = energy density

P = pressure

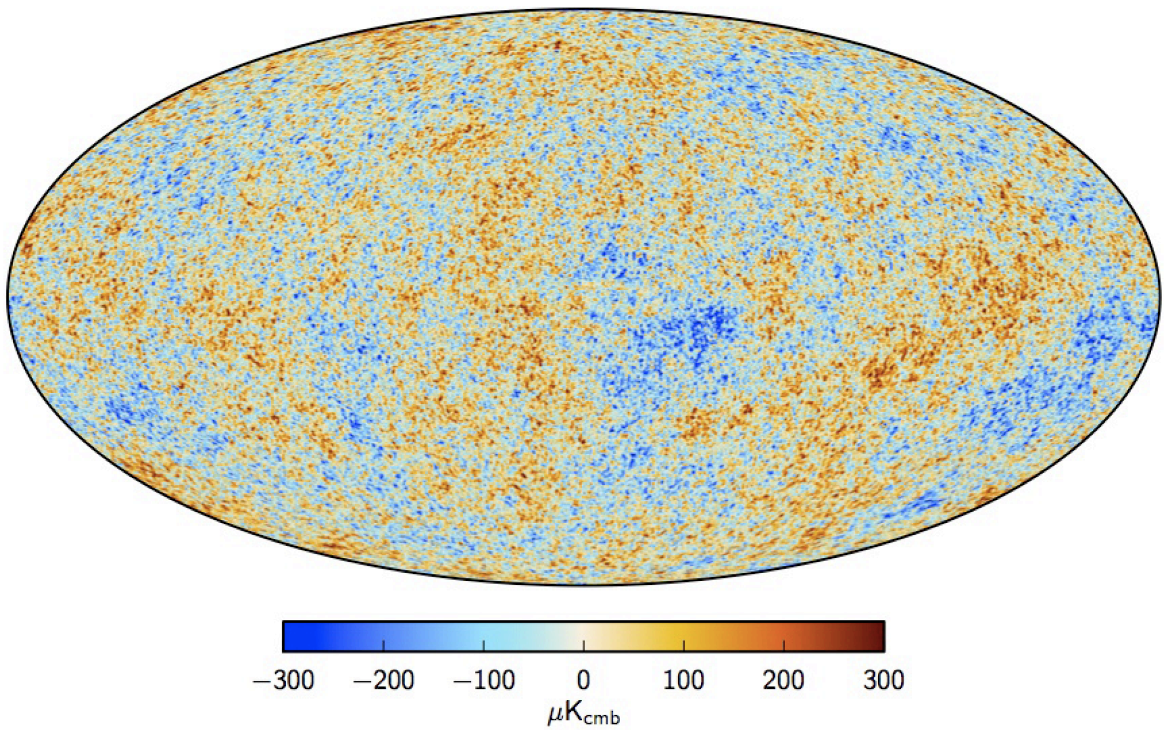
$H_0 = \dfrac{\dot{a}_0}{a_0}$	**Hubble constant**
$q_0 = -\dfrac{\ddot{a}_0 a_0}{\dot{a}_0^2}$	**deceleration parameter**
$\Omega_0 = \dfrac{\rho_0}{\rho_{0c}} \equiv \dfrac{8\pi G \rho_0}{3H_0^2}$	**density parameter**
Λ	**cosmological constant**

cosmological parameters today (t_0)

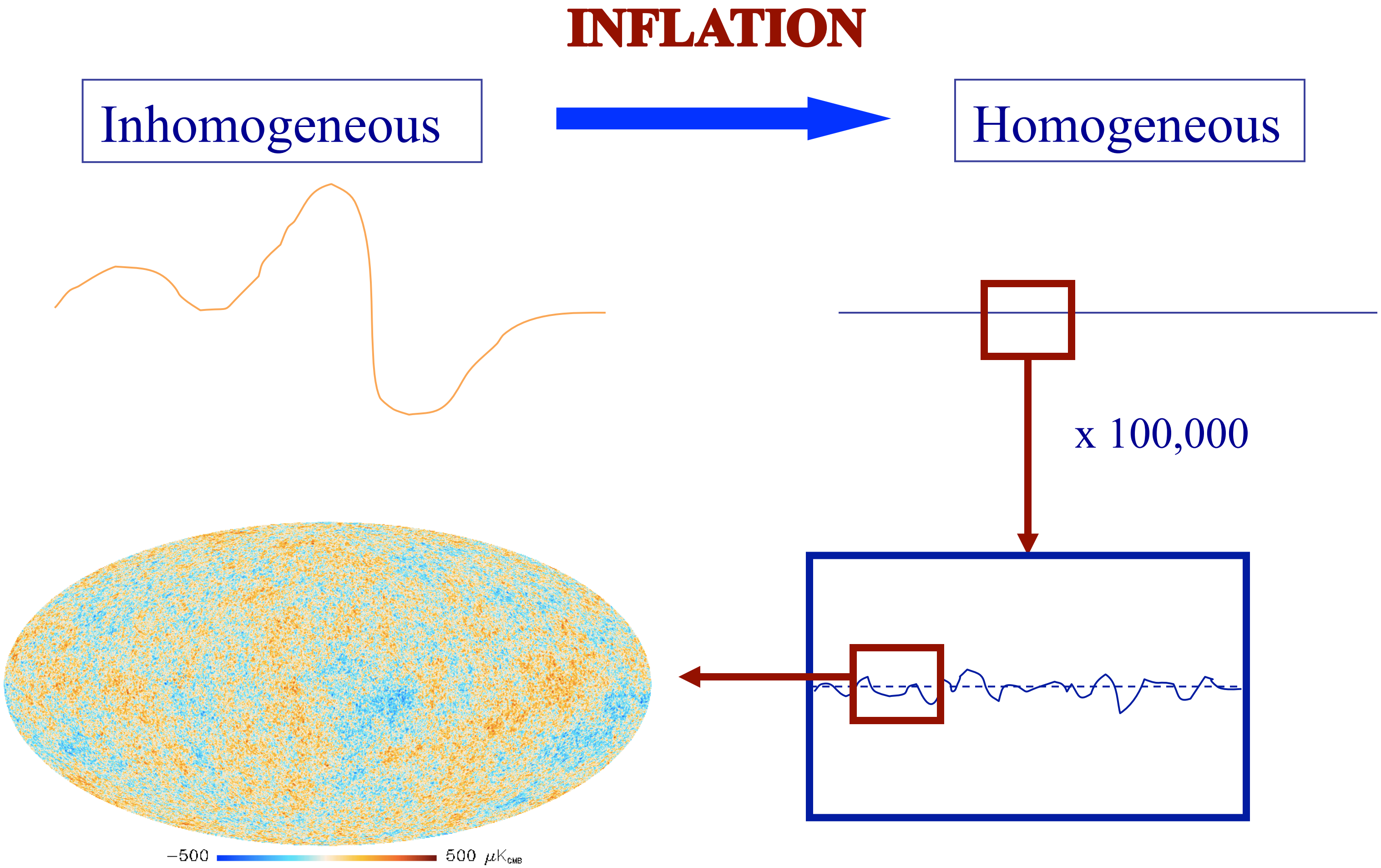
CMB basics

- The Early Universe is nearly, but not perfectly homogeneous and isotropic. Matter and radiation accrete onto overdense regions ➔ anisotropies in the CMB spatial temperature distribution

$$\frac{\Delta T}{\bar{T}} \sim 10^{-5} \qquad \bar{T} = 2.755\,K$$



Initial conditions



Generation of temperature anisotropies

Actors:

✓ Photons-baryons glued together in a single fluid by Compton scattering until last-scattering epoch z~1100.

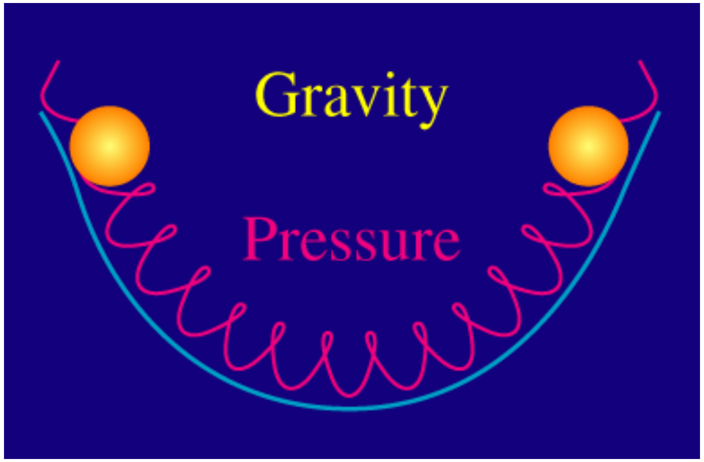
✓ dark matter+ neutrinos+cosmological constant

- ***On large scales (larger than then cosmological horizon at decouoling epoch):***

  density fluctuations at last scattering + gravitational redshift (Sachs-Wolfe effect)

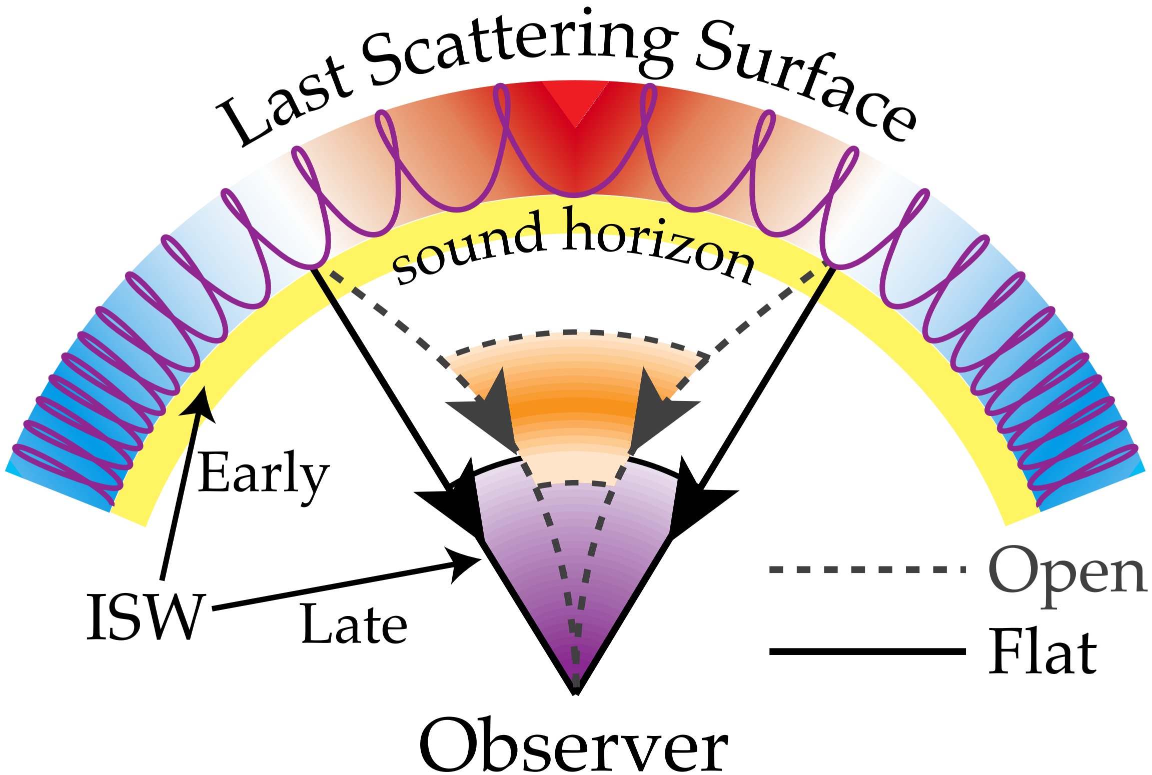
- ***On intermediate scales:***

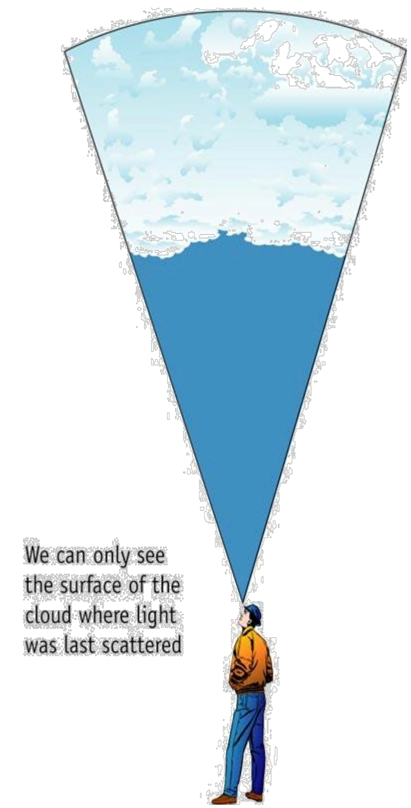
  gravity (mainly due to Dark Matter)+pressure
  == ***acoustic oscillations***



- ***On small scales (scales less than mean free path of photons) :***
  Damping due to photon free streaming (Silk damping)

Generation of temperature anisotropies

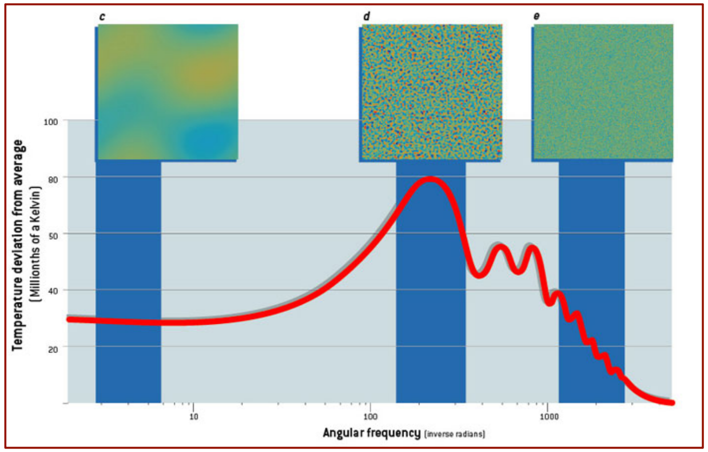




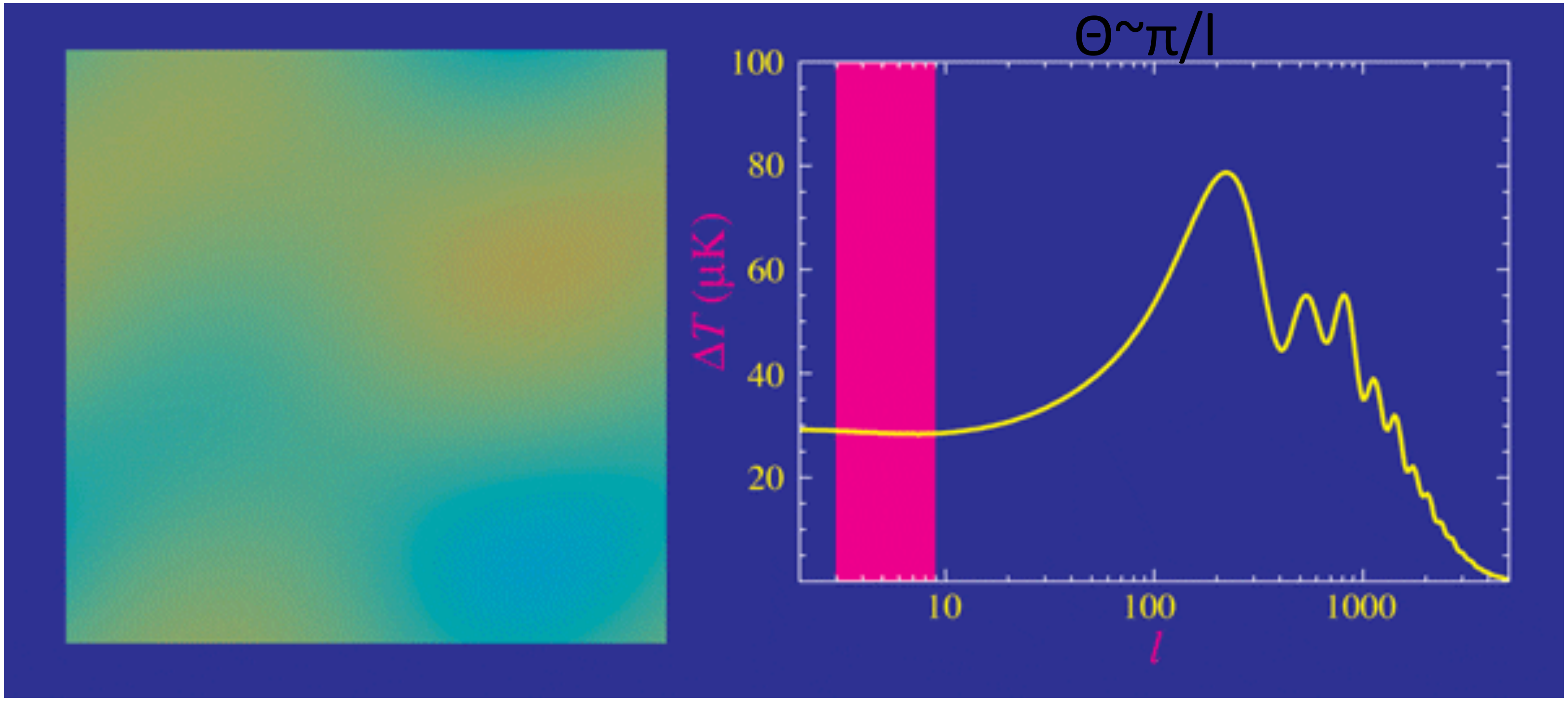
The CMB power spectrum

$$\frac{\Delta T}{T}(\vartheta,\varphi)=\sum_{\ell=2}^{\infty}\sum_{m=-\ell}^{\ell}a_{\ell m}Y_{\ell m}(\vartheta,\varphi)$$

$$\left\langle a^{*}_{\ell_1 m_1}a_{\ell_2 m_2}\right\rangle = C_{\ell_1}\delta_{\ell_1}^{\ell_2}\delta_{m_1}^{m_2}$$



Θ~π/l



Sensitivity

$$\sigma_{\hat{C}_\ell} = \sqrt{\frac{2}{(2\ell+1) f_{sky}}} \left(b_\ell^2 C_\ell + N_\ell \right)$$

instrumental noise

beam

signal

sky coverage

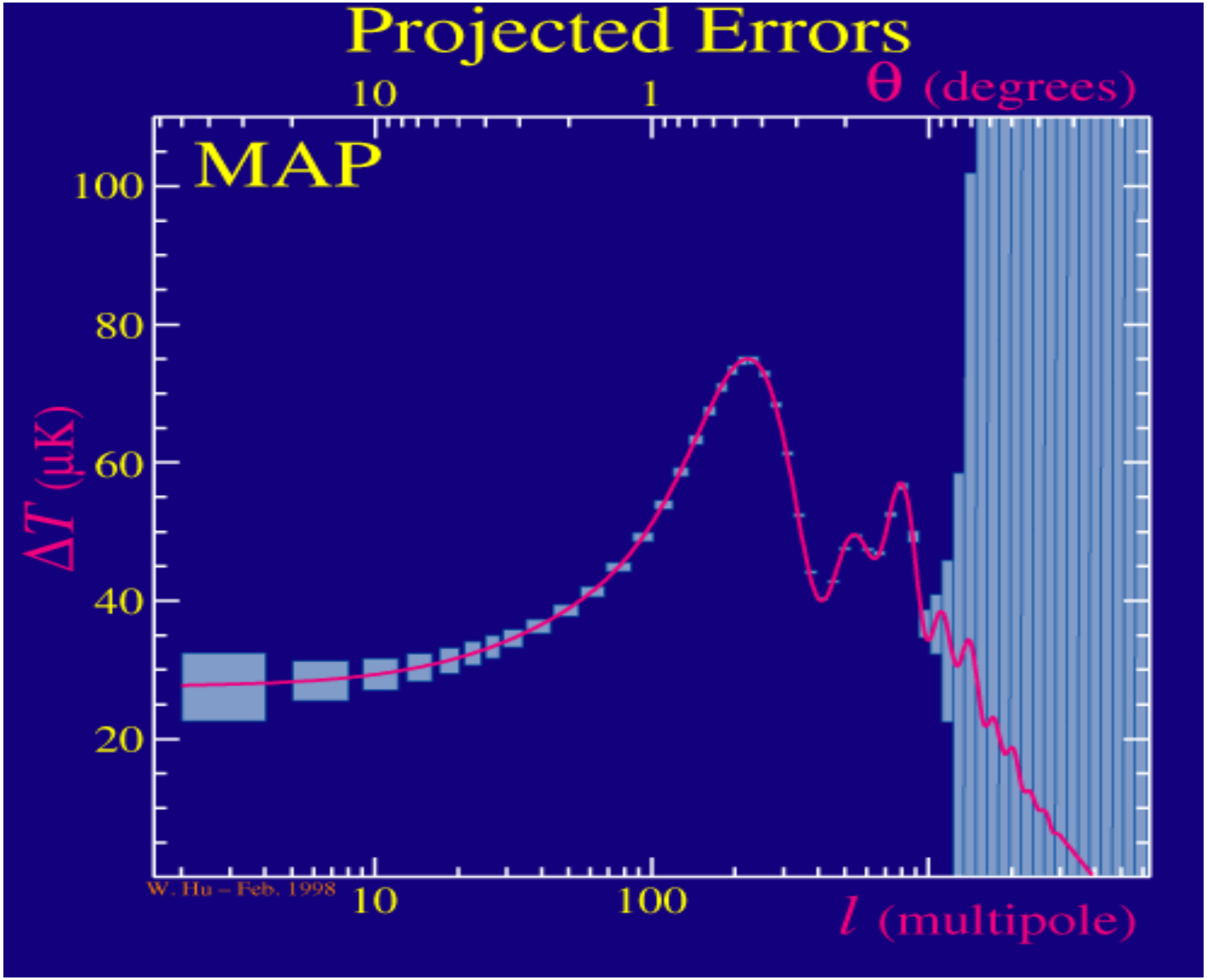
- Even for an ideal noiseless experiment error bars are not 0 due to ***cosmic variance***

- A CMB experiment is:

  ✓ *Cosmic variance dominated* where the error budget is dominated by the cosmic variance term (instrumental noise is negligible, low l)

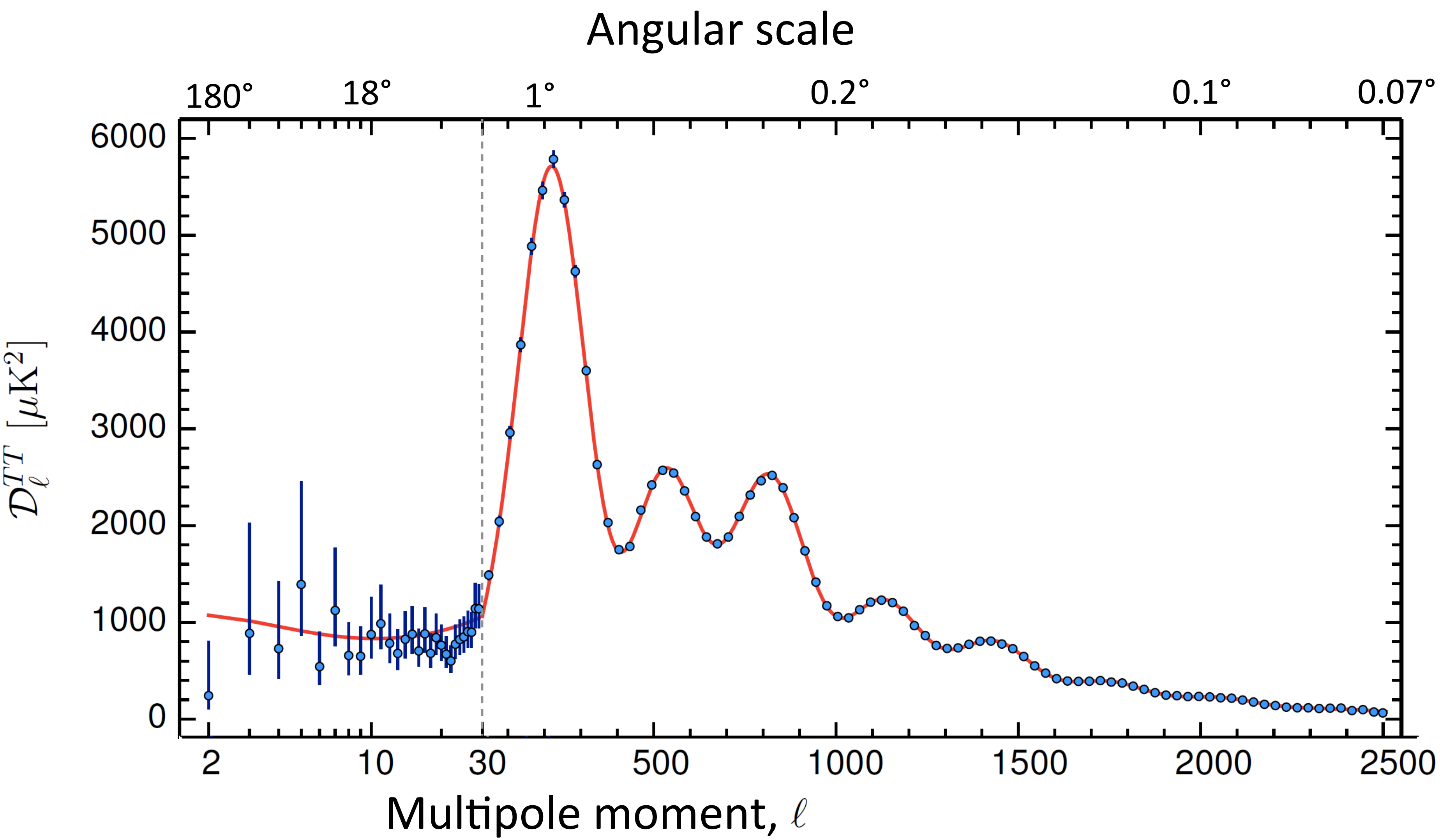
  ✓ *Signal dominated* where $C_l > N_l$ (low l)

  ✓ *Noise dominated* when $N_l > C_l$ (high l)

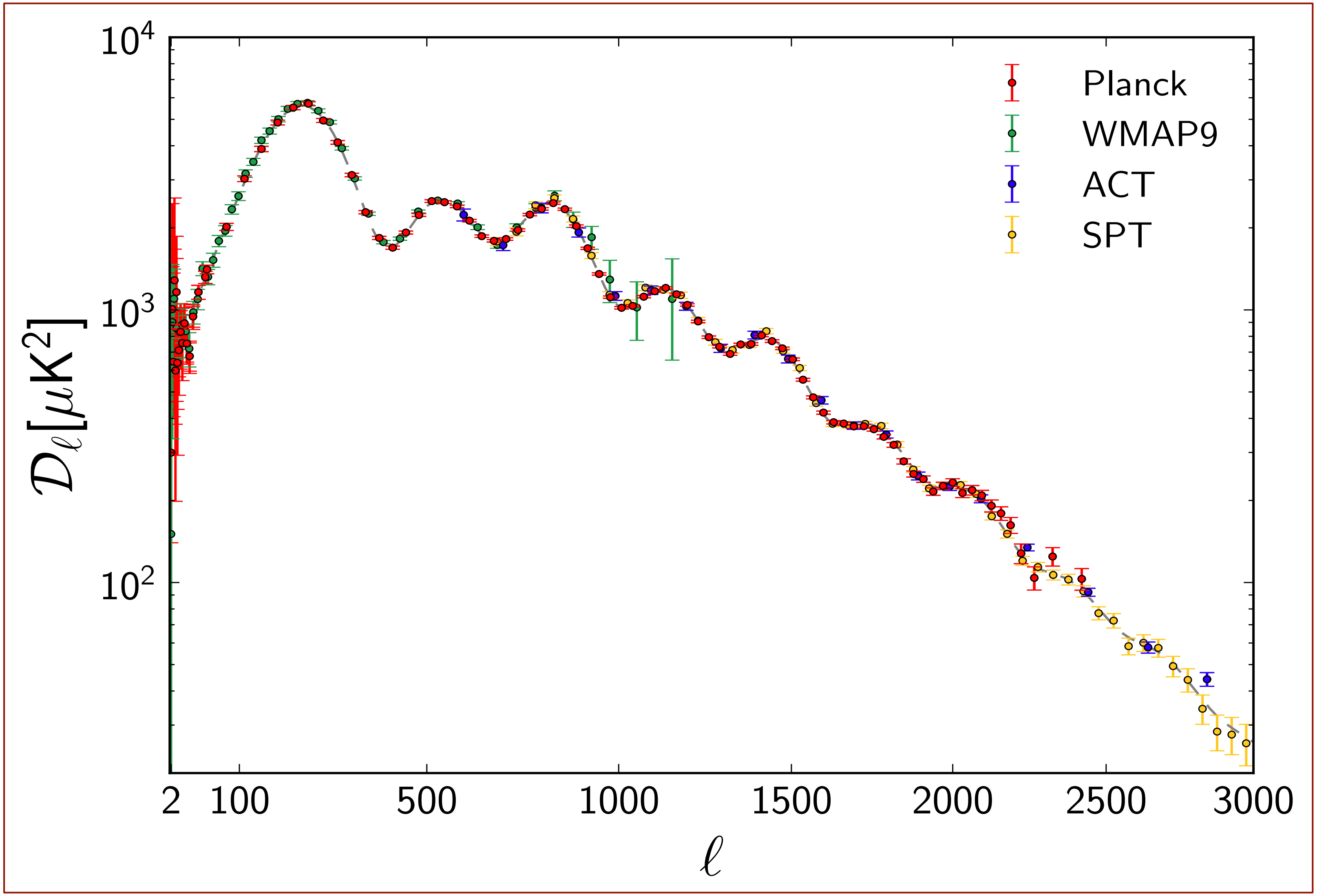


Projected Errors
θ (degrees)
10
1
MAP
100
80
60
40
20
ΔT (μK)
W. Hu – Feb. 1998
10
100
l (multipole)

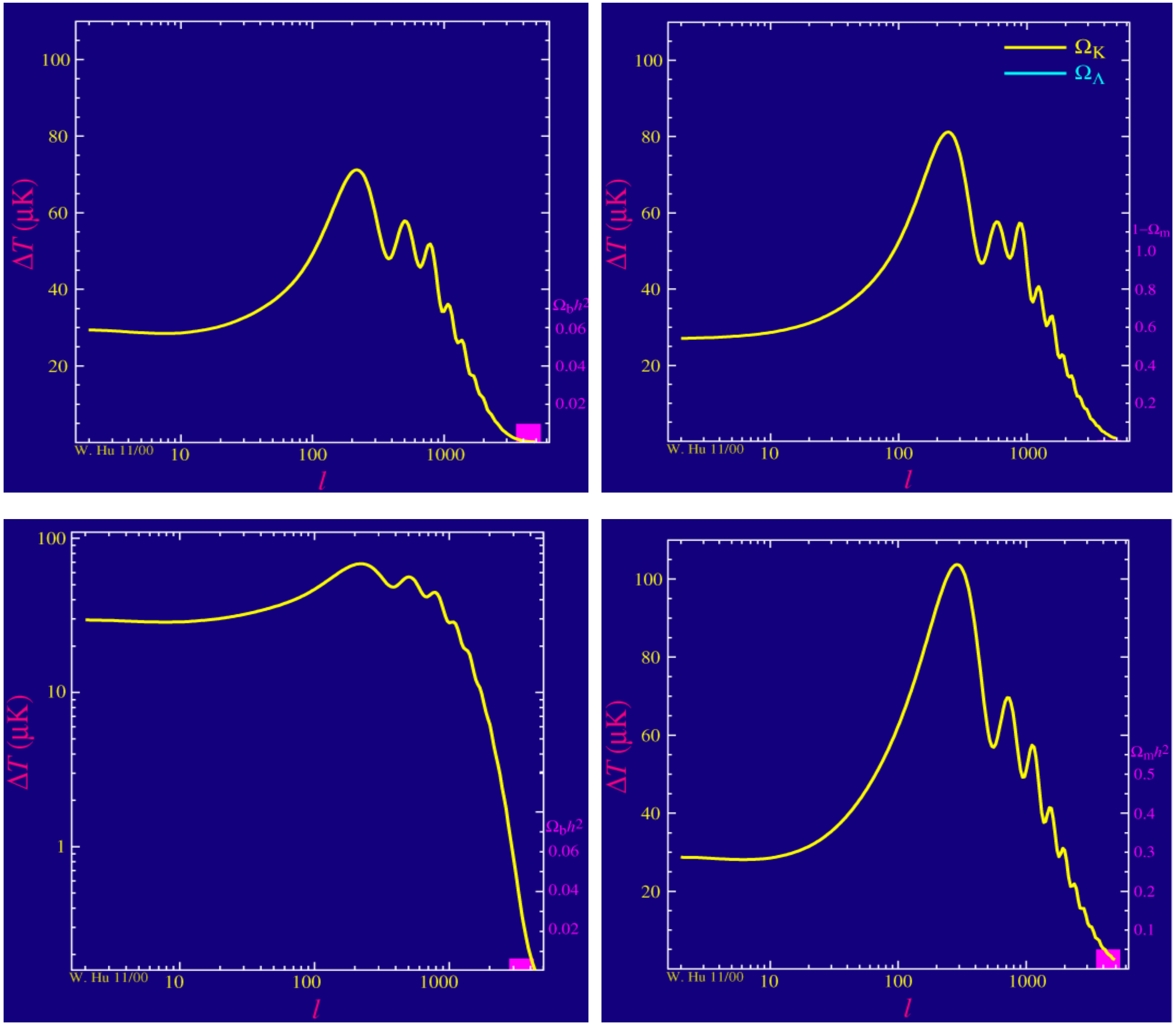
Planck CMB power spectrum



WMAP+*Planck*+ACT+SPT



Effect of changing parameters on C_l



Cosmological parameters

The Universe observed by Planck is well-fit by a 6 parameter ΛCDM model (& strong constraints provided on deviations from this model).

