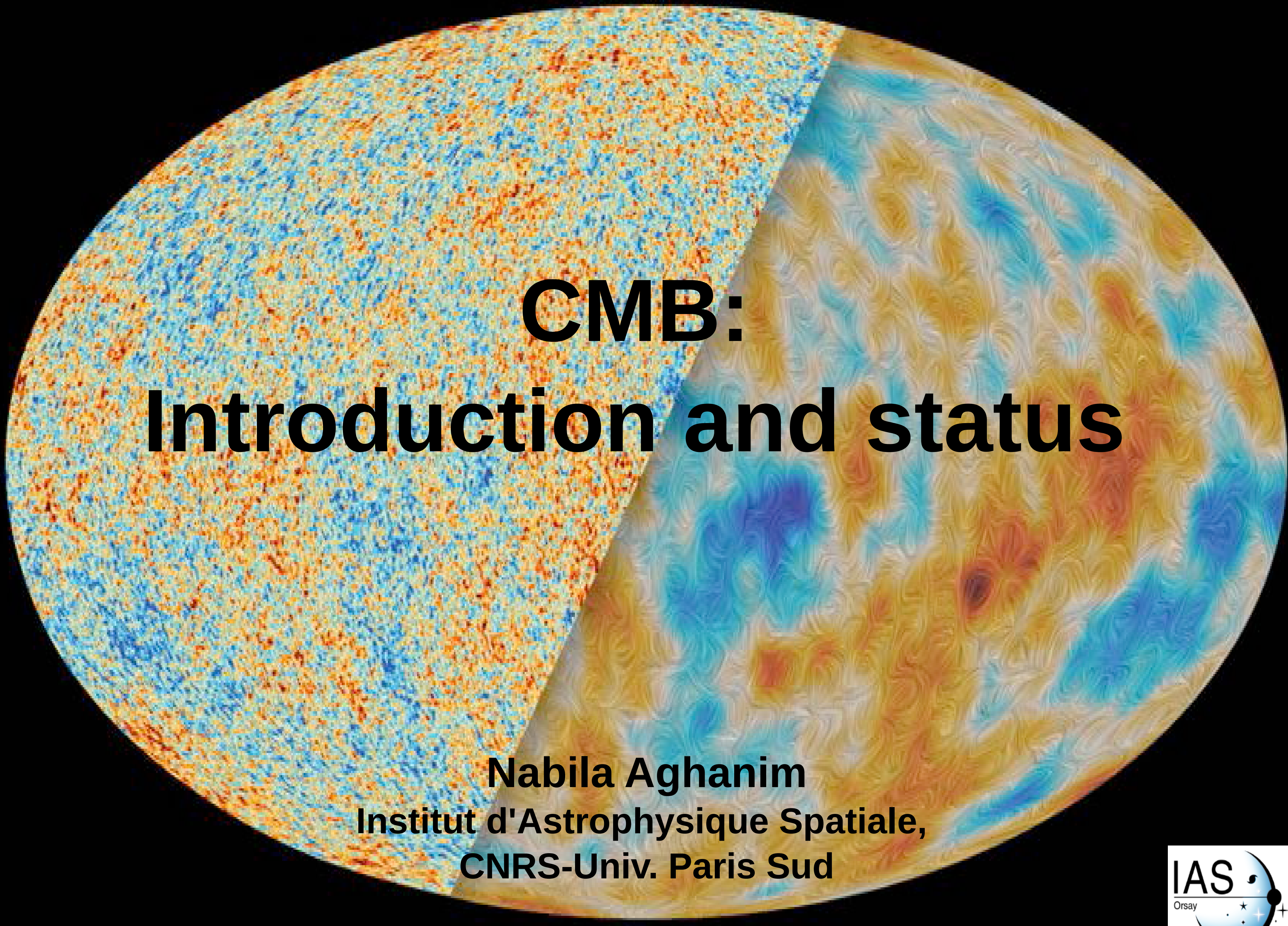


CMB: Introduction and status

Nabila Aghanim
Institut d'Astrophysique Spatiale, CNRS-Univ. Paris Sud

Outline of the session

Introduction
CMB spectrum and spectral distorsions (Talk J. Chluba)
Planck satellite and CMB maps
Foregrounds (Talk R. Genova-Santos)
Component separation (Talk B. Barreiro)
CMB angular power spectrum
Cosmology with CMB
Secondary anisotropies: CMB lensing & thermal Sunyaev-Zel'dovich (SZ)
Secondary anisotropies: kinetic SZ & ISW (Talk C. Hernandez-Monteagudo)
CMB polarisation status & future (Talk J.-A. Rubino-Martin)

CMB introduction & status

Introduction

The CMB maps

The CMB power spectrum

Cosmology with CMB: Main features in primary anistropies

Cosmology with CMB: cosmological parameters

Secondary anisotropies: CMB lensing

Secondary anisotropies: thermal Sunyaev-Zel’dovich

Conclusions

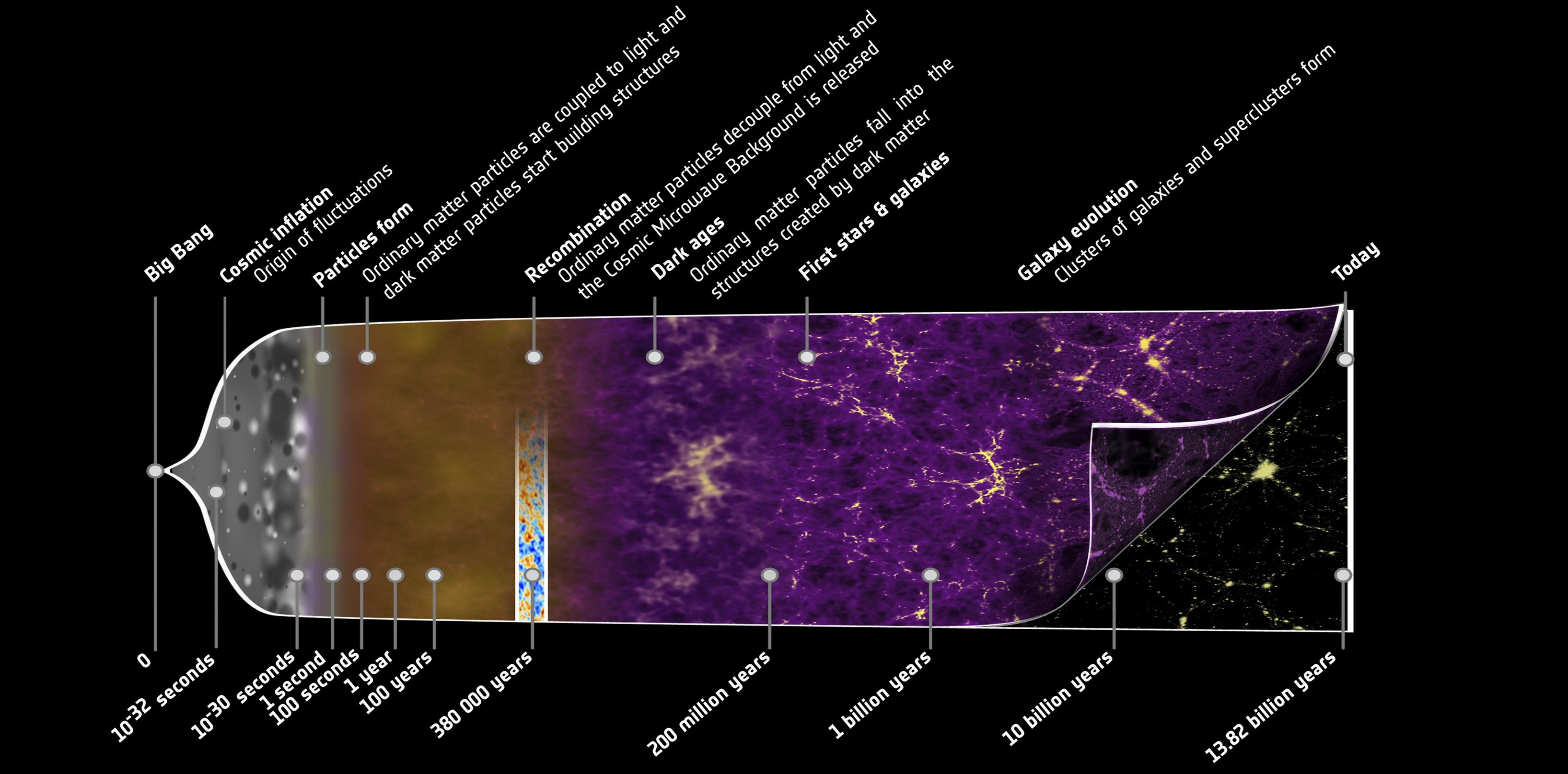
A lot of material from Planck collab.

History of the Universe

Primordial Universe
Photons produced

Photons scattered until
~380000yrs after BB
CMB= Image of Universe

Photons affected by the
cosmic strutures



Cosmic **microwave** background

CMB = Photons from ~380000 yr at a surface of last scatter

Universe was ~ 3000°K at ~380000 yr

Full of visible light (~μm)

Universe expands

Temperature of Universe decreases to ~3 K

Wavelength changes from visible to microwave (~cm) → Discovery by Penzias & Wilson

CMB Frequency spectrum

- Early Universe in thermal equilibrium → Black Body spectrum at 2.73K from COBE/FIRAS in 1992 [Cf. Talk J. Chluba]
- Spectral distorsions → energetics of Universe (primordial & late time)
- PIXIE improvement by a factor 1000 → $\mu<10^{-8}$ and $y<2\times10^{-9}$

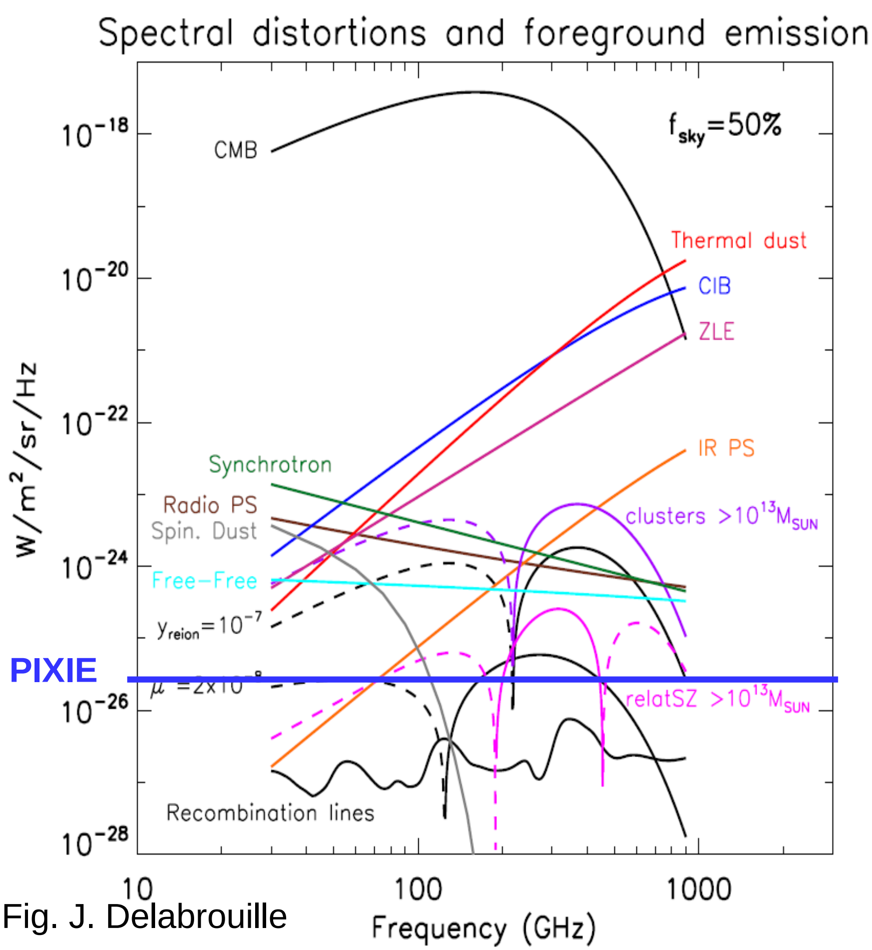
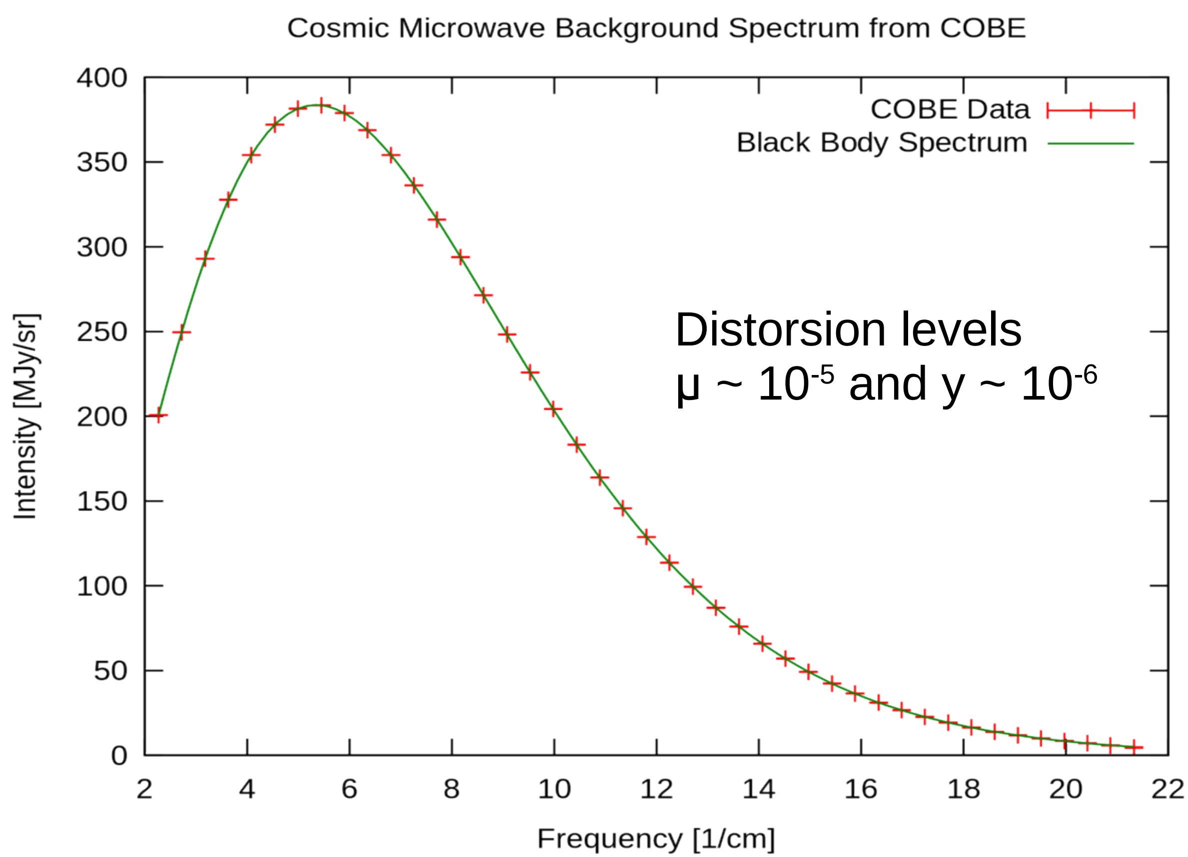


Fig. J. Delabrouille



CMB introduction & status

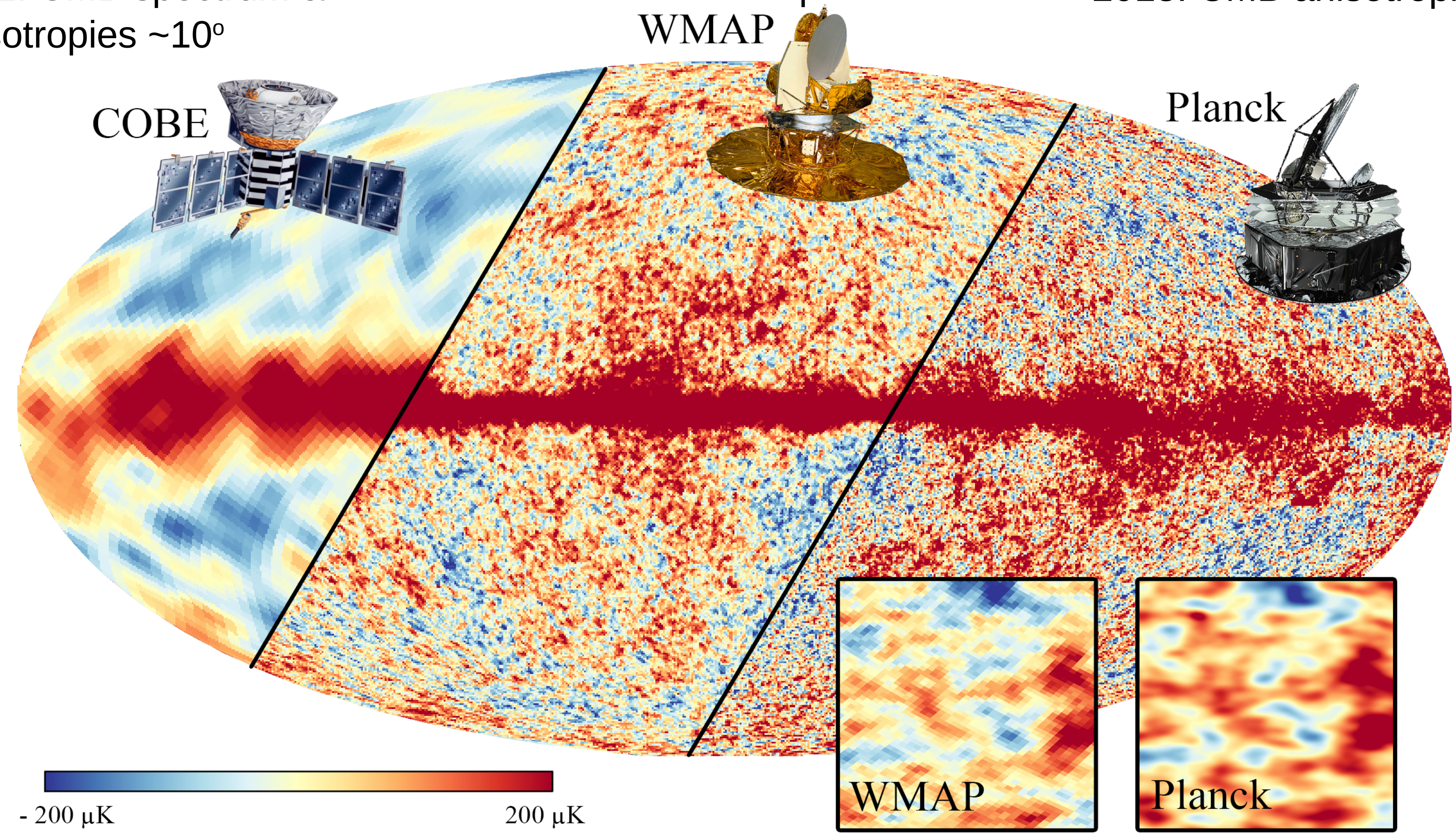
Introduction
The CMB maps
The CMB power spectrum
Cosmology with CMB: Main features in primary anisotropies
Cosmology with CMB: cosmological parameters
Secondary anisotropies: CMB lensing
Secondary anisotropies: thermal Sunyaev-Zel'dovich
Conclusions

History of CMB observations
Three generations of satellites

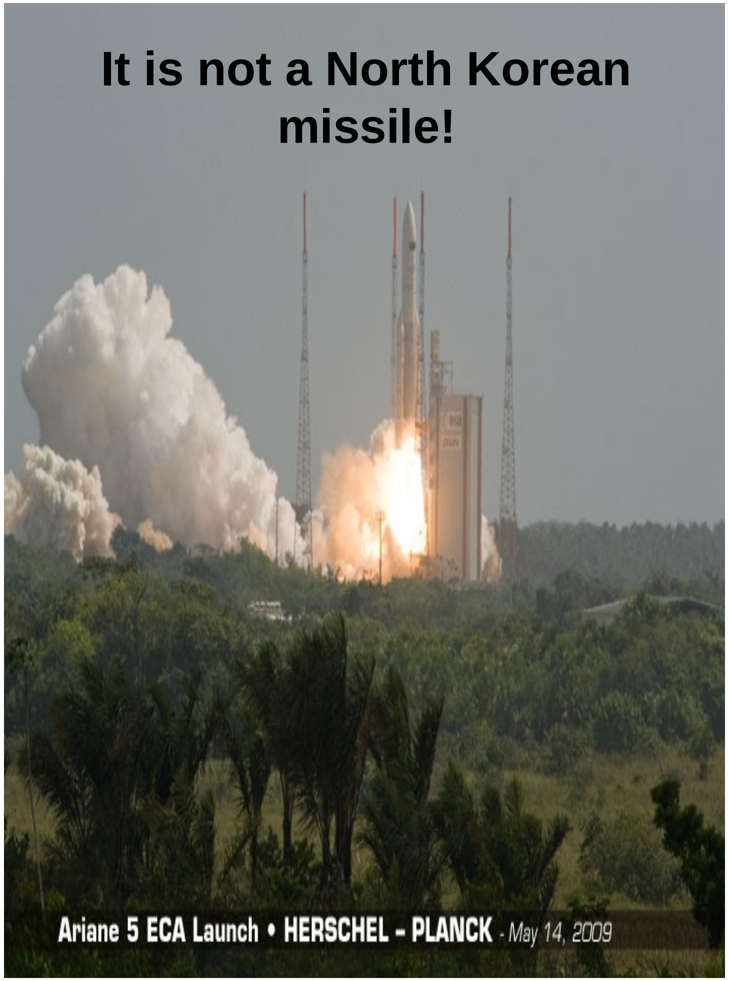
1992: CMB spectrum & anisotropies ~10°

2003: CMB anisotropies >12'

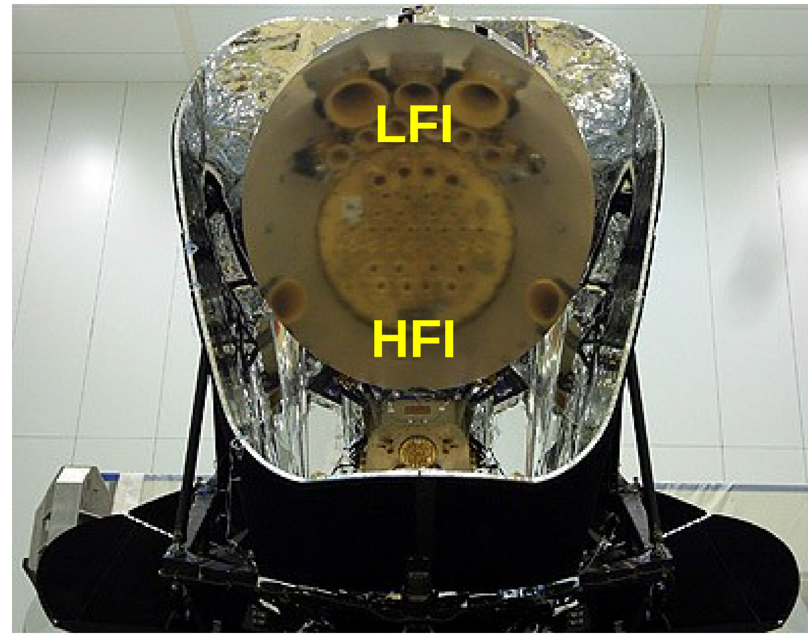
2013: CMB anisotropies >5'



The Planck satellite



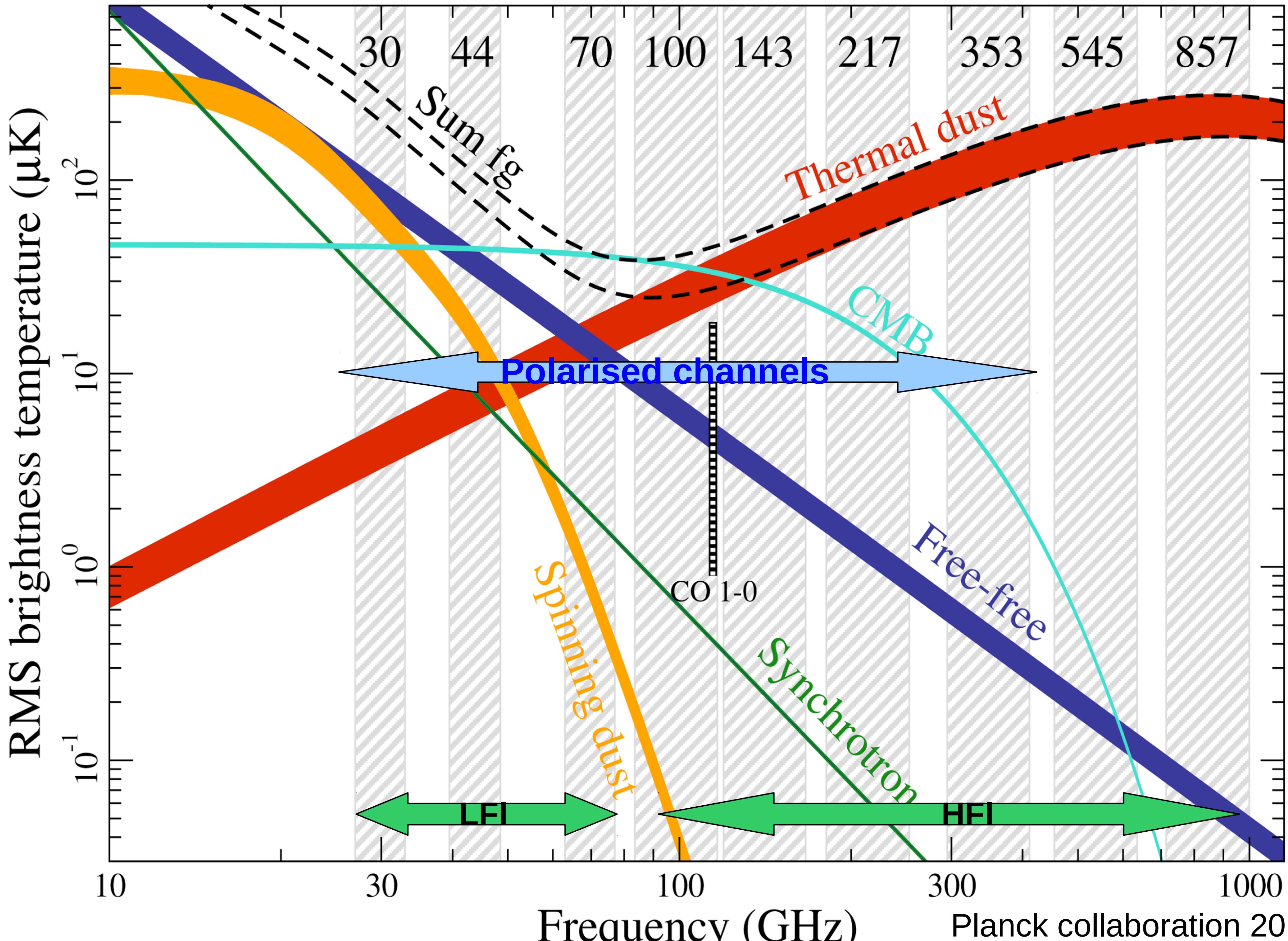
- May ‘09: launch; Aug.: survey starts
- Nov. ‘10: nominal mission (2 surveys)
- Mid-Jan ‘12: extended cryogenic mission (5 surveys)
- Summer ‘13: mission achieved



Ultimate CMB measure of temperature & best measure of polarisation with available technology

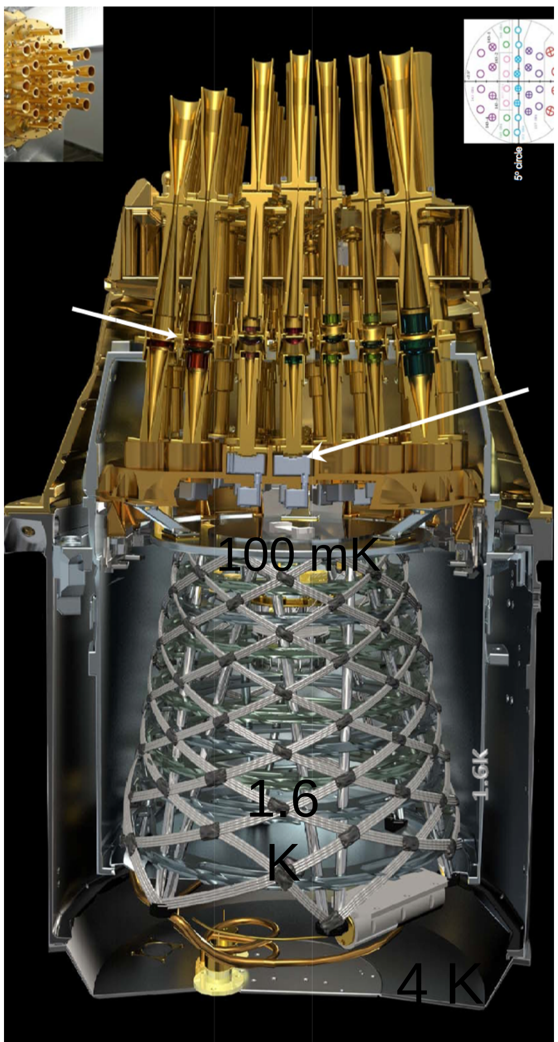
- Two instuments:
  - LFI: 22 radiometers
  - HFI: 56 sensitive bolometers
  - Complex cryogenic cooling chain: 5 stages including 100mK He3&He4 dilution cooler
- All sky & anguar resolution (~5’)
- High sensitivity: limited by astrophysical components

- 9 Frequency channel
- 7 Polarised channels (30 - 353GHz)



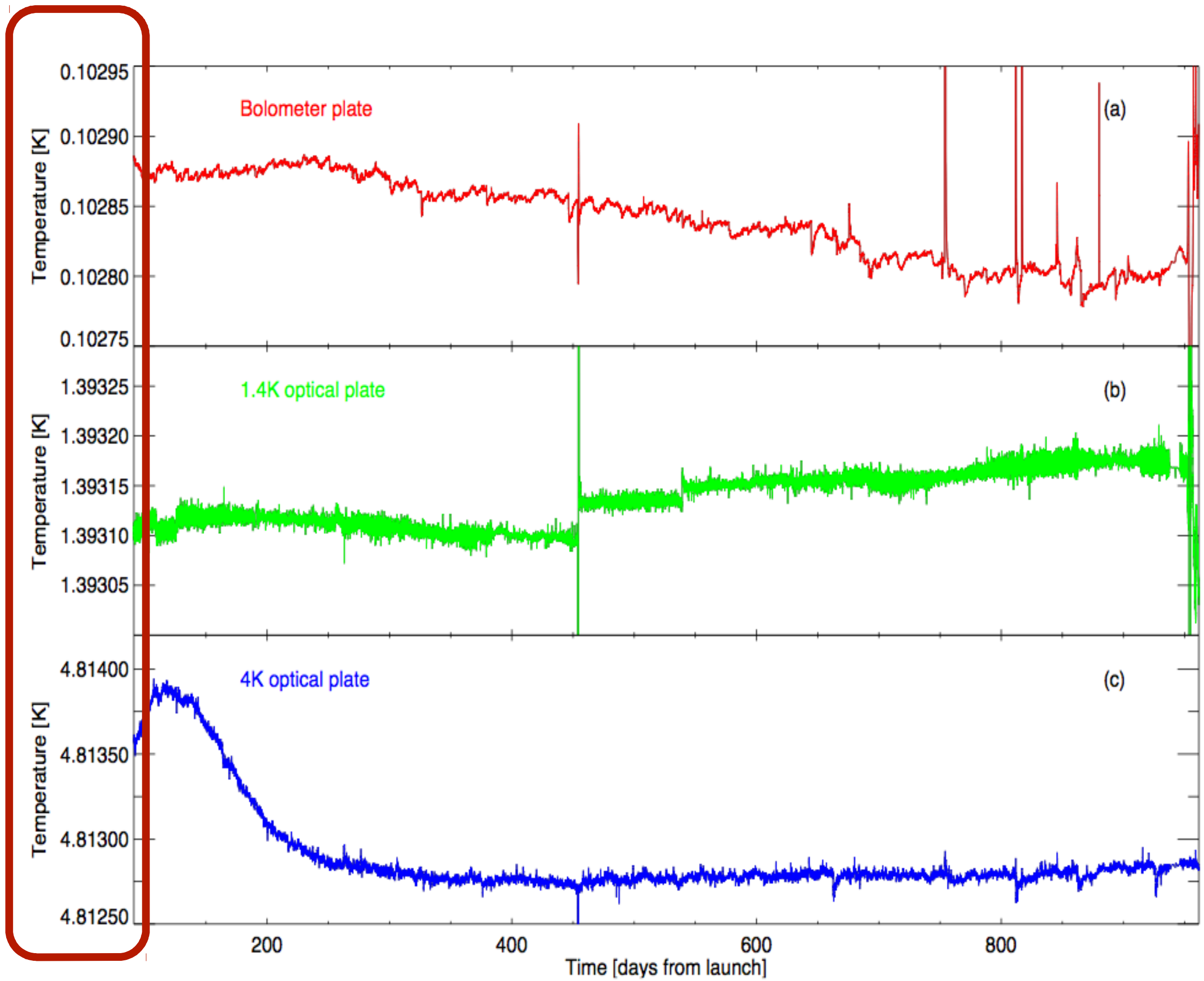
Planck collaboration 2015 I

The Planck satellite



Cryostat He3/He4

Fraction mK stability in space during > 2 years!

