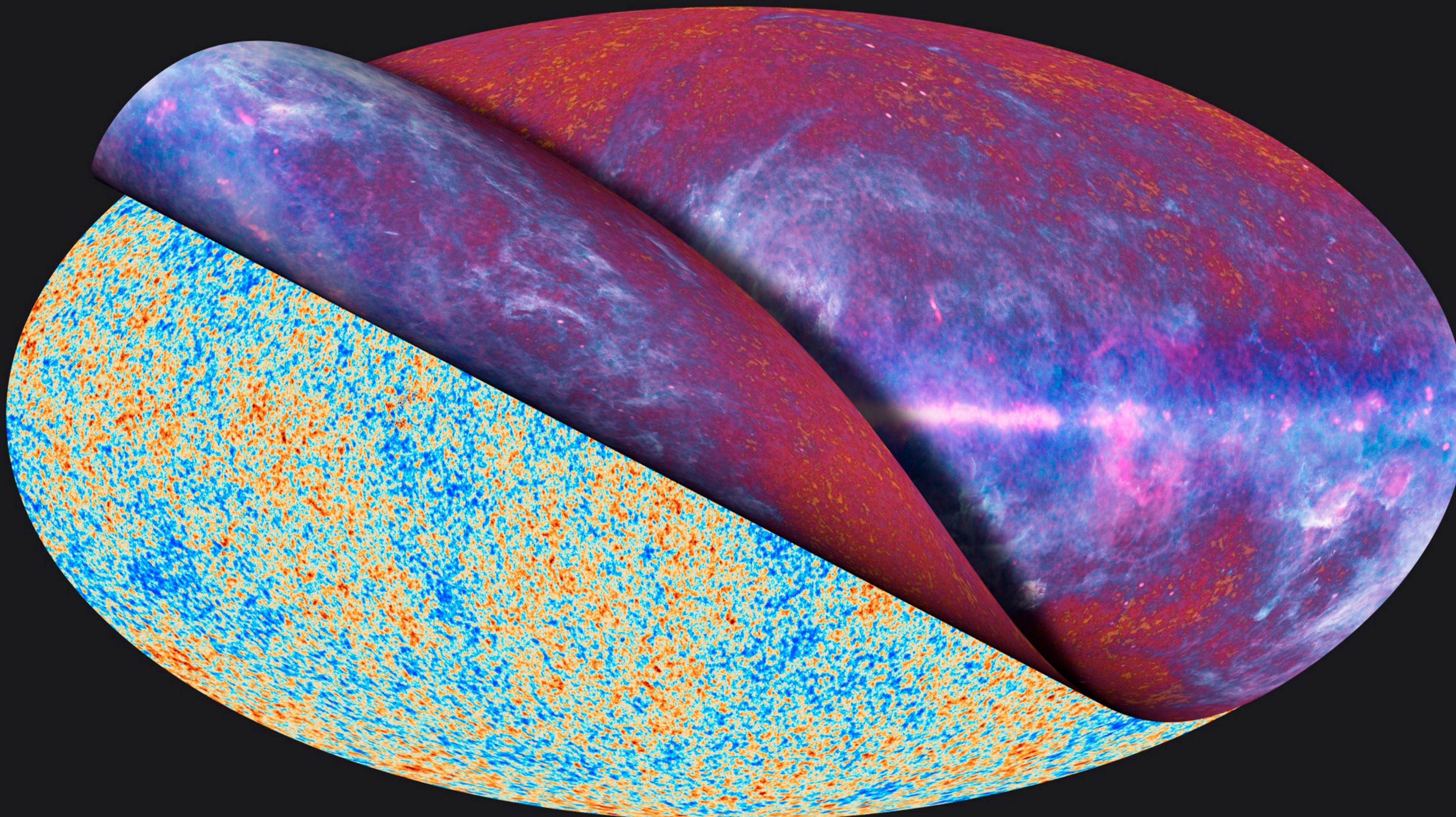


Planck: a selection of the 2015 results

Céline Combet (LPSC)

CPPM, 20/04/2015

1. A quick introduction to the CMB: intensity and polarisation

2. From satellite to channel maps

3. A selection of Planck's 2015 cosmological results

- Component separation: finding the CMB among other things
- Spectra and parameter estimation
- Lensing
- The search for primordial B-modes

4. Conclusions

Cosmological model

- **Cosmological principle**: the universe is homogeneous and isotrope (on large scales)

  → Friedmann-Roberston-Walker metric

$$ds^2 = -dt^2 + a^2(t)\left[\frac{dr^2}{1-\kappa r^2} + r^2\left(d\theta^2 + sin^2\theta d\phi^2\right)\right]$$

scale factor; curvature

- **General relativity** to describe large-scale evolution

  → Friedmann-Lemaître equations

Hubble parameter; energy density; cosmological constant [dark energy]

$$\left(\frac{\dot{a}}{a}\right)^2 = H^2 = \frac{8\pi G\rho}{3} - \frac{\kappa}{a^2} + \frac{\Lambda}{3},$$

$$\frac{\ddot{a}}{a} = -\frac{4\pi G}{3}(\rho + 3p) + \frac{\Lambda}{3}$$

$$\Omega = \frac{\rho}{\rho_c} = \Omega_c + \Omega_b + \Omega_\gamma + \Omega_\nu$$

$$\Omega_\kappa = -\frac{\kappa}{a^2H^2}$$

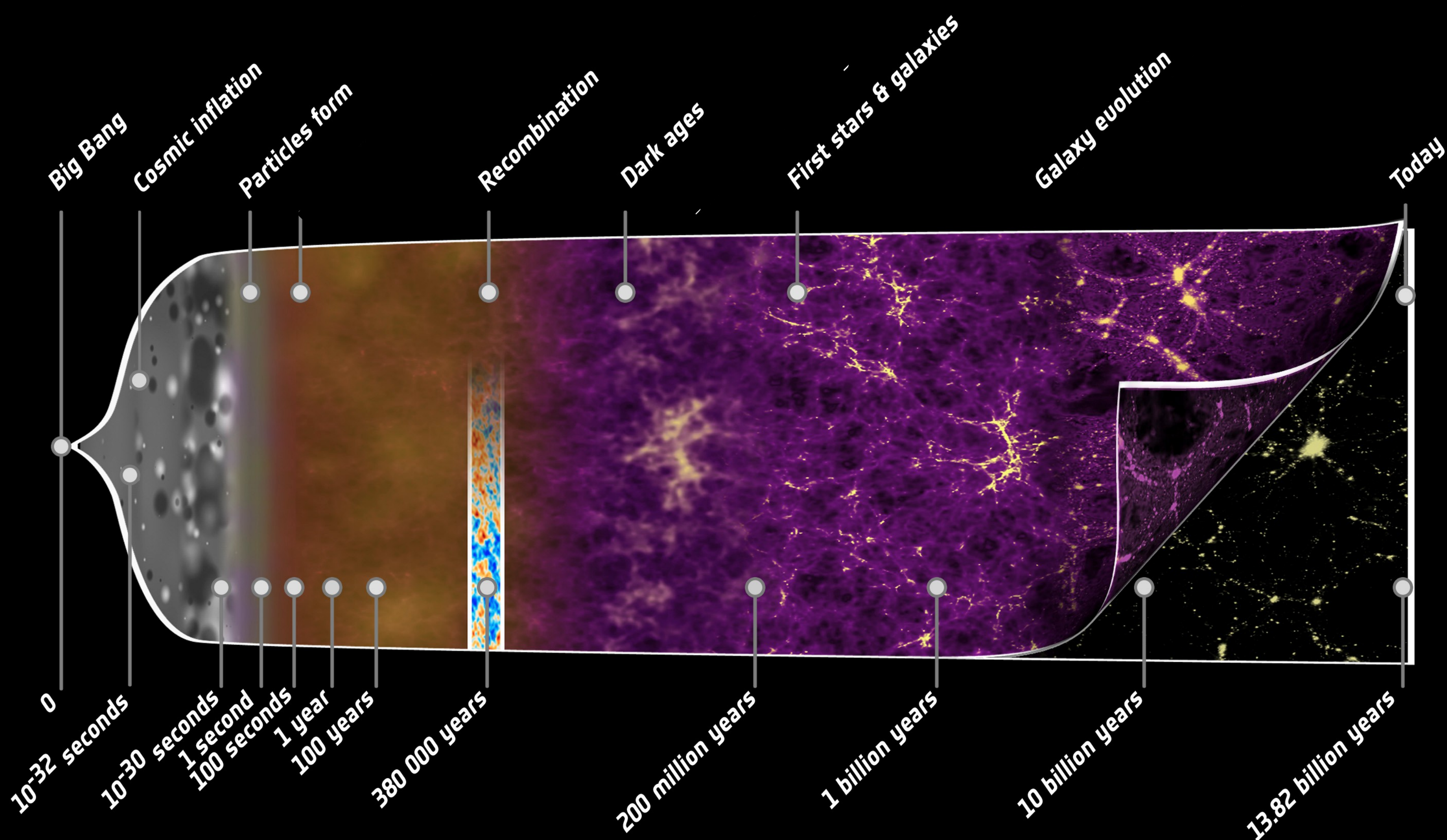
$$\Omega_\Lambda = \frac{\Lambda}{3H^2}$$

