Cosmology results from Planck

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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

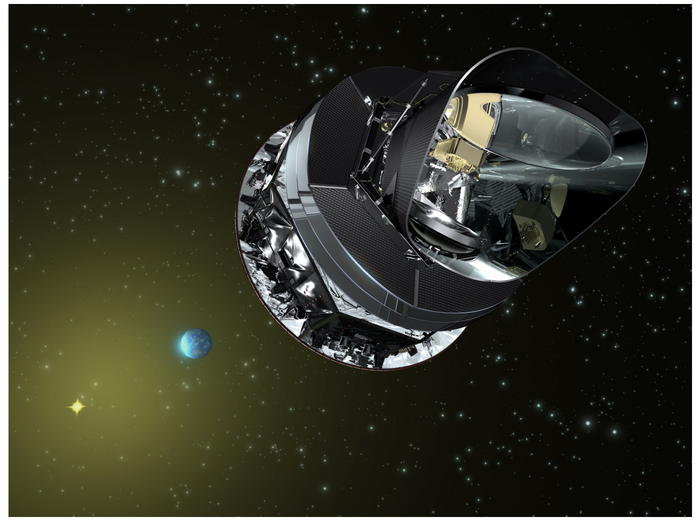
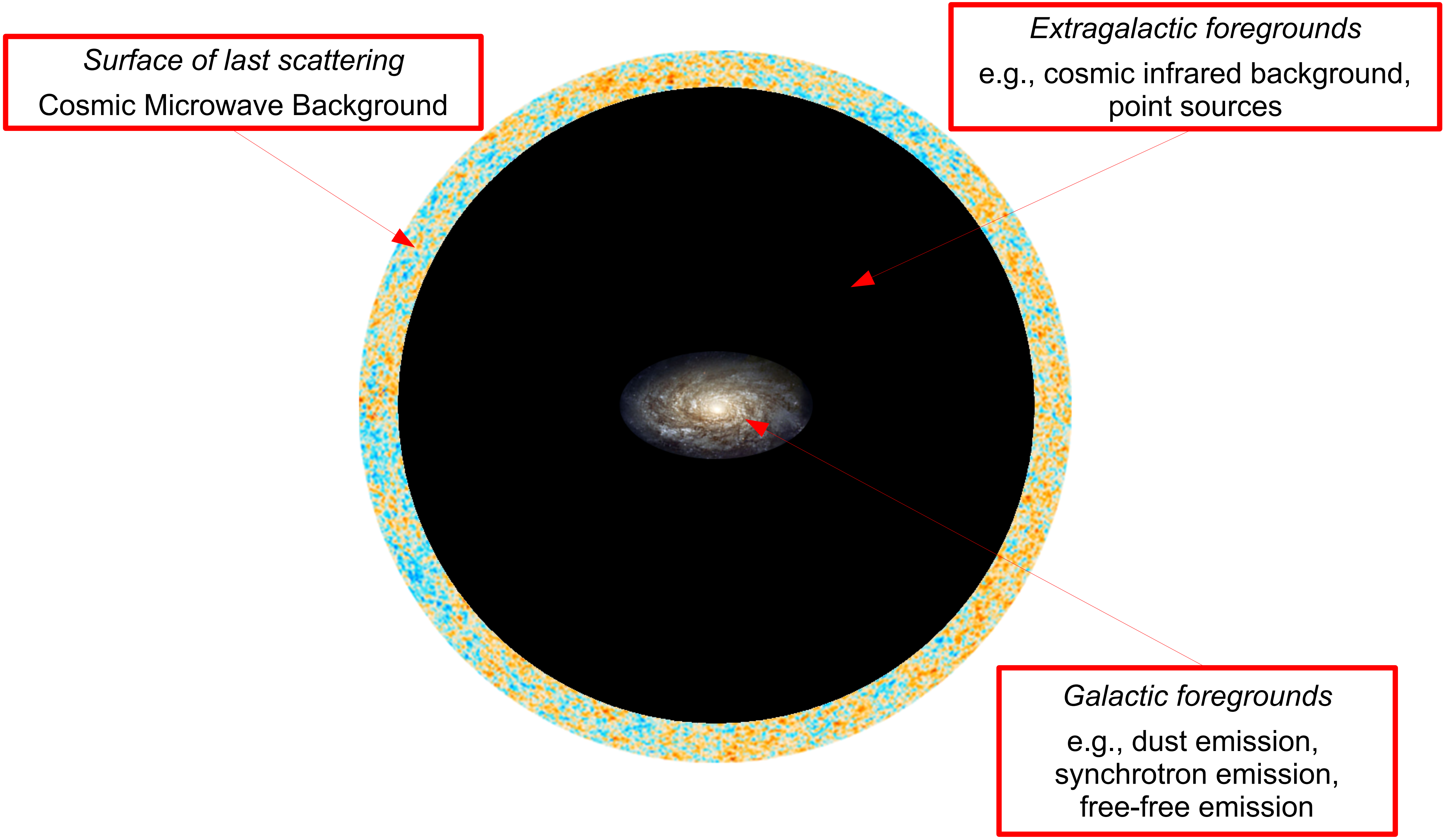


Table 2. *Planck* performance parameters determined from flight data.

	Channel	$N_{detectors}$ [a]	ν_{center} [b] [GHz]	Scanning Beam [c] FWHM [arcm]	Scanning Beam [c] Ellipticity	Noise [d] Sensitivity [μK_{RJ} $s^{1/2}$]	Noise [d] Sensitivity [μK_{CMB} $s^{1/2}$]
LFI	30 GHz	4	28.4	33.16	1.37	145.4	148.5
LFI	44 GHz	6	44.1	28.09	1.25	164.8	173.2
LFI	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
HFI	143 GHz	11	143	7.18	1.04	10.38	17.4
HFI	217 GHz	12	217	4.87	1.22	7.45	23.8
HFI	353 GHz	12	353	4.7	1.2	5.52	78.8
HFI	545 GHz	3	545	4.73	1.18	2.66	0.0259[d]
HFI	857 GHz	4	857	4.51	1.38	1.33	0.0259[d]

What does Planck see? Microwave sources



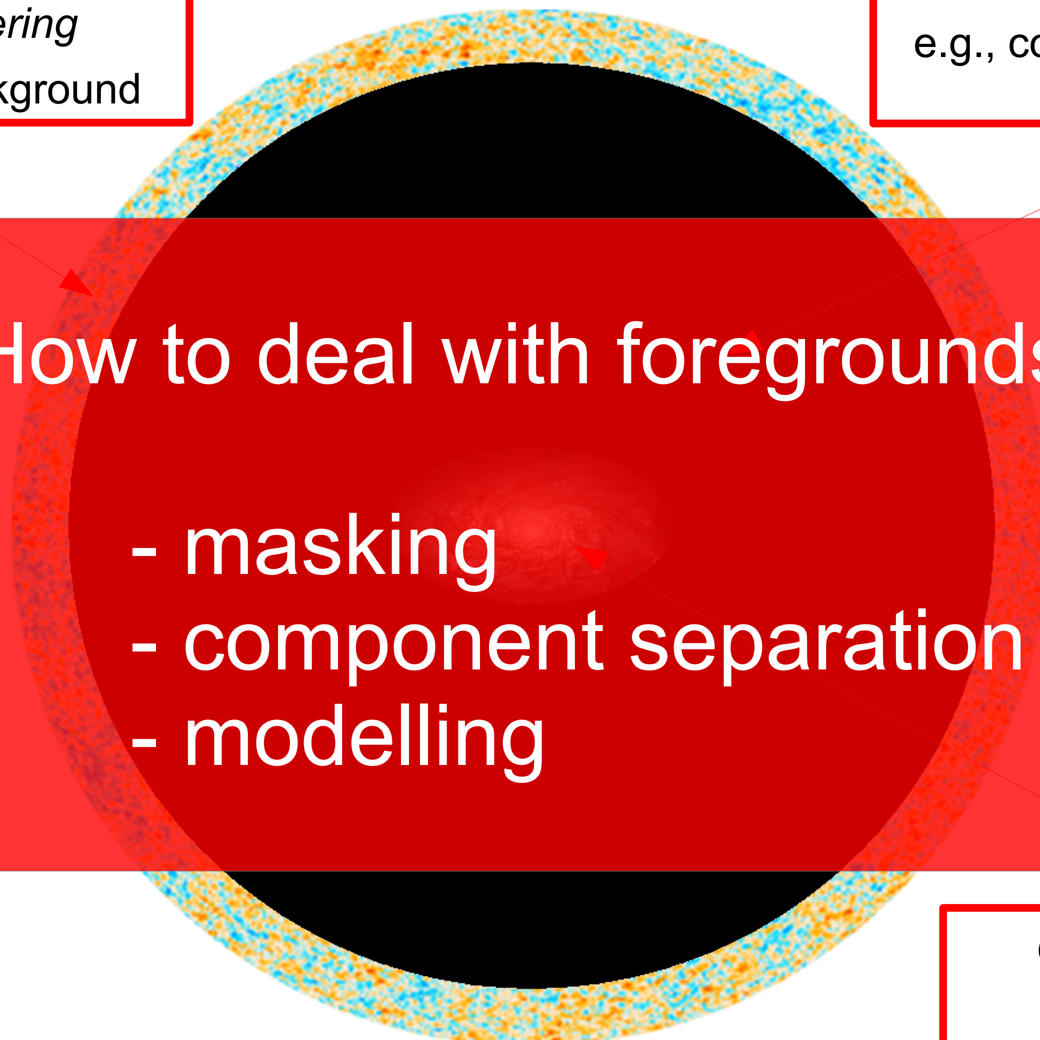
What does Planck see? Microwave sources

Surface of last scattering

Cosmic Microwave Background

Extragalactic foregrounds

e.g., cosmic infrared background, point sources



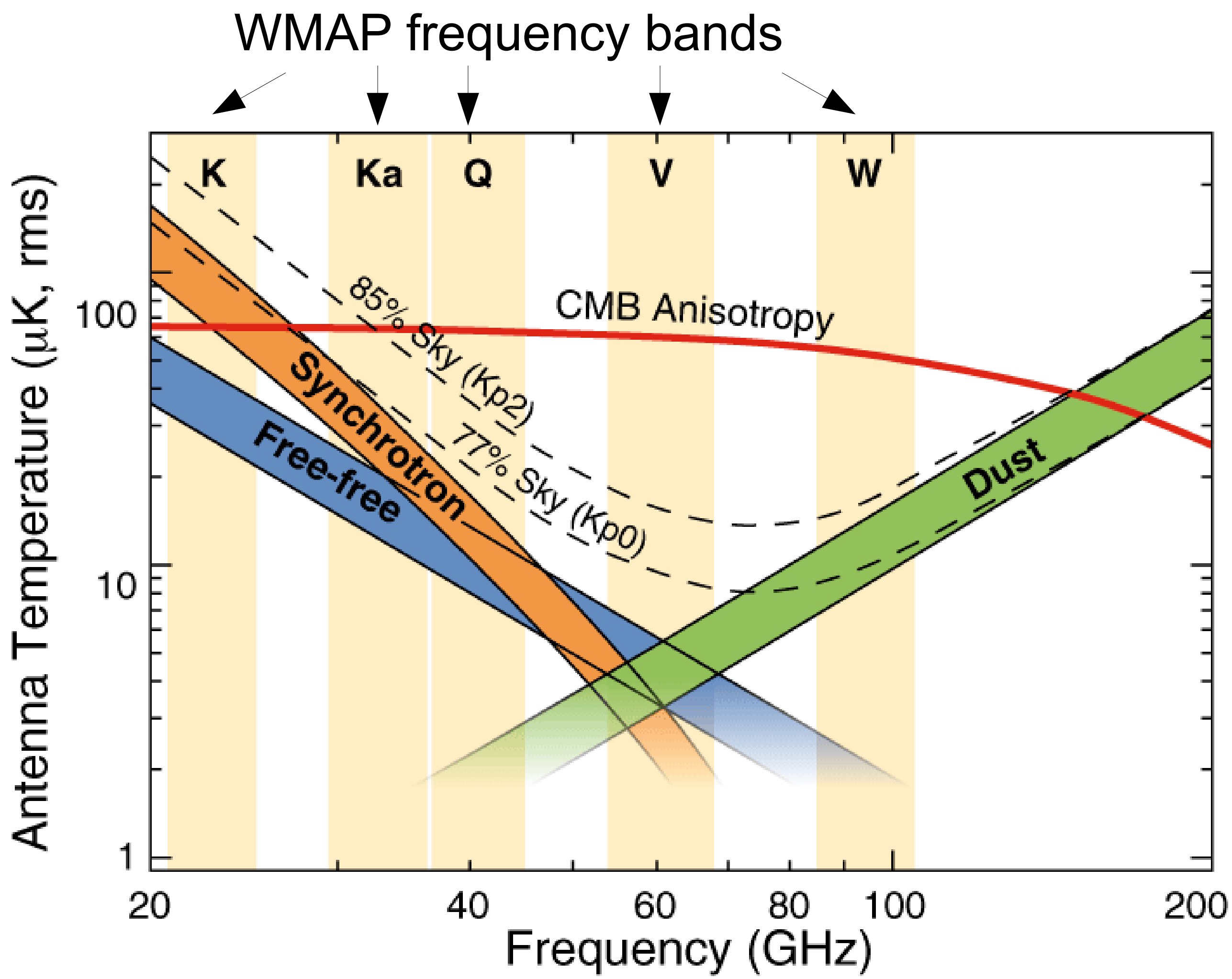
How to deal with foregrounds?

- masking
- component separation
- modelling

Galactic foregrounds

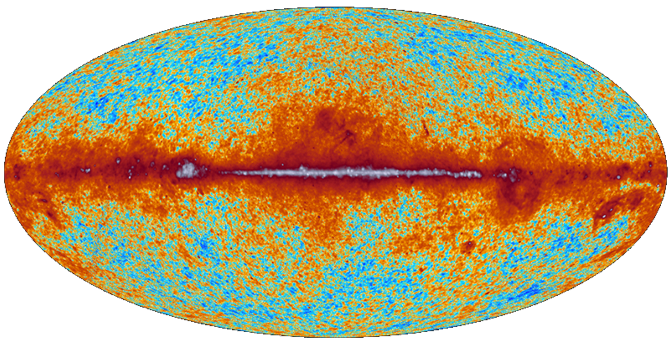
e.g., dust emission, synchrotron emission, free-free emission

Galactic foregrounds

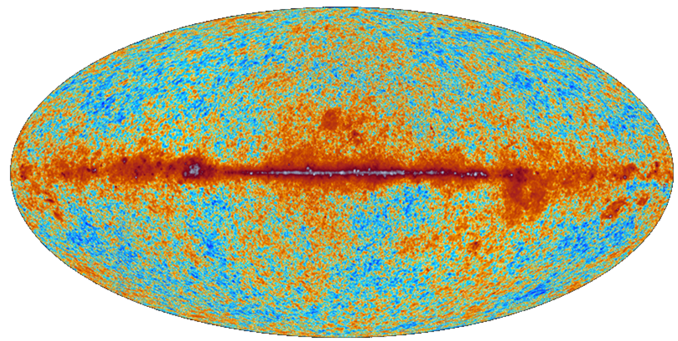


Galactic foregrounds have different frequency dependences
→ use multi-frequency information for separating components