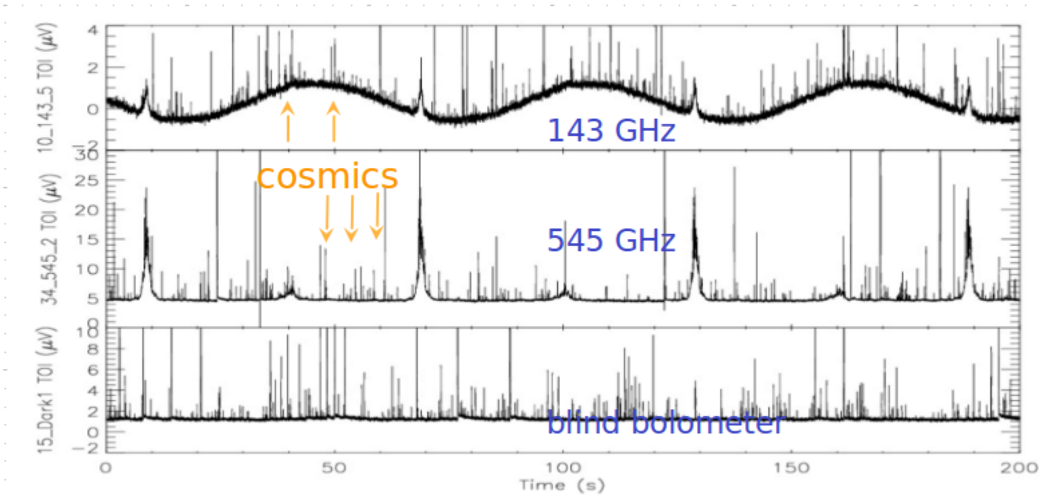


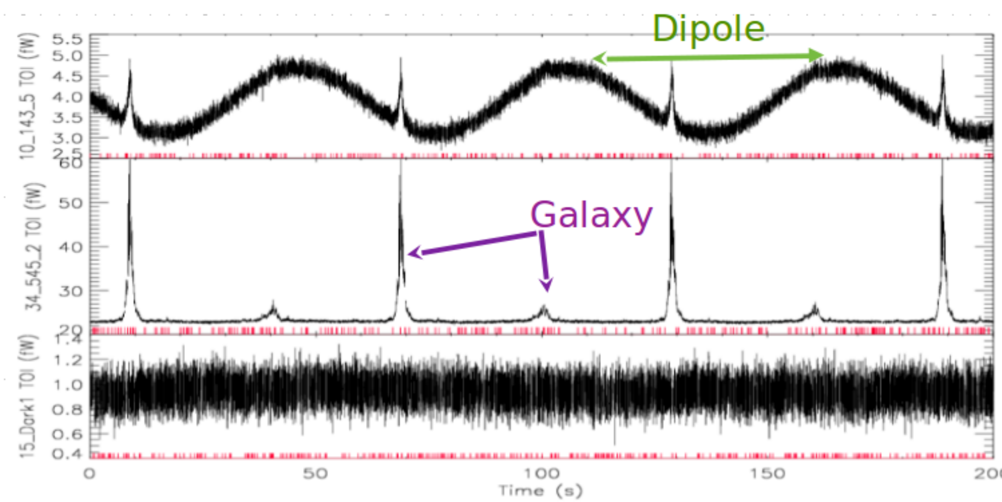
100mK stage

1.4K stage

4K stage

The Planck satellite

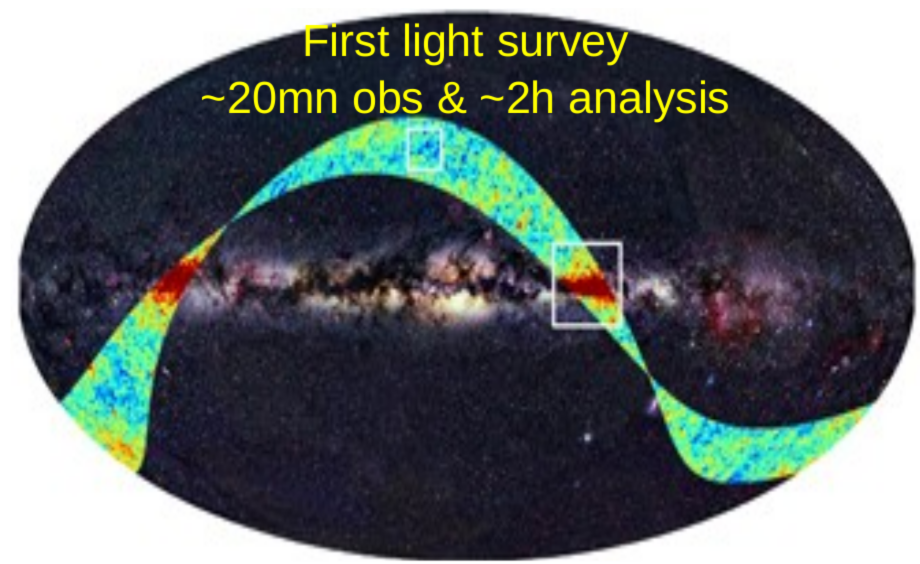




Data reduction:

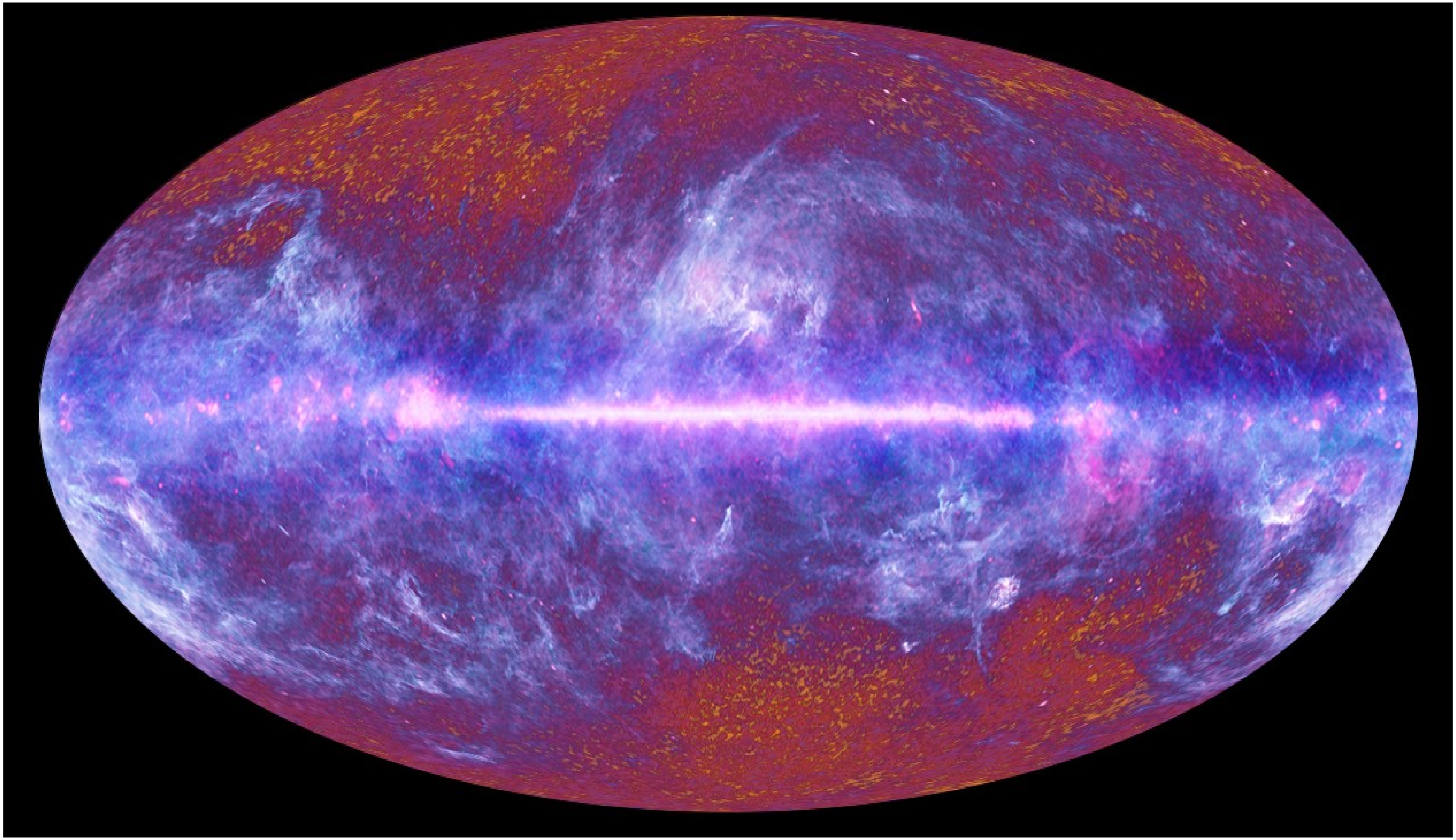
- 1 circle per minute
- 200 sky mesures per sec. & per detector during 29 months
- ~10^{10} samples (72 channels, 29 months)
- 50 Go raw data per detector
- 1 release: >2500 maps
- 1 map: 5 10^{7} pixels (9 freq.)

6 main cosmological parameters



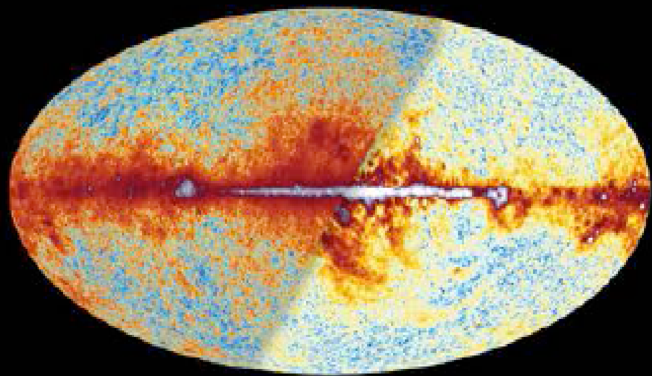
~9 years of data analysis
→ control systematics!

We observe through our Galaxy

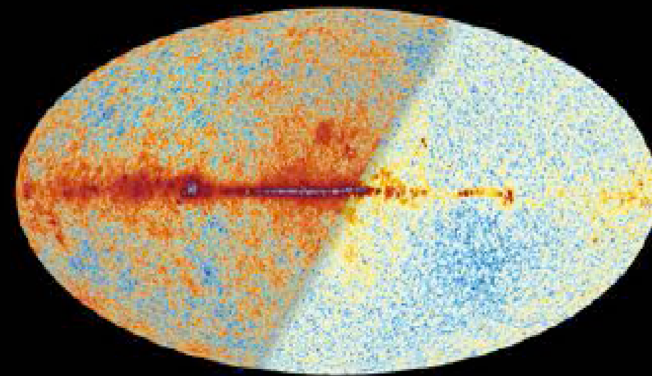


Dust & synchrotron induce the most prominent emissions (cf. Talk R. Genova-Santos)

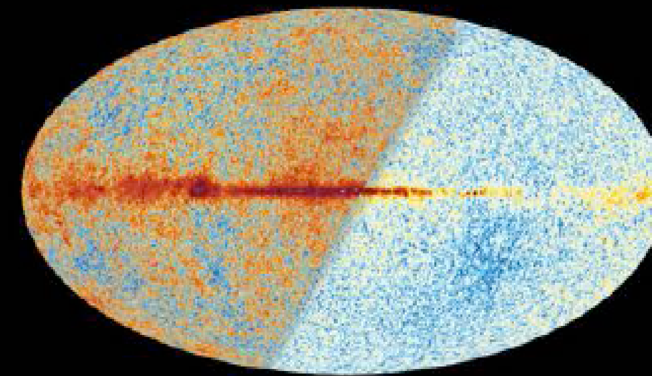
→ Component separation needed to “clean” the CMB (cf. Talk B. Barreiro)



30 GHz

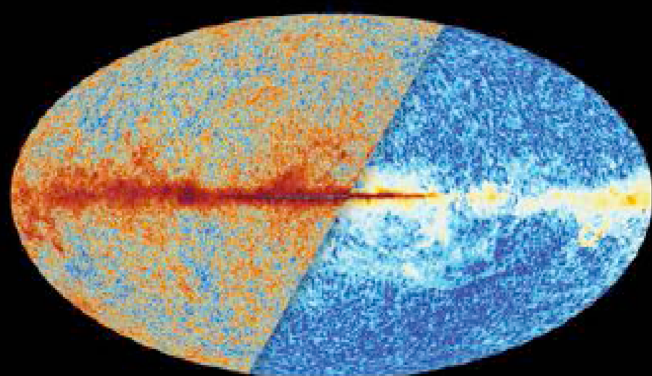


44 GHz

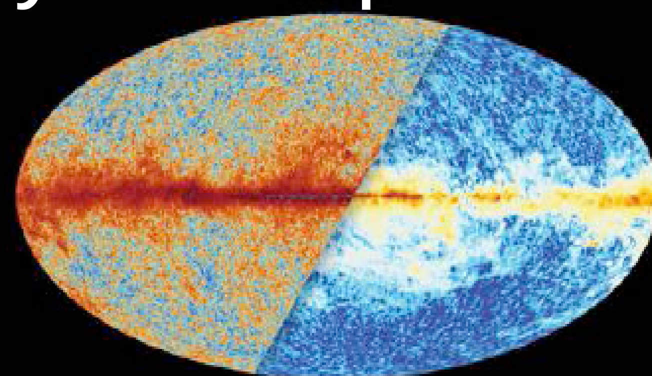


3.5μK.deg,13’ 70 GHz

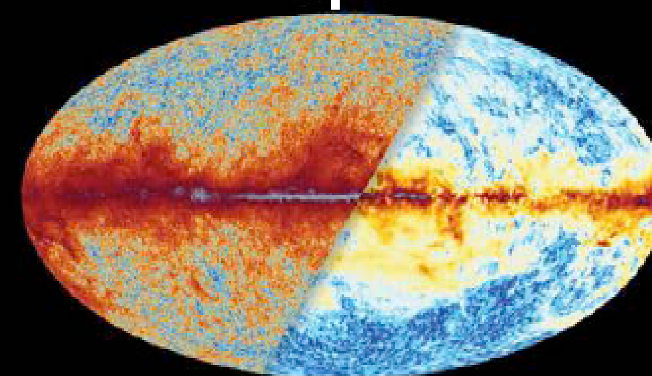
9 intensity and 7 polarisation maps



1.3μK.deg,9.7’ 100 GHz

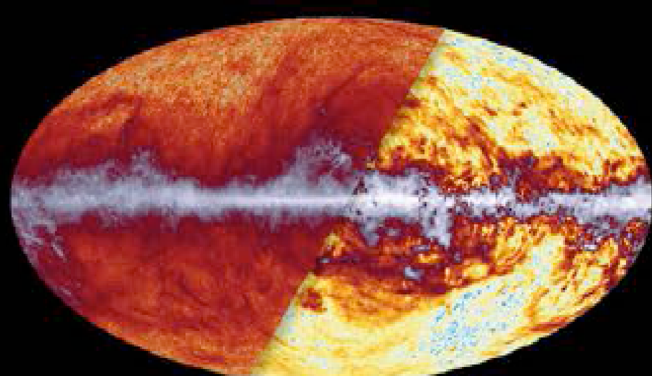


0.5μK.deg,7.3’ 143 GHz

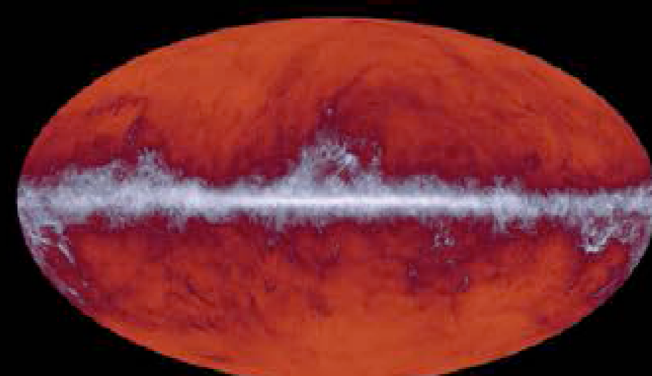


0.8μK.deg,5.0’ 217 GHz

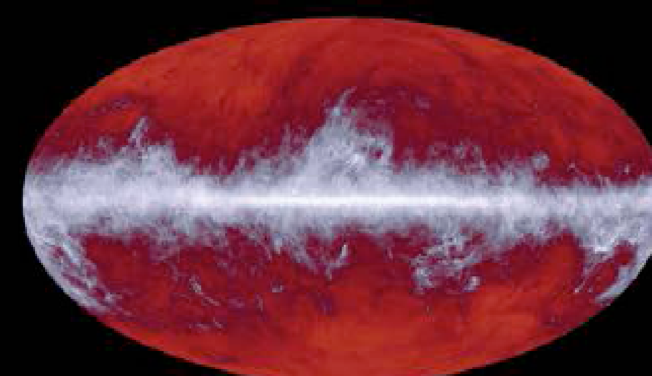
Planck collab. 2015 VI; VIII



353 GHz

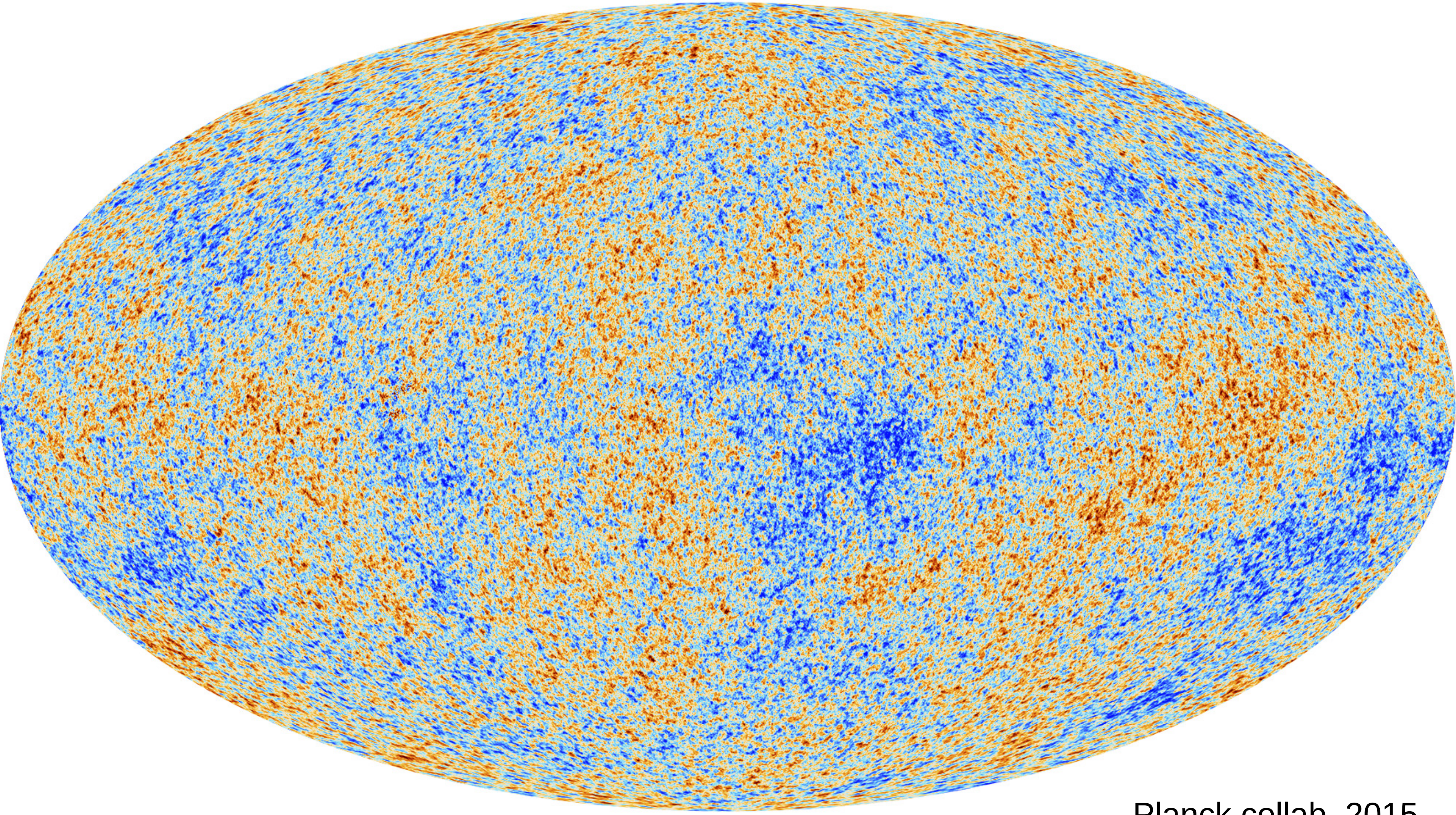


545 GHz



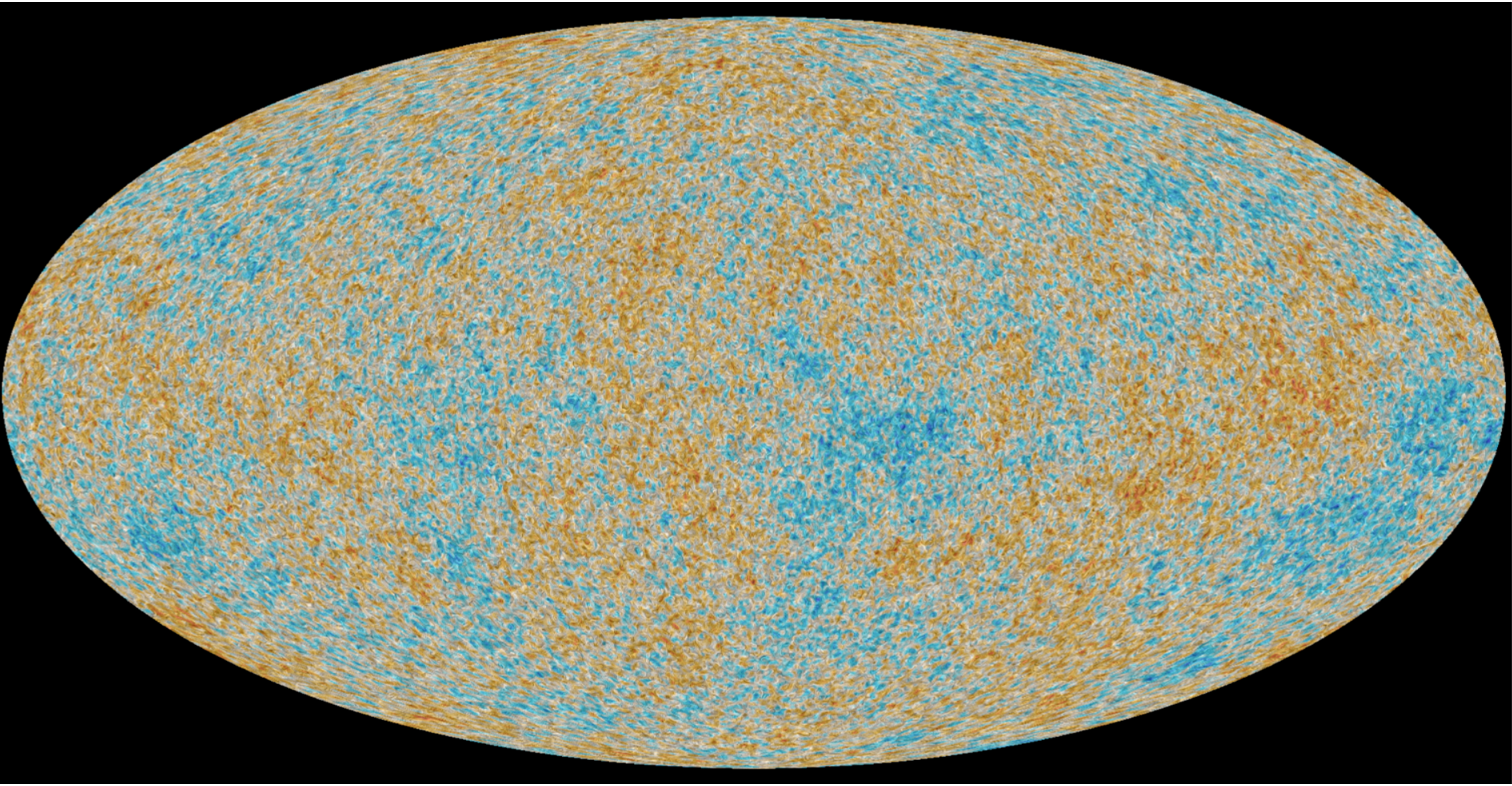
857 GHz

CMB temperature map



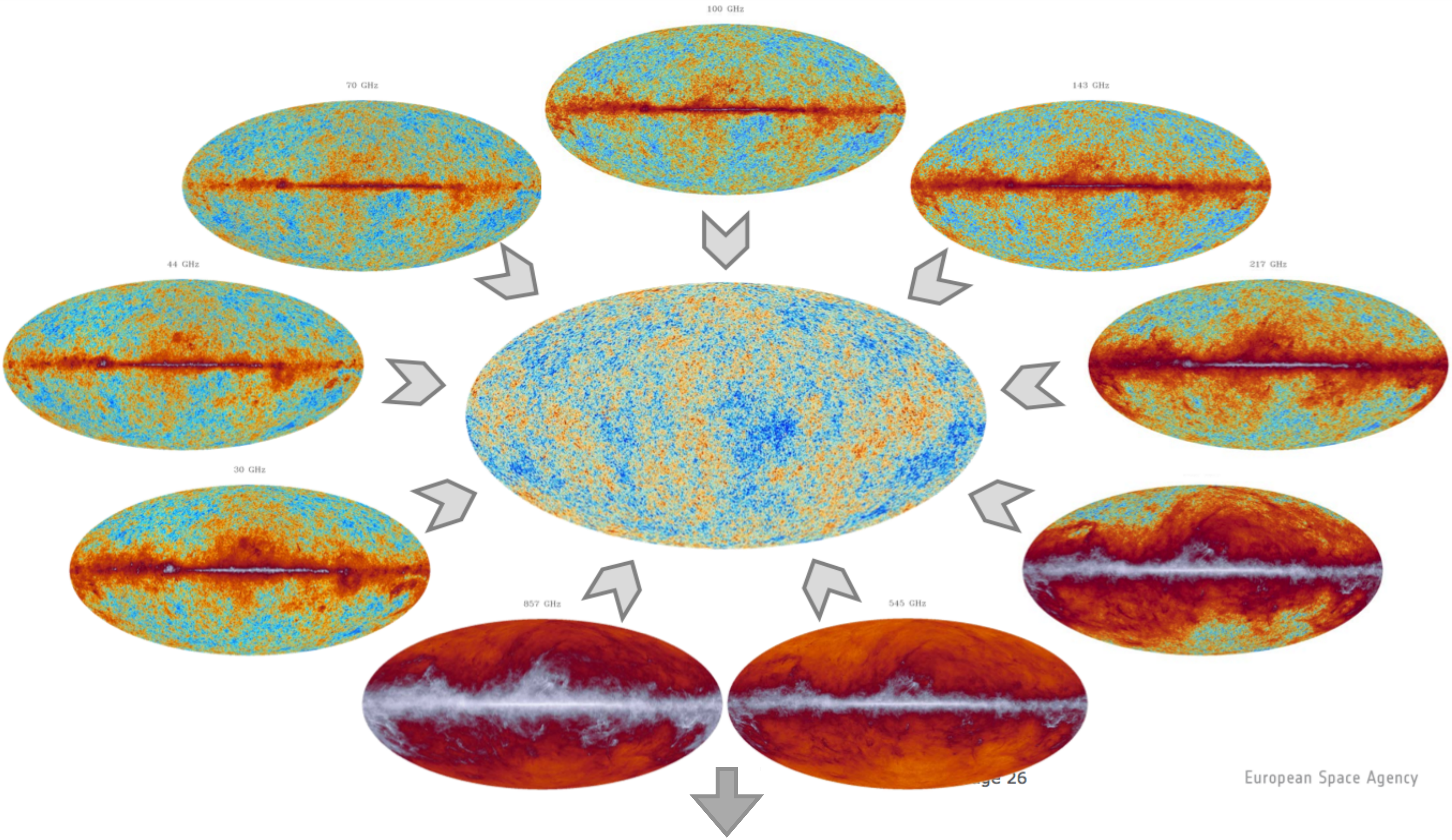
Planck collab. 2015

CMB polarisation map



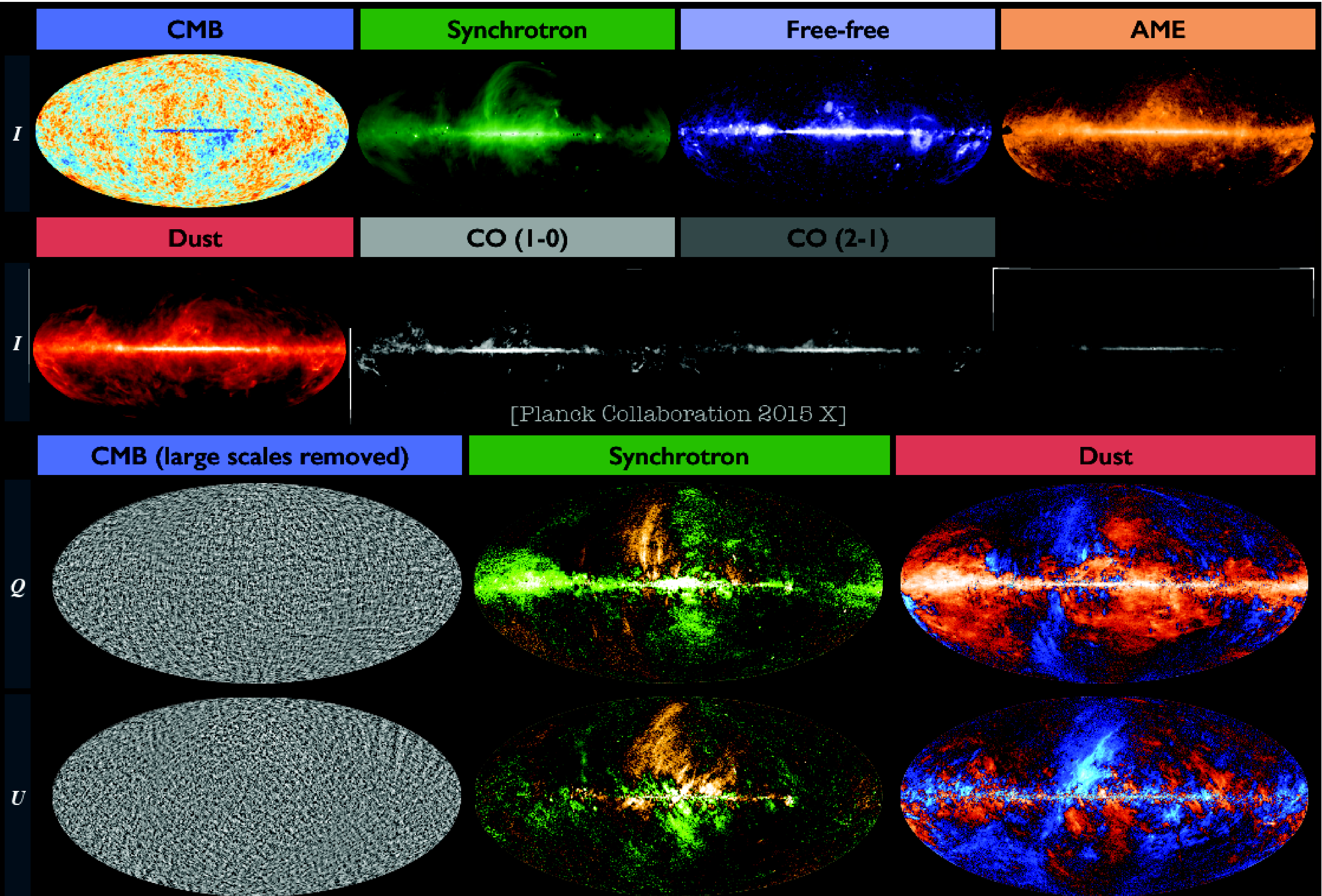
Planck collab. 2015

Component (re)construction



Planck's physical component maps

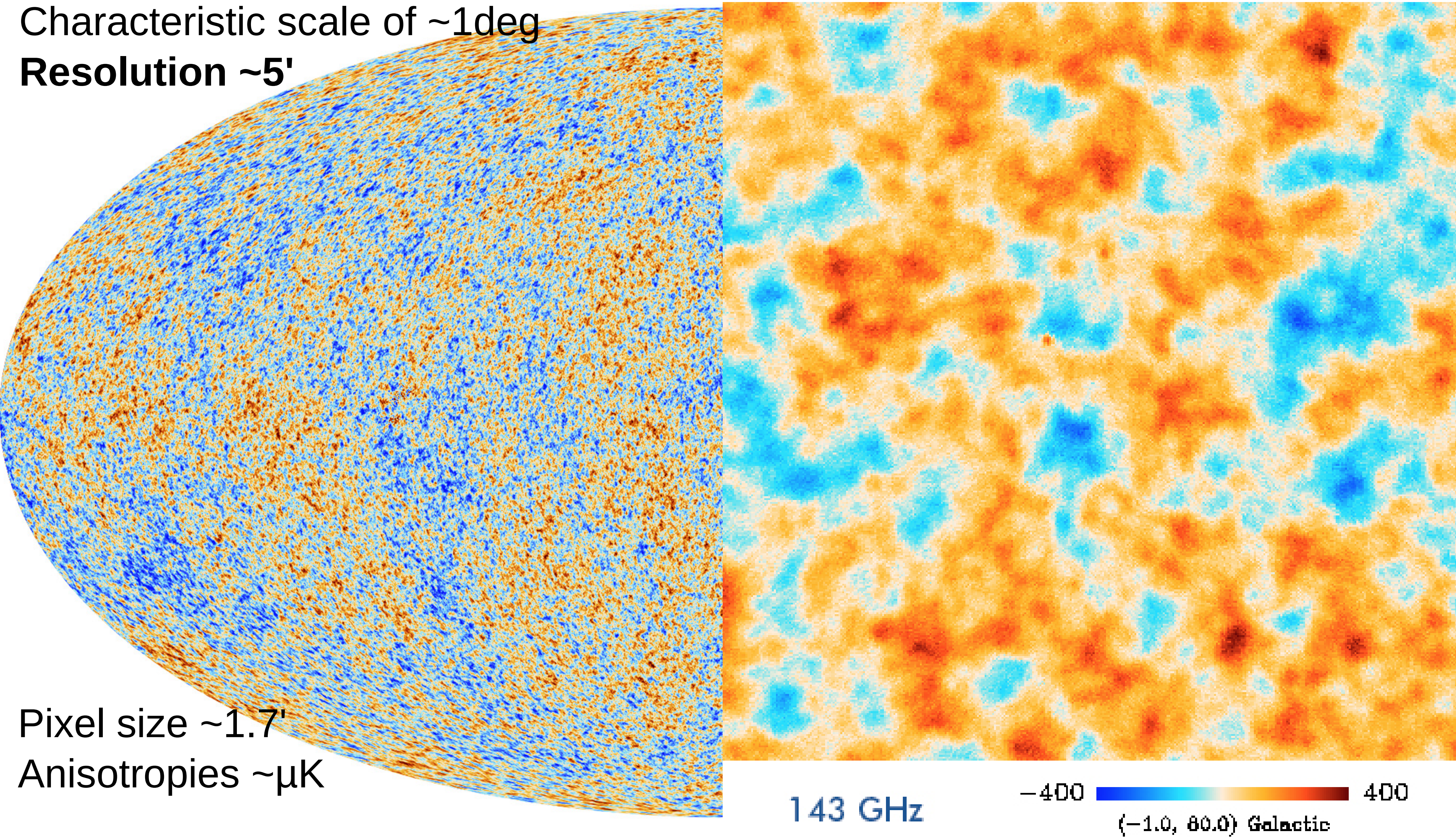
(Cf. Talk B. Barreiro)


CMB
Synchrotron
Free-free
AME
I
Dust
CO (1-0)
CO (2-1)
I
[Planck Collaboration 2015 X]
CMB (large scales removed)
Synchrotron
Dust
Q
U

CMB map: an image of the Universe at 380,000 years old!

