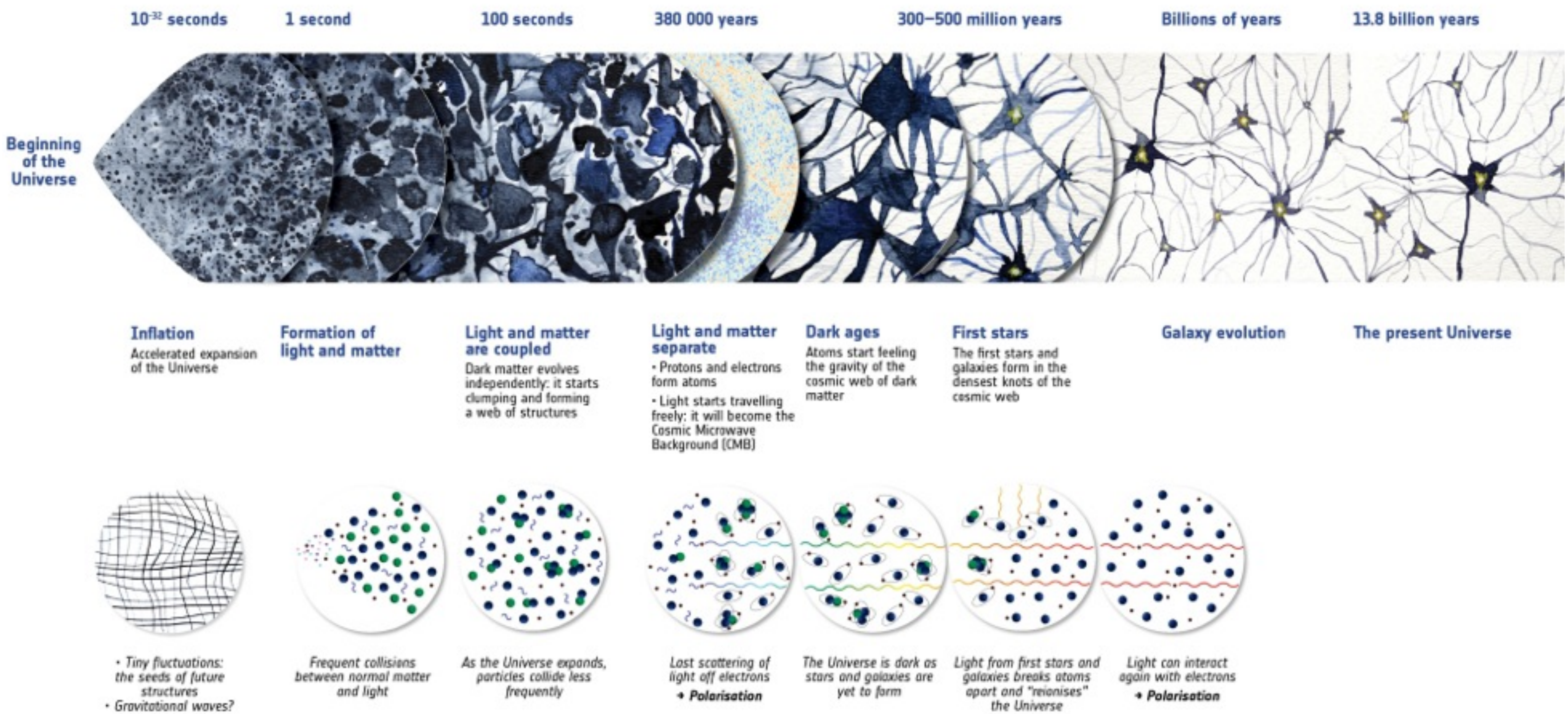
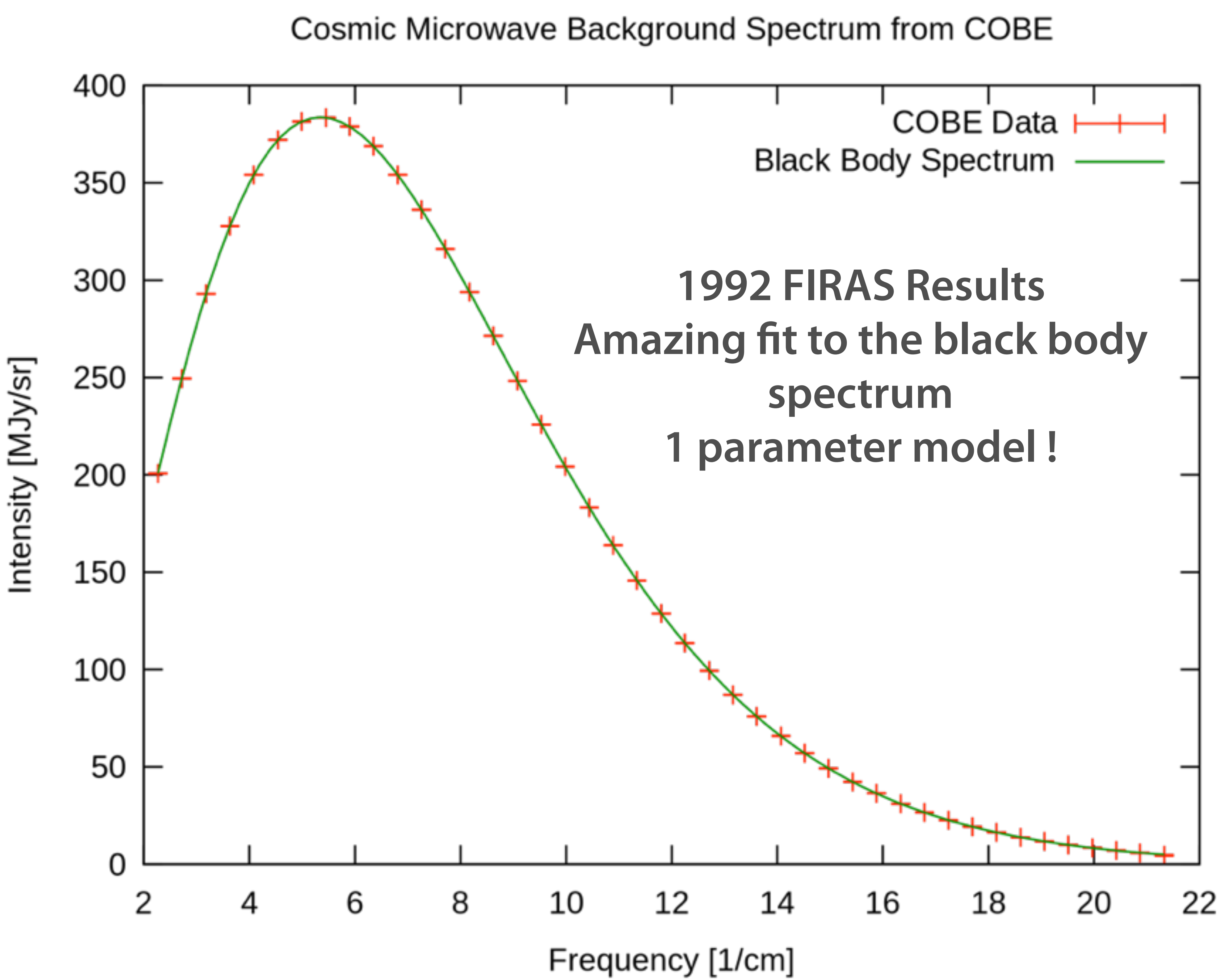
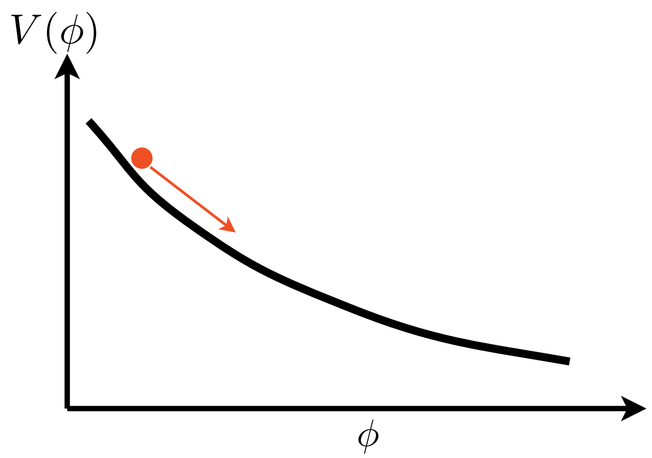
Planck 2015

K. Benabed - Institut d'astrophysique de Paris - UPMC/CNRS
On behalf of the Planck collaboration


10⁻³² seconds
1 second
100 seconds
380 000 years
300–500 million years
Billions of years
13.8 billion years
Beginning of the Universe
Inflation
Accelerated expansion of the Universe
Formation of light and matter
Light and matter are coupled
Dark matter evolves independently: it starts clumping and forming a web of structures
Light and matter separate
• Protons and electrons form atoms
• Light starts travelling freely: it will become the Cosmic Microwave Background (CMB)
Dark ages
Atoms start feeling the gravity of the cosmic web of dark matter
First stars
The first stars and galaxies form in the densest knots of the cosmic web
Galaxy evolution
The present Universe
• Tiny fluctuations: the seeds of future structures
• Gravitational waves?
Frequent collisions between normal matter and light
As the Universe expands, particles collide less frequently
Last scattering of light off electrons
→ Polarisation
The Universe is dark as stars and galaxies are yet to form
Light from first stars and galaxies breaks atoms apart and "reionises" the Universe
Light can interact again with electrons
→ Polarisation


Cosmic Microwave Background Spectrum from COBE
COBE Data
Black Body Spectrum
1992 FIRAS Results
Amazing fit to the black body spectrum
1 parameter model !
Intensity [MJy/sr]
Frequency [1/cm]
0
50
100
150
200
250
300
350
400
2
4
6
8
10
12
14
16
18
20
22

Inflation



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

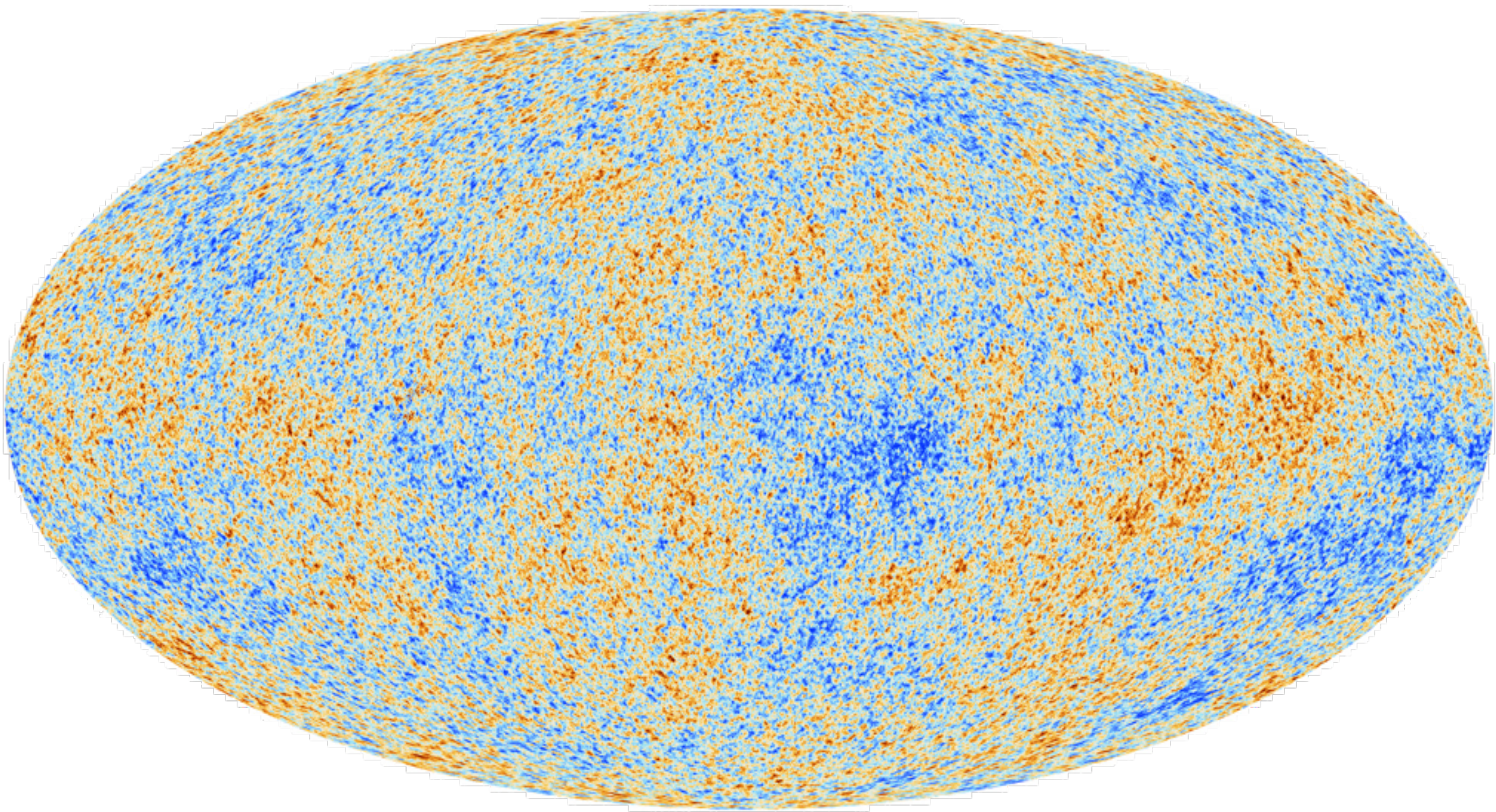
$$\eta_V = \frac{M_{\rm pl}^2 V_{\phi\phi}}{V}\,.$$

$$n_{\rm s} - 1 \approx 2\eta_V - 6\epsilon_V$$

$$n_{\rm t} \approx -2\epsilon_V$$

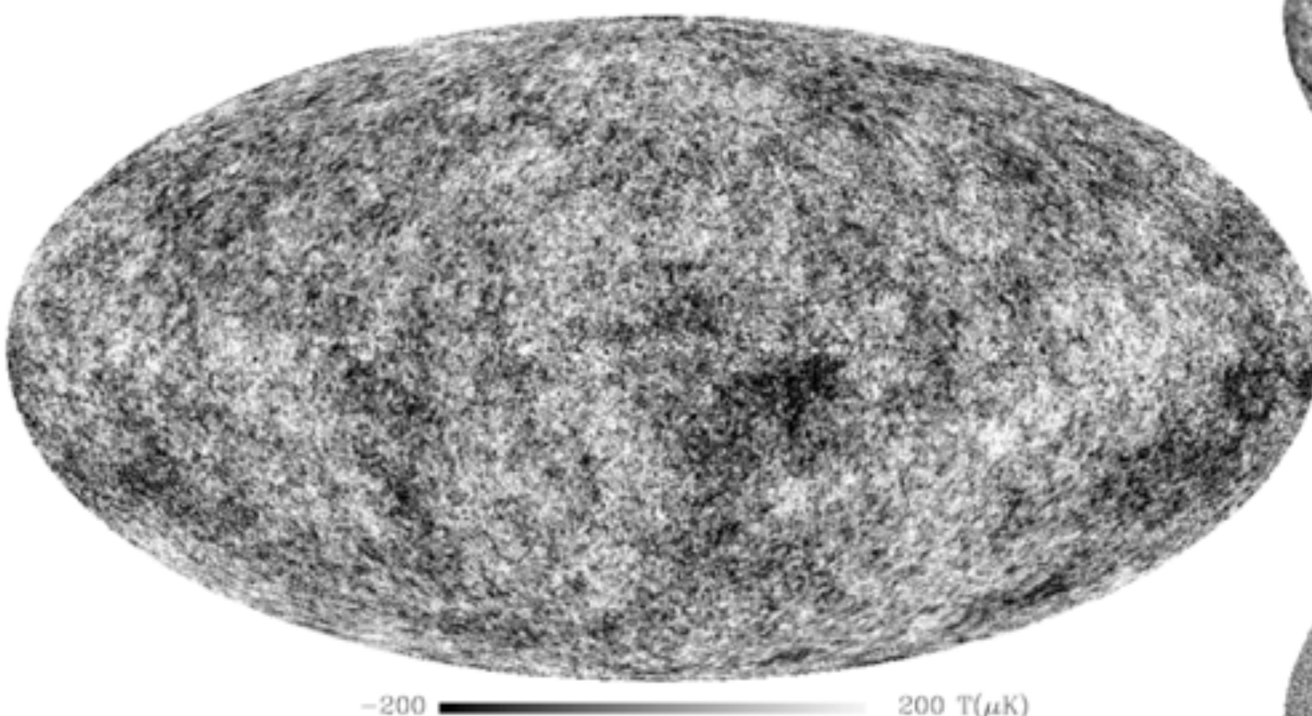
$$r = \frac{\mathcal{P}_{\rm t}(k_*)}{\mathcal{P}_{\mathcal{R}}(k_*)} \approx 16\epsilon \approx -8n_{\rm t}\,,$$

- At early times, a field with negative pressure drives a nearly exponential expansion, slowly evolving in its potential
- Its quantum fluctuations induce the primordial fluctuations
  - Scalar
  - Tensors (Gravitational waves)
- If the roll down the potential is slow enough
  - the spectrum of primordial fluctuation is determined by the first two derivatives of the potential
  - there is no measurable NG

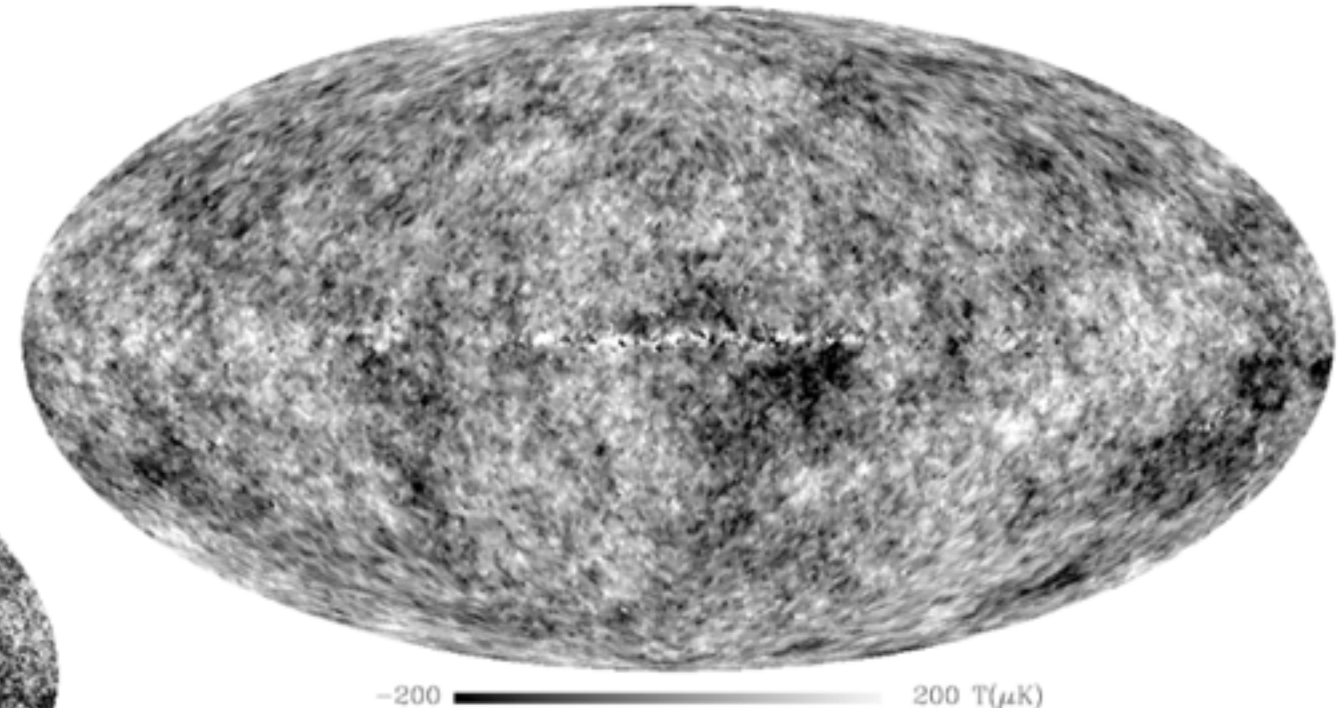


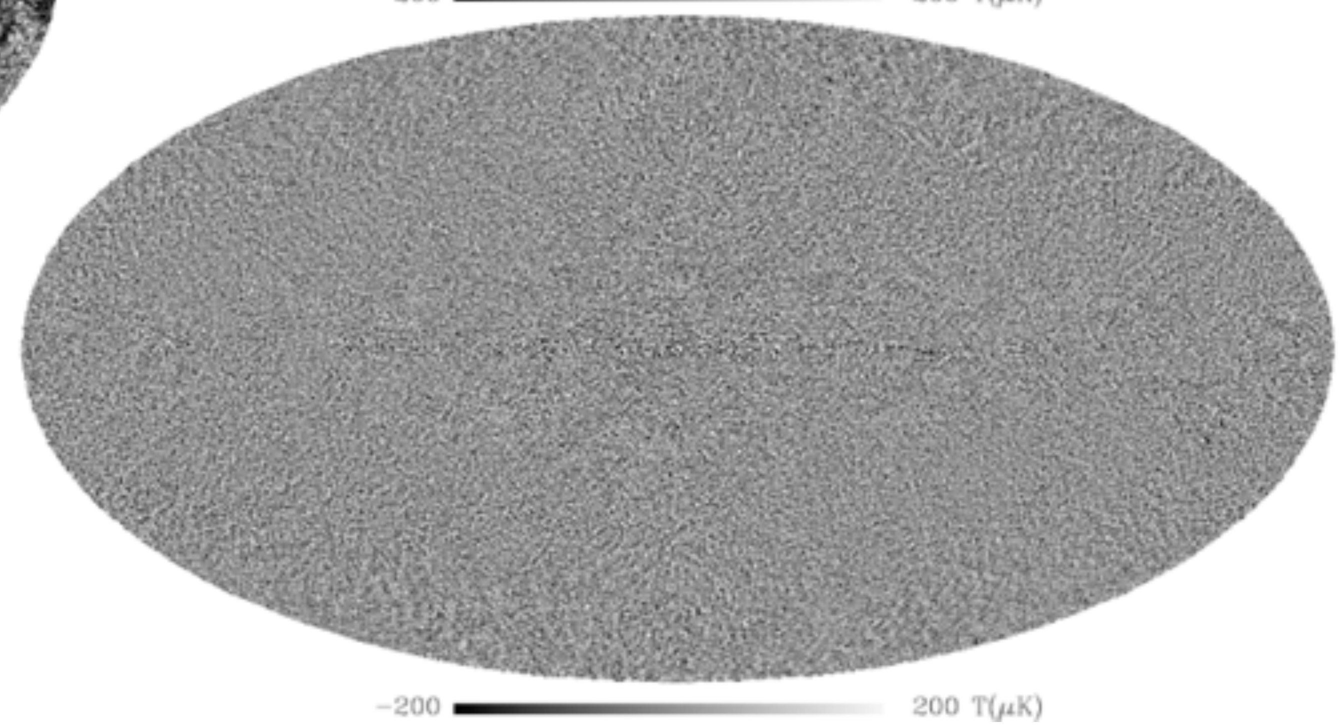
Temperature anisotropies
(microK level)

CMB



Large scales (>1º) primordial perturbations

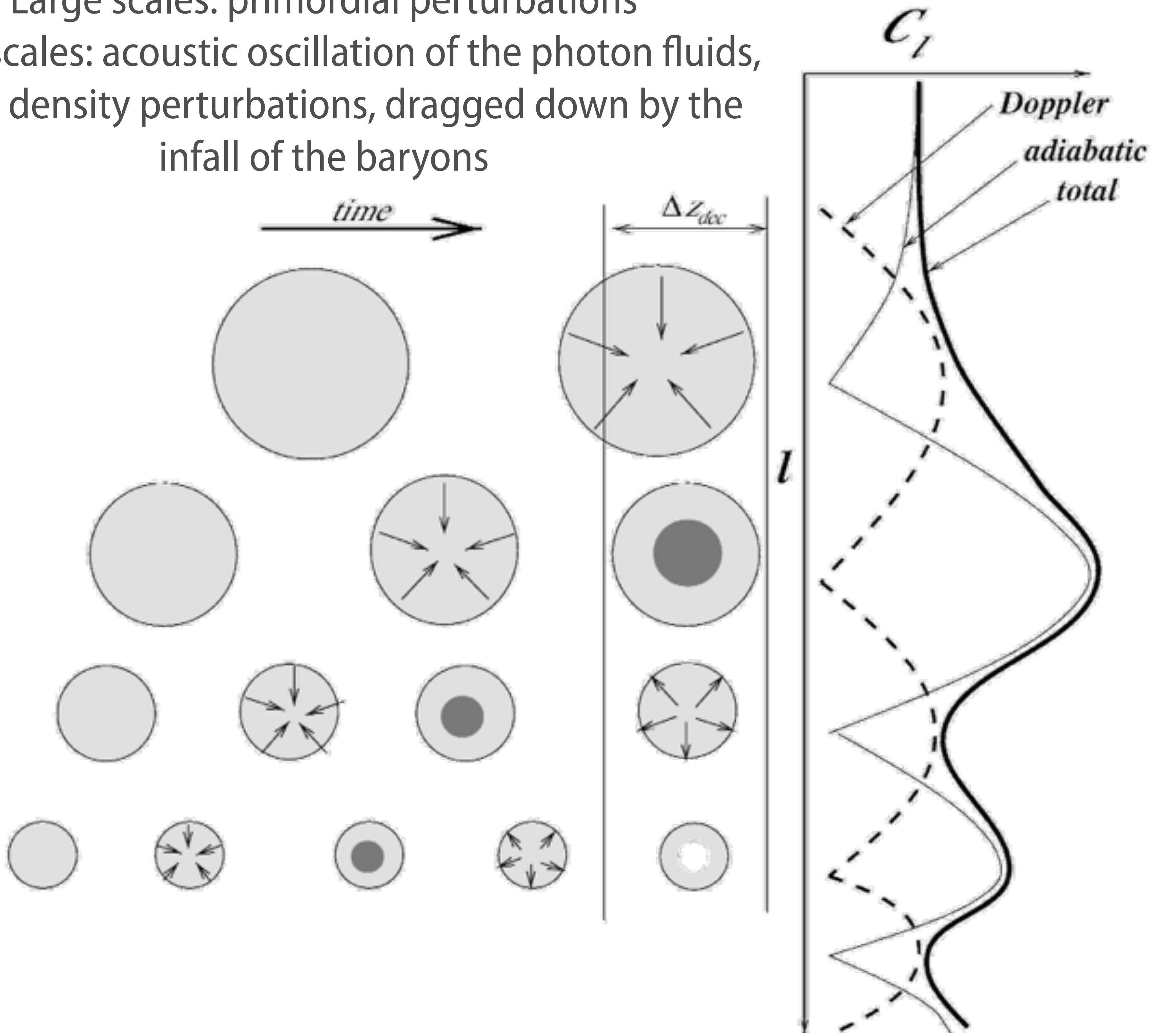




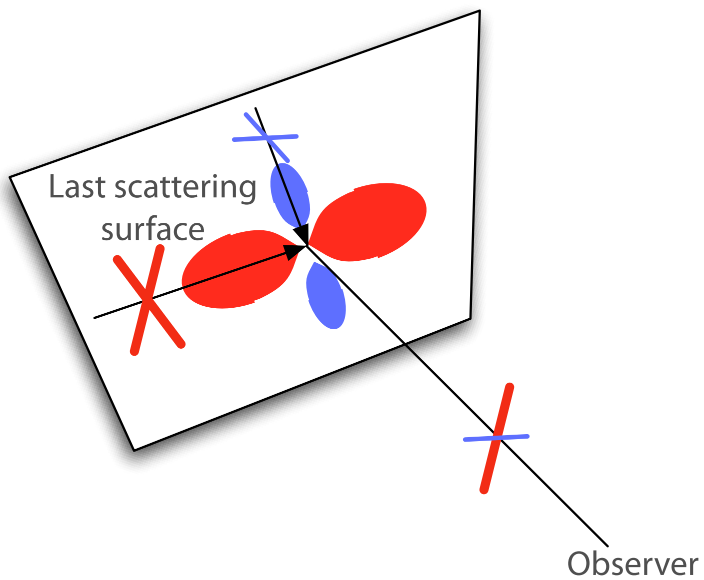
small scales (<1º) acoustic oscillations

A map of the density perturbation

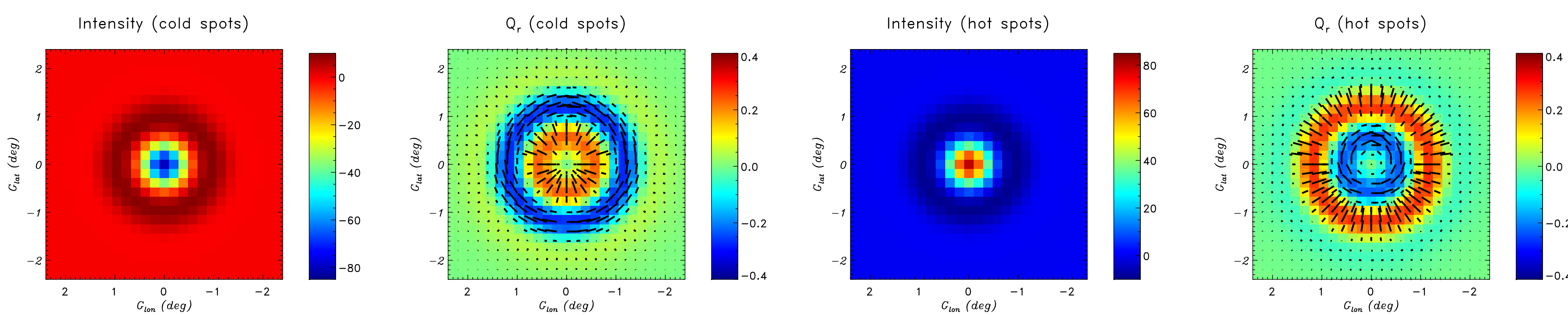
Large scales: primordial perturbations
Small scales: acoustic oscillation of the photon fluids, in the density perturbations, dragged down by the infall of the baryons

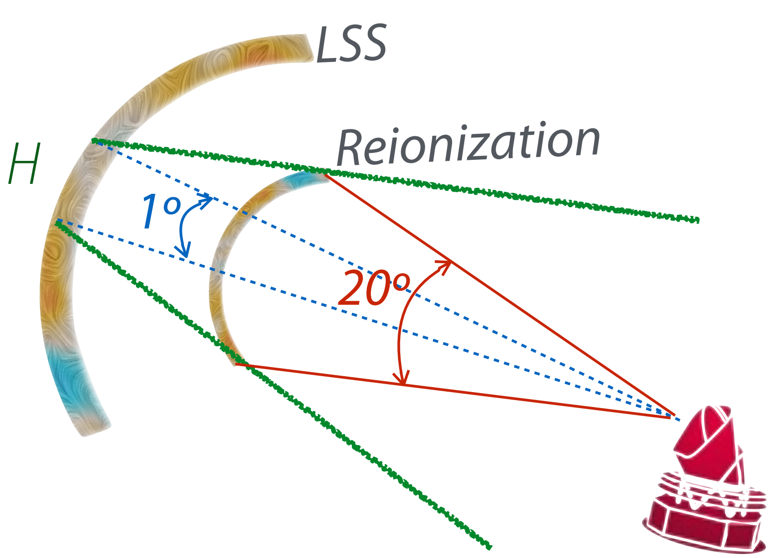


Polarization

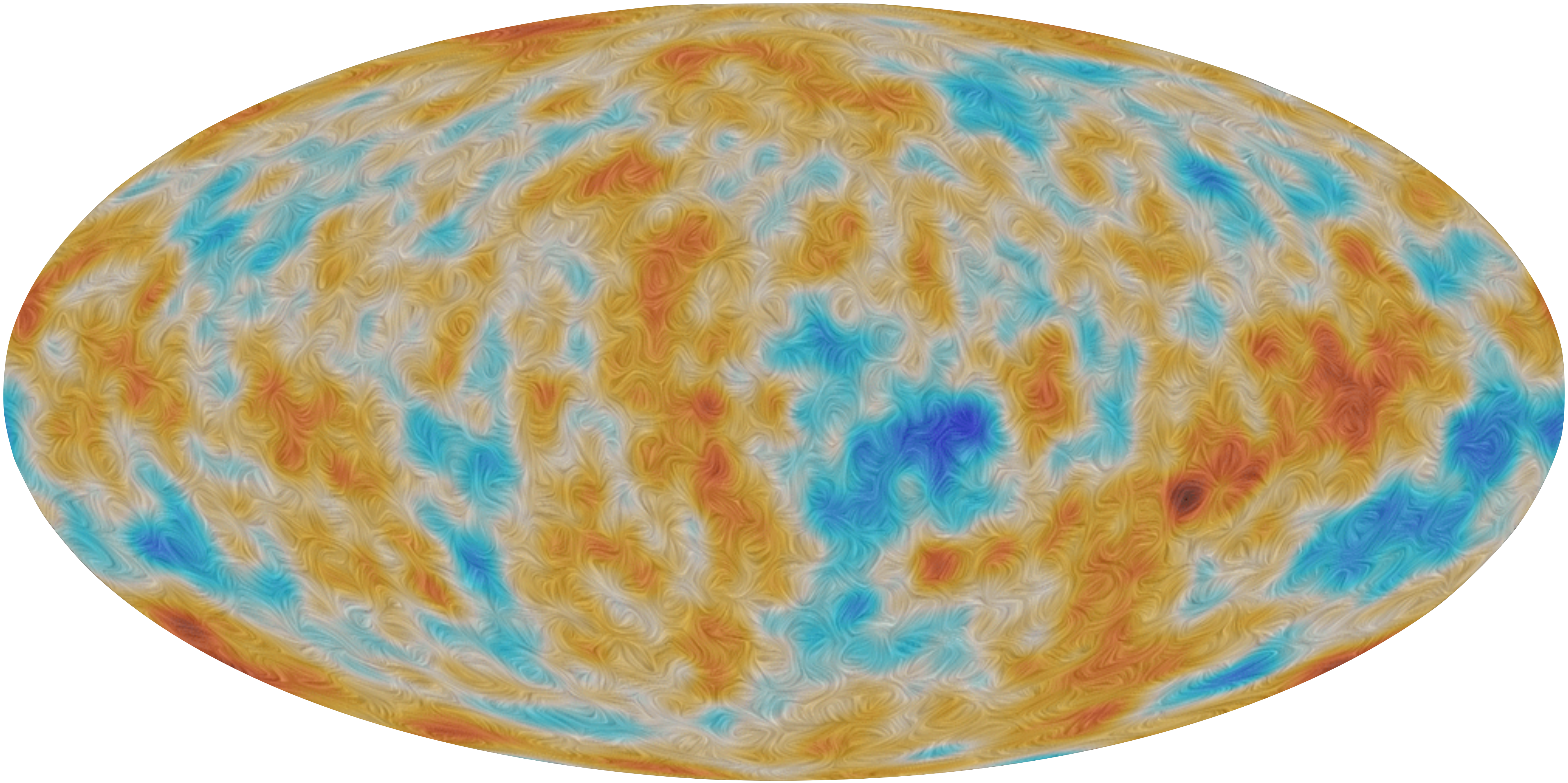


- Quadrupolar anisotropies, seen by the electrons, on the last scatering surface give rise to exces polarization
- Orientation linked to velocity field gradients at recombinaison (tangencial around cold spots, radial around hot spots)





- Secondary scattering during reionization causes large scale polarization signal



Polarization
(10º scale)

What do we learn ?

- Amplitude and slope of the fluctuations
- Sound horizon: location of the first peak
- Total matter: Changes the contrast between the peaks
- Baryon density: Changes the ratio between peak heights
- Reionization fraction: Increase the power at large scale. Good constraint only when using large scale polarization. Marginal constraint from lensing

- Ho: indirect measurement from the above parameters

- Curvature: large scales (ISW) small scales (lensing)
- Neutrino masses: small scales (lensing)

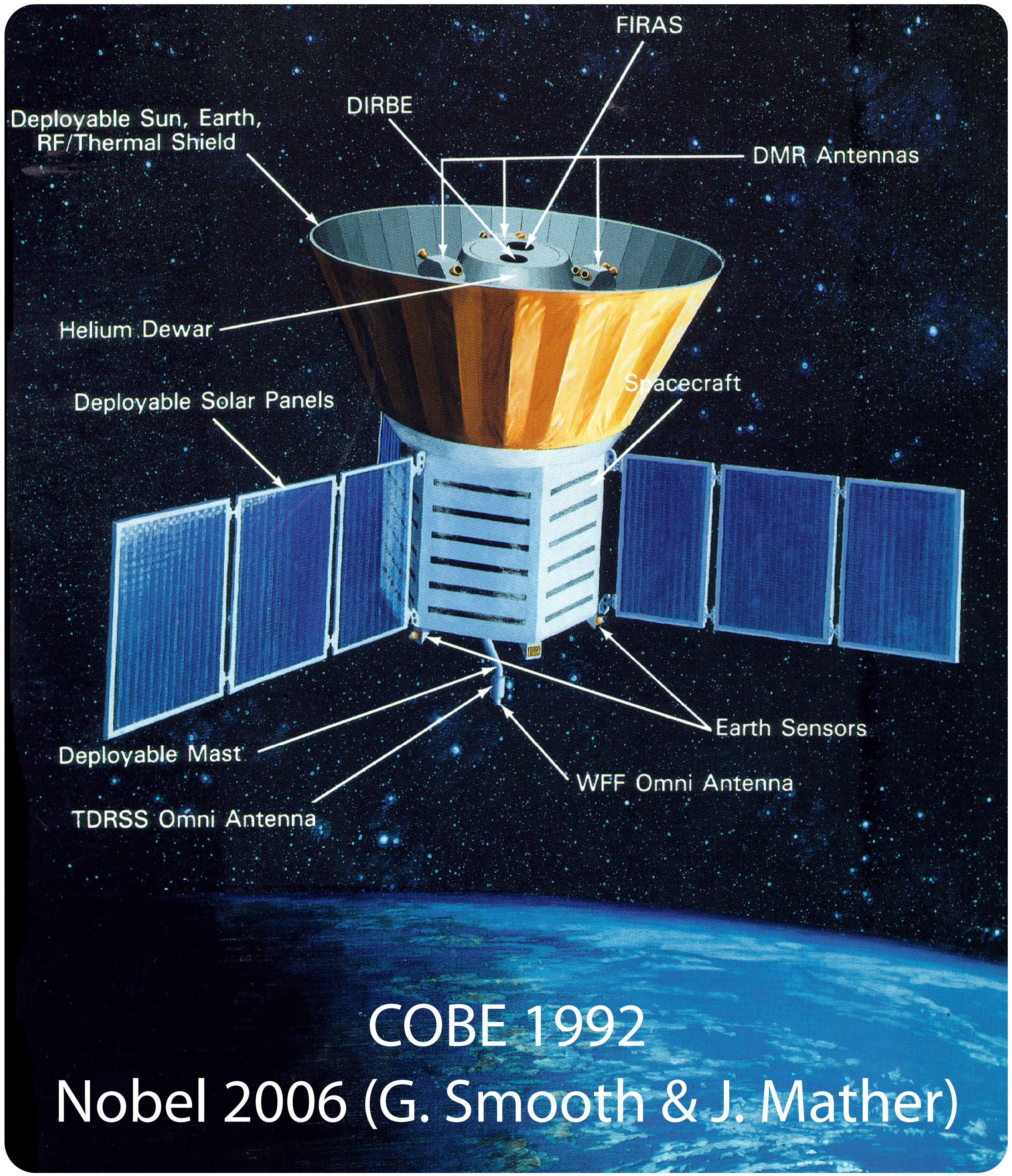
Observing the CMB

Observing the CMB

Just buy a few hundred of those !