$$1 - \Omega_\kappa = \Omega_\Lambda + \sum_i \Omega_i$$

Expansion from hot and dense primordial universe → Big Bang model

Big Bang model alone has issues → Big Bang + Inflation model

The history of the universe



Observations→ΛCDM concordance model

Several independent methods, probing different epochs

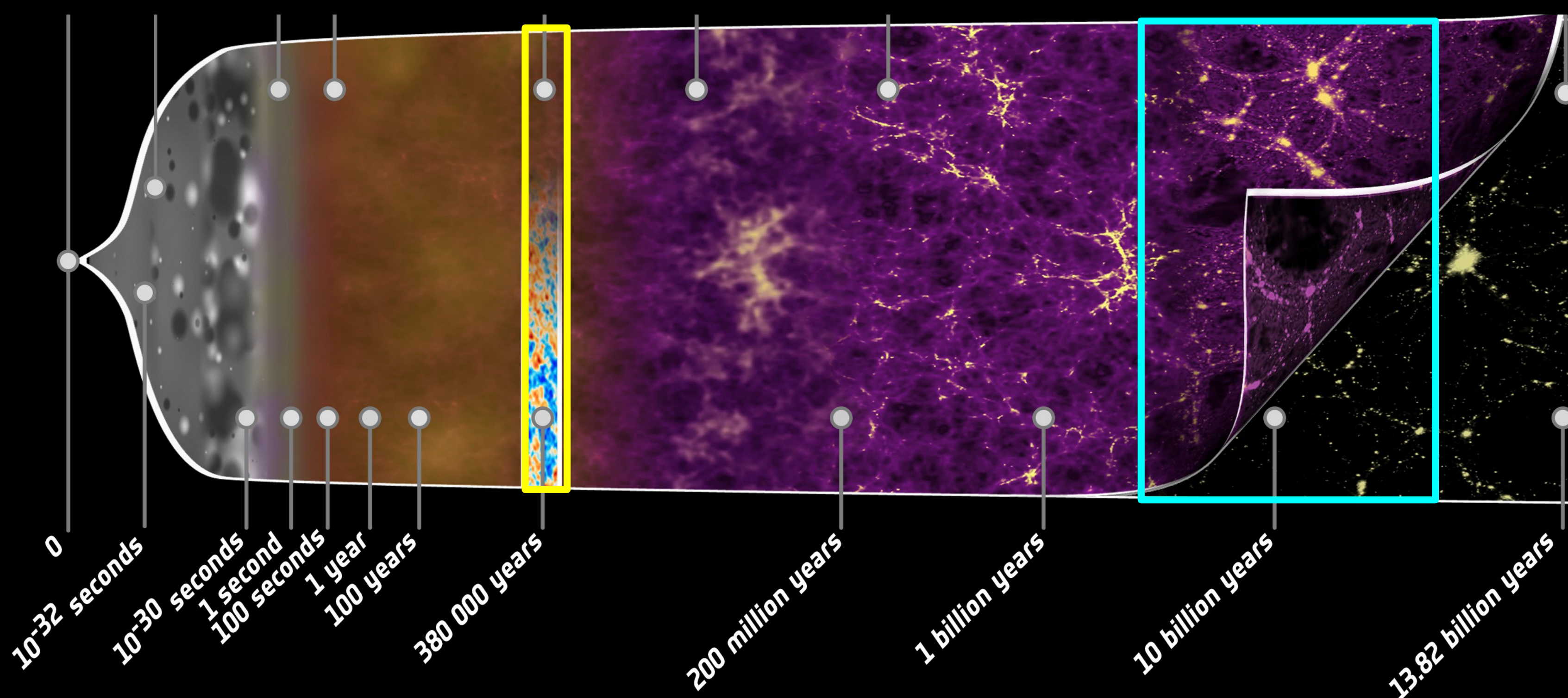
Flat universe, 68% dark energy, 27% dark matter, 5% baryons

- Baryon Acoustic Oscillations (standard ruler)
- Supernovae (standard candles)
- Galaxy counts

$0.1 < z < 1\text{-}2$

CMB experiments

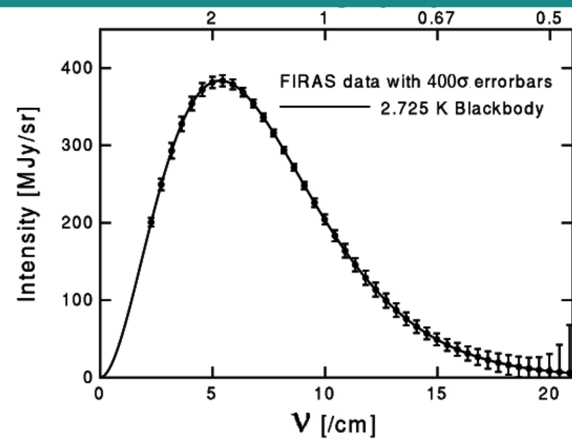
$z \sim 1100$

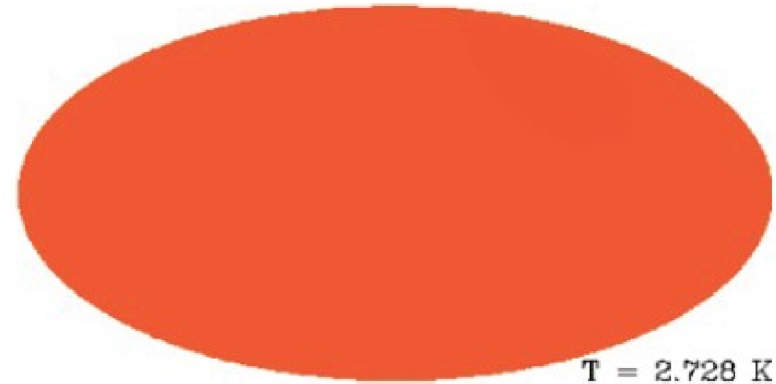


Cosmic Microwave Background

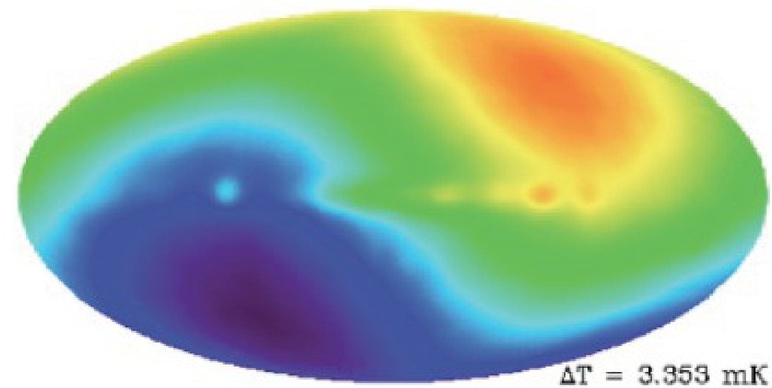
Isotropic blackbody radiation

T = 2.73 K

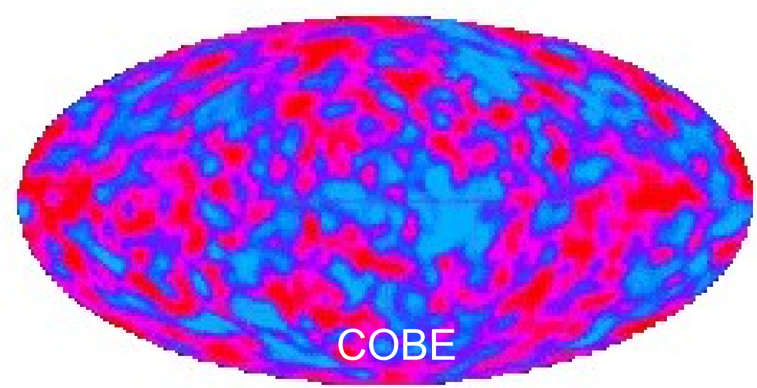




Dipole anisotropy due to solar system movement in CMB reference frame → $T/T \sim 10^{-3}$



Anisotropies due to primordial density fluctuations → $T/T \sim 10^{-5}$



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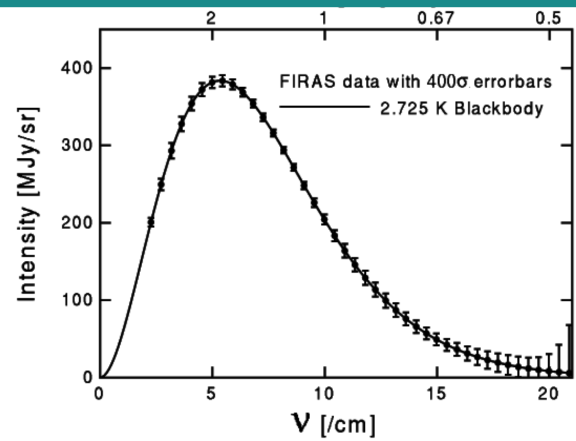

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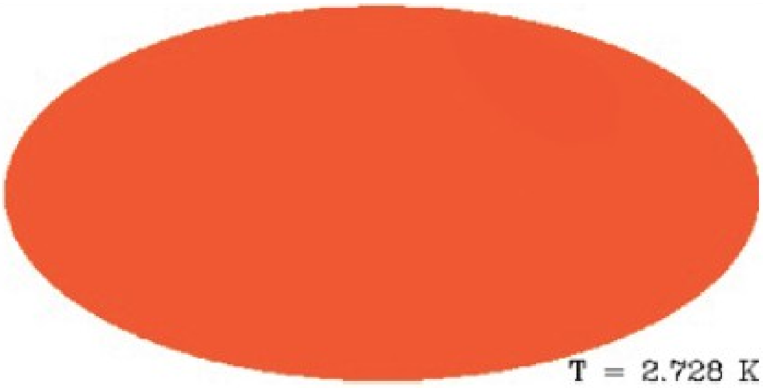

