# Cosmology results from Planck

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CERN

# 21st March: 28 Planck cosmology papers

| Title | Authors | Publication |
|---|---|---|
| Planck 2013 results. I. Overview of products and results | Planck Collaboration | 2013 Submitted to A&A |
| Planck 2013 results. II. Low Frequency Instrument data processing | Planck Collaboration | 2013 Submitted to A&A |
| Planck 2013 results. III. LFI systematic uncertainties | Planck Collaboration | 2013 Submitted to A&A |
| Planck 2013 results. IV. LFI beams | Planck Collaboration | 2013 Submitted to A&A |
| Planck 2013 results. V. LFI calibration | Planck Collaboration | 2013 Submitted to A&A |
| Planck 2013 results. VI. High Frequency Instrument data processing | Planck Collaboration | 2013 Submitted to A&A |
| Planck 2013 results. VII. HFI time response and beams | Planck Collaboration | 2013 Submitted to A&A |
| Planck 2013 results. VIII. HFI calibration and mapmaking | Planck Collaboration | 2013 Submitted to A&A |
| Planck 2013 results. IX. HFI spectral response | Planck Collaboration | 2013 Submitted to A&A |
| Planck 2013 results. X. HFI energetic particle effects | Planck Collaboration | 2013 Submitted to A&A |
| Planck 2013 results. XI. Consistency of the data | Planck Collaboration | 2013 In preparation |
| Planck 2013 results. XII. Component separation | Planck Collaboration | 2013 Submitted to A&A |
| Planck 2013 results. XIII. Galactic CO emission | Planck Collaboration | 2013 Submitted to A&A |
| Planck 2013 results. XIV. Zodiacal emission | Planck Collaboration | 2013 Submitted to A&A |
| Planck 2013 results. XV. CMB power spectra and likelihood | Planck Collaboration | 2013 Submitted to A&A |
| Planck 2013 results. XVI. Cosmological parameters | Planck Collaboration | 2013 Submitted to A&A |
| Planck 2013 results. XVII. Gravitational lensing by large-scale structure | Planck Collaboration | 2013 Submitted to A&A |
| Planck 2013 results. XVIII. The gravitational lensing-infrared background correlation | Planck Collaboration | 2013 Submitted to A&A |
| Planck 2013 results. XIX. The integrated Sachs-Wolfe effect | Planck Collaboration | 2013 Submitted to A&A |
| Planck 2013 results. XX. Cosmology from Sunyaev-Zeldovich cluster counts | Planck Collaboration | 2013 Submitted to A&A |
| Planck 2013 results. XXI. All-sky Compton-parameter map and characterization | Planck Collaboration | 2013 Submitted to A&A |
| Planck 2013 results. XXII. Constraints on inflation | Planck Collaboration | 2013 Submitted to A&A |
| Planck 2013 results. XXIII. Isotropy and statistics of the CMB | Planck Collaboration | 2013 Submitted to A&A |
| Planck 2013 results. XXIV. Constraints on primordial non-Gaussianity | Planck Collaboration | 2013 Submitted to A&A |
| Planck 2013 results. XXV. Searches for cosmic strings and other topological defects | Planck Collaboration | 2013 Submitted to A&A |
| Planck 2013 results. XXVI. Background geometry and topology of the Universe | Planck Collaboration | 2013 Submitted to A&A |
| Planck 2013 results. XXVII. Special relativistic effects on the CMB dipole | Planck Collaboration | 2013 Submitted to A&A |
| Planck 2013 results. XXVIII. The Planck Catalogue of Compact Sources | Planck Collaboration | 2013 Submitted to A&A |
| Planck 2013 results. XXIX. The Planck catalogue of Sunyaev-Zeldovich sources | Planck Collaboration | 2013 Submitted to A&A |
| Planck 2013 results. Explanatory supplement | Planck Collaboration | 2013 ESA |

# Planck at a glance

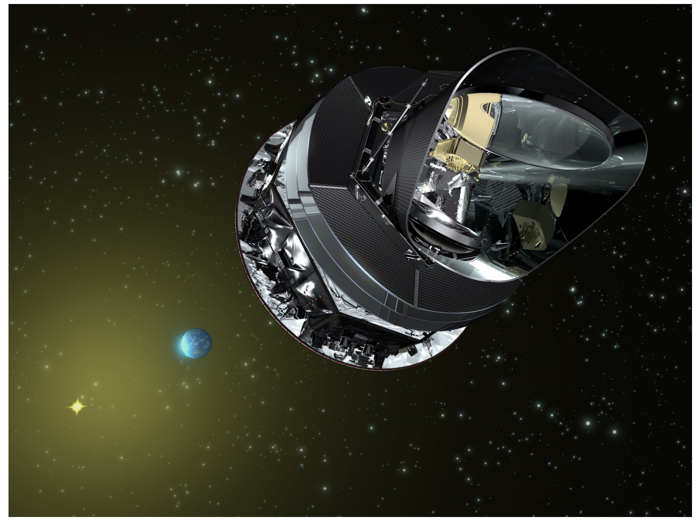
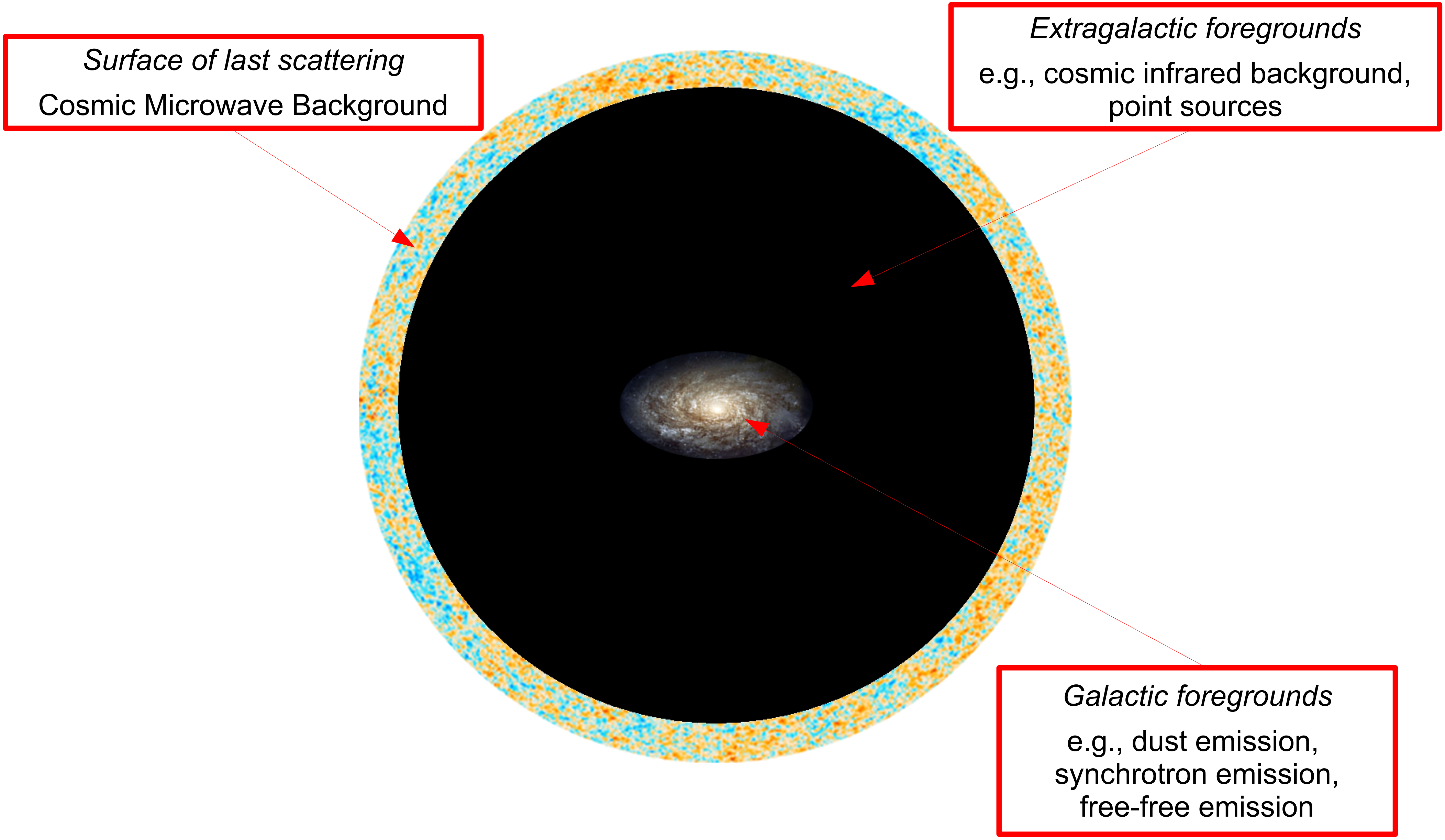


**Table 2.** *Planck* performance parameters determined from flight data.

| | | | | Scanning Beam[c] | | Noise[d] Sensitivity | |
|---|---|---|---|---|---|---|---|
| | Channel | $N_{\mathrm{detectors}}$[a] | $\nu_{\mathrm{center}}$[b] [GHz] | FWHM [arcm] | Ellipticity | [$\mu K_{RJ}$ $s^{1/2}$] | [$\mu K_{CMB}$ $s^{1/2}$] |
| LFI | 30 GHz . . . . . . . . . | 4 | 28.4 | 33.16 | 1.37 | 145.4 | 148.5 |
| | 44 GHz . . . . . . . . . | 6 | 44.1 | 28.09 | 1.25 | 164.8 | 173.2 |
| | 70 GHz . . . . . . . . . | 12 | 70.4 | 13.08 | 1.27 | 133.9 | 151.9 |
| HFI | 100 GHz . . . . . . . . . | 8 | 100 | 9.59 | 1.21 | 31.52 | 41.3 |
| | 143 GHz . . . . . . . . . | 11 | 143 | 7.18 | 1.04 | 10.38 | 17.4 |
| | 217 GHz . . . . . . . . . | 12 | 217 | 4.87 | 1.22 | 7.45 | 23.8 |
| | 353 GHz . . . . . . . . . | 12 | 353 | 4.7 | 1.2 | 5.52 | 78.8 |
| | 545 GHz . . . . . . . . . | 3 | 545 | 4.73 | 1.18 | 2.66 | 0.0259[d] |
| | 857 GHz . . . . . . . . . | 4 | 857 | 4.51 | 1.38 | 1.33 | 0.0259[d] |

# What does Planck see? Microwave sources



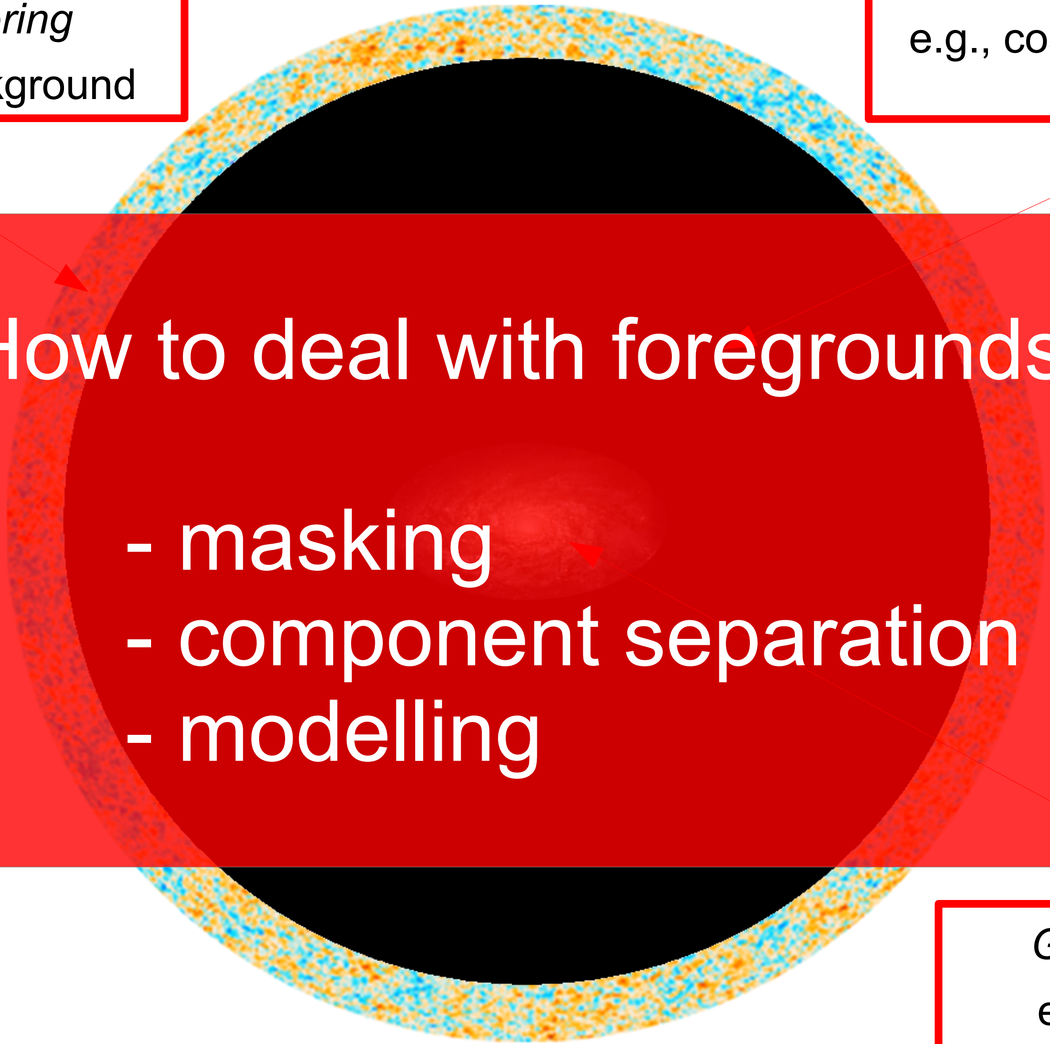
# What does Planck see?
# Microwave sources

*Surface of last scattering*

Cosmic Microwave Background

*Extragalactic foregrounds*

e.g., cosmic infrared background, point sources



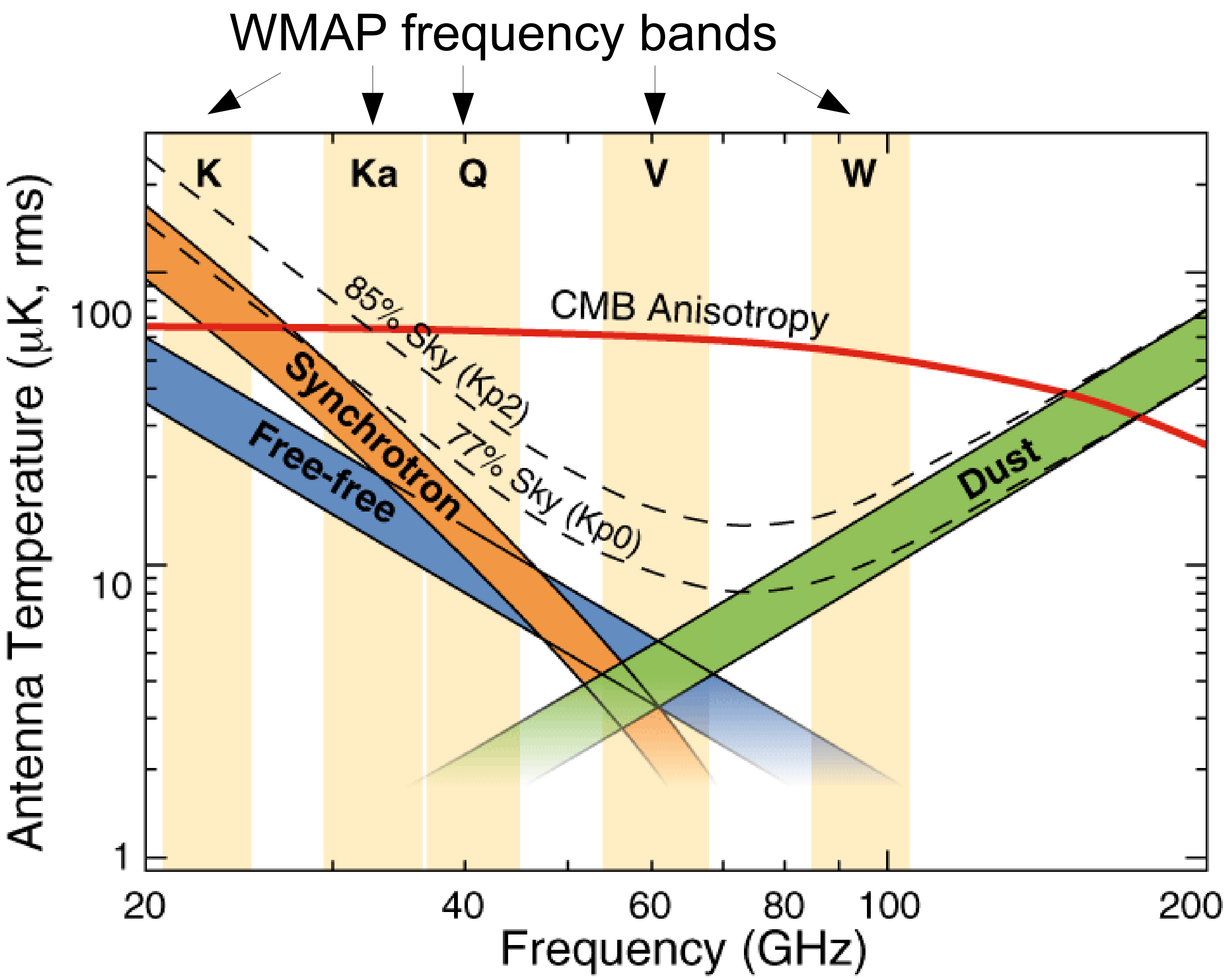
How to deal with foregrounds?