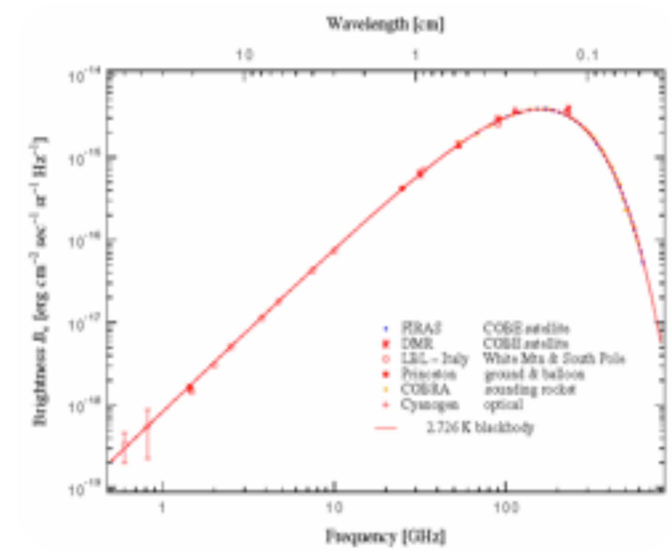
Observing the CMB

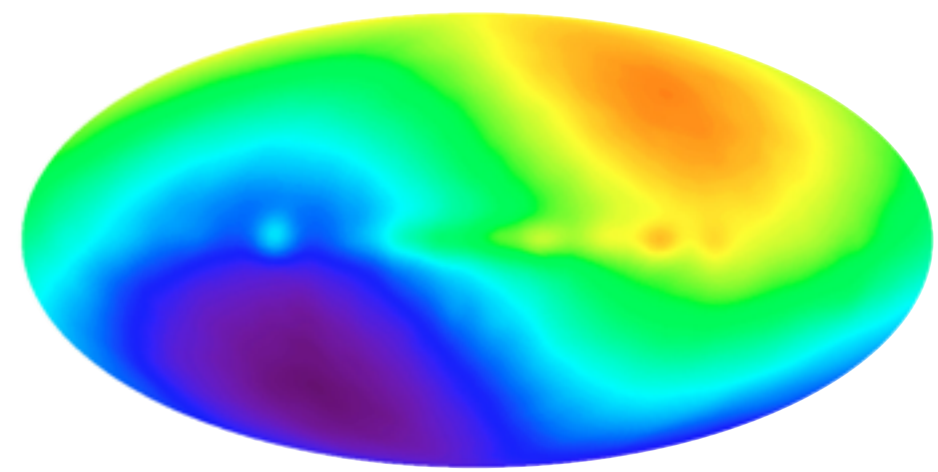
from space

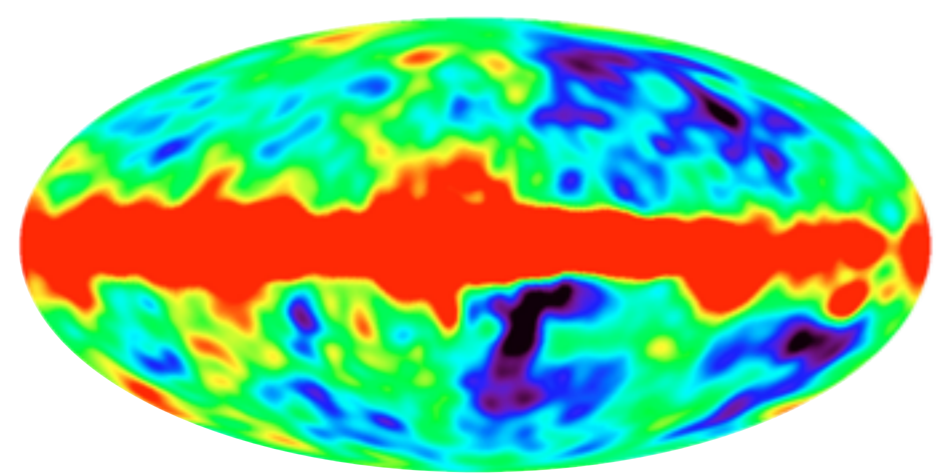


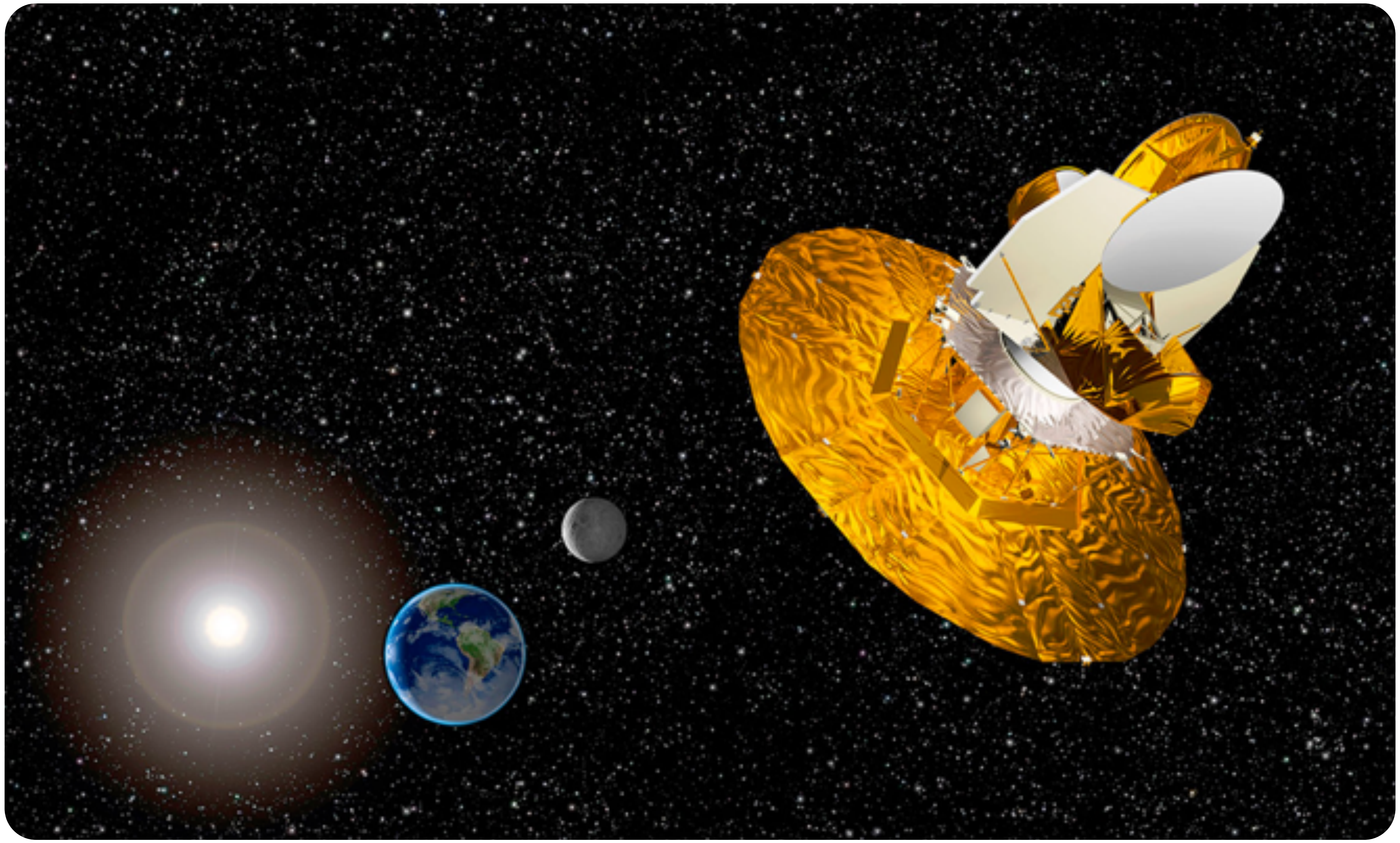
COBE 1992

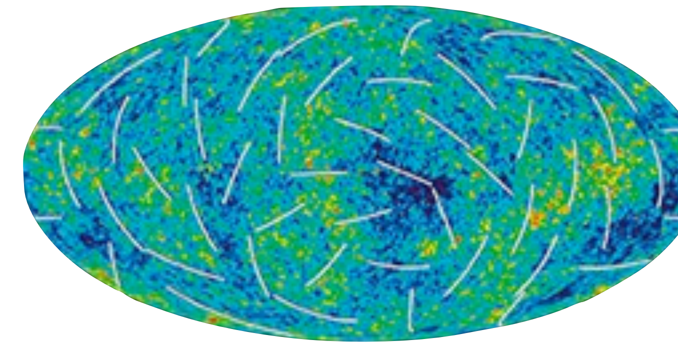
Nobel 2006 (G. Smooth & J. Mather)

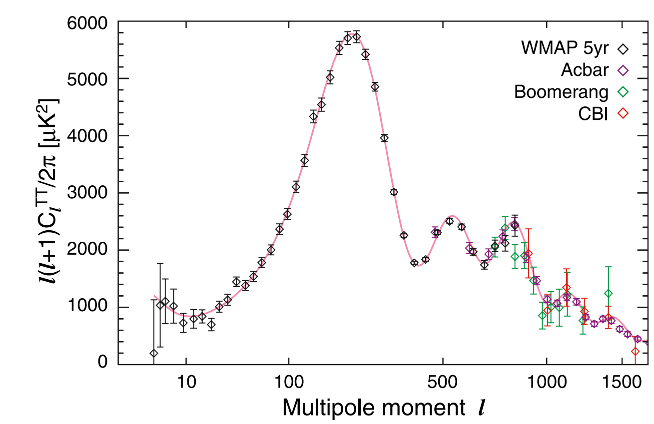


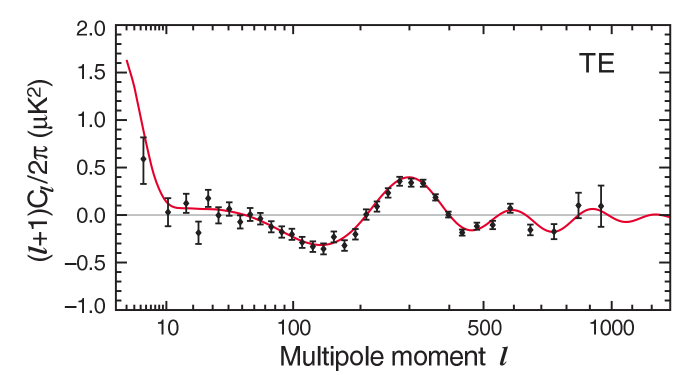












Wilkinson Microwave Anisotropie Probe (WMAP)

2003-2009

First three peaks

TE polarization

Max Planck (1858-1927)

Planck (1993-23/10/2013)

esa

planck

cnes

asi
agenzia spaziale italiana

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.

UK SPACE AGENCY

MAX-PLANCK-GESELLSCHAFT

HFI PLANCK
a look back to the birth of Universe

PLANCK LFI

IAS orsay

IAP

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

A" Aalto University

California Institute of Technology

ioa

Kavli Institute for Cosmology Cambridge KICC

CAVENDISH ASTROPHYSICS

UNIVERSITY OF CAMBRIDGE

CARDIFF UNIVERSITY
PRIFYSGOL CAERDYDD

irfu cea saclay

CEFCA

CESR

CITA–ICAT

IASF

cnrs INSU
Observer & comprendre

cnrs IN2P3
Les deux infinis

ipac

HELSINKI INSTITUTE OF PHYSICS

INSTITUTO DE ASTROFISICA DE CANARIAS

IFCA
Instituto de Física de Cantabria

Imperial College London

UNIVERSITÀ DEGLI STUDI DI MILANO

NÉEL institut

IPAG
Institut de Planétologie et d'Astrophysique de Grenoble

ISDC
DATA CENTRE FOR ASTROPHYSICS

JPL

LAL
LABORATOIRE DE L'ACCÉLÉRATEUR LINÉAIRE

l'Observatoire de Paris
LERMA

LPSC Grenoble
Laboratoire de Physique Subatomique et de Cosmologie

The University of Manchester
MilliLab

Max-Planck-Institut für Astrophysik

NUI MAYNOOTH

INAF
OSSERVATORIO ASTRONOMICO DI PADOVA

UNIVERSITY OF OXFORD

Dipartimento di Fisica
SAPIENZA
Università di Roma

Science & Technology Facilities Council
Rutherford Appleton Laboratory

UNIVERSITÀ degli STUDI di ROMA TOR VERGATA

OSSERVATORIO ASTRONOMICO TRIESTE

UBC

UC
UNIVERSIDAD DE CANTABRIA

UCSB

SISSA

STANFORD UNIVERSITY

ALMA

ESO

US
University of Sussex

HAVERFORD

esa

UNIVERSITY OF HELSINKI

UNIVERSITÉ DE GENÈVE

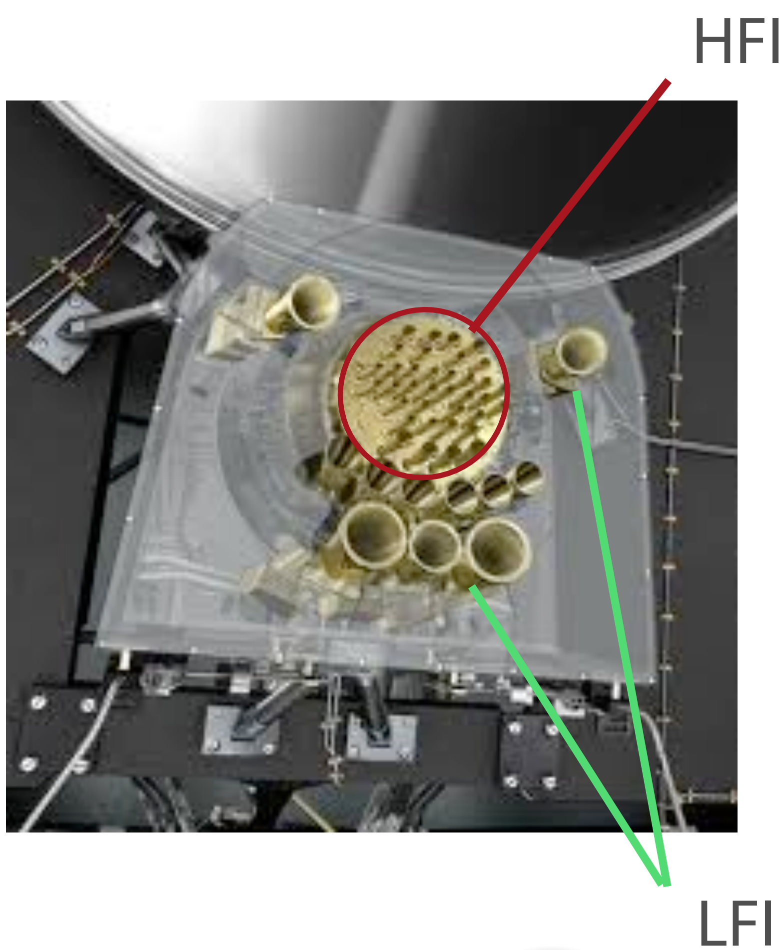
UNIVERSITY OF TORONTO

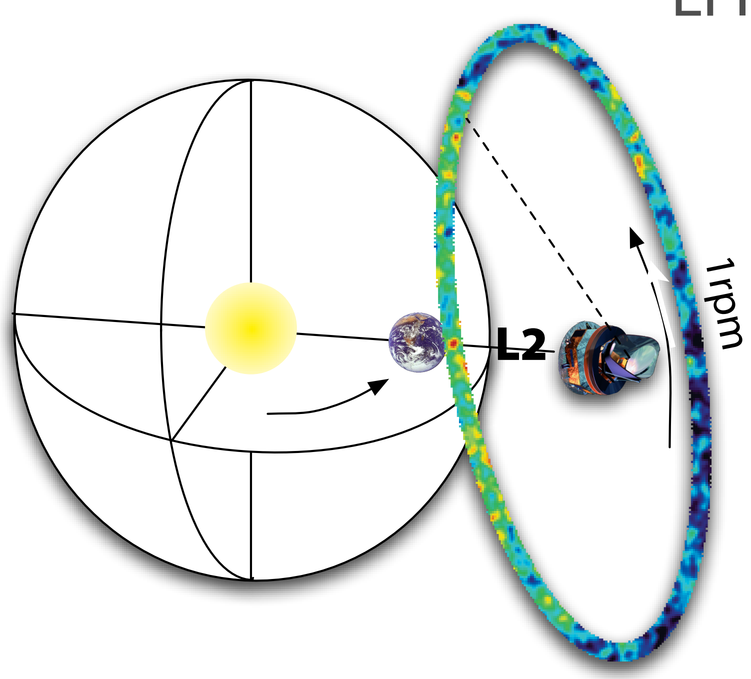
UNIVERSITÉ DE PARIS-SUD XI

ISTI
ISTITUTO DI SCIENZA E TECNOLOGIE DELL'INFORMAZIONE "A. FAEDO"

asdc
ASI Science Data Center

Planck in numbers

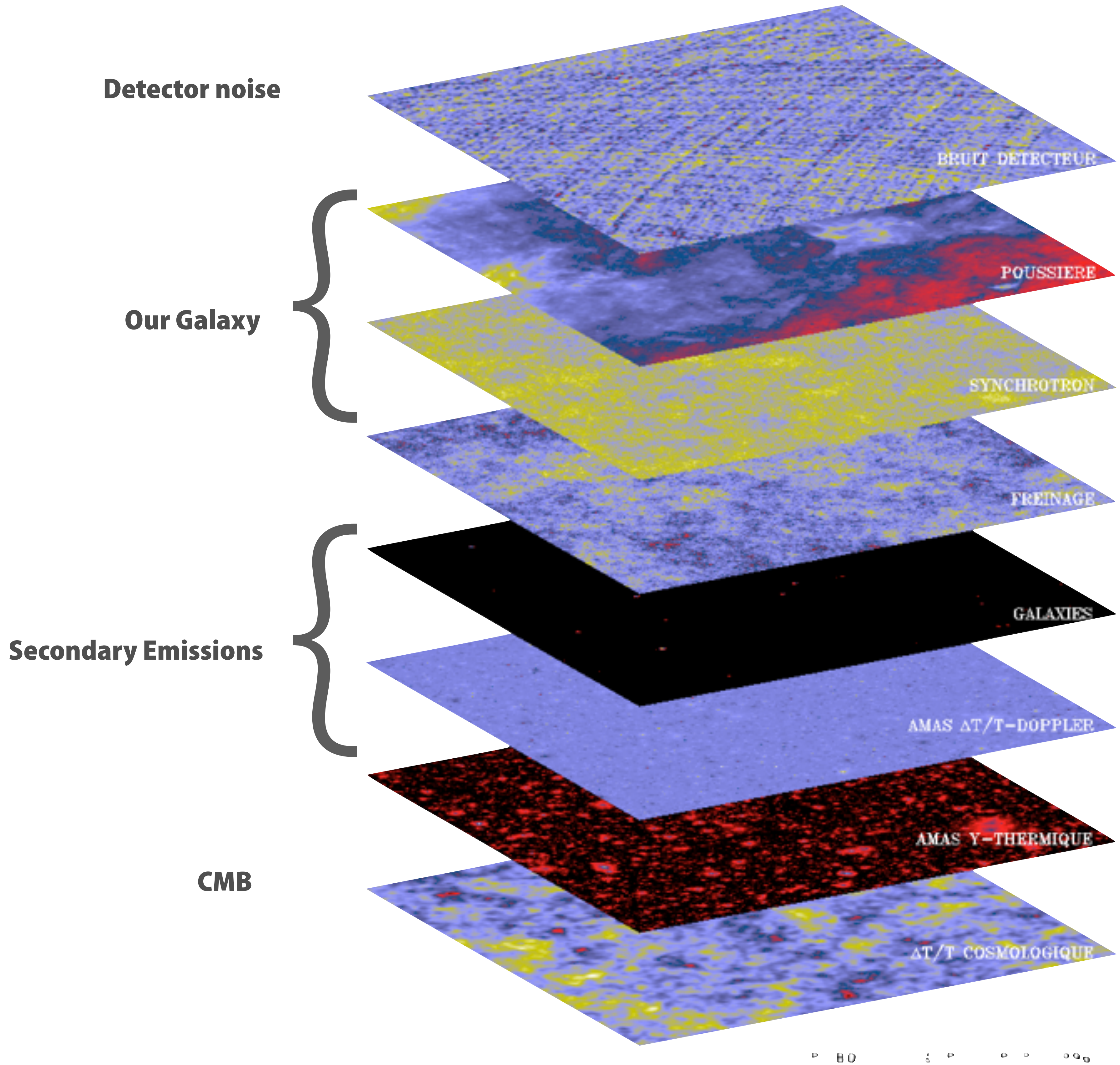


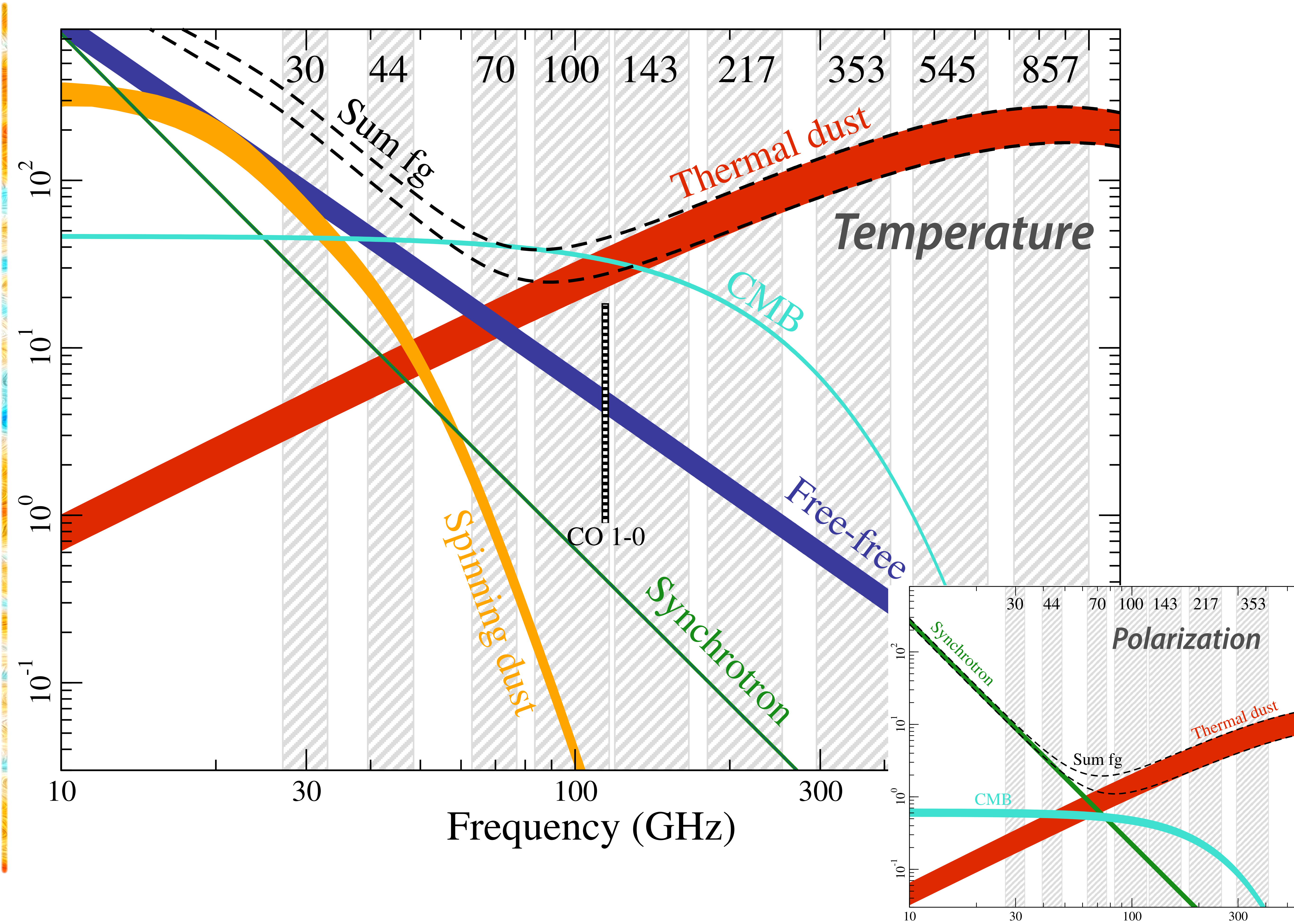


Driving goal

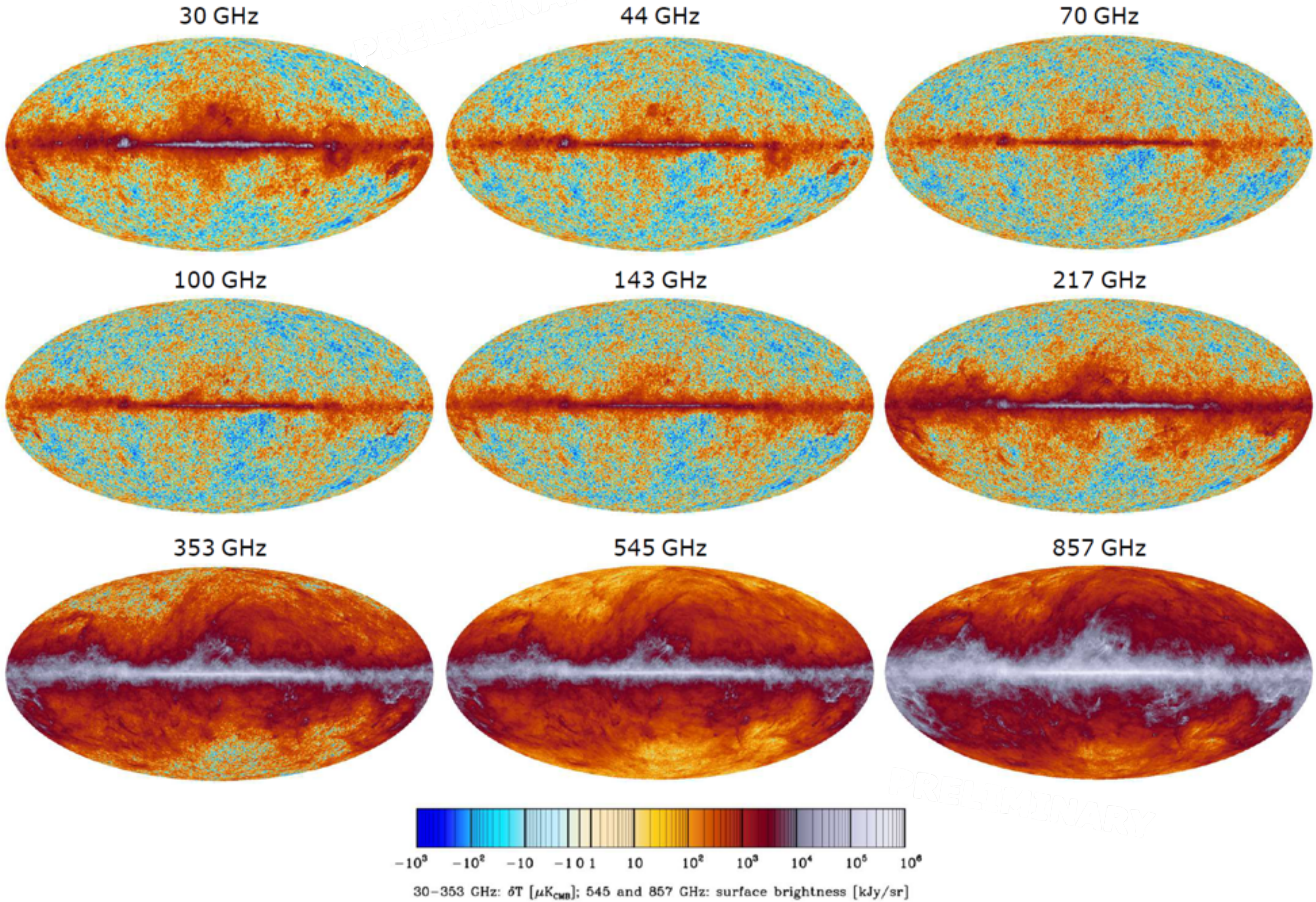
Perform the definitive temperature anisotropies measurement

- Primary 1.5m
- 2 instruments
  - LFI, 3 bands, 22 polarized radiometers
  - HFI, 6 bands, 50 bolometers (32 polarized)
- 4 stage cooler chain, going down to 0.1K
  - *last stage is a He3/He4 dilution cooler*
- Flawless operation !
  - 2yr: 4 sky survey for HFI (until 01/2012)
  - 4yr: 8 sky surveys for LFI
- Data releases
  - 2013 : 1yr survey
  - **2015 : full mission**
  - *2016…*


Detector noise
Our Galaxy
Secondary Emissions
CMB
BRUIT DETECTEUR
POUSSIERE
SYNCHROTRON
FREINAGE
GALAXIES
AMAS ΔT/T-DOPPLER
AMAS Y-THERMIQUE
ΔT/T COSMOLOGIQUE

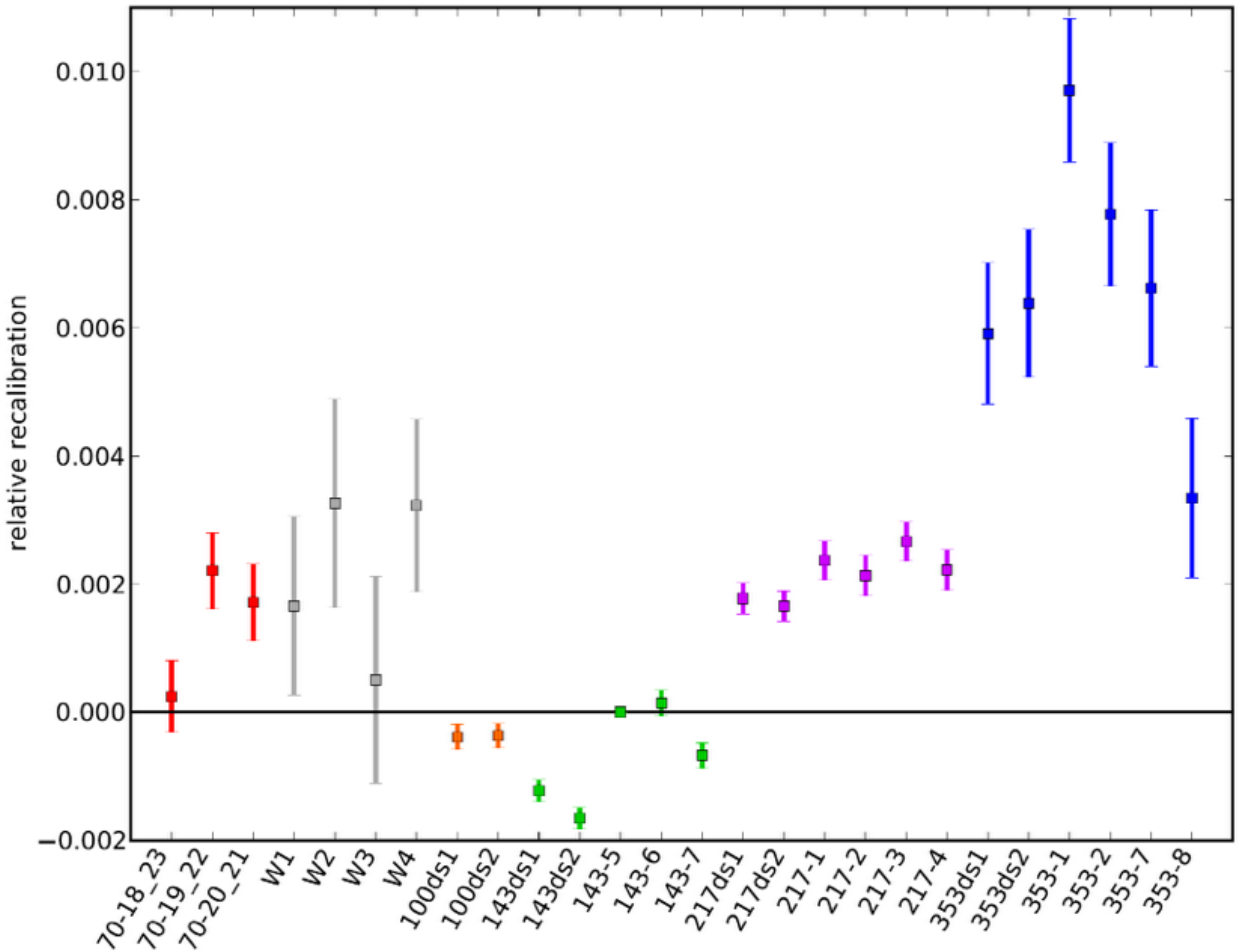


30
44
70
100
143
217
353
545
857
Sum fg
Thermal dust
Temperature
CMB
Free-free
CO 1-0
Spinning dust
Synchrotron
10^{2}
10^{1}
10^{0}
10^{-1}
10
30
100
300
Frequency (GHz)
Polarization
Synchrotron
Thermal dust
Sum fg
CMB