Very good agreement with 2013 analysis

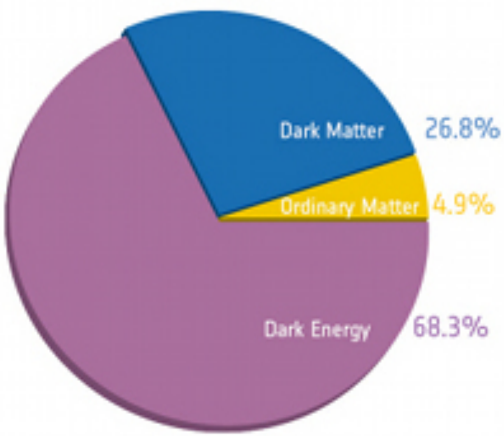
- Baryon density: Ω_b
- Matter density: Ω_m
- Acoustic scale (angular size): θ_{MC}
- Optical depth to reionization: τ
- Amplitude of primordial scalar fluctuations: A_s
- Scalar Spectral index: n_s

Precision cosmology

ΛCDM: The standard cosmological model

just 6 numbers.......
describe the Universe composition and evolution

Homogeneous background

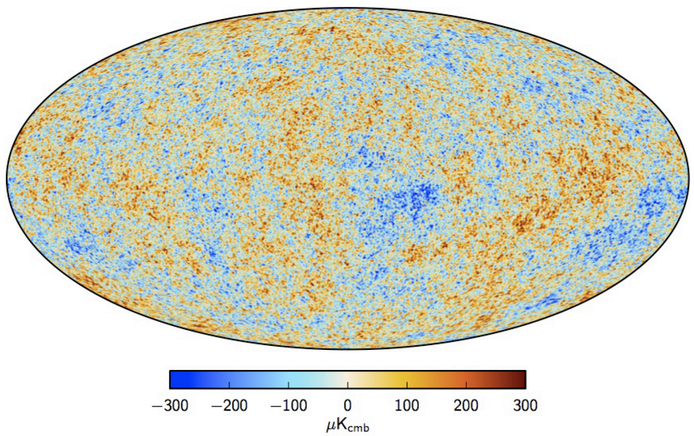


$\Omega_{b,}\ \Omega_{c,}\ \Omega_{\Lambda,} H_{0,}\ \tau$

- atoms 4%
- cold dark matter 23%
- dark energy 73%

Λ?? CDM??

Perturbations



$A_{s,}\ n_{s,}\ r$

- nearly scale-invariant
- adiabatic
- Gaussian

ORIGIN???

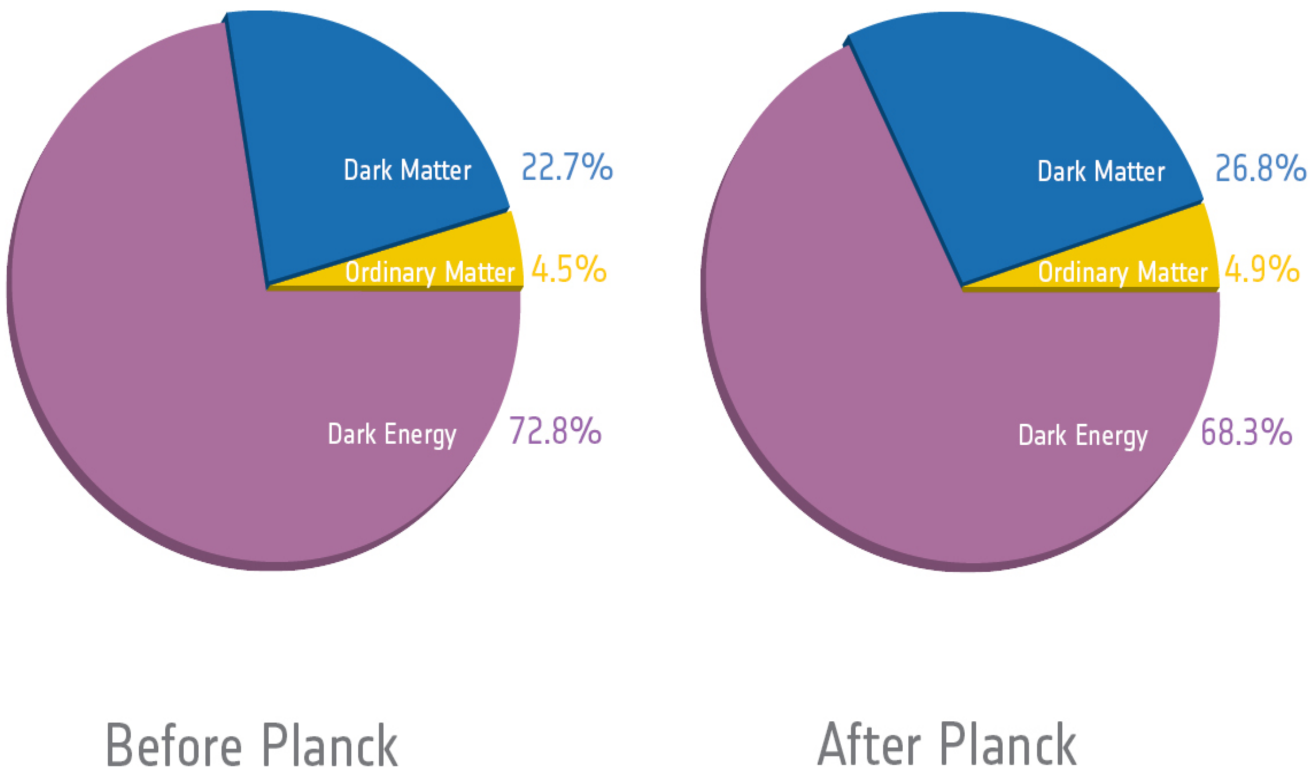
Credit: L. Verde

Planck parameters measurements

Parameter	TT+lowP 68 % limits	TT+lowP+lensing 68 % limits	TT+lowP+lensing+ext 68 % limits	TT,TE,EE+lowP 68 % limits	TT,TE,EE+lowP+lensing 68 % limits	TT,TE,EE+lowP+lensing+ext 68 % limits
$\Omega_b h^2$	0.02222 ± 0.00023	0.02226 ± 0.00023	0.02227 ± 0.00020	0.02225 ± 0.00016	0.02226 ± 0.00016	0.02230 ± 0.00014
$\Omega_c h^2$	0.1197 ± 0.0022	0.1186 ± 0.0020	0.1184 ± 0.0012	0.1198 ± 0.0015	0.1193 ± 0.0014	0.1188 ± 0.0010
$100\theta_{MC}$	1.04085 ± 0.00047	1.04103 ± 0.00046	1.04106 ± 0.00041	1.04077 ± 0.00032	1.04087 ± 0.00032	1.04093 ± 0.00030
τ	0.078 ± 0.019	0.066 ± 0.016	0.067 ± 0.013	0.079 ± 0.017	0.063 ± 0.014	0.066 ± 0.012
$\ln(10^{10} A_s)$	3.089 ± 0.036	3.062 ± 0.029	3.064 ± 0.024	3.094 ± 0.034	3.059 ± 0.025	3.064 ± 0.023
n_s	0.9655 ± 0.0062	0.9677 ± 0.0060	0.9681 ± 0.0044	0.9645 ± 0.0049	0.9653 ± 0.0048	0.9667 ± 0.0040
H_0	67.31 ± 0.96	67.81 ± 0.92	67.90 ± 0.55	67.27 ± 0.66	67.51 ± 0.64	67.74 ± 0.46
Ω_Λ	0.685 ± 0.013	0.692 ± 0.012	0.6935 ± 0.0072	0.6844 ± 0.0091	0.6879 ± 0.0087	0.6911 ± 0.0062
Ω_m	0.315 ± 0.013	0.308 ± 0.012	0.3065 ± 0.0072	0.3156 ± 0.0091	0.3121 ± 0.0087	0.3089 ± 0.0062
$\Omega_m h^2$	0.1426 ± 0.0020	0.1415 ± 0.0019	0.1413 ± 0.0011	0.1427 ± 0.0014	0.1422 ± 0.0013	0.14170 ± 0.00097
$\Omega_m h^3$	0.09597 ± 0.00045	0.09591 ± 0.00045	0.09593 ± 0.00045	0.09601 ± 0.00029	0.09596 ± 0.00030	0.09598 ± 0.00029
σ_8	0.829 ± 0.014	0.8149 ± 0.0093	0.8154 ± 0.0090	0.831 ± 0.013	0.8150 ± 0.0087	0.8159 ± 0.0086
$\sigma_8 \Omega_m^{0.5}$	0.466 ± 0.013	0.4521 ± 0.0088	0.4514 ± 0.0066	0.4668 ± 0.0098	0.4553 ± 0.0068	0.4535 ± 0.0059
$\sigma_8 \Omega_m^{0.25}$	0.621 ± 0.013	0.6069 ± 0.0076	0.6066 ± 0.0070	0.623 ± 0.011	0.6091 ± 0.0067	0.6083 ± 0.0066
z_{re}	$9.9^{+1.8}_{-1.6}$	$8.8^{+1.7}_{-1.4}$	$8.9^{+1.3}_{-1.2}$	$10.0^{+1.7}_{-1.5}$	$8.5^{+1.4}_{-1.2}$	$8.8^{+1.2}_{-1.1}$
$10^9 A_s$	$2.198^{+0.076}_{-0.085}$	2.139 ± 0.063	2.143 ± 0.051	2.207 ± 0.074	2.130 ± 0.053	2.142 ± 0.049
$10^9 A_s e^{-2\tau}$	1.880 ± 0.014	1.874 ± 0.013	1.873 ± 0.011	1.882 ± 0.012	1.878 ± 0.011	1.876 ± 0.011
Age/Gyr	13.813 ± 0.038	13.799 ± 0.038	13.796 ± 0.029	13.813 ± 0.026	13.807 ± 0.026	13.799 ± 0.021
z_*	1090.09 ± 0.42	1089.94 ± 0.42	1089.90 ± 0.30	1090.06 ± 0.30	1090.00 ± 0.29	1089.90 ± 0.23
r_*	144.61 ± 0.49	144.89 ± 0.44	144.93 ± 0.30	144.57 ± 0.32	144.71 ± 0.31	144.81 ± 0.24
$100\theta_*$	1.04105 ± 0.00046	1.04122 ± 0.00045	1.04126 ± 0.00041	1.04096 ± 0.00032	1.04106 ± 0.00031	1.04112 ± 0.00029
z_{drag}	1059.57 ± 0.46	1059.57 ± 0.47	1059.60 ± 0.44	1059.65 ± 0.31	1059.62 ± 0.31	1059.68 ± 0.29
r_{drag}	147.33 ± 0.49	147.60 ± 0.43	147.63 ± 0.32	147.27 ± 0.31	147.41 ± 0.30	147.50 ± 0.24
k_D	0.14050 ± 0.00052	0.14024 ± 0.00047	0.14022 ± 0.00042	0.14059 ± 0.00032	0.14044 ± 0.00032	0.14038 ± 0.00029
z_{eq}	3393 ± 49	3365 ± 44	3361 ± 27	3395 ± 33	3382 ± 32	3371 ± 23
k_{eq}	0.01035 ± 0.00015	0.01027 ± 0.00014	0.010258 ± 0.000083	0.01036 ± 0.00010	0.010322 ± 0.000096	0.010288 ± 0.000071
$100\theta_{s,eq}$	0.4502 ± 0.0047	0.4529 ± 0.0044	0.4533 ± 0.0026	0.4499 ± 0.0032	0.4512 ± 0.0031	0.4523 ± 0.0023

Cosmological parameters 68% confidence limits for the base ΛCDM model from Planck CMB power spectra in combination with lensing reconstruction (``lensing'') and external data (``ext'', BAO+JLA+H_0)

The energy budget of the Universe

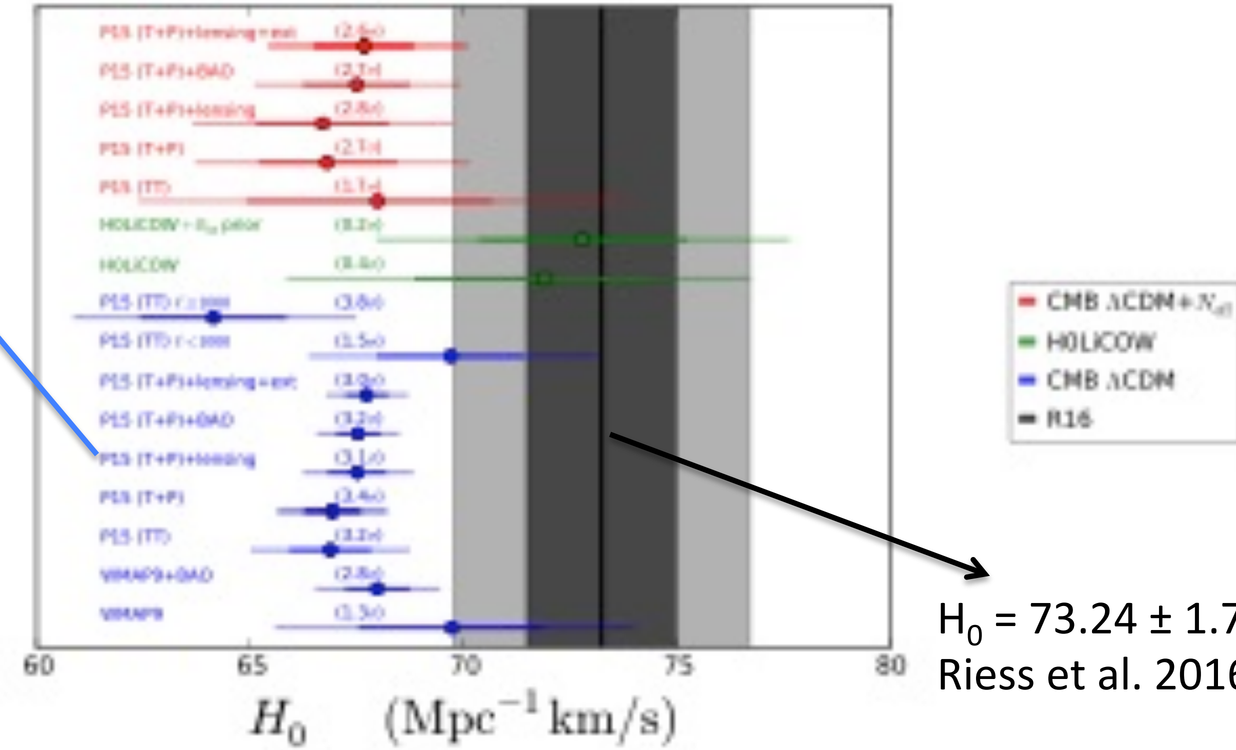


...has changed!

credits: F. Bouchet

The rate of expansion

H_0 = (67.8 ± 0.9) Mpc^{-1} km/s
Planck 2015

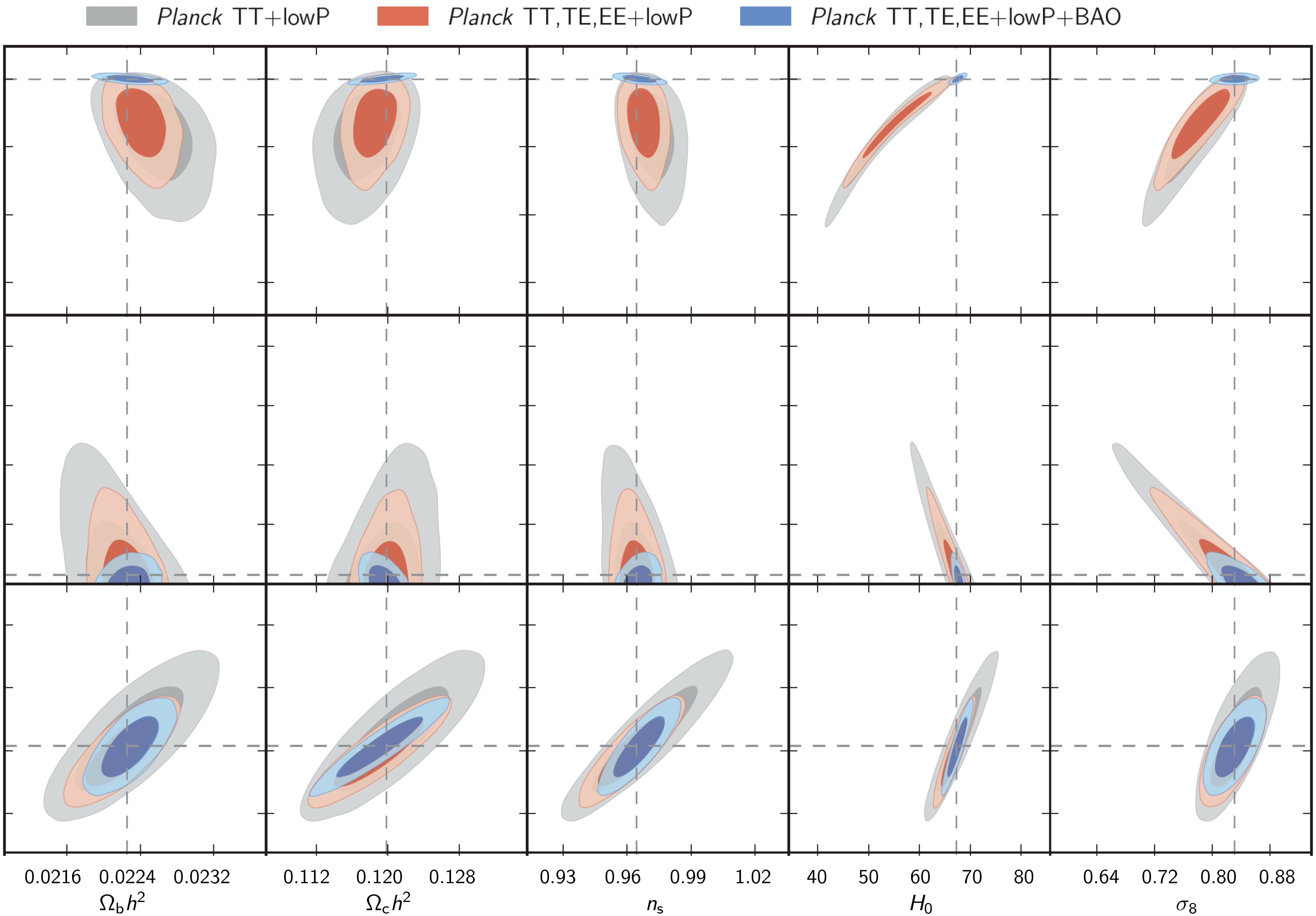


H_0 = 73.24 ± 1.74 Mpc^{-1} km/s
Riess et al. 2016

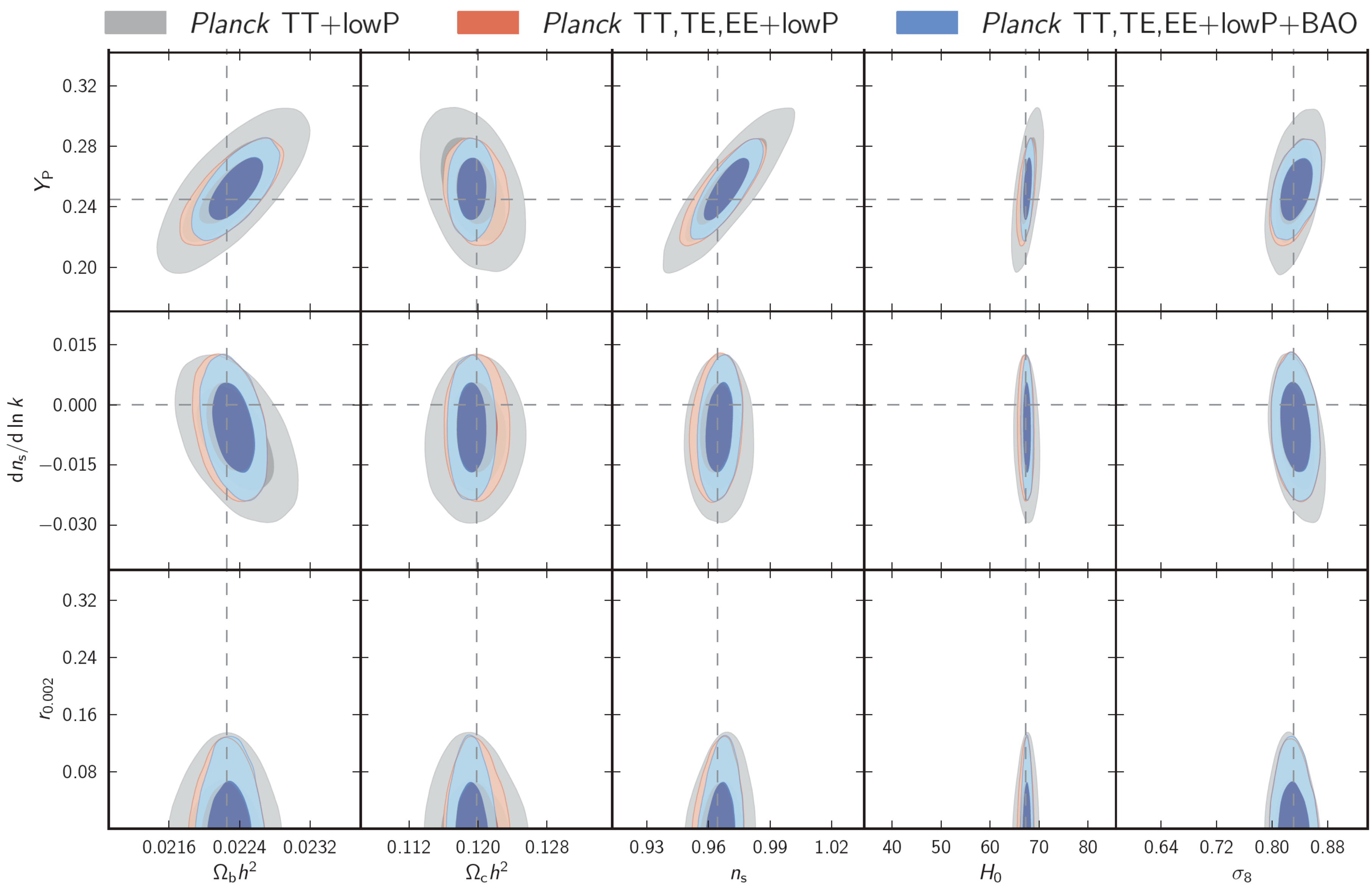
Figure 1. Marginalised 68% and 95% constraints on H_0 from different analysis of CMB data, obtained from Planck Collaboration 2015 public chains [3], WMAP9 [1] (analysed with the same assumptions than Planck) and the results of the work of Addison et al. [25] and Bonvin et al. [24]. We show the constraints obtained in a ΛCDM context in blue, ΛCDM+N_{eff} in red, quasar time-delay cosmography results (taken from H0LiCOW project [24], for a ΛCDM model, with and without relying on a CMB prior for Ω_M) in green and the constraints of the independent direct measurement of [20] in black. We report in parenthesis the tension with respect to the direct measurement.

... has changed too

Extensions to the "minimal" model

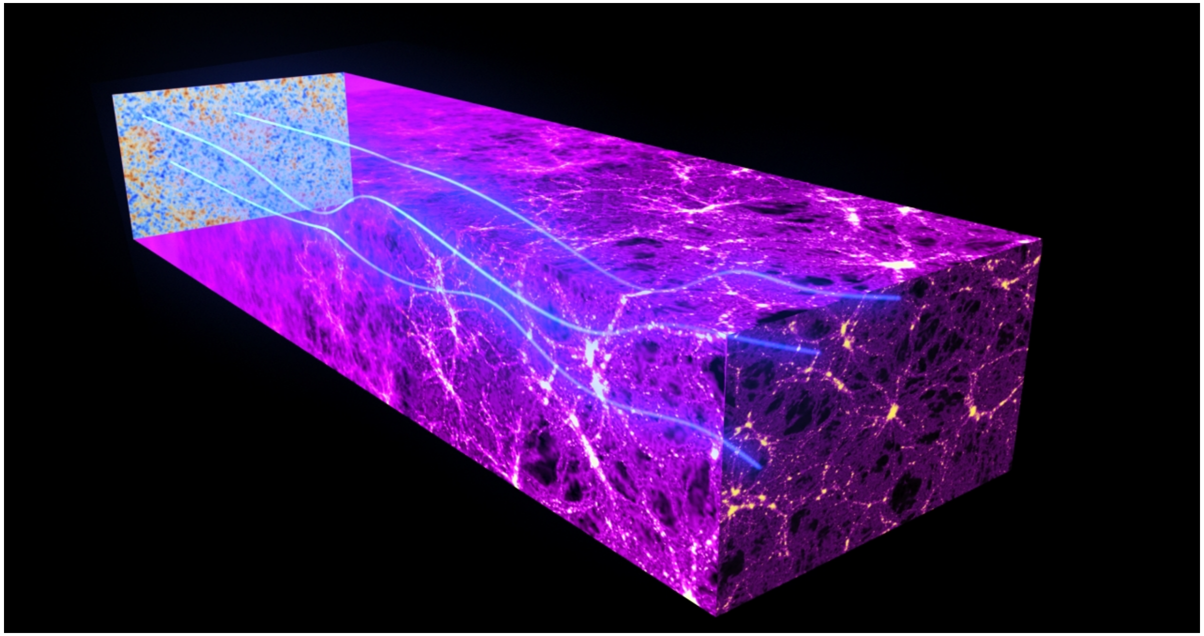


More extensions…



CMB lensing

- Large scale structure deflects the trajectory of CMB photons through gravitational lensing



$$T(\hat{\boldsymbol{n}}) = T^{\text{unl}}(\hat{\boldsymbol{n}} + \nabla\phi(\hat{\boldsymbol{n}})),$$

Deflection angle

$$= T^{\text{unl}}(\hat{\boldsymbol{n}}) + \sum_i \nabla^i \phi(\hat{\boldsymbol{n}}) \nabla_i T(\hat{\boldsymbol{n}}) + O(\phi^2)$$

$$\phi(\hat{\boldsymbol{n}}) = -2 \int_0^{\chi_*} d\chi \frac{f_K(\chi_* - \chi)}{f_K(\chi_*) f_K(\chi)} \Psi(\chi \hat{\boldsymbol{n}}; \eta_0 - \chi)$$

CMB lensing potential

CMB lensing

- Large scale structure deflects the trajectory of CMB photons through gravitational lensing

$$T(\hat{\boldsymbol{n}}) = T^{\text{unl}}(\hat{\boldsymbol{n}} + \nabla\phi(\hat{\boldsymbol{n}})),$$
$$= T^{\text{unl}}(\hat{\boldsymbol{n}}) + \sum_i \nabla^i \phi(\hat{\boldsymbol{n}}) \nabla_i T(\hat{\boldsymbol{n}}) + \mathcal{O}(\phi^2)$$

Deflection angle

$$\phi(\hat{\boldsymbol{n}}) = -2 \int_0^{\chi_*} d\chi \frac{f_K(\chi_* - \chi)}{f_K(\chi_*) f_K(\chi)} \Psi(\chi \hat{\boldsymbol{n}}; \eta_0 - \chi)$$

CMB lensing potential

- **Lensing also affects the Cl directly (smoothing of acoustic peaks)**
- **The lensing potential depends on cosmological parameters and probes completely different redshifts w.r.t primary anisotropies!**
- Can build quadratic estimators of the lensing potential, exploiting the breaking of isotropy i.e. the appearance of off-diagonal term in the a_{lm} covariance matrix (equivalently, the coupling between T and grad T)

CMB lensing

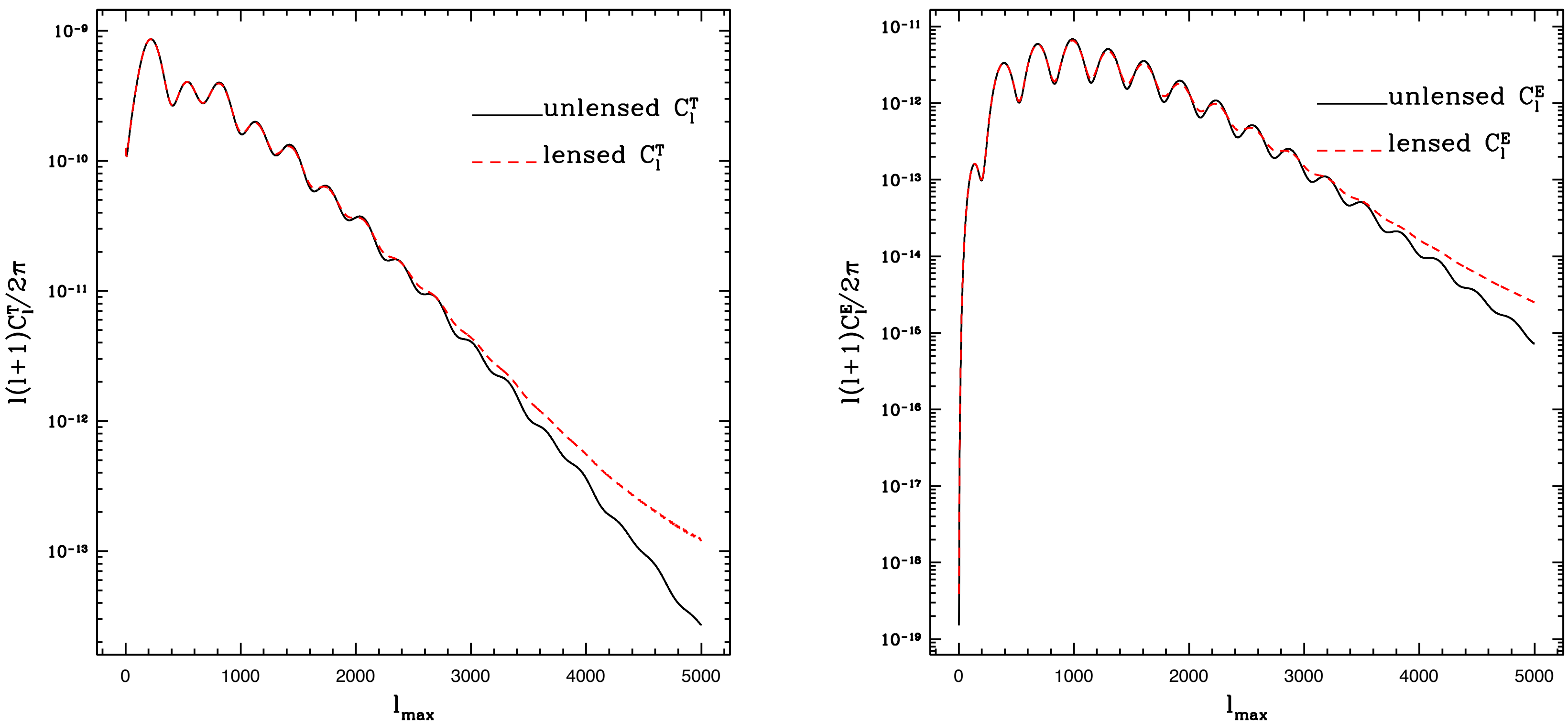
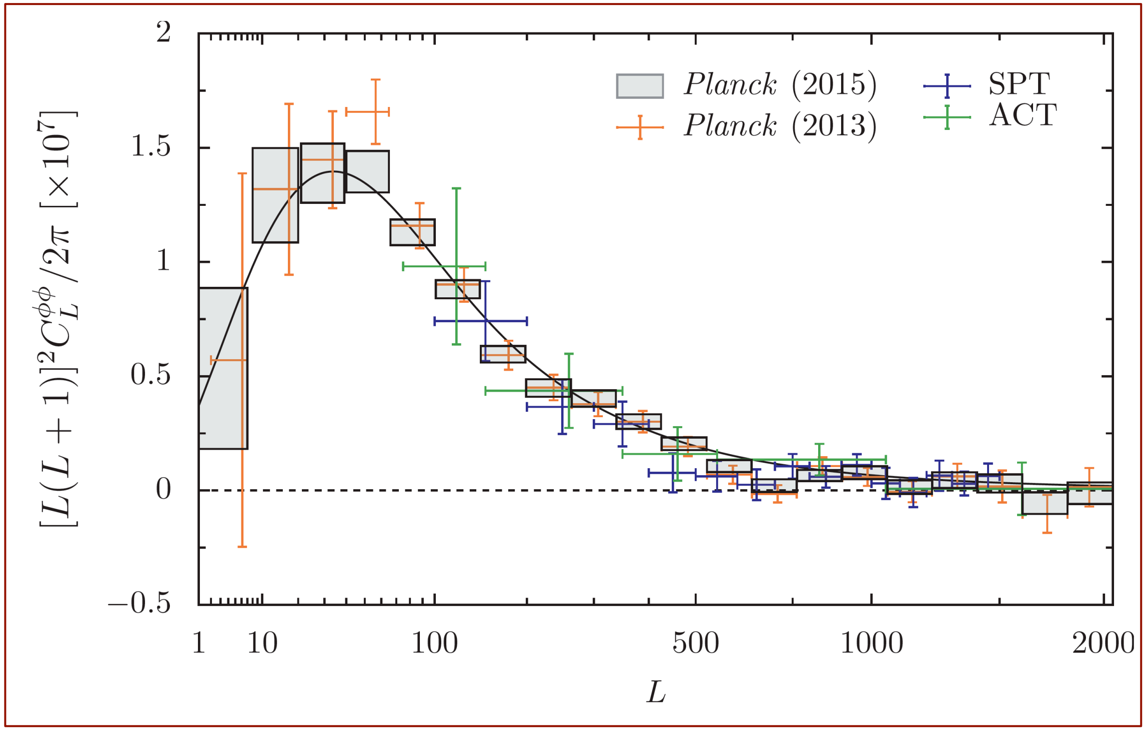
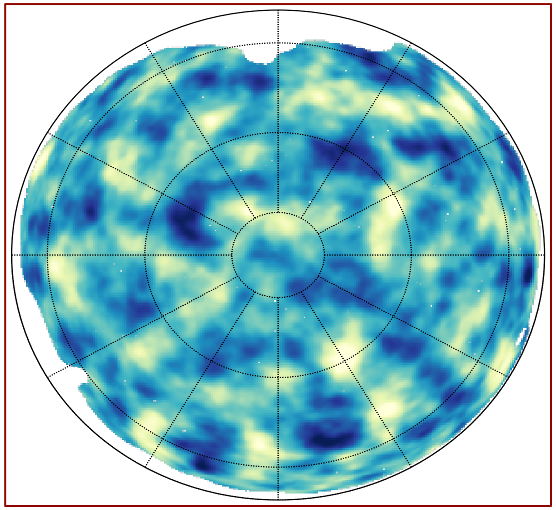


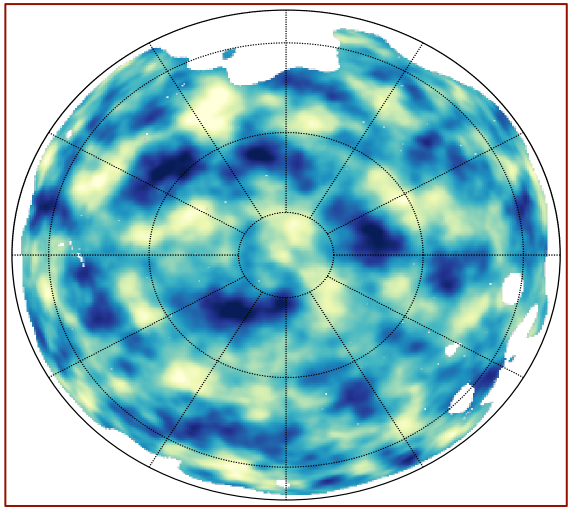
FIG. 1: The lensed (dashed red) and unlensed (solid black) C_l for the concordance ΛCDM cosmology; the temperature power spectra are on the left and the E polarization power spectra are on the right.