Characteristic scale of ~1deg

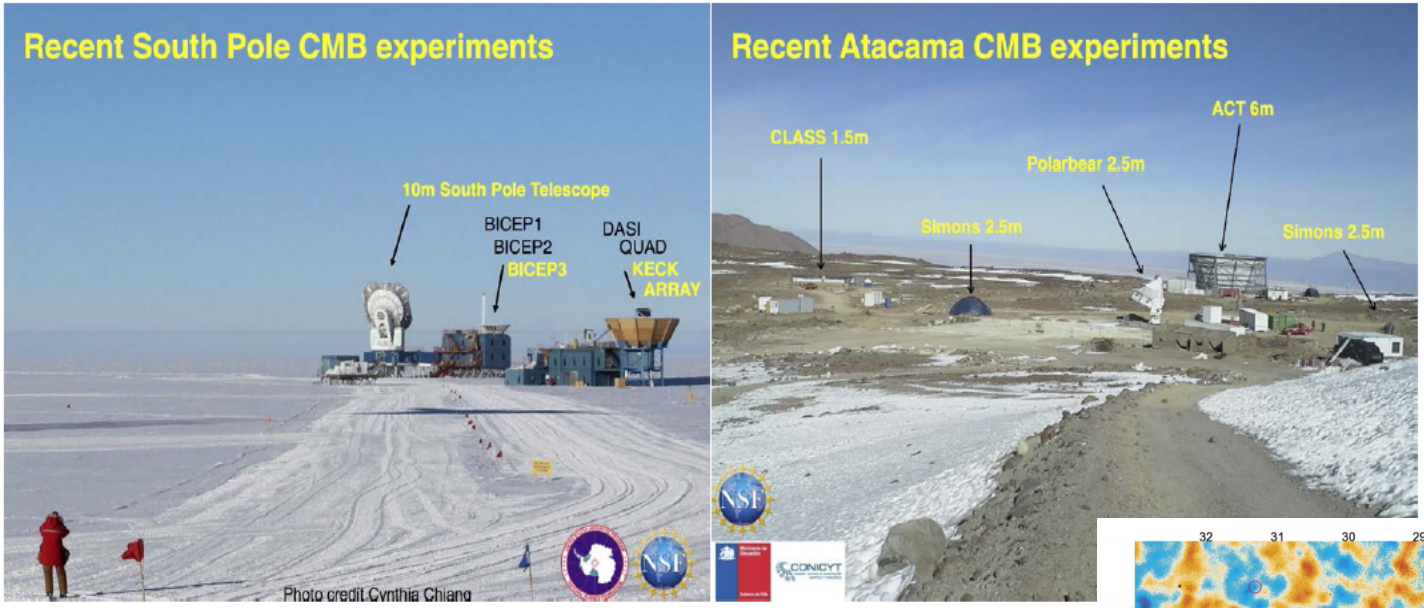
Resolution ~5'



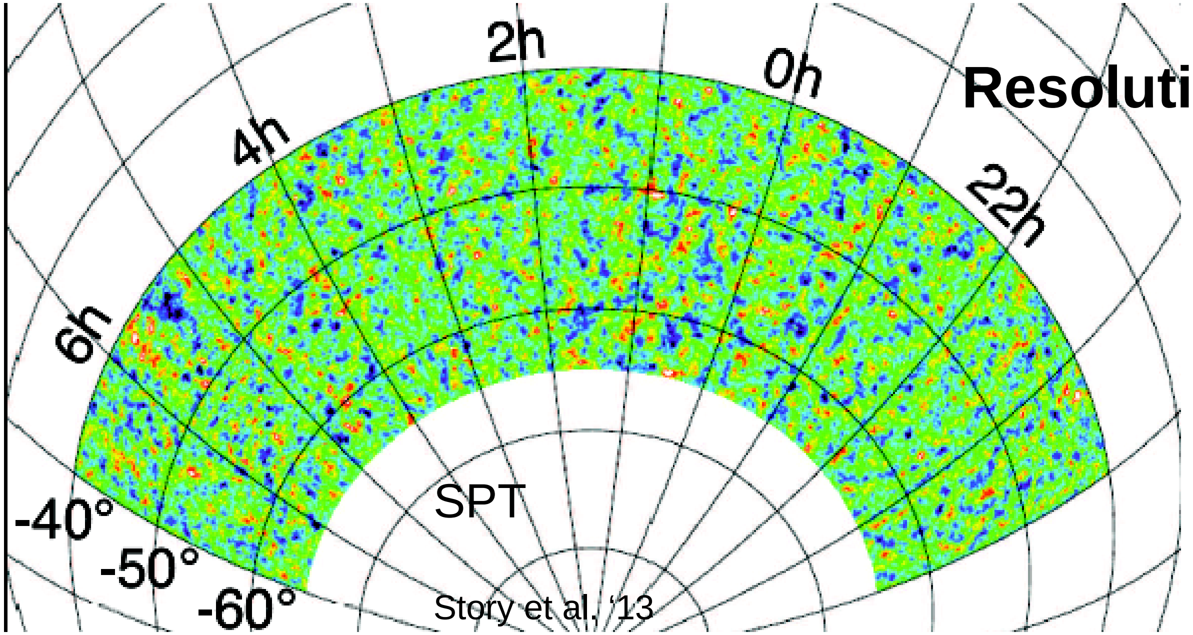
Pixel size ~1.7'

Anisotropies ~μK

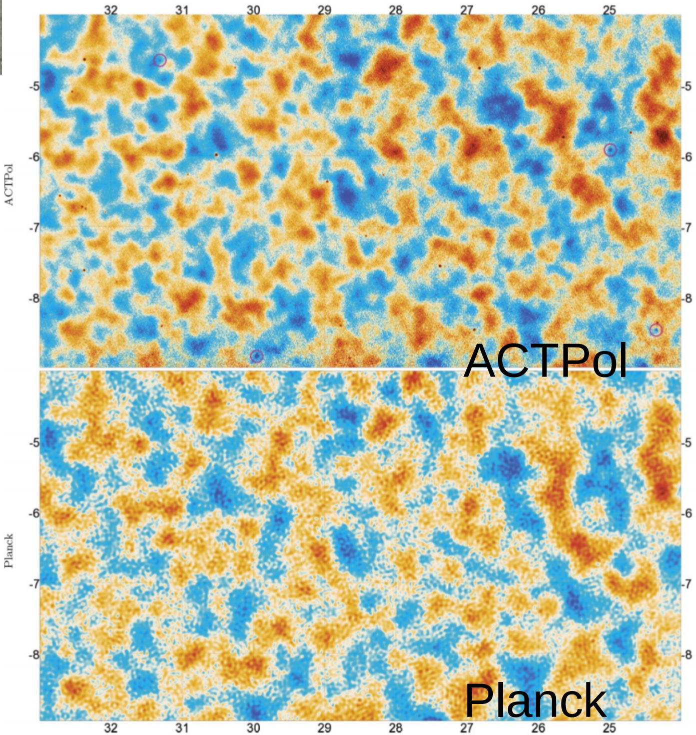
CMB temperature @smaller scales



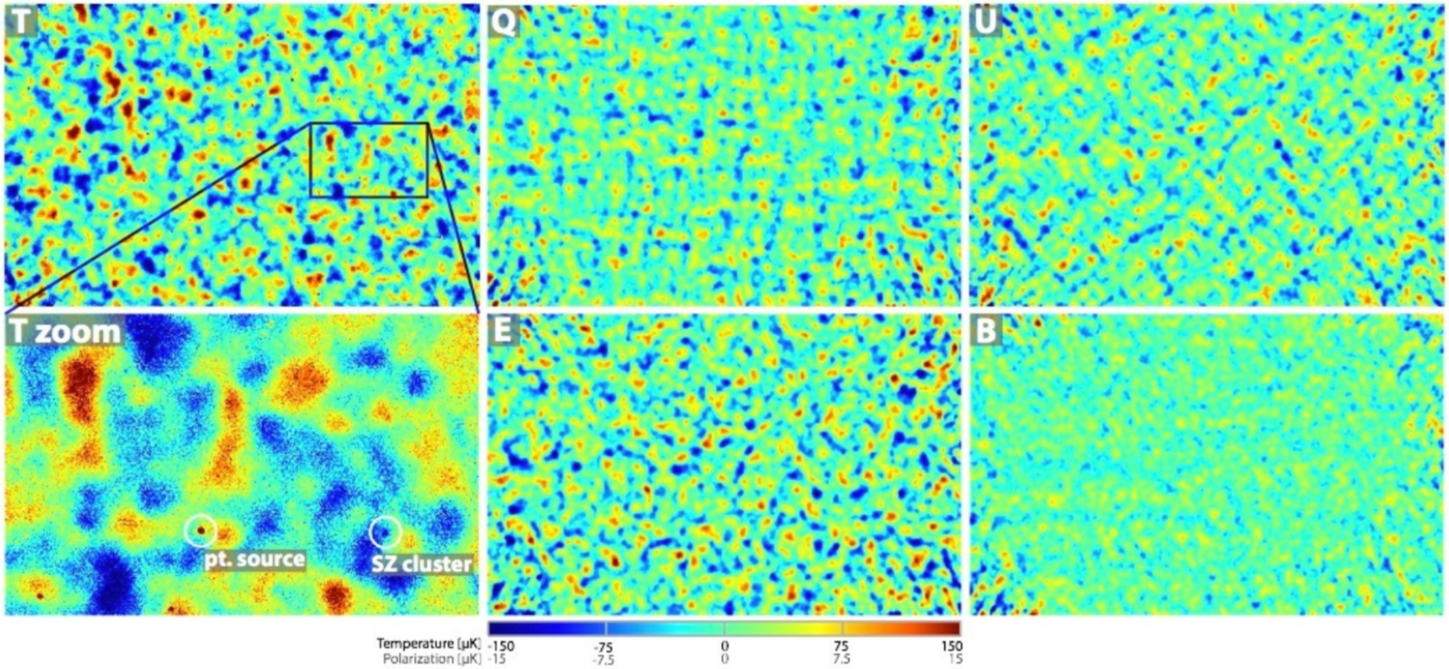
Resolution ~1'



Louis et al. '16



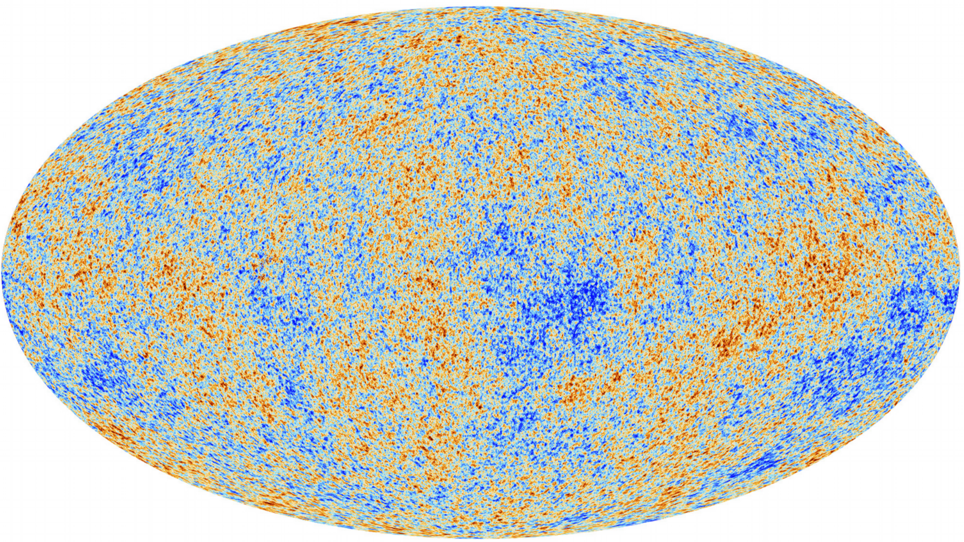
CMB polarisation at smaller scales: e.g. ACTPol

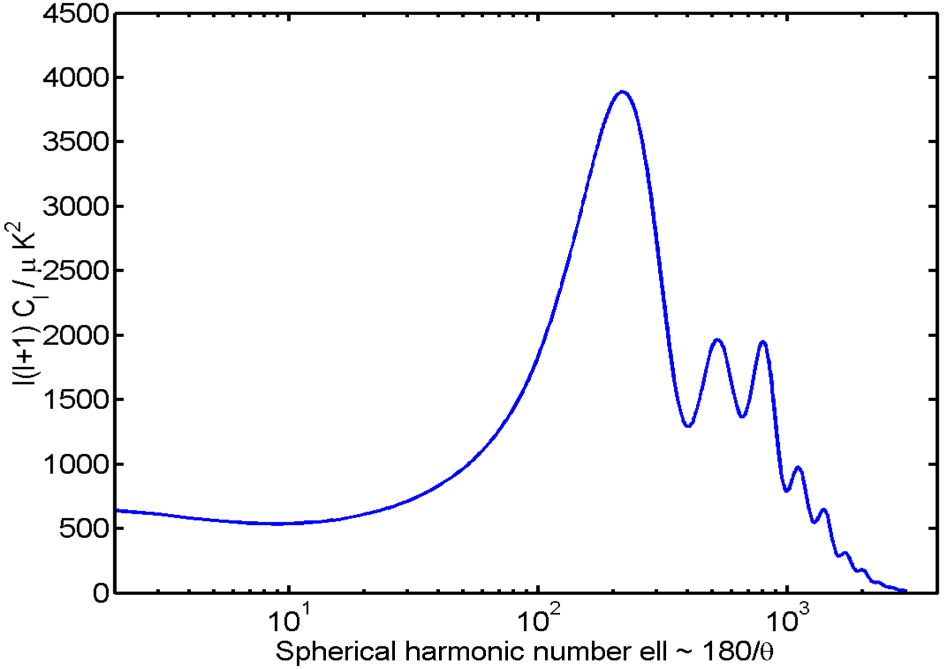


CMB introduction & status

Introduction
The CMB maps
The CMB angular power spectrum
Cosmology with CMB: Main features in primary anisotropies
Secondary anisotropies: CMB lensing
Secondary anisotropies: thermal Sunyaev-Zel'dovich
Conclusions

CMB angular power spectrum





- Quantify clumpiness on different scales → Decompose in spherical harmonic transforms (~Fourier transform on the sphere)
- BB isotropic radiation @T ~ 3K → State of early Universe
- Model predicts CMB is Gaussian and isotropic → all information contained in its angular power spectrum

CMB angular power spectrum

Temperature anisotropies on sky decomposed in harmonic transforms

$$T_{\text{CMB}} = 2.726K$$

$$\Delta T(\theta,\phi) = T(\theta,\phi) - T_{\text{CMB}}$$

Temperature anisotropy as a function of position on the sky

$$a_{\ell m} = \int \frac{\Delta T(\theta,\phi)}{\mathrm{T}_{\text{CMB}}} Y_{\ell m}(\theta,\phi)\ \mathrm{d}\Omega$$

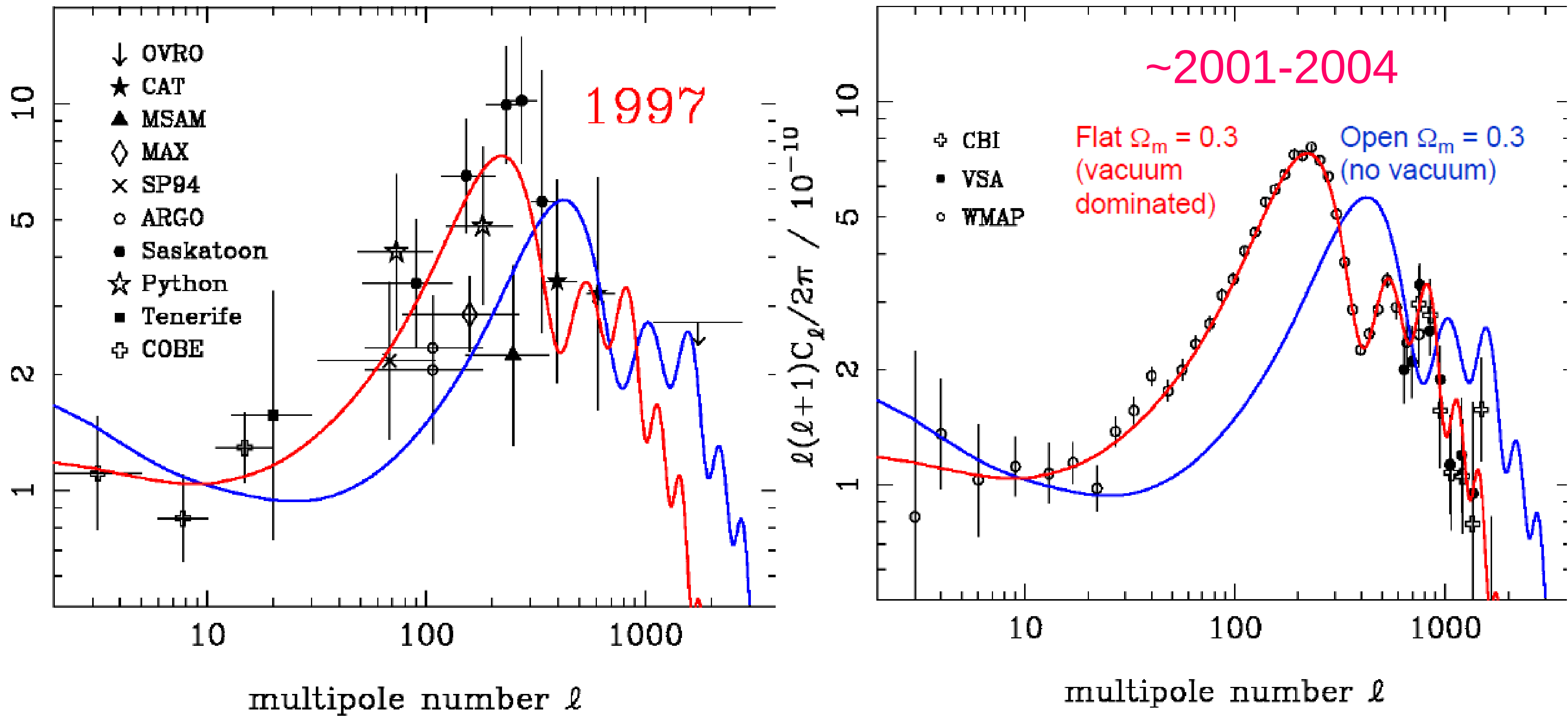
For each multipole there are 2l+1 modes

$$C_\ell = \langle |a_{\ell m}|^2 \rangle$$

Variance of the spherical harmonic coefficients = angular power spectrum (Power in fluctuation of an angular size $\theta=\pi/l$)

(cf talk A. Balaguera-Antolinez)

CMB temperature power spectrum across time



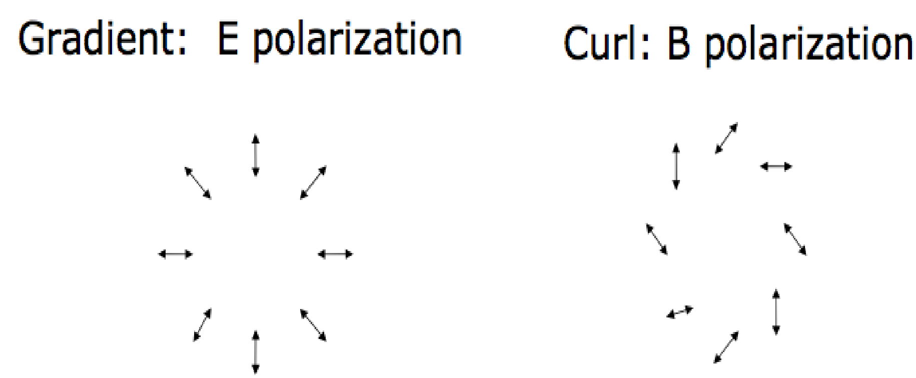
+ BOOMRANG + ARCHEOPS

CMB polarisation across time

Scattering by free electrons at reionisation & recombination:

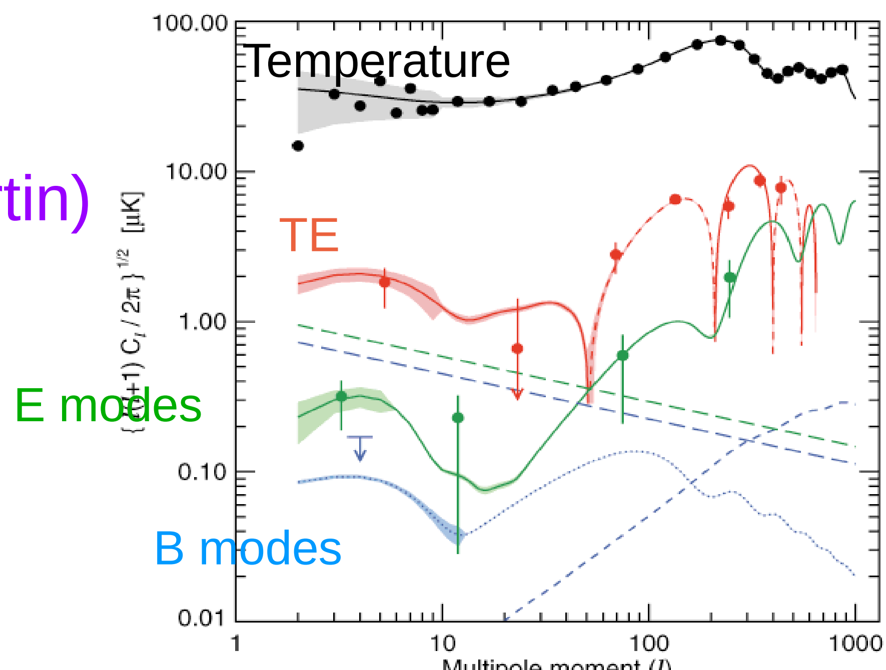
- Density fluctuations (velocity of photon-baryon fluid, quadrupole) → parity invariant pattern: E-modes
- Primordial gravitational waves & lensing → pattern changing sign with parity: B-modes

Polarization E and B modes $P = \begin{pmatrix} Q & U \\ U & -Q \end{pmatrix}$



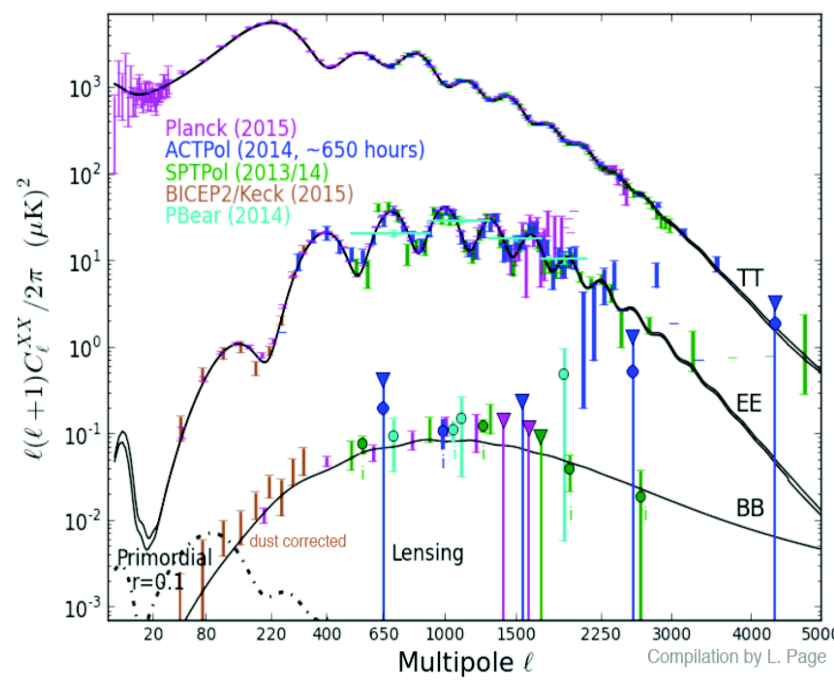
(cf. talk JA. Rubino-Martin)