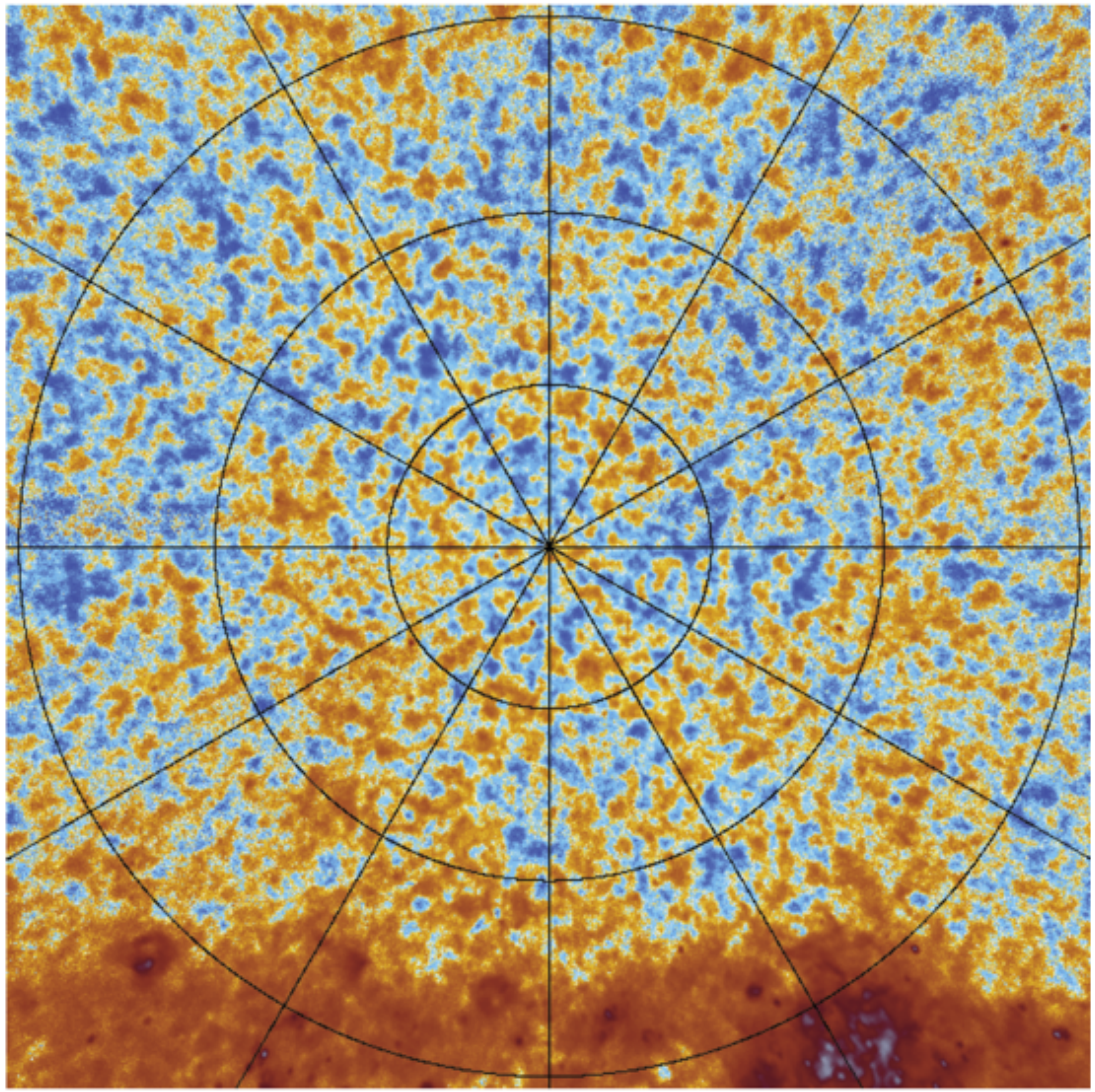
Planck 2015

Microwave sky

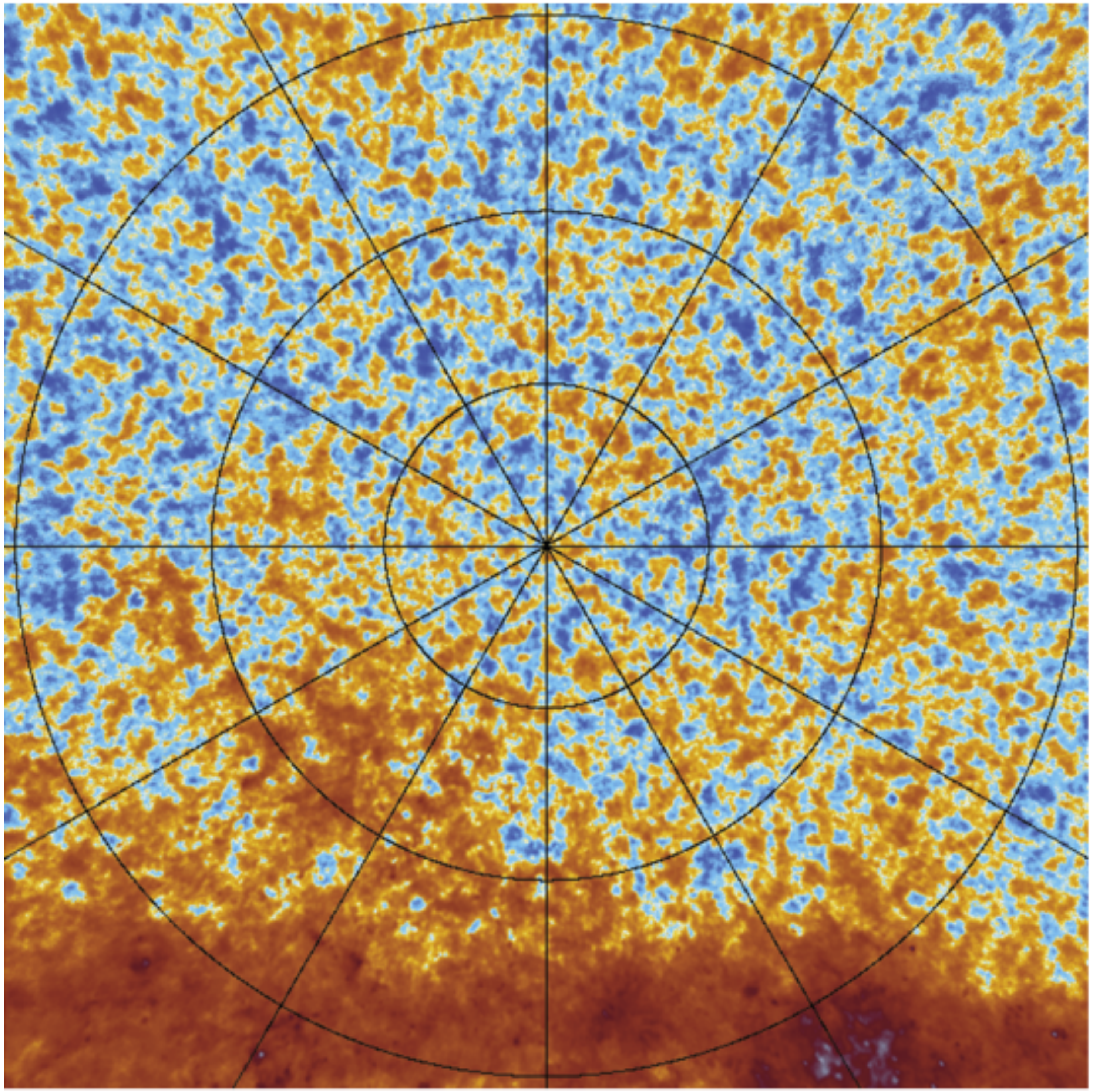


Relative calibration over l=40-495

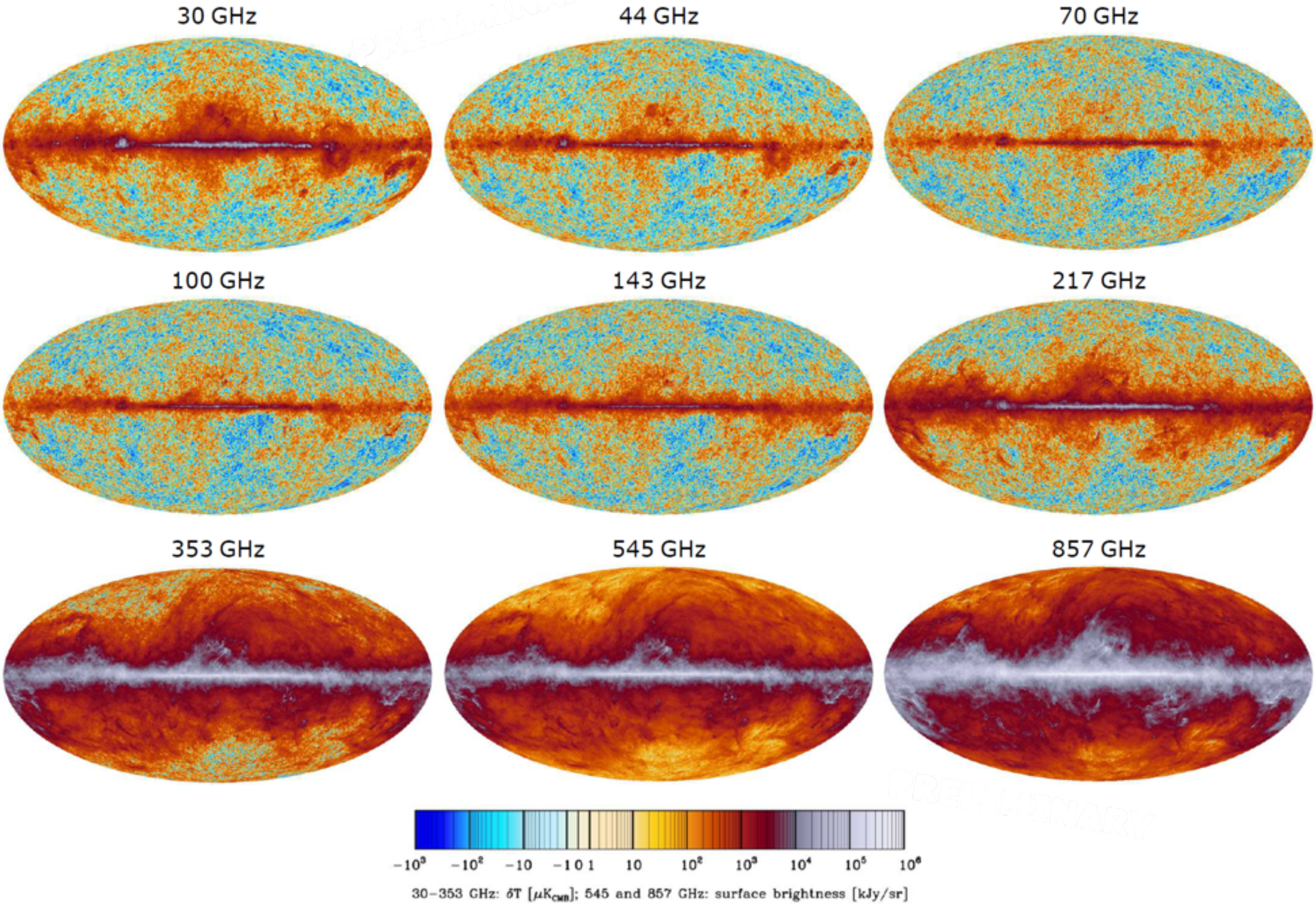
tenth of percent accuracy !



North ecliptic pole - 70GHz

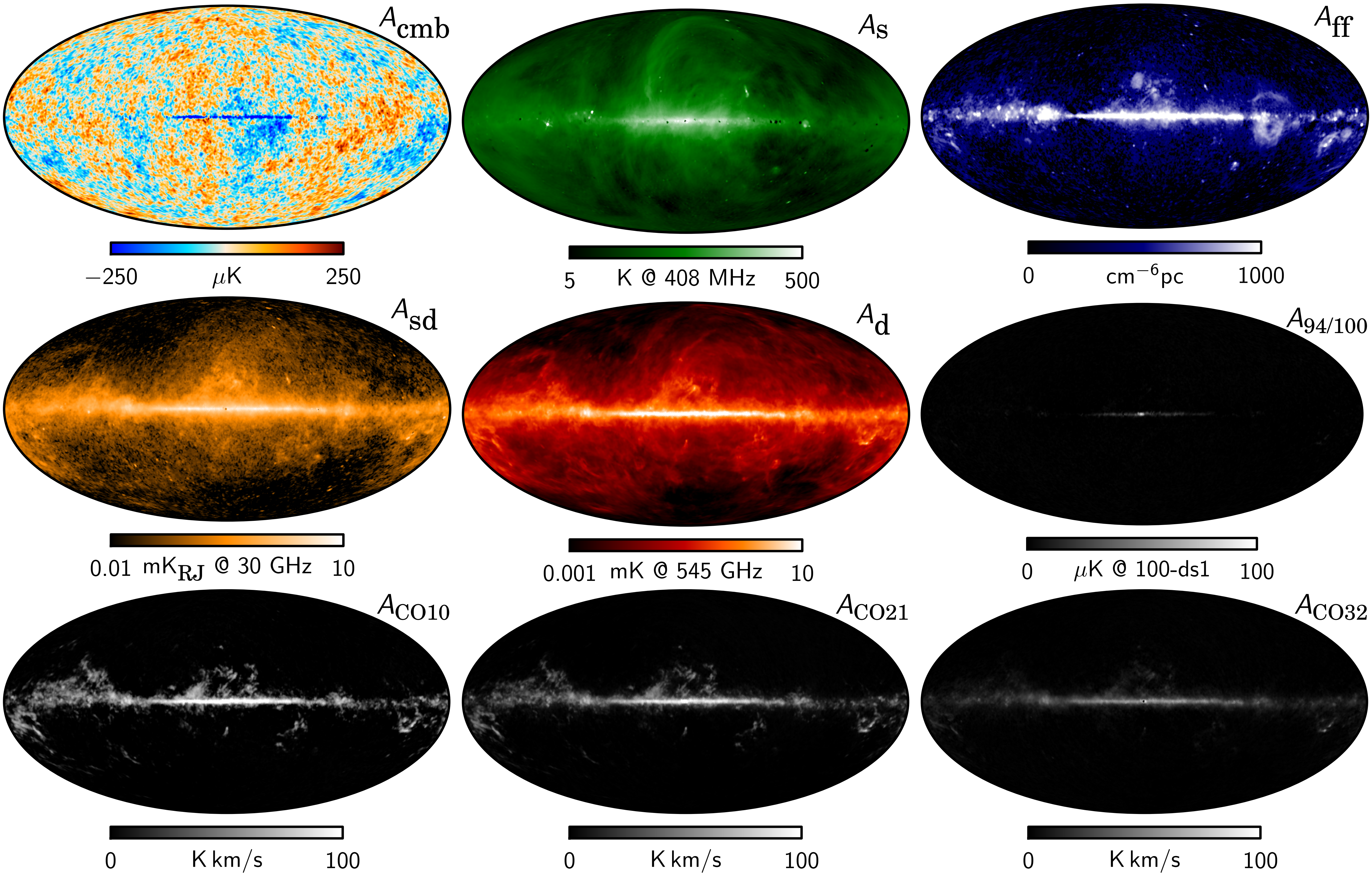


North ecliptic pole - 100GHz



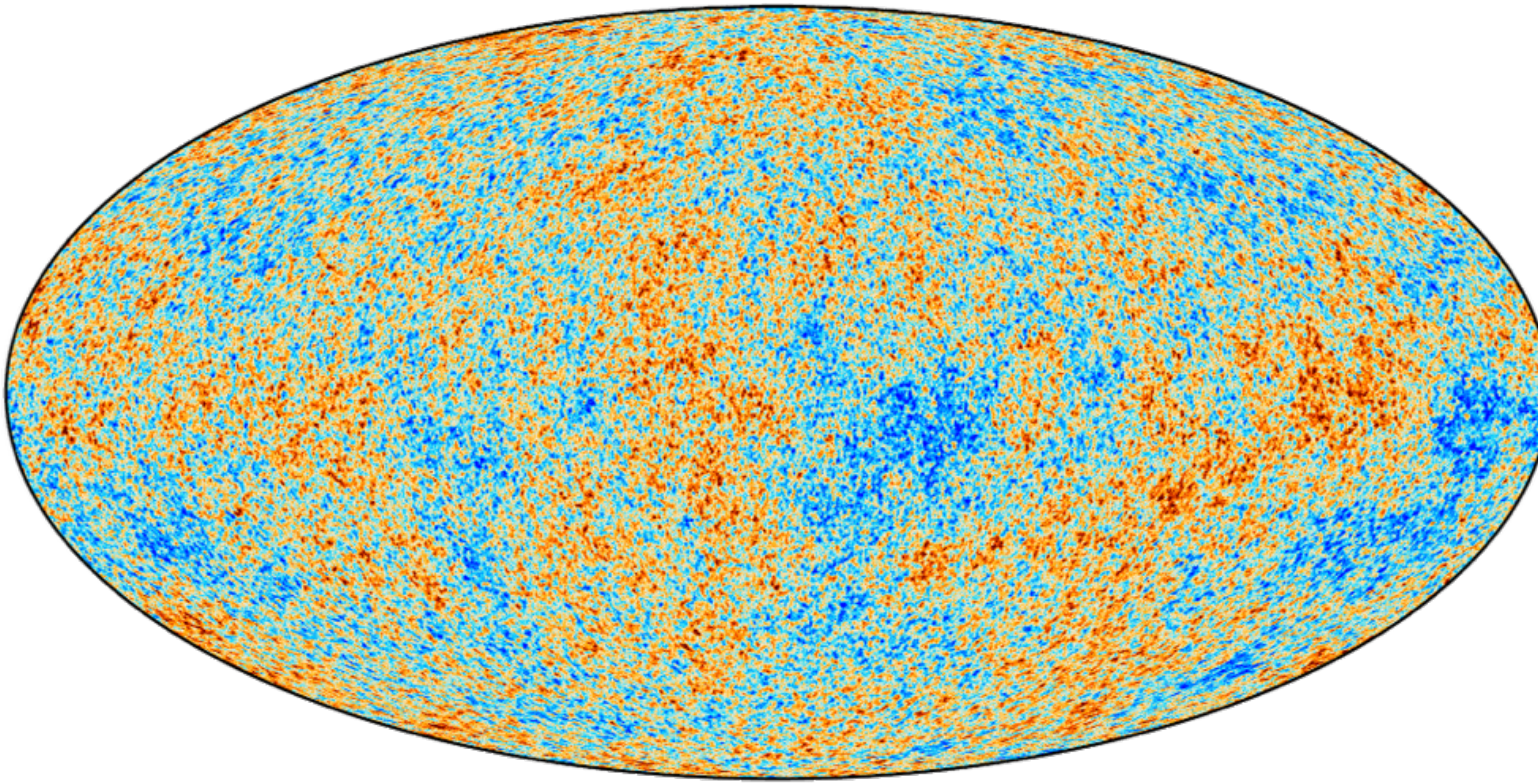
Planck 2015

Microwave sky



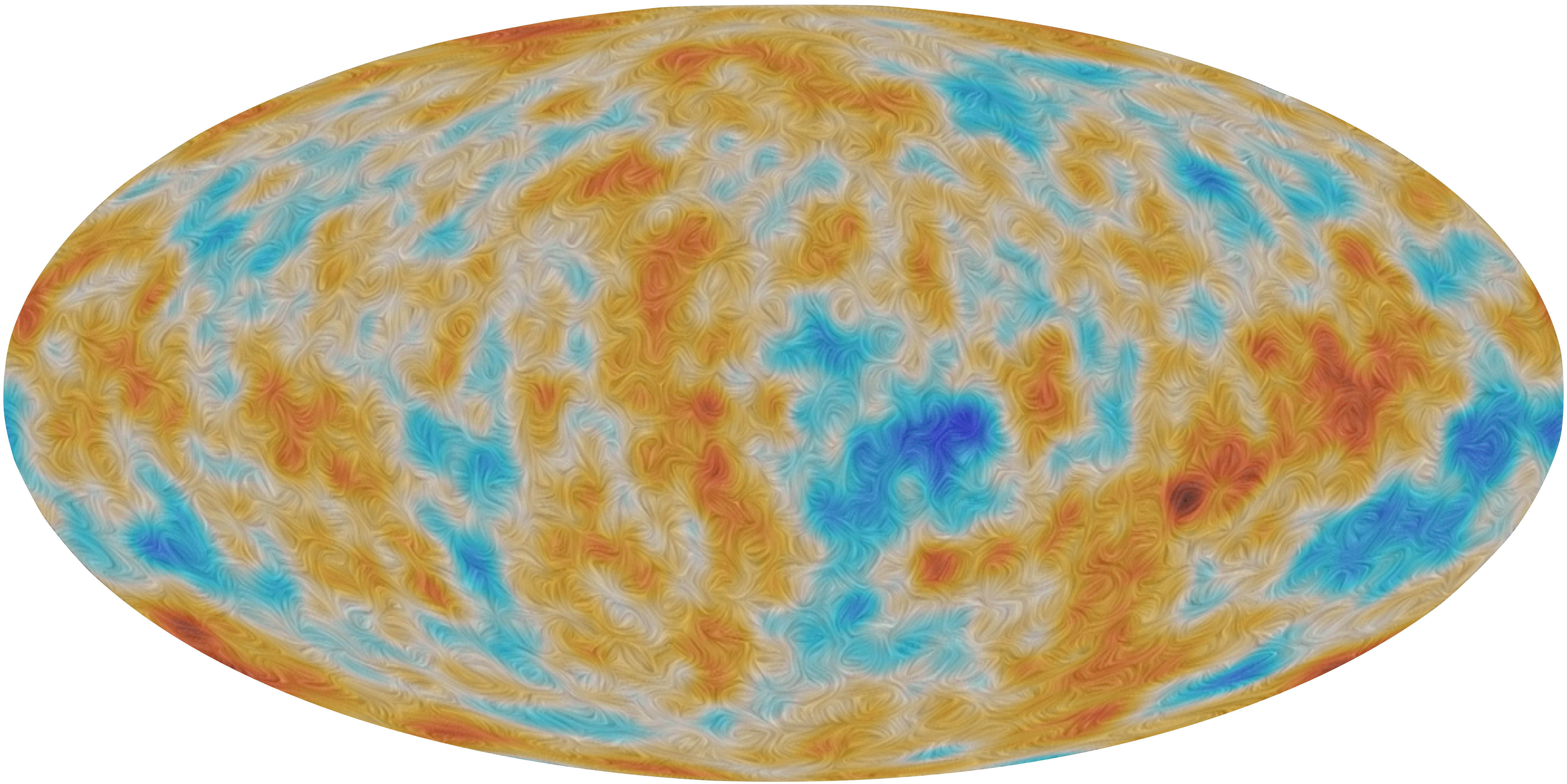
Planck 2015

Components in the microwave sky



Planck 2015

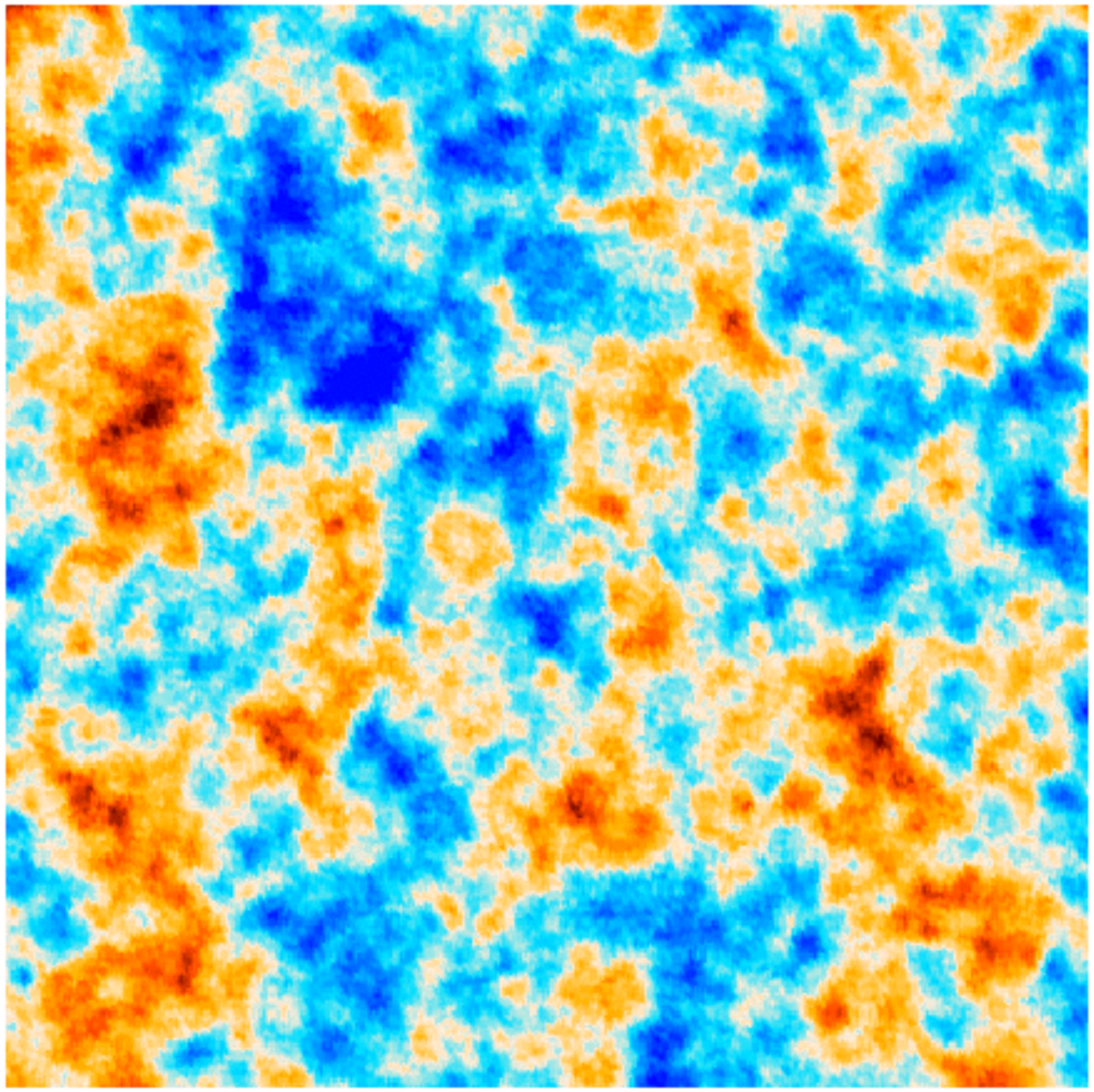
Temperature anisotropies



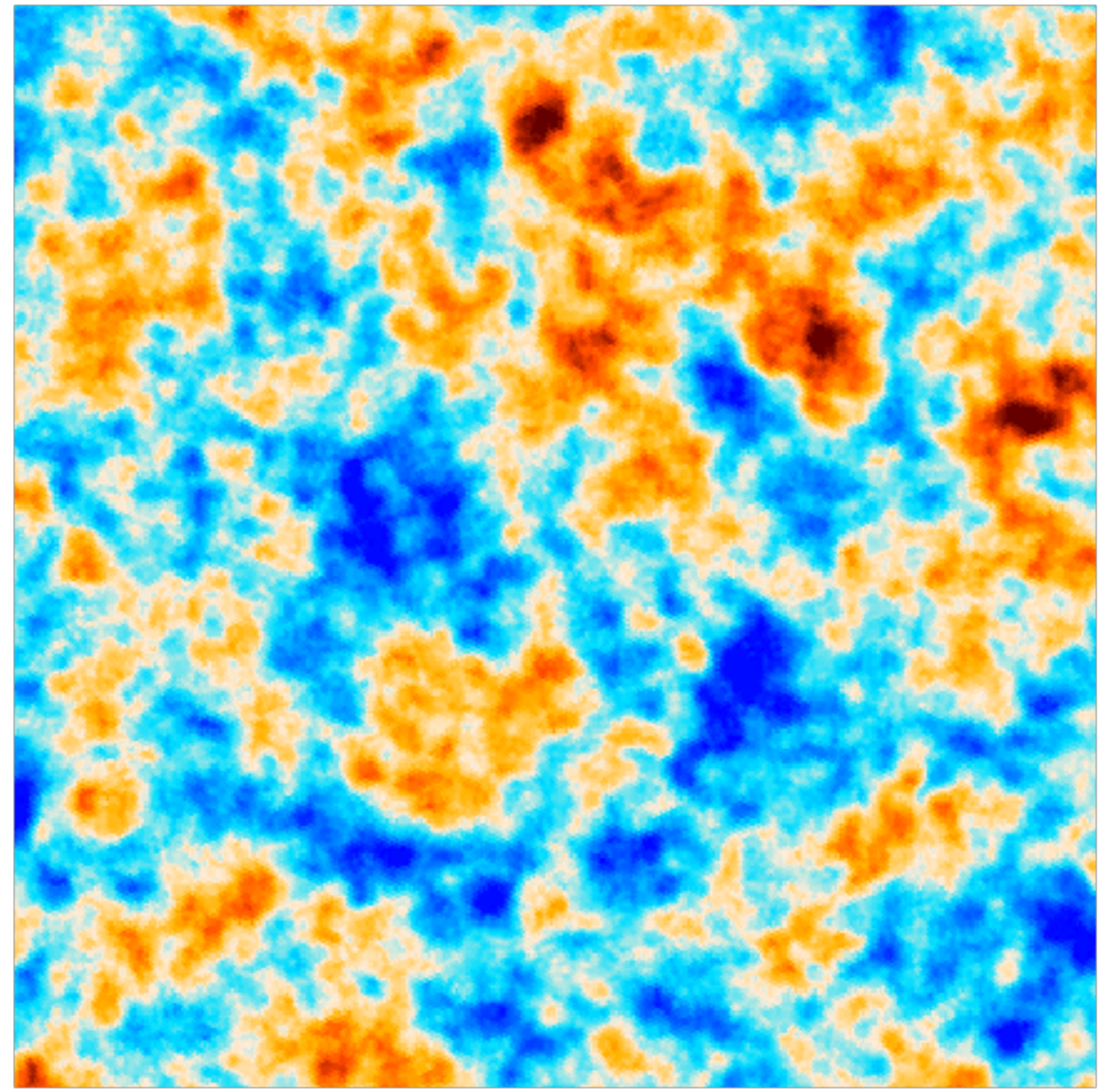
Planck 2015

Polarization

(glon,glat)=(139,43)



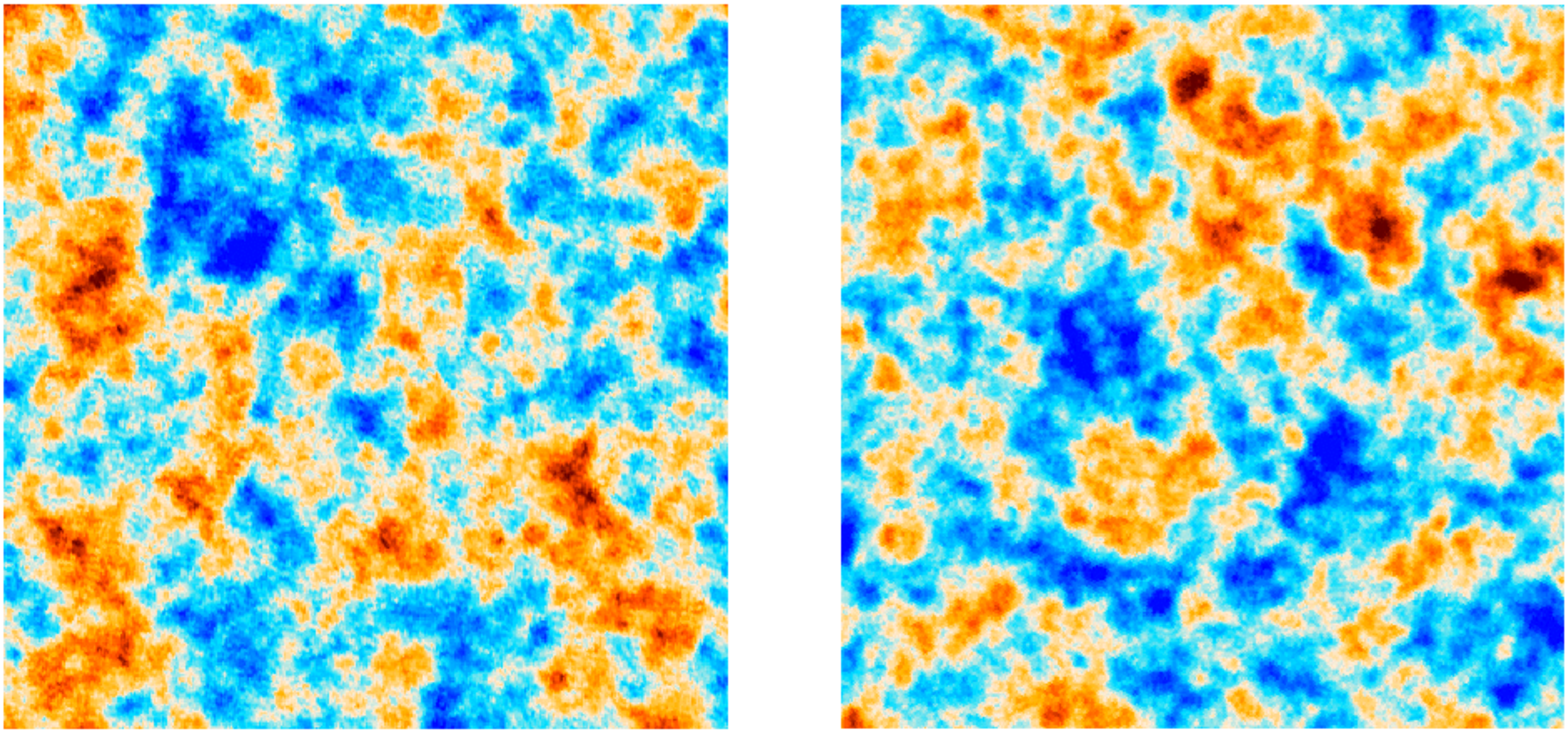
(glon,glat)=(99,-50)



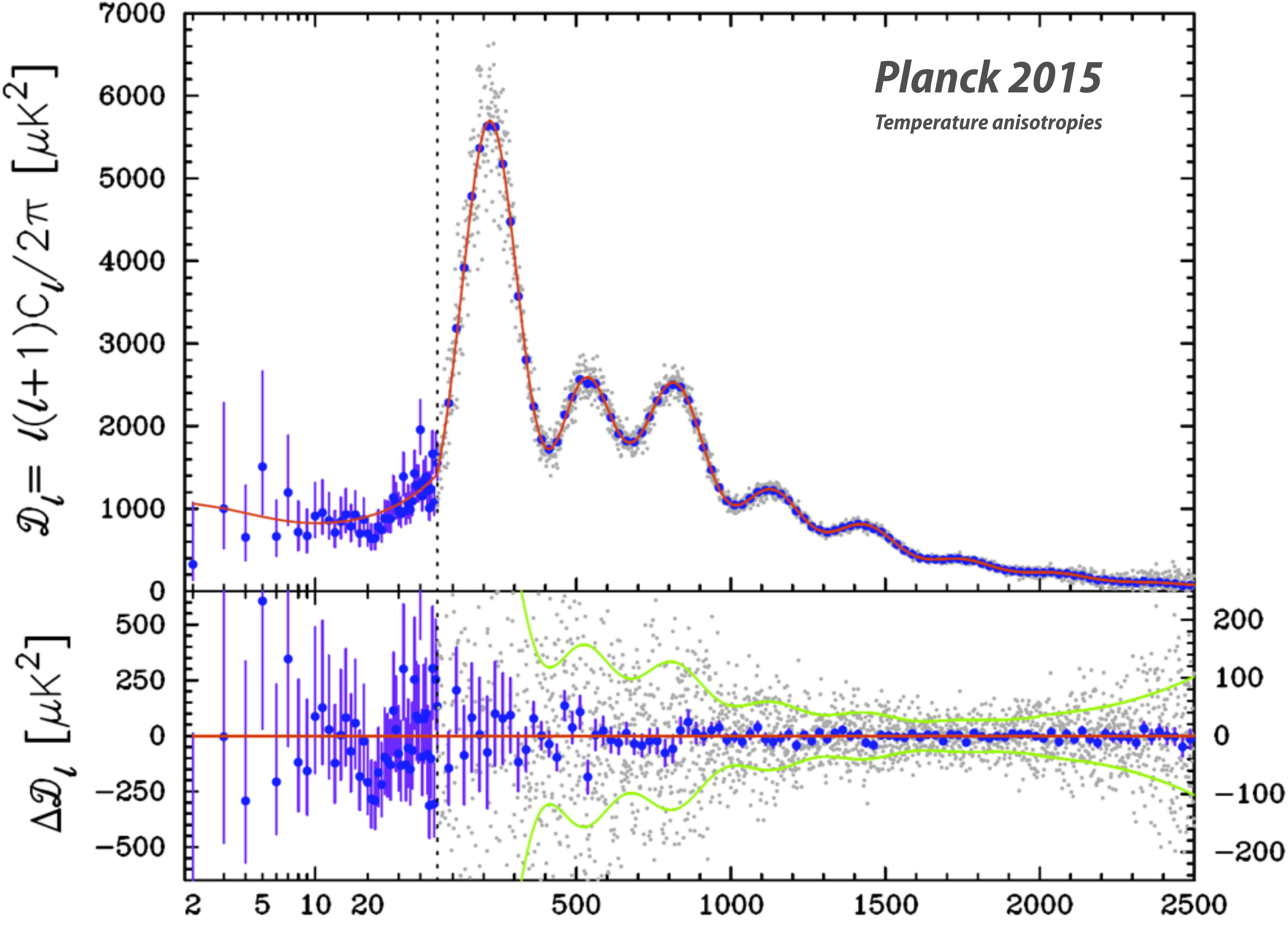
Planck 2015

(glon,glat)=(139,43)

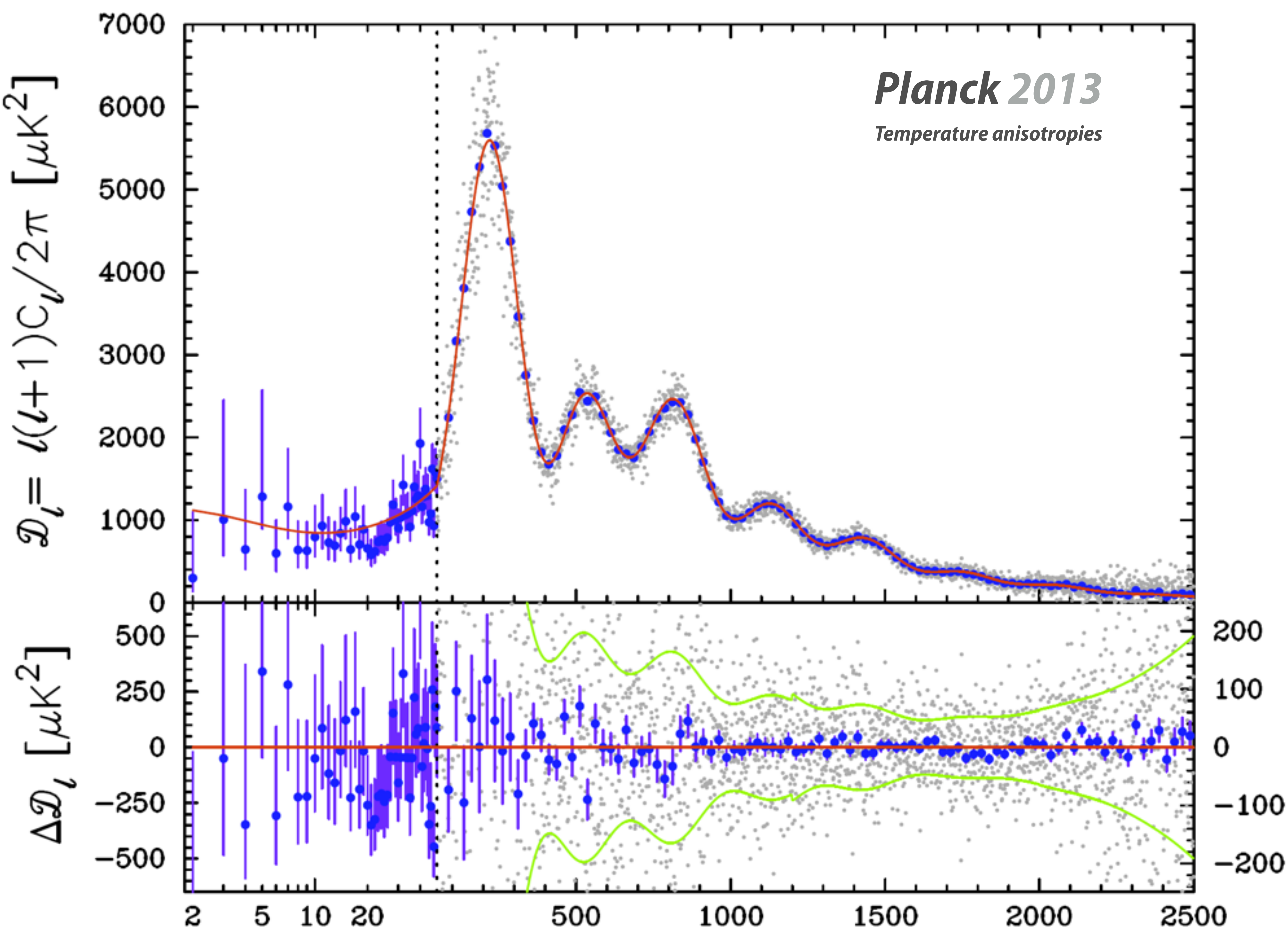
(glon,glat)=(99,-50)



