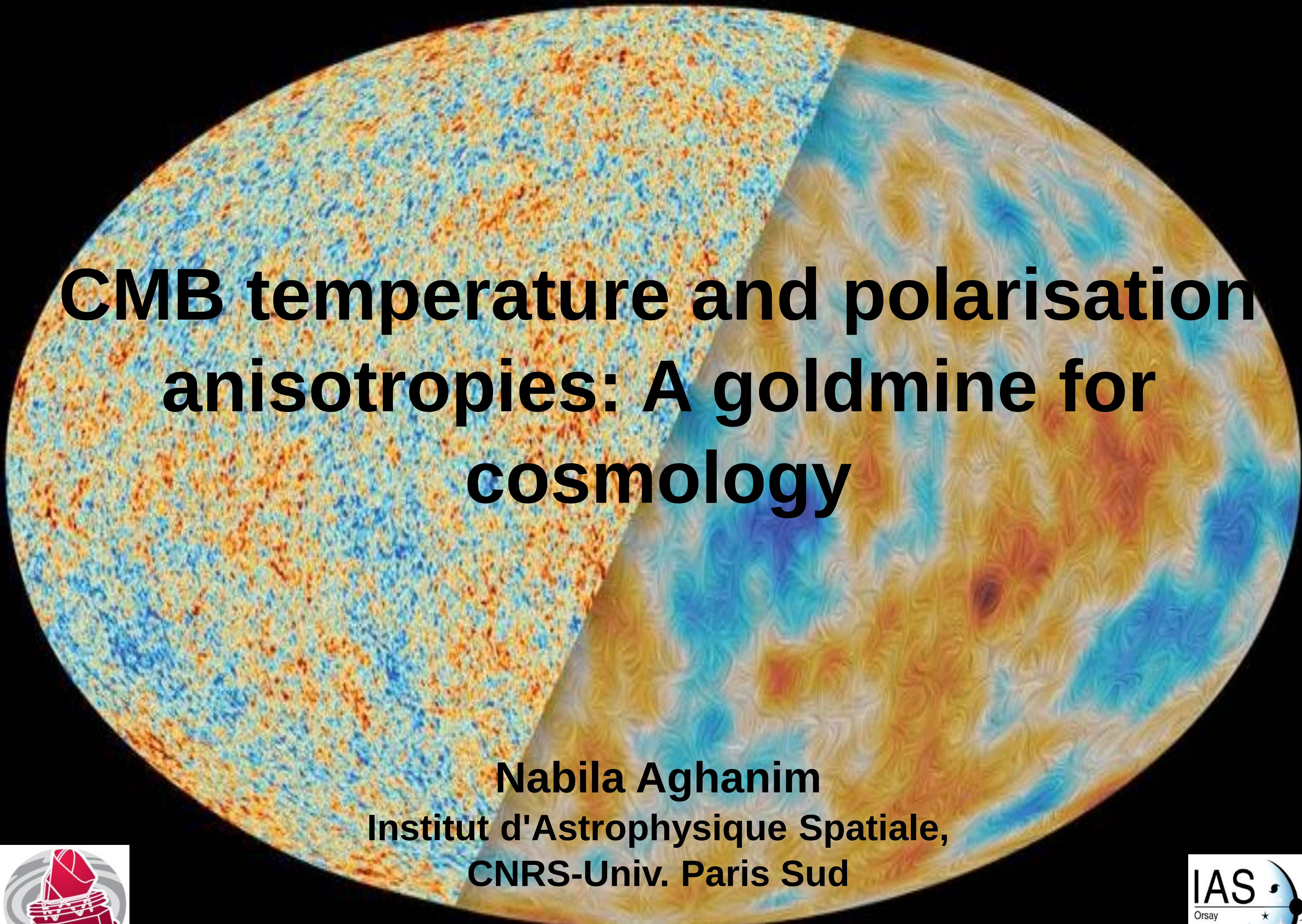


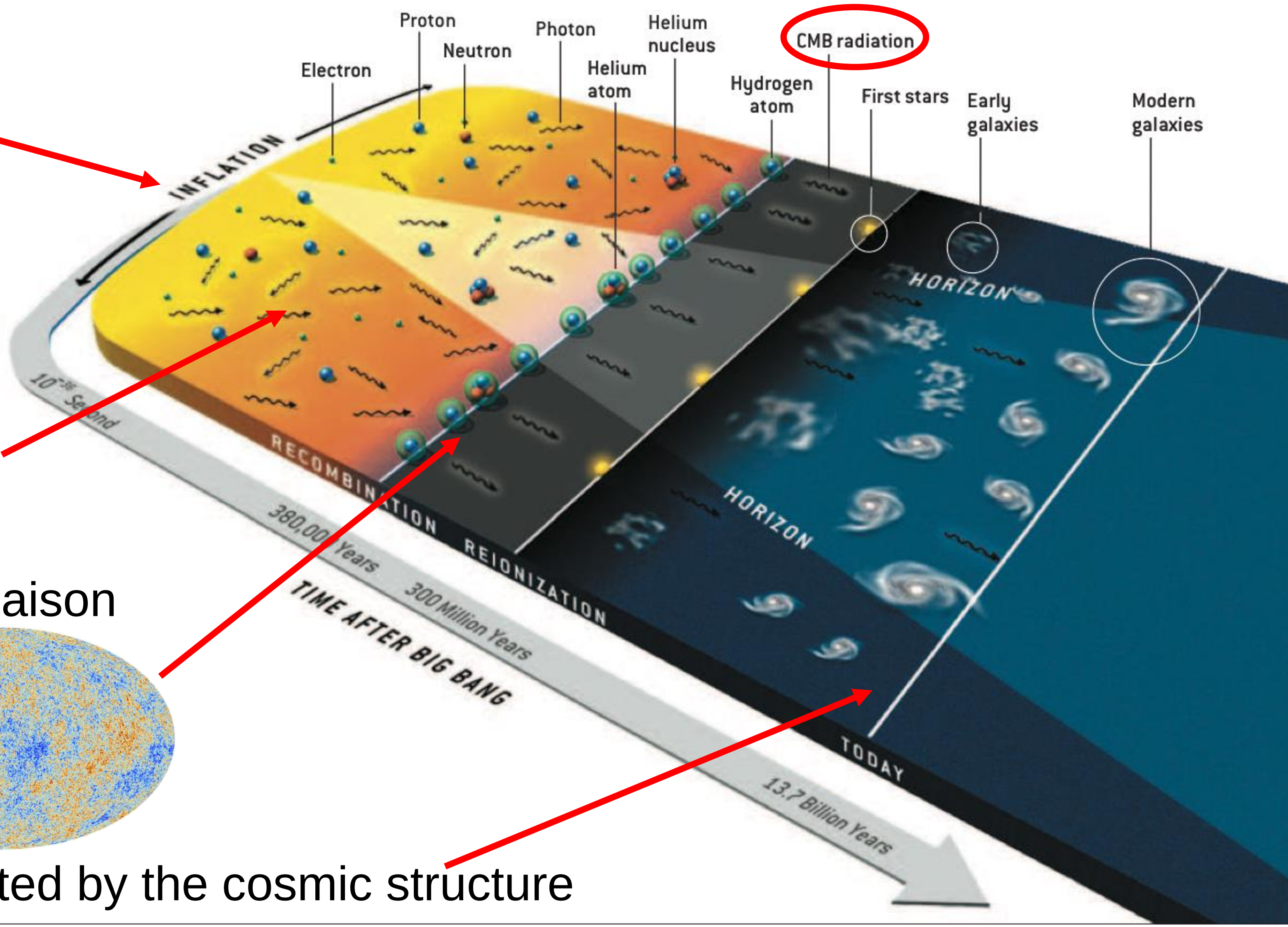
CMB temperature and polarisation anisotropies: A goldmine for cosmology

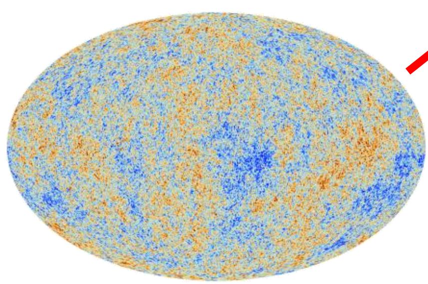
Nabila Aghanim
Institut d'Astrophysique Spatiale, CNRS-Univ. Paris Sud

Primordial Universe

Photons produced

Diffused at recombinaison





Photons affected by the cosmic structure

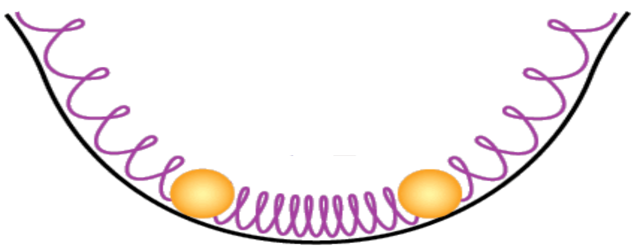
CMB = Photons from 380000yrs at a surface of last scatter + effects of the journey through Universe

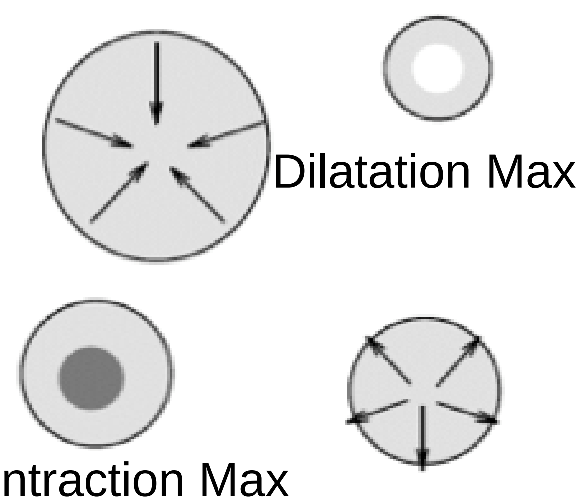
CMB and Seeds of structures

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

CMB Large scales = Sach-Wolfe effect→*Initial conditions*
CMB Small scales = acoustic oscillations→ *content of the Universe*

At small scales ($\theta < 1^o$)



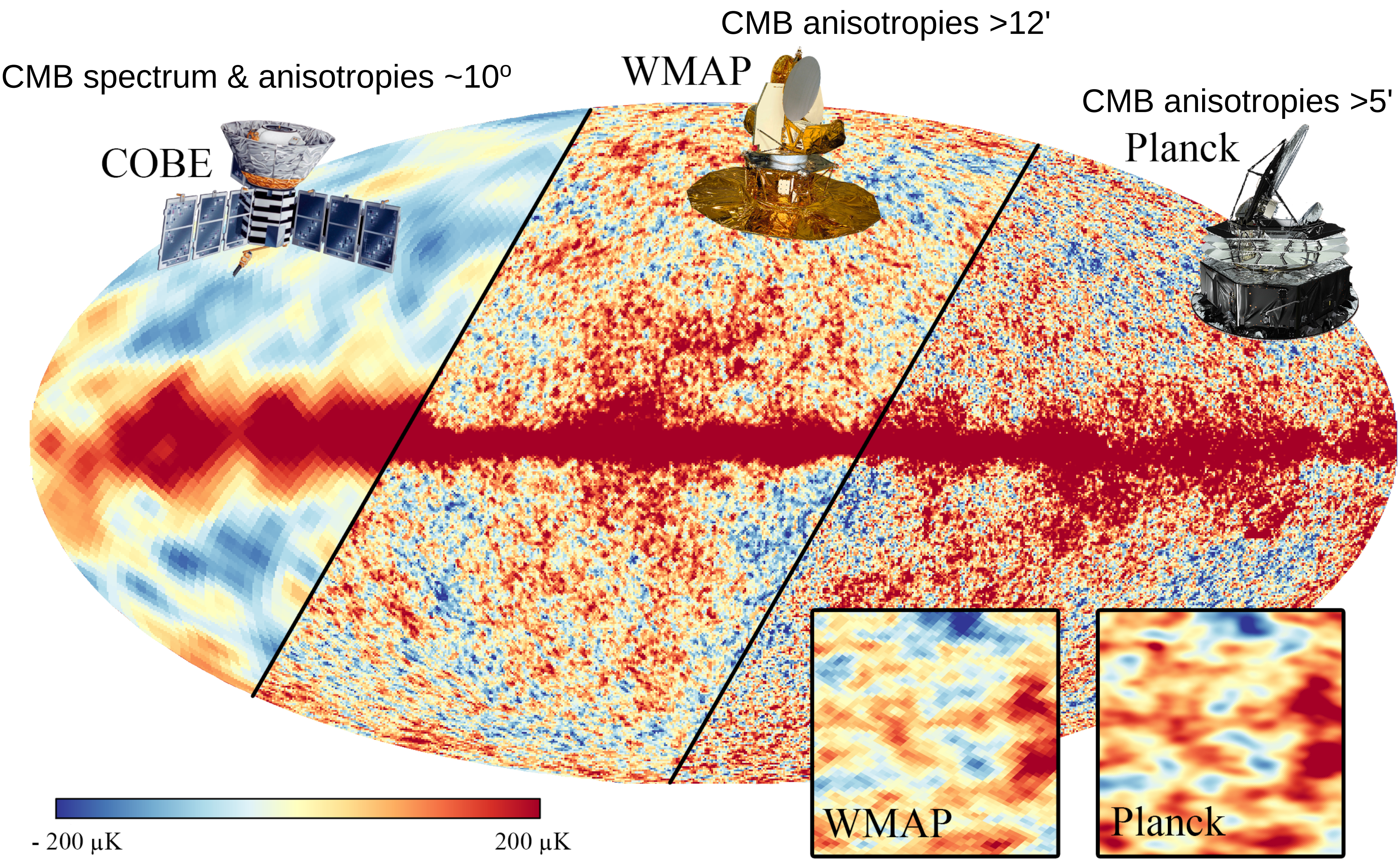


Tight coupling between matter and radiation
Gravitational instability vs pressure from radiation

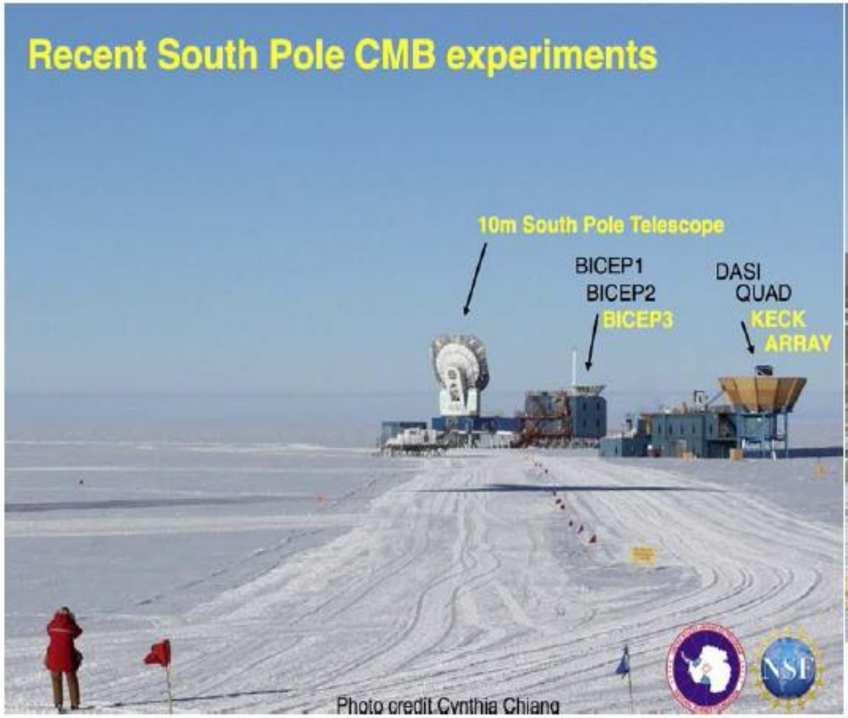
Perturbation oscillate between
- Contraction phases, hotter & denser
- Expansion phases, less hot & dense

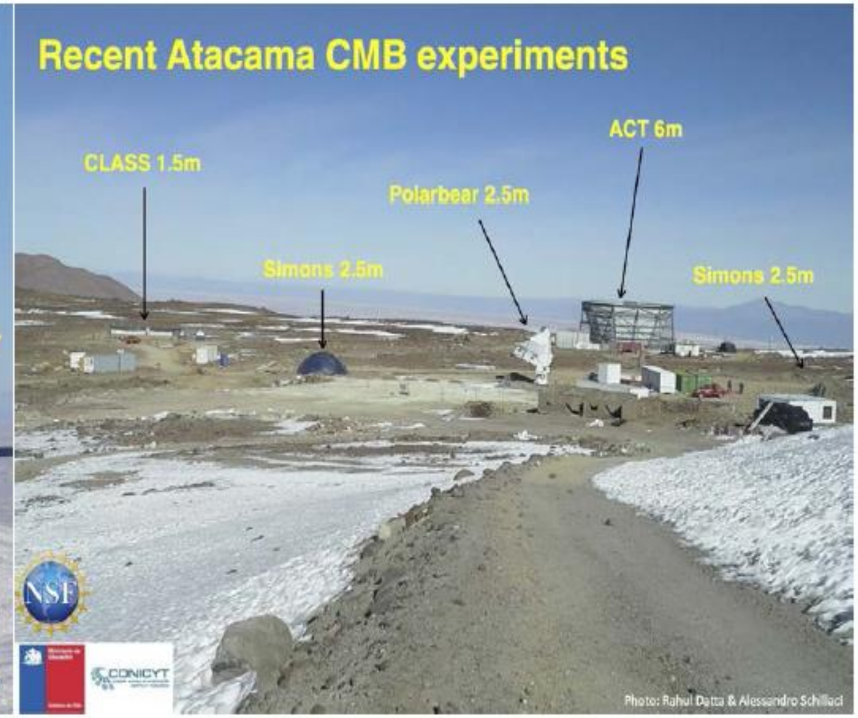
Periodic variation of CMB temperature frozen at recombination = **Acoustic oscillations**

