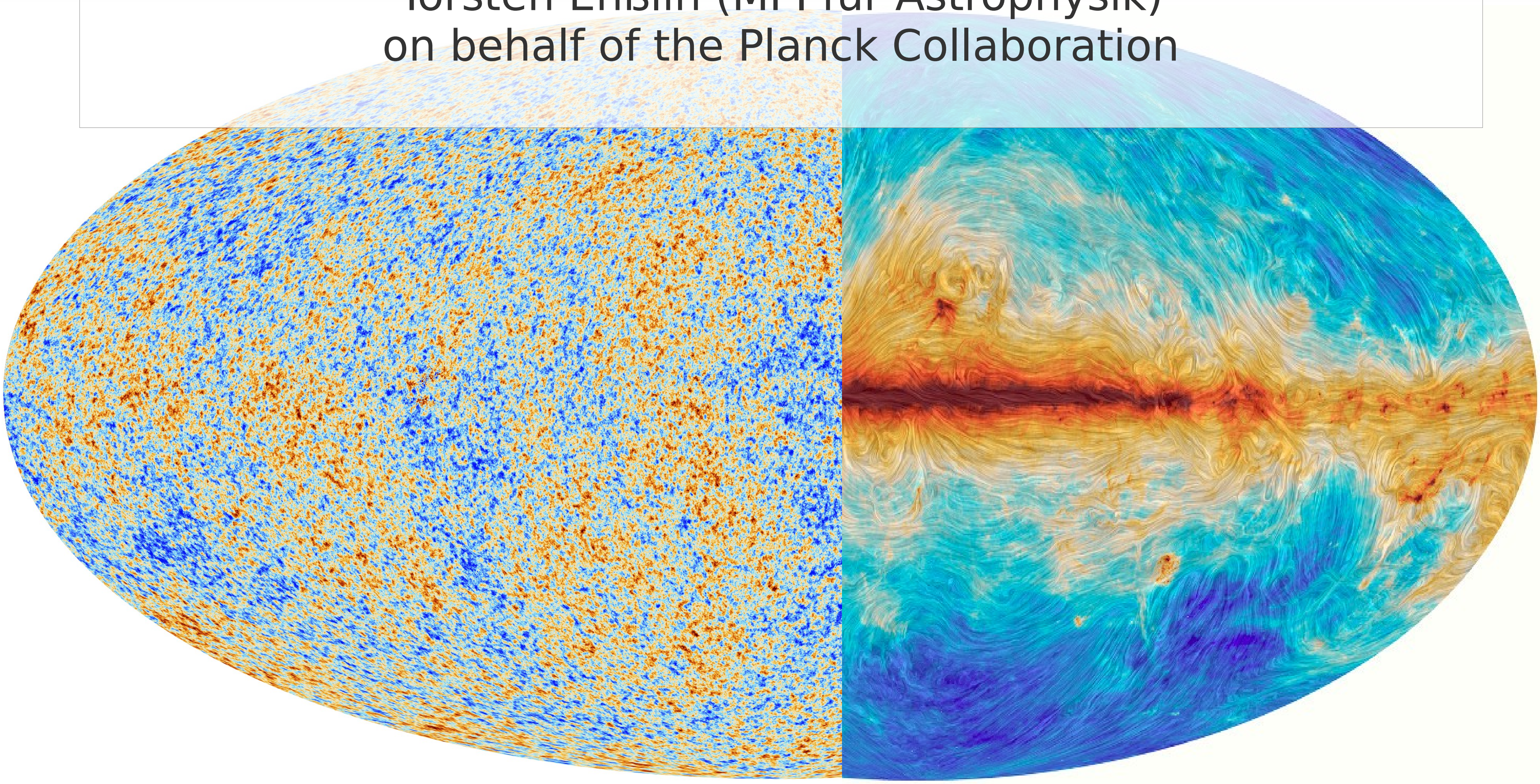
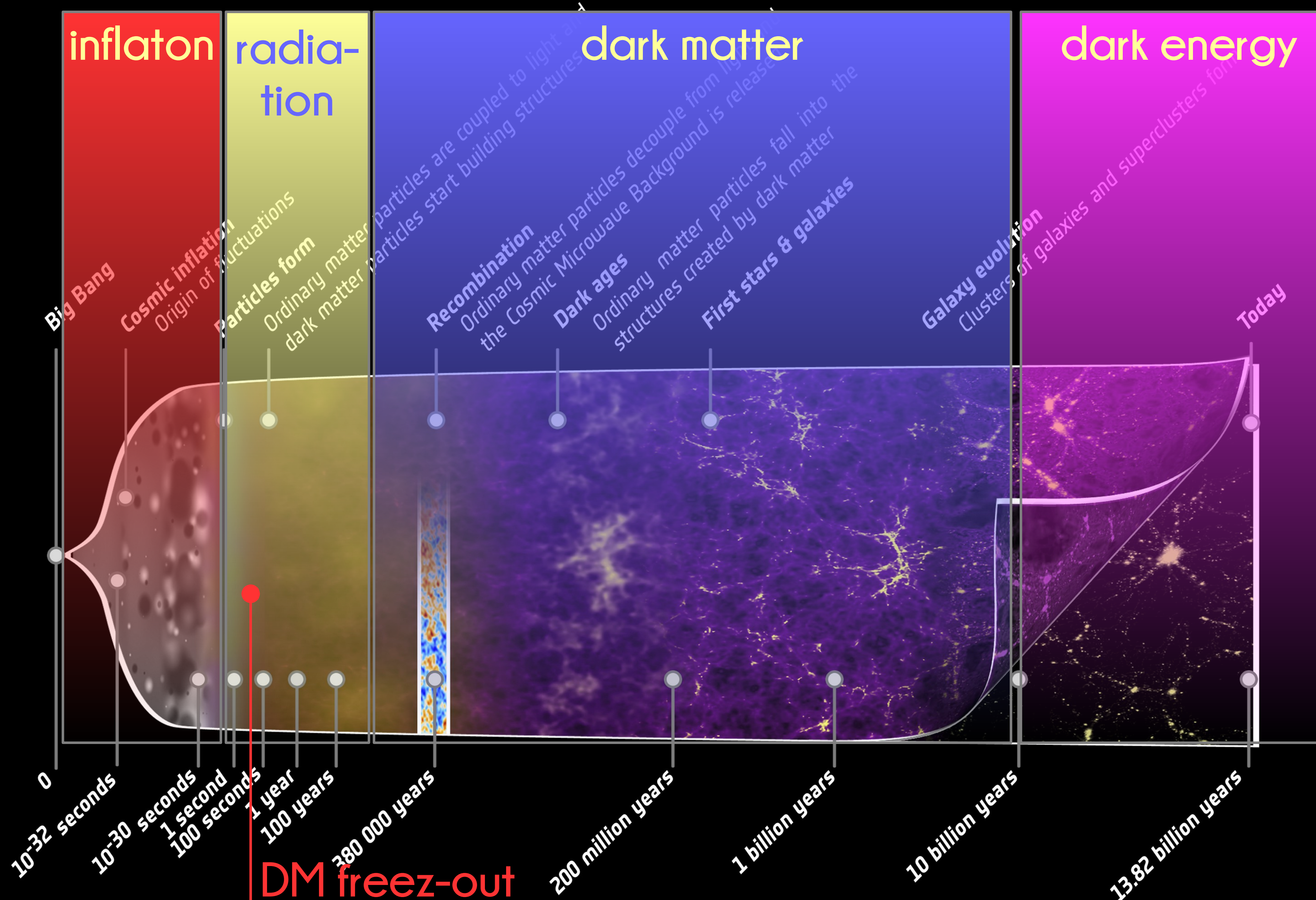
Particle physics in the CMB

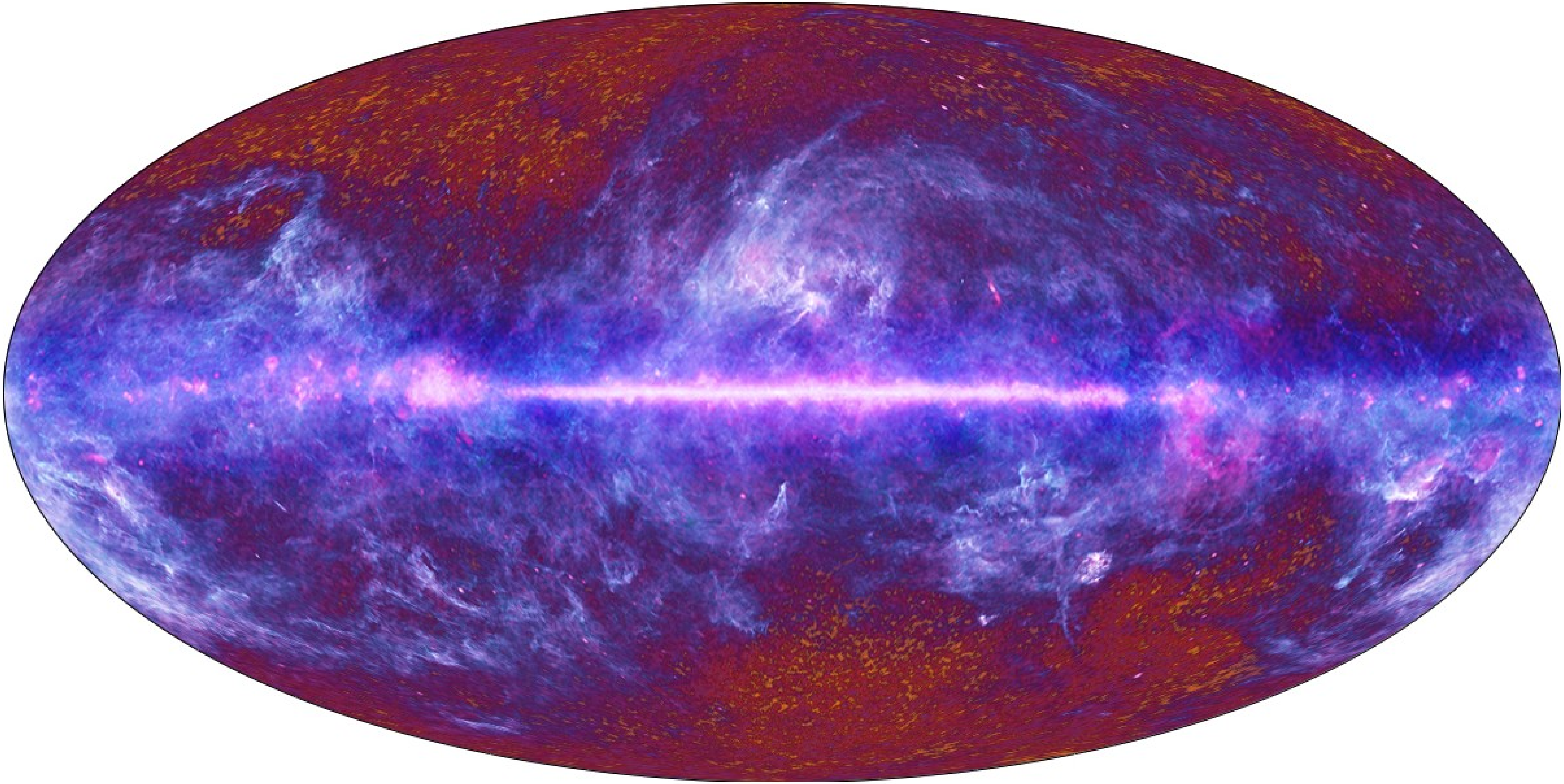
Torsten Enßlin (MPI für Astrophysik)
on behalf of the Planck Collaboration



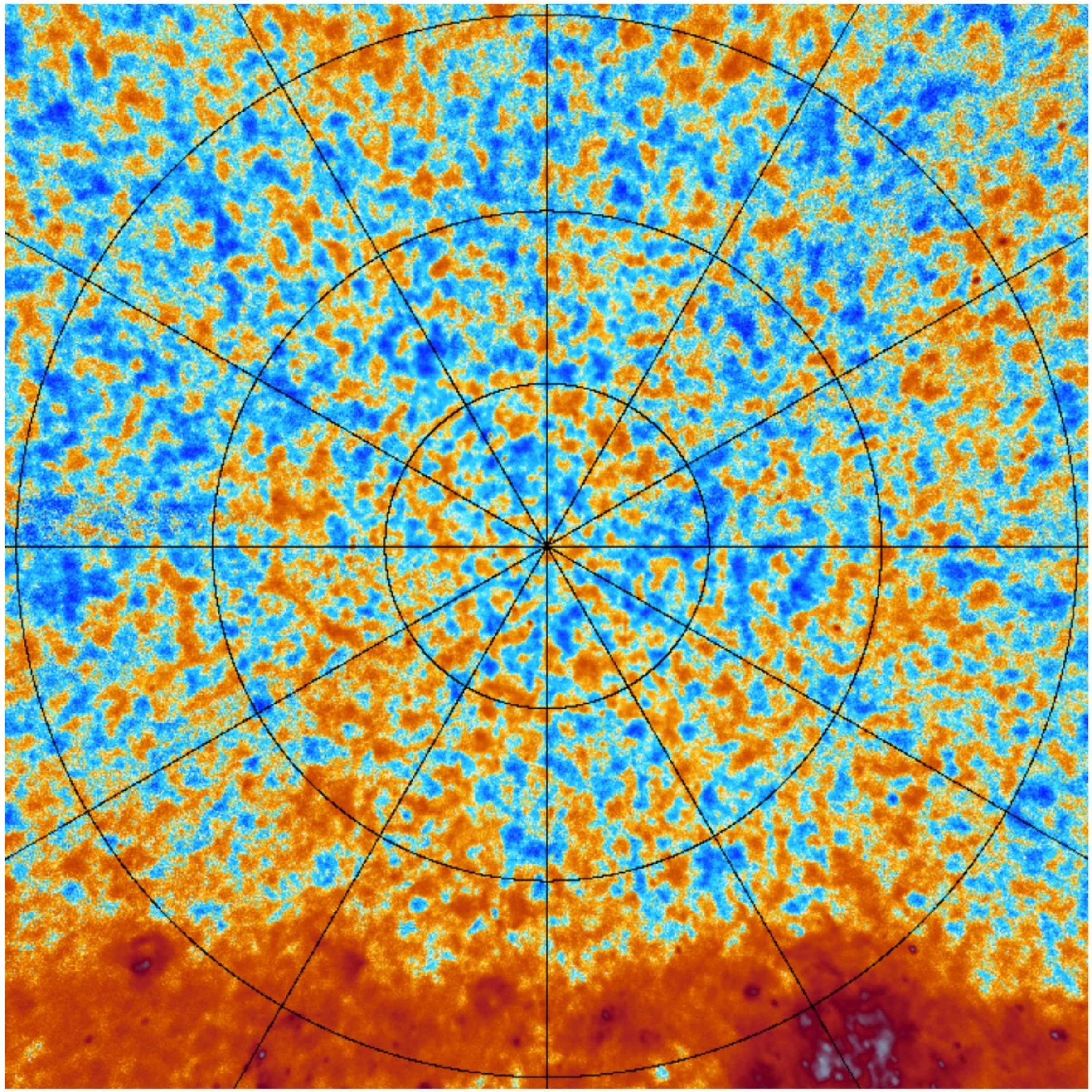


inflaton
radia-tion
dark matter
dark energy
Big Bang
Cosmic inflation
Origin of fluctuations
Particles form
Ordinary matter particles are coupled to light
dark matter particles start building structures
Recombination
Ordinary matter particles decouple from light
the Cosmic Microwave Background is released
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
DM freez-out