Planck lensing measurements

gravitational lensing is detected with an overall significance of 40σ







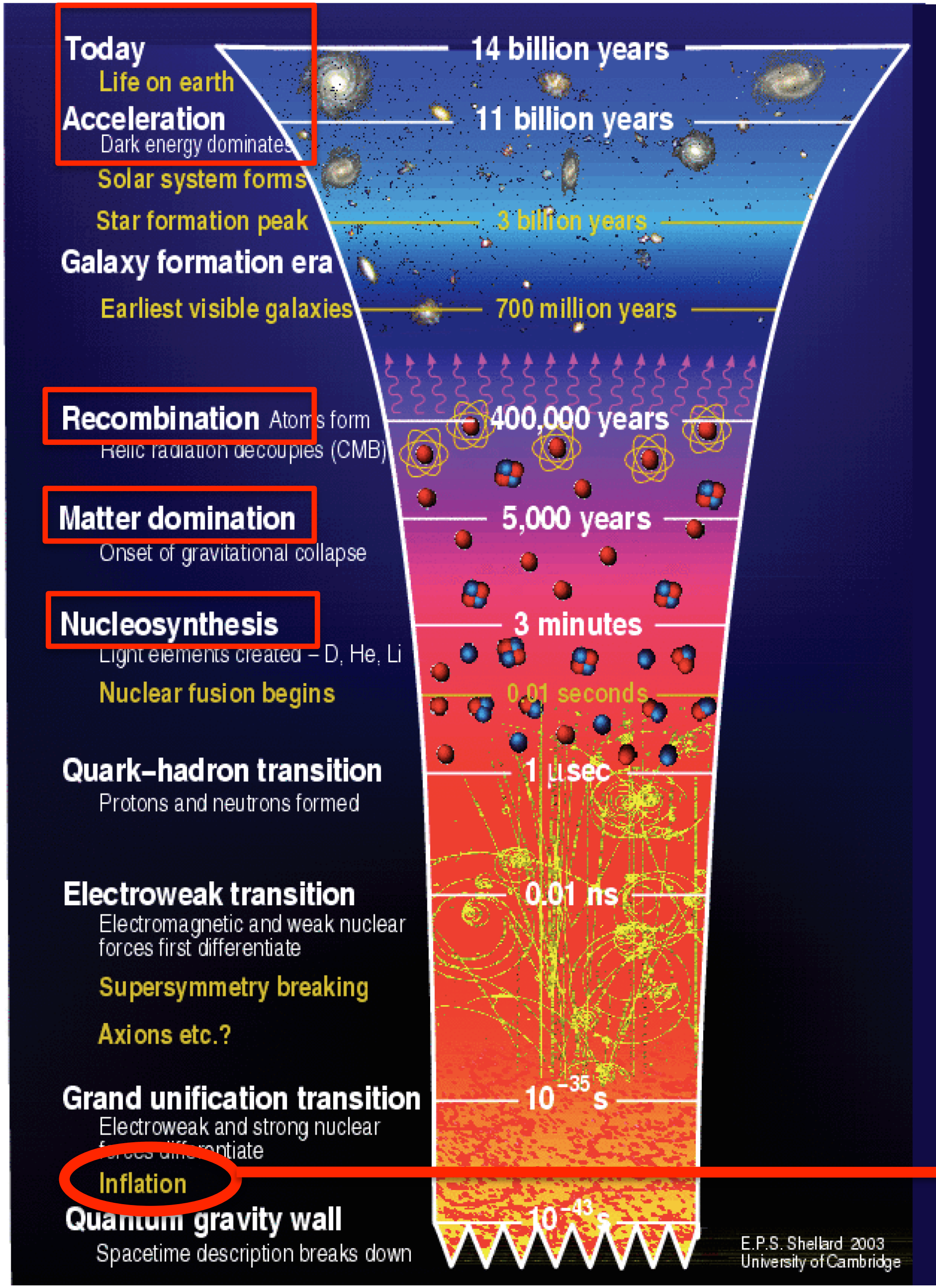
Neutrino masses

- Cosmological measurements constrain $\sum m_\nu$
- ***Massive neutrinos below free streaming scale do not cluster***, thus the gravitational potential decays at small scales during matter domination in this case
- ***Main effect on CMB: changes in lensing (less smoothing of peaks, less power in lensing likelihood at L > 10)***
- Without lensing the constraining power of CMB alone is small. Previous measurements used generally a combination of CMB and LSS data

$$\sum m_\nu < 0.72 \text{ eV} \quad \textit{Planck}\ \text{TT+lowP}$$

$$\left.\begin{array}{c} \sum m_\nu < 0.23 \text{ eV} \\ \Omega_\nu h^2 < 0.0025 \end{array}\right\} \quad 95\%,\ \textit{Planck}\ \text{TT+lowP+lensing+ext.}$$

What about the initial conditions set in the very early universe?



We are here

Z_{rec}~0

Z_{rec}~1100

Z_{eq}~3500

T~1 MeV

We seek information about ***very early times and very high energies E~10^16 GeV***

INFLATION and THE INFLATON

Inflation is a period of accelerated expansion in the early universe.
Attained if the energy density of the universe is dominated by the potential energy of a scalar field (the inflaton)

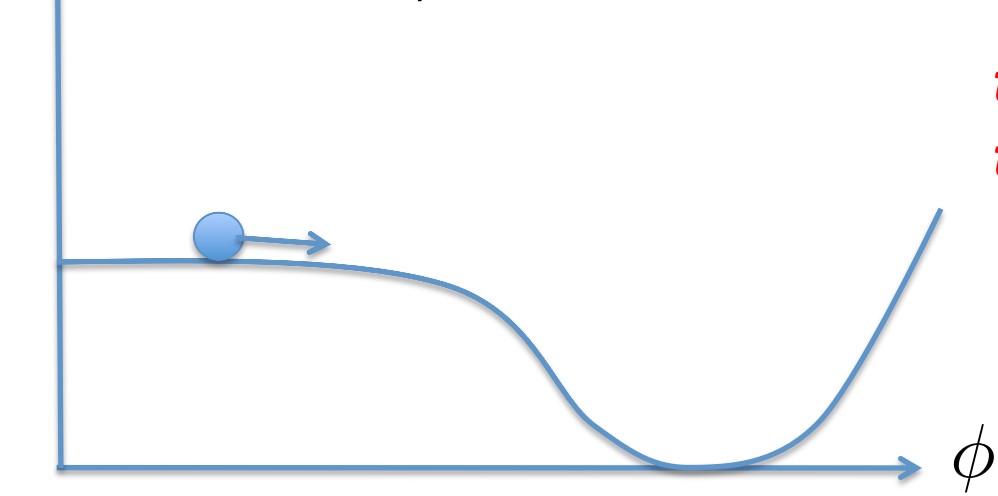
$$V(\phi) >> \frac{1}{2}\dot{\phi}^2 \Longrightarrow p_\phi \simeq -\rho_\phi$$

If $V(\phi) >> \frac{1}{2}\dot{\phi}^2$ ***the inflaton is slowly rolling its potential***: $\phi(t) \approx const.$

$V(\phi)$

$$H^2 = \frac{8\pi G}{3} V(\phi) \simeq const.$$

(effective cosmological constant: inflation is driven by the vacuum energy of the scalar field)



the potential $V(\phi)$ must be flat to achieve inflation

$$\varepsilon = \frac{M_{Pl}^2}{2}\left(\frac{V_\phi}{V}\right)^2 << 1$$

$$\eta = M_{Pl}^2 \frac{V_{\phi\phi}}{V} << 1$$

INFLATION: WHY SO IMPORTANT?

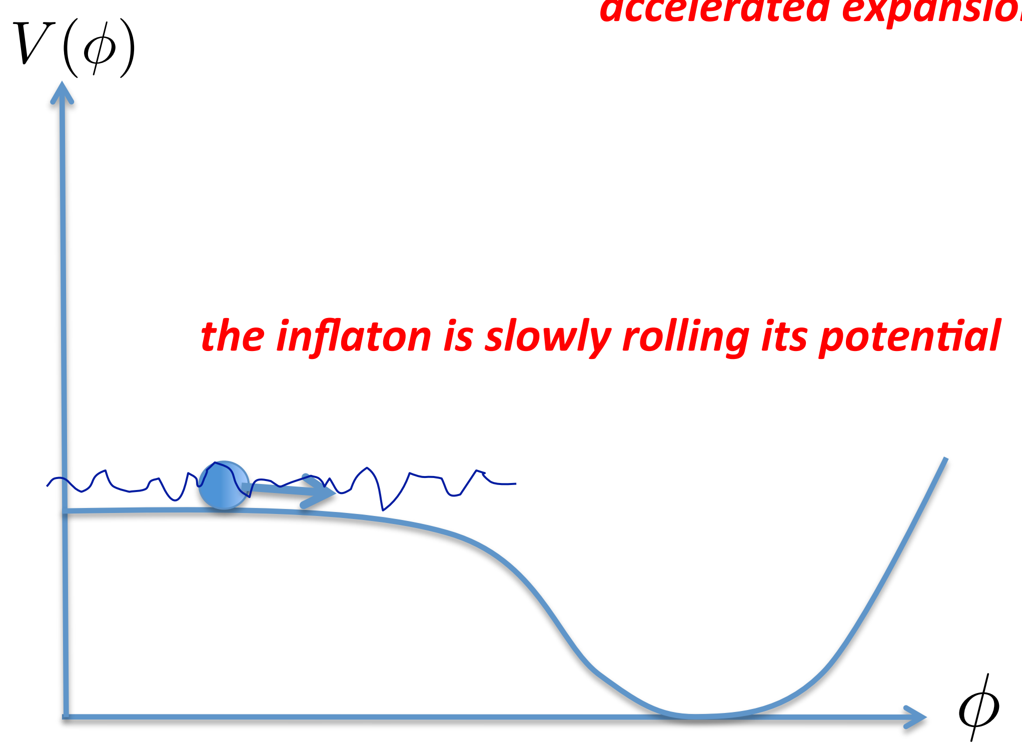
- Inflationary paradigm is one of the most relevant development in modern cosmology. Introduced to solve some shortcomings of the standard Big-Bang model (Guth '81)
  e.g.: why the universe is so nearly spatially flat? (flatness problem)
  why the temperature of CMB photons on opposite sides of the sky is so accurately the same even if they were never in causal contact? (horizon problem)

- ***most importantly:*** inflation offers an elegant ***explanation for the origin of the first density perturbations*** which are the seeds for the CMB anisotropies and the Large-Scale-Structures of the Universe we observe today (e.g. cluster of galaxies).

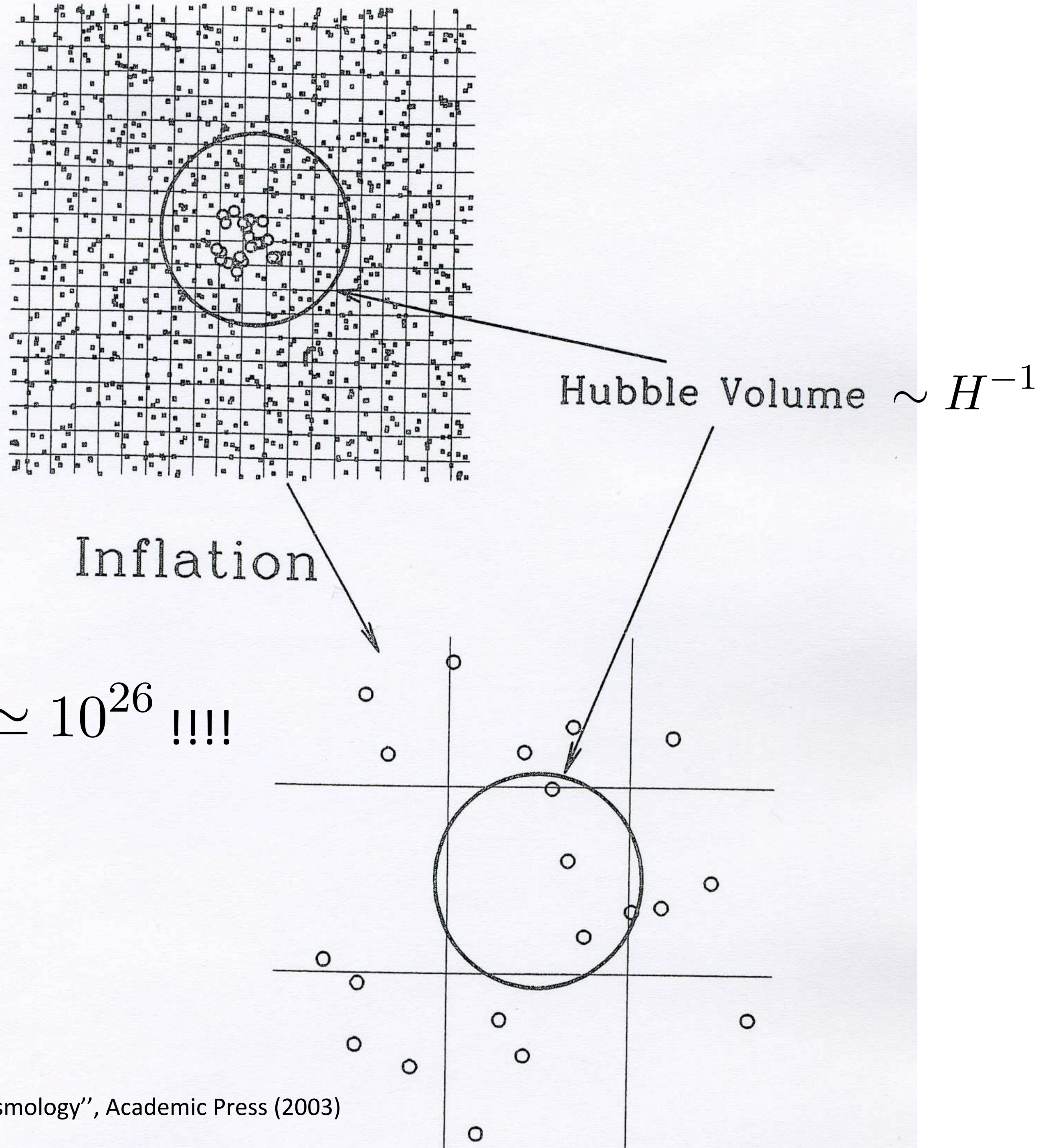
INFLATION

$$V(\phi) >> \frac{1}{2}\dot{\phi}^2 \longrightarrow H^2 = \frac{8\pi G}{3} V(\phi) \simeq const. \longrightarrow a(t) \simeq e^{Ht} \quad \left(H(t) = \frac{\dot{a}}{a} \right)$$

accelerated expansion in the early universe



$$\zeta \sim \frac{\Delta T}{T} \sim \frac{\delta \rho}{\rho} \qquad \zeta \simeq \frac{H \delta \phi}{\dot{\phi}}$$



$$\frac{a_f}{a_i} \geq e^{60} \simeq 10^{26} \text{ !!!!}$$

From S. Dodelson ``Modern Cosmology'', Academic Press (2003)

Generating the primordial density perturbations

✓ first step: take a scalar field during an inflationary (quasi-de-Sitter) phase

$$\ddot{\phi} + 3H\dot{\phi} - \frac{\nabla^2 \phi}{a^2} = -\frac{\partial V}{\partial \phi}$$

split the scalar field into a ``classical'' background expectation value (on the vacuum state) and **quantum fluctuations** around the mean value

$$\phi(\mathbf{x}, t) = \phi(t) + \delta\phi(\mathbf{x}, t)$$

✓ ***Perturb linearly*** the equation of motion of the scalar field around its background value

$$\ddot{\delta\phi} + 3H\dot{\delta\phi} - \frac{\nabla^2 \delta\phi}{a^2} = -\frac{\partial^2 V}{\partial \phi^2}\,\delta\phi$$

Generating the primordial density perturbations

The inflaton field is special: it dominates the energy density of the universe during inflation

$$\delta\phi \rightarrow \delta\rho \simeq V'(\phi)\delta\phi \simeq -3H\dot{\phi}\,\delta\phi$$

Fluctuations in the inflaton produce fluctuations in the universe expansion from place to place, so that each region in the universe goes through the same expansion history but at slightly different times:

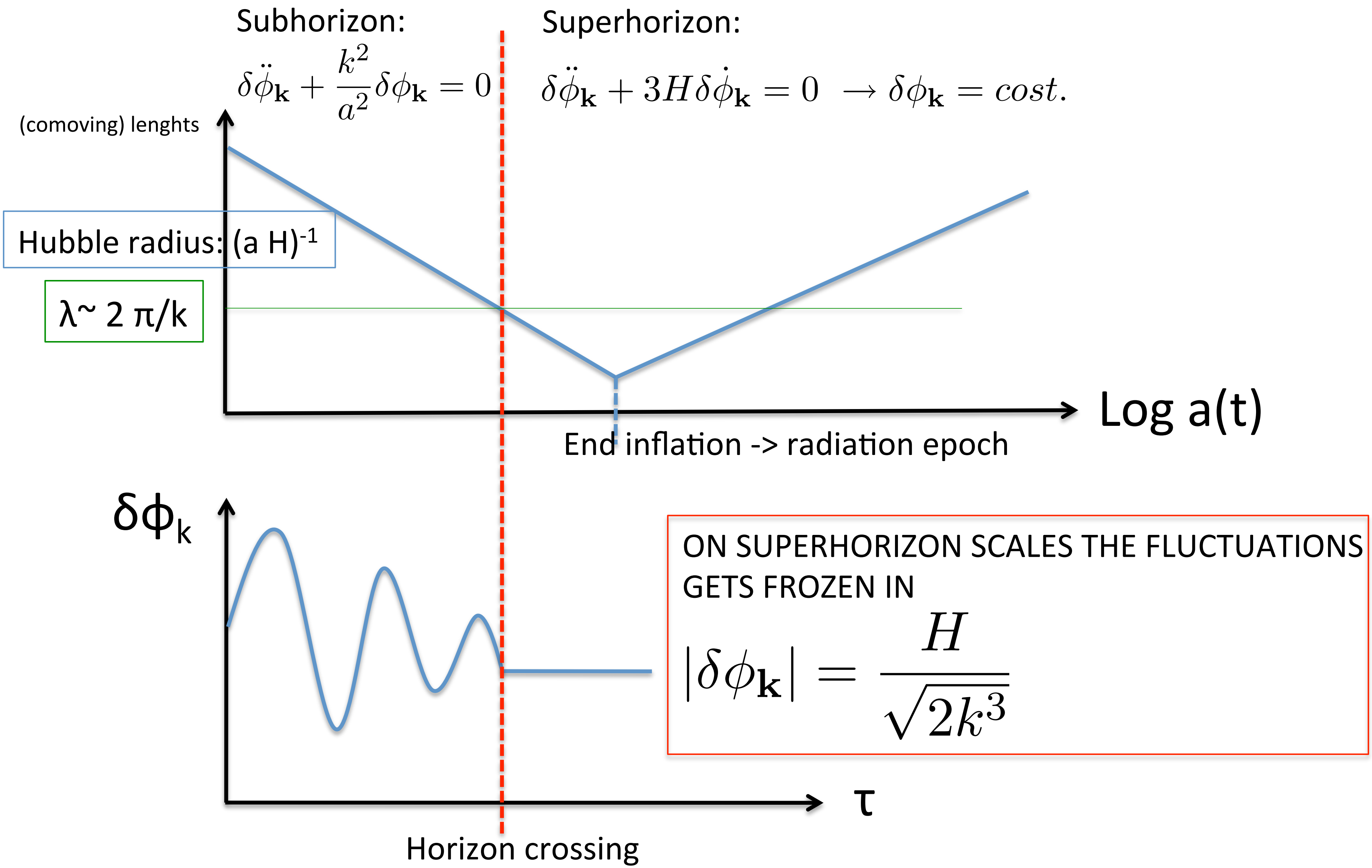
$\delta t = -\dfrac{\delta\phi}{\dot{\phi}}$; now remember that $\text{number of e-foldings}\, N = \ln(a_f/a_i) = \int_{t_i}^{t_f} H dt$

$$\rightarrow \text{additional expansion}\, \zeta = \delta N = H\delta t$$

$$\boxed{\zeta = H\delta t \quad = -H\frac{\delta\phi}{\dot{\phi}} \simeq -H\frac{\delta\rho}{\dot{\rho}}}$$

ζ remains constant on superhorizon scales **(ζ is the uniform energy density curvature pert.)**

N.B.: to obtain the last expression for ζ just use $\dot{\rho_\phi} = -3H(\rho_\phi + p_\phi) = -3H\dot{\phi}^2$



Subhorizon:
$\delta\ddot{\phi}_{\mathbf{k}} + \frac{k^2}{a^2}\delta\phi_{\mathbf{k}} = 0$
Superhorizon:
$\delta\ddot{\phi}_{\mathbf{k}} + 3H\delta\dot{\phi}_{\mathbf{k}} = 0 \;\rightarrow\; \delta\phi_{\mathbf{k}} = cost.$
(comoving) lenghts
Hubble radius: $(a\,H)^{-1}$
$\lambda \sim 2\,\pi/k$
Log a(t)
End inflation -> radiation epoch
$\delta\phi_k$
ON SUPERHORIZON SCALES THE FLUCTUATIONS GETS FROZEN IN
$|\delta\phi_{\mathbf{k}}| = \frac{H}{\sqrt{2k^3}}$
τ
Horizon crossing

So what’s going on?

On microscopic scales (well inside the horizon) microphysics is at work: use quantum field theory. There are quantum fluctuations of the scalar field; if averaged over macroscopic interval of time they vanish (quantum fluctuations of vacuum: particles are continuosly created and destroyed).

However the space-time background is exponentially inflating so their physical wavelengths grow exponentially

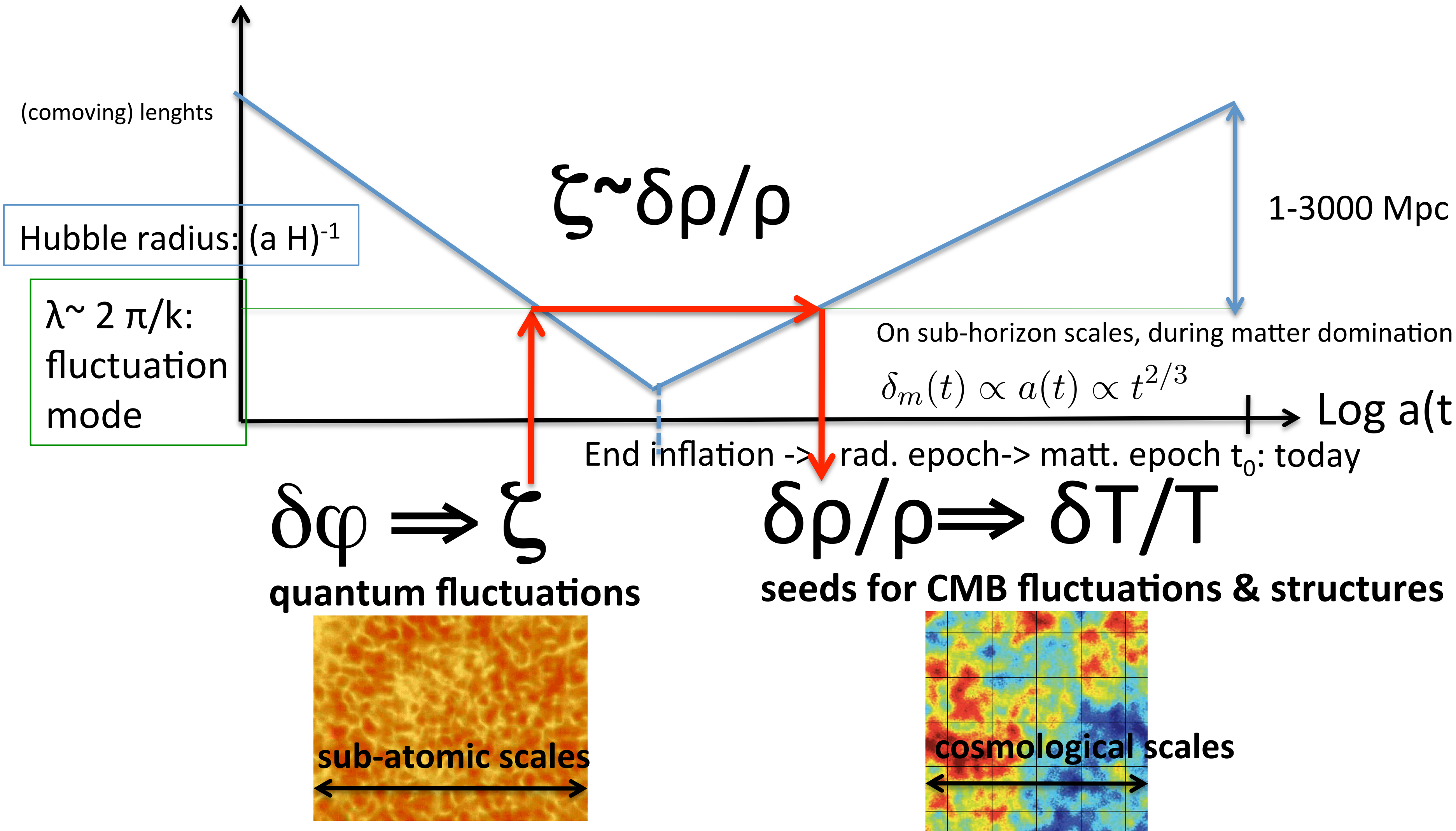
$$\lambda_{phys} \propto a(t) \propto e^{Ht}$$

until they become greater then the horizon H^{-1} (which remains almost constant). On super-horizon scales the fluctuations get frozen (because of the friction term $3H\dot{\delta\phi}$). The fluctuations do not vanish if averaged on macroscopic time interval: a classical fluctuation has been generated.

Said in other words: if on superhorion scales $\delta\phi \neq 0$ over macroscopic time interval then the final result is a state with a net number of particles. This is a gravitational mechanism of amplification. The crucial point is the “in” and “out” (of the horizon) state of the fluctuations

Structure formation within the inflationary scenario

Quantum fluctuations are streched from microscopic to cosmological scales



Observational predictions

- **Primordial density (scalar) perturbations**

$$\mathcal{P}_\zeta(k) = \frac{16}{9}\frac{V^2}{M_{\rm Pl}^4\dot{\phi}^2}\left(\frac{k}{k_0}\right)^{n-1}$$

amplitude

spectral index: $n-1 = 2\eta - 6\epsilon$
(or ``tilt'')

$$\epsilon = \frac{M_{\rm Pl}^2}{16\pi}\left(\frac{V'}{V}\right)^2 \ll 1;\ \eta = \frac{M_{\rm Pl}^2}{8\pi}\left(\frac{V''}{V}\right) \ll 1$$

- **Primordial (tensor) gravitational waves**

$$\mathcal{P}_{\rm T}(k) = \frac{128}{3}\frac{V}{M_{\rm Pl}^4}\left(\frac{k}{k_0}\right)^{n_{\rm T}}$$

Tensor spectral index: $n_{\rm T} = -2\epsilon$

- **Tensor-to-scalar perturbation ratio**

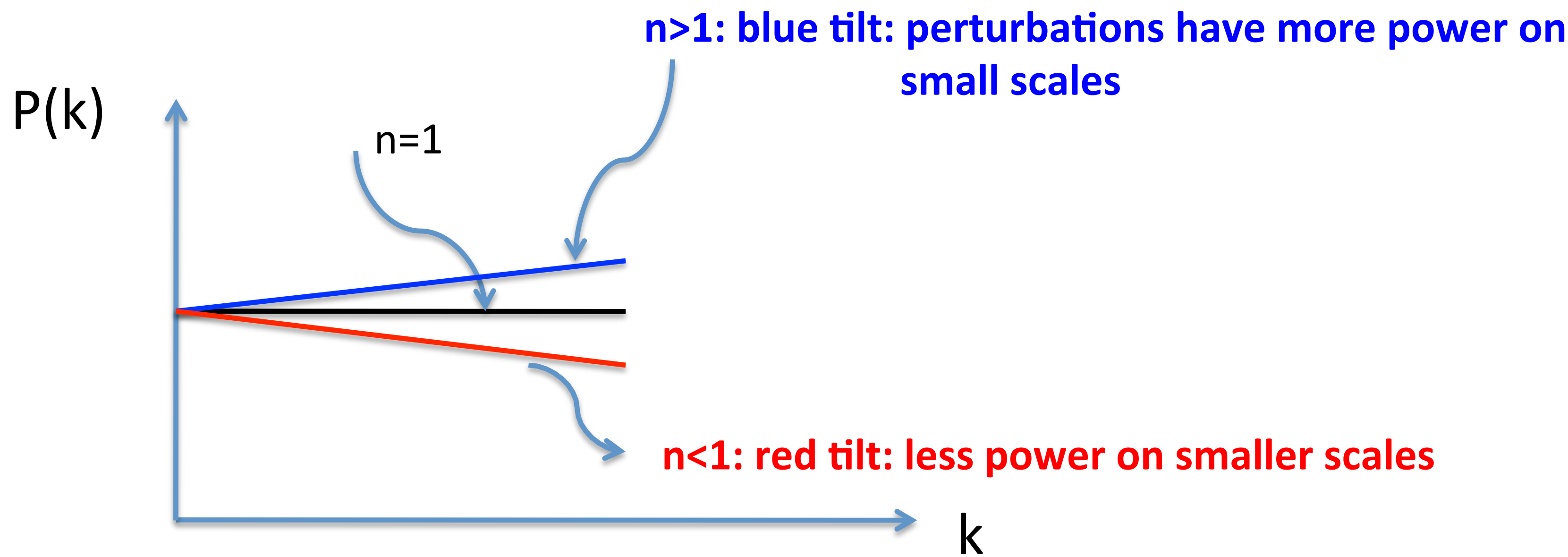
$$r = \frac{\mathcal{P}_{\rm T}}{\mathcal{P}_\zeta} = 16\epsilon$$

- **Consistency relation** (valid for *all* single field models of slow-roll inflation):

$$r = -8n_T$$

Varying the Spectral index

If n=1: Harrison-Zel' dovich spectrum (exact scale-invariance)



$$\boxed{n - 1 = 2\eta - 6\epsilon}$$ ***parametrizes deviation from scale-invariance:***

n=1 would signal some underlying symmetry;

measuring n ≠ 1 would signal a dynamical process for generating the initial density fluctuations (inflation??)