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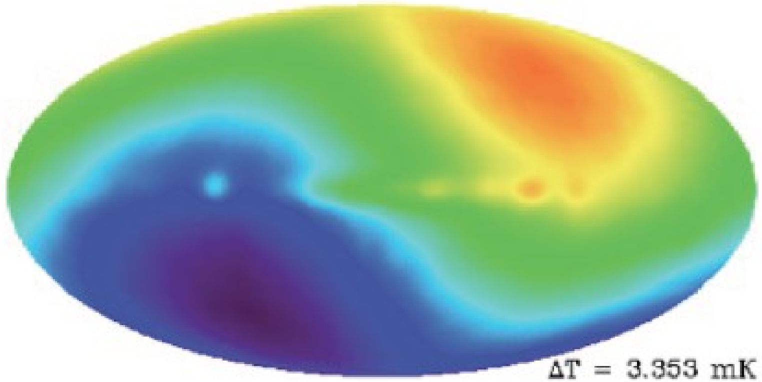

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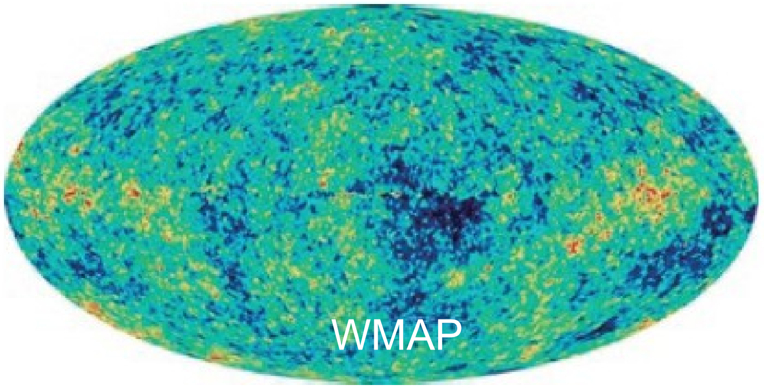

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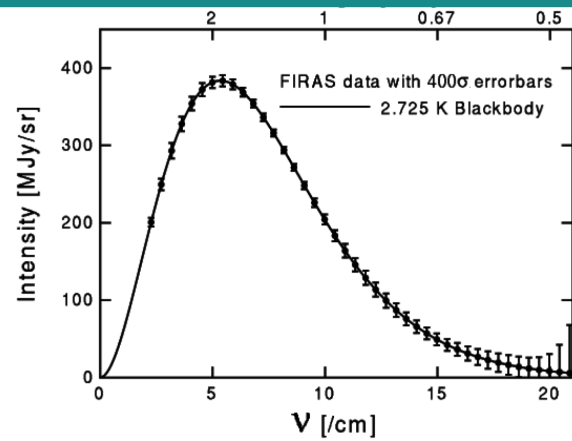

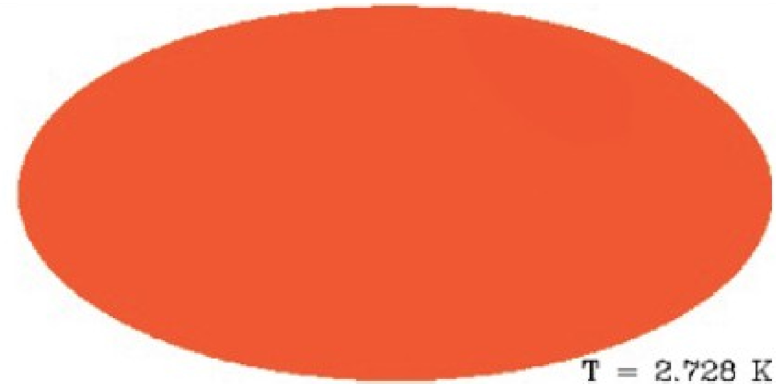

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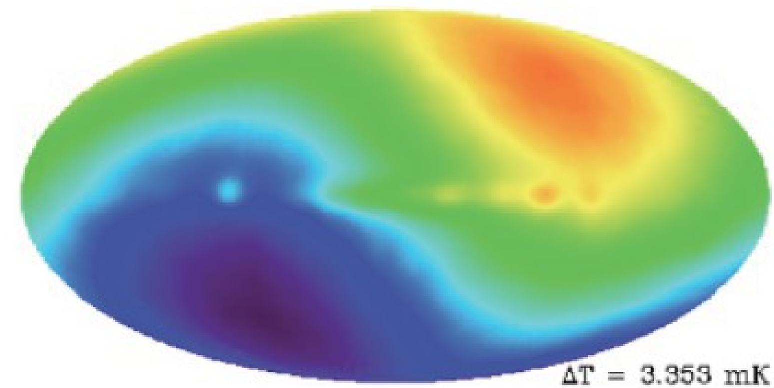

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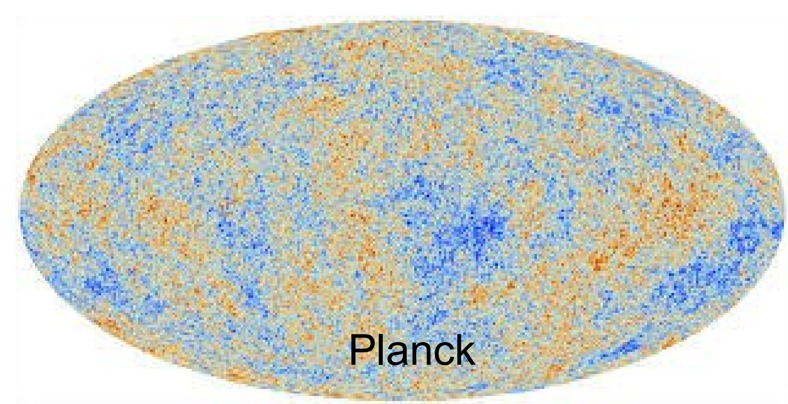
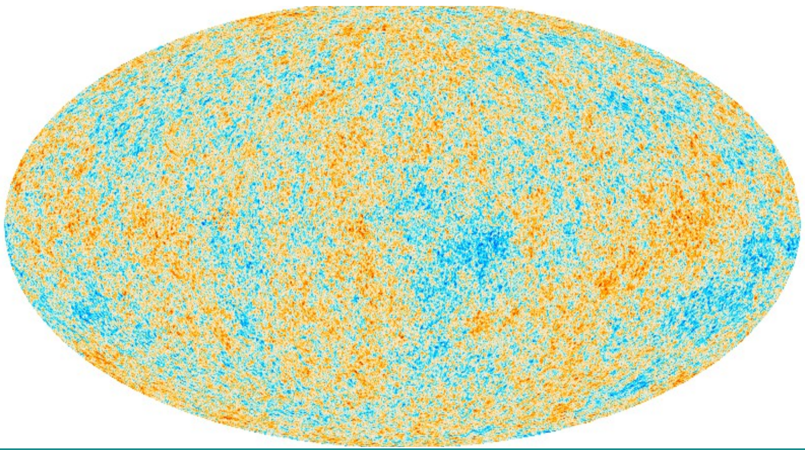


CMB temperature analysis

1. Map of CMB anisotropies

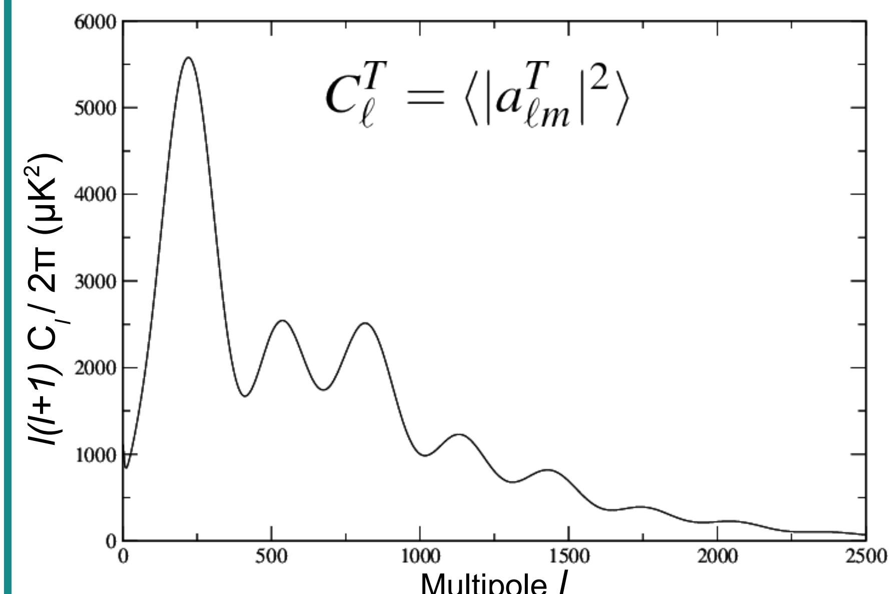


2. Spherical harmonics decomposition

$$\frac{\Delta T}{T} = \sum_{\ell=0}^{\infty} \sum_{m=-\ell}^{\ell} a_{\ell m}^T Y_{\ell m}$$

$$a_{\ell m}^T = \int \frac{\Delta T}{T}(\vec{n}) Y_{\ell m}^{\star}(\vec{n}) d\vec{n}$$

3. Power spectrum



4. Cosmological parameter estimation

Spectrum sensitive to cosmological parameters, e.g.

