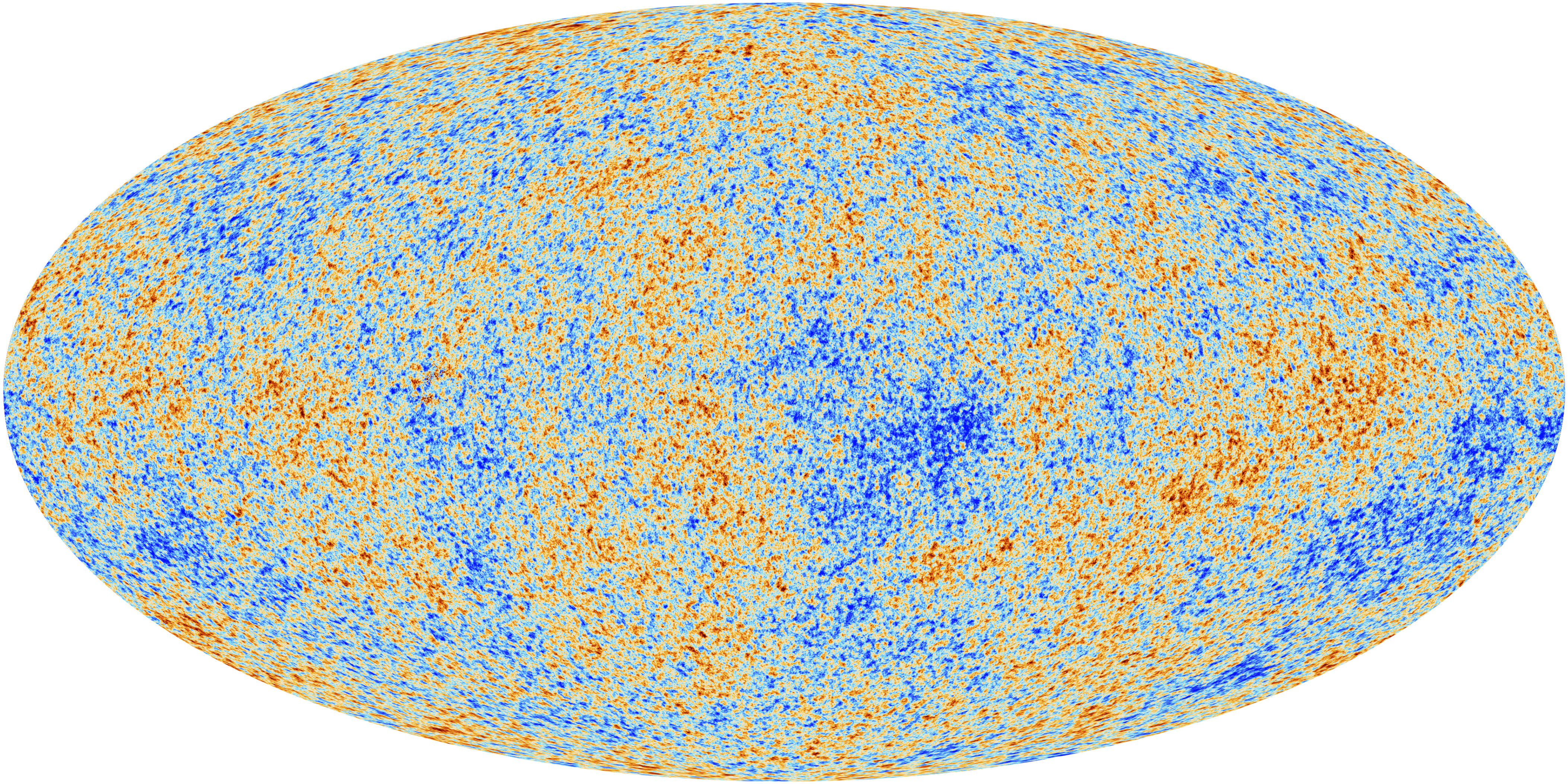
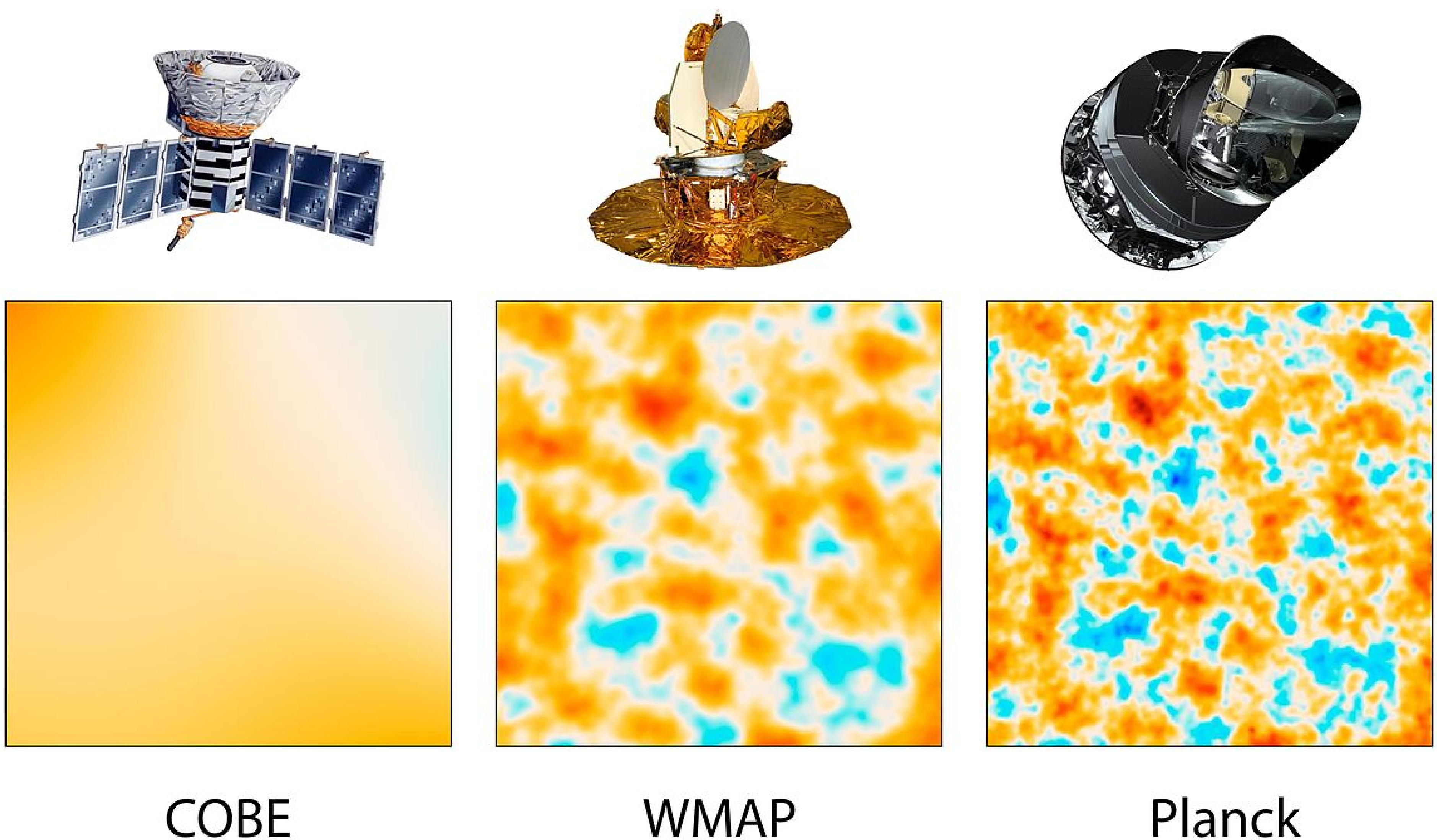
An almost perfect Universe
results from the Planck mission

Torsten Enßlin (MPI für Astrophysik)
on behalf of the Planck Collaboration



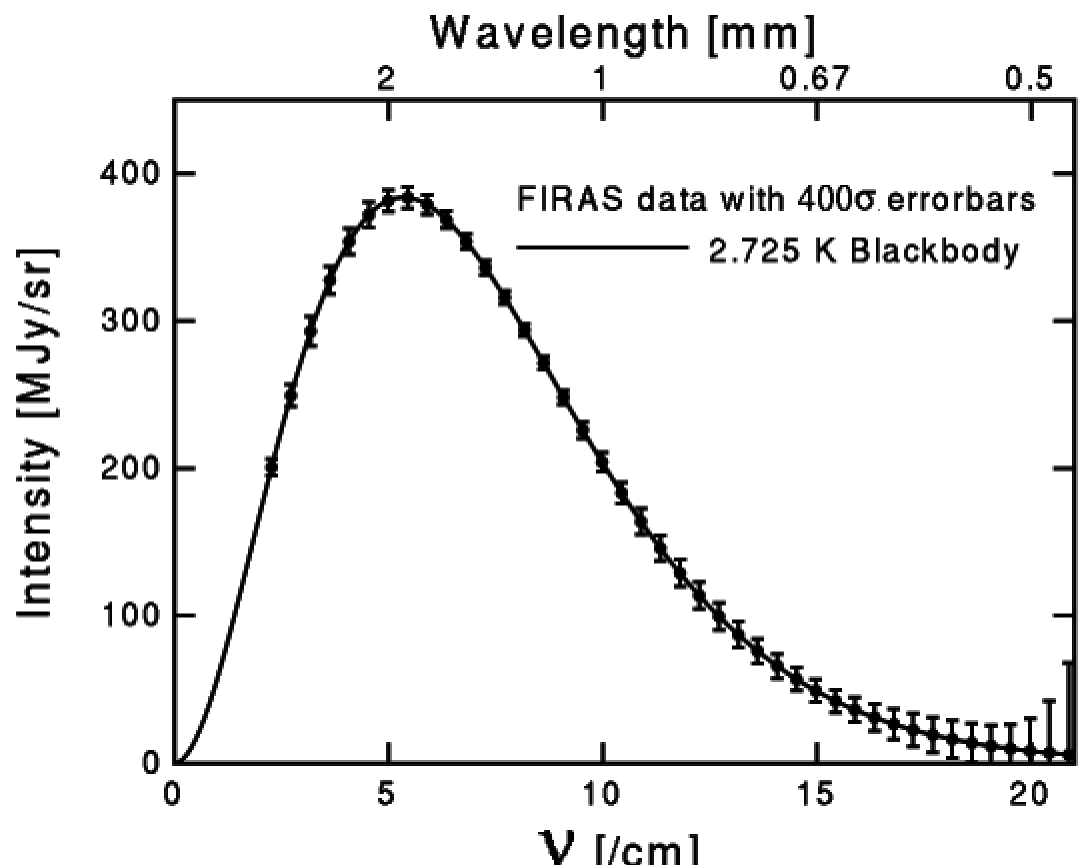
Why Planck?



Why Planck?

$$M_{\rm pl} = \sqrt{\frac{\hbar c}{8\pi G}}$$

$$I(\nu) = \frac{2\,h\,\nu^3}{c^2}\,\frac{1}{e^{\frac{h\,\nu}{k_{\rm B}\,T}} - 1}$$



What is Planck doing?

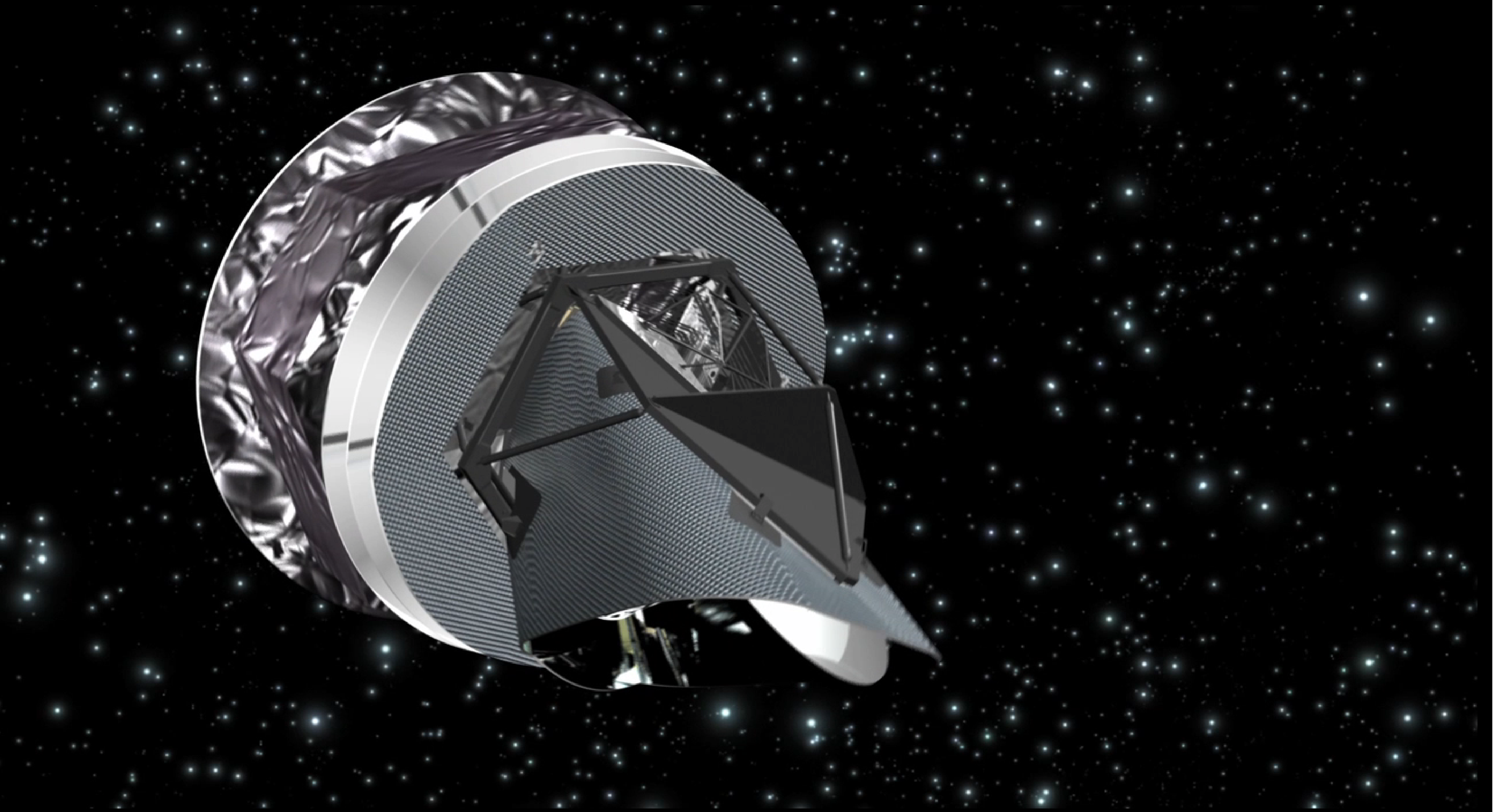
Gaussian statistics

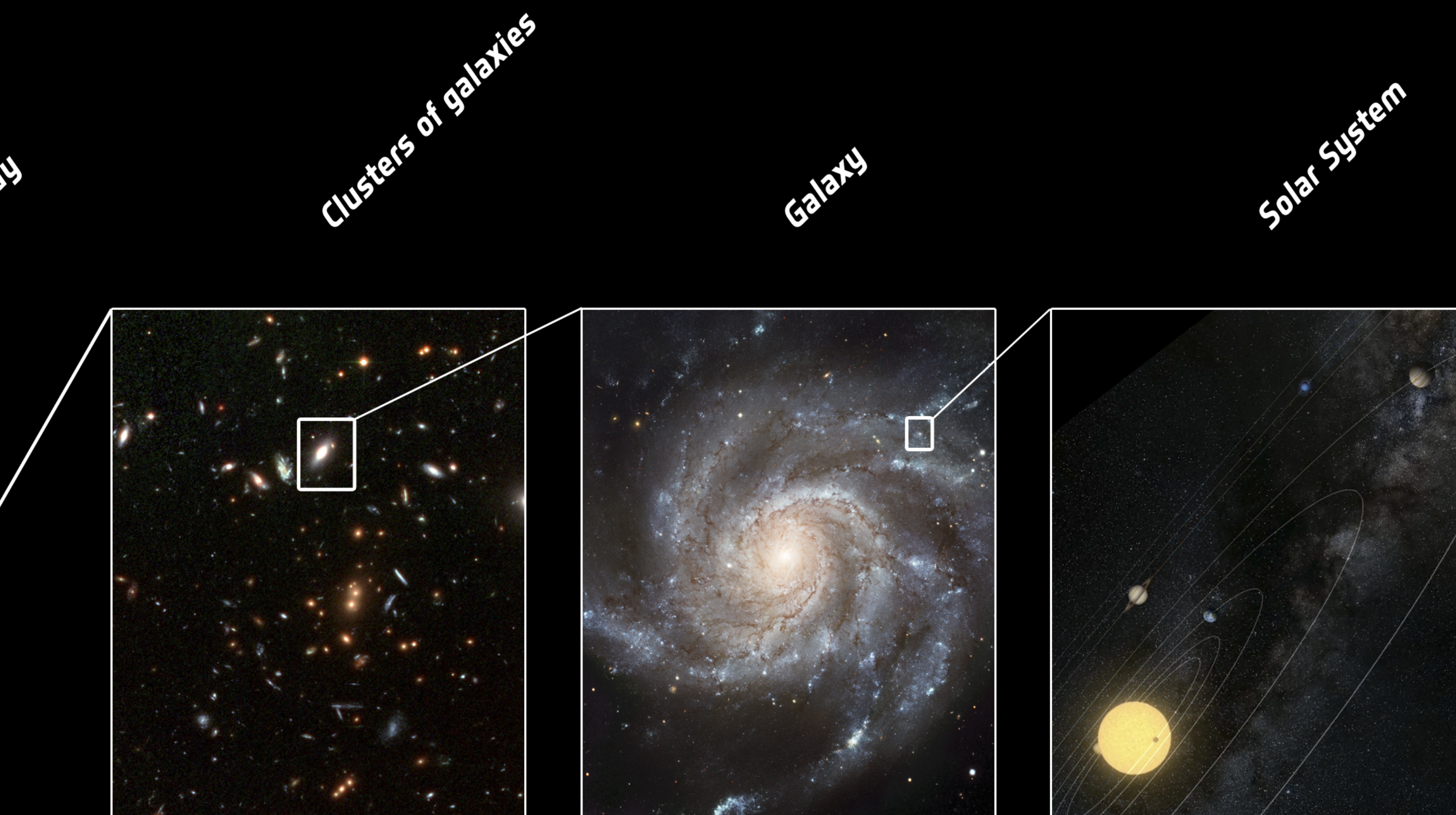
$$f(x) = \frac{1}{\sigma\sqrt{2\pi}} e^{-\frac{(x-\mu)^2}{2\sigma^2}}$$