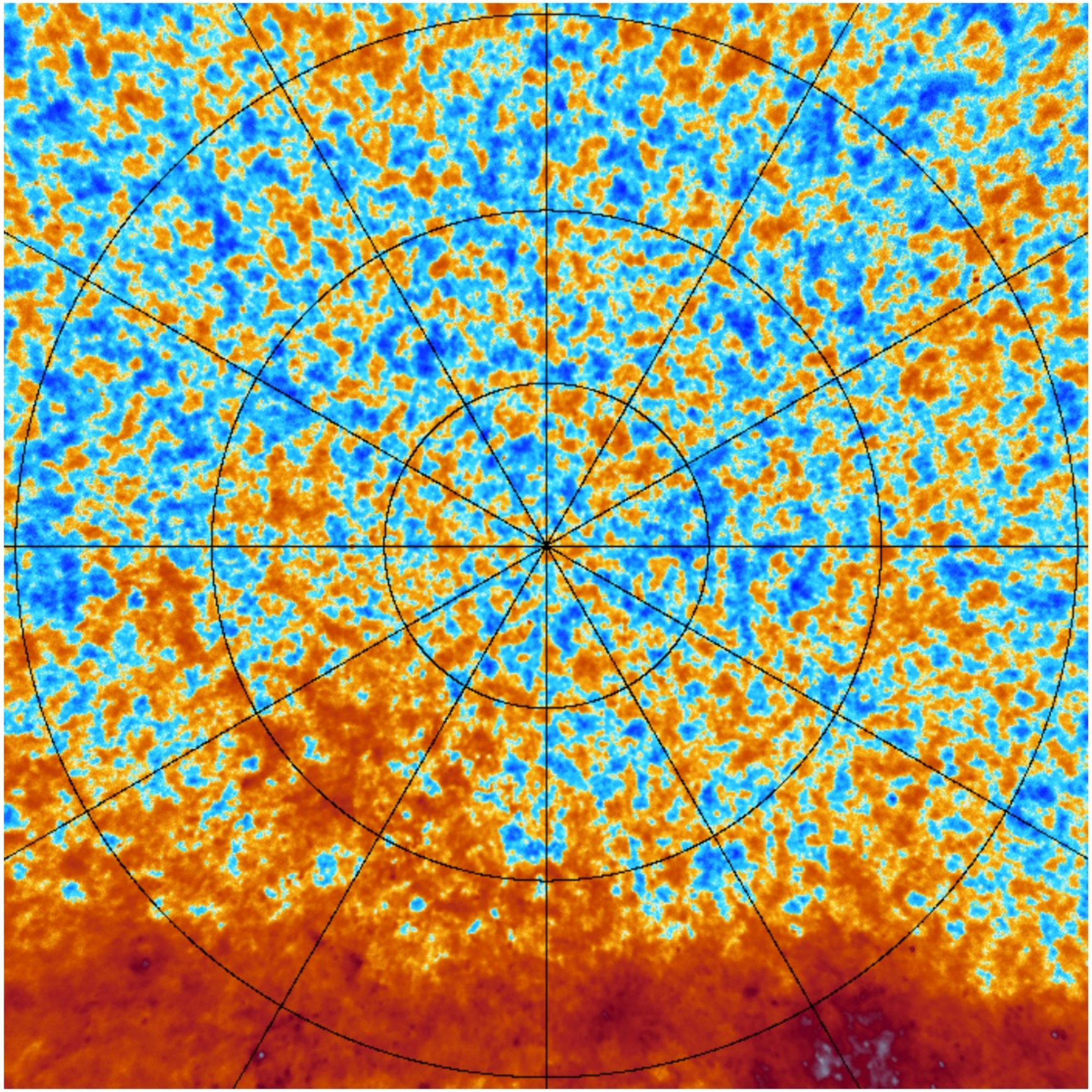
The microwave sky



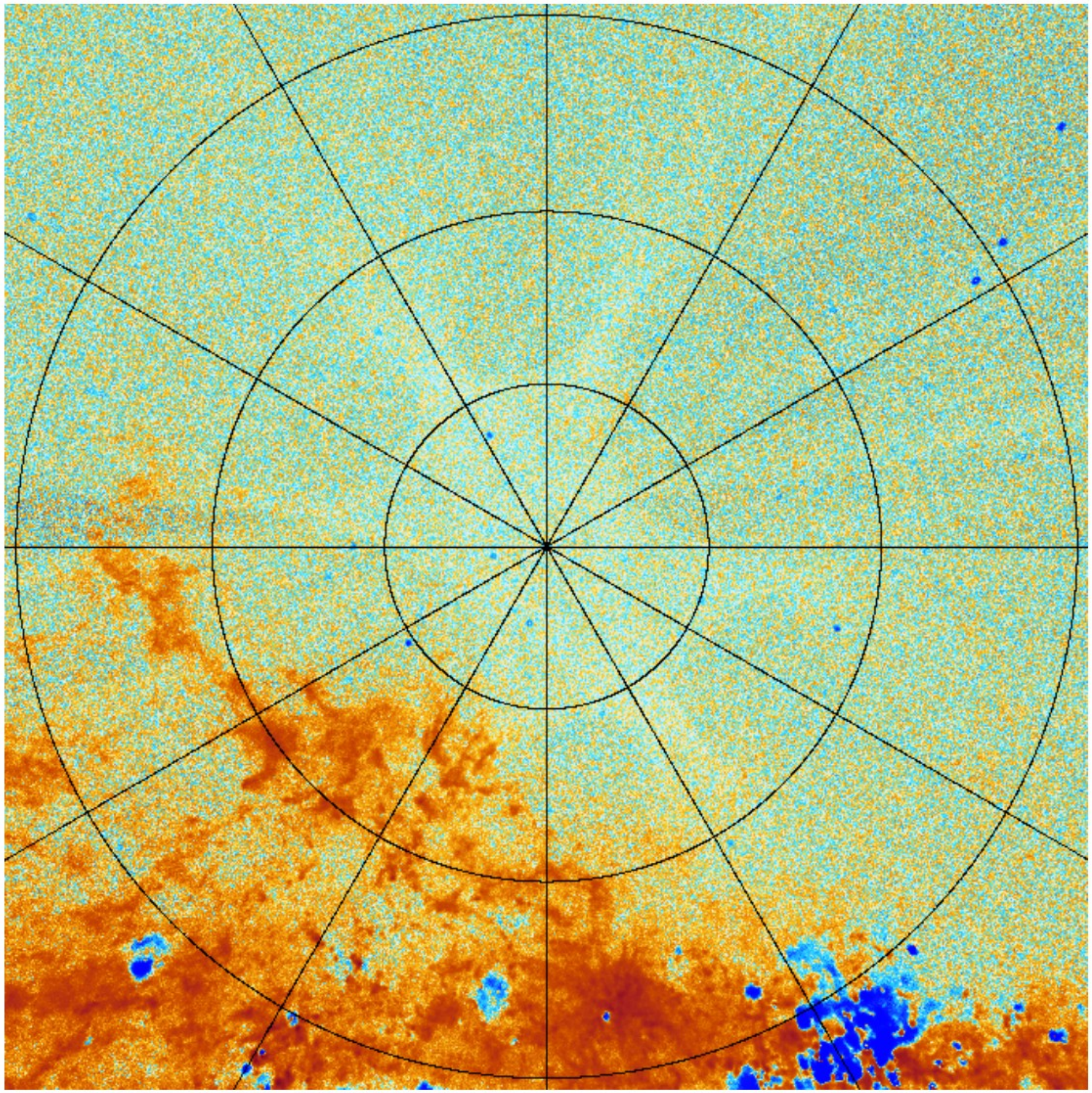
North Ecliptic Pole: 70



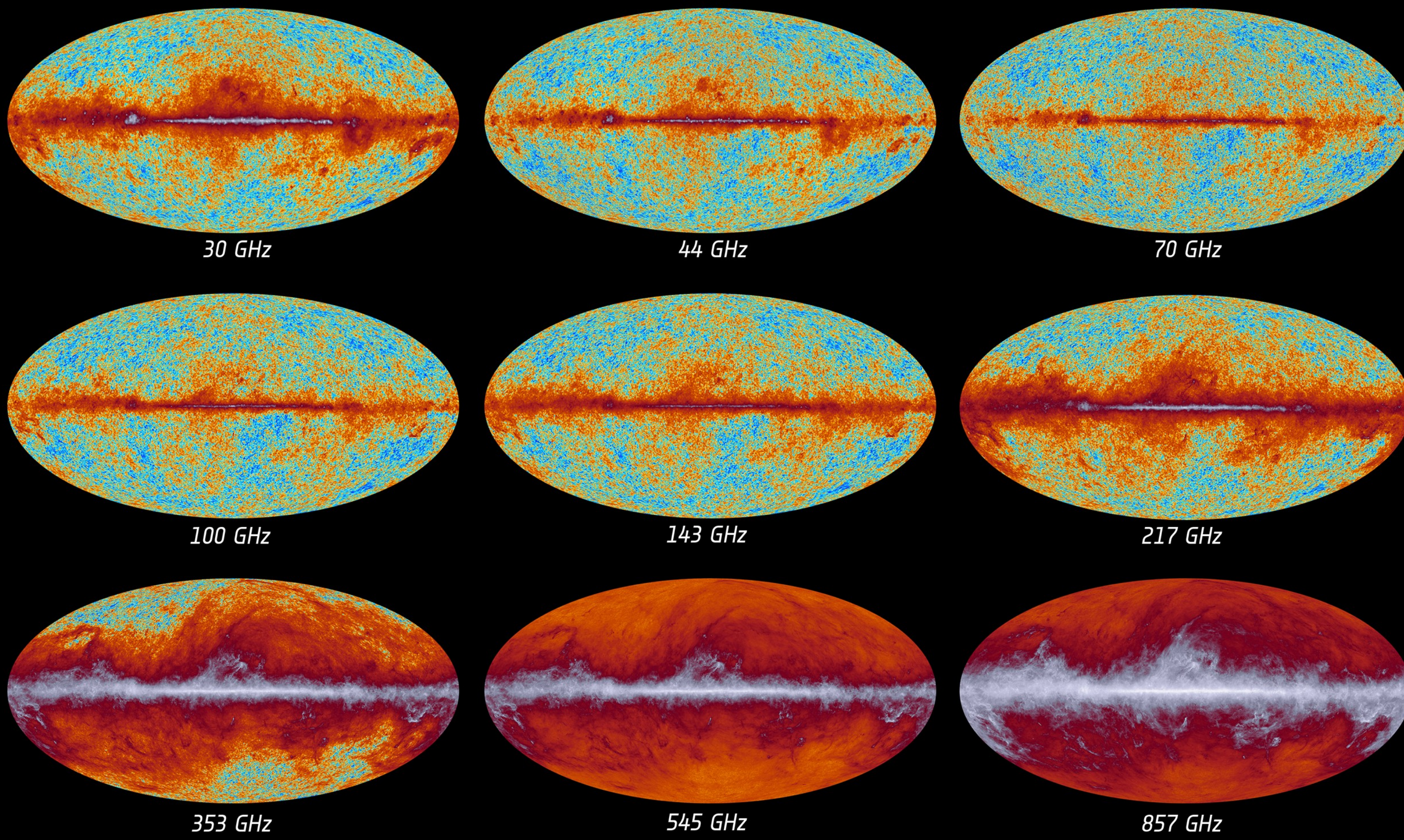
North Ecliptic Pole: 100

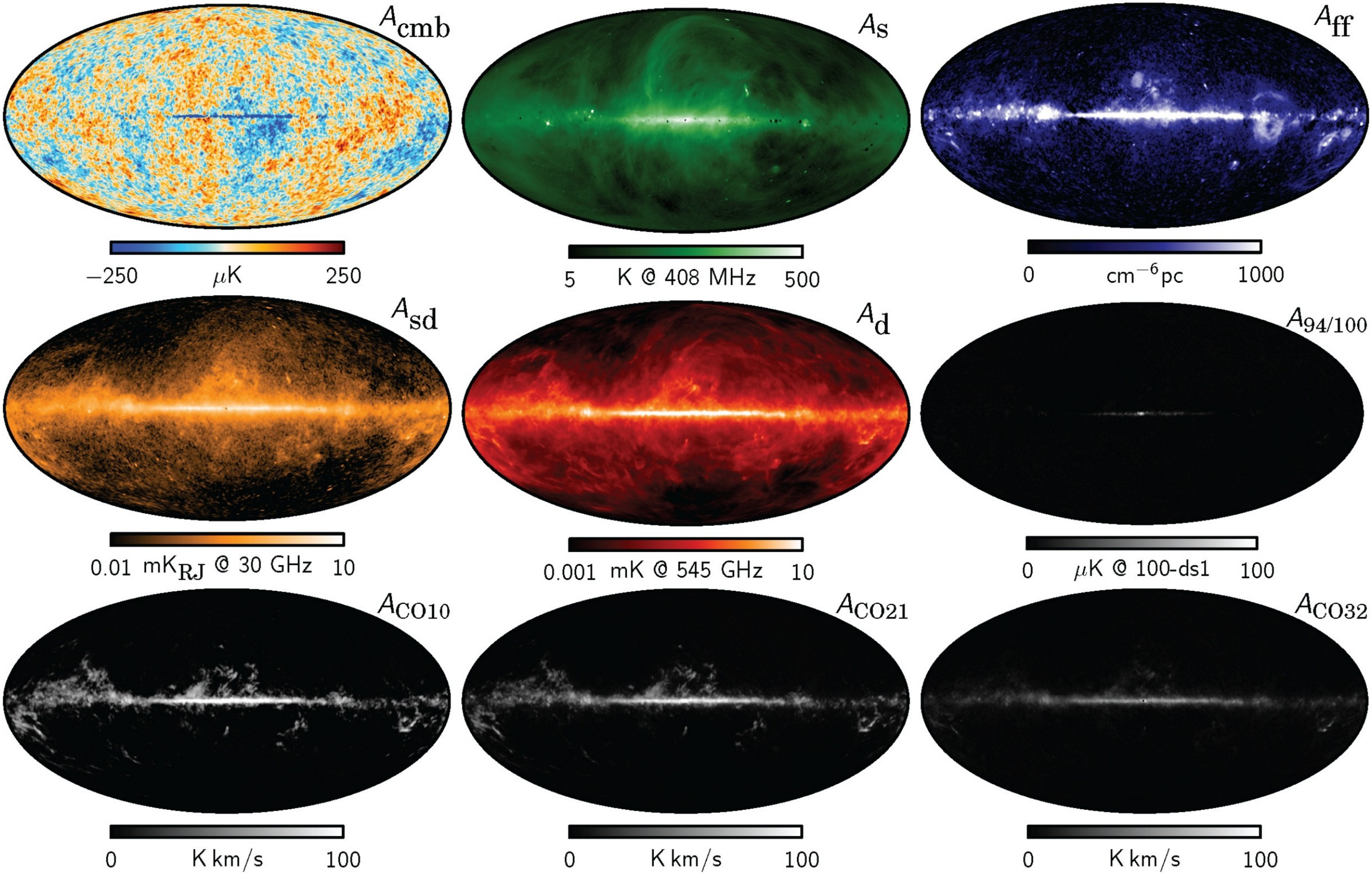


North Ecliptic Pole: Diff



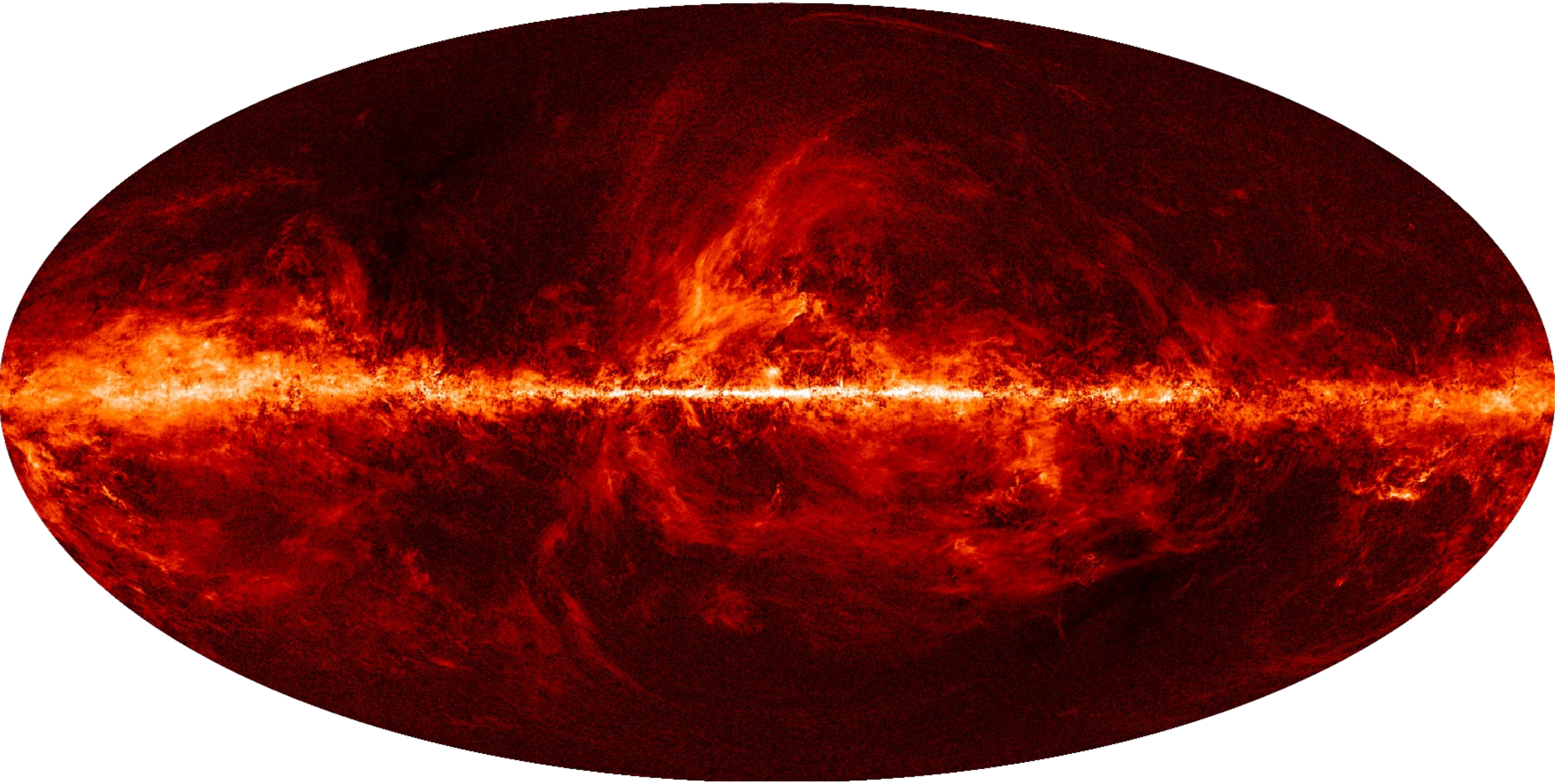
The sky as seen by Planck



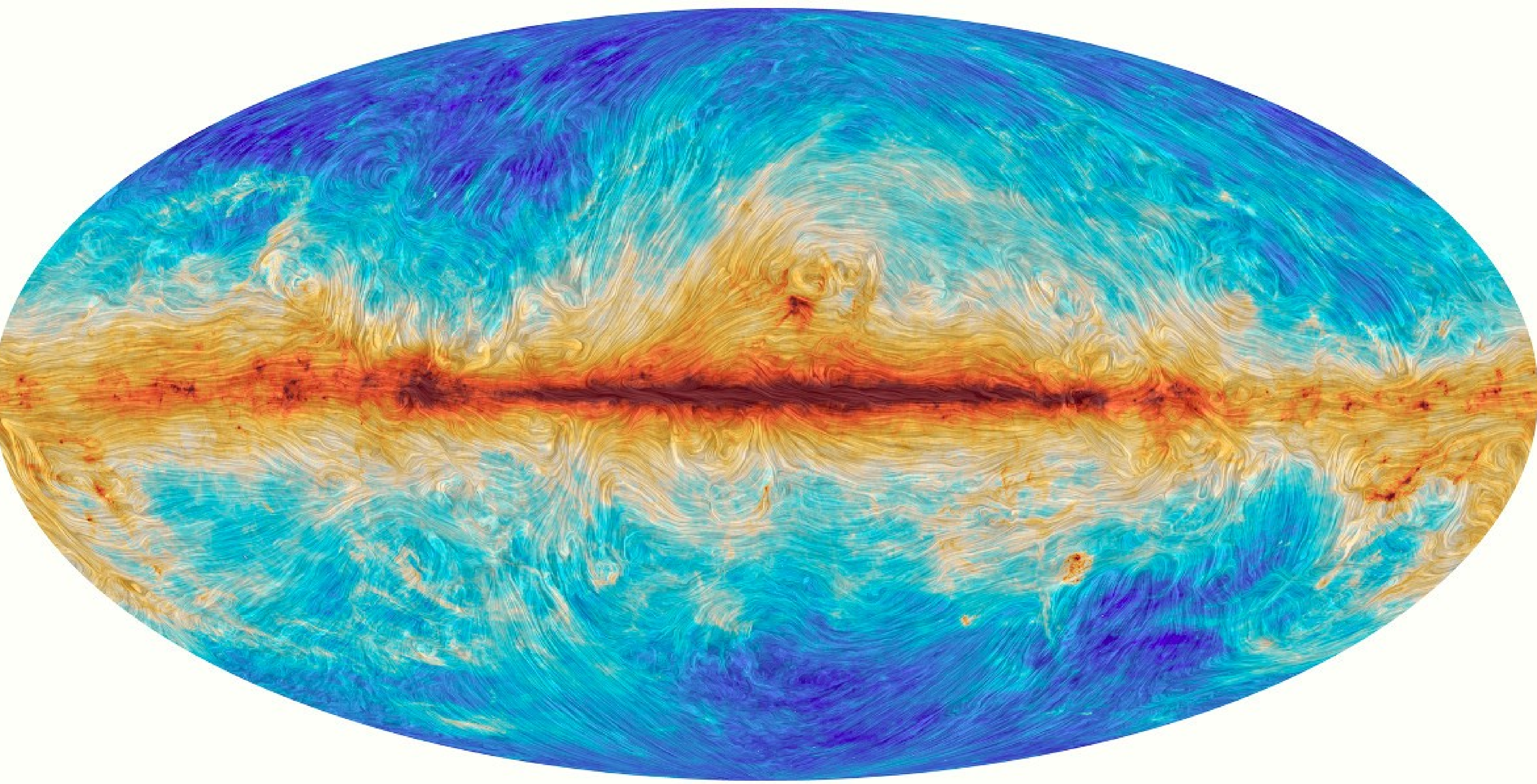


$A_{\rm cmb}$
−250 μK 250
$A_{\rm s}$
5 K @ 408 MHz 500
$A_{\rm ff}$
0 cm^{-6}pc 1000
$A_{\rm sd}$
0.01 mK$_{\rm RJ}$ @ 30 GHz 10
$A_{\rm d}$
0.001 mK @ 545 GHz 10
$A_{94/100}$
0 μK @ 100-ds1 100
$A_{\rm CO10}$
0 K km/s 100
$A_{\rm CO21}$
0 K km/s 100
$A_{\rm CO32}$
0 K km/s 100