Curvature Ω_κ

Matter content Ω_b, Ω_c

Reionisation optical depth

Primordial perturb. spectrum $P(k) = A_s \left(\frac{k}{k_0}\right)^{n_s - 1}$

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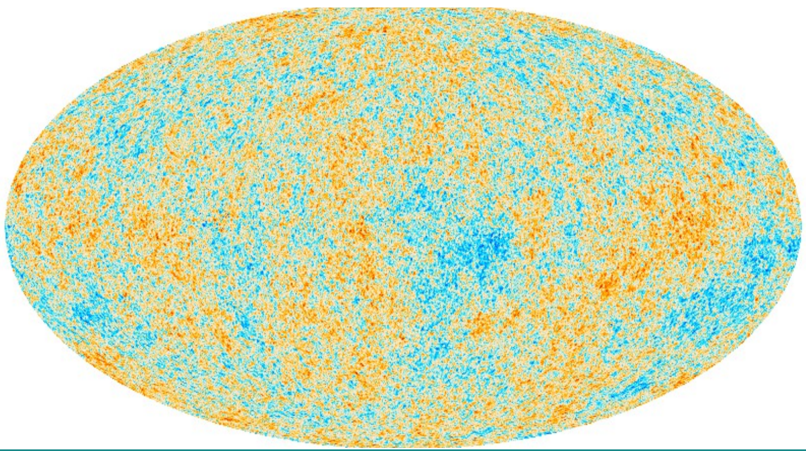

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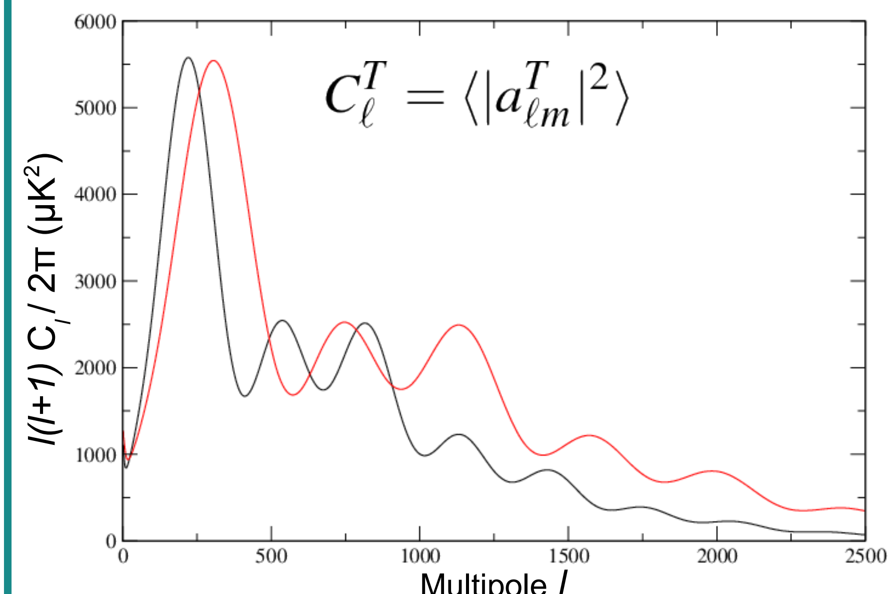

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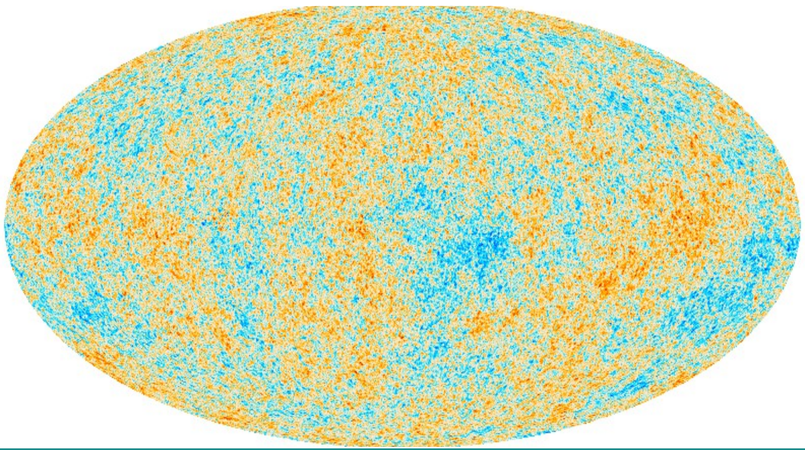

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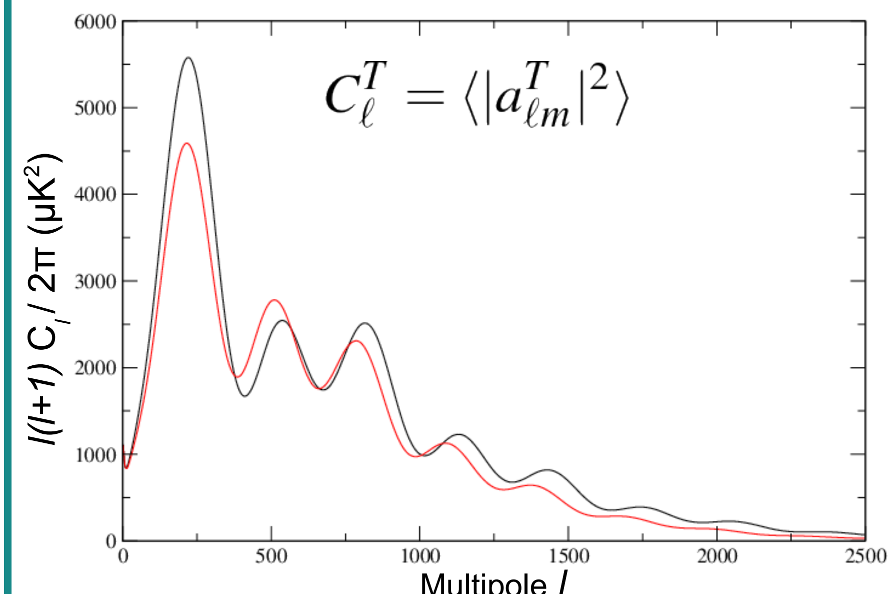

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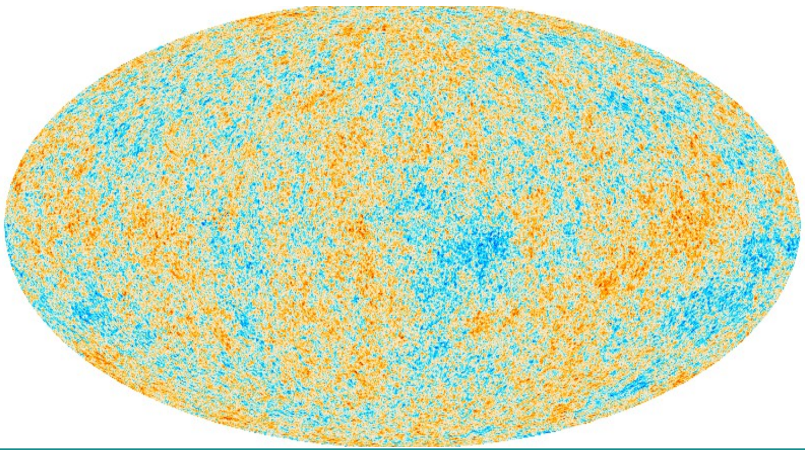

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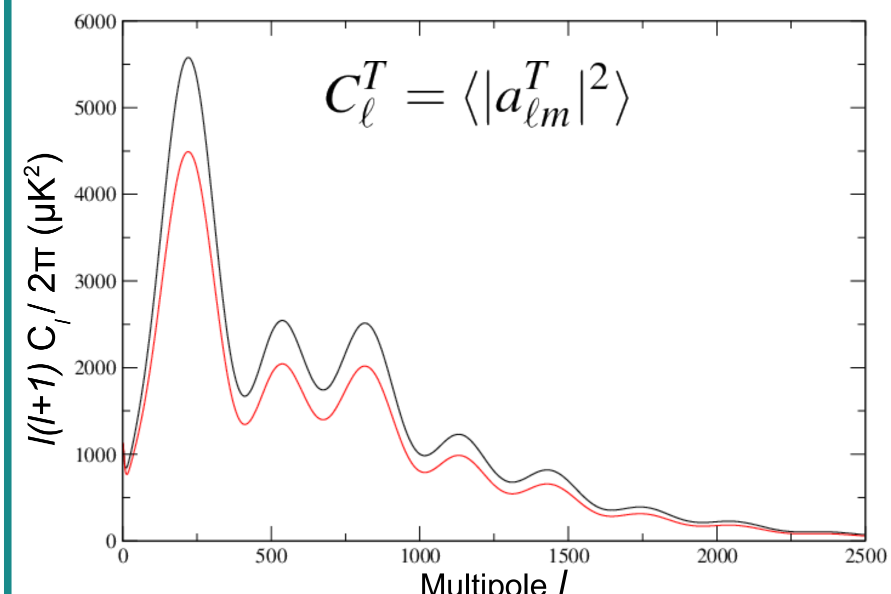