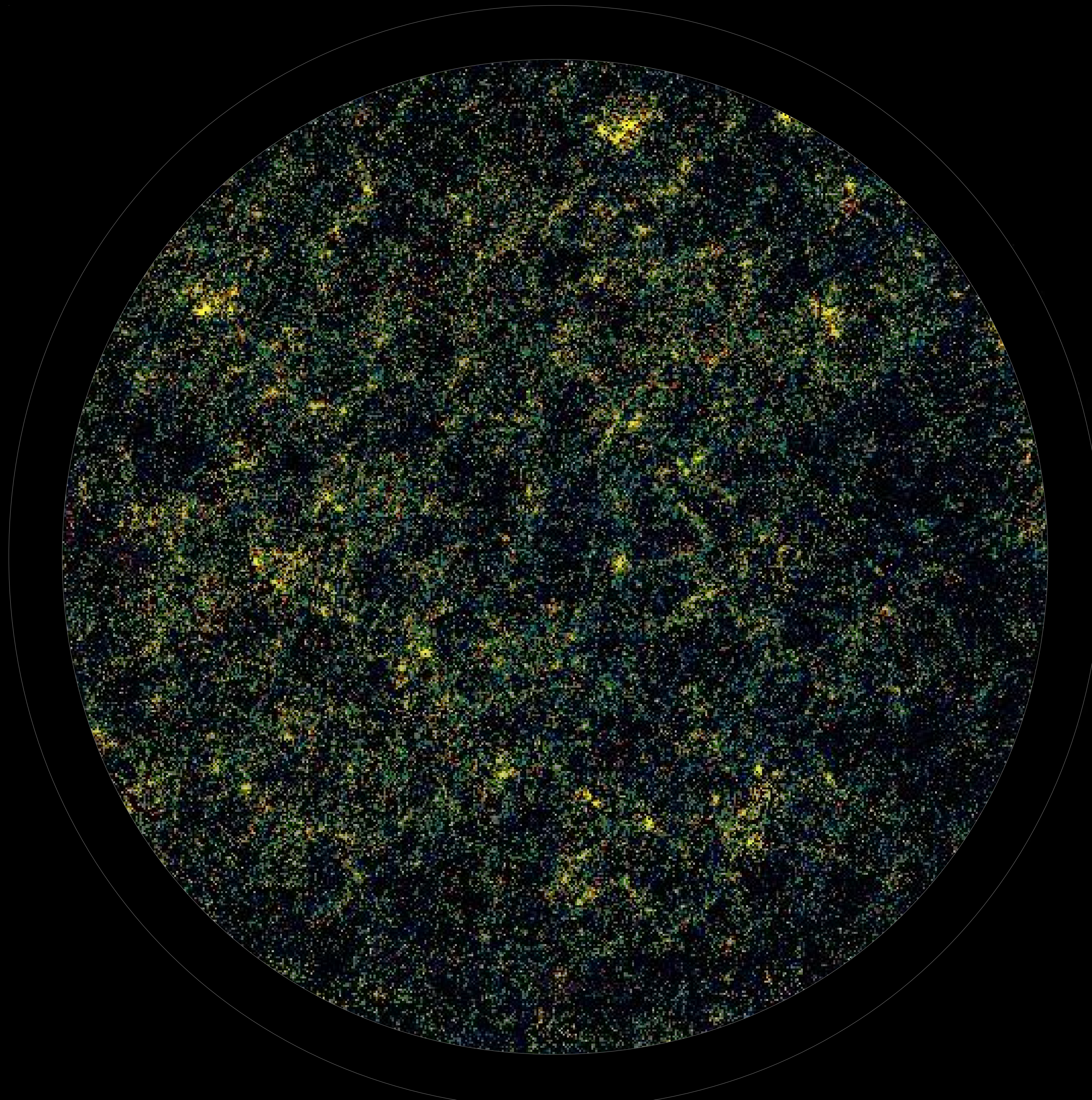
$$\mu = 2.725 \text{ Kelvin}$$

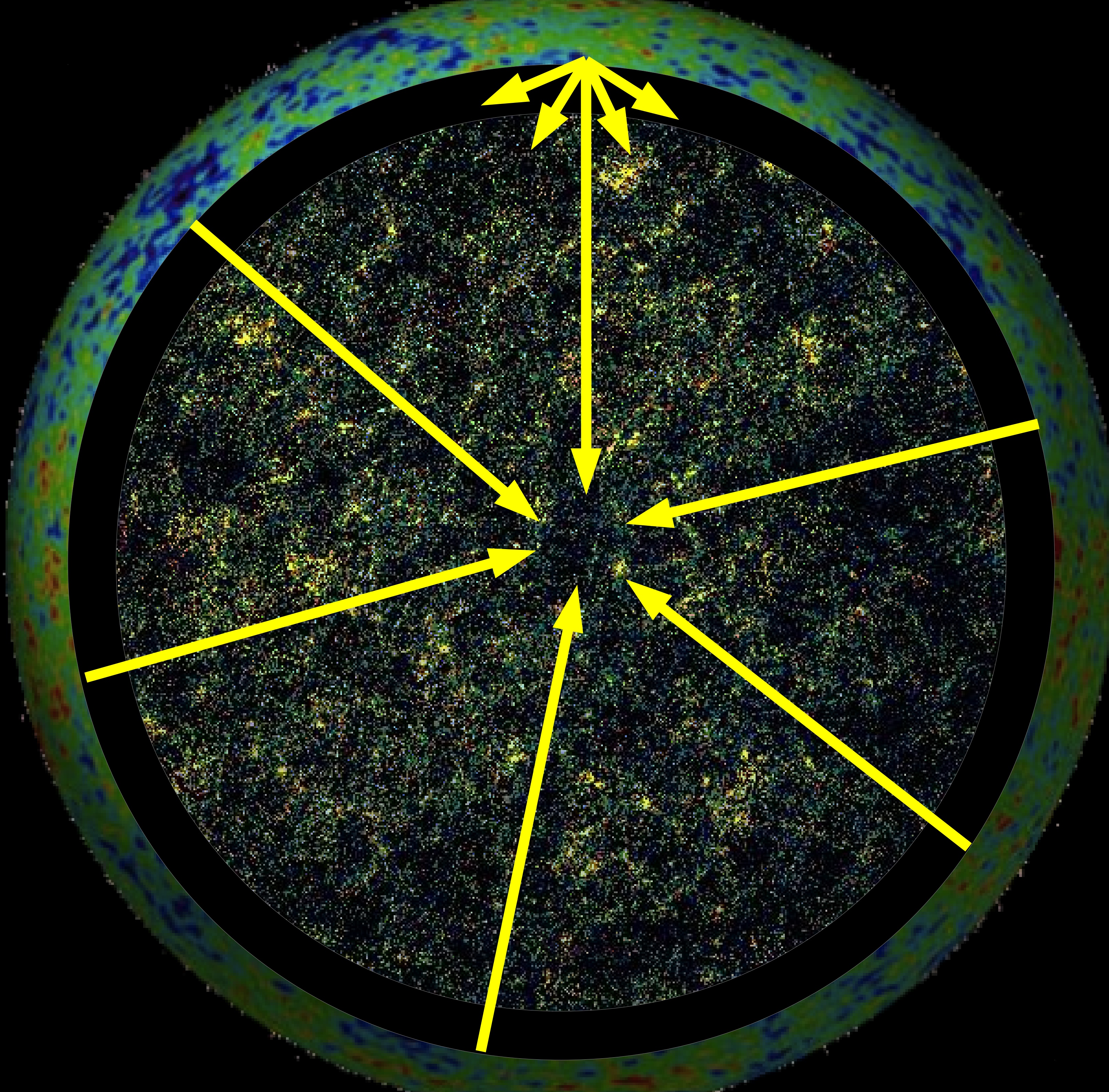
$$\sigma = 0.00001 \text{ Kelvin}$$

Testing inflation

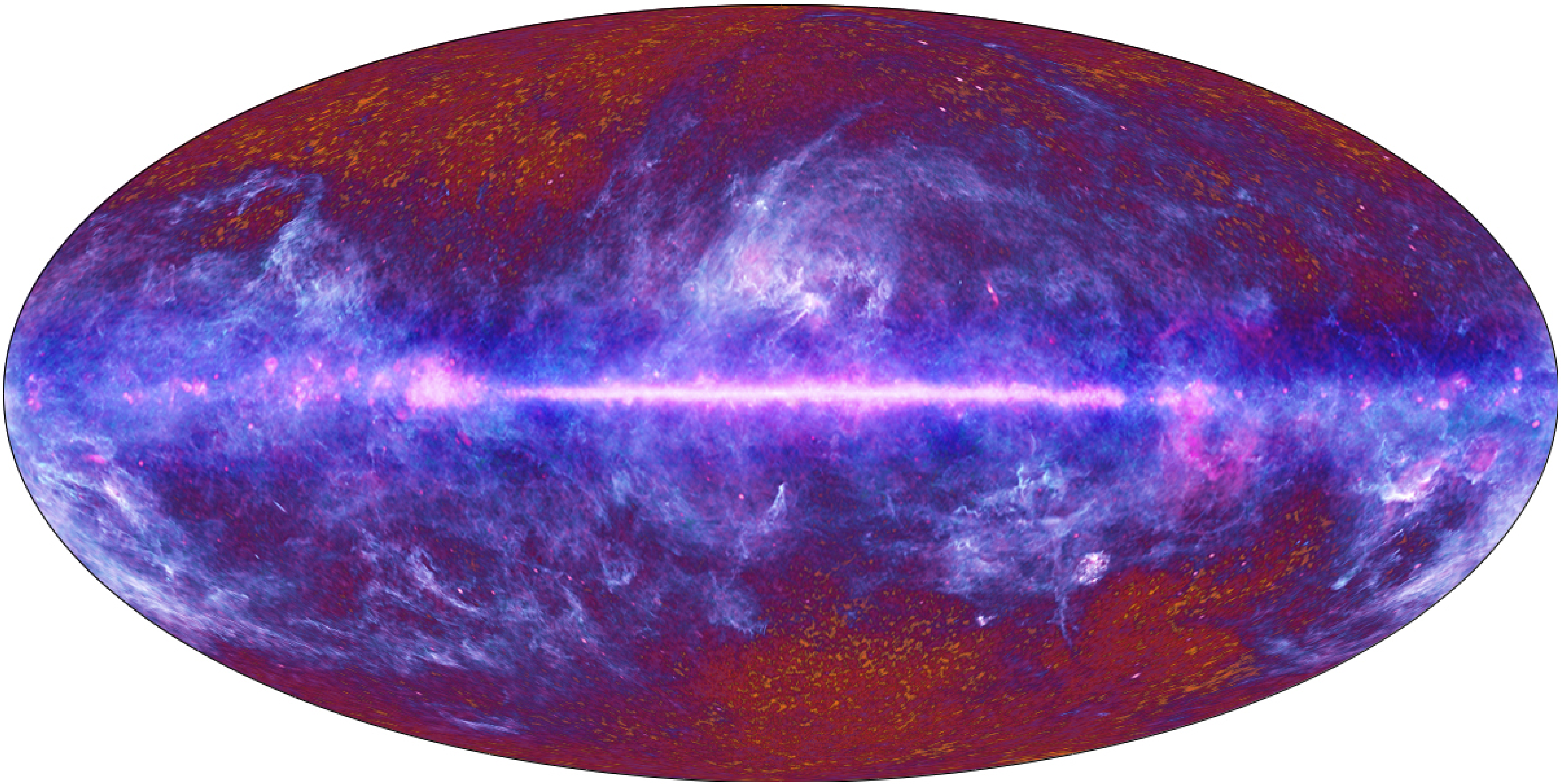



Clusters of galaxies
Galaxy
Solar System

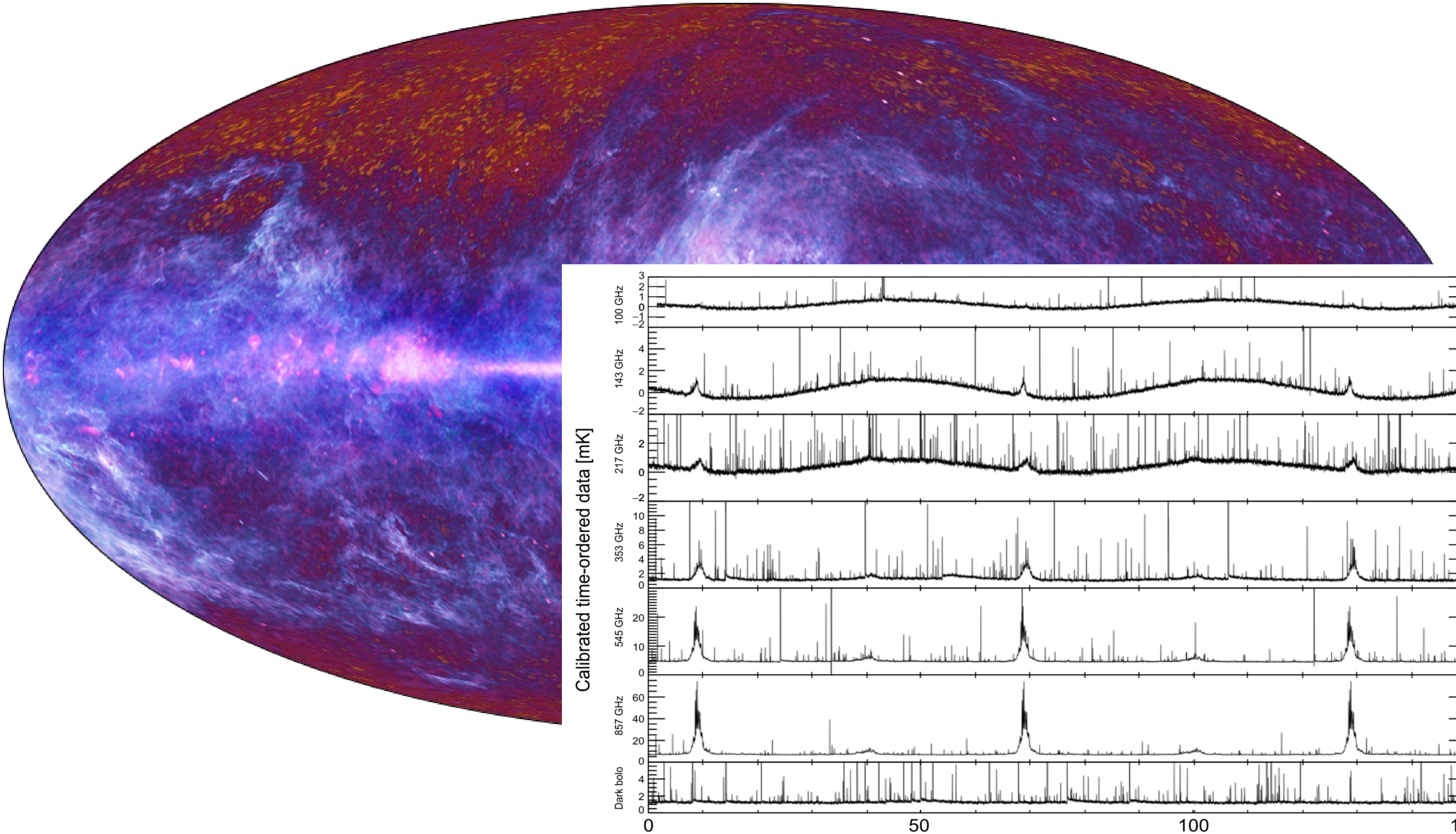




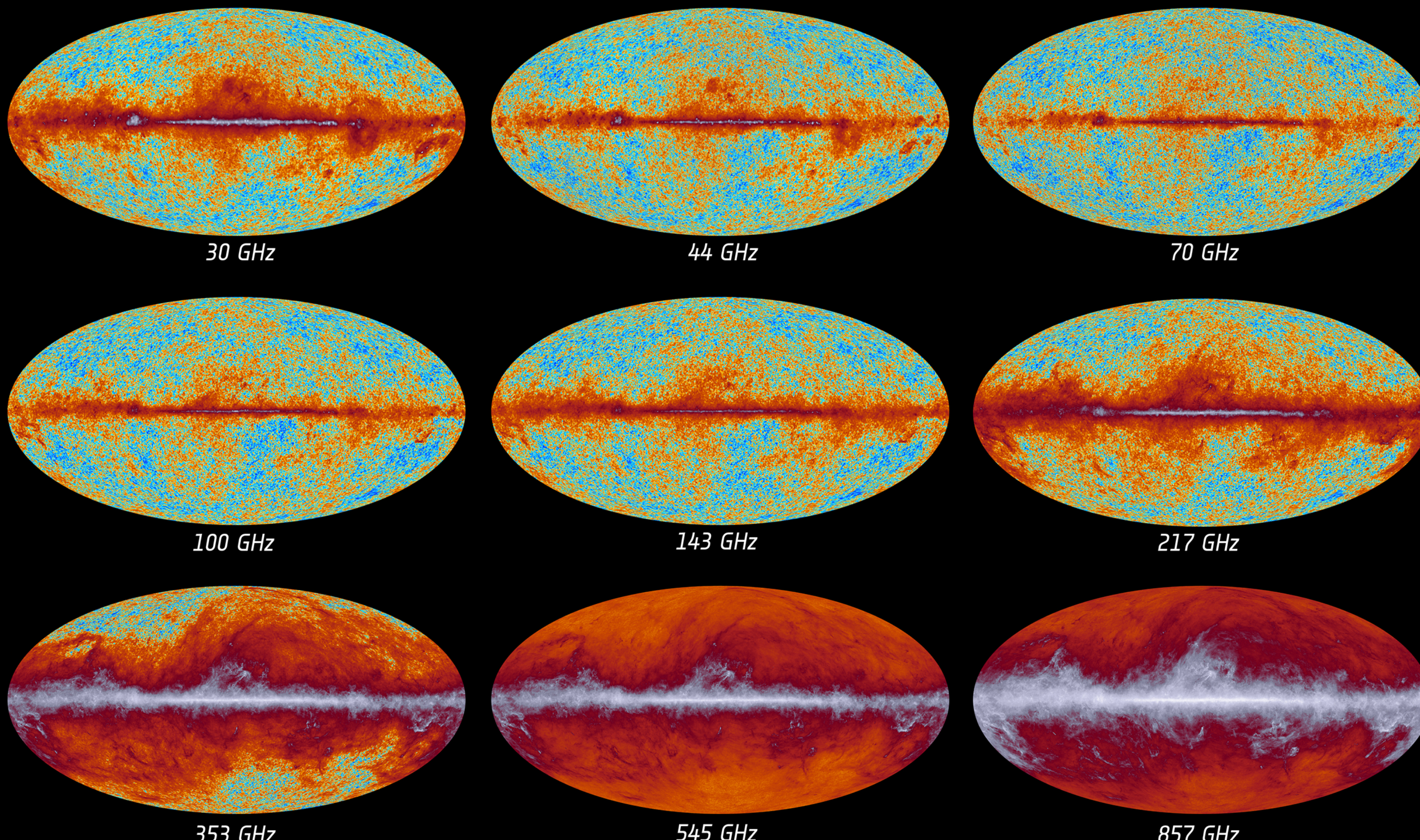
The microwave sky

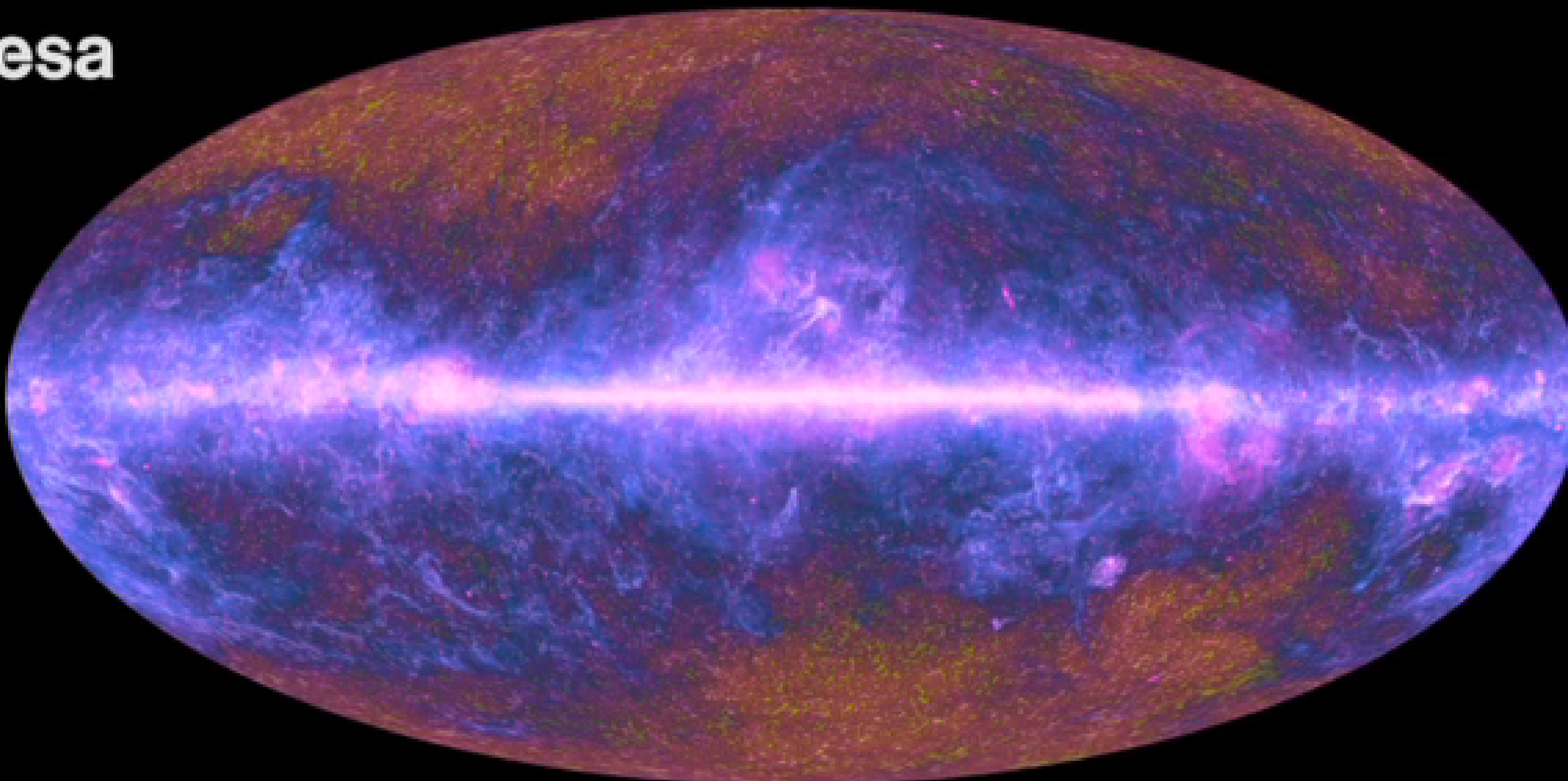


The timelines

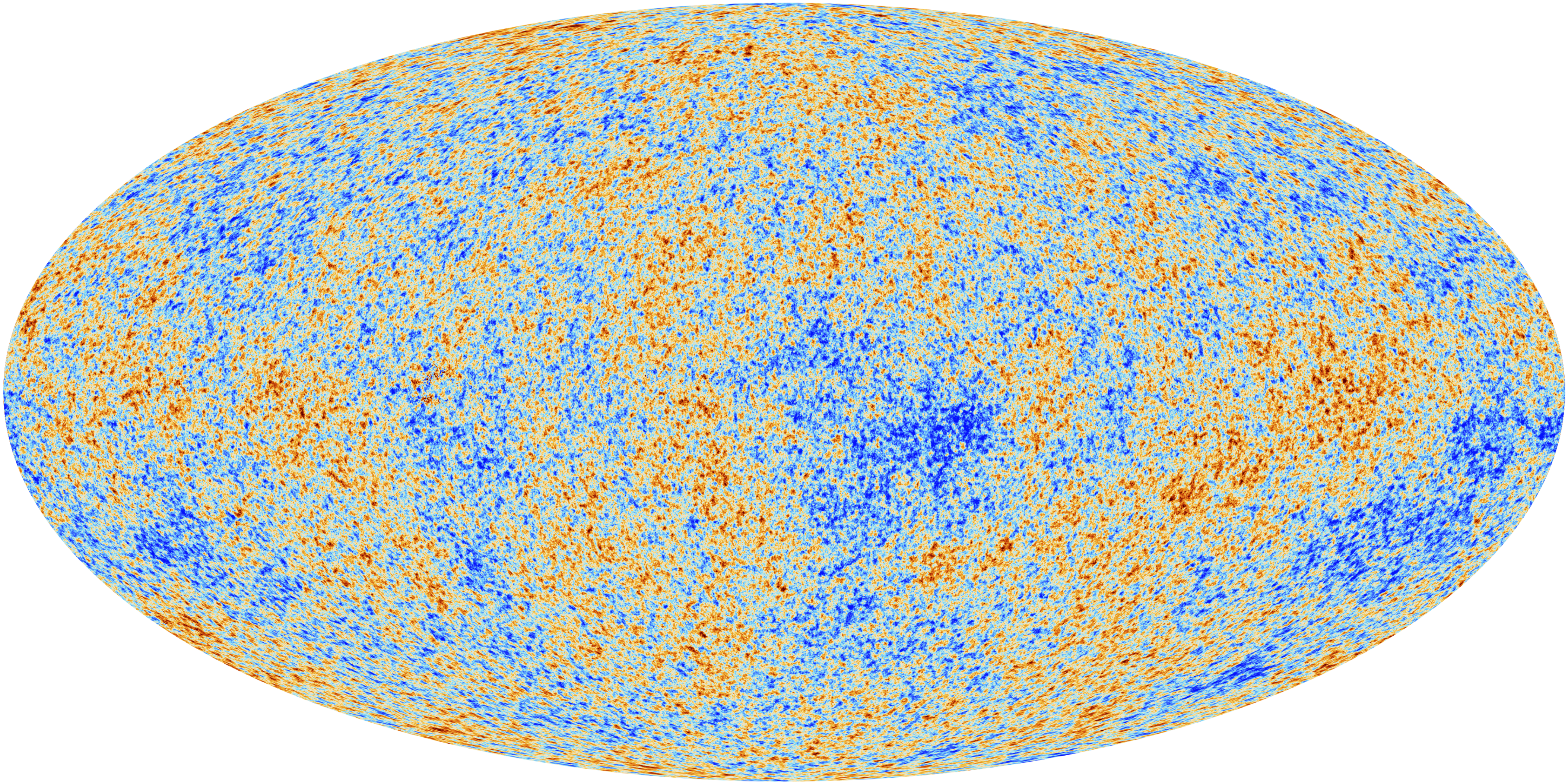


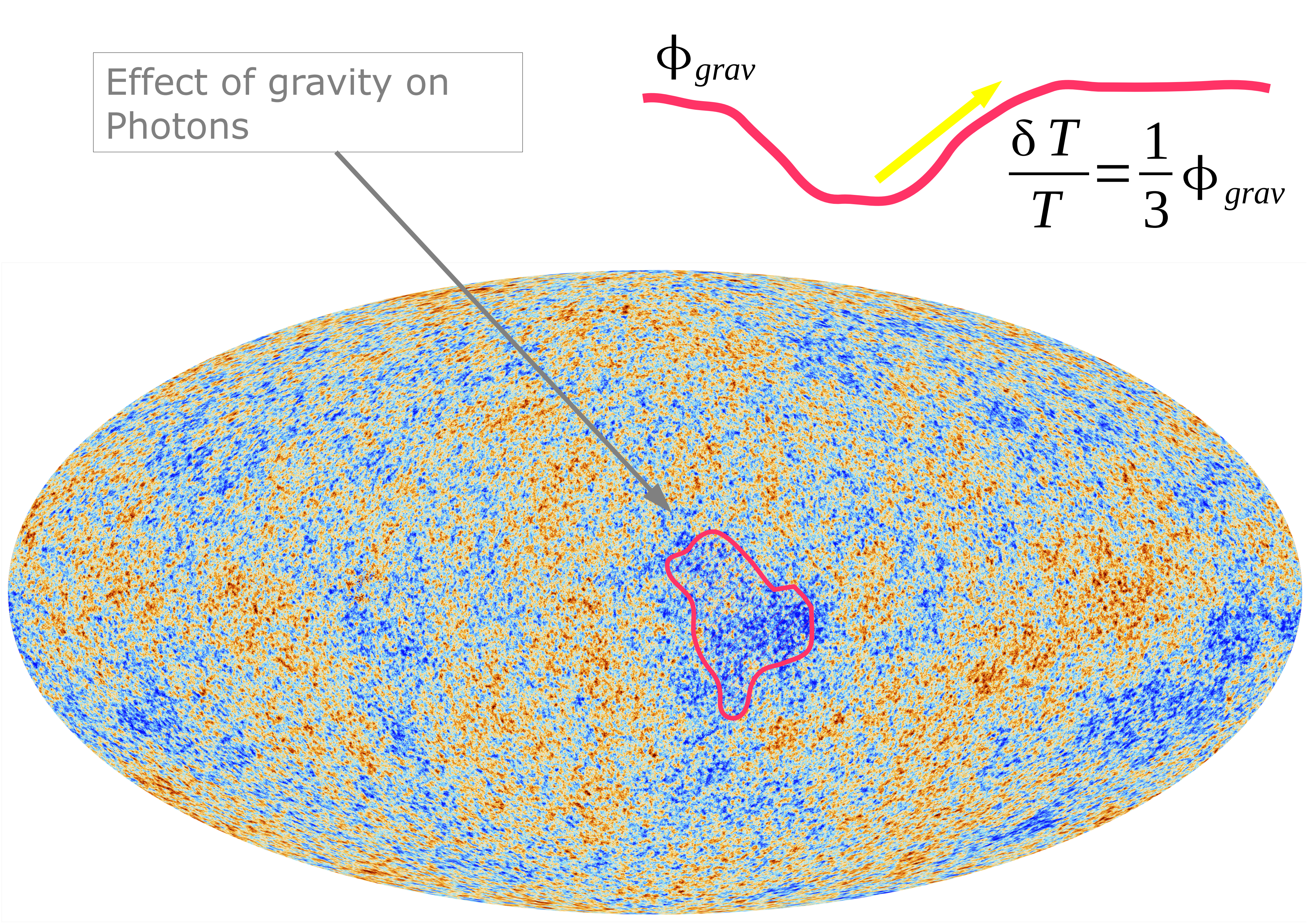
The sky as seen by Planck

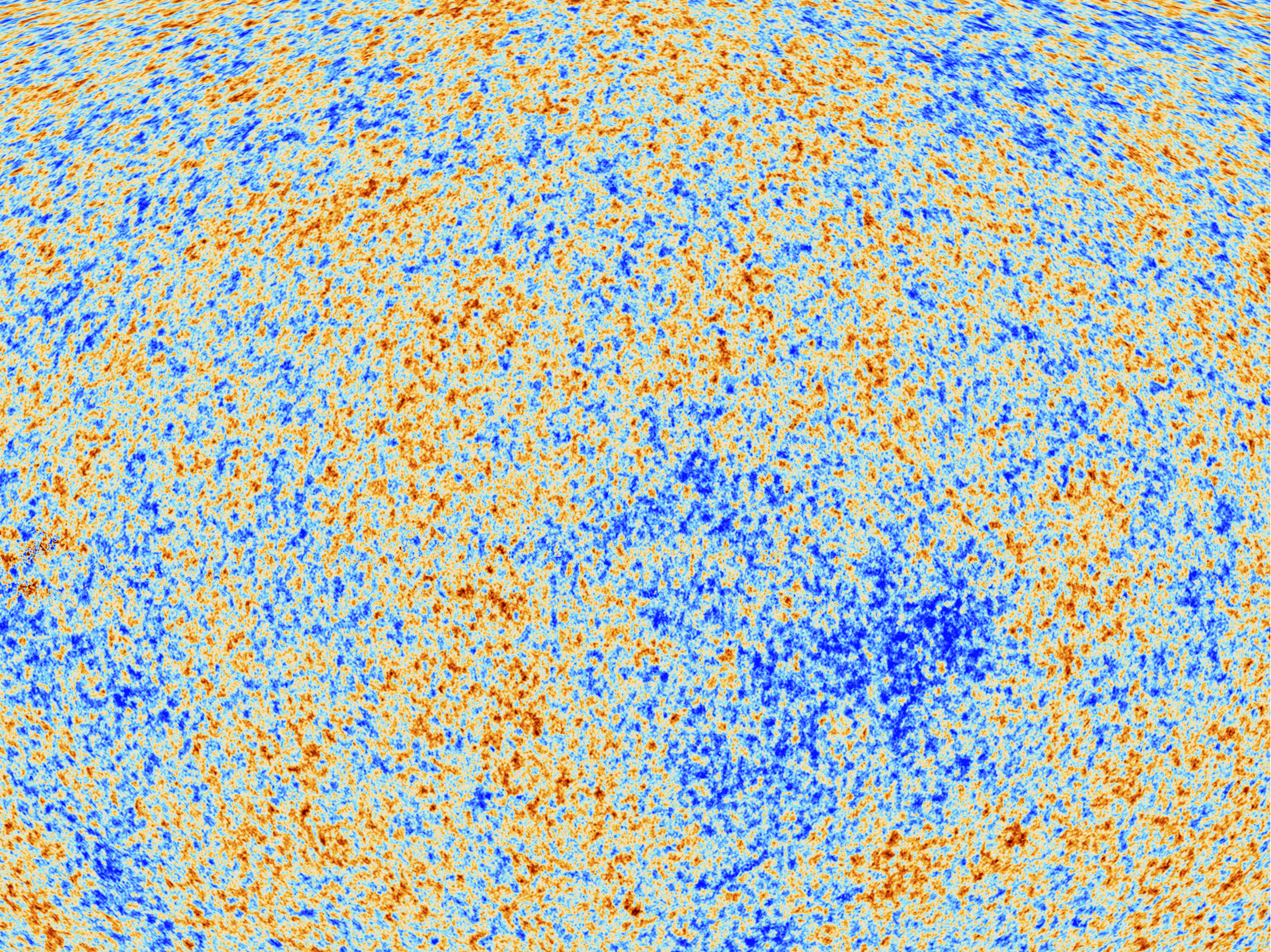


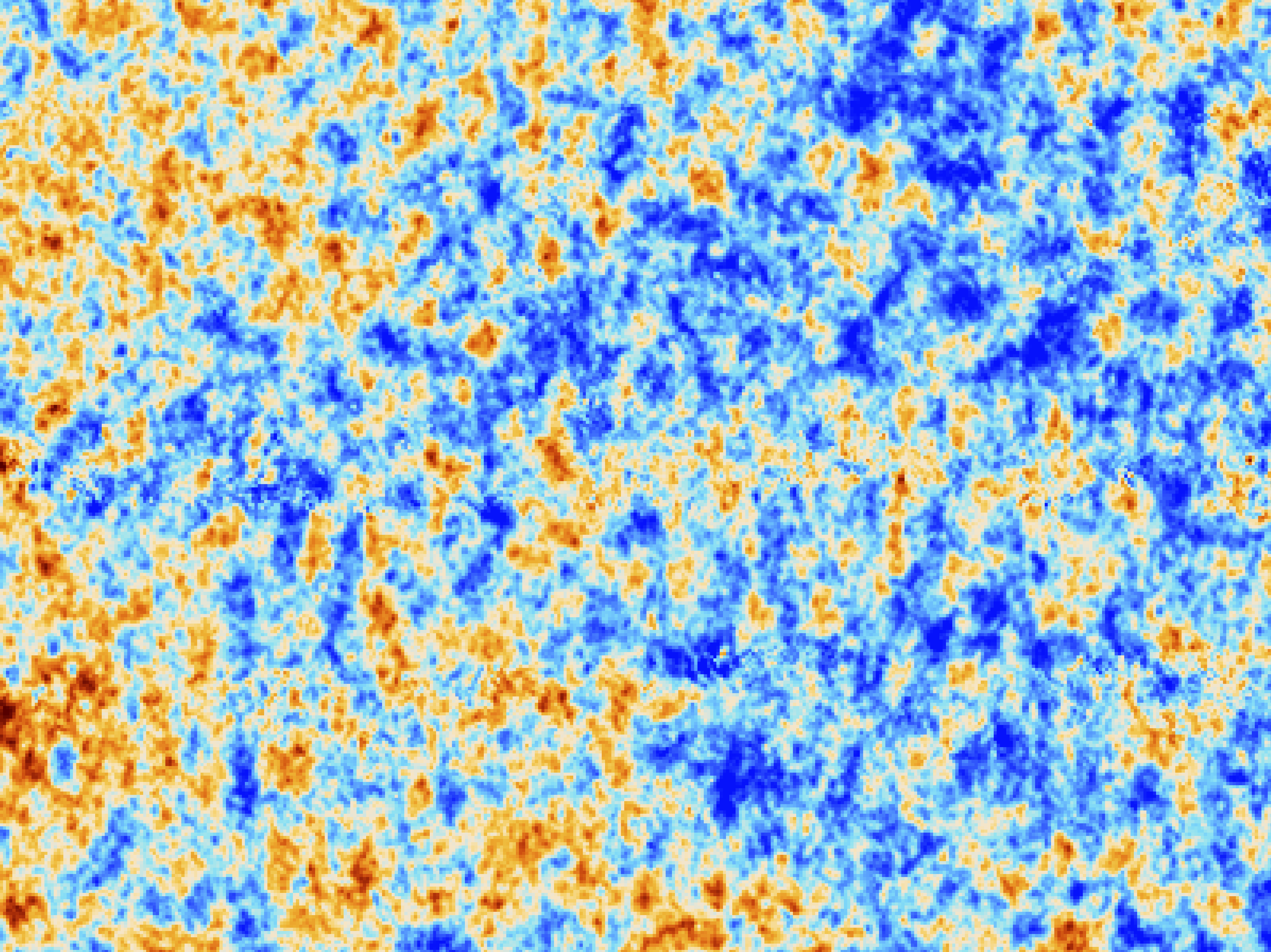

Individual sources
+
Radio emission from the Milky Way
+
Dust emission from the Milky Way
+
Cosmic Microwave Backgound