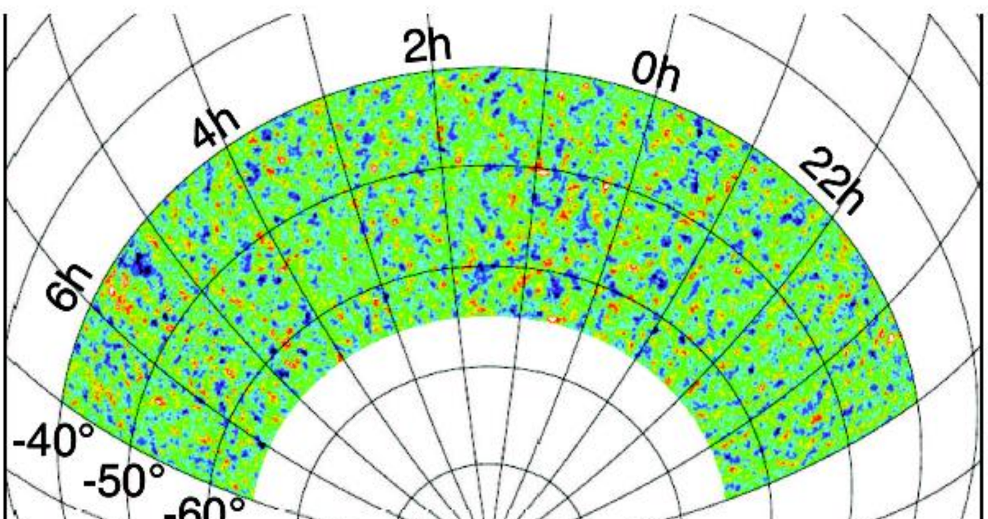
Three generations of CMB satellites



Ground-based experiments

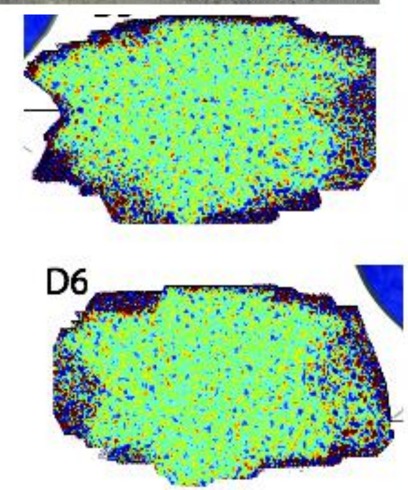






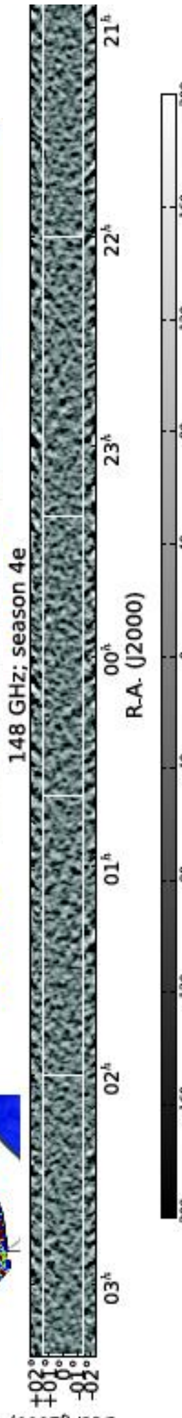
SPT, Story et al 2013

CMB anisotropies >1'