Observational predictions

One can also consider a running of the spectral index and a running of the running

$$\mathcal{P}_\zeta = A_\zeta \left(\frac{k}{k_*}\right)^{n_s - 1 + \frac{1}{2} dn_s/d\ln k \ln(k/k_*) + \frac{1}{8} d^2 n_s/d\ln k^2 (\ln(k/k_*))^2 + \ldots}$$

$$n_s - 1 = -6\varepsilon + 2\eta$$

$$dn_s / d\ln k = -2\xi + 16\varepsilon\eta - 24\varepsilon^2 \qquad \xi^2 = M_P^2 V' V''' / V^2$$

N.B: a negative running can reduce power on the largest scales!!
a running of the running can allow for even stronger suppression on large scales, while leaving small scales power almost unchanged

Primordial gravitational waves

GWs are tensor perturbations of the metric. Restricting ourselves to a flat FRW background (and disregarding scalar and vector modes)

$$\mathbf{ds^2=a^2(\tau)[-\, d\tau^2 + (\delta_{ij} + h_{ij}(\underline{x},\tau))\, dx^i\, dx^j]}$$

where h_{ij} are tensor modes which have the following properties

$h_{ij} = h_{ji}$ (symmetric)

$h^i_{\ i} = 0$ (traceless)

$h^i_{\ j|i} = 0$ (transverse)

and satisfy the equation of motion

$$h''_{ij} + 2\frac{a'}{a} h'_{ij} - \nabla^2 h_{ij} = 0$$

' = d/dτ

Primordial gravitational waves

GWs have only (9→6-1-3=) 2 independent degrees of freedom, corresponding to the 2 polarization states of the graviton

$$h_{ij}(\vec{x},\tau) = \int \frac{d^3k}{(2\pi)^3} e^{i\vec{k}\bullet\vec{x}} h(\vec{x},\tau)\varepsilon_{ij}(\vec{k})$$

polarization tensor

$$h'' + 2\frac{a'}{a}h' + k^2 h = 0$$

free massless, minimally coupled scalar field

behaviour:

k « aH (outside the horizon) **h ≈ const + decaying mode**

k » aH (inside the horizon) **h ≈ $e^{\pm ik\tau}/a$** gravitational wave; it freely streams, experiencing redshift and dilution, like a free photon

$$h = \frac{H}{\pi M_{\rm Pl}}$$

$$\sqrt{H} \propto V(\phi)^{1/4} \equiv E_{\rm inf}$$

Energy scale of inflation!

Here h means the amplitude of the power spectrum

Why gravity waves of inflation are important?

- A ***smoking gun*** of a period of inflation in the early universe: a stochastic background of gravitational waves is predicted by inflation independently of the specific inflationary model

- The amplitude of the inflationary gravity waves probes the ***energy scale of inflation***

$$\boxed{V^{1/4} = 1.06 \times 10^{16}\, GeV \left(\frac{r}{0.01} \right)^{1/4}}$$

GUT SCALE

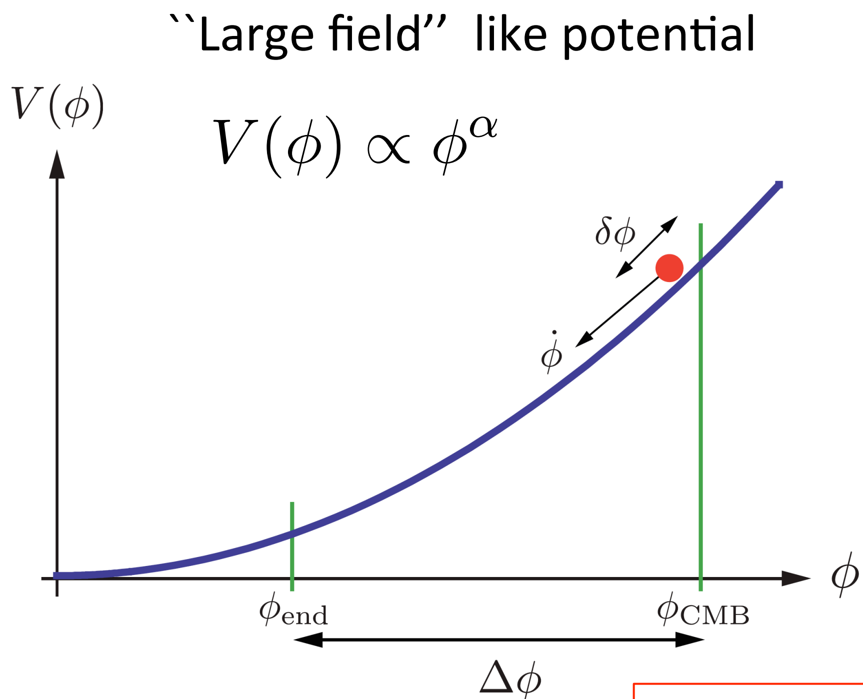
- ***a detection would provide a firm observational link to physics of the early universe, characterized by energies never achievable in labs***

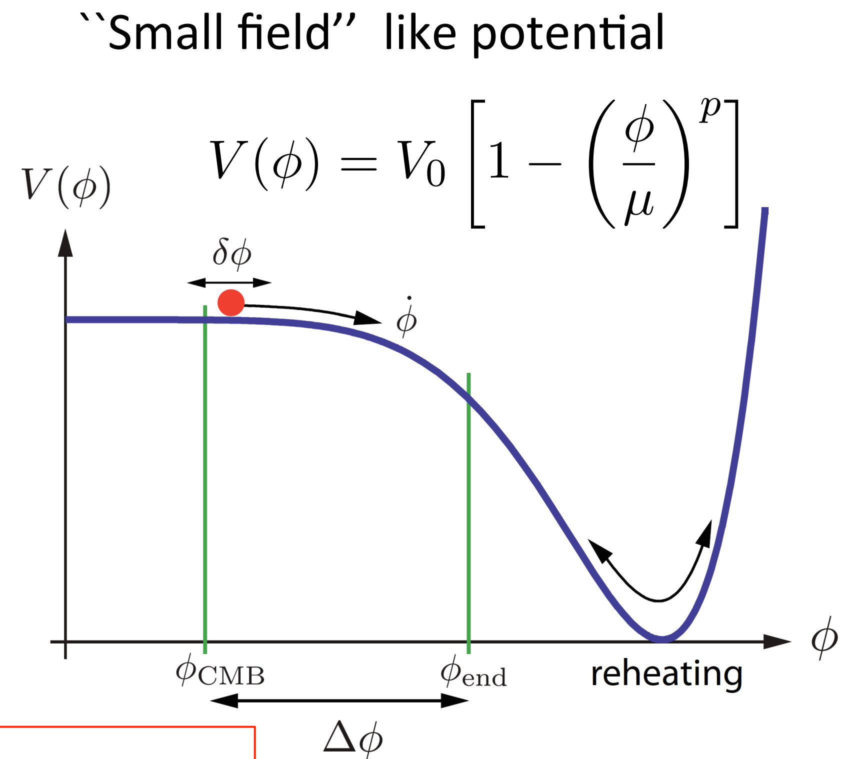
- inflationary gravity waves generate a unique imprint into the CMB polarization pattern ***(the so called B-modes of polarization)***

Classifying inflationary models

Roughly speaking: ``Large field'' models can produce a high level of gravity waves;
``small field'' models produce a low level of gravity waves

$$r = \frac{\mathcal{P}_{\rm T}}{\mathcal{P}_\zeta} = \epsilon$$





$$\boxed{\frac{\Delta\phi}{m_{\rm Pl}} \simeq \left(\frac{N}{30}\right) \times \left(\frac{r}{0.01}\right)^{1/2}}$$

Inflaton dynamics and the level of gravity waves

"Large field" models can produce a high level of gravity waves ($r>0.01$)

"Small field" models produce a low level of gravity waves ($r<0.01$)

$$\boxed{\frac{\Delta\phi}{m_{\rm Pl}} \simeq \left(\frac{N}{30}\right) \times \left(\frac{r}{0.01}\right)^{1/2}}$$

$30 \leq N \leq 60.$

So the bigger is the field excursion during inflation the bigger is the amplitude of the gravity waves

Planck parameters measurements

Parameter	TT+lowP 68 % limits	TT+lowP+lensing 68 % limits	TT+lowP+lensing+ext 68 % limits	TT,TE,EE+lowP 68 % limits	TT,TE,EE+lowP+lensing 68 % limits	TT,TE,EE+lowP+lensing+ext 68 % limits
$\Omega_b h^2$	0.02222 ± 0.00023	0.02226 ± 0.00023	0.02227 ± 0.00020	0.02225 ± 0.00016	0.02226 ± 0.00016	0.02230 ± 0.00014
$\Omega_c h^2$	0.1197 ± 0.0022	0.1186 ± 0.0020	0.1184 ± 0.0012	0.1198 ± 0.0015	0.1193 ± 0.0014	0.1188 ± 0.0010
$100\theta_{MC}$	1.04085 ± 0.00047	1.04103 ± 0.00046	1.04106 ± 0.00041	1.04077 ± 0.00032	1.04087 ± 0.00032	1.04093 ± 0.00030
τ	0.078 ± 0.019	0.066 ± 0.016	0.067 ± 0.013	0.079 ± 0.017	0.063 ± 0.014	0.066 ± 0.012
$\ln(10^{10} A_s)$	3.089 ± 0.036	3.062 ± 0.029	3.064 ± 0.024	3.094 ± 0.034	3.059 ± 0.025	3.064 ± 0.023
n_s	0.9655 ± 0.0062	0.9677 ± 0.0060	0.9681 ± 0.0044	0.9645 ± 0.0049	0.9653 ± 0.0048	0.9667 ± 0.0040
H_0	67.31 ± 0.96	67.81 ± 0.92	67.90 ± 0.55	67.27 ± 0.66	67.51 ± 0.64	67.74 ± 0.46
Ω_Λ	0.685 ± 0.013	0.692 ± 0.012	0.6935 ± 0.0072	0.6844 ± 0.0091	0.6879 ± 0.0087	0.6911 ± 0.0062
Ω_m	0.315 ± 0.013	0.308 ± 0.012	[illegible]	[illegible]	[illegible]	0.3089 ± 0.0062
$\Omega_m h^2$	0.1426 ± 0.0020	0.1415 ± 0.0019	[illegible]	[illegible]	[illegible]	0.14170 ± 0.00097
$\Omega_m h^3$	0.09597 ± 0.00045	0.09591 ± 0.00045	[illegible]	[illegible]	[illegible]	0.09598 ± 0.00029
σ_8	0.829 ± 0.014	0.8149 ± 0.0093	0.8154 ± 0.0090	0.831 ± 0.013	0.8150 ± 0.0087	0.8159 ± 0.0086
$\sigma_8 \Omega_m^{0.5}$	0.466 ± 0.013	0.4521 ± 0.0088	0.4514 ± 0.0066	0.4668 ± 0.0098	0.4553 ± 0.0068	0.4535 ± 0.0059
$\sigma_8 \Omega_m^{0.25}$	0.621 ± 0.013	0.6069 ± 0.0076	0.6066 ± 0.0070	0.623 ± 0.011	0.6091 ± 0.0067	0.6083 ± 0.0066
z_{re}	$9.9^{+1.8}_{-1.6}$	$8.8^{+1.7}_{-1.4}$	$8.9^{+1.3}_{-1.2}$	$10.0^{+1.7}_{-1.5}$	$8.5^{+1.4}_{-1.2}$	$8.8^{+1.2}_{-1.1}$
$10^9 A_s$	$2.198^{+0.076}_{-0.085}$	2.139 ± 0.063	2.143 ± 0.051	2.207 ± 0.074	2.130 ± 0.053	2.142 ± 0.049
$10^9 A_s e^{-2\tau}$	1.880 ± 0.014	1.874 ± 0.013	1.873 ± 0.011	1.882 ± 0.012	1.878 ± 0.011	1.876 ± 0.011
Age/Gyr	13.813 ± 0.038	13.799 ± 0.038	13.796 ± 0.029	13.813 ± 0.026	13.807 ± 0.026	13.799 ± 0.021
z_*	1090.09 ± 0.42	1089.94 ± 0.42	1089.90 ± 0.30	1090.06 ± 0.30	1090.00 ± 0.29	1089.90 ± 0.23
r_*	144.61 ± 0.49	144.89 ± 0.44	144.93 ± 0.30	144.57 ± 0.32	144.71 ± 0.31	144.81 ± 0.24
$100\theta_*$	1.04105 ± 0.00046	1.04122 ± 0.00045	1.04126 ± 0.00041	1.04096 ± 0.00032	1.04106 ± 0.00031	1.04112 ± 0.00029
z_{drag}	1059.57 ± 0.46	1059.57 ± 0.47	1059.60 ± 0.44	1059.65 ± 0.31	1059.62 ± 0.31	1059.68 ± 0.29
r_{drag}	147.33 ± 0.49	147.60 ± 0.43	147.63 ± 0.32	147.27 ± 0.31	147.41 ± 0.30	147.50 ± 0.24
k_D	0.14050 ± 0.00052	0.14024 ± 0.00047	0.14022 ± 0.00042	0.14059 ± 0.00032	0.14044 ± 0.00032	0.14038 ± 0.00029
z_{eq}	3393 ± 49	3365 ± 44	3361 ± 27	3395 ± 33	3382 ± 32	3371 ± 23
k_{eq}	0.01035 ± 0.00015	0.01027 ± 0.00014	0.010258 ± 0.000083	0.01036 ± 0.00010	0.010322 ± 0.000096	0.010288 ± 0.000071
$100\theta_{s,eq}$	0.4502 ± 0.0047	0.4529 ± 0.0044	0.4533 ± 0.0026	0.4499 ± 0.0032	0.4512 ± 0.0031	0.4523 ± 0.0023

n=1 excluded at 5.6 sigma!!

Observational constraints: *Planck*

Amplitude of primordial density (scalar) perturbations

$$\ln(10^{10} A_s) = 3.062 \pm 0.029 \quad (68\%\,\mathrm{CL})$$

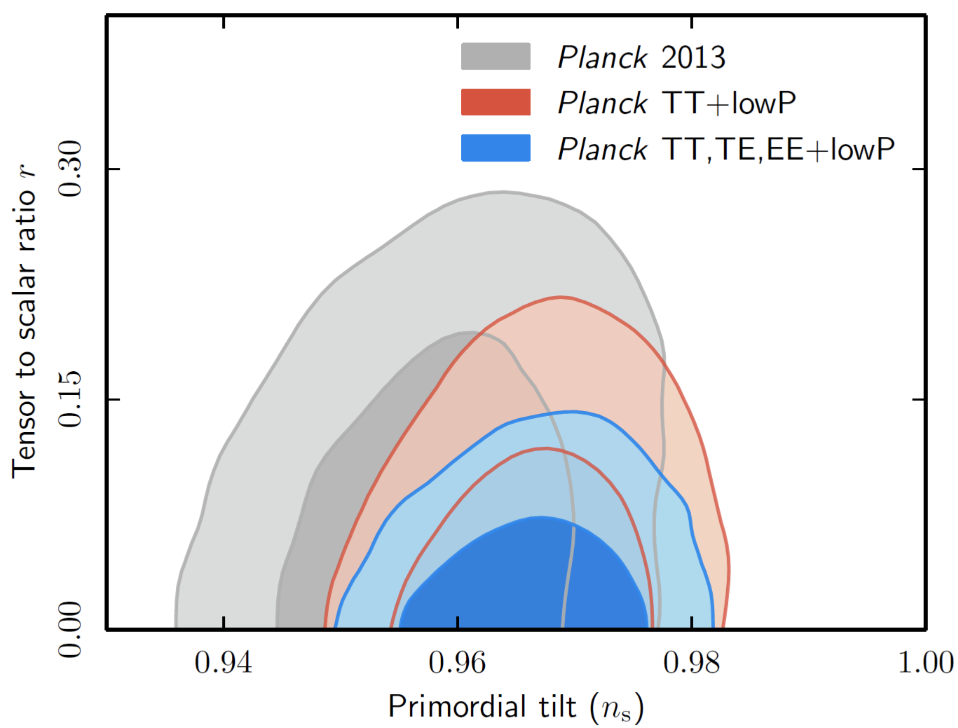
Spectral index of primordial density (scalar) perturbations

$$n_s = 0.9677 \pm 0.0060 \quad (68\%\,\mathrm{CL})$$

n=1 (Harrison Zeld' ovich spectrum) excluded at than 5.6 sigmas!

Constraints on tensor modes

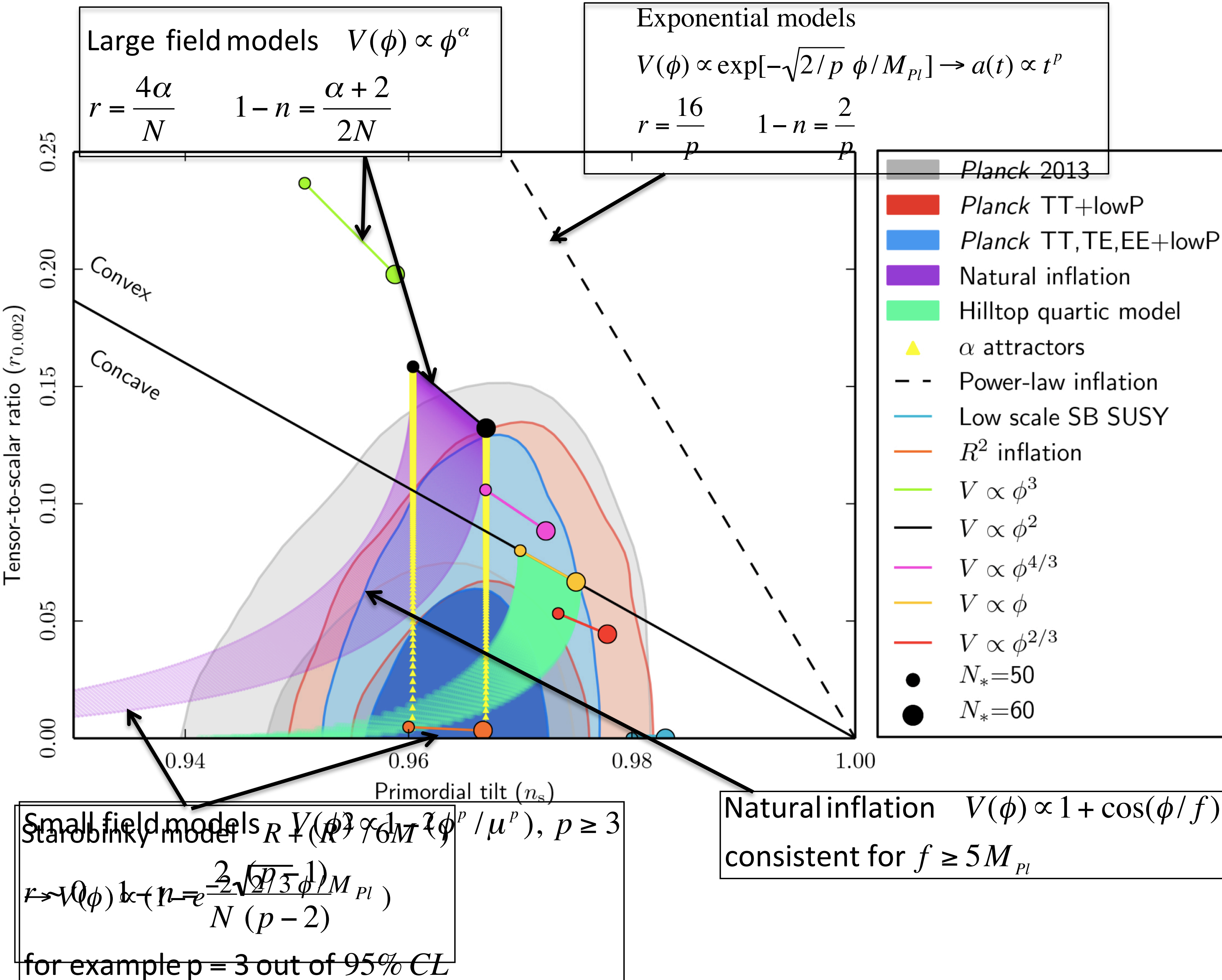
Model	Parameter	*Planck* TT+lowP	*Planck* TT+lowP+lensing	*Planck* TT+lowP+BAO	*Planck* TT,TE,EE+lowP
ΛCDM+r	n_s	0.9666 ± 0.0062	0.9688 ± 0.0061	0.9680 ± 0.0045	0.9652 ± 0.0047
	$r_{0.002}$	< 0.103	$\boxed{< 0.114}$	< 0.113	< 0.099
	$-2\Delta \ln \mathcal{L}_{max}$	0	0	0	0
ΛCDM+r +$dn_s/d\ln k$	n_s	0.9667 ± 0.0066	0.9690 ± 0.0063	0.9673 ± 0.0043	0.9644 ± 0.0049
	$r_{0.002}$	< 0.180	< 0.186	< 0.176	< 0.152
	r	< 0.168	< 0.176	< 0.166	< 0.149
	$dn_s/d\ln k$	$-0.0126^{+0.0098}_{-0.0087}$	$-0.0076^{+0.0092}_{-0.0080}$	-0.0125 ± 0.0091	-0.0085 ± 0.0076
	$-2\Delta \ln \mathcal{L}_{max}$	-0.81	-0.08	-0.87	-0.38



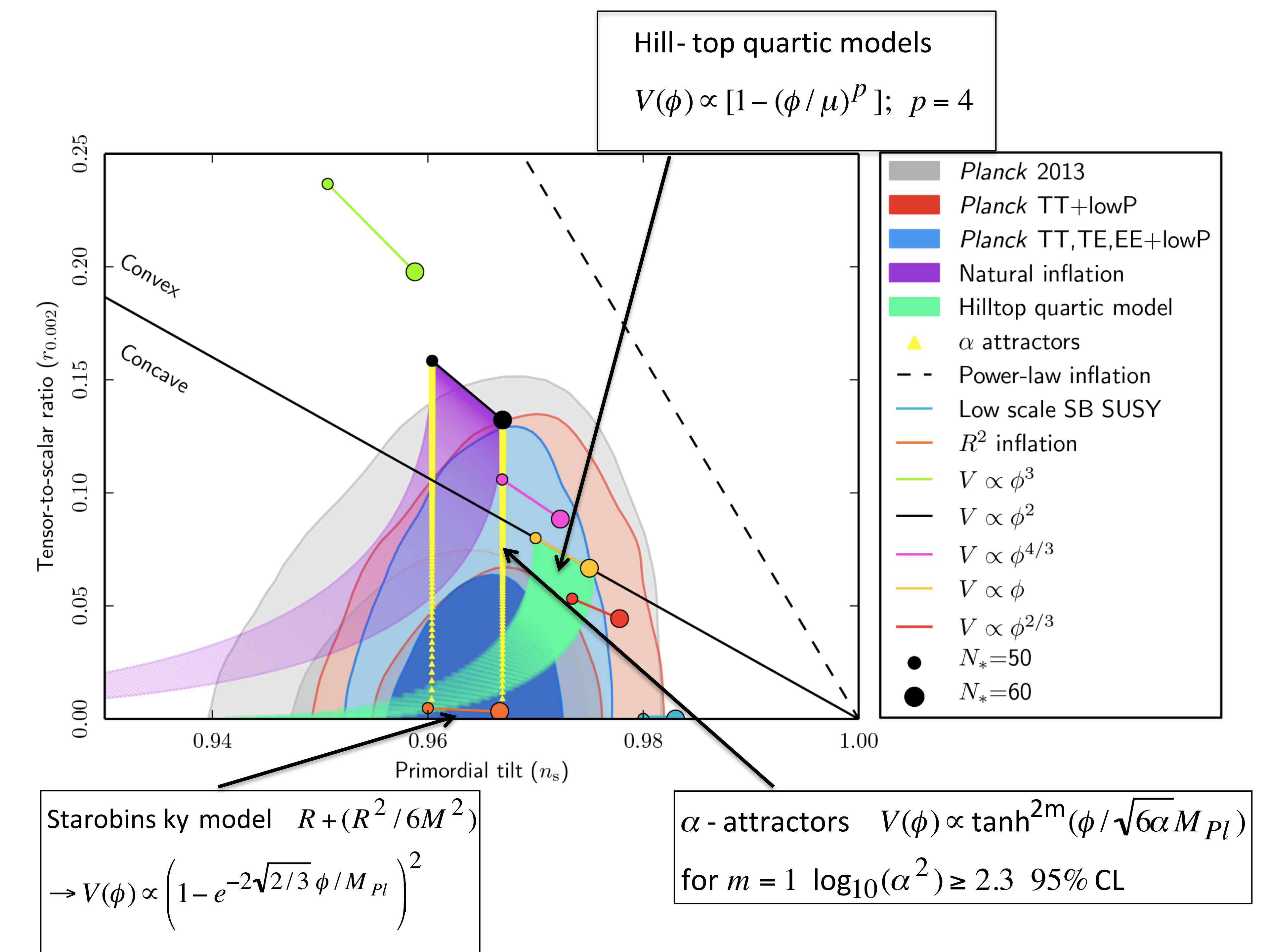
Energy scale of inflation

$$V^{1/4} < 1.9 \times 10^{16} \quad \text{GeV}$$

What are the implications for inflationary models ?



Large field models $V(\phi) \propto \phi^{\alpha}$
$r = \frac{4\alpha}{N}$ $1-n = \frac{\alpha+2}{2N}$
Exponential models
$V(\phi) \propto \exp[-\sqrt{2/p}\,\phi/M_{Pl}] \to a(t) \propto t^{p}$
$r = \frac{16}{p}$ $1-n = \frac{2}{p}$
Planck 2013
Planck TT+lowP
Planck TT,TE,EE+lowP
Natural inflation
Hilltop quartic model
α attractors
Power-law inflation
Low scale SB SUSY
R^2 inflation
$V \propto \phi^3$
$V \propto \phi^2$
$V \propto \phi^{4/3}$
$V \propto \phi$
$V \propto \phi^{2/3}$
N_*=50
N_*=60
Convex
Concave
Tensor-to-scalar ratio $(r_{0.002})$
0.00
0.05
0.10
0.15
0.20
0.25
0.94
0.96
0.98
1.00
Primordial tilt (n_s)
Small field models $V(\phi) \propto 1-(\phi^{p}/\mu^{p}),\ p \geq 3$
$r \to 0$ $1-n = \frac{2}{N}\frac{(p-1)}{(p-2)}$
for example p = 3 out of 95% CL
Starobinky model $R + (R^2/6M^2)$
$V(\phi) \propto (1-e^{-2\sqrt{2/3}\,\phi/M_{Pl}})$
Natural inflation $V(\phi) \propto 1+\cos(\phi/f)$
consistent for $f \geq 5M_{Pl}$



Hill- top quartic models
$V(\phi) \propto [1-(\phi/\mu)^p]; \ p=4$
Planck 2013
Planck TT+lowP
Planck TT,TE,EE+lowP
Natural inflation
Hilltop quartic model
α attractors
Power-law inflation
Low scale SB SUSY
R^2 inflation
$V \propto \phi^3$
$V \propto \phi^2$
$V \propto \phi^{4/3}$
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$N_*=50$
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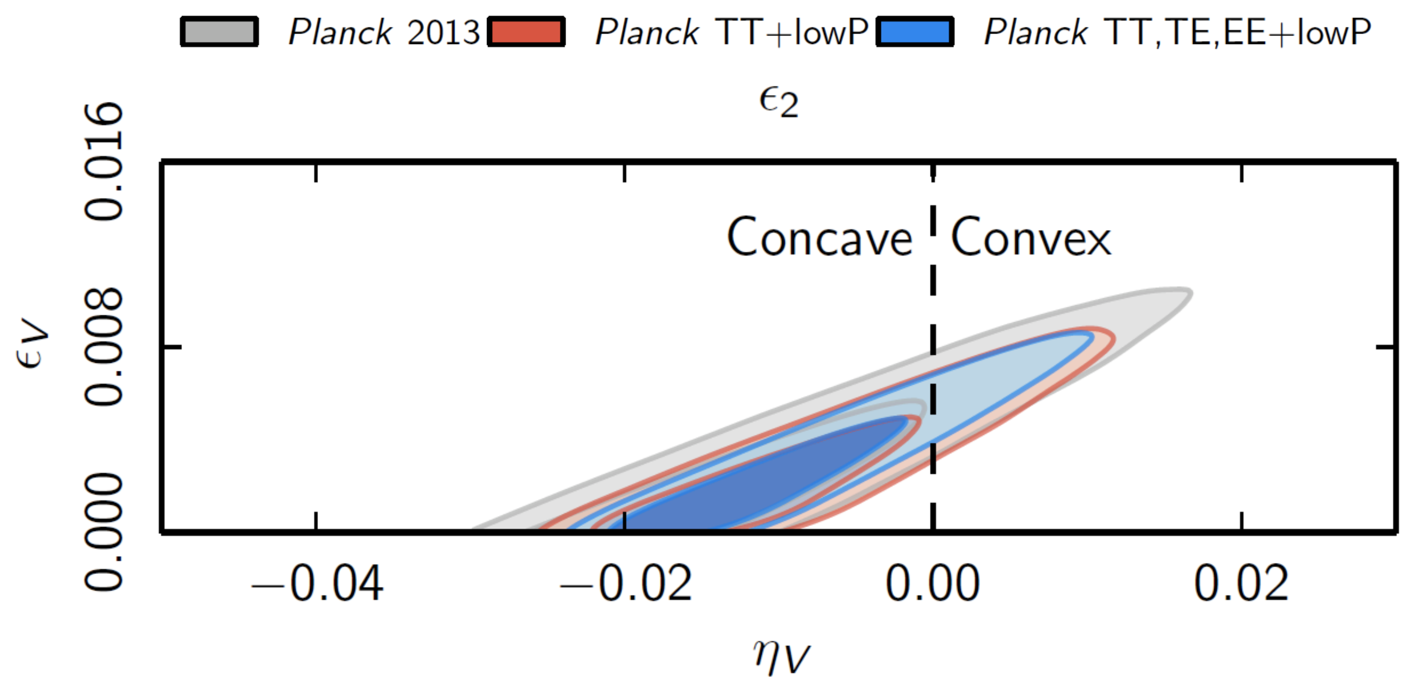
Convex
Concave
Tensor-to-scalar ratio ($r_{0.002}$)
0.25
0.20
0.15
0.10
0.05
0.00
0.94
0.96
0.98
1.00
Primordial tilt (n_s)
Starobins ky model $R+(R^2/6M^2)$
$\rightarrow V(\phi) \propto \left(1-e^{-2\sqrt{2/3}\,\phi/M_{Pl}}\right)^2$
α - attractors $V(\phi) \propto \tanh^{2m}(\phi/\sqrt{6\alpha}M_{Pl})$
for $m=1$ $\log_{10}(\alpha^2) \geq 2.3$ 95% CL

Constraints on slow-roll parameters

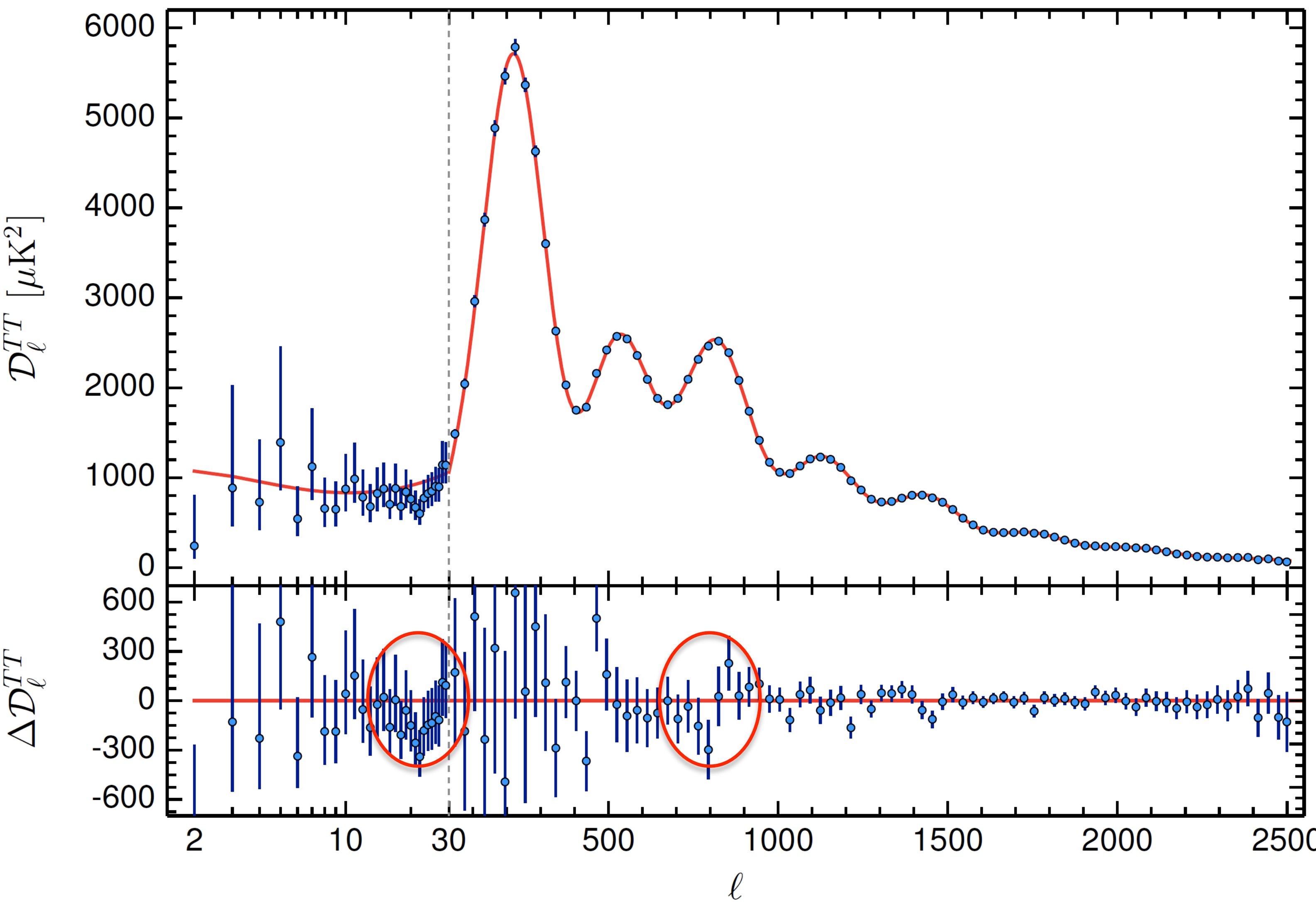


$\epsilon_V < 0.012$ (95 % CL, *Planck* TT+lowP)