All emissions at microwave & submillimetre wavelengths

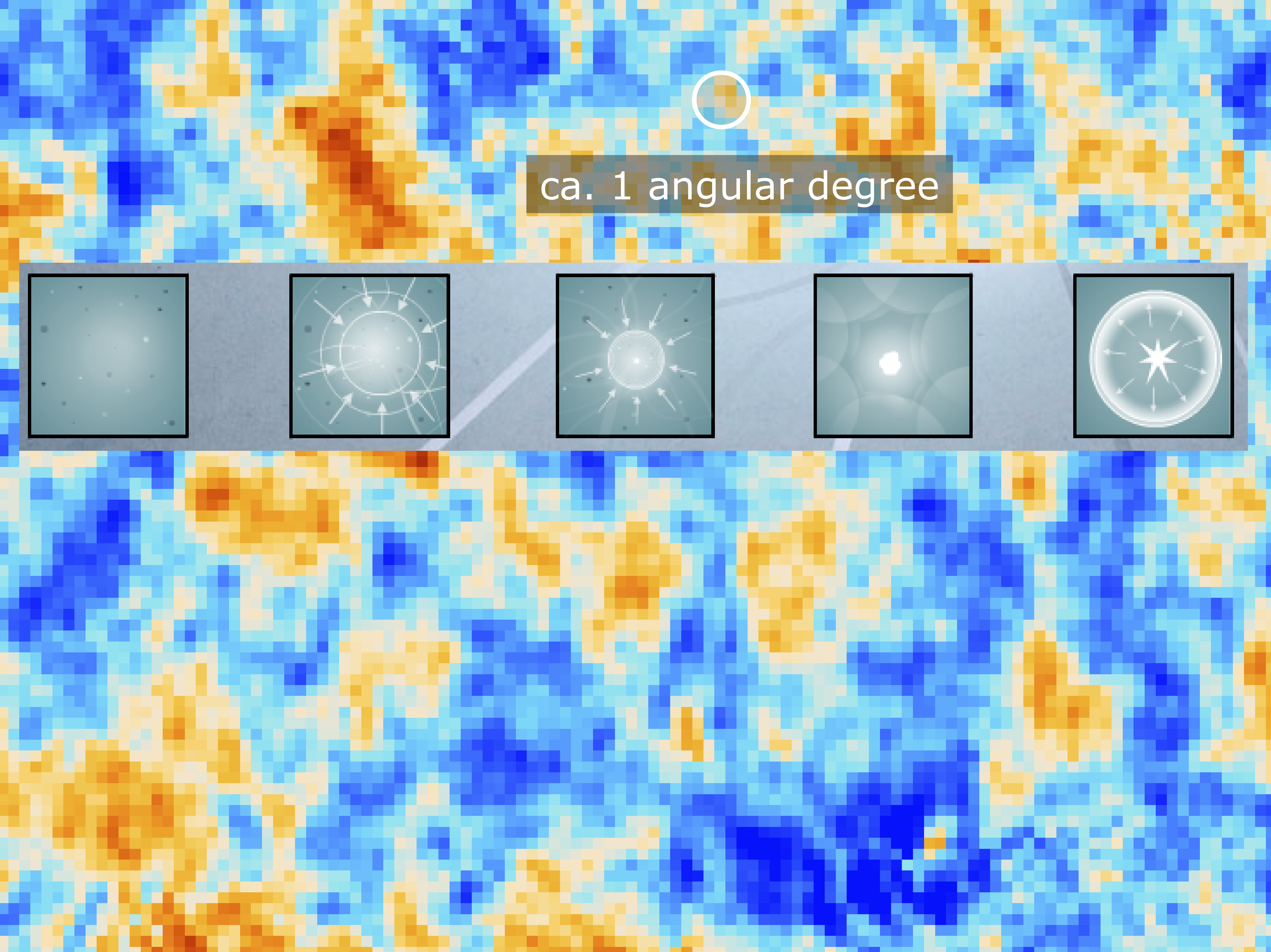
The cosmic microwave background




Effect of gravity on Photons
ϕ_{grav}
$\frac{\delta T}{T} = \frac{1}{3}\phi_{grav}$

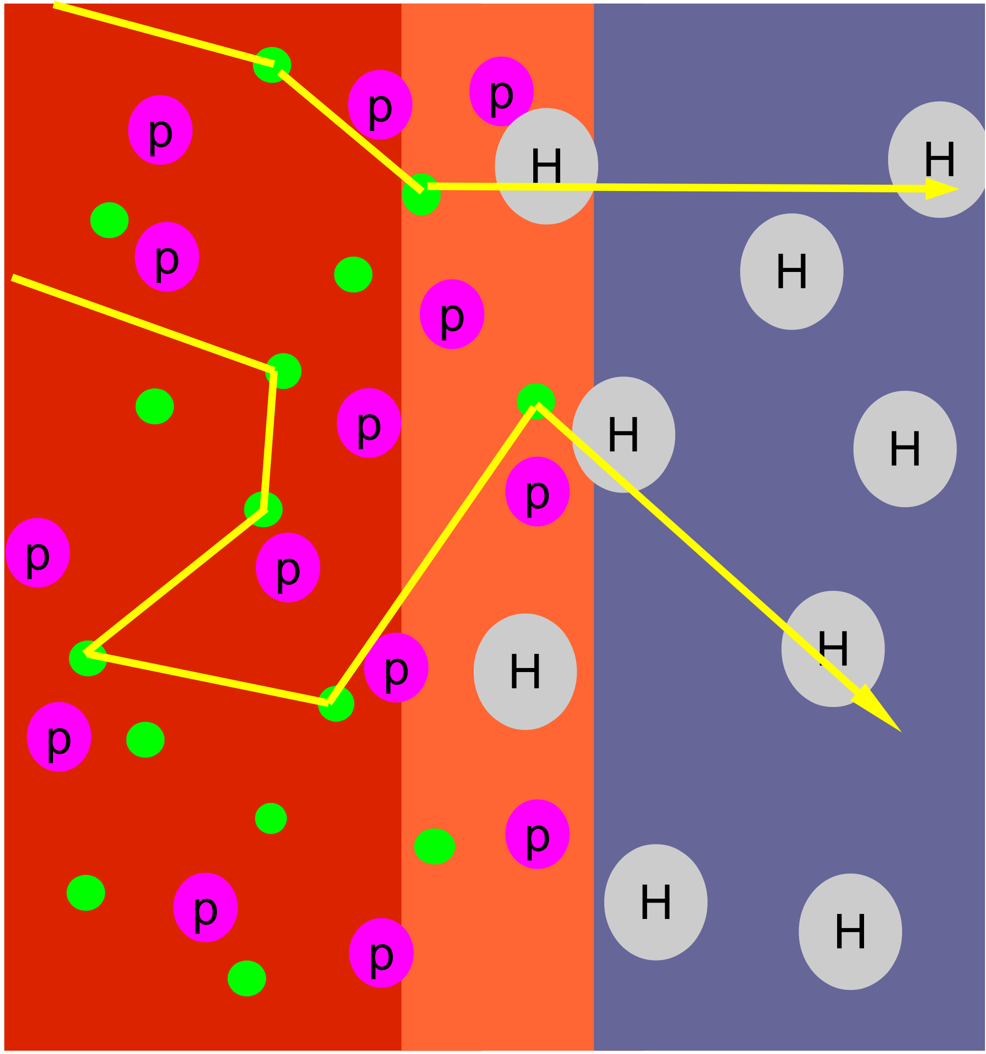




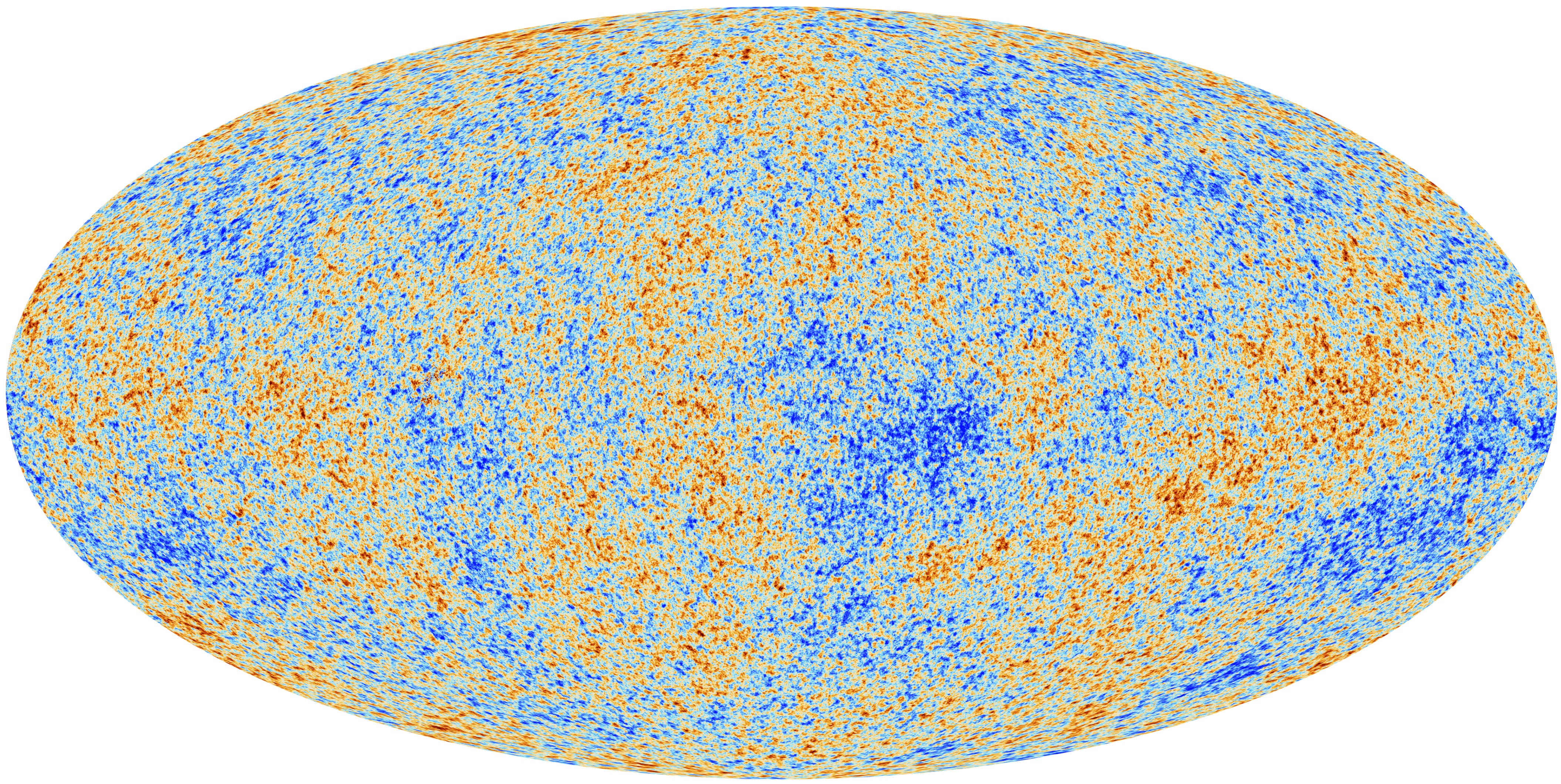

ca. 1 angular degree

Recombination & photon diffusion

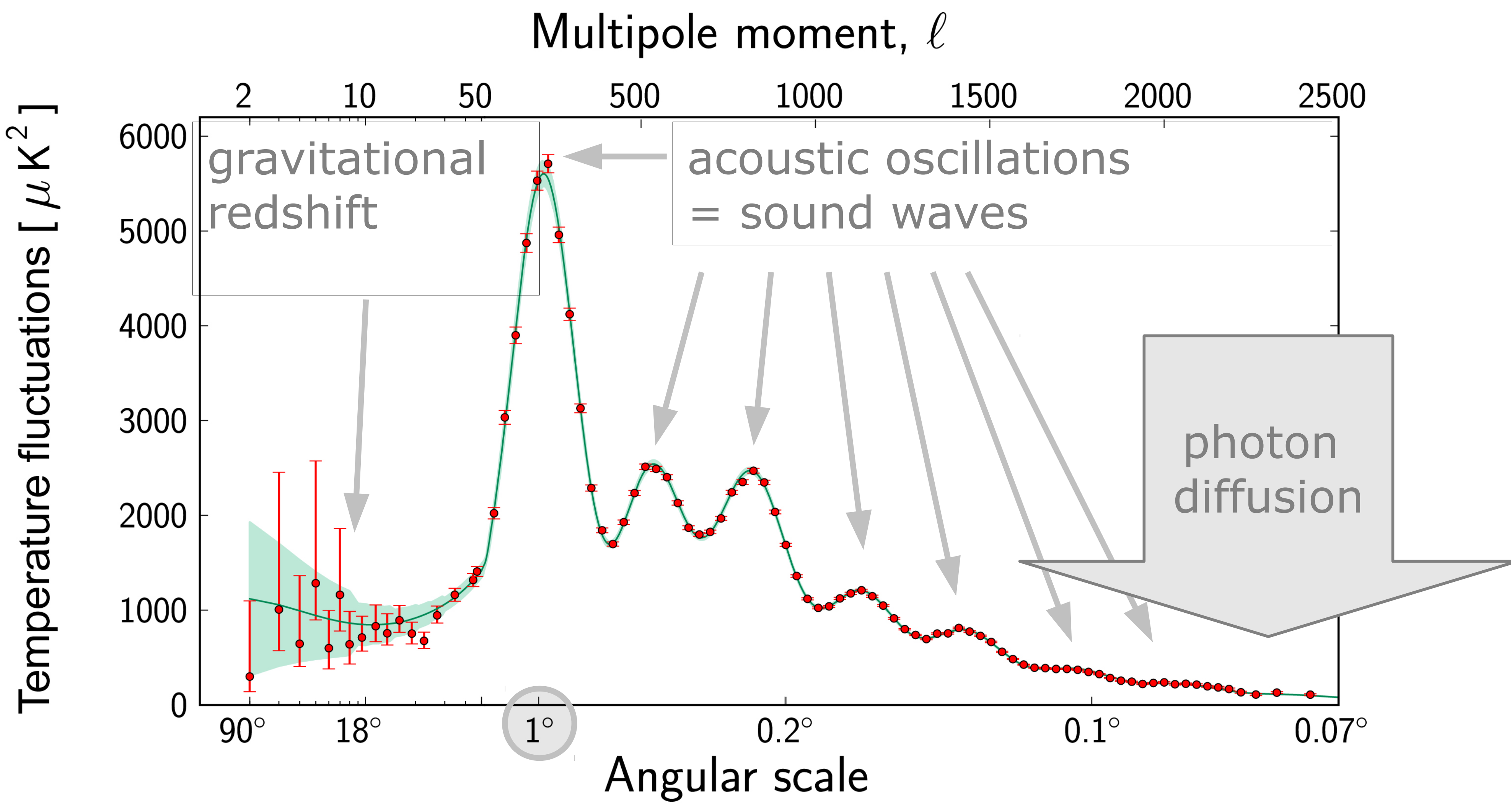
- Before recominaton: photons scatter on free electrons
- After: photons free-stream through Universe
- Observed CMB light from surface of last scattering
- Finite duration of recombination permitted photons to diffuse
- Struktures smaller than 5 arcmin are erased (1/6 of moon diameter)
- Planck resolution: 5 arcmin