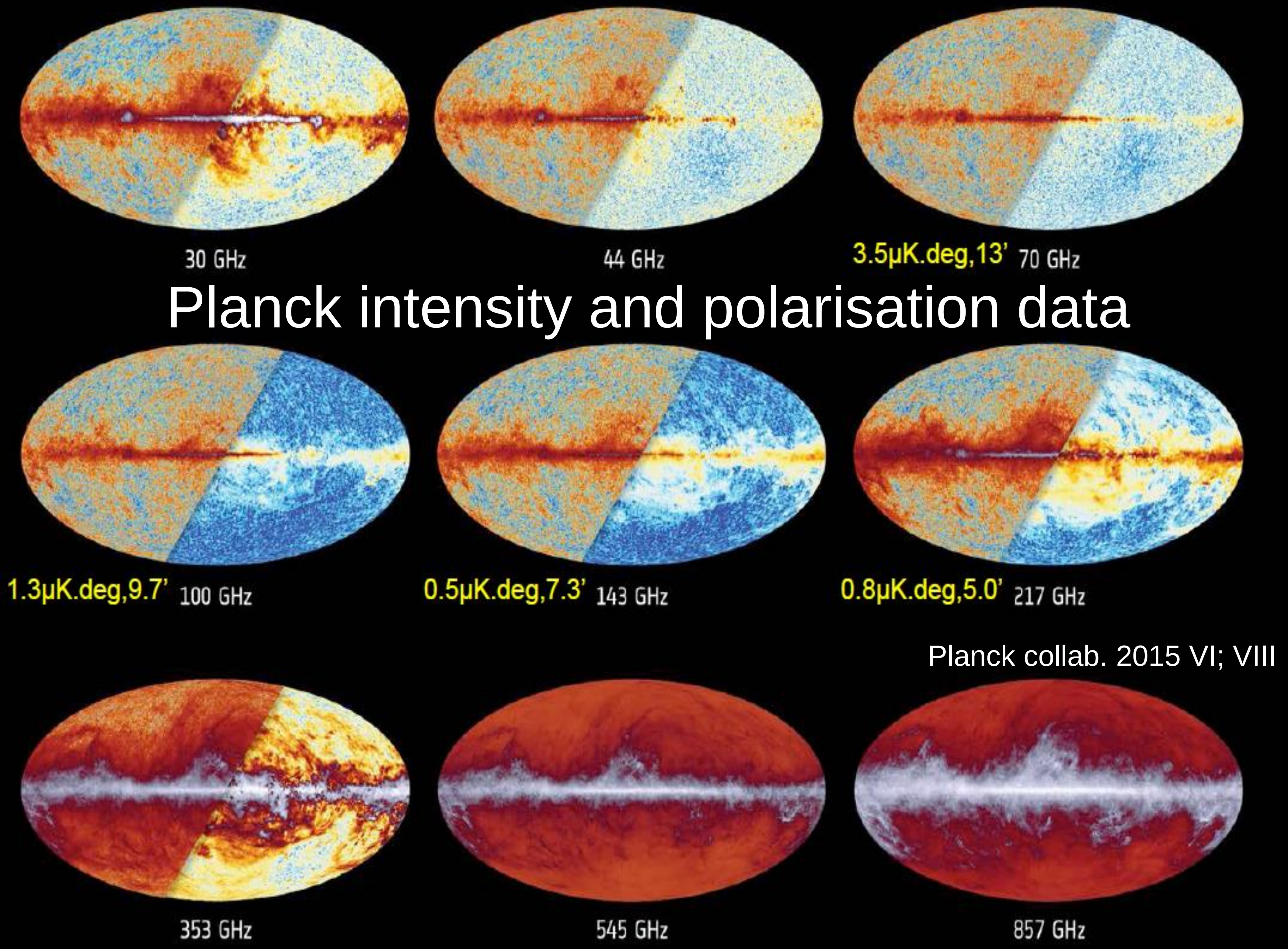


ACTPol, Naess et al 2014

ACT, Das et al 2013

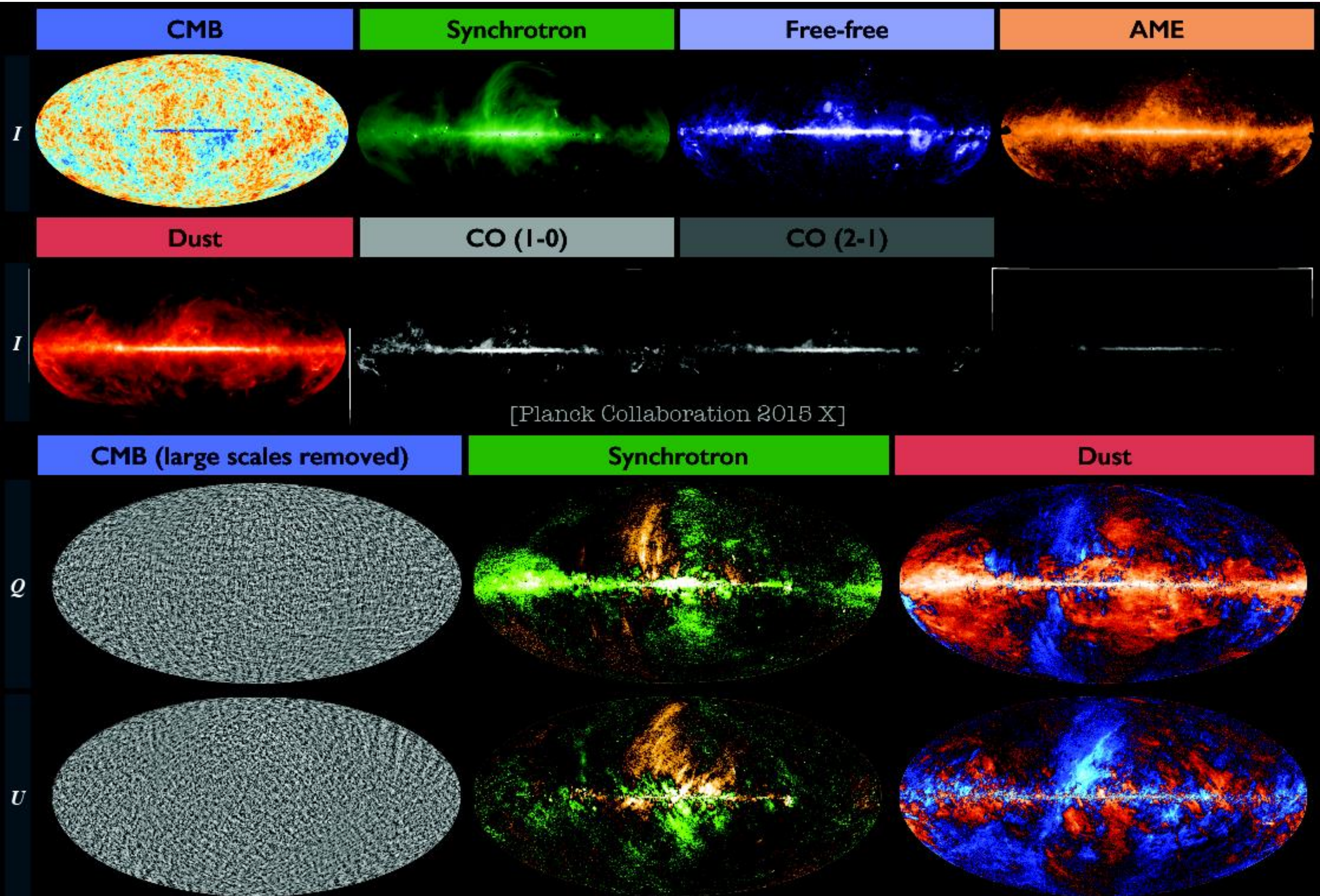


Planck intensity and polarisation data



Planck collab. 2015 VI; VIII

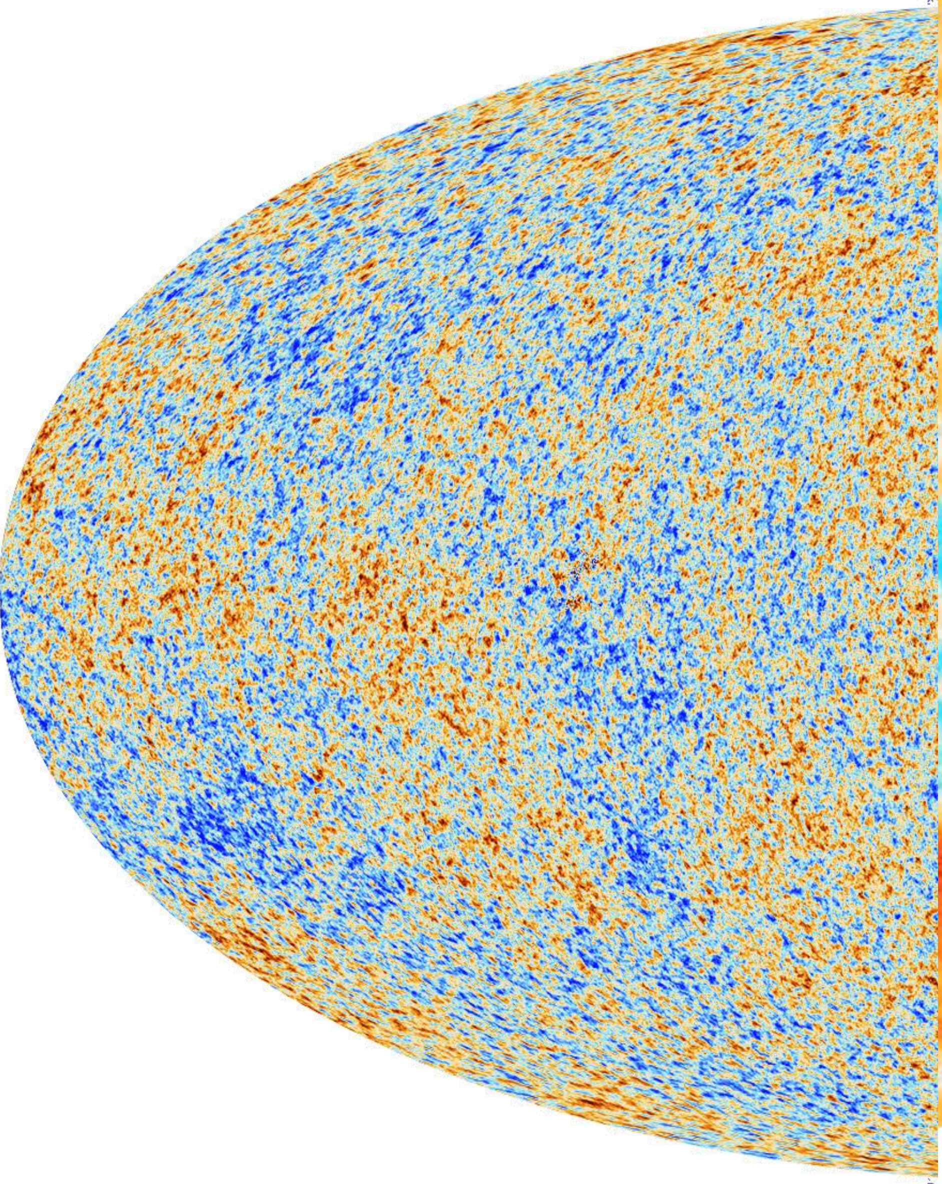
Planck's physical component maps

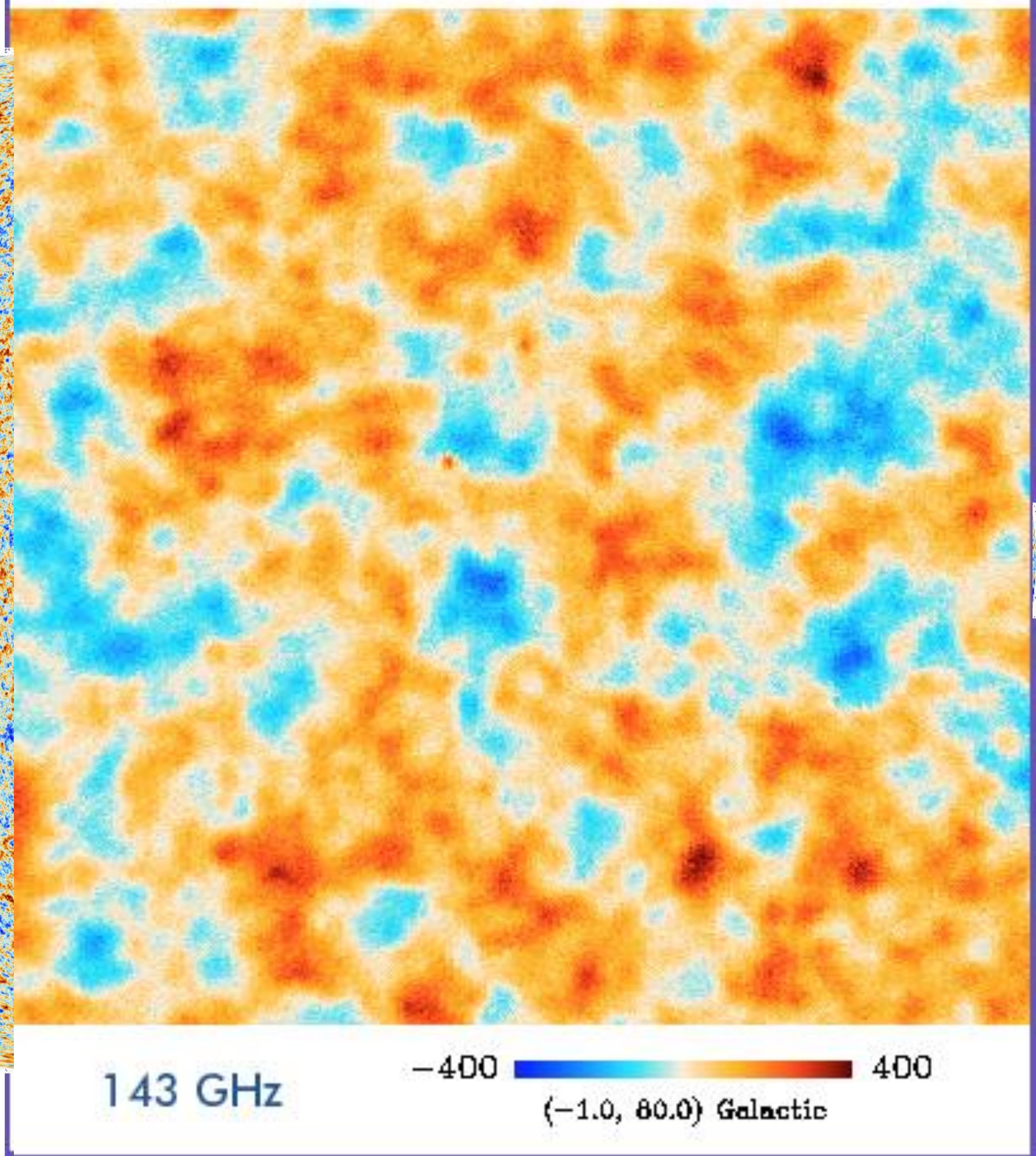


Planck's CMB map

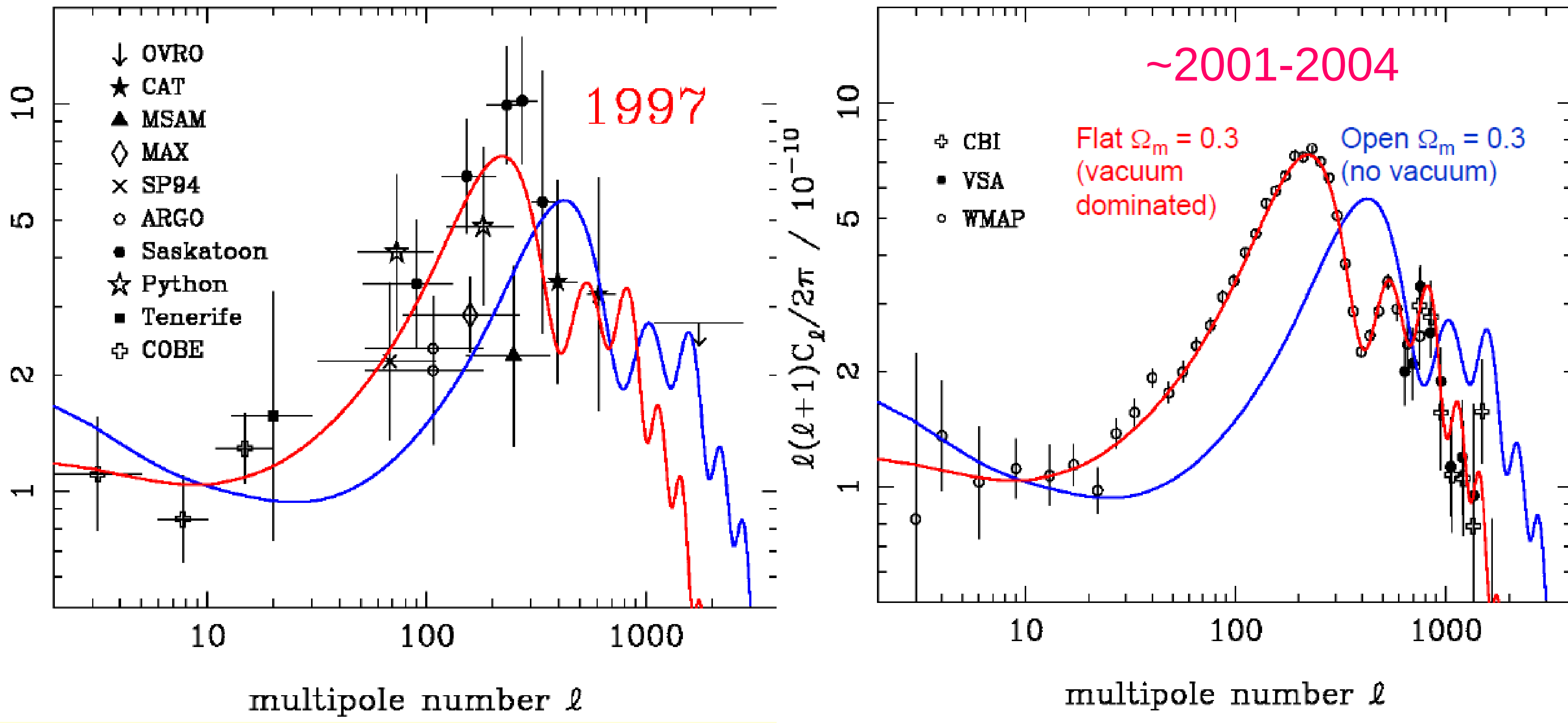
2015

Universe at 2.10^{-5} of its present age

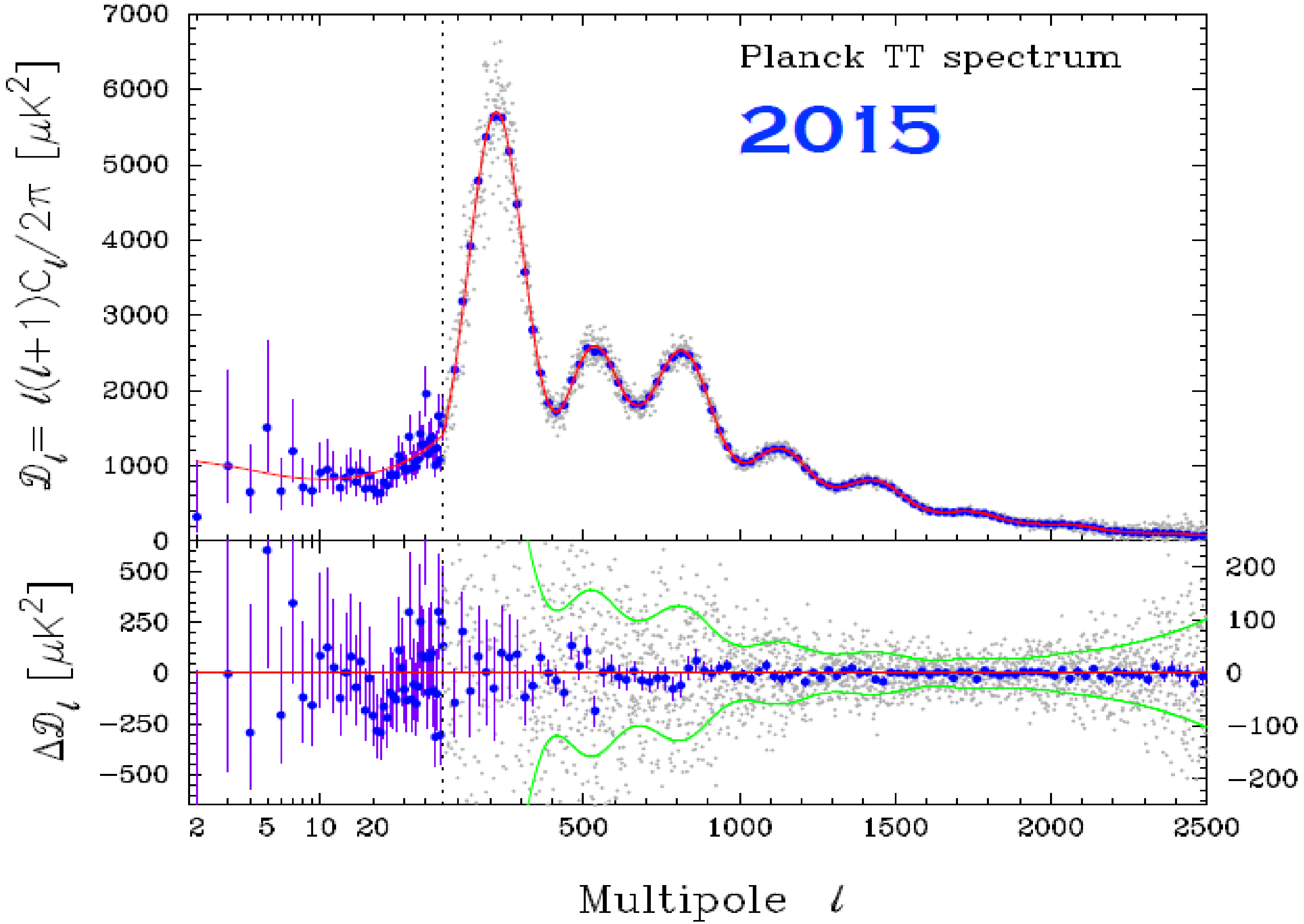




CMB anisotropies across time

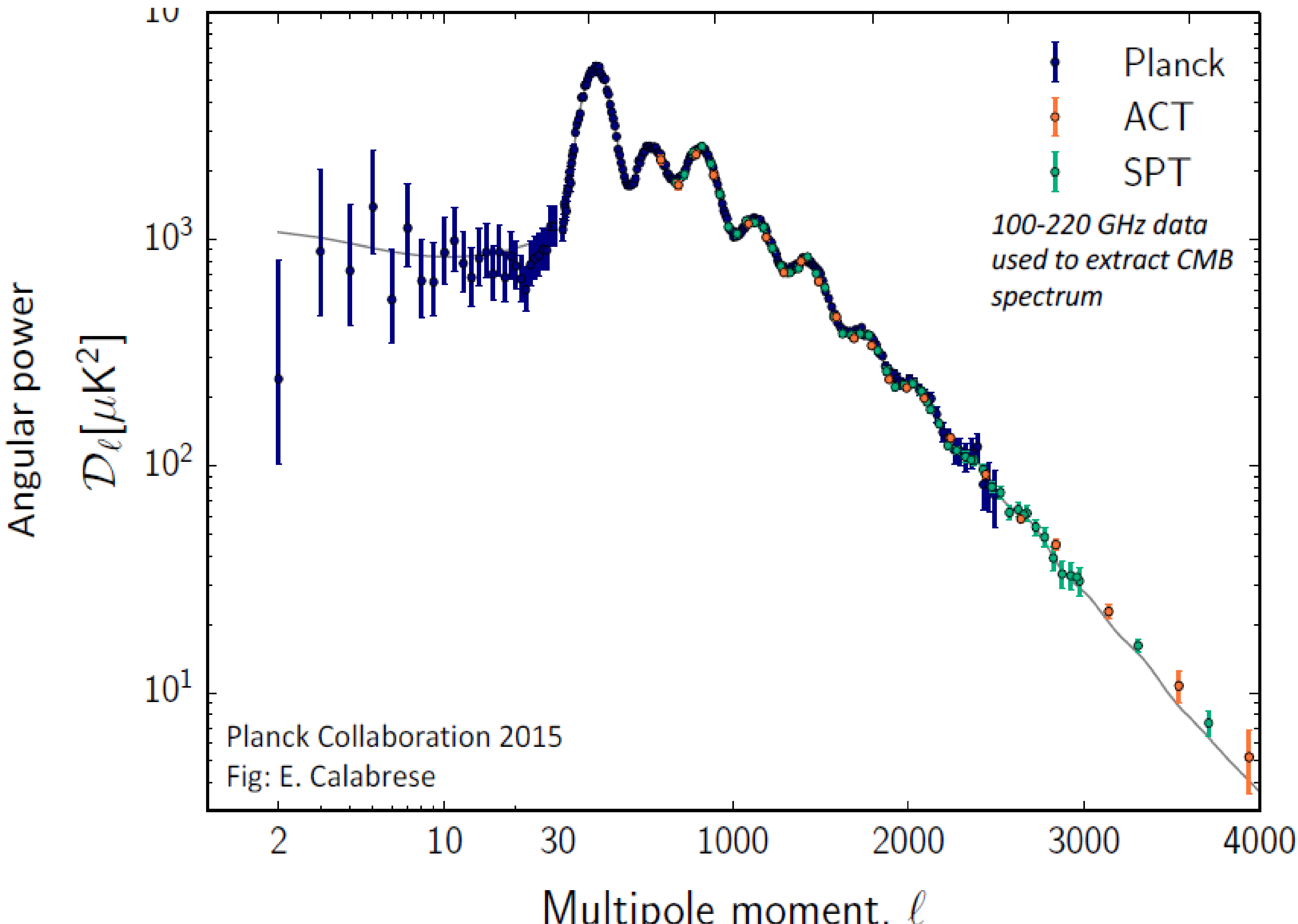


Planck 2015: CMB power spectrum



Planck collaboration 2015 XIII

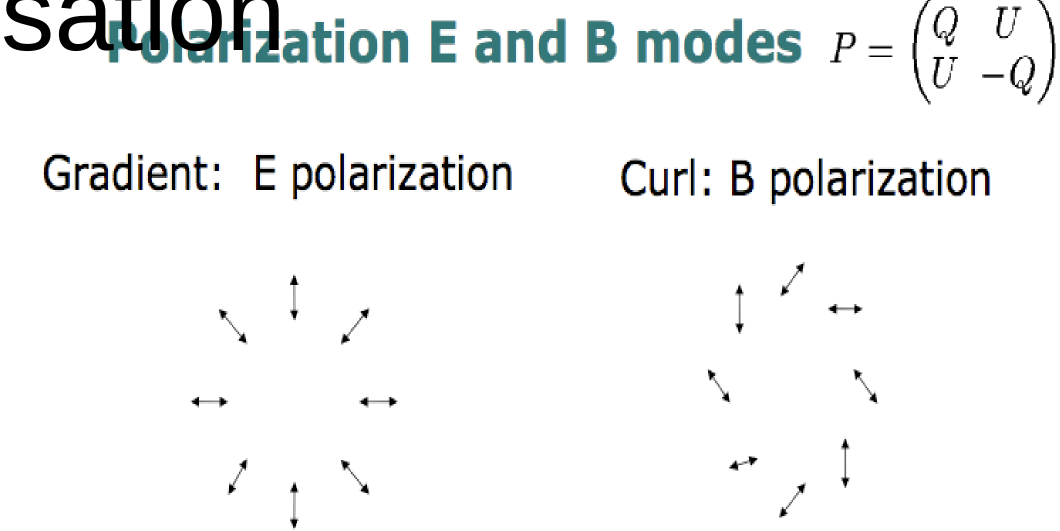
CMB anisotropies across scales: Planck/ACT/SPT