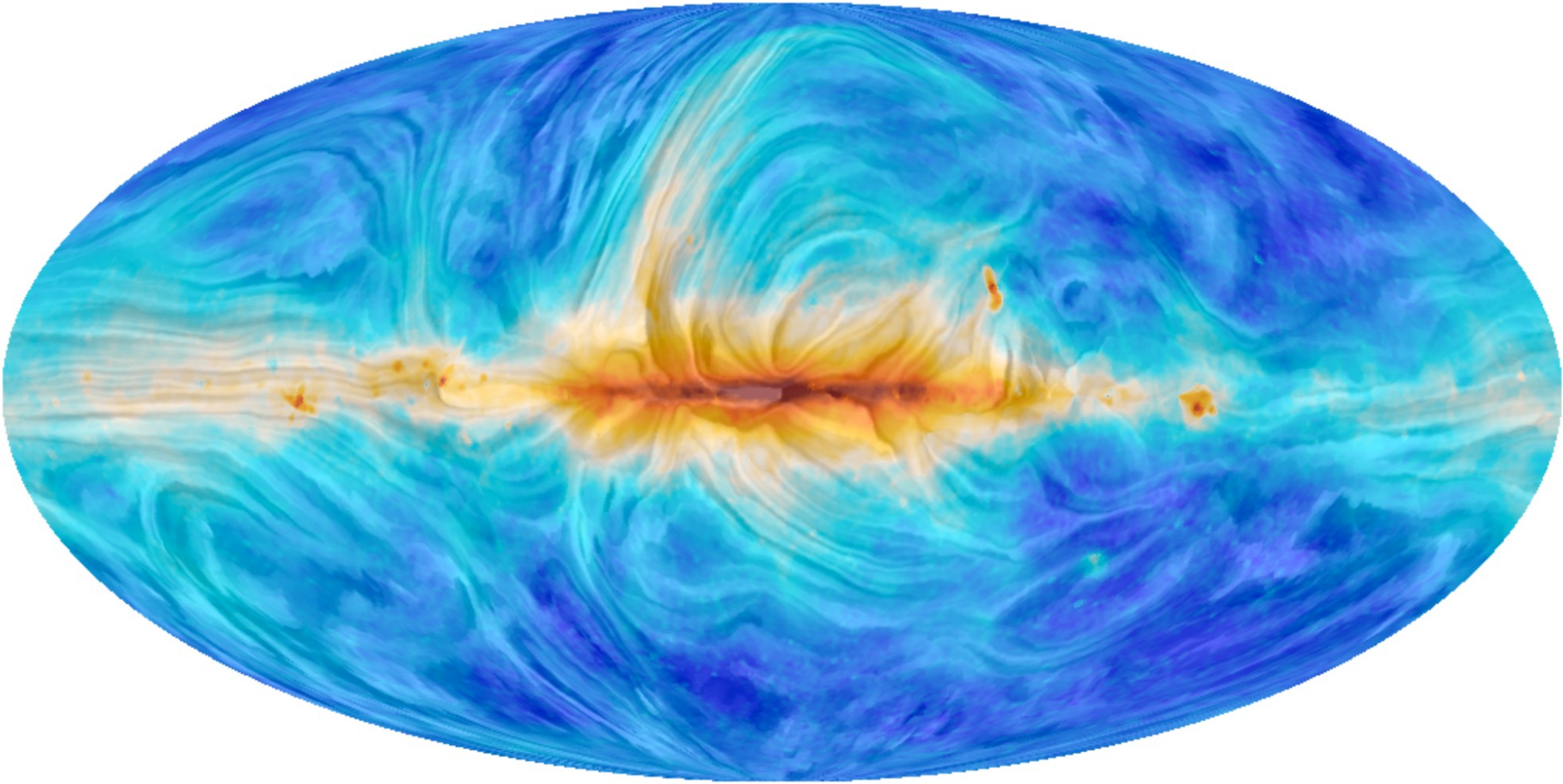
Polarized Dust Emission



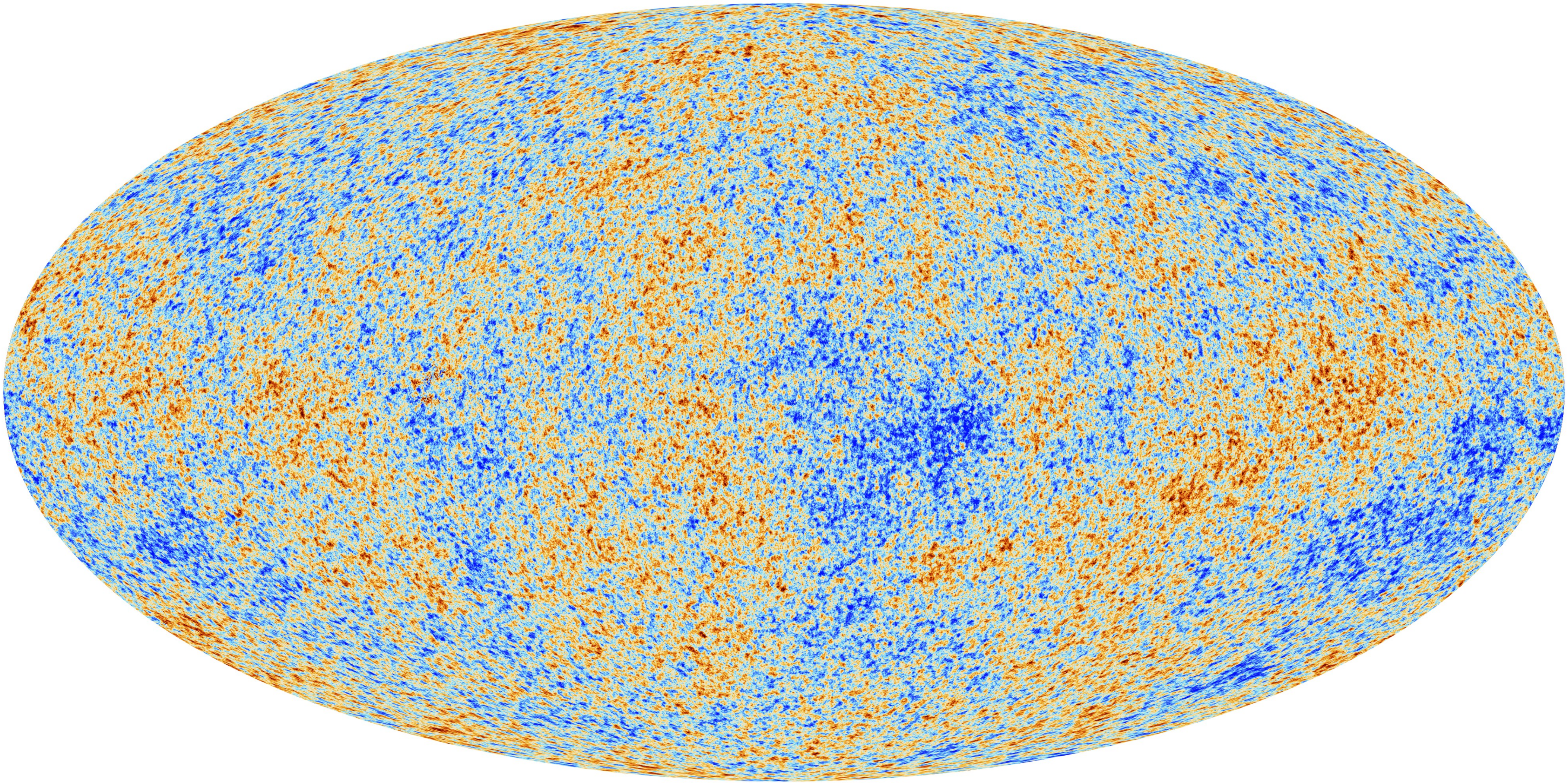
Dust Intensity & Polarization



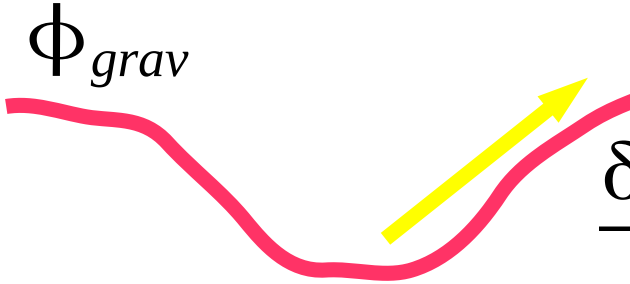
Synchrotron Emission



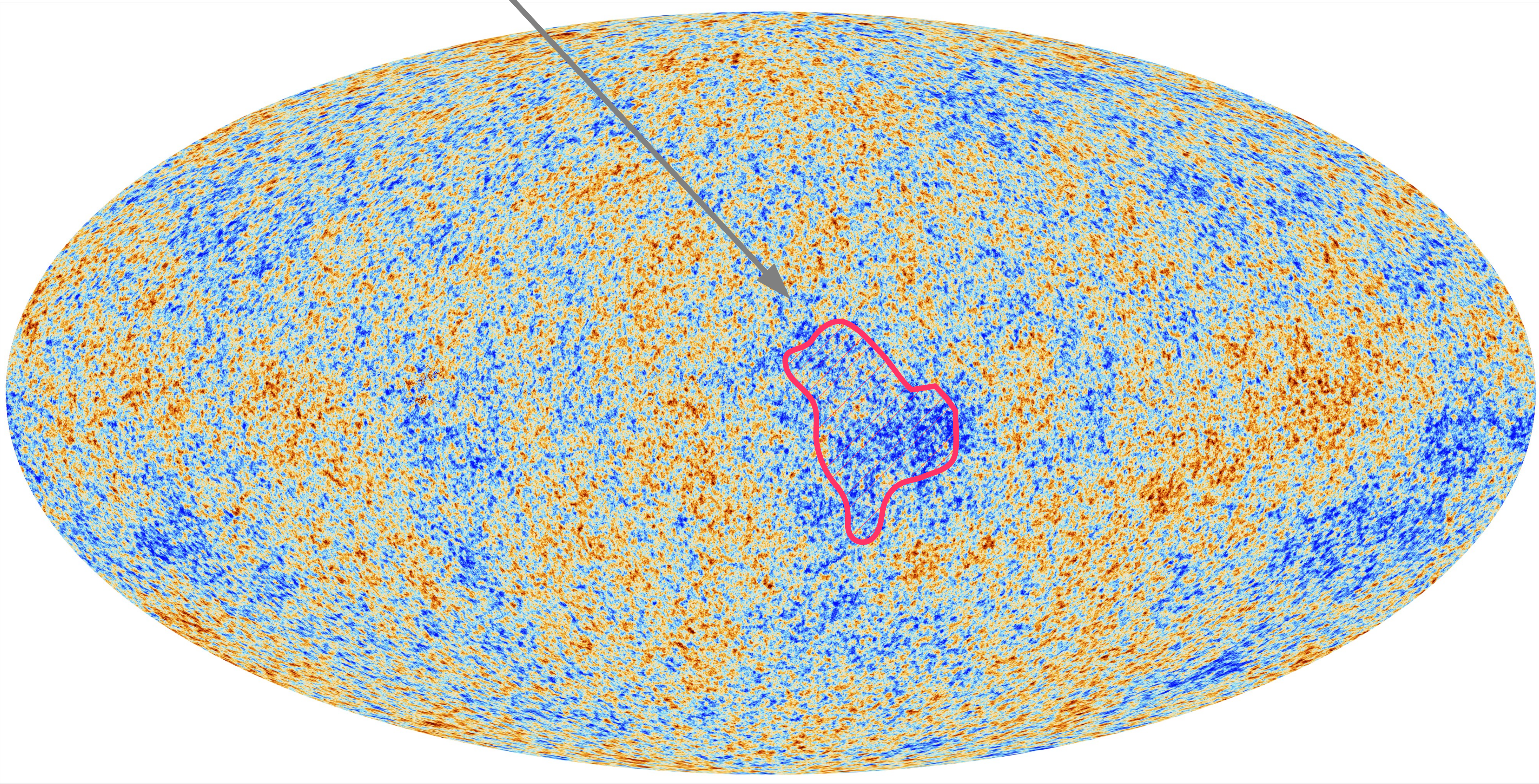
The cosmic microwave background

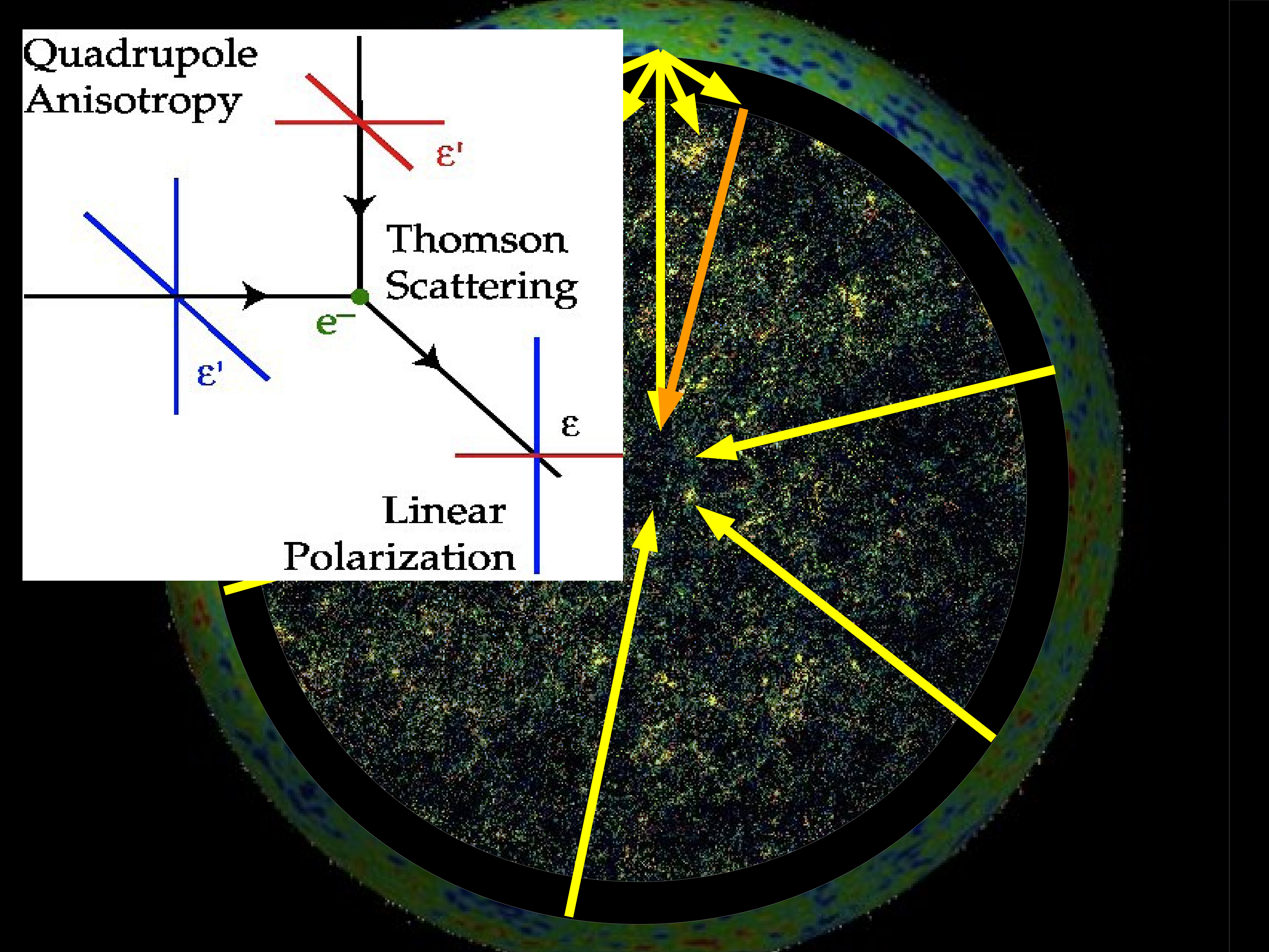


Effect of gravity on Photons

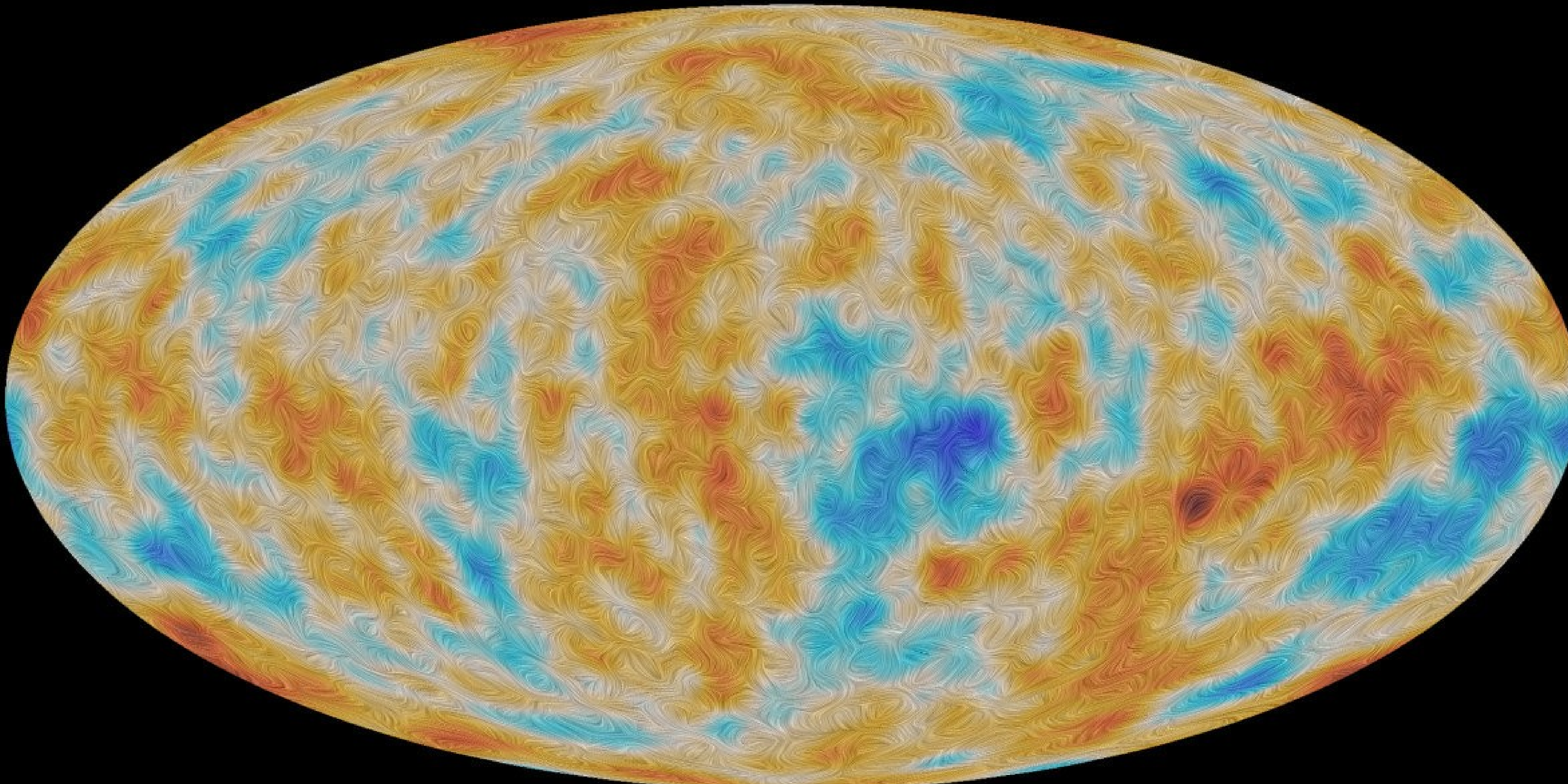


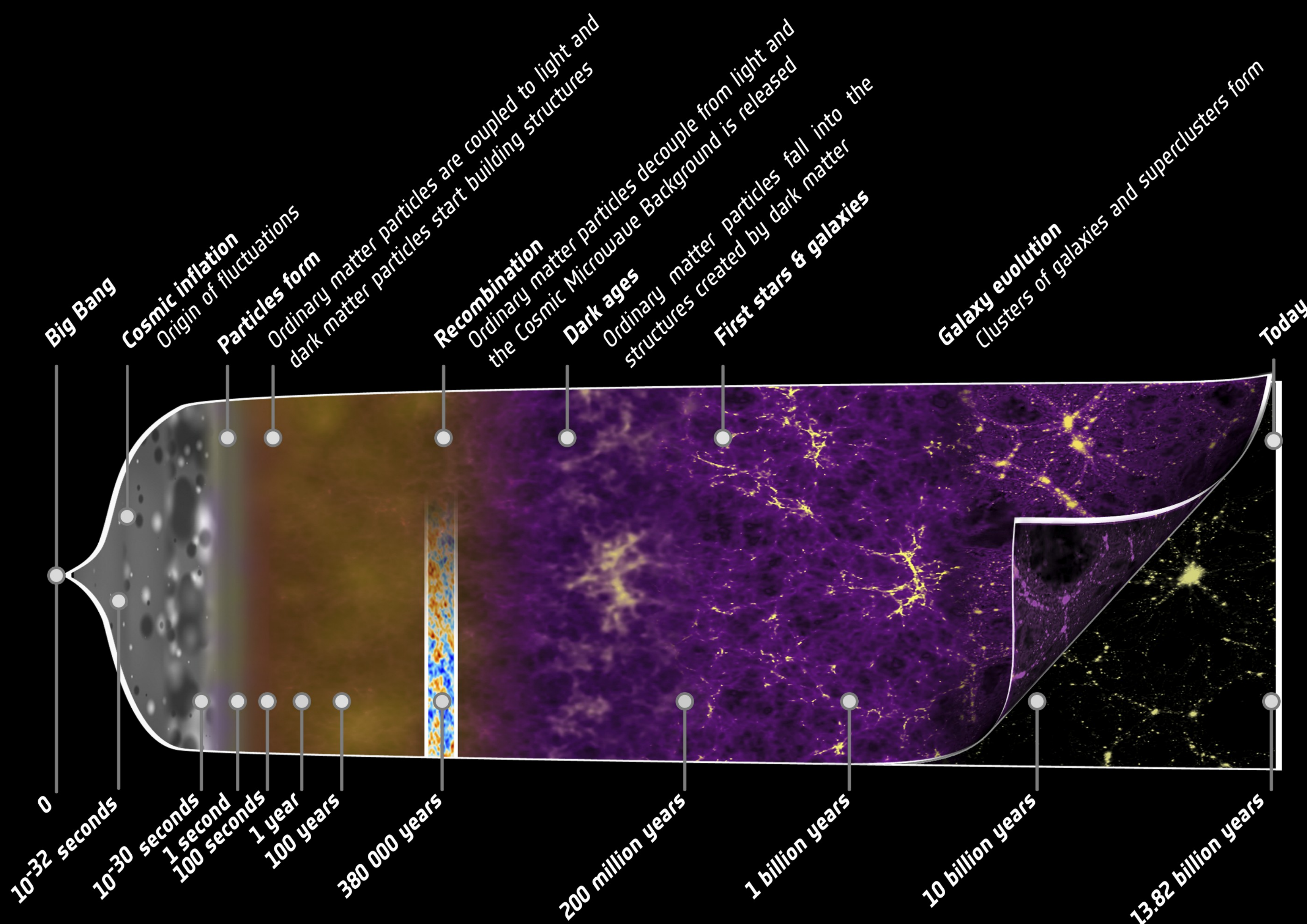
$$\frac{\delta T}{T} = \frac{1}{3}\phi_{grav}$$