~2007



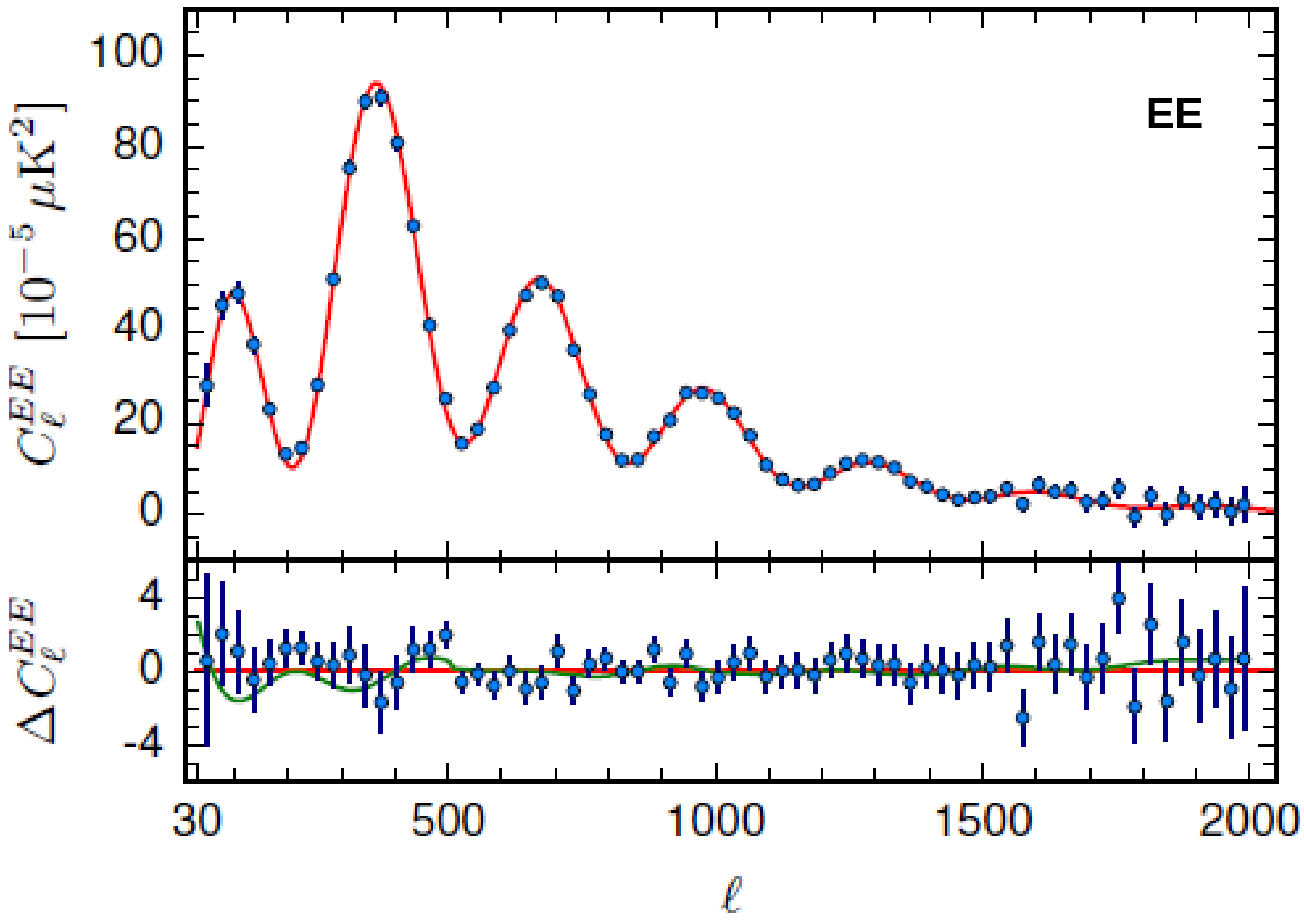
Page et al 07; Bennet et al '12

Mid 2015

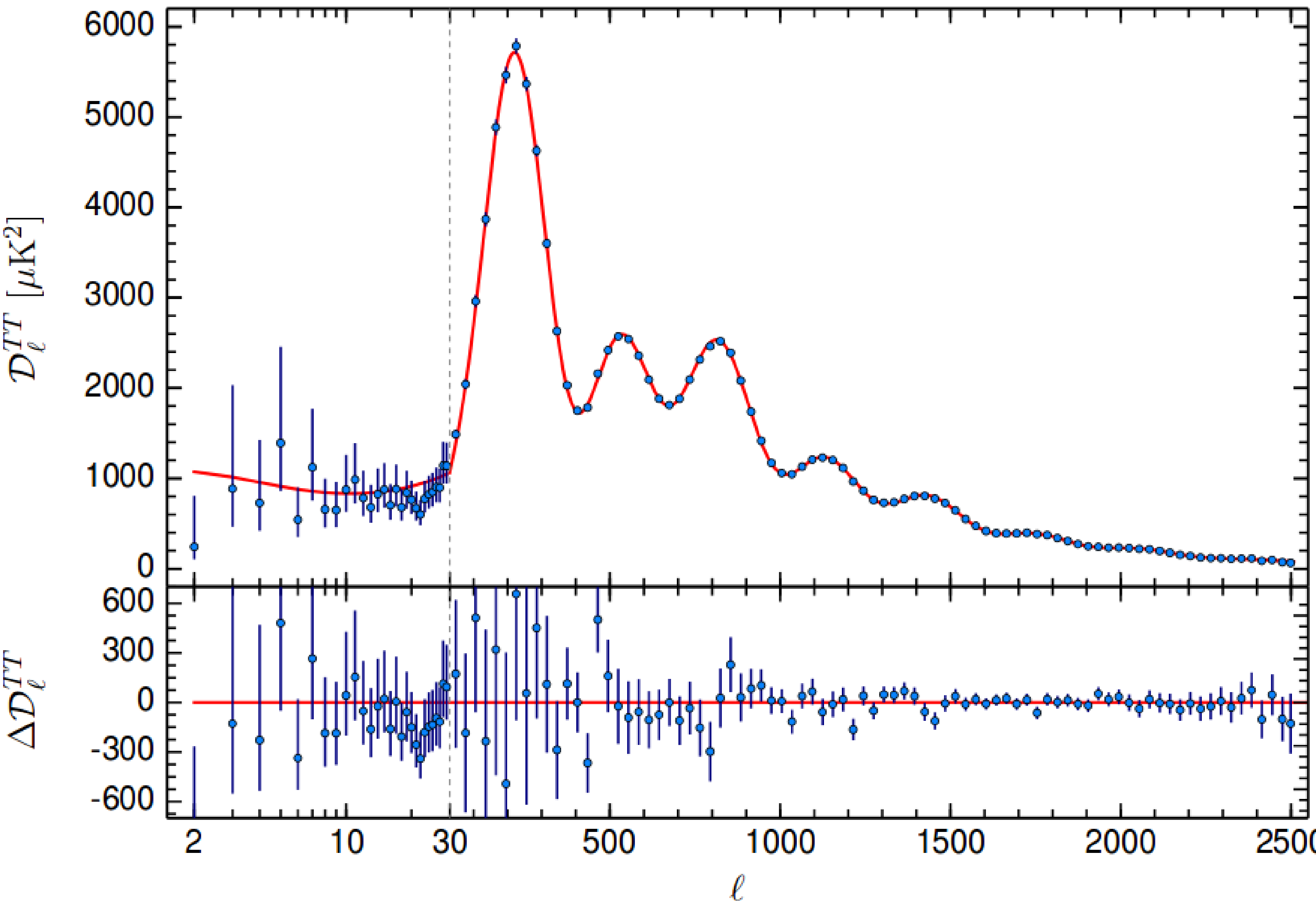


CMB polarisation power spectrum

Intermediate angular scale polarisation spectra from Planck 2015

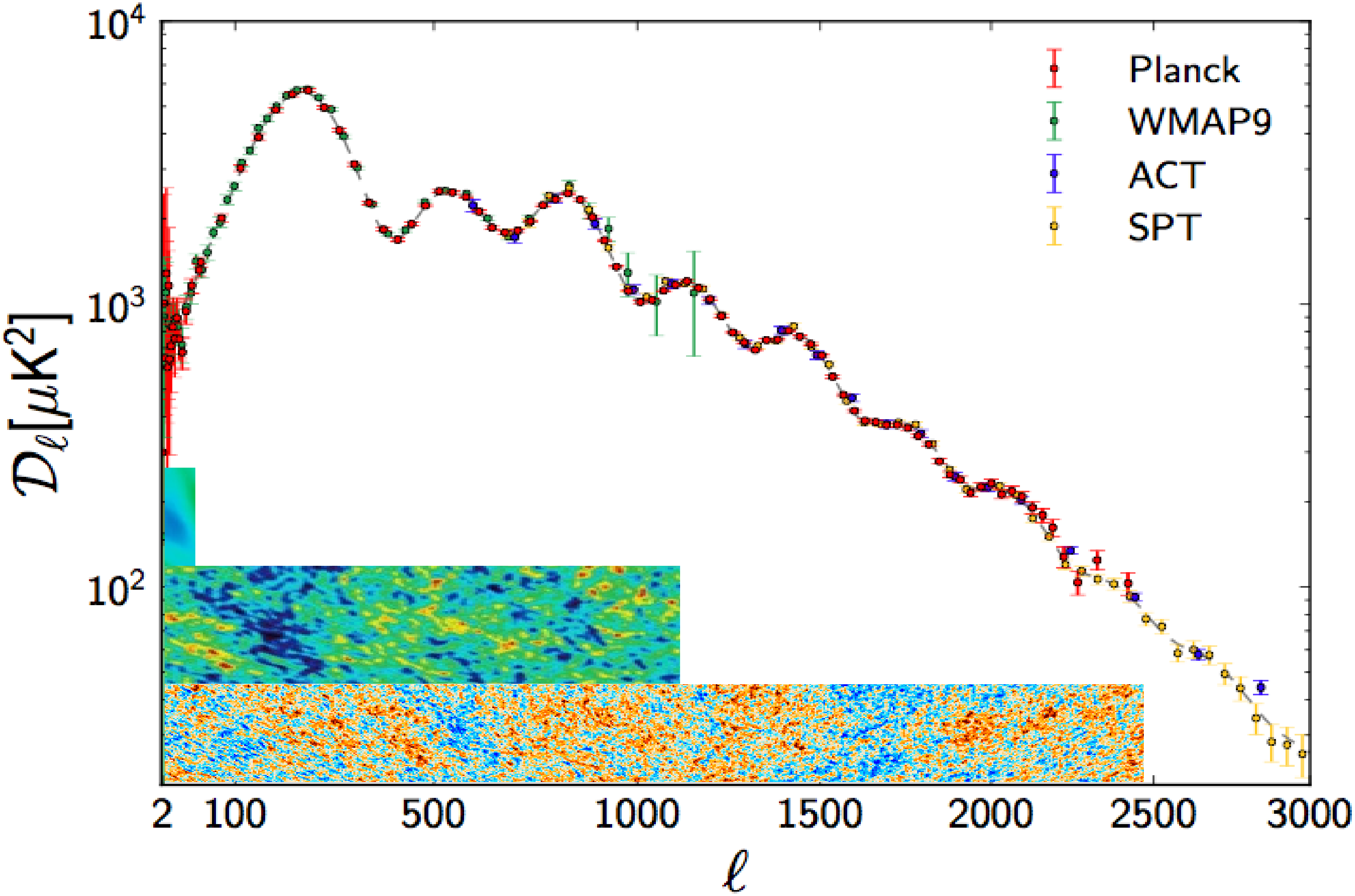


Planck's CMB angular power spectrum



Planck collaboration 2015 XI

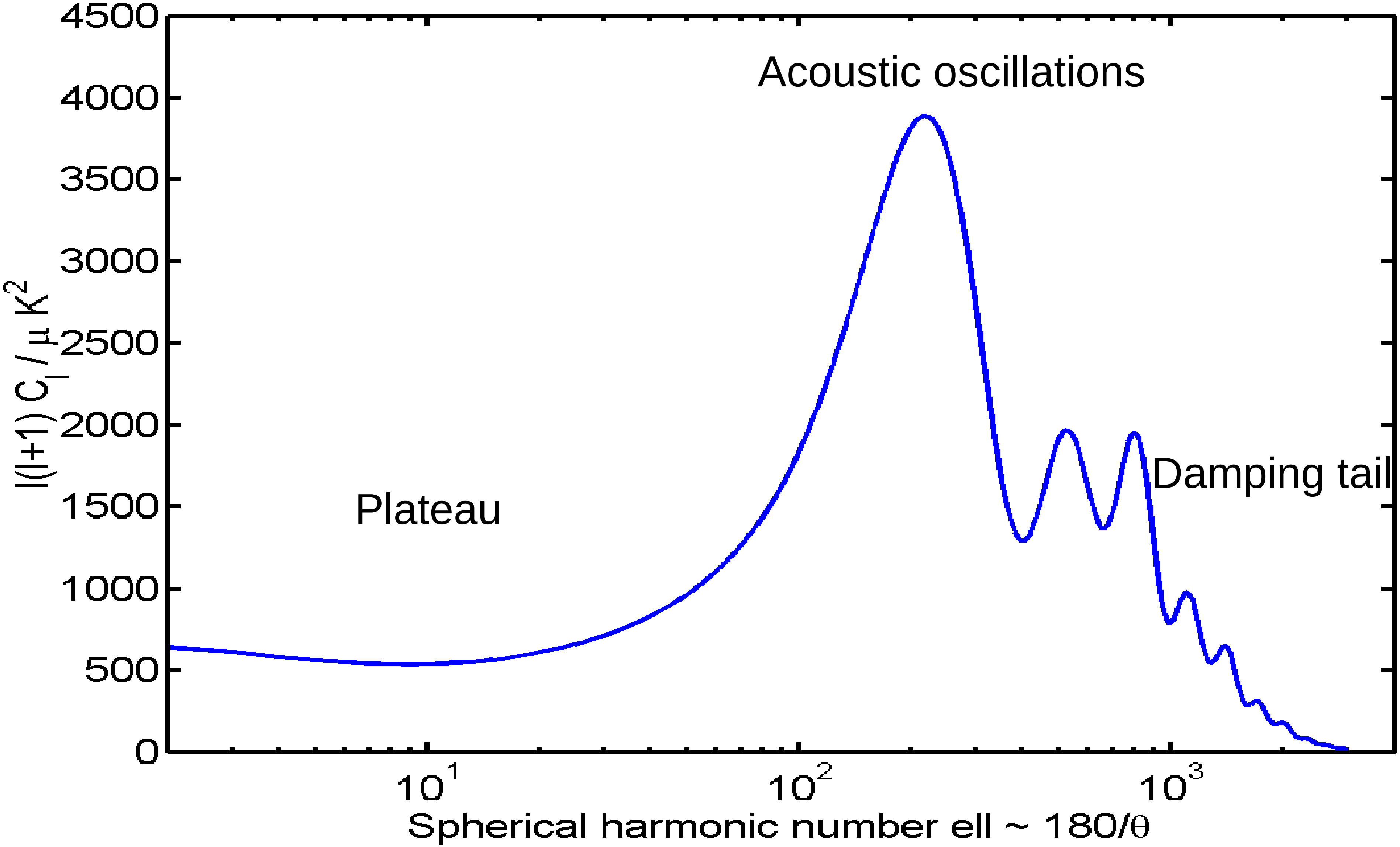
CMB temperature anisotropies across scales: Planck/ACT/SPT



CMB introduction & status

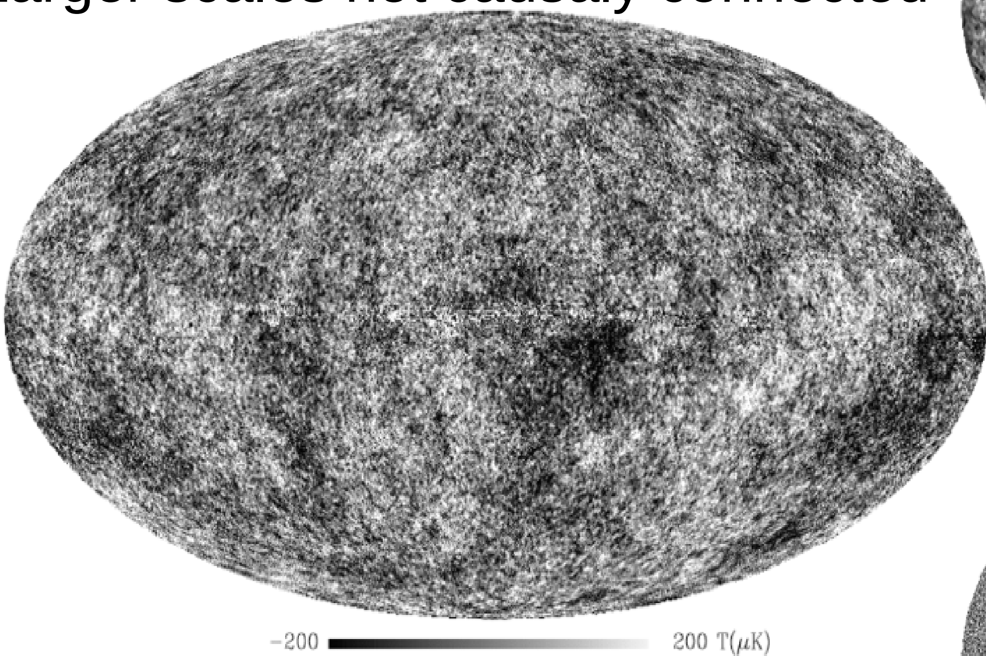
Introduction
The CMB maps
The CMB angular power spectrum
Cosmology with CMB: Main features in primary anisotropies
Secondary anisotropies: CMB lensing
Secondary anisotropies: thermal Sunyaev-Zel’dovich
Conclusions

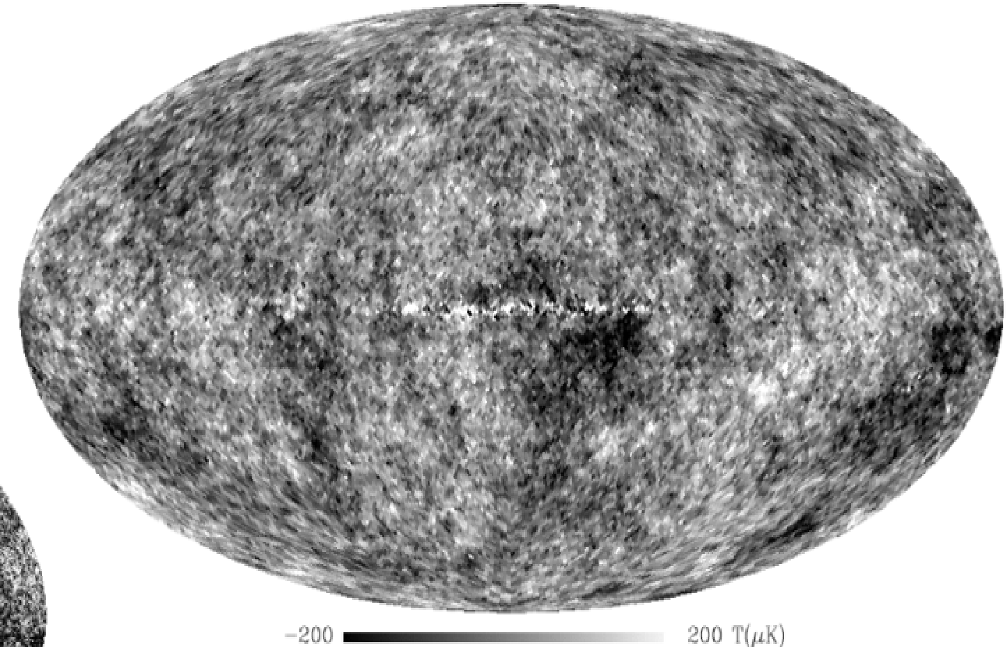
Three regimes of CMB power spectrum

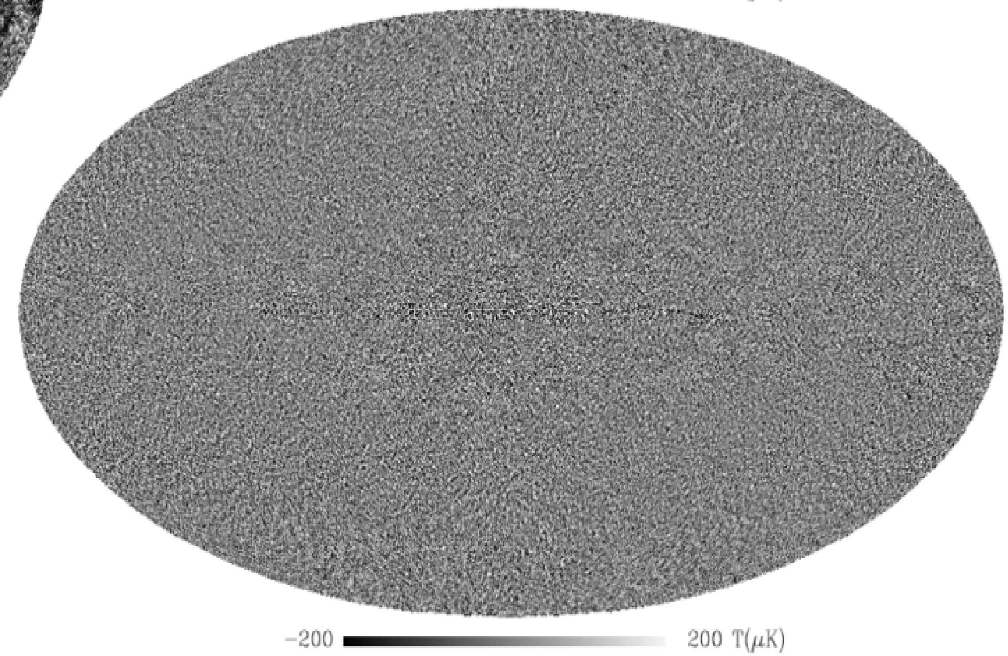


Large scales (>1º) primordial perturbations

@z~1000 Universe homogeneous
Horizon size ~ c x time since Big-Bang → @z~1000 it is ~ 1°
Larger scales not causaly connected



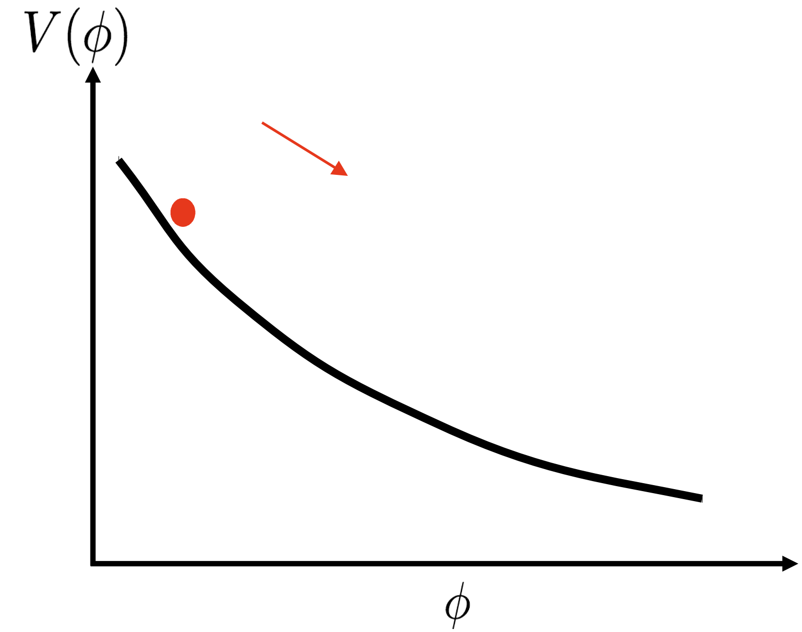




Small scales (<1º) acoustic oscillations

Inflation scenario

At early times, a field, slowly evolving in its potential, with negative pressure drives a nearly exponential expansion



- It expands horizon scale to greater than observable universe size → Causality
- Its quantum fluctuations induce the primordial density perturbations
- If the roll down the potential is slow enough the spectrum of primordial fluctuation determined by the first two derivatives of the potential
- It predicts no measurable NonGaussianity

$$P_s(k) = A_s \left(\frac{k}{k_0}\right)^{n_s}$$

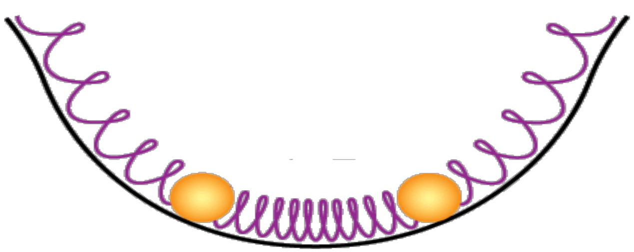
Cosmology with CMB

Inflation (?) imprints quantum fluctuations that evolve and produce oscillations in the primordial plasma

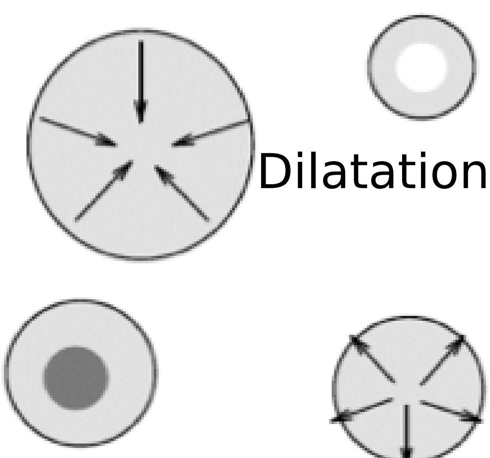
CMB Large scales = Sach-Wolfe effect → *Initial conditions*

CMB Small scales = acoustic oscillations → *content of the Universe*

At small scales (< 1^o)



Tight coupling between matter and radiation
Gravitational instability vs pressure from radiation



Perturbation oscillate between

- Contraction phases, hotter & denser
- Expansion phases, less hot & dense

Periodic variation of CMB temperature frozen at recombination = **Acoustic oscillations**

Cosmology with CMB: Main features
Acoustic peaks

Bouncing fluid causes peak structures in the power spectrum

Consider scale which had time only to collapse under gravity since big-bang

→ It is at maximum temperature → hot-spot

Scale = collapse speed x time allowed
~ sound speed x age of Universe @z~1000 ~ 1 degree
→ First acoustic peak

Second peak = collapse & expand to max
Third peak = collapse & expand & collapse
etc..
Expect peaks to be equally spaced

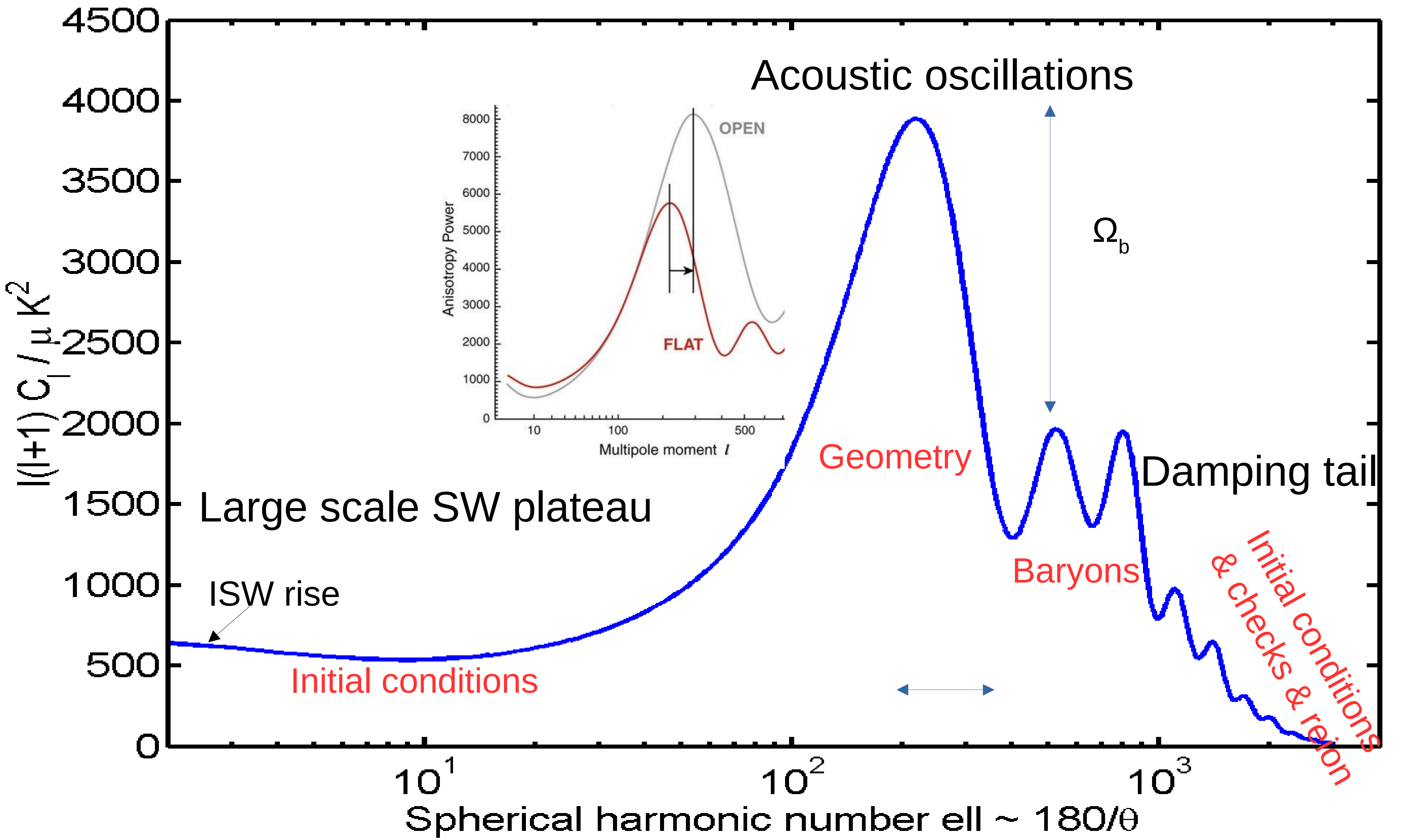
Cosmology with CMB: Main features Plateau

At large scales no Causal connexion → fluctuations directly related to initial density perturbations

- Sachs-Wolf effect → Gravitational redshift = photons climb out of density perturbations potential wells: cold spots →deep wells
- Integrated Sachs-Wolf effect: relative energy gain/loss of photons while crossing LSS →additional temperature fluctuations

(cf. Talk C. Hernandez-Monteagudo)

Cosmology with CMB

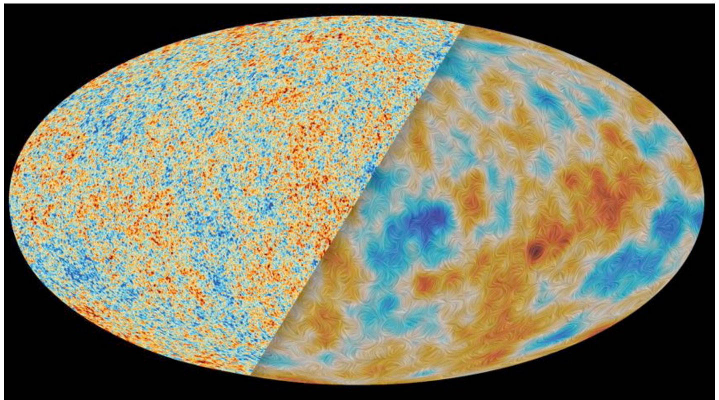


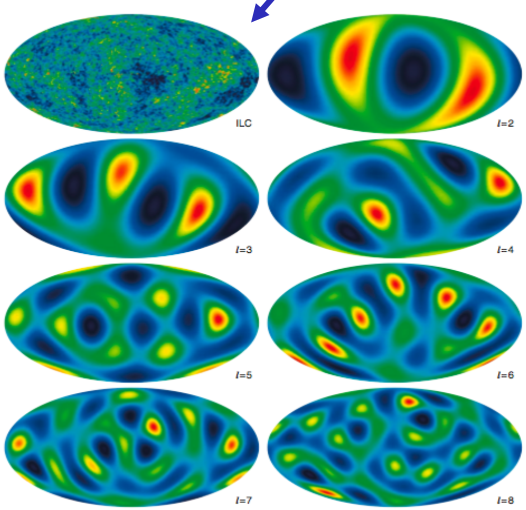
Cosmology with CMB

- **Amplitude** of the fluctuations: plateau
- **Sound horizon**: first-peak location
- **Total matter**: changes the contrast between the peaks
- **Baryon density**: ratio between peak heights (inertia)
- **Reionisation optical depth**: damping tail & large scale polarisation (marginally from lensing
- $\mathbf{H_0}$: derived from above parameters
- **Curvature**: large scales (SW) small scales (lensing)
- **Neutrino mass**: small scales (lensing)

Universe content, Universe dynamics, clumpiness, promordial gravitational waves, reionisation epoch, …

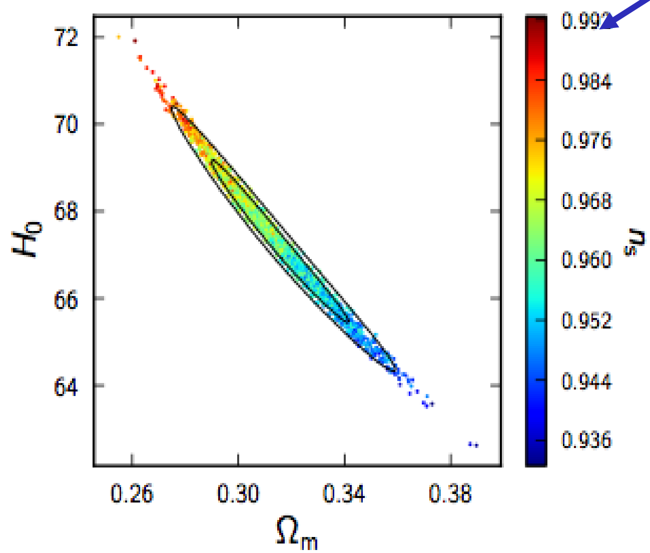
From data to cosmological parameters

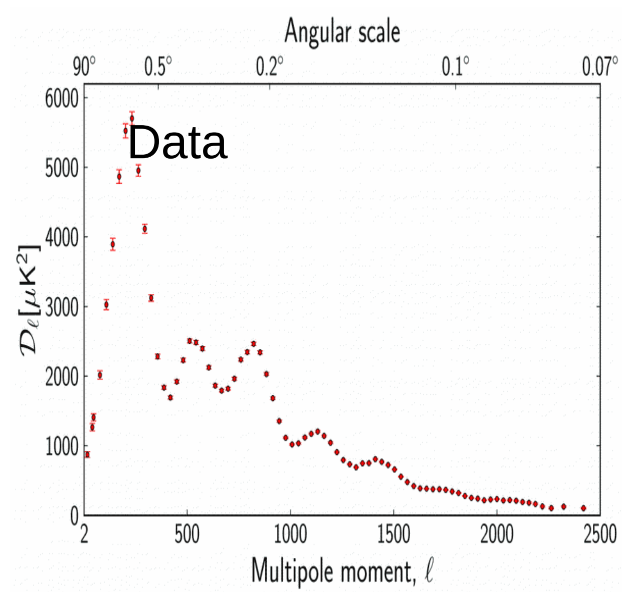


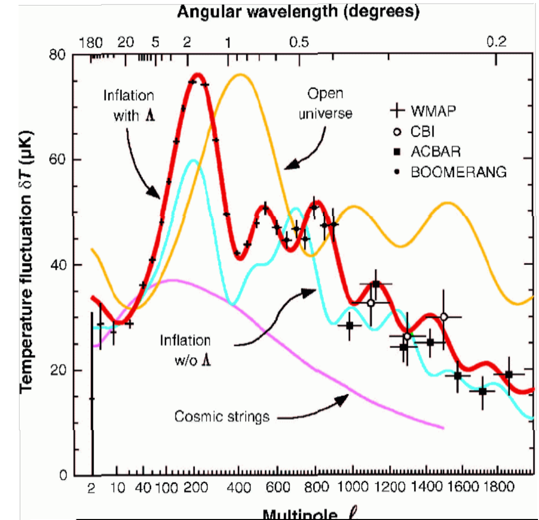


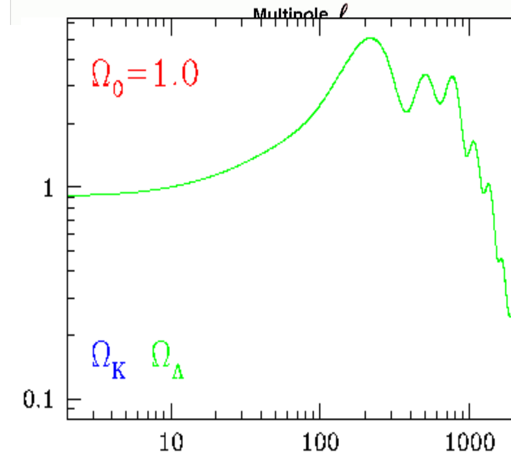
$$\frac{\Delta T(\mathbf{n})}{T_0} = \sum_{\ell=0}^{\infty} \sum_{m=-\ell}^{\ell} a_{\ell m}^T Y_{\ell m}(\mathbf{n})$$

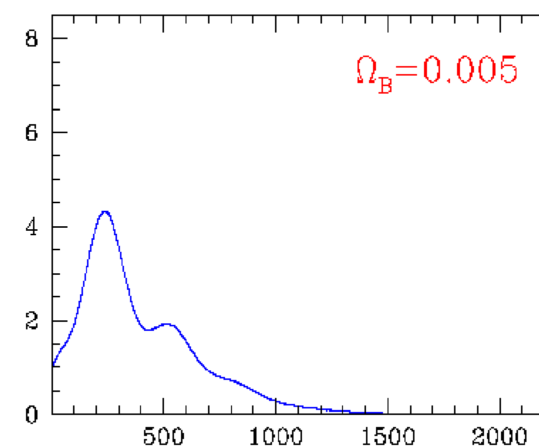
$$C_\ell^{TT} = \langle a_{\ell m}^T \cdot a_{\ell m}^{T\star} \rangle$$







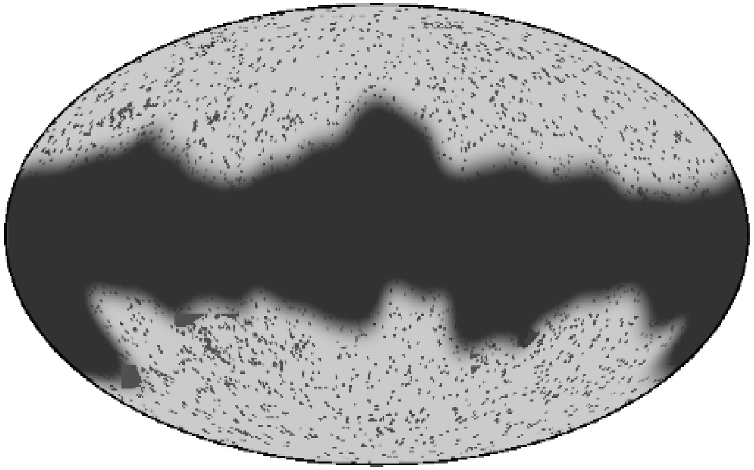




Cosmology with CMB

$$C_\ell^{model} \; ? \equiv ? \; C_\ell^{data}$$

- Data: no maps but auto and cross frequency spectra @100, 143, 217GHz
- No foreground cleaning but masked galactic plane & sources and modeling of CMB & contaminants:
  - Residual galactic dust emission
  - Point sources (radio and IR)
  - Cosmic IR background (CIB)
  - Thermal and kinetic SZ



Cosmology with CMB

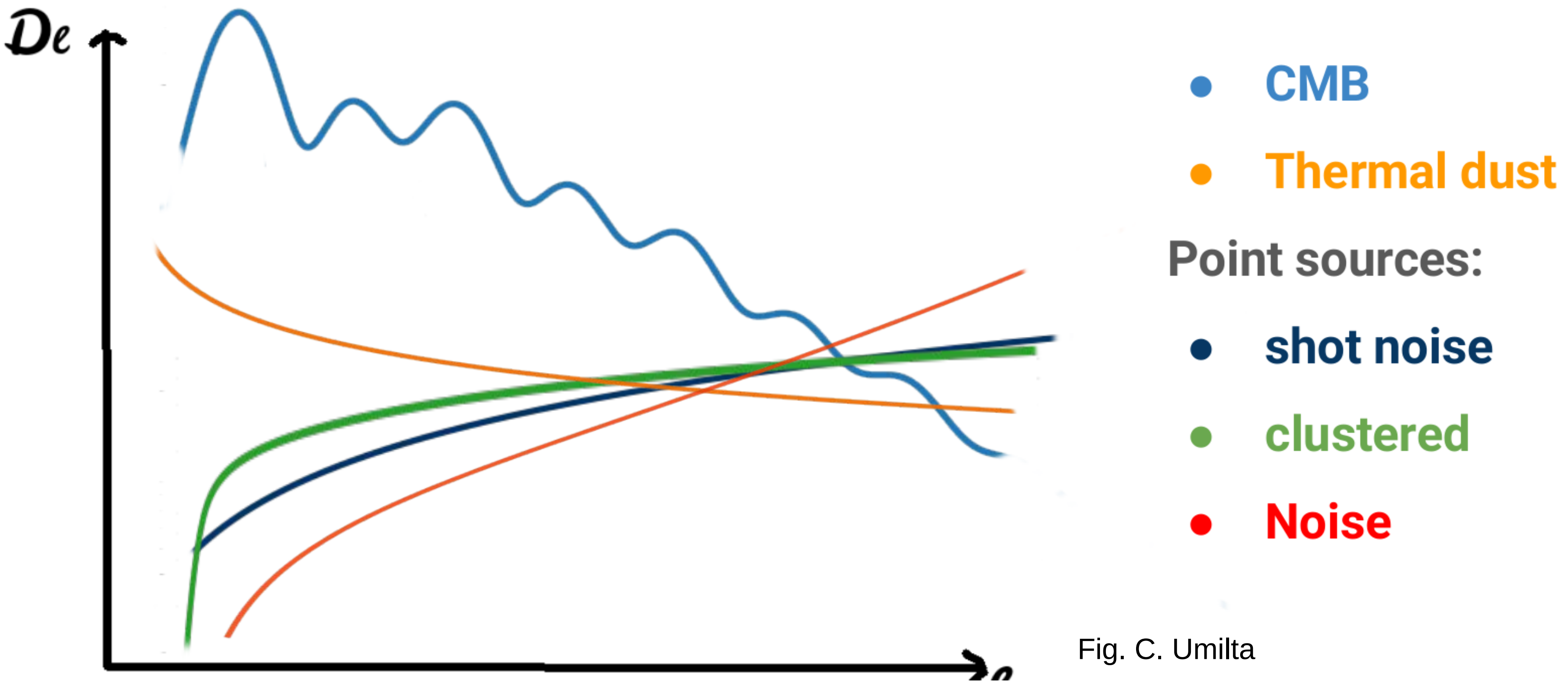


Fig. C. Umilta

In terms of power spectrum, foregrounds are observed as additional components

$$C_\ell^{model} = C_\ell^{CMB} + C_\ell^{dust} + C_\ell^{cib+sz} + C_\ell^{poisson} + C_\ell^{ksz}$$