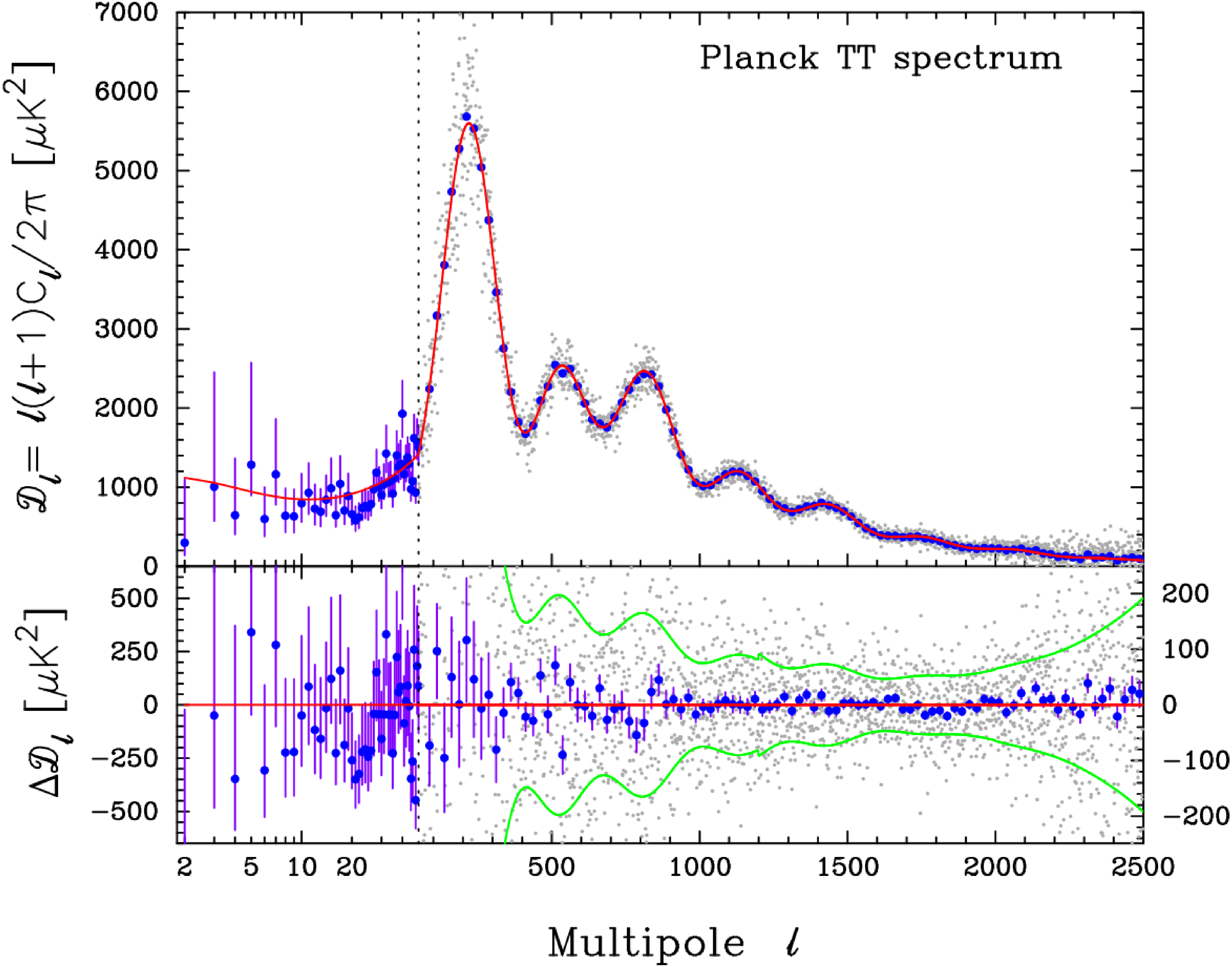


The cosmic microwave background



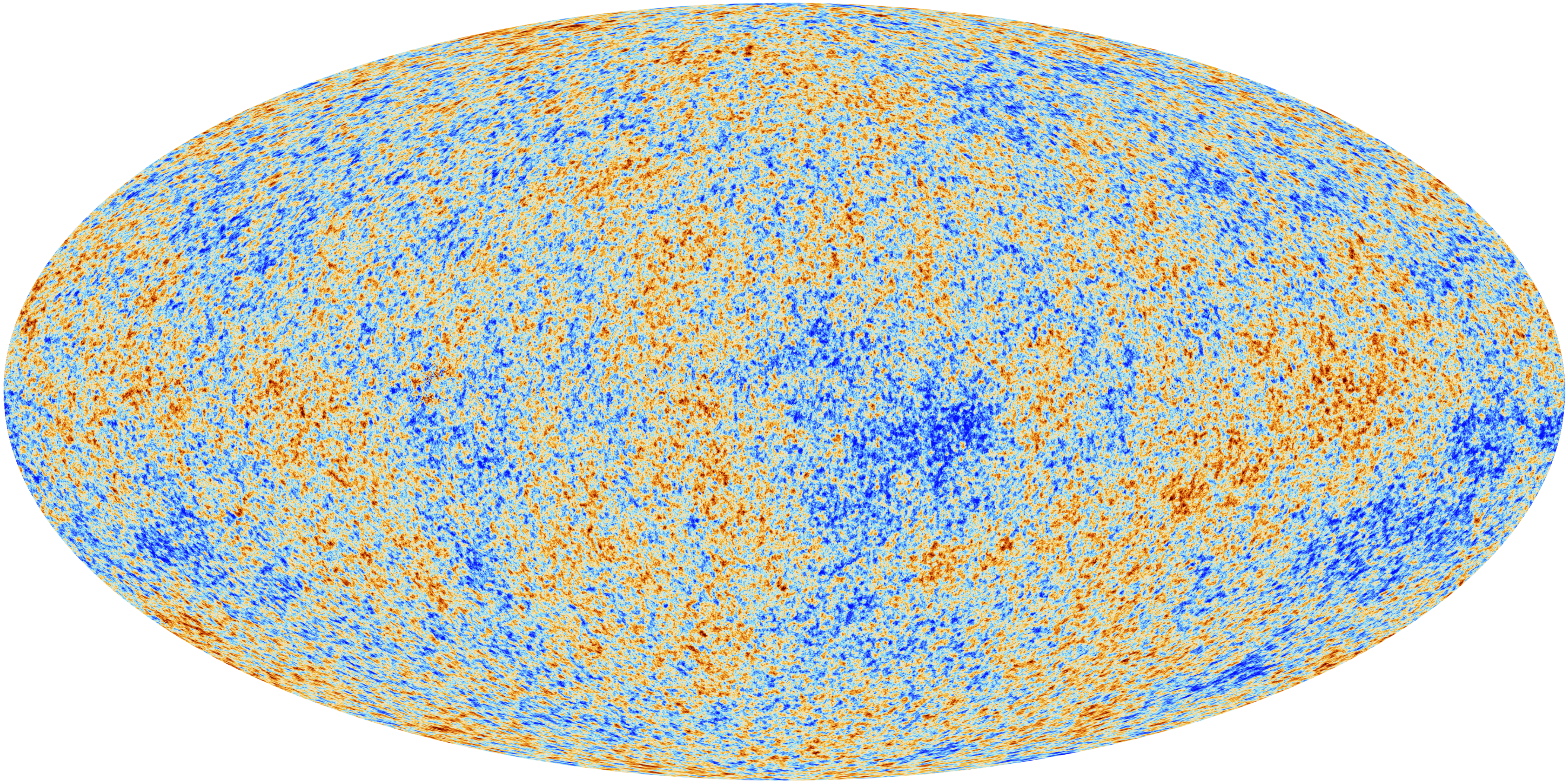
Angular power spectrum



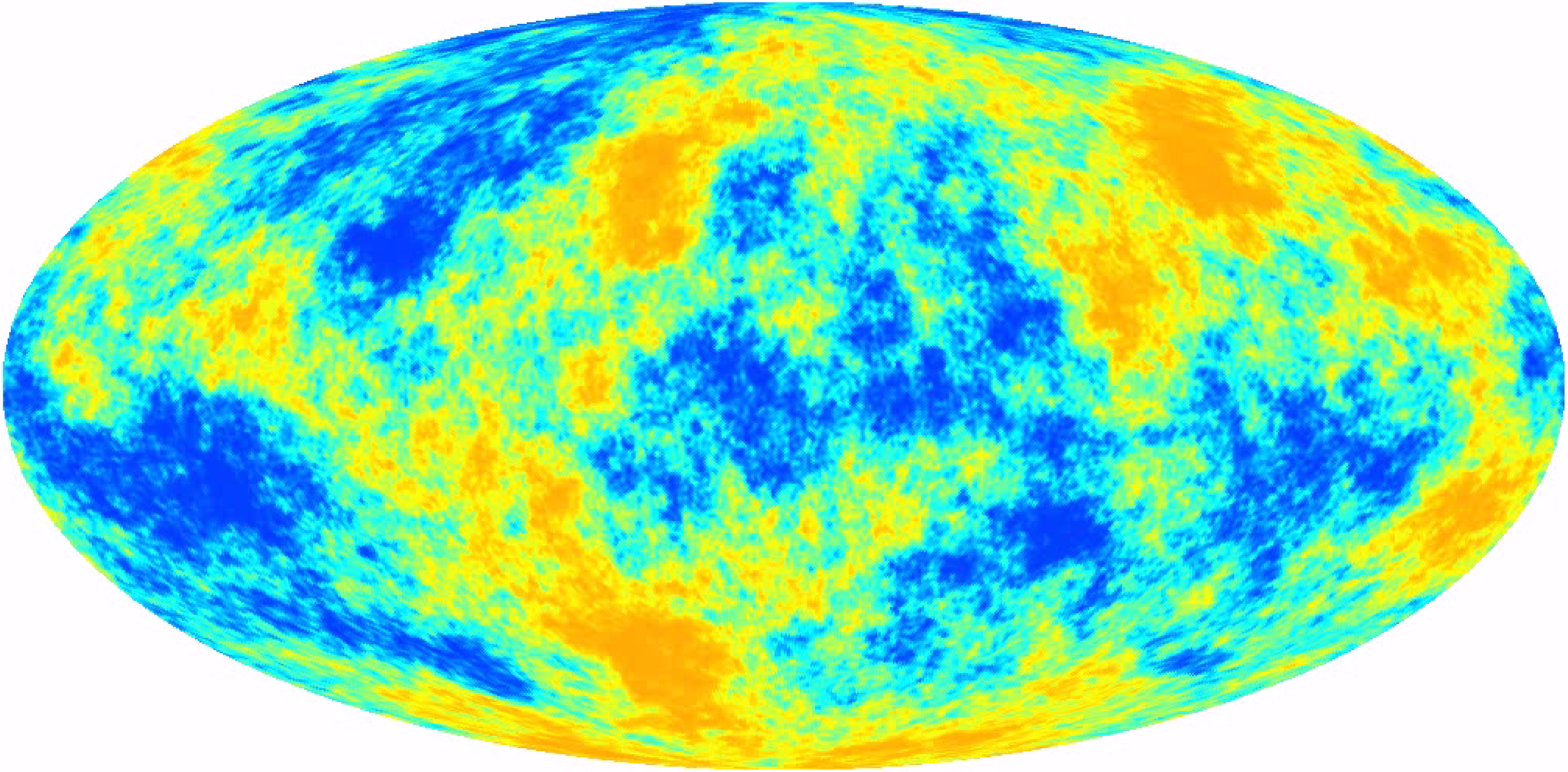


Planck TT spectrum
$\mathcal{D}_\ell = \ell(\ell+1)C_\ell/2\pi\ [\mu K^2]$
$\Delta\mathcal{D}_\ell\ [\mu K^2]$
Multipole ℓ