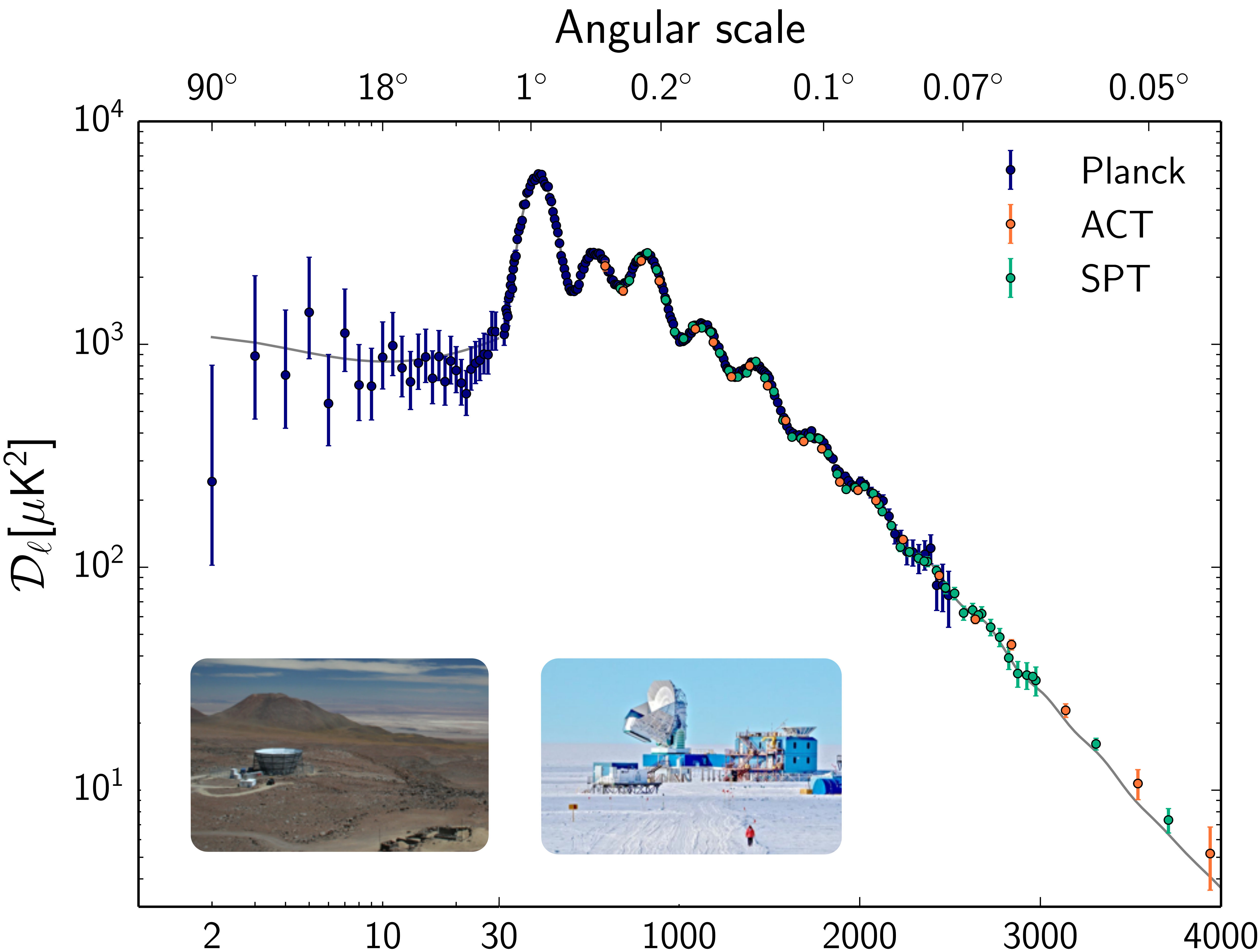
Planck 2013

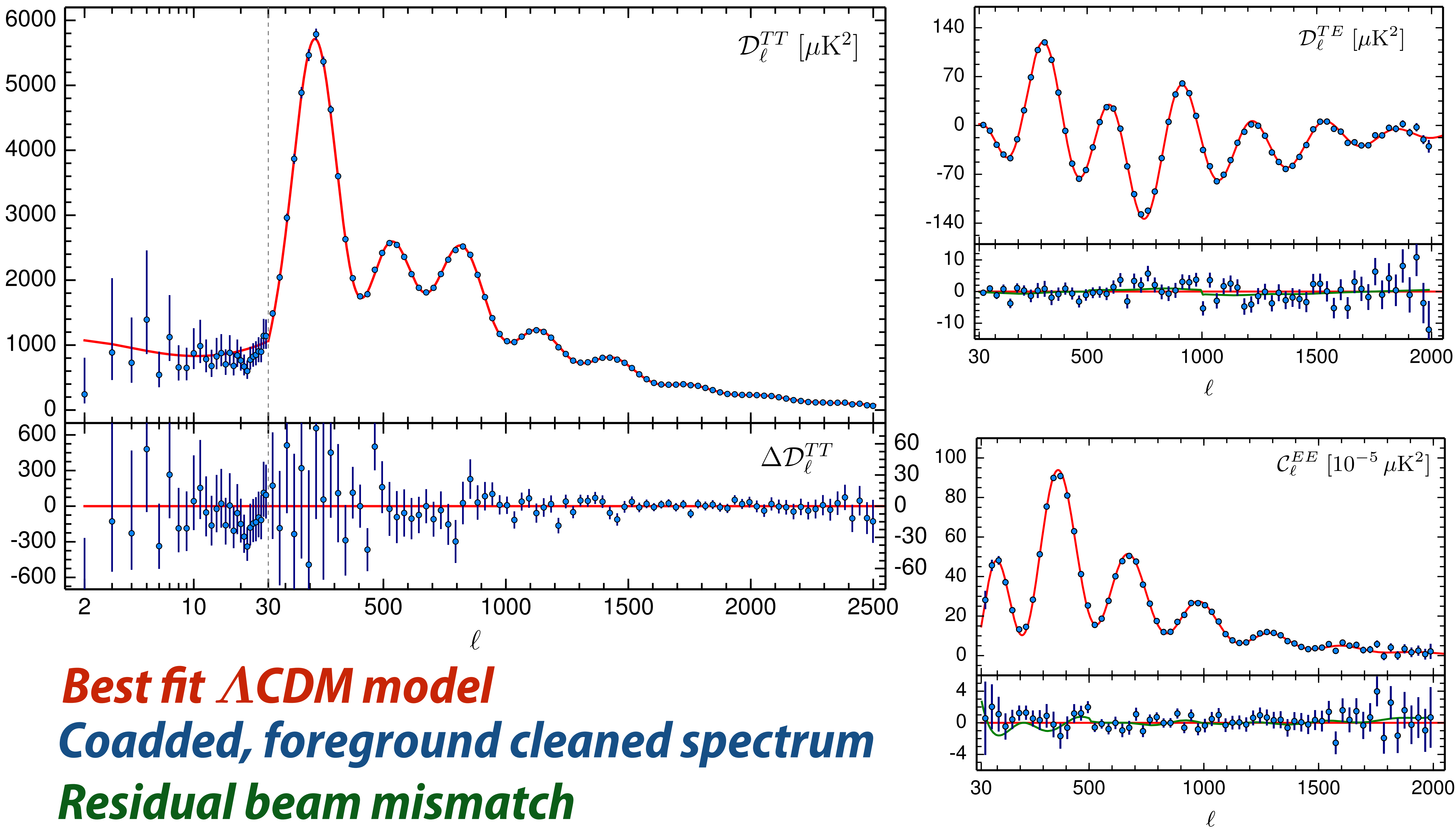


Planck 2015
Temperature anisotropies
$\mathcal{D}_\ell = \ell(\ell+1)C_\ell/2\pi \ [\mu K^2]$
$\Delta\mathcal{D}_\ell \ [\mu K^2]$
7000
6000
5000
4000
3000
2000
1000
0
500
250
0
−250
−500
200
100
0
−100
−200
2
5
10
20
500
1000
1500
2000
2500



Planck 2013
Temperature anisotropies
$\mathcal{D}_\ell = \ell(\ell+1)C_\ell/2\pi\ [\mu K^2]$
$\Delta\mathcal{D}_\ell\ [\mu K^2]$
7000
6000
5000
4000
3000
2000
1000
0
500
250
0
−250
−500
200
100
0
−100
−200
2
5
10
20
500
1000
1500
2000
2500


Angular scale
90°
18°
1°
0.2°
0.1°
0.07°
0.05°
10^4
10^3
10^2
10^1
$\mathcal{D}_\ell[\mu K^2]$
Planck
ACT
SPT
2
10
30
1000
2000
3000
4000



Best fit ΛCDM model

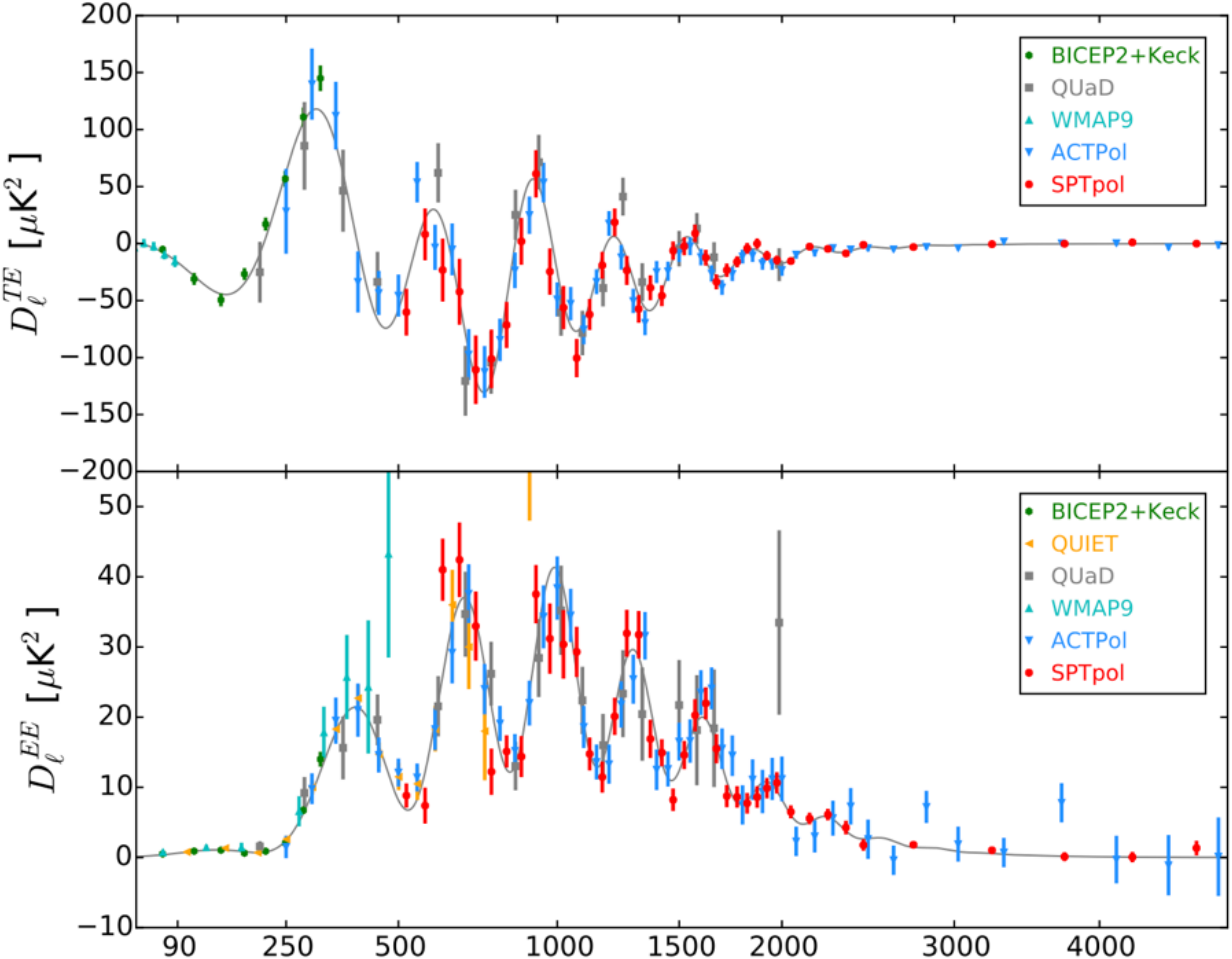
Coadded, foreground cleaned spectrum

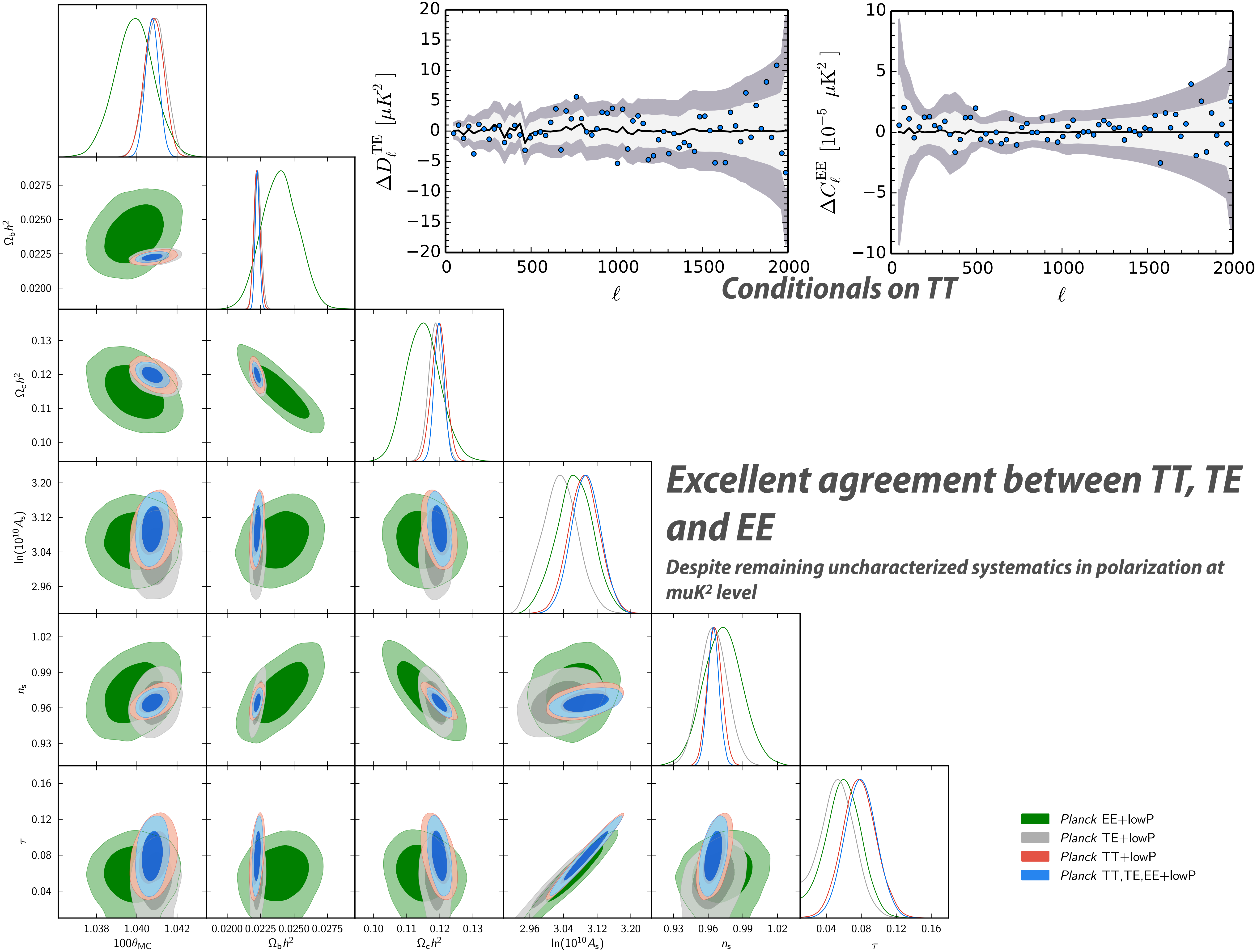
Residual beam mismatch

expected dominant residual contribution at muK² level

Pre Planck 2015 state of the art

Crites et al. 2014





Conditionals on TT

Excellent agreement between TT, TE and EE

Despite remaining uncharacterized systematics in polarization at muK² level

[1] Parameter	[2] 2013N(DS)	[3] 2013F(DS)	[4] 2013F(CY)	[5] 2015F(CHM)	[6] 2015F(CHM) (Plik)	$([2]-[6])/\sigma_{[6]}$	$([5]-[6])/\sigma_{[5]}$
$100\theta_{MC}$	1.04131 ± 0.00063	1.04126 ± 0.00047	1.04121 ± 0.00048	1.04094 ± 0.00048	1.04086 ± 0.00048	0.71	0.17
$\Omega_b h^2$	0.02205 ± 0.00028	0.02234 ± 0.00023	0.02230 ± 0.00023	0.02225 ± 0.00023	0.02222 ± 0.00023	−0.61	0.13
$\Omega_c h^2$	0.1199 ± 0.0027	0.1189 ± 0.0022	0.1188 ± 0.0022	0.1194 ± 0.0022	0.1199 ± 0.0022	0.00	−0.23
H_0	67.3 ± 1.2	67.8 ± 1.0	67.8 ± 1.0	67.48 ± 0.98	67.26 ± 0.98	0.03	0.22
n_s	0.9603 ± 0.0073	0.9665 ± 0.0062	0.9655 ± 0.0062	0.9682 ± 0.0062	0.9652 ± 0.0062	−0.67	0.48
Ω_m	0.315 ± 0.017	0.308 ± 0.013	0.308 ± 0.013	0.313 ± 0.013	0.316 ± 0.014	−0.06	−0.23
σ_8	0.829 ± 0.012	0.831 ± 0.011	0.828 ± 0.012	0.829 ± 0.015	0.830 ± 0.015	−0.08	−0.07
τ	0.089 ± 0.013	0.096 ± 0.013	0.094 ± 0.013	0.079 ± 0.019	0.078 ± 0.019	0.85	0.05
$10^9 A_s e^{-2\tau}$	1.836 ± 0.013	1.833 ± 0.011	1.831 ± 0.011	1.875 ± 0.014	1.881 ± 0.014	−3.46	−0.42

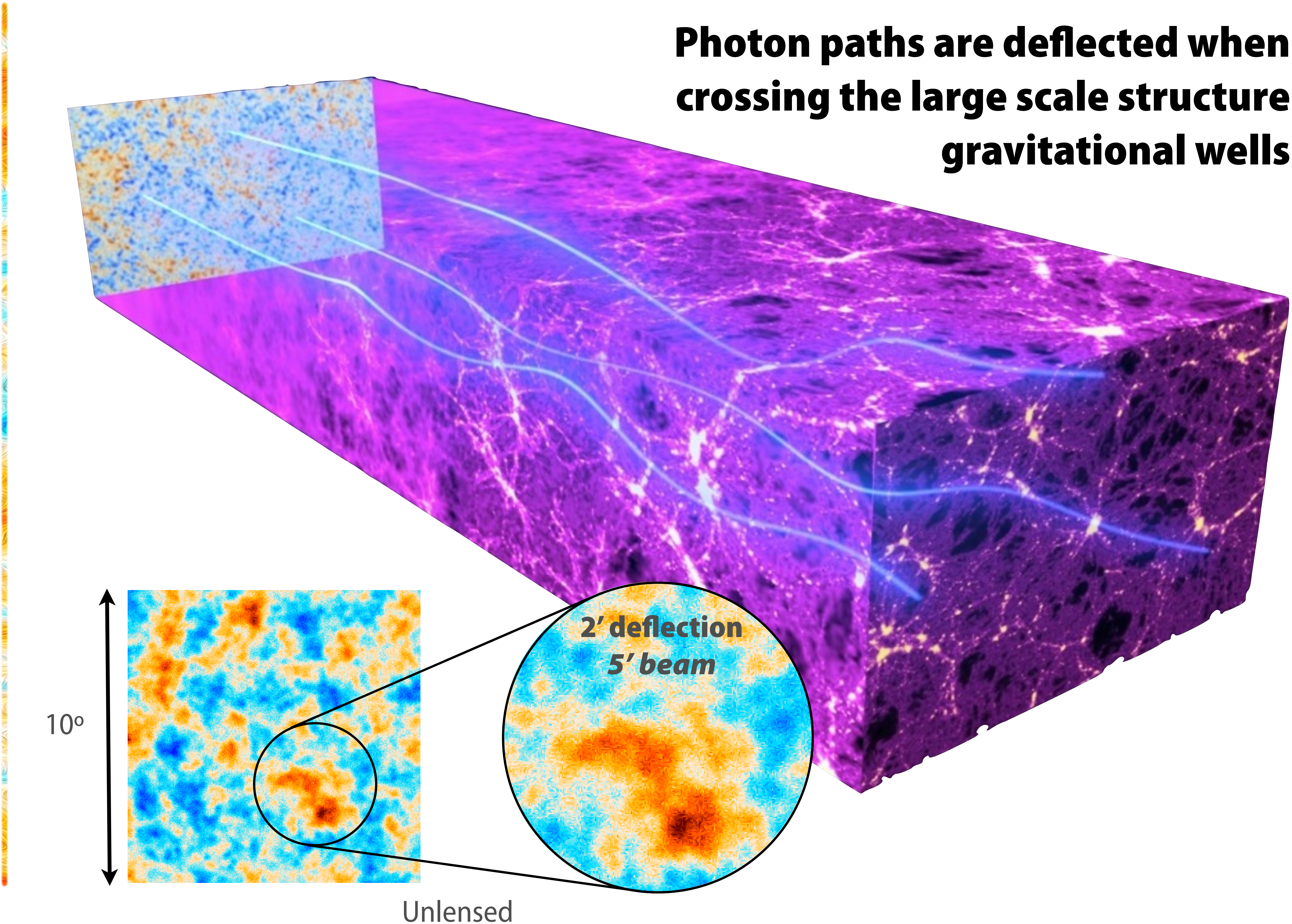
Results stable against

2013 vs 2015

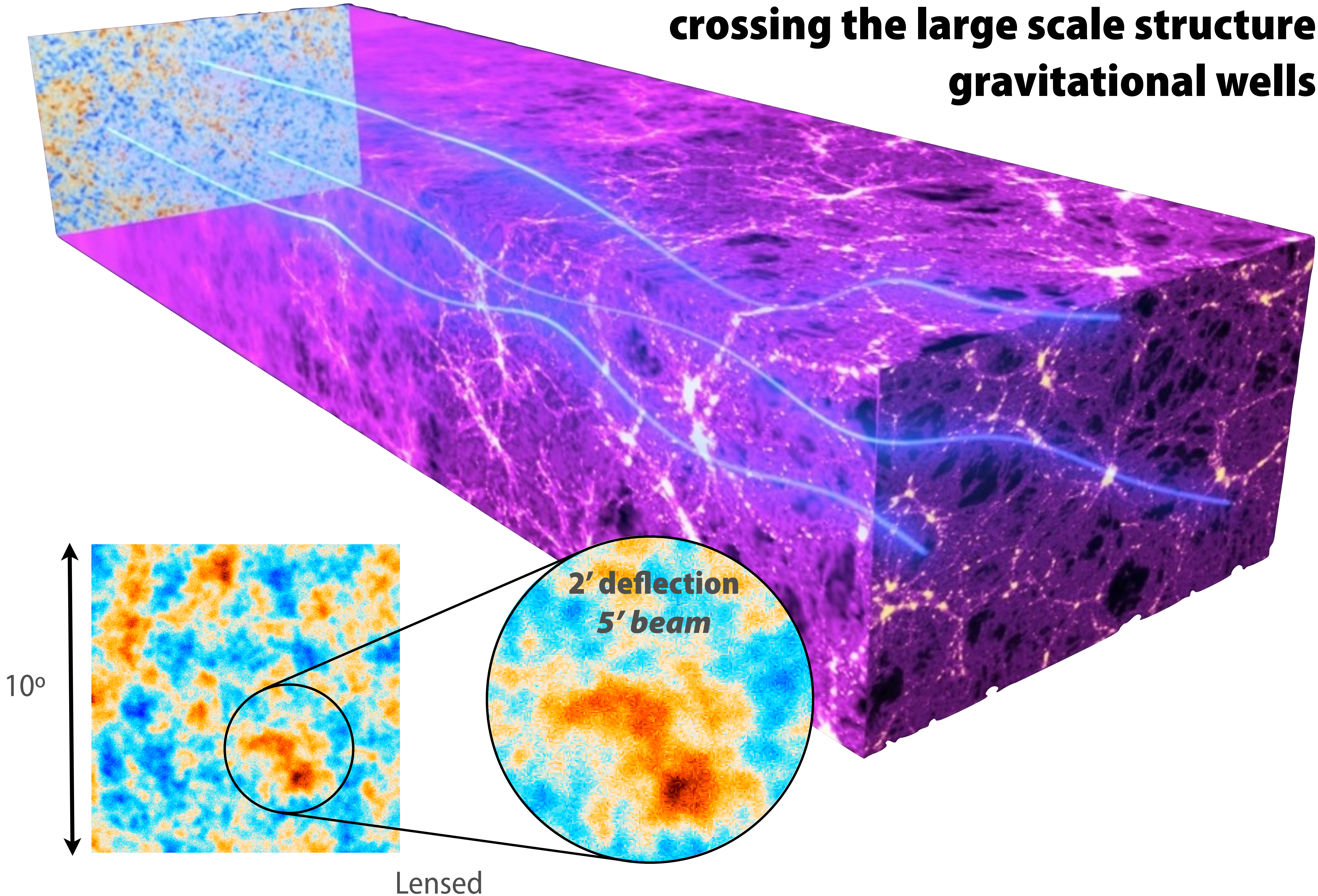
different methods

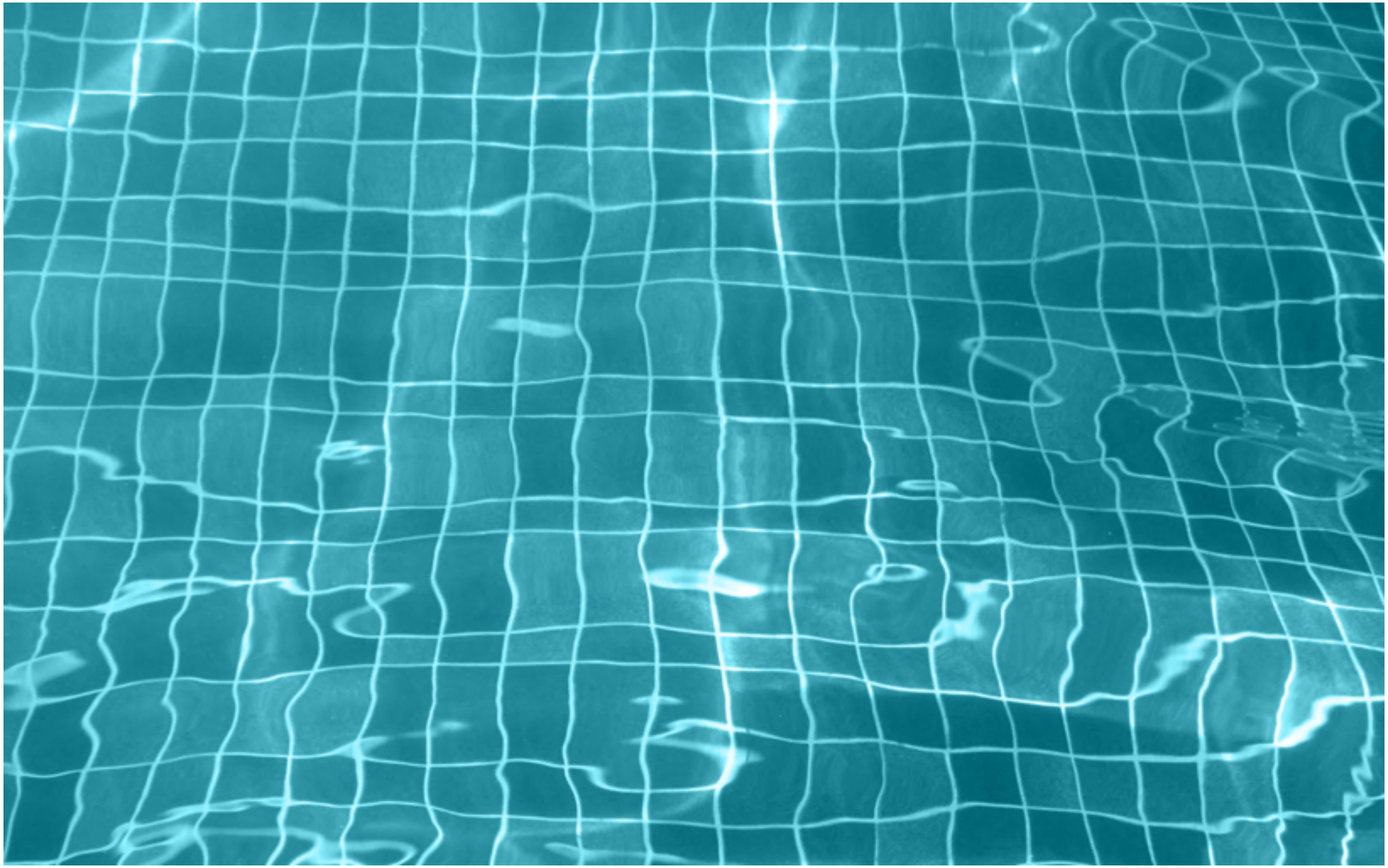
different datasets

Parameter	[1] *Planck* TT+lowP	[2] *Planck* TE+lowP	[3] *Planck* EE+lowP	[4] *Planck* TT,TE,EE+lowP	$([1]-[4])/\sigma_{[1]}$
$\Omega_b h^2$	0.02222 ± 0.00023	0.02228 ± 0.00025	0.0240 ± 0.0013	0.02225 ± 0.00016	−0.1
$\Omega_c h^2$	0.1197 ± 0.0022	0.1187 ± 0.0021	$0.1150^{+0.0048}_{-0.0055}$	0.1198 ± 0.0015	0.0
$100\theta_{MC}$	1.04085 ± 0.00047	1.04094 ± 0.00051	1.03988 ± 0.00094	1.04077 ± 0.00032	0.2
τ	0.078 ± 0.019	0.053 ± 0.019	$0.059^{+0.022}_{-0.019}$	0.079 ± 0.017	−0.1
$\ln(10^{10} A_s)$	3.089 ± 0.036	3.031 ± 0.041	$3.066^{+0.046}_{-0.041}$	3.094 ± 0.034	−0.1
n_s	0.9655 ± 0.0062	0.965 ± 0.012	0.973 ± 0.016	0.9645 ± 0.0049	0.2
H_0	67.31 ± 0.96	67.73 ± 0.92	70.2 ± 3.0	67.27 ± 0.66	0.0
Ω_m	0.315 ± 0.013	0.300 ± 0.012	$0.286^{+0.027}_{-0.038}$	0.3156 ± 0.0091	0.0
σ_8	0.829 ± 0.014	0.802 ± 0.018	0.796 ± 0.024	0.831 ± 0.013	0.0
$10^9 A_s e^{-2\tau}$	1.880 ± 0.014	1.865 ± 0.019	1.907 ± 0.027	1.882 ± 0.012	−0.1


Photon paths are deflected when crossing the large scale structure gravitational wells
2′ deflection
5′ beam
10º
Unlensed

Photon paths are deflected when crossing the large scale structure gravitational wells

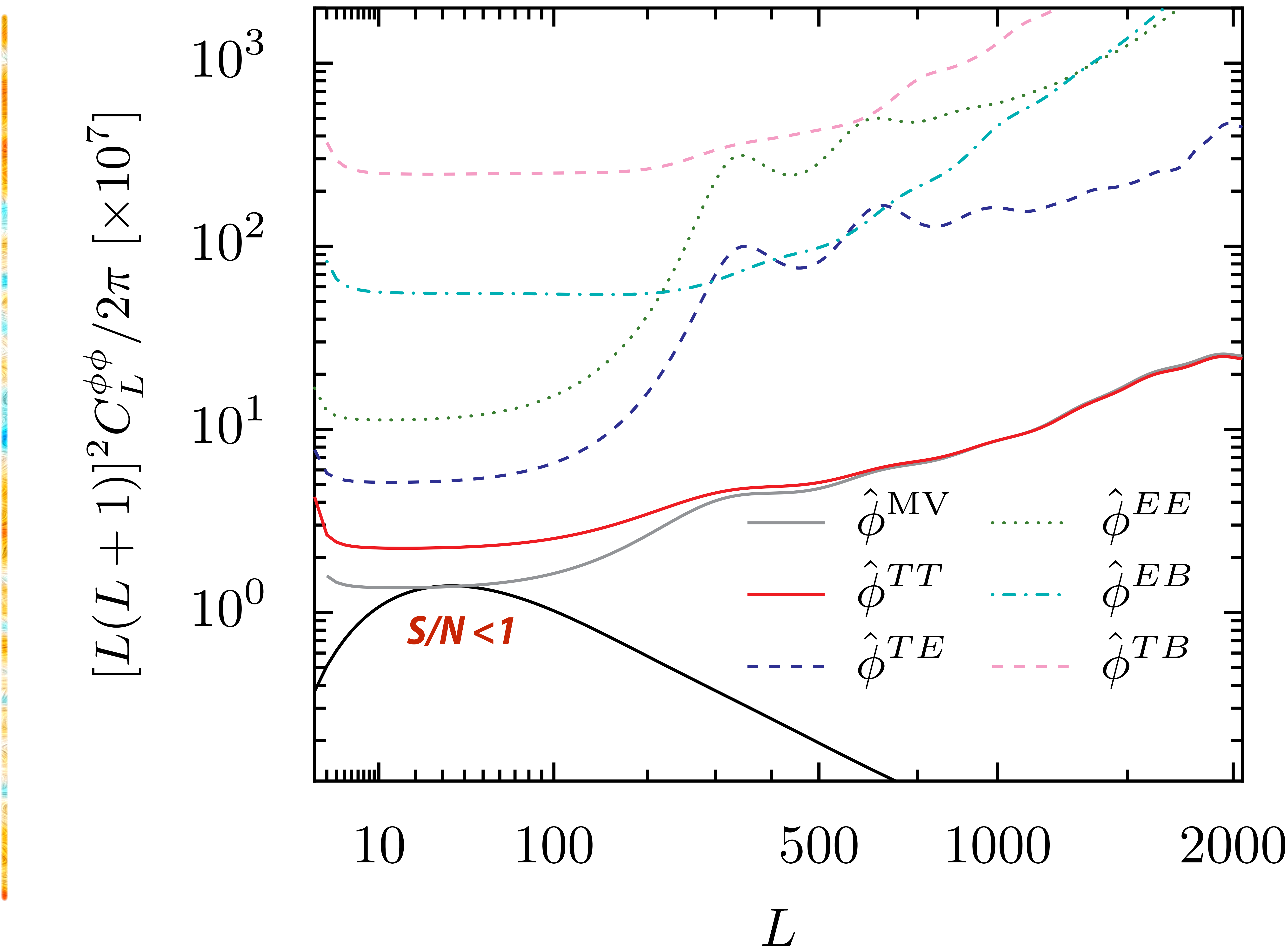




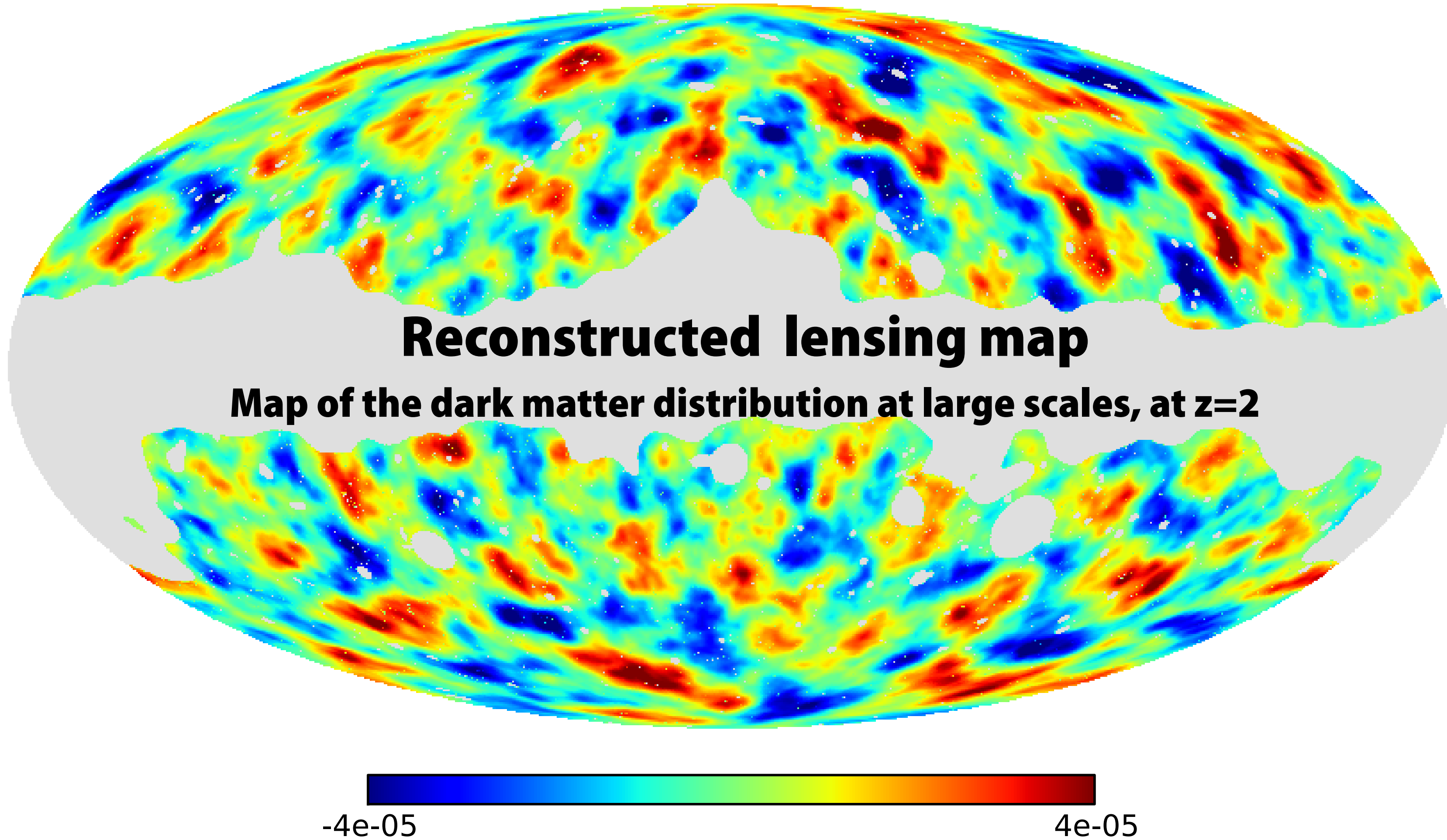
If I know the size of the tiles, I can reconstruct the water movements.