Cosmology with CMB
Probability of model given data
→ likelihood

Error bars

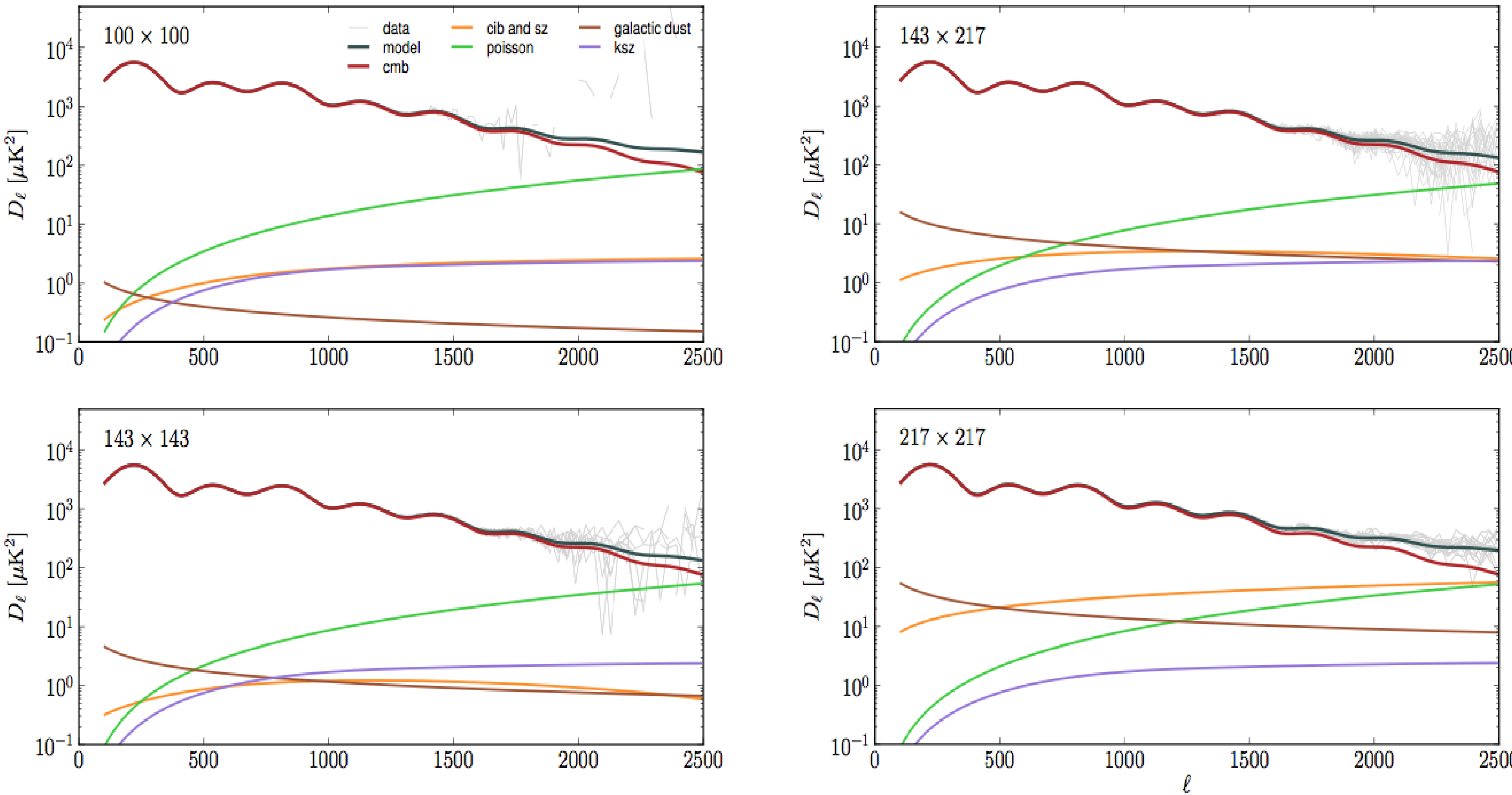
$$-\ln\mathcal{L}\left(\hat{\mathbf{C}}|\mathbf{C}(\theta)\right) = \frac{1}{2}\left(\hat{\mathbf{C}} - \mathbf{C}(\theta)\right)^T \mathbf{\Sigma}^{-1}\left(\hat{\mathbf{C}} - \mathbf{C}(\theta)\right) + c$$

Data: angular spectra from three channels 100 143 and 217 GHz on a tailored multipole range

Model with cosmological parameters (CAMB, CLASS) & foreground parameters

Parameter	Prior range	Definition
$A^{\rm PS}_{100}$	[0, 400]	Contribution of Poisson point-source power to $\mathcal{D}^{100\times100}_{3000}$ for *Planck* (in μK^2)
$A^{\rm PS}_{143}$	[0, 400]	As for $A^{\rm PS}_{100}$ but at 143 GHz
$A^{\rm PS}_{217}$	[0, 400]	As for $A^{\rm PS}_{100}$ but at 217 GHz
$A^{\rm PS}_{143\times217}$	[0, 400]	As for $A^{\rm PS}_{100}$ but at 143×217 GHz
$A^{\rm CIB}_{217}$	[0, 200]	Contribution of CIB power to $\mathcal{D}^{217}_{3000}$ at the *Planck* CMB frequency for 217 GHz (in μK^2)
$A^{\rm tSZ}$	[0, 10]	Contribution of tSZ to $\mathcal{D}^{143\times143}_{3000}$ at 143 GHz (in μK^2)
$A^{\rm kSZ}$	[0, 10]	Contribution of kSZ to $\mathcal{D}_{3000}$ (in μK^2)
$\xi^{\rm tSZ\times CIB}$	[0, 1]	Correlation coefficient between the CIB and tSZ
$A^{{\rm dust}TT}_{100}$	[0, 50] (7 ± 2)	Amplitude of Galactic dust power at $\ell = 200$ at 100 GHz (in μK^2)
$A^{{\rm dust}TT}_{143}$	[0, 50] (9 ± 2)	As for $A^{{\rm dust}TT}_{100}$ but at 143 GHz
$A^{{\rm dust}TT}_{143\times217}$	[0, 100] (21 ± 8.5)	As for $A^{{\rm dust}TT}_{100}$ but at 143×217 GHz
$A^{{\rm dust}TT}_{217}$	[0, 400] (80 ± 20)	As for $A^{{\rm dust}TT}_{100}$ but at 217 GHz

Cosmoloy with CMB: Probability of model given data → likelihood



217GHz channel dominates cosmological constraints at small scales. Foreground ~ order magnitude of CMB

Cosmology with CMB:
Base ΛCDM model

6 parameters

- Primordial spectrum $\mathcal{P}_{\mathcal{R}}(k) = A_s \left(\frac{k}{k_0}\right)^{n_s - 1}$
- Expansion rate H_0
- Matter densities $\Omega_b h^2$ $\Omega_c h^2$
- Reionisation optical depth τ

Hypotheses (relaxed for extensions to ΛCDM)

- Flat Universe $\Omega_k = 0$
- No running spectral index $dn_s / d\ln k = 0$
- No tensor contribution $\mathcal{P}_t(k) = A_t \left(\frac{k}{k_0}\right)^{n_t} = 0$
- 3 neutrinos species $N_{eff} = 3$
- Low neutrino mass $\sum m_\nu = 0.06\ eV$

Cosmology with CMB: Cosmological parameters

Base ΛCDM model = 6 parameters: baryon density, CDM density, Λ, A_s, n_s, τ

28(18) fold diminution in constraint volume vs WMAP9(+SPT) → Error-bars reduced by a factor 2 when including polarisation in 2015

	Planck (CMB+lensing)		*Planck*+WP+highL+BAO	
Parameter	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
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
Age/Gyr	13.784	13.796 ± 0.058	13.7965	13.798 ± 0.037
$100\theta_*$	1.04164	1.04156 ± 0.00066	1.04163	1.04162 ± 0.00056
r_{drag}	147.74	147.70 ± 0.63	147.611	147.68 ± 0.45
$r_{drag}/D_V(0.57)$	0.07207	0.0719 ± 0.0011		

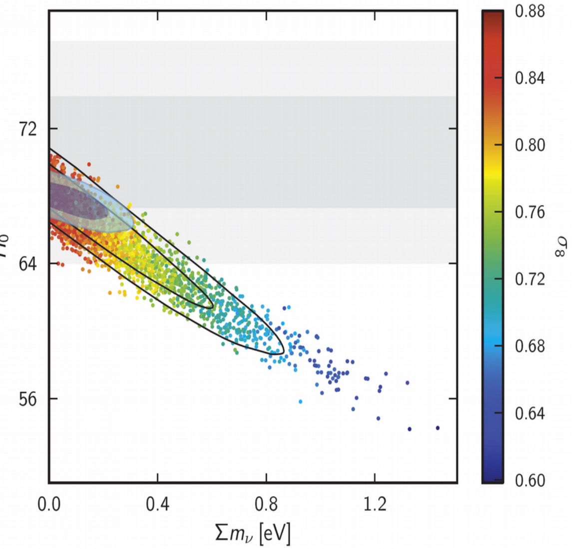
Cosomological parameters

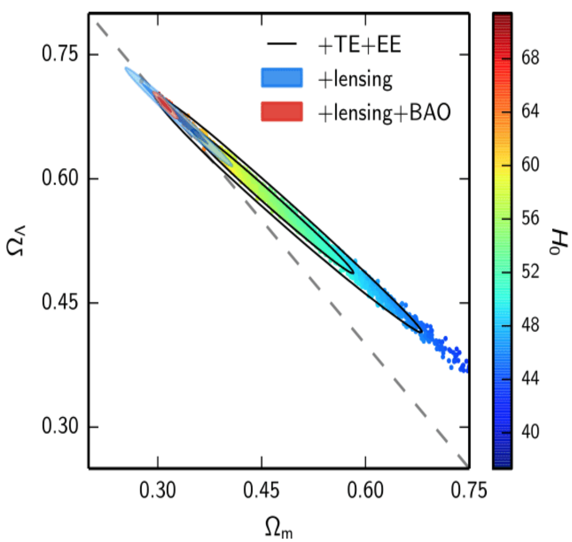
	WMAP	Planck 2013	Planck 2015
$\Omega_b h^2$	0.02264 ± 0.00050	0.02205 ± 0.00028	0.02225 ± 0.00016
$\Omega_b h^2$	0.1138 ± 0.0045	0.1199 ± 0.0027	0.1198 ± 0.0015
H_0	70.0 ± 2.2	67.3 ± 1.2	67.27 ± 0.66
$10^9 A_S$	2.189 ± 0.090	2.196 ± 0.060	2.207 ± 0.074
n_S	0.972 ± 0.013	0.960 ± 0.007	0.964 ± 0.005
τ	0.089 ± 0.014	0.089 ± 0.014	0.079 ± 0.017
σ_8	0.821 ± 0.023	0.834 ± 0.027	0.831 ± 0.013

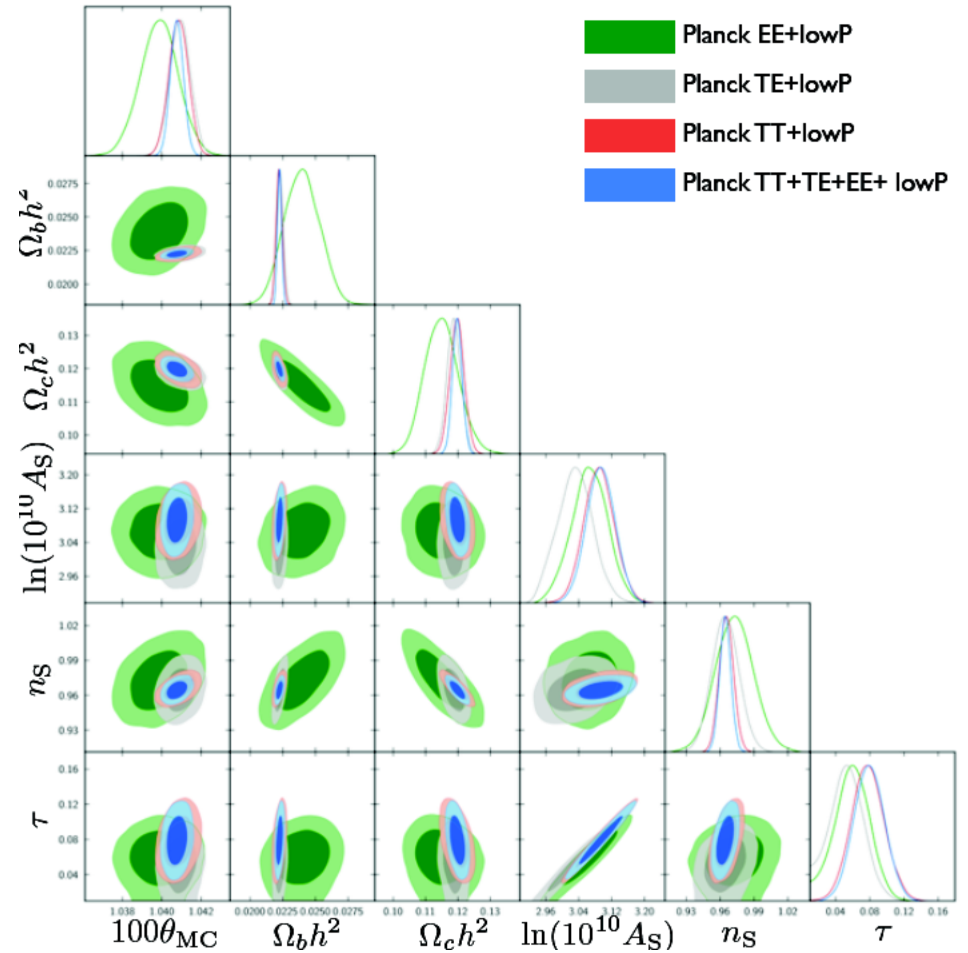
0.055 ± 0.009
(Planck collab. '16)

- Enormous precision: 0.03%; 0.6% & 1.1% on sound horizon; baryon and CDM densities
- Optical depth decreased → **use of HFI low-l polarisation**
- No obvious need for extensions nor for extra relativistic species

Cosmological parameters







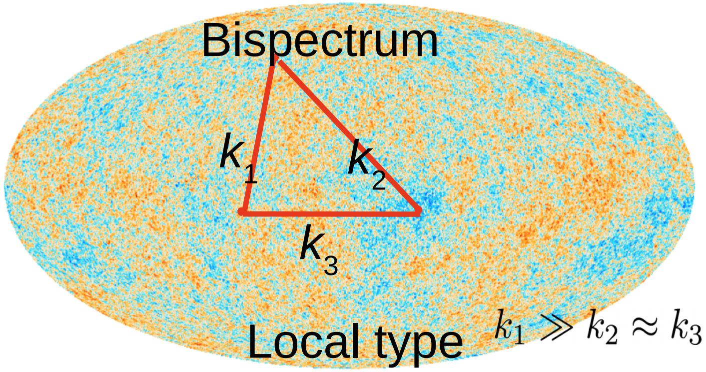
CMB degeneracy → assume flat space or use late-time tracers CMB lensing or BAO

From Planck TT: h=0.673 from Planck+BAO: h=0.676

Tight limits on curvature (<0.005), neutrino mass (<0.194 eV), dark energy equ. state (-1.019), dark-matter annihilation, etc.

Cosmology with CMB: Inflation

Quantum origin of primordial fluctuations
Simplest inflation predicts:

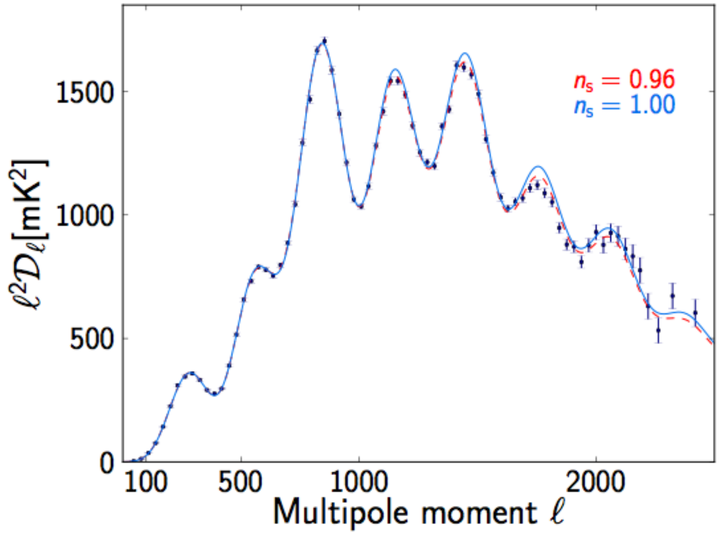


- Flat space → Planck 2015 : curvature ~ -0.004
- Adiabatic fluctuations → TE Planck 2015
- Nearly Gaussian statistics → Planck 2015

$$f_{\rm NL}^{\rm local} = 0.8 \pm 5.0,\ f_{\rm NL}^{\rm equil} = -4 \pm 43, \text{ and } f_{\rm NL}^{\rm ortho} = -26 \pm 21$$

- Deviation from scale invariant initial spectrum

(0.96 <ns< 0.97) → Planck 2015 : 0.9645 ± 0.0049



Scale invariant spectrum excluded at 7σ

Primordial gravity waves → quest & challenges of B-mode polarisation ? (cf. Talk JA. Rubino-Martin)

Cosmology with CMB: Summary

Simple cosmological model established ?

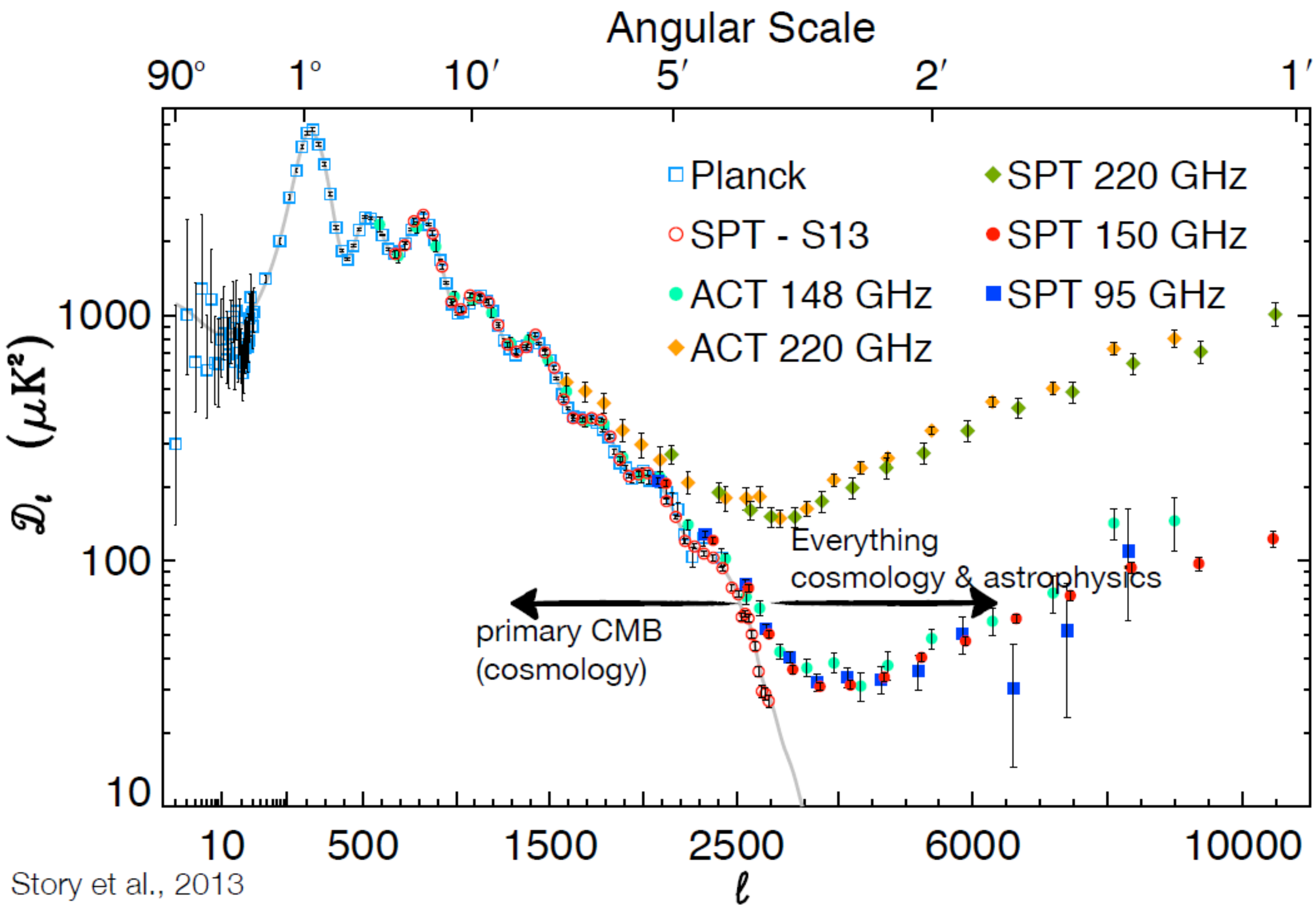
- Spatially flat Universe
- Gaussian, adiabatic, close to scale invariant initial perturbations
- No evidence for running spectral index
- No evidence for dynamical DE
- No evidence for extra relativistic species
-

But

Some “small” tensions/disagreements: H_0 (cf. Talk J. Sorce), Ω_m and σ_8 from LSS tracers, slight “lensing excess” in the power spectrum, etc.

Prospects for CMB temperature

End of primary temperature anistropy era ?



Story et al., 2013
George et al., 2014
Das et al., 2014

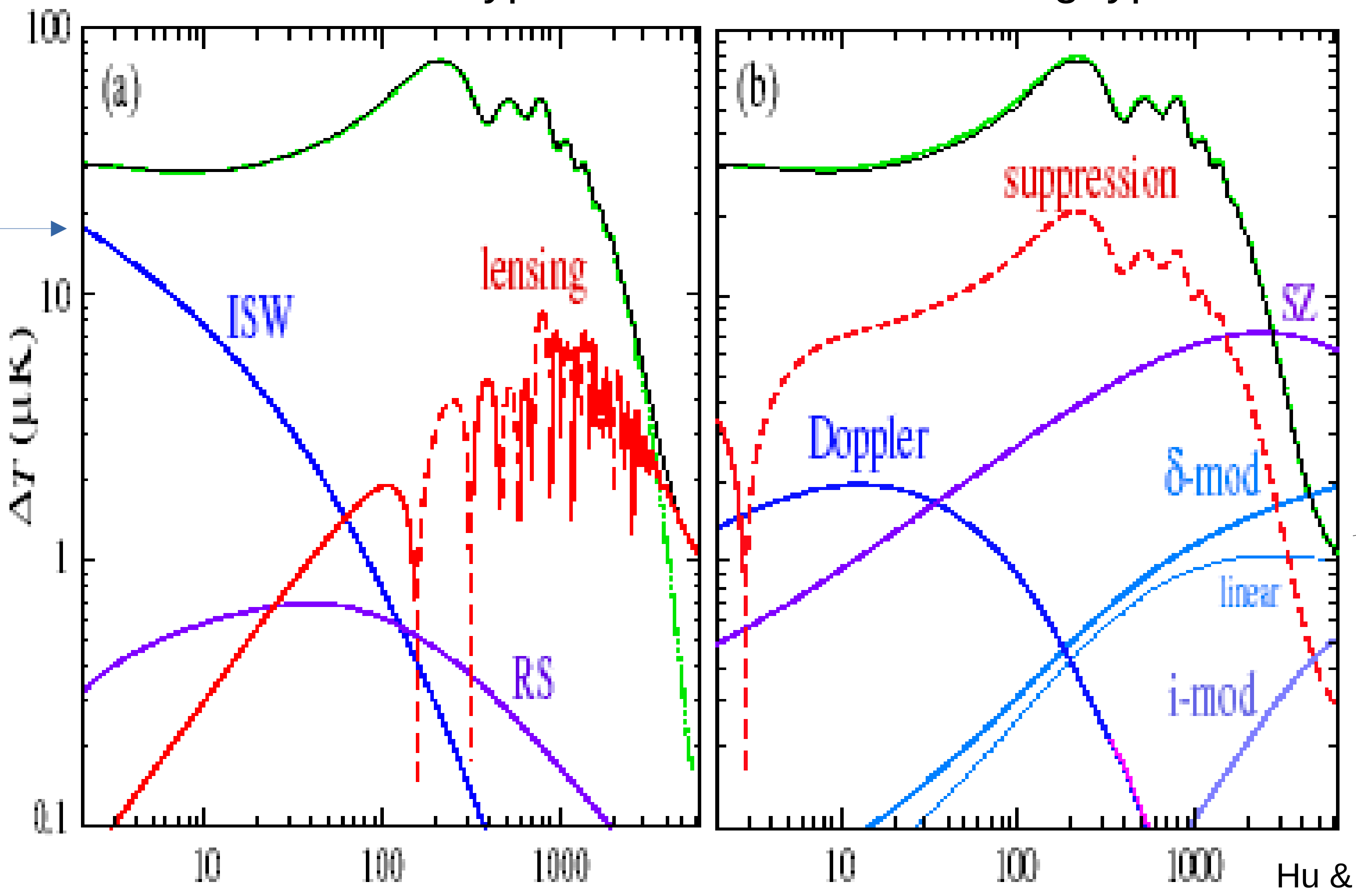
Next → Cosmology from small-scale CMB (lensing & t+kSZ effects) … but limitations due to foregrounds

CMB secondary anisotropies

After recombination CMB photons travel "almost" unaffected …
Secondary effects additional or perturbed fluctuations

Gravitational type Scattering type

ISW, cf. C. Hernandez-Monteagudo



kSZ, cf. C. Hernandez-Monteagudo

Hu & Dedelson '02

CMB introduction & status

Introduction
The CMB maps
The CMB angular power spectrum
Cosmology with CMB: Main features in primary anisotropies
Secondary anisotropies: CMB lensing
Secondary anisotropies: themal Sunyaev-Zel'dovich
Conclusions

CMB Lensing

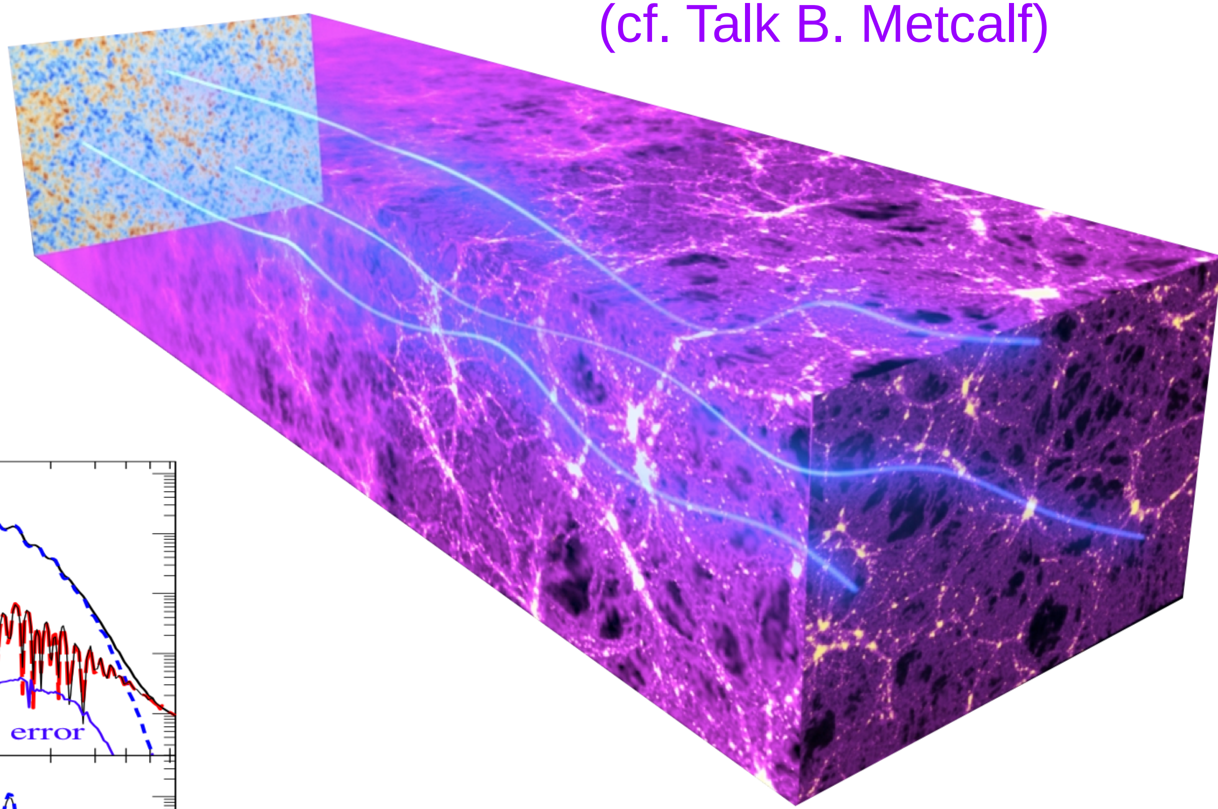
Weak gravitational lensing of the LSS DM distribution @z~2 disturbs the observed CMB → small variation of CMB anisotropies & length correlation

Typical deflection: 2.5'

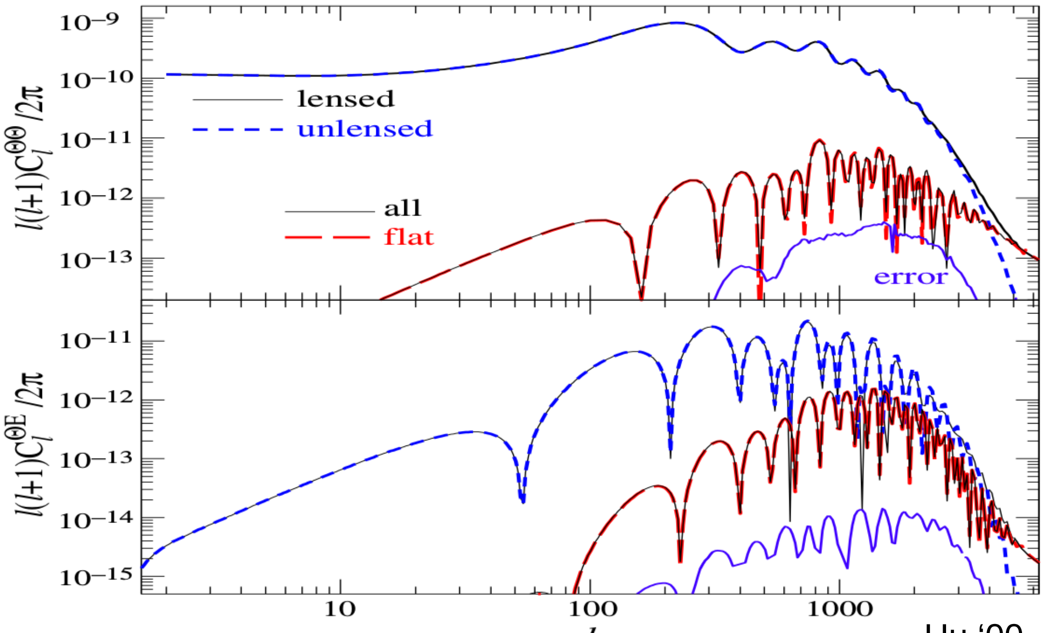
(cf. Talk B. Metcalf)

$$\tilde{T}(\boldsymbol{x}) = T(\boldsymbol{x} + \boldsymbol{\nabla}\phi)$$

$$(\tilde{Q} \pm i\tilde{U})(\boldsymbol{x}) = (Q \pm iU)(\boldsymbol{x} + \boldsymbol{\nabla}\phi)$$



$$\bar{\phi} = \Delta^{-1}\vec{\nabla}\cdot[C^{-1}T\,\vec{\nabla}(C^{-1}T)]$$



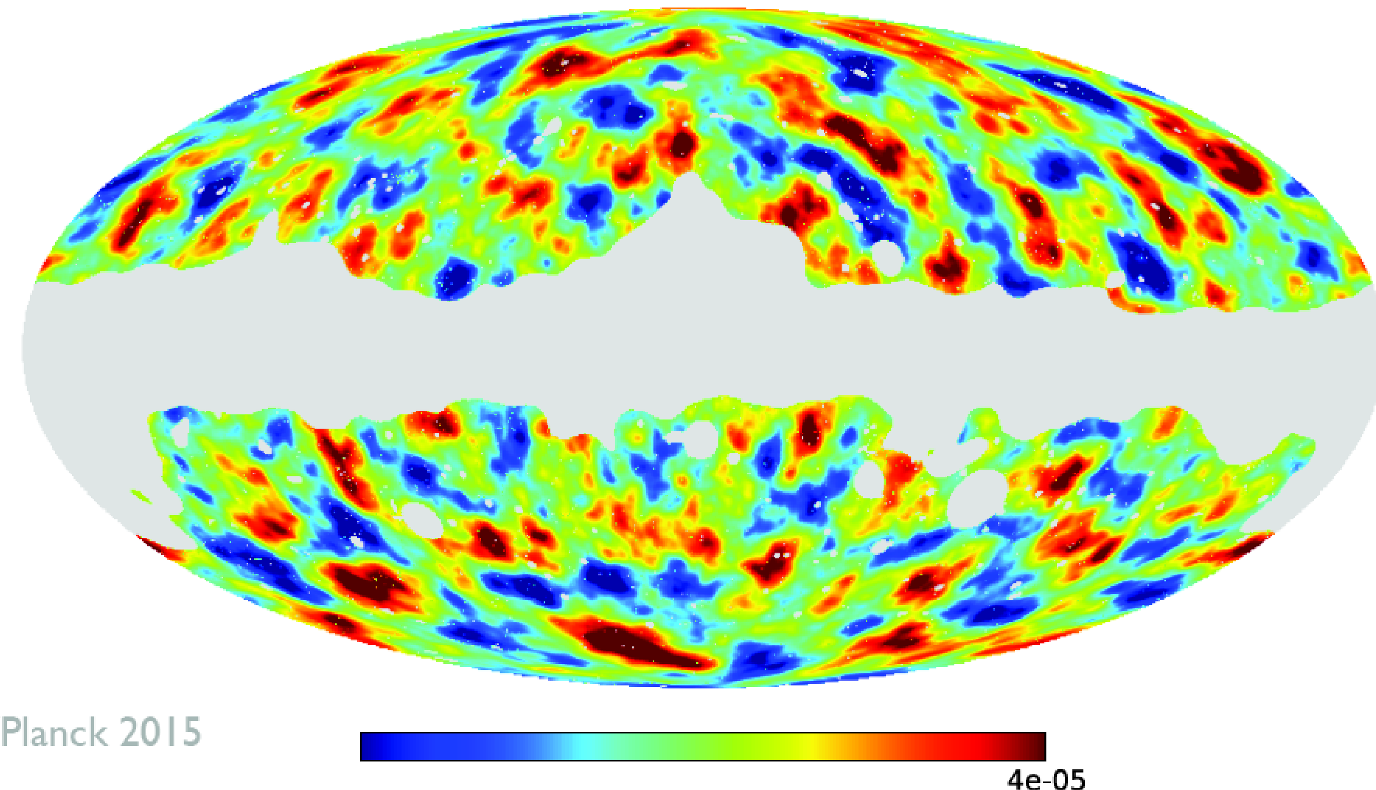
Hu '00

Smooths TT, TE and EE power

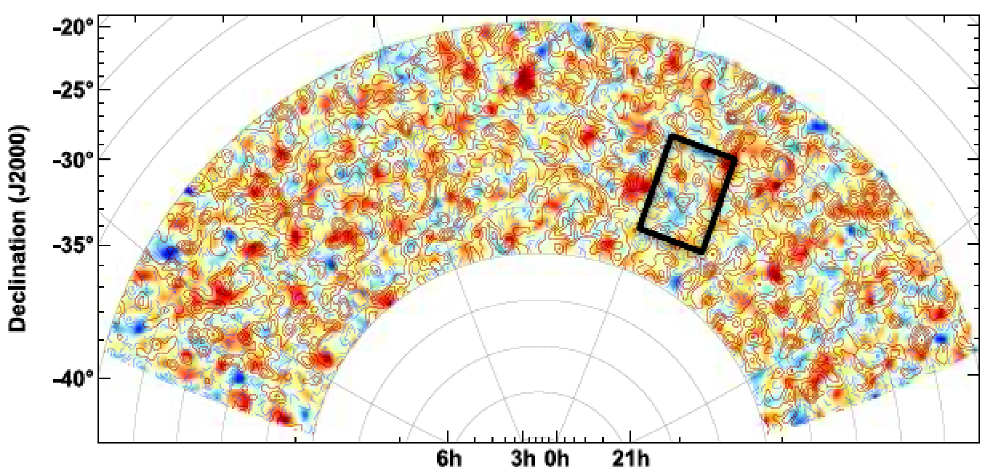
Generates TT, TE, EE power at arcmin scales