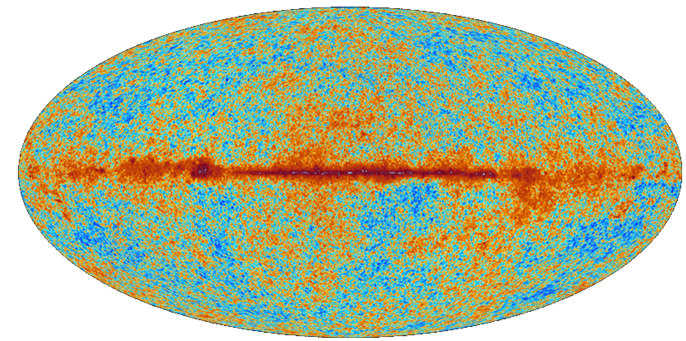
Planck's view of the microwave sky



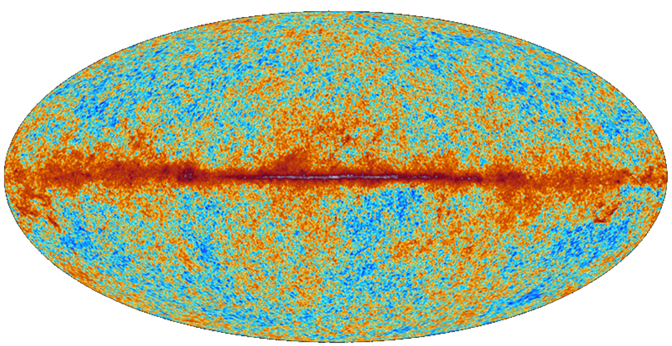
30 Ghz



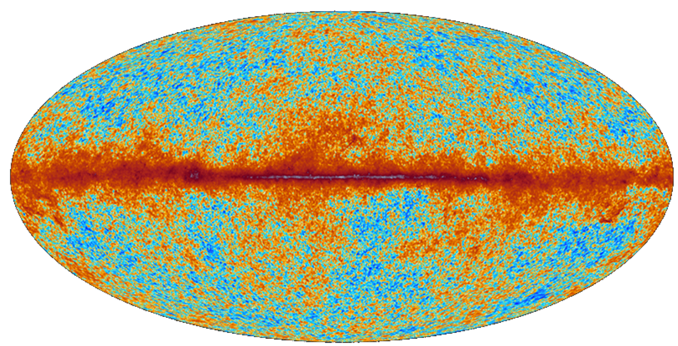
44 Ghz



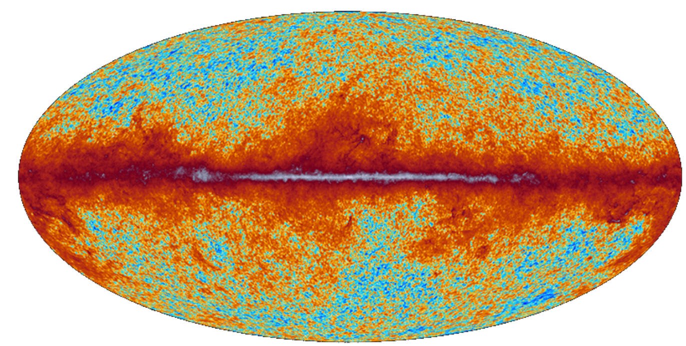
70 Ghz



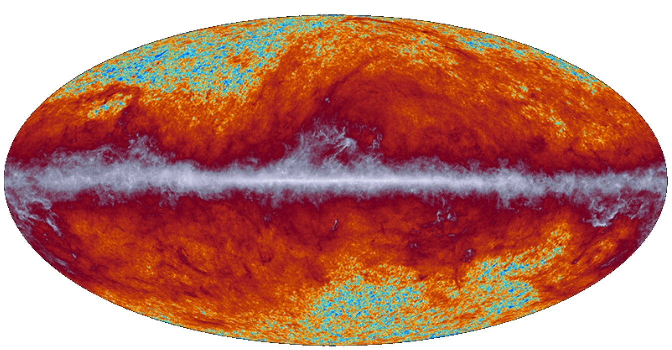
100 GHz



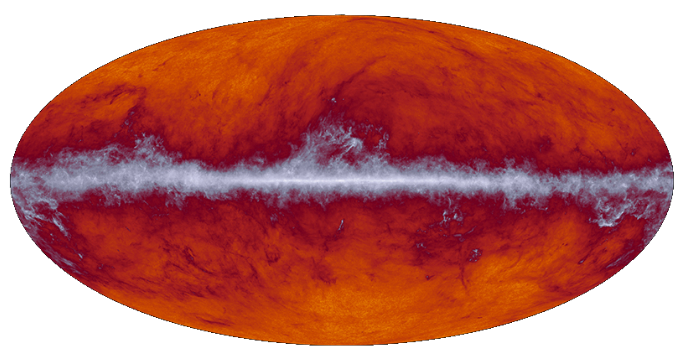
143 Ghz



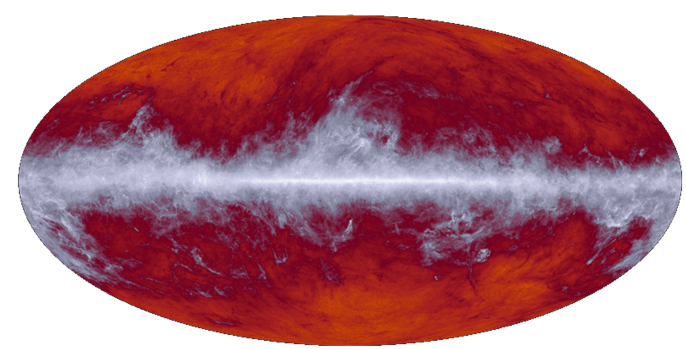
217 Ghz



353 Ghz

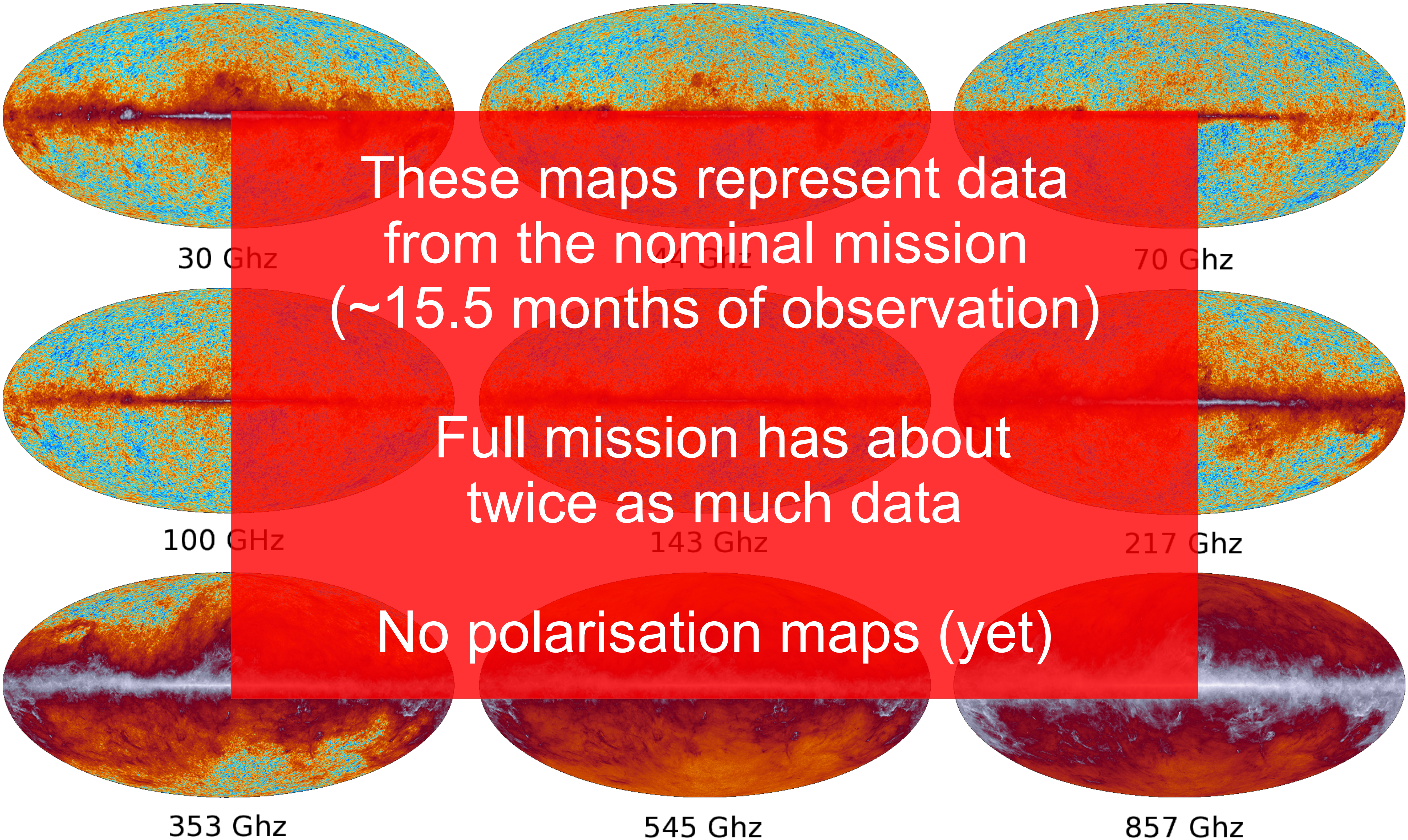


545 Ghz



857 Ghz

Planck's view of the microwave sky

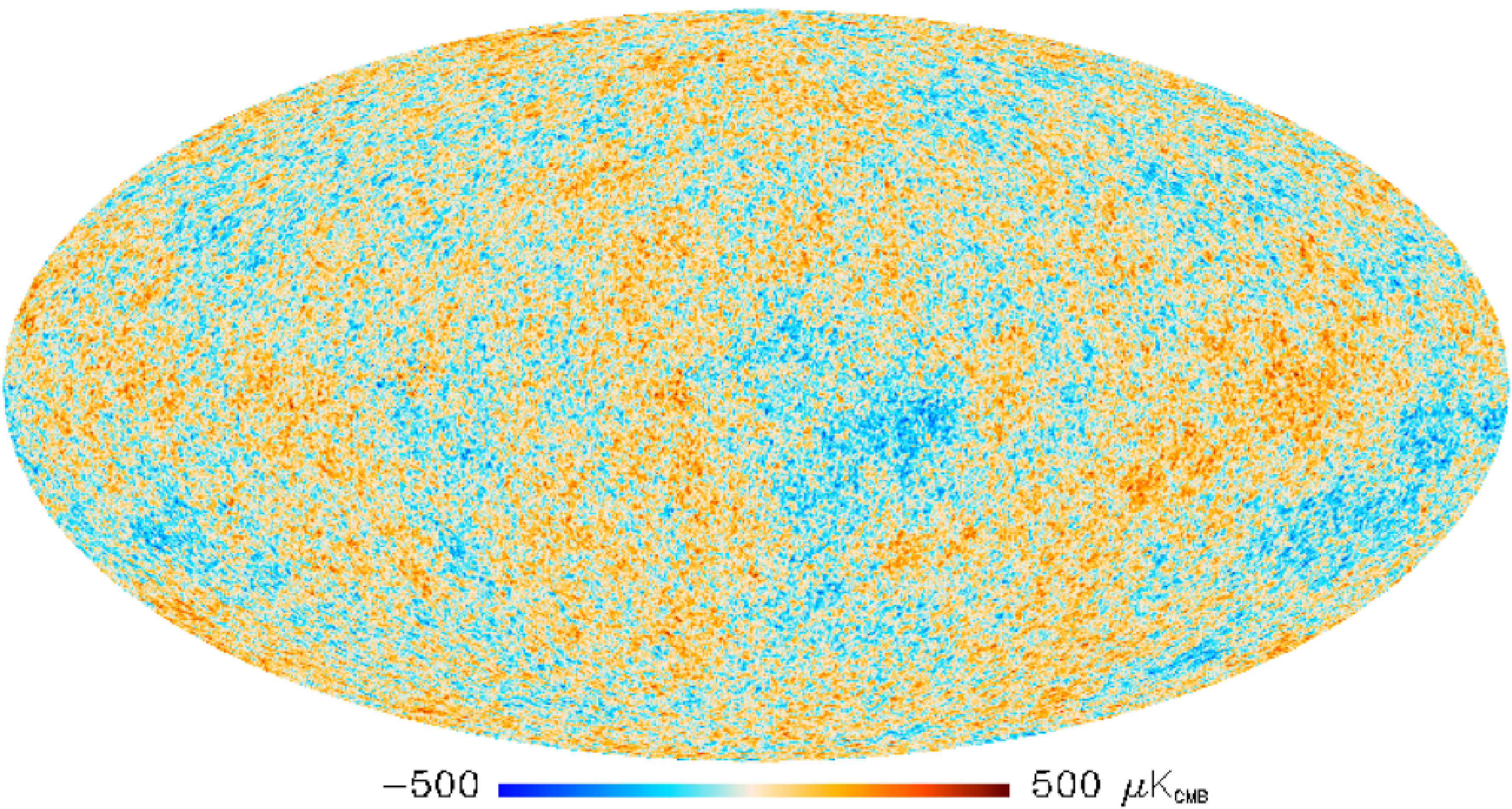


These maps represent data from the nominal mission (~15.5 months of observation)

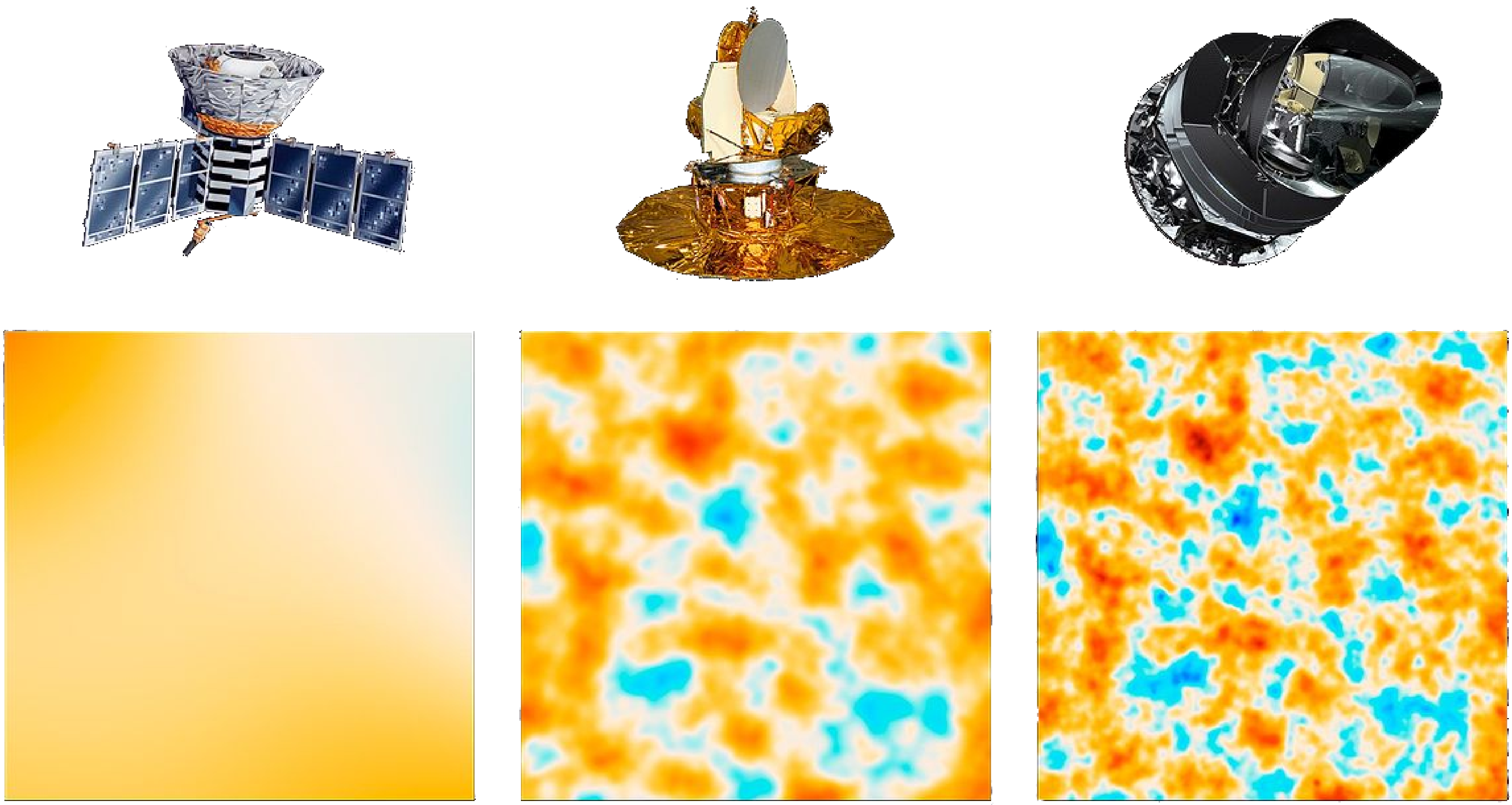
Full mission has about twice as much data

No polarisation maps (yet)

Cleaned map of CMB temperature anisotropies



From COBE to Planck

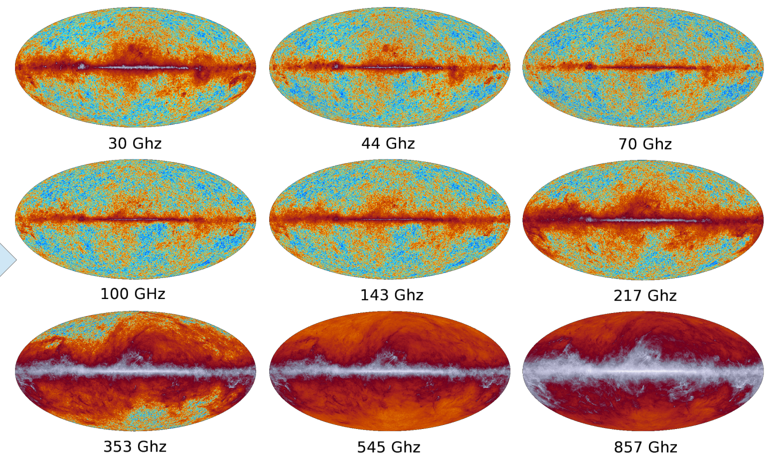


COBE-DMR
7°

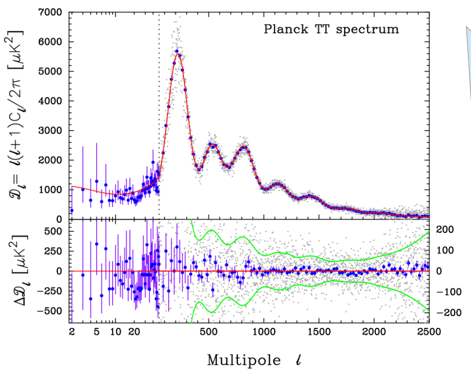
WMAP
0.3°

Planck
< 0.1°

Cosmological observables

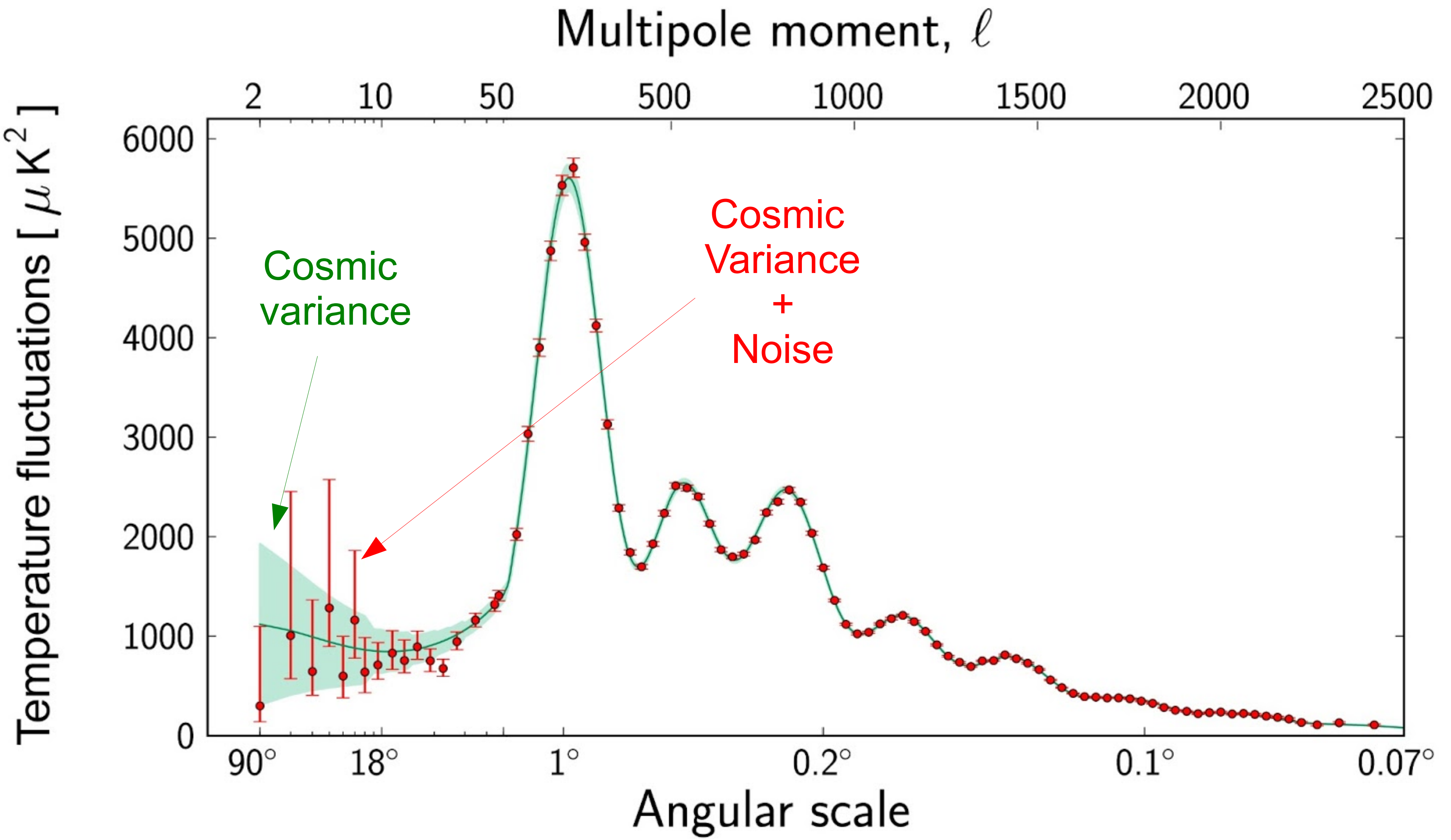


2-point correlation

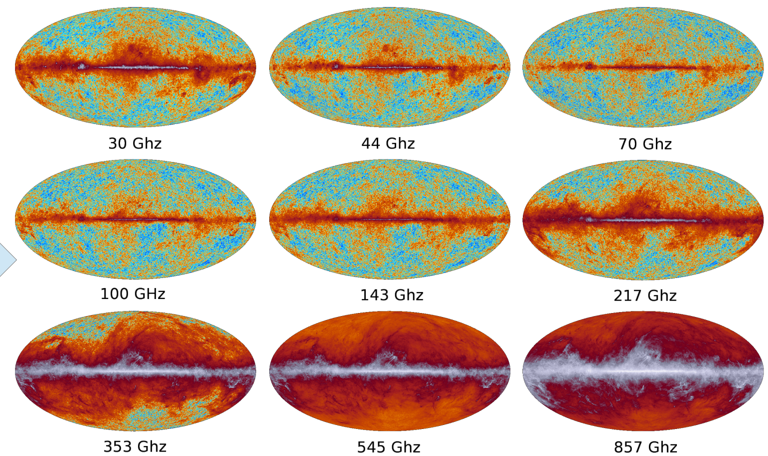


Angular power spectrum

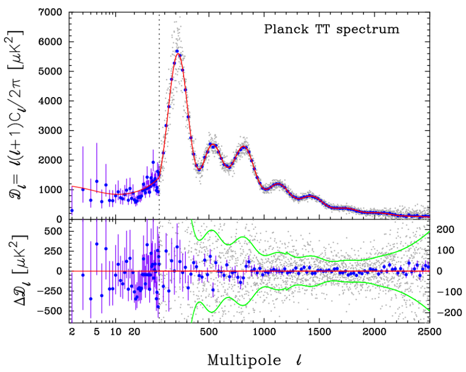
Planck (temperature) angular power spectrum