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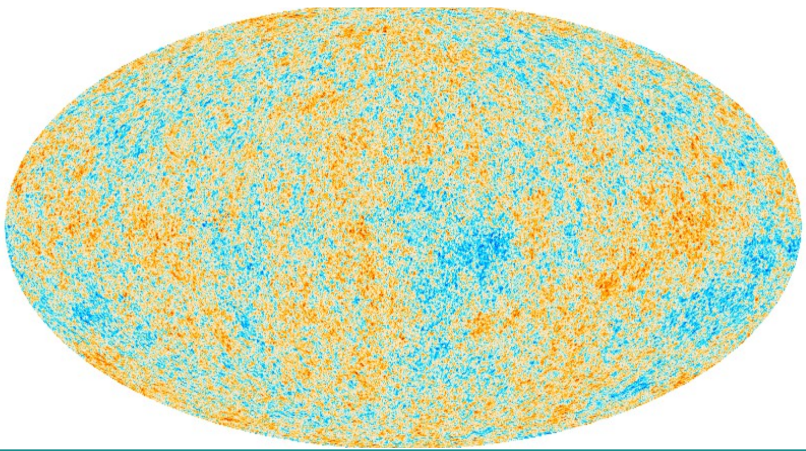

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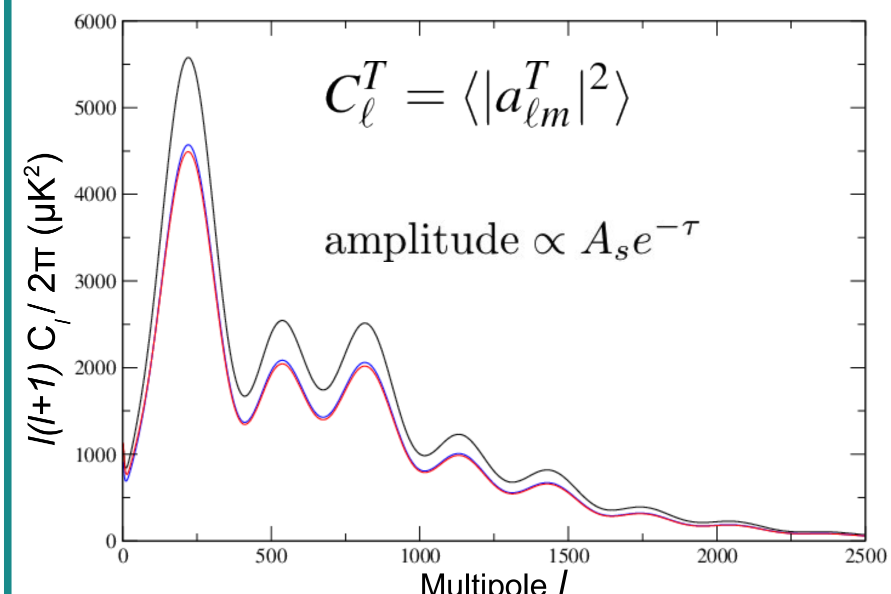

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Spectrum sensitive to cosmological parameters, e.g.

Curvature Ω_κ

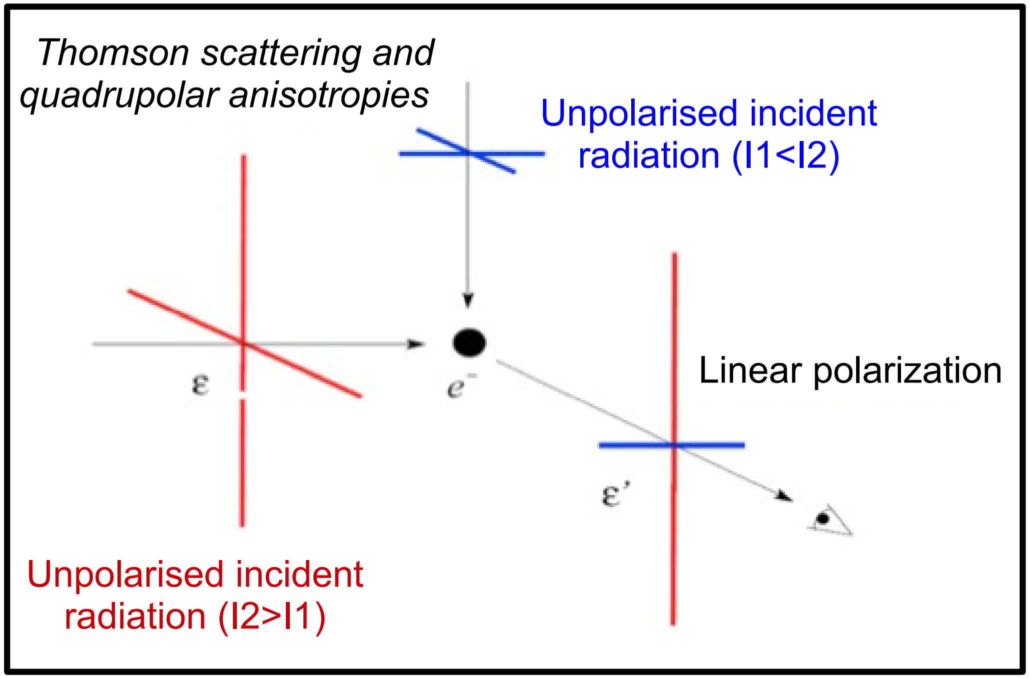
Matter content $\Omega_b,\ \Omega_c$

Reionisation optical depth

Primordial perturb. spectrum $P(k) = A_s \left(\frac{k}{k_0}\right)^{n_s - 1}$

Degeneracies among parameters can be broken using additional information: polarisation, lensing...

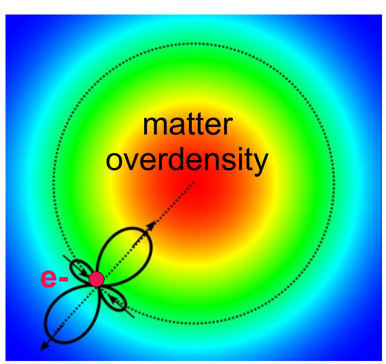
CMB polarisation



- CMB polarisation is produced by **Thomson scattering** in the presence of quadrupolar anisotropies
- **Imprints the CMB** at 2 epochs
  → recombination (last scattering)
  → reionisation (new free e-)
- Polarisation described by the Stokes parameters:
  I → intensity
  Q, U → linear polarisation
  [V → circular polarisation = 0 for CMB]

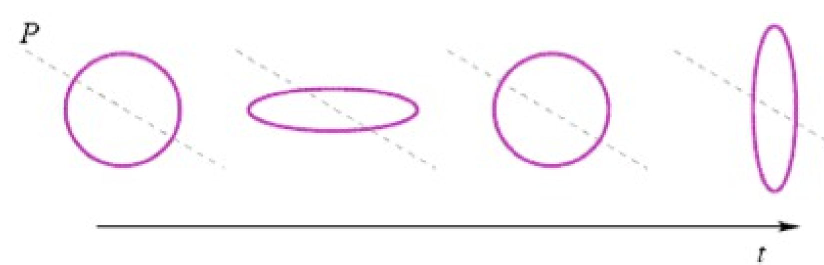
Sources of quadrupolar anisotropies

scalar perturbations (over/under-densities)



Sanselme (2013)

tensor perturbations (gravitational waves)



CMB polarisation

$$(Q \pm iU)(\mathbf{n}) = \sum_{l,m} a_{\pm 2,lm} \cdot {}_{\pm 2}Y_{lm}(\mathbf{n})$$

$$a^E_{lm} = -\frac{a_{2,lm} + a_{-2,lm}}{2} \quad \text{and} \quad a^B_{lm} = i\frac{a_{2,lm} + a_{-2,lm}}{2}$$

$$E(\mathbf{n}) = \sum_{l,m} a^E_{lm} Y_{lm}(\mathbf{n}) \quad \text{and} \quad B(\mathbf{n}) = \sum_{l,m} a^B_{lm} Y_{lm}(\mathbf{n})$$

- Q and U depend on frame of reference
- E and B are frame-independent quantities

Production of E and B modes depends on the type of perturbation:

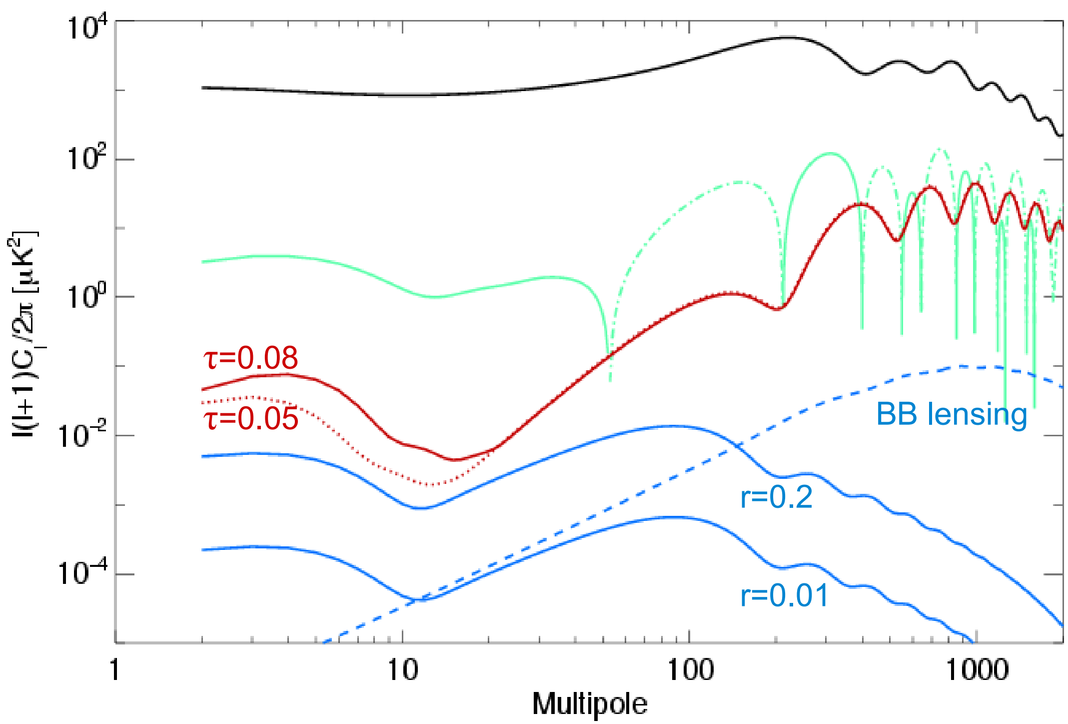
- **Scalar perturbations → E only**
- **Tensor perturbations → E and B**