- masking
- component separation
- modelling

*Galactic foregrounds*

e.g., dust emission, synchrotron emission, free-free emission

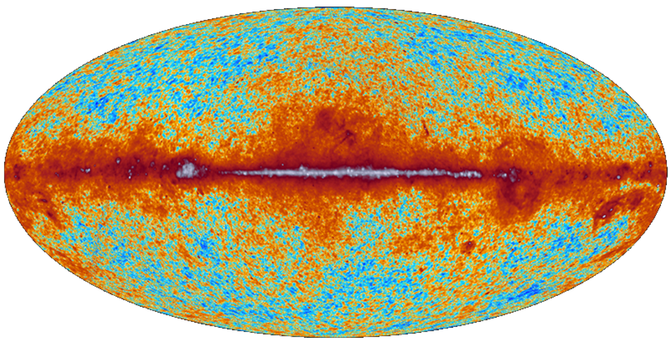
# Galactic foregrounds



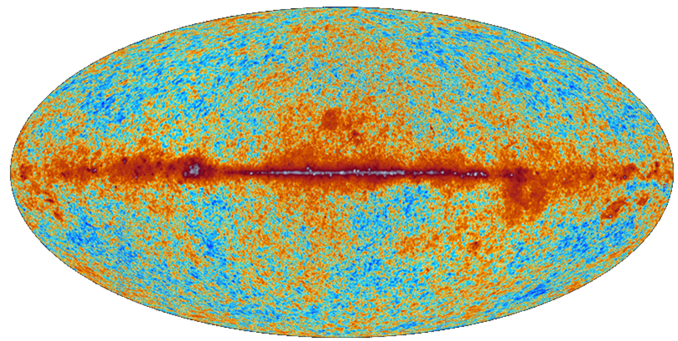

Galactic foregrounds have different frequency dependences

→ use multi-frequency information for separating components

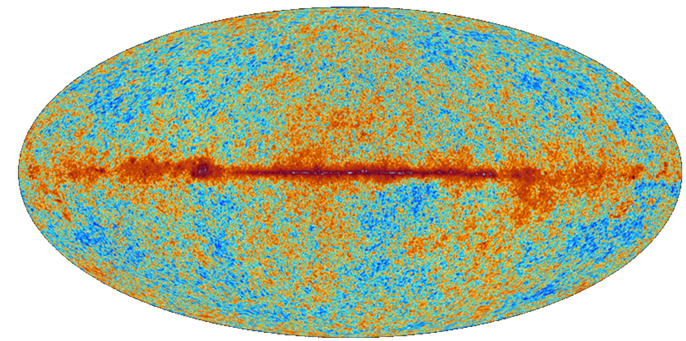
# Planck's view of the microwave sky



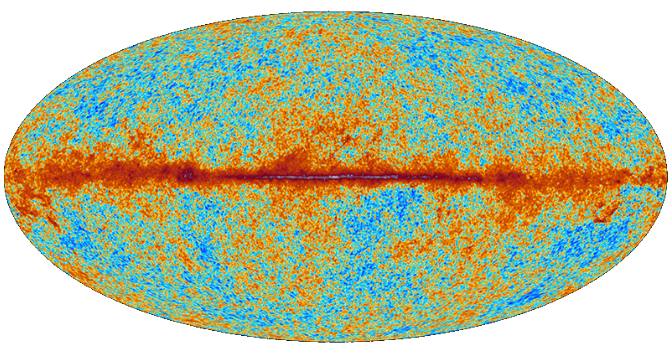
30 Ghz



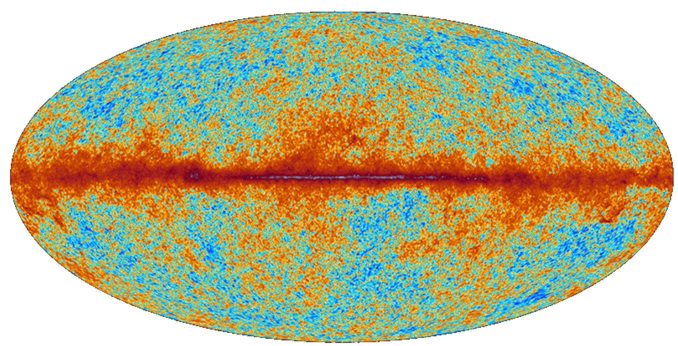
44 Ghz



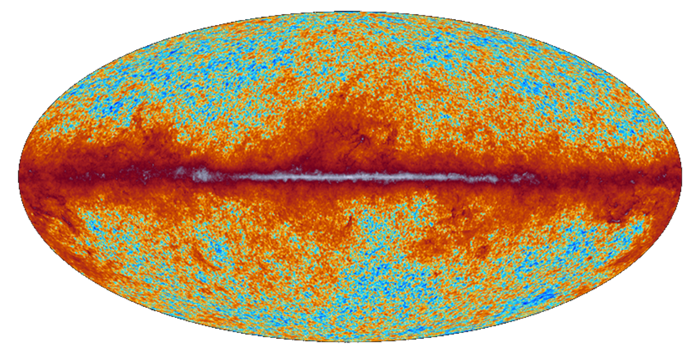
70 Ghz



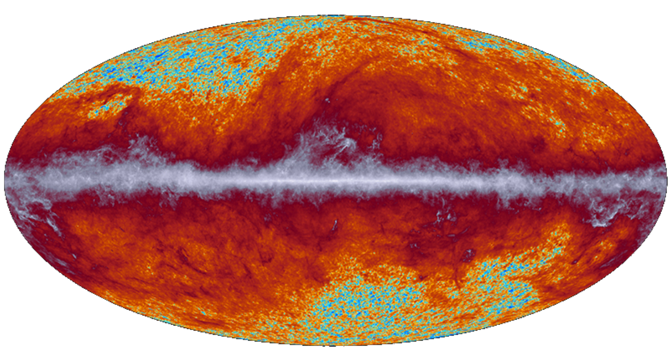
100 GHz



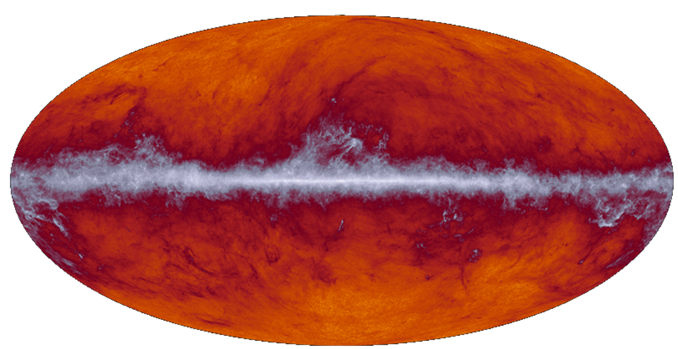
143 Ghz



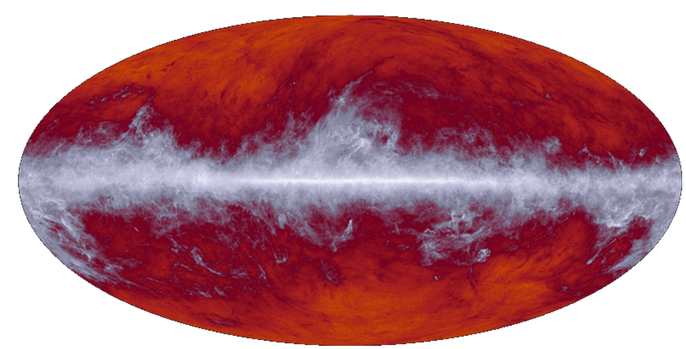
217 Ghz



353 Ghz

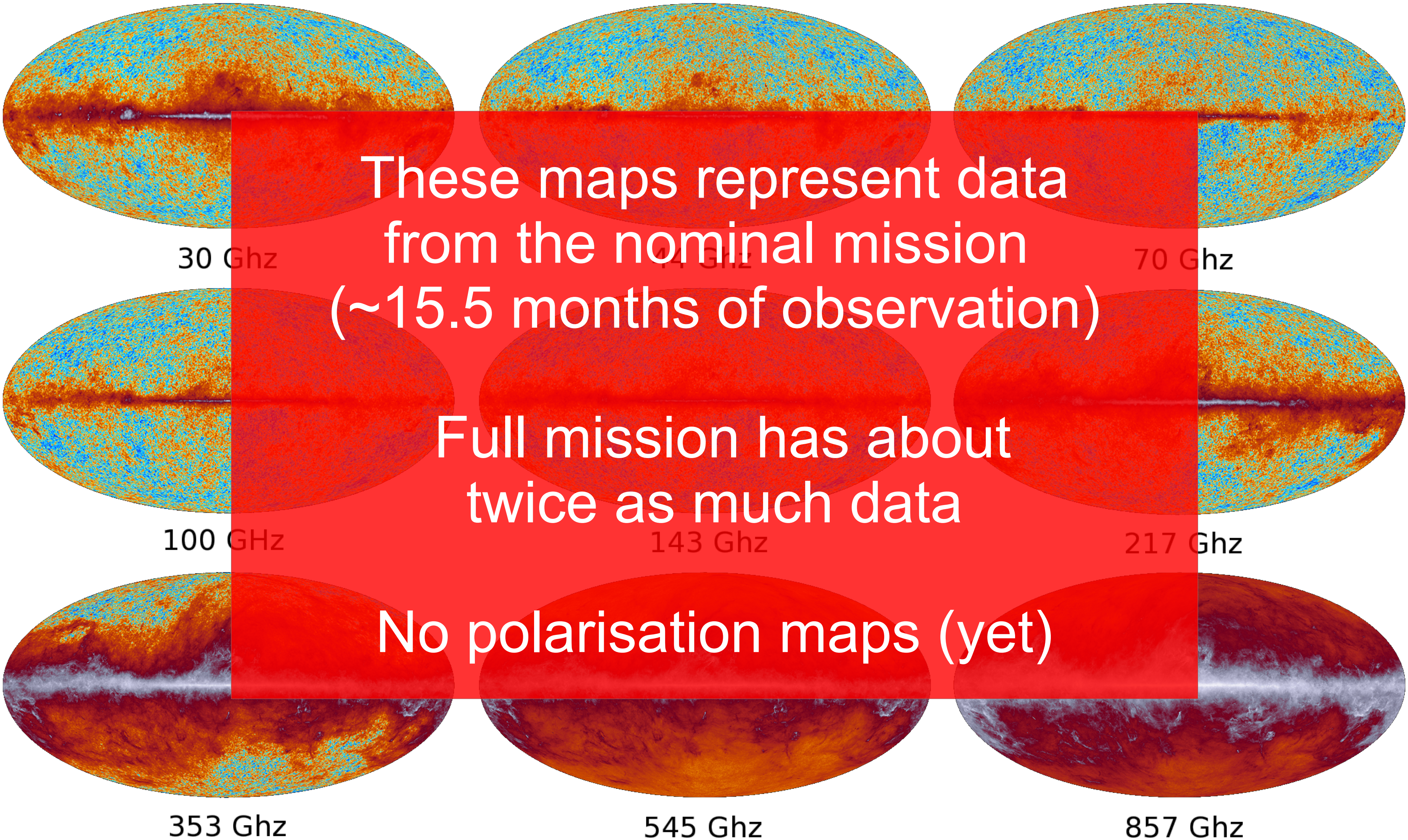


545 Ghz



857 Ghz

# Planck's view of the microwave sky

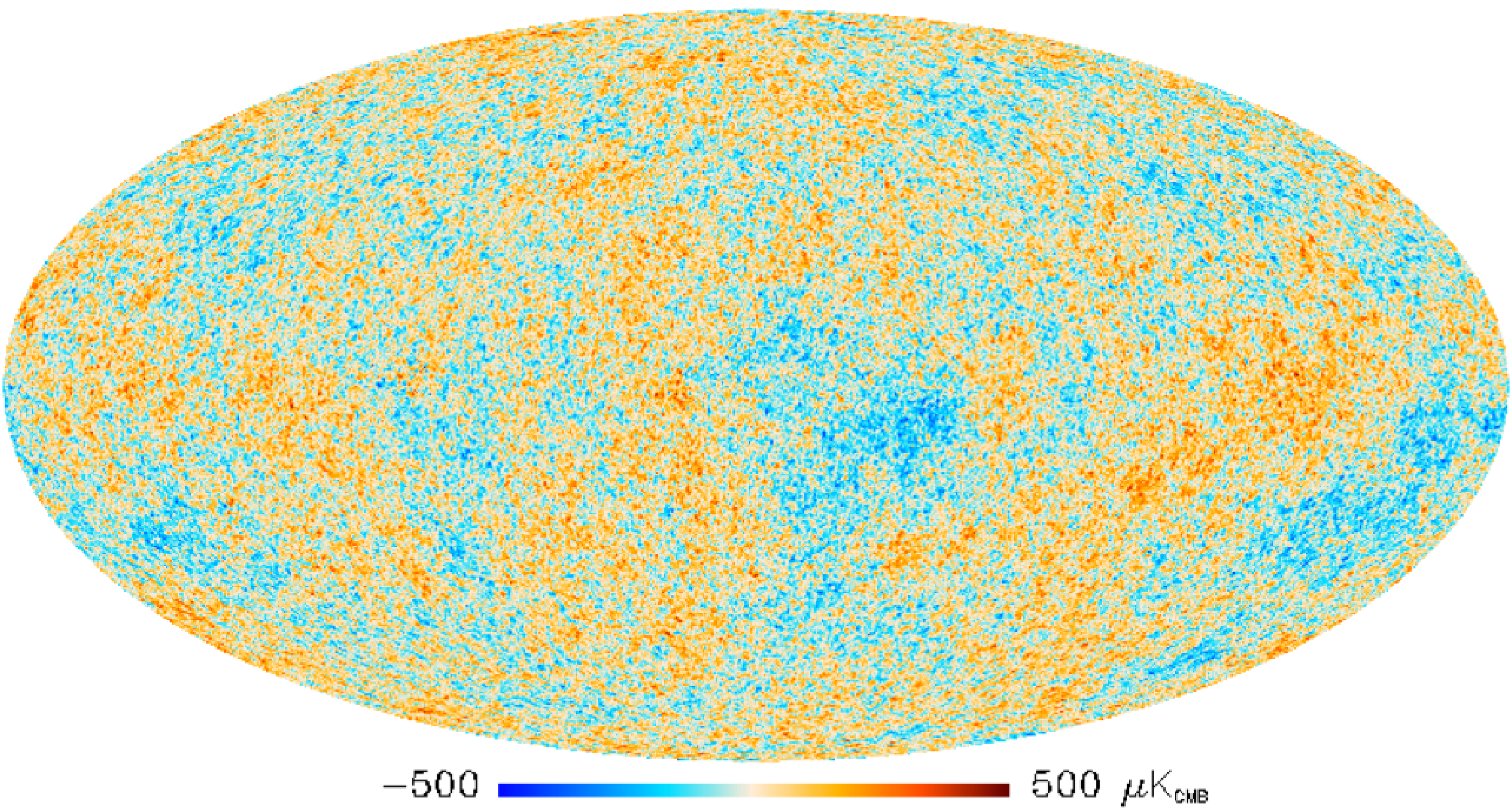



These maps represent data from the nominal mission (~15.5 months of observation)

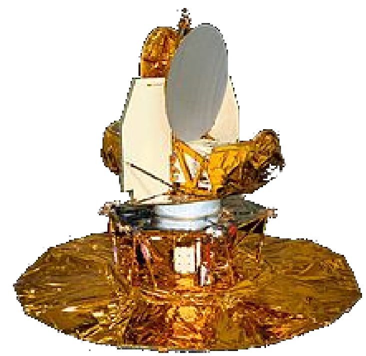
Full mission has about twice as much data

No polarisation maps (yet)

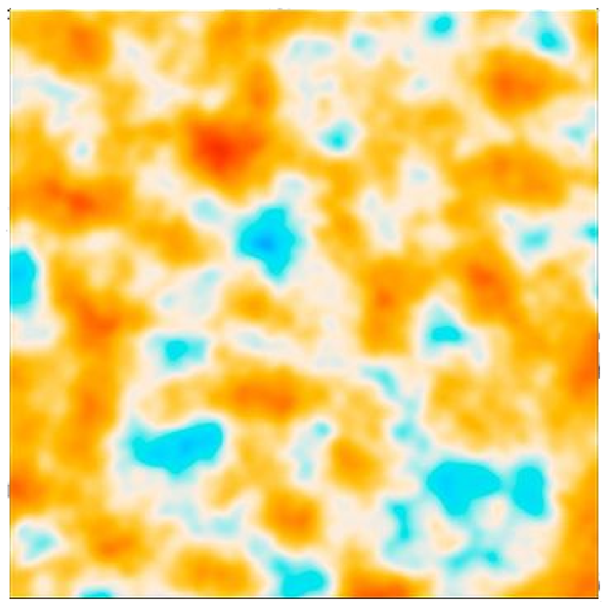
# Cleaned map of CMB temperature anisotropies



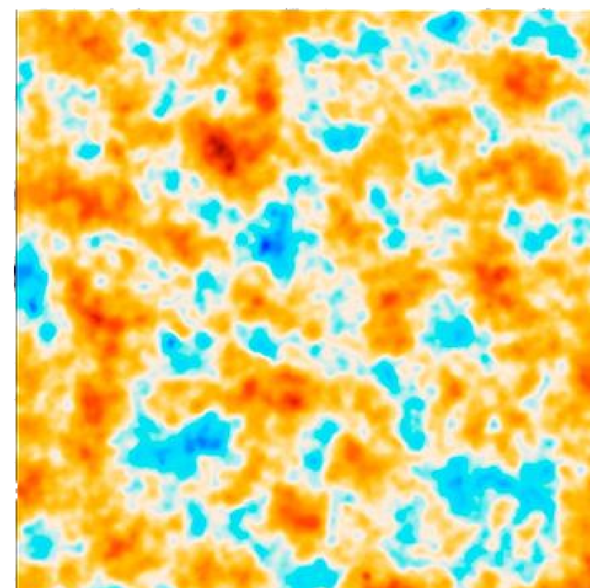
# From COBE to Planck



COBE
7°

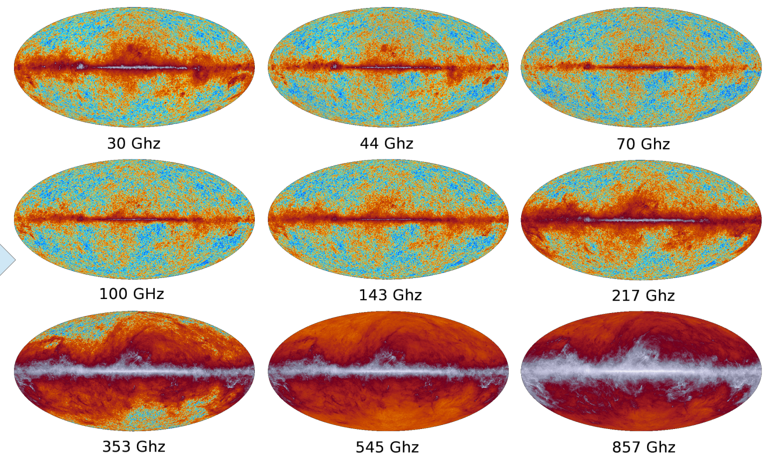


WMAP
0.3°

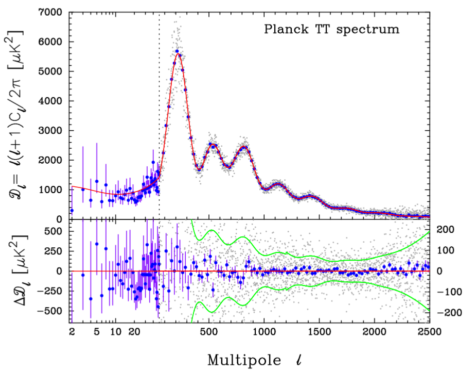


Planck
< 0.1°

# Cosmological observables

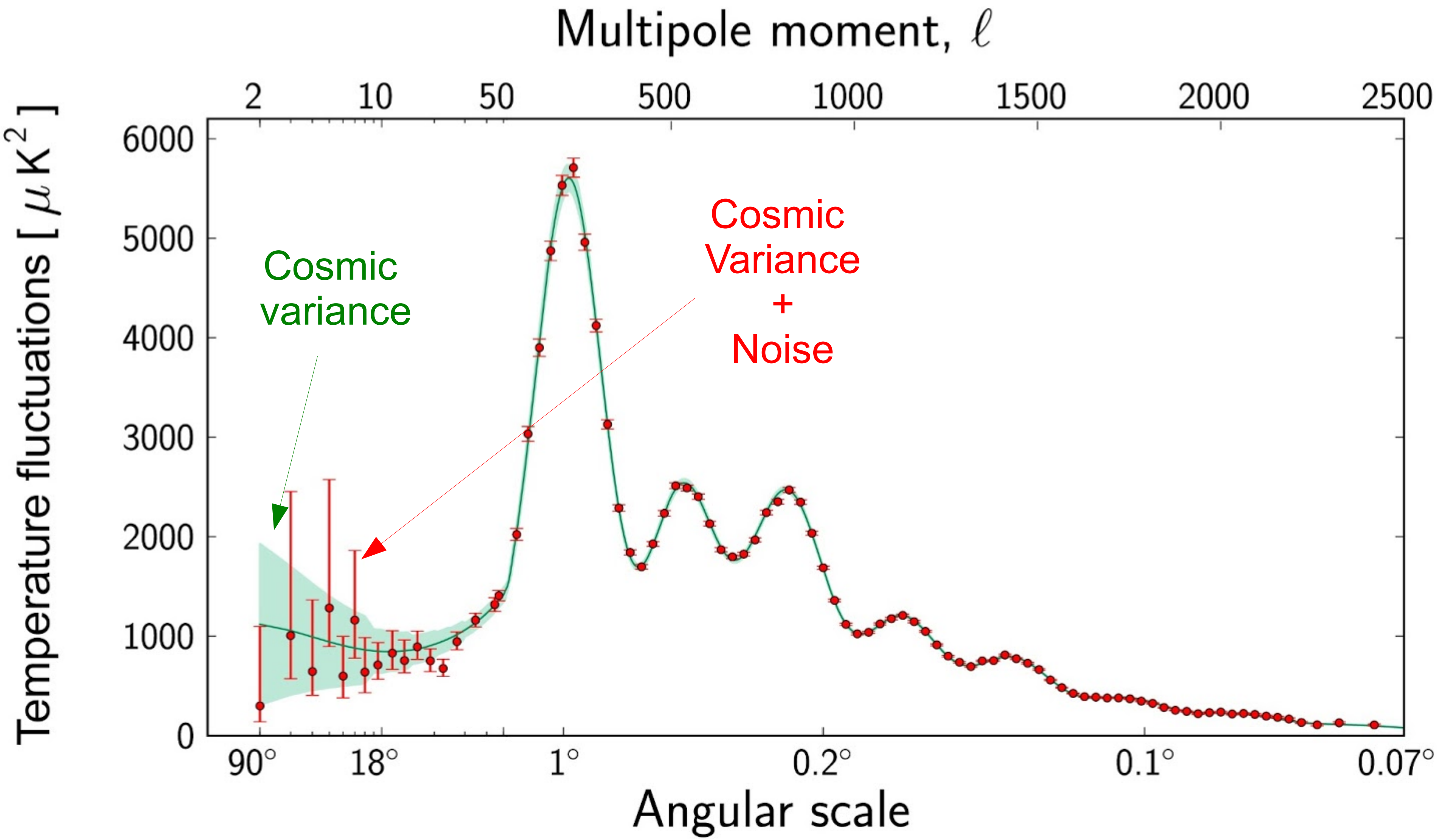



2-point correlation

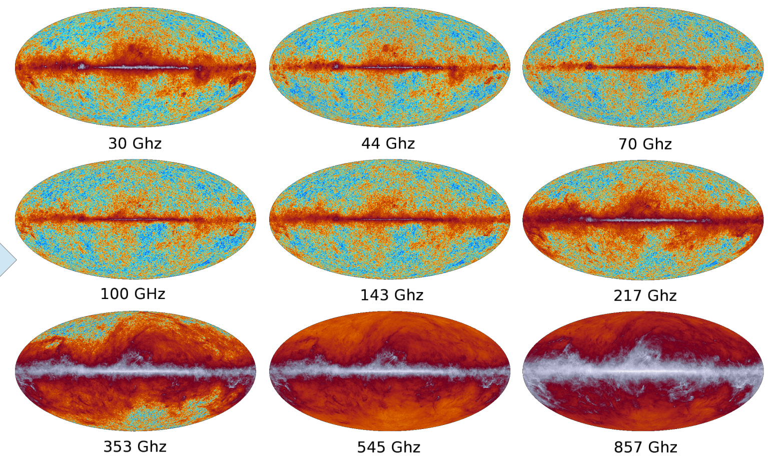



Angular power spectrum

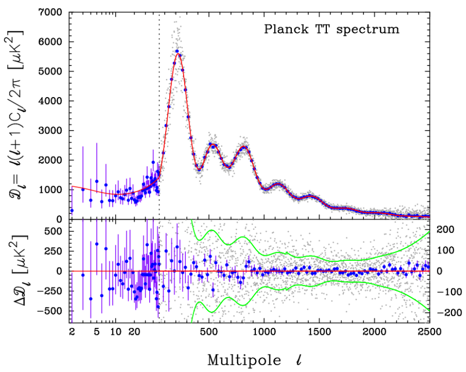
# Planck (temperature) angular power spectrum