Cosmological observables

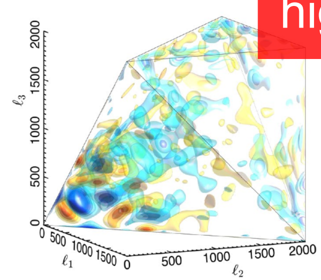


2-point correlation

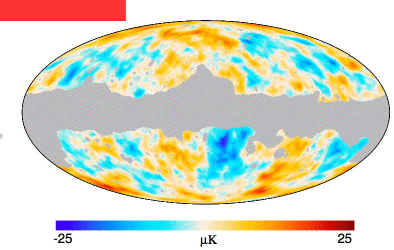


Angular power spectrum

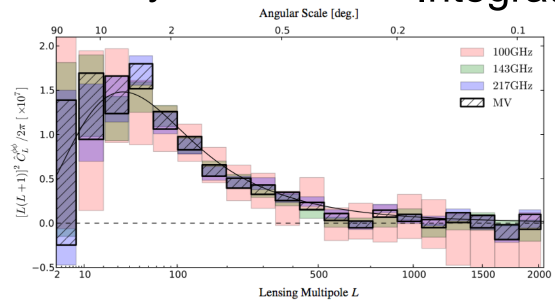
higher order correlations



Primordial non-Gaussianity

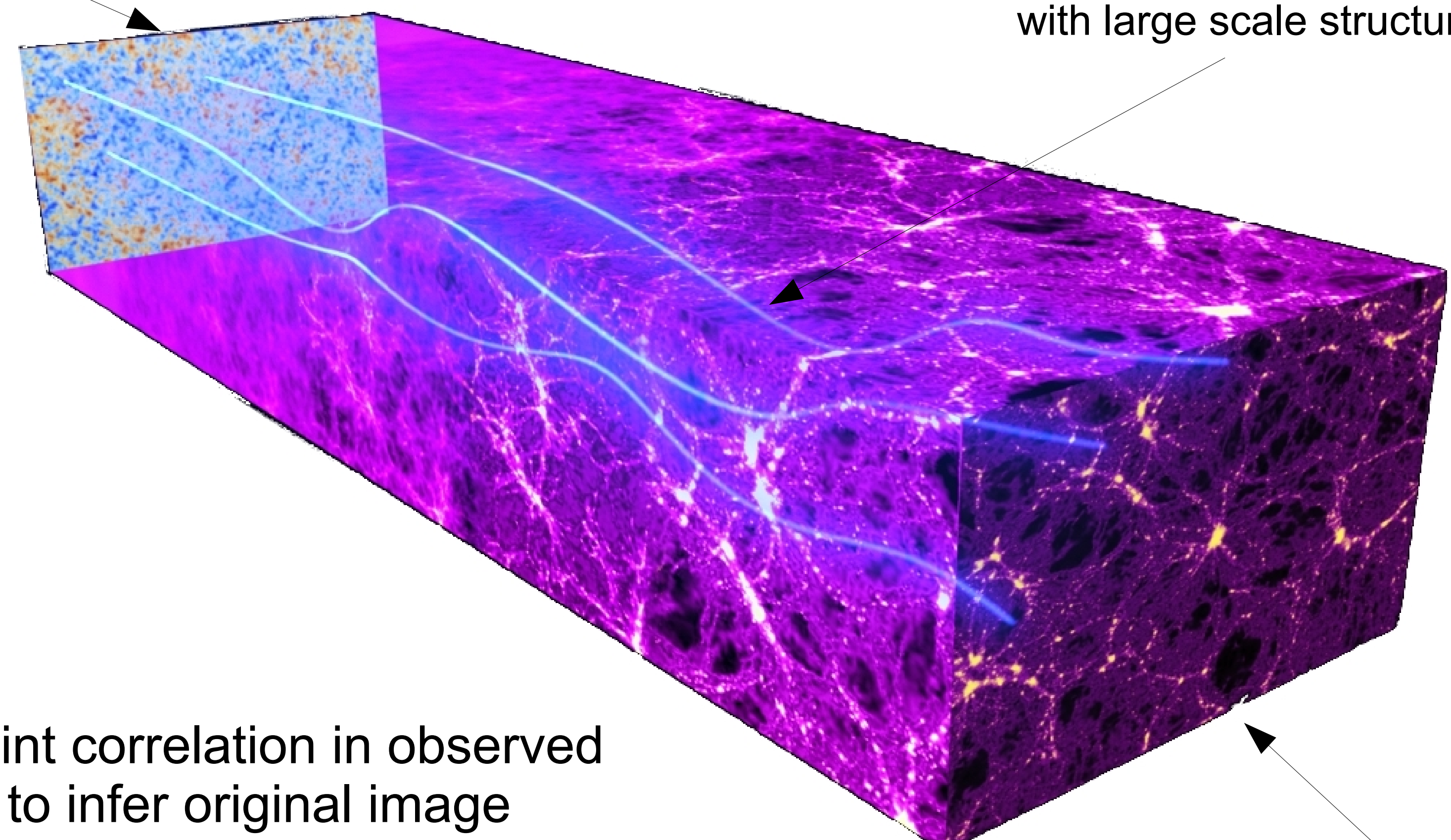


Integrated Sachs-Wolfe effect



Power spectrum of the lensing potential

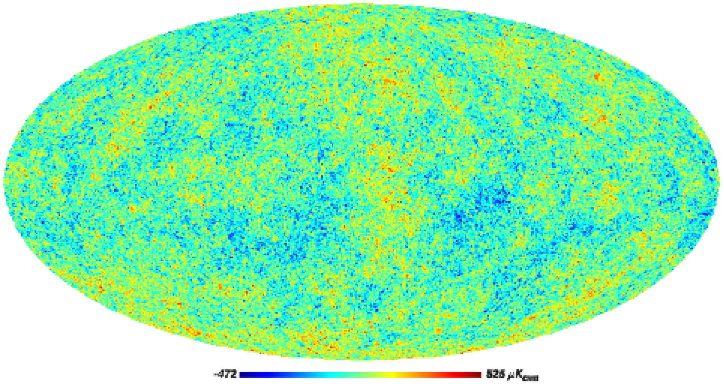
Weak gravitational lensing of the CMB



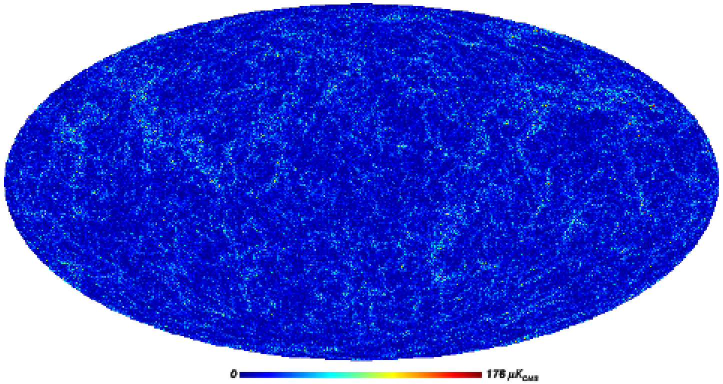
Use 4-point correlation in observed maps to infer original image
→ reconstruct deflection angle
→ construct map of lensing potential

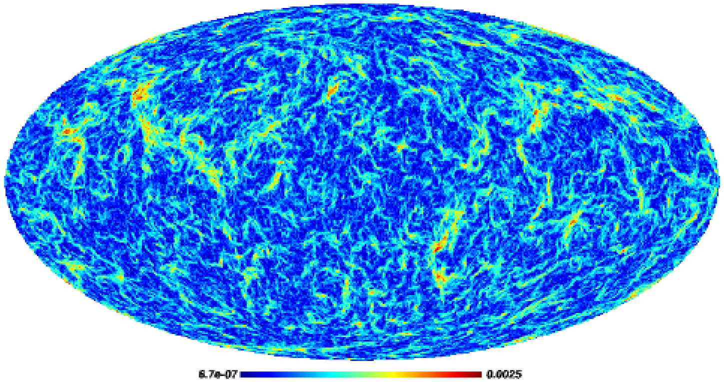
Weak gravitational lensing of the CMB

(simulated) lensed
CMB temperature map

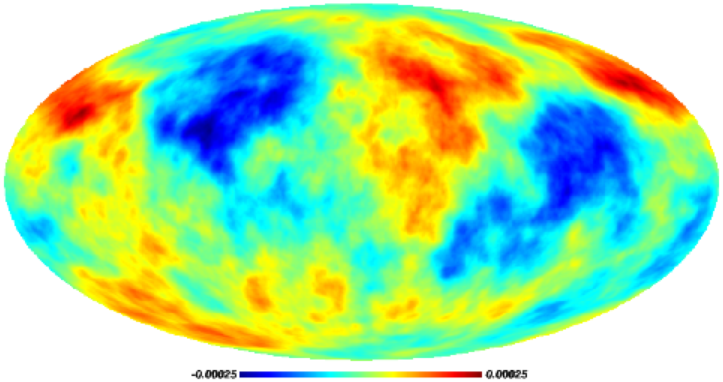


difference to unlensed
CMB temperature map



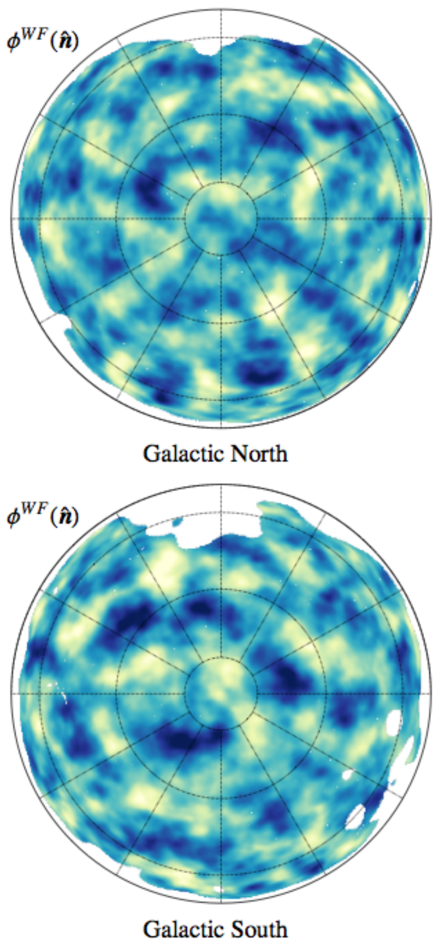


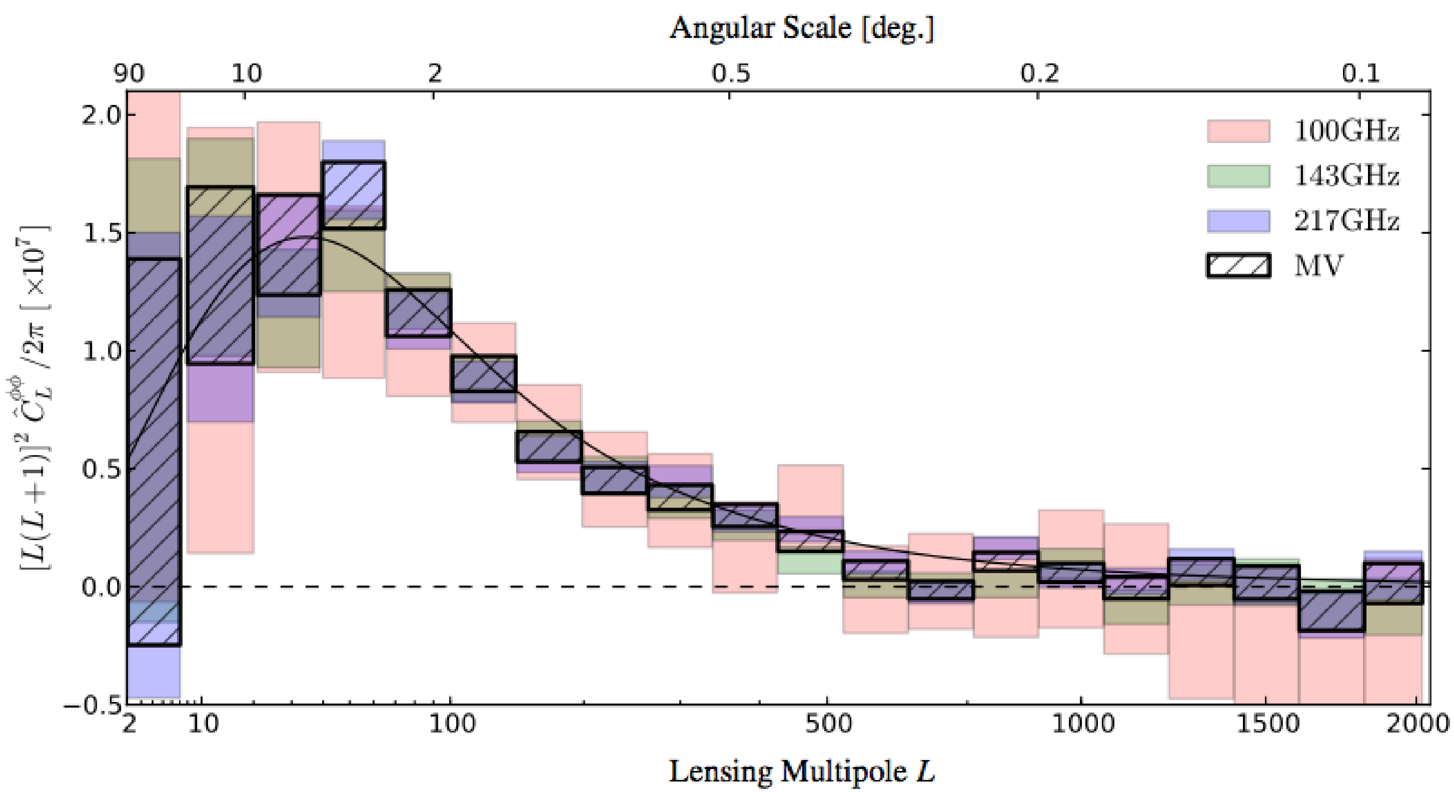
map of the deflection angle



map of the lensing potential

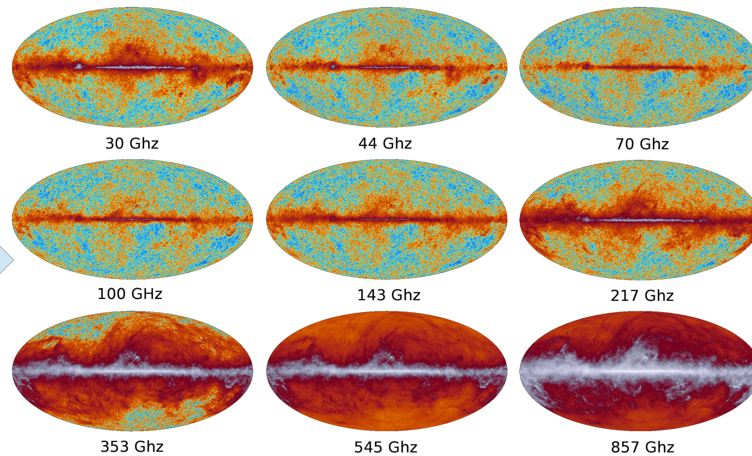
Planck lensing potential and its angular power spectrum





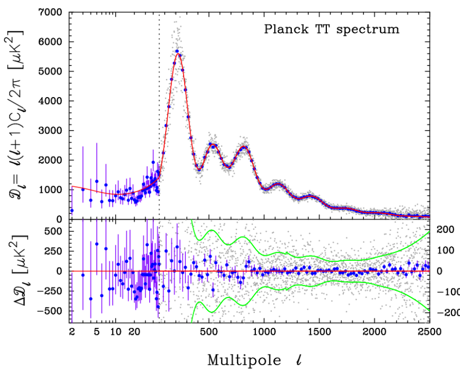
25σ detection of CMB lensing!

Cosmological observables

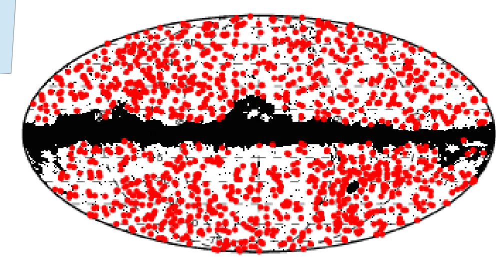


2-point correlation

SZ-effect

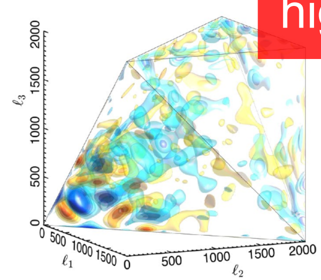


Angular power spectrum

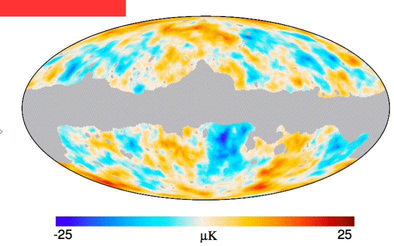


Galaxy clusters
→ cluster mass function
(when combined with
X-ray data)

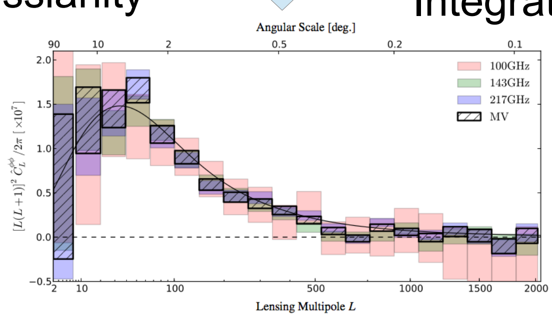
higher order correlations



Primordial non-Gaussianity



Integrated Sachs-Wolfe effect



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” (ΛCDM) model still stands strong

Significant improvements in constraints on nearly all interesting cosmological parameters

The ΛCDM model and its parameters

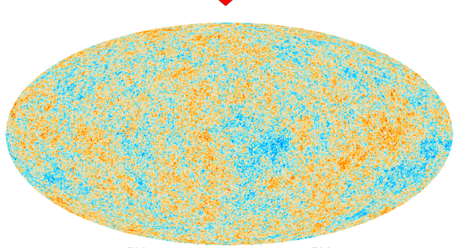
General relativity

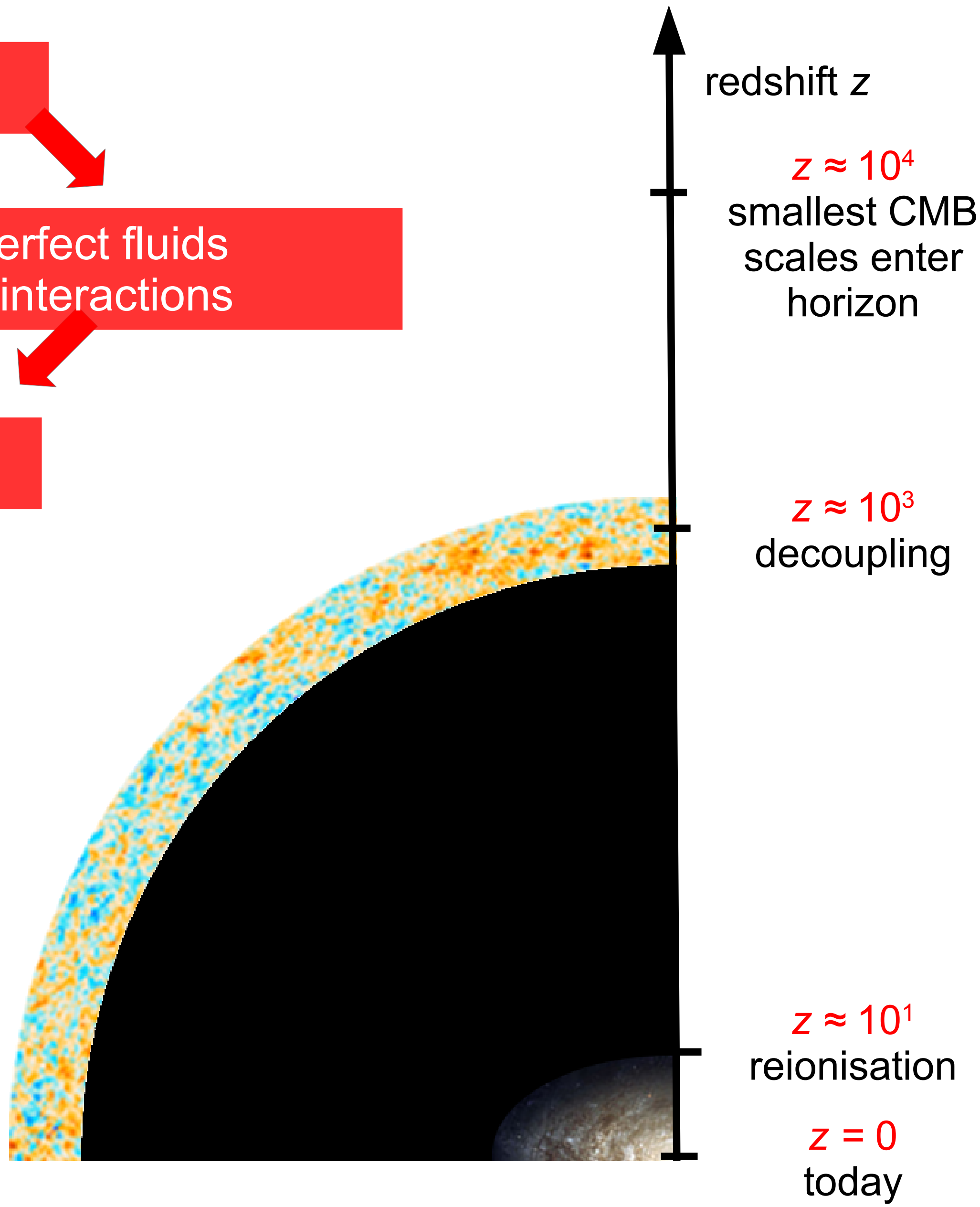
Homogeneous, isotropic and spatially flat background