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

CMB polarization on larger scales





Big Bang
Cosmic inflation
Origin of fluctuations
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0
10^{-32} seconds
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1 second
100 seconds
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380 000 years
200 million years
1 billion years
10 billion years
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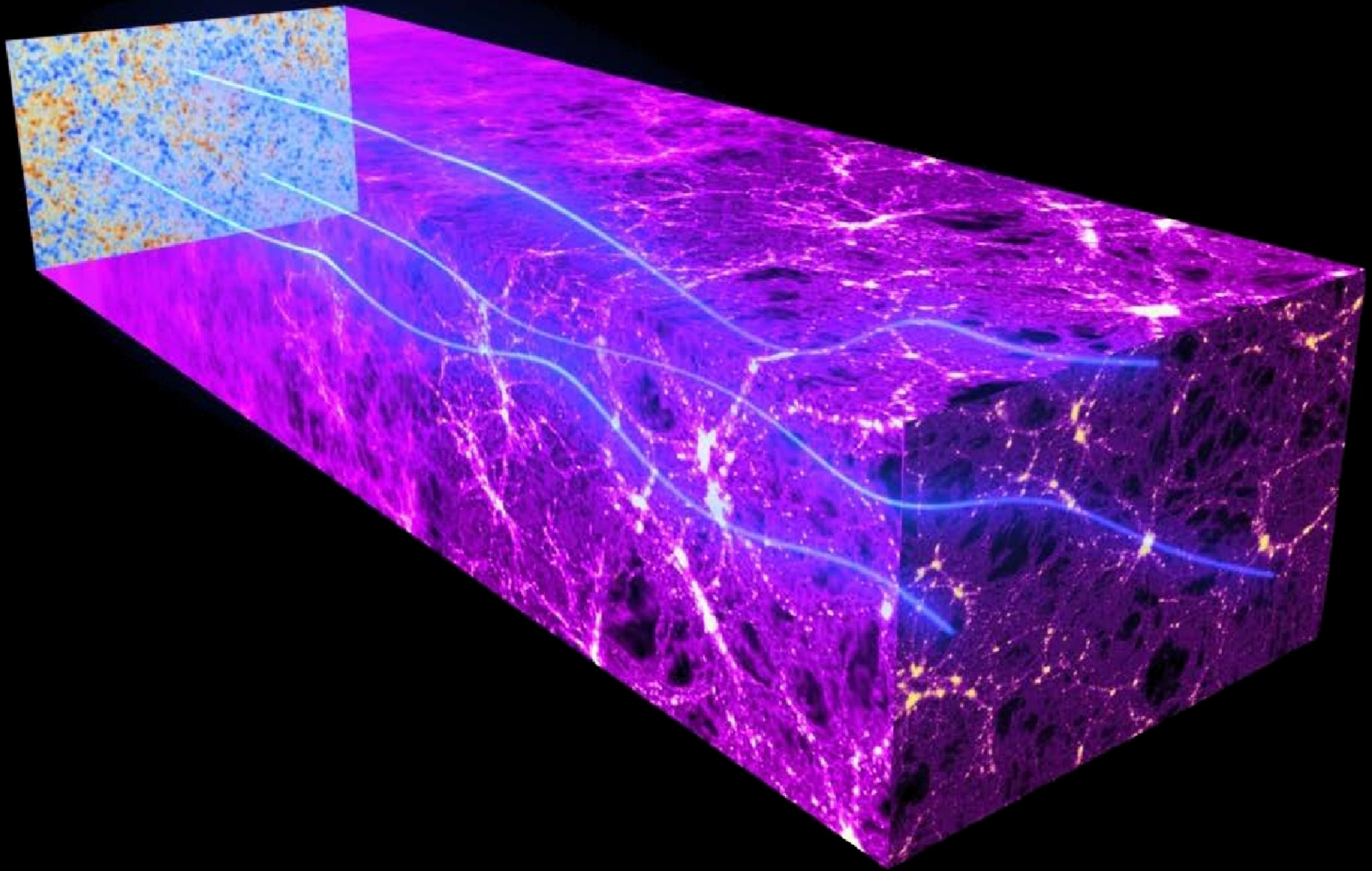
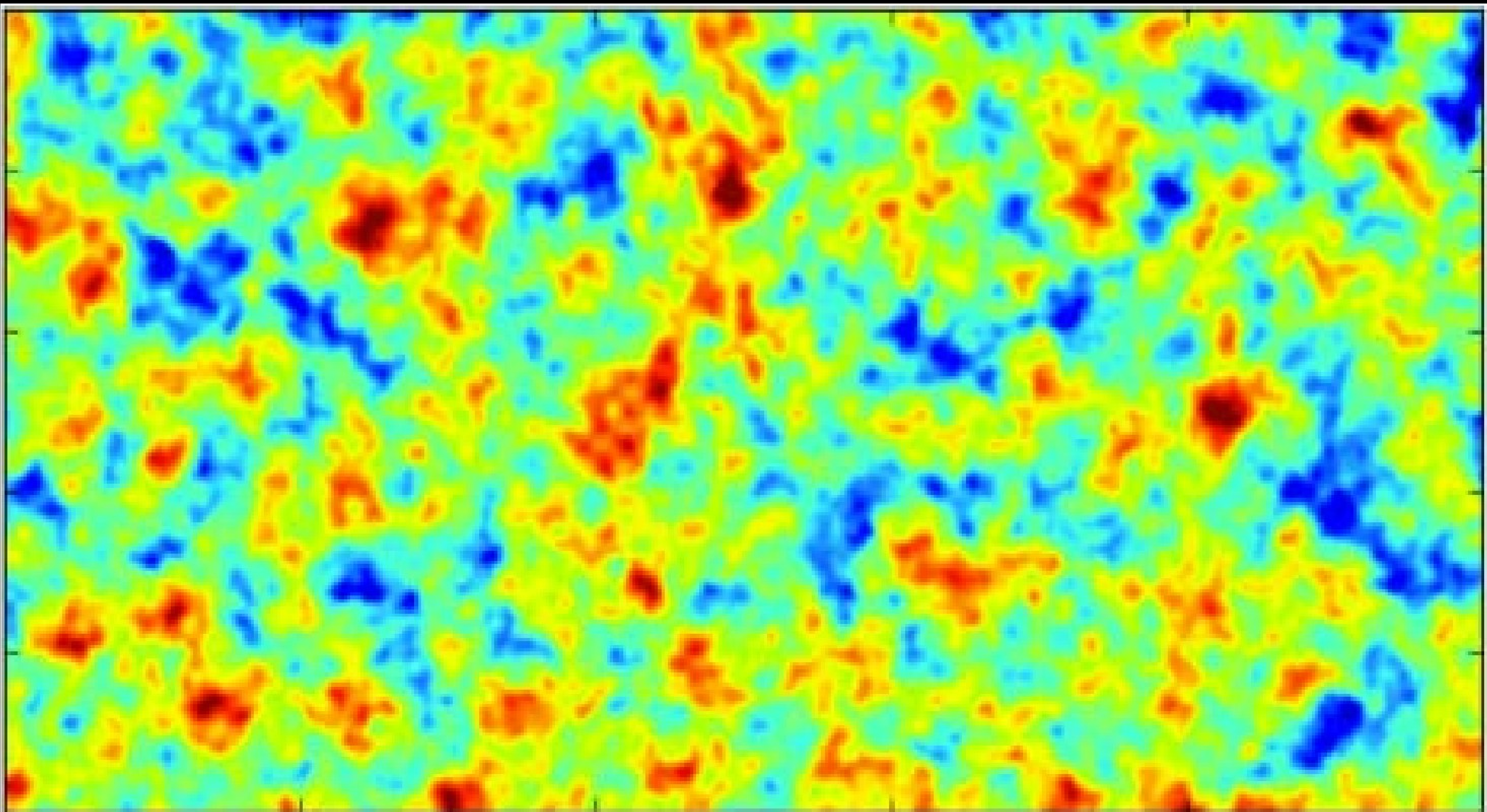
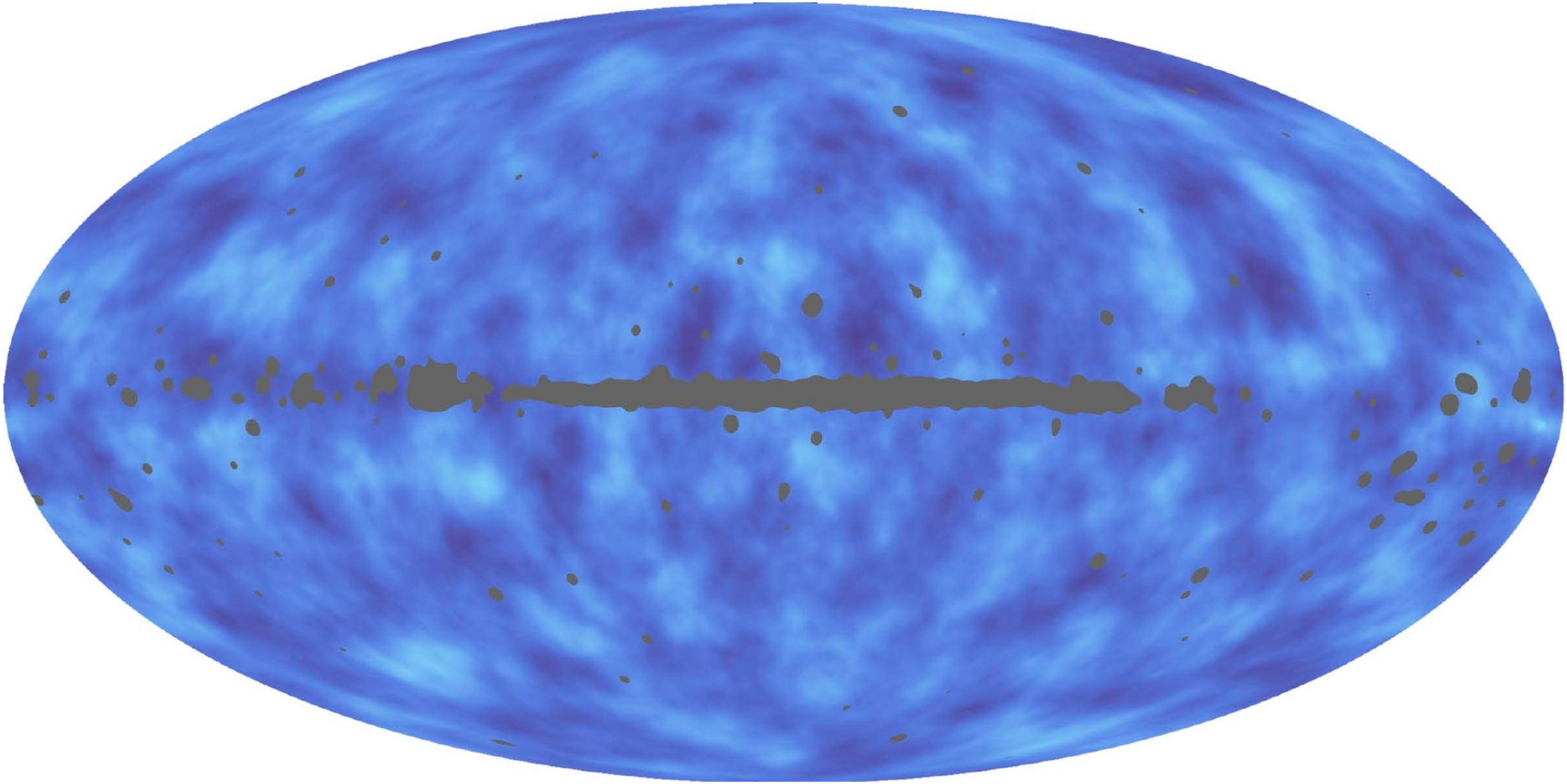
gravitational lensing