# Cosmological observables

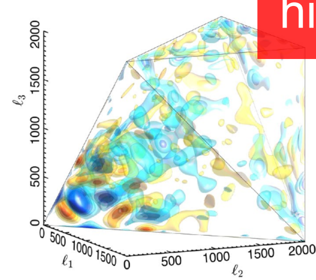



2-point correlation

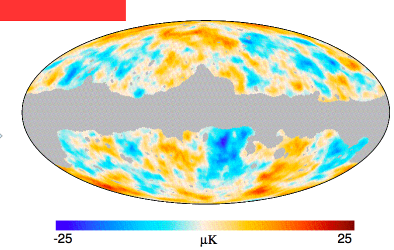



Angular power spectrum

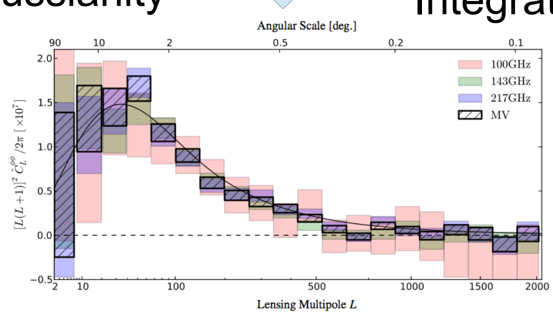
higher order correlations



Primordial non-Gaussianity




Integrated Sachs-Wolfe effect

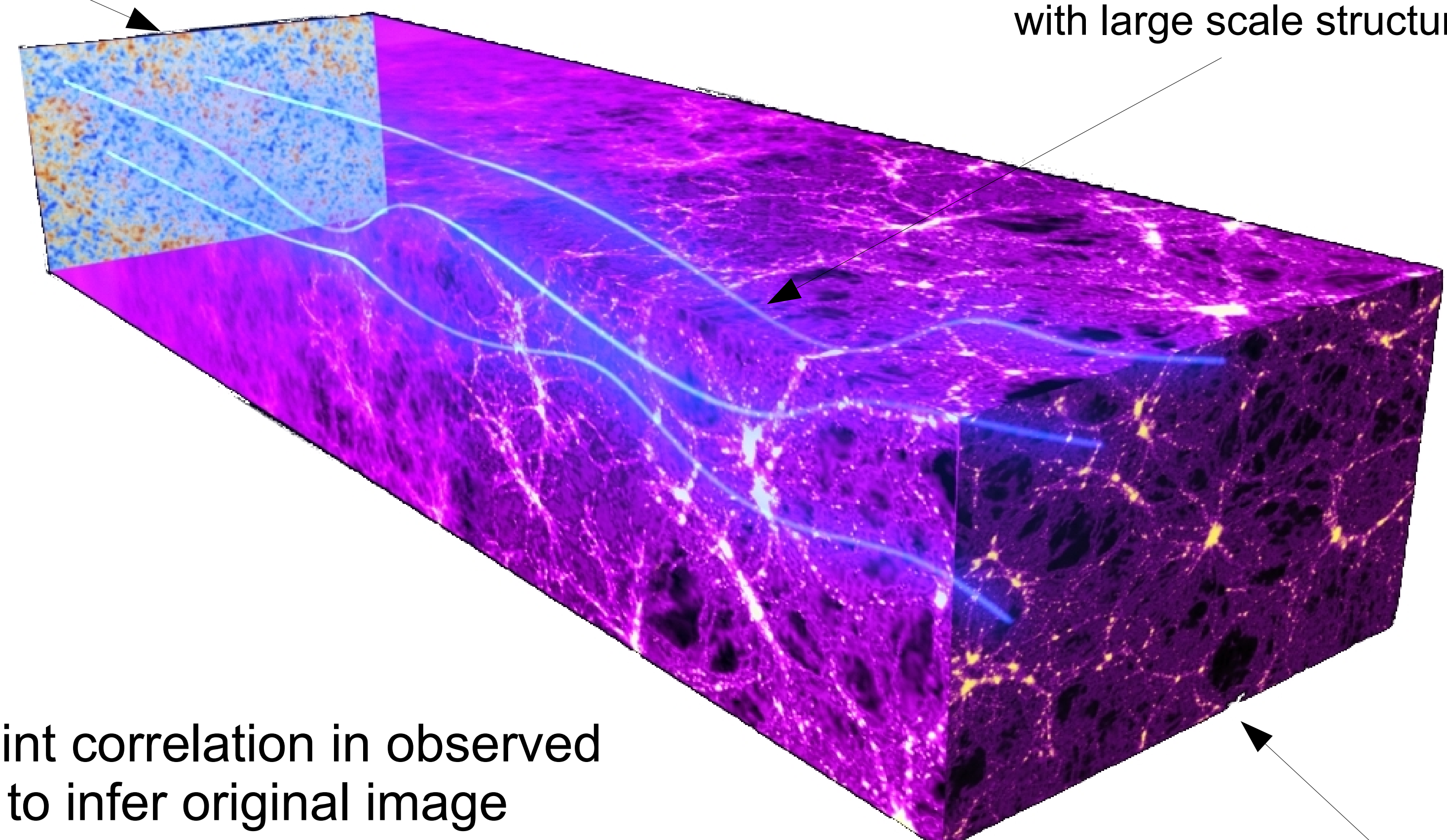



Power spectrum of the lensing potential

# Weak gravitational lensing of the CMB

Last scattering surface

CMB photons get deflected through gravitational interaction with large scale structure



We observe a slightly distorted image of the original CMB

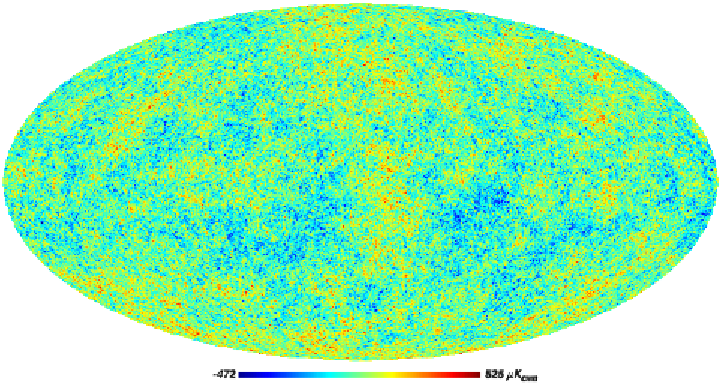
Use 4-point correlation in observed maps to infer original image

→ reconstruct deflection angle

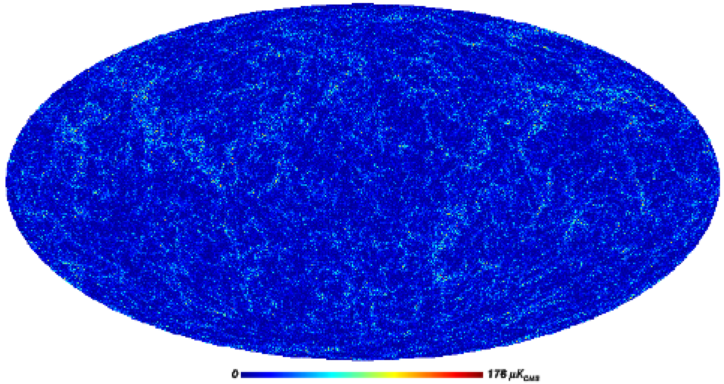
→ construct map of lensing potential

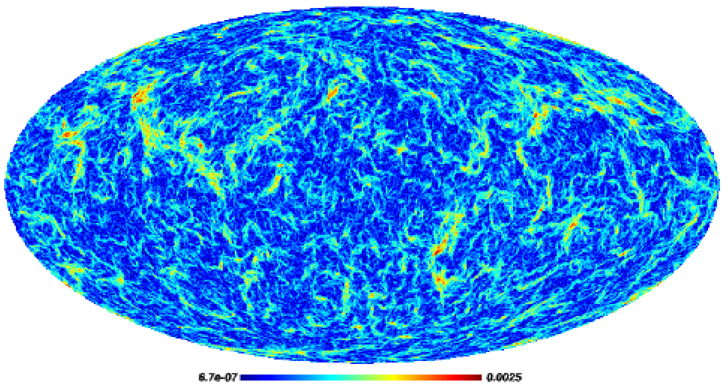
# Weak gravitational lensing of the CMB

(simulated) lensed
CMB temperature map

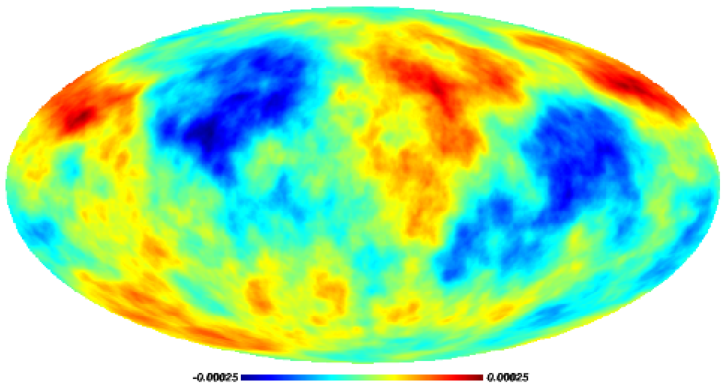



difference to unlensed
CMB temperature map



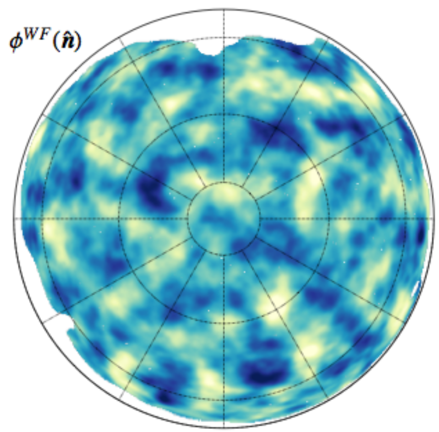




map of the deflection angle

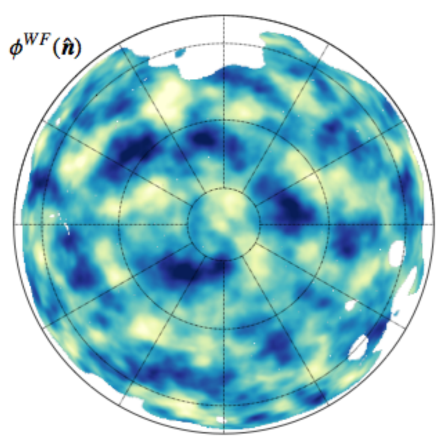



map of the lensing potential

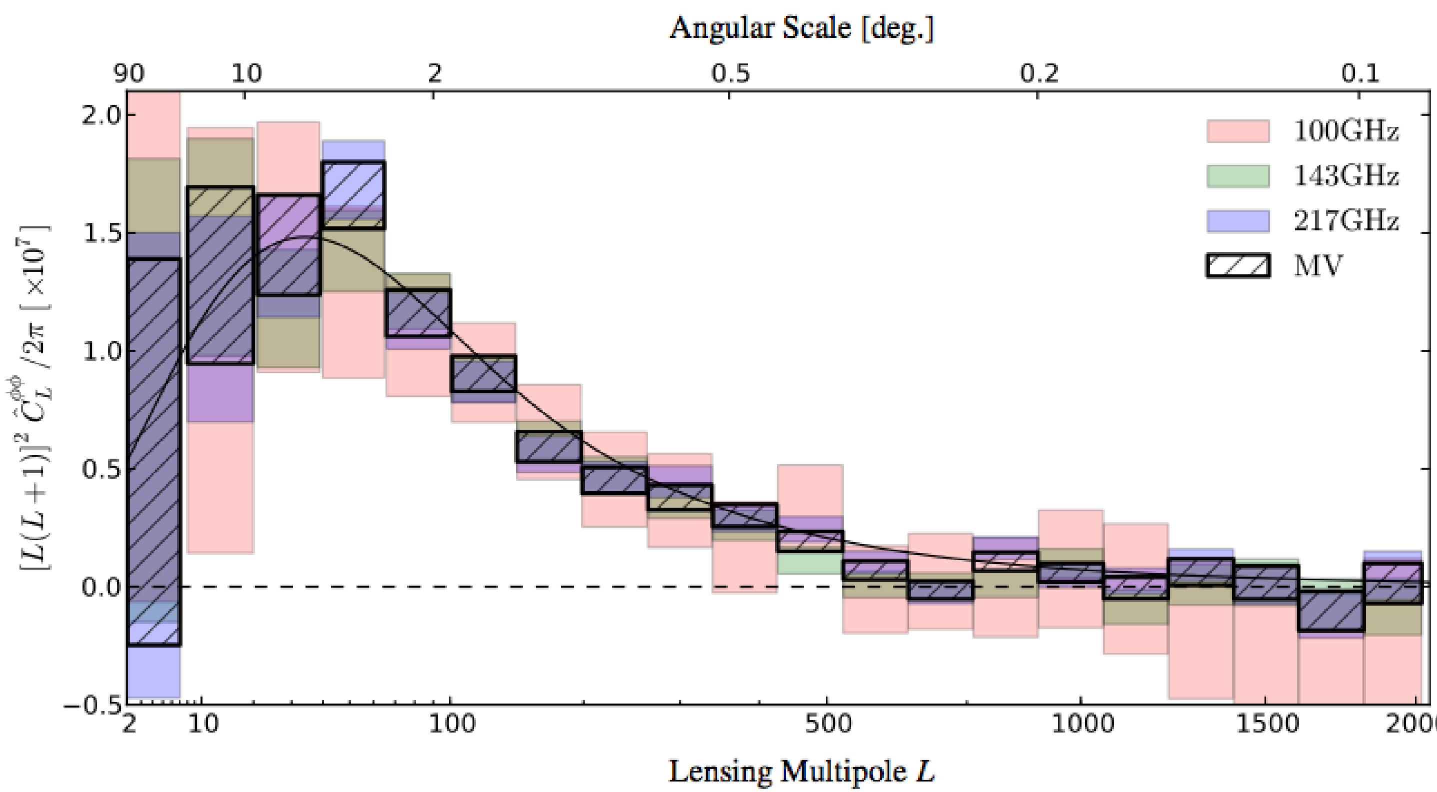
# Planck lensing potential and its angular power spectrum




Galactic North

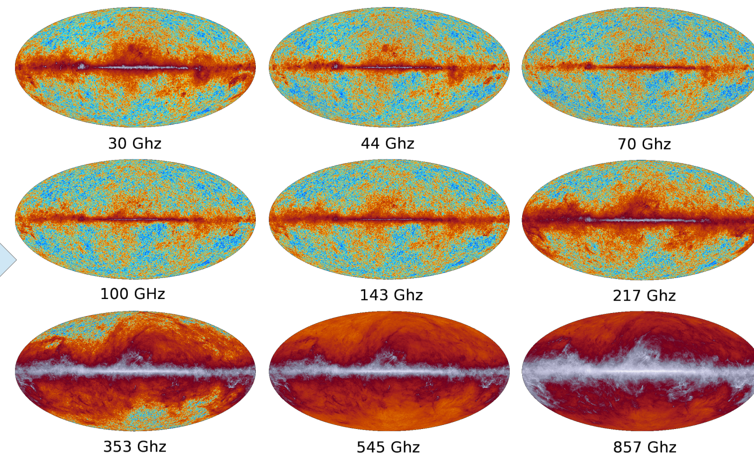



Galactic South



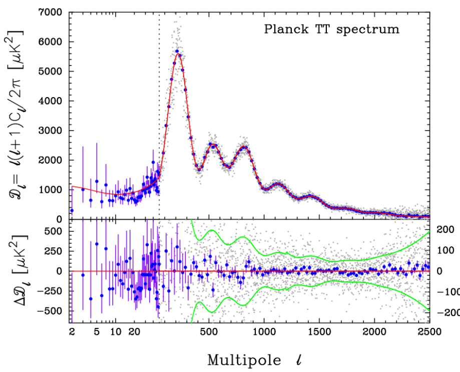

25σ detection of CMB lensing!

# Cosmological observables



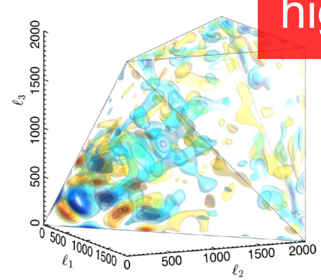

2-point correlation

SZ-effect

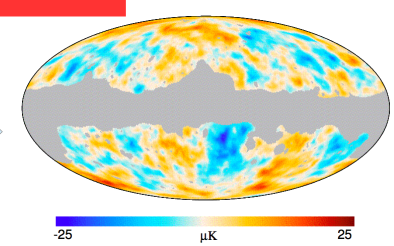



Angular power spectrum

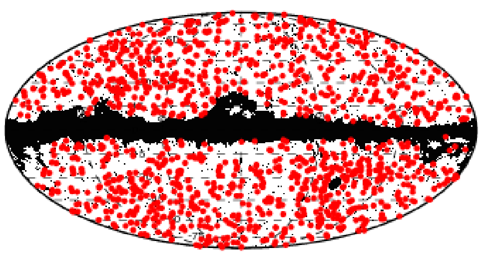
higher order correlations



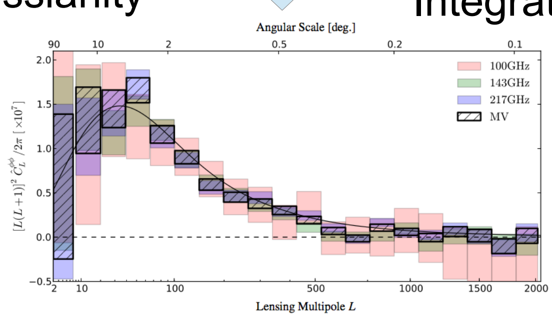
Primordial non-Gaussianity




Integrated Sachs-Wolfe effect



Galaxy clusters
→ cluster mass function
(when combined with
X-ray data)




Power spectrum of the lensing potential

# What have we learnt about cosmology?

# A maximally boring Universe?

No real surprises, no paradigm changes

The cosmological “standard” ($\Lambda$CDM) model still stands strong

Significant improvements in constraints on nearly all interesting cosmological parameters

# The ΛCDM model and its parameters

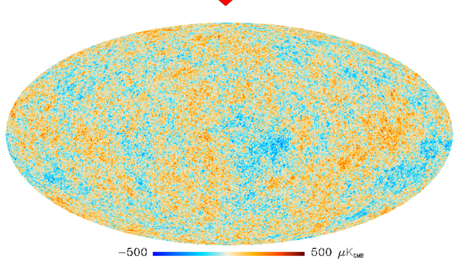
General relativity

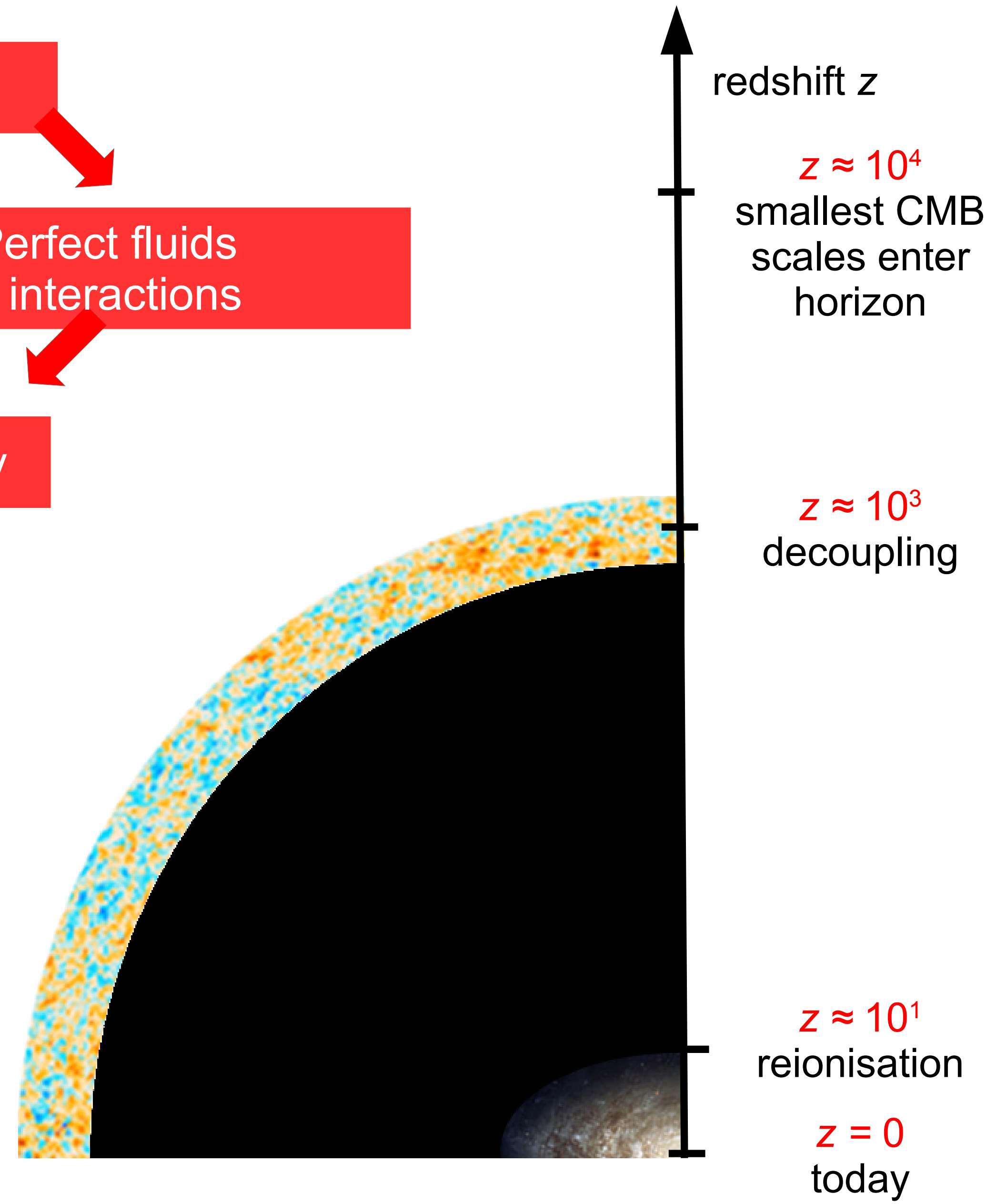
Homogeneous, isotropic and spatially flat background