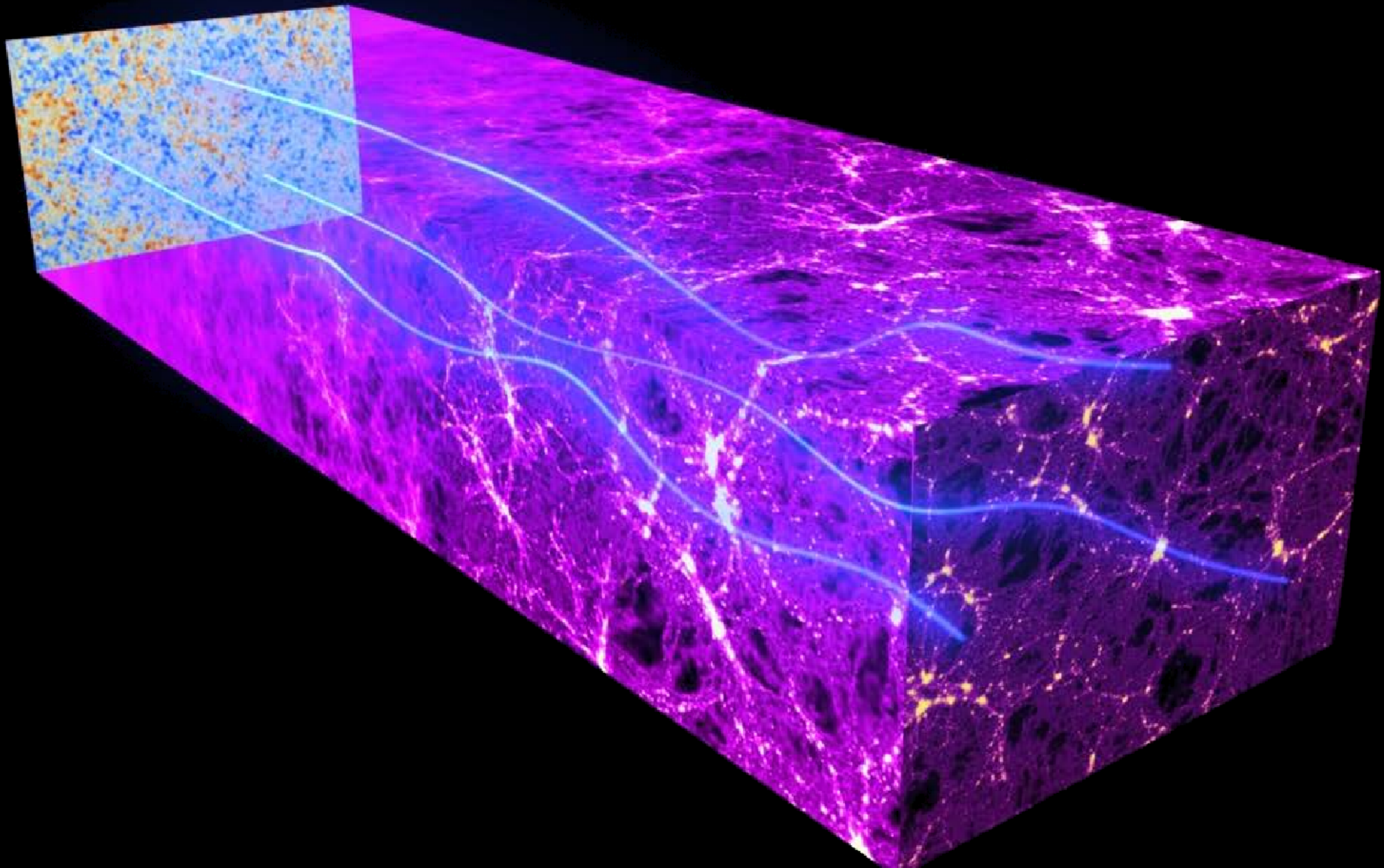
The cosmic microwave background



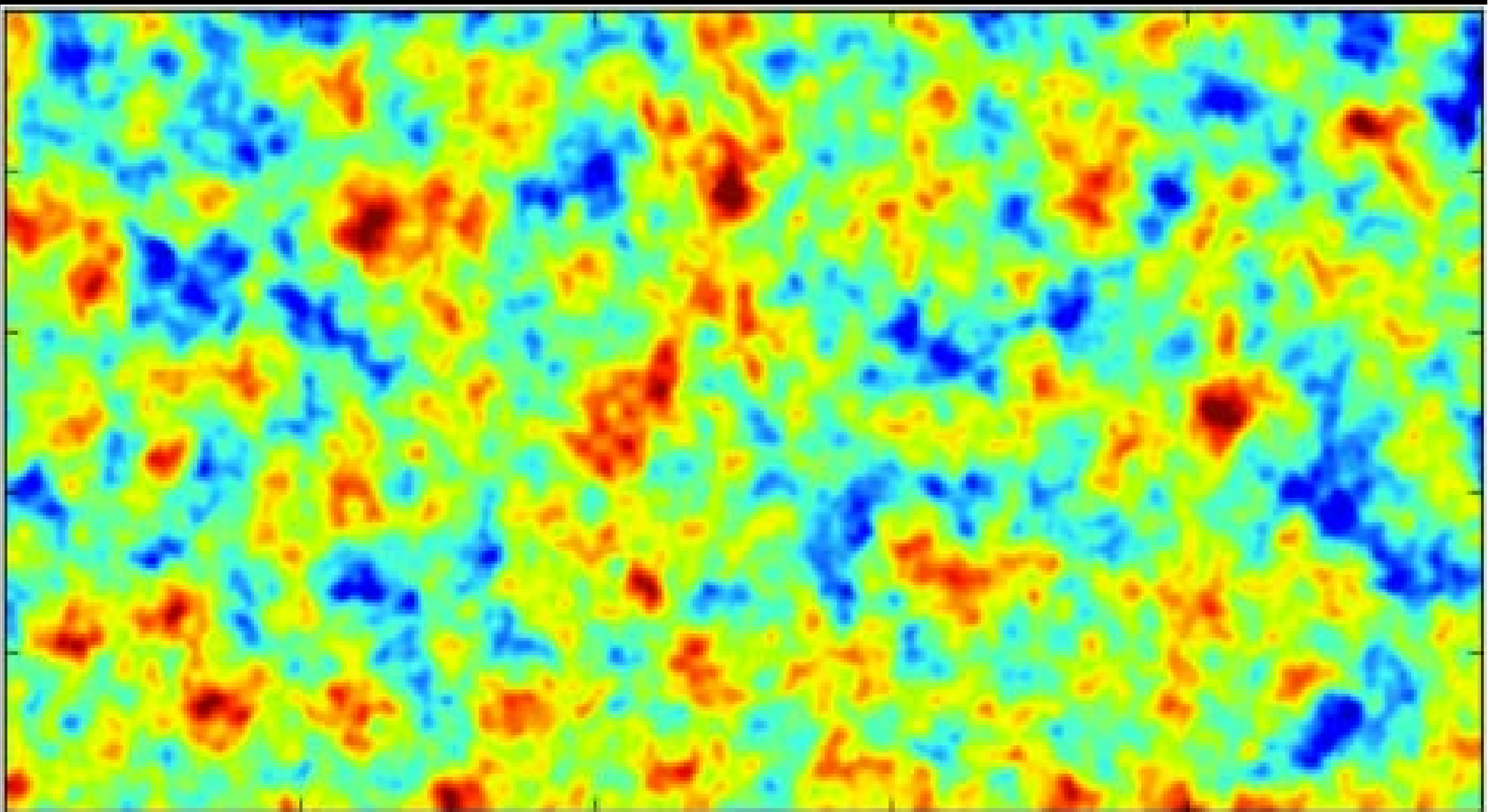
Simulation



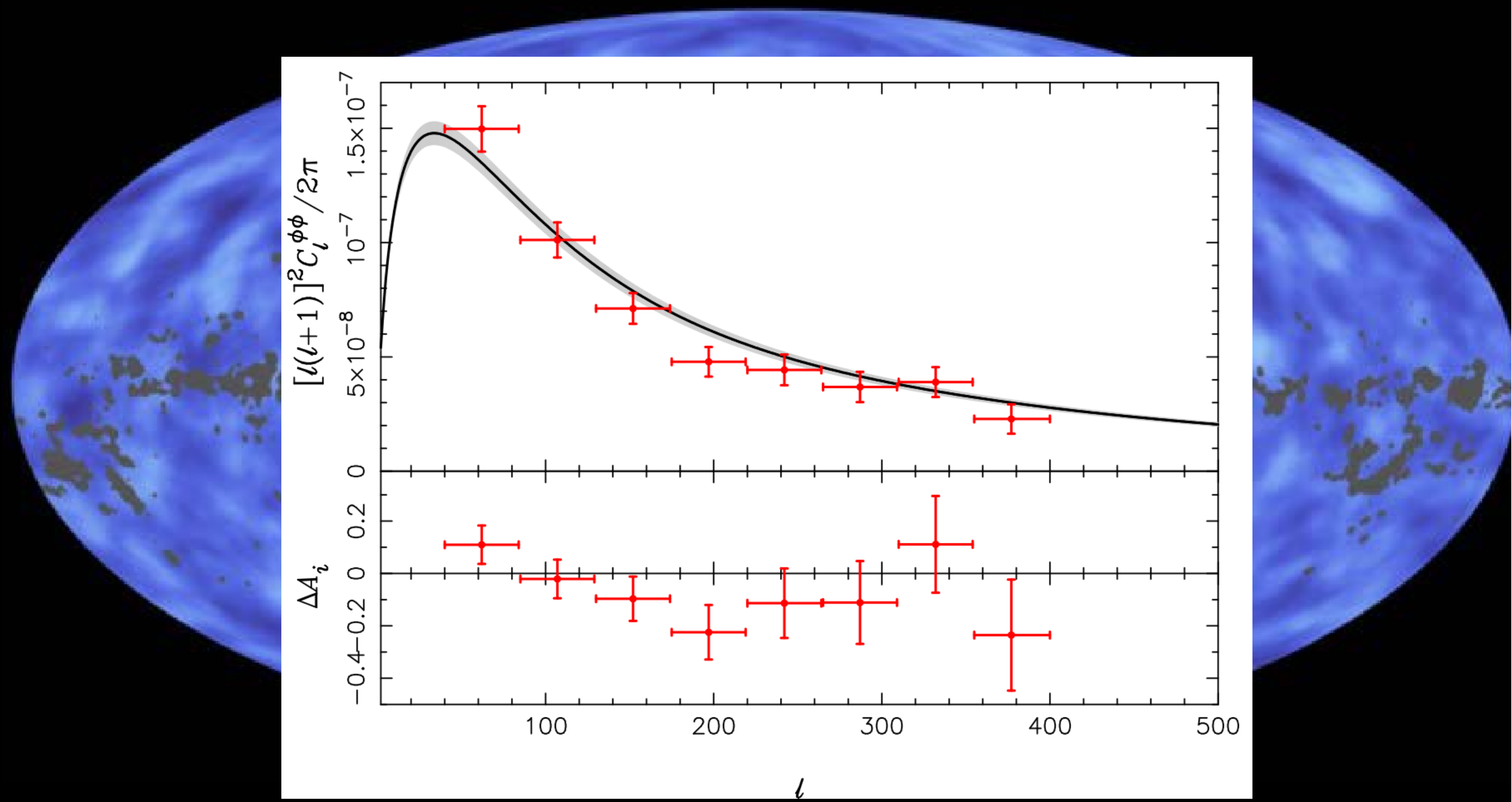
gravitational lensing



gravitational lensing



projected mass distribution



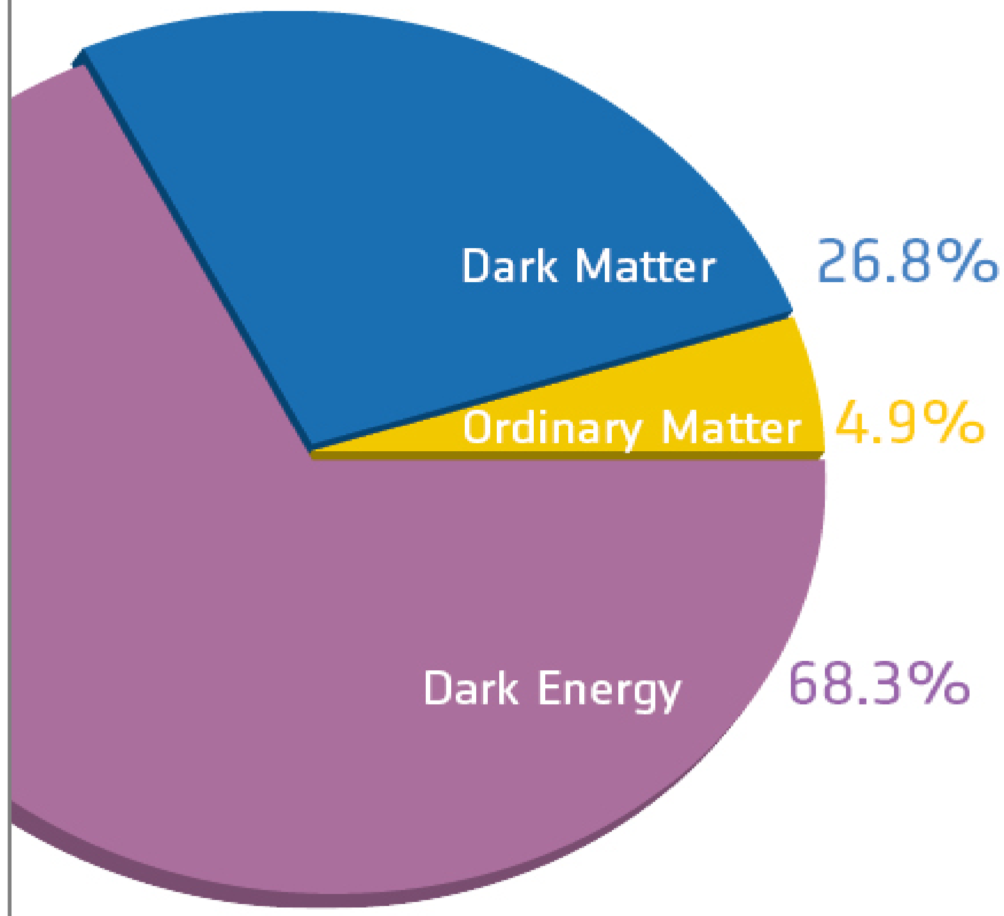
Precision cosmology

Acoustic scale is most precisely known cosmic parameter:
1.19345 ± 0.00076°

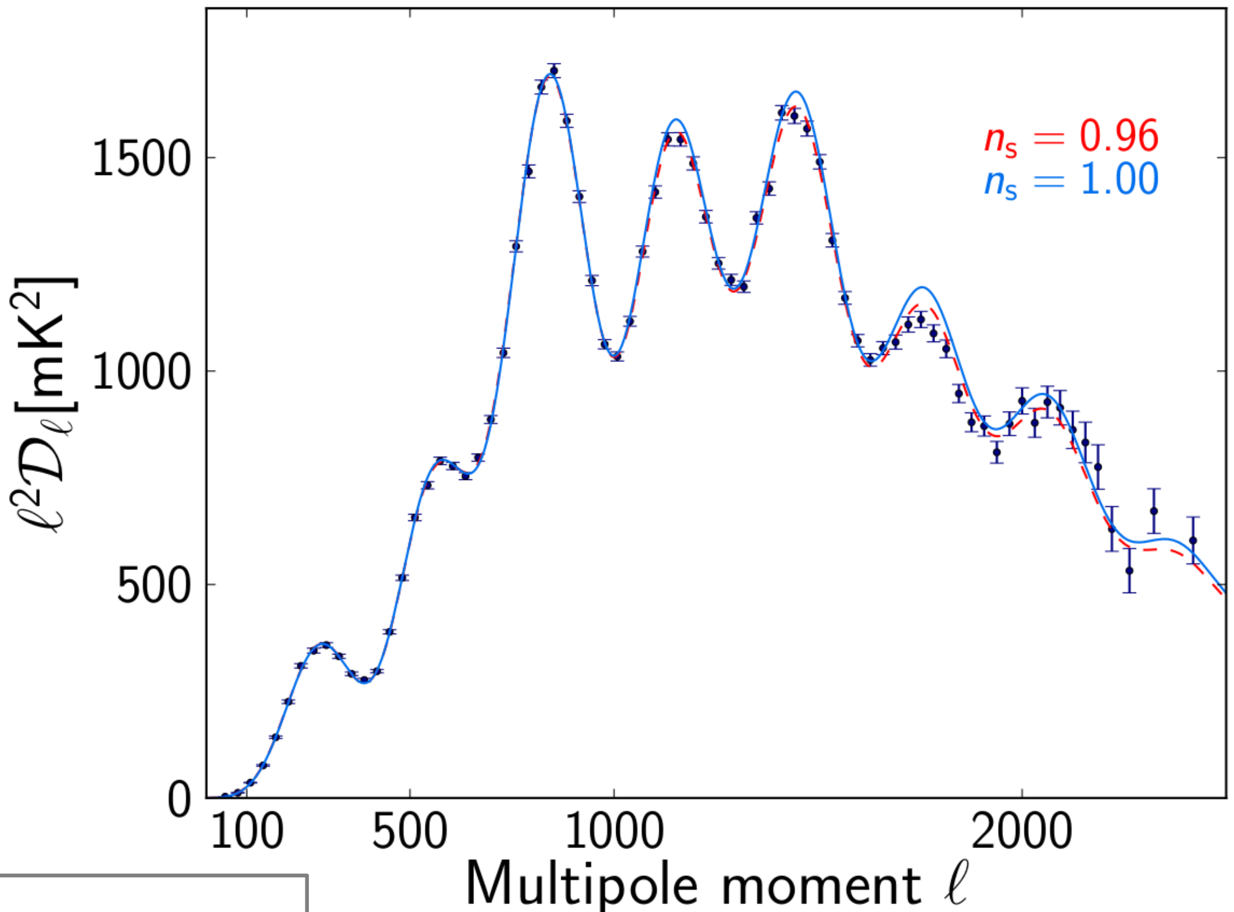
Expansion rate of the Universe, the Hubble constant:
H_0 = 67.15 km/s/Mpc
(previously 69.32 km/s/Mpc)

Age of the Universe:
13.82 billion years
(previously 13.77 billion years)

Primordial spectral index: 0.96
Significant deviation from scale Invariance as predicted by inflation



Precision cosmology



Primordial spectral index: 0.96
Significant deviation from scale
Invariance as predicted by inflation

	Planck (CMB+lensing)	
Parameter	Best fit	68 % limits
$\Omega_b h^2$	0.022242	0.02217 ± 0.00033
$\Omega_c h^2$	0.11805	0.1186 ± 0.0031
$100\theta_{MC}$	1.04150	1.04141 ± 0.00067
τ	0.0949	0.089 ± 0.032
n_s	0.9675	0.9635 ± 0.0094
$\ln(10^{10} A_s)$	3.098	3.085 ± 0.057

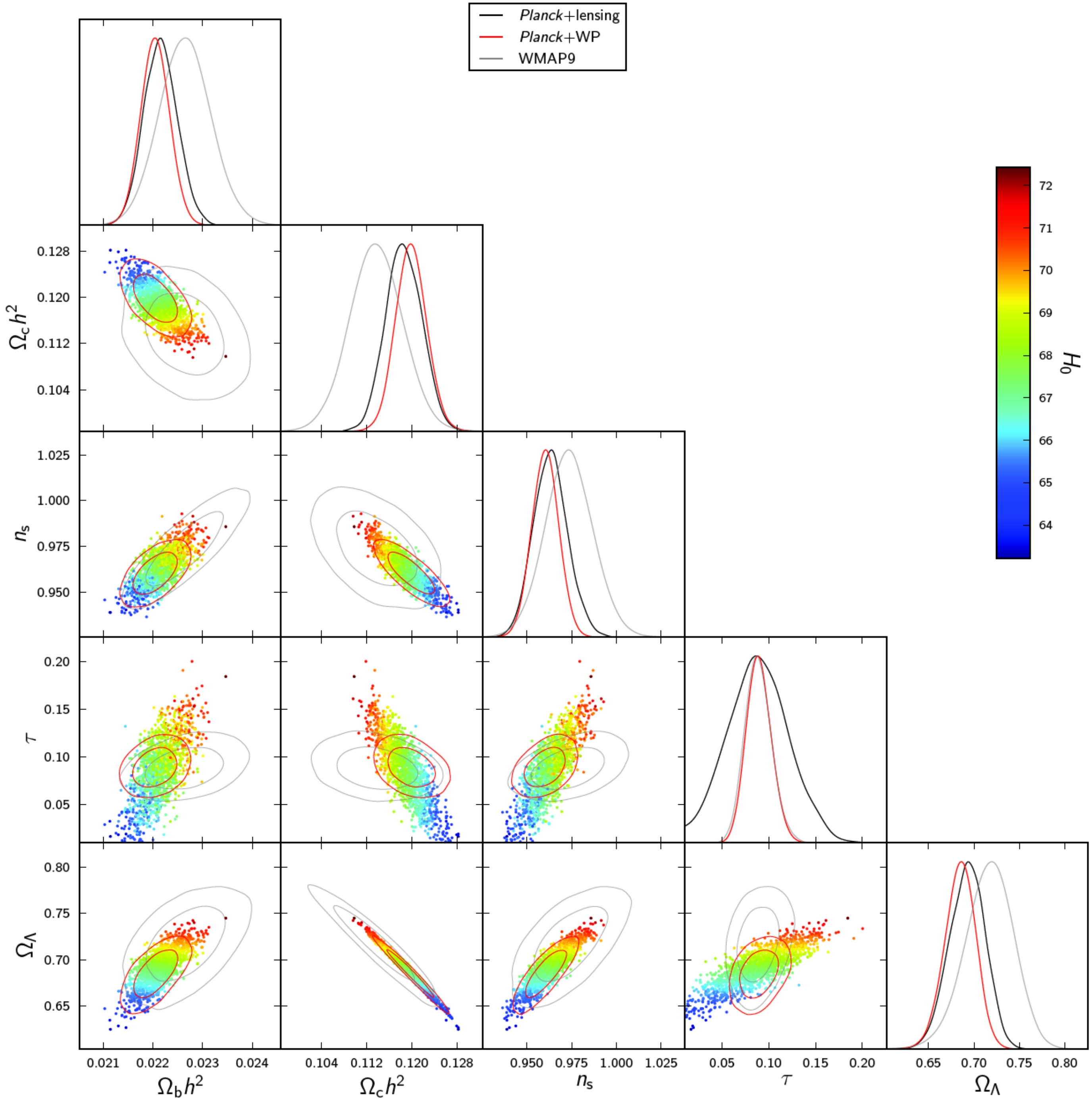
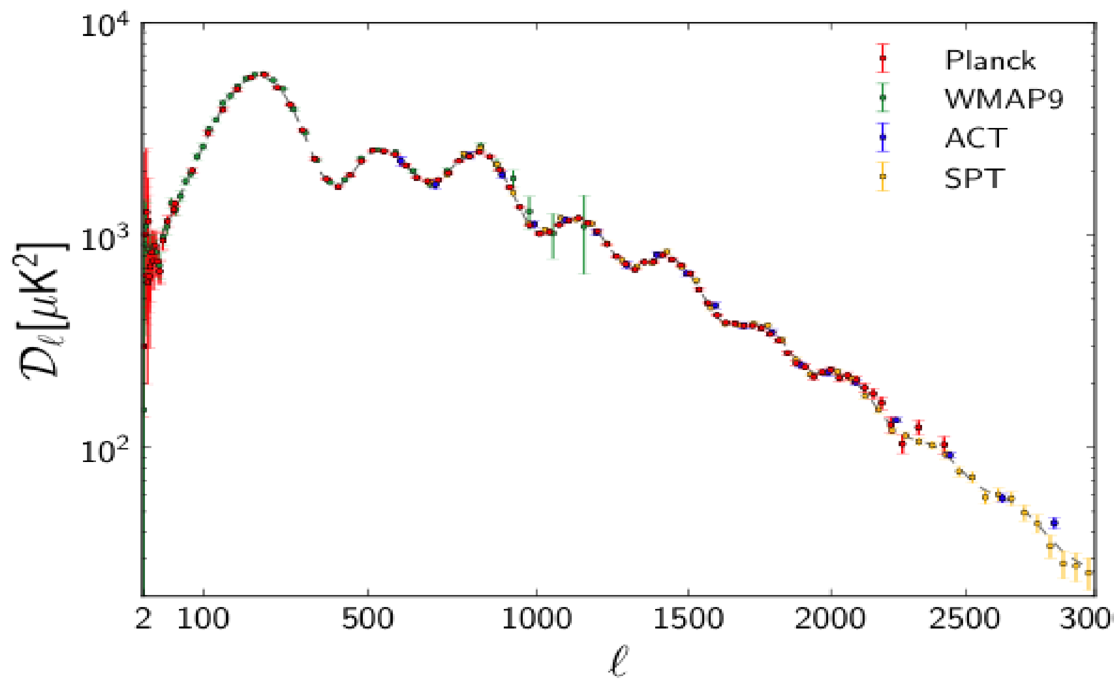


Fig. 2. Comparison of the base ΛCDM model parameters for *Planck*+lensing only (colour coded samples), and the 68% and 95% constraint contours adding *WMAP* low-ℓ polarization (WP, red contours), compared to textitWMAP9 (Bennett et al., 2012, grey contours).

Parameter	*Planck* (CMB+lensing) Best fit	*Planck* (CMB+lensing) 68 % limits	*Planck*+WP+highL+BAO Best fit	*Planck*+WP+highL+BAO 68 % limits
$\Omega_b h^2$	0.022242	0.02217 ± 0.00033	0.022161	0.02214 ± 0.00024
$\Omega_c h^2$	0.11805	0.1186 ± 0.0031	0.11889	0.1187 ± 0.0017
$100\theta_{MC}$	1.04150	1.04141 ± 0.00067	1.04148	1.04147 ± 0.00056
τ	0.0949	0.089 ± 0.032	0.0952	0.092 ± 0.013
n_s	0.9675	0.9635 ± 0.0094	0.9611	0.9608 ± 0.0054
$\ln(10^{10} A_s)$	3.098	3.085 ± 0.057	3.0973	3.091 ± 0.025



Parameter	*Planck* (CMB+lensing)		*Planck*+WP+highL+BAO	
	Best fit	68 % limits	Best fit	68 % limits
$\Omega_b h^2$	0.022242	0.02217 ± 0.00033	0.022161	0.02214 ± 0.00024
$\Omega_c h^2$	0.11805	0.1186 ± 0.0031	0.11889	0.1187 ± 0.0017
$100\theta_{MC}$	1.04150	1.04141 ± 0.00067	1.04148	1.04147 ± 0.00056
τ	0.0949	0.089 ± 0.032	0.0952	0.092 ± 0.013
n_s	0.9675	0.9635 ± 0.0094	0.9611	0.9608 ± 0.0054
$\ln(10^{10} A_s)$	3.098	3.085 ± 0.057	3.0973	3.091 ± 0.025
Ω_Λ	0.6964	0.693 ± 0.019	0.6914	0.692 ± 0.010
Ω_m	0.3036	0.307 ± 0.019		
σ_8	0.8285	0.823 ± 0.018	0.8288	0.826 ± 0.012
z_{re}	11.45	$10.8^{+3.1}_{-2.5}$	11.52	11.3 ± 1.1
H_0	68.14	67.9 ± 1.5	67.77	67.80 ± 0.77
$10^9 A_s$	2.215	$2.19^{+0.12}_{-0.14}$		
$\Omega_m h^2$	0.14094	0.1414 ± 0.0029		
$\Omega_m h^3$	0.09603	0.09593 ± 0.00058		
Y_P	0.247785	0.24775 ± 0.00014		
Age/Gyr	13.784	13.796 ± 0.058	13.7965	13.798 ± 0.037
z_*	1090.01	1090.16 ± 0.65		
r_*	144.58	144.96 ± 0.66		
$100\theta_*$	1.04164	1.04156 ± 0.00066	1.04163	1.04162 ± 0.00056
z_{drag}	1059.59	1059.43 ± 0.64		
r_{drag}	147.74	147.70 ± 0.63	147.611	147.68 ± 0.45
k_D	0.13998	0.13996 ± 0.00062		
$100\theta_D$	0.161196	0.16129 ± 0.00036		
z_{eq}	3352	3362 ± 69		
$100\theta_{eq}$	0.8224	0.821 ± 0.013		
$r_{drag}/D_V(0.57)$	0.07207	0.0719 ± 0.0011		