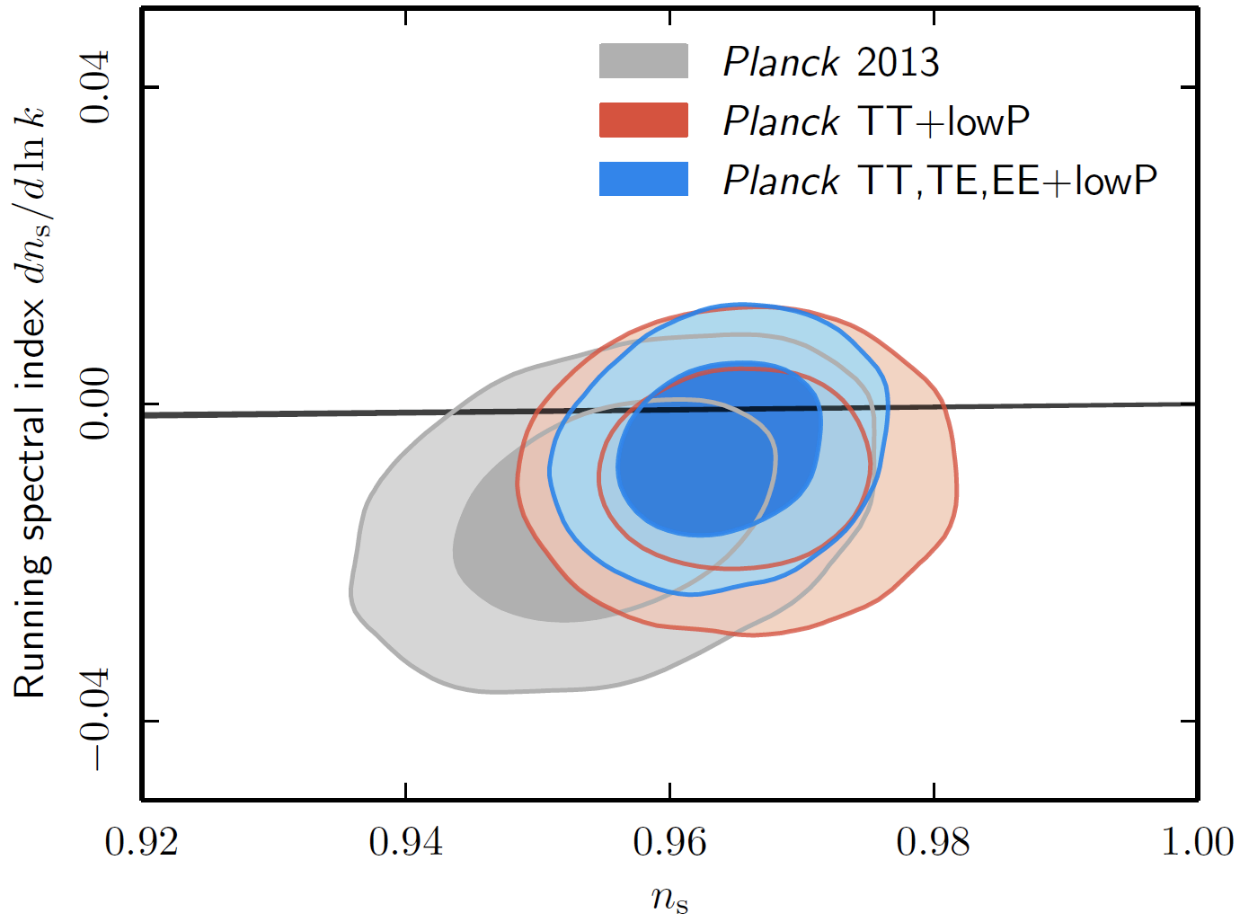
$\eta_V = -0.0080^{+0.0088}_{-0.0146}$ (68 % CL, *Planck* TT+lowP)

$\xi_V = 0.0070^{+0.0045}_{-0.0069}$ (68 % CL, *Planck* TT+lowP)

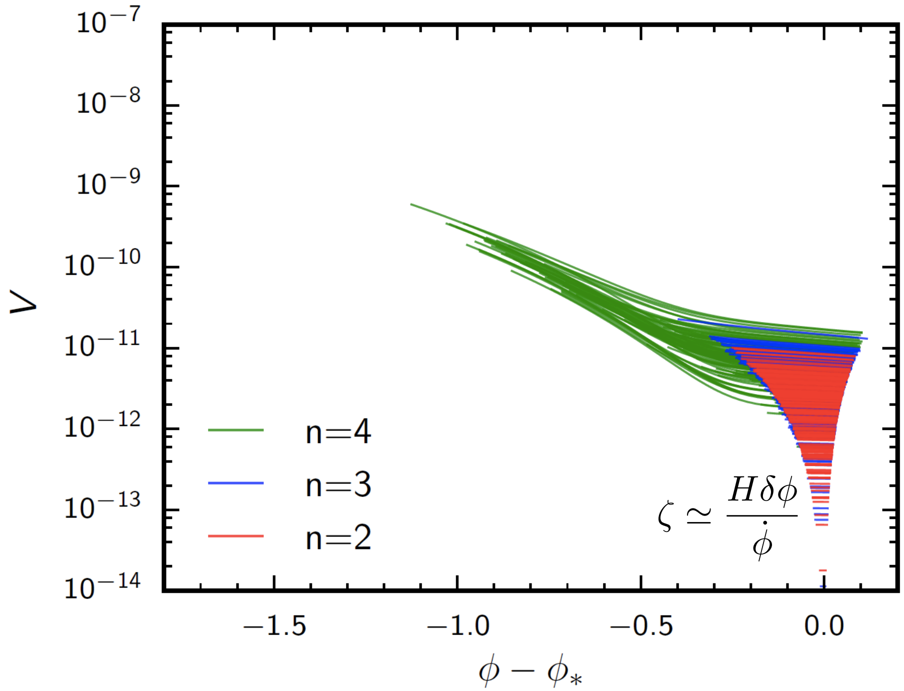
ANGULAR POWER SPECTRUM OF TEMPERATURE CMB ANISOTROPIES MEASURED BY *PLANCK*



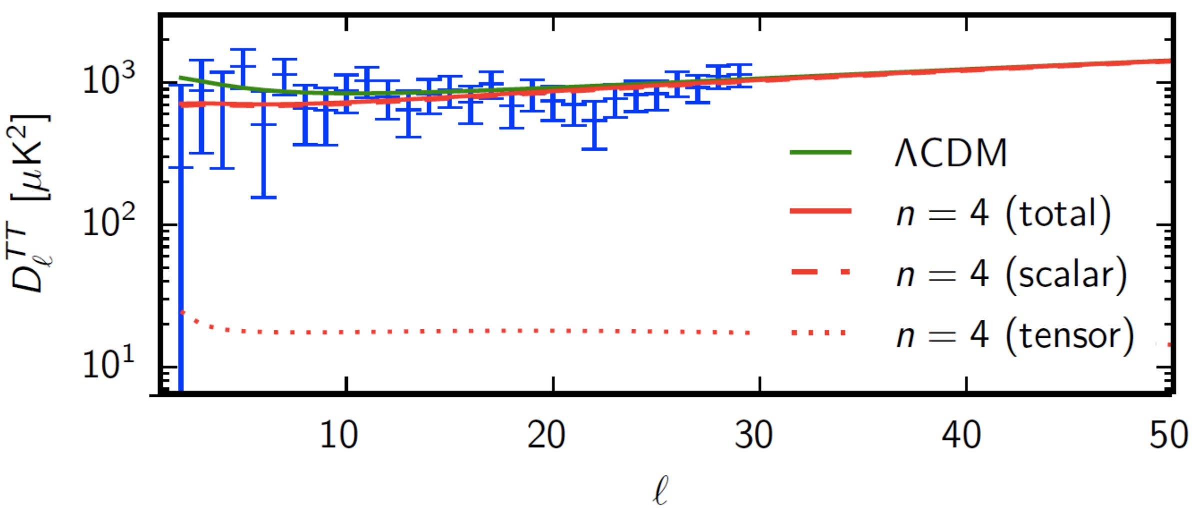
Running of the spectral index



Reconstructing the inflationary potential



$$\zeta \simeq \frac{H\delta\phi}{\dot{\phi}}$$



No significant evidence of departures from a featureless Power spectrum

Primordial non-Gaussianity

Primordial NG

$\zeta(\mathbf{x})$: primordial perturbations

If the fluctuations are Gaussian distributed then their statistical properties are completely characterized by the two-point correlation function, $\langle\zeta(\mathbf{x}_1)\zeta(\mathbf{x}_2)\rangle$ or its Fourier transform, the power-spectrum.

Thus a non-vanishing ***three point function***, or its Fourier transform, the ***bispectrum is an indicator of non-Gaussianity***

$$\left\langle \Phi(\vec{k}_1)\Phi(\vec{k}_2)\Phi(\vec{k}_3)\right\rangle = (2\pi)^3\delta^{(3)}(\vec{k}_1+\vec{k}_2+\vec{k}_3)\underbrace{f_{NL}}_{\text{Amplitude}}\underbrace{F(k_1,k_2,k_3)}_{\text{Shape}}$$

$$\rightarrow \quad \left\langle \frac{\Delta T}{T}(n_1)\frac{\Delta T}{T}(n_2)\frac{\Delta T}{T}(n_3)\right\rangle$$

Primordial NG

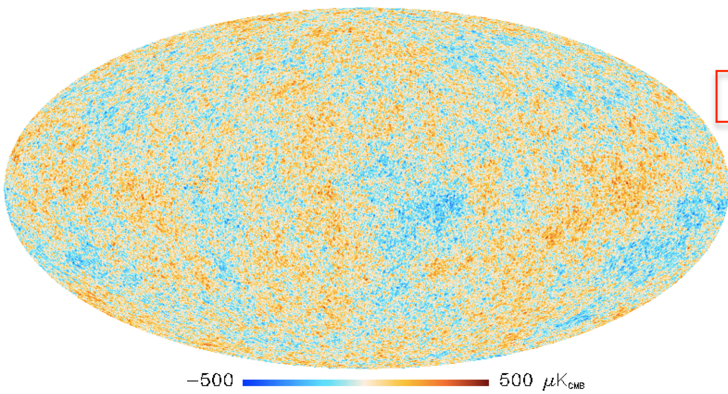
Gaussian ⟺ free (i.e. non-interacting) field, linear theory

Collection of independent harmonic oscillators
(no mode-mode coupling)

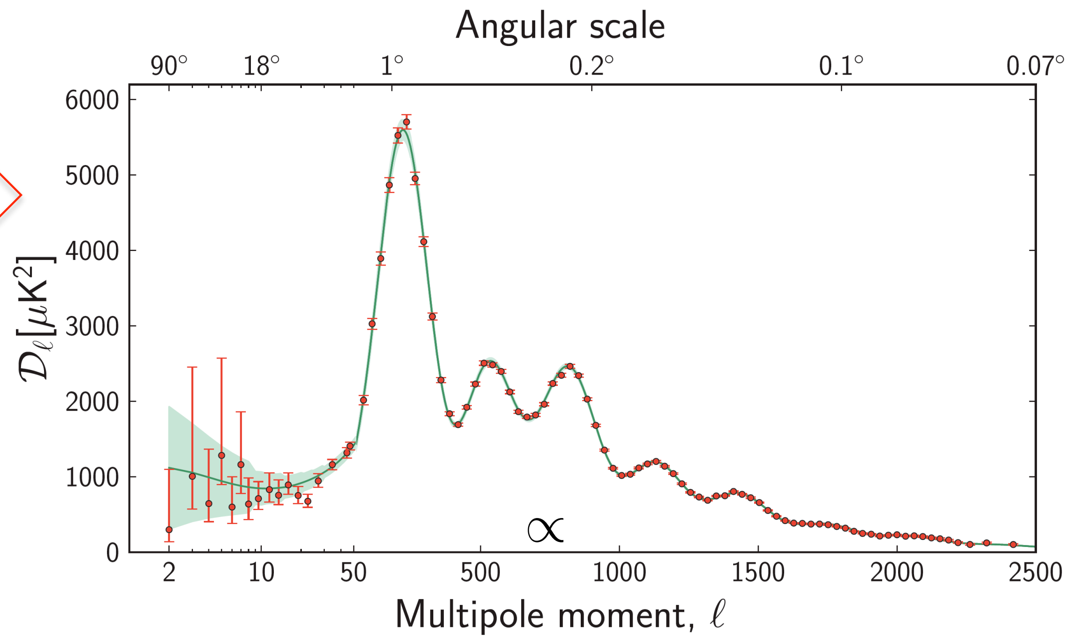
Physical origin of primordial NG:
self-interactions of the inflaton field, e.g. $\lambda\,\phi^3$,
interactions between different fields,
non-linear evolution of the fields during inflation,
gravity itself is non linear.....

Why primordial NG is important?

Bispectrum vs power spectrum information



Planck 2013 Results. I. Overview of products and scientific results

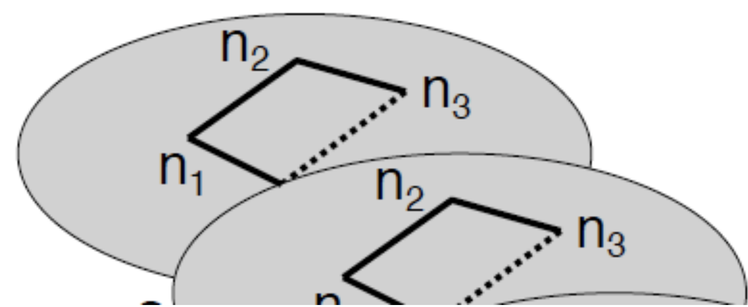


Planck 2013 Results. XV. CMB power spectra and likelihood

$5{\times}10^6$ pixels compressed into ~2500 numbers: O.K. only if gaussian

If not we could miss precious information

Measure 3 point-function and higher-order



One (among many) good reason:

f_{NL} and shape are model dependent:
e.g.: standard single-field models of slow-roll inflation predict

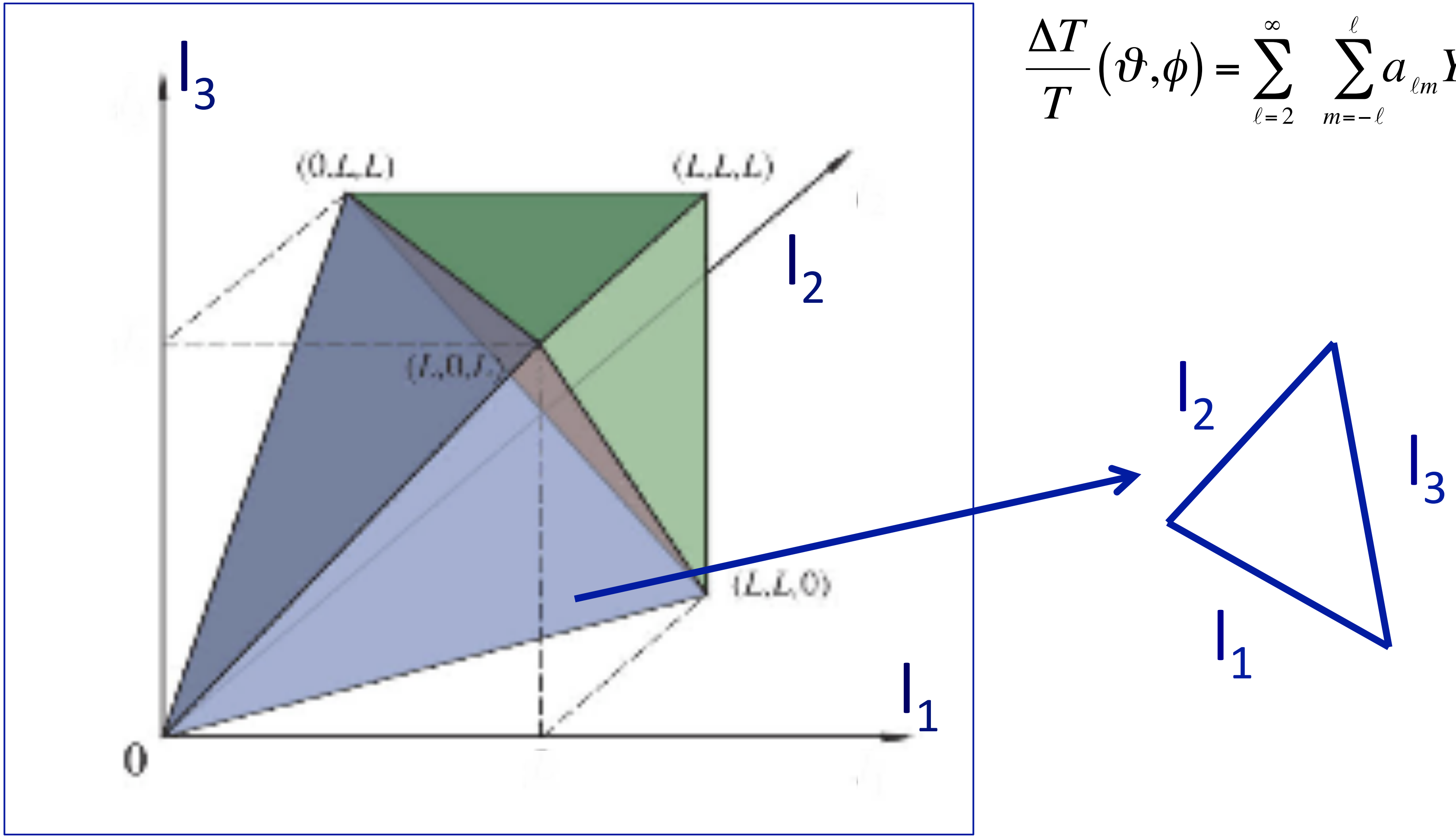
$$f_{NL} \sim O(\varepsilon,\eta) \ll 1$$

(Acquaviva, Bartolo, Riotto, Matarrese 2002; Maldacena 2002)

A detection of a primordial $|f_{NL}|\sim 1$ would rule out the standard single-field models of inflation

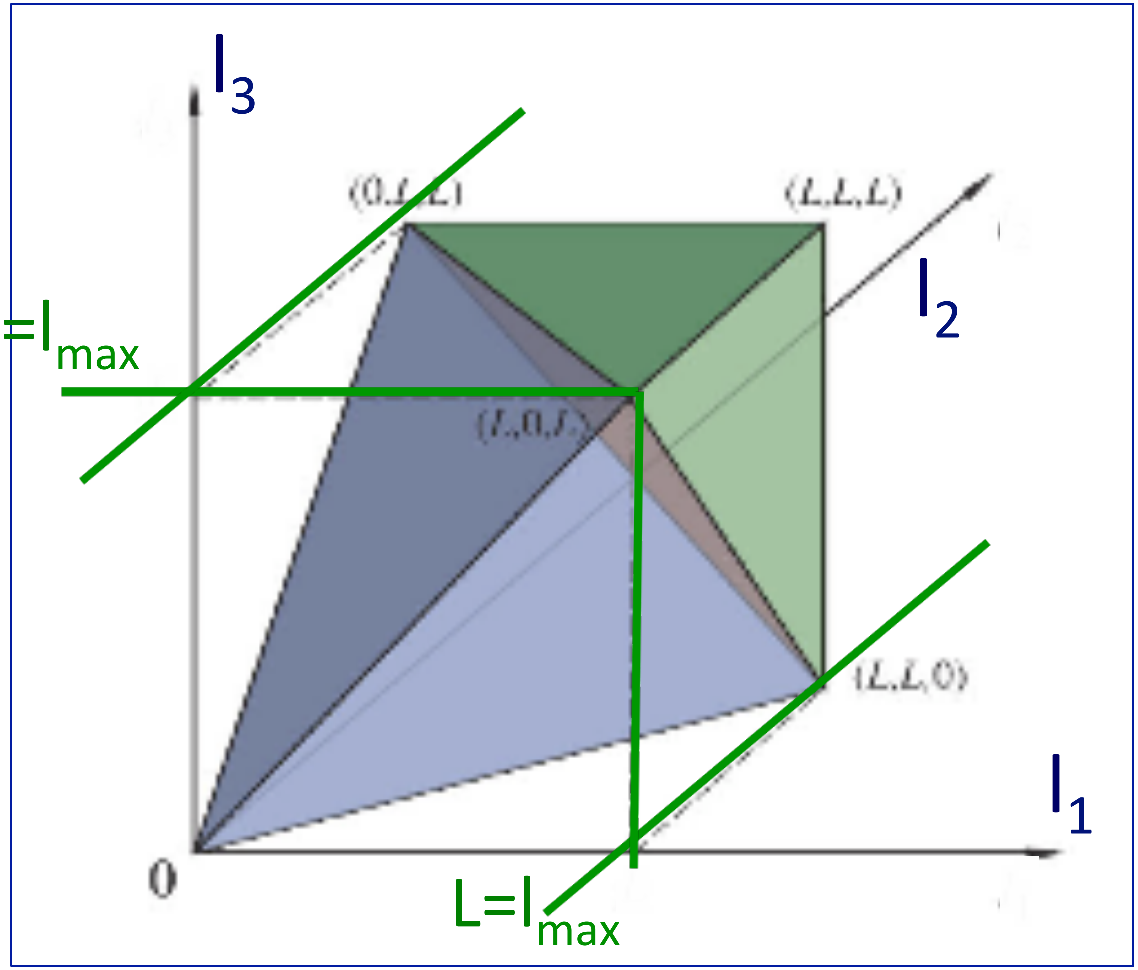
CMB bispectrum definition

$$\frac{\Delta T}{T}(\vartheta,\phi)=\sum_{\ell=2}^{\infty}\sum_{m=-\ell}^{\ell}a_{\ell m}Y_{\ell m}(\vartheta,\phi)$$



$$B_{\ell_1\ell_2\ell_3}=\sum_m\begin{pmatrix}\ell_1 & \ell_2 & \ell_3\\ m_1 & m_2 & m_3\end{pmatrix}\left\langle a_{\ell_1}^{m_1}a_{\ell_2}^{m_2}a_{\ell_3}^{m_3}\right\rangle;\quad B_{\ell_1\ell_2\ell_3}=h_{\ell_1\ell_2\ell_3}b_{\ell_1\ell_2\ell_3}$$

CMB bispectrum definition

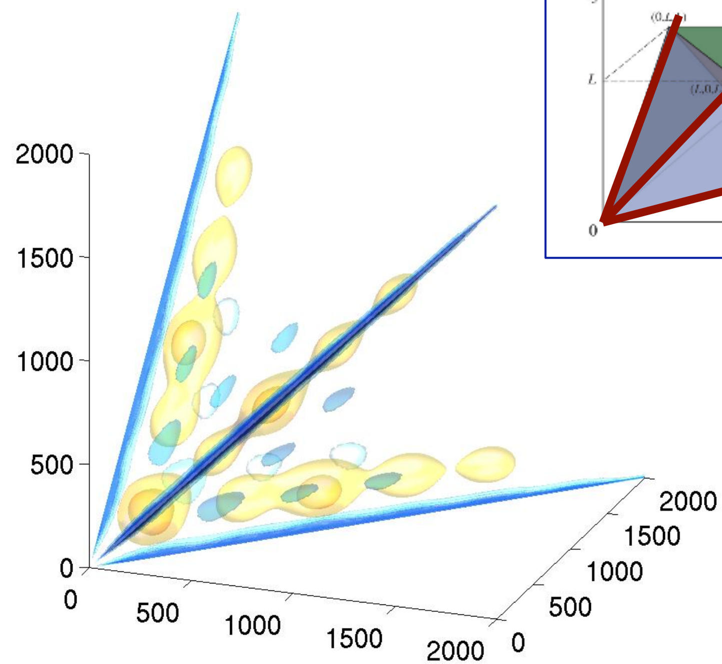


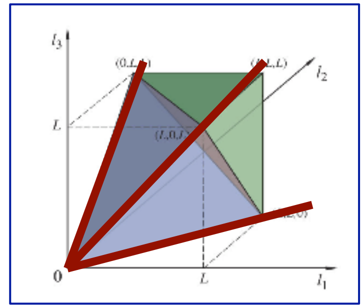
$$\frac{\Delta T}{T}(\vartheta,\phi)=\sum_{\ell=2}^{\infty}\sum_{m=-\ell}^{\ell}a_{\ell m}Y_{\ell m}(\vartheta,\phi)$$

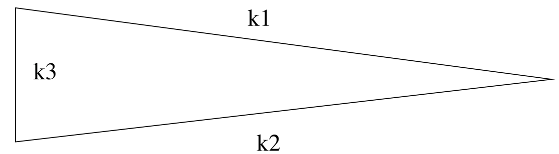
$$B_{\ell_1\ell_2\ell_3}=\sum_m\begin{pmatrix}\ell_1 & \ell_2 & \ell_3\\ m_1 & m_2 & m_3\end{pmatrix}\left\langle a_{\ell_1}^{m_1}a_{\ell_2}^{m_2}a_{\ell_3}^{m_3}\right\rangle;\ B_{\ell_1\ell_2\ell_3}=h_{\ell_1\ell_2\ell_3}b_{\ell_1\ell_2\ell_3}$$

SHAPES OF NG:LOCAL NG

Bispectrum peaks for squeezed triangles $k_3 << k_1 \sim k_2$







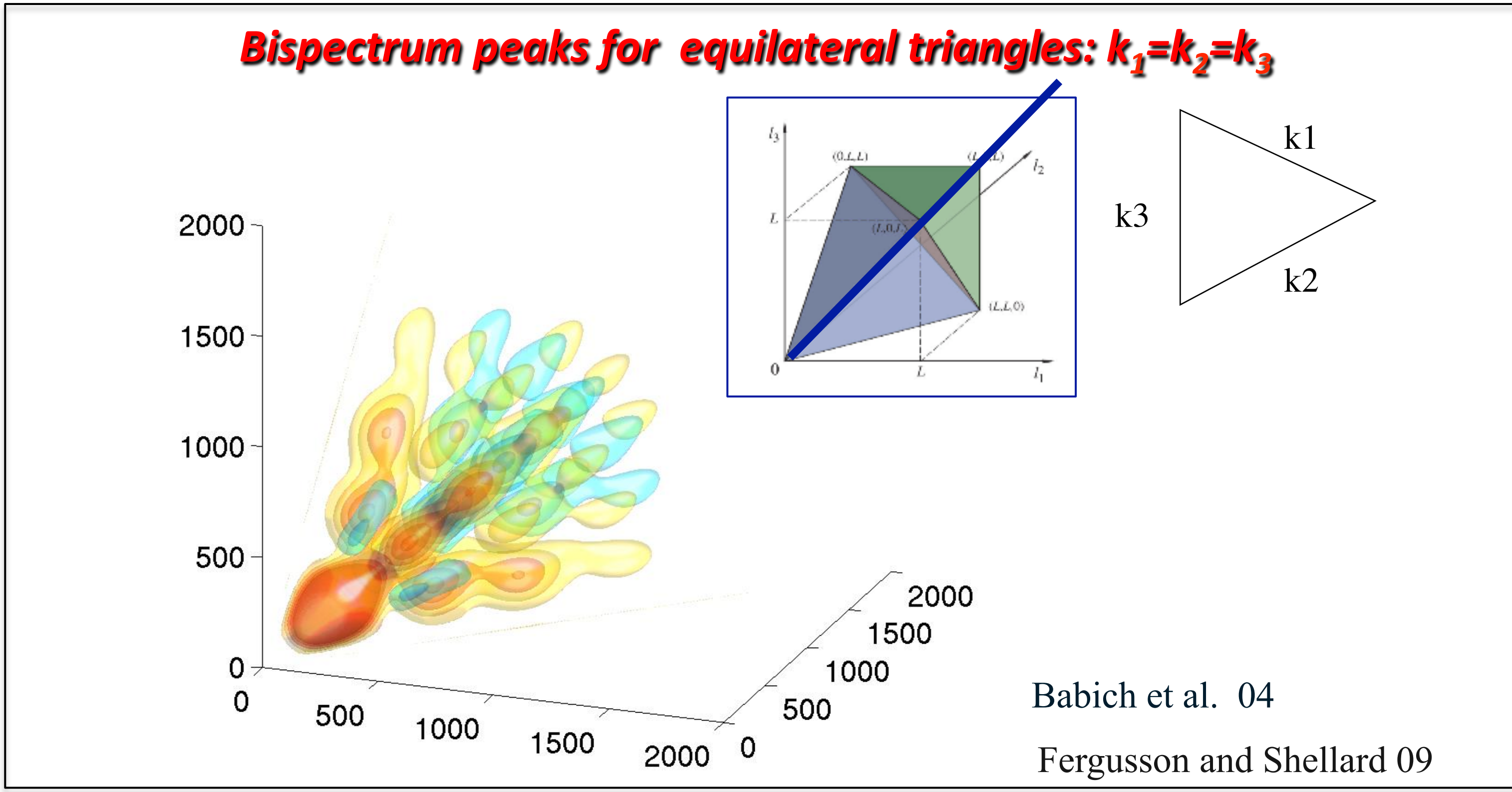
Babich et al. 04

Fergusson and Shellard 09

$$\zeta(\mathbf{x}) = \zeta_g(\mathbf{x}) + \frac{3}{5} f_{\mathrm{NL}} \zeta_g^2(\mathbf{x})$$

Non-linearities develop outside the horizon during or immediately after inflation (e.g. ***multifield models of inflation***)

EQUILATERAL NG

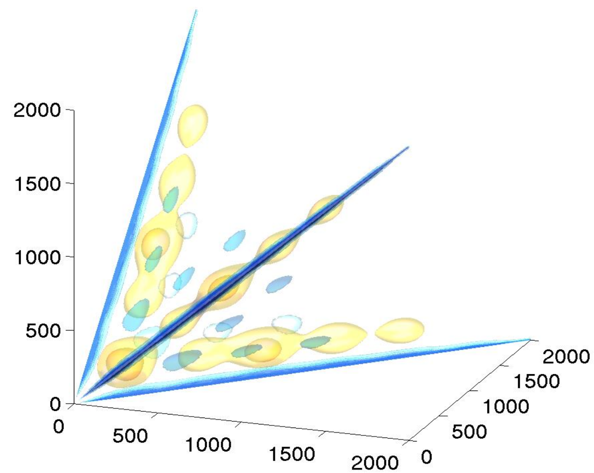


Single field models of inflation with non-canonical kinetic term L=P(φ, X) where X=(∂ φ)^2 (DBI or K-inflation) where NG comes from higher derivative interactions of the inflaton field

Example: $\delta\dot{\phi}(\nabla\delta\phi)^2$

LESSON: NG…IT'S NOT JUST A NUMBER

Measuring the amplitude and shape of non-Gaussianities, with their huge amount of information associated to triangular configurations is analogous to measuring a cross section as a function of the angle of the outgoing particles in particle and collider physics



Constraints on f_{NL} translates into constraints of the coefficients of the interactions of the inflaton Lagrangian (e.g. Senatore et al. 0905.37462)

Limits set by Planck

See Planck 2015 results. XVII. Constraints on primordial non-Gaussianity

Observational limits set by Planck

	f_{NL}(KSW)	
Shape and method	Independent	ISW-lensing subtracted
`SMICA` (T)		
Local	10.2 ± 5.7	**2.5 ± 5.7**
Equilateral	−13 ± 70	**−16 ± 70**
Orthogonal	−56 ± 33	**−34 ± 33**
`SMICA` (T+E)		
Local	6.5 ± 5.0	**0.8 ± 5.0**
Equilateral	3 ± 43	**−4 ± 43**
Orthogonal	−36 ± 21	**−26 ± 21**

e.g. models with non-standard kinetic terms

e.g. multi-field models of inflation

Implications for inflation models

- The standard models of single-field slow-roll inflation has survived the most stringent tests of Gaussianity to-date: ***deviations from primordial Gaussianity are less than 0.01% level. This is a fantastic achievement, one of the most precise measurements in cosmology!***

$$\Phi(\mathbf{x}) = \underbrace{\Phi^{(1)}(\mathbf{x})}_{\sim 10^{-5}} + \underbrace{f_{\mathrm{NL}}}_{\sim\text{few}} \underbrace{\left(\Phi^{(1)}(\mathbf{x})\right)^2}_{\sim 10^{-10}} + \ldots\ldots$$