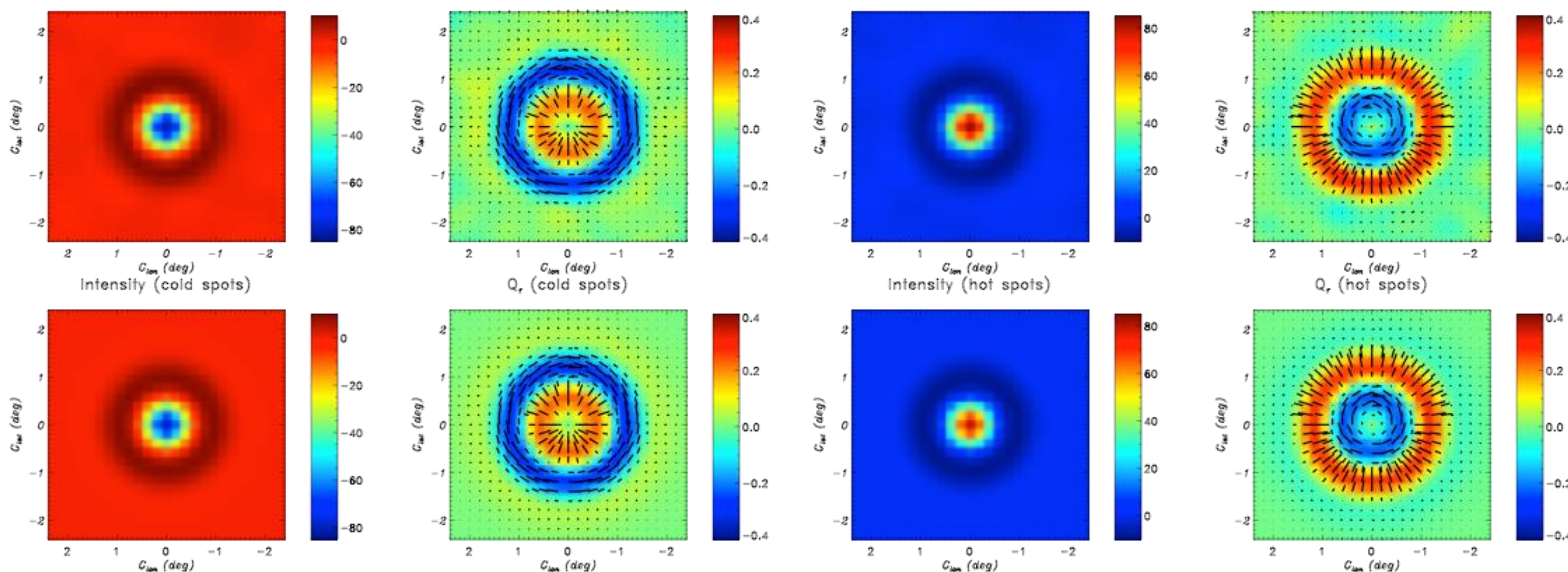
CMB polarisation

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

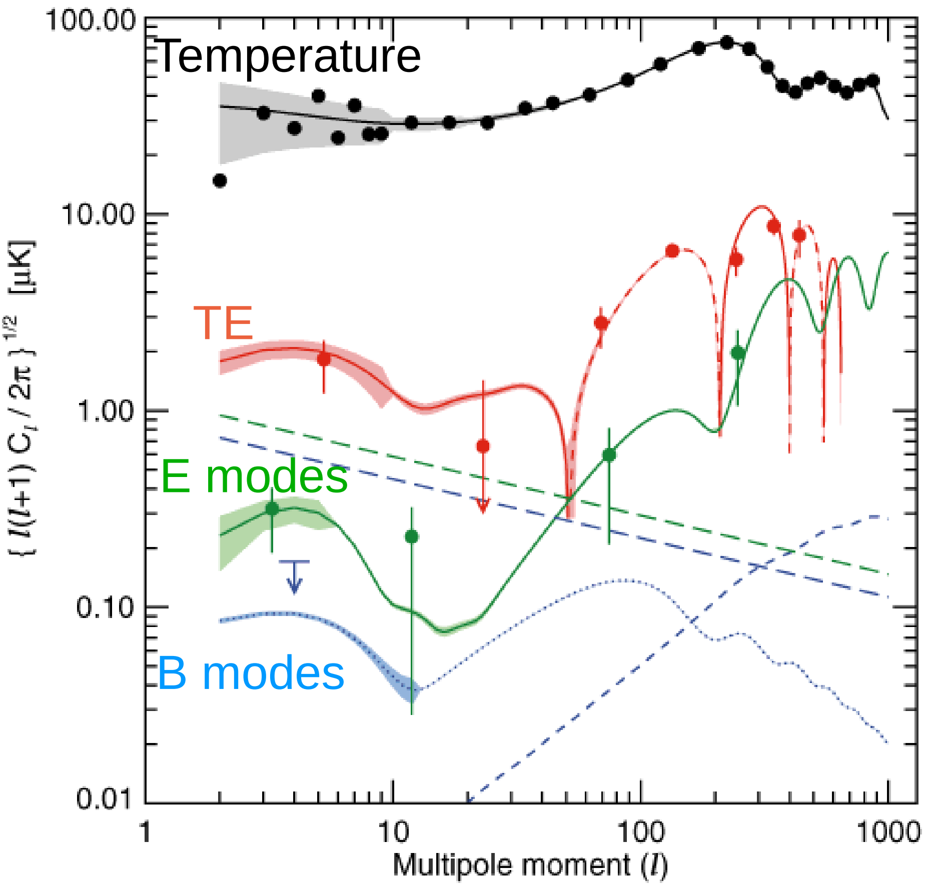


Stacking of Planck E-mode polarisation on tempreature peaks & throughs

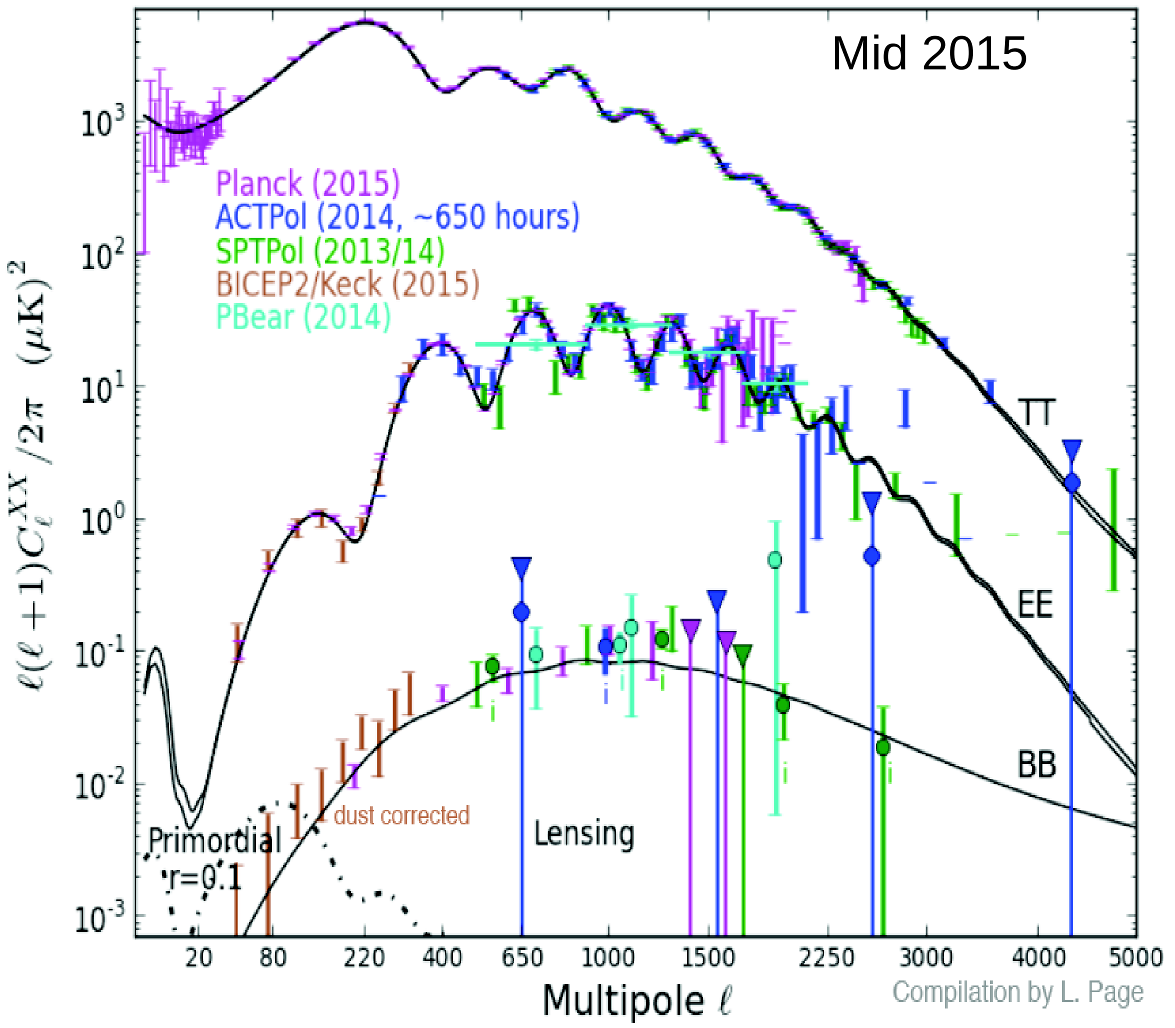


CMB polarisation across time

~2007



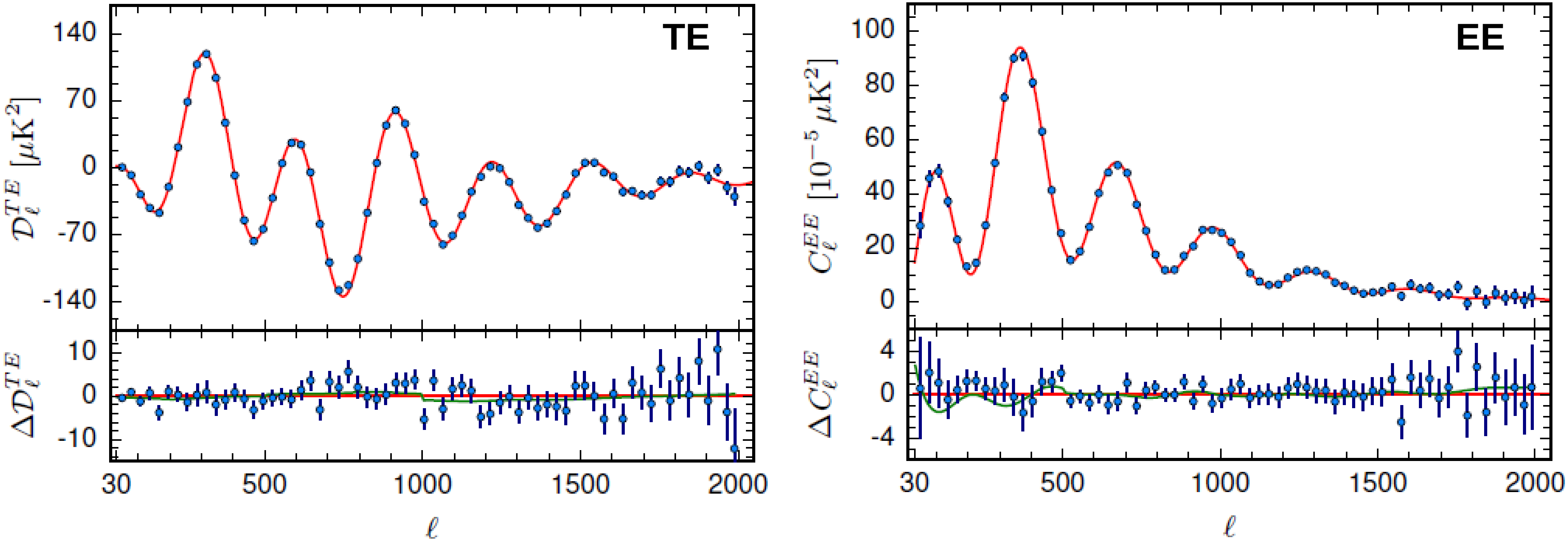
Page et al 07; Bennet et al '12



Planck 2015: CMB polarisation power spectrum

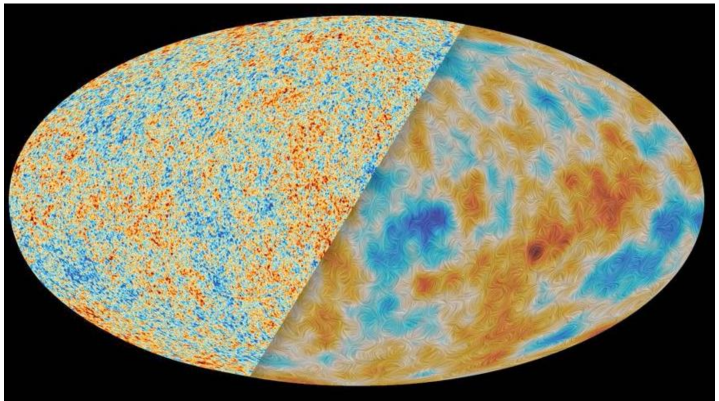
Intermediate angular scale polarisation spectra with Planck Analysis in 2015 with large scale polarisation from LFI 70GHz→

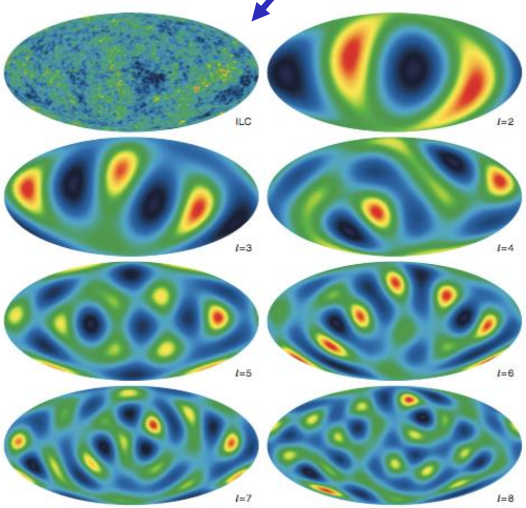
Forthcoming: use HFI low-l polarisation



Additional constraints on ΛCDM parameters & stronger limits on possible extensions

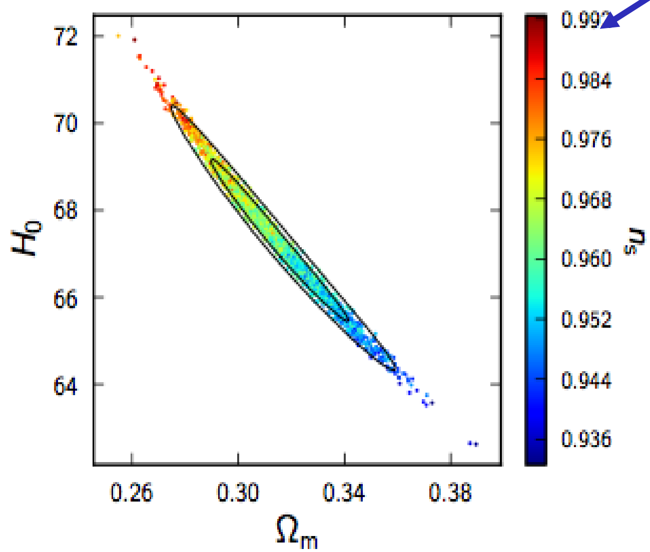
From data to cosmological parameters

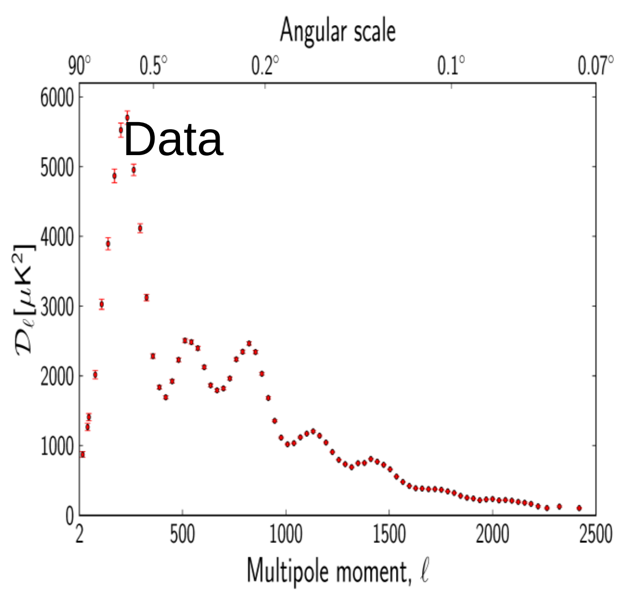


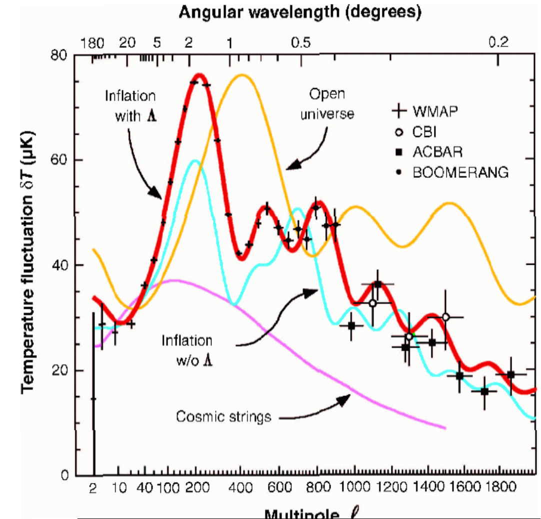


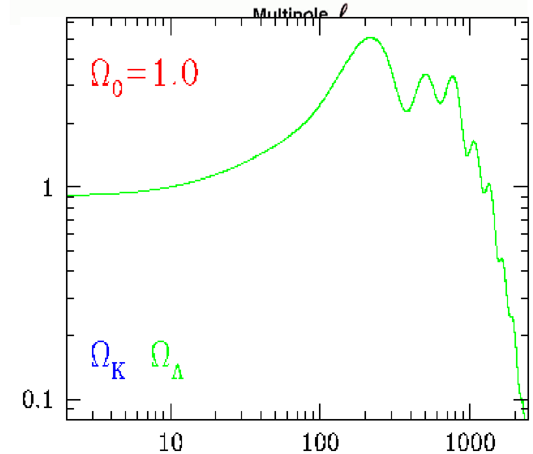
$$\frac{\Delta T(\mathbf{n})}{T_0} = \sum_{\ell=0}^{\infty} \sum_{m=-\ell}^{\ell} a_{\ell m}^{T} Y_{\ell m}(\mathbf{n})$$