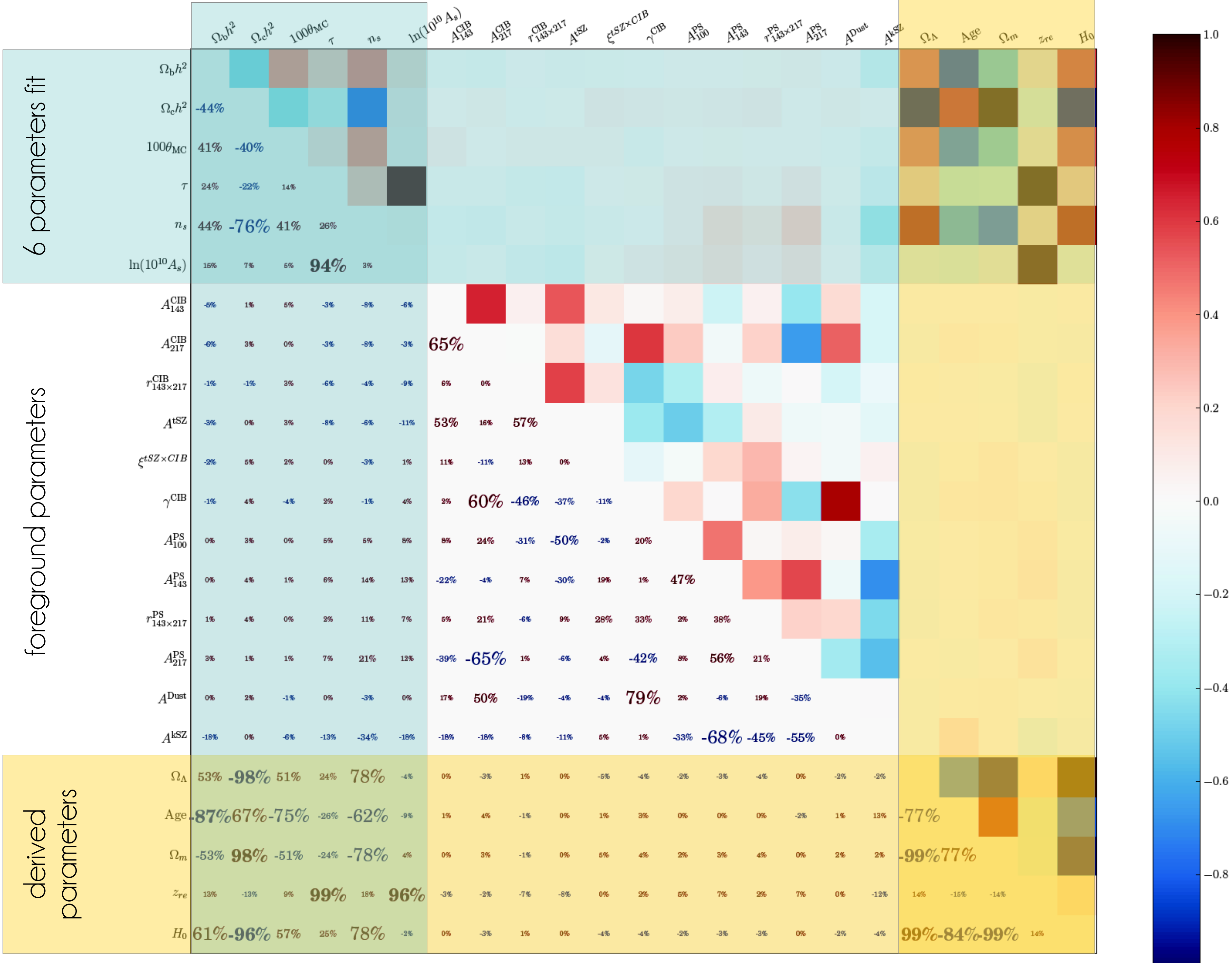
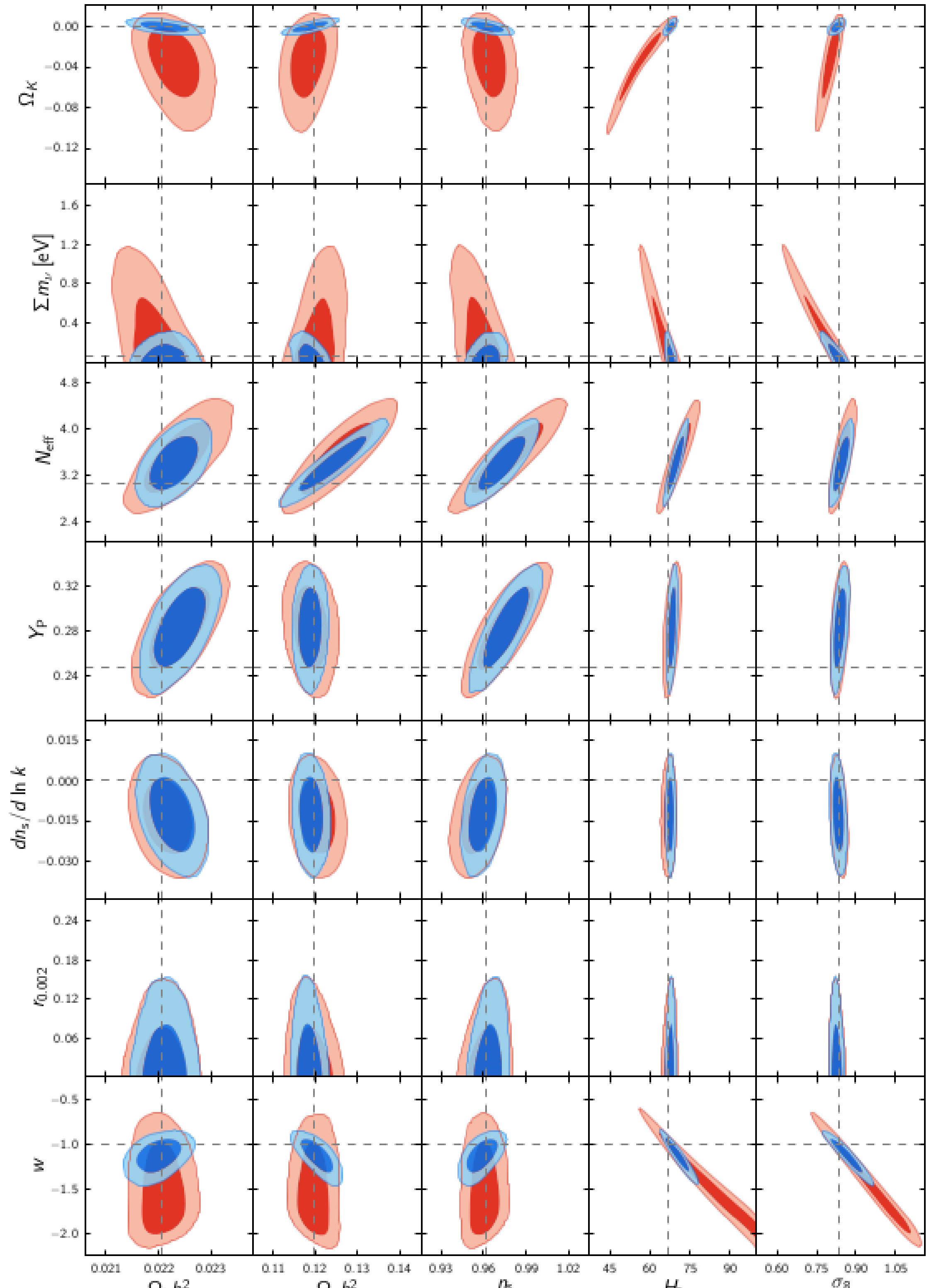


Figure 21. Correlation matrix between all the cosmological (top block), foreground (middle block), and derived (bottom block) parameters, estimated using the `Plik` likelihood.

Extended p

curvature of the Universe, mass
spectral curvature, gra
adiabatic in

Parameter	*Planck*+WP Best fit	*Planck*+WP 95% limits	*Planck*+V Best fit	9
Ω_K	-0.0105	$-0.037^{+0.043}_{-0.049}$	0.0000	0.
Σm_ν [eV]	0.022	< 0.933	0.002	
$N_{\rm eff}$	3.08	$3.51^{+0.80}_{-0.74}$	3.08	
$Y_{\rm P}$	0.2583	$0.283^{+0.045}_{-0.048}$	0.2736	(
$dn_s/d\ln k$	-0.0090	$-0.013^{+0.018}_{-0.018}$	-0.0102	–
$r_{0.002}$	0.000	< 0.120	0.000	
w	-1.20	$-1.49^{+0.65}_{-0.57}$	-1.076	-



Data consistency

acoustic-scale distance ratio

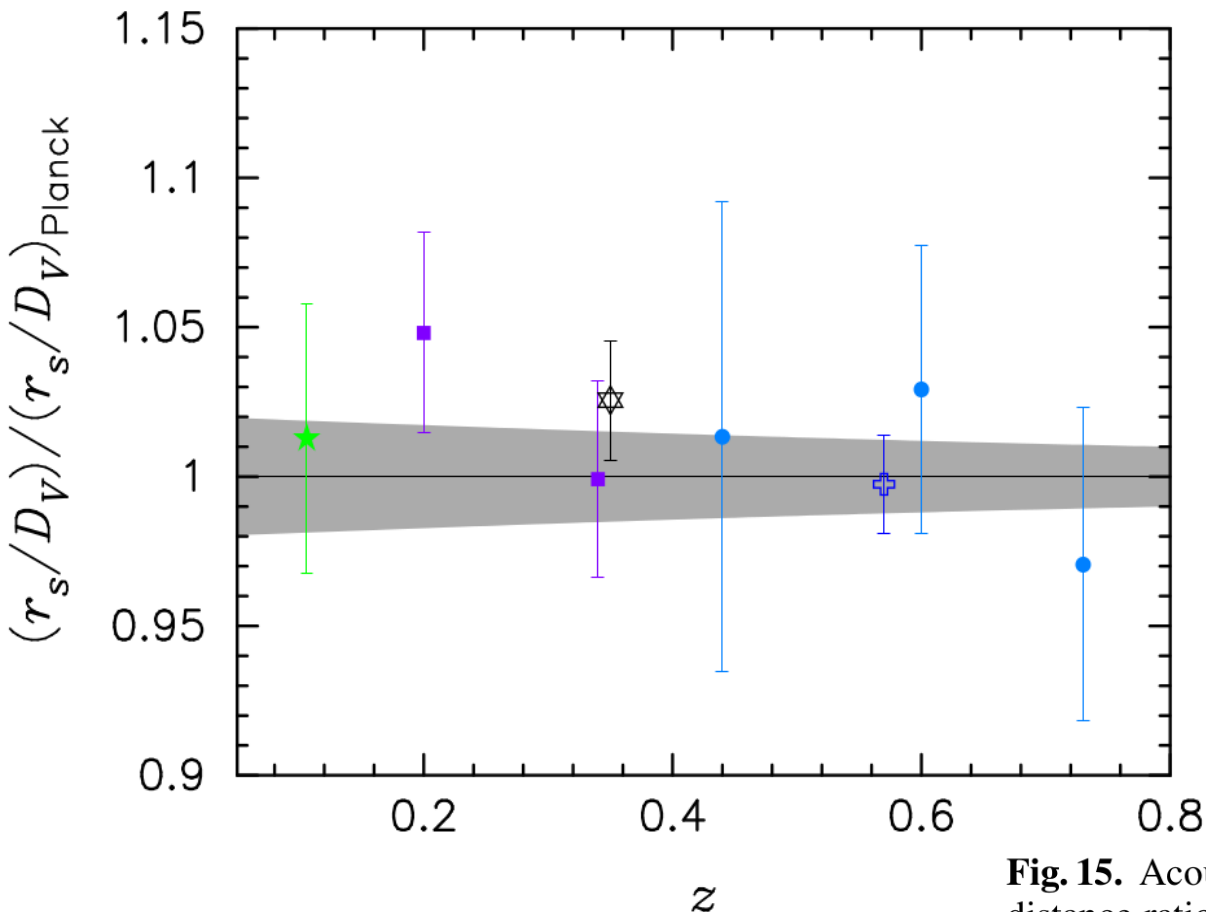
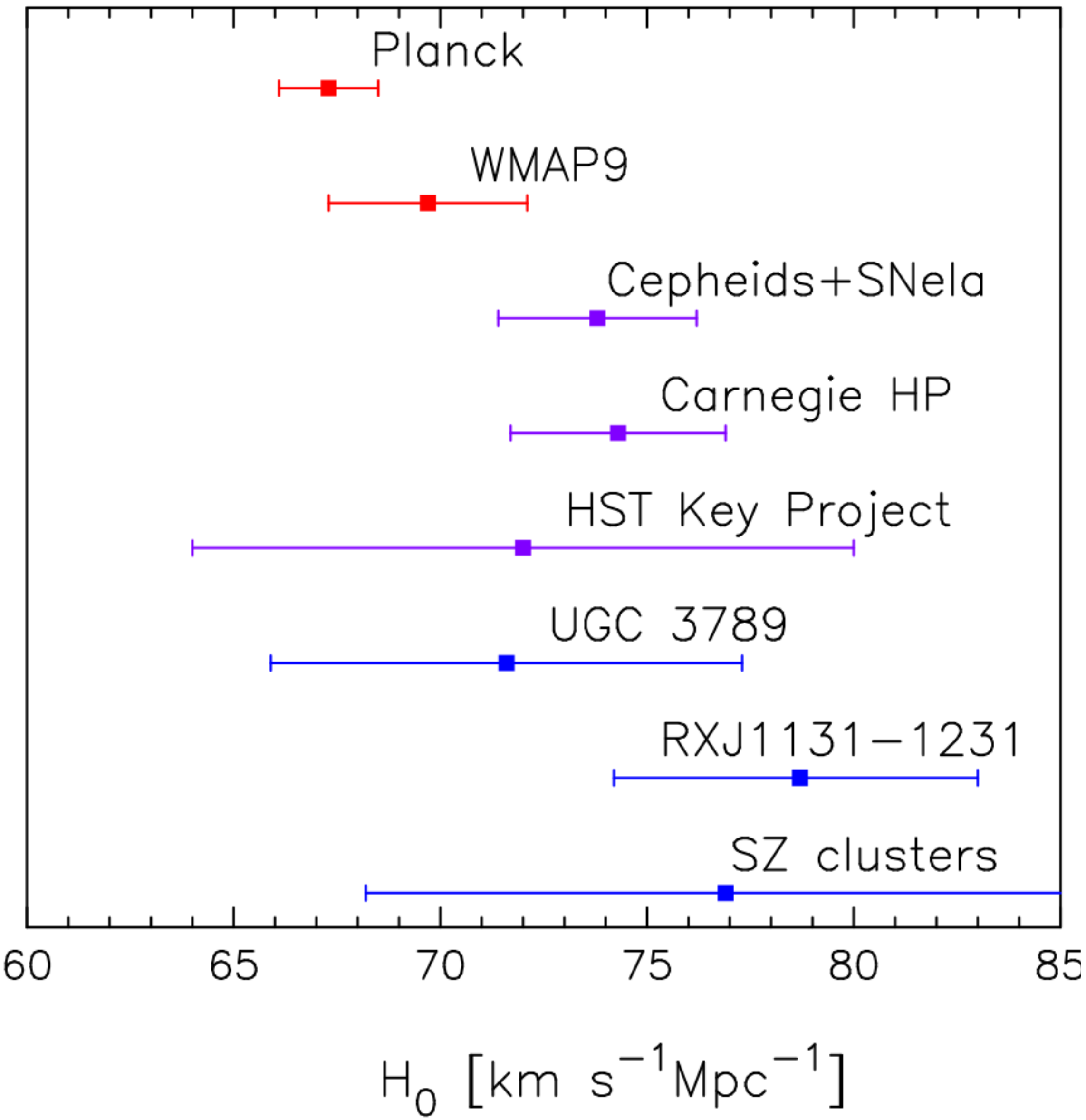
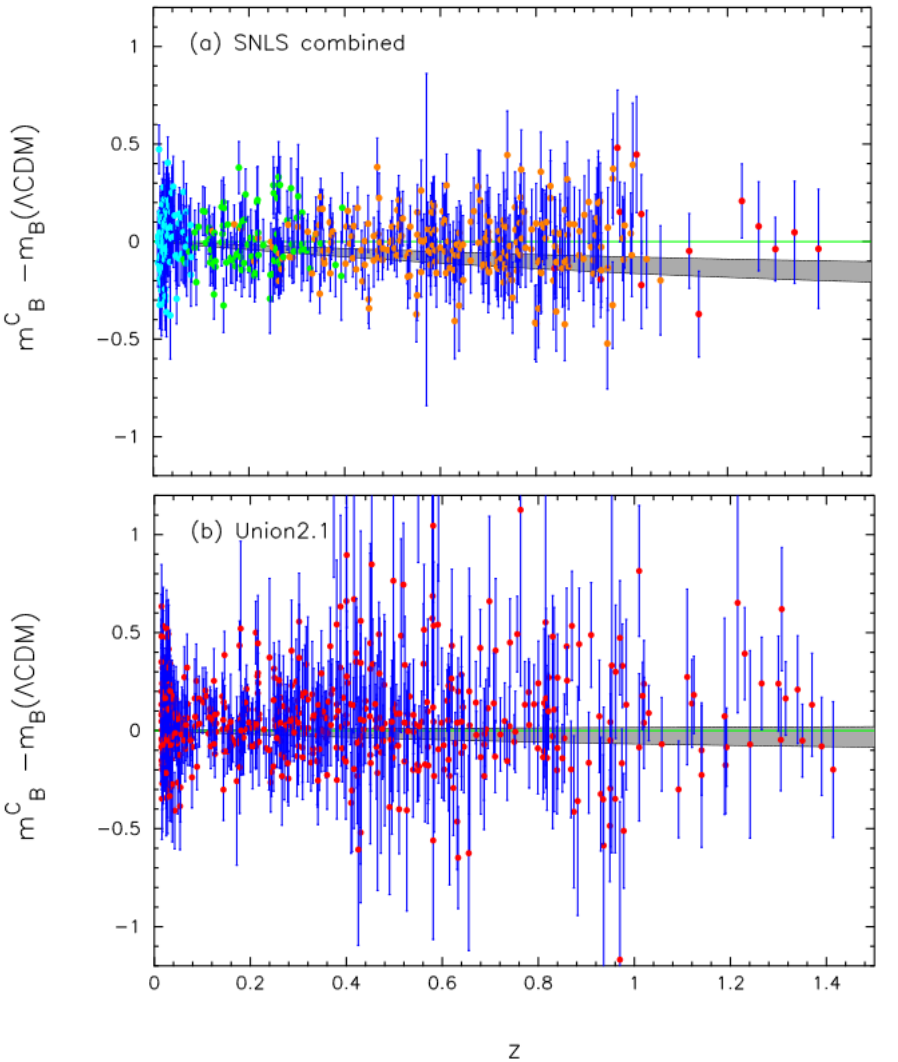


Fig. 15. Acoustic-scale distance ratio $r_s/D_V(z)$ divided by the distance ratio of the *Planck* base ΛCDM model. The points are colour coded as follows: green star (6dF); purple squares (SDSS DR7 as analyzed by Percival et al., 2010); black star (SDSS DR7 as analyzed by Padmanabhan et al., 2012); blue cross (BOSS DR9); and blue circles (WiggleZ). The grey band shows the approximate $\pm 1\sigma$ range allowed by *Planck* (computed from the `CosmoMC` chains).

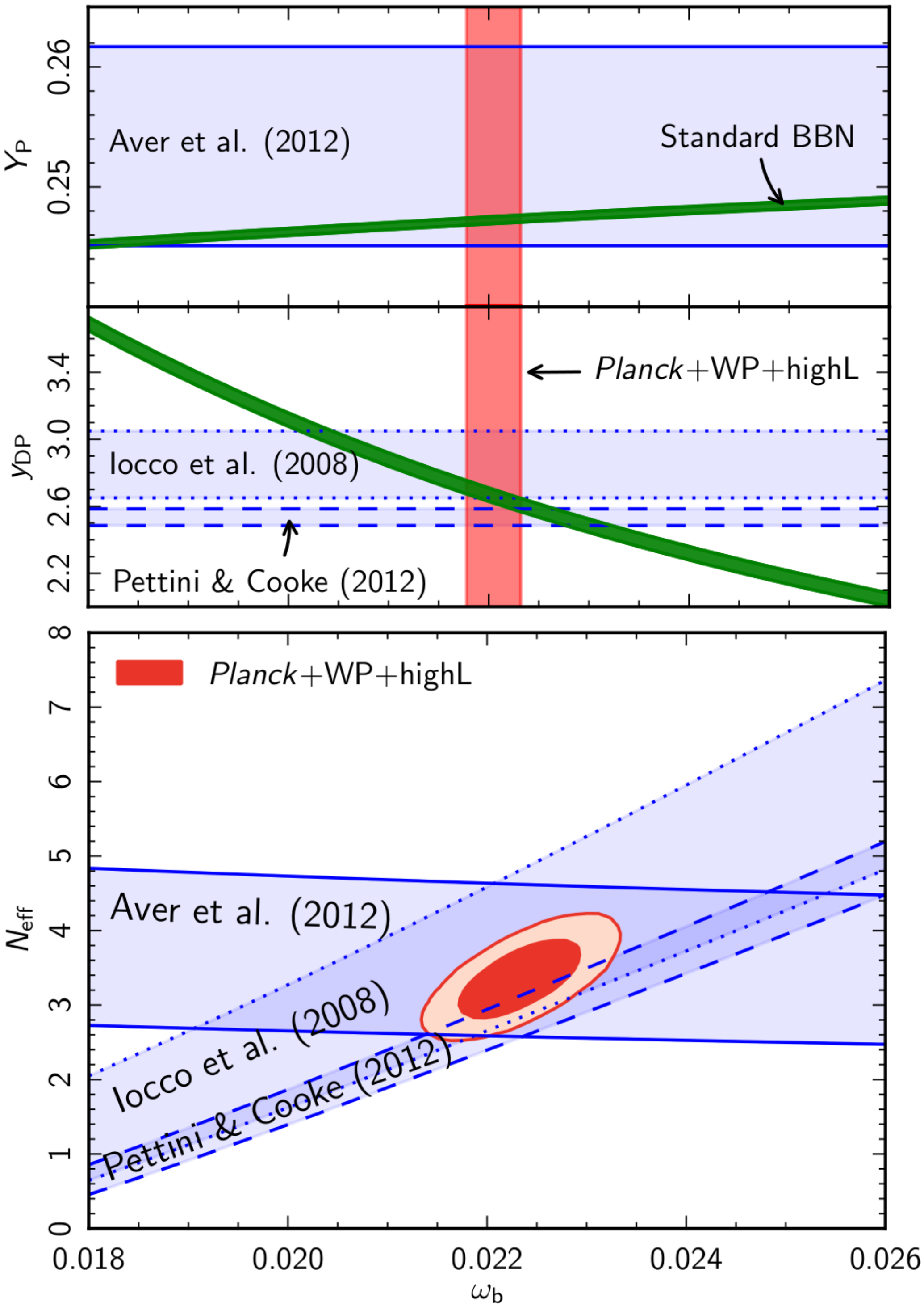
Data consistency

Hubble constant & Lambda





Data consistency
Big Bang Nucleosynthesis



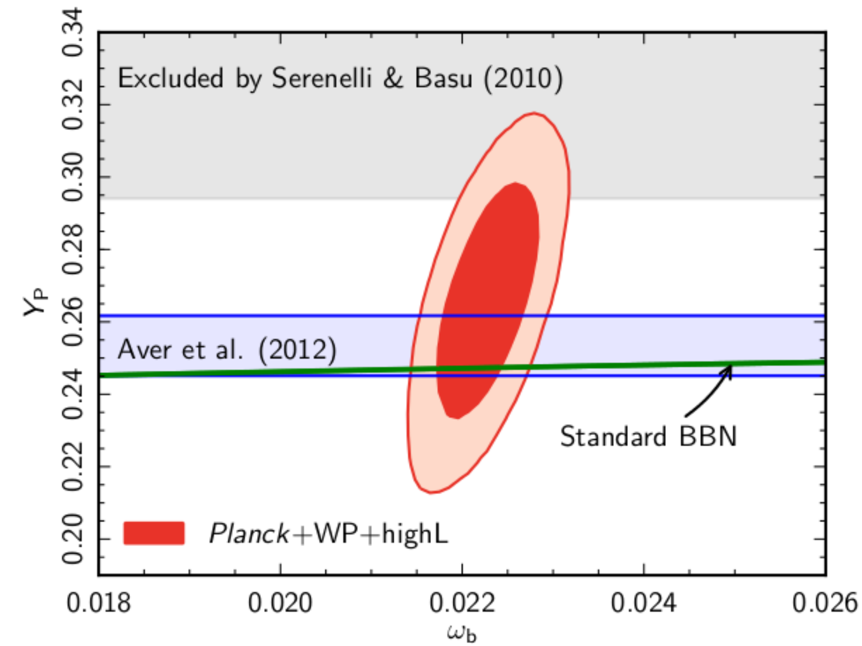


Fig. 30. The green stripe shows the predictions of standard BBN for the primordial abundance of helium 4 as a function of the baryon density (with 68% CL errors on nuclear reaction rates). The horizontal band shows observational bounds on helium 4 compiled by Aver et al. (2012) (68% CL), while the grey region in the upper part of the figure delineates the conservative 95% upper bound inferred from solar helium abundance by (Serenelli & Basu, 2010). Finally, we show the 68% and 95% joint contours on (ω_b, Y_P) inferred from *Planck*+WP+highL, when Y_P is left as a free parameter in the CMB analysis. Both BBN predictions and CMB results assume $N_{eff} = 3.046$ and no significant lepton asymmetry.