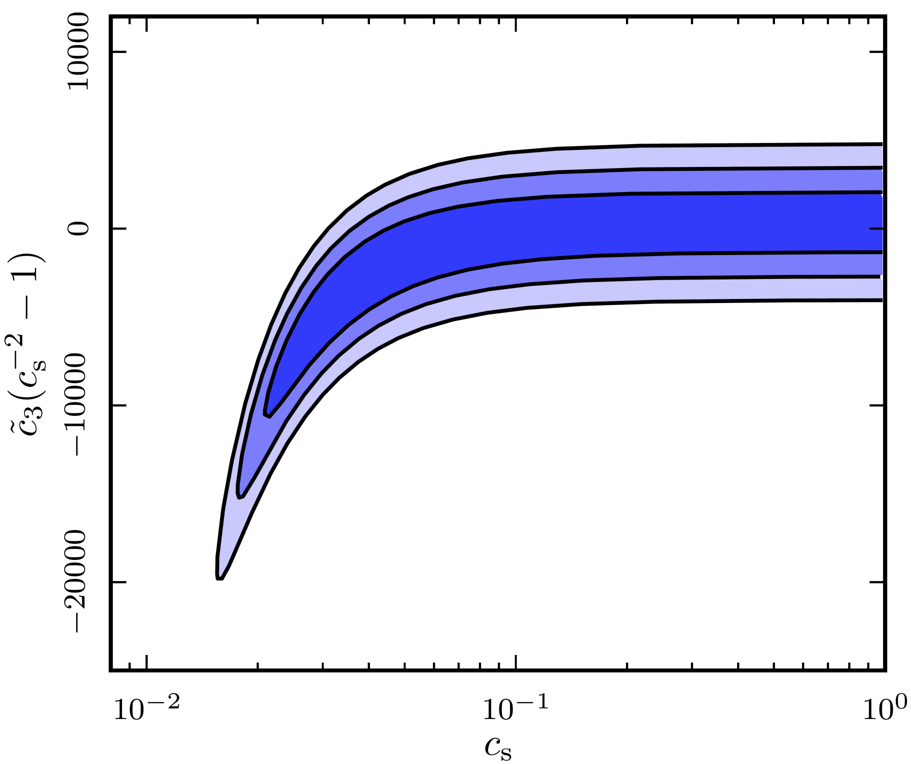
- ***The NG constraints*** on different primordial bispectrum shapes ***severly limit/rule out specific key (inflationary) mechanisms alternative to the standard models of inflation***

General single-field models of inflation: Implications for Effective Field Theory of Inflation

$$S = \int d^4x\,\sqrt{-g}\Big[-\frac{M_{\rm Pl}^2\dot H}{c_s^2}\left(\dot\pi^2 - c_s^2\frac{(\partial_i\pi)^2}{a^2}\right) - M_{\rm Pl}^2\dot H(1-c_s^{-2})\dot\pi\frac{(\partial_i\pi)^2}{a^2} + \left(M_{\rm Pl}^2\dot H(1-c_s^{-2}) - \frac{4}{3}M_3^4\right)\dot\pi^3\Big]$$

$$f_{\rm NL} \propto \frac{1}{c_s^2}$$

(Cheung et al. 08; Weinberg 08)
for extensions see also N.B., Fasiello, Matarrese, Riotto 10)



Constraints obtained from

$$f_{\rm NL}^{\rm equil} = -16 \pm 70 \quad (68\%\ {\rm CL})$$

$$f_{\rm NL}^{\rm ortho} = -34 \pm 33 \quad (68\%\ {\rm CL})$$

$$\boxed{c_s \geq 0.02 \ \text{ at } 95\%\ \text{CL}}$$

Multi-field models of inflation: the curvaton case

$$\Phi(\boldsymbol{x}) = \Phi_L(\boldsymbol{x}) + f_{\rm NL}^{\rm local}\left(\Phi_L^2(\boldsymbol{x}) - \langle\Phi_L^2(\boldsymbol{x})\rangle\right)$$

A second scalar field, different from the inflaton and subdominant during inflation, decays after inflation with its fluctuations converted on super-horizon scale to the final gravitational perturbations

$$f_{\rm NL}^{\rm local} = \frac{5}{4r_{\rm D}} - \frac{5r_{\rm D}}{6} - \frac{5}{3}$$

$$r_D = \frac{3\rho_{\rm curvaton}}{3\rho_{\rm curvaton} + 4\rho_{\rm radiation}}$$

$$r_{\rm D} > 0.16 \quad (95\%\ {\rm CL})$$

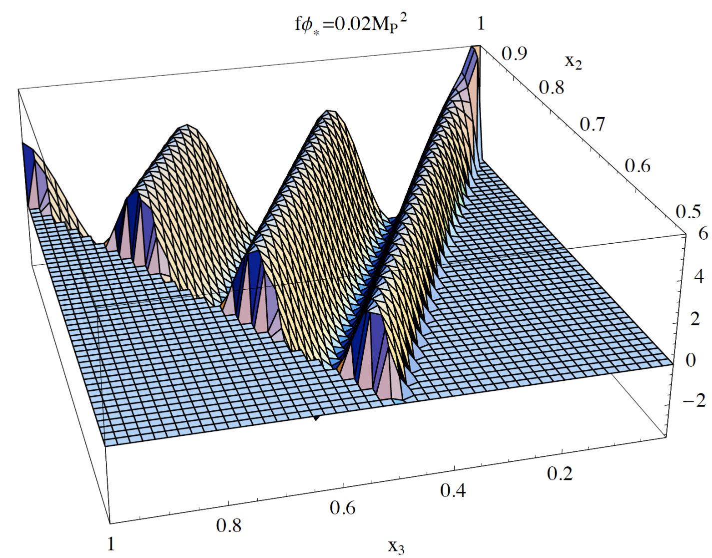
Models with non-standard shapes of NG

Feature and resonant models: oscillating bispectra due to

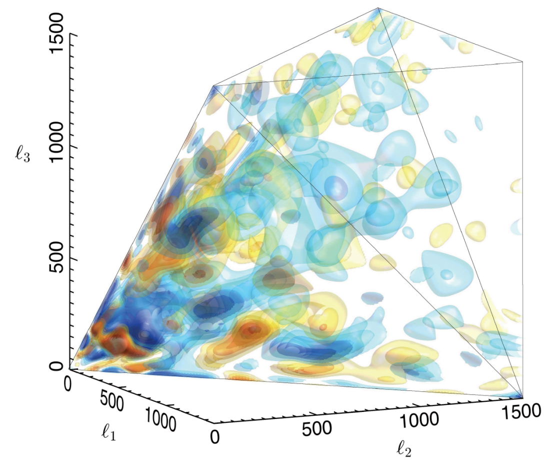
✓ a sharp feature (e.g. step-like) in the inflaton potential
(Wang & Kamionkowski 2000; Chen et al. 07)

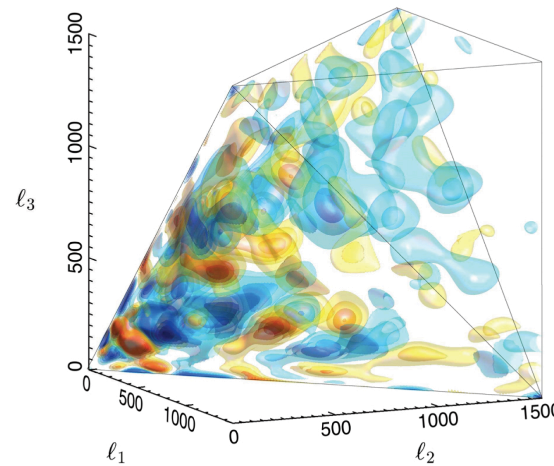
✓periodic features: e.g. ***axion inflation*** $V(\phi)=V_0(\phi)[1+\lambda \cos(\phi/f)]$
(recent interest in axion monodromy inflation motivated by string theory
e.g. McAllister et al. 2010; Siverstein & Westphal 08; Flauger et al 09;
Flauger and Pajer 2011).

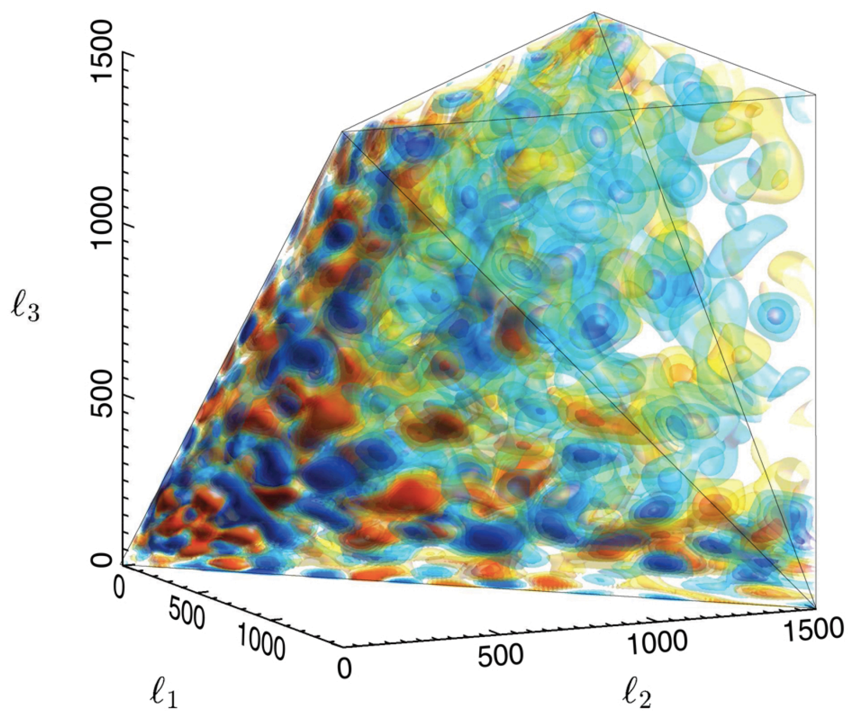
Inflaton quantum perturbations can resonate with oscillatory features of the background evolution generating large interactions (NG)



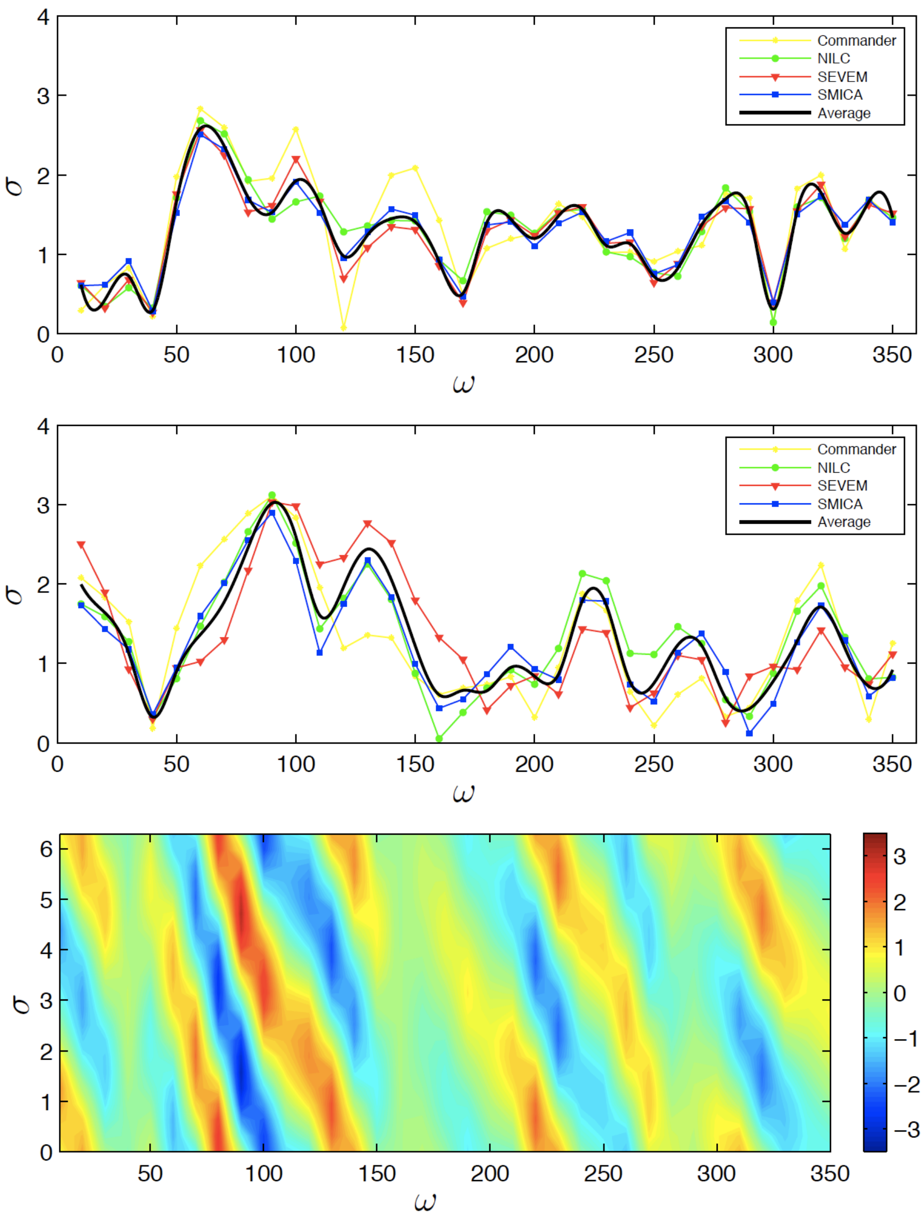
The CMB bispectrum as seen by Planck





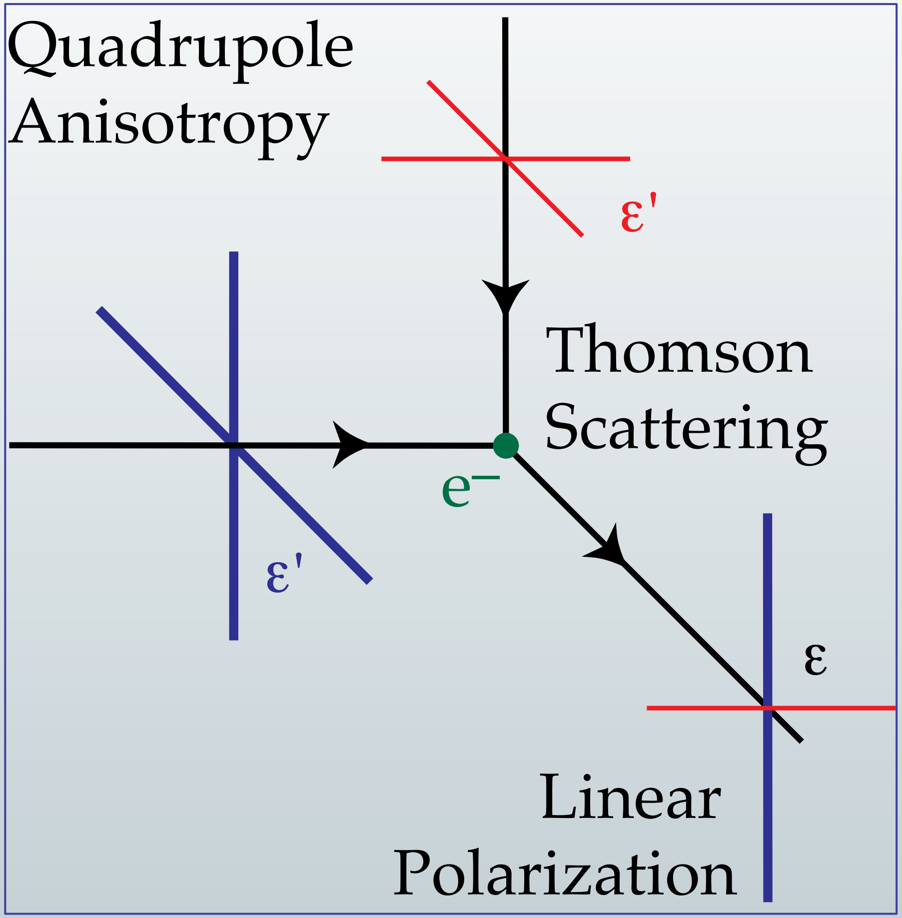


Non-standard shapes of NG: feature models



Cauton here!!!
Feature models reveal interesting signatures, and they seem to be able to match the oscillation features at l<900 and the apparent signal in the flattened limit in the reconstructed bispectrum; however the statistical significance is lower than 2 σ when corrected for ``look elsewhere'' effects

CMB polarization



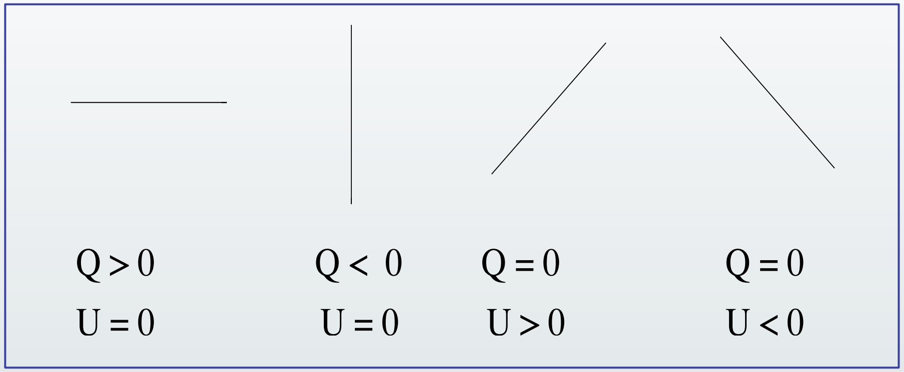
$$\frac{d\sigma}{d\Omega} = \frac{3\sigma_T}{8\pi}\left|\hat{\varepsilon}' \cdot \hat{\varepsilon}\right|$$

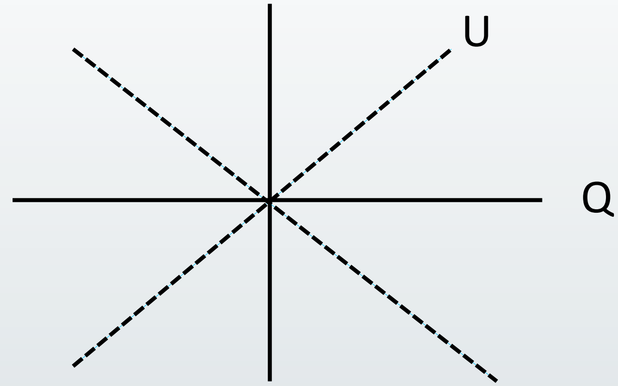
- Thomson scattering generates linear polarized radiation if the intensity of the incident radiation presents a quadrupole moment

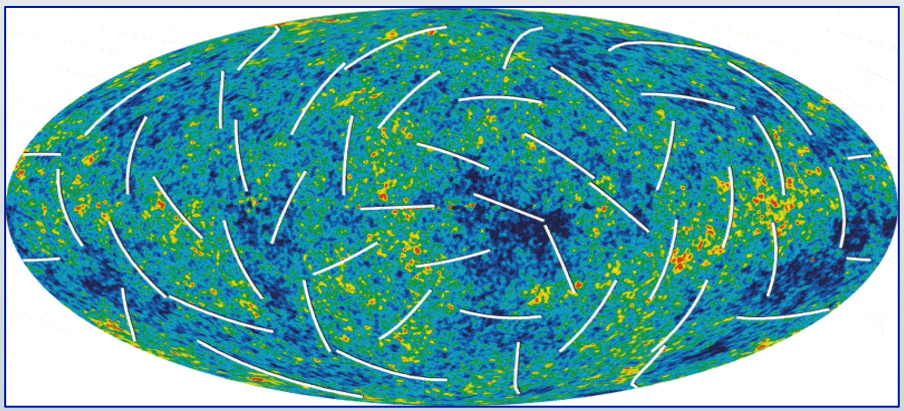
- An incident quadrupole can arise from
  1. Anisotropies in the density of photons surrounding the electron (scalar perturbations)
  2. **A quadrupolar stretching of space due to a passing gravitational wave**

Assume we observed polarization in the CMB. Can we tell whether the source is a scalar or a tensor?

Stokes Q, U parameters







You can think of describing polarization using a "headless vector" P with:

$$|P| = \sqrt{Q^2 + U^2} \longrightarrow$$ Intensity

$$\alpha = \frac{1}{2}\arctan\frac{U}{Q} \longrightarrow$$ Orientation with respect to x-axis

E, B polarization modes

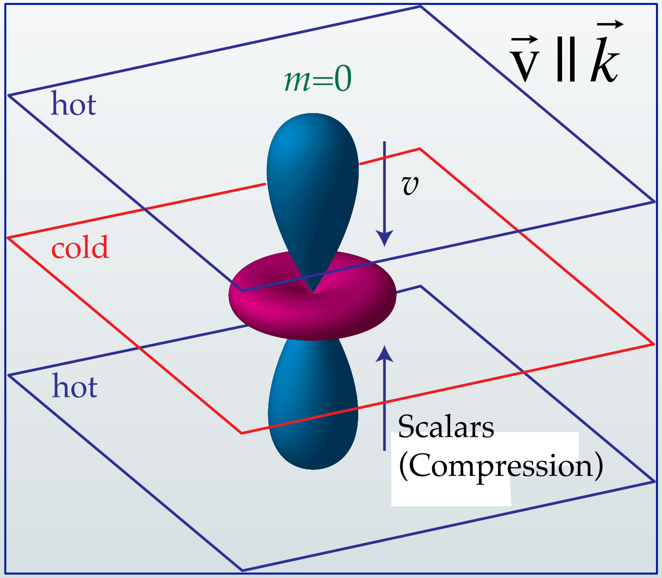
- A vector can always be decomposed into a curl-free (electric) and a divergenceless (magnetic) component.

$$\vec{v} = \vec{\nabla}\phi + \vec{\nabla} \times \vec{A}$$

- P=(Q,U) does not transform as vector but as a trace-free symmetric 2x2 tensor. A decomposition similar to the vector case still exists but it involves *second* (covariant) derivatives of two scalar fields called the E and B mode, in analogy with the vector case

- The usefulness of the E-B decomposition of CMB polarization will be clear shortly. as an anticipation: **scalar (Density) perturbations can generate only an E-mode, while tensor (GW) perturbations source both E and B modes.**

CMB polarization from scalar perturbations



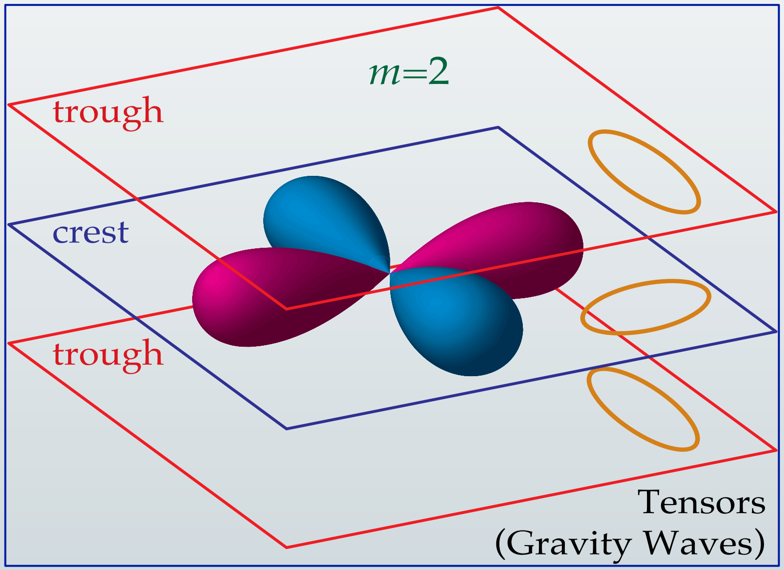
Hu and White 1997

- Consider a plane wave density perturbation
- Before recombination, photons flow from underdense (CMB hot spots) to overdense (CMB cold spots) regions
- An electron sitting in the middle of e.g. an overdense region sees a larger incident radiation intensity in the direction of the flow, and lower intensity from the plane orthogonal to the flow

A net vertical polarization is generated for the photon scattered out of the screen. ***Rotating k in the plane of the screen does not change the polarization state***

$\vec{v} \parallel \vec{k} \Longrightarrow$ **curl-free polarization (pure E-mode)**

CMB polarization from tensor perturbations

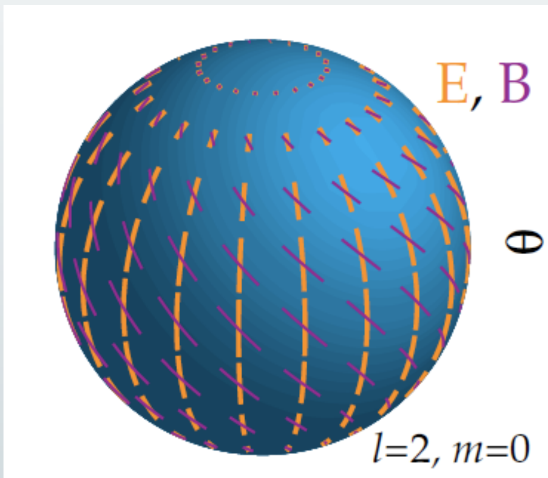


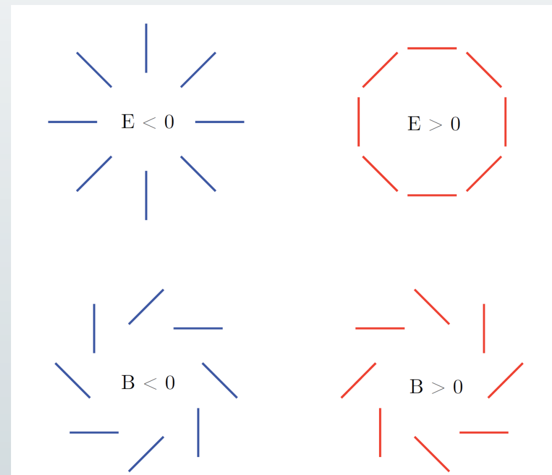
Hu and White 1997

- GW stretch a circular ring of test particles into an ellipse like in figure
- The lobes are no longer aligned with the velocity flows
- That allows to generate a curl polarization pattern.
- **GW generate both E and B modes!**

CMB polarization

Curl-free E-modes polarization:
generated by density perturbations and by gravitational waves

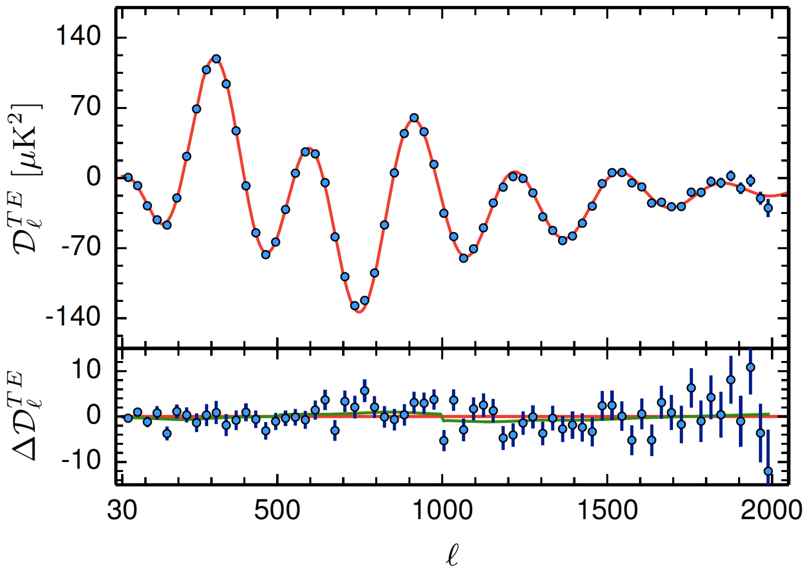


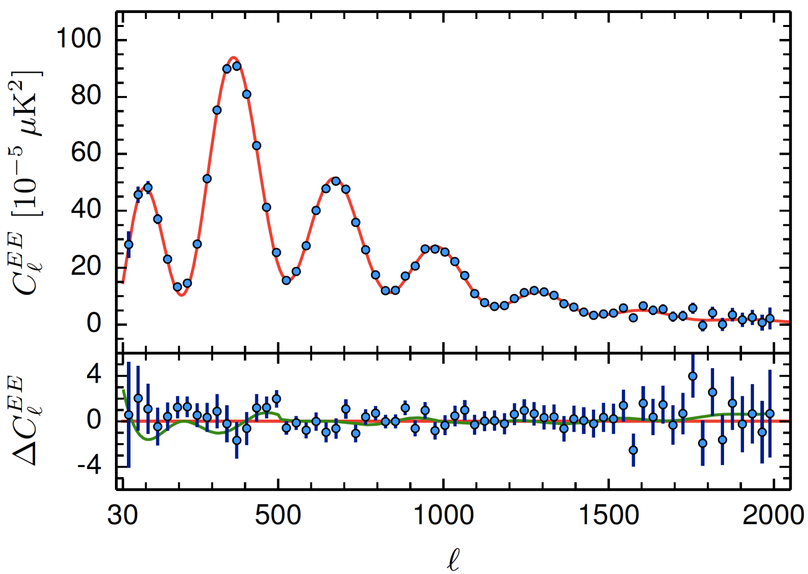


Curl B-modes polarization:
Can be produced only by gravitational waves

Primordial B-modes is a smoking gun for inflation

CMB POLARIZATION (E-mode) MEASURED BY *PLANCK*





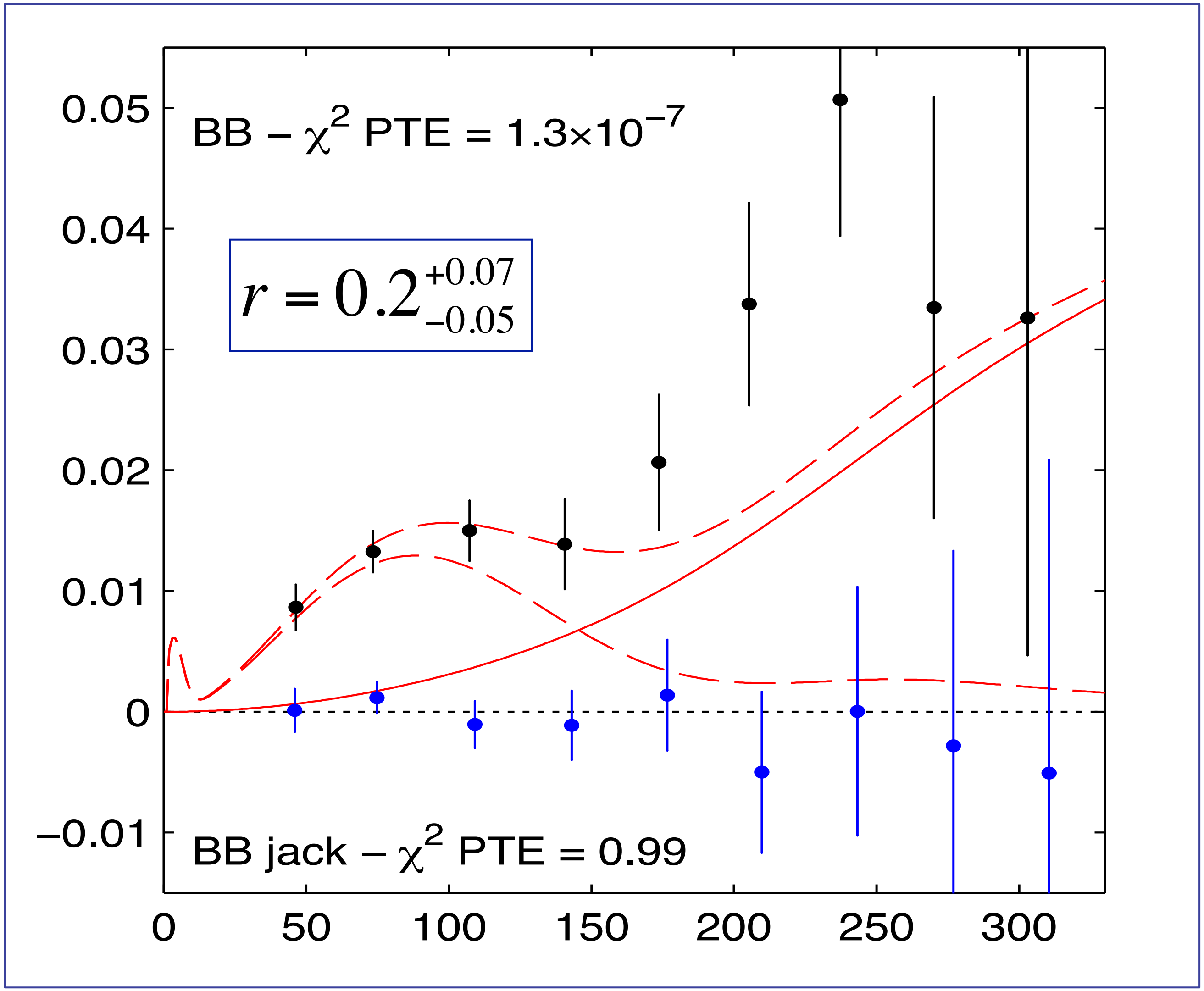
CMB POLARIZATION (E-mode) MEASURED BY *PLANCK*