Perfect fluids + interactions

Linear perturbation theory

Photon perturbation at early time



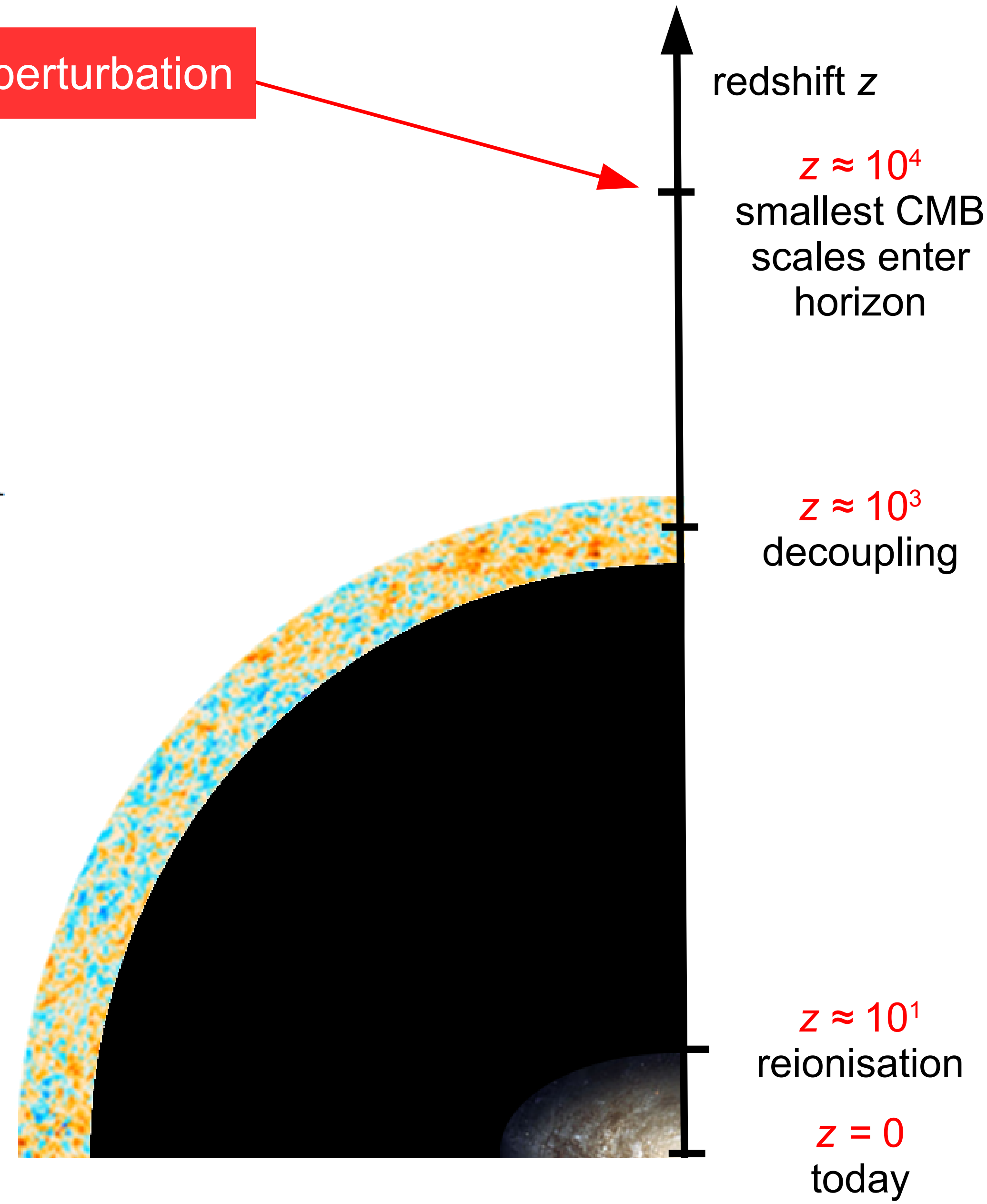
# The ΛCDM model and its parameters

Initial curvature perturbation

Spectral index of initial curvature perturbation

$$\mathcal{P}_0(k) = A_s \left(\frac{k}{k_*}\right)^{n_s - 1}$$

Amplitude of initial curvature perturbation

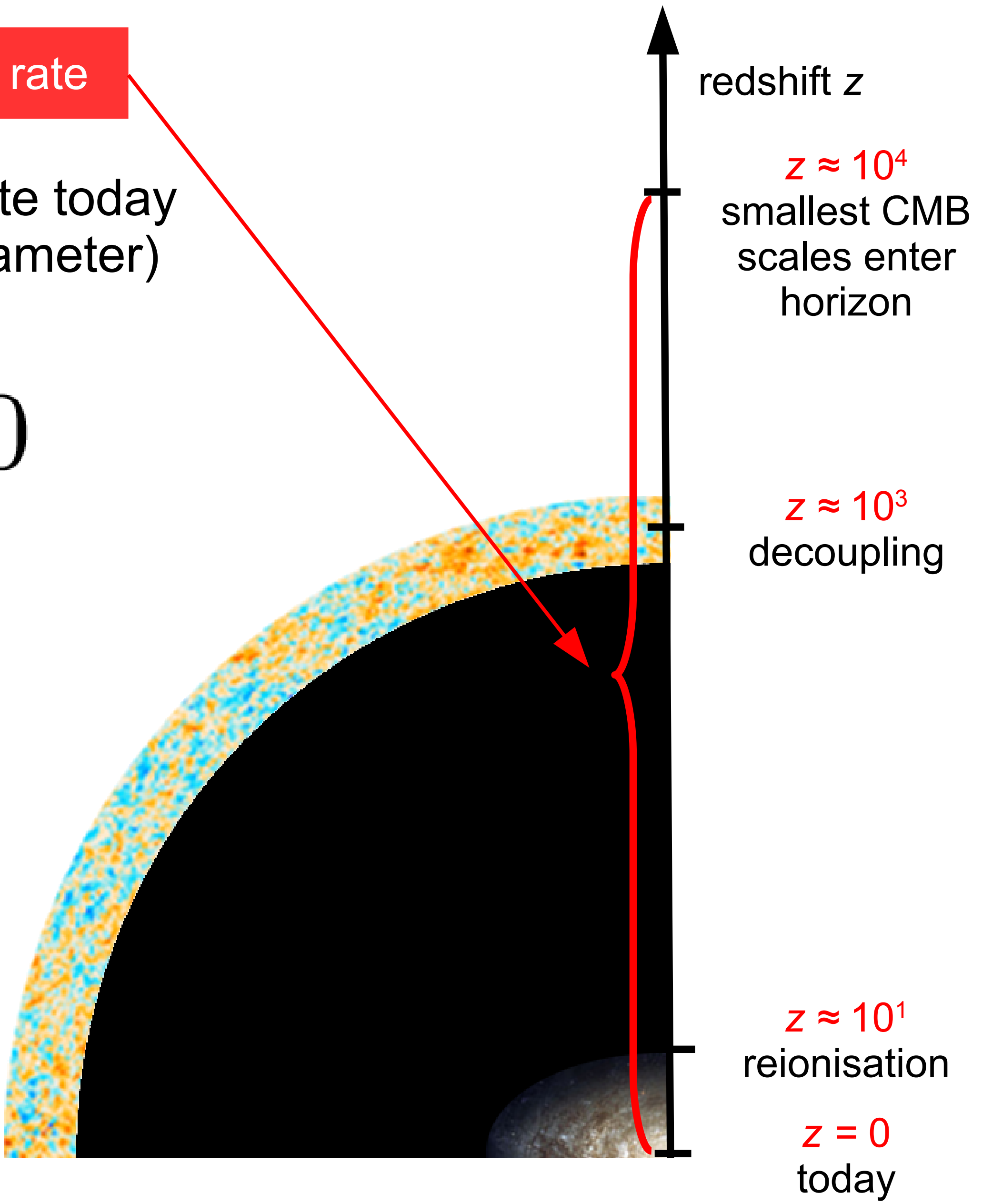


# The ΛCDM model and its parameters

Energy content ⟷ Expansion rate

Expansion rate today
(Hubble parameter)

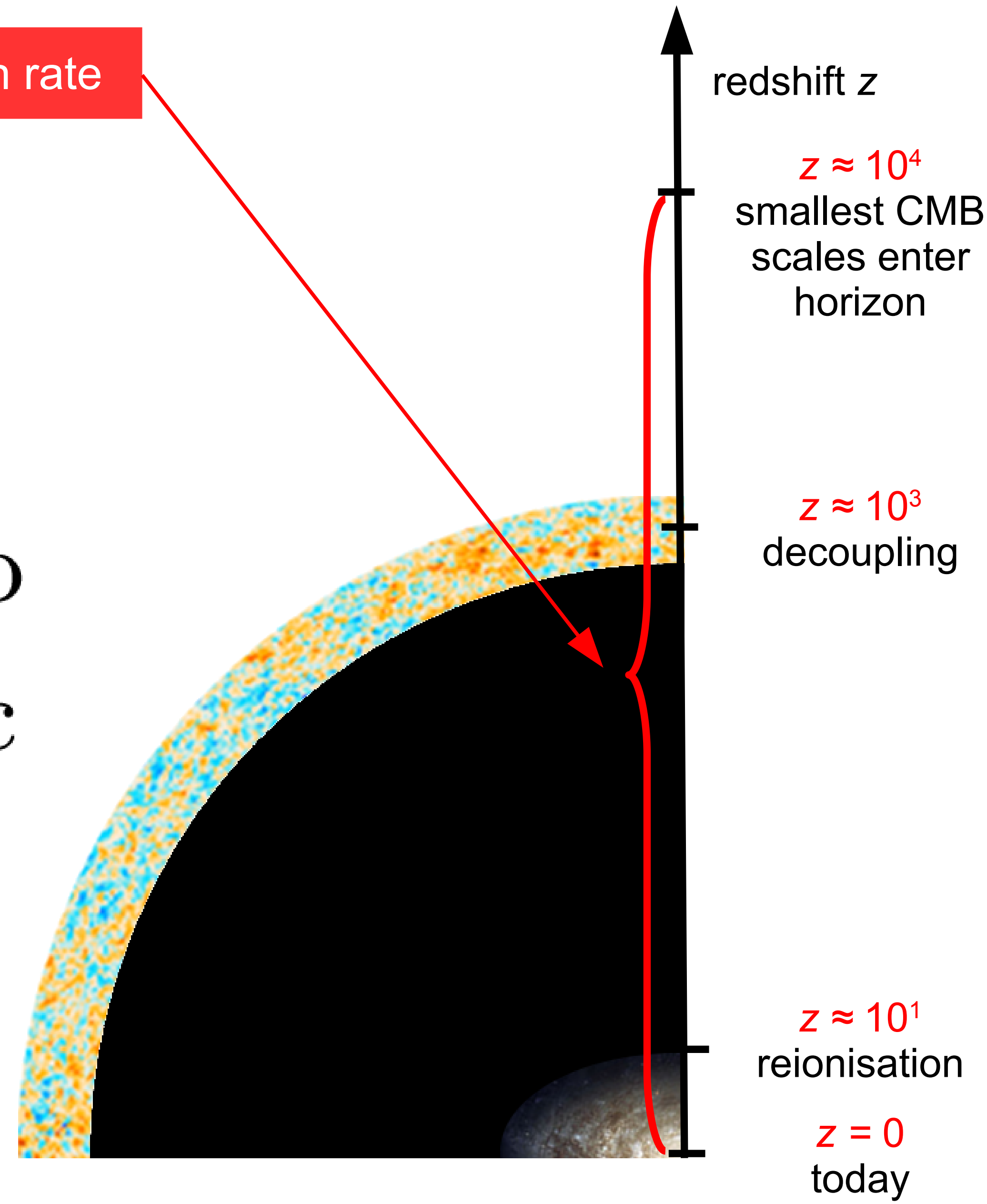
$$H_0$$



# The ΛCDM model and its parameters

**Energy content** ⟷ **Expansion rate**

- Photons (CMB)
  measured by FIRAS
- Neutrinos (CνB)
  3 species, minimal masses
- "Baryonic" matter — $\omega_b$
  electrons, hydrogen and helium
- Dark matter — $\omega_c$
  assumed to be "cold"
- Dark energy
  cosmological constant



# The ΛCDM model and its parameters

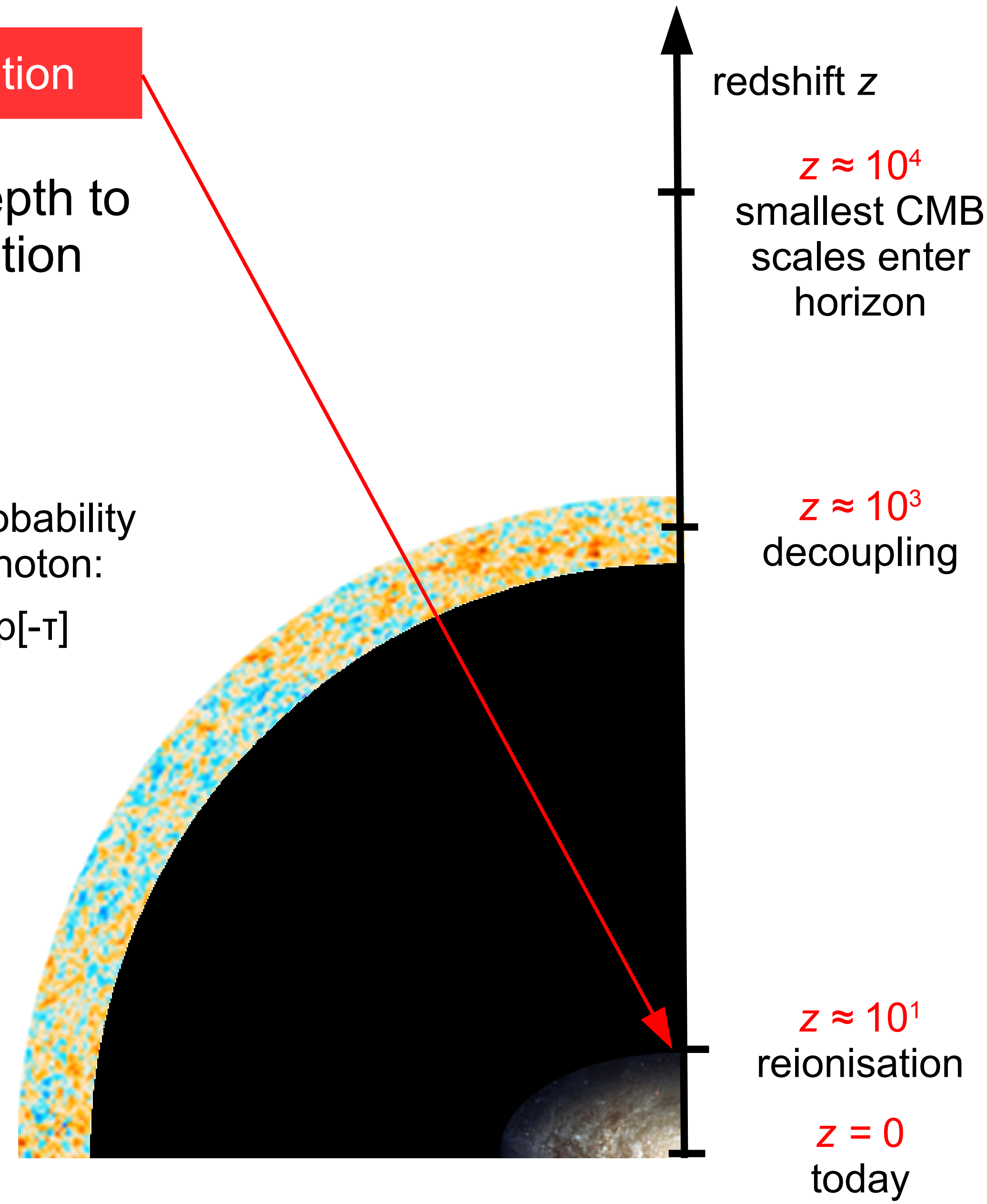
**Reionisation**

Optical depth to reionisation

$$\tau$$

Scattering probability of a CMB photon:

$p = 1 - \exp[-\tau]$



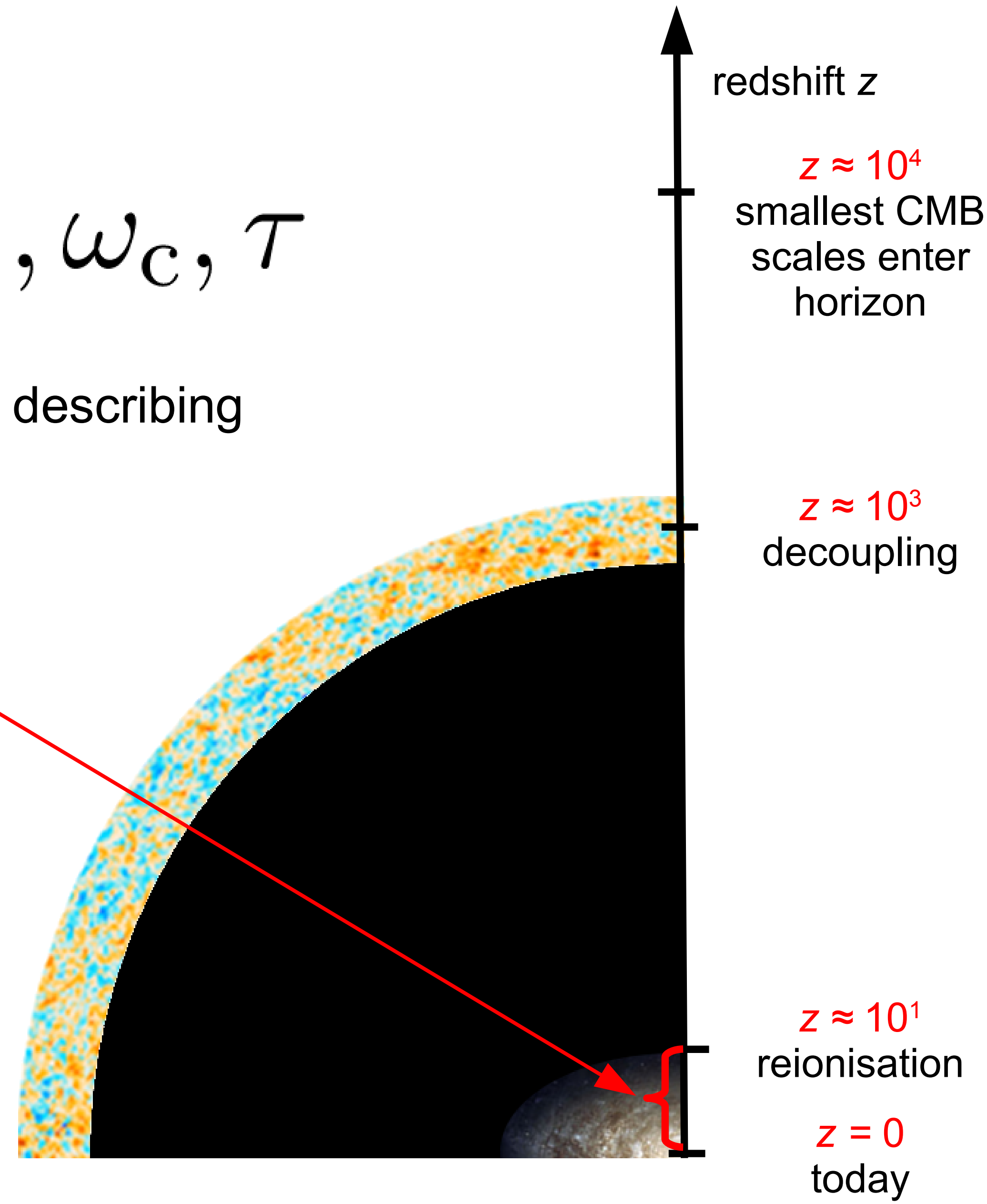
# The ΛCDM model and its parameters

Altogether 6 cosmological parameters:

$$A_{\rm s}, n_{\rm s}, H_0, \omega_{\rm b}, \omega_{\rm c}, \tau$$

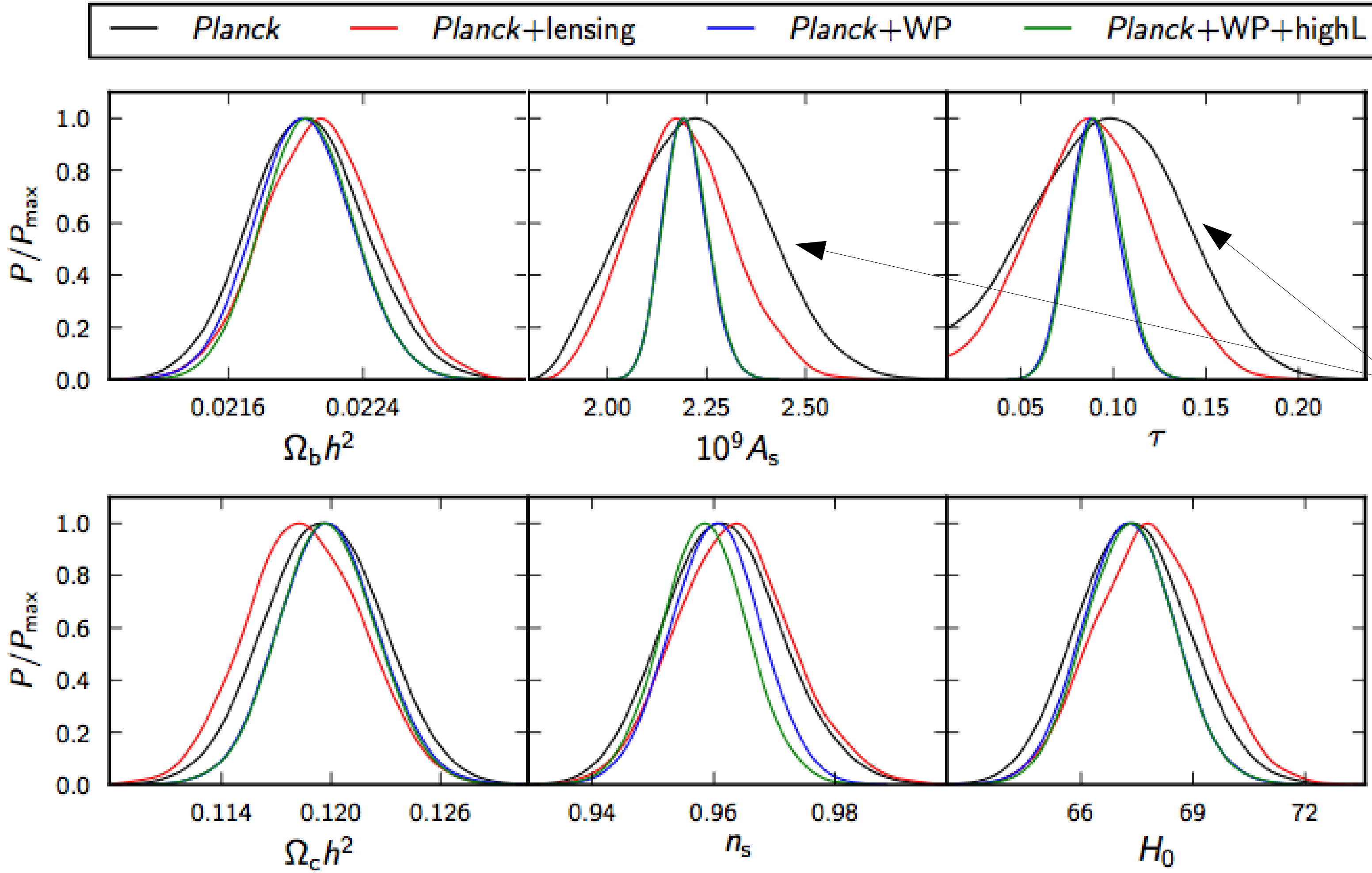
plus another 14 “nuisance” parameters, describing