Power spectra: auto and cross spectra

$$C_l^{XY} = \frac{1}{2l+1} \sum_{m=-l}^{m=l} a^X_{lm} a^{Y\star}_{lm} \quad \text{for} \quad X, Y \in [T, E, B]$$

- Polarisation complements temperature data → consistency check
- Polarisation (at low-l) → "reionisation bump" lifts $A_s - \tau$ degeneracy
- BB around l = 50 – 100 → smoking gun for gravitational waves

TT, EE, BB, TE, ~~TB~~, ~~EB~~



1. A quick introduction to the CMB: intensity and polarisation

2. From satellite to channel maps [Planck 2015 II, VI, VII, VII]

3. A selection of Planck's 2015 cosmological results

- Component separation: finding the CMB among other things
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- Lensing
- The search for primordial B-modes

4. Conclusions

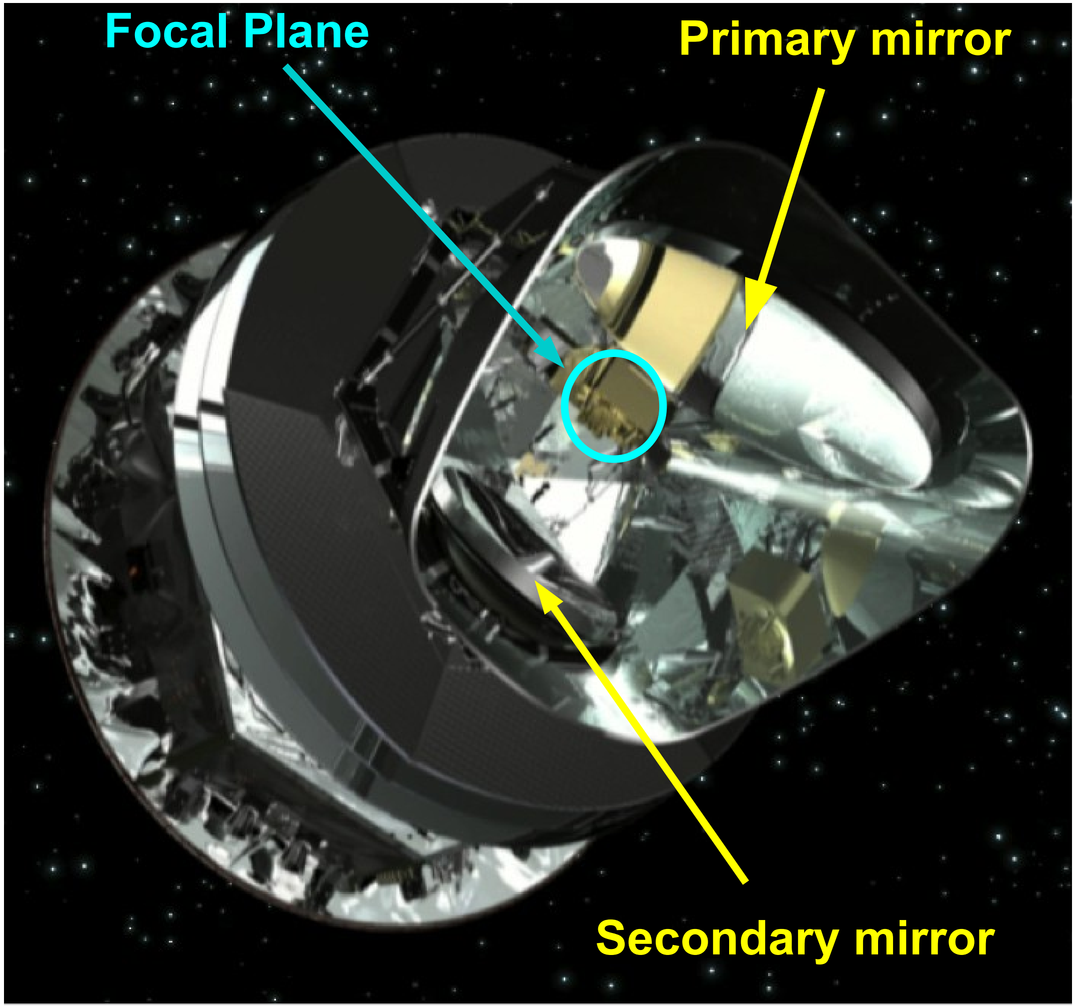
The Planck mission

- **14 May 2009**: Ariane 5 launch
  → Joint launch with Herschel
  → all the way to L2 point
- **August 2009**: beginning of operations
- **14 August 2013**: de-orbiting

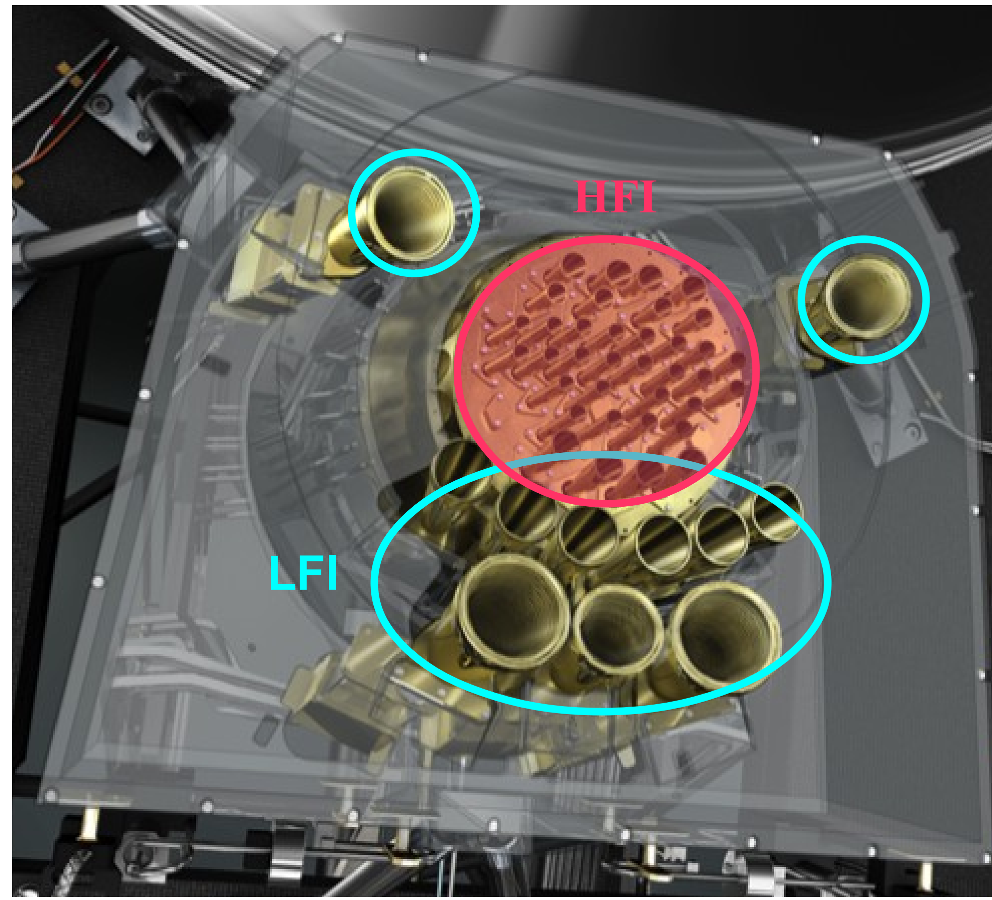
Goals

- Ultimate measurement of CMB anisotropies in temperature
- Unprecedented measurement of CMB polarisation
- Galactic/extragalactic science