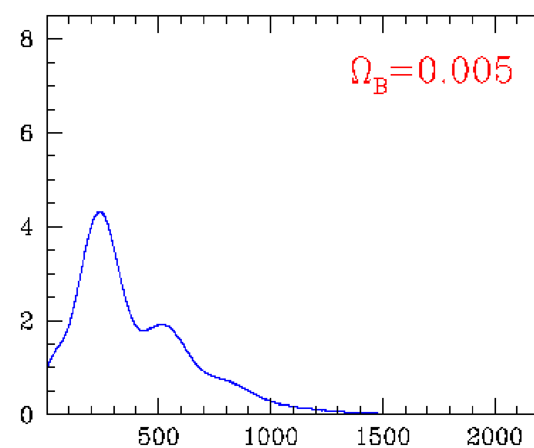
$$C_\ell^{TT} = \langle a_{\ell m}^{T} \cdot a_{\ell m}^{T\star} \rangle$$



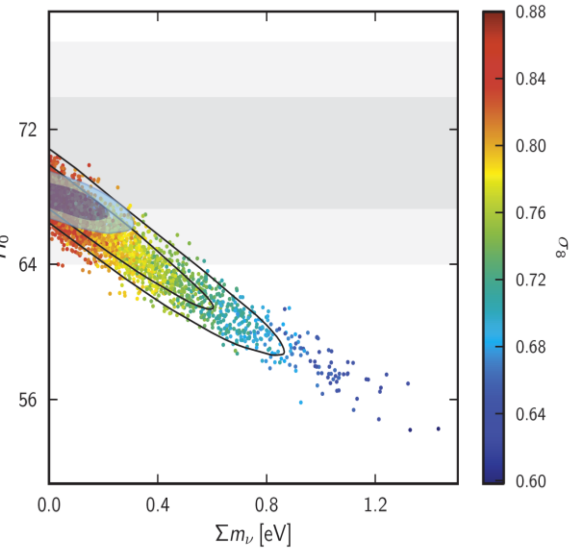


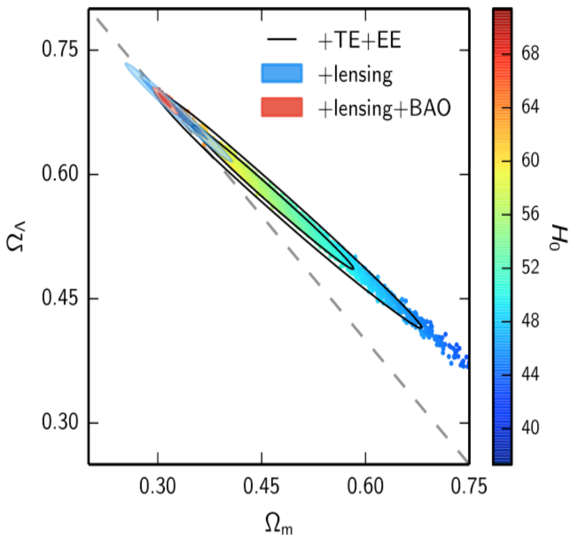


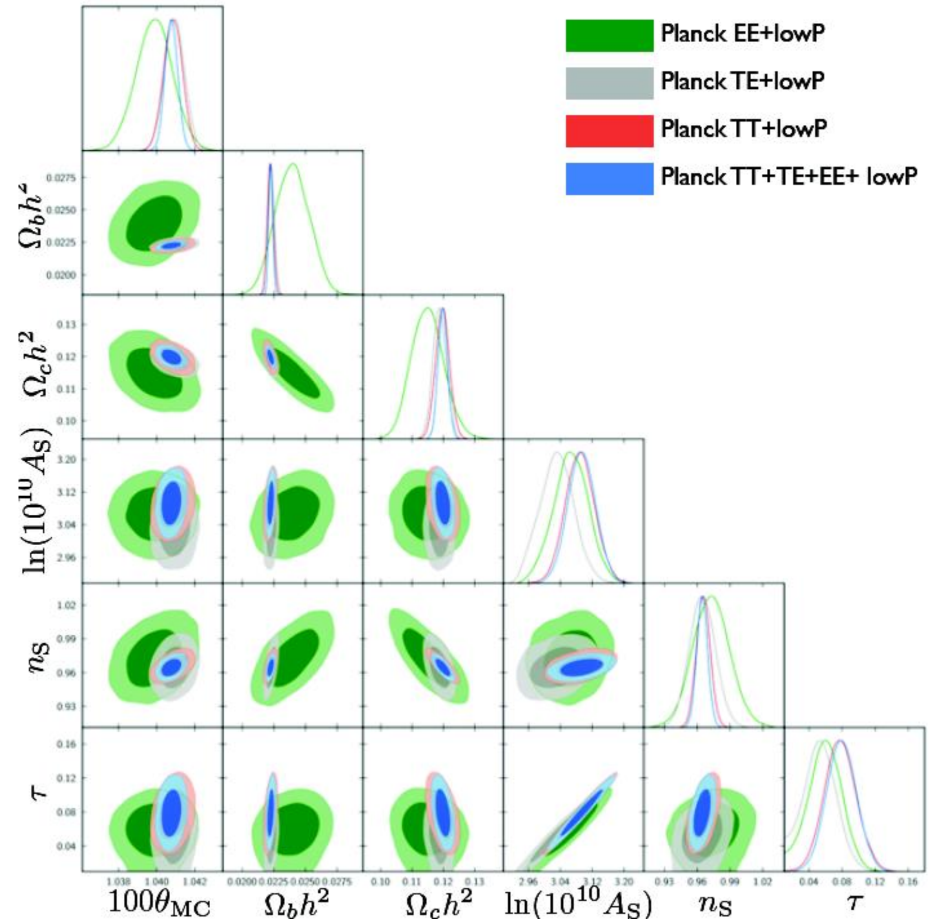




Cosmological parameters







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

Base ΛCDM model = 6 parameters: baryon density, CDM density, Λ, As, ns, tau
Error-bars reduced by a factor 2 when including polarisation in 2015
Tight limits on curvature (<0.005), neutrino mass (<0.194 eV), dark energy equ. state (-1.019), dark-matter annihilation, etc.

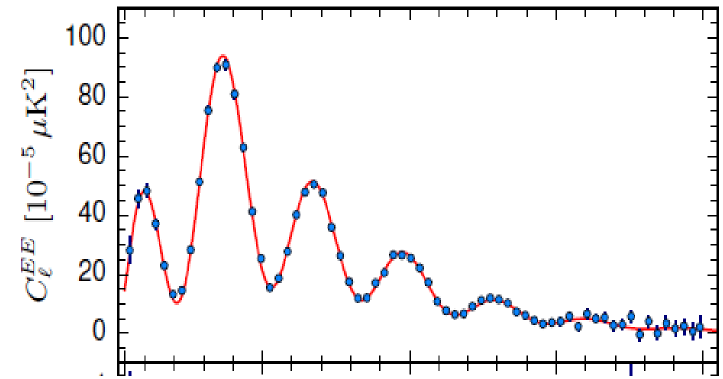
Cosomological parameters

	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

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

Evidence for simple inflationary models

Quantum origin for the primordial density fluctuations.
Simplest inflation predicts:

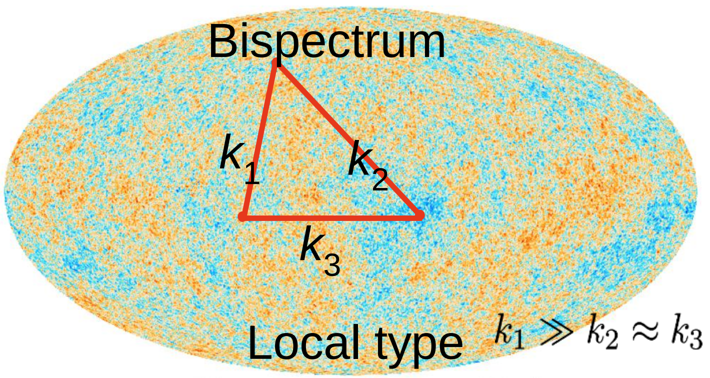


- Flat space → Planck 2015 : curvature ~ -0.004

- Adiabatic fluctuations → Planck 2015

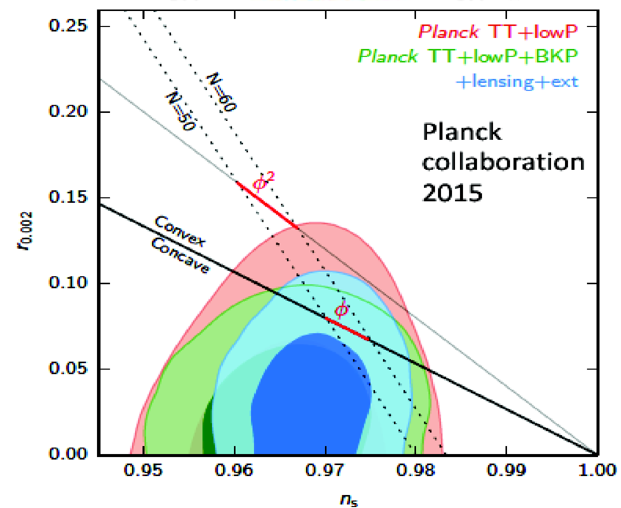
- Nearly Gaussian statistics → Planck 2015

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



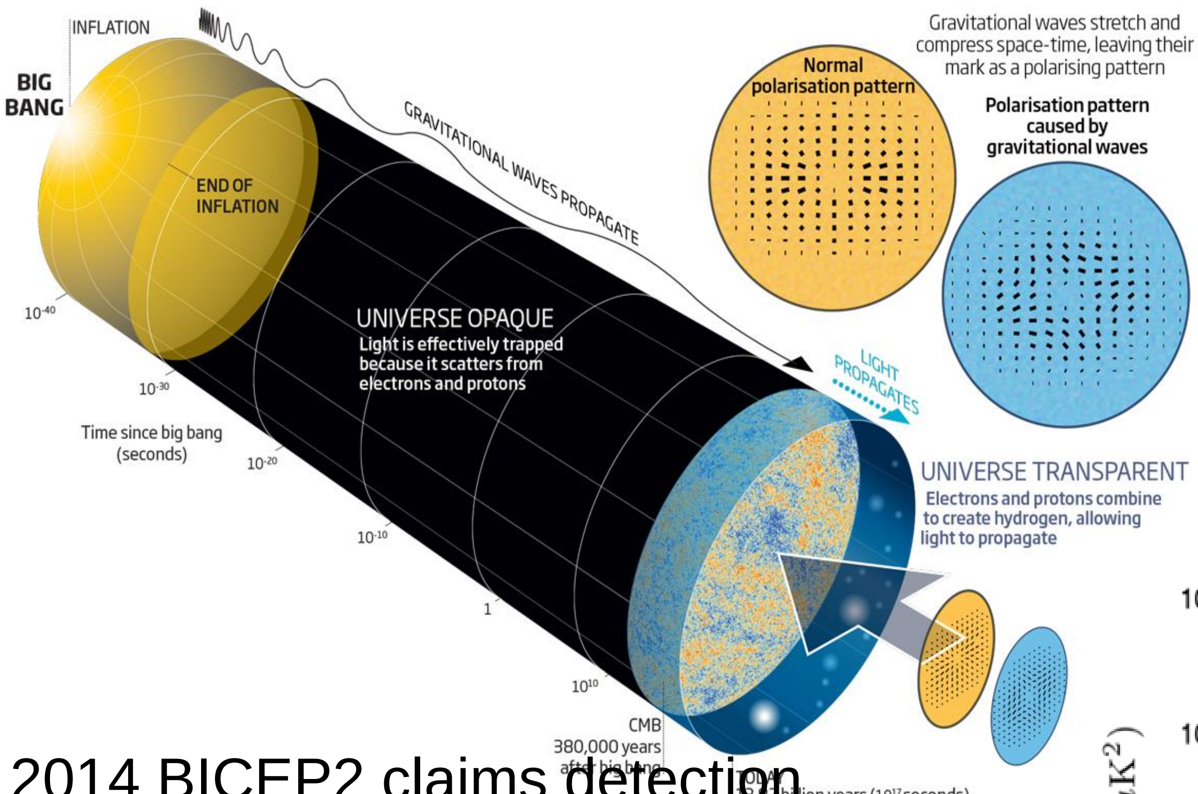
- Deviation from scale invariant initial spectrum (0.96 <ns< 0.97) → Planck 2015 : 0.9645 ± 0.0049

n_s=1 scale invariant spectrum excluded at 7σ
Allowed region for inflation models reduced by 30% w.r.t. 2013 →quadratic models disfavored

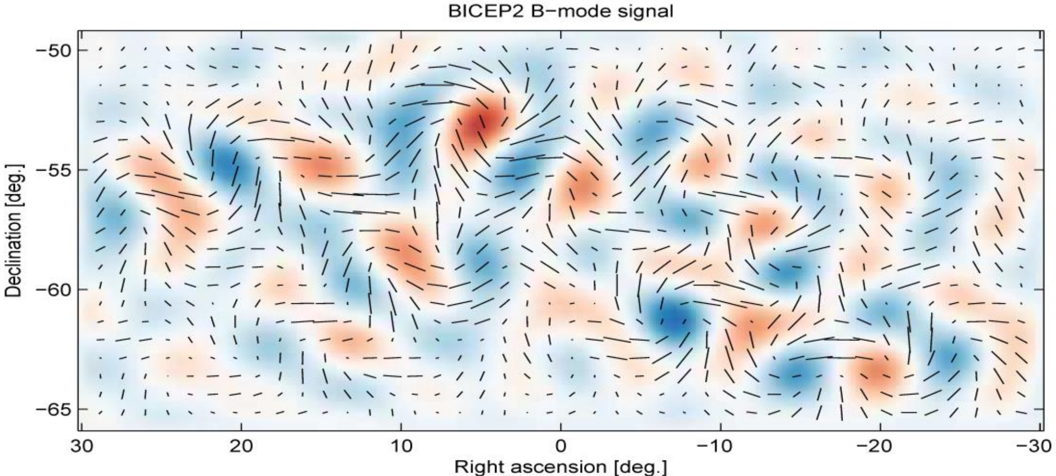


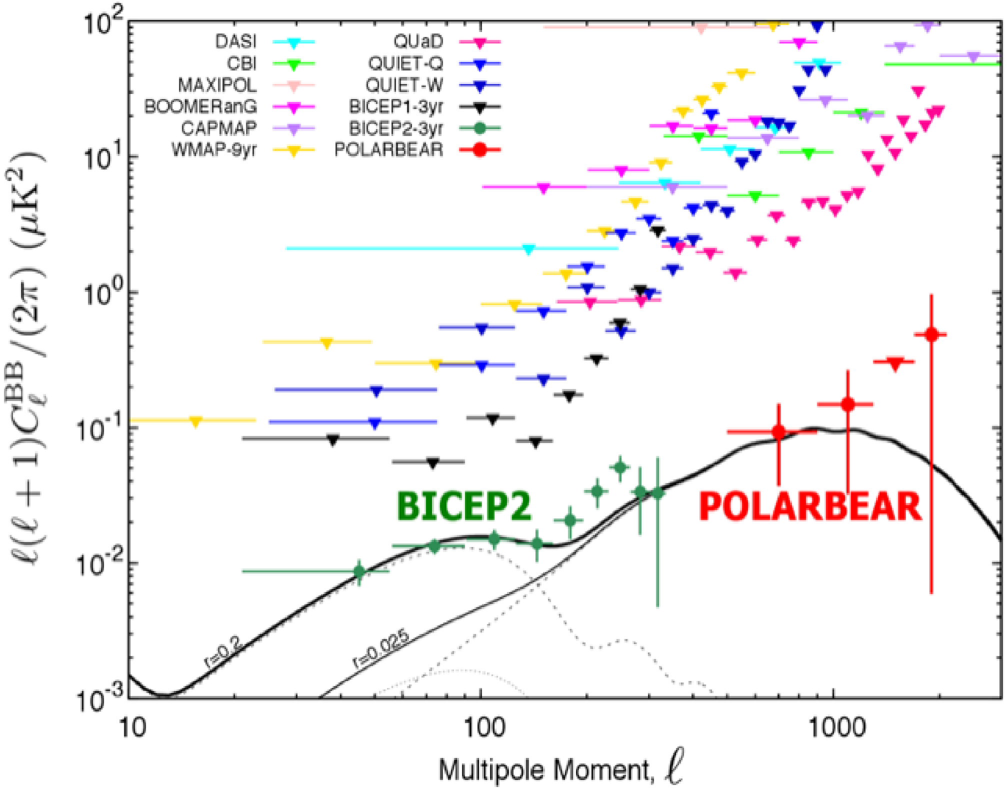
- Production of primordial gravity waves → quest for B-mode polarisation ?