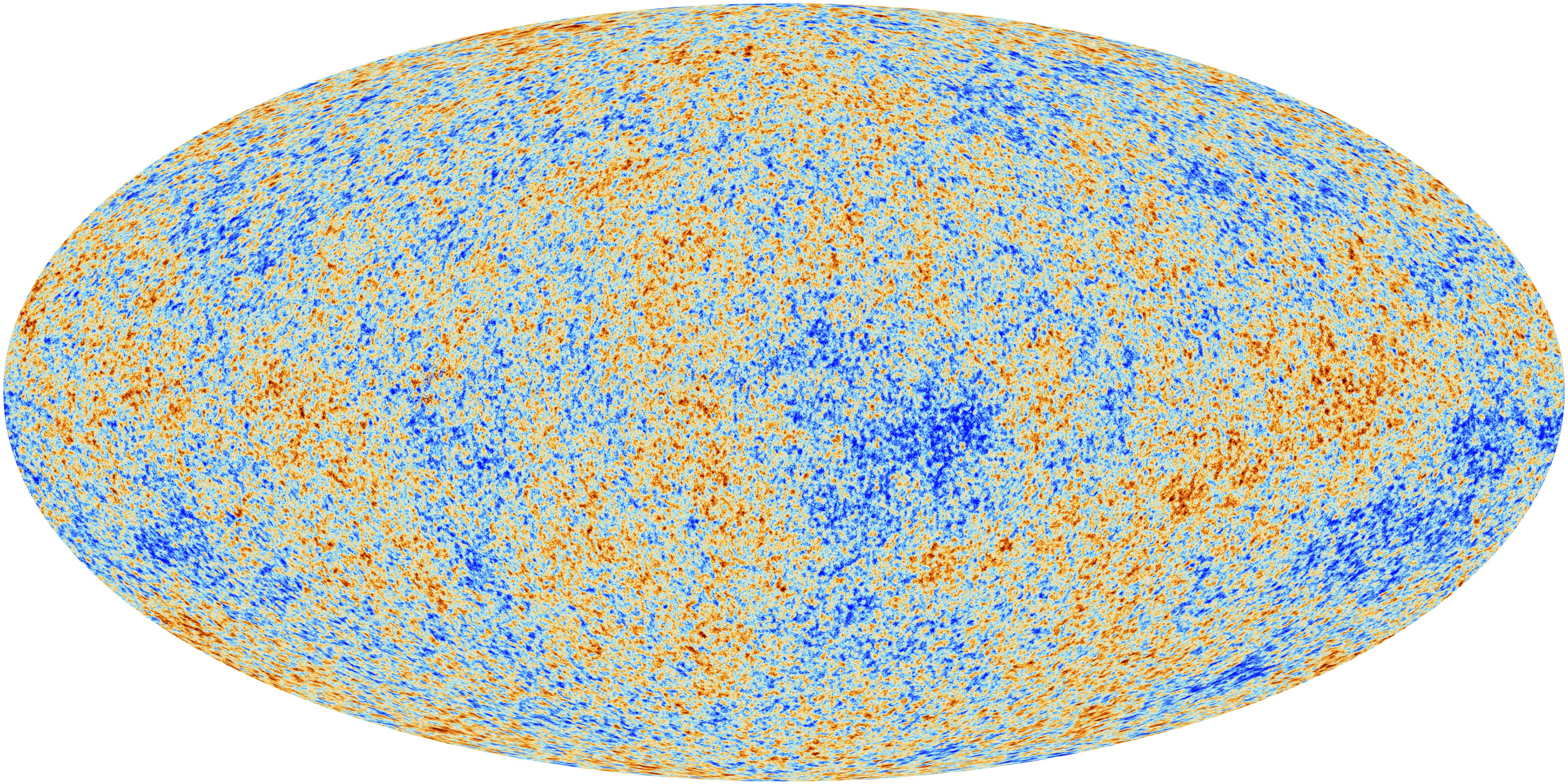
gravitational lensing



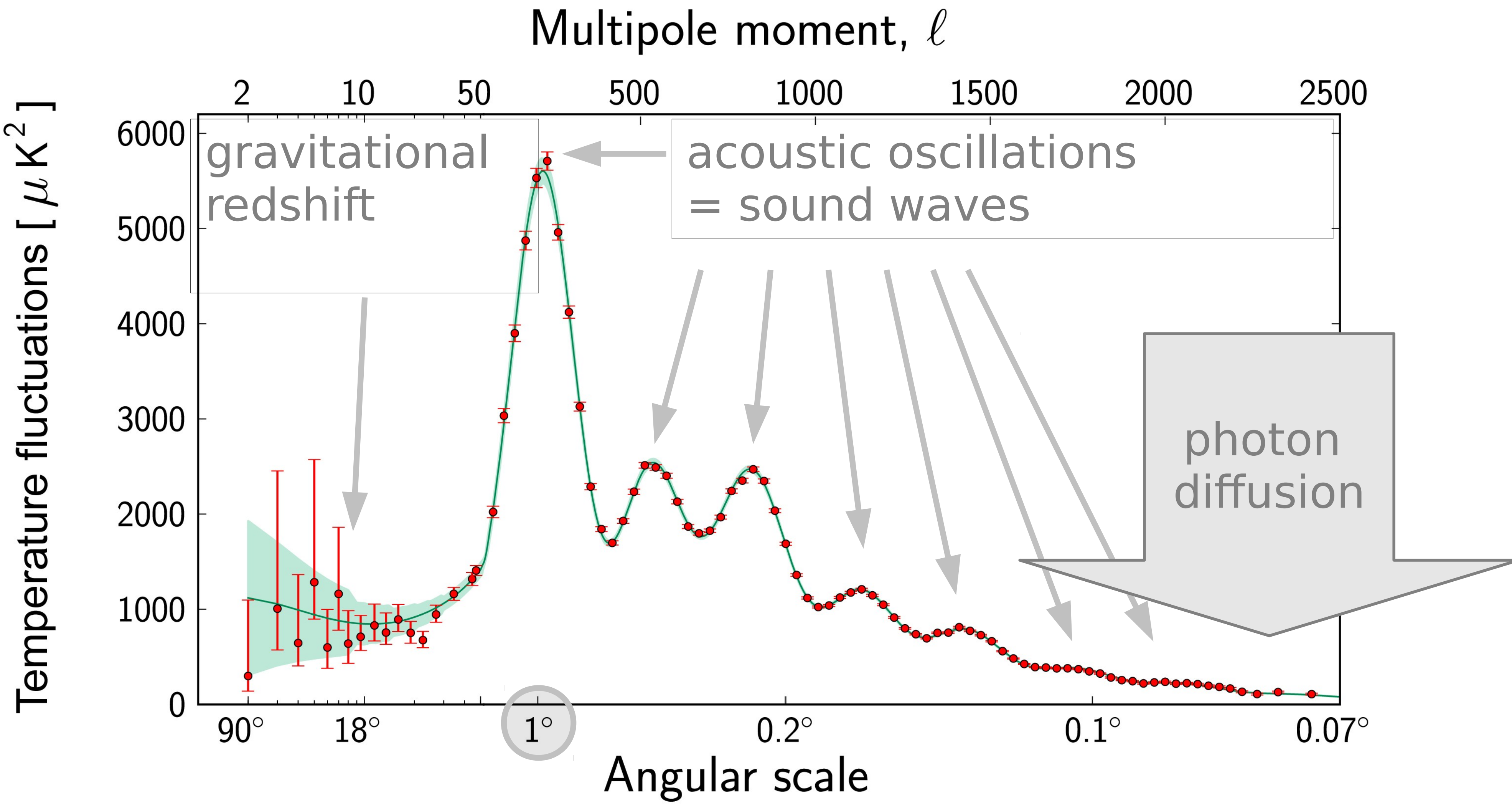
projected mass distribution

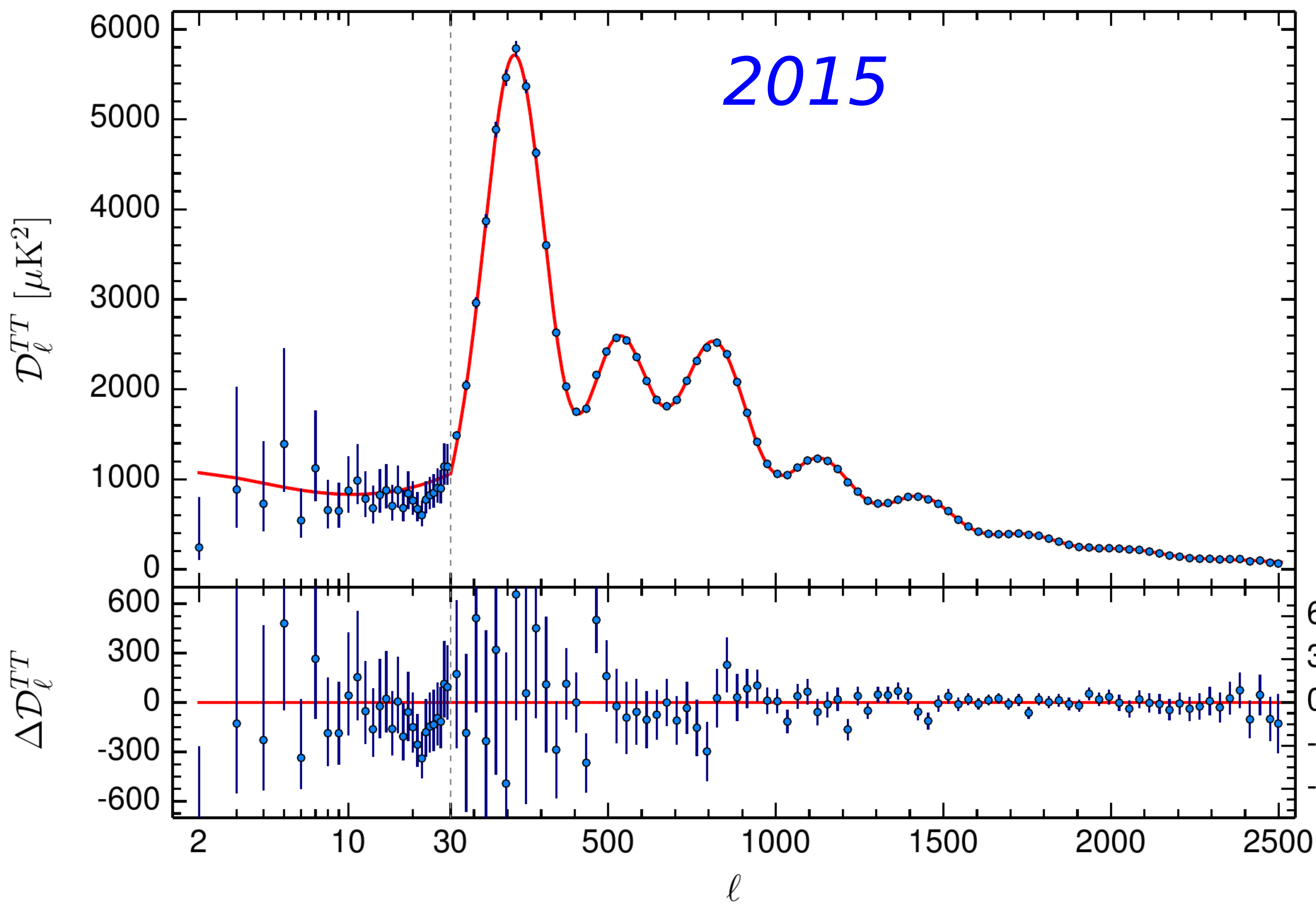


The cosmic microwave background



Angular power spectrum

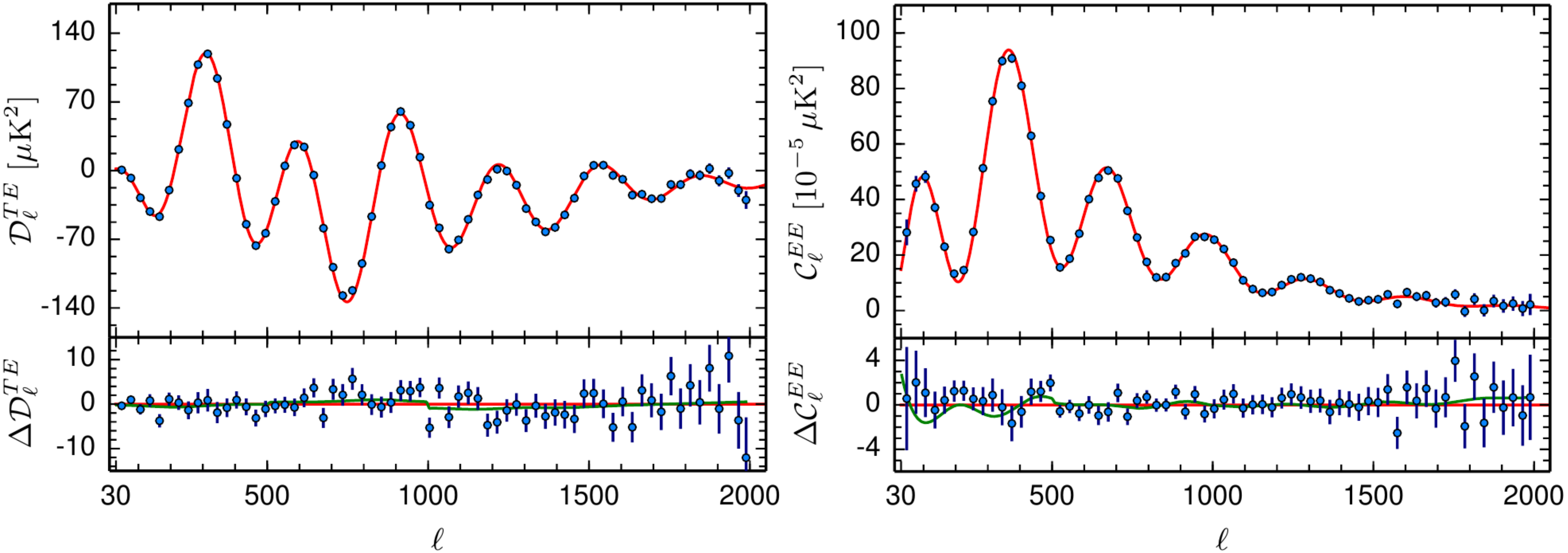




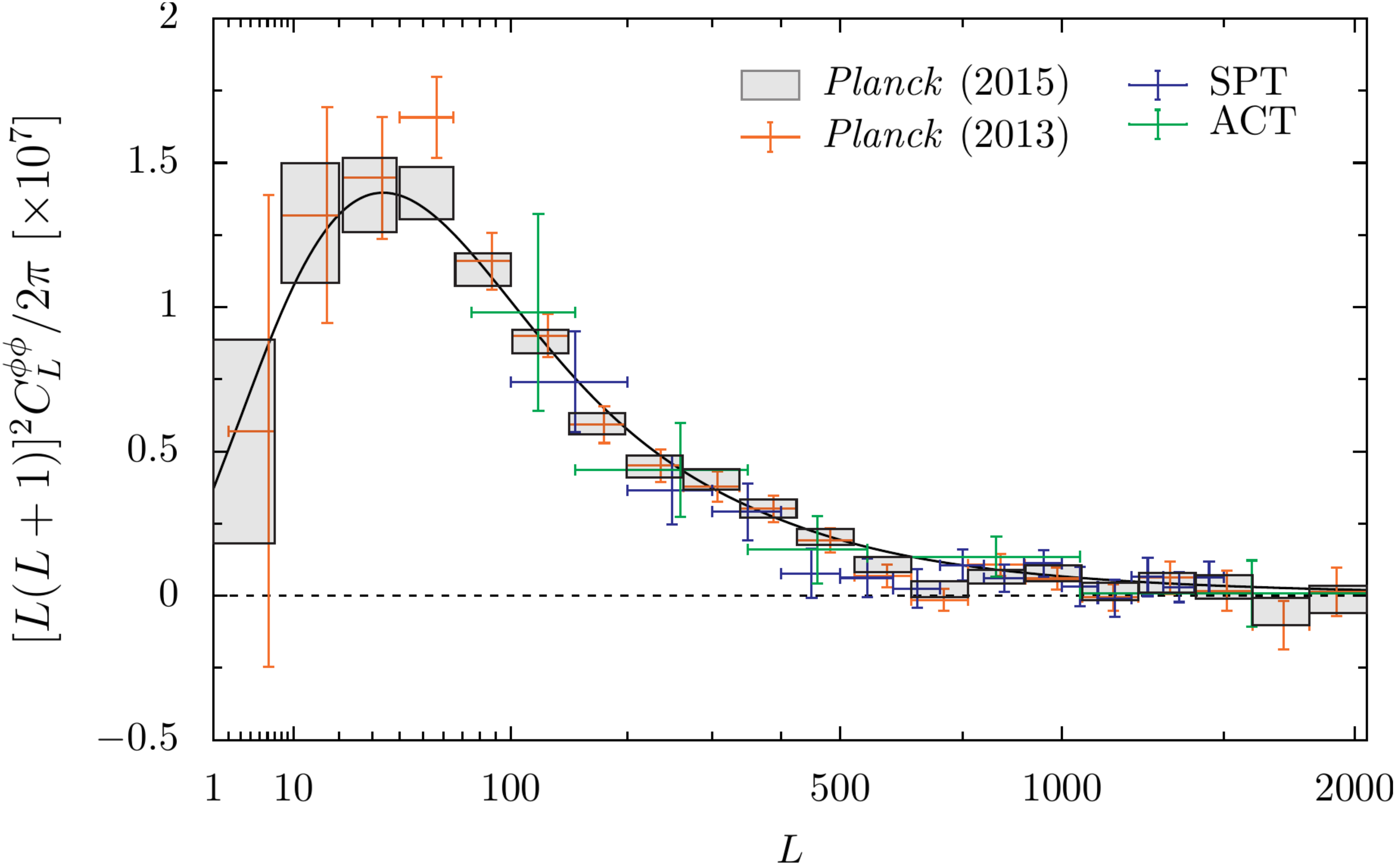
2015
$\mathcal{D}_\ell^{TT}$ [μK^2]
6000
5000
4000
3000
2000
1000
0
$\Delta\mathcal{D}_\ell^{TT}$
600
300
0
-300
-600
60
30
0
-30
-60
2
10
30
500
1000
1500
2000
2500
ℓ

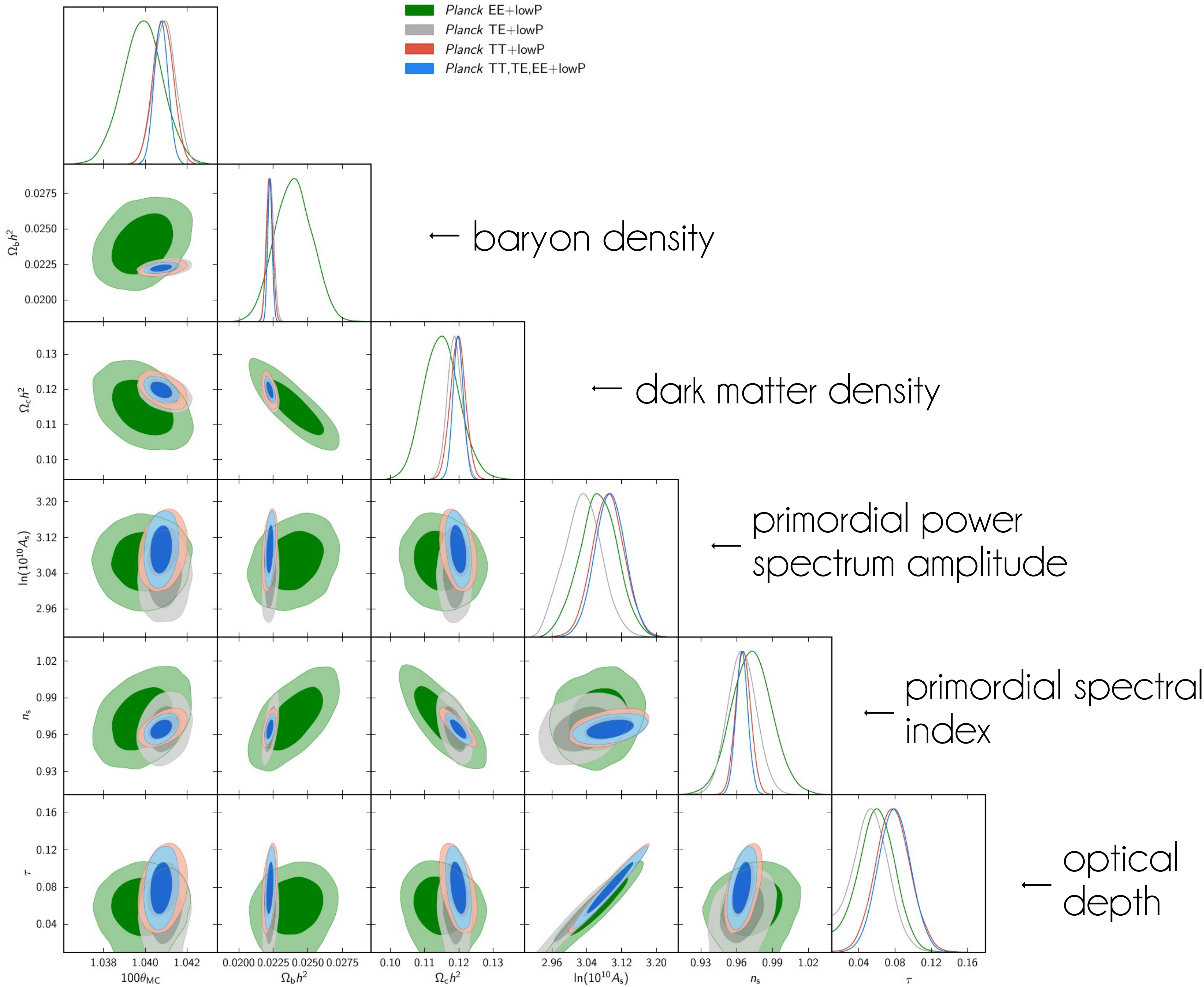
Polarization spectra

TE EE



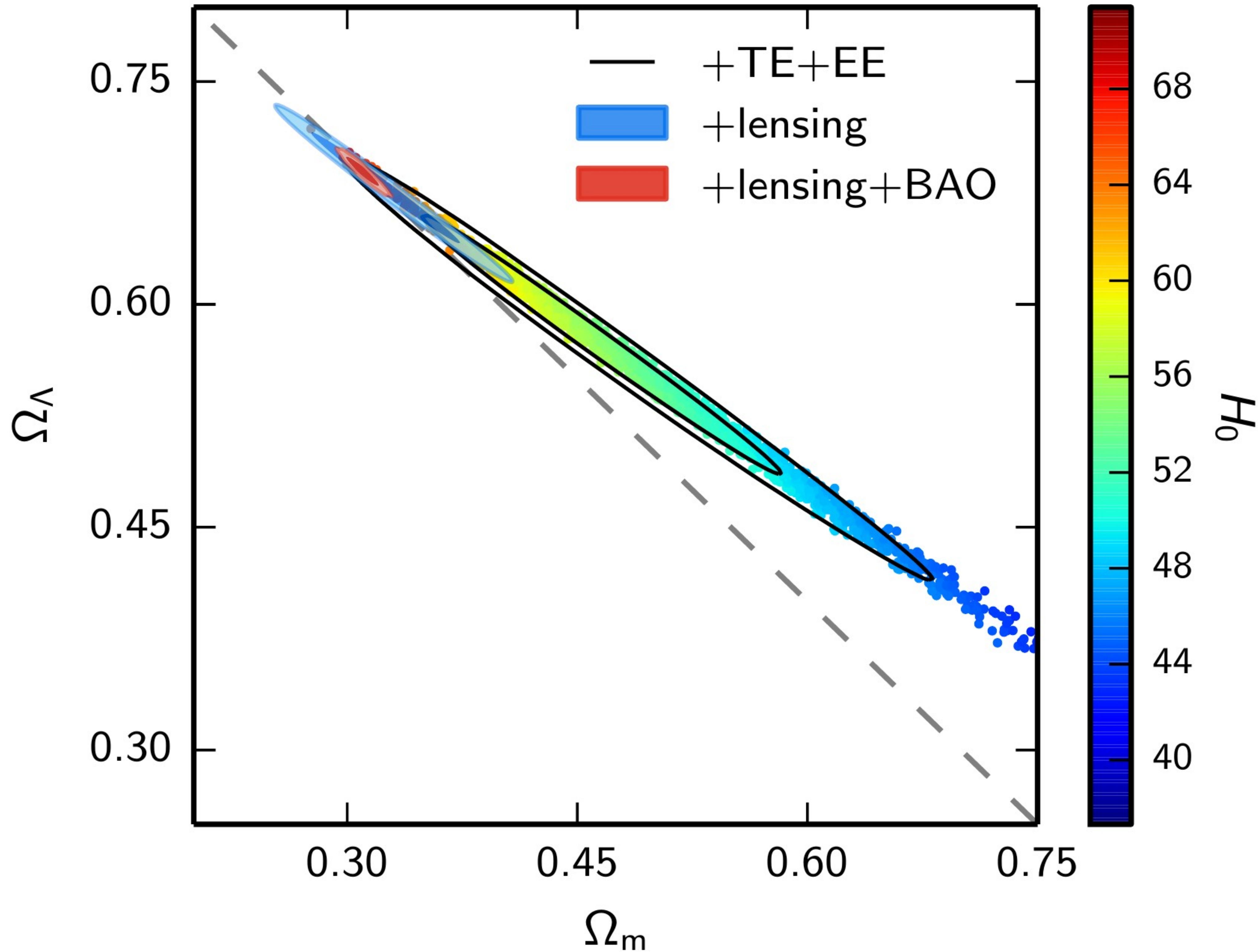
Lensing Power Spectrum





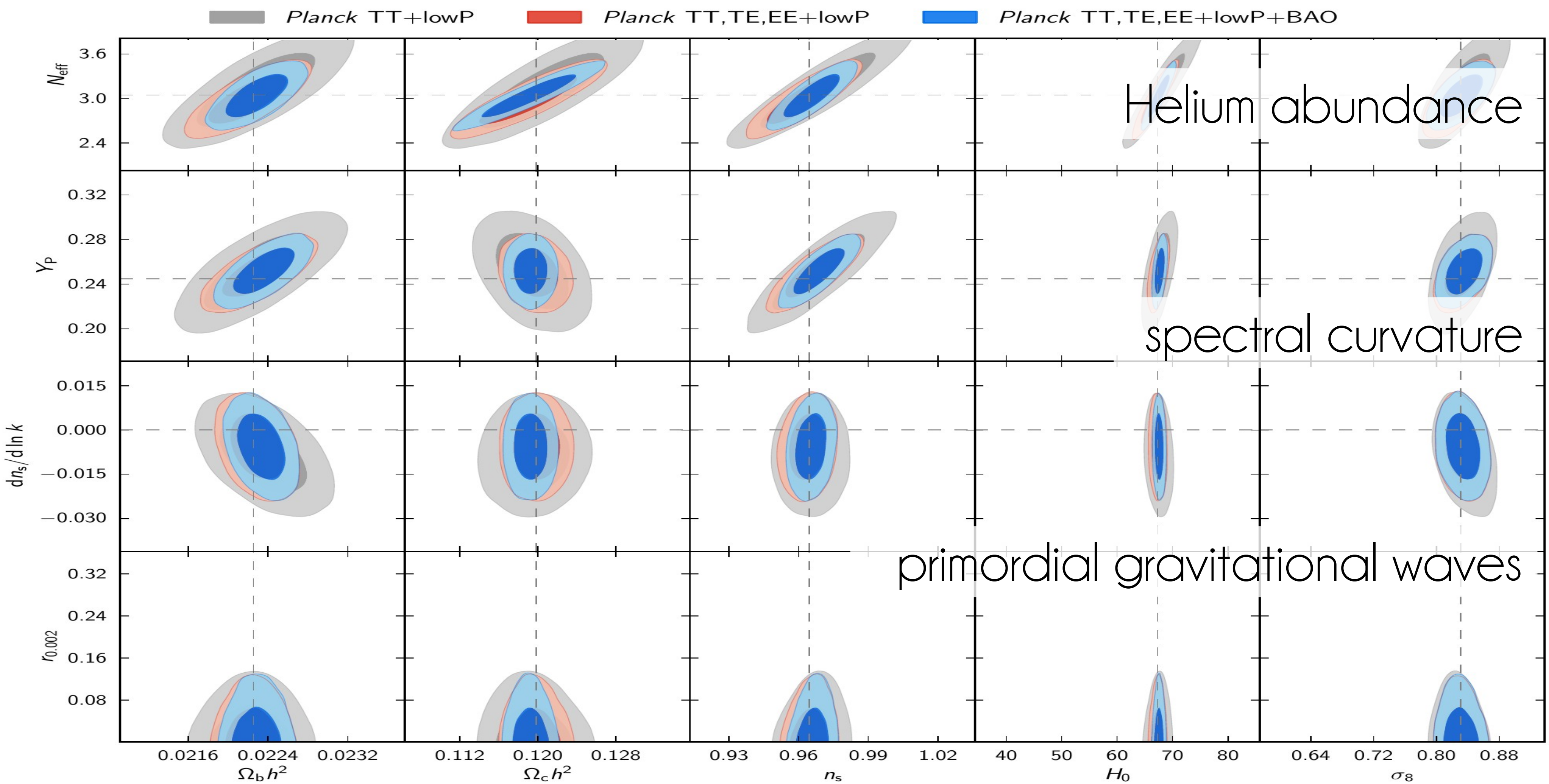
Planck EE+lowP
Planck TE+lowP
Planck TT+lowP
Planck TT,TE,EE+lowP
← baryon density
← dark matter density
← primordial power spectrum amplitude
← primordial spectral index
← optical depth
$\Omega_b h^2$
$\Omega_c h^2$
$\ln(10^{10} A_s)$
n_s
τ
$100\theta_{MC}$