- perturbations from
  - the cosmic infrared background (4)
  - unresolved point sources (4)
  - the Sunyaev-Zeldovich effect (3)
- beam shape uncertainties (1)
- relative calibration uncertainties (2)



# Basic ΛCDM parameters CMB only

Planck temperature data only | + Planck lensing data | + WMAP large-scale polarisation data | + ACT/SPT small-scale temperature data



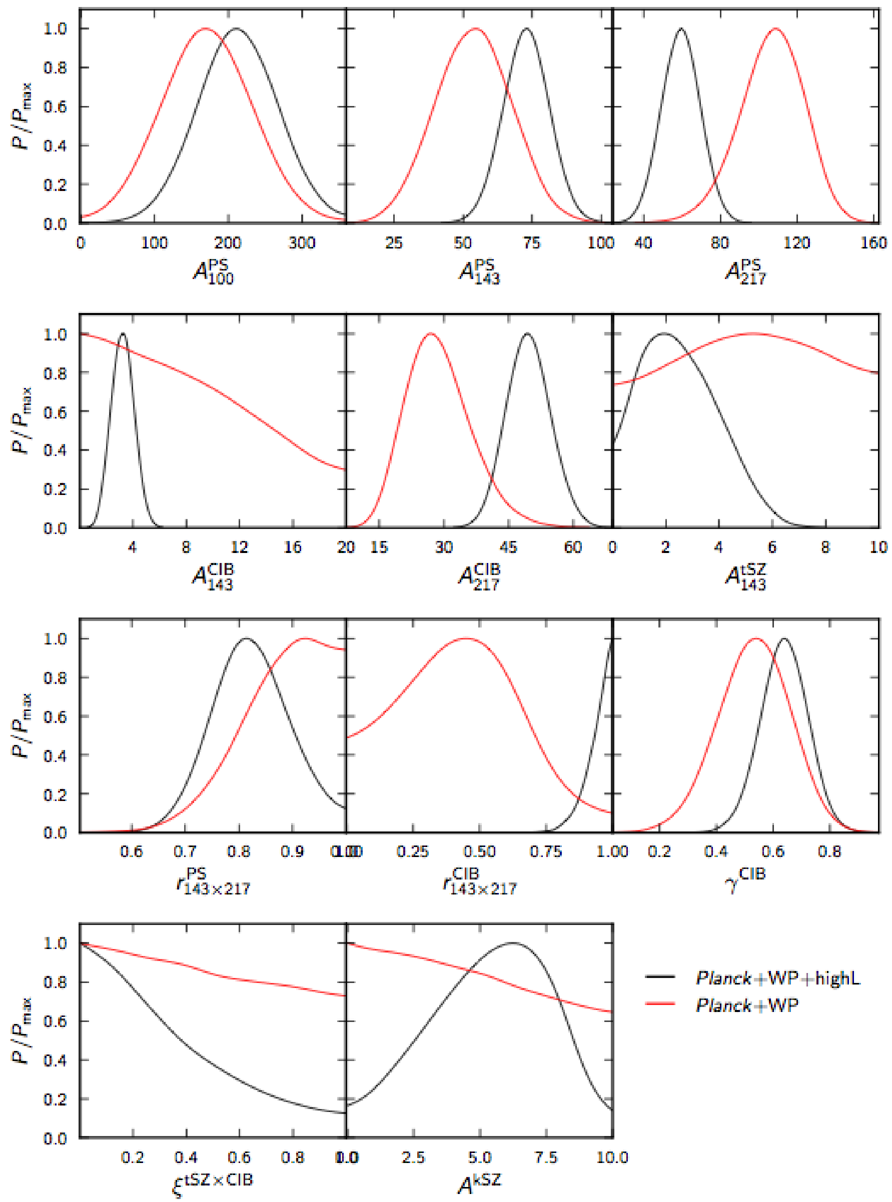

Overall amplitude of temperature data constrains $e^{-2\tau}A_s$

→ strong degeneracy between τ and $A_s$

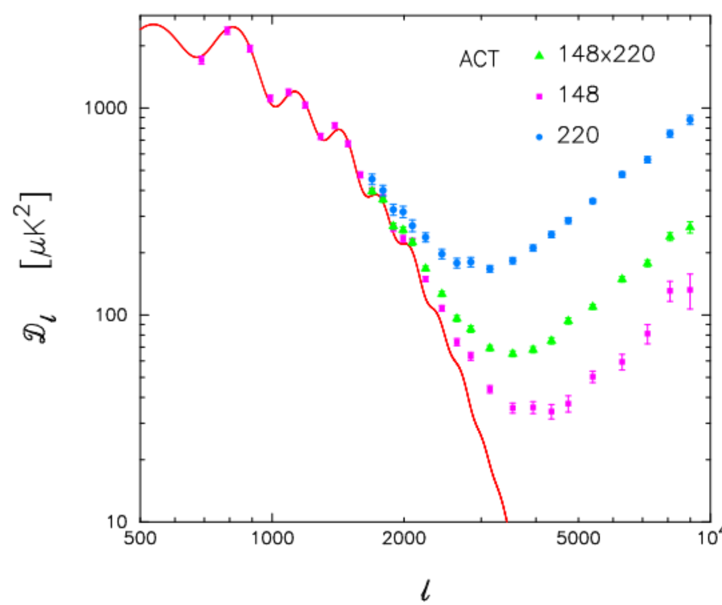
Can be broken by adding lensing or polarisation data

Other parameters well-constrained by temperature data alone

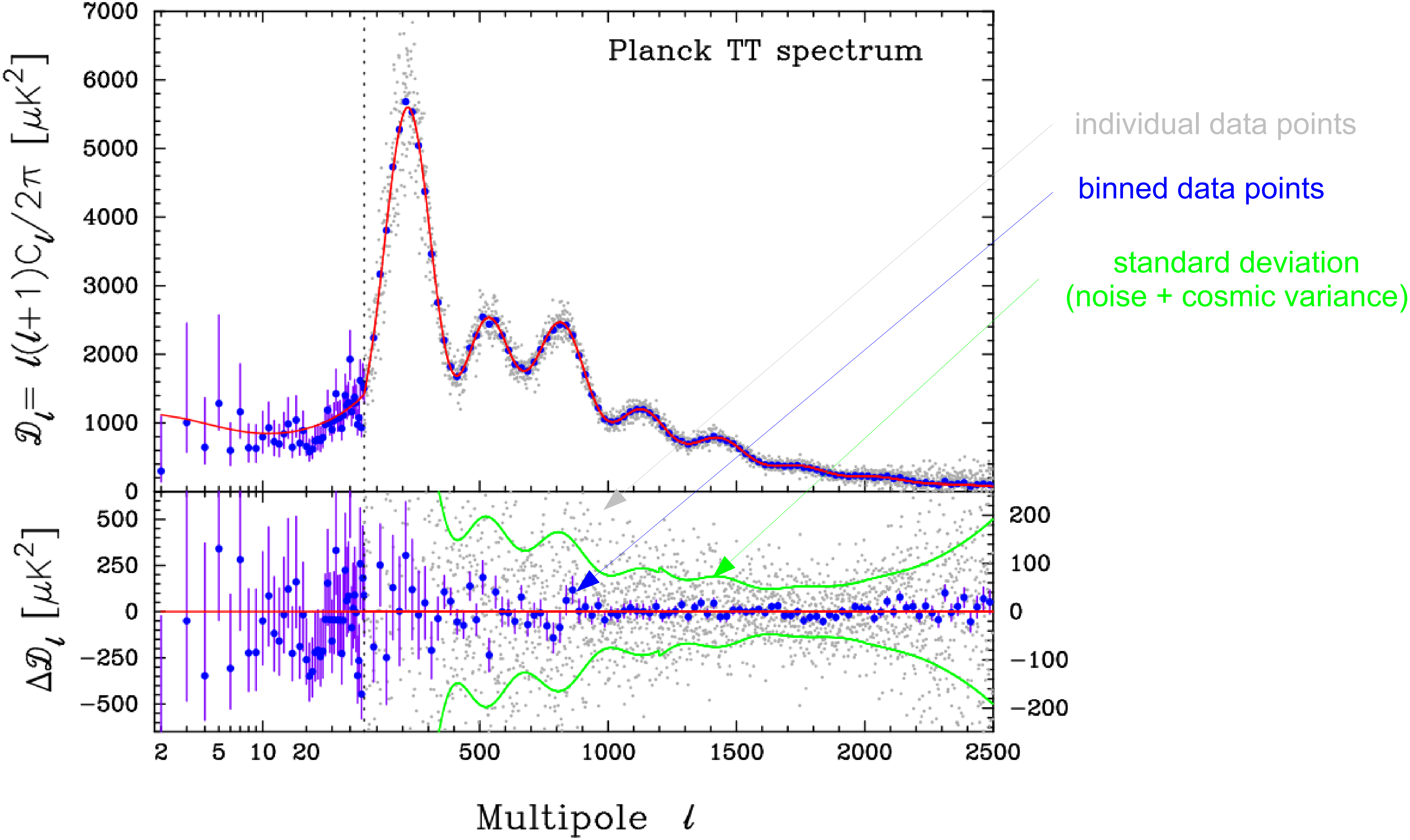
# Basic ΛCDM nuisance parameters




highL-CMB temperature data from ACT and SPT (up to multipole 10000) help constrain the nuisance parameters



# Planck (temperature) angular power spectrum



# Goodness-of-fit of ΛCDM

**Table 6.** Goodness-of-fit tests for the *Planck* spectra. The $\Delta\chi^2 = \chi^2 - N_\ell$ is the difference from the mean assuming the model is correct, and the last column expresses $\Delta\chi^2$ in units of the dispersion $\sqrt{2N_\ell}$.

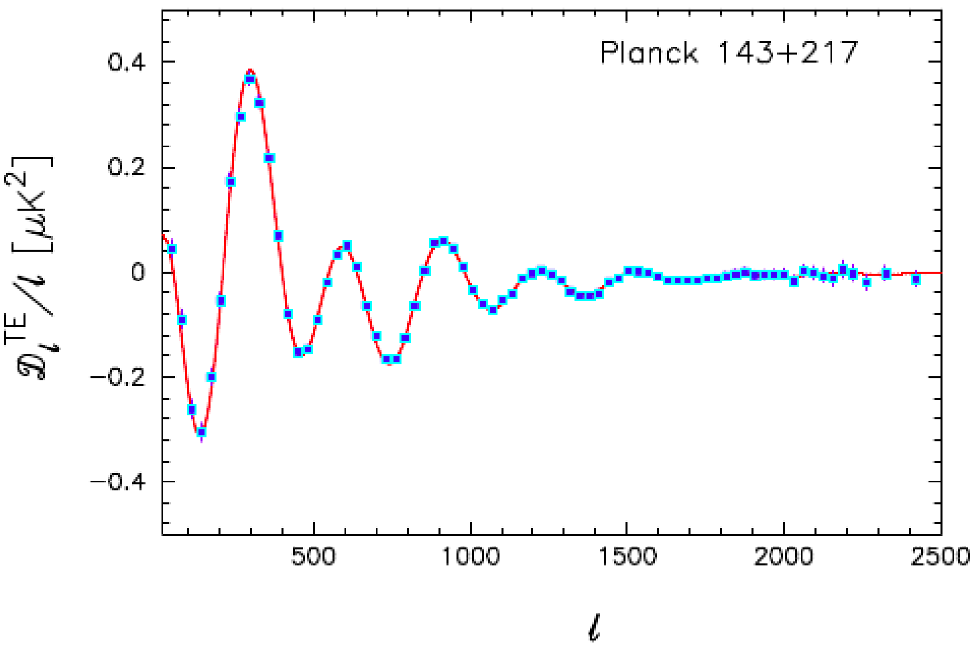
| Spectrum | $\ell_{\min}$ | $\ell_{\max}$ | $\chi^2$ | $\chi^2/N_\ell$ | $\Delta\chi^2/\sqrt{2N_\ell}$ |
|---|---|---|---|---|---|
| $100\times100$ | 50 | 1200 | 1158 | 1.01 | 0.14 |
| $143\times143$ | 50 | 2000 | 1883 | 0.97 | −1.09 |
| $217\times217$ | 500 | 2500 | 2079 | 1.04 | 1.23 |
| $143\times217$ | 500 | 2500 | 1930 | 0.96 | −1.13 |
| All | 50 | 2500 | 2564 | 1.05 | 1.62 |

# Planck polarisation angular power spectra

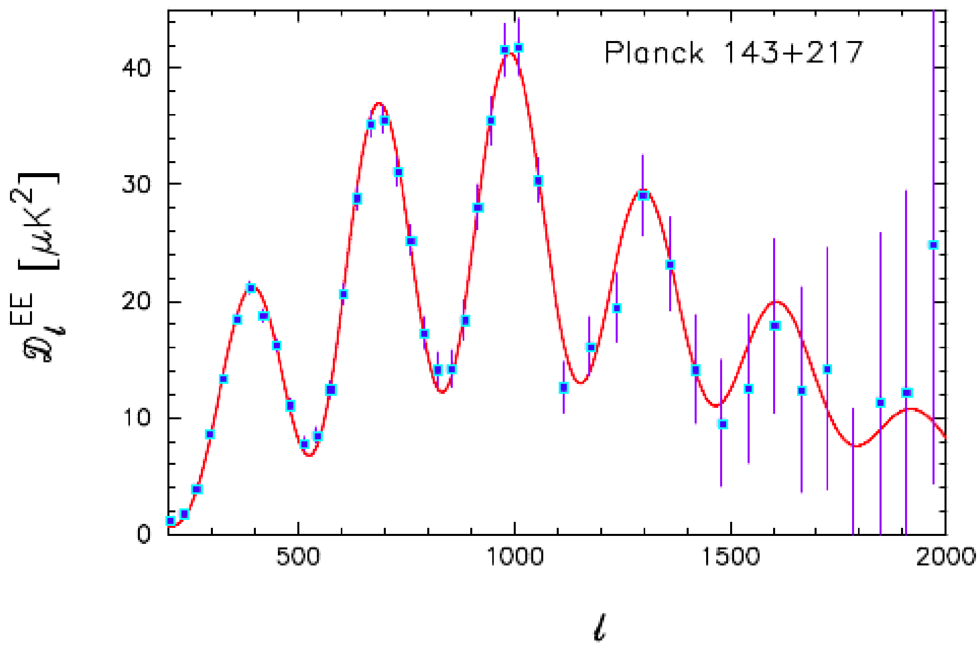
Best-fit ΛCDM model plotted against Planck polarisation data

Note: this is *not* a fit to these data!

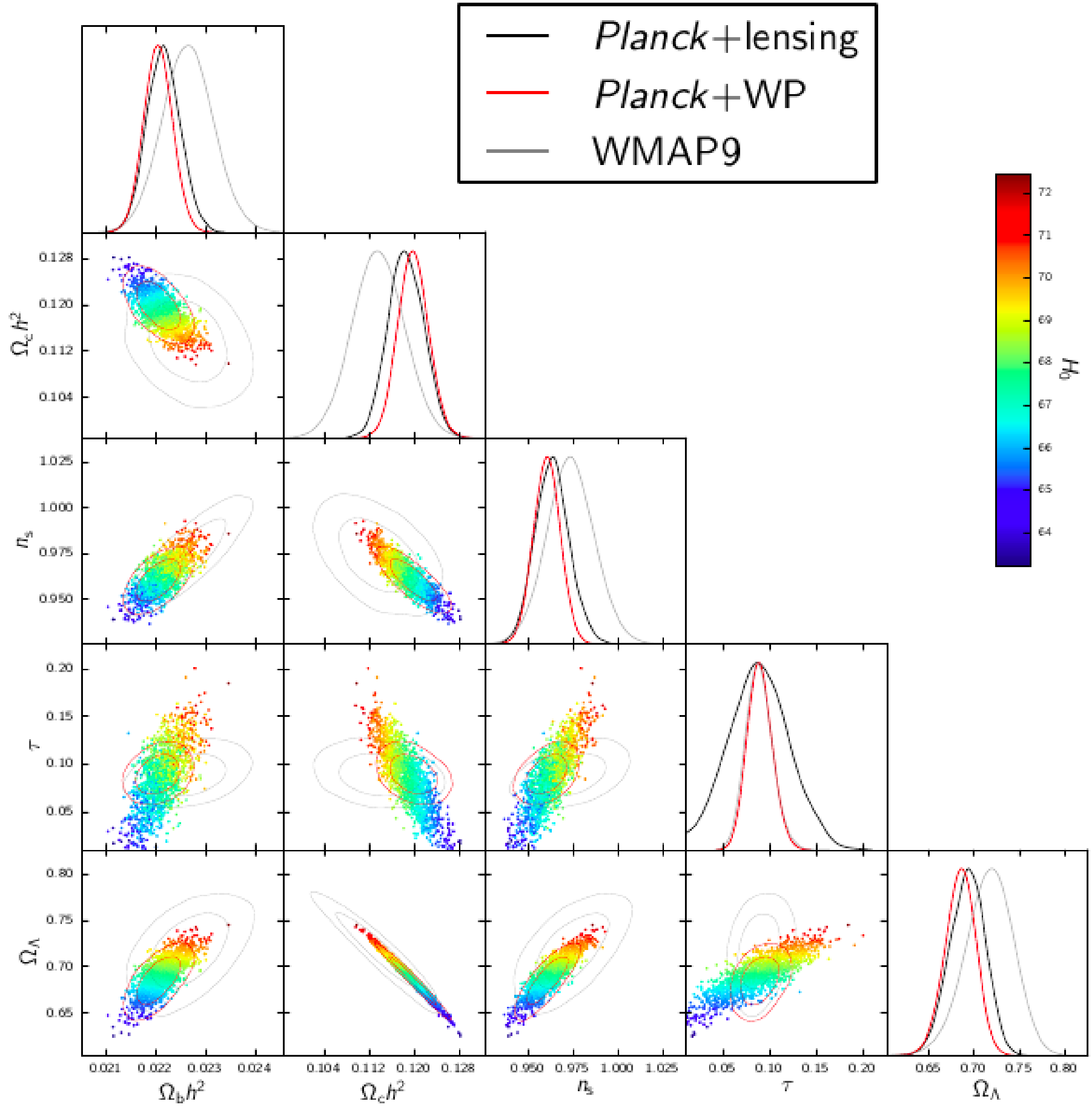
TE cross-correlation




EE auto-correlation



# ΛCDM parameters vs. WMAP

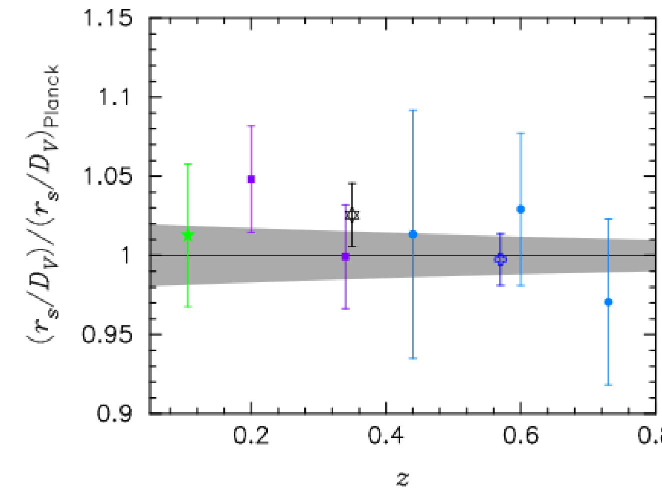


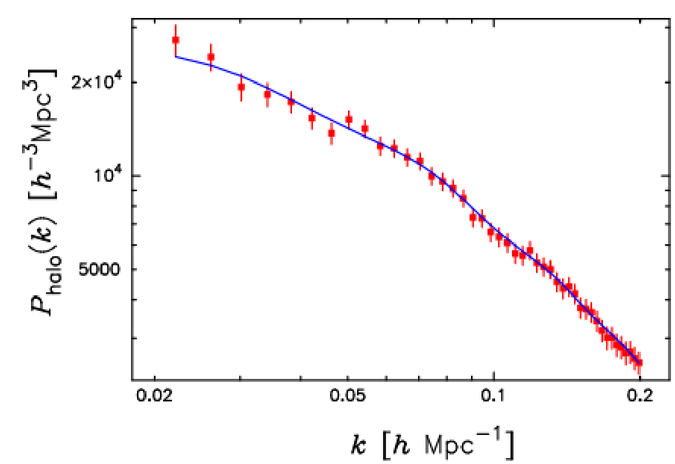
# Consistency with other data sets

- Very good consistency:
  - WMAP, ACT and high-l part of SPT data
  - Measurements of the Baryon Acoustic Oscillation scale (BAO)
  - Halo power spectrum