Perfect fluids + interactions

Linear perturbation theory

Photon perturbation at early time





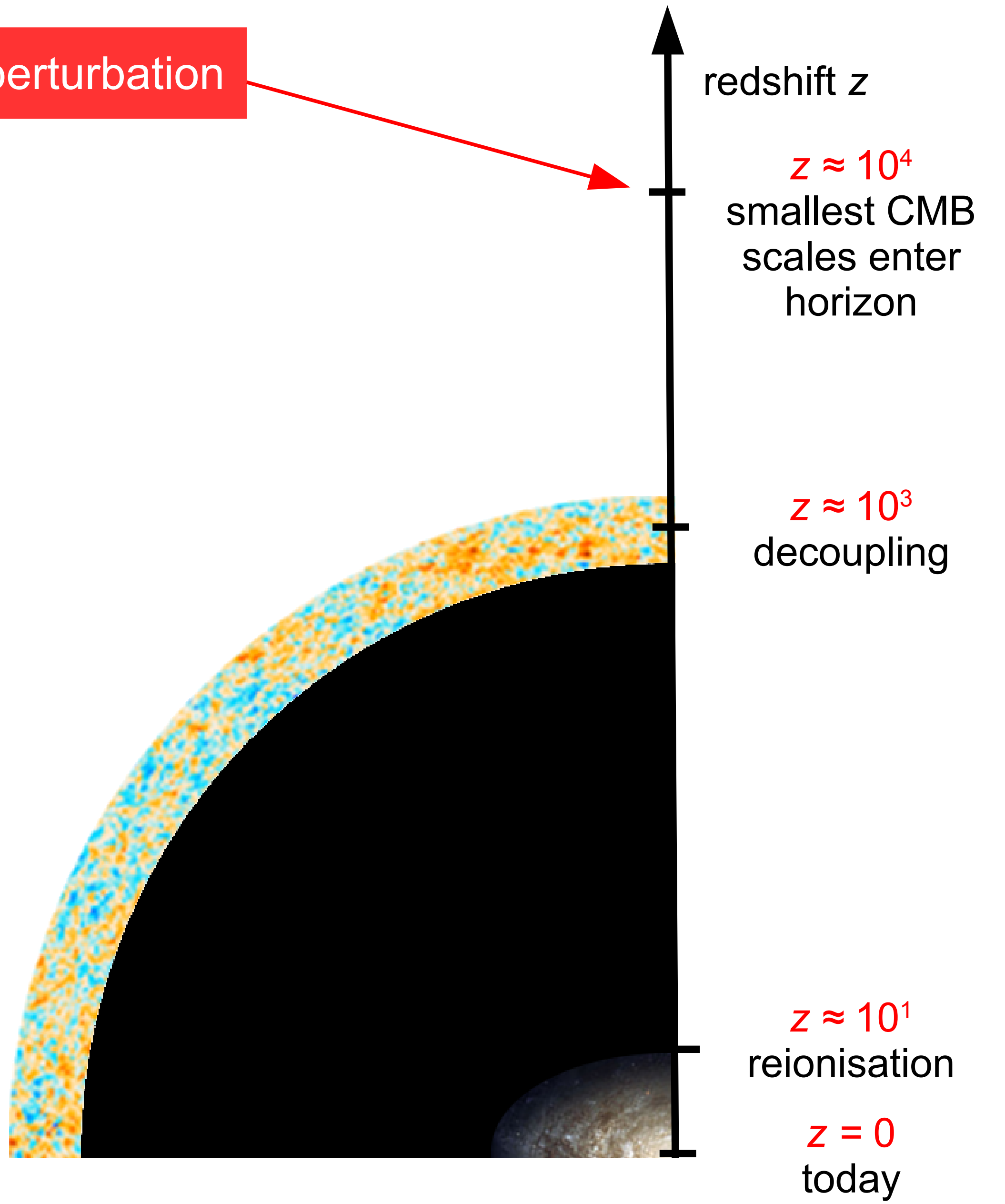
The ΛCDM model and its parameters

Initial curvature perturbation

Spectral index of initial curvature perturbation

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

Amplitude of initial curvature perturbation

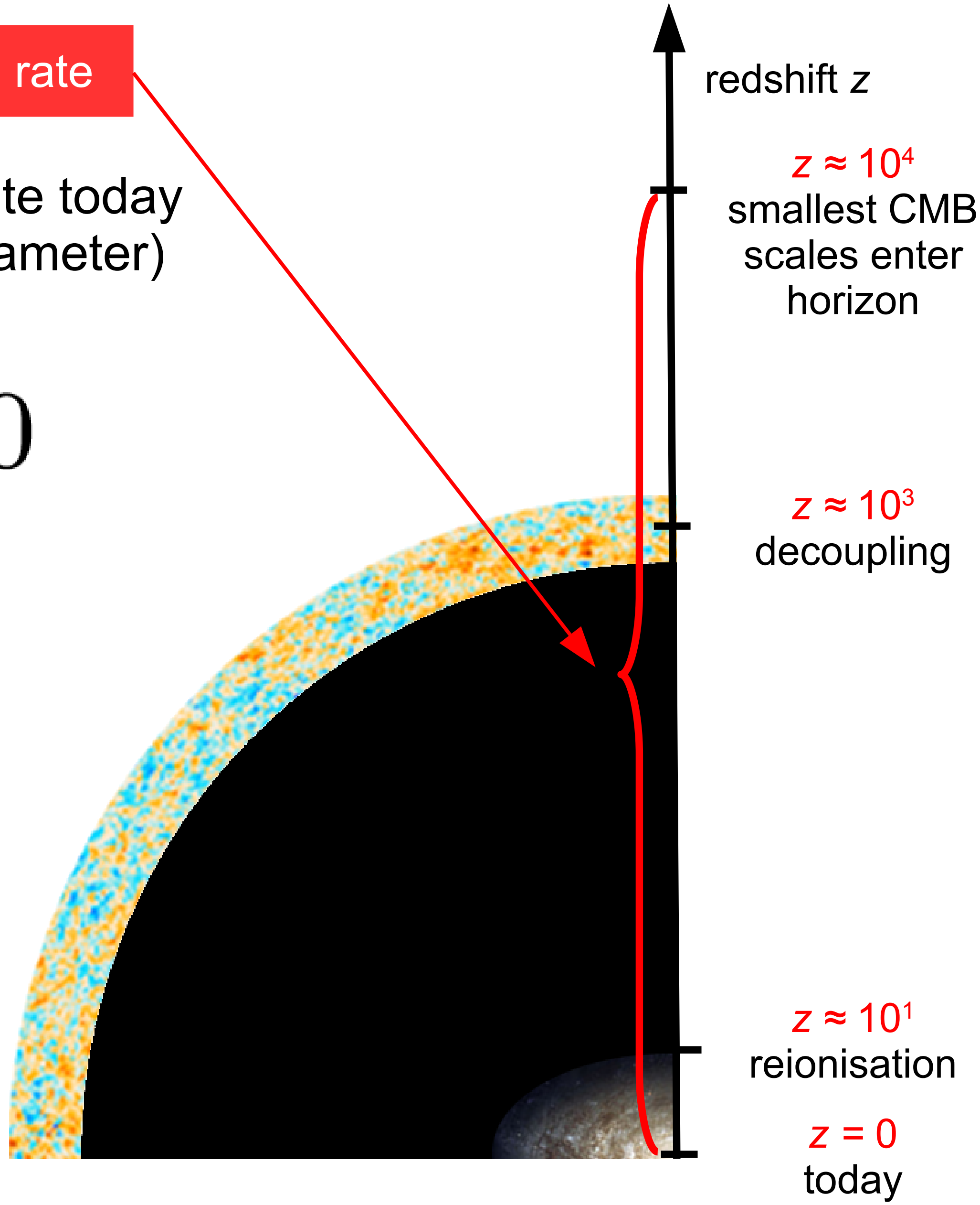


The ΛCDM model and its parameters

Energy content ⟷ Expansion rate

Expansion rate today
(Hubble parameter)

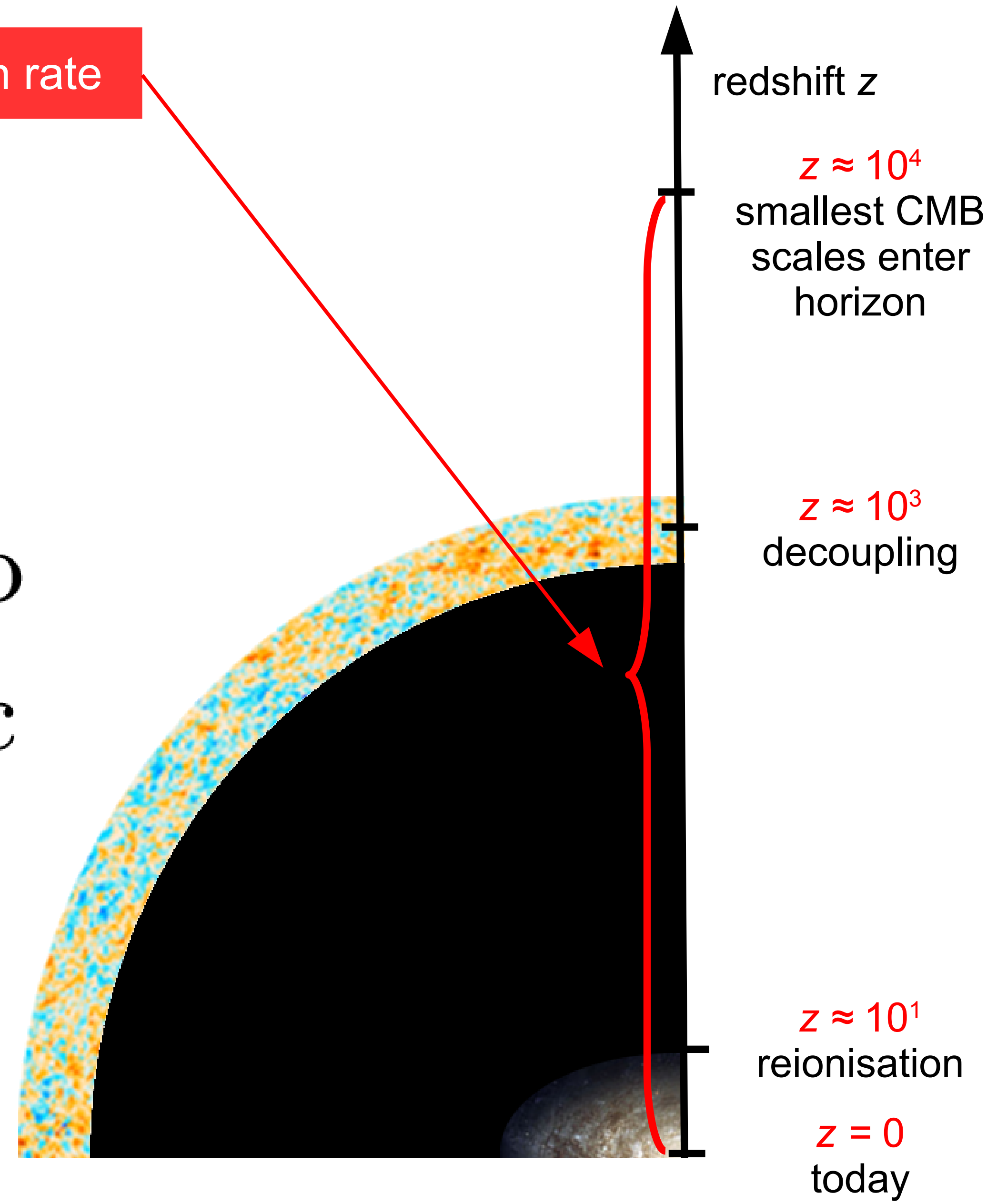
$$H_0$$



The ΛCDM model and its parameters

Energy content ⟷ Expansion rate

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



The ΛCDM model and its parameters

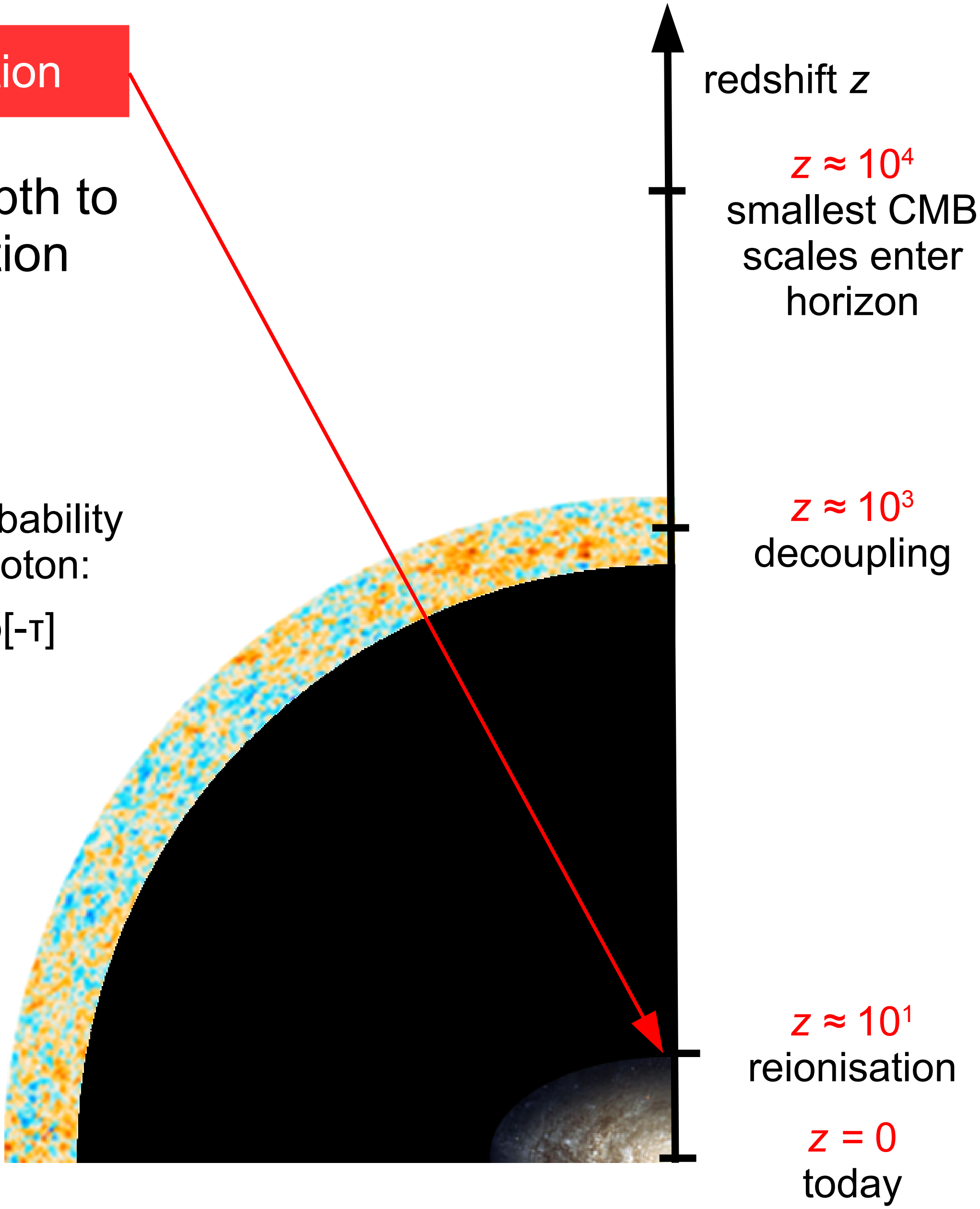
Reionisation

Optical depth to reionisation

τ

Scattering probability of a CMB photon:

p = 1 - exp[-τ]



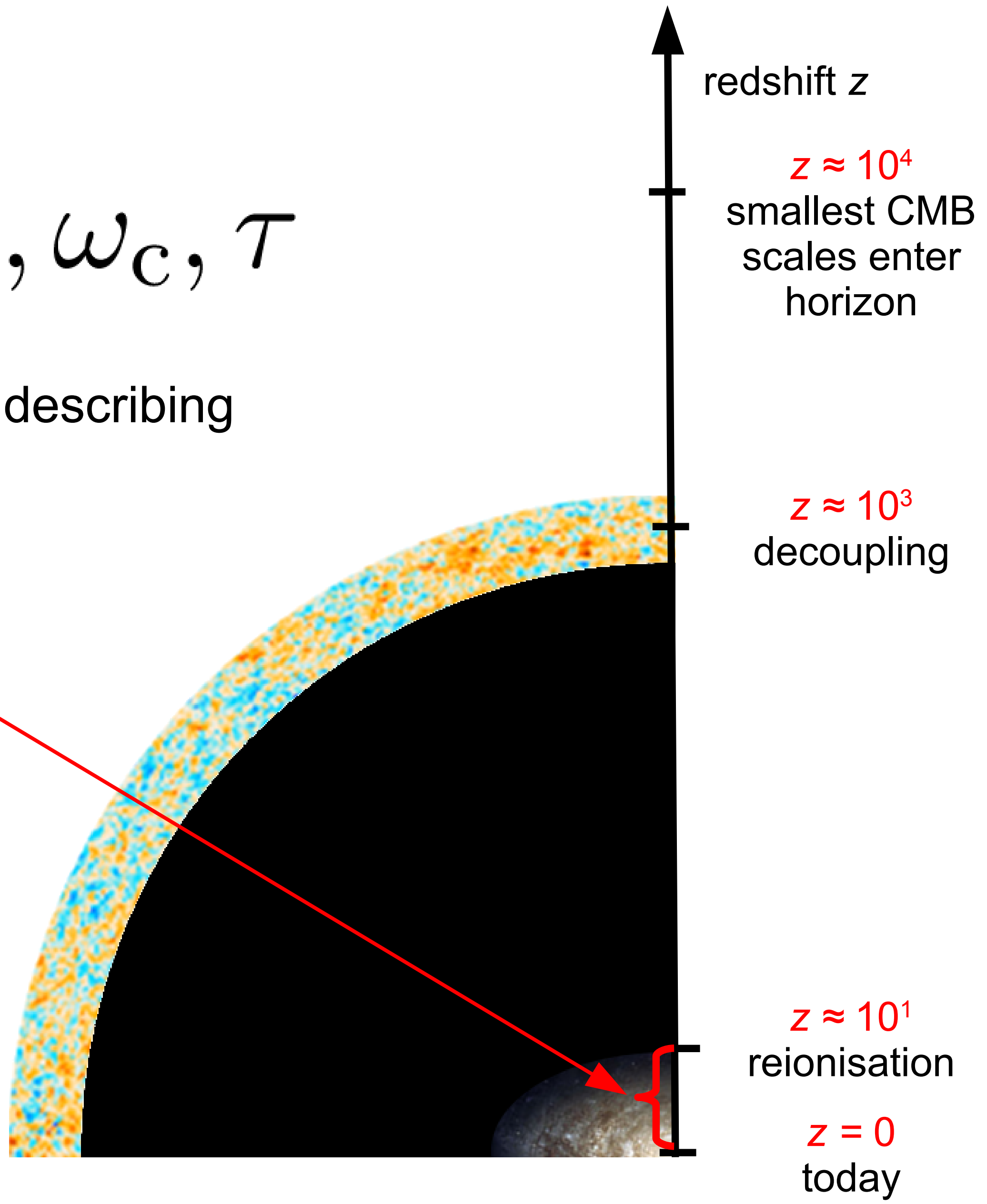
The ΛCDM model and its parameters

Altogether 6 cosmological parameters:

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

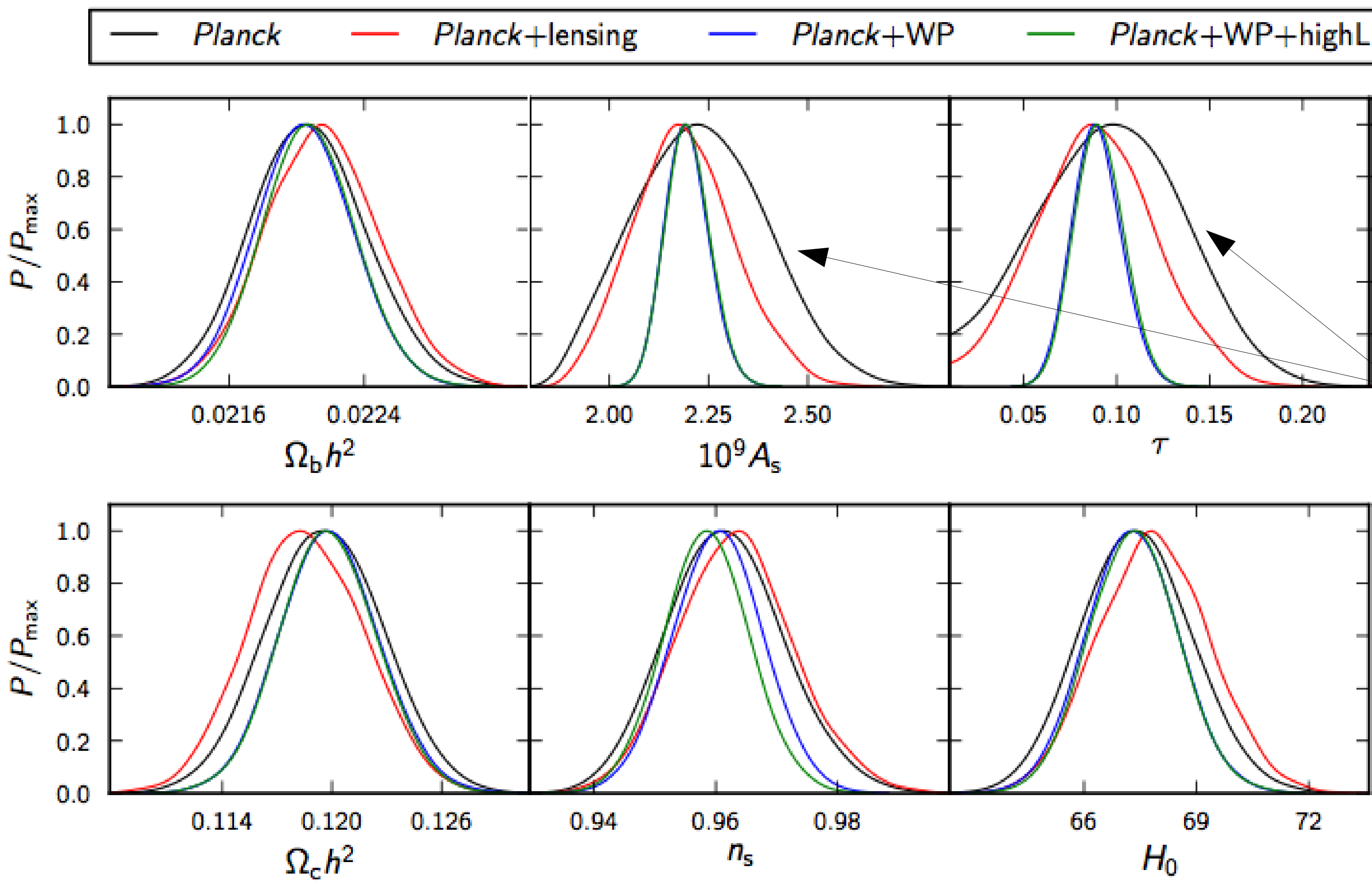
plus another 14 "nuisance" parameters, describing