Generates B-modes from E-modes

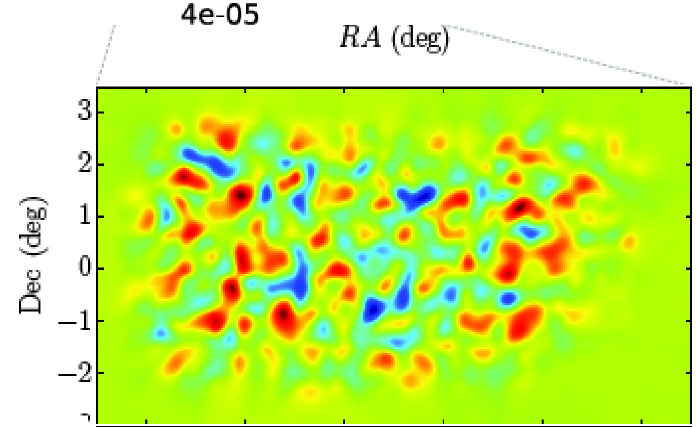
Reconstructed projected mass map



ESA/Planck 2015



SPT, Geach et al 2013

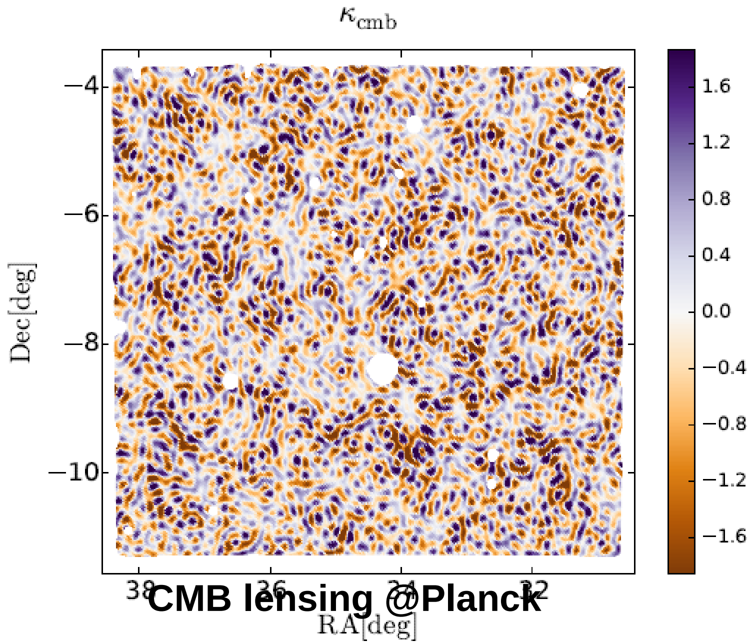


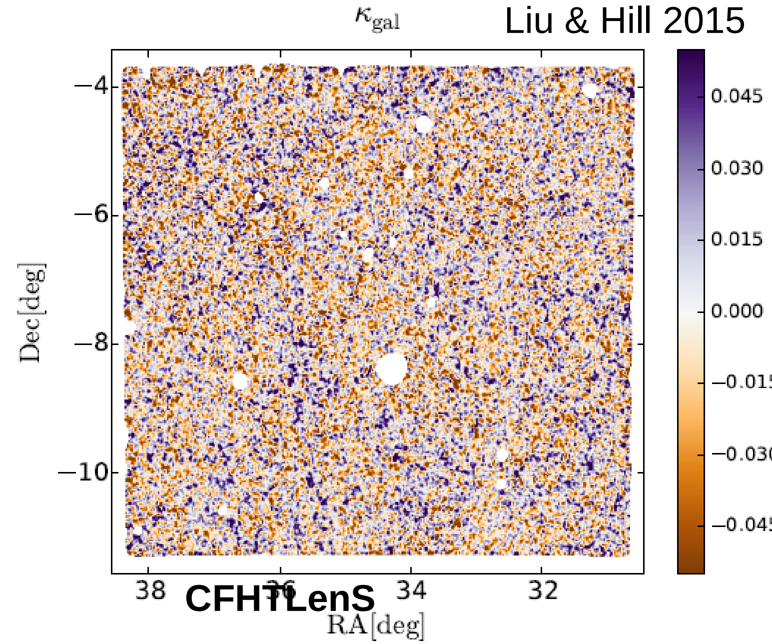
ACTPol, Allison et al 2015

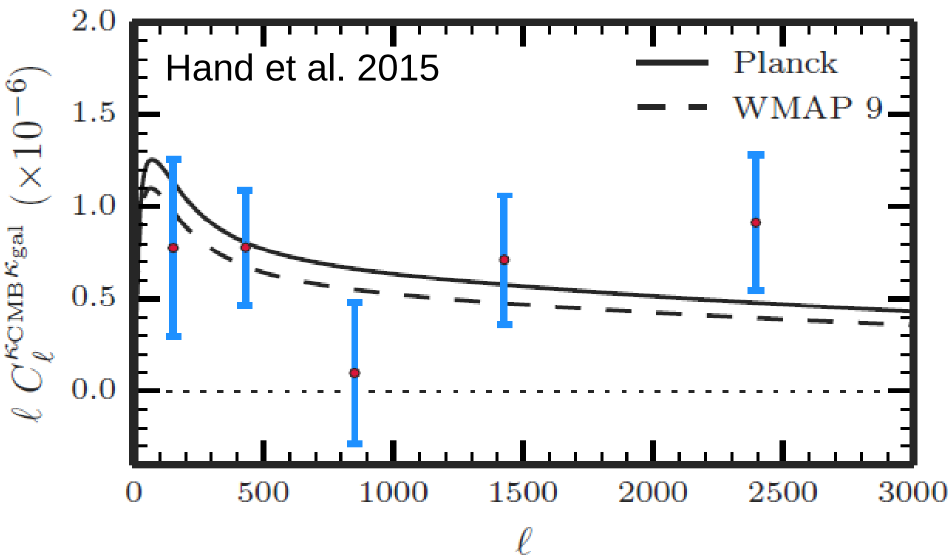
CMB lensing:
Cross-correlation with Galaxy lensing

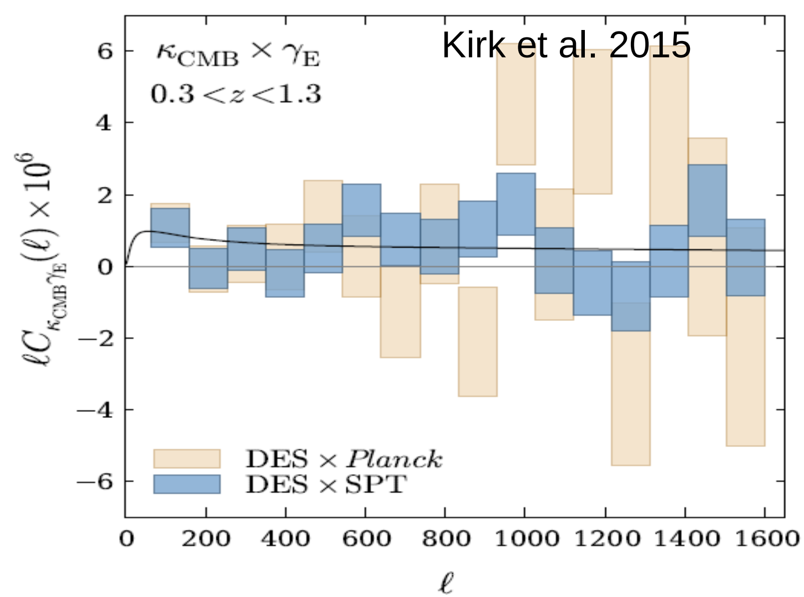
Liu & Hill 2015

Detection @~3-4 б with ACT, Planck, SPT and DES, CFHTLenS, S82

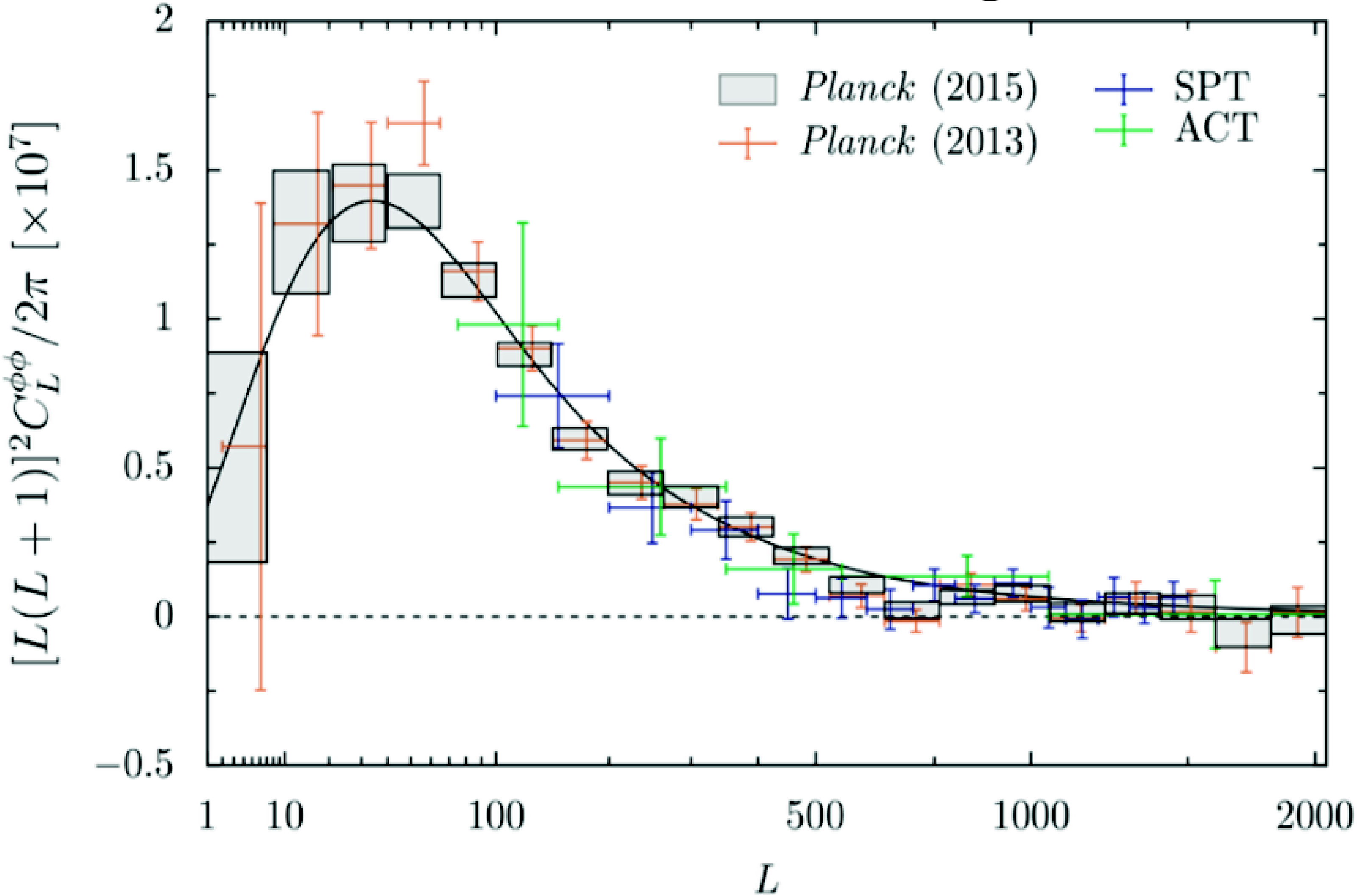








CMB lensing



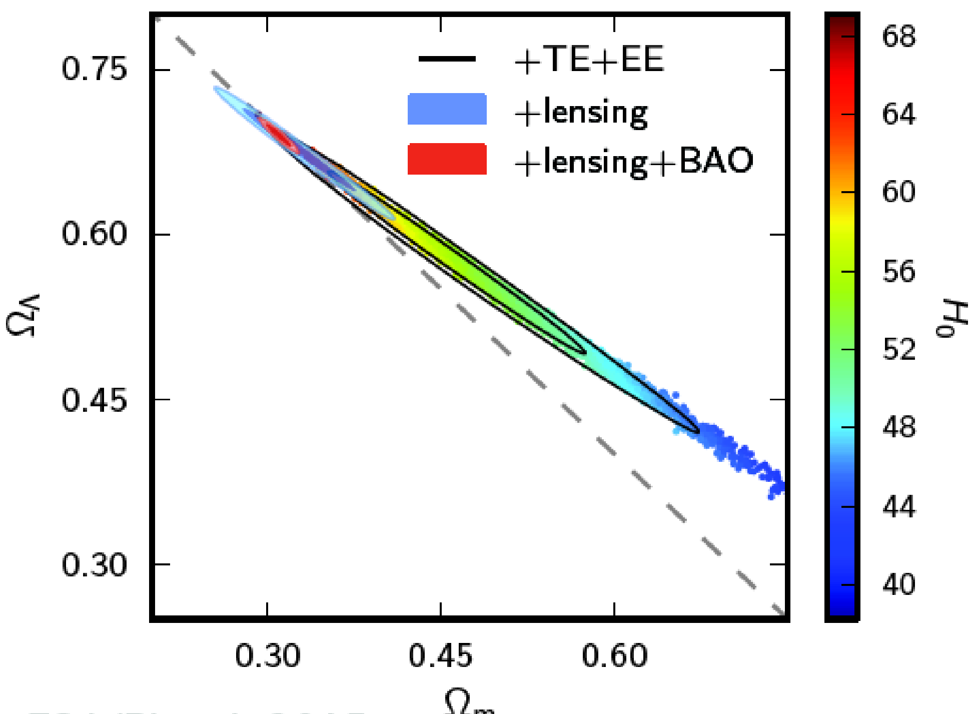
CMB lensing measurement at 40σ over 70% of the sky
Amplitude constrained to 2.5% (error-bars improved by factor ~2)
Lensing x B-modes detected at ~10σ

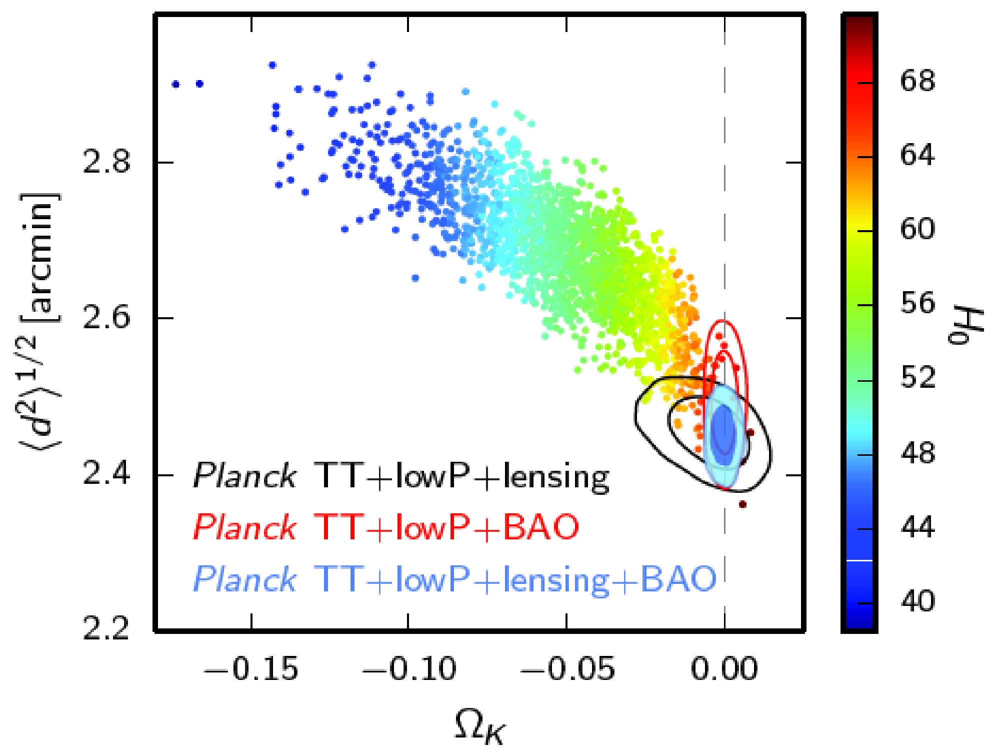
Planck collab. 2015

CMB lensing

Lensing probes clustering of matter and growth rate → helps breaking degeneracy in CMB
Give access to neutrino mass, curvature, dark energy
Complements LSS surveys to probe further dark energy

Lensing limits curvature to <2% and neutrino mass to <0.23eV





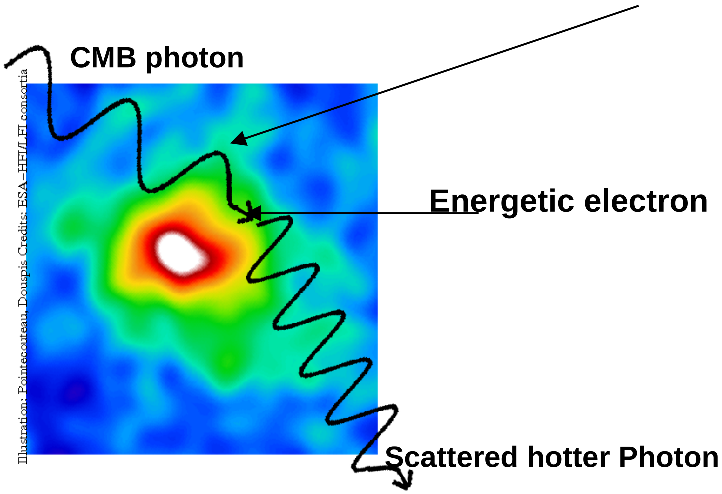
ESA/Planck 2015

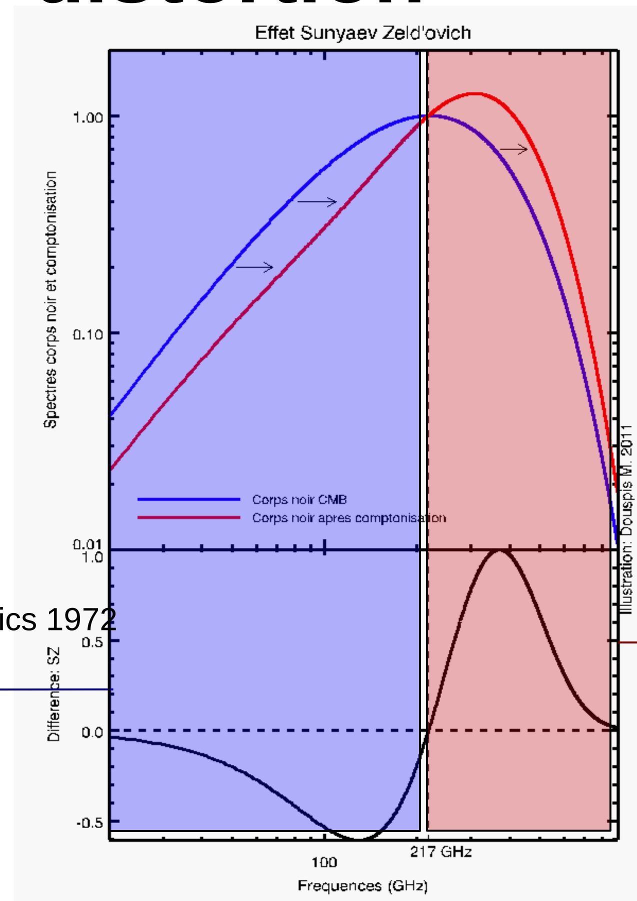
CMB introduction & status

Introduction
The CMB maps
The CMB angular power spectrum
Cosmology with CMB: Main features in primary anisotropies
Secondary anisotropies: CMB lensing
Secondary anisotropies: thermal Sunyaev-Zel'dovich
Conclusions

The SZ effect: CMB Spectral distortion

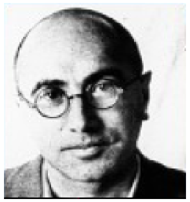
Hot & ionised gas





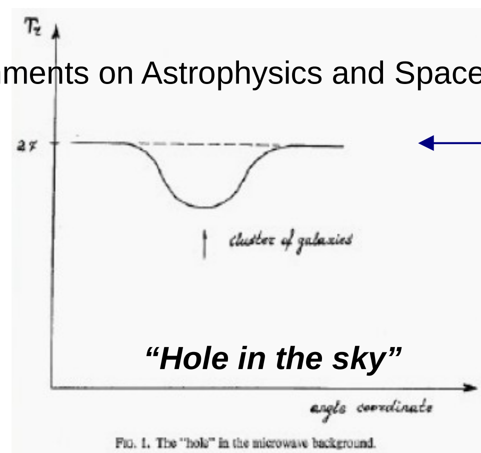
R. A. Sunyaev

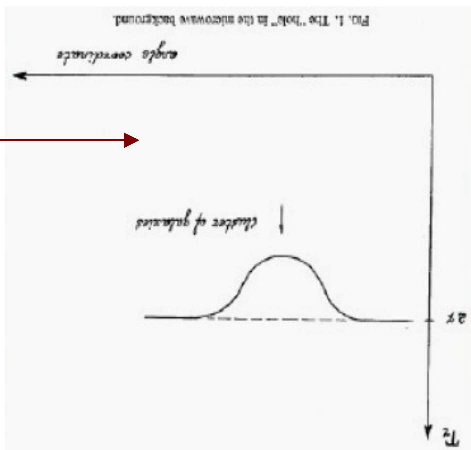
Ya. B. Zeldovich

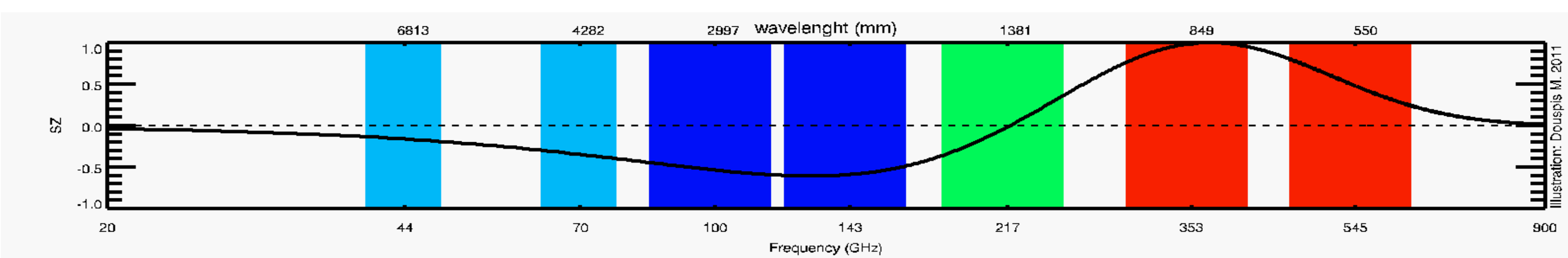


$$y = \int \frac{k_B T_e}{m_e c^2} n_e \sigma_T dl$$

SZ,Comments on Astrophysics and Space Physics 1972

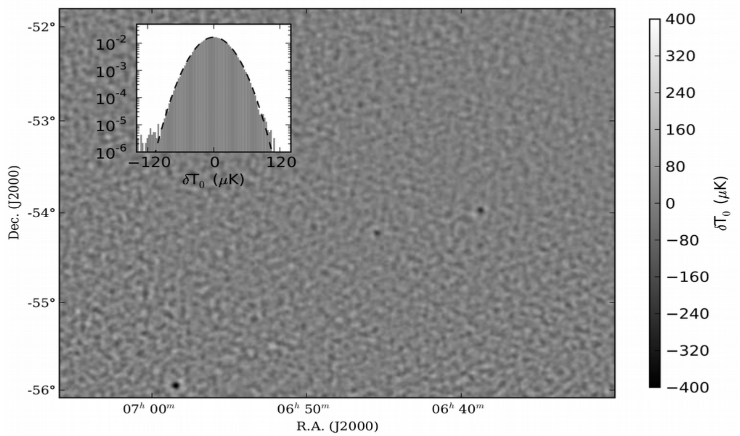




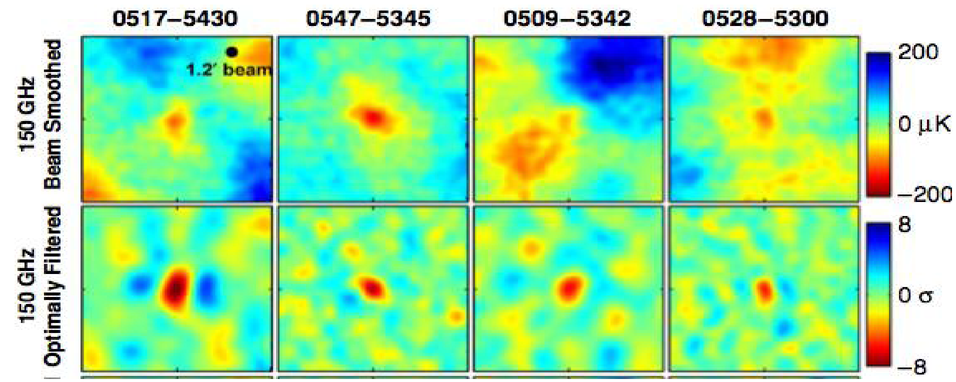


The SZ “survey” revolution

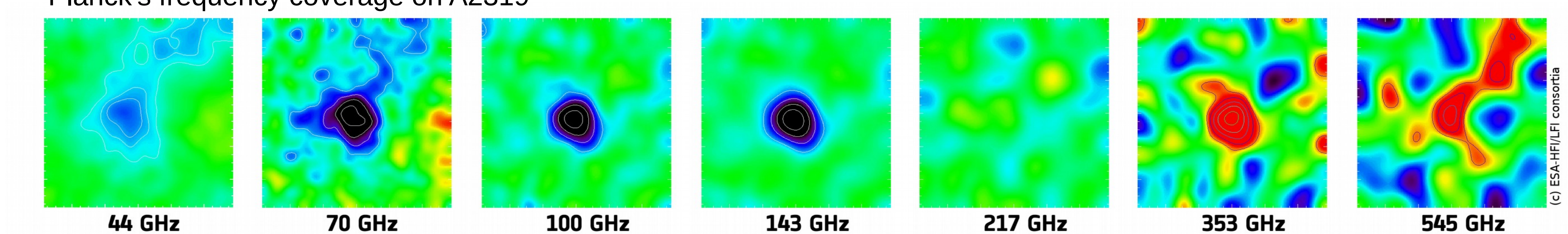
ACT (Marriage et al ‘10) [~1.4' @148GHz]



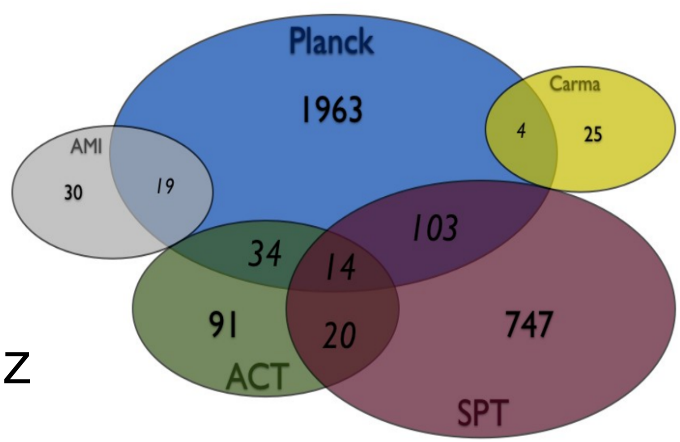
First blind detections by SPT (Staniszewski et al ‘09) SPT [~1.1' @150GHz]



Planck's frequency coverage on A2319



Three Planck catalogs:
ESZ @2011 (189 clusters)
PSZ1 @2013 (1227 SZ sources)
PSZ2 @2014 (1653 SZ sources)



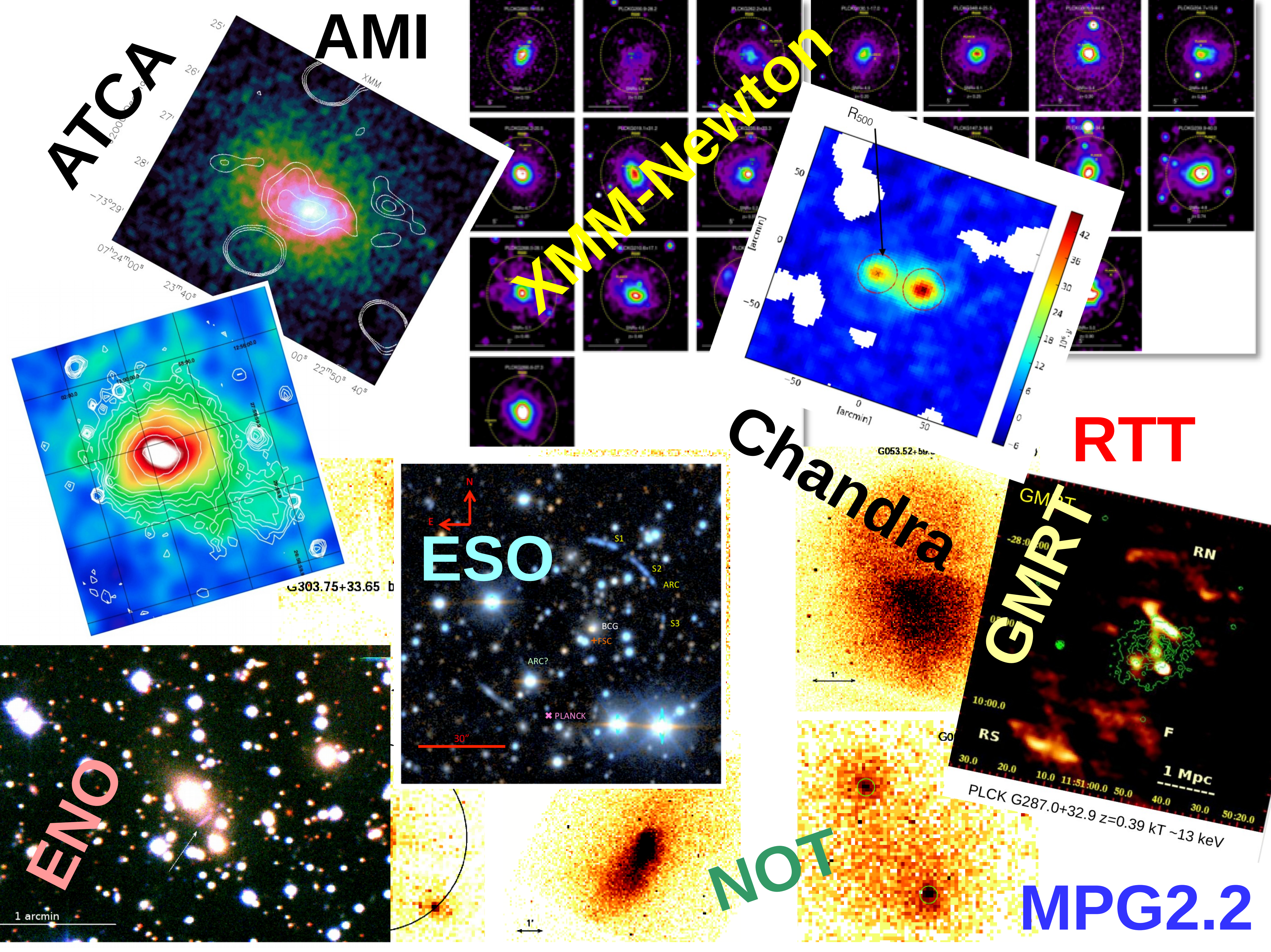
Szcluster-db@IAS:**2690 SZ sources** incl. 1750 with z

What are the properties of SZ Planck clusters

Nearly all known clusters accessible to Planck were detected.
Planck detected hundreds of candidates most of them confirmed as new clusters

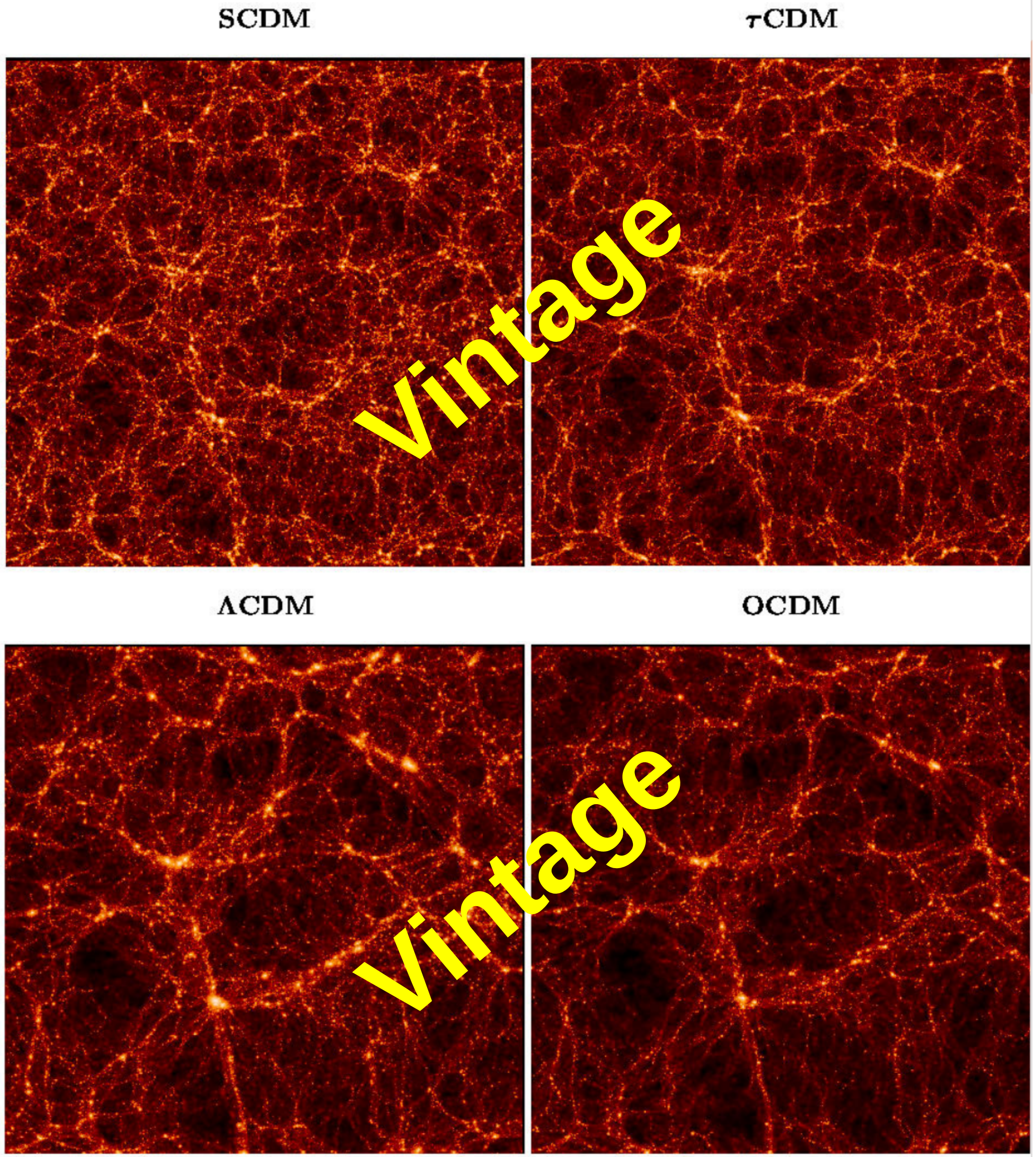
A very large follow-up effort to confirm, measure redshift & study SZ canditates/sources:

- XMM-Newton programmes (PI. M. Arnaud, PI. E. Pointecouteau)
- NOT spectroscopic follow-up (PI. H. Dahle)
- RTT (PI. R. Sunyaev)
- ENO follow-up (PI. J.A. Rubino-Martin)
- MPG2-2.m/WFI (PI. S. White)
- ESO-LP (PI. N. Aghanim)
- MEGACAM (PI. G. Pratt & van der Burg et al 2015)
- Chandra-Planck Legacy programme follow up the ESZ clusters (X-ray Visionary programme, PI. C. Jones + Guaranteed HRC time PI. S. Murray)
- MACS-Planck radio-halo cluster project (PI. C. Ferrari, ATCA & GMRT)
- NIKA2-LP (PI. F. Mayet & J. Macias-Perez)
- AMI (PI. A. Lasenby)
- ...