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
f_{2000}^{143}	29.9 ± 2.9	30.4 ± 2.9	30.3 ± 2.8	29.5 ± 2.7	30.2 ± 2.7	30.0 ± 2.7
$f_{2000}^{143\times217}$	32.4 ± 2.1	32.8 ± 2.1	32.7 ± 2.0	32.2 ± 1.9	32.8 ± 1.9	32.6 ± 1.9
f_{2000}^{217}	106.0 ± 2.0	106.3 ± 2.0	106.2 ± 2.0	105.8 ± 1.9	106.2 ± 1.9	106.1 ± 1.8

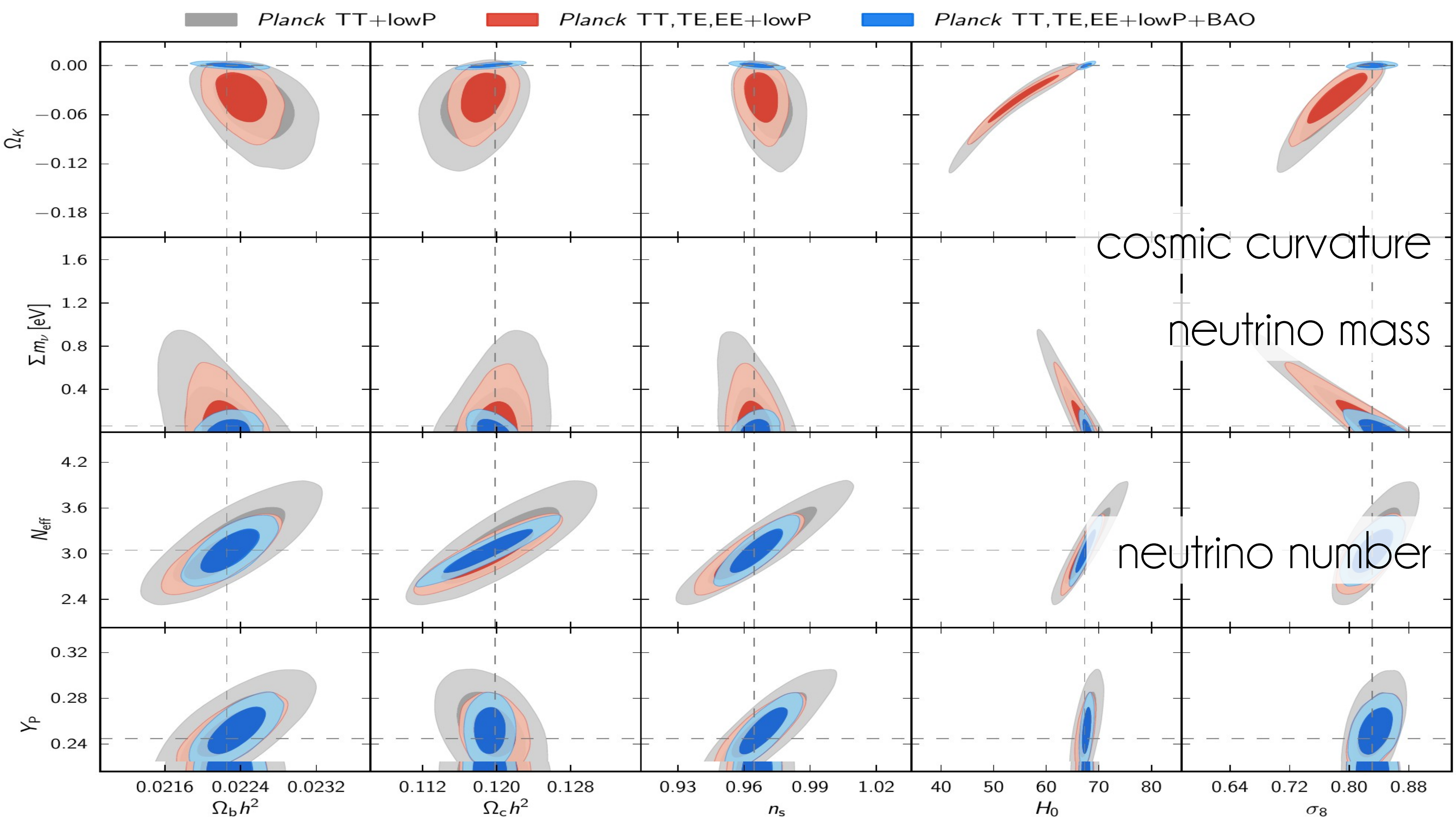


+TE+EE
+lensing
+lensing+BAO
0.75
0.60
0.45
0.30
0.30
0.45
0.60
0.75
Ω_Λ
Ω_m
68
64
60
56
52
48
44
40
H_0

Parameter Space Extensions



Parameter Space Extensions



DM annihilation

- DM might annihilate into any SM particle
- These loos energy mainly via collisions with CMB photons and cosmic electrons

→ heat input & re-ionization (after recombination)

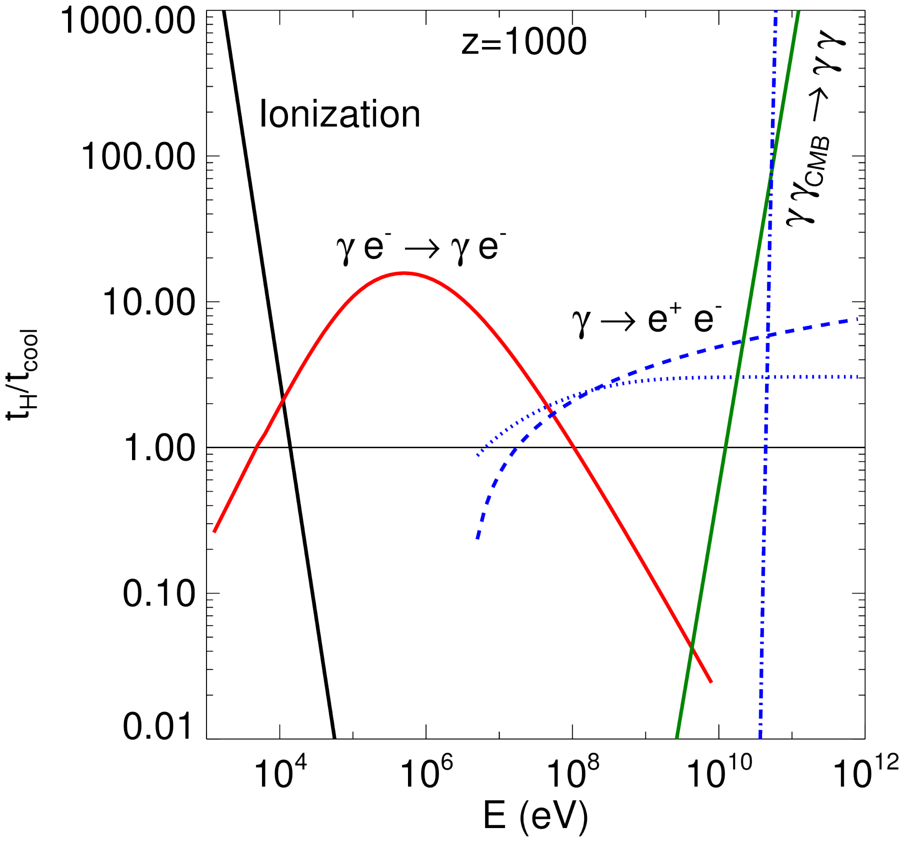
Main parameter is re-ionization efficiency

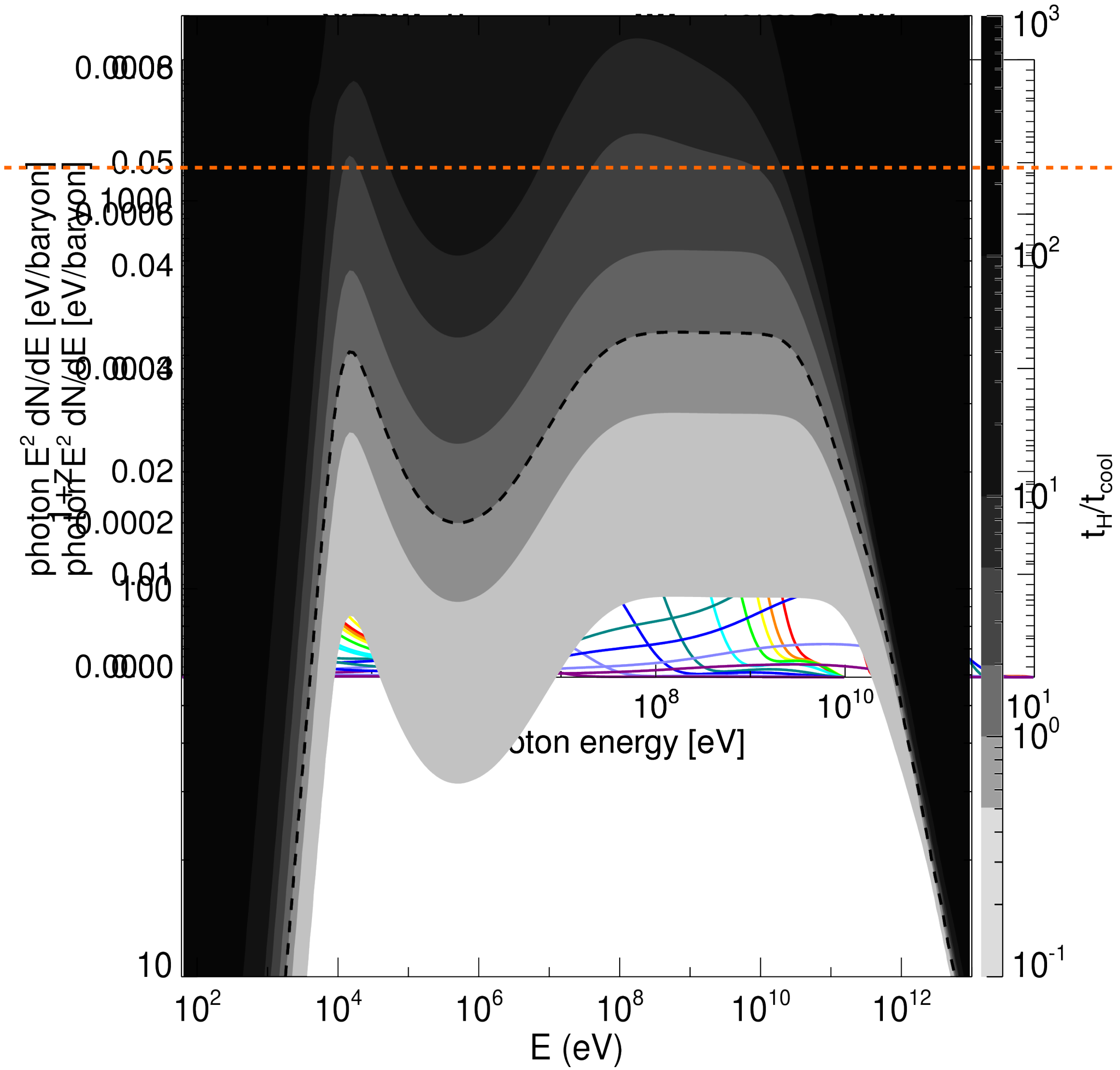
$$\frac{dE}{dtdV}(z) = 2\,g\,\rho^2_{\mathrm{crit}}c^2\Omega^2_{\mathrm{c}}(1+z)^6 p_{\mathrm{ann}}(z)$$

$$p_{\mathrm{ann}}(z) \equiv f(z)\frac{\langle\sigma v\rangle}{m_\chi}$$

Photon cooling

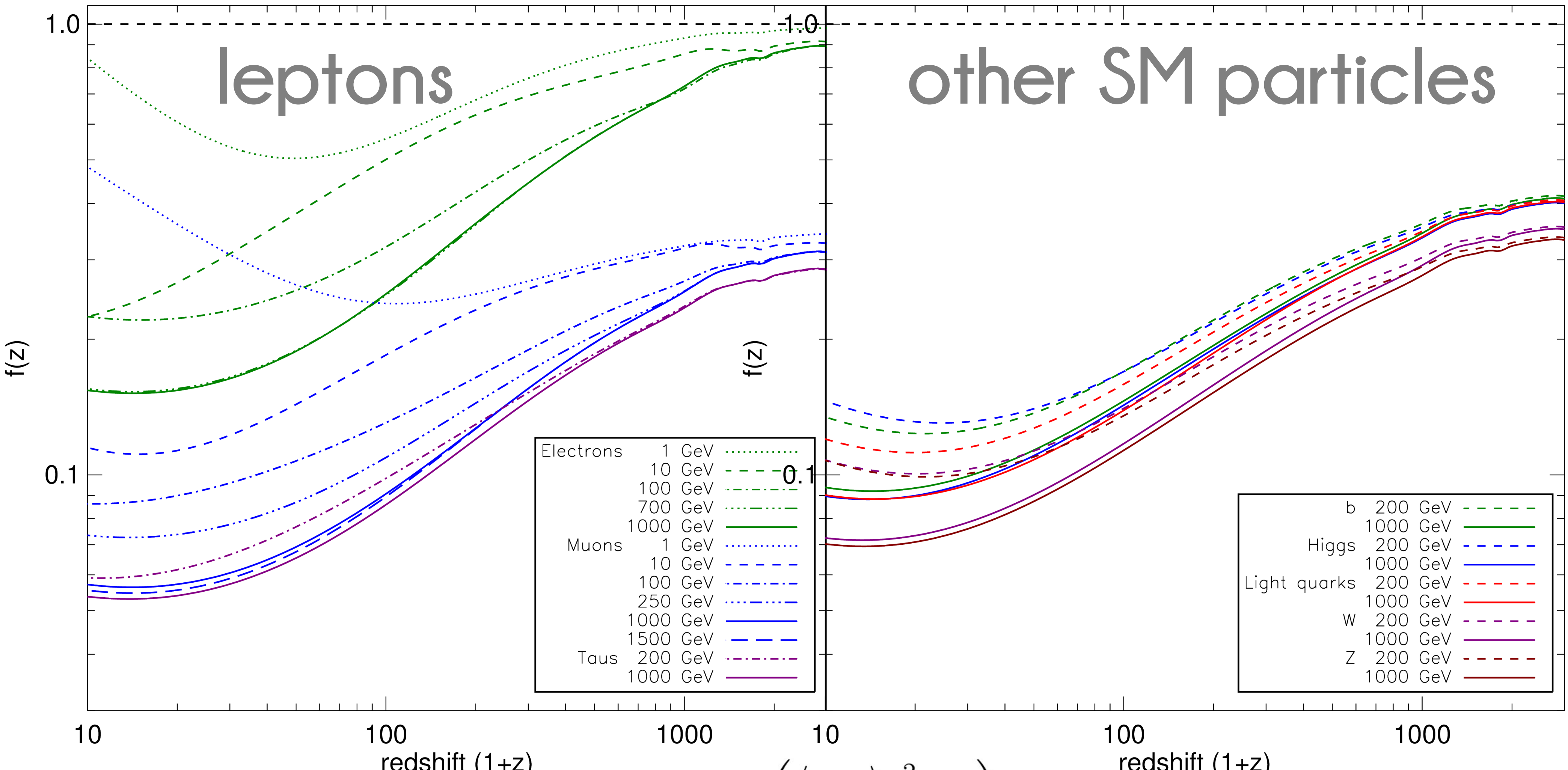
Slatyer, Padmanabhan, Finkbeiner (arXiv:0906.11972)





Energy deposition fractions

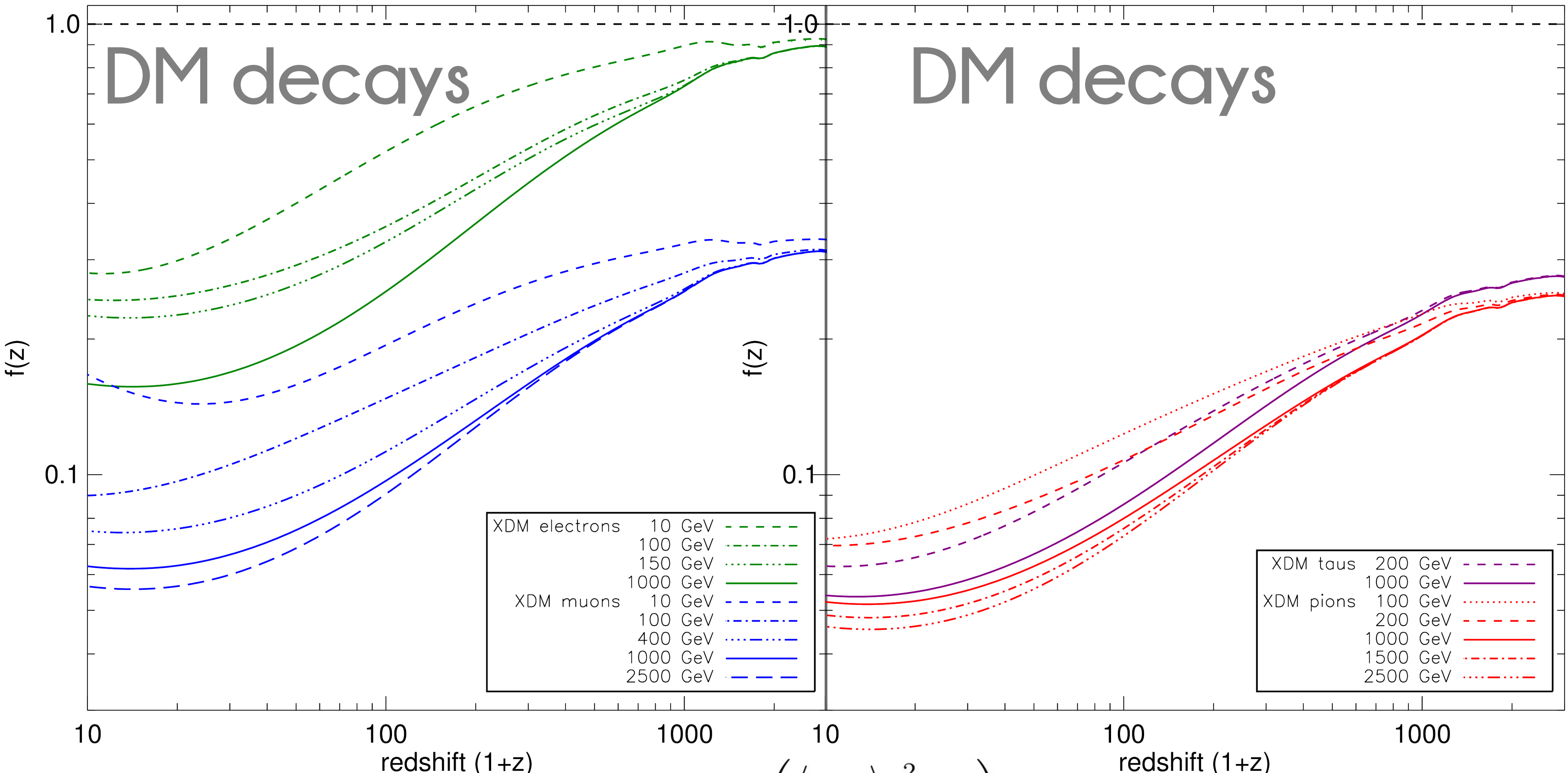
Slatyer, Padmanabhan, Finkbeiner (arXiv:0906.11972)



$$\epsilon_{DM} = 2 f M_{\mathrm{DM}} \left(\frac{\langle \sigma_A v \rangle n_{\mathrm{DM},0}^2}{n_{\mathrm{H},0}} \right) (1+z)^3$$

Energy deposition fractions

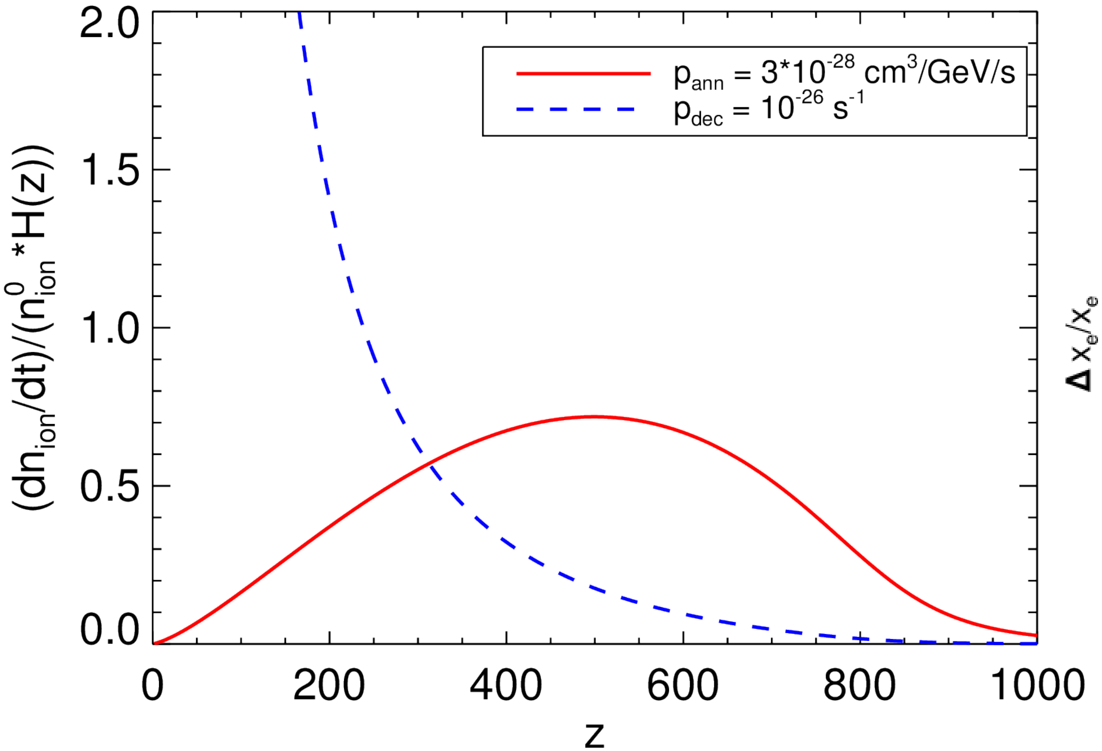
Slatyer, Padmanabhan, Finkbeiner (arXiv:0906.11972)