- 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



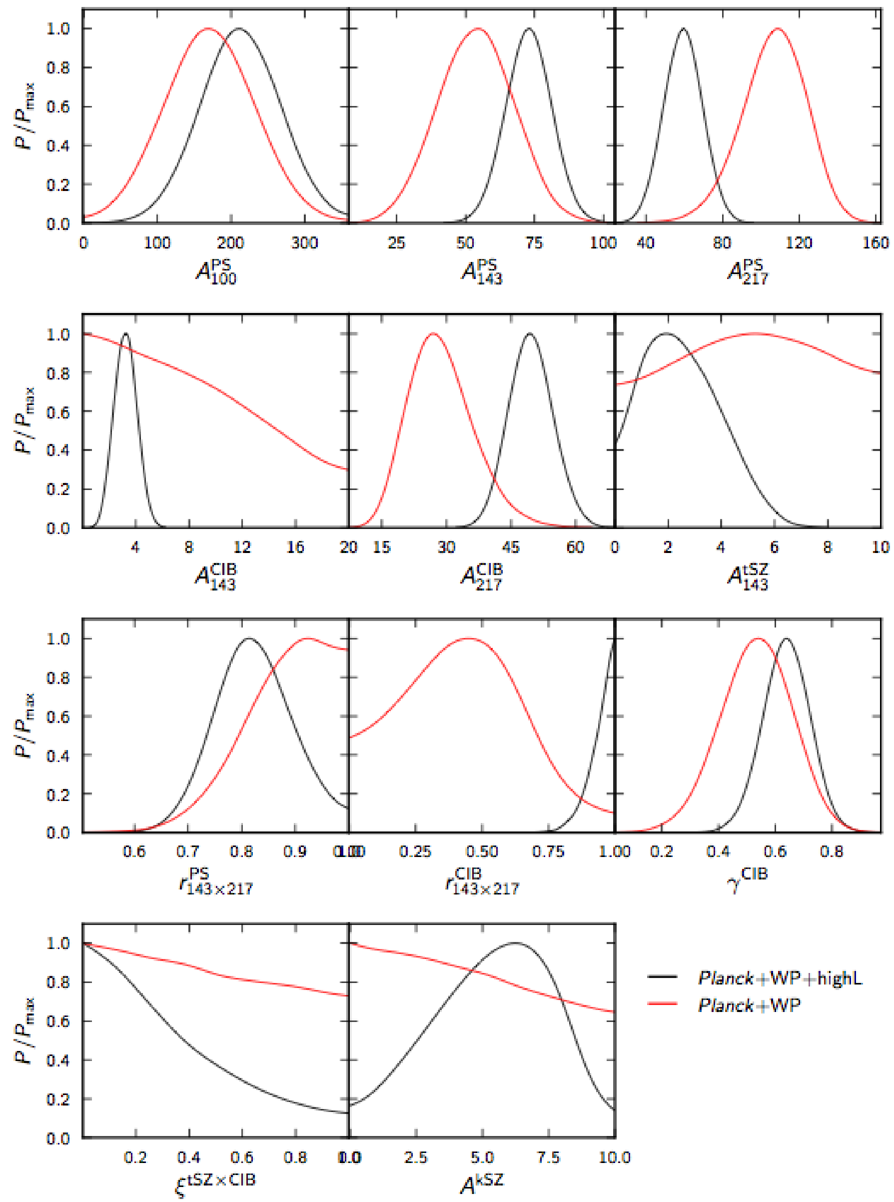
Overall amplitude of temperature data constrains $e^{-2\tau}A_s$

→ strong degeneracy between τ and A_s

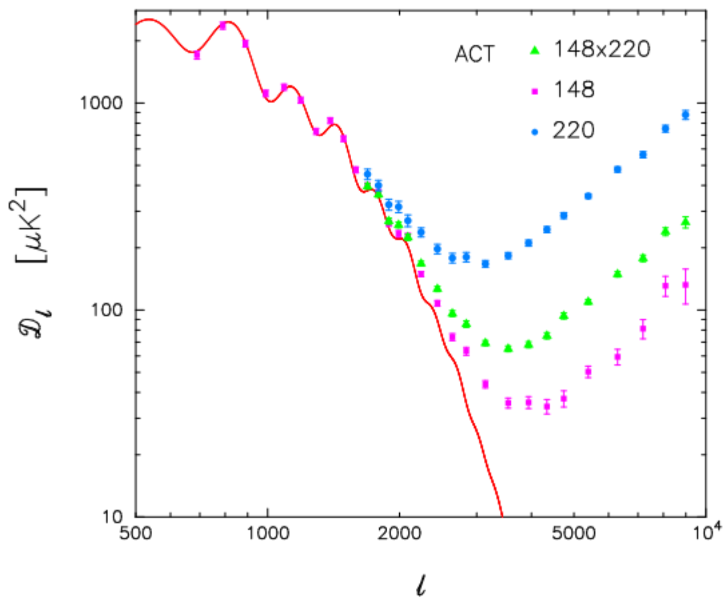
Can be broken by adding lensing or polarisation data

Other parameters well-constrained by temperature data alone

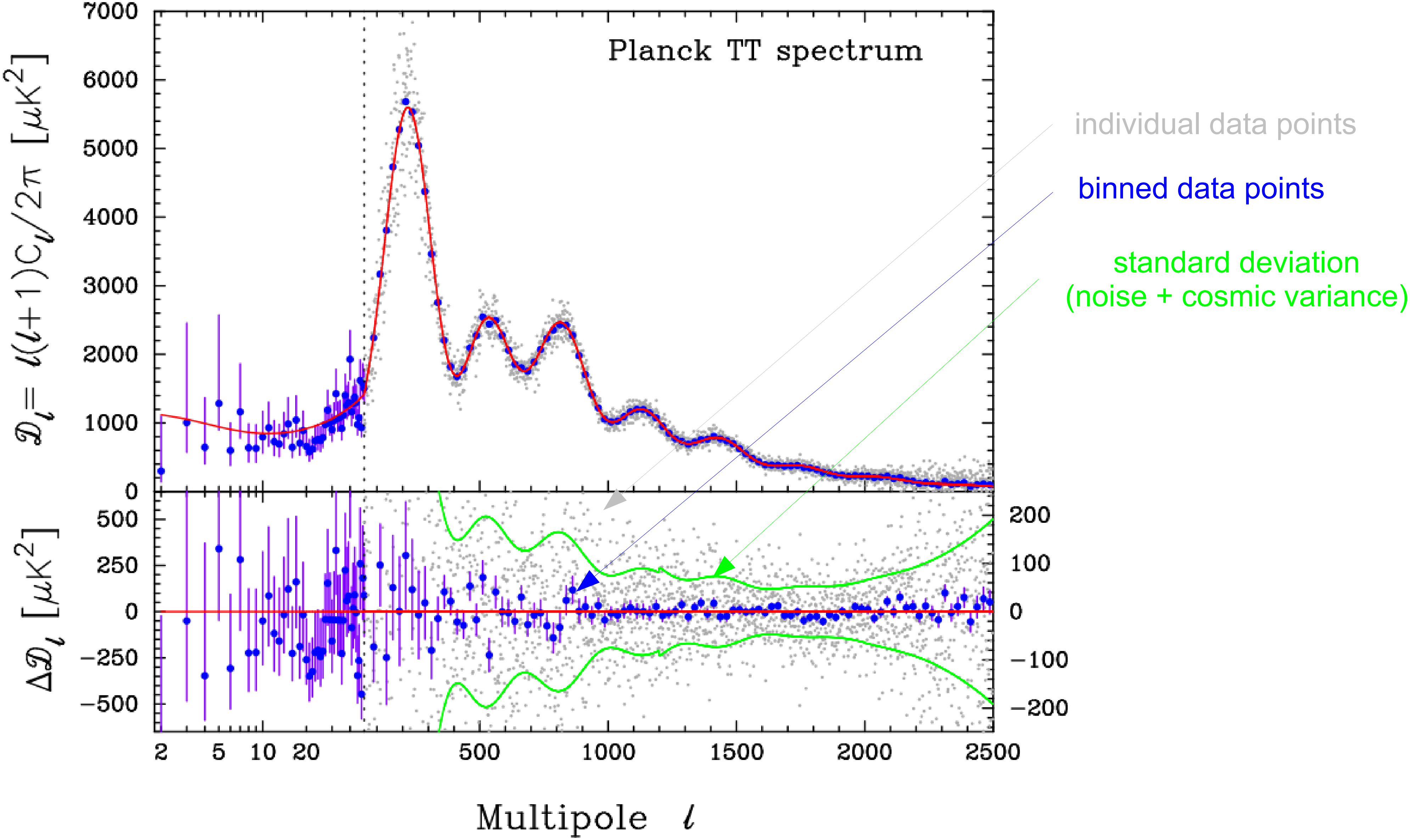
Basic ΛCDM nuisance parameters



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 $\sqrt{2N_\ell}$.

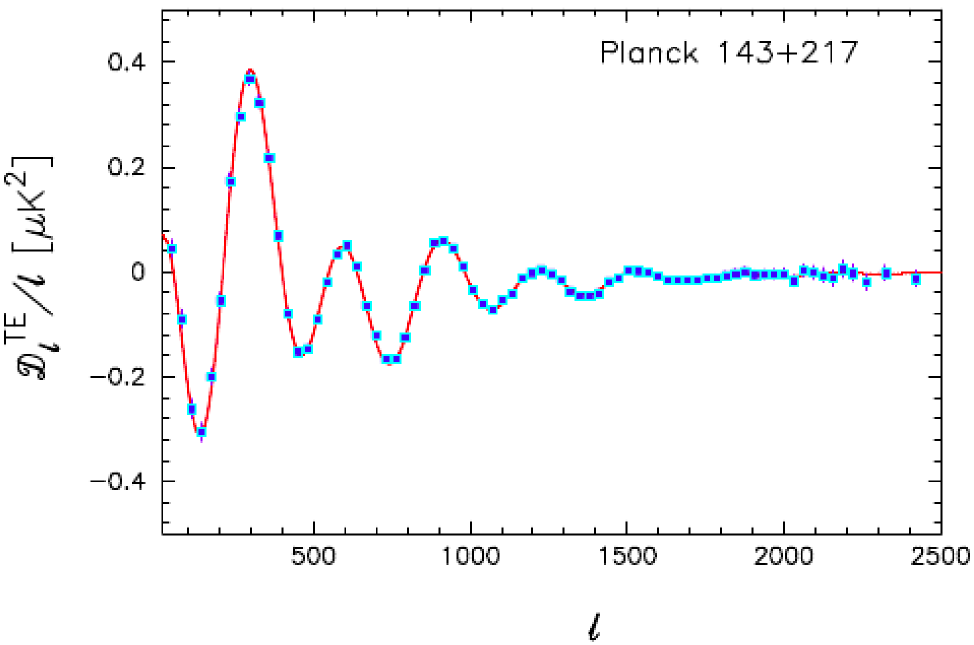
Spectrum	ℓ_{min}	ℓ_{max}	χ^2	χ^2/N_ℓ	$\Delta\chi^2/\sqrt{2N_\ell}$
100×100	50	1200	1158	1.01	0.14
143×143	50	2000	1883	0.97	−1.09
217×217	500	2500	2079	1.04	1.23
143×217	500	2500	1930	0.96	−1.13
All	50	2500	2564	1.05	1.62

Planck polarisation angular power spectra

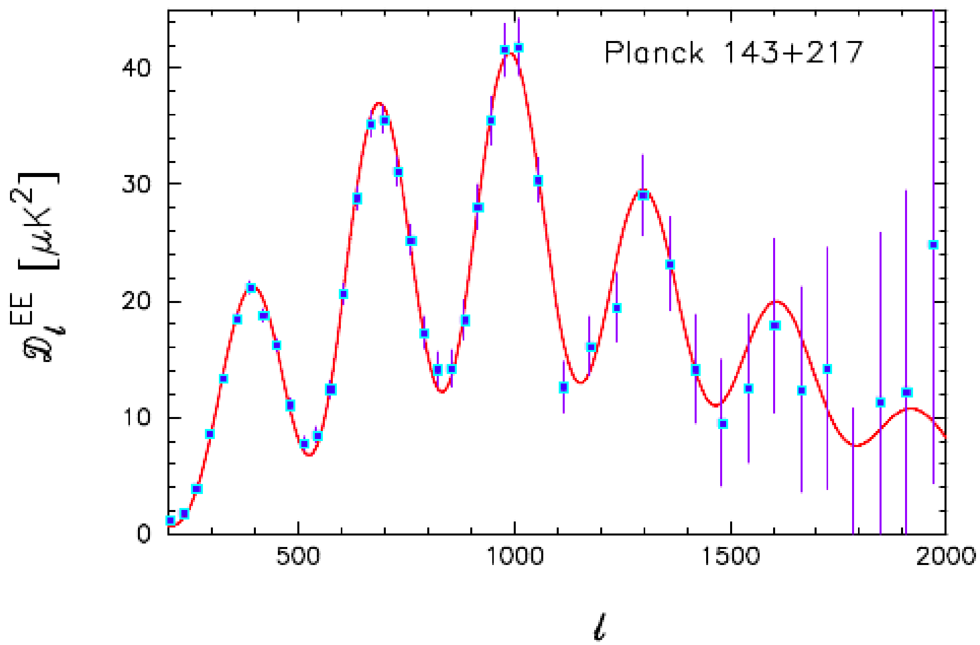
Best-fit ΛCDM model plotted against Planck polarisation data

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

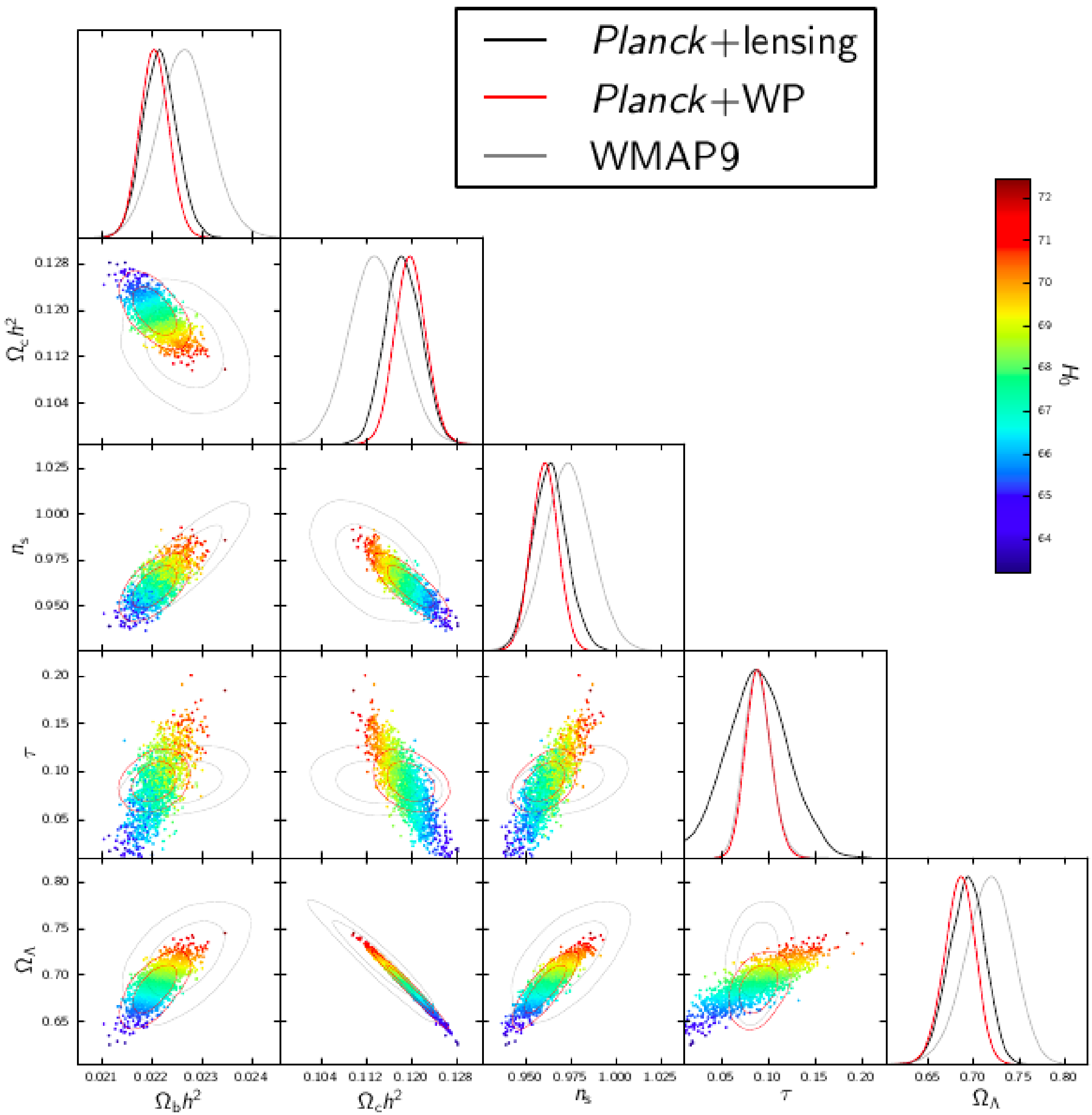
TE cross-correlation



EE auto-correlation



ΛCDM parameters vs. WMAP

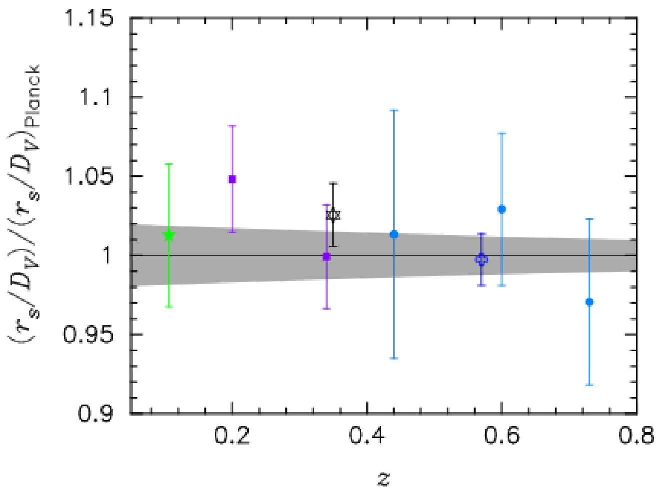


Consistency with other data sets

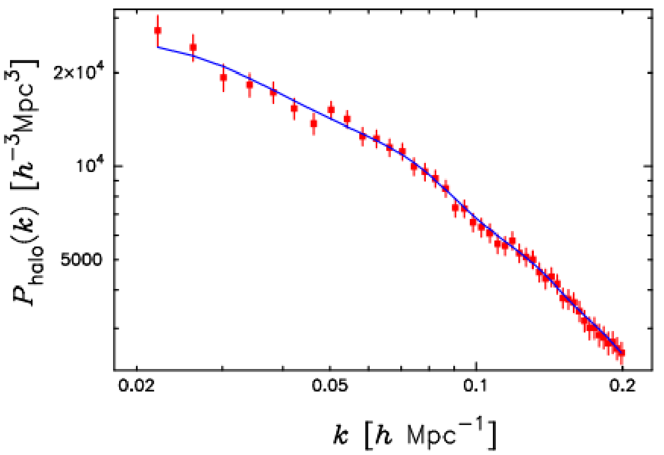
CMB

Galaxy redshift surveys

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



  - Halo power spectrum

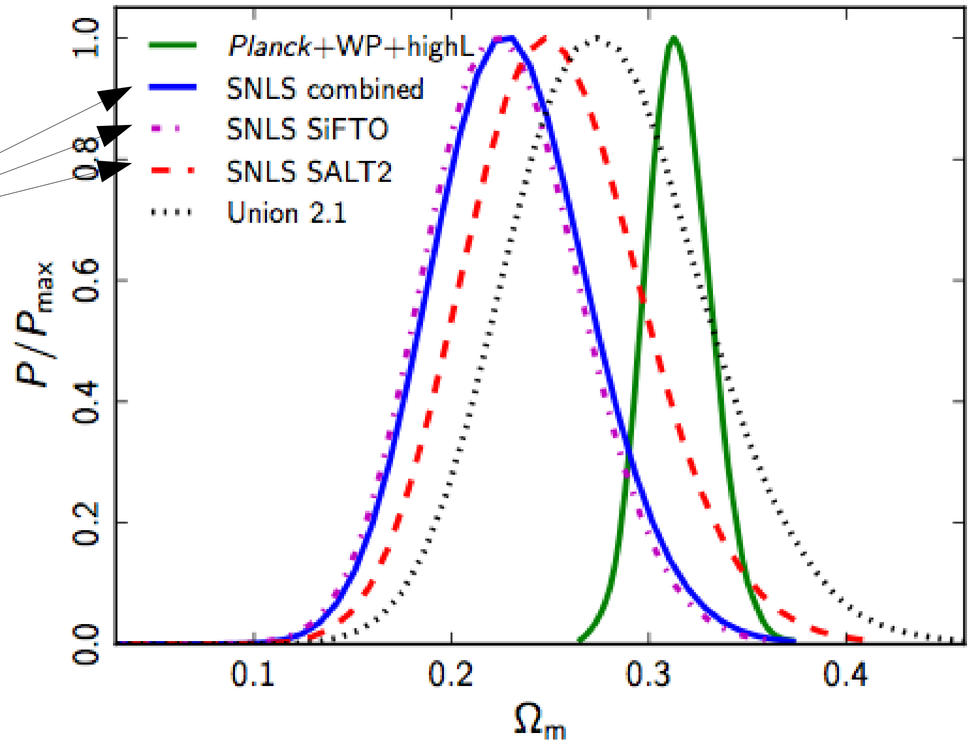


Consistency with other data sets

Supernova light-curves

- Reasonable consistency:
  - Type Ia supernova luminosity distances

Different light-curve-fitting methods



Consistency with other data sets

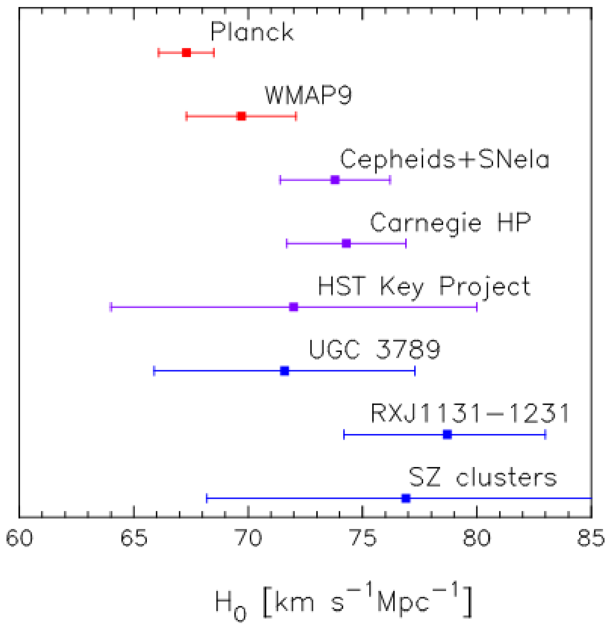
- Some inconsistency:
  - Cluster counts (~3σ)
  - CFHTLenS cosmic shear (~3σ)
  - SPT intermediate-scale data (~2.5σ)
    most likely a calibration issue with SPT
  - Measurements of the Hubble parameter (~2.5σ)