CMB

Galaxy redshift surveys



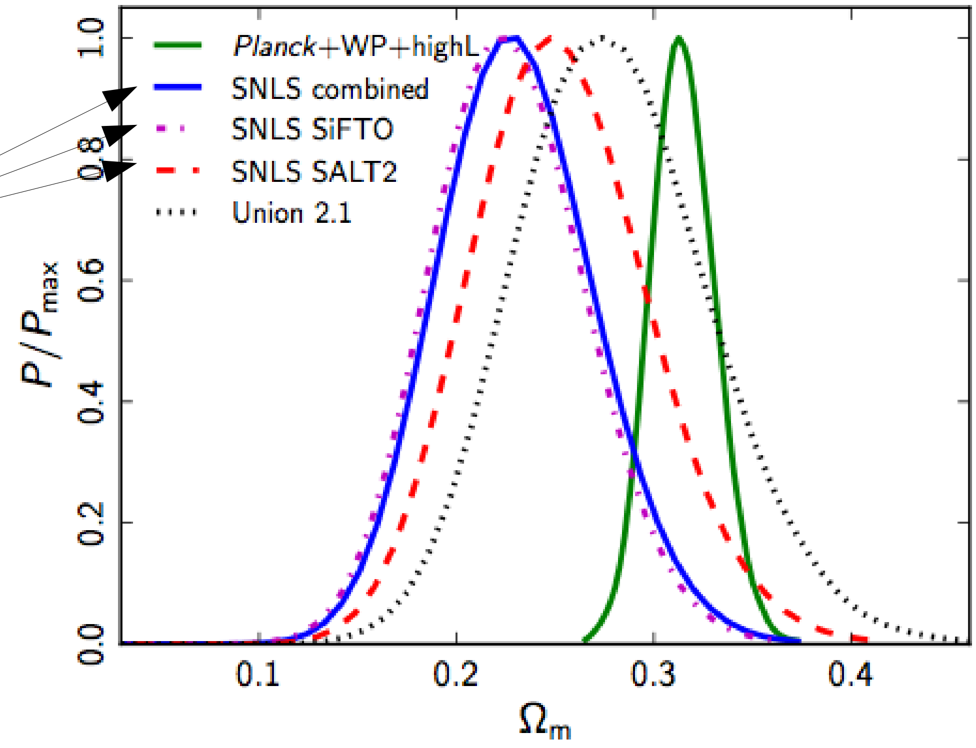



# Consistency with other data sets

- Reasonable consistency:
  - Type Ia supernova luminosity distances

Supernova light-curves

Different light-curve-fitting methods



# Consistency with other data sets

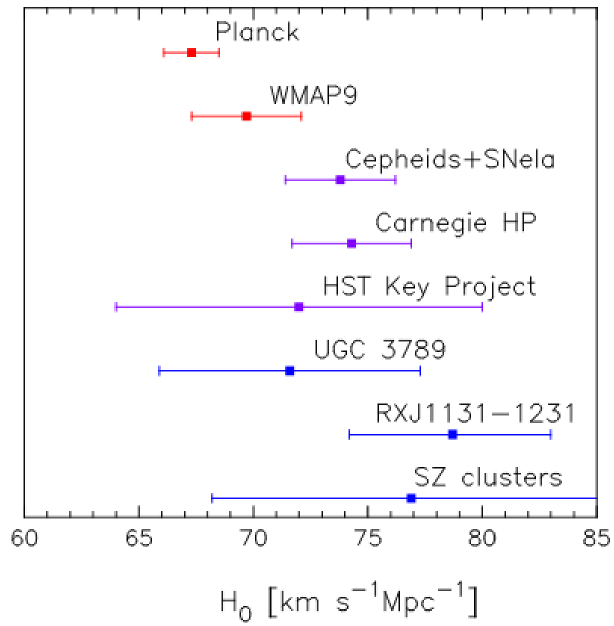
- Some inconsistency:
  - Cluster counts (~3σ)
  - CFHTLenS cosmic shear (~3σ)
  - SPT intermediate-scale data (~2.5σ)
    most likely a calibration issue with SPT
  - Measurements of the Hubble parameter (~2.5σ)

CMB + x-ray

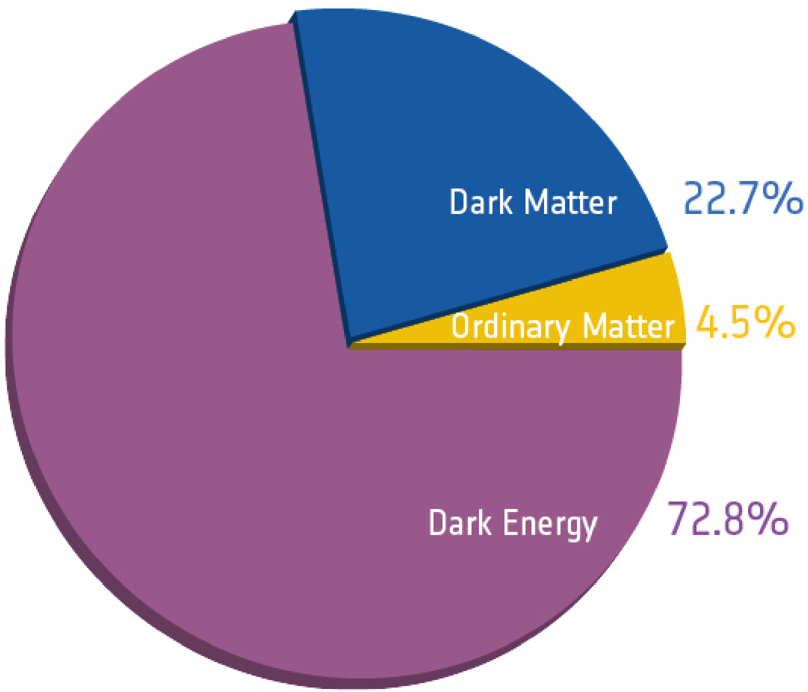
Galaxy weak lensing

CMB

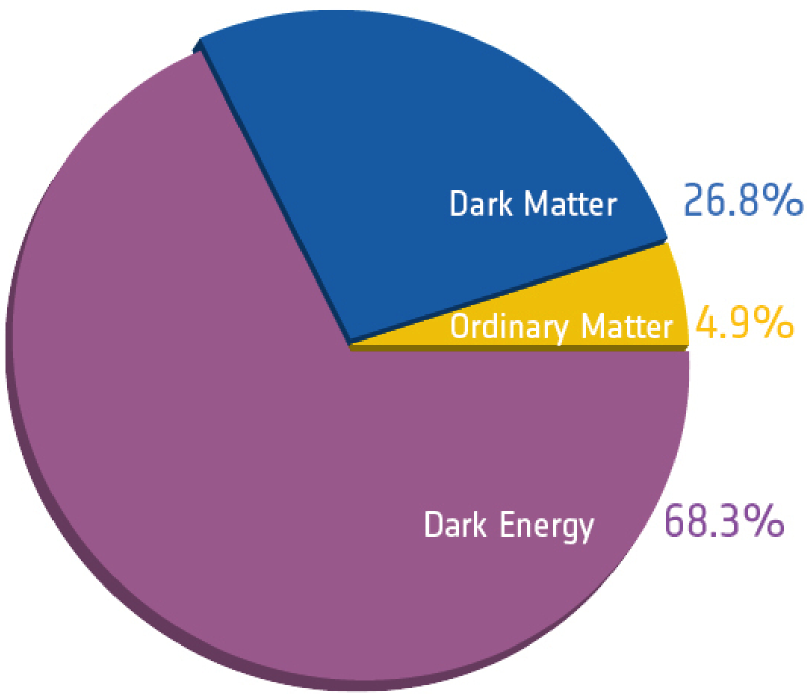
Supernova light-curves (+ astro)



# Total energy budget




Before Planck




After Planck

Change is due to shift in determination of the Hubble parameter

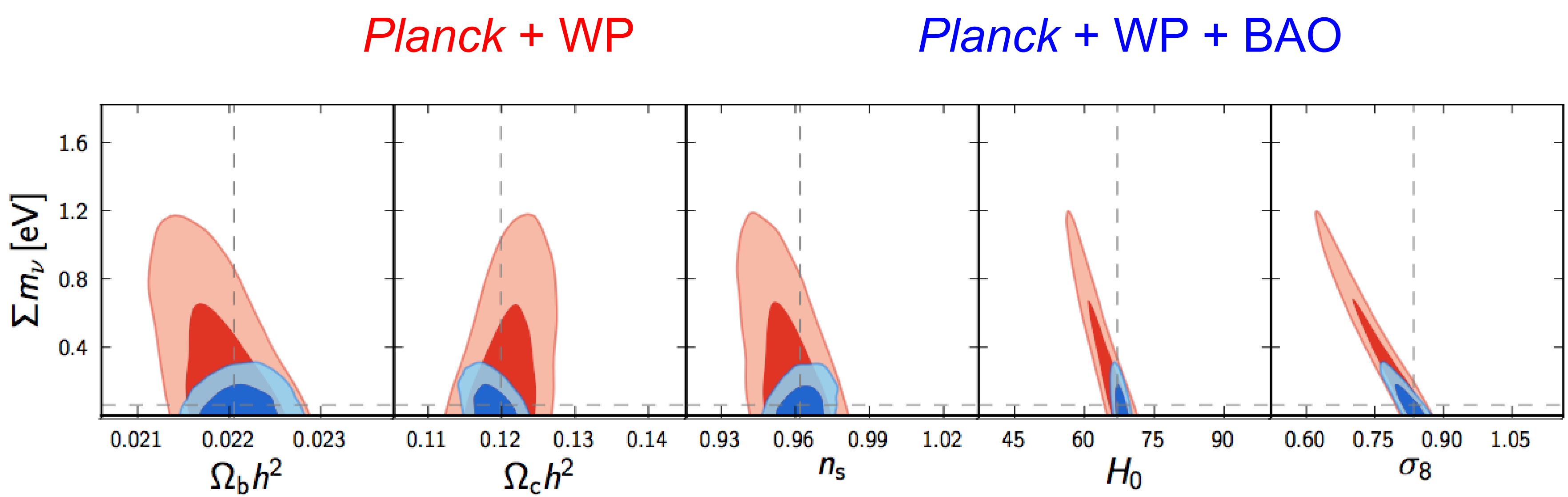
# Different models/data combinations: “the grid”

- Basic ΛCDM model plus eighteen different extensions
- Each of them fit with up to thirty-four combinations of Planck with external data sets
- Almost 400 pages of tables with parameter constraints
- Available online under:

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

# Constraints on the energy content

# Neutrino mass constraints




| | *Planck*+WP | | *Planck*+WP+BAO | | *Planck*+WP+highL | | *Planck*+WP+highL+BAO | |
|---|---|---|---|---|---|---|---|---|
| Parameter | Best fit | 95% limits | Best fit | 95% limits | Best fit | 95% limits | Best fit | 95% limits |
| $\Sigma m_\nu$ [eV] . . . . . . | 0.022 | $< 0.933$ | 0.002 | $< 0.247$ | 0.023 | $< 0.663$ | 0.000 | $< 0.230$ |

No evidence for neutrino masses

# Effective number of neutrino species

photon energy density

fermions vs. bosons

lower neutrino temperature

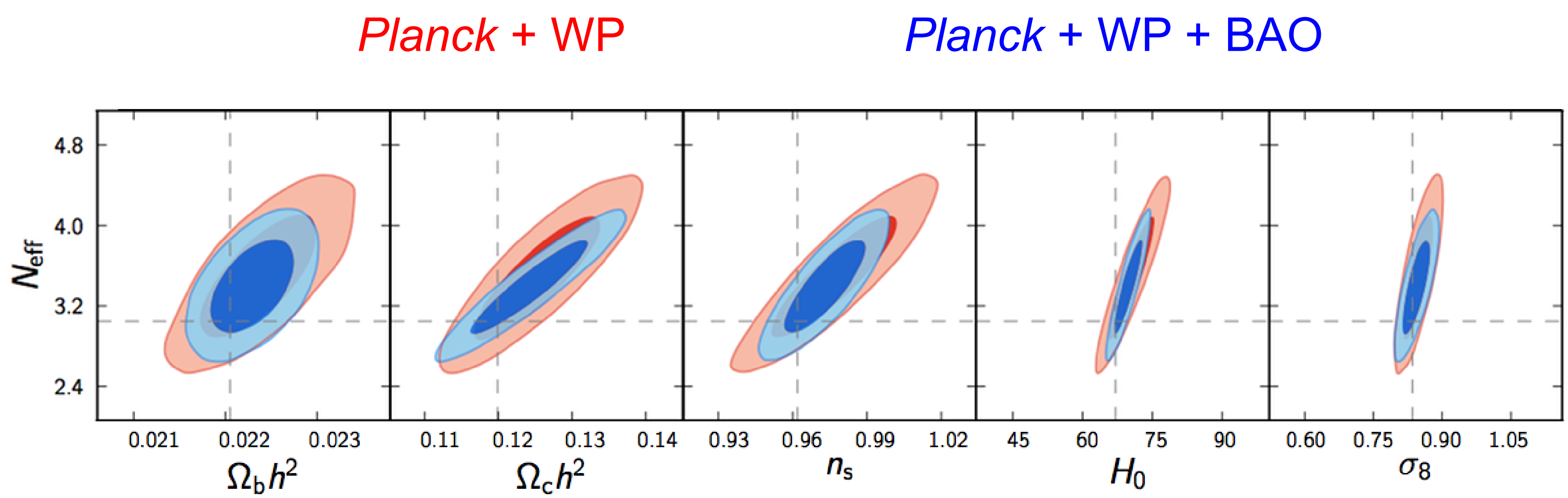
$$\rho_{\mathrm{r}} = \rho_{\gamma} \left[ 1 + N_{\mathrm{eff}} \frac{7}{8} \left( \frac{4}{11} \right)^{4/3} \right]$$

radiation energy density

effective number of neutrino species

Standard value: 3.046

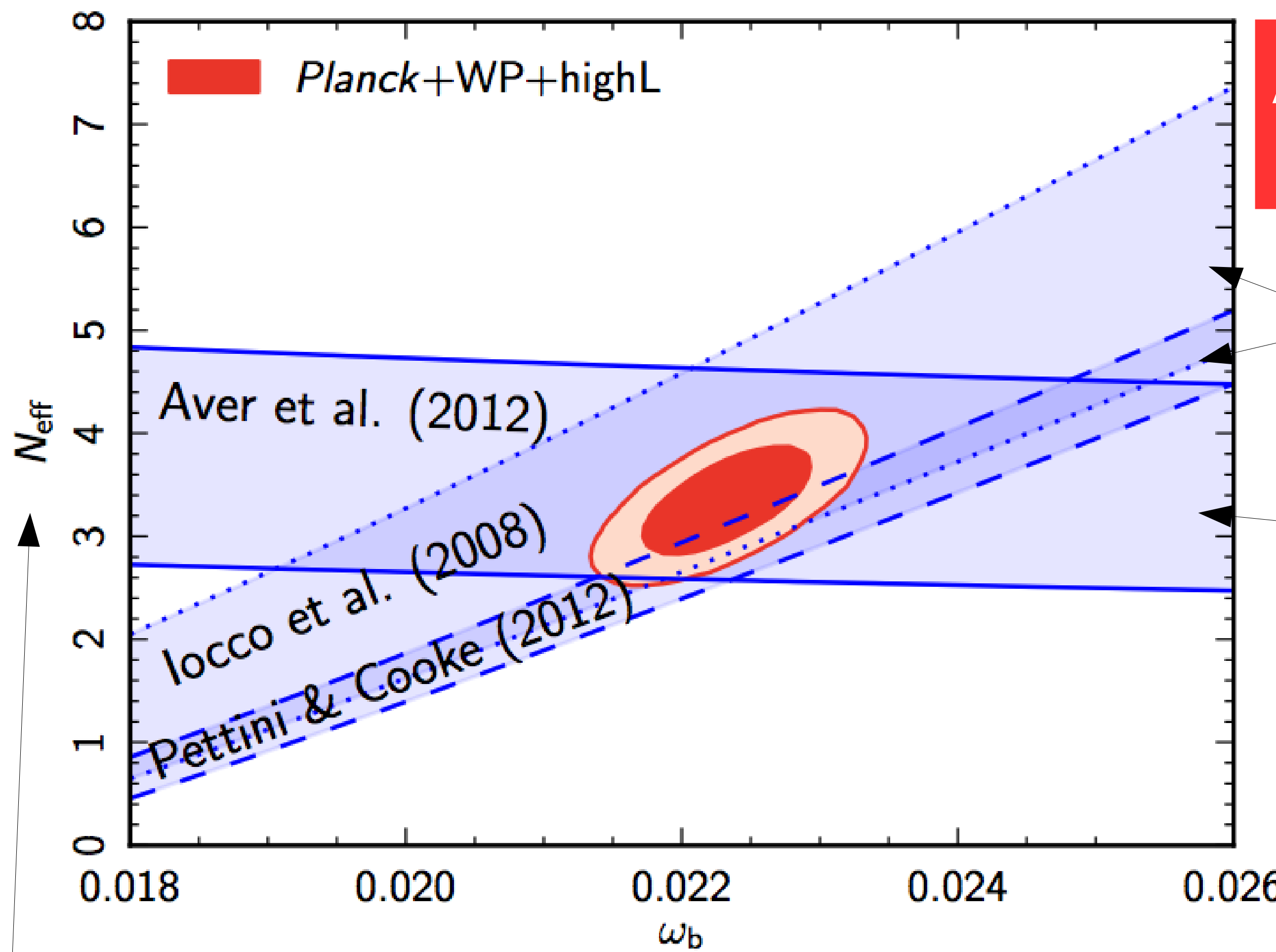
# Effective number of neutrino species




| | *Planck*+WP | | *Planck*+WP+BAO | | *Planck*+WP+highL | | *Planck*+WP+highL+BAO | |
|---|---|---|---|---|---|---|---|---|
| Parameter | Best fit | 95% limits | Best fit | 95% limits | Best fit | 95% limits | Best fit | 95% limits |
| $N_{\rm eff}$ . . . . . . . . . . | 3.08 | $3.51^{+0.80}_{-0.74}$ | 3.08 | $3.40^{+0.59}_{-0.57}$ | 3.23 | $3.36^{+0.68}_{-0.64}$ | 3.22 | $3.30^{+0.54}_{-0.51}$ |

No evidence for extra (“dark”) radiation

# Consistency with BBN and primordial element abundances




Astrophysically measured element abundances

Deuterium abundance + BBN

Helium abundance + BBN

Effective number of neutrino species

Baryon density

# Dark energy equation of state

dark energy pressure

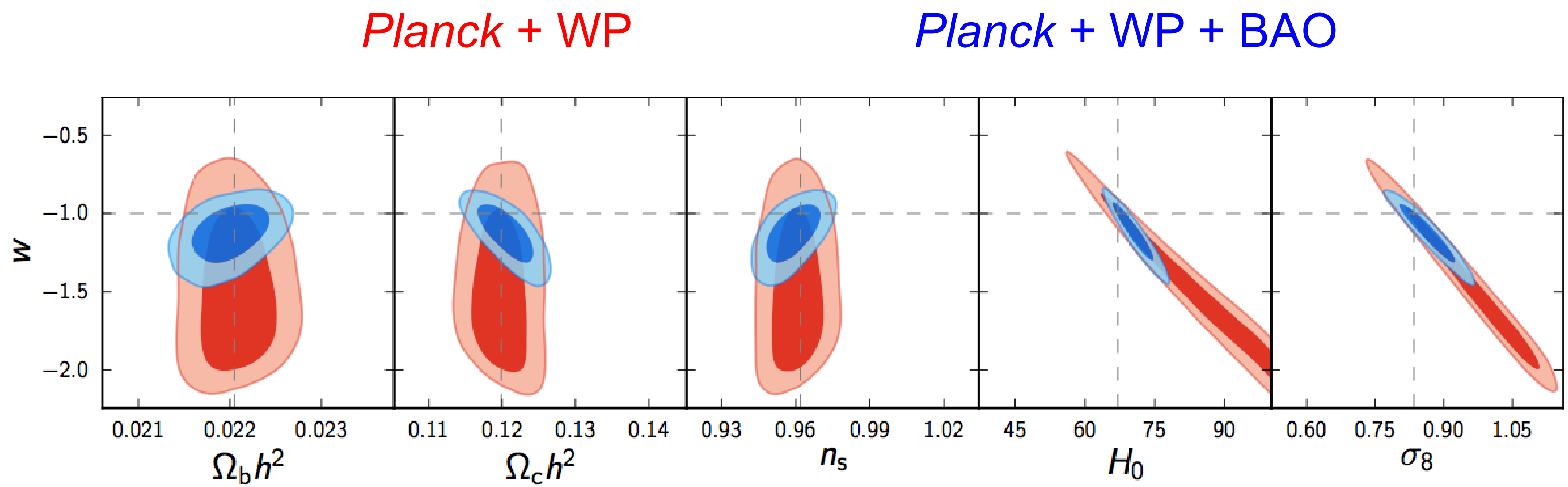
dark energy energy density

$$p_{\mathrm{DE}} = w\, \rho_{\mathrm{DE}}$$

dark energy equation of state parameter

Cosmological constant: $w = -1$

# Dark energy constraints




| | *Planck*+WP | | *Planck*+WP+BAO | | *Planck*+WP+highL | | *Planck*+WP+highL+BAO | |
|---|---|---|---|---|---|---|---|---|
| Parameter | Best fit | 95% limits | Best fit | 95% limits | Best fit | 95% limits | Best fit | 95% limits |
| $w$ . . . . . . . . . . . | −1.20 | $-1.49^{+0.65}_{-0.57}$ | −1.076 | $-1.13^{+0.24}_{-0.25}$ | −1.20 | $-1.51^{+0.62}_{-0.53}$ | −1.109 | $-1.13^{+0.23}_{-0.25}$ |