- Low level of systsematics in polarization (of the order of a few (μk^2))
  (probably due to leakage temp -> polarization from beam mismatches)

- Therefore polarization results must be considered as a first snapshot
  of the 2015 release of polarization

- However: high level of consistency between TT and the full
  TT TE EE likelihoods
  (which show that systematic effects are small)

BICEP2 results of March 2014: BB power spectrum



r=0 excluded at the 5.9 σ level

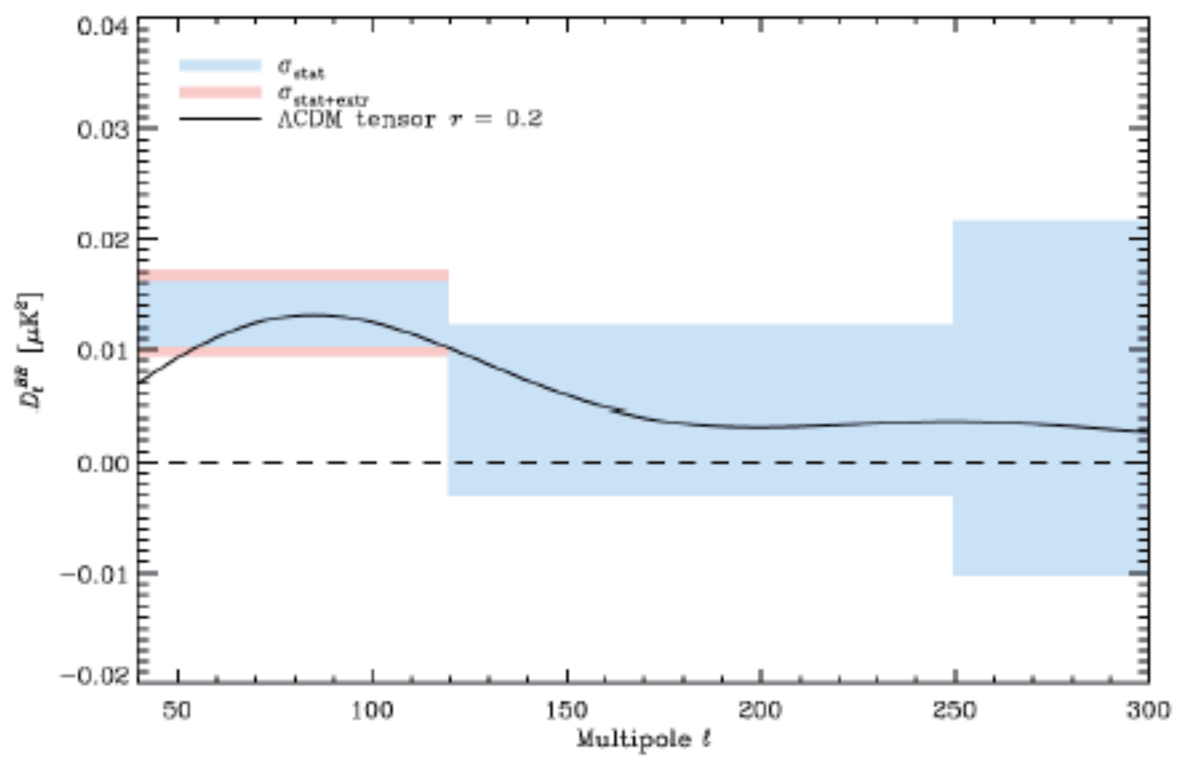
BICEP2/Keck & *Planck* joint analysis

(Phys.Rev.Lett. 114 (2015) 10)

These results show:

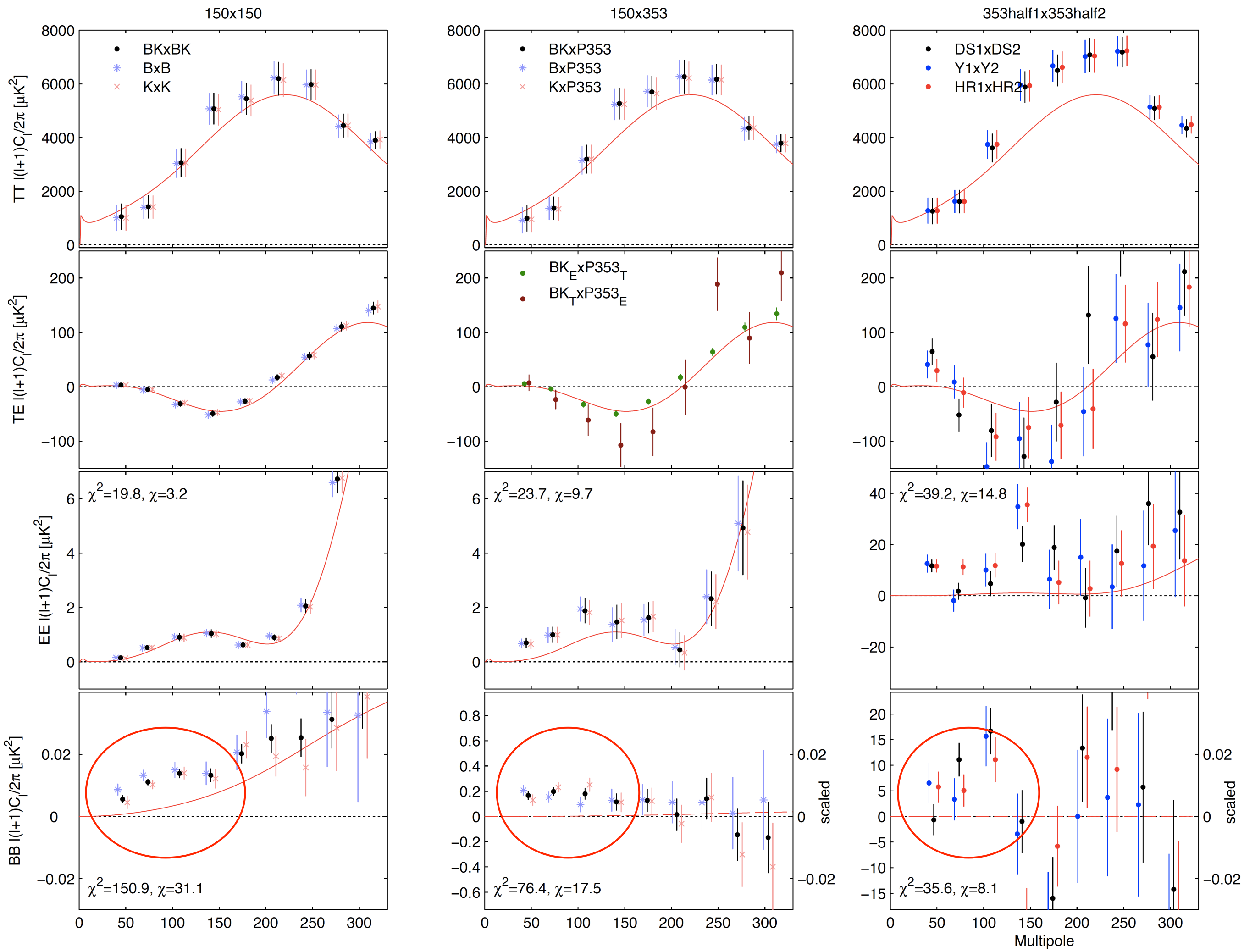
- *Planck measurements of the polarization from dust have been crucial to properly interpret the signal measured by BICEP2*
- *the understanding and handling/removal of foregrounds is crucial for the search of a primordial signal in the B-modes*

Planck analysis of polarized dust



Planck 353 GHz D^{BB} angular power spectrum extrapolated to 150 GHz (box centres). The shaded boxes represent the 1 sigma uncertainties: blue for the statistical uncertainties from noise; and red adding in quadrature the uncertainty from extrapolation to 150 GHz. The *Planck* 2013 best-fit CDM D_{BB} CMB model based on temperature anisotropies, with a tensor amplitude fixed at r = 0.2, is overplotted as a black line.

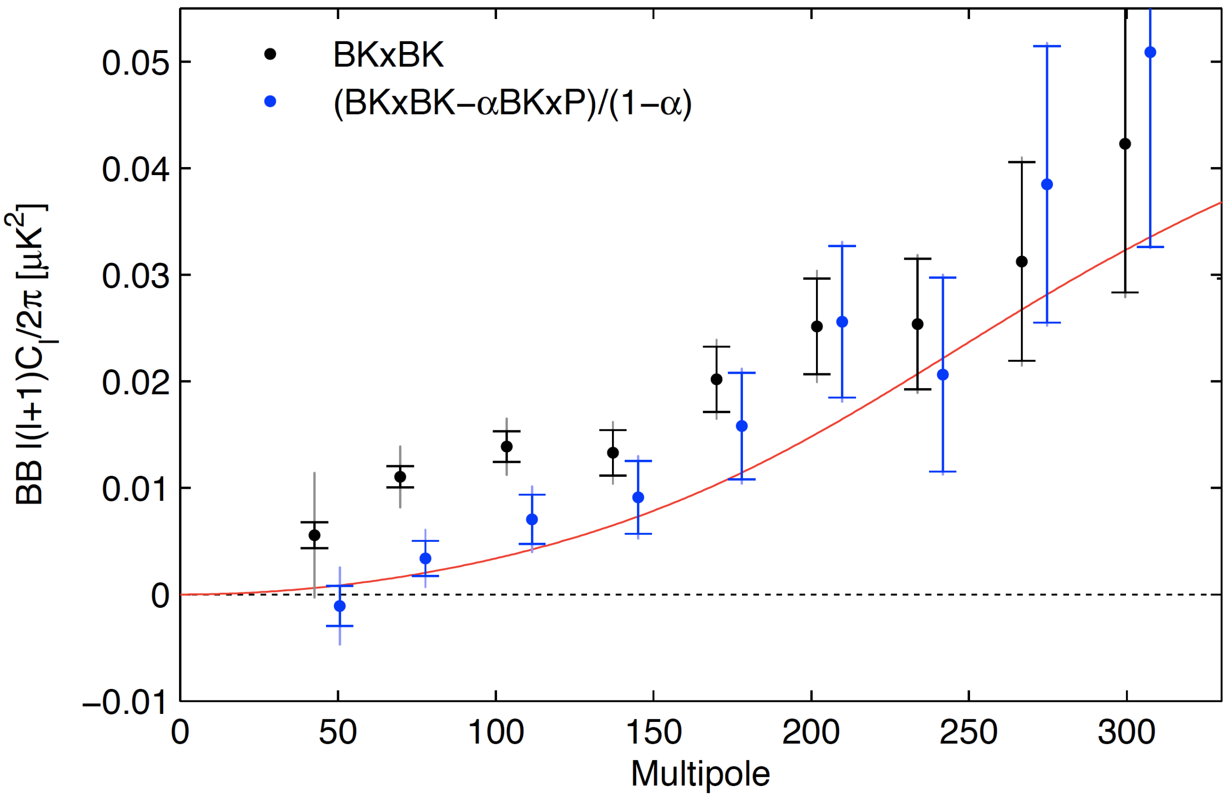
BICEP2/Keck & *Planck joint analysis*



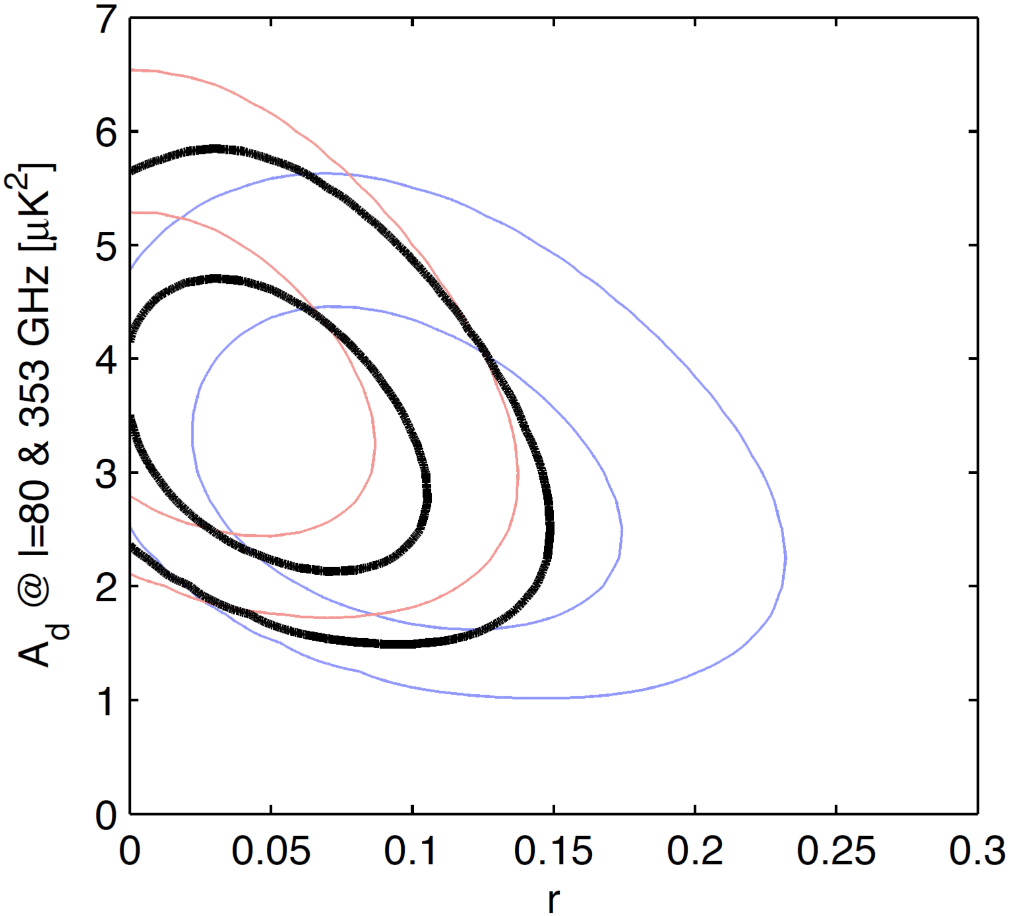
B-modes detected with high significance in the BK150 GHz × P353 GHz.

A substantial amount of BK150 × BK150 appears to be due to dust

BICEP2/Keck & *Planck* joint analysis



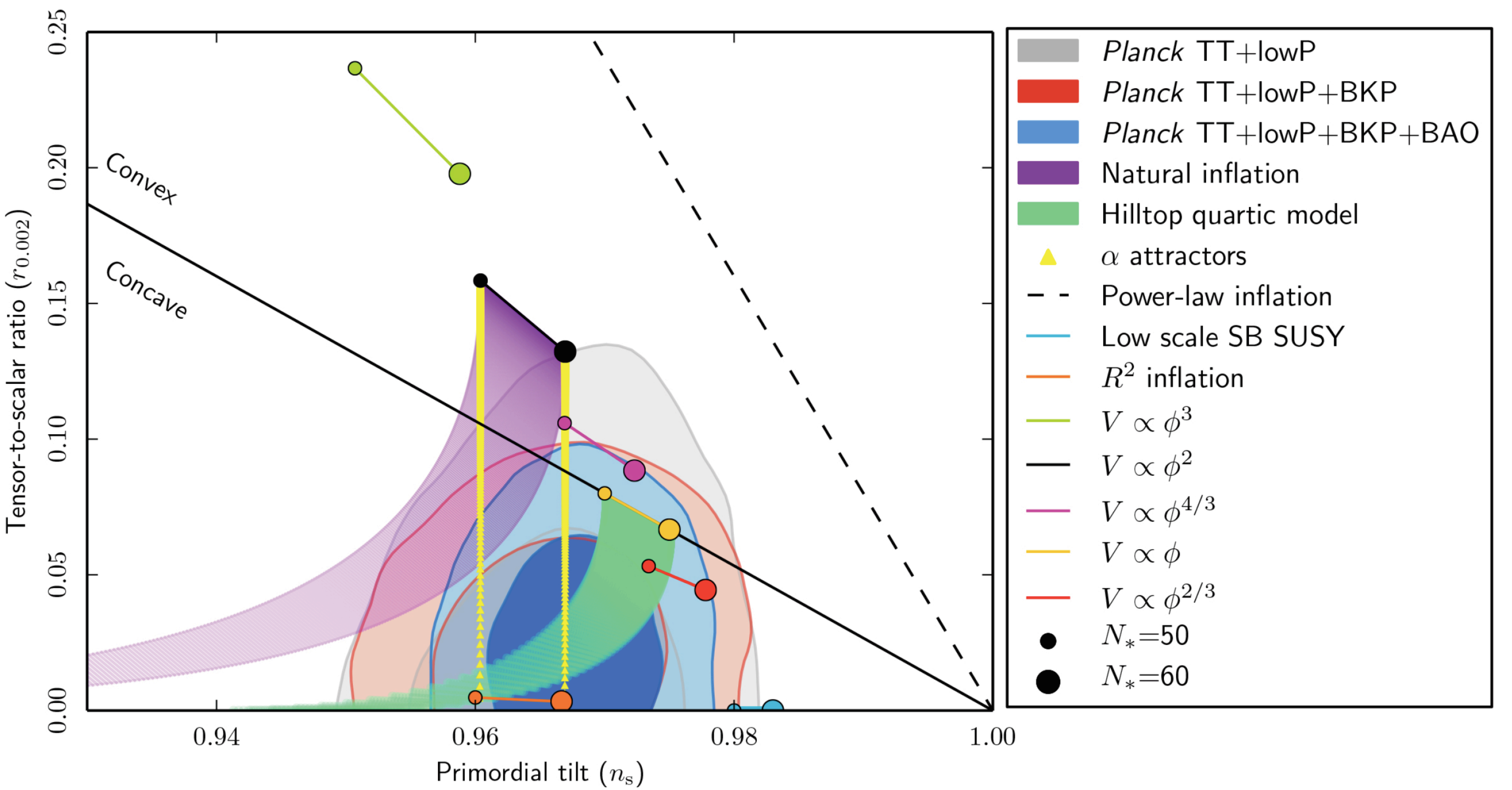
BICEP2/Keck & *Planck joint analysis*



r<0.12 @95% CL

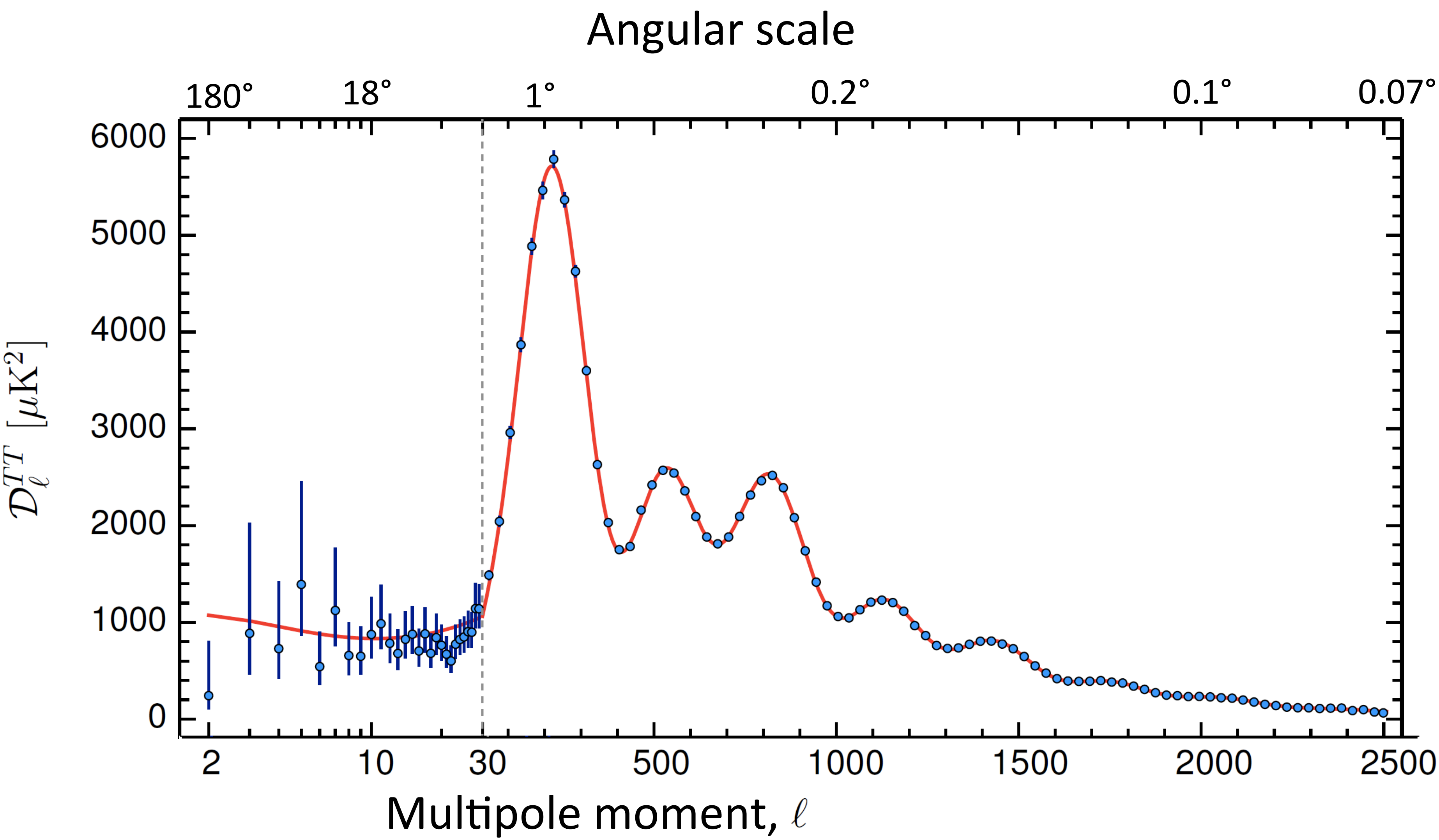
Adding BICEP2/Keck – *Planck correlation*

$$r_{0.002} < 0.08 \quad (95\,\%\ \mathrm{CL},\ \textit{Planck}\ \mathrm{TT{+}lowP{+}BKP})$$

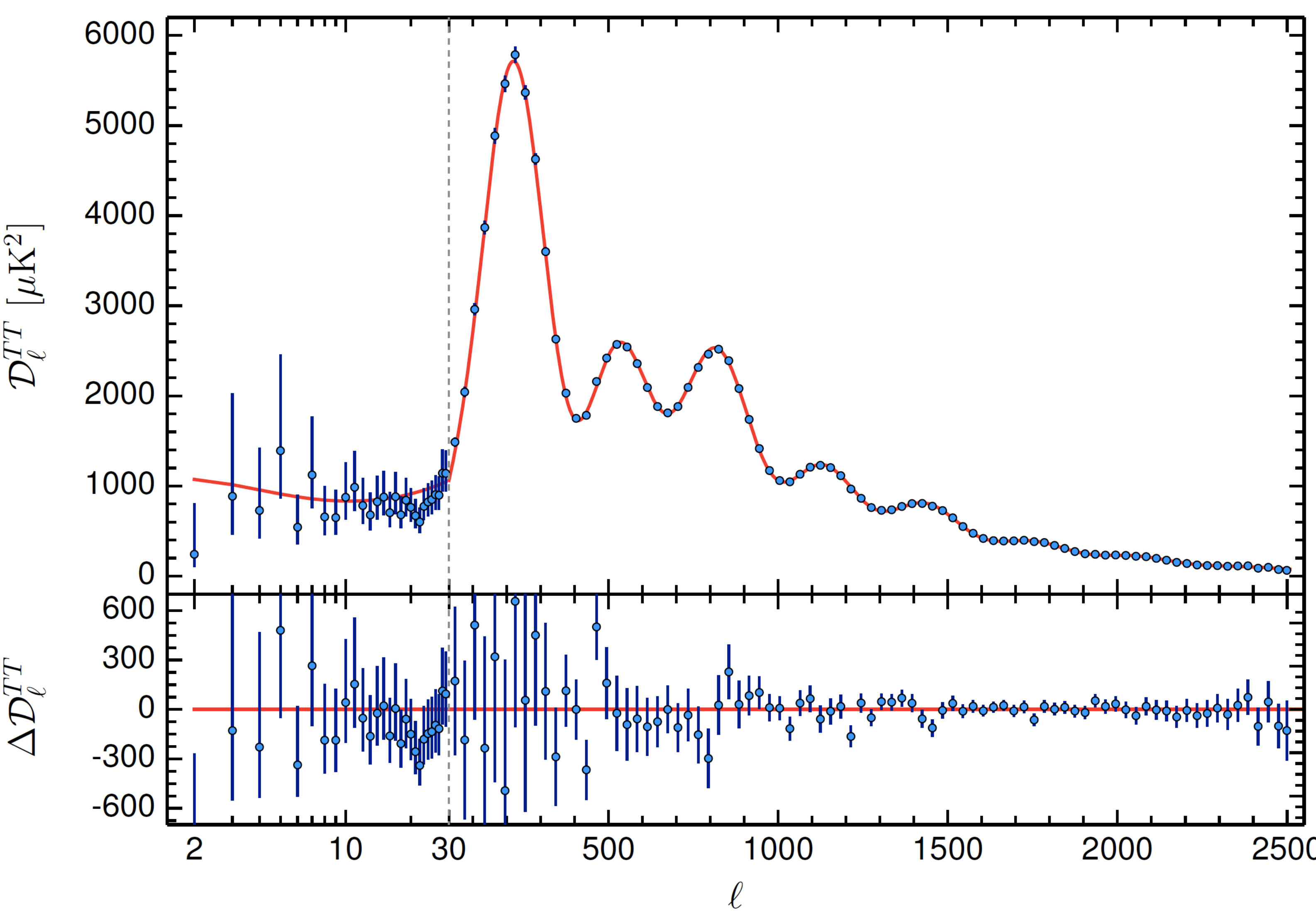


This constraint is stronger that using T only, because the BKP likelihood directly constrain The B-modes and so it is insensitive to change of the scalar power spectrum

A perfect Universe?



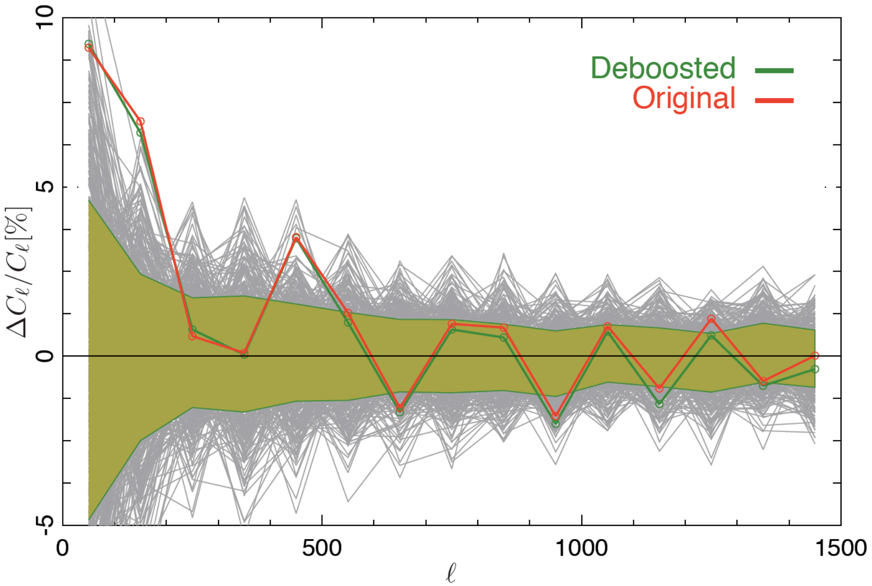
Zooming on the largest scales *l*<50...



CMB ``Anomalies’’

Hemispherical power asymmetry

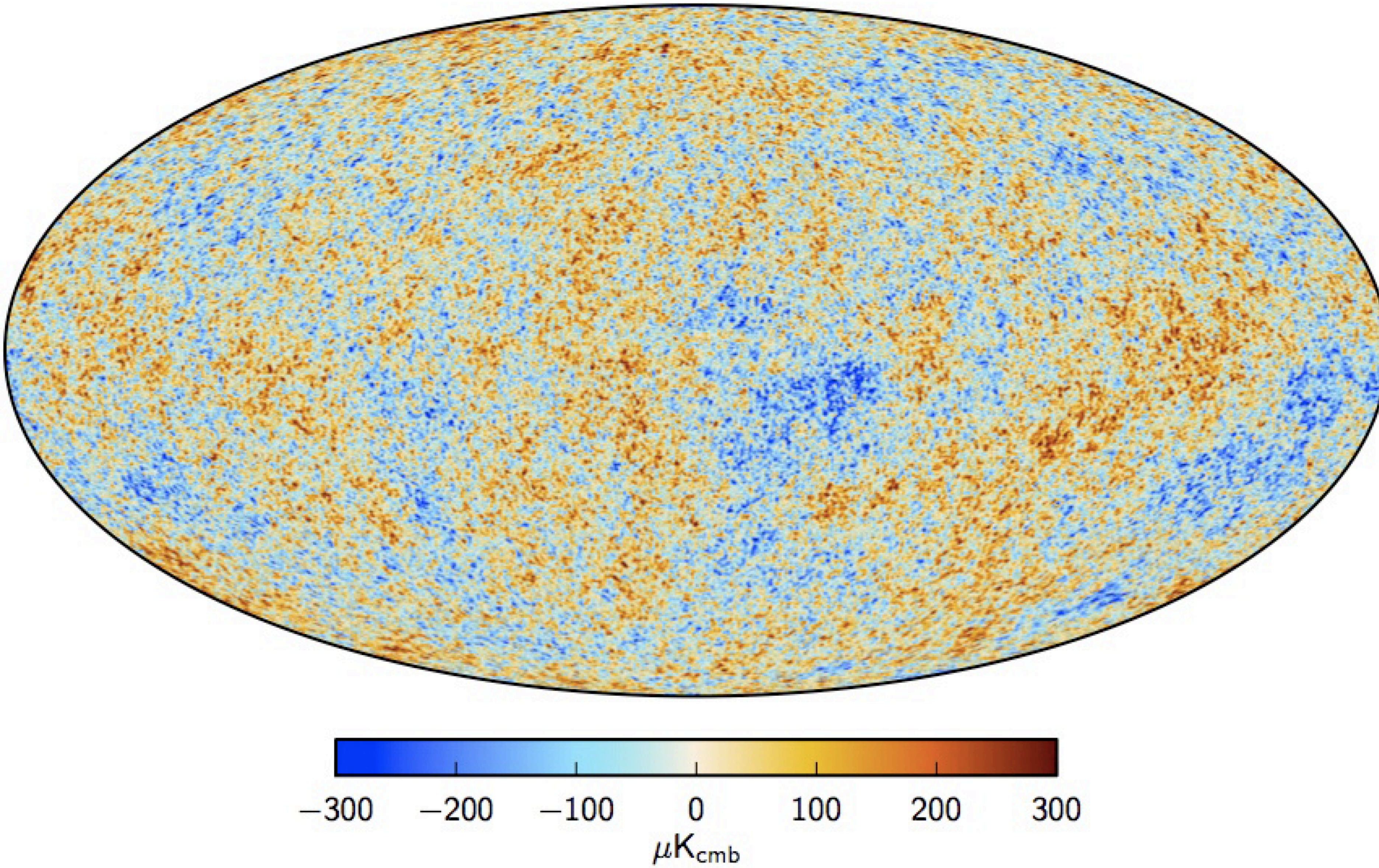
The ``northen’’ hemisphere w.r.t a privileged direction shows a deficit of power. Already seen by WAMP



$$\frac{\Delta T}{T}(\hat{n}) = (1 + A \bullet \hat{n})\,\frac{\Delta T}{T}^{iso}(\hat{n})$$

$$A = 0.067 \pm 0.023$$

The CMB @ Planck resolution



The future of CMB: B-modes

- A huge experimental and theoretical effort is ongoing to detect the CMB B-mode polarization

- Crucial reason: a detection of B-modes would be a smoking-gun test of inflation

The future of CMB: B-modes

- Around 2014-2015, a new era in Cosmology has started, the so called B-mode era. The constraints on inflationary GWs set by the B-modes of CMB polarization started to be competitive with the ones from temperature alone since the BICEP 2/Keck Array/ Planck joint CMB analysis (and the discovery in 2014 of the lensing induced B-mode by the Polarbear telescope).

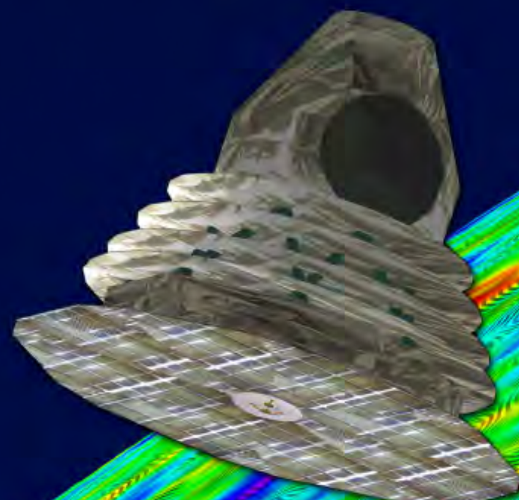
- A variety of ground-based, balloon-borne and satellite experiments are ongoing or have been proposed for the (near-term/far) future.

  e.g.: ACTPol, Polarbear, CLASS, Piper,Spider, EBEX,......;

  satellites: CORE, PRISM, LIteBIRd,PIXIE.