CMB + X-ray

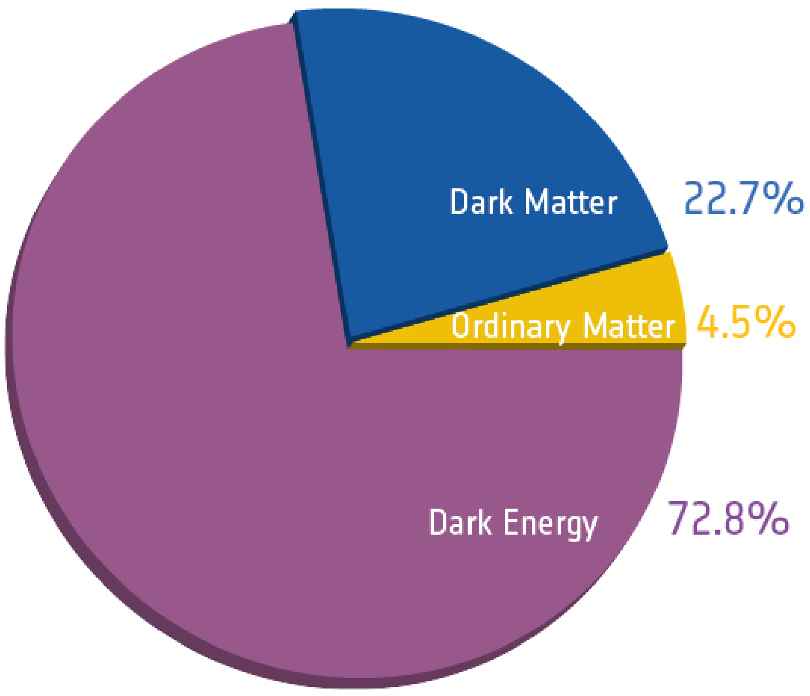
Galaxy weak lensing

CMB

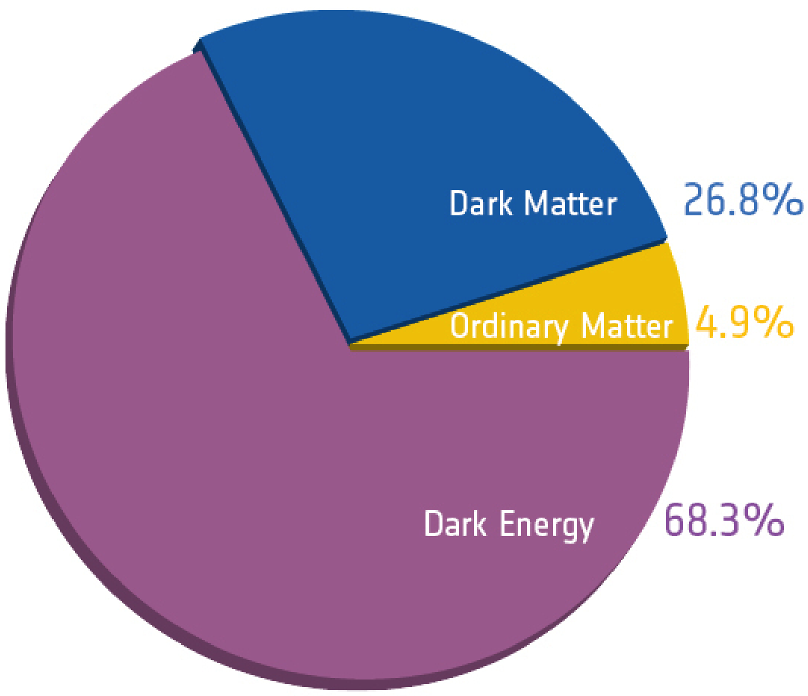
Supernova light-curves (+ astro)



Total energy budget



Before Planck



After Planck

Change is due to shift in determination of the Hubble parameter

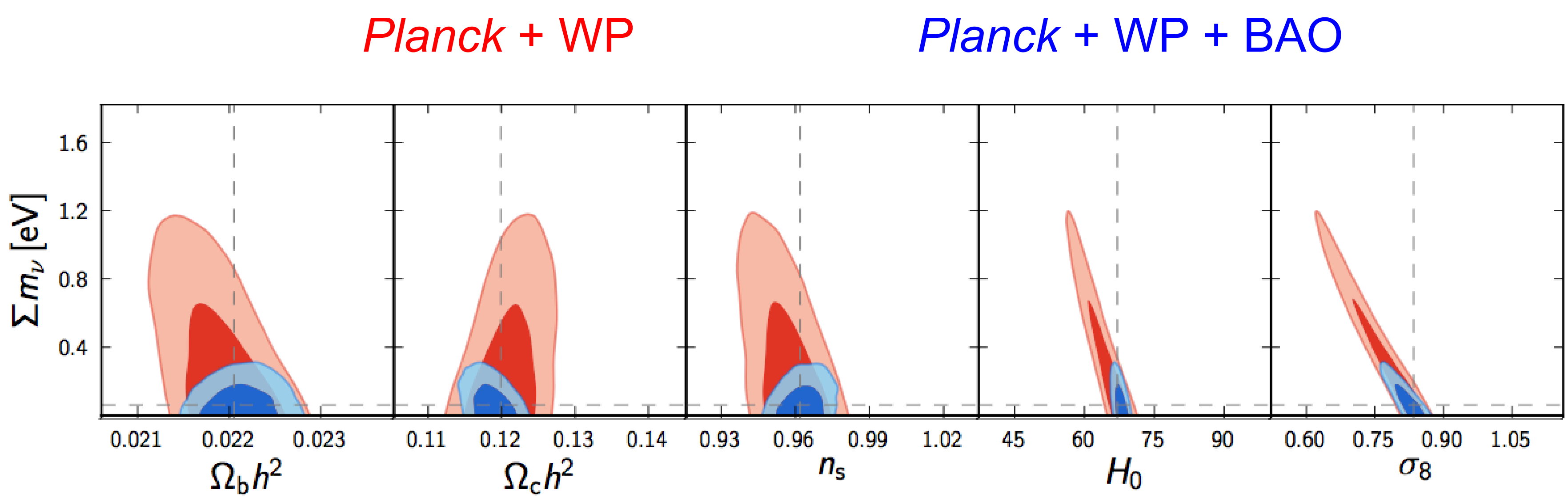
Different models/data combinations: “the grid”

- 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
Σm_ν [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

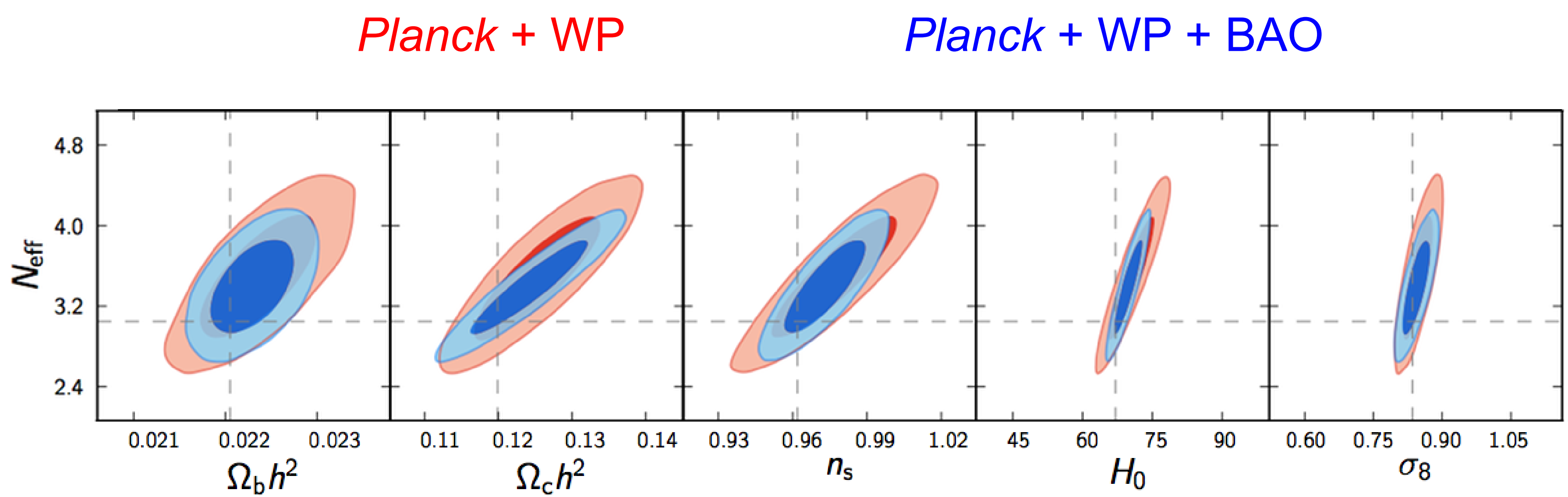
$$\rho_{\mathrm{r}} = \rho_{\gamma}\left[1 + N_{\mathrm{eff}}\frac{7}{8}\left(\frac{4}{11}\right)^{4/3}\right]$$

radiation energy density

effective number of neutrino species

Standard value: 3.046

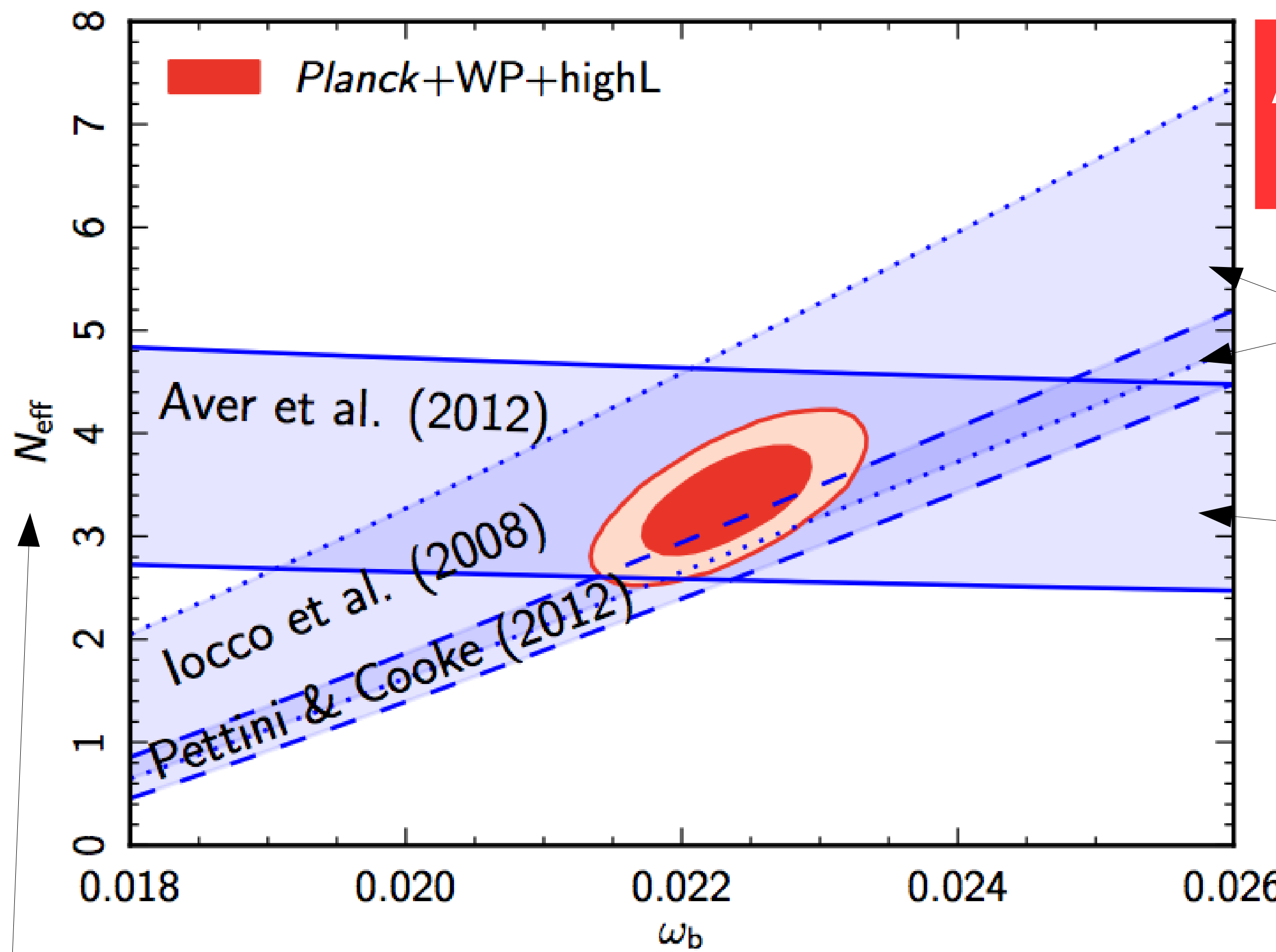
Effective number of neutrino species



	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_{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

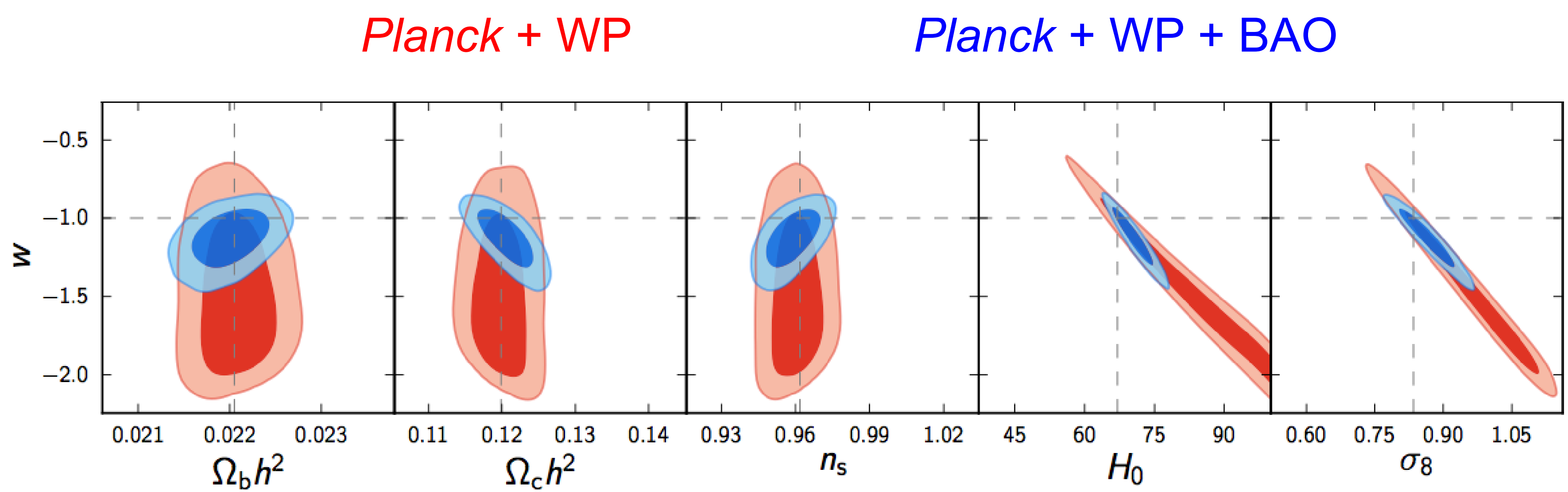
dark energy
energy density

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

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

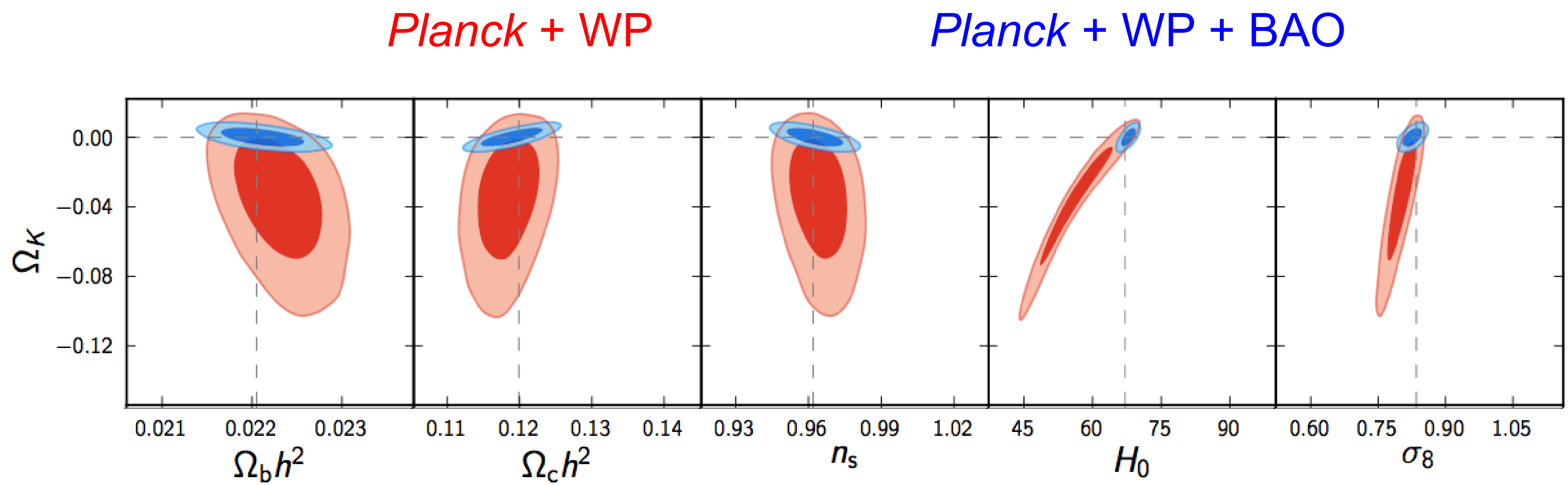
$$\frac{1}{\rho_{\mathrm{c}}} \sum_i \rho_i = 1 + \Omega_k$$

critical density

curvature parameter

Spatial flatness: $\Omega_k = 0$

Spatial curvature constraints

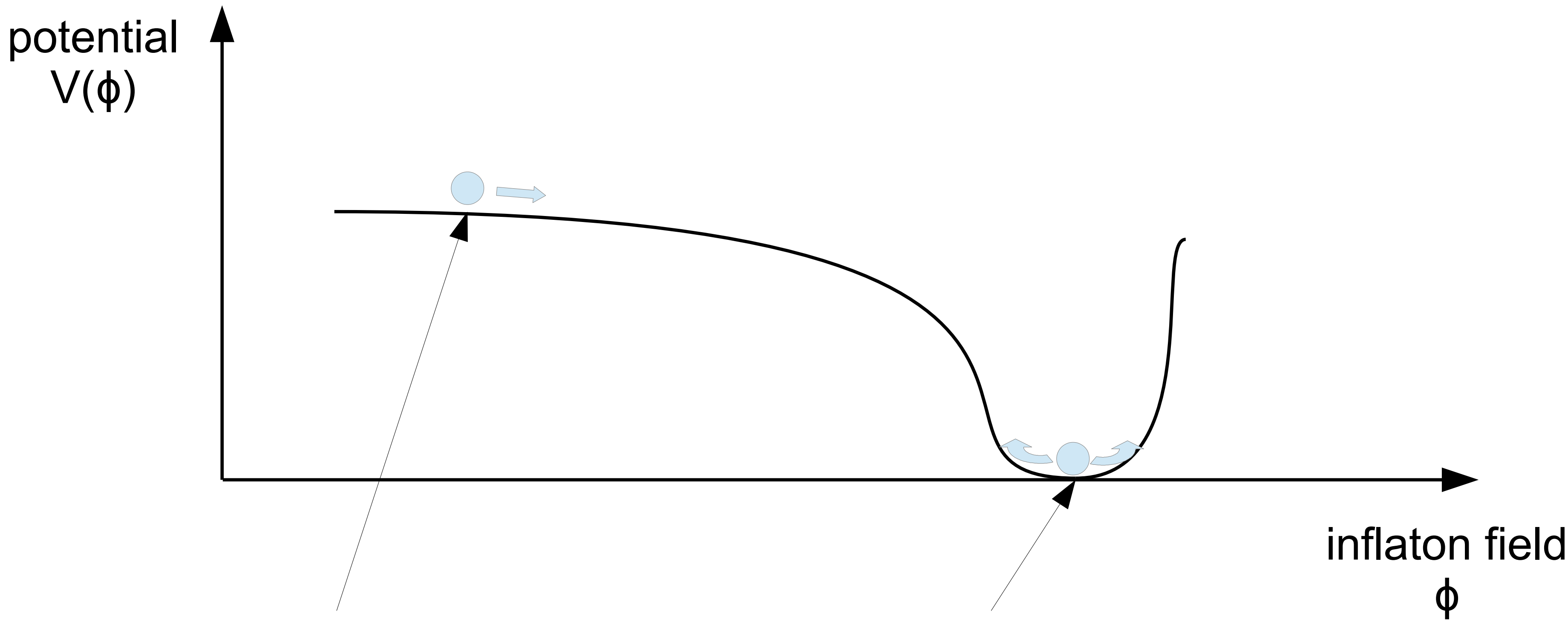


	Planck+WP		*Planck*+WP+BAO		*Planck*+WP+highL		*Planck*+WP+highL+BAO	
Parameter	Best fit	95% limits	Best fit	95% limits	Best fit	95% limits	Best fit	95% limits
Ω_K	−0.0105	$-0.037^{+0.043}_{-0.049}$	0.0000	$0.0000^{+0.0066}_{-0.0067}$	−0.0111	$-0.042^{+0.043}_{-0.048}$	0.0009	$-0.0005^{+0.0065}_{-0.0066}$