ATCA
AMI
XMM-Newton
Chandra
RTT
GMRT
ESO
ENO
NOT
MPG2.2
PLCK G287.0+32.9 z=0.39 kT ~13 keV
G303.75+33.65
1 arcmin
1 Mpc
RN
RS
F
BCG
PLANCK
ARC
S1
S2
S3
N
E
30"

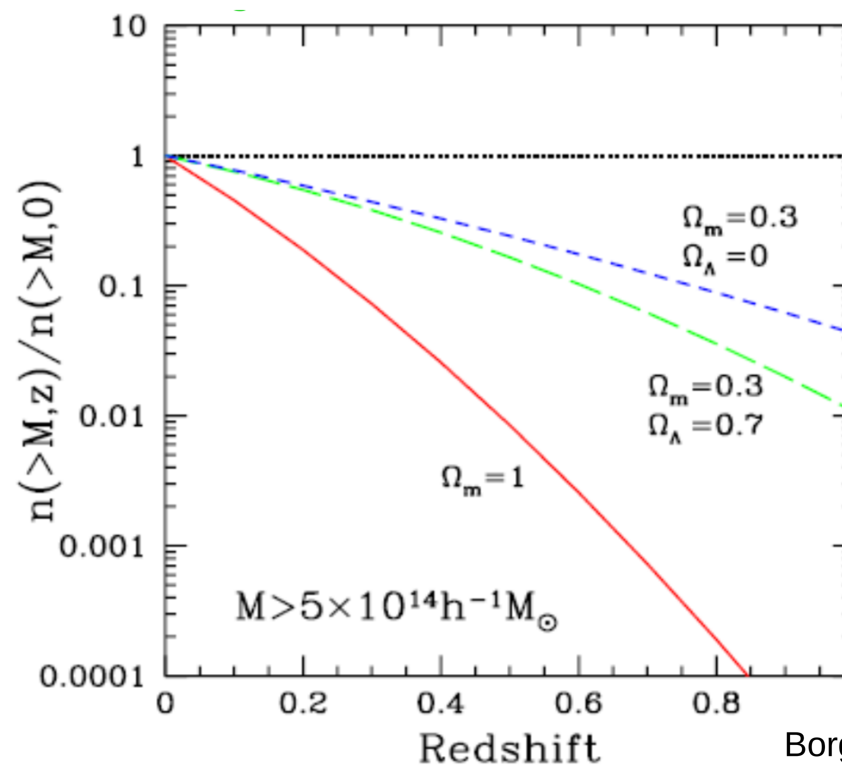
Cosmological parameters with cluster counts



Virgo consortium

Volume element & growth rate changed with cosmology

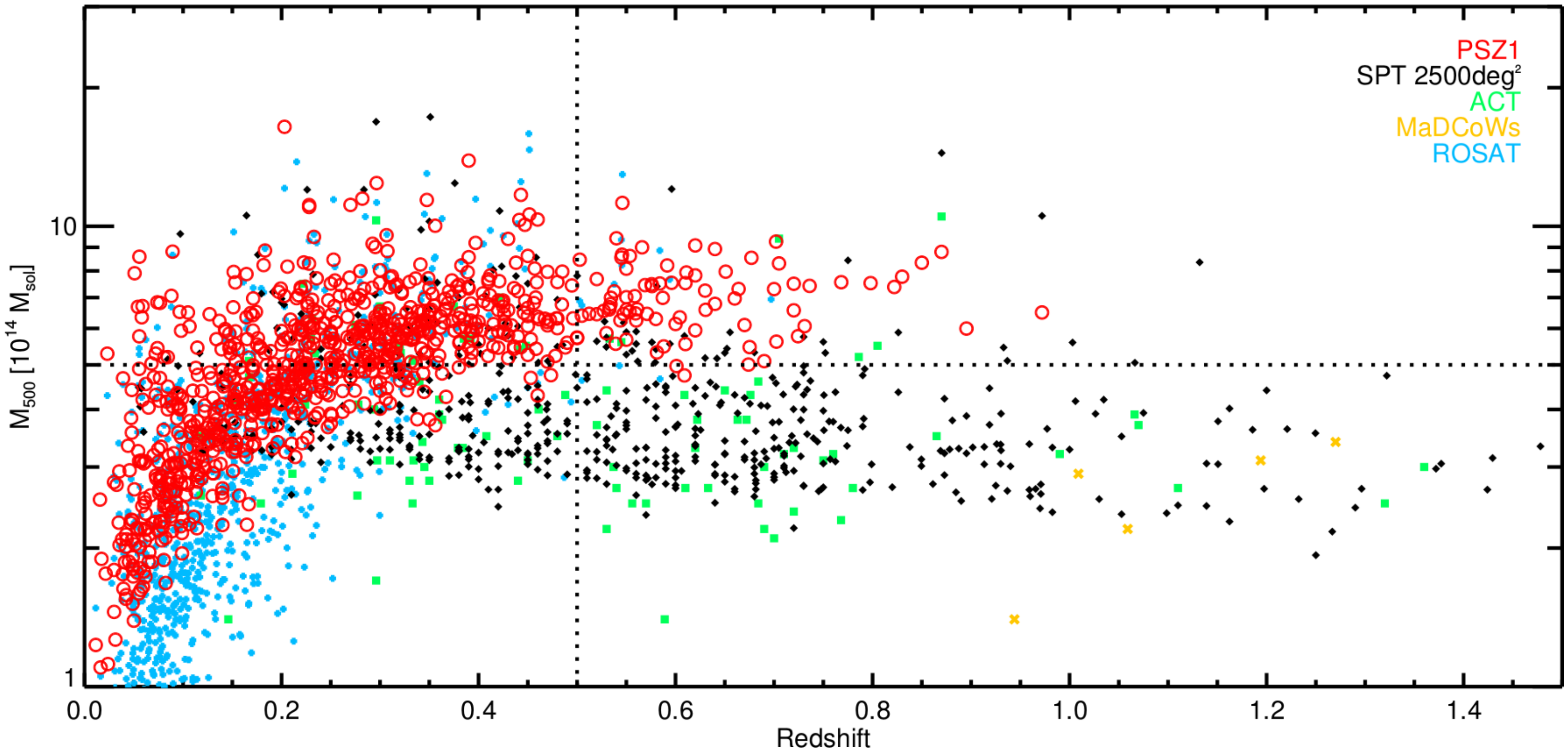
Number counts & evolution of mass function → constrain cosmological parameters: normalisation, DM, DE, ...



Borgani '06

SZ catalog: properties

Planck collab. '15



Distribution in the M–z plane of Planck SZ clusters compared with those of SZ & X-ray surveys

SZ selected clusters → no redshift dimming → quasi mass-selected

Planck: Largest catalog of massive clusters M_{med}= 4.3x$10^{14}M_{sun}$ (< 1.5×10^{15} M_{sun})

→ Access to high M – z region: less sensitive to gas modeling & rare objects

SPT & ACT catalogs: higher z & lower masses

Cosmology with SZ from Planck: Cluster number counts

Compare observed clusters to models
Likelihood: Probability of observed number counts given prediction from theory & survey characteristics

$$\frac{dN}{dz} = \int d\Omega \int dM_{500}\, \hat{\chi}(z, M_{500}, l, b)\, \frac{dN}{dz\, dM_{500}\, d\Omega}$$

Mass function: number of DM halos from simulations
Cosmology sample: constructed from the full Planck catalog
Selection function: survey characteristics (noise, depth, …) from noise maps
Scaling SZ-mass: relating SZ observable to halo mass

Sample: Compromise between large number of clusters and high purity
→Selection in S/N on 65% cleanest sky
→ 439 clusters @S/N≥6

Selection function: Completeness depend on detection-filter size & position on the sky

$$\chi_{\rm erf}(Y_{500}, \theta_{500}, l, b) = \frac{1}{2}\left[1 + {\rm erf}\left(\frac{Y_{500} - X\,\sigma_{Y_{500}}(\theta_{500}, l, b)}{\sqrt{2}\,\sigma_{Y_{500}}(\theta_{500}, l, b)}\right)\right]$$

Cosmological parameters with counts: Scaling relation

Relate global/observed quantities and mass.
Complex physics →simplified assumptions:

- Hydrostatic equilibrium
- No pressure from relativistic particles, magnetic fields, etc
- No multi-temperature structure

Mass $\propto M_{gas}$, $\propto T^{3/2}$, $\propto L_X^{3/4}$ — From X-rays

$\propto L_{optical}$, $\propto \sigma^2_{v,gal}$ — From optical

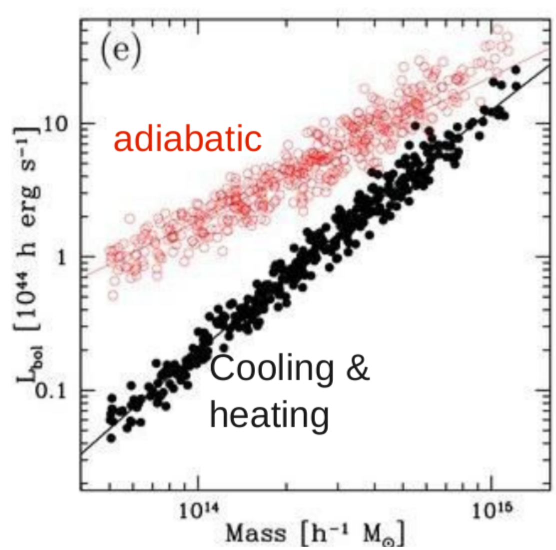
$\propto Y^{3/5}_{SZE}$ — From SZ

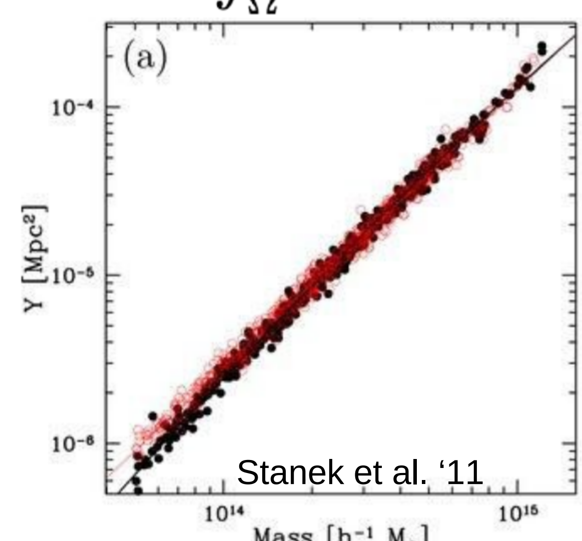
$$E_X \propto \int_V n_e^2 \Lambda(T) dV$$

$$F_\nu \propto \int_\Omega (P = n_e T) d\Omega$$

- X-rays: Stronger dependence on non-gravitational physics
  →High scatter L_X-M relation & bias

- SZ: Weaker dependence
  →Low scatter Y_{SZ}-M relation (~unbiased selection)



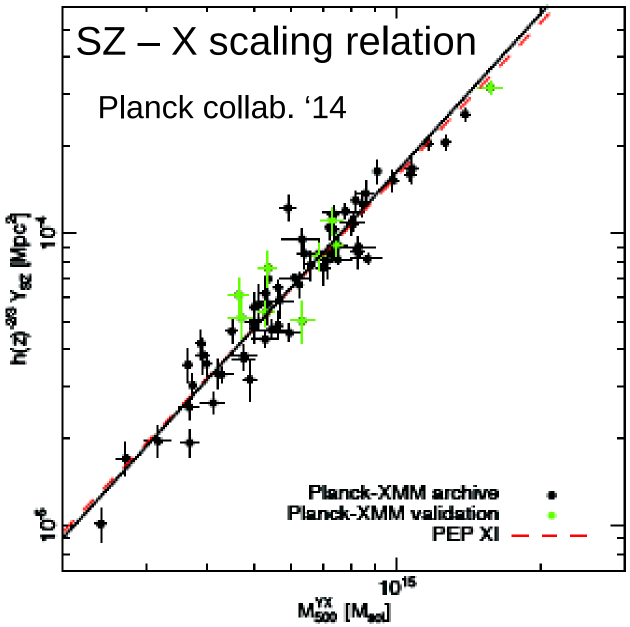


Cosmological parameters with counts: Scaling relation

Y_{sz} measured in Planck & Y_X from X-ray data [$Y_X \rightarrow M_X$ and $Y_X \rightarrow Y_{SZ}$] → **$Y_{SZ} – M_X$**

M_X = (1-b) M_{sim} or (1-b) M_{WL} [b: ratio hydro to true mass]

$$E^{-\beta}(z)\left[\frac{D_A^2(z)\,\bar{Y}_{500}}{10^{-4}\,\mathrm{Mpc}^2}\right] = Y_*\left[\frac{h}{0.7}\right]^{-2+\alpha}\left[\frac{\boxed{(1-b)}\,M_{500}}{6\times10^{14}\,\mathrm{M_{sol}}}\right]^{\alpha}$$

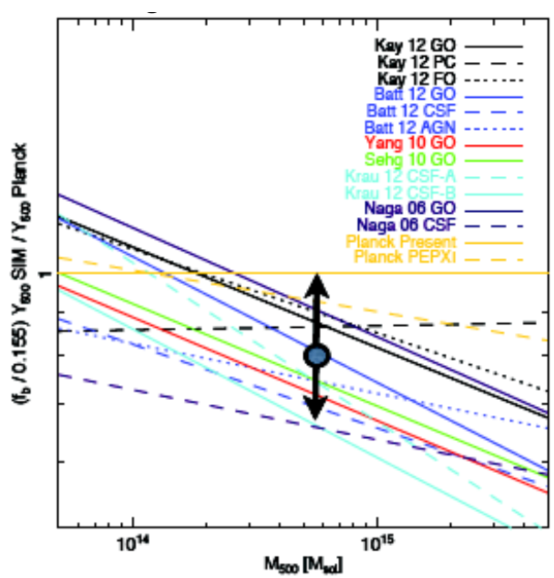


Y_{SZ} – M_X rescaled relation

- Hydrodynamical simulations → (1-b) ~0.7 to 1.0
- Weak Lensing from WtG → (1-b)~0.68 (von der Linden et al. '14)
- Weak Lensing from PSZ2LenS → (1-b)~0.76 (Sereno et al. '17)
- Weak Lensing from CCCP → (1-b)~0.78 (Hoekstra et al. '15)
- CMB lensing mass → (1-b)~1 (Planck collab. '16)

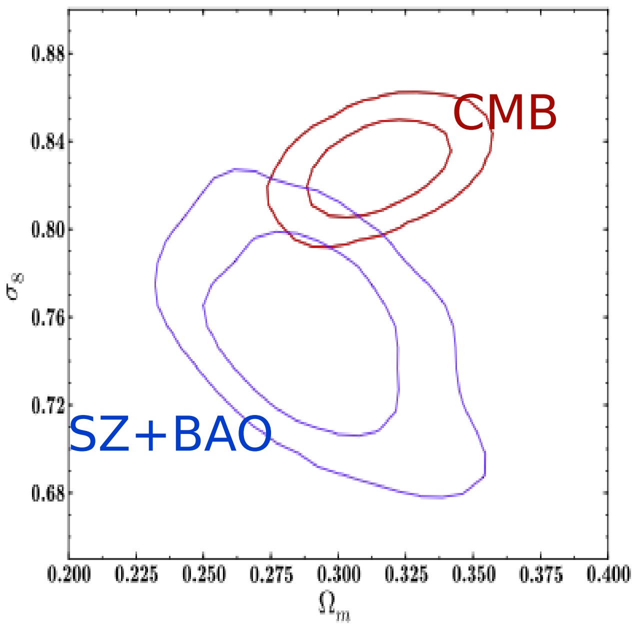
& many others

+ Mass estimates from velocity dispersions

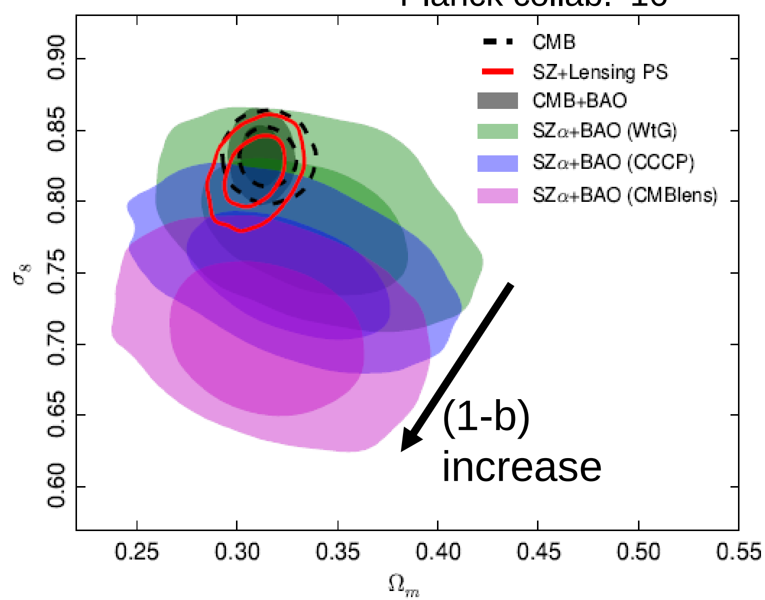


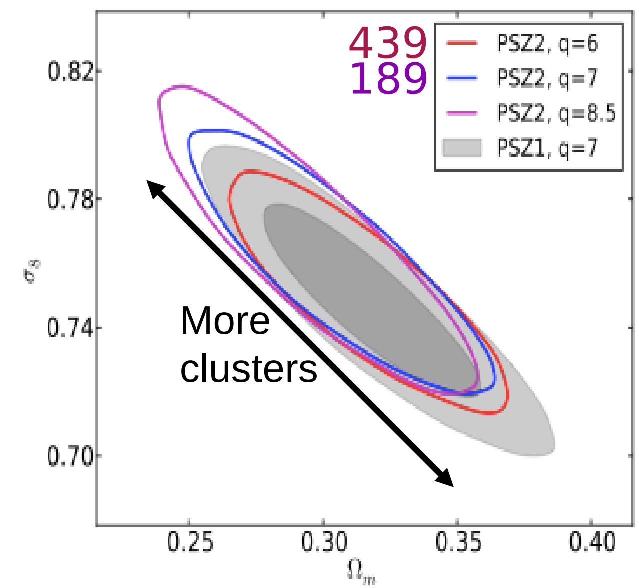
Cosmological parameters from Planck SZ counts:
CMB/cluster tension on σ_8

Planck collab. '14



Planck collab. '16





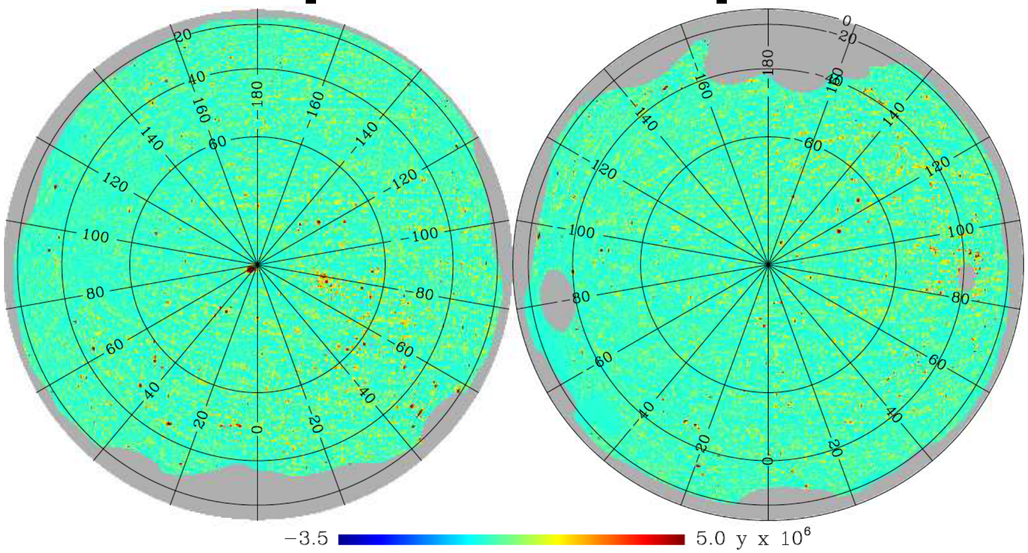
Planck 2014:
Sample: 189 @S/N≥7
Rescaling to sims

~3σ tension between
CMB and SZ counts

Planck 2016:
Larger: 439 @S/N≥6 → Not limited by statistical errors
Rescaling to weak lensing

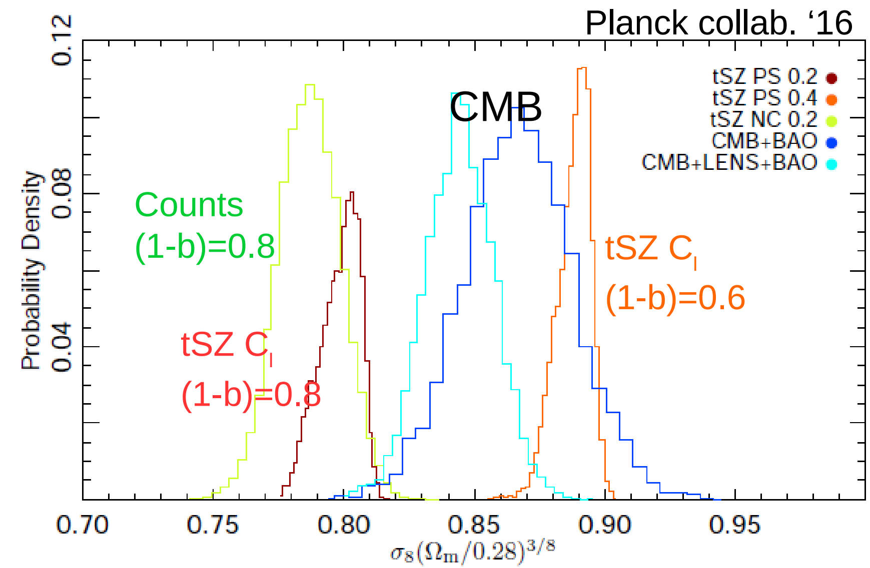
→ Tension remains
→ **CMB preferred mass bias (1-b)~0.58**

Cosmological parameters with SZ power spectrum from Planck

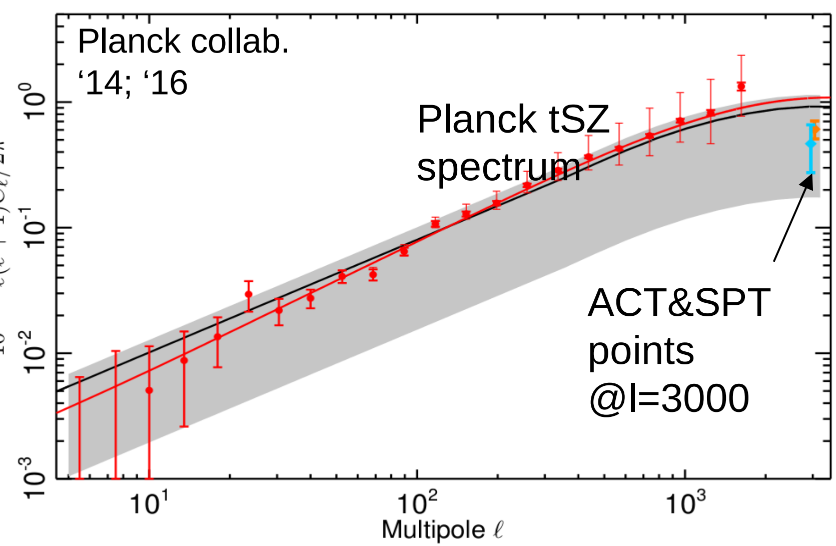


Likelihood on cosmological parameters & CIB/PS amplitude

$$C_\ell^{model} = C_\ell^{SZ} + C_\ell^{cib} + C_\ell^{PS}$$
$$C_\ell^{SZ} = C_\ell^{SZ}(\Omega_M, \sigma_8)$$



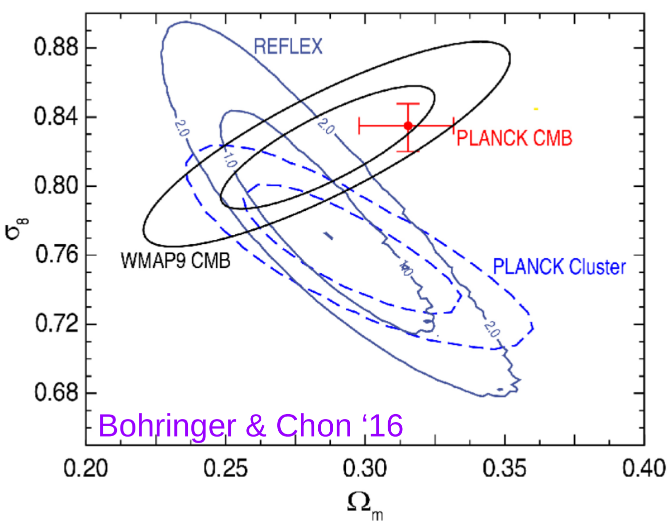
Planck tSZ C_l from 3 deg. to 10'



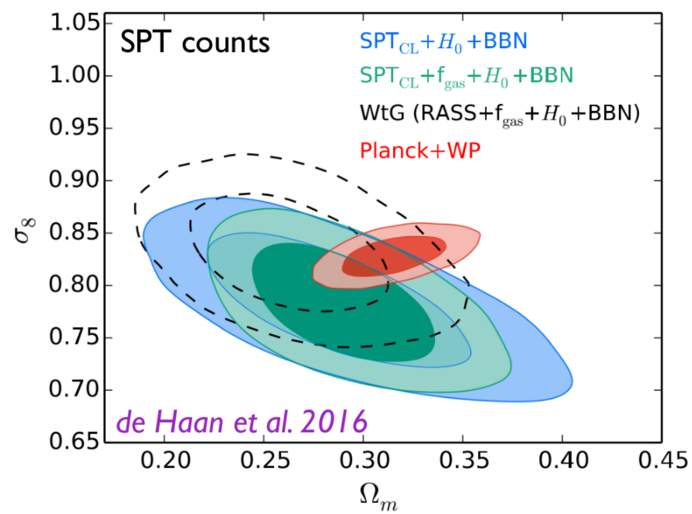
Marginalised likelihood distribution for tSZ and CMB analyses → tension

Higher order moments (Skweness & bispectrum) → σ_8= 0.74 to 0.78

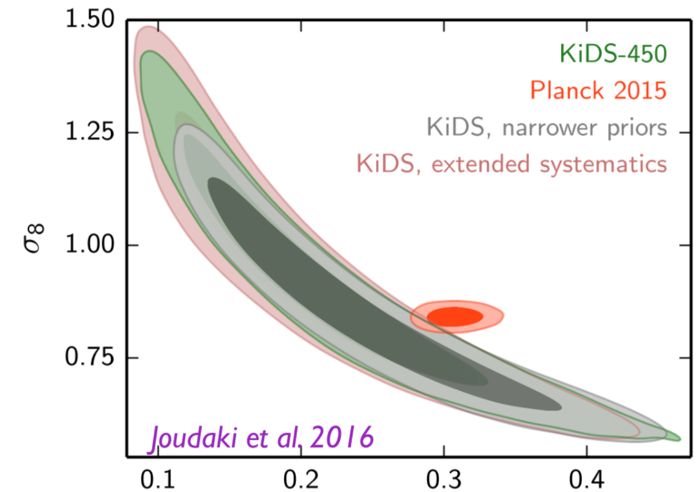
Cosmological parameters from SZ, X-ray & lensing surveys

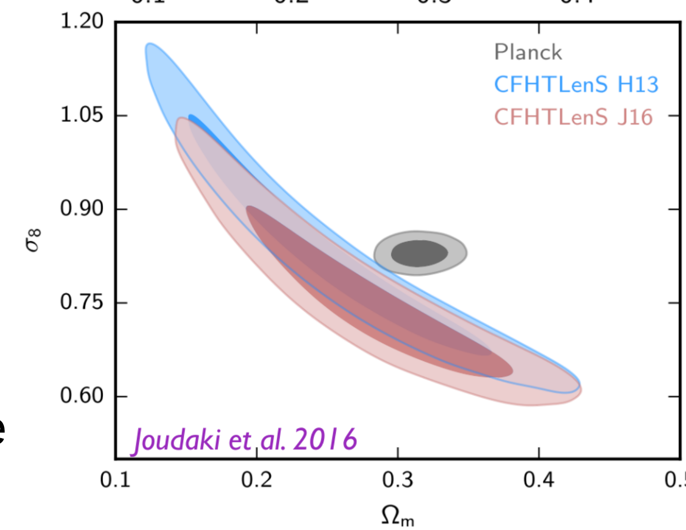


σ_8-Ω_m from X-ray luminosity function of REFLEX-II
→ agreement with Planck SZ clusters (Planck Collab. '16)
→ tension with CMB



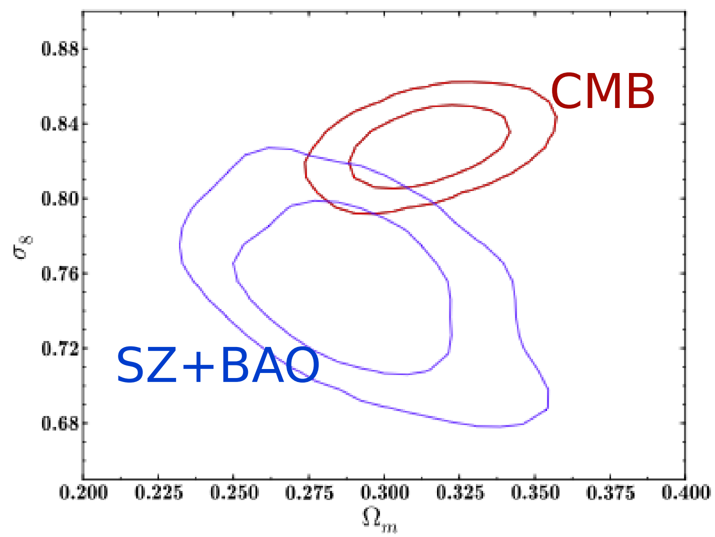
σ_8-Ω_m from 377 SPT clusters with lensing-based priors on the scaling relation

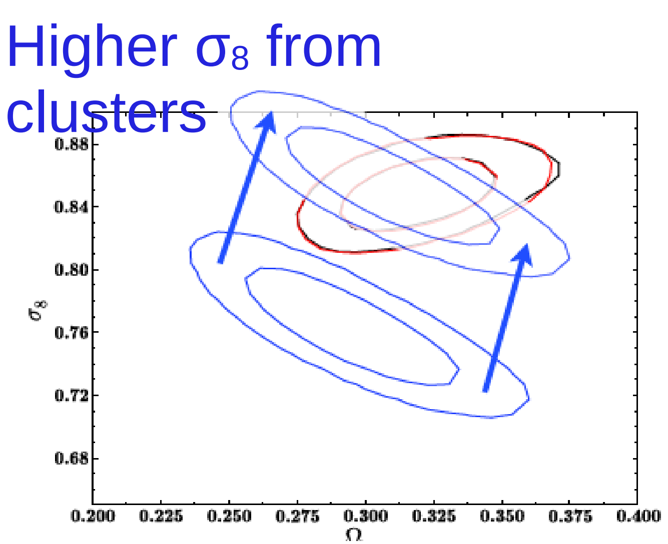




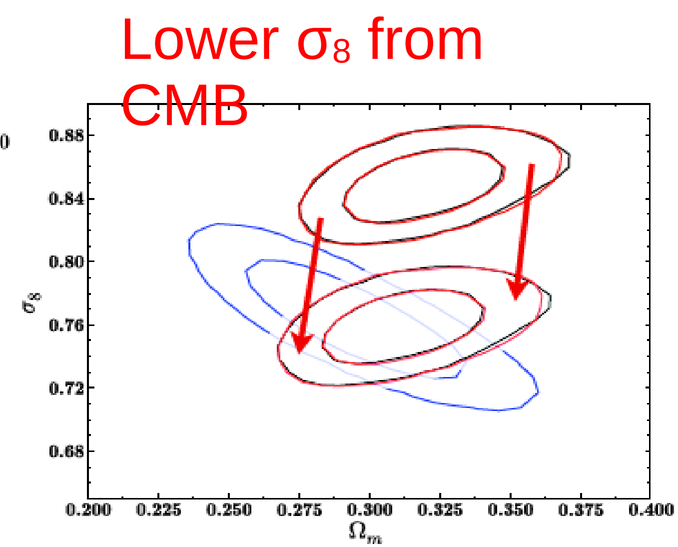
σ_8-Ω_m from weak lensing → ~2σ tension regardless of cosmological priors (Heymans et al. '13; Hildebrandt et al. '17)

Reducing Planck SZ – CMB tension?