No evidence for departure from cosmological constant

# Spatial curvature

sum of energy densities

Friedmann equation

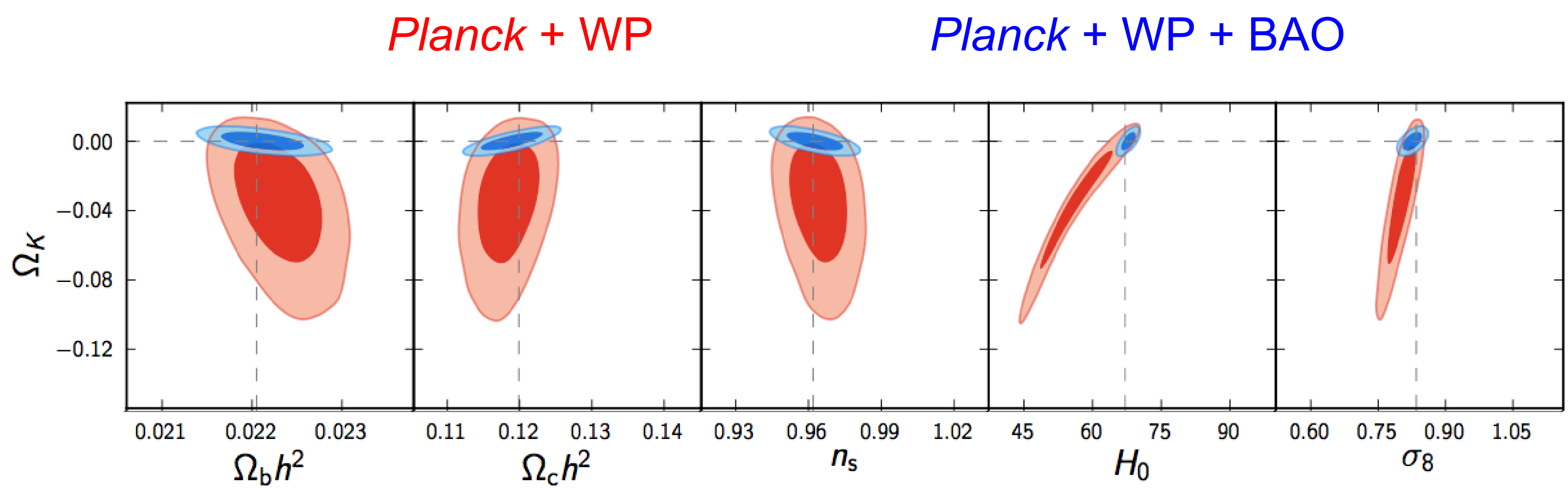
$$\frac{1}{\rho_c}\sum_i \rho_i = 1 + \Omega_k$$

critical density

curvature parameter

Spatial flatness: $\Omega_k = 0$

# Spatial curvature constraints

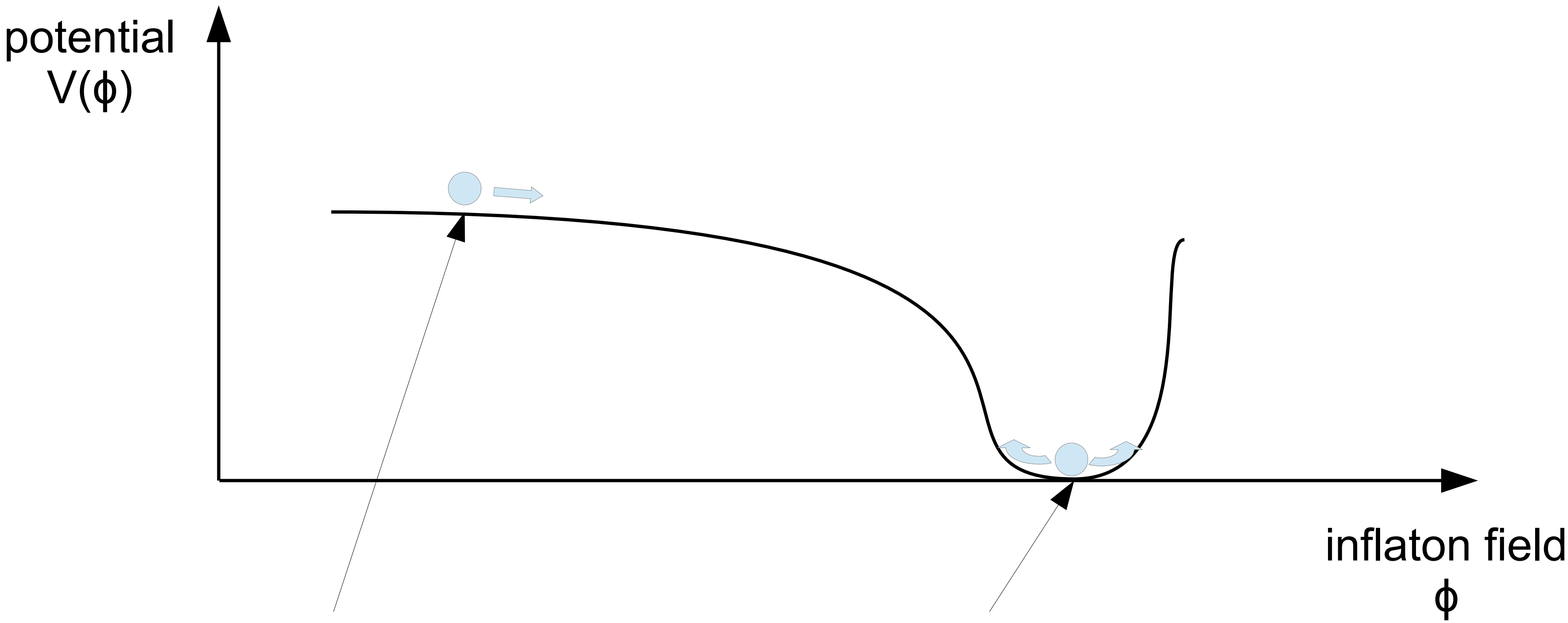



| | *Planck*+WP | | *Planck*+WP+BAO | | *Planck*+WP+highL | | *Planck*+WP+highL+BAO | |
|---|---|---|---|---|---|---|---|---|
| Parameter | Best fit | 95% limits | Best fit | 95% limits | Best fit | 95% limits | Best fit | 95% limits |
| $\Omega_K$ . . . . . . . . . . | −0.0105 | $-0.037^{+0.043}_{-0.049}$ | 0.0000 | $0.0000^{+0.0066}_{-0.0067}$ | −0.0111 | $-0.042^{+0.043}_{-0.048}$ | 0.0009 | $-0.0005^{+0.0065}_{-0.0066}$ |

No evidence for non-zero spatial curvature

# Initial perturbations: inflation

# The origin of the primordial perturbations: inflation



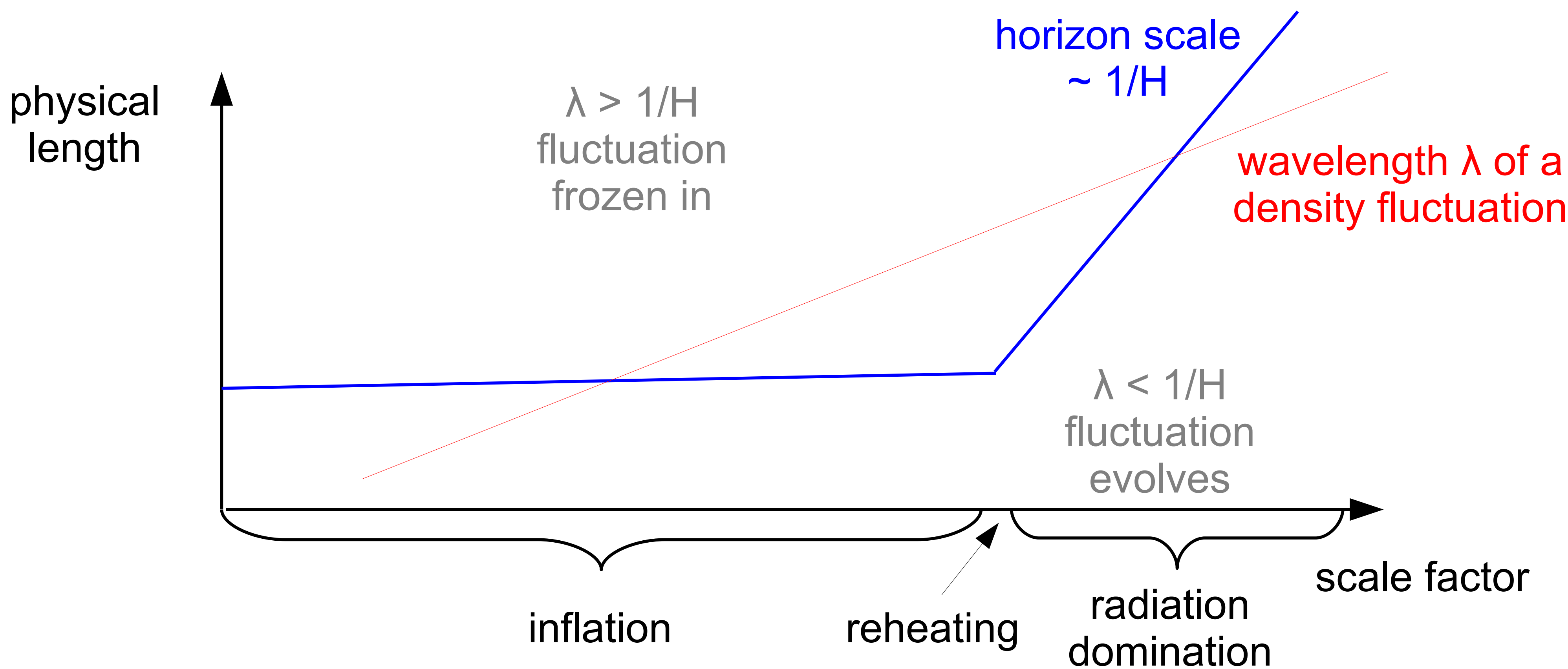

Potential energy domination:

- Scale factor grows exponentially with time
- Hubble parameter close to constant
- Space is flattened

Reheating

- Potential energy is converted to standard model particles

# The origin of the primordial perturbations: inflation




Quantum fluctuations of ϕ are stretched beyond the horizon and freeze in

# Predictions of the simplest models

single-field canonical slow-roll inflation

- Adiabatic initial conditions
- Nearly Gaussian initial fluctuations $f_{NL} < 1$
- Background of gravitational waves (tensor perturbations, model-dependent)
- Almost (but not exactly) scale-invariant curvature perturbations
- Spatial flatness $\Omega_K \sim 10^{-5}$ ✓

# The scale-invariant (HZ-) spectrum

*Planck* + WP data

| | HZ | ΛCDM |
|---|---|---|
| $10^5\Omega_b h^2$ | $2296 \pm 24$ | $2205 \pm 28$ |
| $10^4\Omega_c h^2$ | $1088 \pm 13$ | $1199 \pm 27$ |
| $100\,\theta_{MC}$ | $1.04292 \pm 0.00054$ | $1.04131 \pm 0.00063$ |
| $\tau$ | $0.125^{+0.016}_{-0.014}$ | $0.089^{+0.012}_{-0.014}$ |
| $\ln(10^{10}A_s)$ | $3.133^{+0.032}_{-0.028}$ | $3.089^{+0.024}_{-0.027}$ |
| $n_s$ | — | $0.9603 \pm 0.0073$ |
| $N_{eff}$ | — | — |
| $Y_P$ | — | — |
| $-2\Delta\ln(\mathcal{L}_{max})$ | 27.9 | 0 |

Scale-invariant spectrum ($n_s$ = 1, "white noise") is now ruled out at more than 5σ from *Planck* + WP data alone

Even for extended models, still disfavoured at 3σ, when combined with BAO data

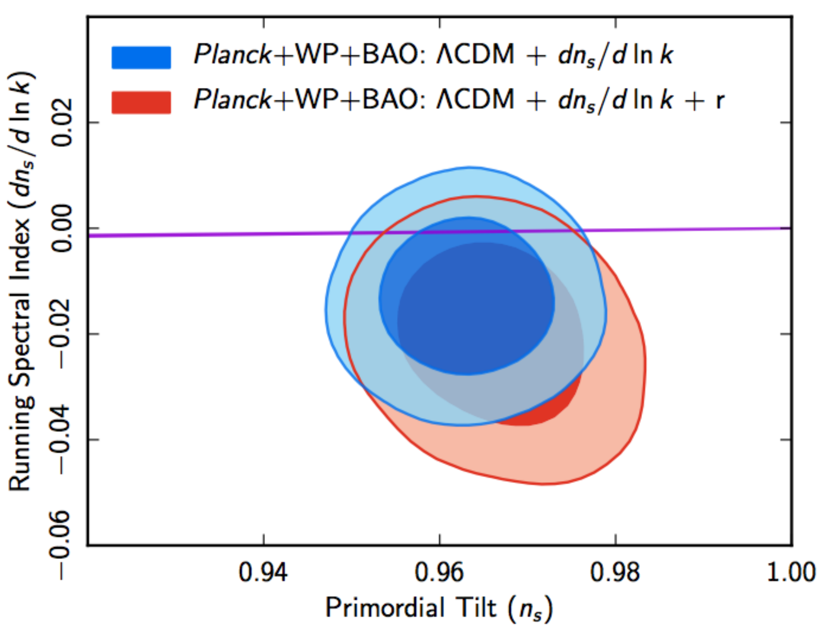
→ strong argument for dynamical generation of primordial perturbation

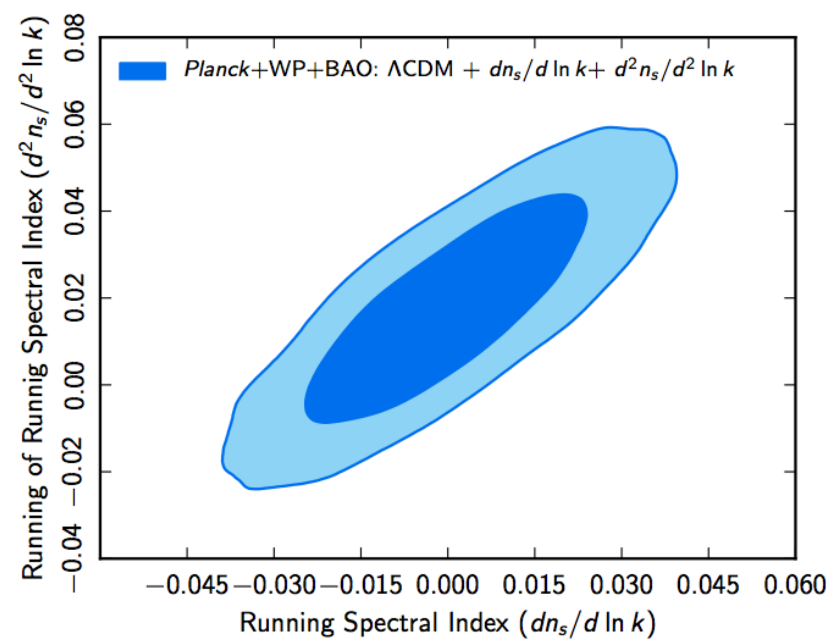
# Higher order terms in the power spectrum