No evidence for non-zero spatial curvature

Initial perturbations: inflation

The origin of the primordial perturbations: inflation



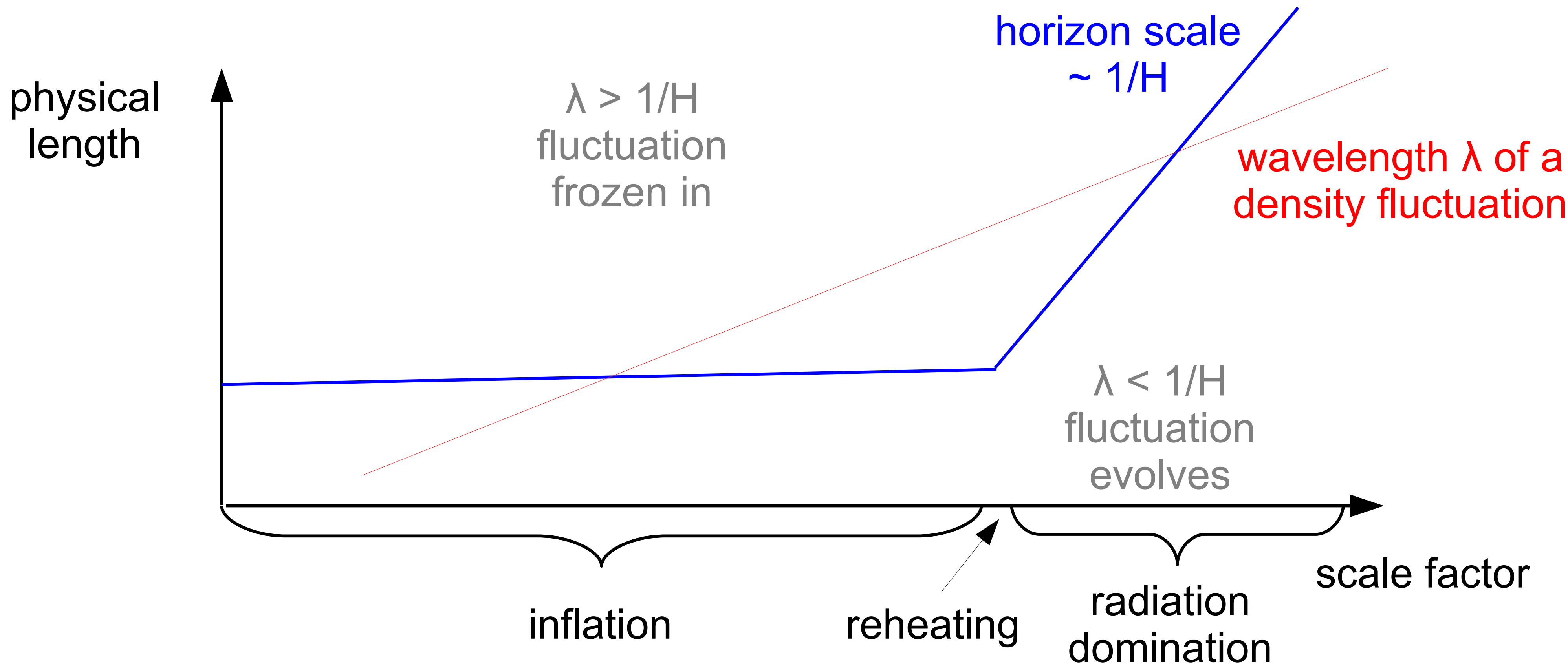
Potential energy domination:

- 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 ± 24	2205 ± 28
$10^4\Omega_c h^2$	1088 ± 13	1199 ± 27
$100\,\theta_{MC}$	1.04292 ± 0.00054	1.04131 ± 0.00063
τ	$0.125^{+0.016}_{-0.014}$	$0.089^{+0.012}_{-0.014}$
$\ln(10^{10}A_s)$	$3.133^{+0.032}_{-0.028}$	$3.089^{+0.024}_{-0.027}$
n_s	—	0.9603 ± 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

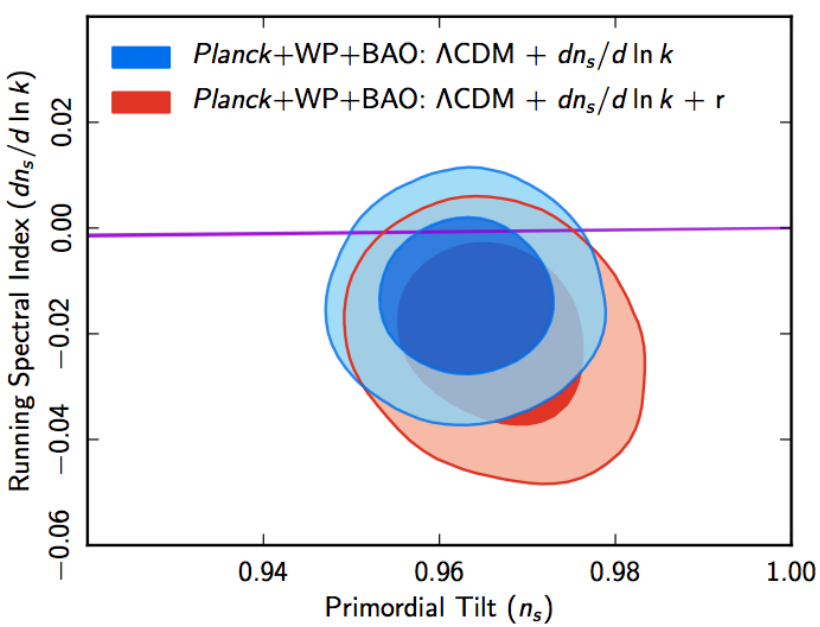
→ strong argument for dynamical generation of primordial perturbation

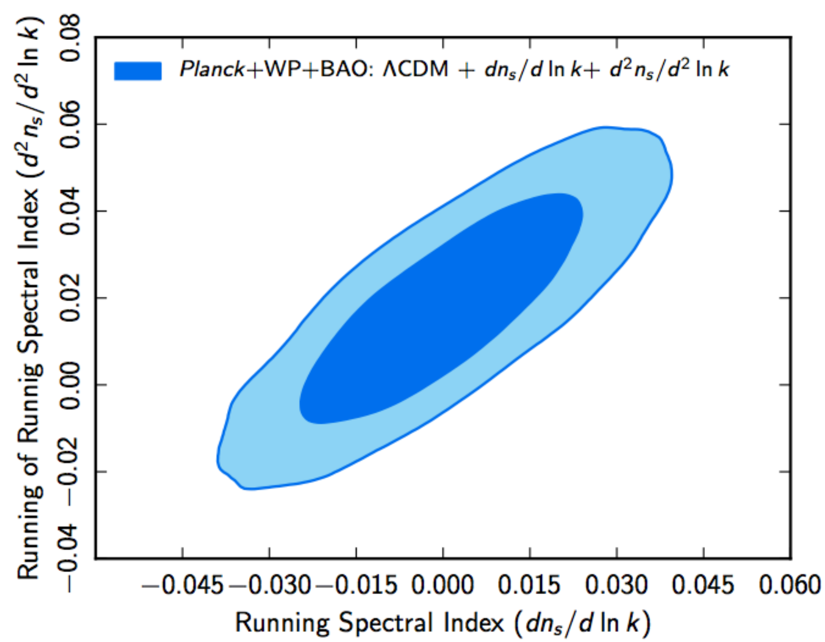
Higher order terms in the power spectrum

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

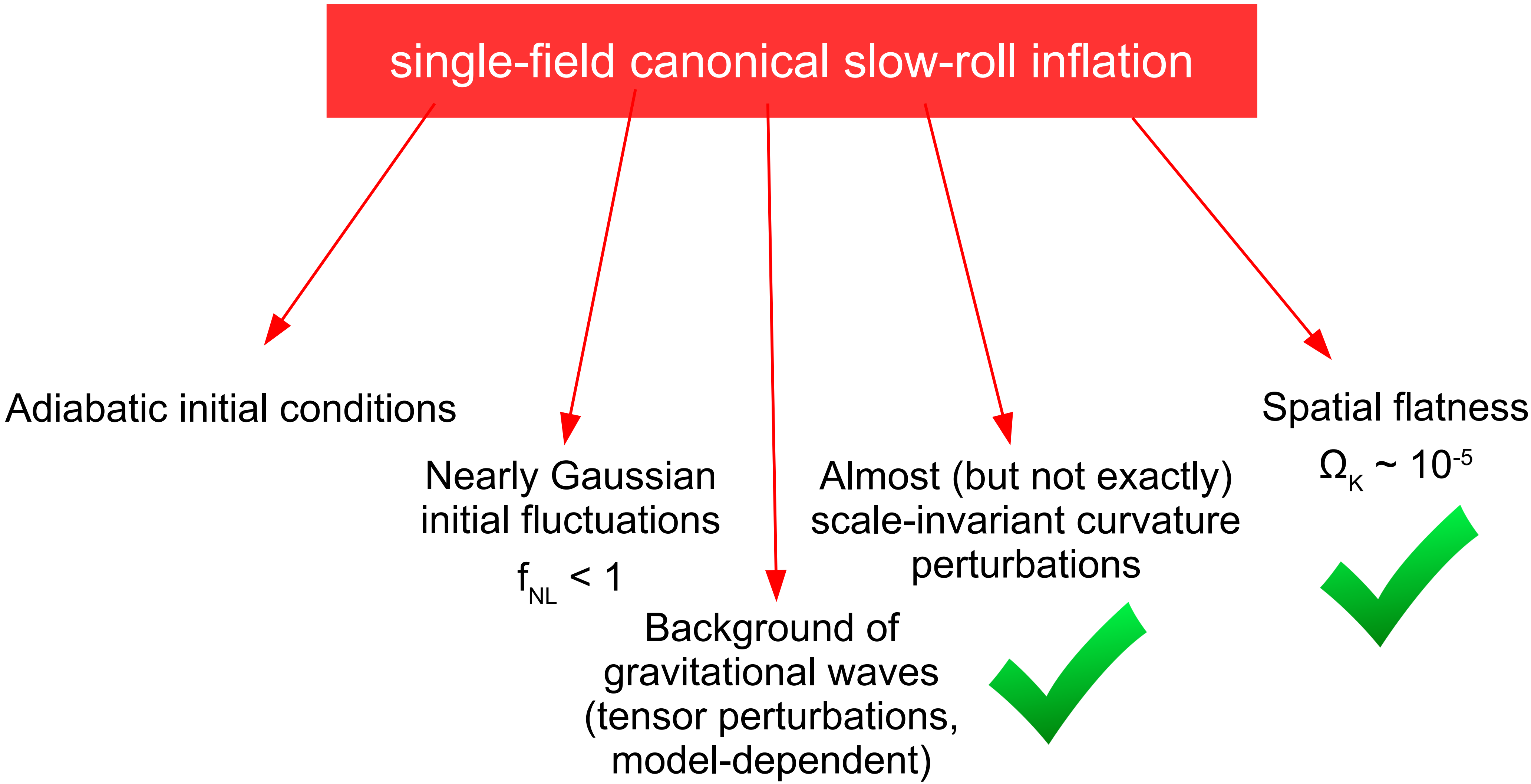
running of the spectral index

running of the running of the spectral index

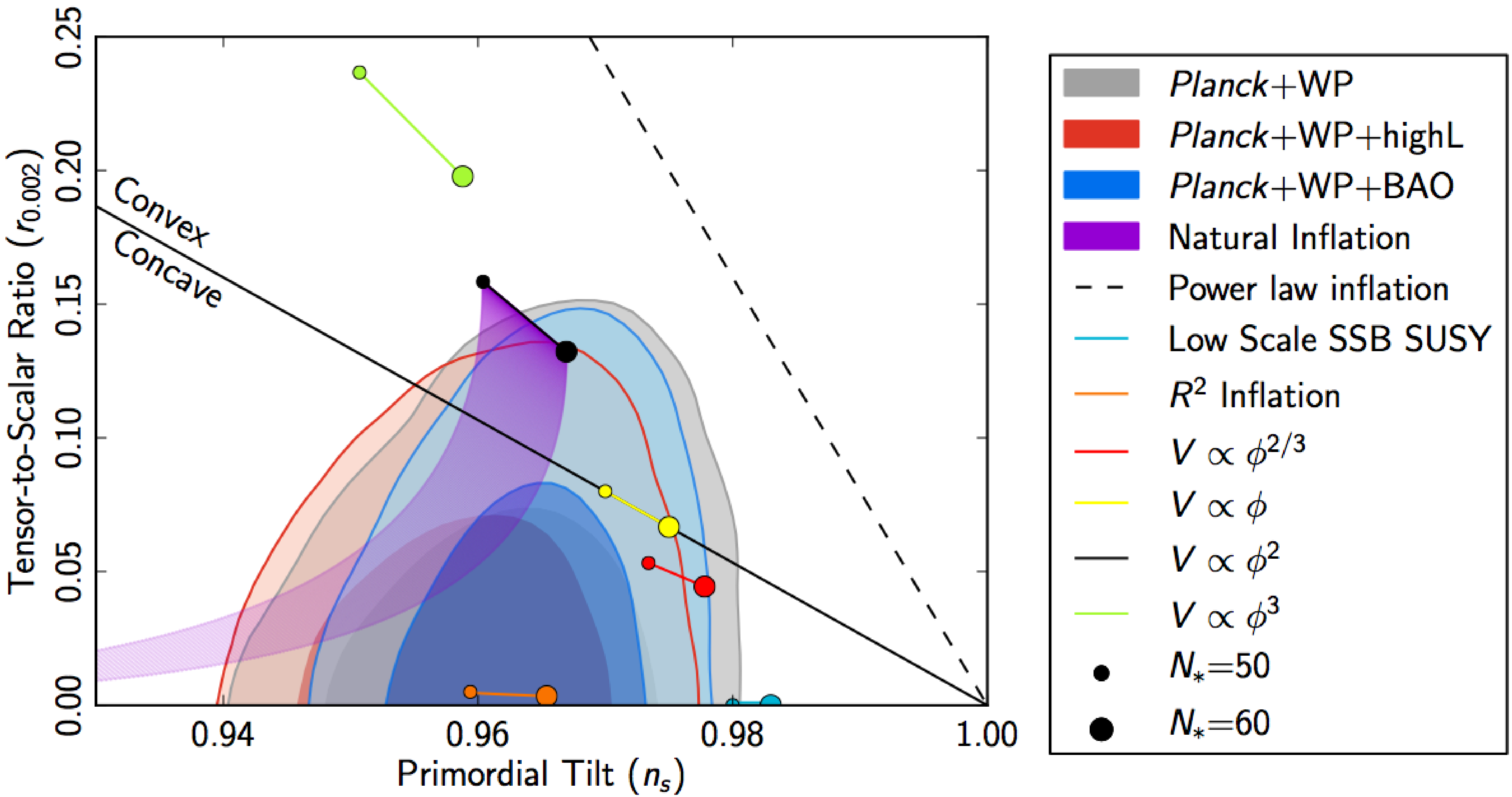




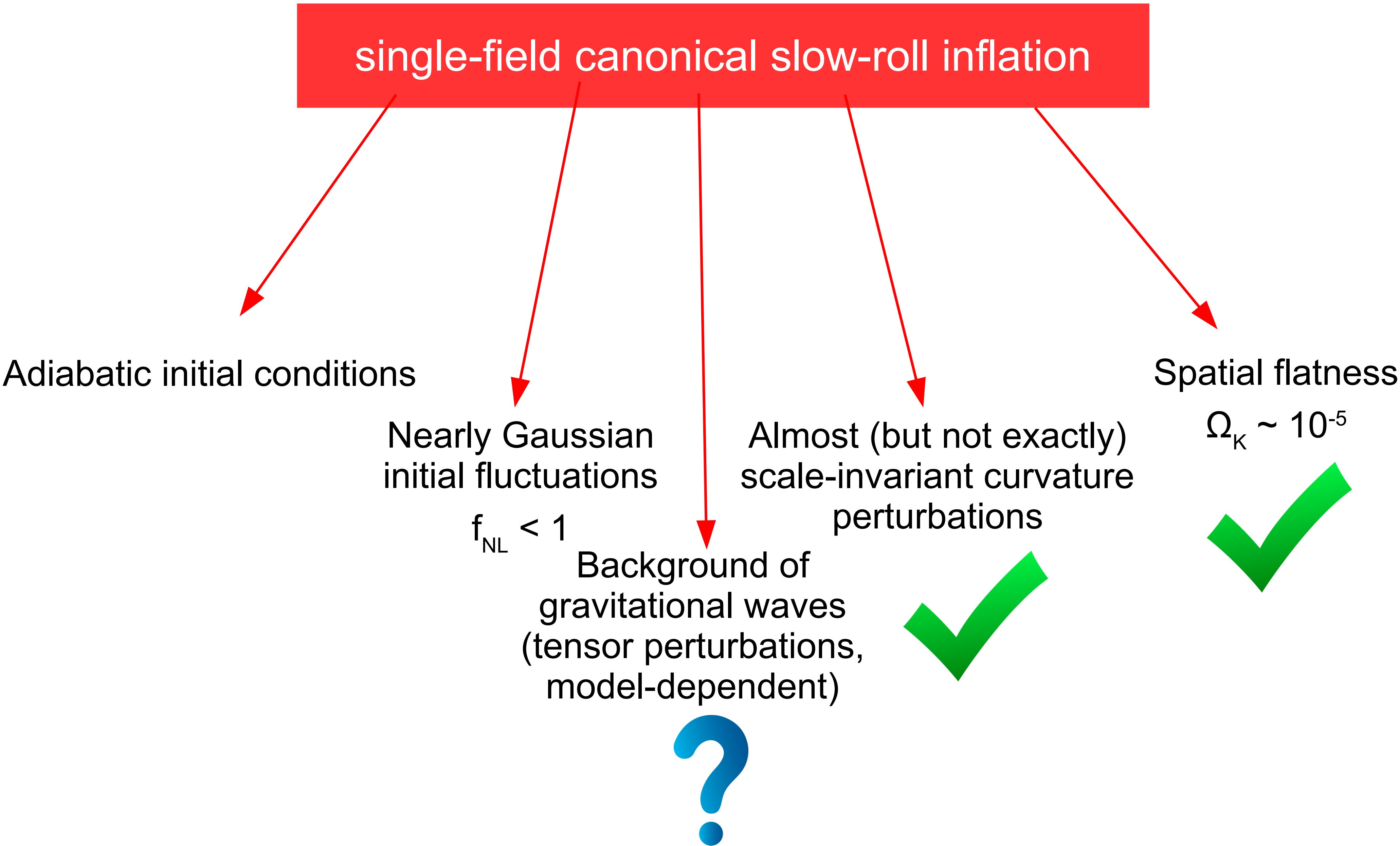
Predictions of the simplest models



Constraints on a selection of inflation models



Predictions of the simplest models



Non-Gaussianity

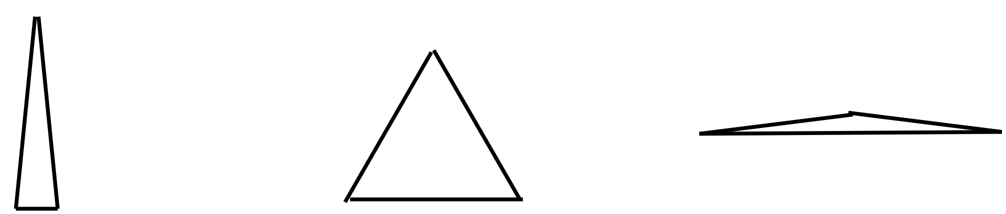
$$\langle \Phi(\vec{k}_1)\Phi(\vec{k}_2)\Phi(\vec{k}_3)\rangle = (2\pi)^3\,\delta^{(3)}(\vec{k}_1+\vec{k}_2+\vec{k}_3)\; f_{\rm NL}\;F(k_1,k_2,k_3)$$