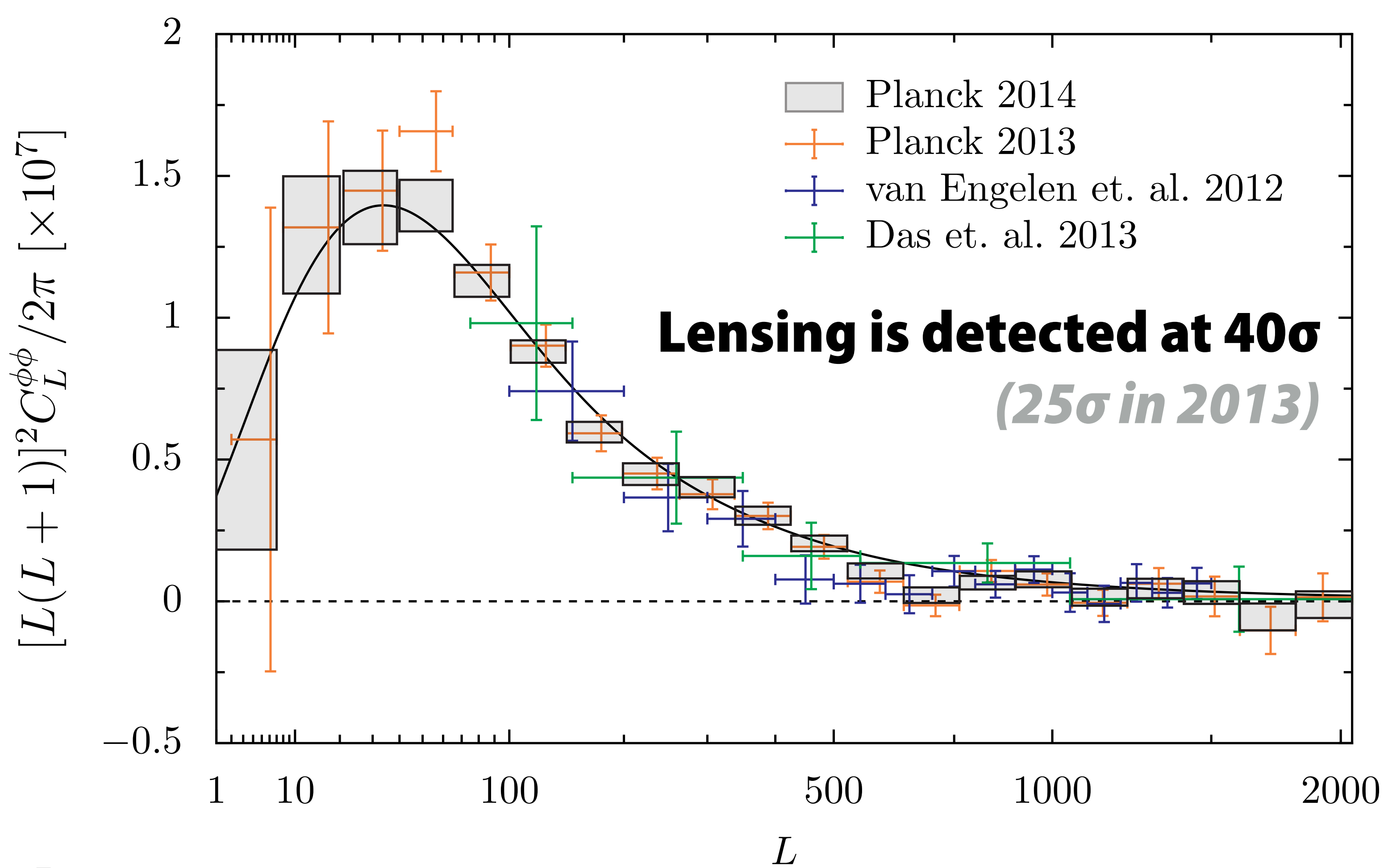
To some extent…

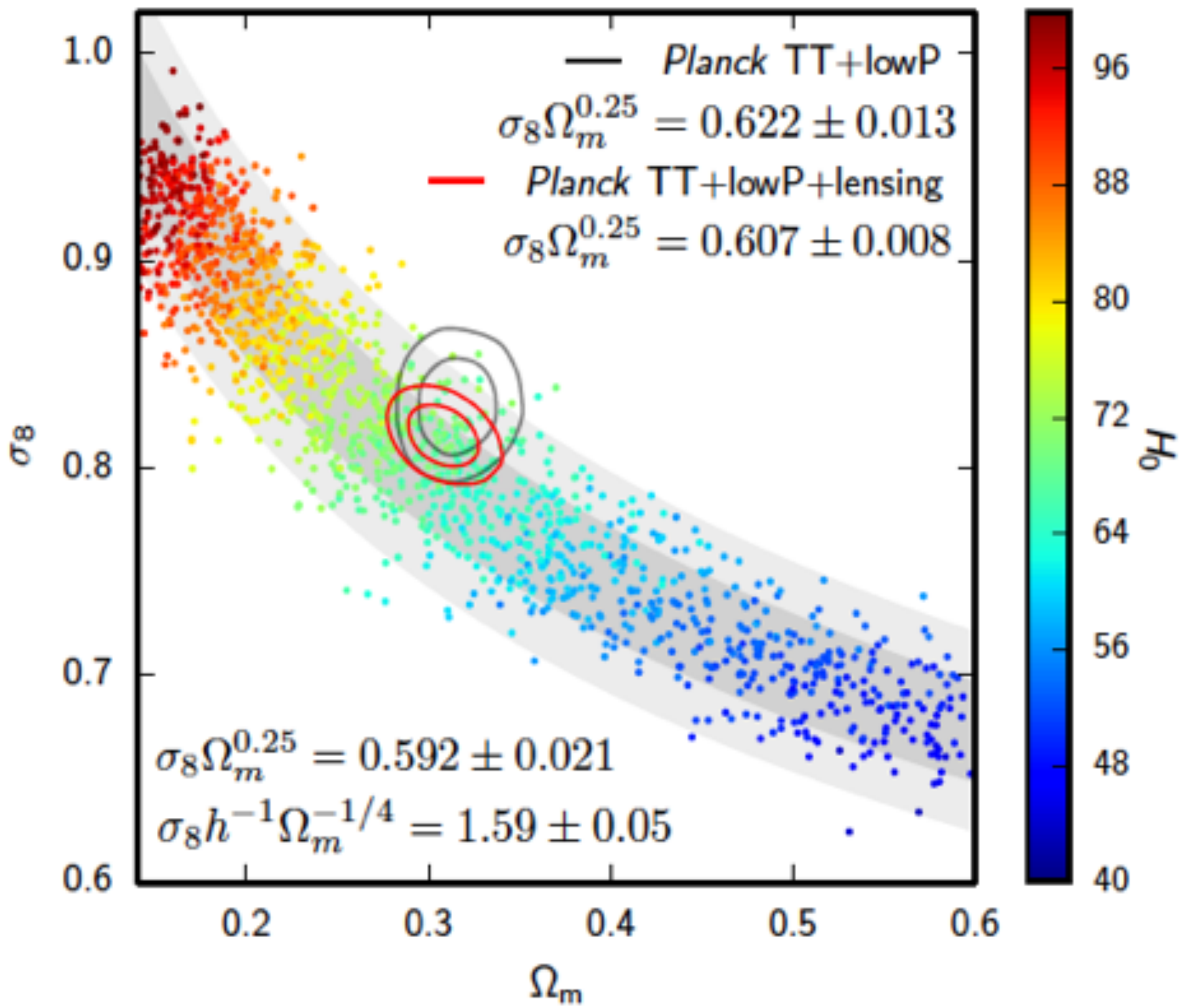
If I know about some regularity property of the tiling, I can reconstruct the water movements.

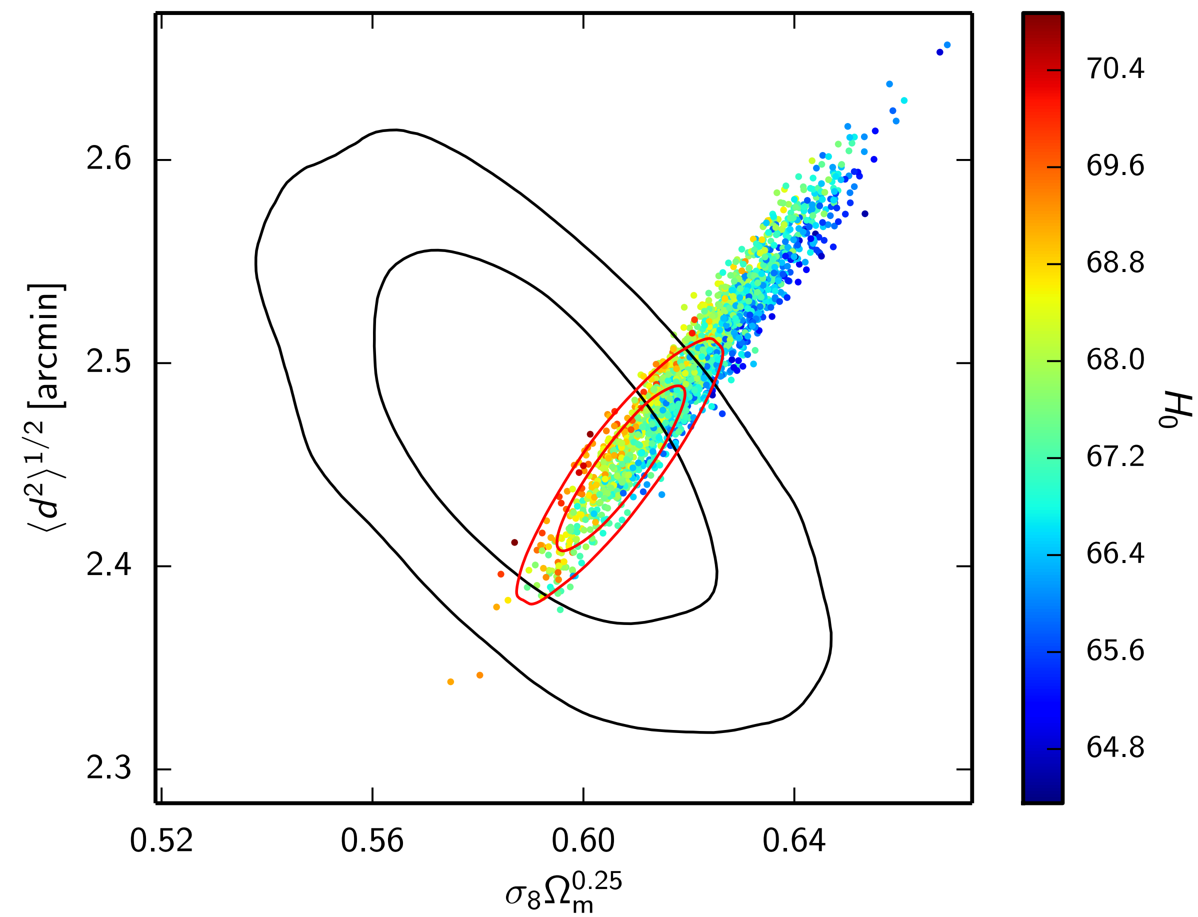


10^3
10^2
10^1
10^0
$[L(L+1)]^2 C_L^{\phi\phi}/2\pi\ [\times 10^7]$
10
100
500
1000
2000
L
S/N <1
$\hat{\phi}^{\mathrm{MV}}$
$\hat{\phi}^{TT}$
$\hat{\phi}^{TE}$
$\hat{\phi}^{EE}$
$\hat{\phi}^{EB}$
$\hat{\phi}^{TB}$

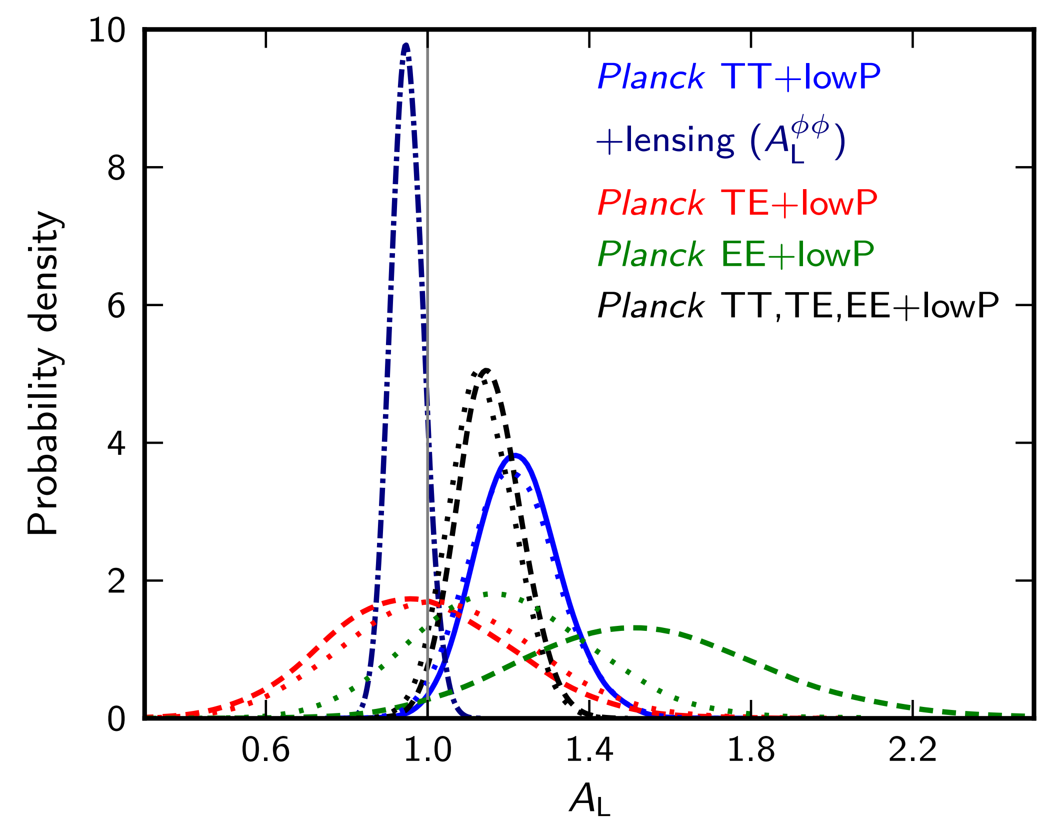

Reconstructed lensing map
Map of the dark matter distribution at large scales, at z=2
-4e-05
4e-05


Planck 2014
Planck 2013
van Engelen et. al. 2012
Das et. al. 2013
Lensing is detected at 40σ
(25σ in 2013)
$[L(L+1)]^2 C_L^{\phi\phi}/2\pi\ [\times 10^7]$
L
2
1.5
1
0.5
0
−0.5
1
10
100
500
1000
2000



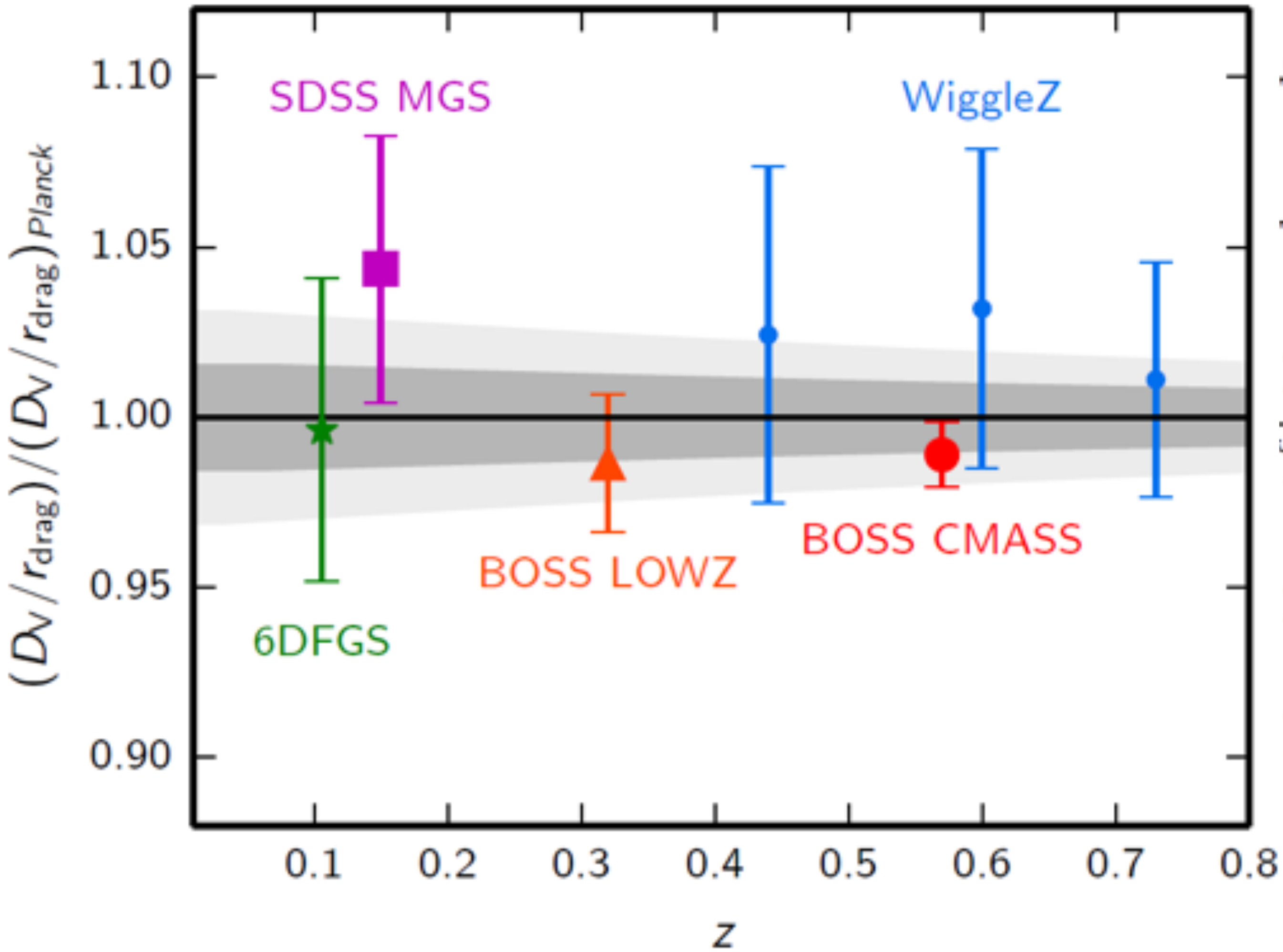


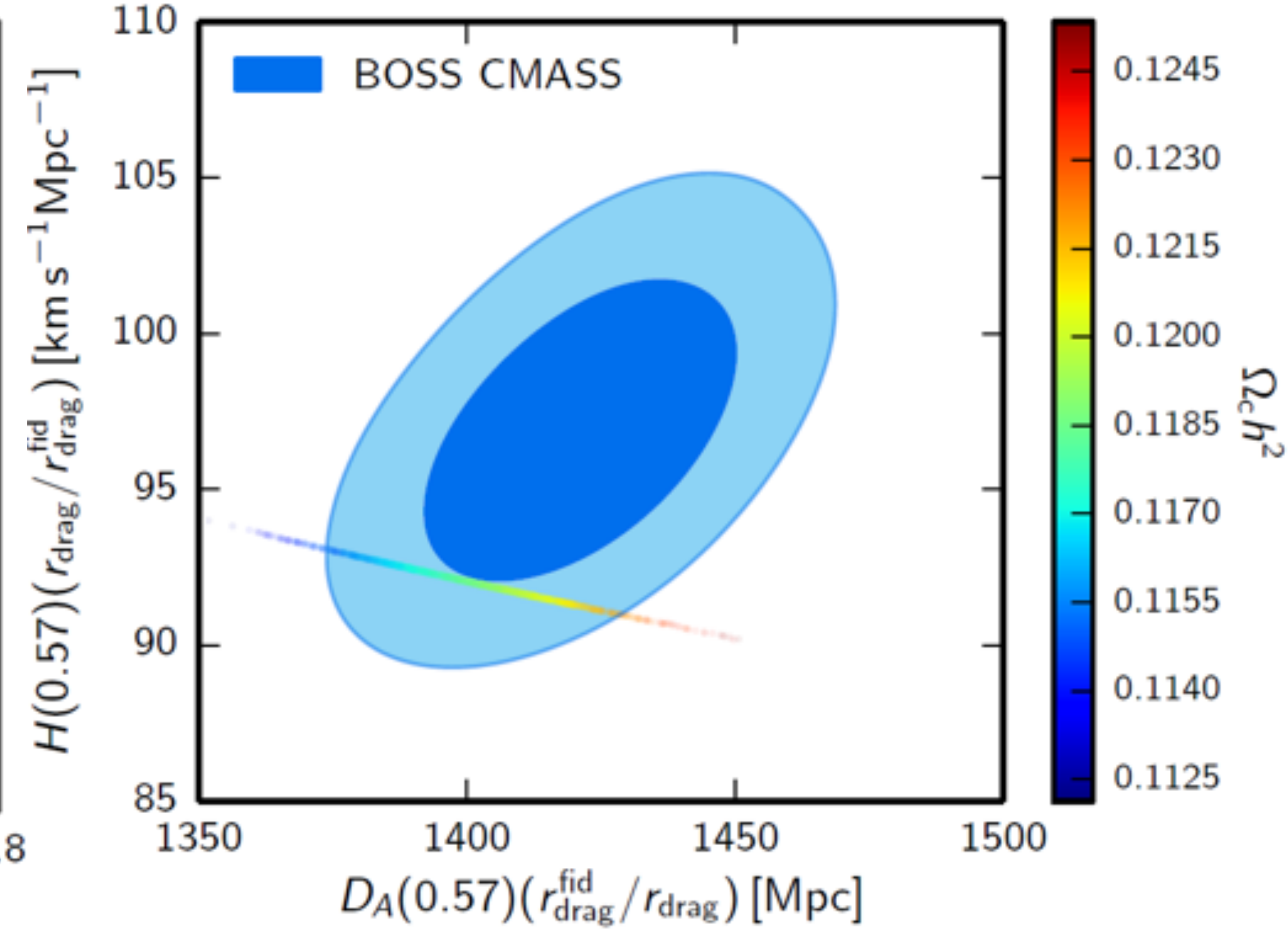
Good agreement between CMB and CMB Lensing.



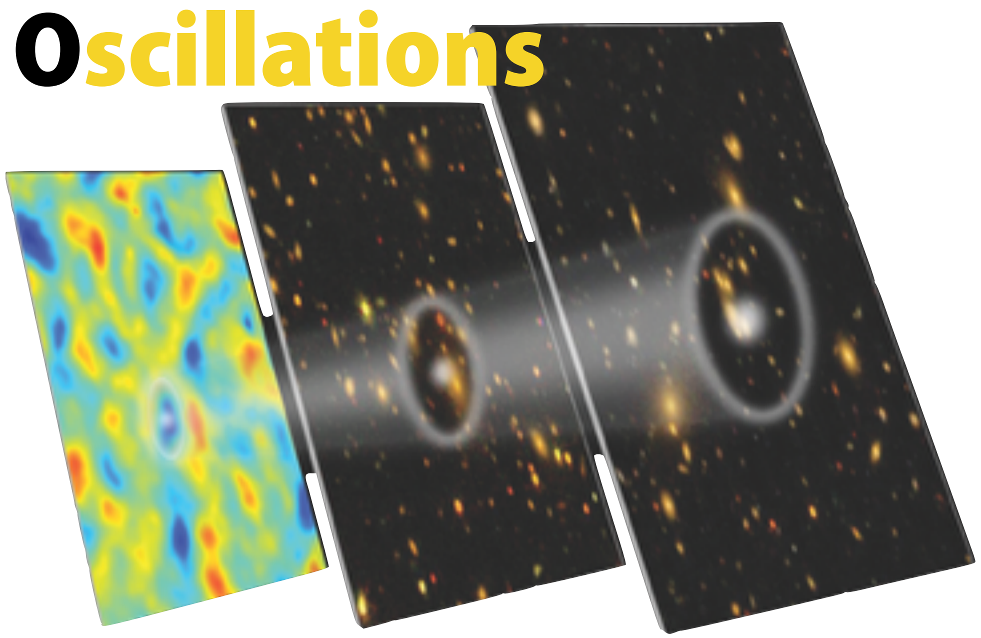
CMB Lensing wants slightly less deflection than CMB.

CMB wants a bit too much of that…



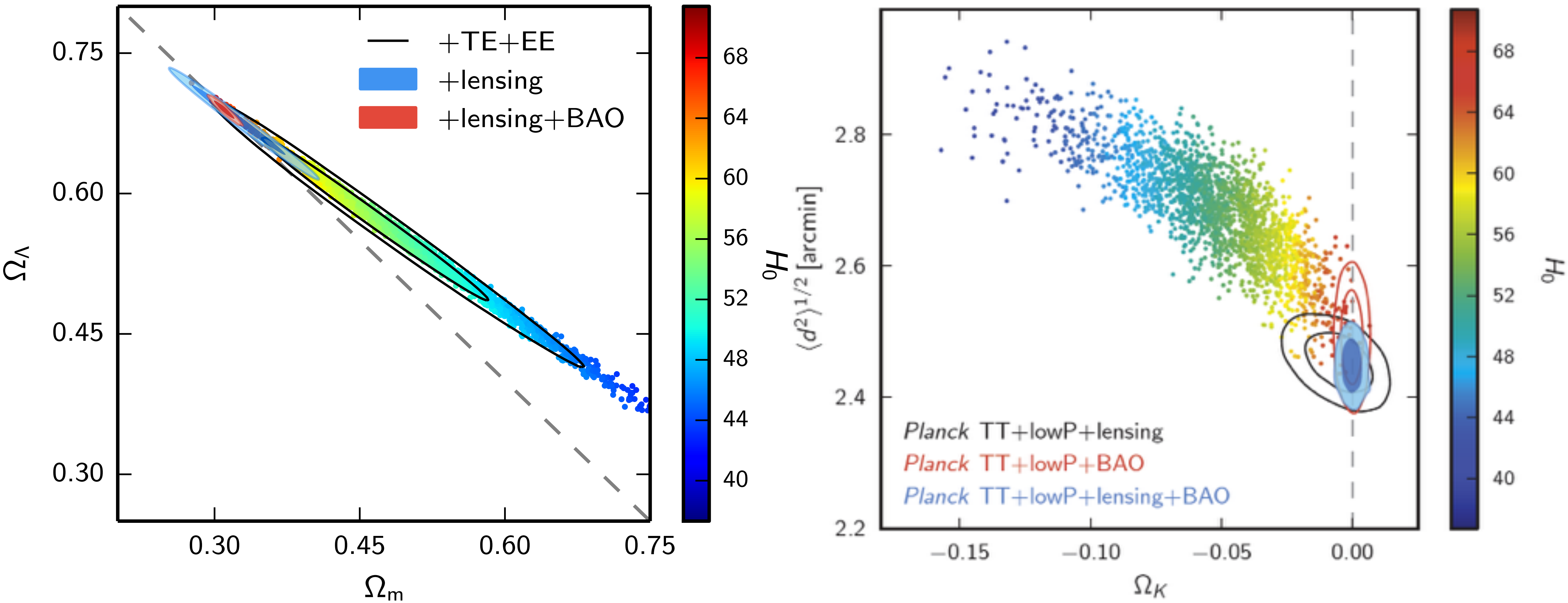


Baryon **A**coustic **O**scillations



Good agreement between CMB and BAO.

BAO provides a geometrical constraint
BAO helps tighten the matter density constraints.

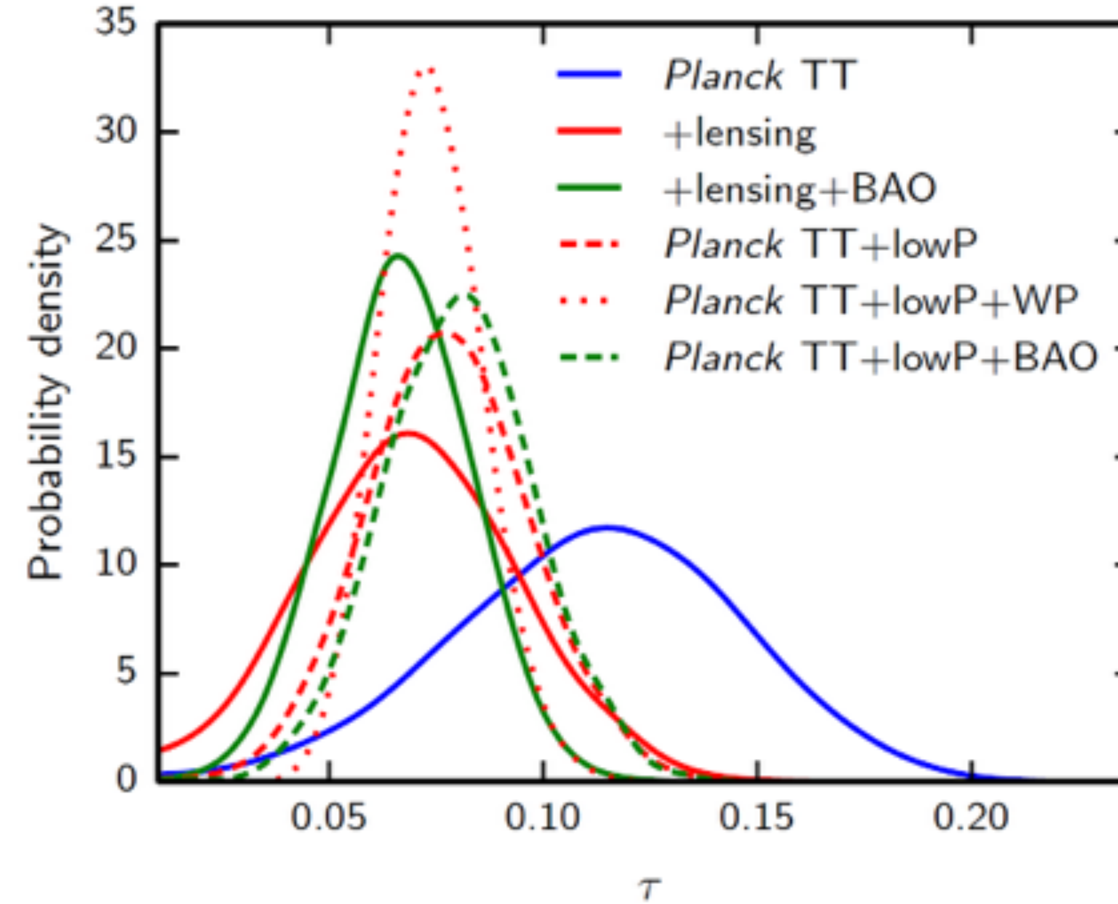


A flat universe with dark energy

$$\Omega_K = 0.000 \pm 0.005 \ (95\%)$$

Decrease in the reionization redshift

Large scale polarization breaks the degeneracy between optical depth and fluctuation amplitude.
Both Planck and WMAP dust cleaned by Planck show the same decrease.
Lensing and BAO provides Polarization independent constraints in excellent agreement.



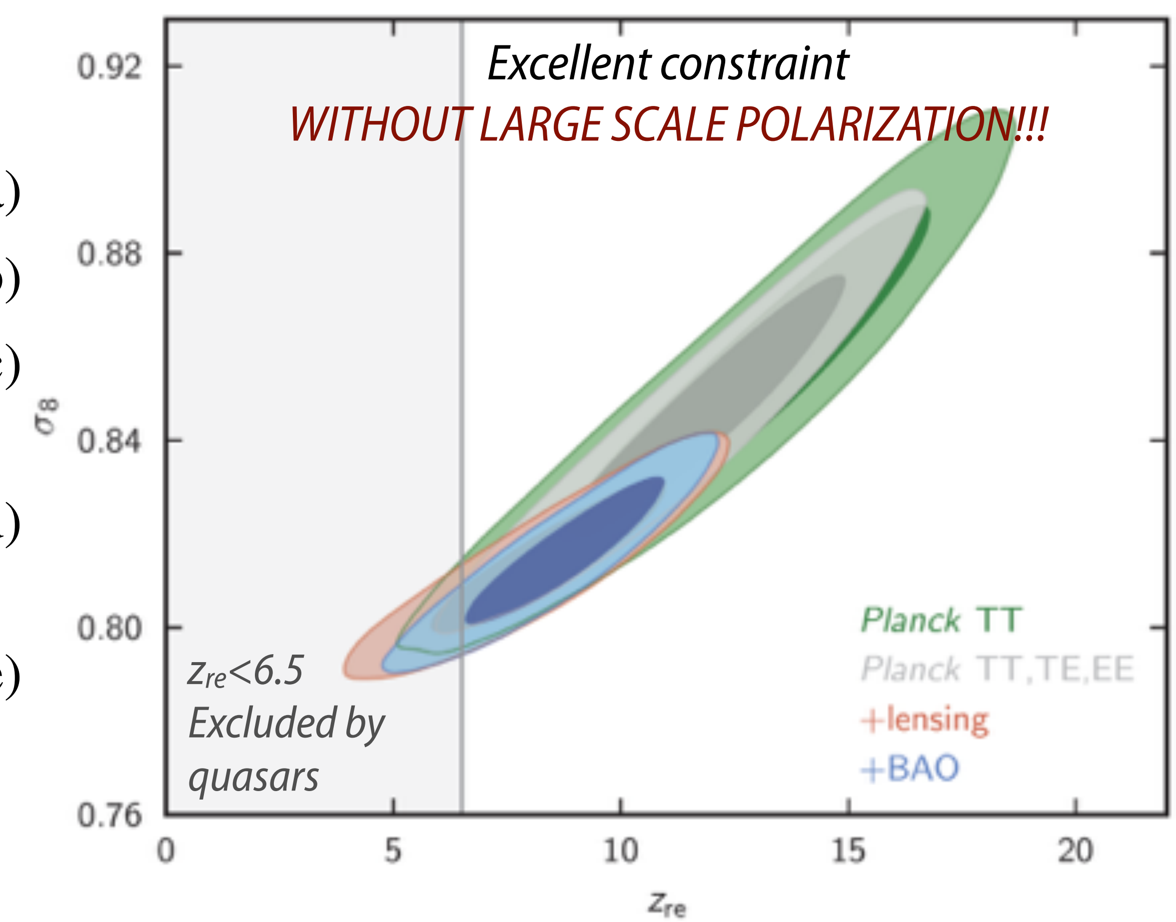
$$\tau = 0.078^{+0.019}_{-0.019}, \; z_{re} = 9.9^{+1.8}_{-1.6}, \; \textit{Planck}\ \mathrm{TT{+}lowP}; \qquad (17a)$$

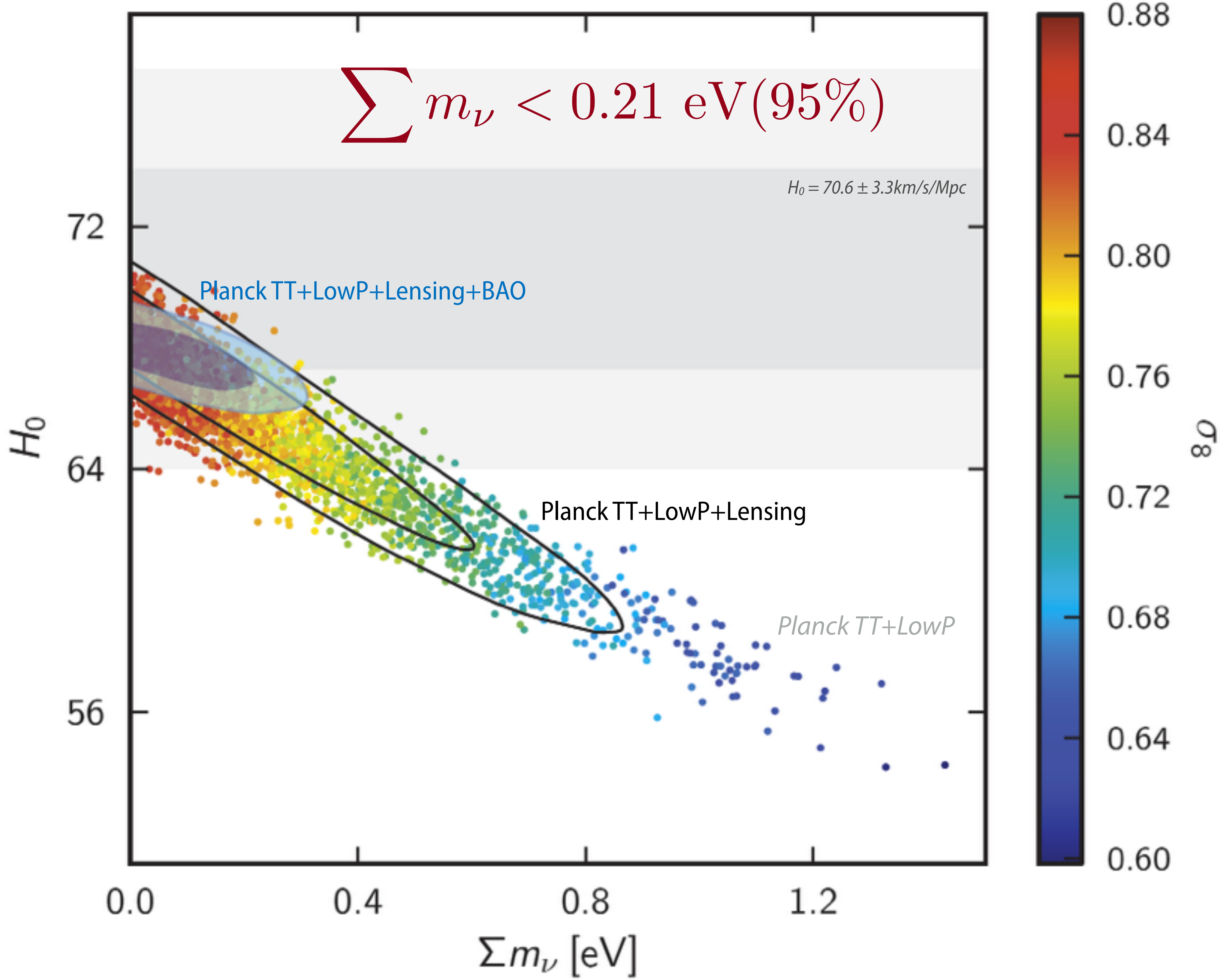
$$\tau = 0.070^{+0.024}_{-0.024}, \; z_{re} = 9.0^{+2.5}_{-2.1}, \; \textit{Planck}\ \mathrm{TT{+}lensing}; \qquad (17b)$$

$$\tau = 0.066^{+0.016}_{-0.016}, \; z_{re} = 8.8^{+1.7}_{-1.4}, \; \textit{Planck}\ \mathrm{TT{+}lowP{+}lensing}; \qquad (17c)$$