CORE

Cosmic ORigins Explorer



A satellite mission for probing cosmic origins, neutrinos masses and the origin of stars and magnetic fields

through a high sensitivy survey of the microwave polarisation of the entire sky

A proposal in response to the European Space Agency Cosmic Vision 2015-2025 Call

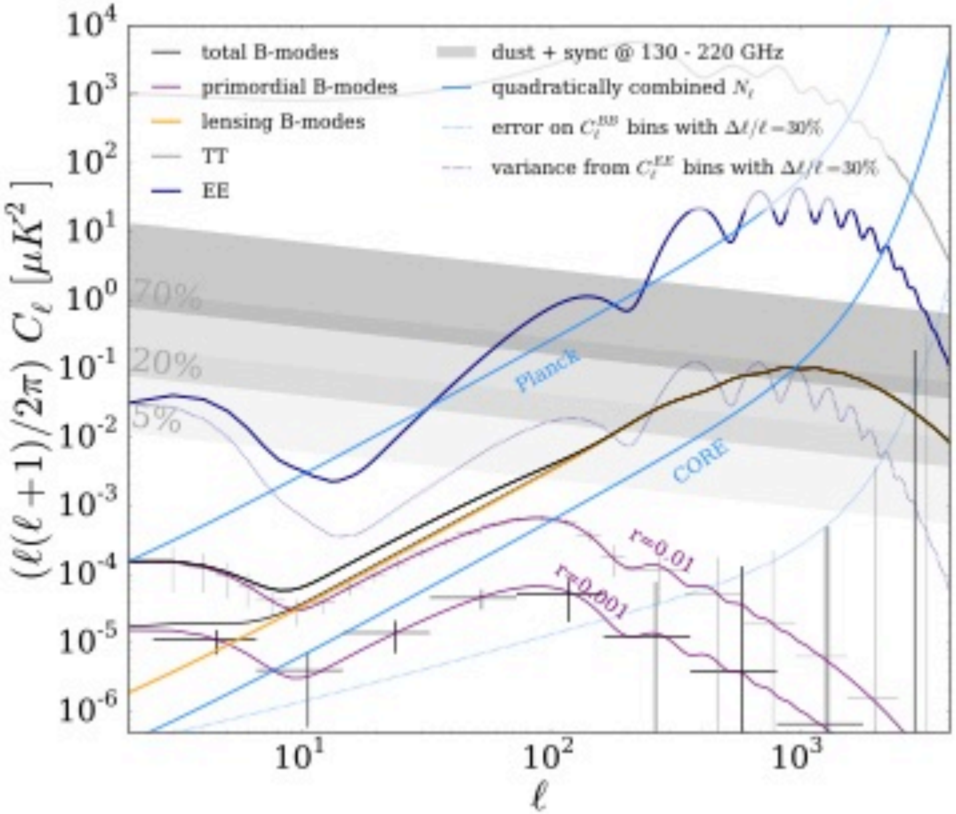
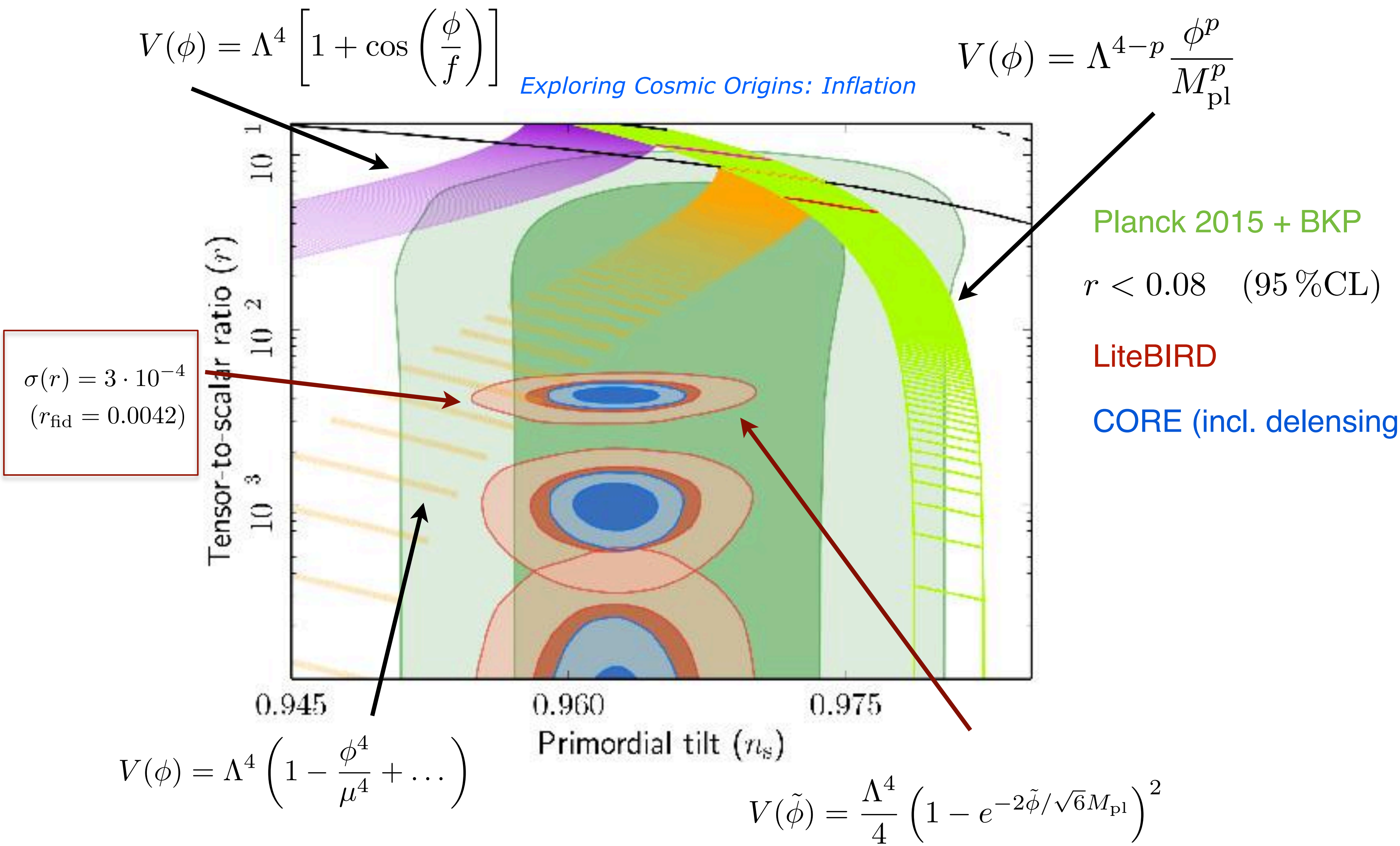


Figure 1. CMB polarisation angular power spectra C_ℓ^{EE} (dark blue), C_ℓ^{BB} from gravitational lensing of E modes by large-scale structure (orange), C_ℓ^{BB} from inflationary gravitational waves r (purple, for two values of the tensor-to-scalar ratio), and total C_ℓ^{BB} for $r = 0.01$ (black). Two fundamental sources of error for measurements of these power spectra with *CORE* are shown for comparison: expected noise level (light blue); and average foreground emission over 70%, 20%, and 5% of the sky (grey bands, from dark to light). Each of the grey bands shows the span of foreground contamination from 130 GHz (lower limit of the band) to 220 GHz (upper limit). Uncertainties in power spectrum estimation over bands of $\Delta\ell/\ell = 0.3$ coming from E modes and noise sample variance (representative of the level at which errors must be understood to take full advantage of the survey raw sensitivity) are shown as dotted lines. The error bars on the primordial B-mode spectra for $r = 0.01$ and $r = 0.001$, corresponding to 1σ in bins ranging from $\Delta\ell/\ell \simeq 0.2$ (for $r = 0.01$, at low ℓ) to 0.75 (for $r = 0.001$), illustrate the sensitivity that will be achieved for inflationary science assuming perfect component separation over 70% of sky and reduction of the contamination by lensing using small-scale CMB E and B modes measured by *CORE*.

Inflationary Models with CORE



CORE could achieve a sensitivity on r two orders of magnitude below the current one

See http://www.cosmosnet.it

CMB-Stage4

- Next generation CMB ground-based program to pursue inflation, neutrino properties, dark energy and new discoveries.
- ~500,000 detectors in the 30 - 300 GHz using multiple telescopes and sites to map most of the sky
- including the existing CMB experiments (e.g., ACT, BICEP/Keck, CLASS, POLARBEAR/Simons Array & SPT)

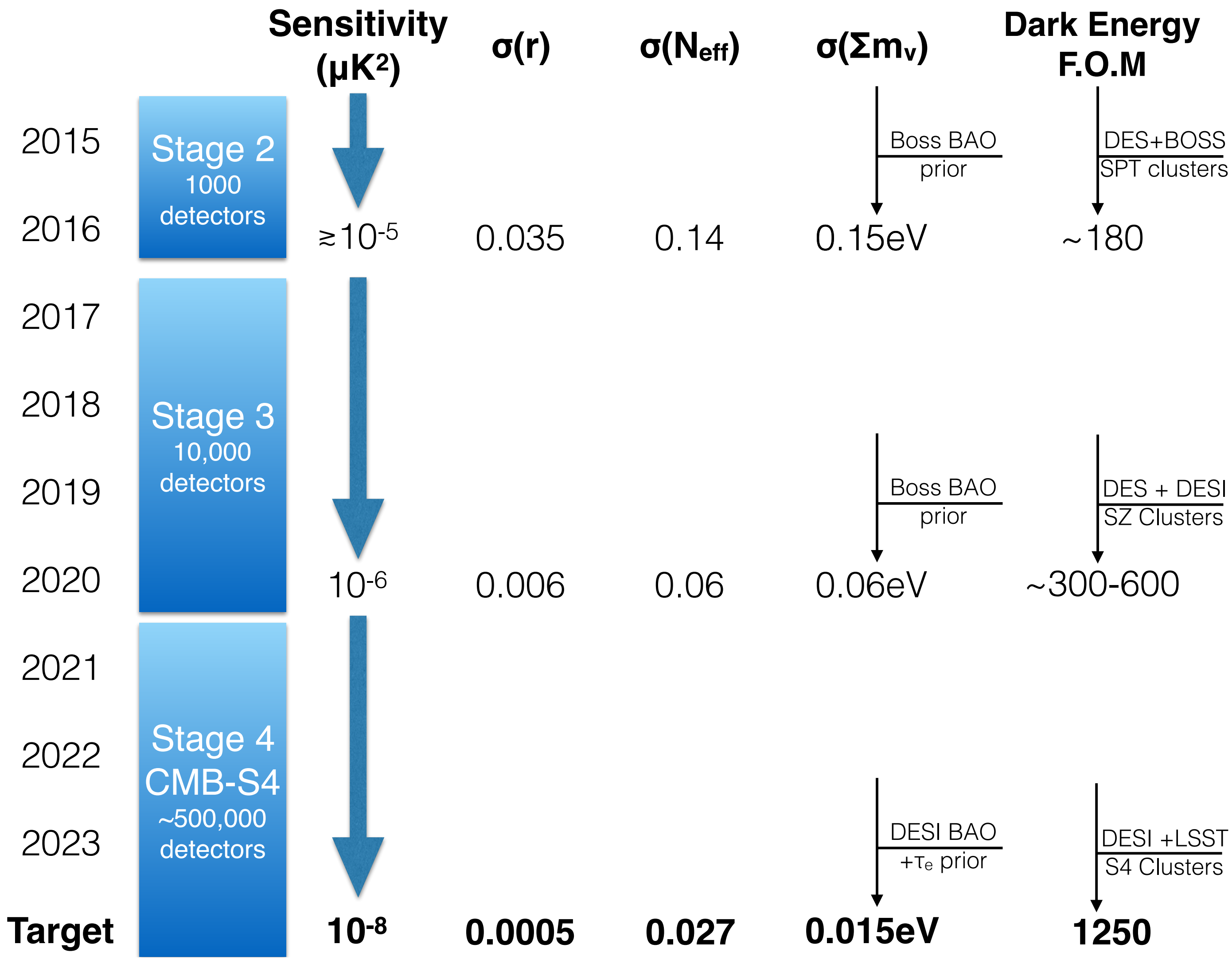


Figure 3. *Schematic timeline showing the expected increase in sensitivity (μK^2) and the corresponding improvement for a few of the key cosmological parameters for Stage-3, along with the threshold-crossing aspirational goals targeted for CMB-S4.*

From arXiv:1610.02743

CMB-Stage4

South Pole Telescope (SPT)

BICEP-3

Keck-Array

CLASS

ACT

South Pole

Artacama (Chile)

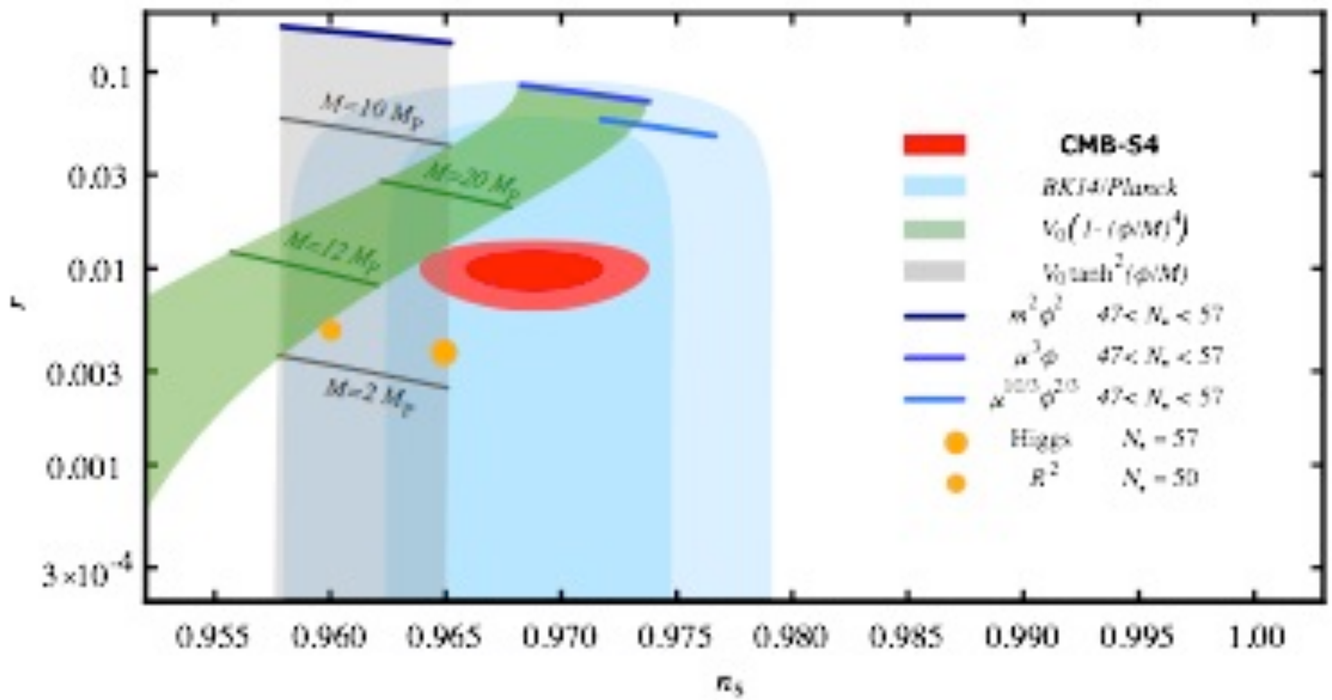


Figure 10. *Forecast of CMB-S4 constraints in the n_s–r plane for a fiducial model with $r = 0.01$. Constraints on r are derived from the expected CMB-S4 sensitivity to the B-mode power spectrum as described in Section 2.3. Constraints on n_s are derived from expected CMB-S4 sensitivity to temperature and E-mode power spectra as described in Section 8.10.2. Also shown are the current best constraints from a combination of the BICEP2/*Keck Array *experiments and Planck [8]. Chaotic inflation with $V(\phi) = \mu^{4-p}\phi^p$ for $p = 2/3, 1, 2$ are shown as blue lines for $47 < N_* < 57$ (with smaller N_* predicting lower values of n_s). The Starobinsky model and Higgs inflation are shown as small and large filled orange circles, respectively. The lines show the classes of models discussed in Section 2.5. The green band shows the predictions for quartic hilltop models, and the gray band shows the prediction of a sub-class of α-attractor models [60].*

From arXiv:1610.02743

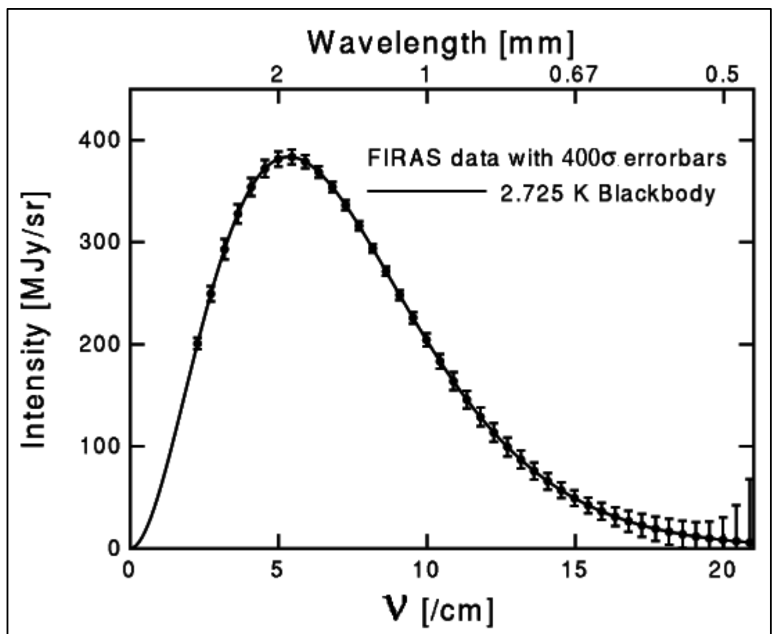
A (re)new(ed) window to cosmology: CMB spectral distortions

- We know there must be tiny deviations from a perfect black body of the CMB spectrum in the frequency domain

- Not detected yet (apart y-distortions from Sunyaev-Zel'dovich effect)

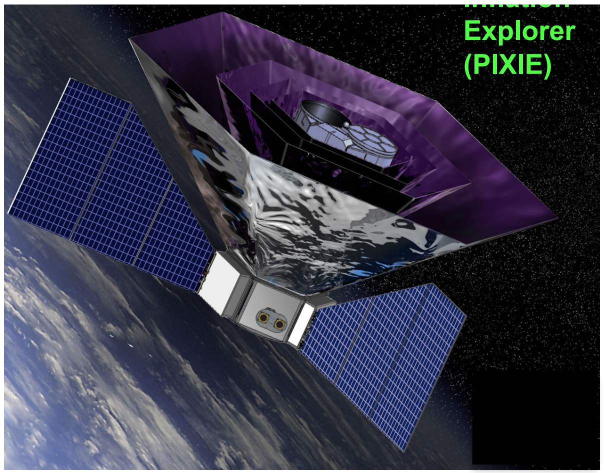
- $\frac{\Delta I_\nu}{I_\nu} < 10^{-4} \qquad \mu < 9 \times 10^{-5} \qquad y < 1.5 \times 10^{-5} \quad (95\%$ C.L)

FROM COBE/FIRAS

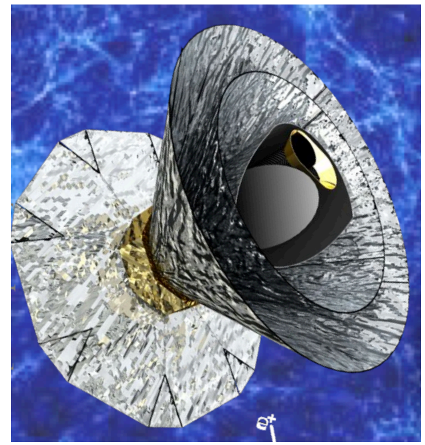


CMB spectral distortions

- Various planned and proposed satellite missions can achieve the required sensitivity to measure the primordial μ and y spectral distortions: these are predicted to be $\langle\mu\rangle \approx 1.9\times10^{-9}$ and $\langle y\rangle \approx 4.2\times10^{-8}$



Sensitive to a minimum $\langle\mu\rangle_{min} \approx 10^{-9}$



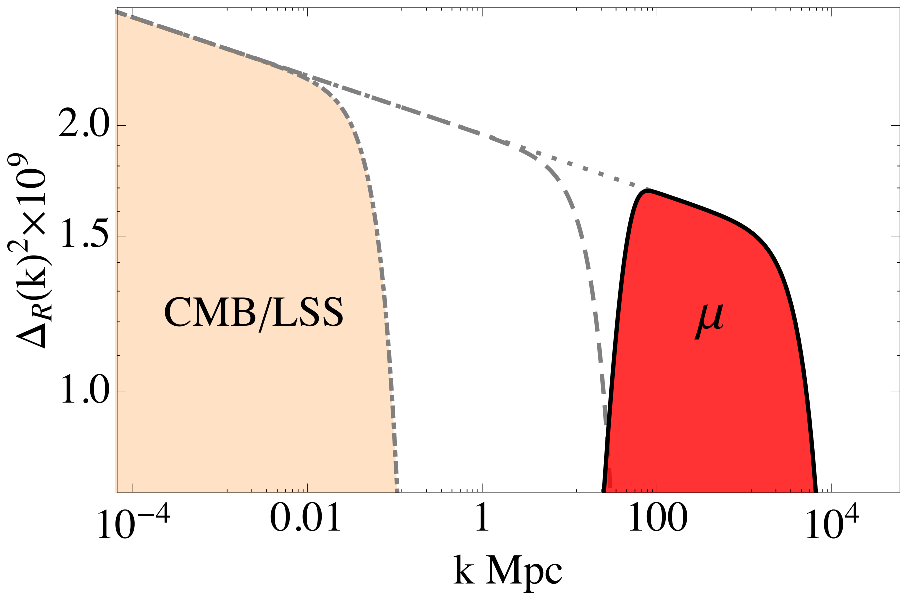
PRISM

Sensitive to a minimum $\langle\mu\rangle_{min} \approx 10^{-8}$

- Besides being a probe of the standard ΛCDM model (including inflation) it can unveil new physics, e.g. about
  - decaying and annihilating dark matter particles
  - black holes and cosmic strings

  and it can allow to measure a whole series of signals like y-distortions from re-ionized gas

A powerful source of information

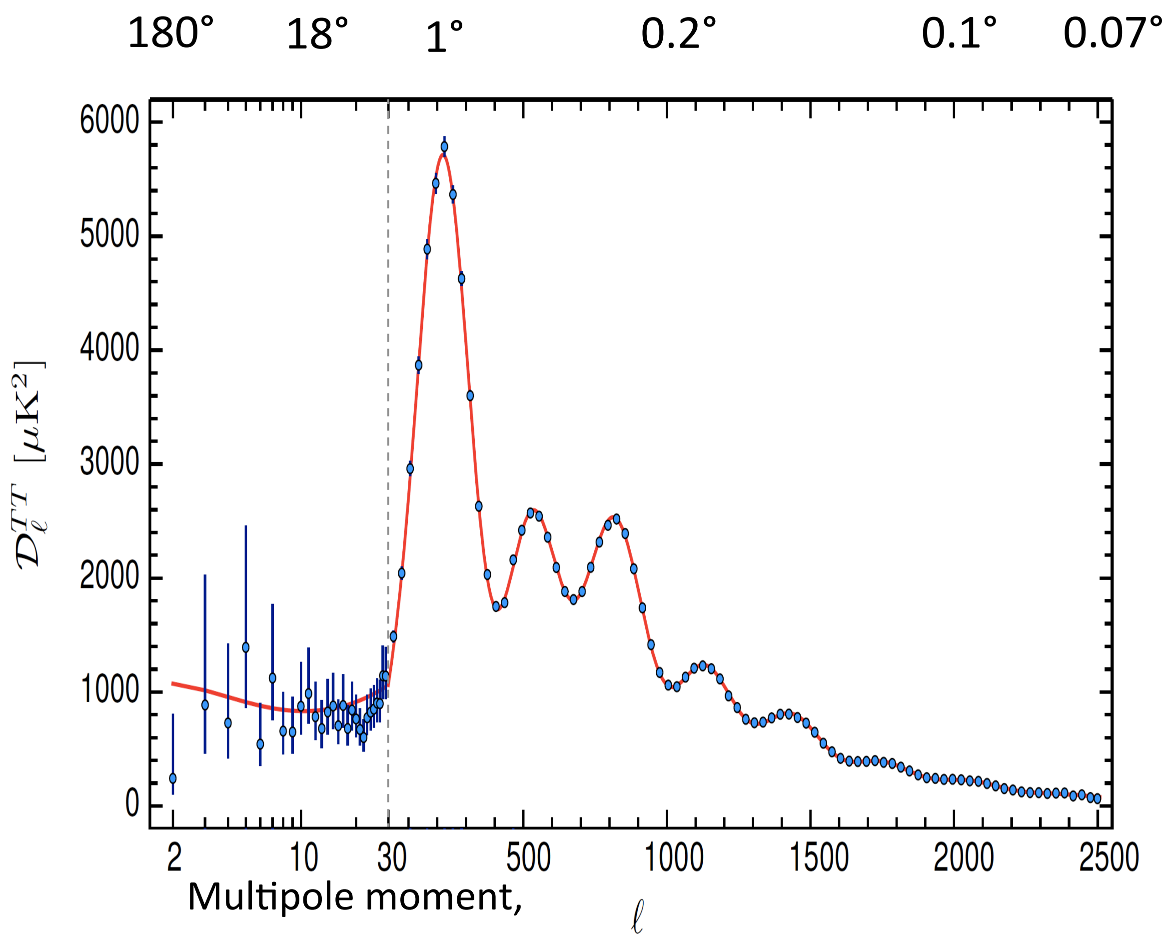


(From Pajer & Zaldarriaga 2012)

- CMB spectral distortions expected in the standard ΛCDM modeL: **a very promising, yet nearly completely unexploited observational window!**

  (see, e.g., Kathri and Sunyaev 2013, arXiv: 1303.7212; Chluba 2016, arXiv: 1603.02496)

- **In particular can probe very small scales 10^{-4} - 0.02 Mpc!**



180°
18°
1°
0.2°
0.1°
0.07°
6000
5000
4000
3000
2000
1000
0
$\mathcal{D}_\ell^{TT}\ [\mu\mathrm{K}^2]$
2
10
30
500
1000
1500
2000
2500
Multipole moment, ℓ

CMB μ distortions

- Example:

Energy injection from ***dissipation of acoustic waves due to Silk dampin***

The relevant redshit range is $5\times10^4 = z_f < z < z_i = 2\times10^6$

and the relevant scales are $k_D(z_i)$ = 12000 Mpc^{-1} and $k_D(z_f)$ = 46 Mpc^{-1}

$$\mu \approx \frac{1.4}{4}\left[\langle\delta_\gamma^2(x)\rangle_p\right]_{z_f}^{z_i} \qquad \Delta_\gamma(k) \simeq 3\cos(kr)\exp[-k^2/k_D^2(z)]$$

- The monopole

$$\langle\mu\rangle \simeq \int d\ln k\,\Delta_\zeta^2(k)\Big[e^{-2k^2/k_D^2}\Big]_f^i$$

It is predicted to be 1.9×10^{-8} for the best fit ΛCDM

An example: spectral distortions and primordial non-Gaussianity

- Pajer & Zaldarriaga 2012 and in Ganc and Komatsu 2012 pointed out that the cross-correlation between CMB μ-distortion and CMB temperature fluctuations can be a diagnostic very sensitive to local-typ bispectra from inflation

- Can reach sensitivity to f_{NL}~0.01-0.001!!! (for an ideal experiment.....)

An example: spectral distortions and primordial non-Gaussianity

- A simple explanation:
  Local primordial non-Gaussianity correlate short- with long-mode perturbations, so it induces a correlation between the dissipation pro
  on small scales

$$\mu \sim \delta_\gamma^2 \sim \zeta_{\mathbf{k_1}} \zeta_{\mathbf{k_2}}$$

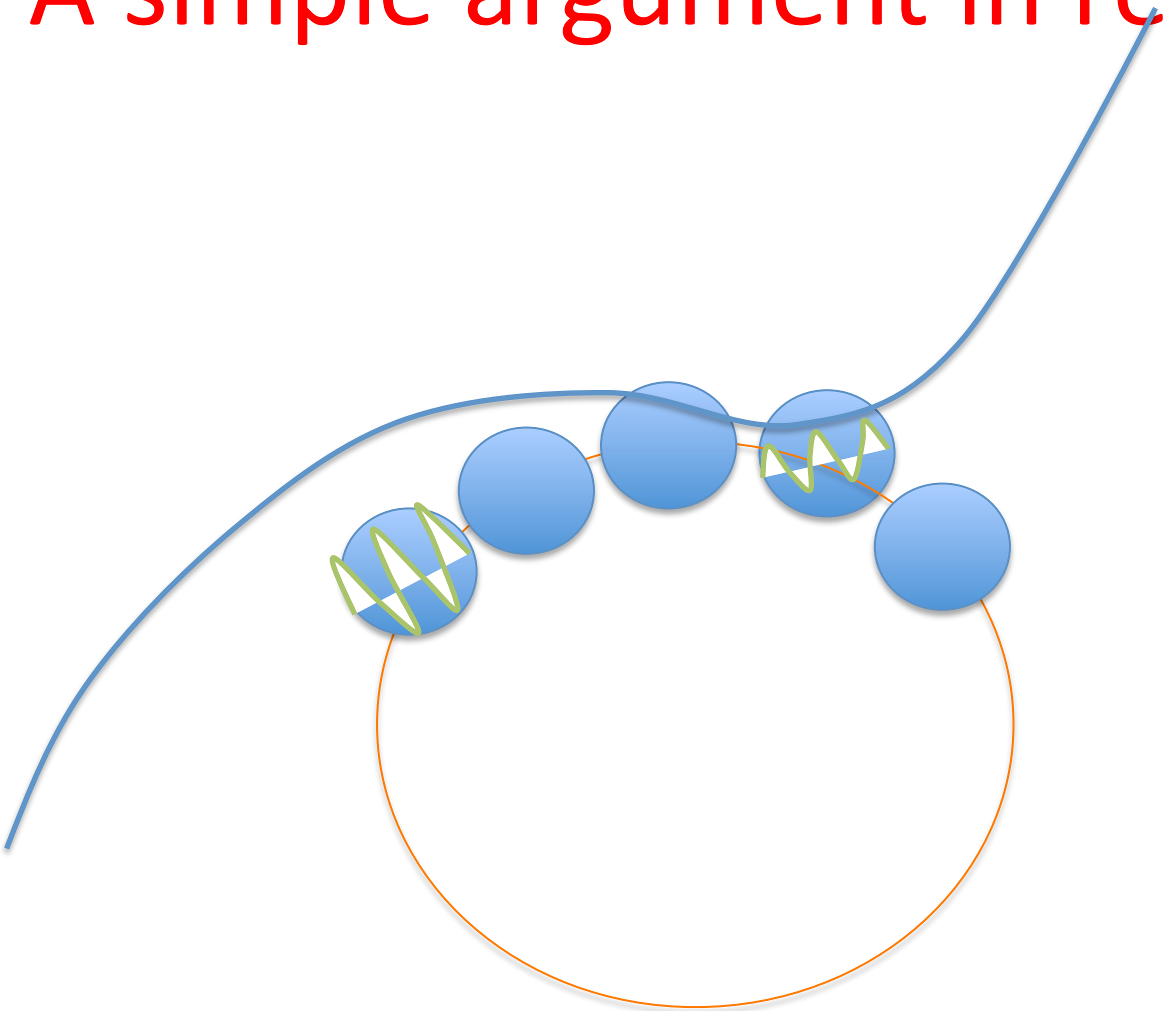
and the long-mode fluctuations in the CMB

$$\delta T/T \sim \zeta_{\mathbf{k}}$$

$$\downarrow$$

$$C_\ell^{\mu T} \sim \langle \zeta_{\mathbf{k_1}} \zeta_{\mathbf{k_2}} \zeta_{\mathbf{k_3}} \rangle$$

A simple argument in real space



If there is a local model of non-Gaussianity, then the small scale power spectrum of curvature perturbation $\Delta^2_\varsigma(k,x)$ will be modulated from patch to patch, by the long-wavelength curvature fluctuation and correlated to it

Conclusions

- The Universe observed by Planck is well-fit by a 6 parameter ΛCDM model. Very good agreement with 2013 analysis, but with increased precision. Some tensions with other dataset disappeared , others remain. Planck data

- provide strong constraints on deviations from this base ΛCDM model from an analysis of an extensive grid of models
- firmly establish a deviation from scale invariance for primordial matter perturbations, a key indicator of cosmic inflation
- detect with high significance lensing of the CMB by intervening matter, providing evidence for dark energy from the CMB alone
- find no evidence for significant deviations from Gaussianity in the statistics of CMB anisotropies, providing one of the tightest tests on standard single-field models of inflation
- find a low value of the Hubble constant, in tension with the value derived from the standard distance ladder
- find a deficit of power at low-ls w.r.t. our best-fit model
- confirm the anomalies at large angular scales first detected by WMAP
- establish the number of neutrino species at 3
- A first consistency check with polarization data performed: they will be crucial in support these conclusions