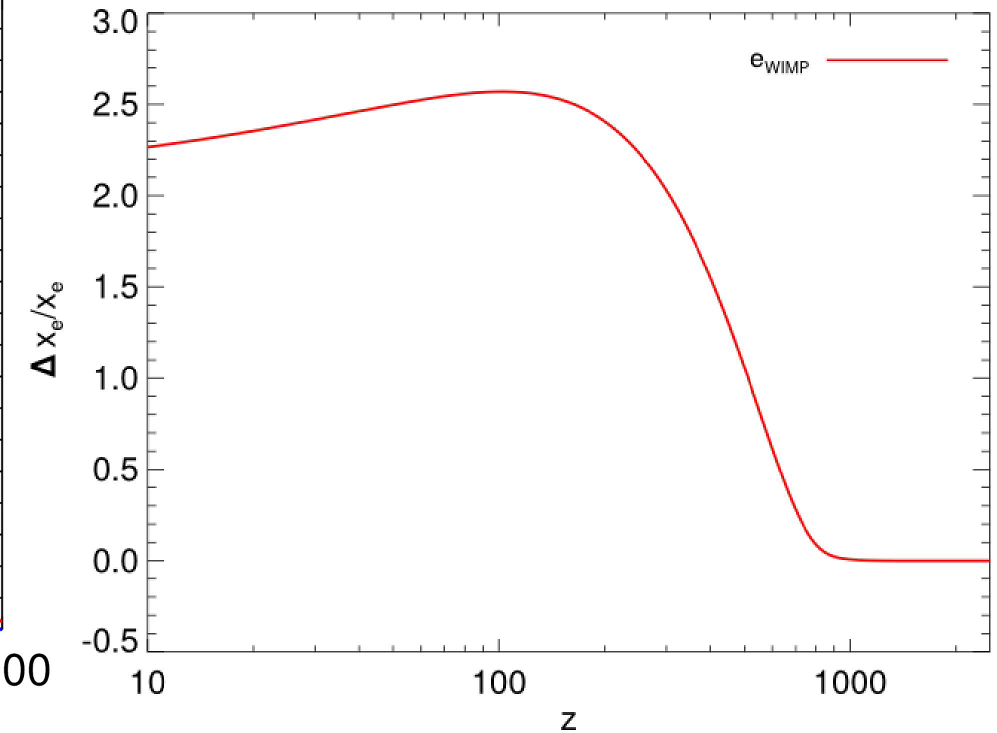


$$\epsilon_{DM} = 2 f M_{\rm DM} \left(\frac{\langle \sigma_A v \rangle n_{\rm DM,0}^2}{n_{\rm H,0}} \right) (1+z)^3$$

Changed ionization history

Finkbeiner, Galli, Lin, Slatyer (arXiv:1109.6322)





$$p_{\mathrm{ann}}(z) \equiv f(z)\frac{\langle \sigma v\rangle}{m_\chi}$$

Angular-spectral distortions

Slatyer, Padmanabhan, Finkbeiner (arXiv:0906.11972)

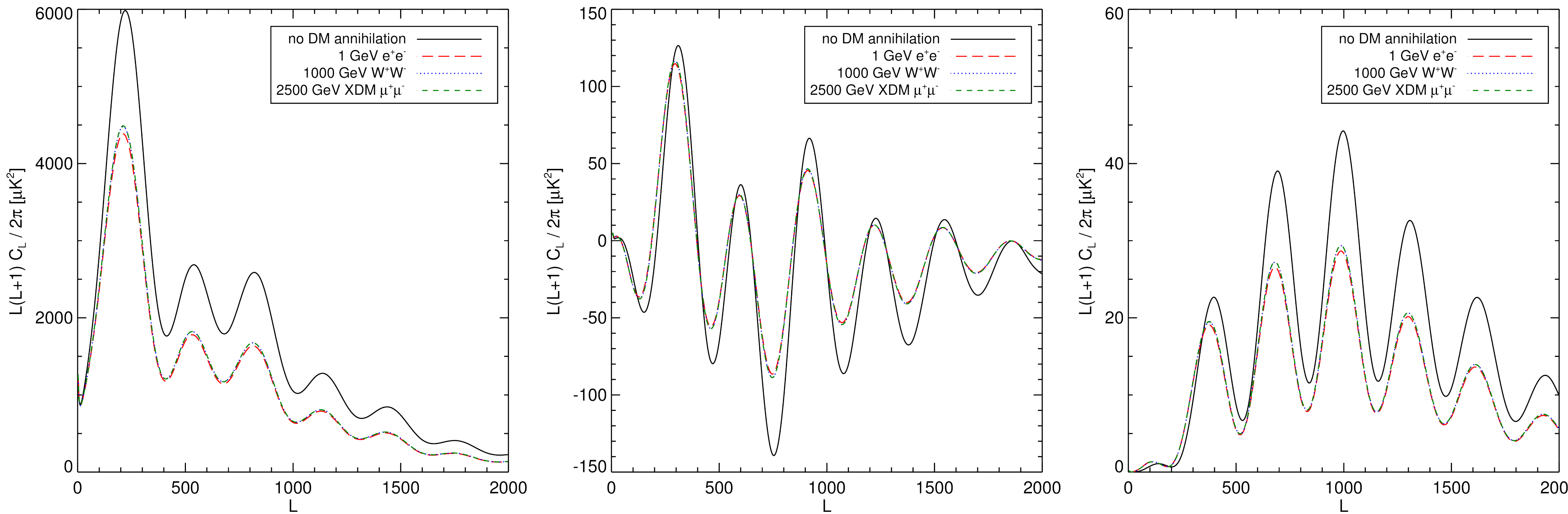
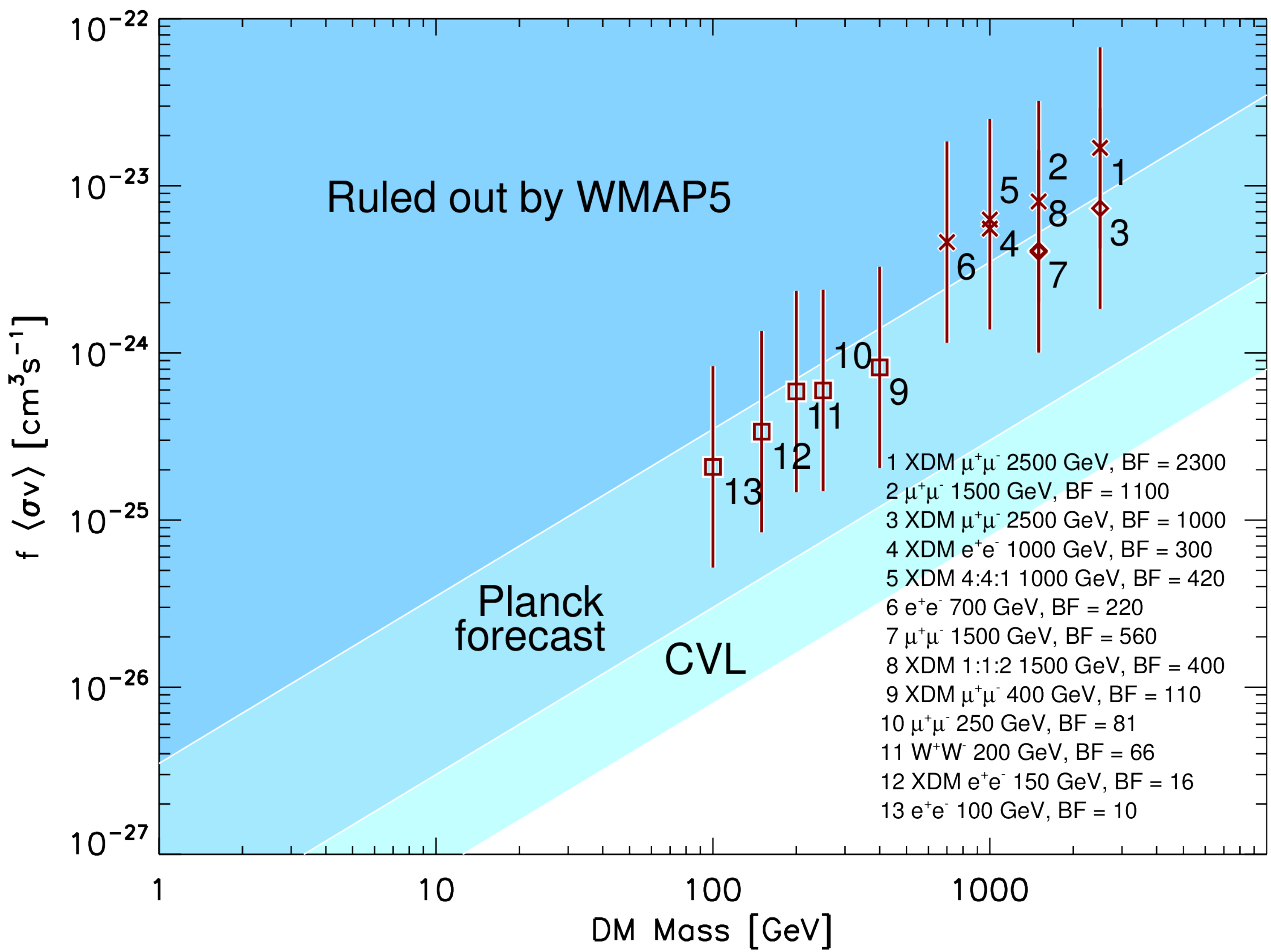


FIG. 5: CMB power spectra for three different DM annihilation models, with power injection normalized to that of a 1 GeV WIMP with thermal relic cross section and $f = 1$, compared to a baseline model with no DM annihilation. The models give similar results for the TT (*left*), TE (*middle*), and EE (*right*) power spectra. This suggests that the CMB is sensitive to only one parameter, the average power injected around recombination. All curves employ the WMAP5 fiducial cosmology: the effects of DM annihilation can be compensated to a large degree by adjusting n_s and σ_8 [**?**].

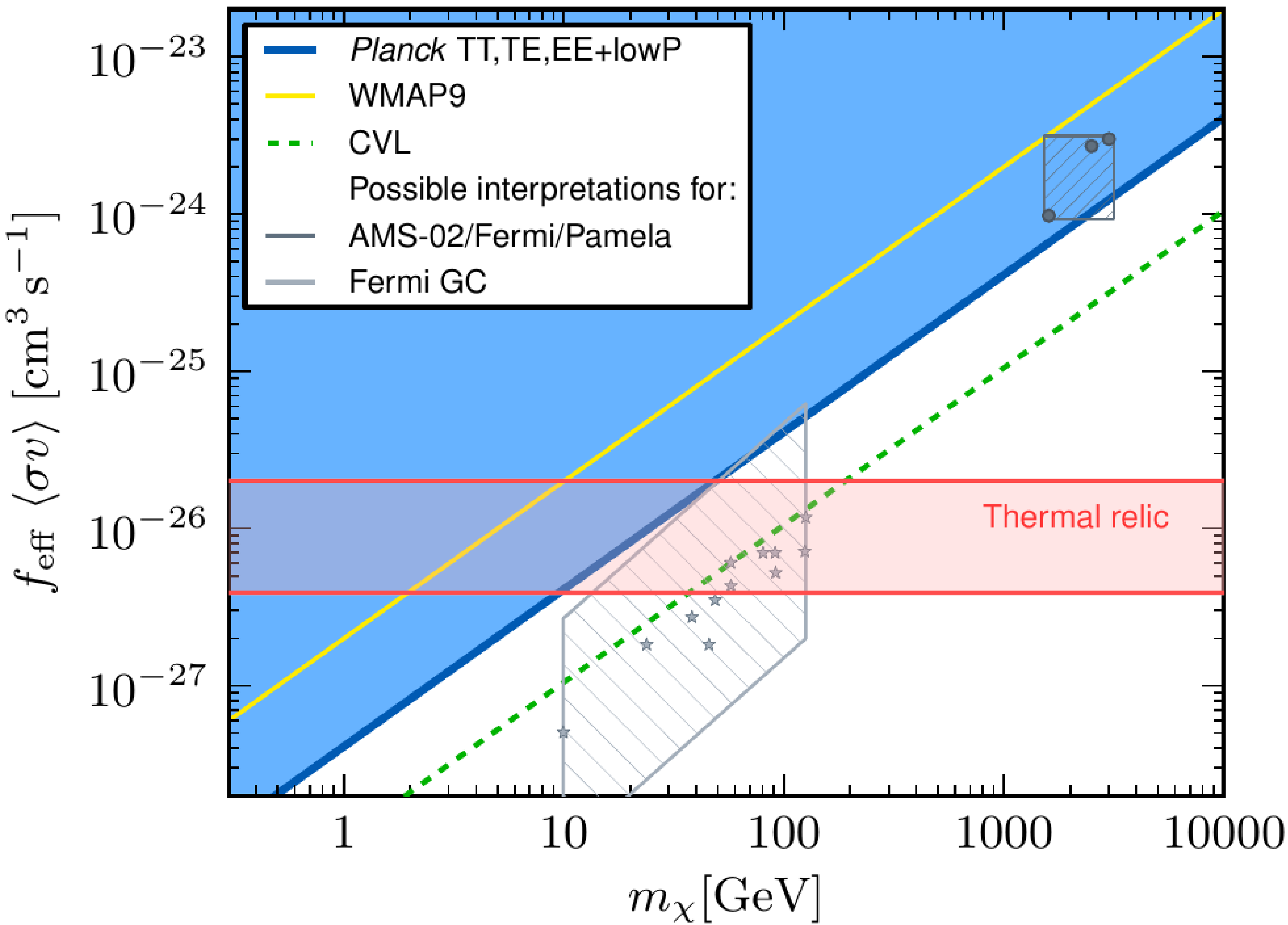
WMAP contraints

Slatyer, Padmanabhan, Finkbeiner (arXiv:0906.11972)



Planck DM constraints

Planck Collaboration (arXiv:1502.01589)



Planck DM constraints

Planck Collaboration (arXiv:1502.01589)

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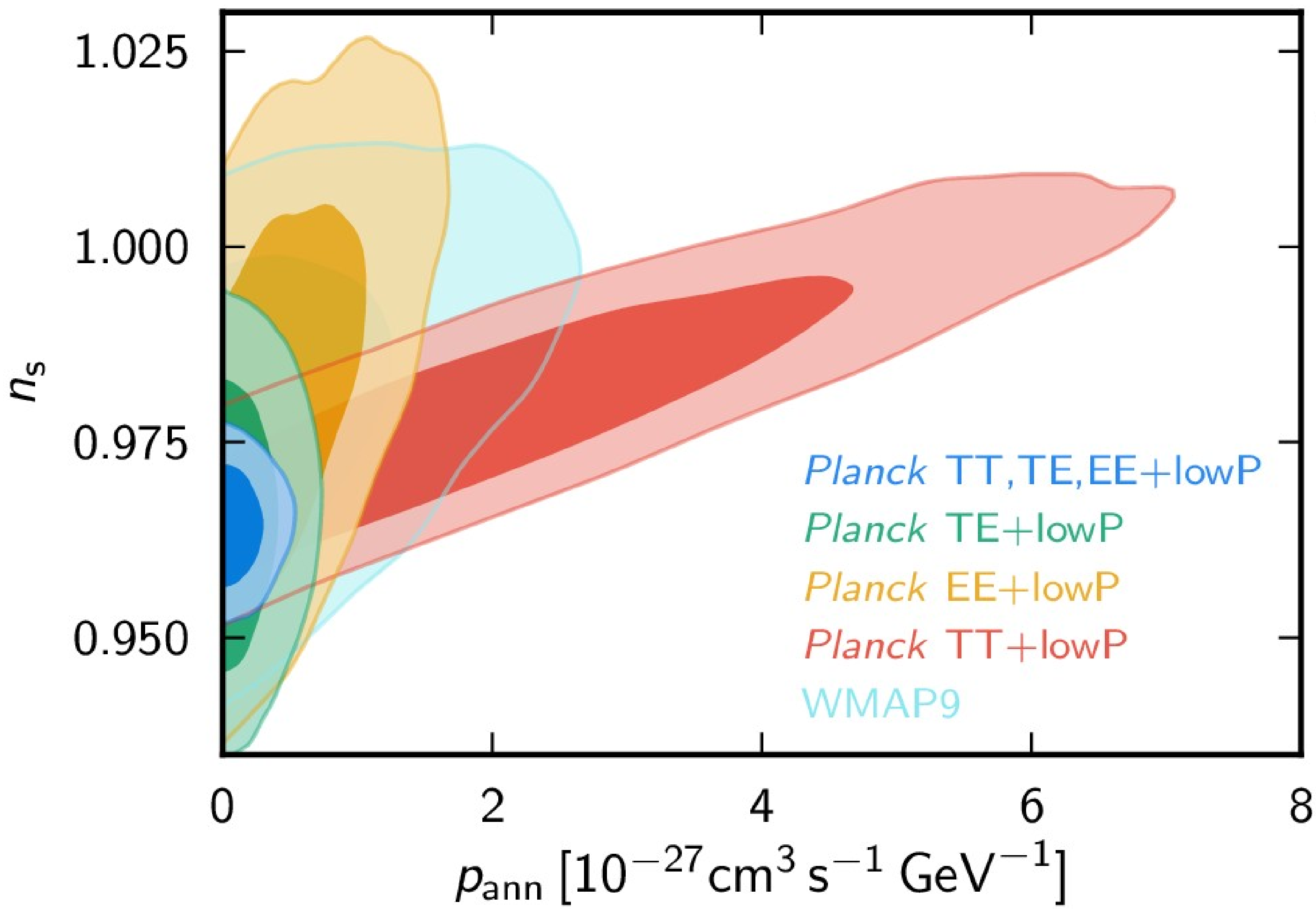
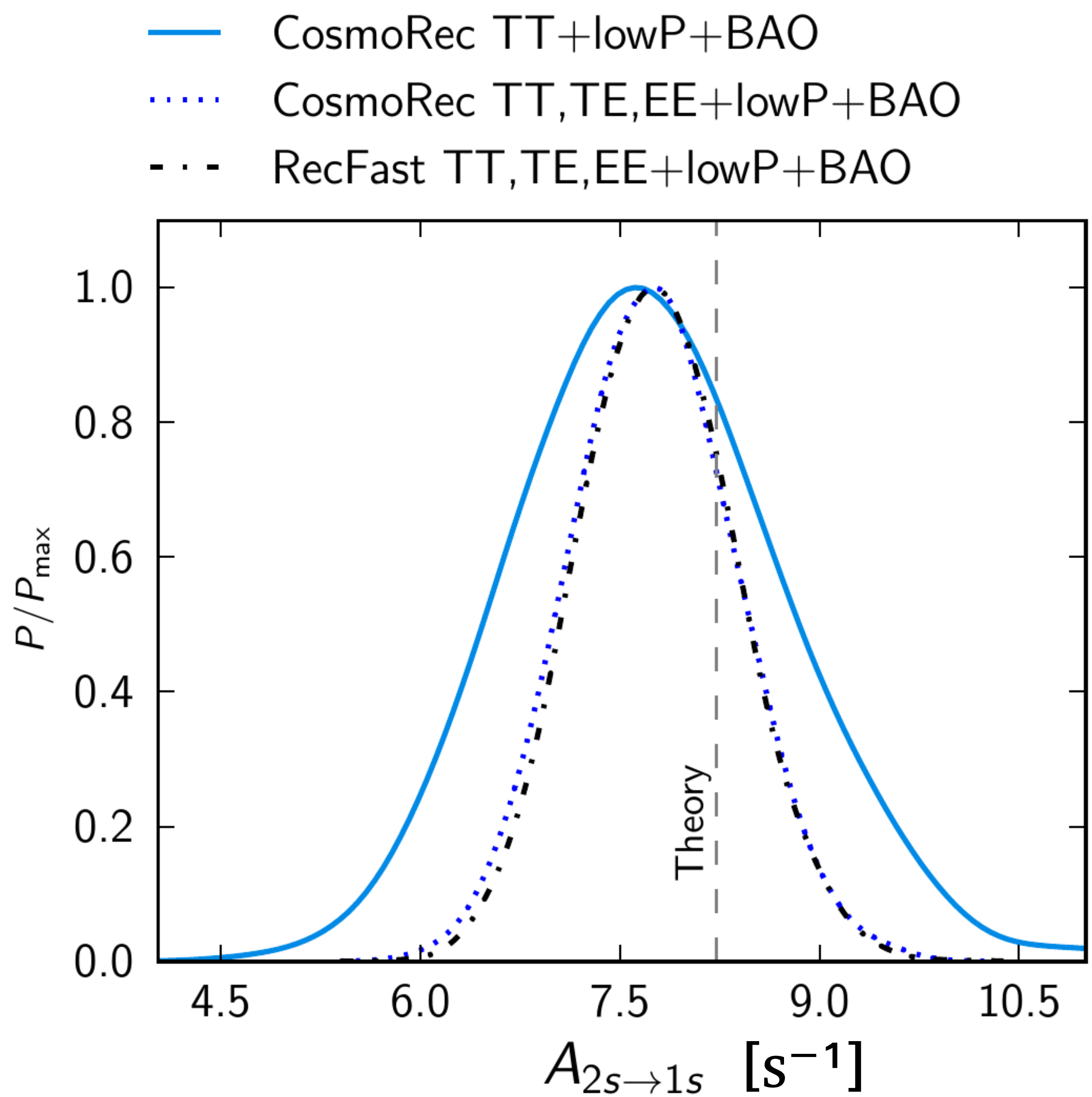
$$p_{\rm ann}(z) \equiv f(z)\frac{\langle\sigma v\rangle}{m_\chi}$$