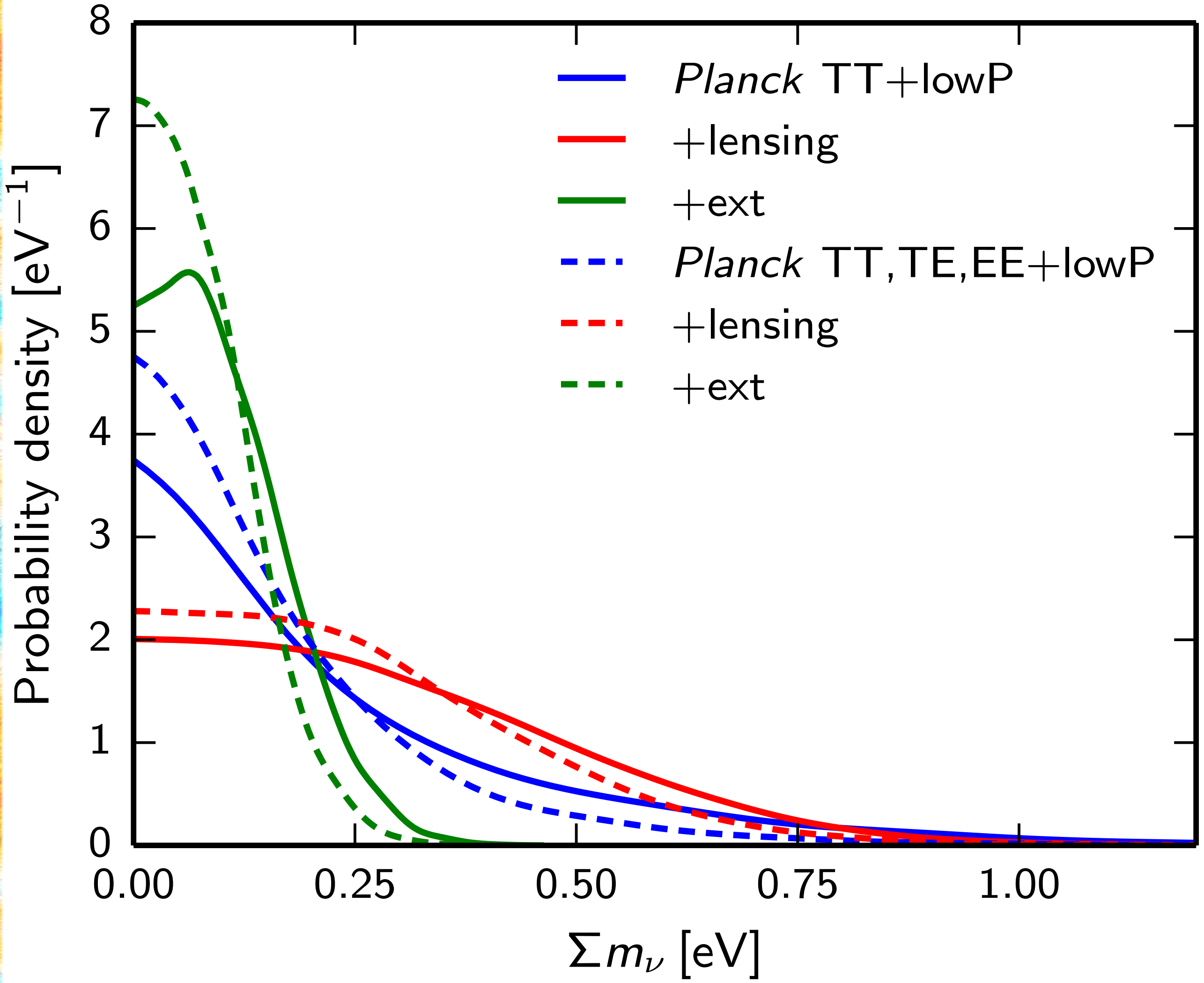
$$\tau = 0.067^{+0.016}_{-0.016}, \; z_{re} = 8.9^{+1.7}_{-1.4}, \; \textit{Planck}\ \mathrm{TT{+}lensing{+}BAO}; \qquad (17d)$$

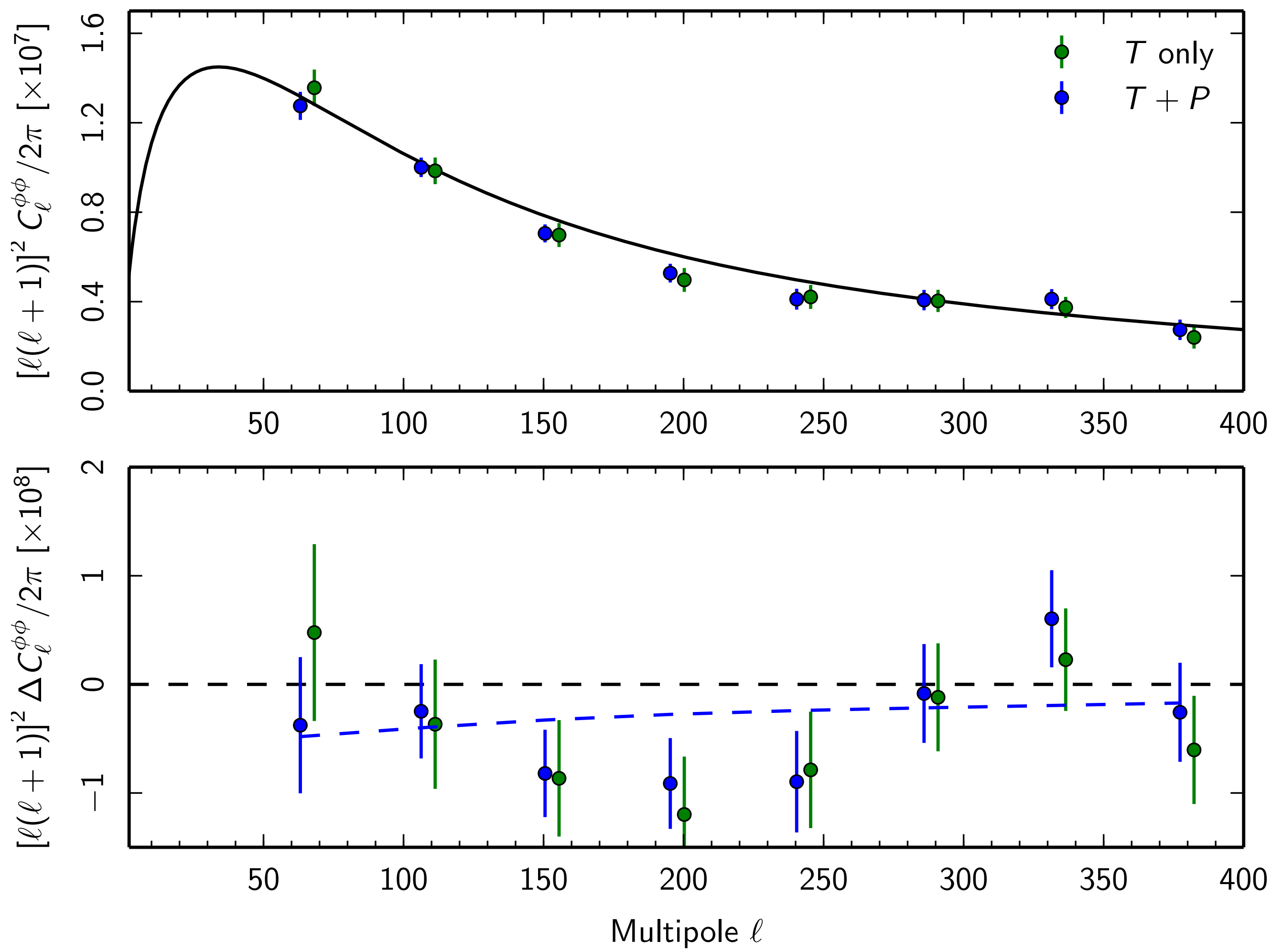
$$\tau = 0.066^{+0.013}_{-0.013}, \; z_{re} = 8.8^{+1.3}_{-1.2}, \; \textit{Planck}\ \mathrm{TT{+}lowP{+}lensing{+}BAO}. \qquad (17e)$$





$\sum m_\nu < 0.21$ eV(95%)
$H_0 = 70.6 \pm 3.3$km/s/Mpc
Planck TT+LowP+Lensing+BAO
Planck TT+LowP+Lensing
Planck TT+LowP
H_0
72
64
56
0.0
0.4
0.8
1.2
Σm_ν [eV]
σ_8
0.88
0.84
0.80
0.76
0.72
0.68
0.64
0.60

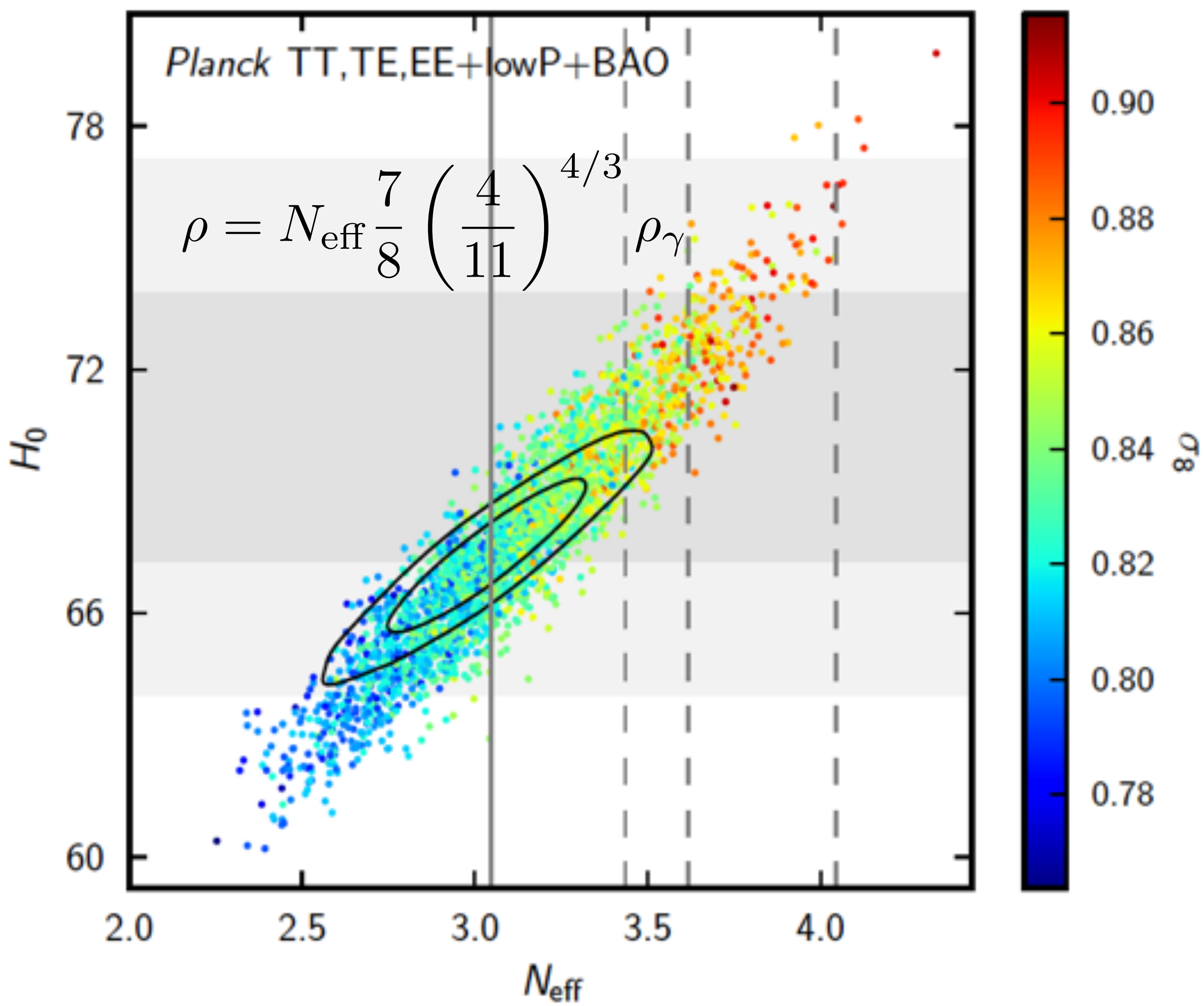




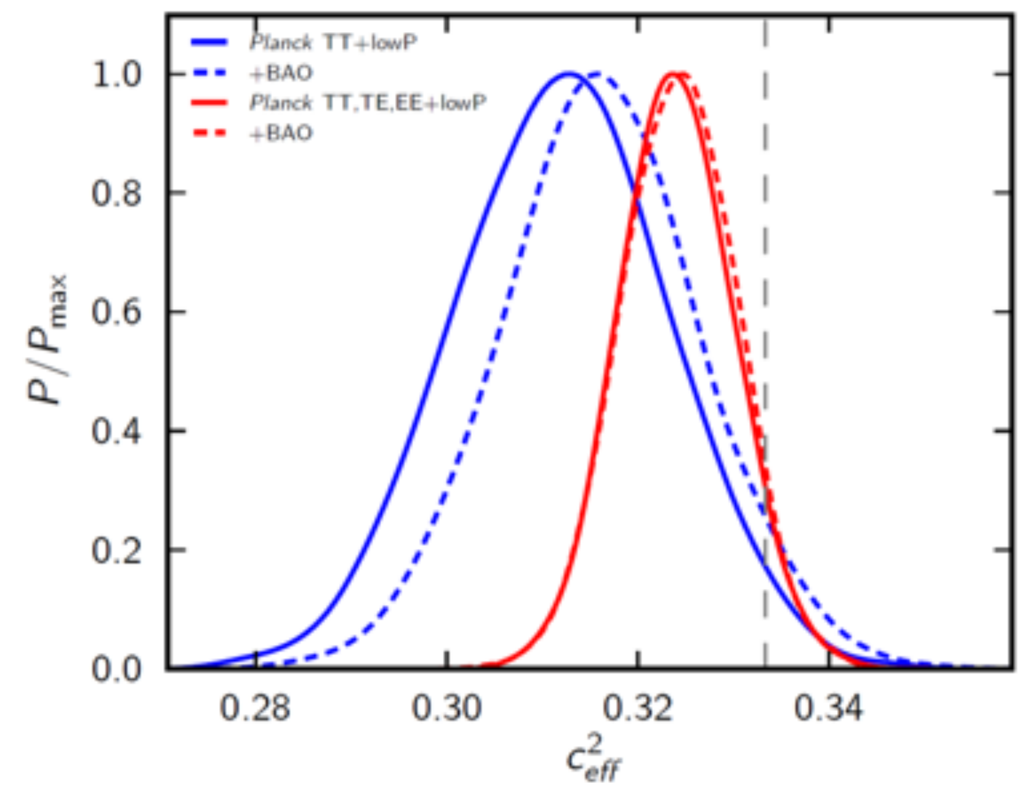
Small tension with CMB lensing

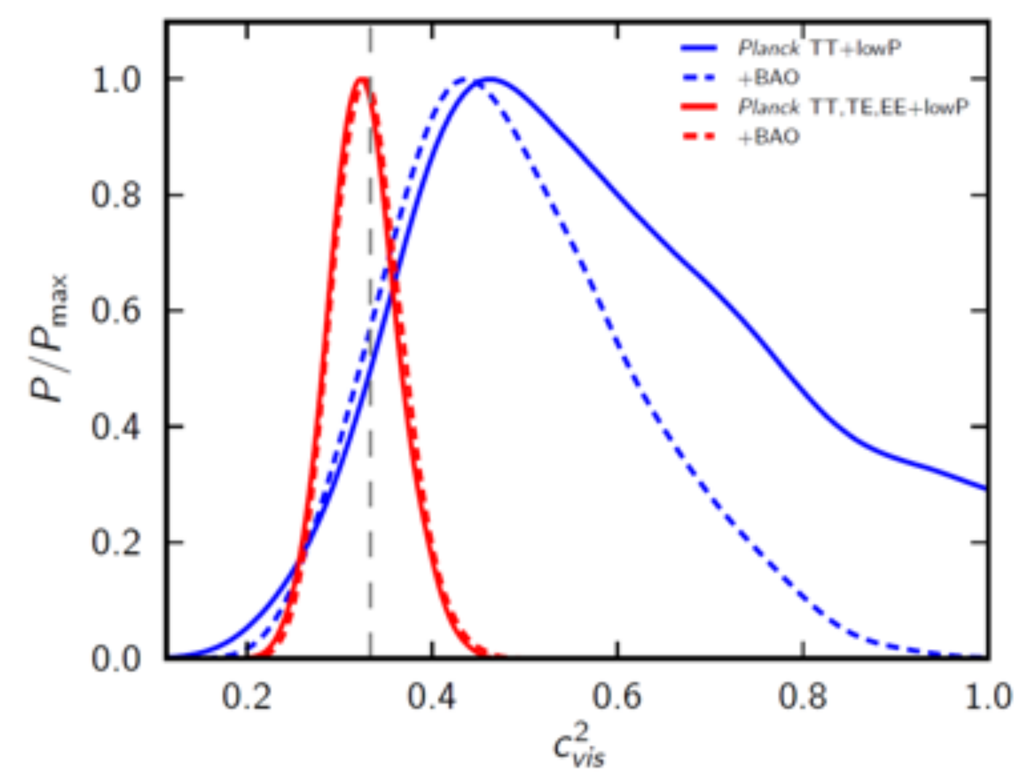
Was already there in 2013.

Probably due to low multipoles in the l=200 region



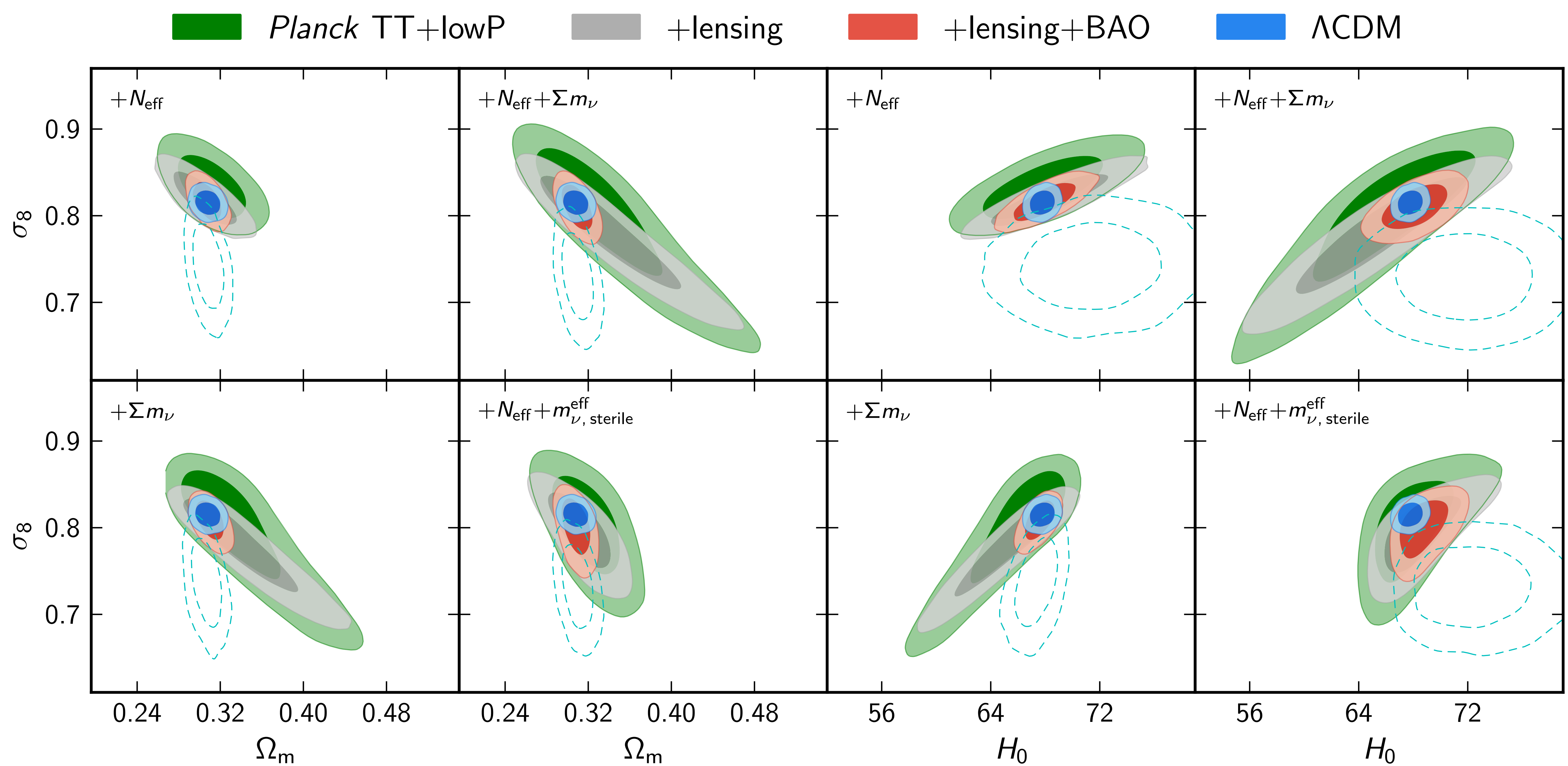
$$\rho = N_{\rm eff}\,\frac{7}{8}\left(\frac{4}{11}\right)^{4/3}\rho_\gamma$$





3 families of neutrinos

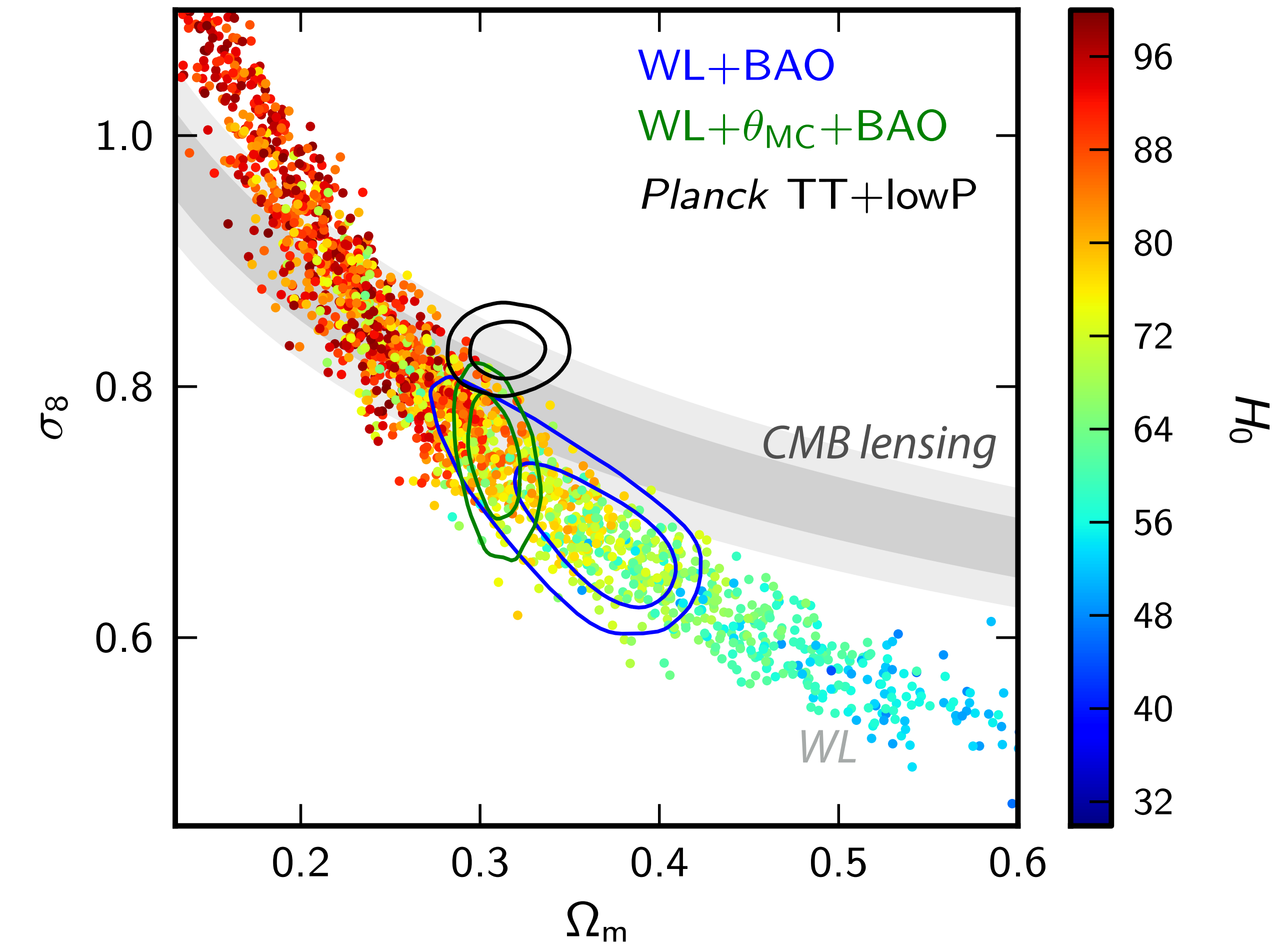
No significant deviation from the c_{eff}^2=1/3 and c_{vis}^2=1/3 expected for free streaming particules

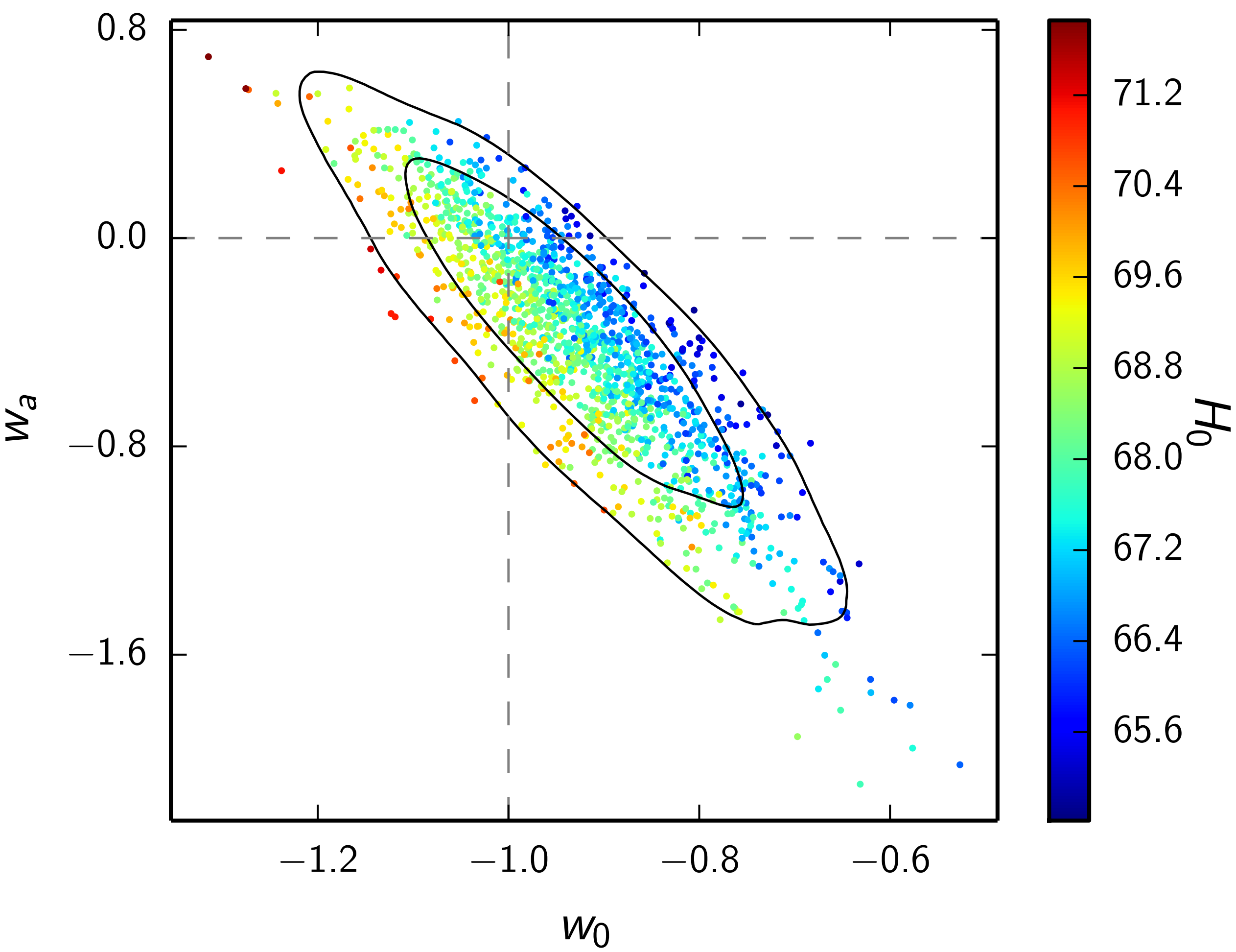


Neutrino summary

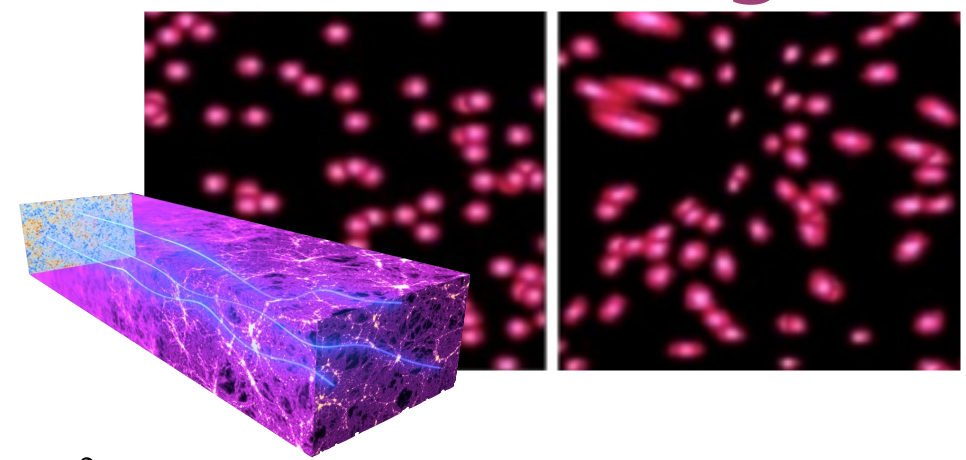
No significant tension with the concordance model

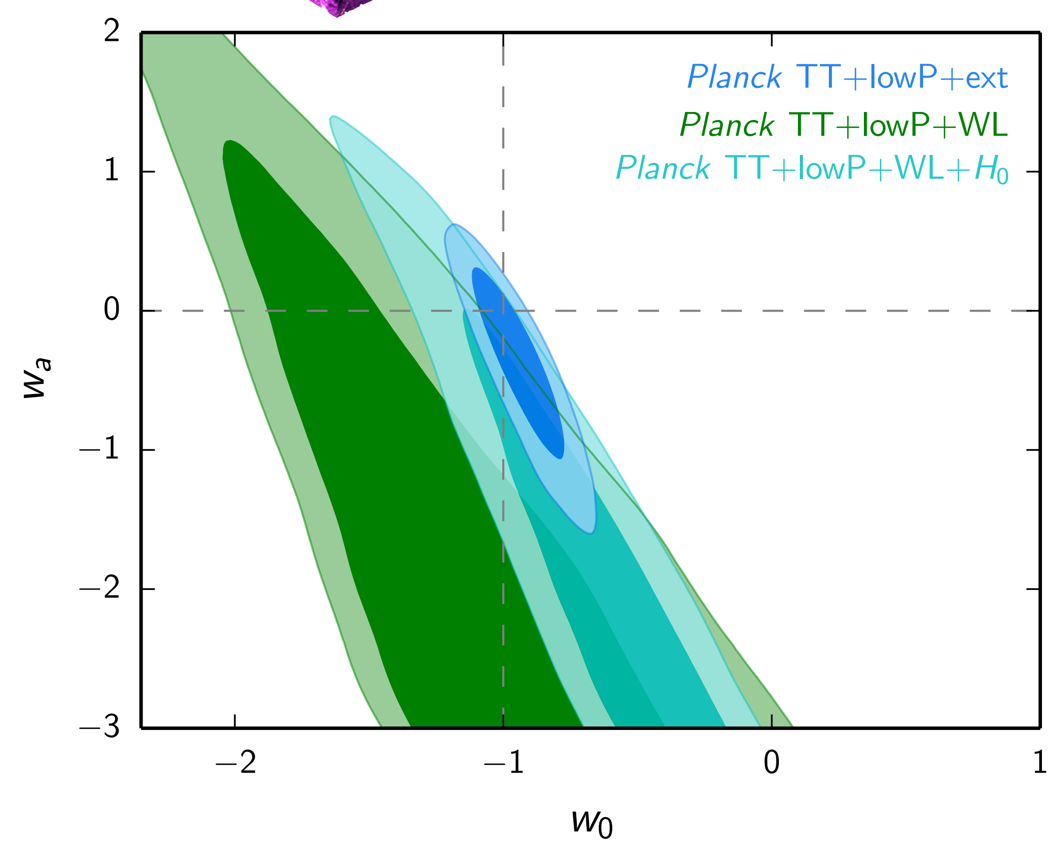
But that change when using other datasets like WL lensing