Polarisation and primordial B-modes

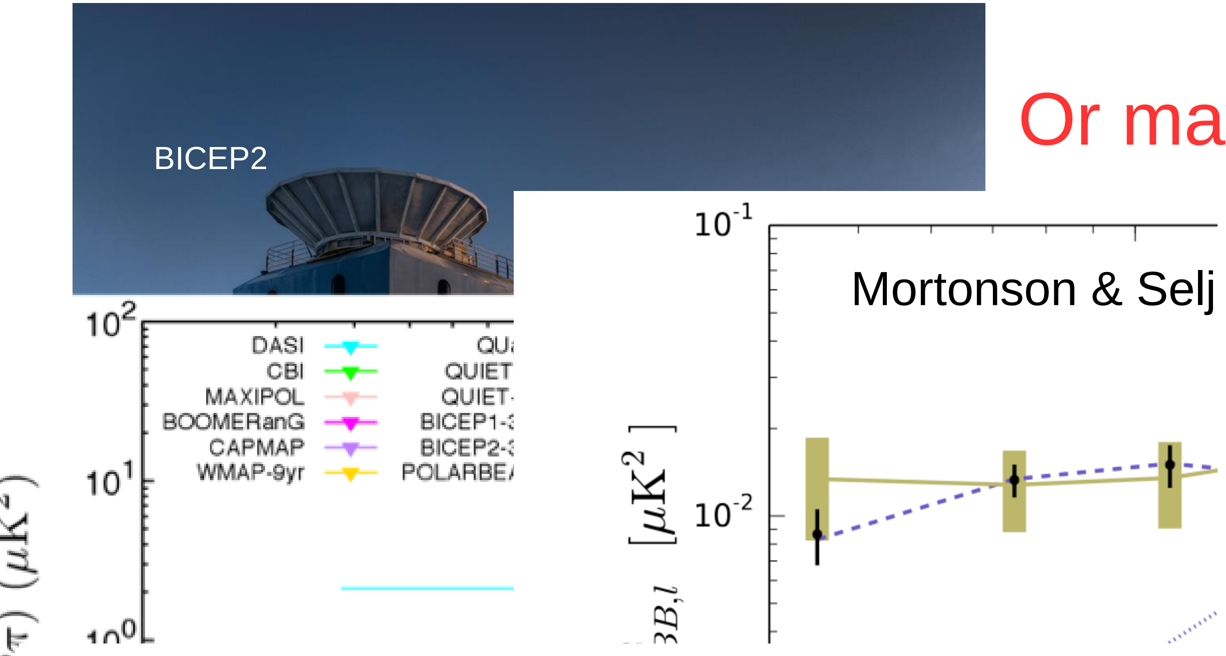


2014 BICEP2 claims detection of primordial B-mode

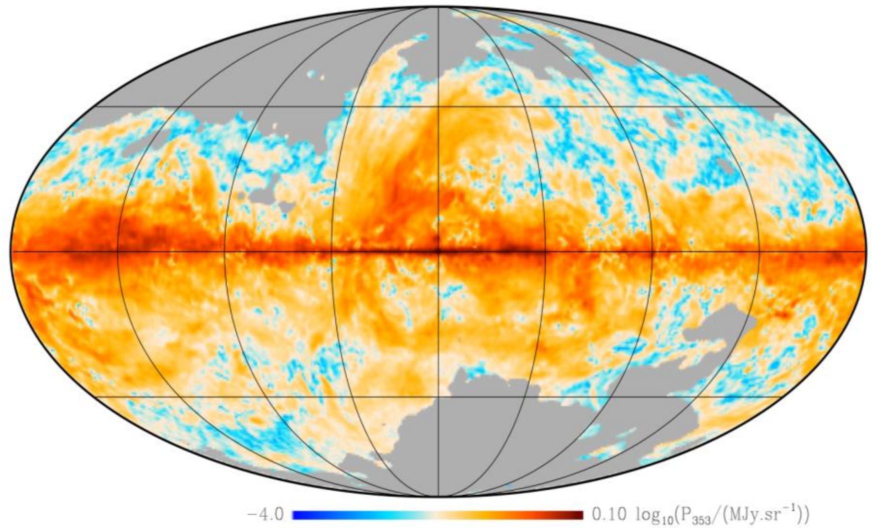


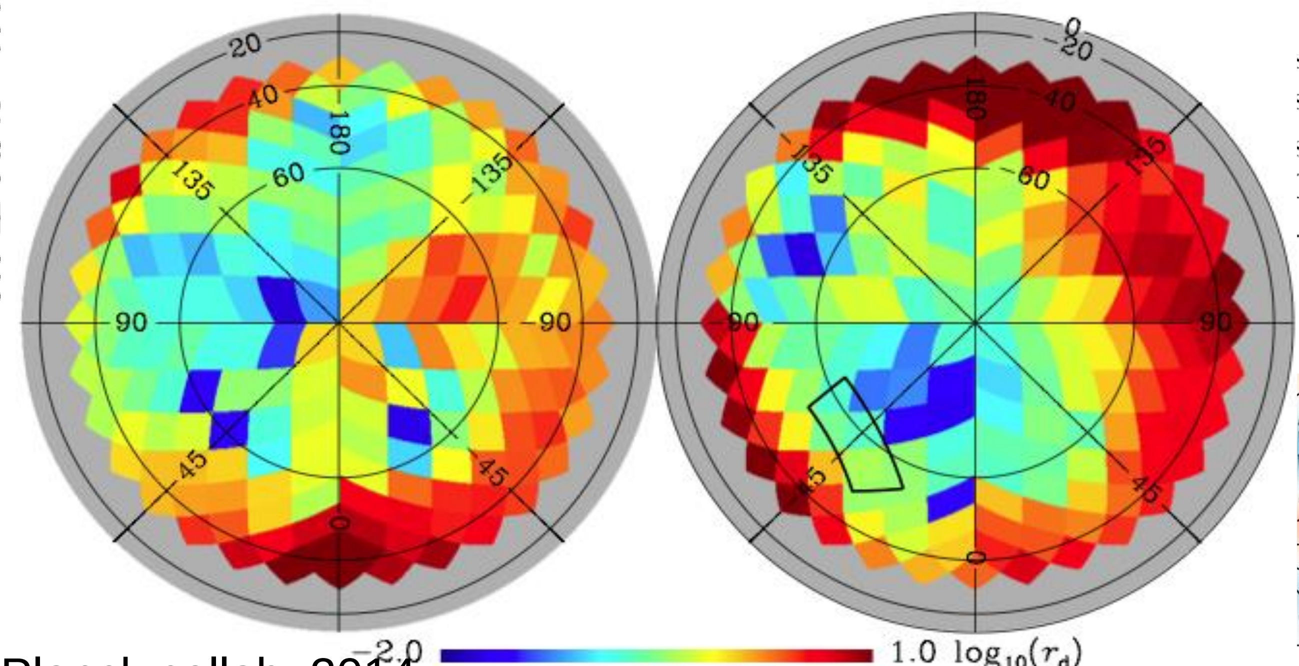


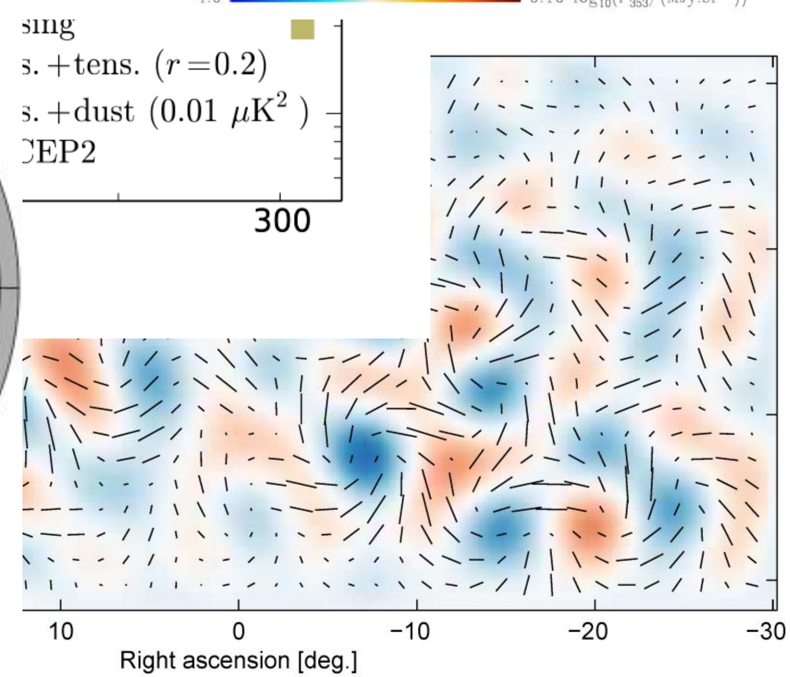
Polarisation and primordial B-modes



Or may be simply galactic dust?



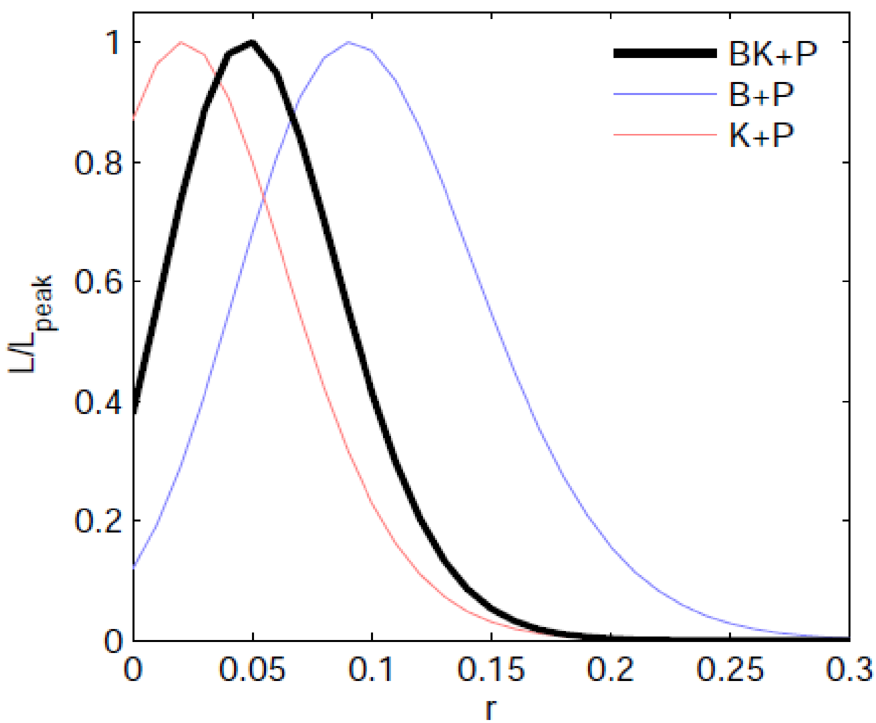


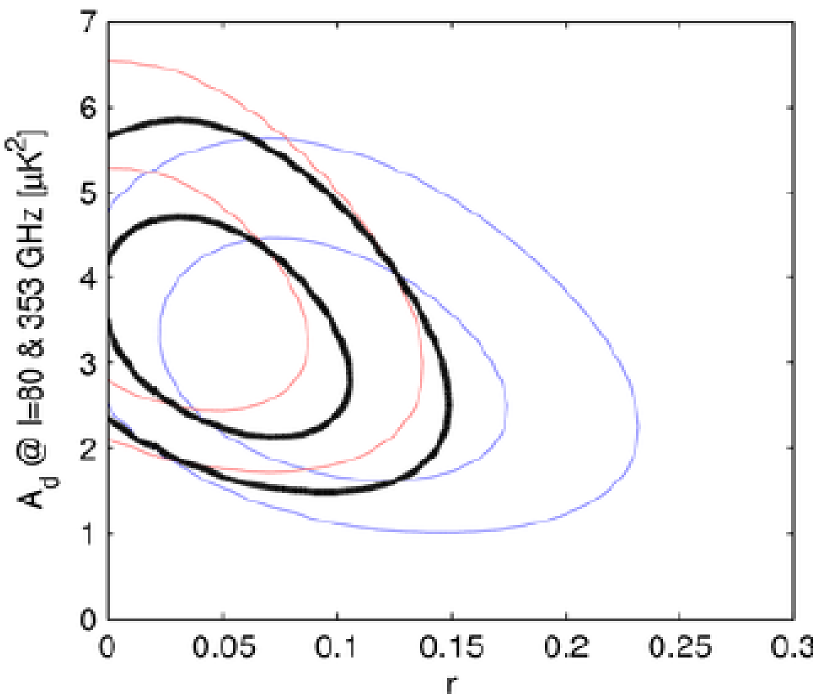


Planck collab. 2014

Polarisation, primordial B-modes, and dust

BICEP2/KECK and Planck collab. 2015





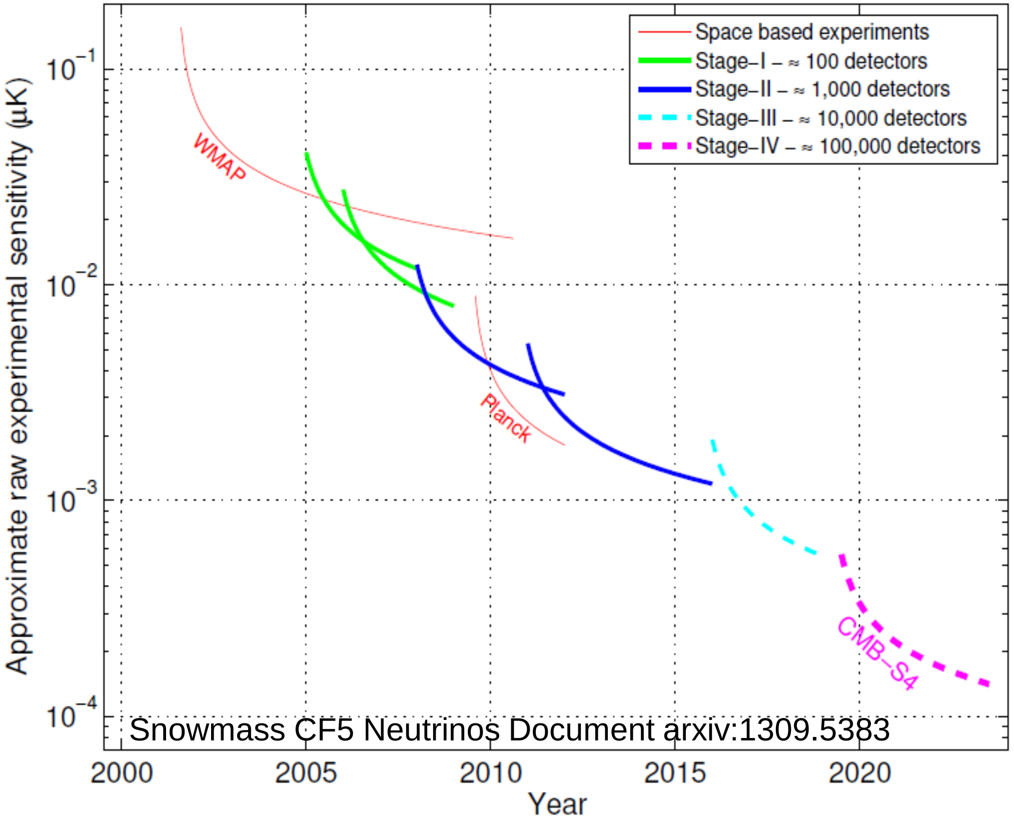
Planck/BICEP2/KECK limit from direct measurement r<0.12
Planck limit from intensity (model dependent) r<0.11

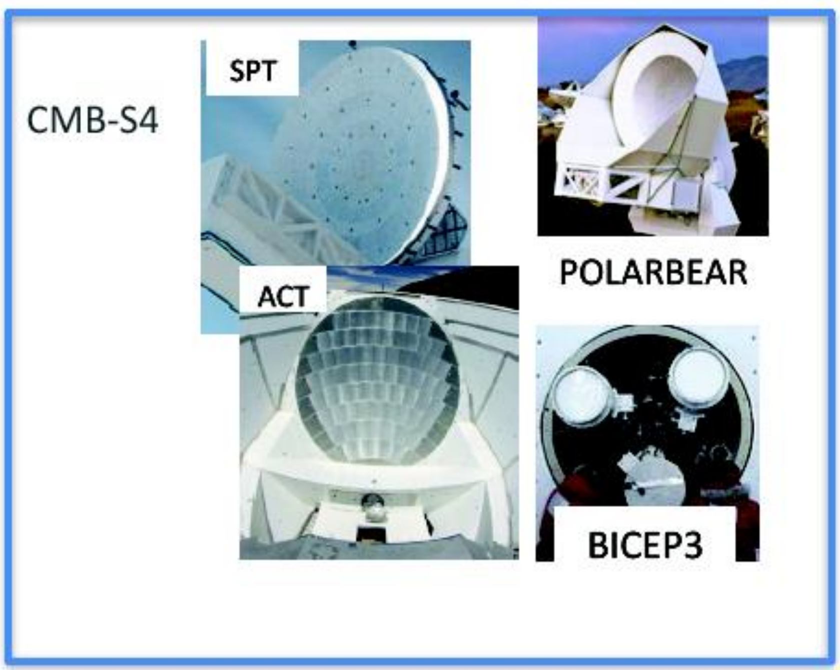
Combined limit r<0.09

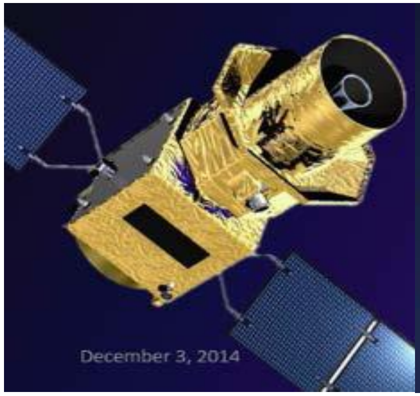
Prospects for CMB polarisation

Polarisation over the whole sky by WMAP and Planck. Beyond need:

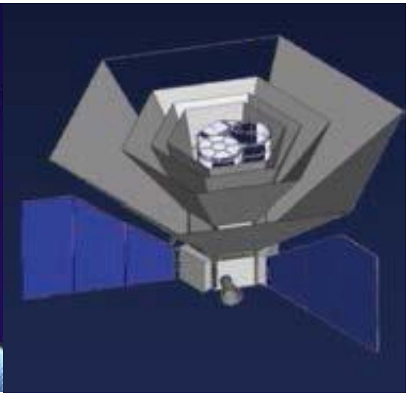
- Higher resolution & sensitivity
- Characterised systematics
- Large angular scales



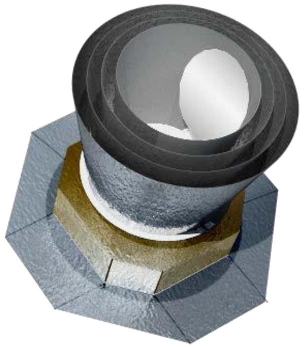




PIXIE (NASA)



LiteBIRD (JAXA)



CORE+ (ESA)

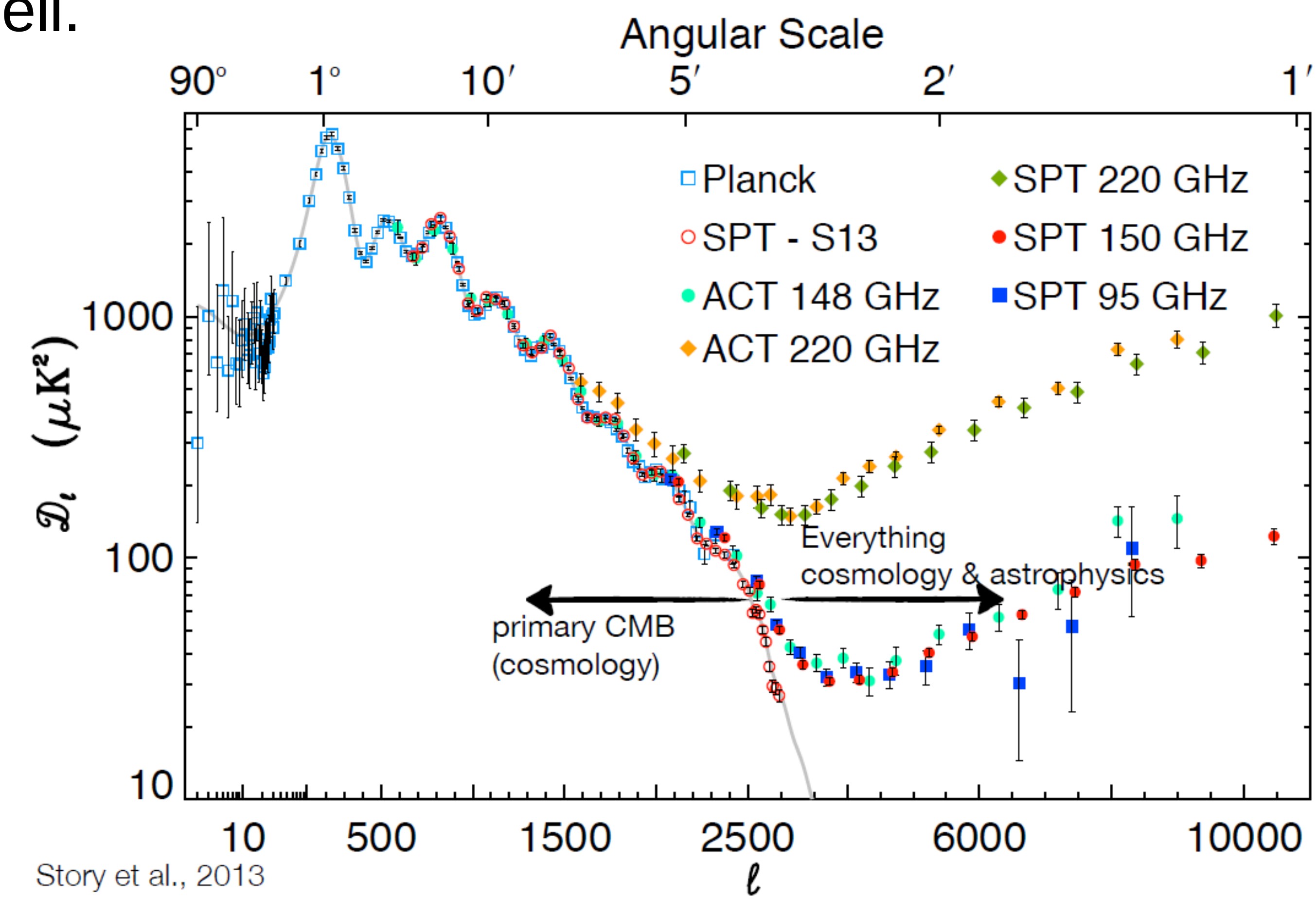
Prospects for CMB temperature

End of primary temperature anistropy era ?

Quest for B-mode polarisation will provide more and better CMB temperature data at high ell.

Cosmology from lensing & from SZ effect (thermal and kinetic)

Main limitation due to foreground, e.g. dusty galaxies



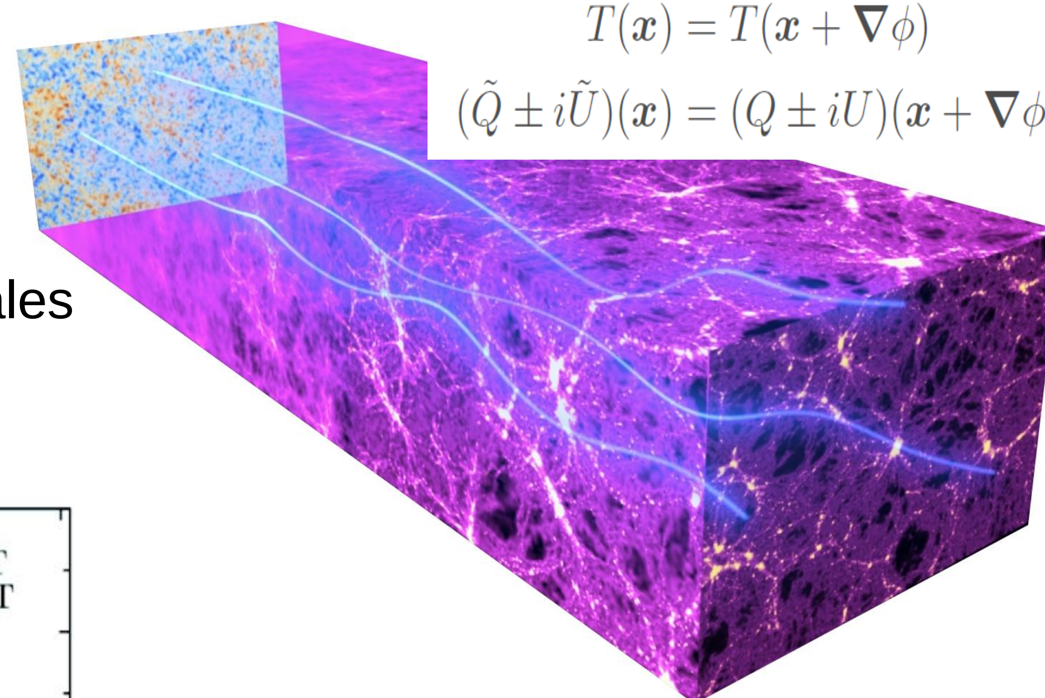
Story et al., 2013
George et al., 2014
Das et al., 2014

CMB Lensing

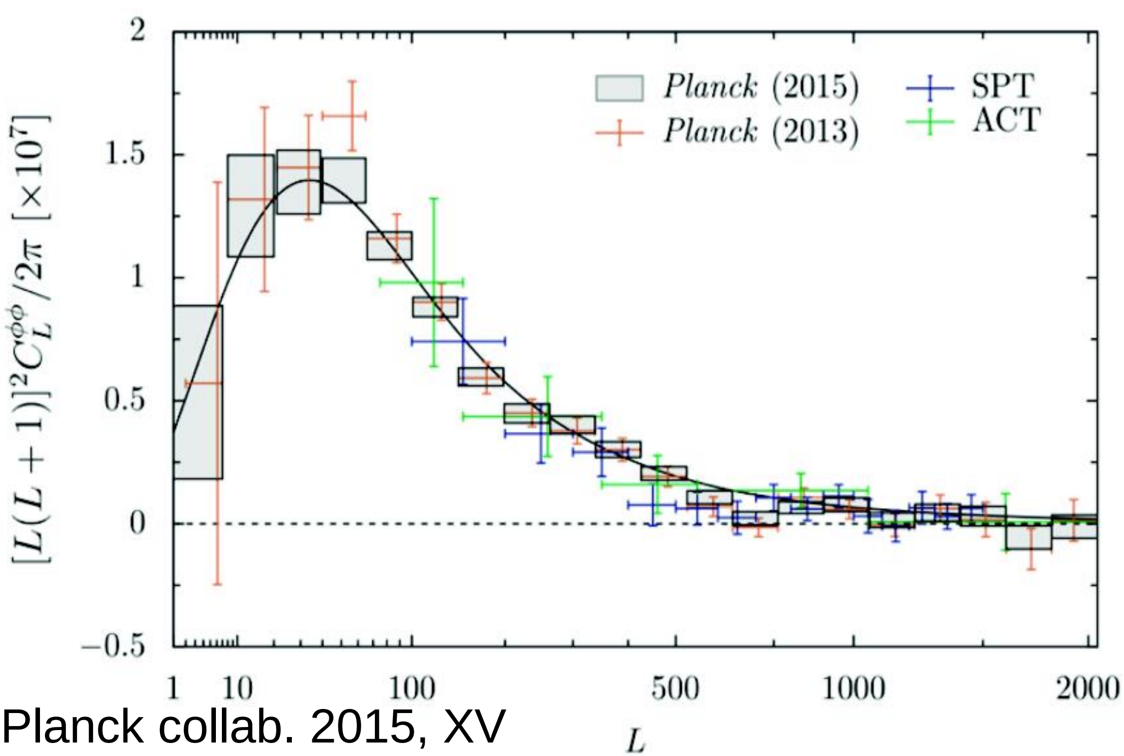
Weak lensing from LSS @z~2 → integrated mass along line of sight
small variation of CMB anisotropies
Typical deflection: 2.5'

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

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



Smooths TT, TE and EE power
Generates TT, TE, EE power at arcmin scales
Generates B-modes from E-modes

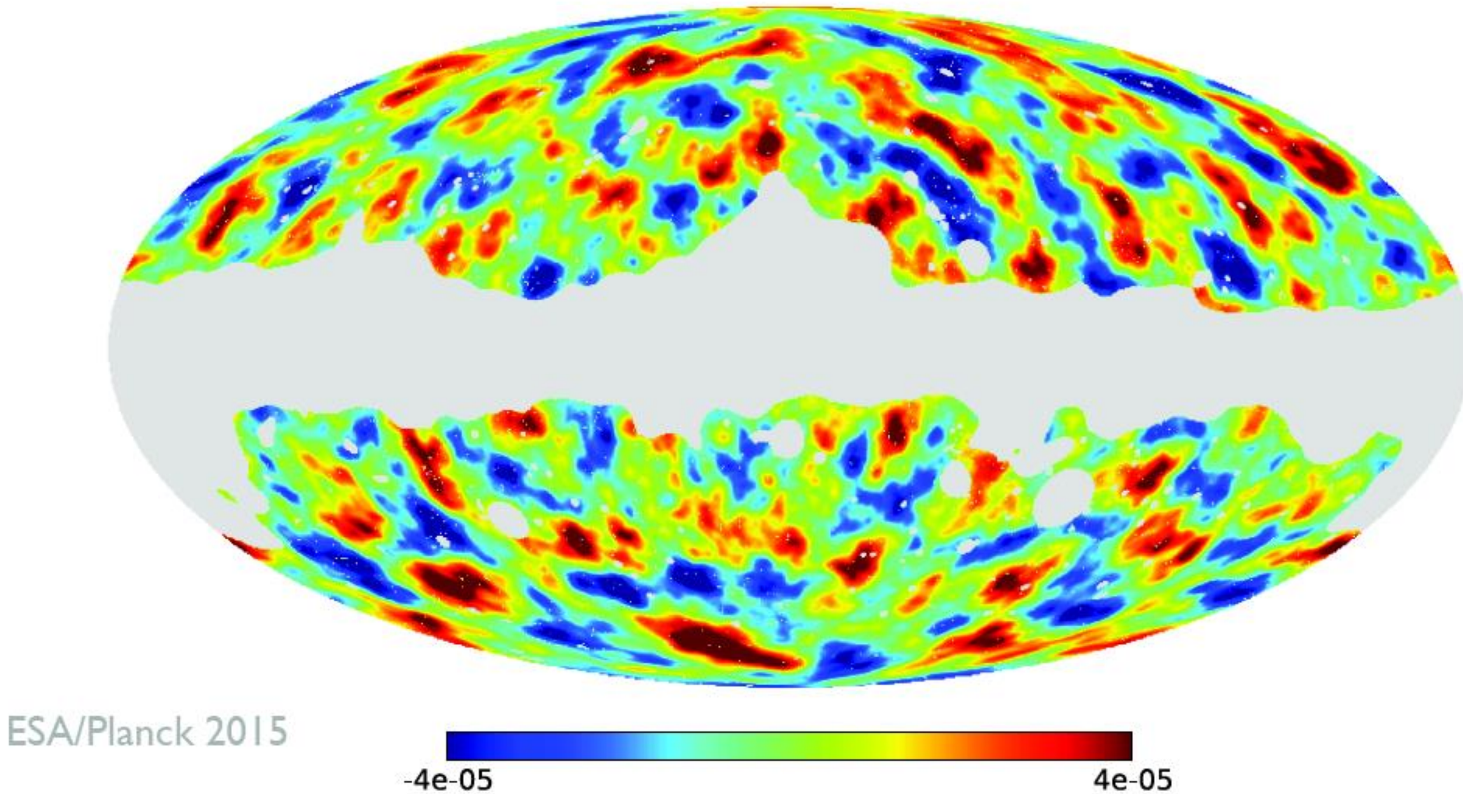


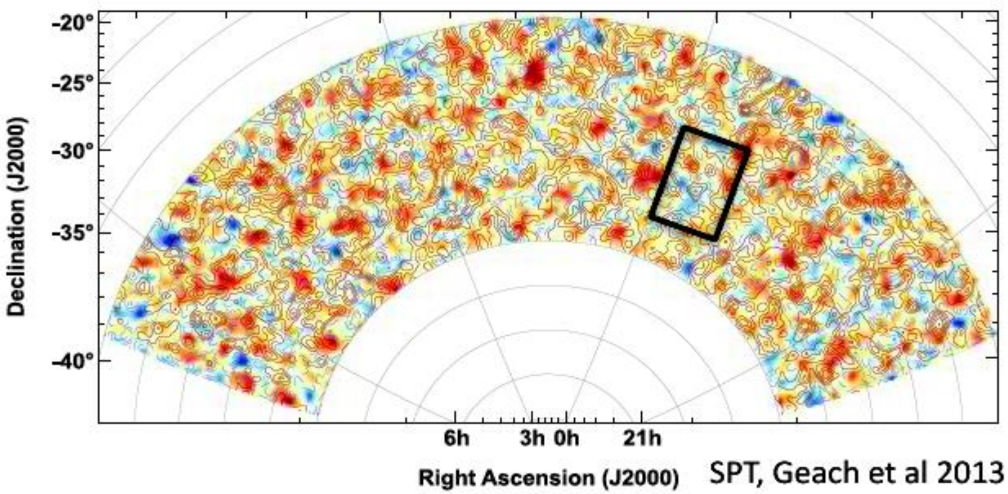
Planck collab. 2015, XV

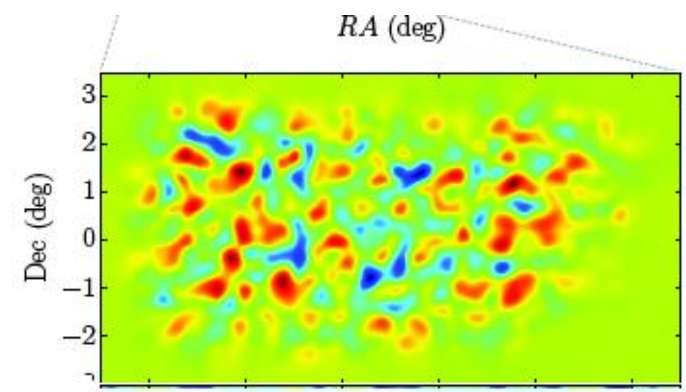
CMB lensing measurement at 40σ over 70% of the sky with Planck