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

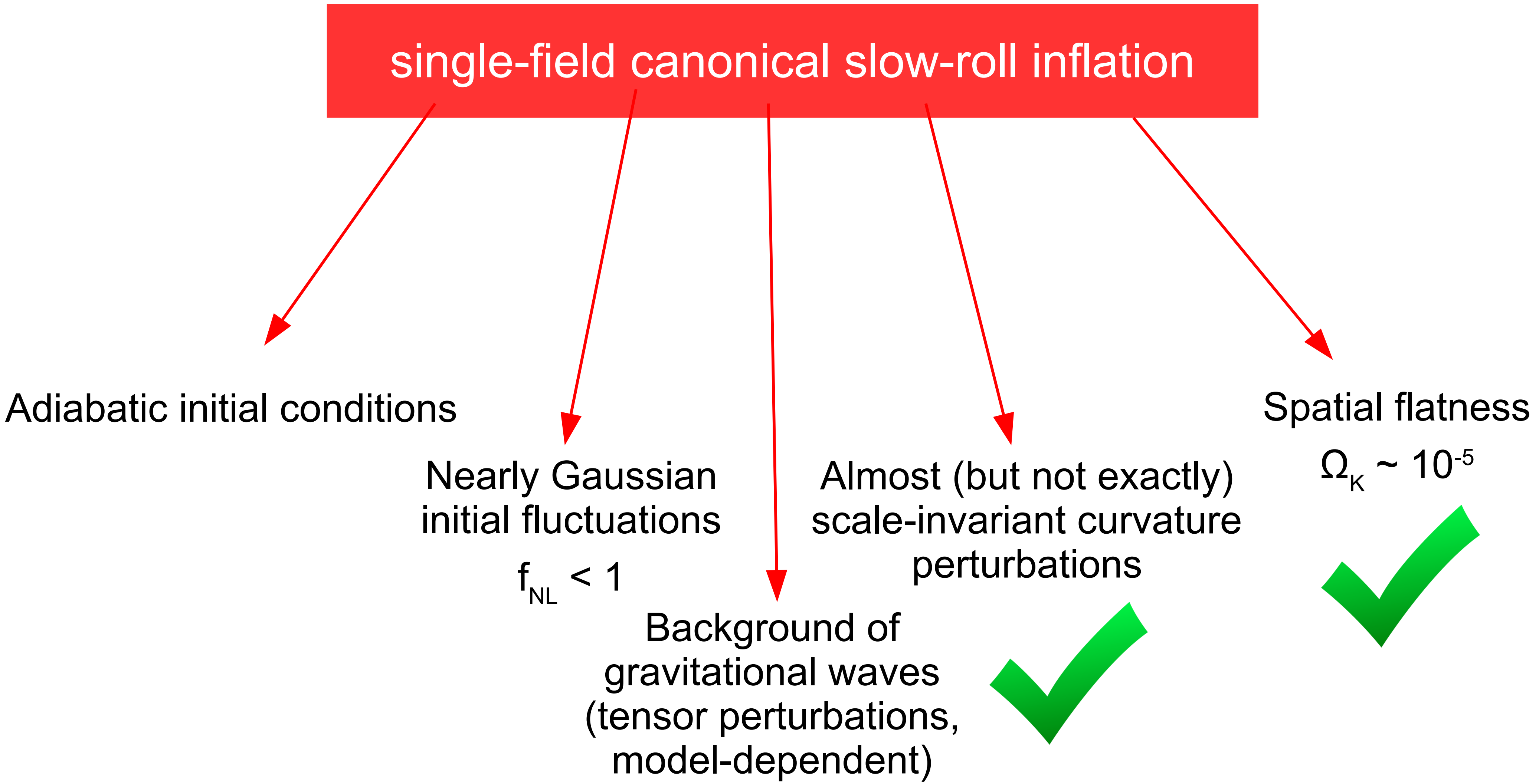
running
of the spectral index

running of the running
of the spectral index

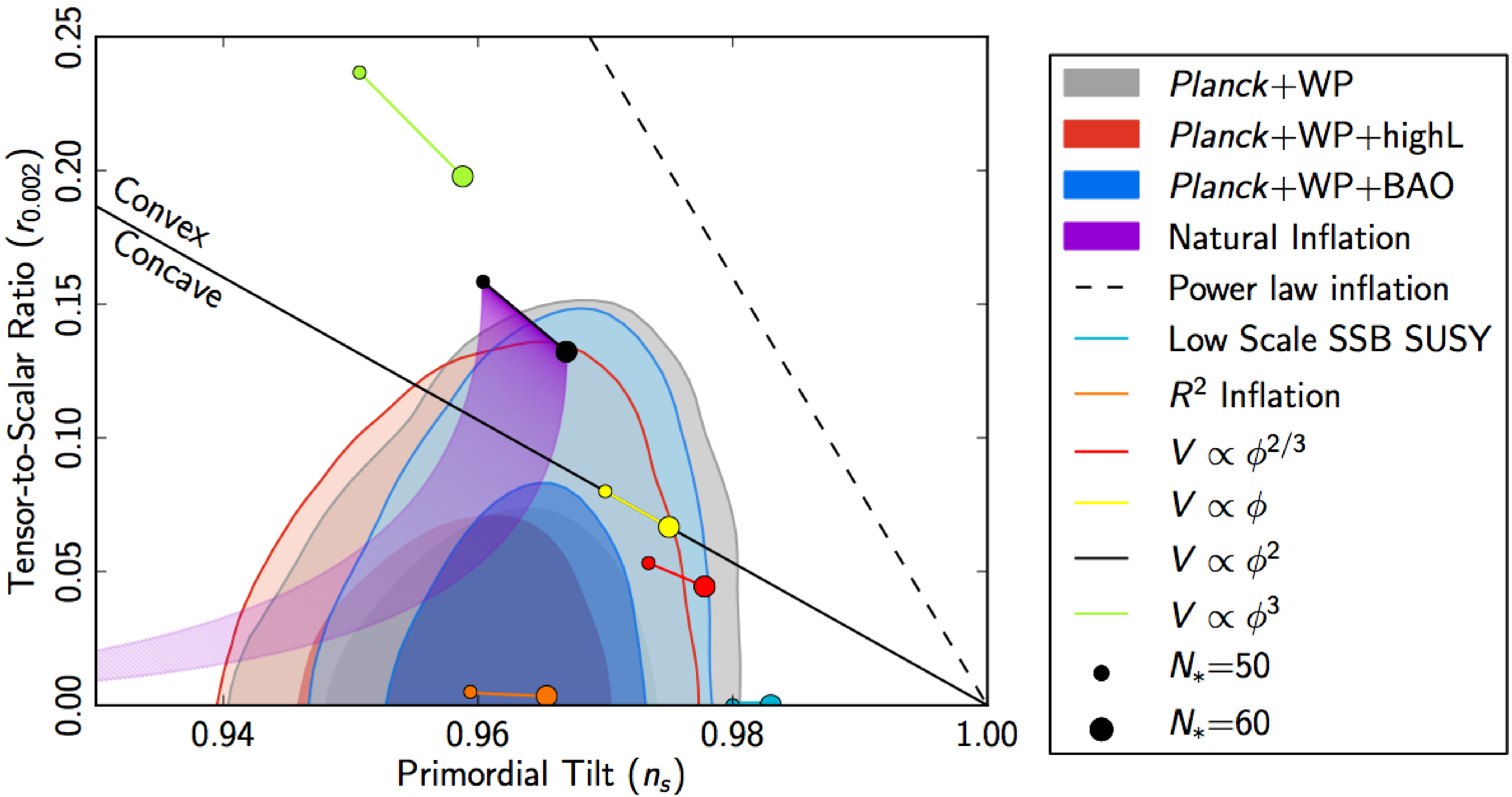


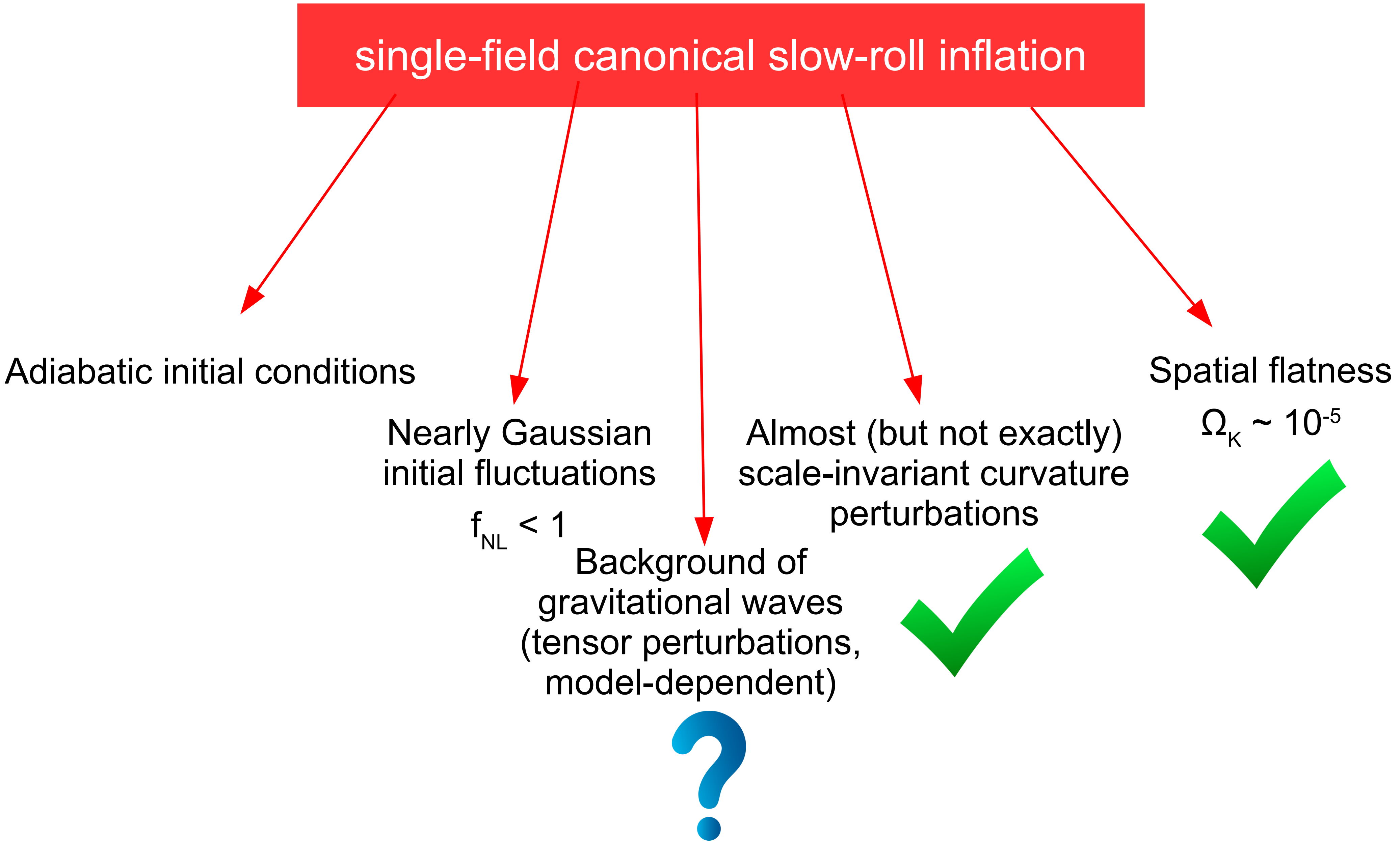
# Predictions of the simplest models



# Constraints on a selection of inflation models



# Predictions of the simplest models



# Non-Gaussianity

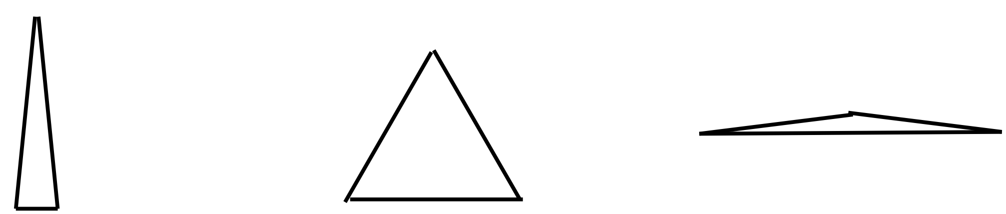
$$\underbrace{\langle \Phi(\vec{k}_1)\Phi(\vec{k}_2)\Phi(\vec{k}_3)\rangle}_{\text{Three-point correlation}} = (2\pi)^3\, \delta^{(3)}(\vec{k}_1 + \vec{k}_2 + \vec{k}_3)\, \underbrace{f_{\rm NL}\; F(k_1, k_2, k_3)}_{\text{Bispectrum}}$$

Three-point correlation

Bispectrum

enforces triangular configurations

Three limiting cases



| $f_{\rm NL}$ | | |
|---|---|---|
| Local | Equilateral | Orthogonal |
| 2.7 ± 5.8 | −42 ± 75 | −25 ± 39 |

# Predictions of the simplest models

single-field canonical slow-roll inflation

Adiabatic initial conditions

Nearly Gaussian initial fluctuations

$f_{NL} < 1$ ✓

Background of gravitational waves (tensor perturbations, model-dependent) ?

Almost (but not exactly) scale-invariant curvature perturbations ✓

Spatial flatness

$\Omega_K \sim 10^{-5}$ ✓

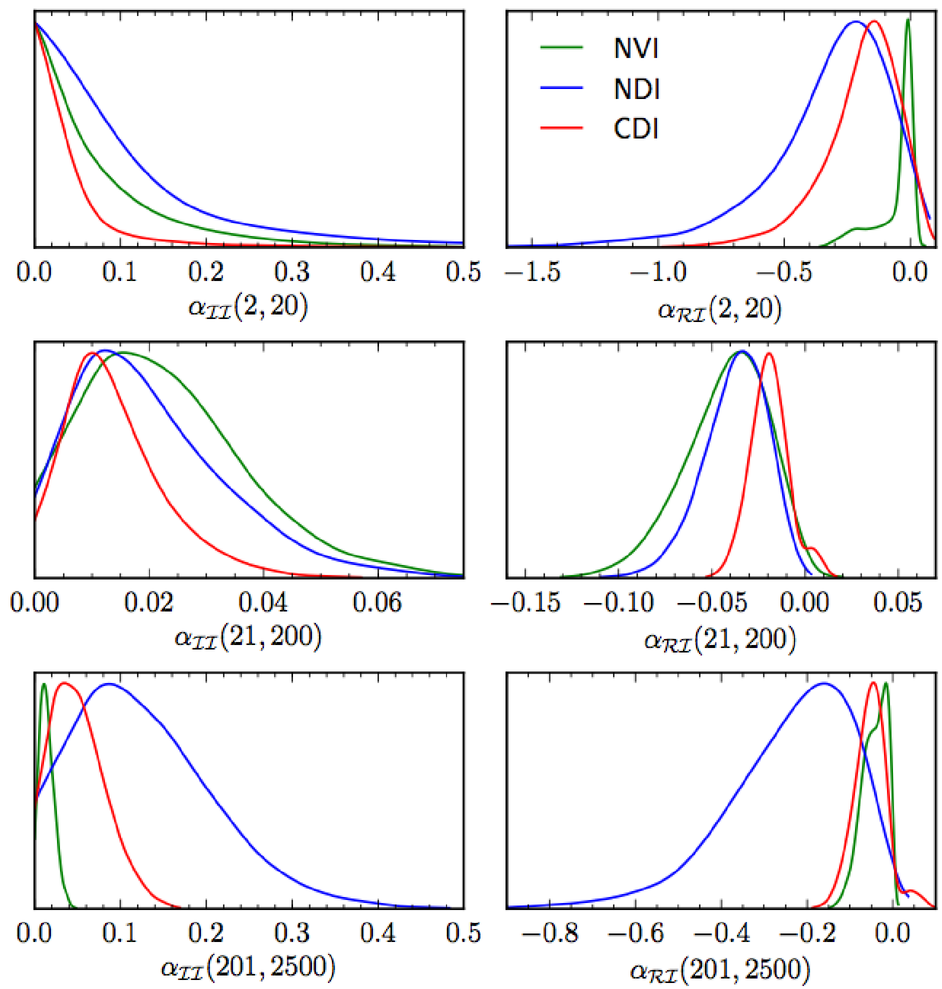
# Adiabaticity: constraints on isocurvature perturbations

Isocurvature fraction at ...

Large scales

Intermediate scales

Small scales




Types of isocurvature

Neutrino velocity

Neutrino density

CDM density

# Predictions of the simplest models

single-field canonical slow-roll inflation

is in a good shape!

Adiabatic initial conditions

Nearly Gaussian initial fluctuations

$f_{NL} < 1$

Background of gravitational waves (tensor perturbations, model-dependent)

?

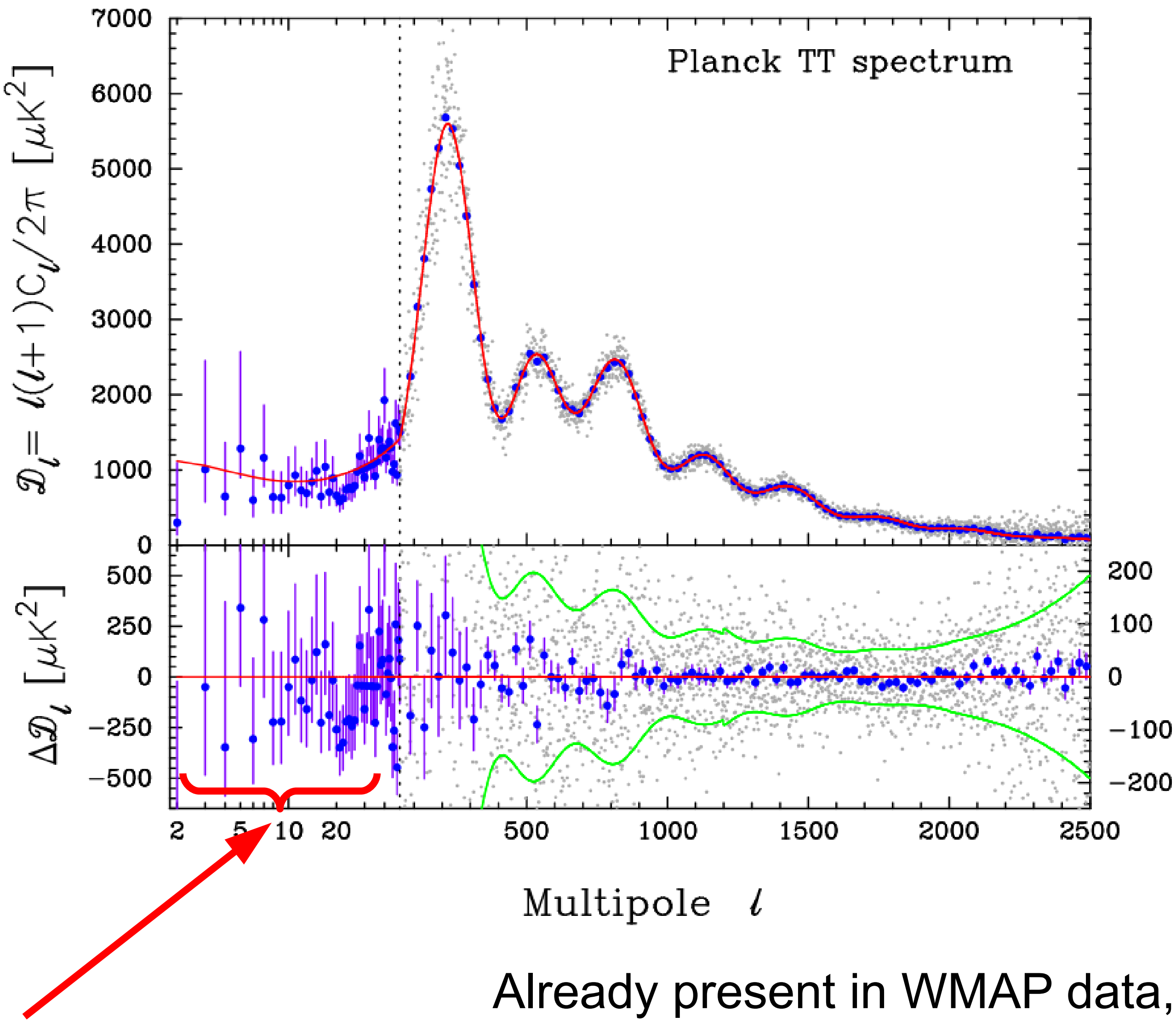
Almost (but not exactly) scale-invariant curvature perturbations

Spatial flatness

$\Omega_K \sim 10^{-5}$

# Anomalies?

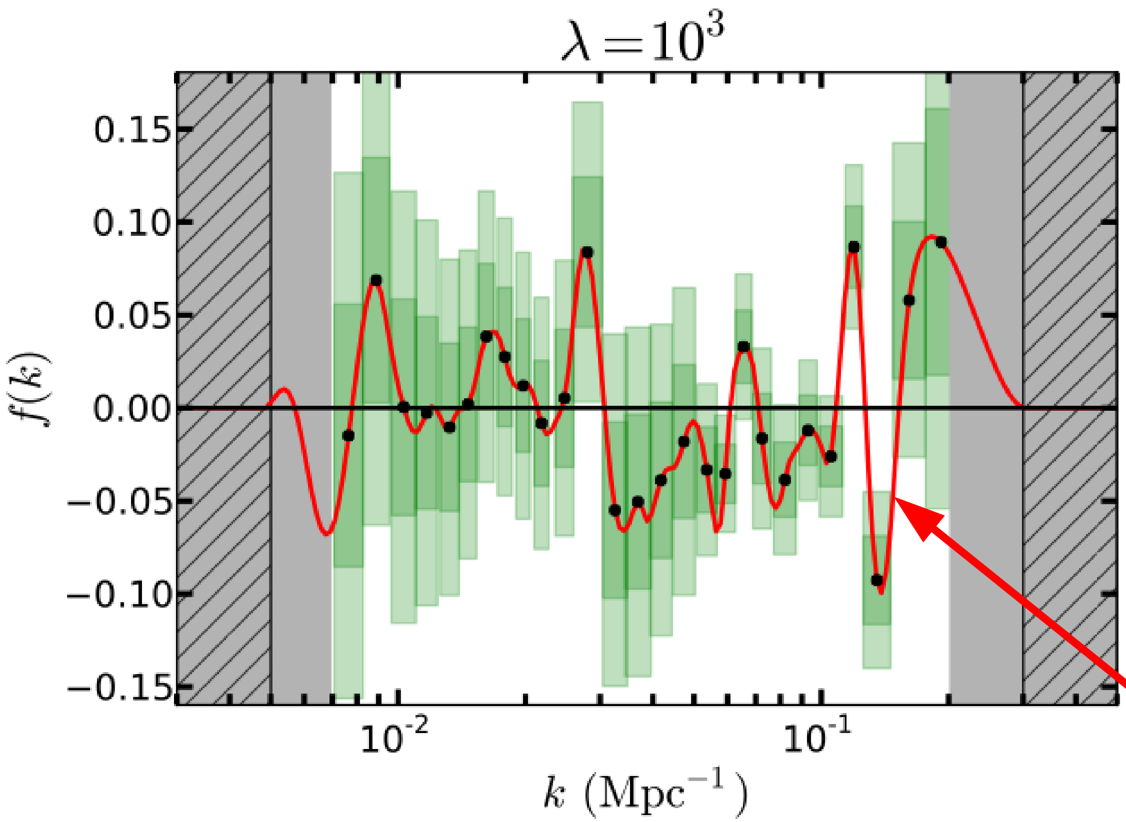
# A lack of power at large scales?

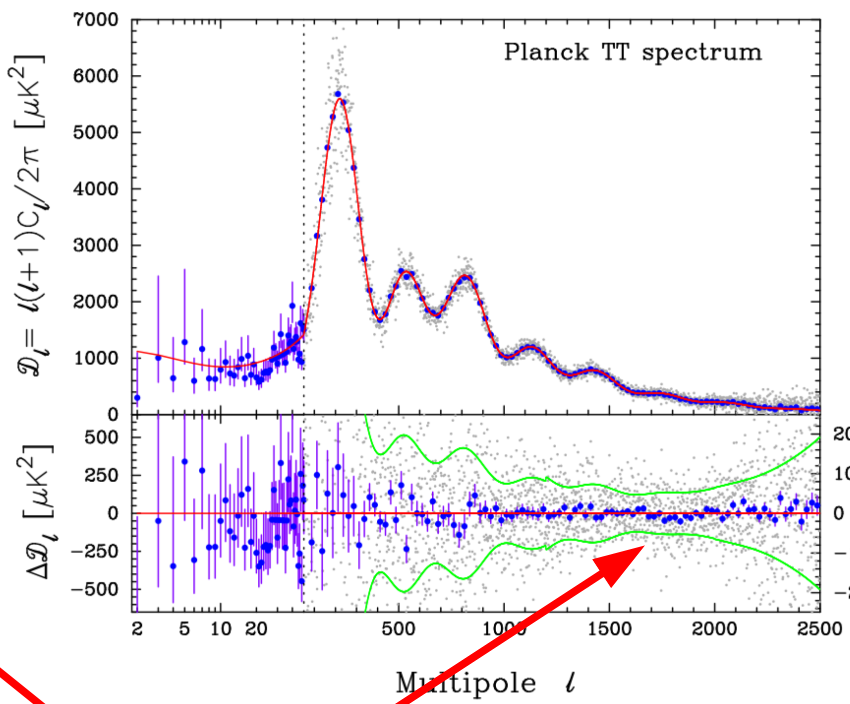



Already present in WMAP data,
but exacerbated by better smale scale data

# A feature at small scales?

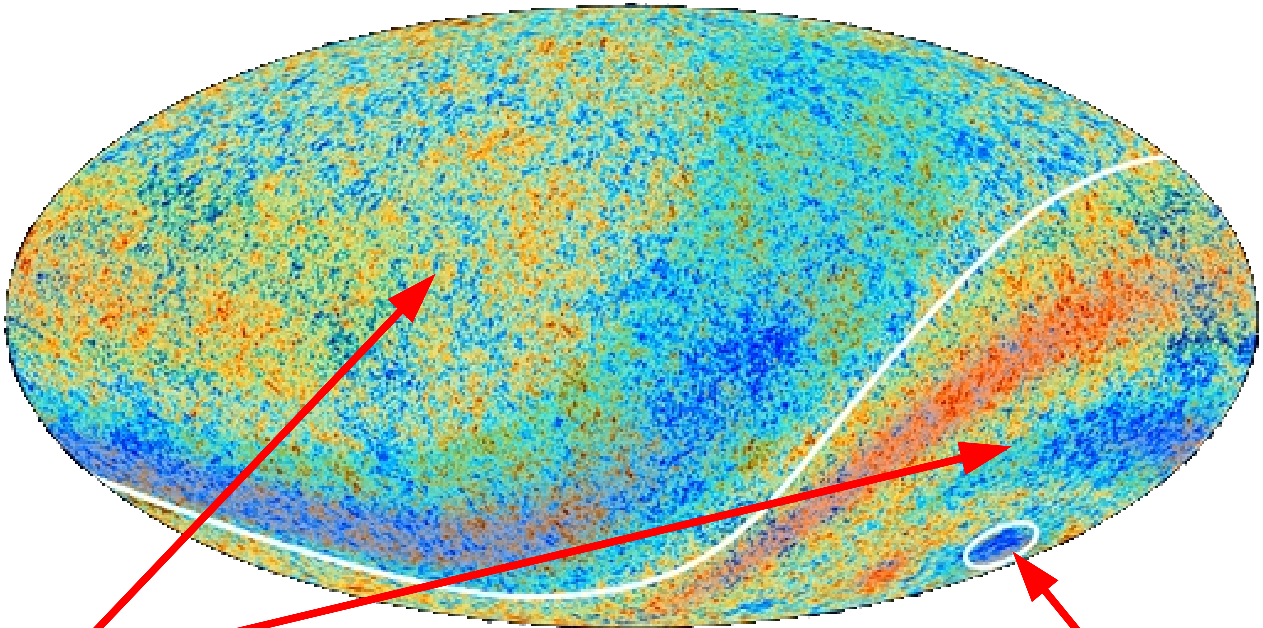
Non-parametric reconstruction of the primordial power spectrum



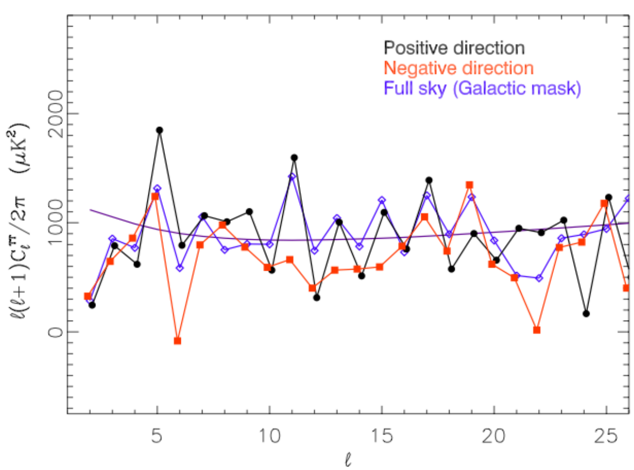

About 3σ significance

# Violation of statistical isotropy?



Hemispherical difference in power?

The “cold spot”




Already known from WMAP data, confirmation that these features are not due to data processing

# Conclusions

- Planck has delivered an exquisite measurement of the CMB temperature anisotropies, extracting close to the maximum achievable amount of information from this observable
- The ΛCDM model continues to provide an overall very good description of the data, the Universe did not have any surprises in store for us
- In addition, interesting measurements of CMB lensing, ISW effect, SZ clusters, the CMB dipole and constraints on primordial non-Gaussianity
- Old and new anomalies of weak to moderate significance still unexplained
- Planck full mission data (including polarisation data) will be released next year