Data consistency
Tensions & Agreements

Tensions:

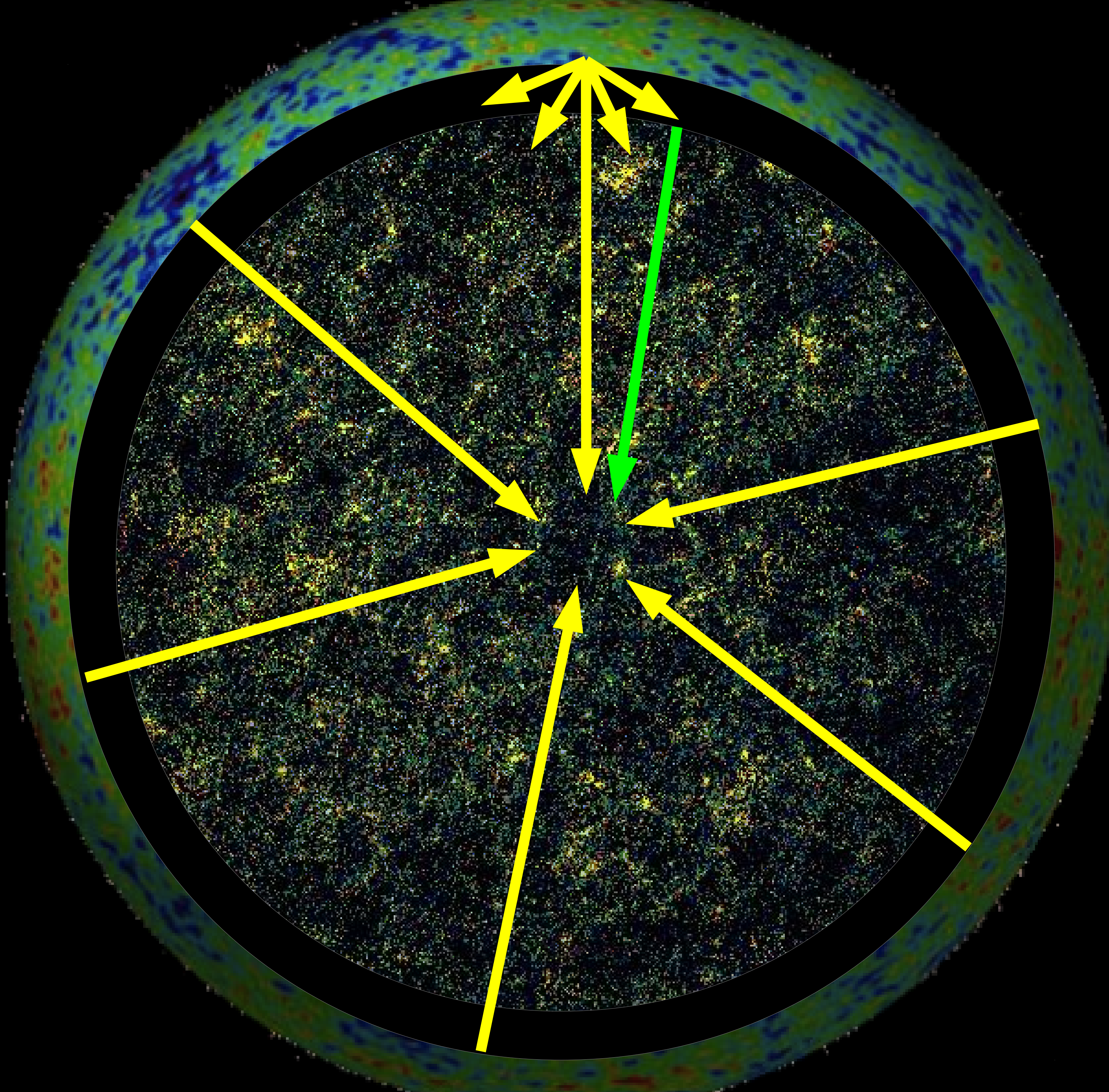
Hubble constant:
with WMAP
with SN measurements (might go away)

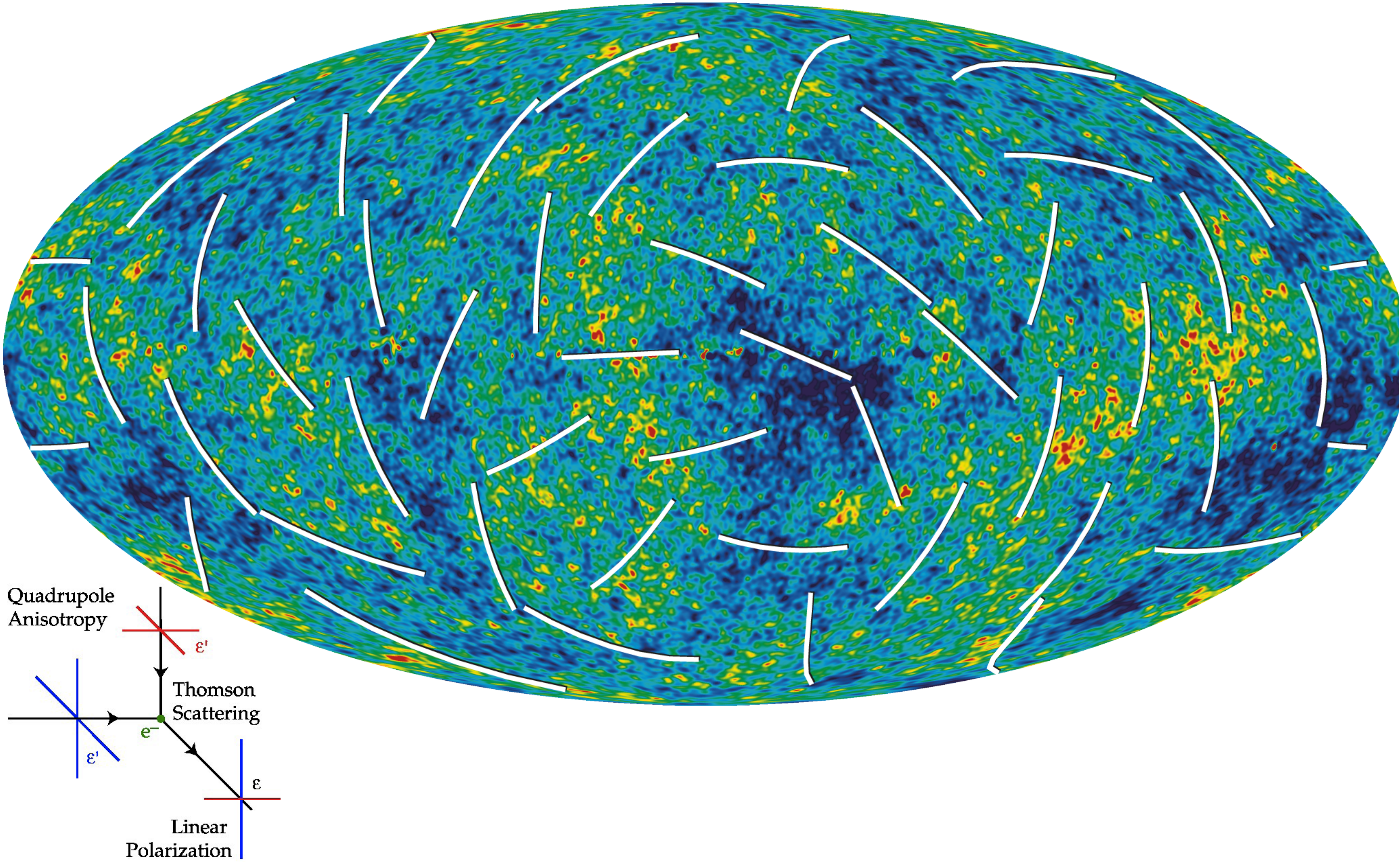
primordial power spectrum amplitude:
with WMAP (2%)
with Planck SZ cluster counts

All tensions only one to a few sigmas

Agreements:

With LSS power spectrum, with BAOs, with BBN





Quadrupole
Anisotropy
ε'
Thomson
Scattering
e⁻
ε'
ε
Linear
Polarization

Polarization teaser

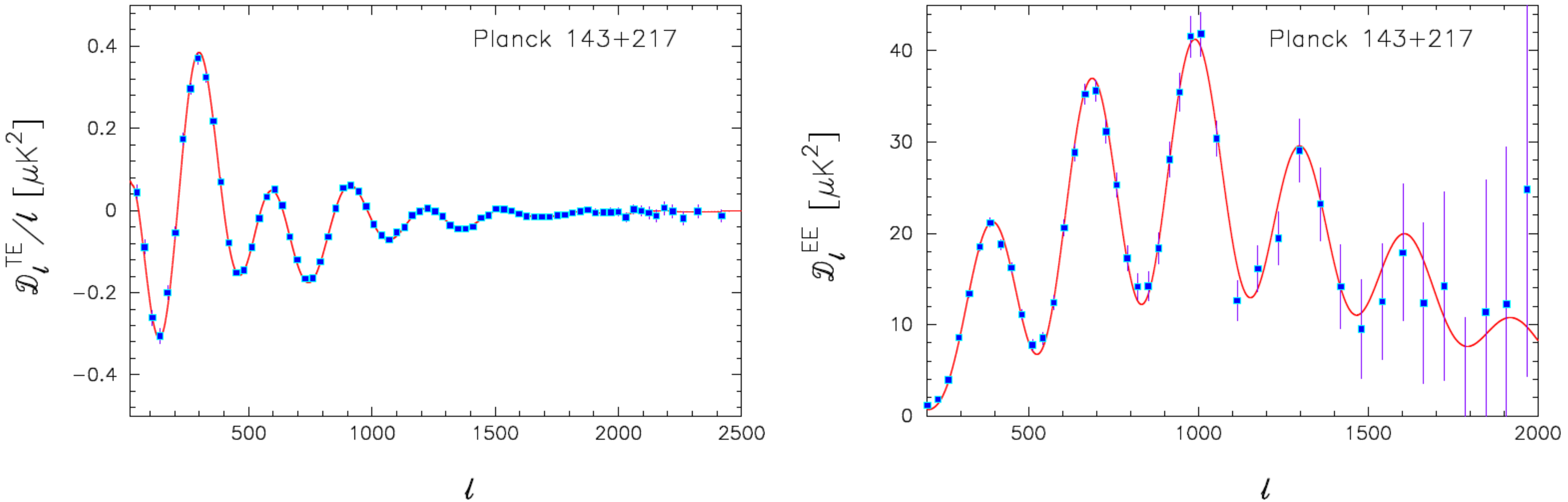


Fig. 11. *Planck TE* (left) and *EE* spectra (right) computed as described in the text. The red lines show the polarization spectra from the base ΛCDM *Planck*+WP+highL model, *which is fitted to the TT data only*.

non-Gaussian statistics

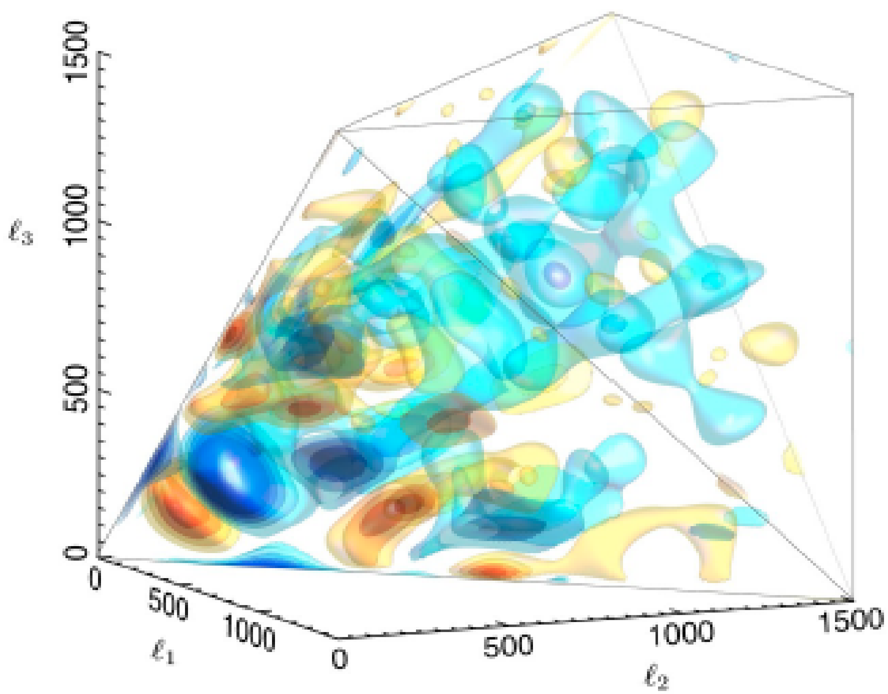
$$f(x) = \frac{1}{\sigma\sqrt{2\pi}} e^{-\frac{(x-\mu)^2}{2\sigma^2}}$$

$$\mu = 2.725 \text{ Kelvin}$$

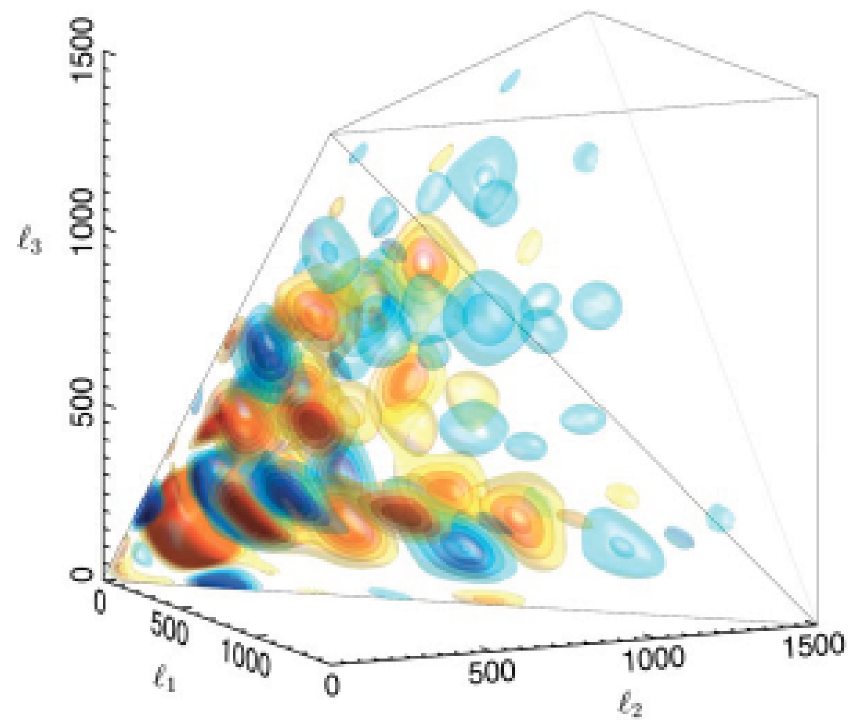
$$\sigma = 0.000\,01 \text{ Kelvin}$$

Bispektrum

non-Gaussian statistics

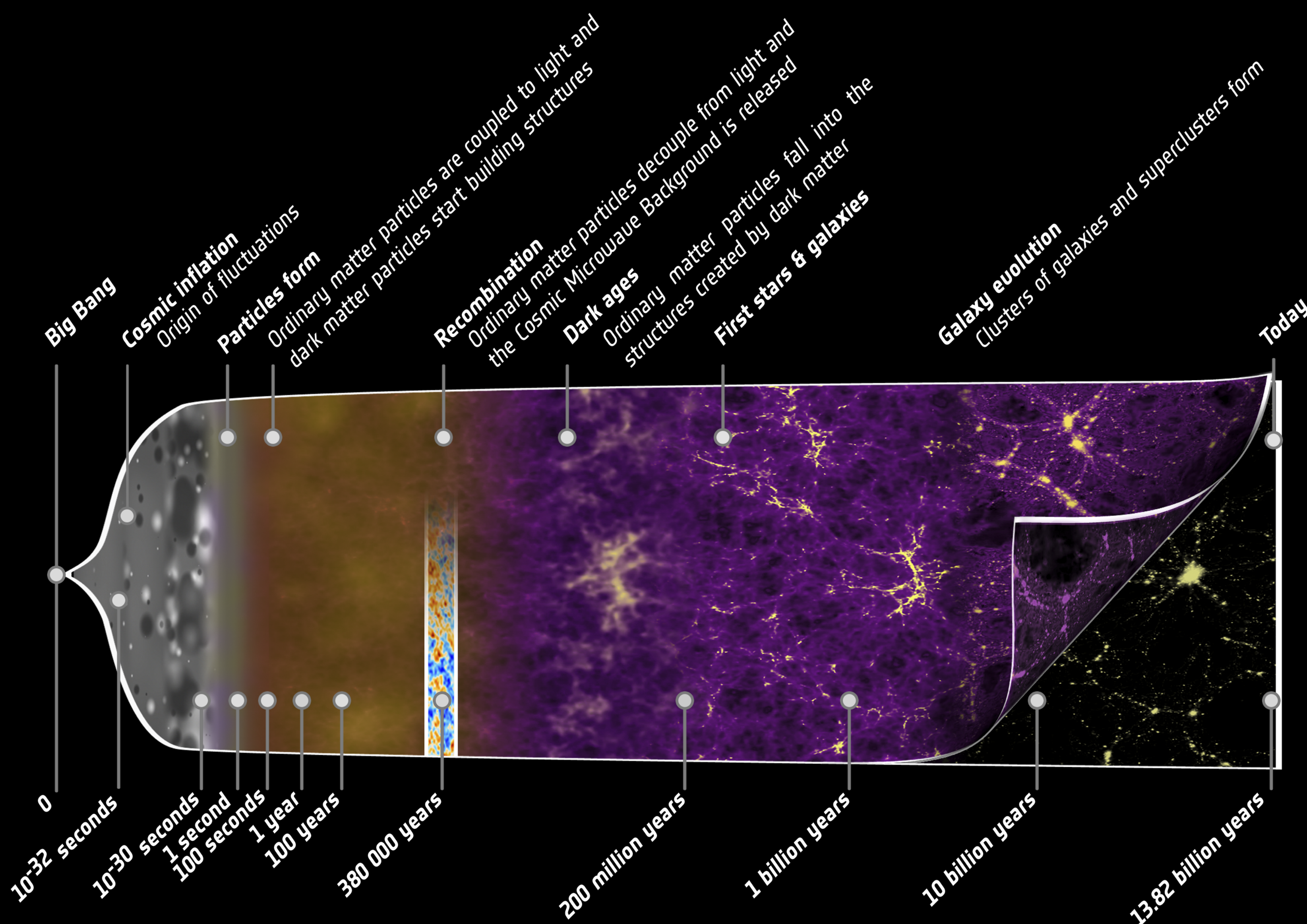


Data

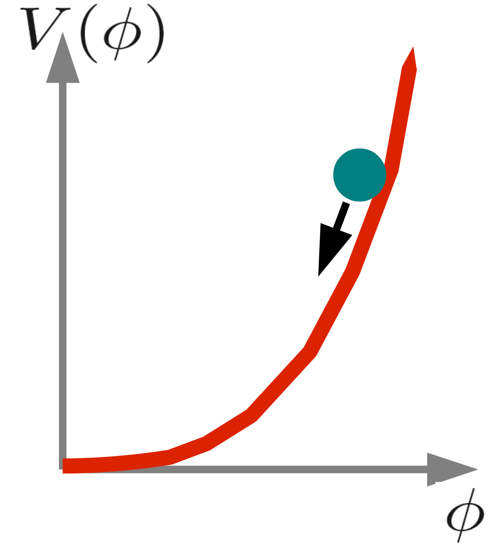


Best Fit Model

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


Big Bang
Cosmic inflation
Origin of fluctuations
Particles form
Ordinary matter particles are coupled to light and dark matter particles start building structures
Recombination
Ordinary matter particles decouple from light and the Cosmic Microwave Background is released
Dark ages
Ordinary matter particles fall into the structures created by dark matter
First stars & galaxies
Galaxy evolution
Clusters of galaxies and superclusters form
Today
0
10-32 seconds
10-30 seconds
1 second
100 seconds
1 year
100 years
380 000 years
200 million years
1 billion years
10 billion years
13.82 billion years

Inflation



$$\ddot{\phi}(t) + 3\,H(t)\,\dot{\phi}(t) + V_\phi = 0$$

$$H^2 = \frac{1}{3\,M_{\rm pl}^2}\left(V(\phi) + \frac{1}{2}\dot{\phi}^2\right)$$

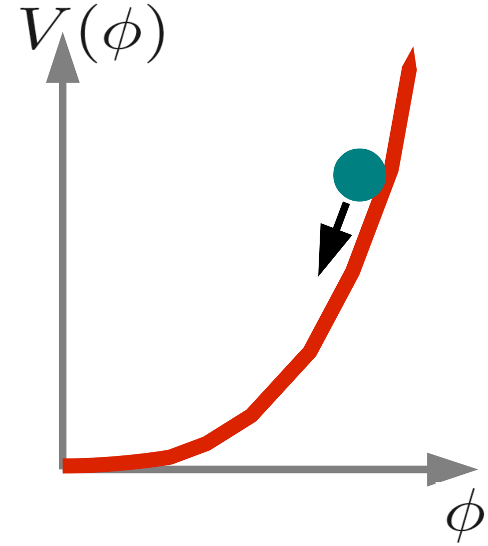
slow role inflation

$$\epsilon_V = \frac{M_{\rm pl}^2 V_\phi^2}{2\,V^2}$$

$$\eta_V = \frac{M_{\rm pl}^2 V_{\phi\phi}}{V}$$

slow role parameters

Inflation



$$N_* = \int_{t_*}^{t_e} \mathrm{d}t\, H \approx \frac{1}{M_{\rm pl}^2} \int_{\phi_*}^{\phi_e} \mathrm{d}\phi\, \frac{V}{V_\phi}$$

$$A_s \approx \frac{V}{24\pi^2 M_{\rm pl}^4 \epsilon_V}$$

$$A_t \approx \frac{2V}{3\pi^2 M_{\rm pl}^4}$$

$$r = \frac{\mathcal{P}_t(k_*)}{\mathcal{P}_{\mathcal{R}}(k_*)} \approx 16\epsilon \approx -8n_t$$

$$n_s - 1 \approx 2\eta_V - 6\epsilon_V$$

$$n_t \approx -2\epsilon_V$$

$$\mathrm{d}n_s/\mathrm{d}\ln k \approx -16\epsilon_V\eta_V + 24\epsilon_V^2 + 2\xi_V^2$$

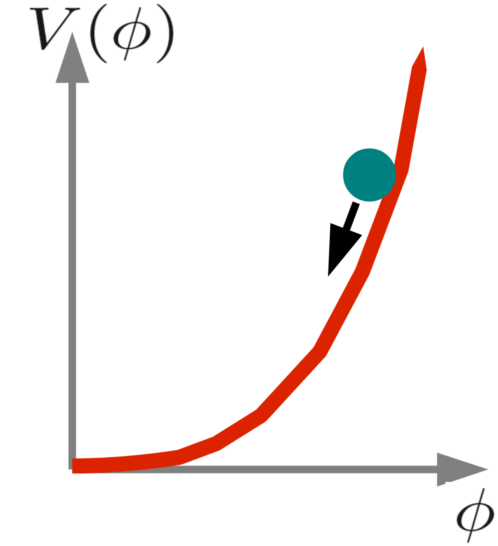
$$\mathrm{d}n_t/\mathrm{d}\ln k \approx -4\epsilon_V\eta_V + 8\epsilon_V^2$$

$$\mathrm{d}^2 n_s/\mathrm{d}\ln k^2 \approx -192\epsilon_V^3 + 192\epsilon_V^2\eta_V - 32\epsilon_V\eta_V^2 - 24\epsilon_V\xi_V^2 + 2\eta_V\xi_V^2 + 2\varpi_V^3,$$