Amplitude constrained to 2.5%
Error-bars improved by factor ~2

Reconstructed projected mass map





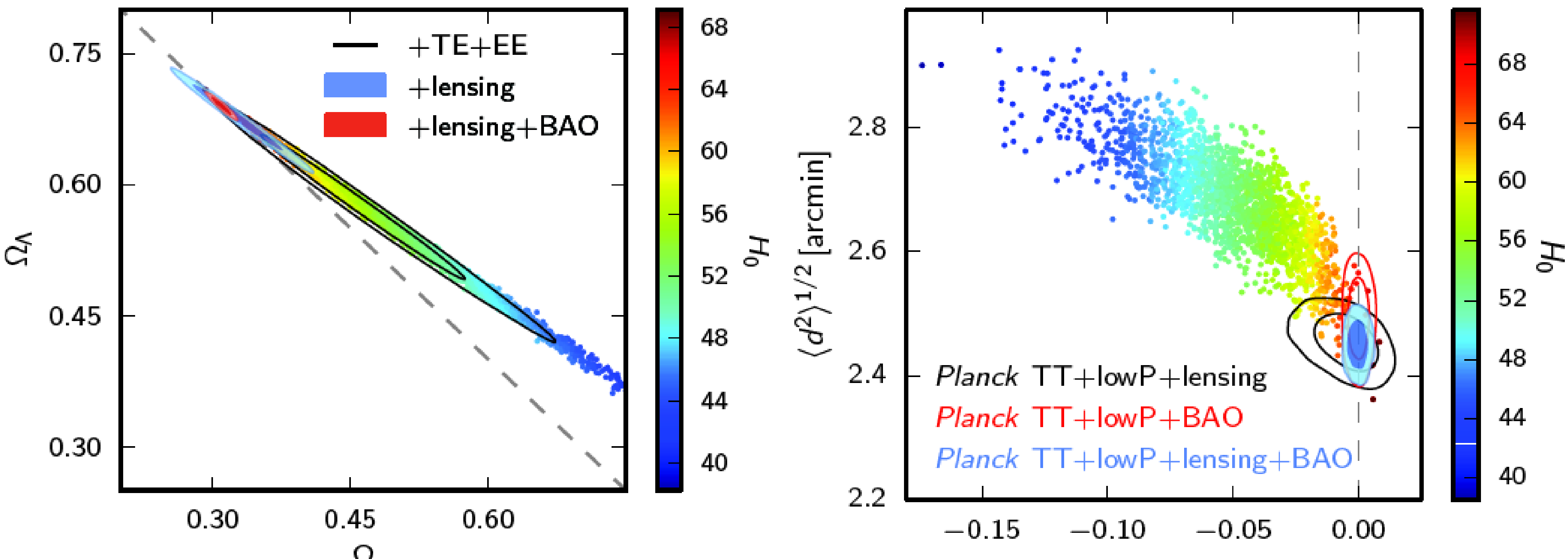


ACTPol, Allison et al 2015

CMB Lensing

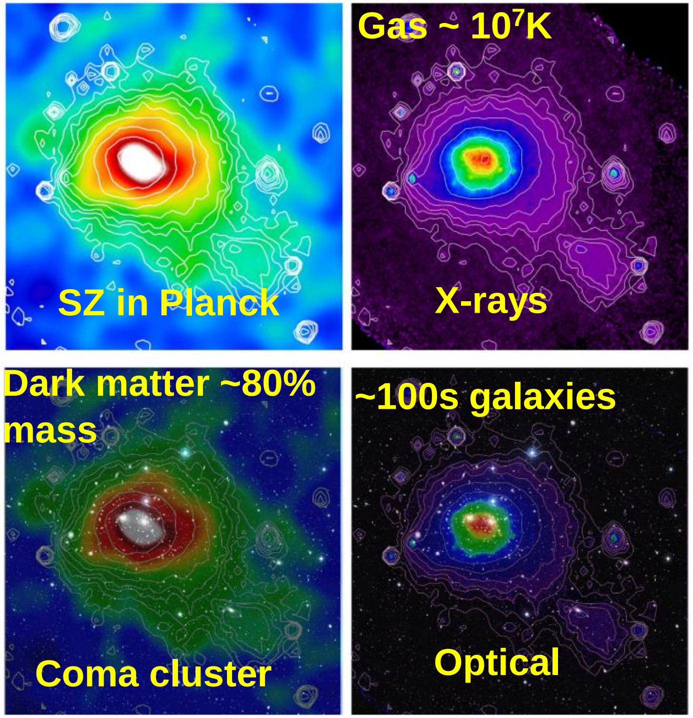
Lensing probes clustering of matter and growth rate it helps breaking degeneracy in CMB
Give access to neutrino mass, curvature, dark energy
Complements LSS surveys to probe further dark energy

Lensing limits curvature to <2% and neutrino mass to <0.7eV

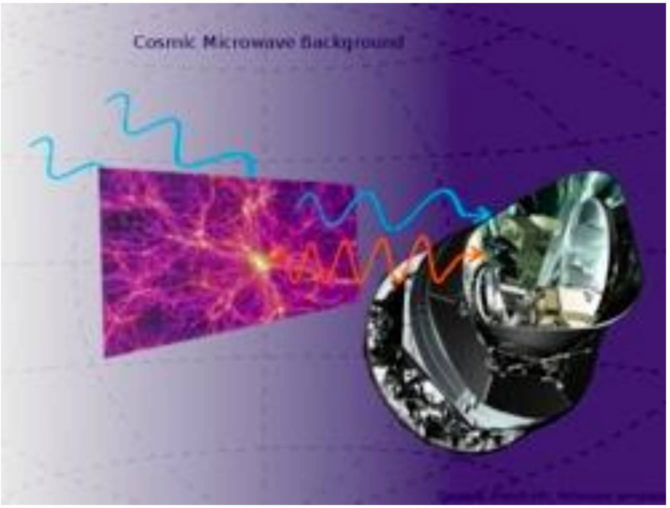


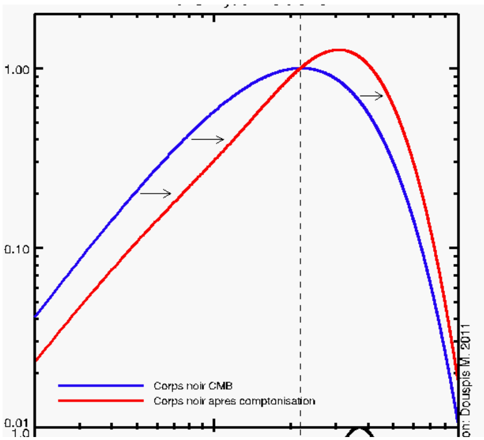
ESA/Planck 2015

Sunyaev-Zeldovich effect in Clusters

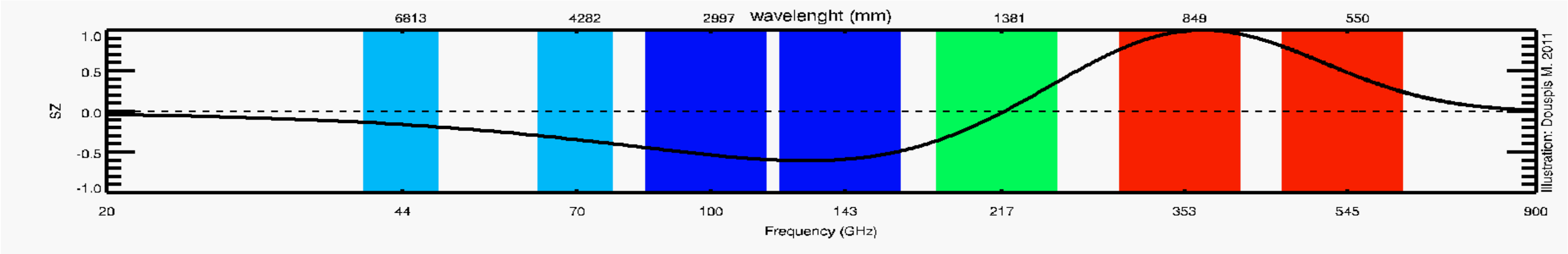


Inverse Compton distortion = Sunyaev-Zeldovich effect





Blind and simultaneous measurement of "positive" and "negative" SZ effect



SZ Frequency dependence on stacks of clusters from *Planck*

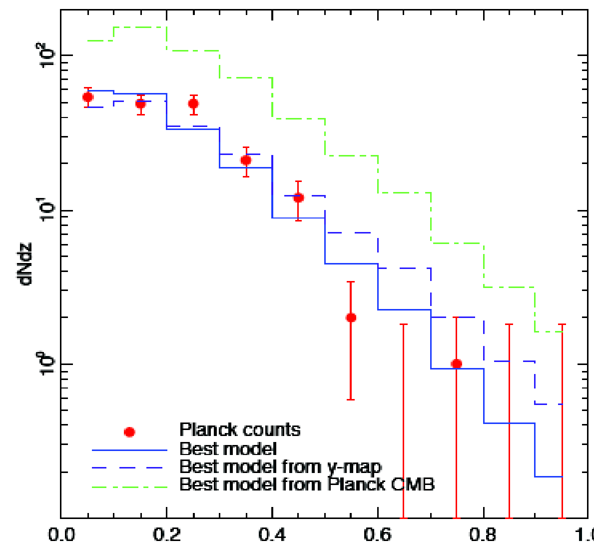
SZ effect: Cosmology with clusters

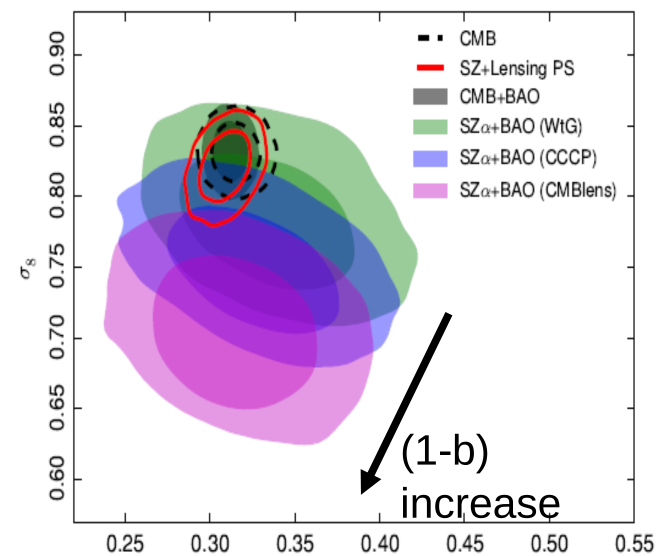
Tracing the growth of structure with clusters →Tension between Planck predictions from CMB cosmology and measured cluster counts: Hints of new physics or mass calibration issue ?

$$\bar{Y}_{500} \propto (M^{X}_{500})^{\alpha} \propto [(1-b)M_{500}]^{\alpha}$$

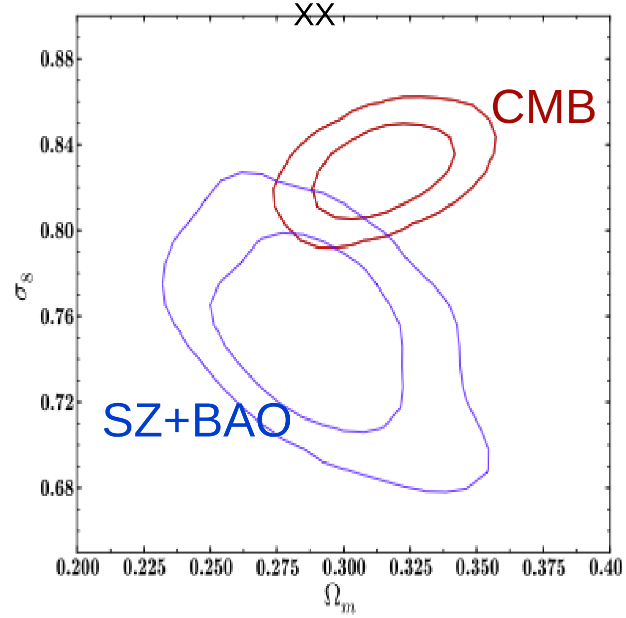
$$M_{X} = (1-b)M$$

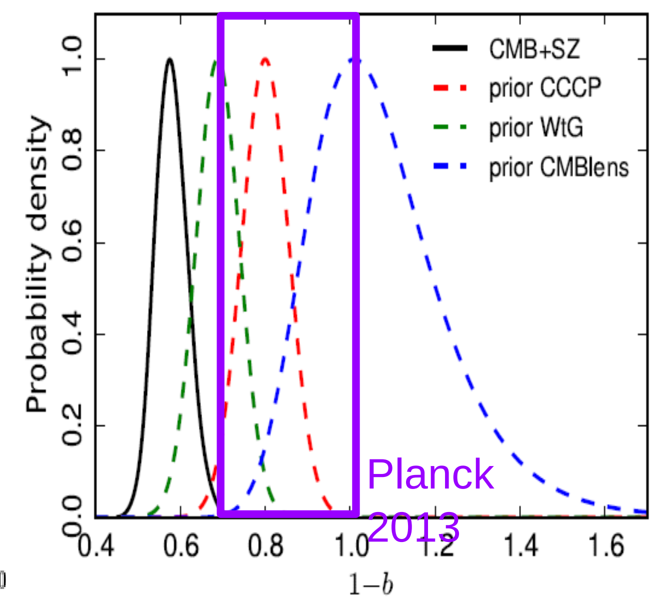
Powerful means of mass calibration: lensing, CMB lensing





Planck collab. 2013, XX





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 potntial, etc.)

- CMB polarisation anisotropies measured oved whole sky

E-mode limited by systematics → progress expected from Planck

ACTpol & SPTpol will cover small scales

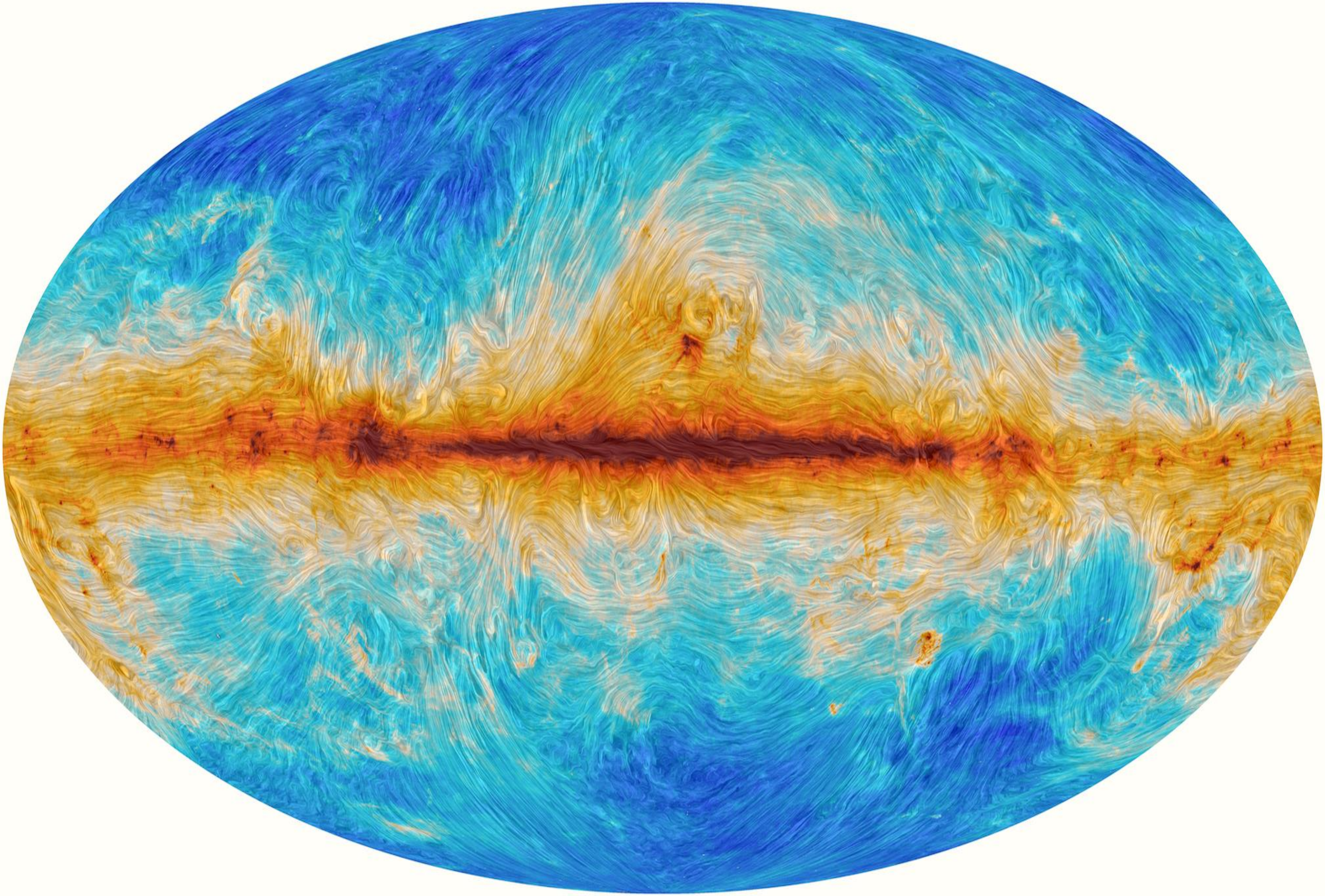
- B-mode from lensing now detected (BICEP2, POLARBEAR, Planck, SPTpol)

- B-mode @large scales limits r<0.09 (Plank/BICEP2/Keck)

Many planned projects

Ultimate measurement may be limited by foregrounds

- Base ΛCDM model constinues to be a good fit to CMB data including polarisation



Thank you