Three-point correlation

enforces triangular configurations

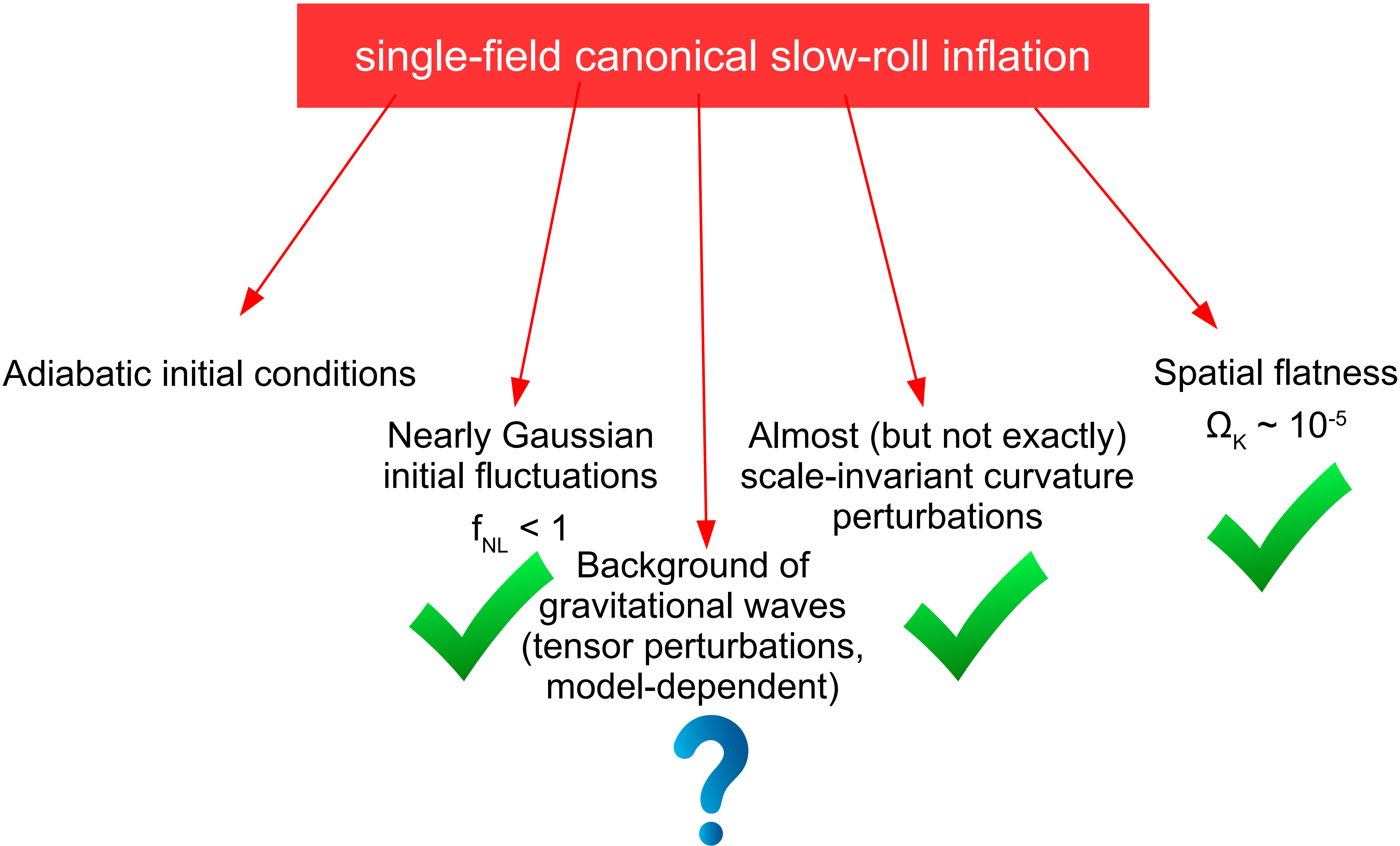
Bispectrum

Three limiting cases



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

Predictions of the simplest models



Adiabaticity: constraints on isocurvature perturbations

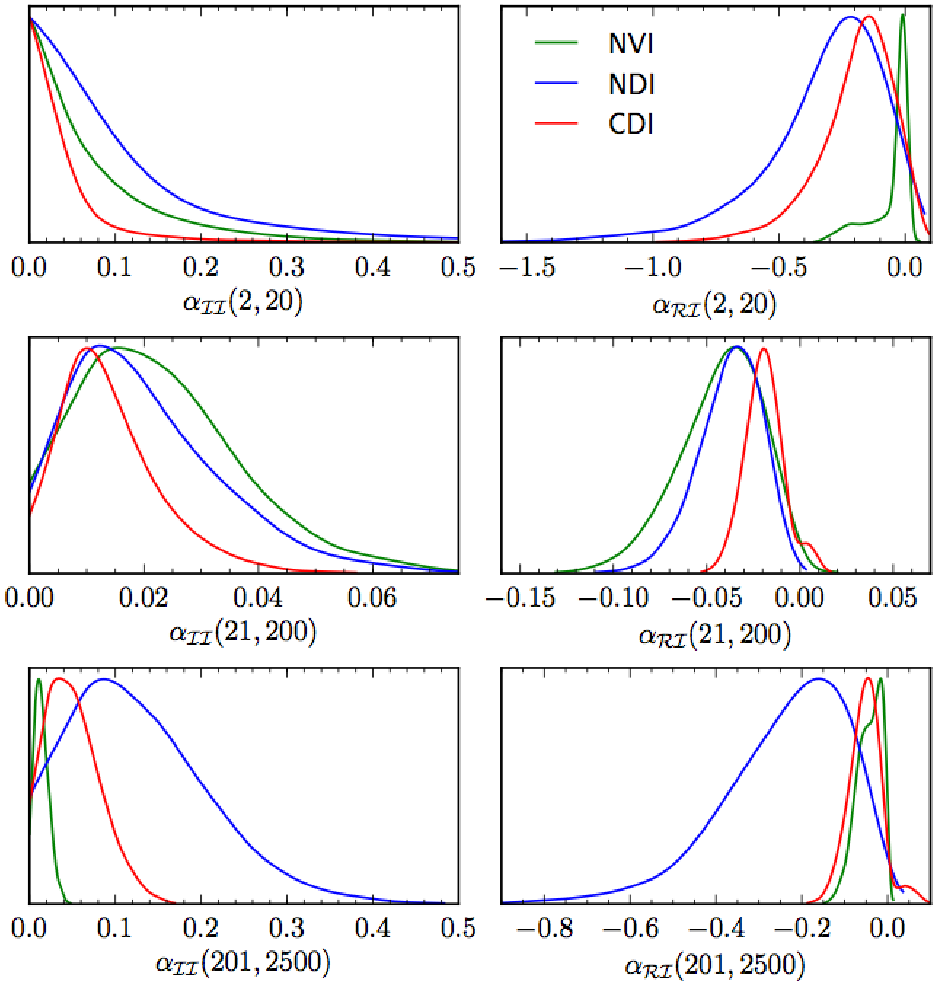
Isocurvature fraction at ...

Types of isocurvature

Large scales

Intermediate scales

Small scales



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

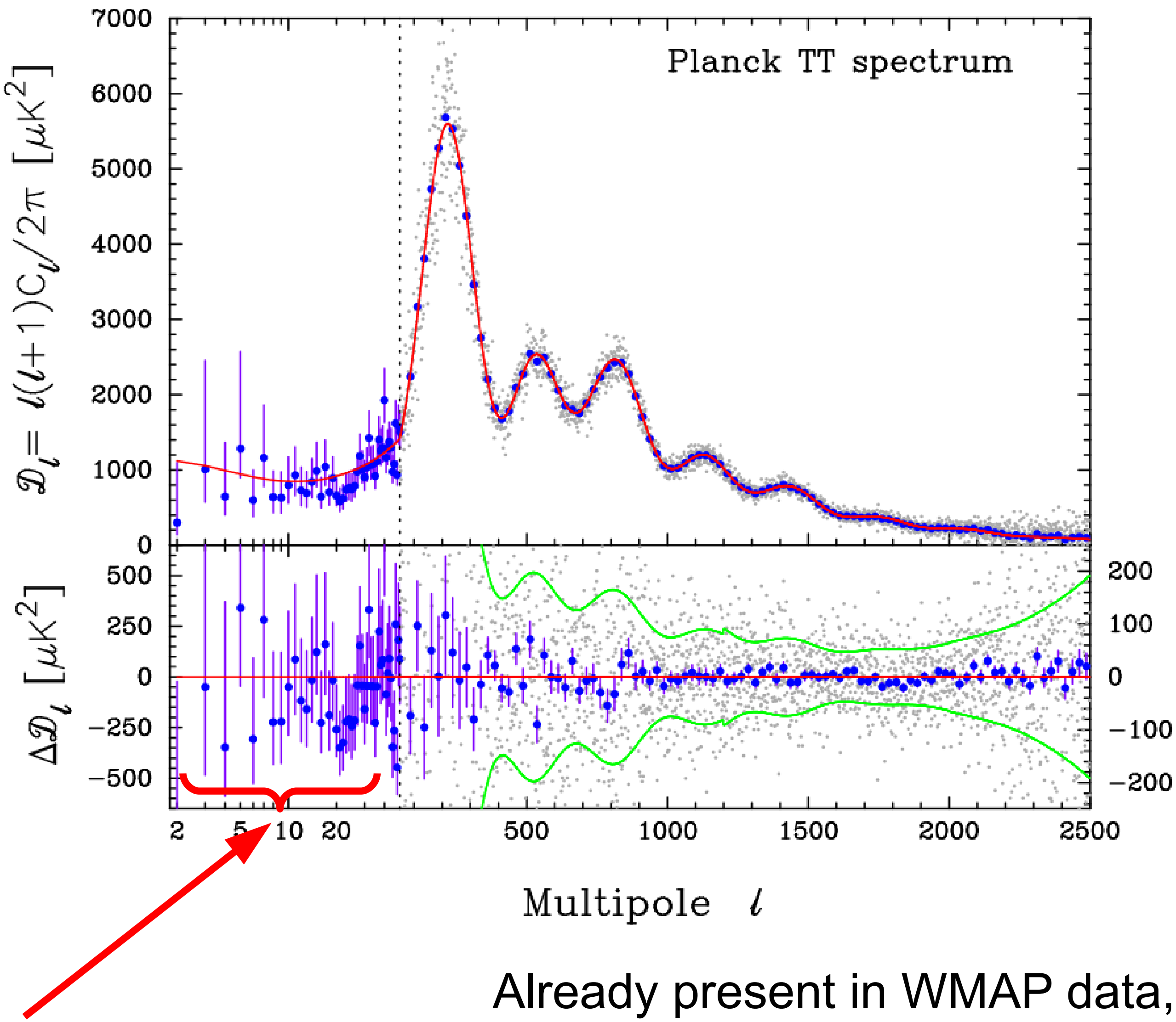
Spatial flatness

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

?

Anomalies?

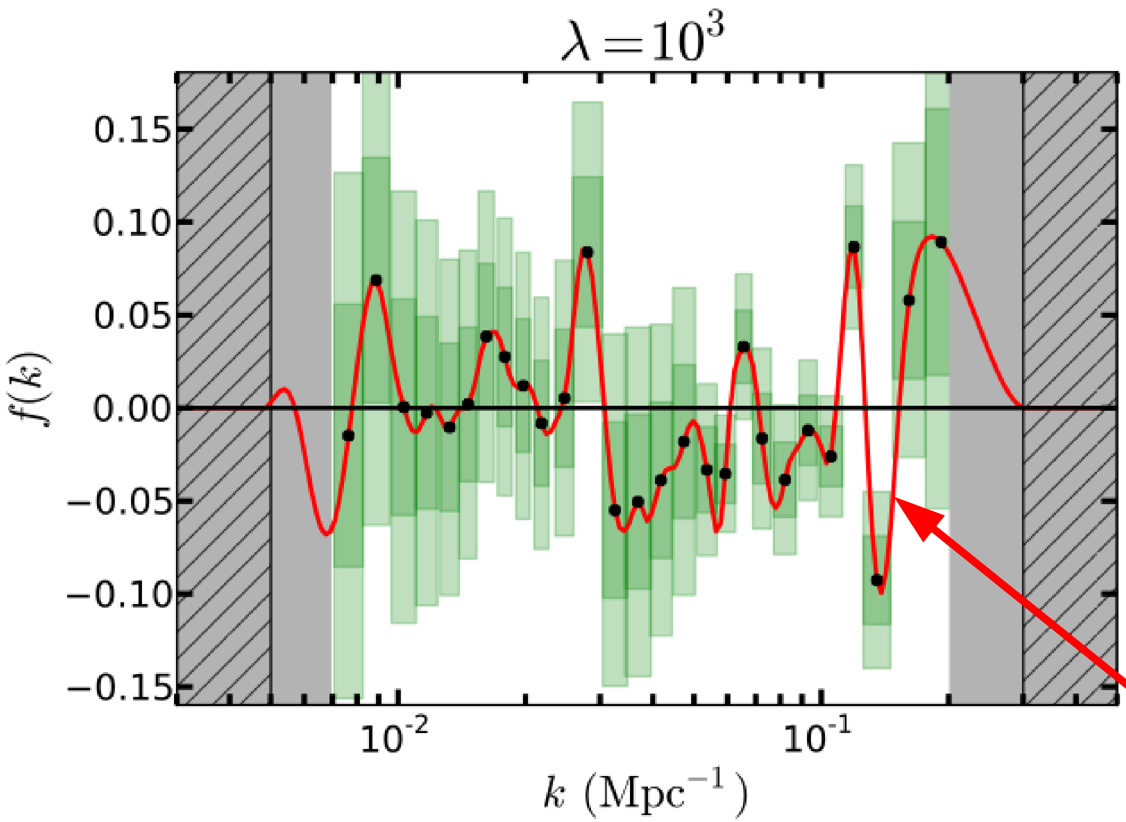
A lack of power at large scales?

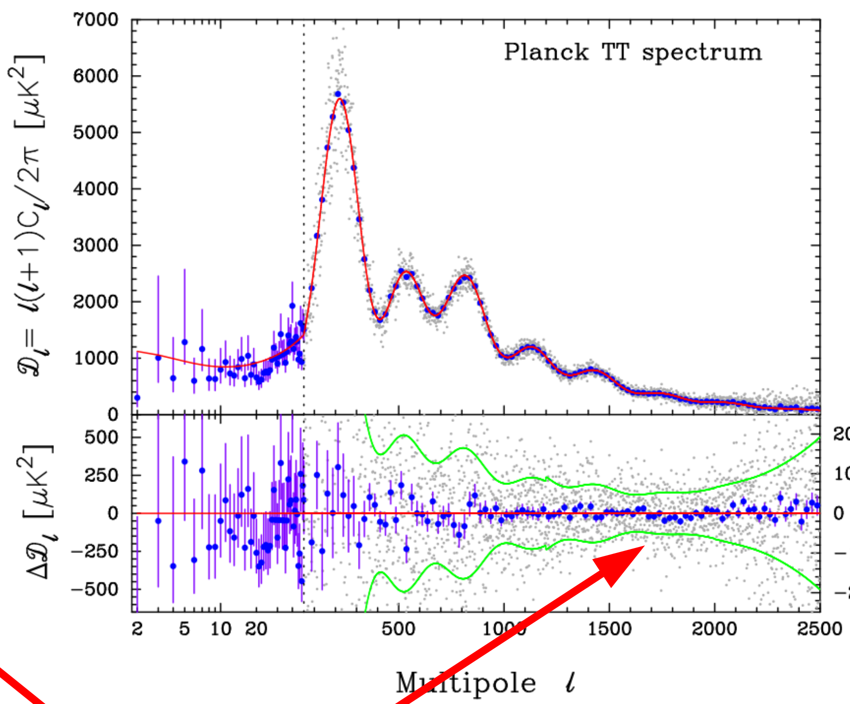


Already present in WMAP data,
but exacerbated by better smale scale data

A feature at small scales?

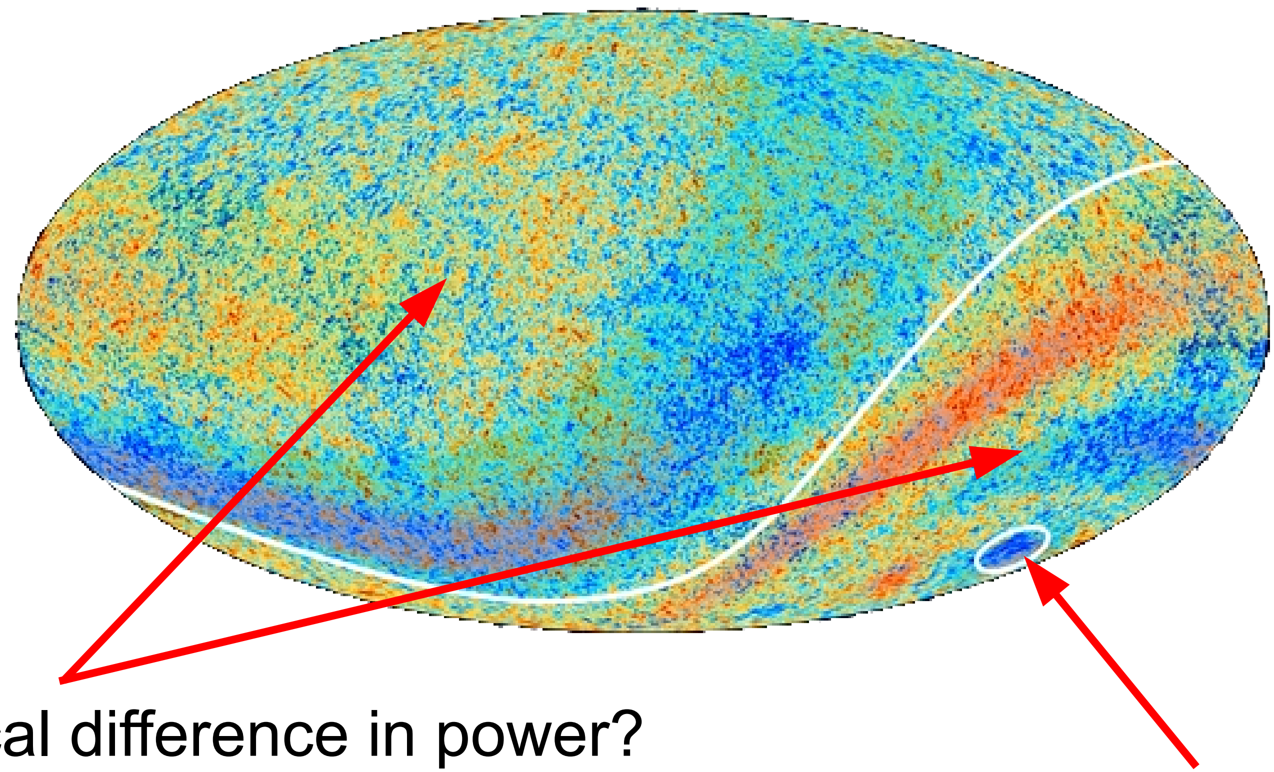
Non-parametric reconstruction of the primordial power spectrum





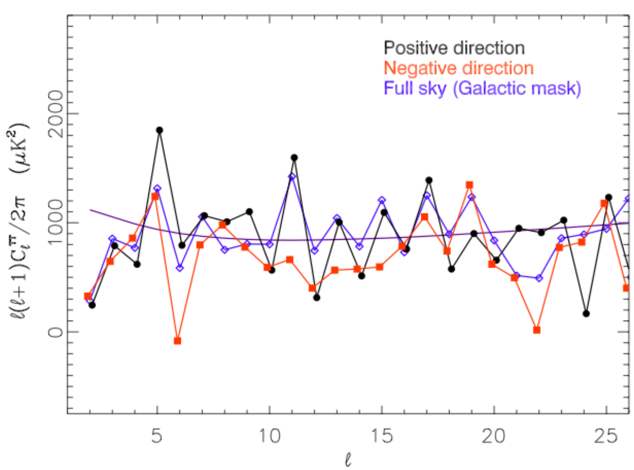
About 3σ significance

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