The Planck satellite



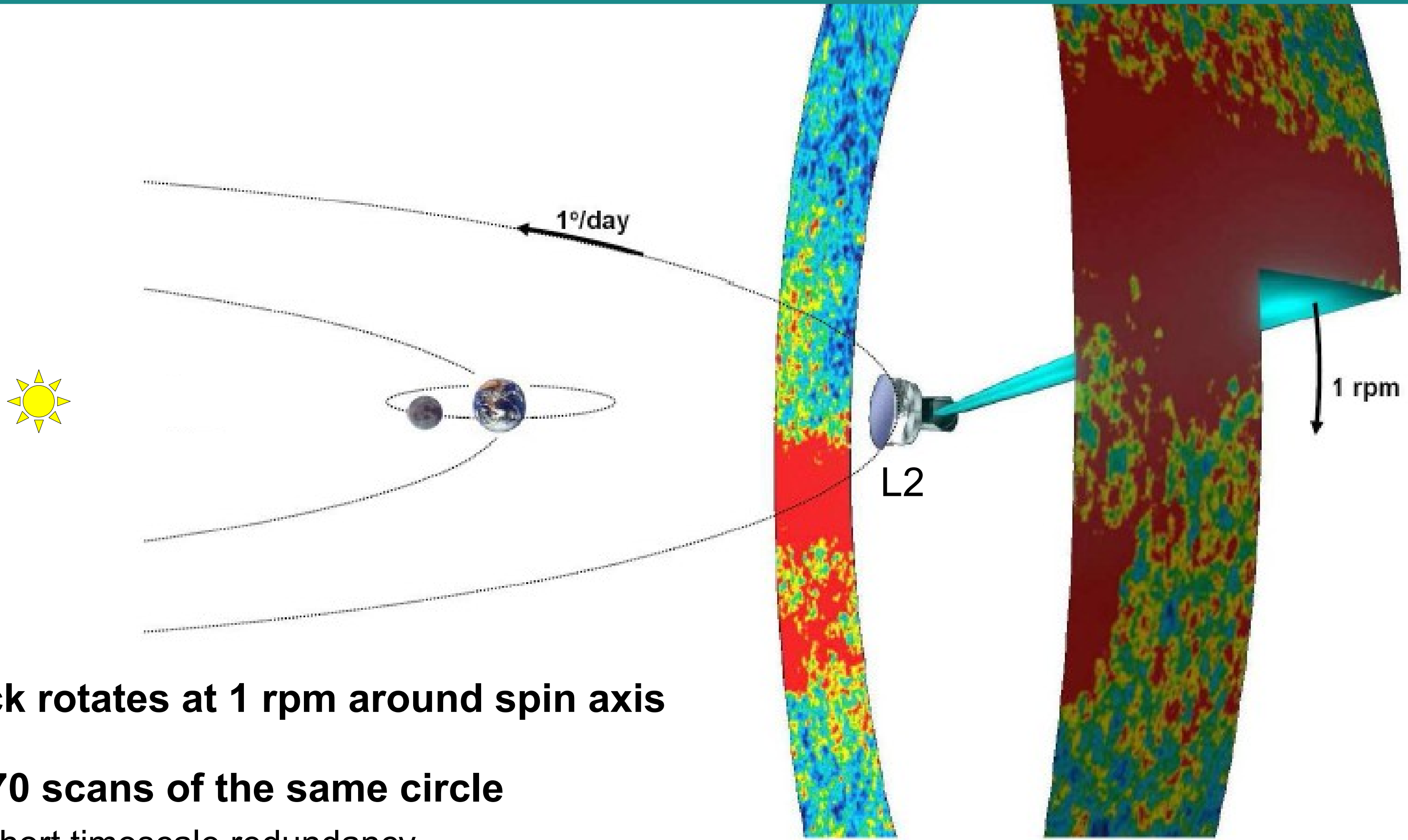
Focal Plane



LFI: Low Frequency Instrument (33 → 70 GHz) – 11 radiometers @ 20 K (H sorption cooler)

HFI: High Frequency Instrument (100 → 857 GHz) – 52 bolometers @ 0.1 K (^{3}He/^{4}He dilution)

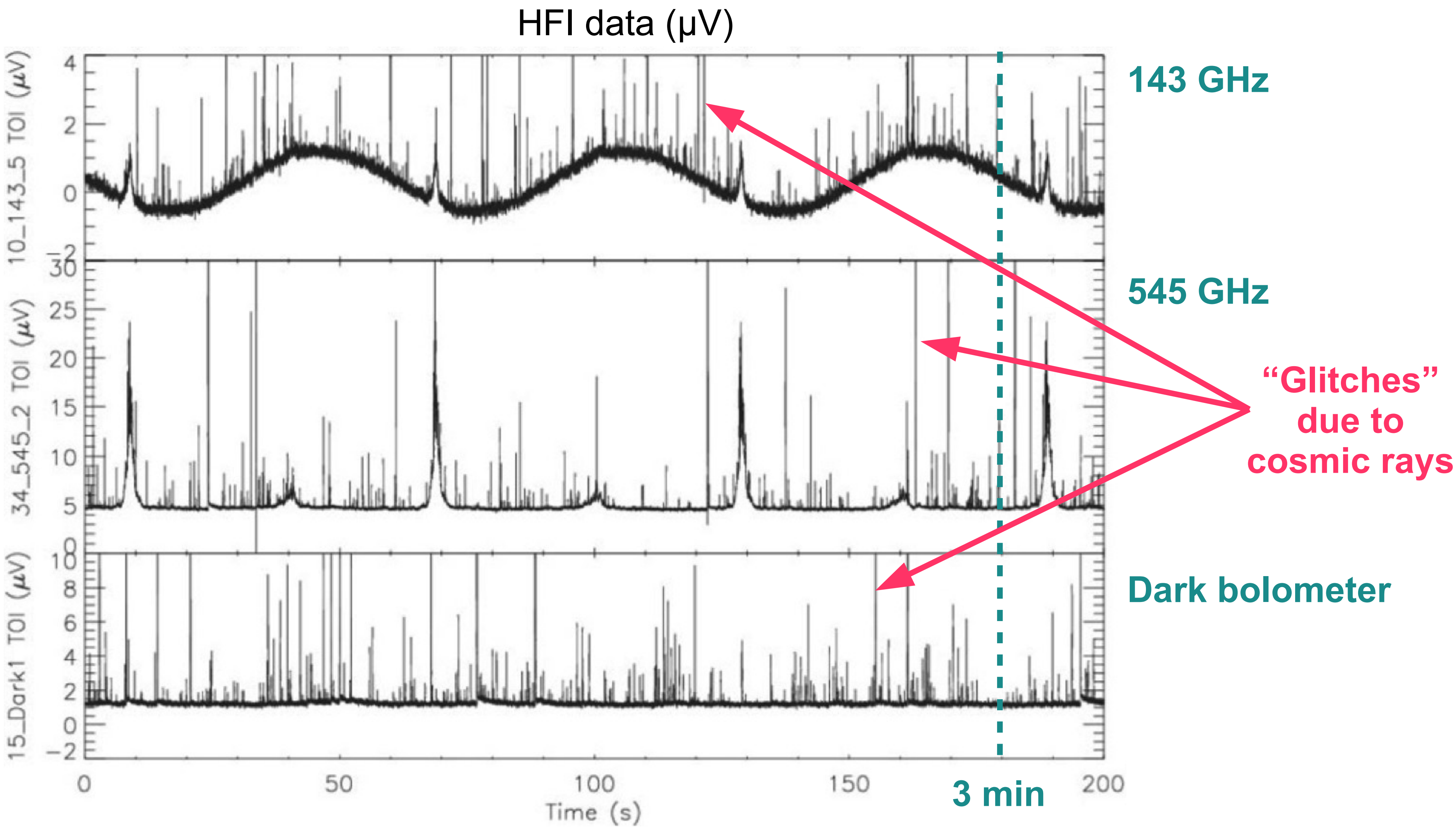
Scanning strategy



- **Planck rotates at 1 rpm around spin axis**
- **40 – 70 scans of the same circle**
  → short timescale redundancy
  → useful to characterise noise of each detector
- **Planck covers the full sky in ~ 6 months**
  → long timescale redundancy
  → systematic effects identification