Hydrogen $2s \rightarrow 1s$ transition rate



Constraints on neutrino masses

Assuming normal mass hierarchy
Planck base model assumes $\sum m_\nu \approx 0.06$ eV

Larger neutrino mass permits for a smaller σ_8
→ reducing tension with
cluster abundance (X-ray, SZ by Planck)
& CMB lensing (Planck)

Neutrino mass affects
- background expansion (absorb-able by H_0)
- early ISW effect (by getting non-rel.)
- late time lensing (by diminishing small-scale power)

Constraints on neutrino masses

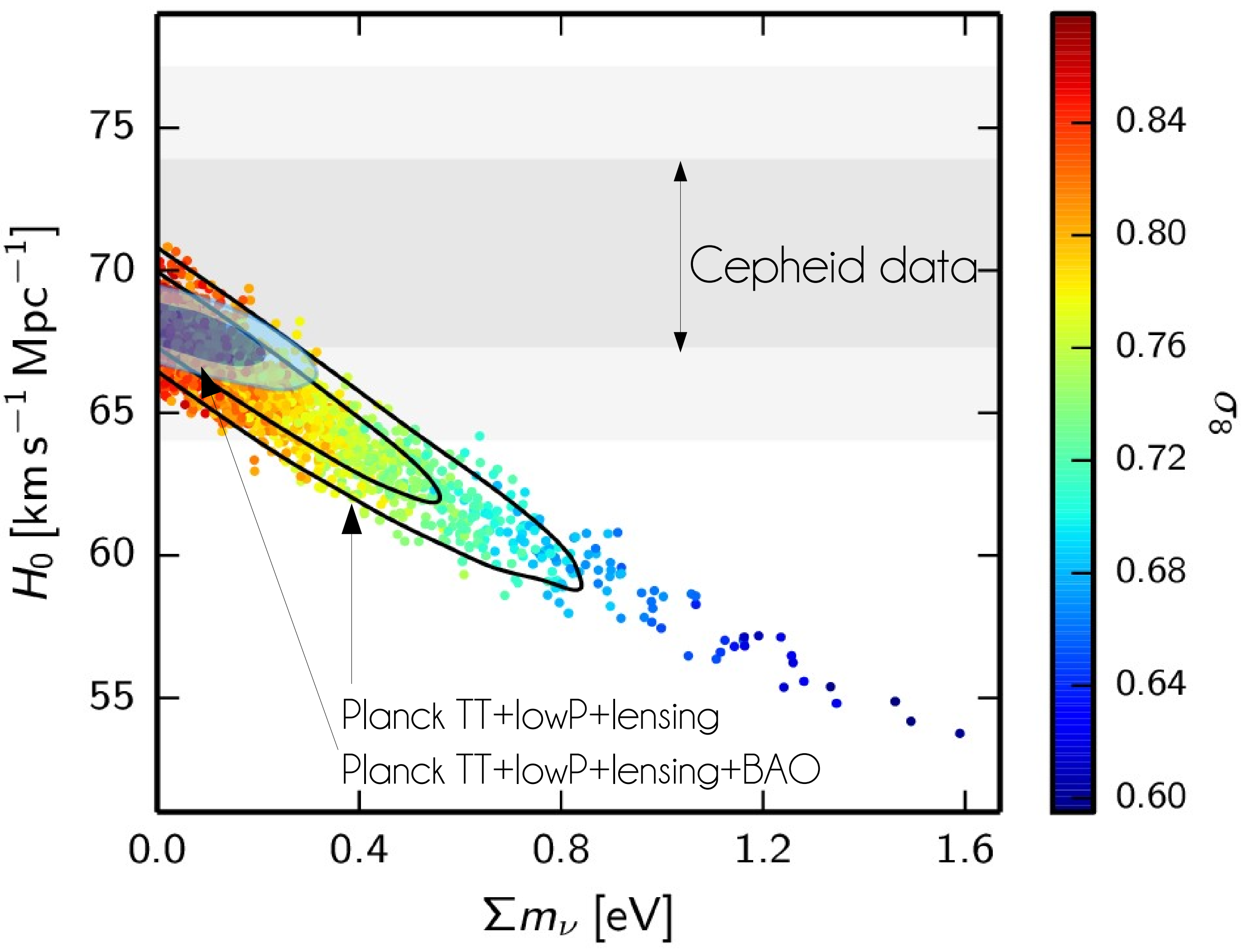
$$\sum m_\nu < 0.72 \text{ eV} \quad \textit{Planck} \text{ TT+lowP} ;$$

$$\sum m_\nu < 0.21 \text{ eV} \quad \textit{Planck} \text{ TT+lowP+BAO} ;$$

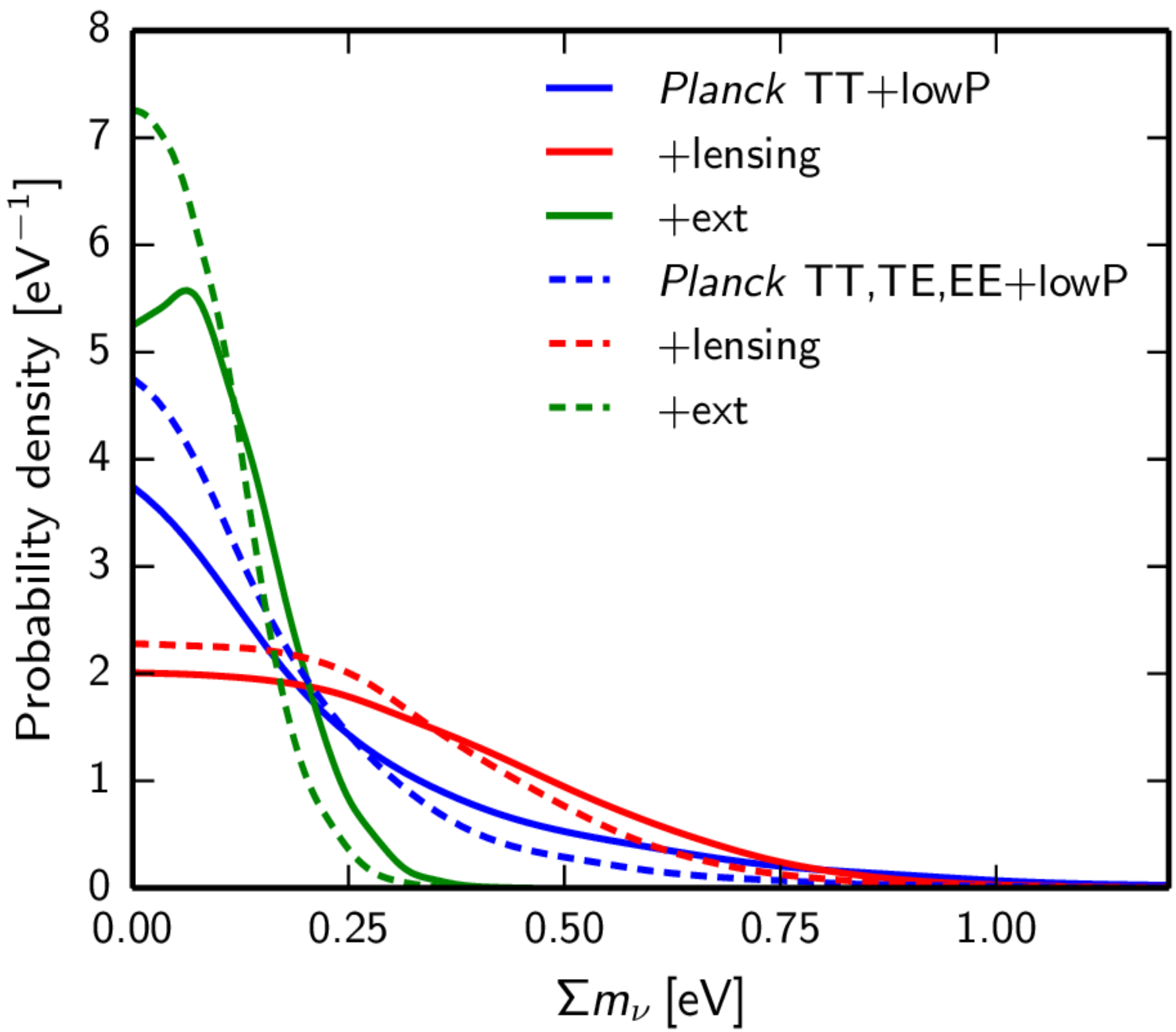
$$\sum m_\nu < 0.49 \text{ eV} \quad \textit{Planck} \text{ TT, TE, EE+lowP} ;$$

$$\sum m_\nu < 0.17 \text{ eV} \quad \textit{Planck} \text{ TT, TE, EE+lowP+BAO} .$$

Constraints on neutrino masses



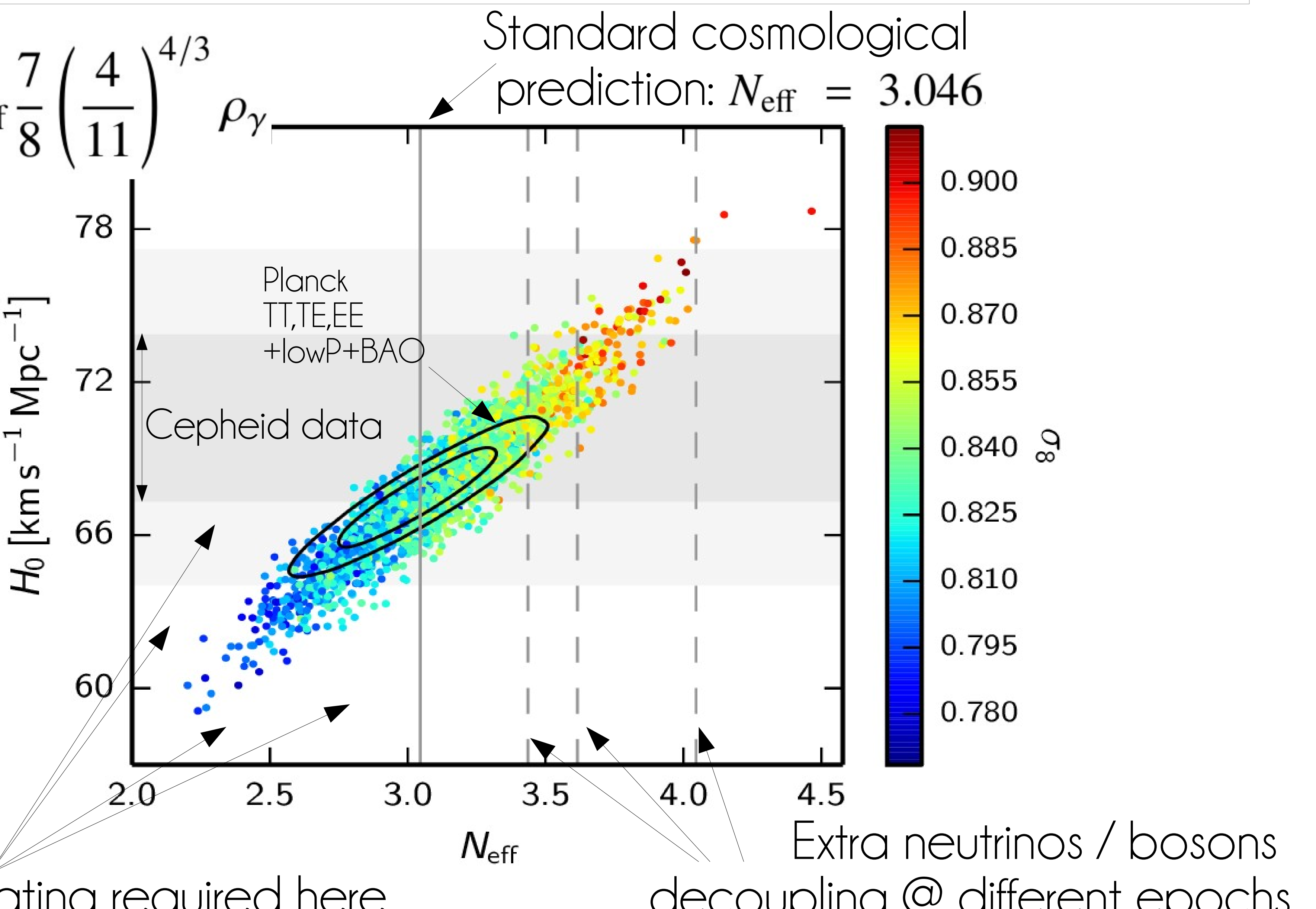
Constraints on neutrino masses



Neutrino number

effective number of relativistic (non-photon) d.o.f. @ recombination

$$\rho = N_{\mathrm{eff}} \frac{7}{8}\left(\frac{4}{11}\right)^{4/3} \rho_\gamma$$



Neutrino number

effective number of relativistic (non-photon) d.o.f. @ recombination

$$\rho = N_{\rm eff}\frac{7}{8}\left(\frac{4}{11}\right)^{4/3}\rho_\gamma$$

Standard cosmological prediction: $N_{\rm eff} = 3.046$

$$\begin{aligned}
N_{\rm eff} &= 3.13 \pm 0.32 \quad \textit{Planck}\ \text{TT+lowP}\,;\\
N_{\rm eff} &= 3.15 \pm 0.23 \quad \textit{Planck}\ \text{TT+lowP+BAO}\,;\\
N_{\rm eff} &= 2.99 \pm 0.20 \quad \textit{Planck}\ \text{TT, TE, EE+lowP}\,;\\
N_{\rm eff} &= 3.04 \pm 0.18 \quad \textit{Planck}\ \text{TT, TE, EE+lowP+BAO}\,.
\end{aligned}$$

Big Bang Nucleosynthese:

$$N_{\rm eff} = \begin{cases} 3.11^{+0.59}_{-0.57} & \text{He+}\textit{Planck}\ \text{TT+lowP},\\ 3.14^{+0.44}_{-0.43} & \text{He+}\textit{Planck}\ \text{TT+lowP+BAO},\\ 2.99^{+0.39}_{-0.39} & \text{He+}\textit{Planck}\ \text{TT,TE,EE+lowP}, \end{cases}$$

$$N_{\rm eff} = \begin{cases} 2.95^{+0.52}_{-0.52} & \text{D+}\textit{Planck}\ \text{TT+lowP},\\ 3.01^{+0.38}_{-0.37} & \text{D+}\textit{Planck}\ \text{TT+lowP+BAO},\\ 2.91^{+0.37}_{-0.37} & \text{D+}\textit{Planck}\ \text{TT,TE,EE+lowP}, \end{cases}$$

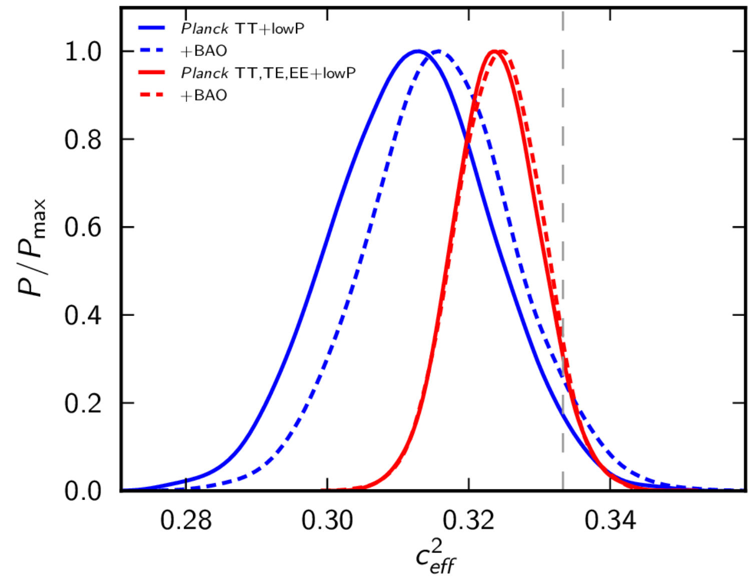
Perturbations in neutrino background

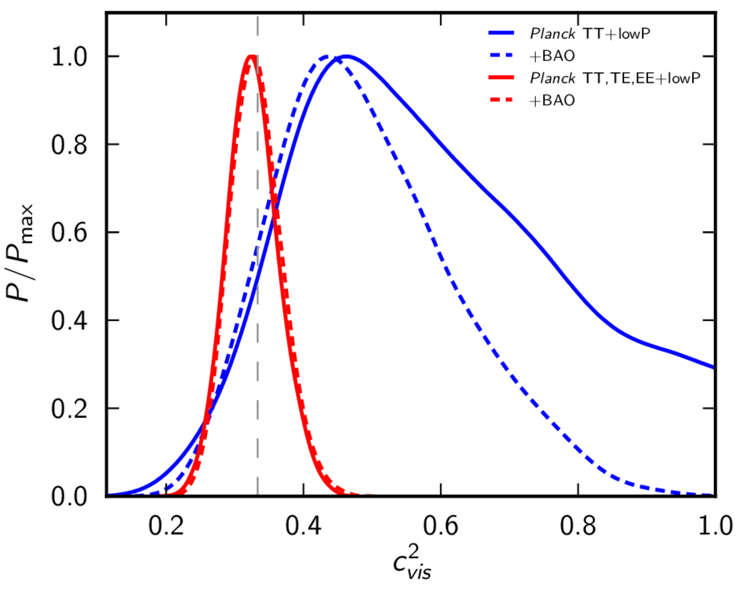
$$\dot{\delta}_\nu = \frac{\dot{a}}{a}\left(1 - 3c_{\rm eff}^2\right)\left(\delta_\nu + 3\frac{\dot{a}}{a}\frac{q_\nu}{k}\right) -$$

$$\dot{q}_\nu = k\, c_{\rm eff}^2\left(\delta_\nu + 3\frac{\dot{a}}{a}\frac{q_\nu}{k}\right) - \frac{\dot{a}}{a}q_\nu -$$

$$\dot{\pi}_\nu = 3k\, c_{\rm vis}^2\left(\frac{2}{5}q_\nu + \frac{4}{15k}\right.$$

$$\dot{F}_{\nu,\ell} = \frac{k}{2\ell+1}\left(\ell F_{\nu,\ell-1} -\right.$$





Conclusions

Planck has – so far – confirmed
the standard models
of cosmology & particle physics.

esa

planck

cnes

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NASA

cnrs

DTU Space
National Space Institute

INAF Istituto Nazionale di Astrofisica

Science & Technology Facilities Council

CSIC
Consejo Superior de Investigaciones Científicas

National Research Council of Italy

Gobierno de España
Ministerio de Ciencia e Innovación

CSA ASC

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

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HFI PLANCK
a look back to the birth of Universe

PLANCK LFI

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IAP

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IFCA Instituto de Física de Cantabria

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Università degli Studi di Milano

Néel institut

IPAG

ISDC Data Centre for Astrophysics

JPL

LAL Laboratoire de l'Accélérateur Linéaire

l'Observatoire de Paris LERMA

LPSC Grenoble

NERSC

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