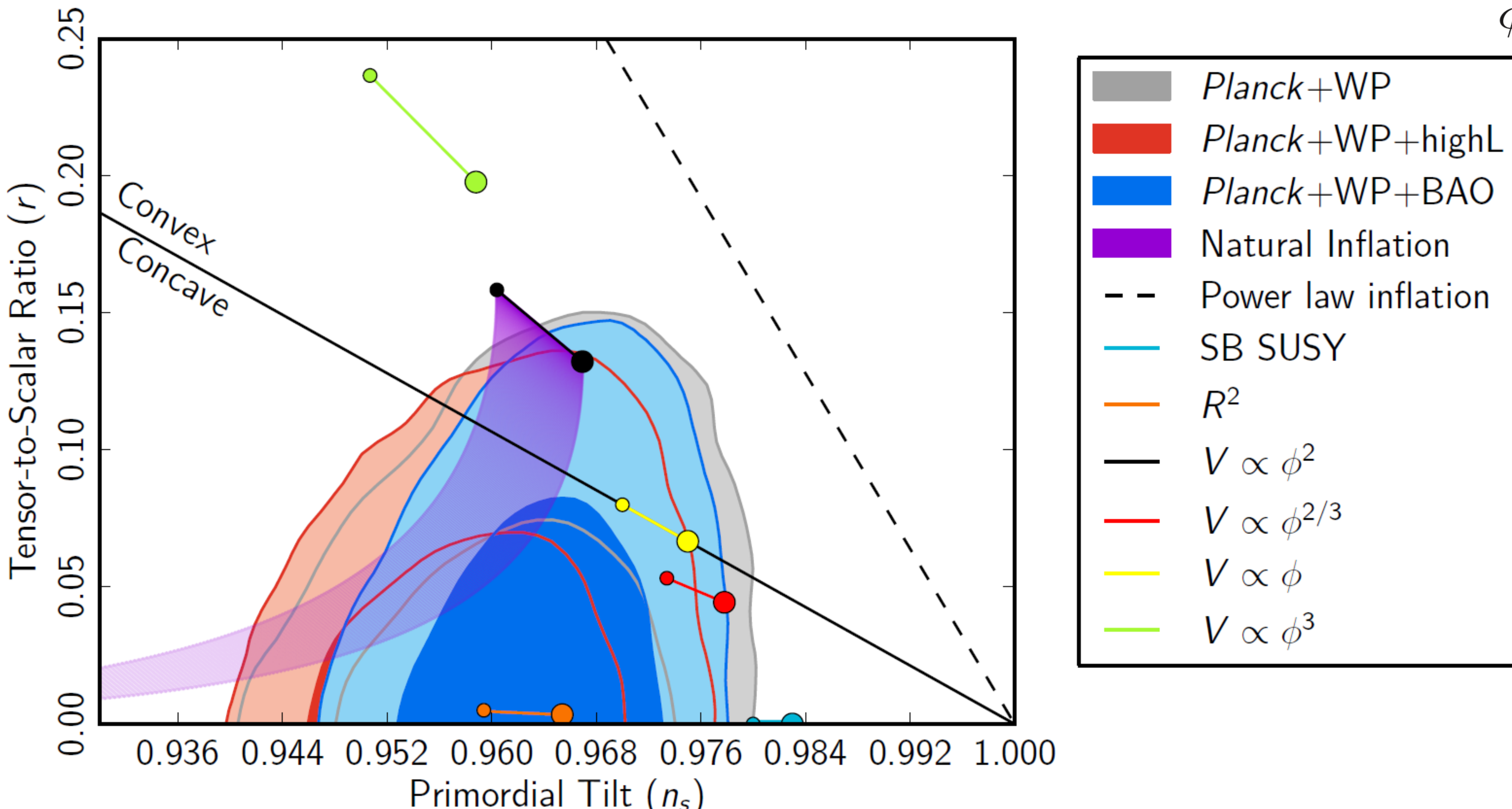
$$\epsilon_V = \frac{M_{\rm pl}^2 V_\phi^2}{2V^2}$$

$$\eta_V = \frac{M_{\rm pl}^2 V_{\phi\phi}}{V}$$

Inflation

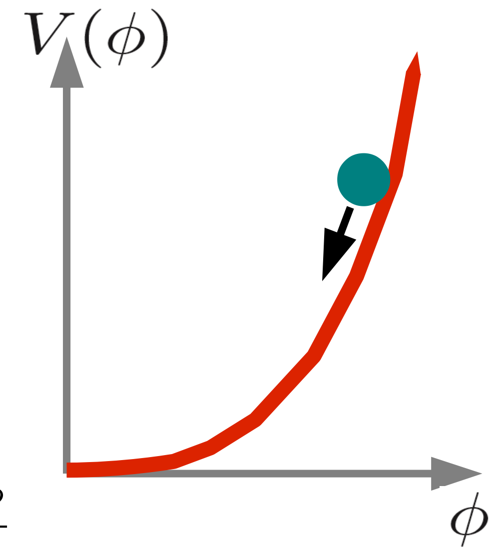


$V(\phi)$
ϕ



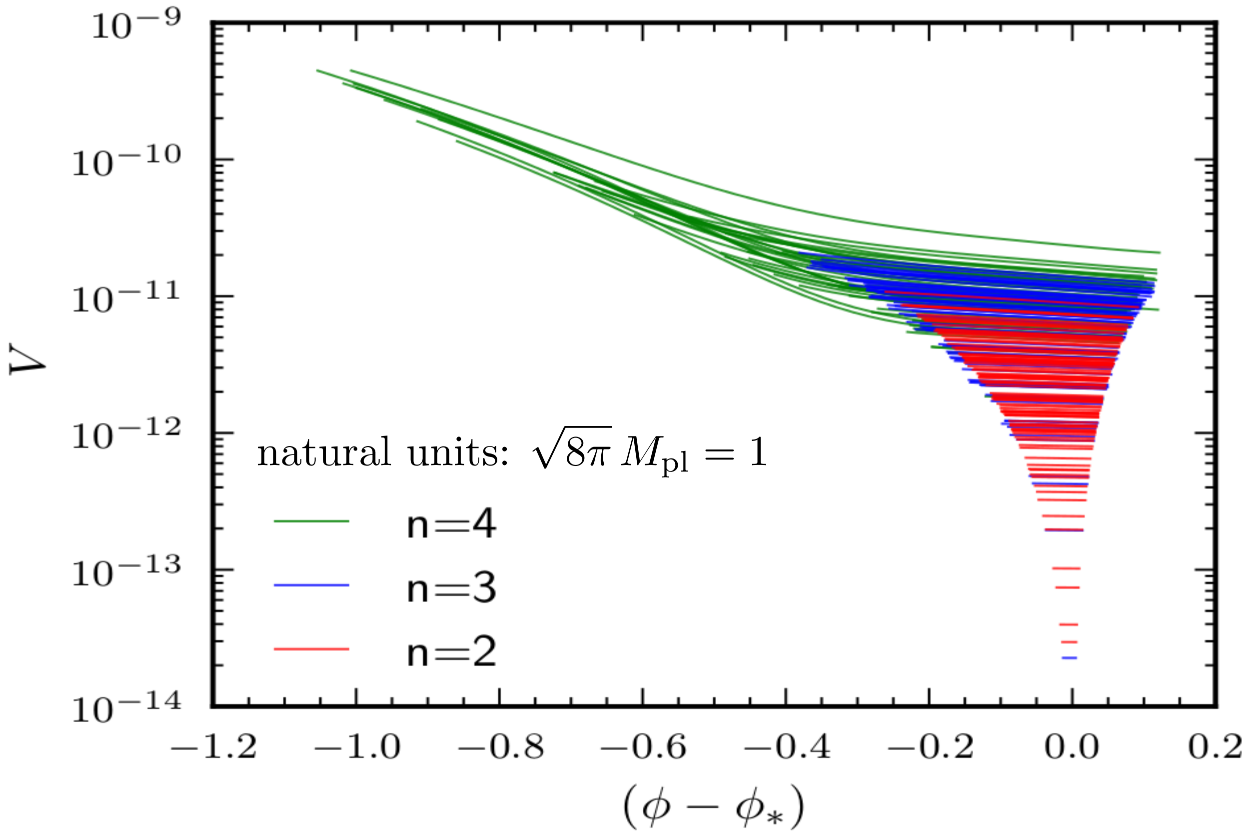
Tensor-to-Scalar Ratio (r)
Primordial Tilt (n_s)
0.00
0.05
0.10
0.15
0.20
0.25
0.936
0.944
0.952
0.960
0.968
0.976
0.984
0.992
1.000
Convex
Concave
Planck+WP
Planck+WP+highL
Planck+WP+BAO
Natural Inflation
Power law inflation
SB SUSY
R^2
$V \propto \phi^2$
$V \propto \phi^{2/3}$
$V \propto \phi$
$V \propto \phi^3$

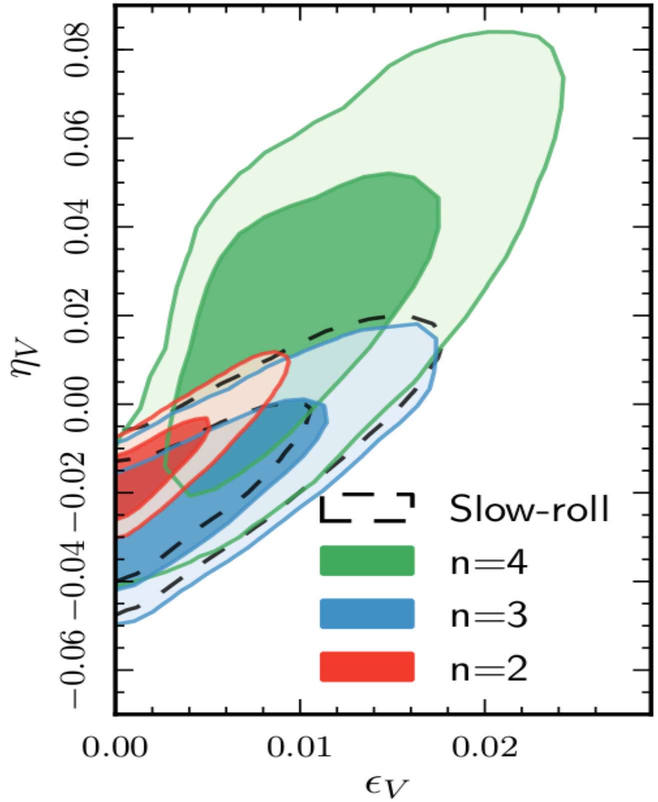
Inflation



$$\epsilon_V = \frac{M_{\rm pl}^2 V_\phi^2}{2\,V^2}$$

$$\eta_V = \frac{M_{\rm pl}^2 V_{\phi\phi}}{V}$$





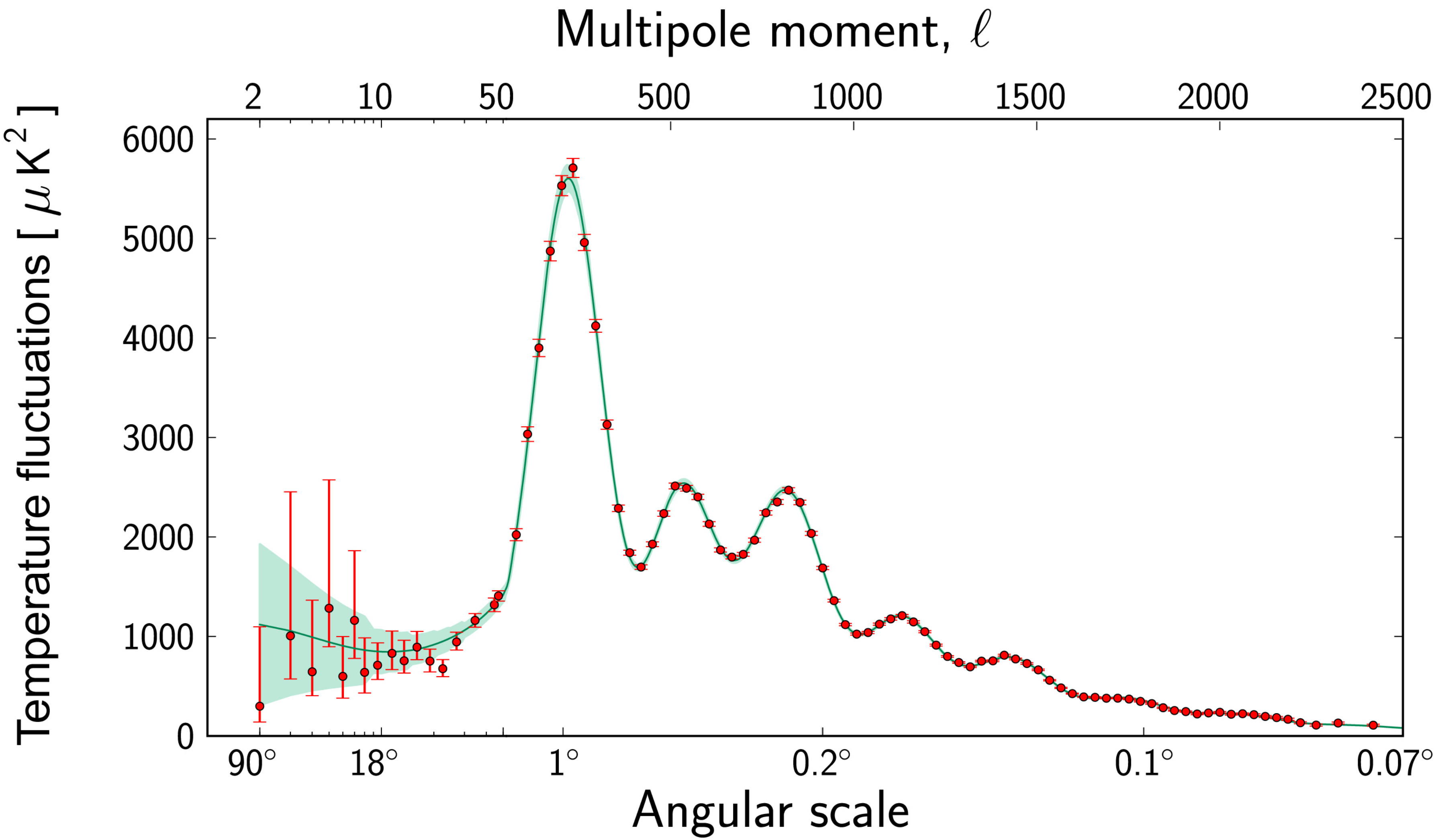
Anomalies

„Missing Power“

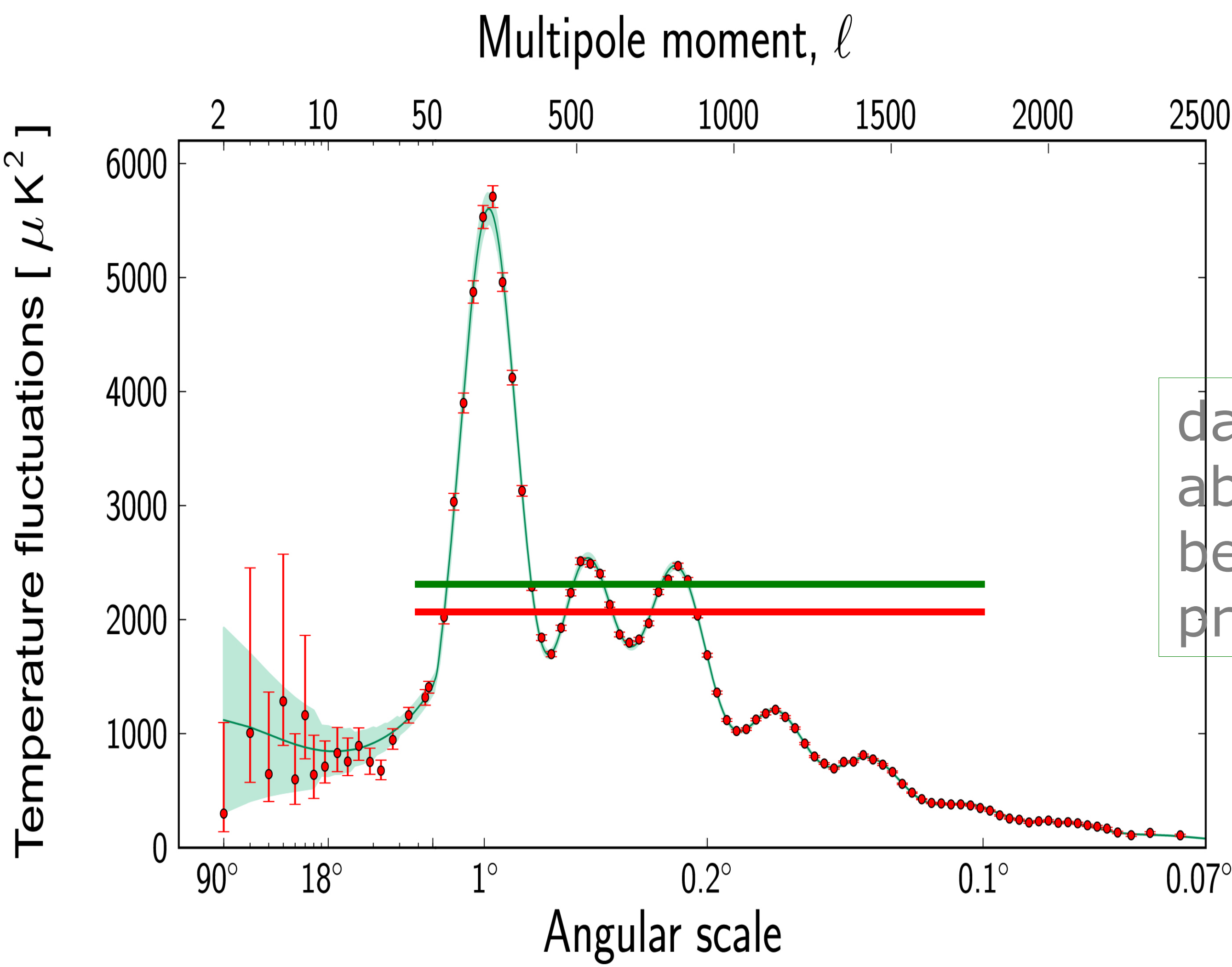
Hemisphere Asymmetry

„Cold Spot“

„Missing Power“

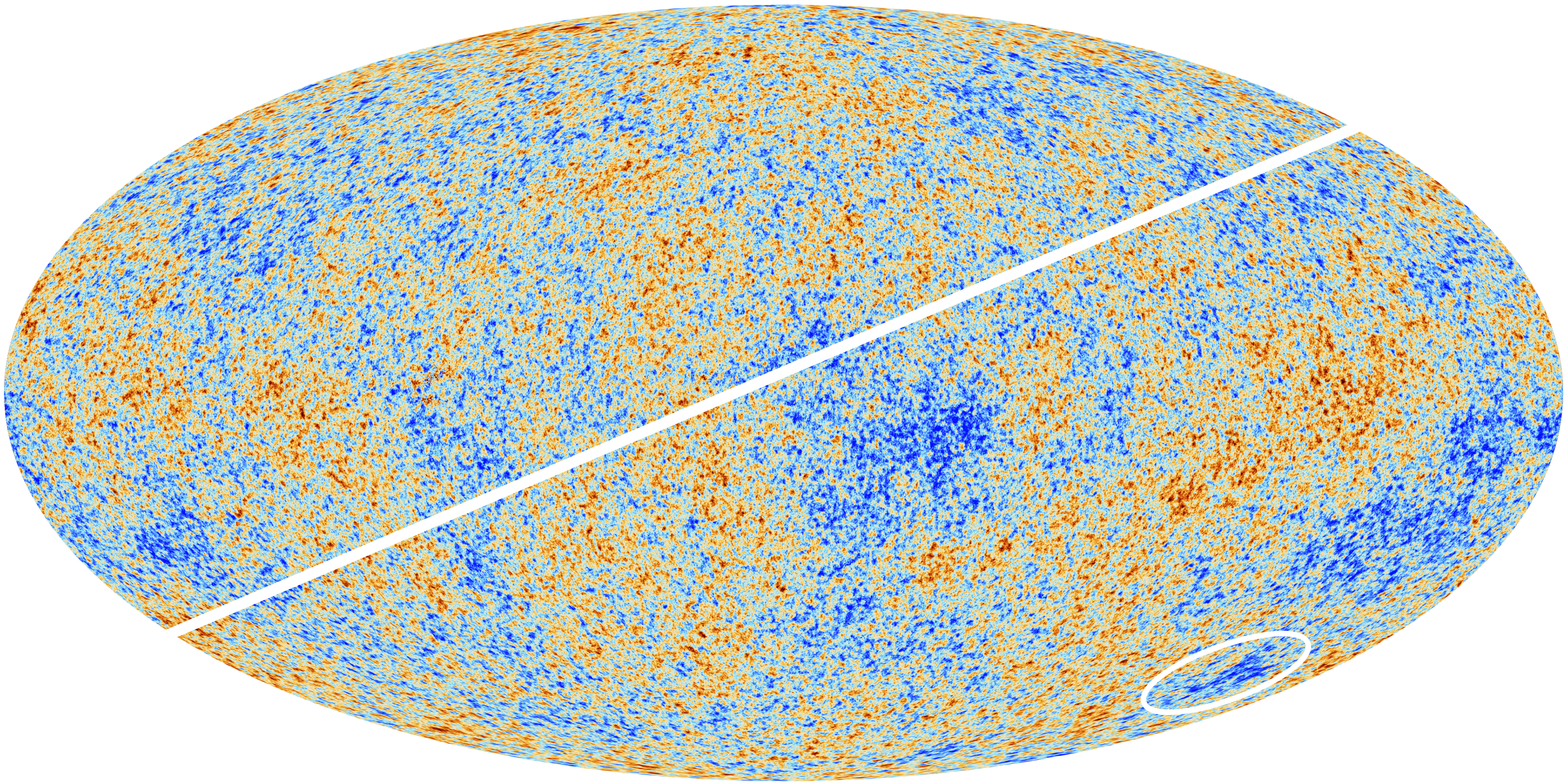


„Missing Power“



data are about 10% below model prediction

Hemissphere Asymmetry and „Cold Spot"



Anomalies

Planck confirms: anomalies previously seen by WMAP are CMB features!

But what is their meaning?

Signatures of new physics

(Universe inhomogeneous on largest scales, view on beginning of inflation, …)

or simply statistical fluctuations?

(with the large number of tests applied, a few outliers are to be expected)

Conclusions

Planck provided us with an amazingly consistent cosmological picture

Planck confirmed the quantum fluctuation origin of the cosmic structures

A few discrepancies and anomalies remain, but wouldn't life be boring otherwise?

The scientific results that we present today are the product of the Planck Collaboration, including individuals from more than 50 scientific institutes in Europe, the USA and Canada