Weak Lensing



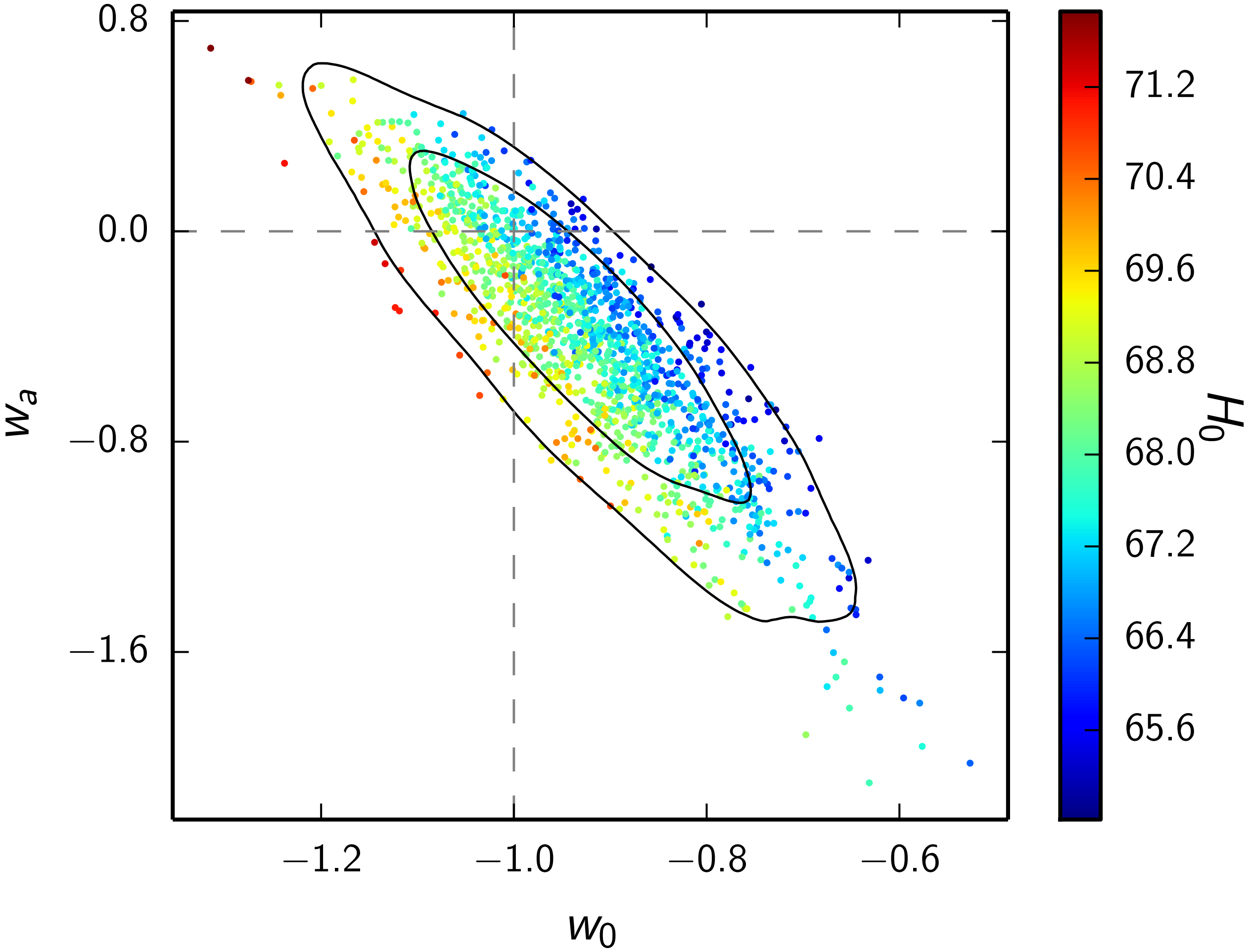


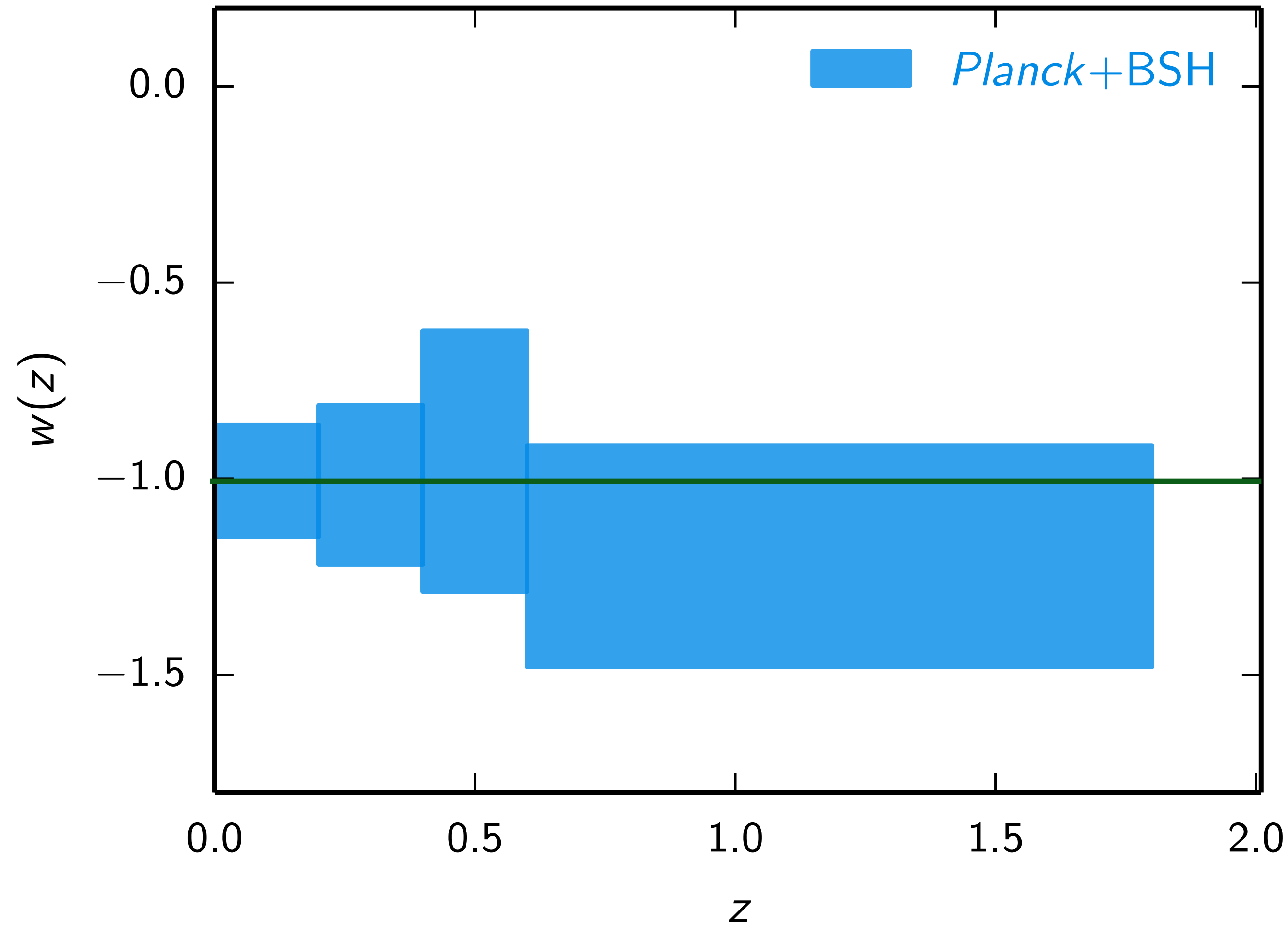
Tension with WL on galaxies

WL wants smaller σ_8

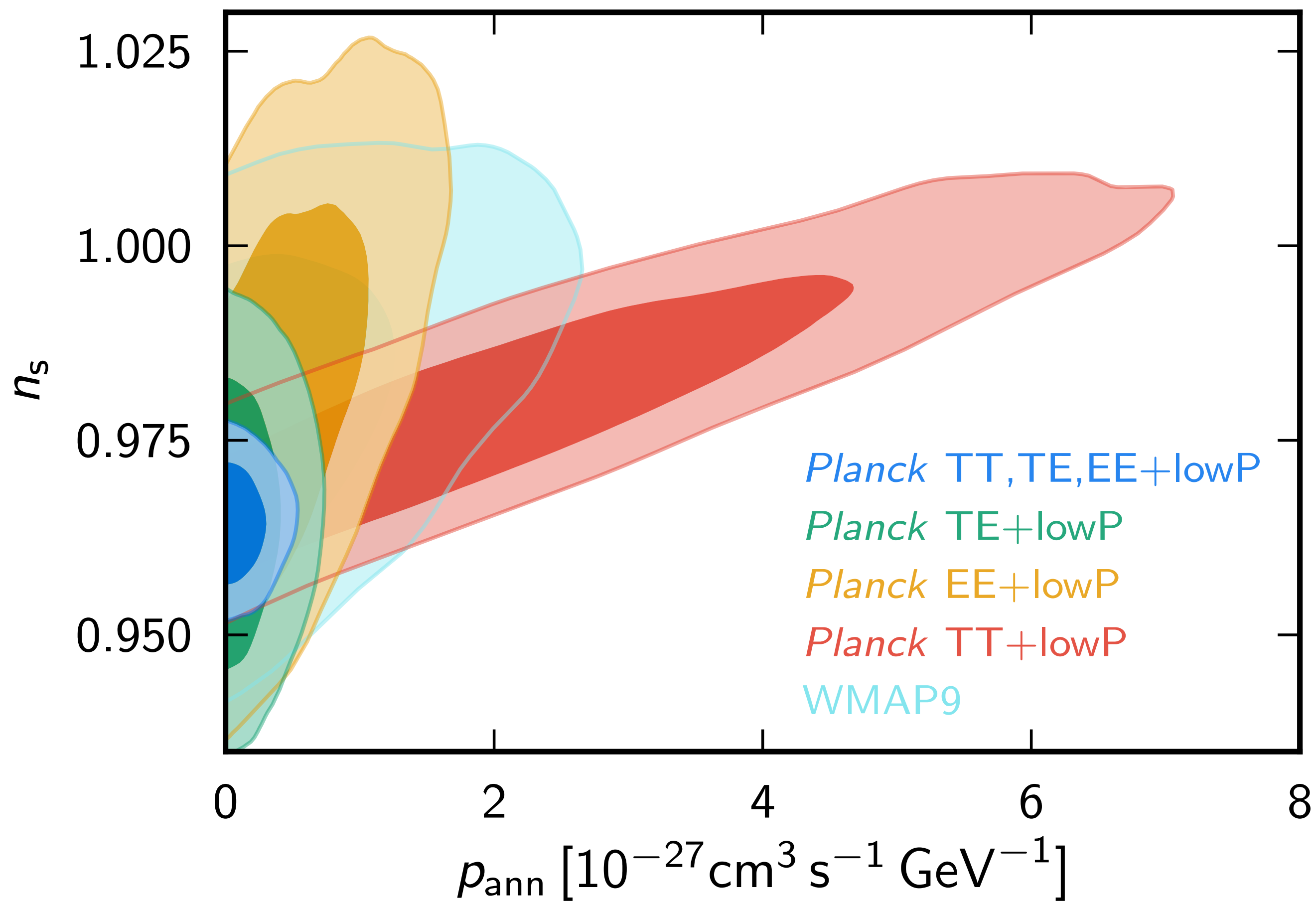
Seems to be driven by the WL small scales

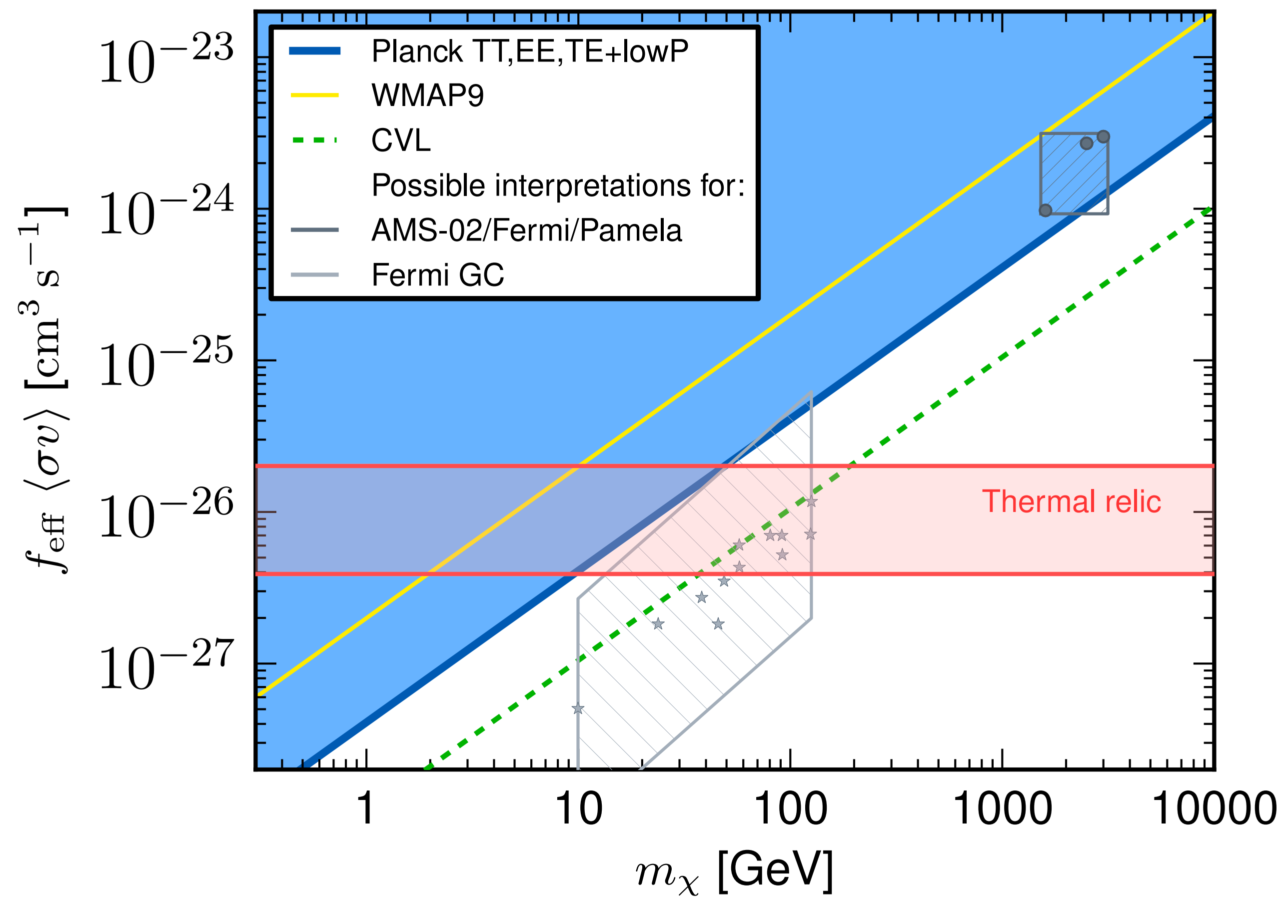
- *uncertainty on the non-linear regime*
- *baryonic feedback as small scales*





Dark Energy still compatible with a cosmological constant





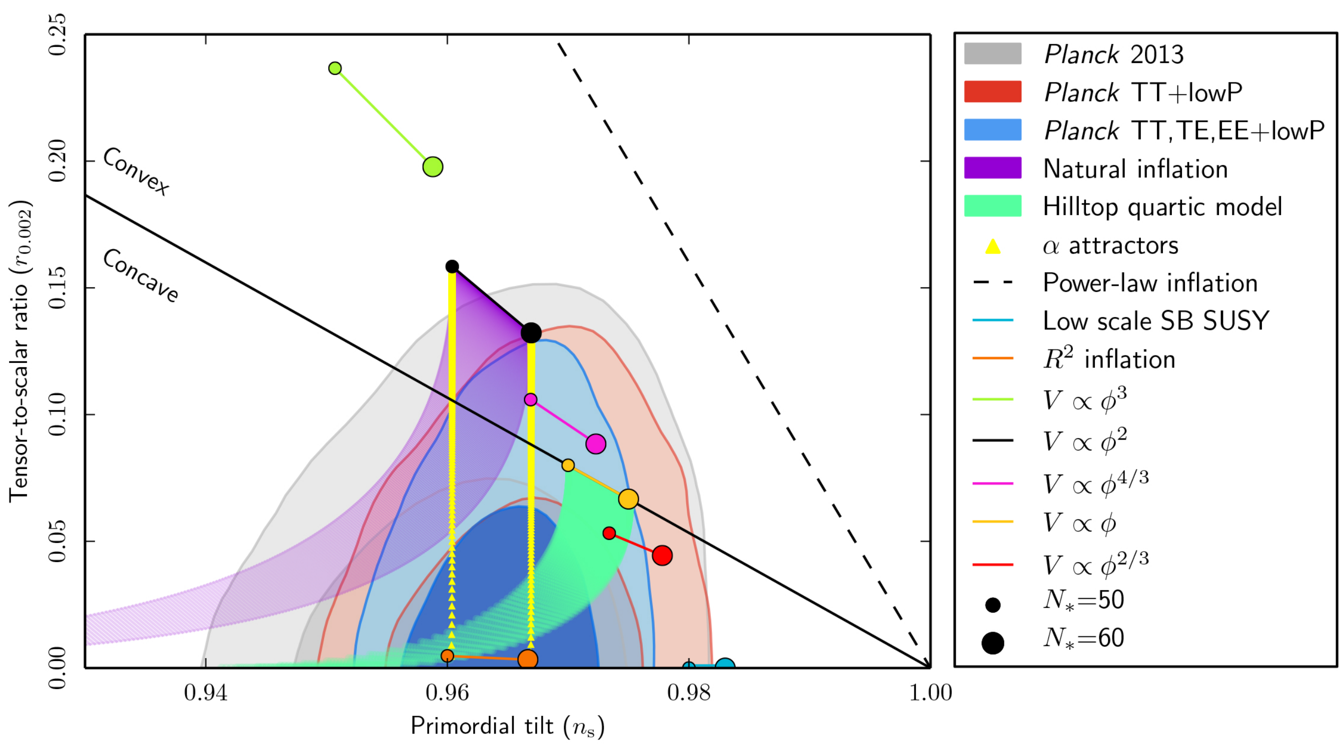
Polarization improves the constraint on Dark Matter annihilation

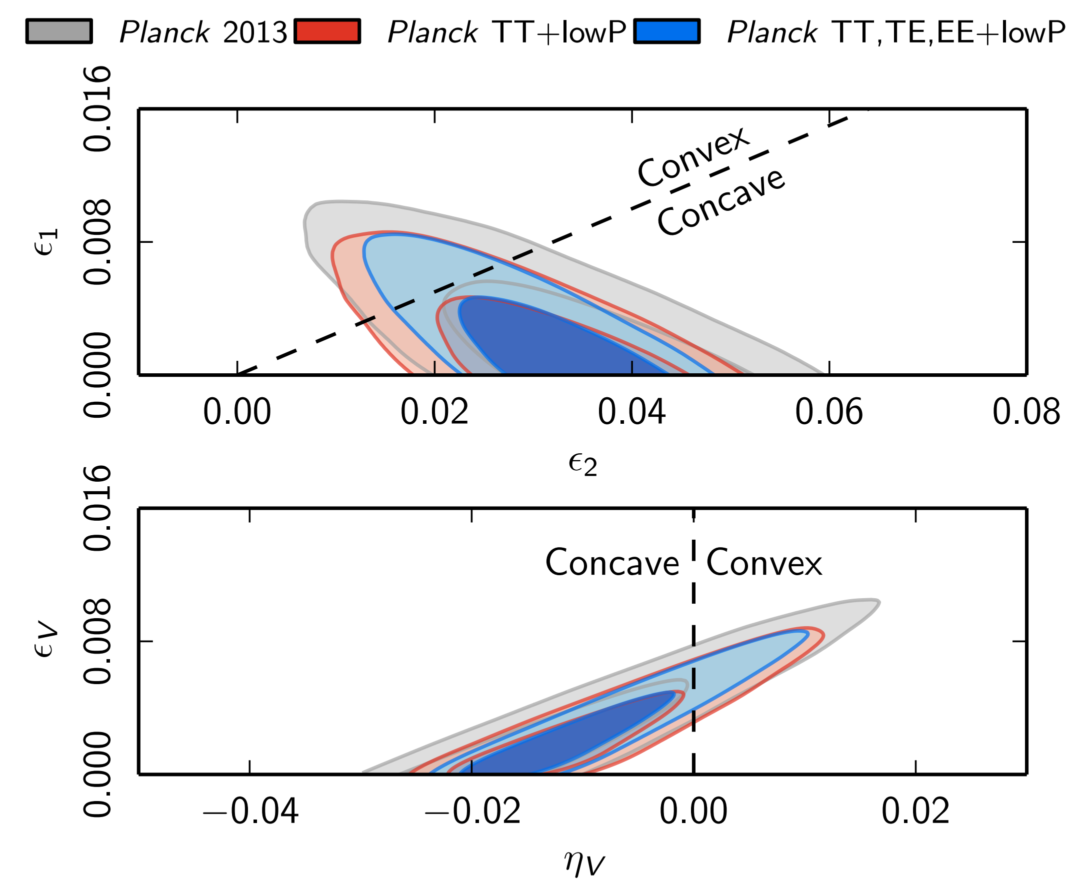
Dark matter annihilation injects energy during the recombination

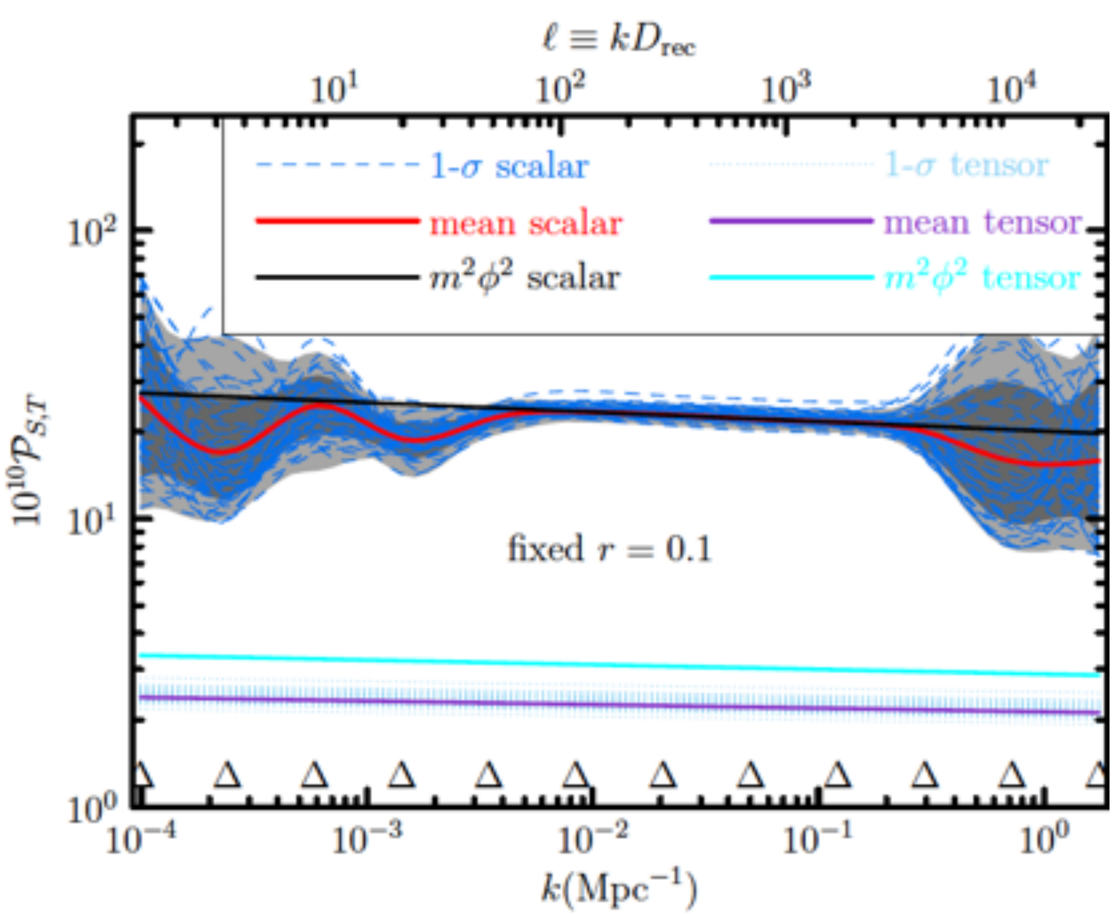
- *smooths Temperature anisotropies power spectrum*
- *enhance large scale Polarisation*

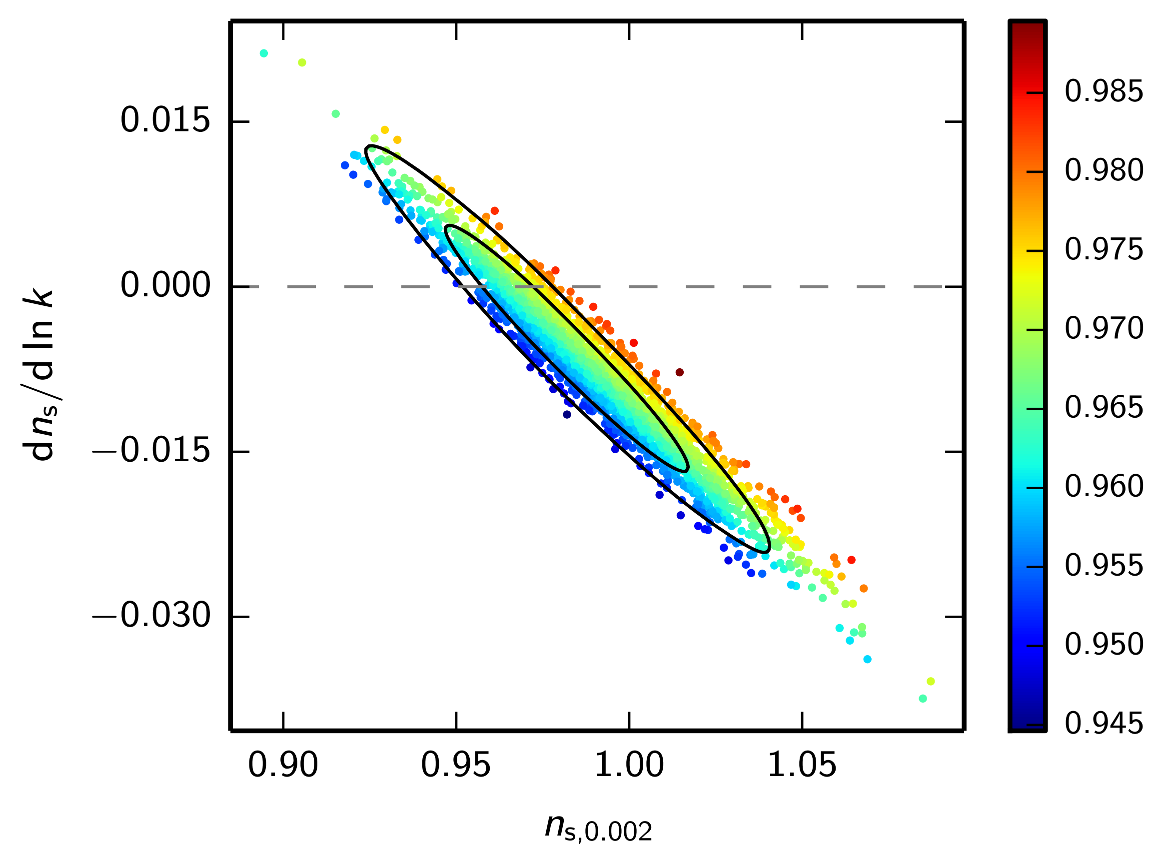
Rules out some of the simplest DM annihilation models for AMS-02/Fermi/Pamela

Constraints on Inflation



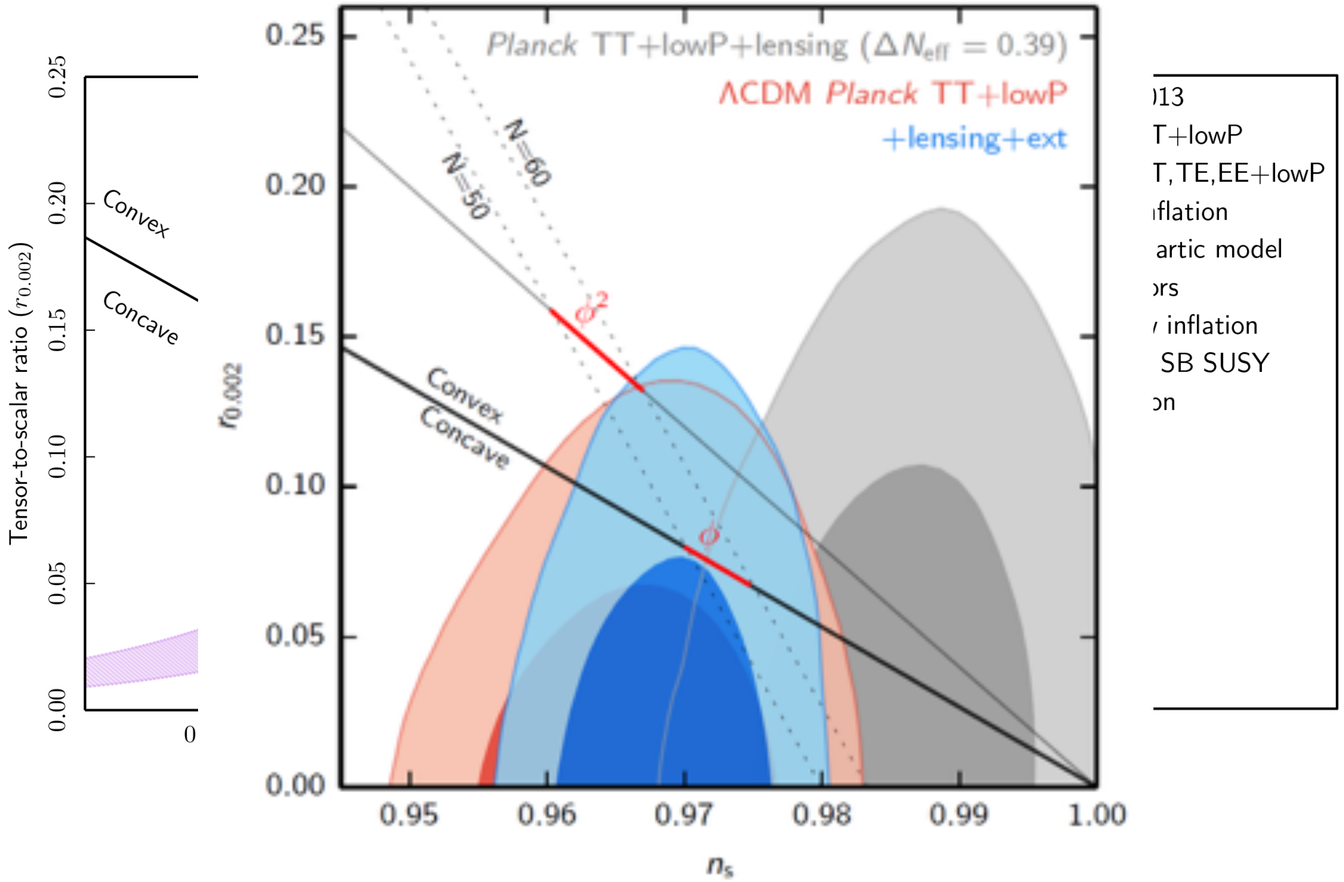


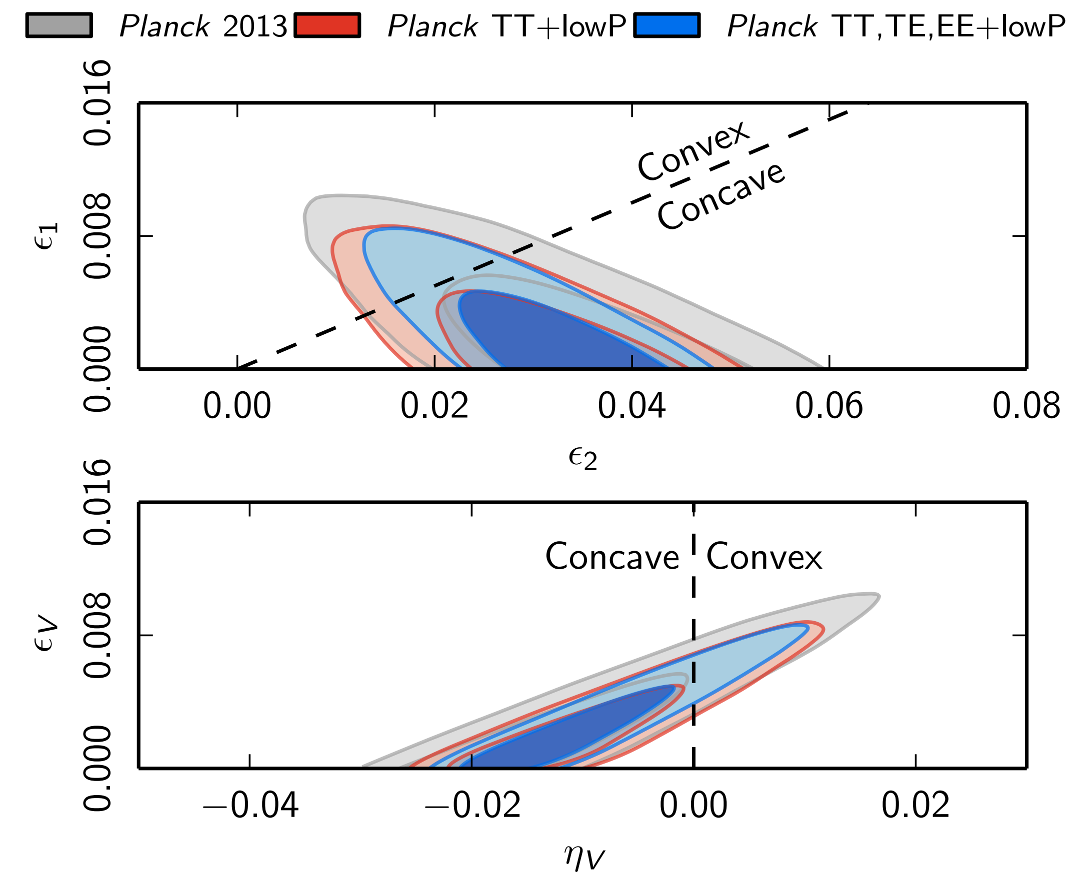


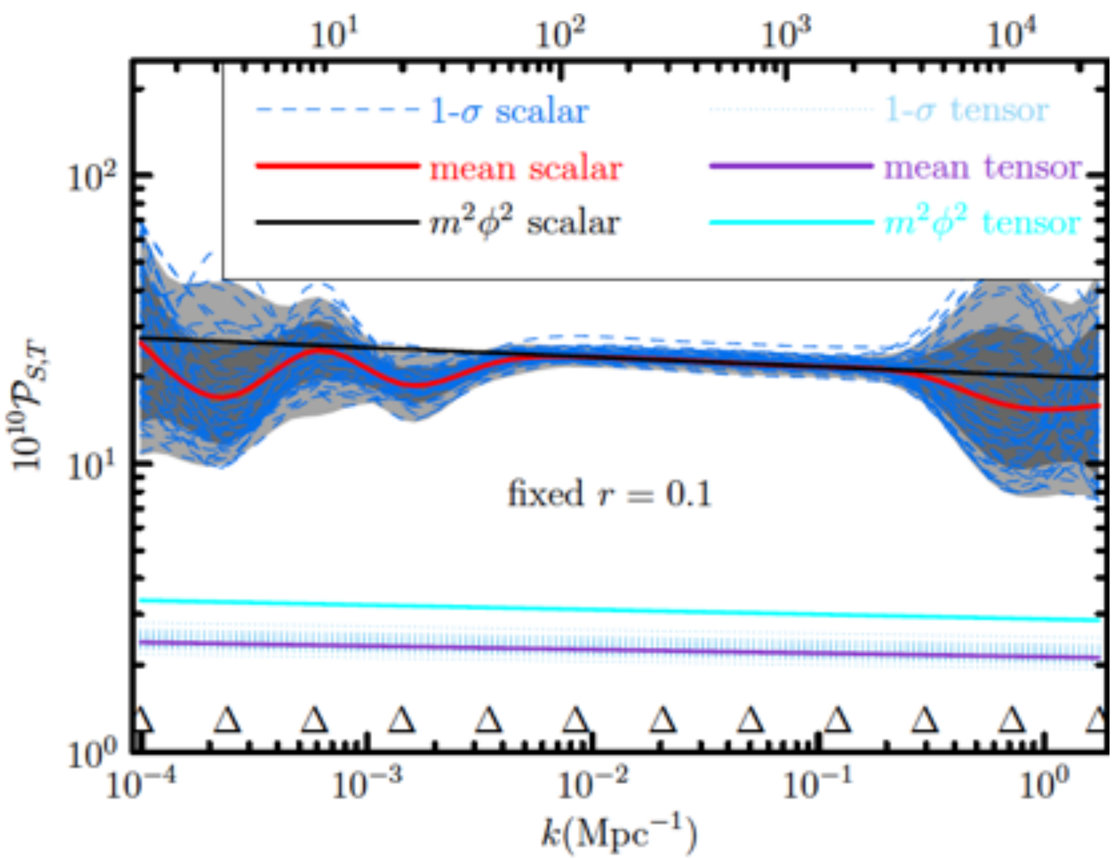


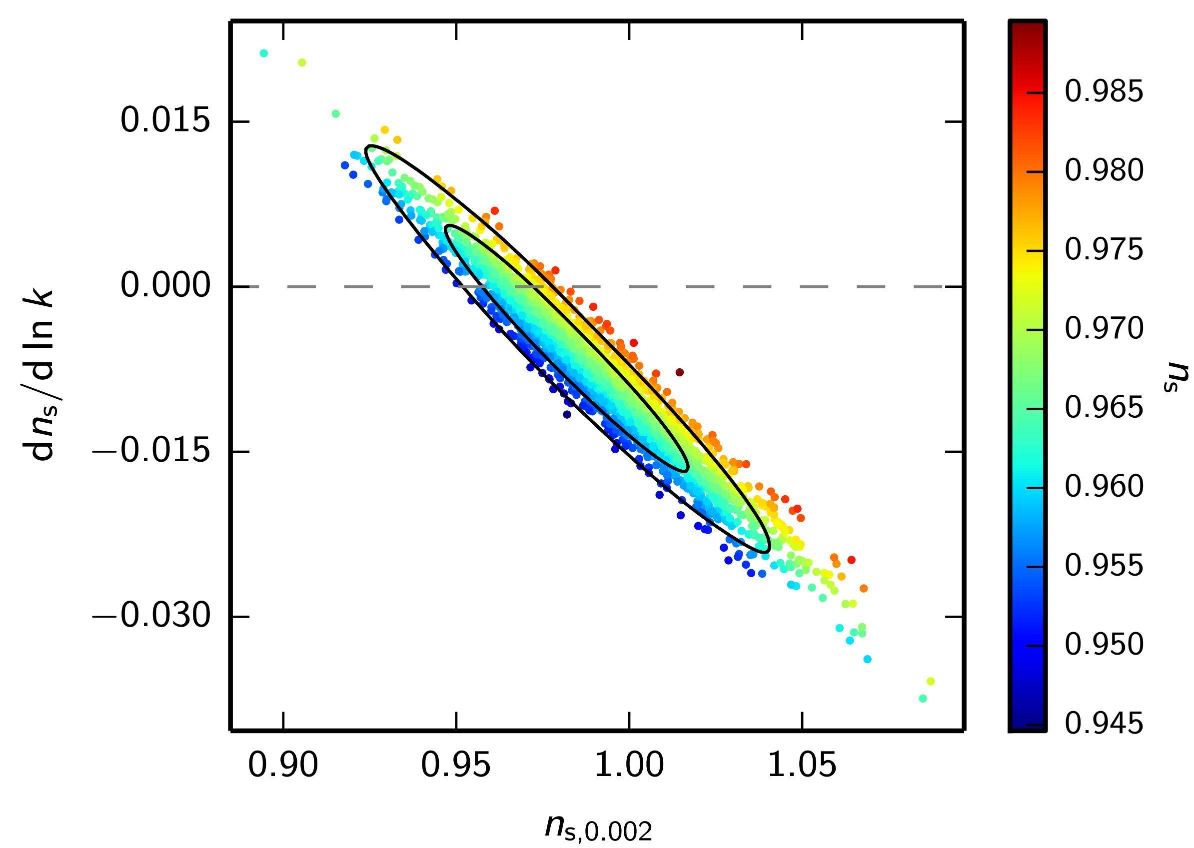
Constraints on Inflation

Beware that some results are model dependent…

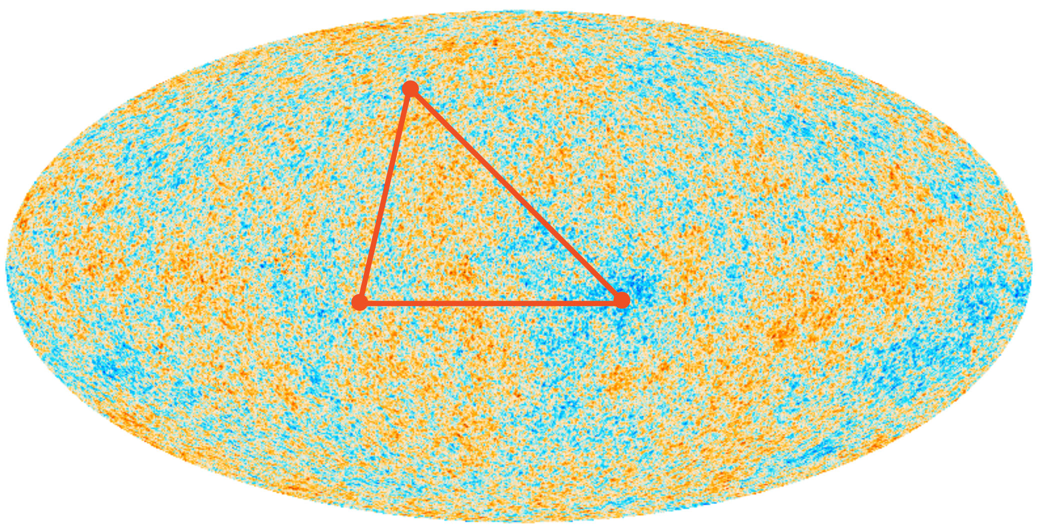






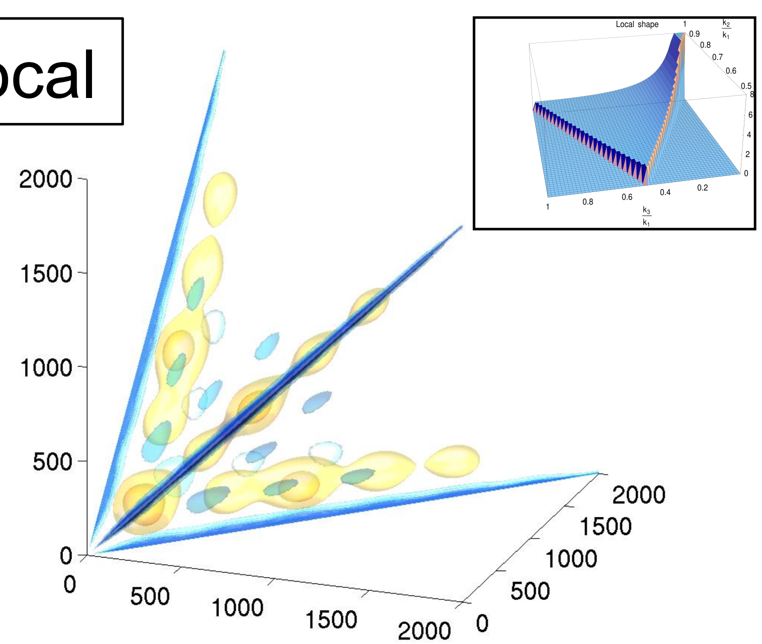


Non Gaussianity (3pt)