- Missing half massive low z clusters
- Change scaling relation
- Change in bias



- Variation of initial spectrum
- Change transfer function, e.g. neutrinos

Cosmological parameters from Planck SZ counts (revisited)

SZ counts same as Planck collab, ‘16
Prior on mass bias from CCCP lensing (1-b)=0.78
Sampling cosmology & mass scaling parameters

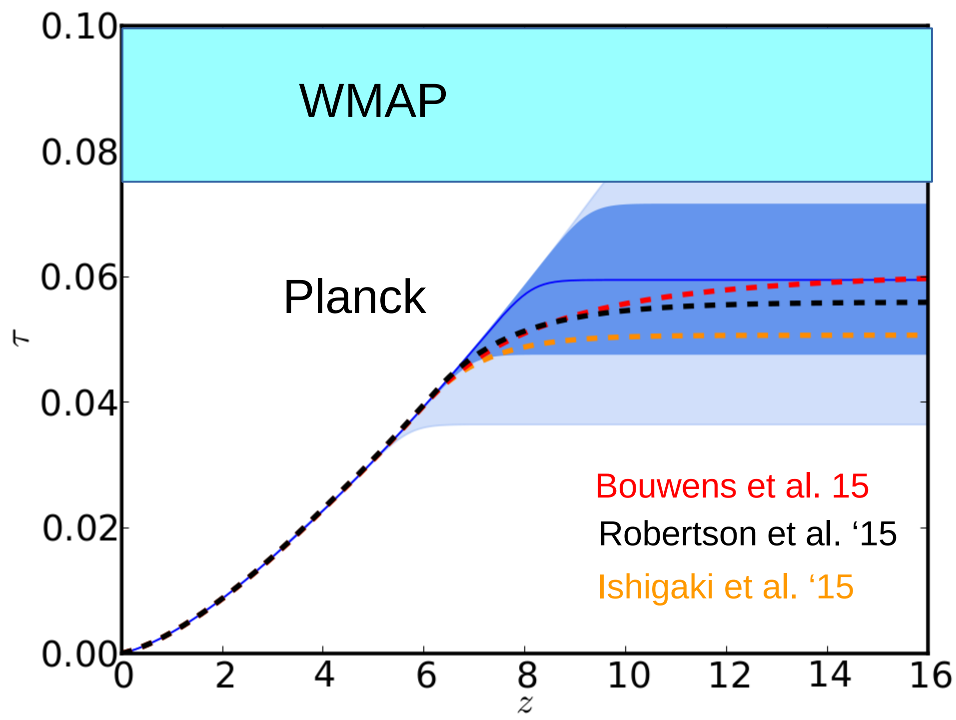
Planck-HFI low-l polarisation rather than WMAP prior or LFI polarisation

→ **τ reduced from 0.089 to [0.05, 0.06]**
(Planck collab. ‘16,)

→ Reduced tension between CMB and astrophysics probes of the reionisation

(cf. Talk J.A. Rubino-Martin)

Planck collab. ‘16



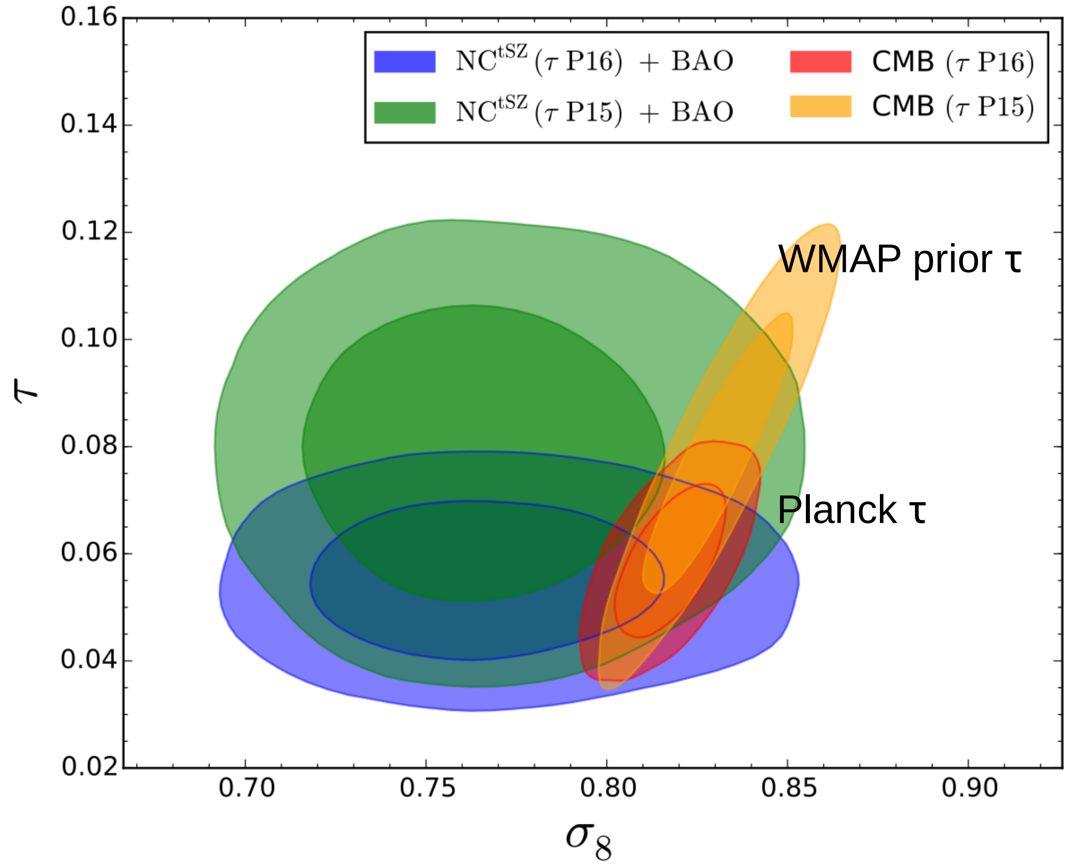
Evolution of τ from CMB and astrophysical probes (high-z galaxy UV/IR fluxes, GP, etc)

Cosmological parameters from Planck SZ counts (revisited)

SZ counts same as Planck collab. ‘16
Prior on mass bias from CCCP lensing (1-b)=0.78
Sampling cosmology & mass scaling parameters

Planck-HFI low-l polarisation rather than WMAP prior or LFI polarisation
→ **τ = 0.055 ± 0.009** (Planck collab. ‘16)

Salvati et al. ‘17

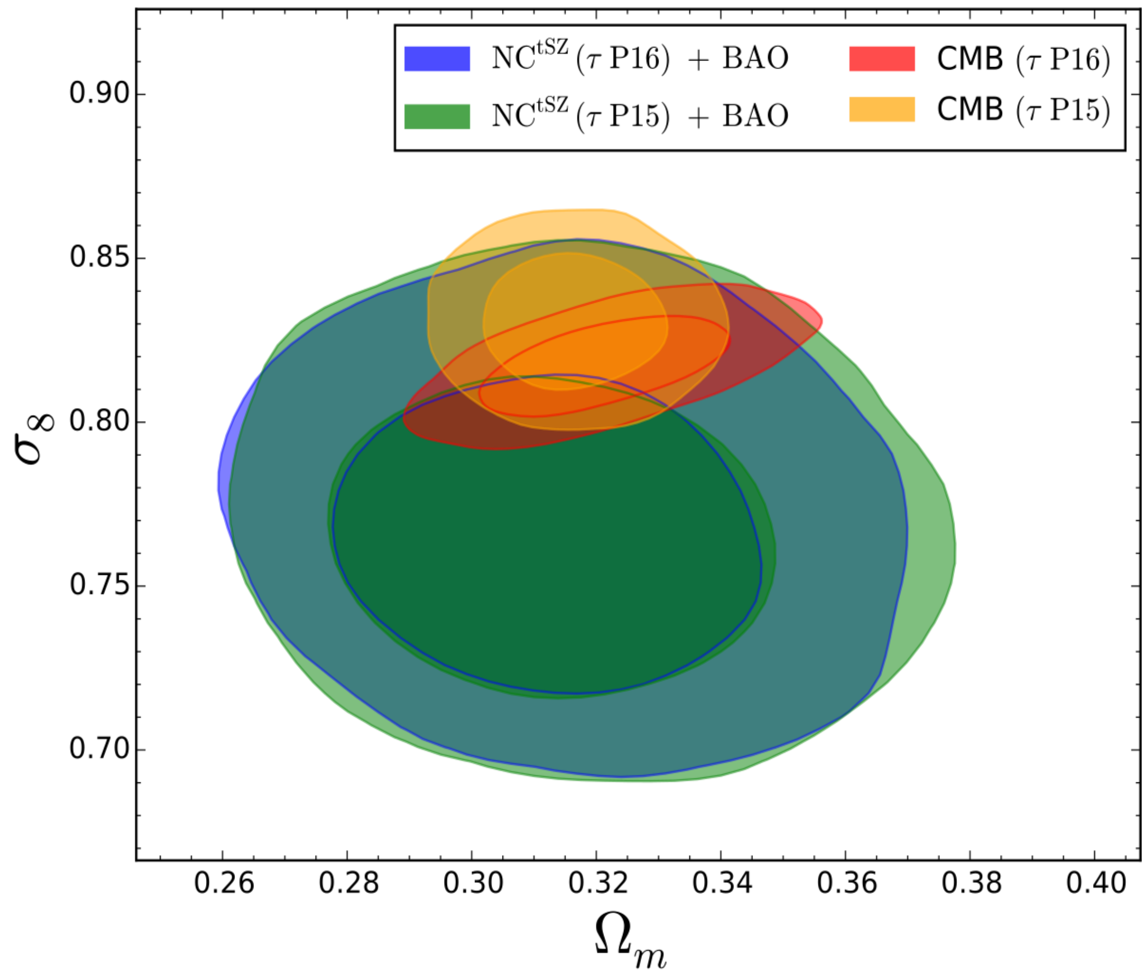


Cosmological parameters from Planck SZ counts (revisited)

Salvati et al. '17

SZ counts same as Planck '16
Prior on mass bias from CCCP lensing (1-b)=0.78
Sampling cosmology & mass scaling parameters

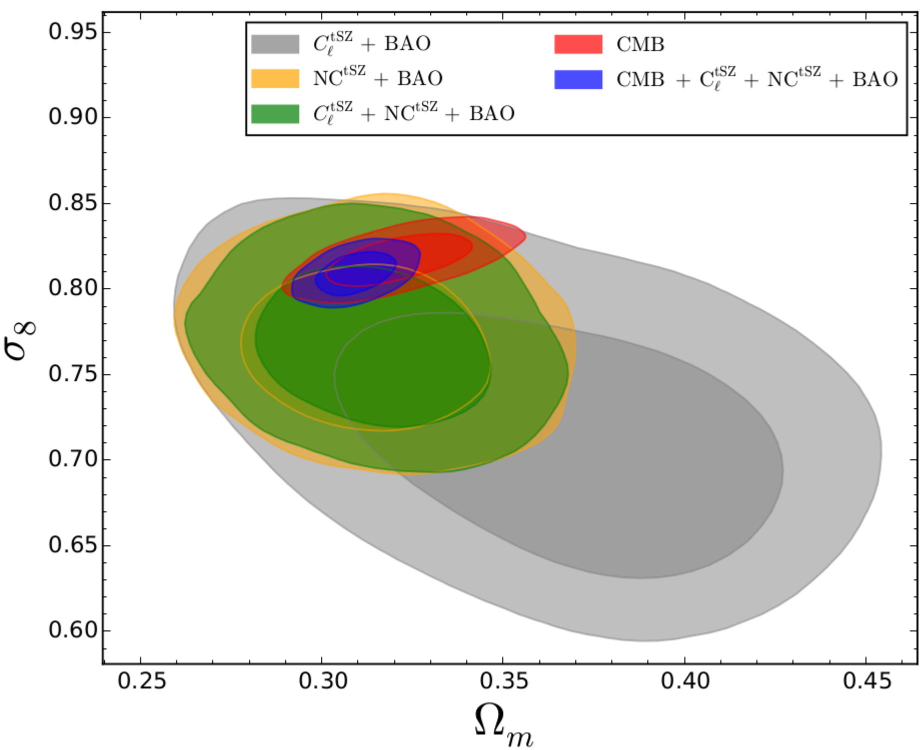
From WMAP prior on τ to Planck-HFI low-l polarisation
→ **$\tau = 0.055 \pm 0.009$** (Planck collab. '16)
→ SZ constraints unchanged

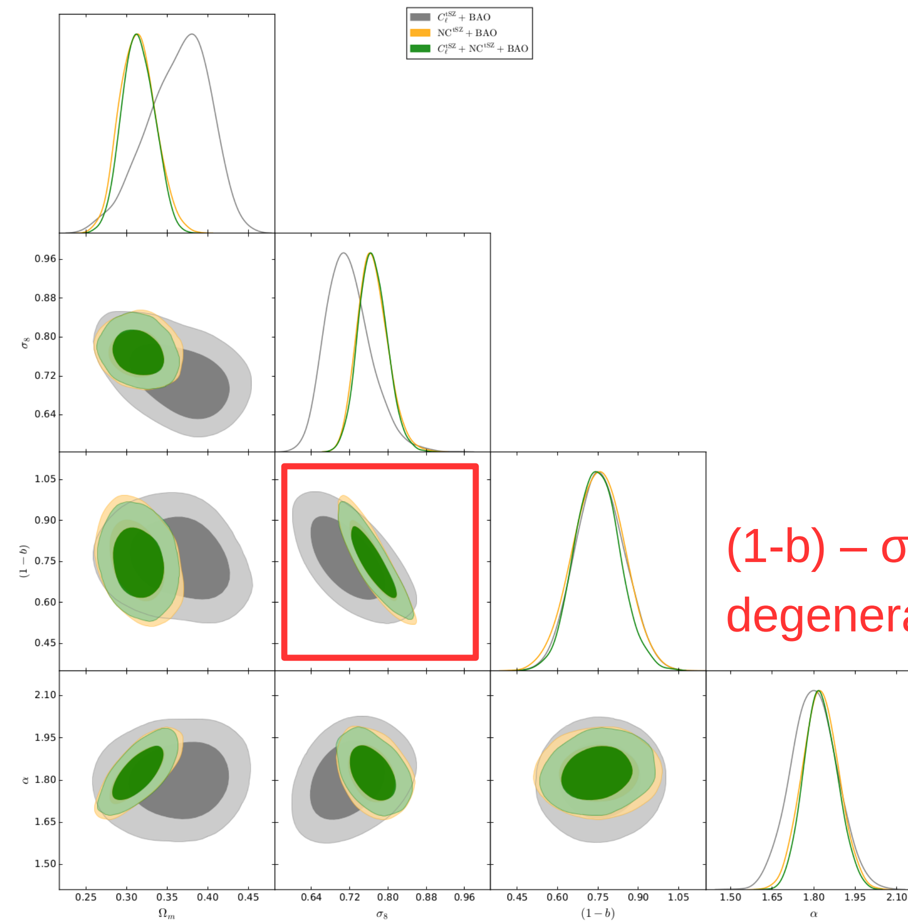


Tension on σ_8 between Planck CMB and SZ cluster counts reduced from ~2.4σ to ~1.5σ

Cosmology with combined SZ counts & spectrum from Planck

Salvati et al. '17





(1-b) – σ_8 degeneracy

Complementary tSZ counts & C_l

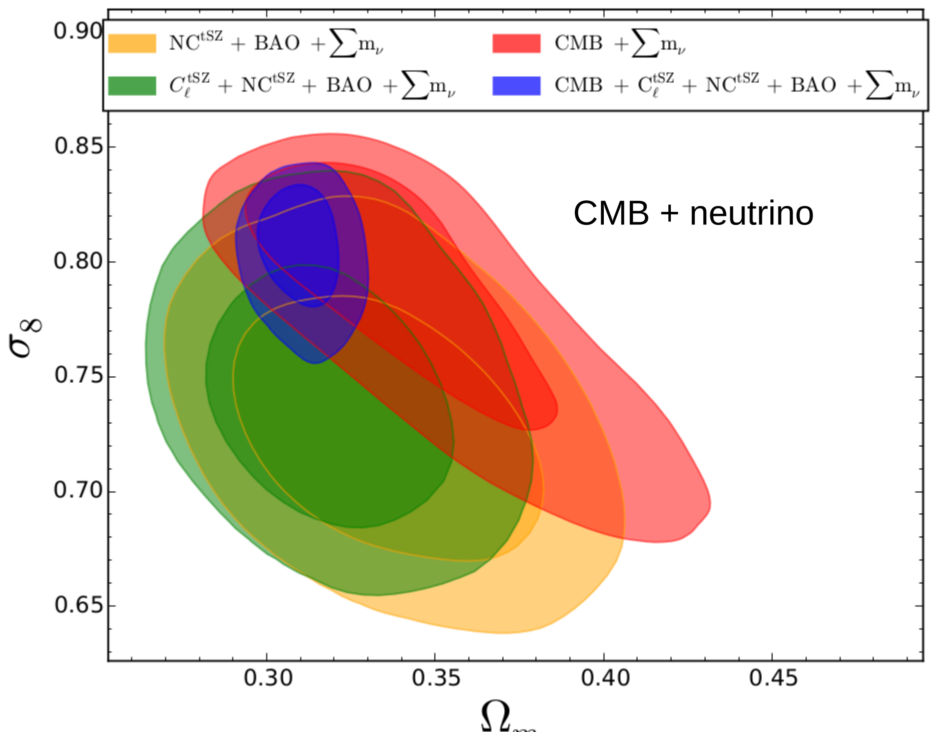
SZ-CMB discrepancy from counts & pow.spec. **~1.6σ on σ_8**

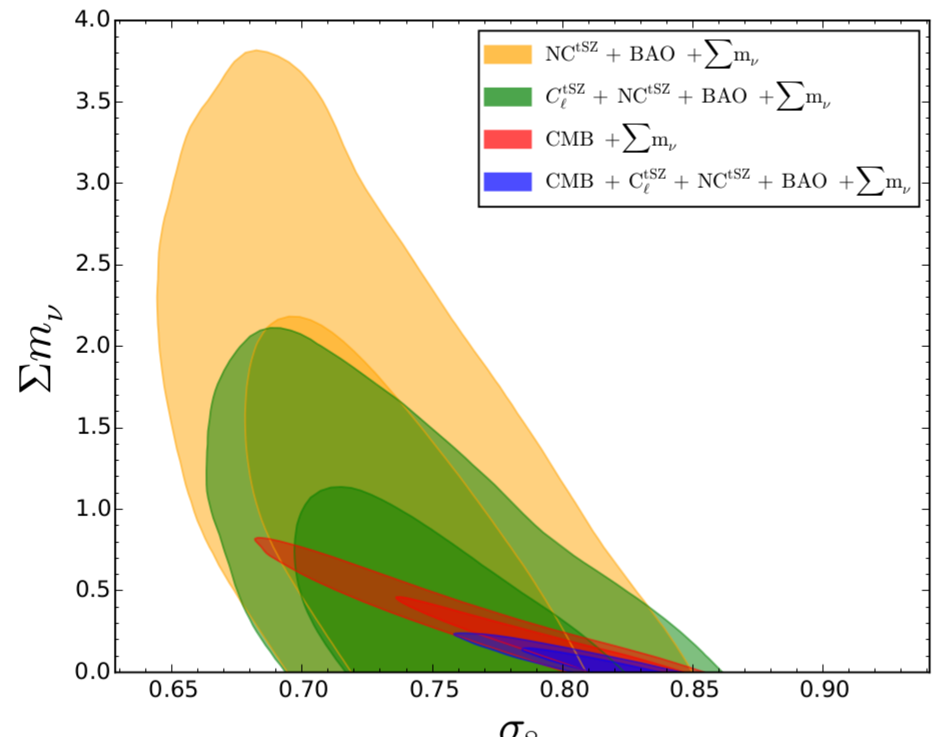
Degeneracy between σ_8 and mass bias → To reconcile CMB and ...

- tSZ counts → (1-b)~0.62 needed
- tSZ counts & C_l → (1-b)~0.64 needed

Cosmological parameters with combined SZ counts & spectrum from Planck

Salvati et al. ‘17





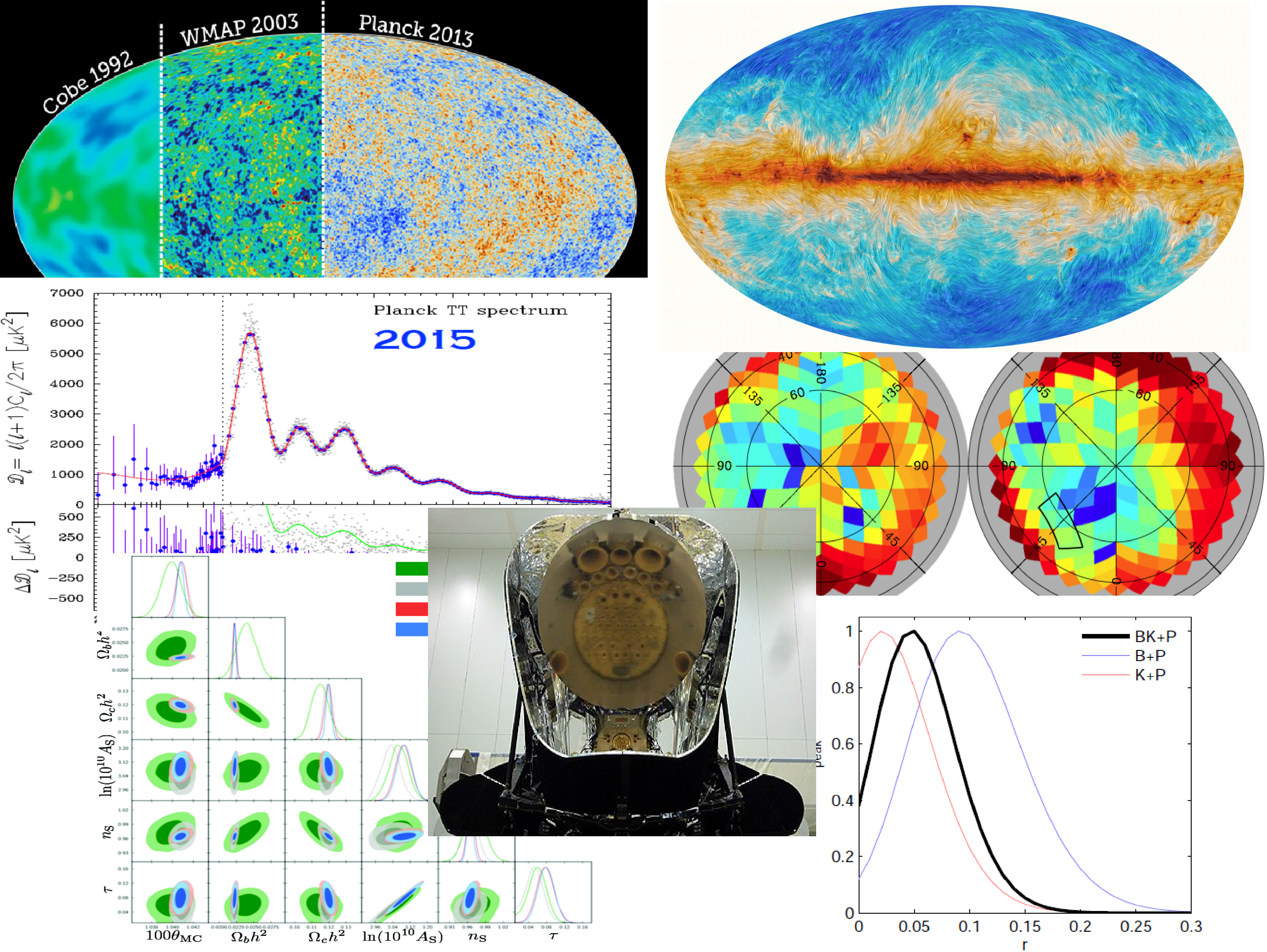
Including massive neutrino
→ reduced constraining power
→ (1-b)~0.66 needed to reconcile CMB and tSZ counts & C_l

$\Sigma m_v<1.53$eV from tSZ counts & C_l alone ($\Sigma m_v<0.49$eV from CMB alone)

$\Sigma m_v<0.19$eV from CMB+ tSZ probes

Conclusions

- CMB temperature anisotropies well measured
  - Down to 5' over whole sky & down to 1' on large areas
  - Planck/ACT/SPT complementary for low-z cosmological probes (SZ, lensing)
- Base ΛCDM model continues to be a good fit to CMB data
- Secondary CMB (tSZ & lensing) actual cosmology probes
- **Next challenges:** small-scale CMB, combinations/correlations with LSS; resolving/understanding tension between CMB and others
-
- CMB E-mode polarisation measured over whole sky
  - affected by systematics → progress expected from Planck 2018 release
  - ACTpol & SPTpol will cover small scales on large areas
- B-mode from lensing now detected (BICEP2, POLARBEAR, Planck, SPTpol, etc.)
- **Next challenges:** B-mode @large scales from primordial gravitational waves


Cobe 1992
WMAP 2003
Planck 2013
Planck TT spectrum
2015
$\mathcal{D}_\ell = \ell(\ell+1)C_\ell/2\pi\ [\mu K^2]$
$\Delta\mathcal{D}_\ell\ [\mu K^2]$
$100\theta_{MC}$
$\Omega_b h^2$
$\Omega_c h^2$
$\ln(10^{10}A_S)$
n_S
τ
BK+P
B+P
K+P
r

Cosmological test with SZ clusters: T_{CMB} evolution

Departure from adiabatic expansion

- Variation of fundamental constants
- non-conservation of photons (e.g. decaying DE)

$$T_{CMB}(z) = T_{CMB}(z=0)\,(1+z)^{1-\beta}$$

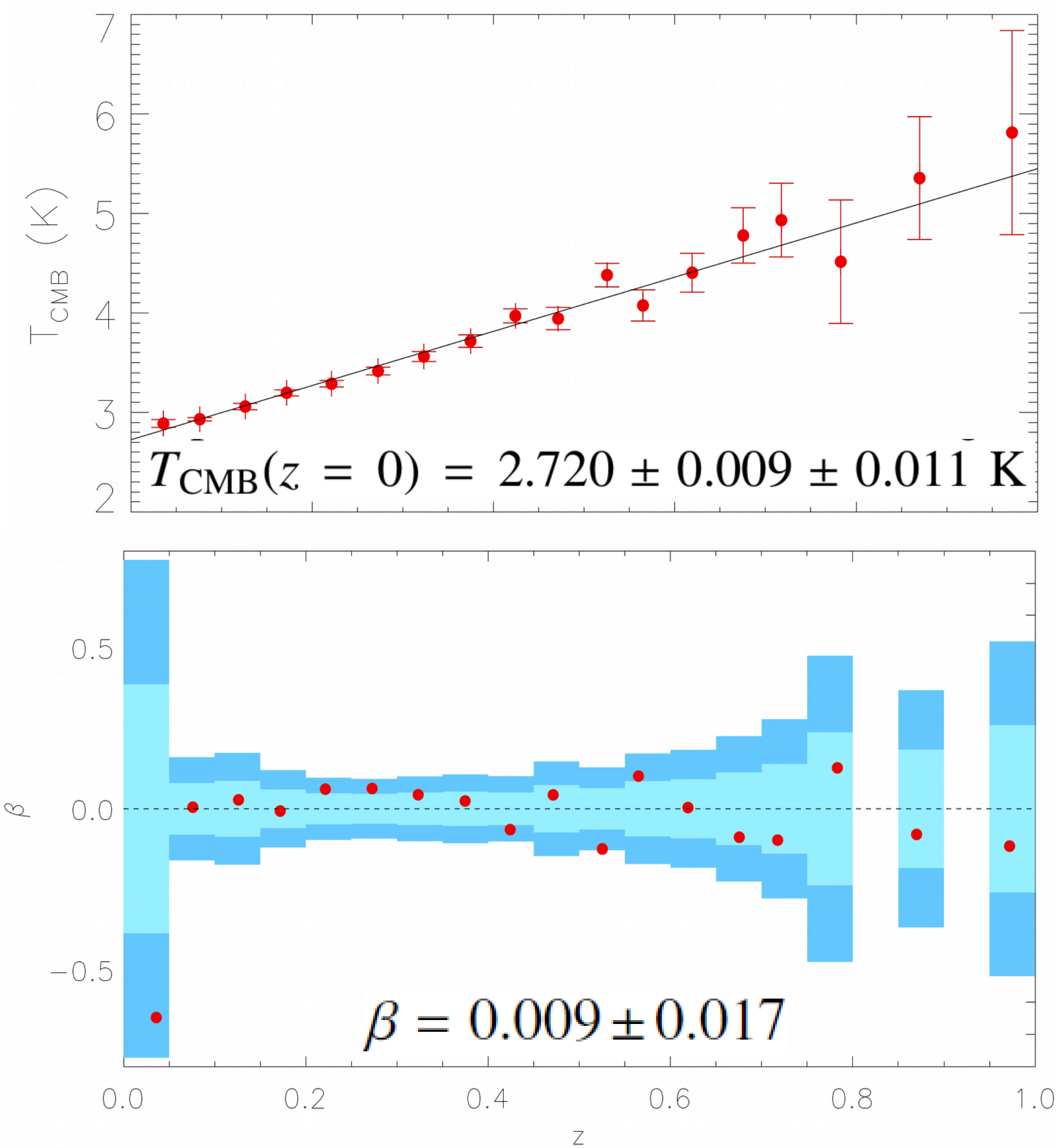
Use of SZ from a few clusters (e.g. Rephaeli '95, Batistelli et al. '02)

Planck: 813 clusters (z<1; 20 bins)

T_{CMB} compared (no fit) to adiabatic expansion for T_0=2.726K

Derived β

Hurier et al. '13



Cosmological test with SZ clusters: T_{CMB} evolution

$\beta = 0.009 \pm 0.017$ — 813 binned Planck clusters (Hurier et al. '13)

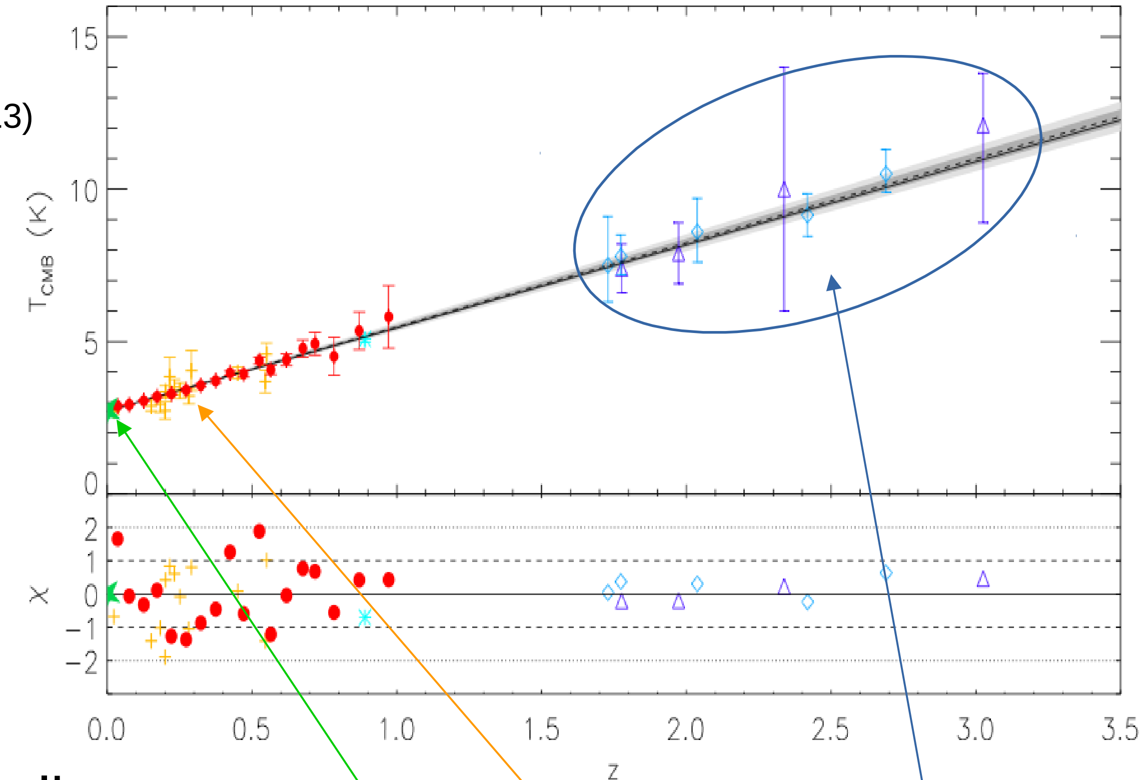
$\beta = 0.017 \pm 0.003$ — 158 individual SPT clusters (Saro et al. '14)

$\beta = 0.022 \pm 0.018$ — 104 individual Planck clusters (Luzzi et al. '15)

+ atomic/molecular lines @z>1

$\beta = 0.006 \pm 0.013$

Hurier et al. '13



SZ clusters (Battistelli et al. '02, Luzzi et al. '09)

COBE/FIRAS (Fixen et al. '09)

Mol./Atomic lines (Mueller et al. '13, Noterdaeme et al. '11)

Tightest constraints on deviation from linear evolution → **Adiabatic expansion**

Implied **constraints w_{eff} in decaying DE** model (Lima '96; Jetzer et al. '11) → $w_{eff} = -0.995 \pm 0.011$