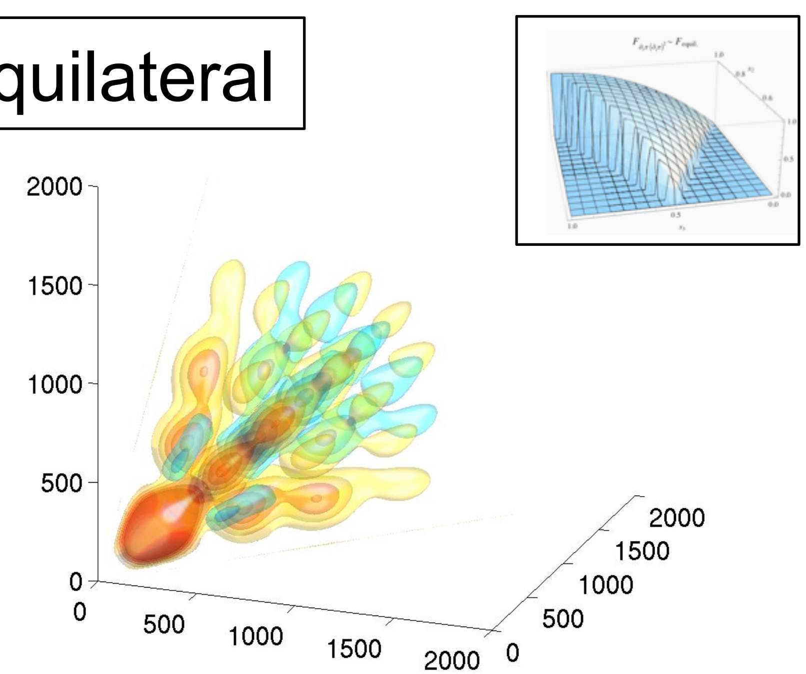
- Negligible NG in single field inflation
- Looking for particular Non-Dog
  - Specific shapes of the 3pt
- Detection limited by the ISW-lensing correlation

Local



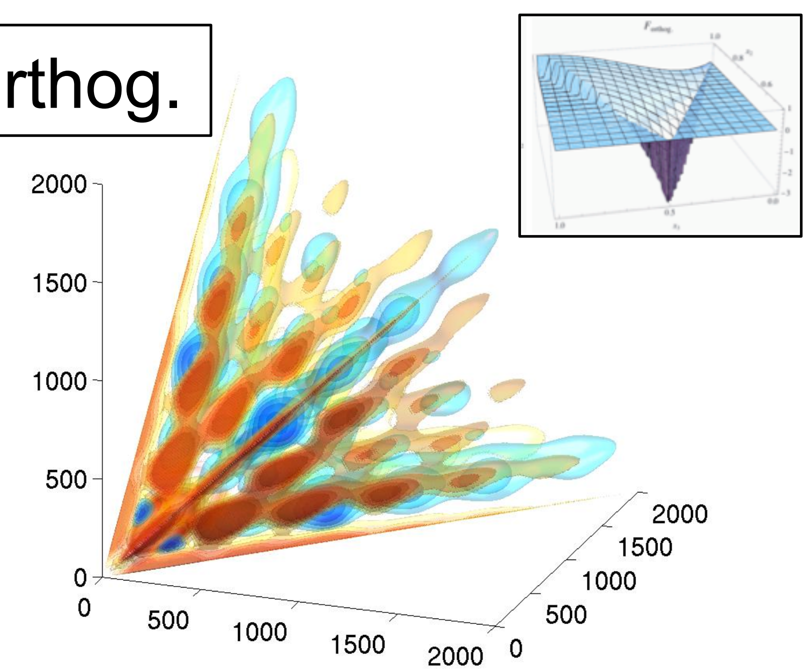
$$k_1 \gg k_2 \approx k_3$$

Equilateral



$$k_1 \approx k_2 \approx k_3$$

Orthog.



$$k_1 \approx 2k_2 \approx 2k_3$$

Non Gaussianity (3pt)

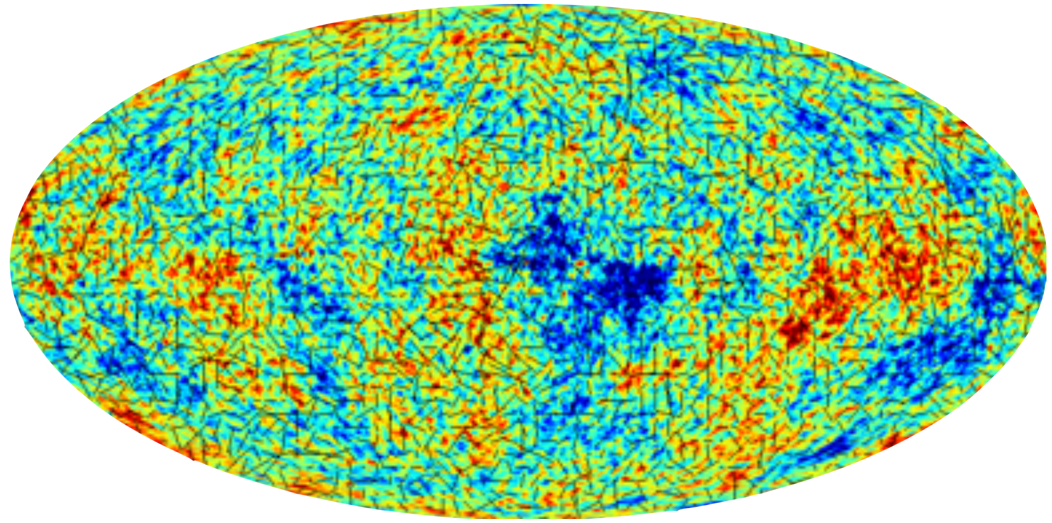
2013

	Independent				ISW-lensing subtracted		
	KSW	Binned	Modal		KSW	Binned	Modal
SMICA							
Local	9.8 ± 5.8	9.2 ± 5.9	8.3 ± 5.9	. . . . .	**2.7 ± 5.8**	2.2 ± 5.9	1.6 ± 6.0
Equilateral	−37 ± 75	−20 ± 73	−20 ± 77	. . . . .	**−42 ± 75**	−25 ± 73	−20 ± 77
Orthogonal	−46 ± 39	−39 ± 41	−36 ± 41	. . . . .	**−25 ± 39**	−17 ± 41	−14 ± 42

2015

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

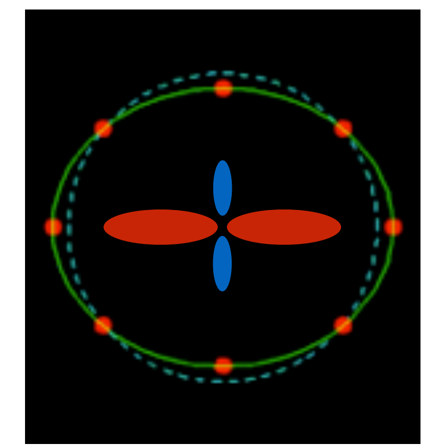
Addition of Polarization shrunk the constraint volume by a factor 3

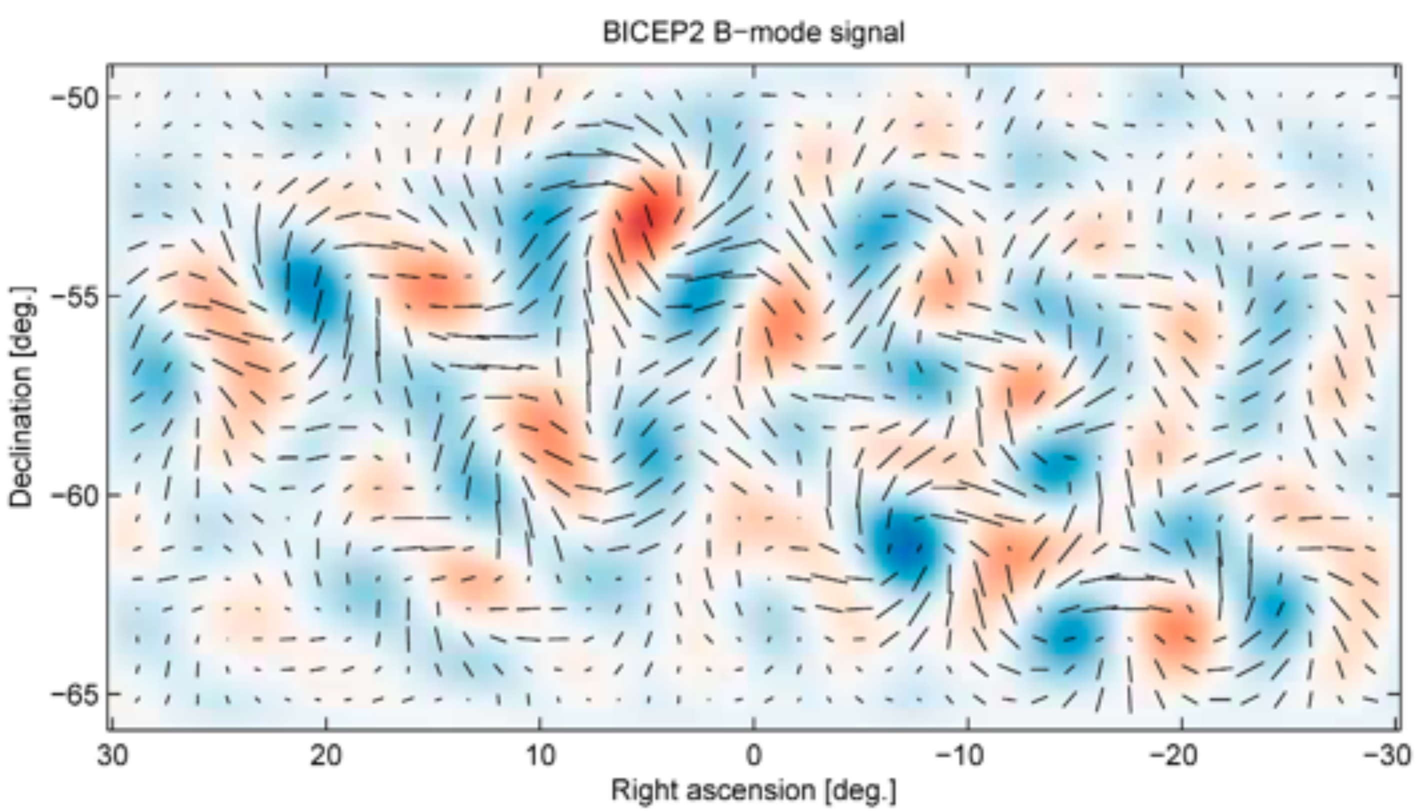


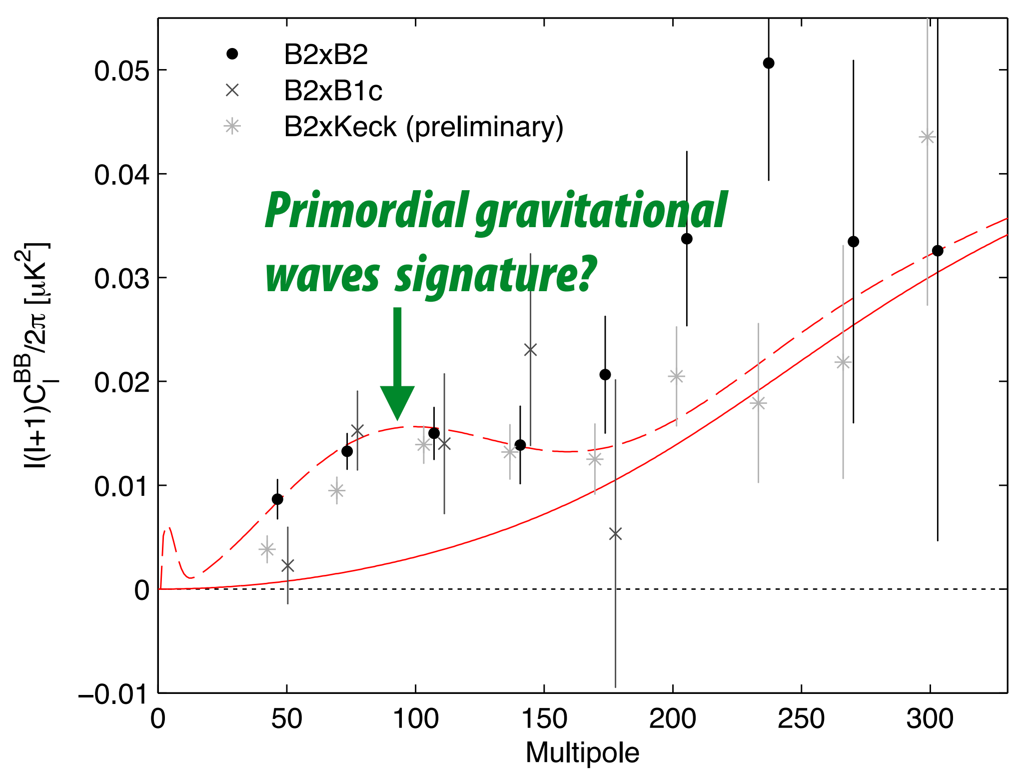
March 2014

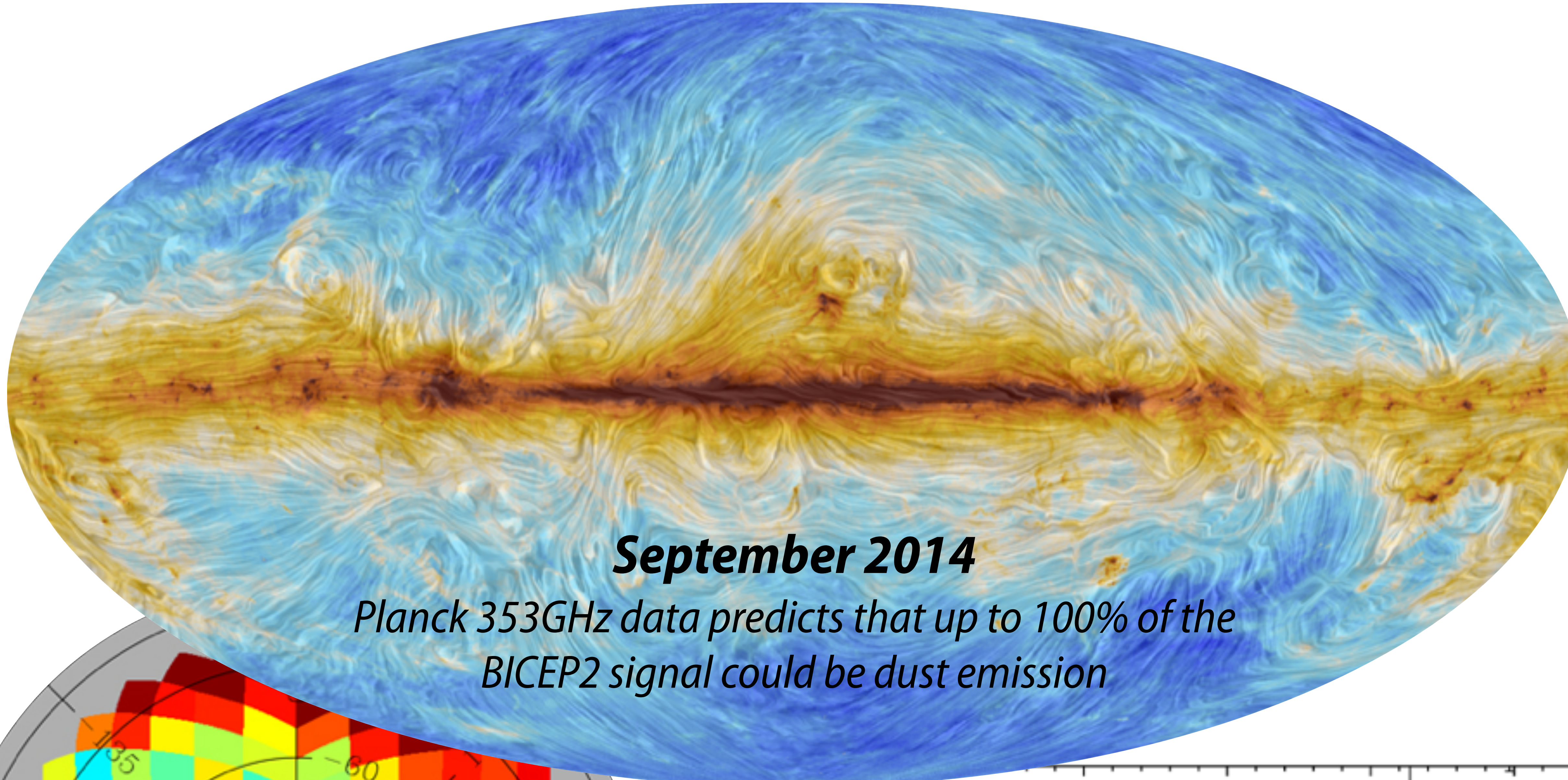
Bicep2 announce a detection of primordial B Polarization at large scale.

Large scale B polarization is a signature of the gravitational waves background



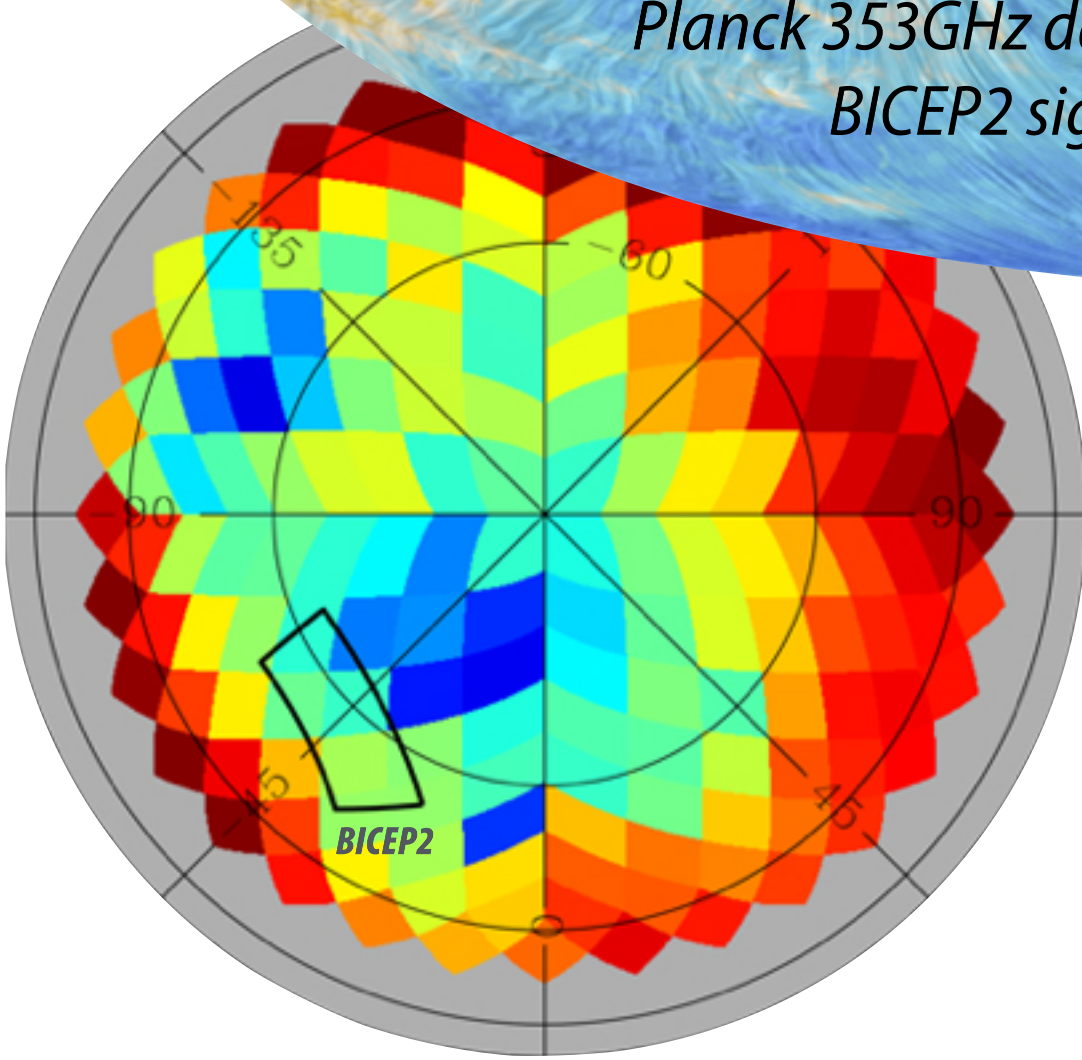


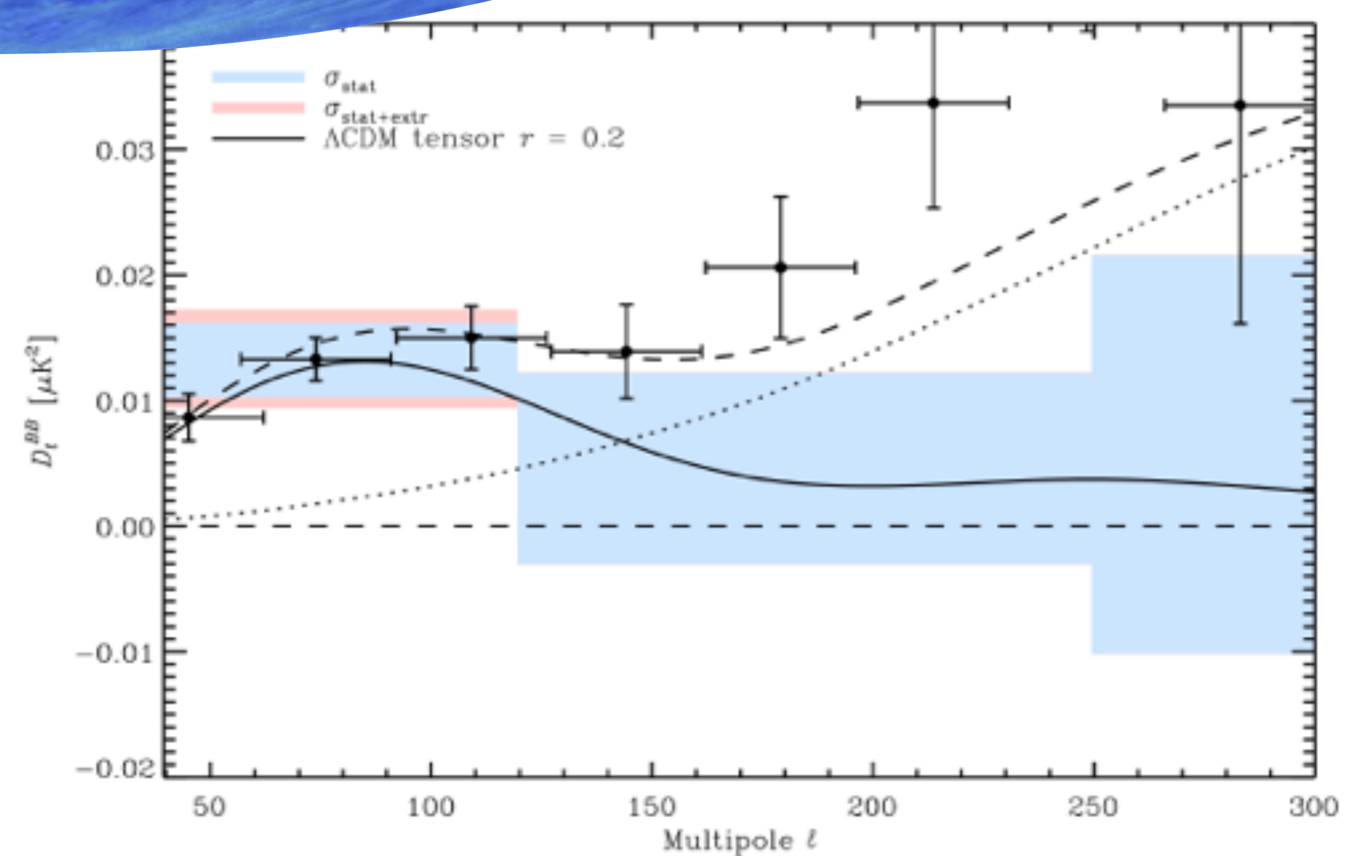




September 2014

Planck 353GHz data predicts that up to 100% of the BICEP2 signal could be dust emission



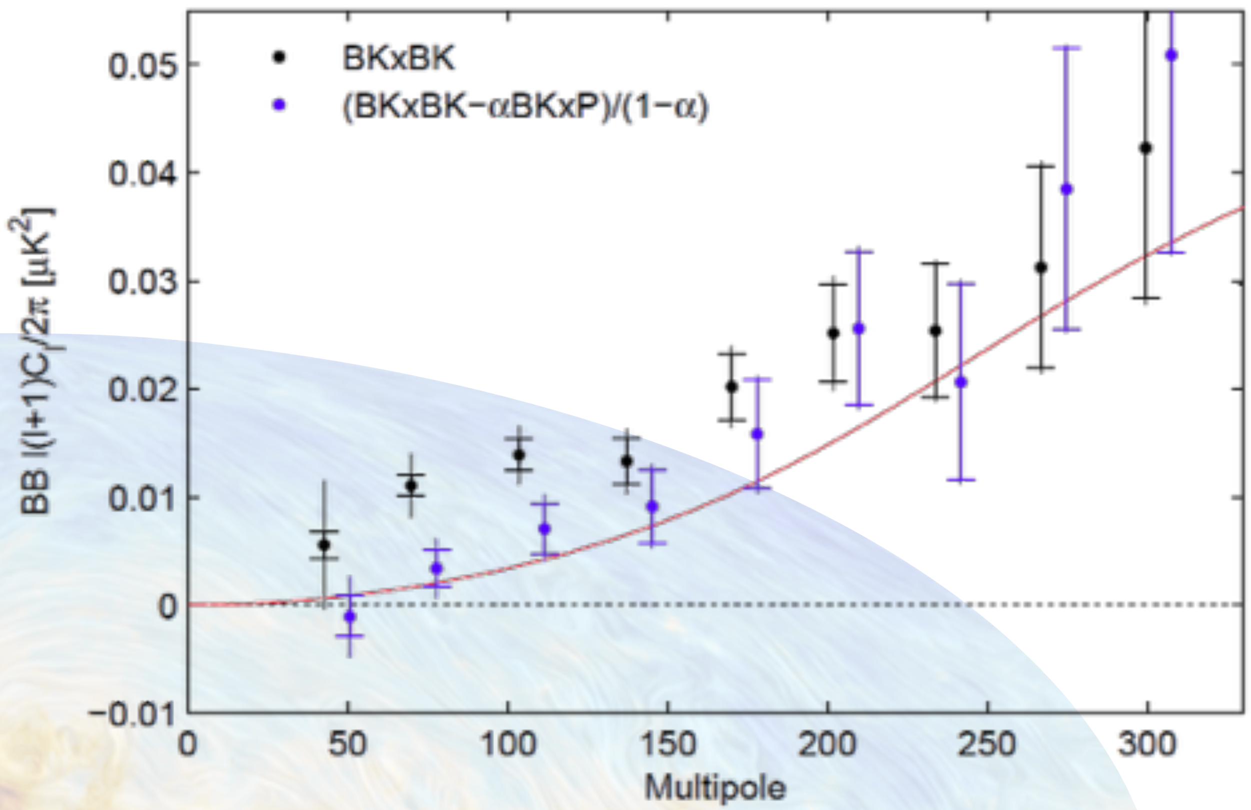


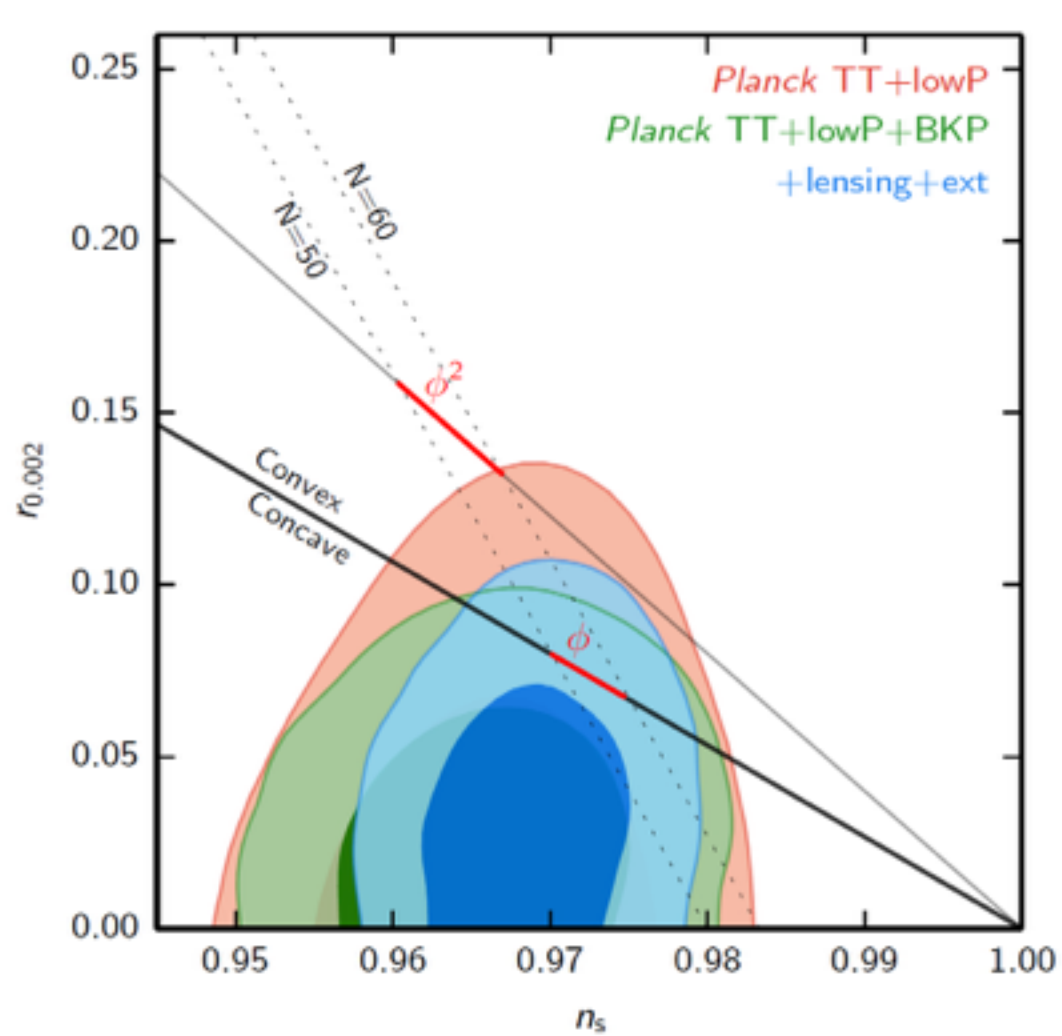
February 2015

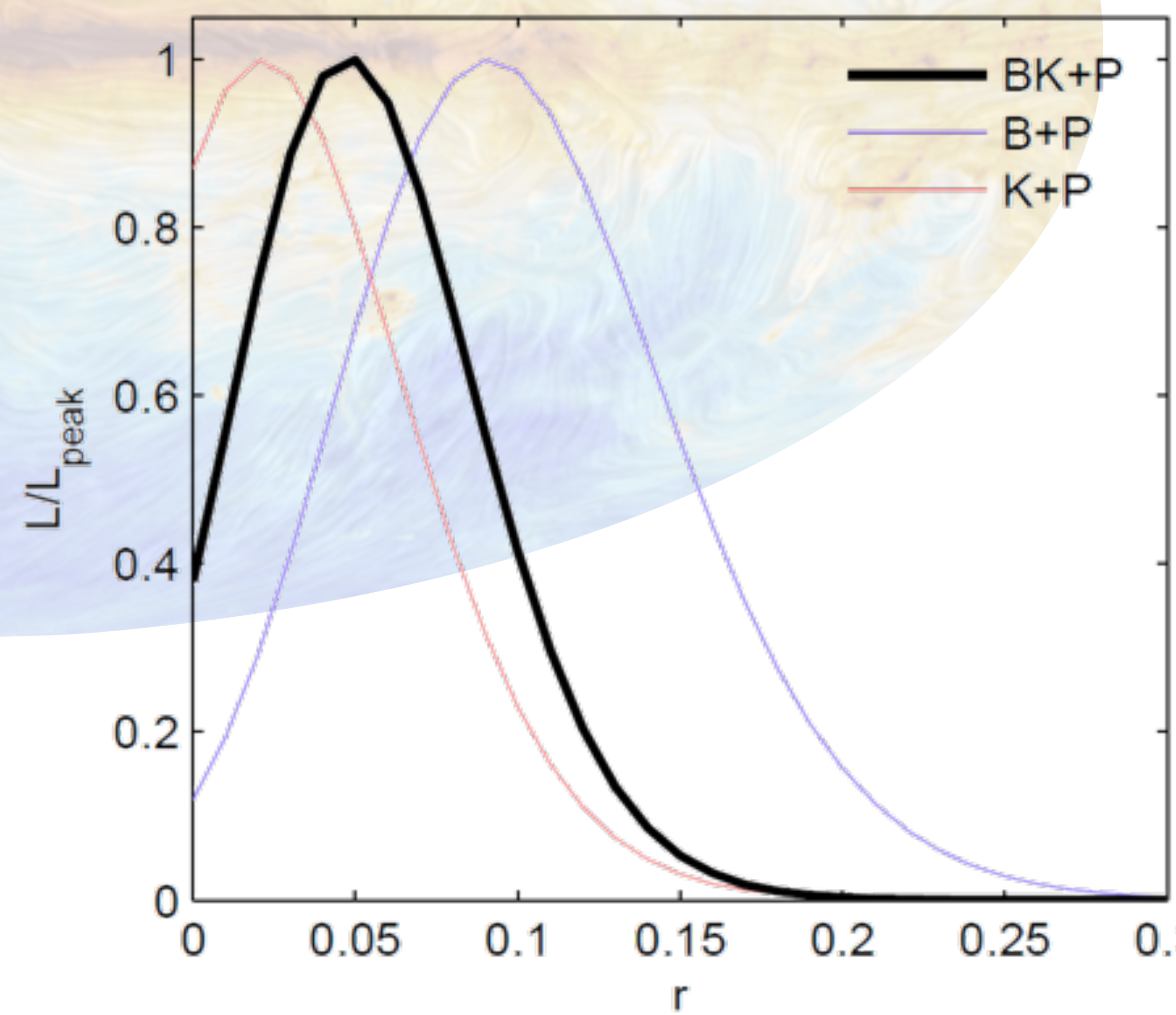
- *Joint Planck 353/Bicep2-Keck analysis*
- *No significant primordial B Polarization after 353GHz cleaning*
- *BKP constraint on r similar to Planck*
- *Joint constraint improves the upper limit*

$$r_{0.002} < 0.11, \quad \textit{Planck}\ \text{TT+lowP+lensing+ext},$$
$$r_{0.002} < 0.09, \quad \textit{Planck}\ \text{TT+lowP+lensing+ext+BKP}.$$

- *Polarized dust emission is the key…*







Planck 2015 - Take away

- More data in T, better processed and analysed
- P, even with possible residuals is already quite powerful, constraints comparable to BAO

- Some tension with external datasets on the amplitude of matter fluctuations
  - where we actually have theoretical uncertainties

- ΛCDM is just fine
  - no convincing evidence for any simple extension
- Inflation is fine
  - no NG
  - power spectrum consistent with simplest inflation models
- Still no primordial gravitational waves detection