→ **TOI**
Time-Ordered Information

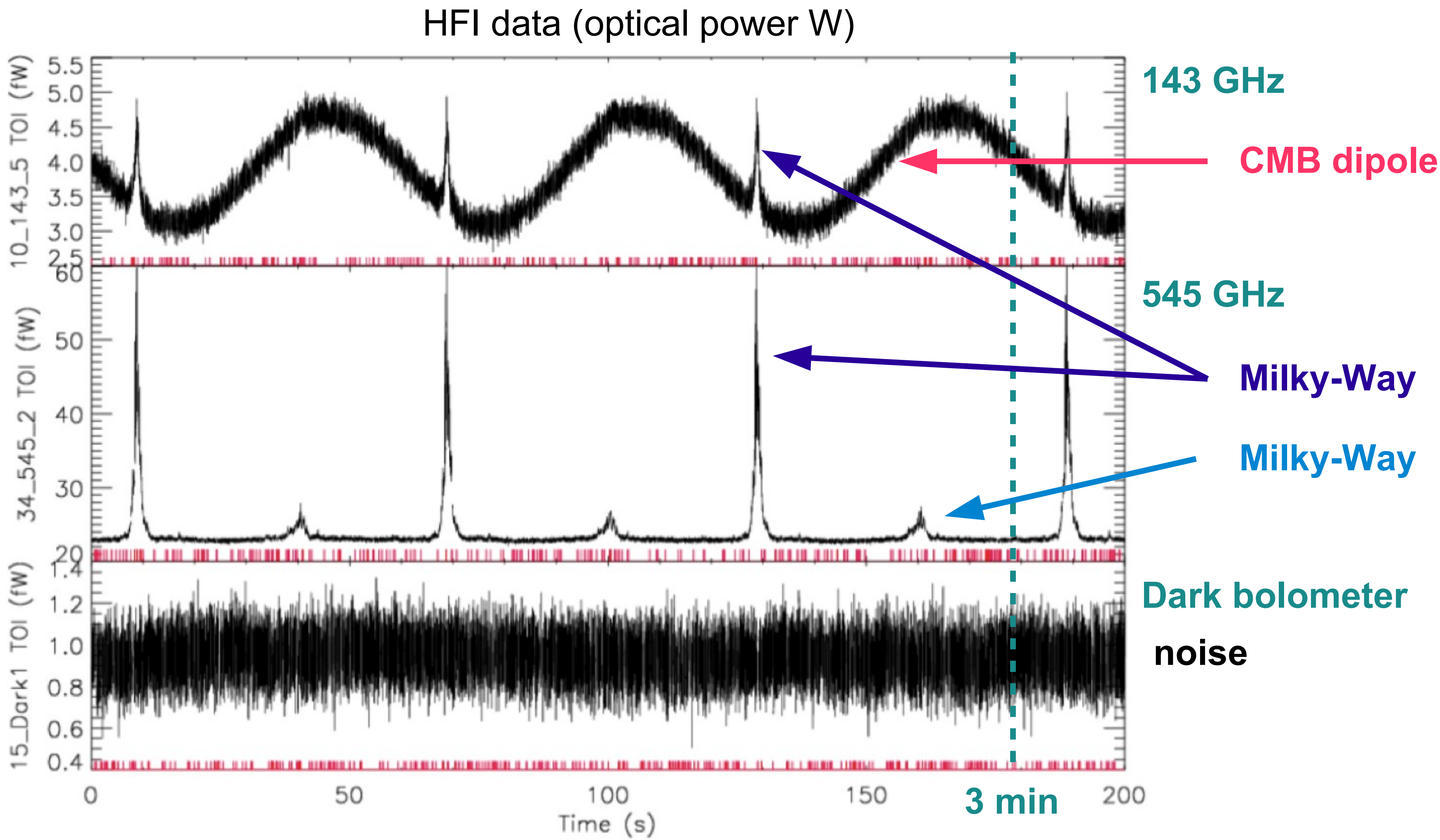
Raw TOI



TOI processing – several important steps

Deglitching & flagging, Gain nonlinearity correction, Thermal drift decorrelation, 4K cooler line removal, Transfer functions deconvolution, Jump correction, Sample flagging

Cleaned TOI

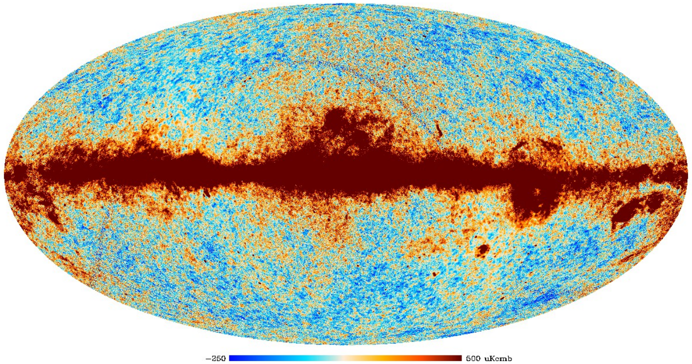


Cleaned TOI are used as input by the map-making team

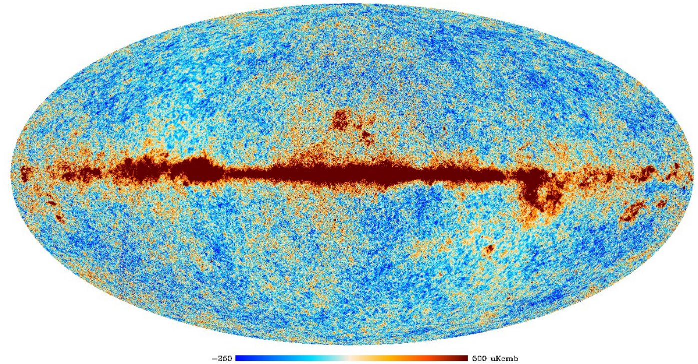
9 Planck intensity maps

[Planck 2015 results. VI, VIII]

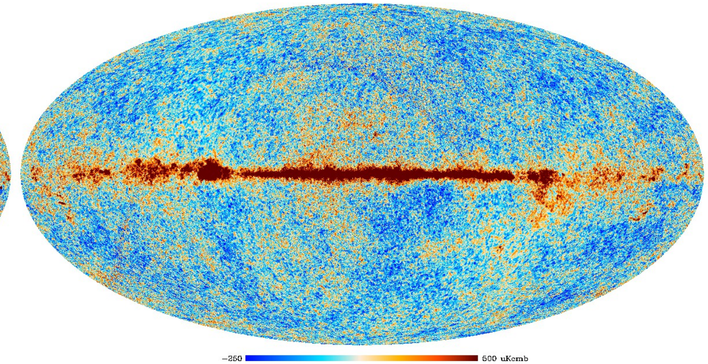
30 GHz



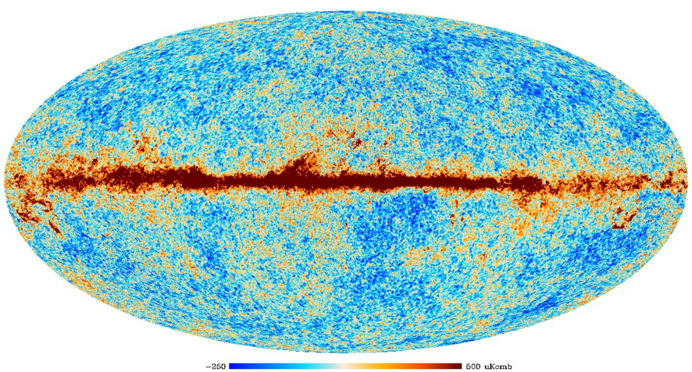
44 GHz



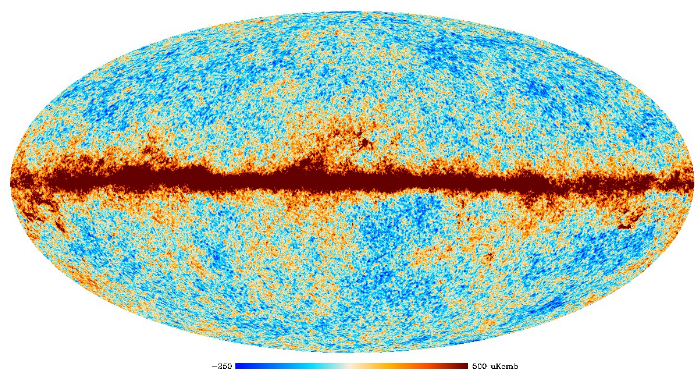
70 GHz



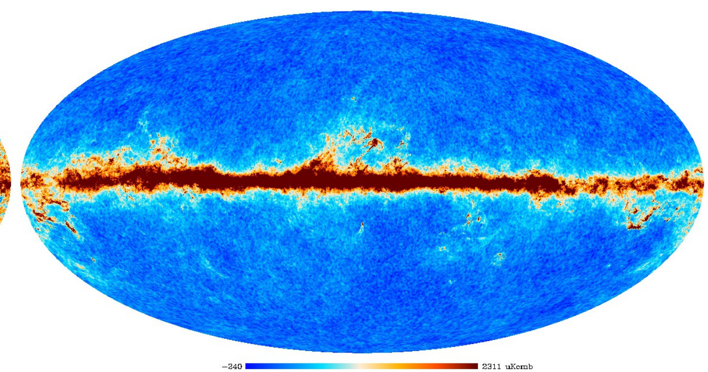
100 GHz



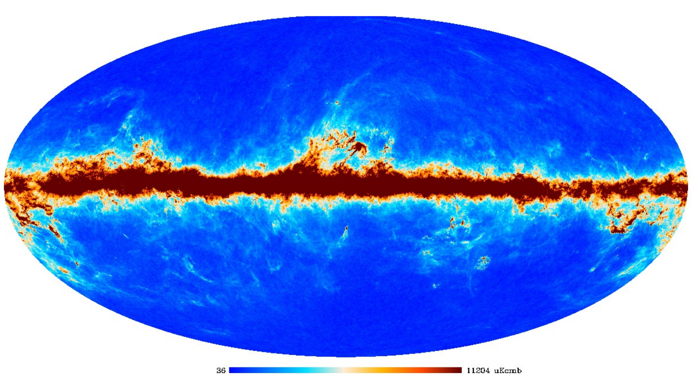
143 GHz



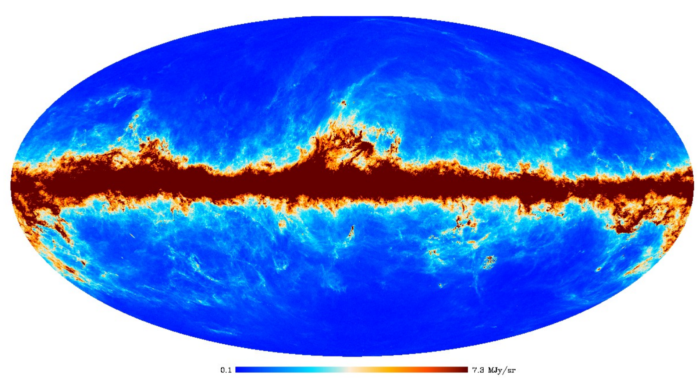
217 GHz



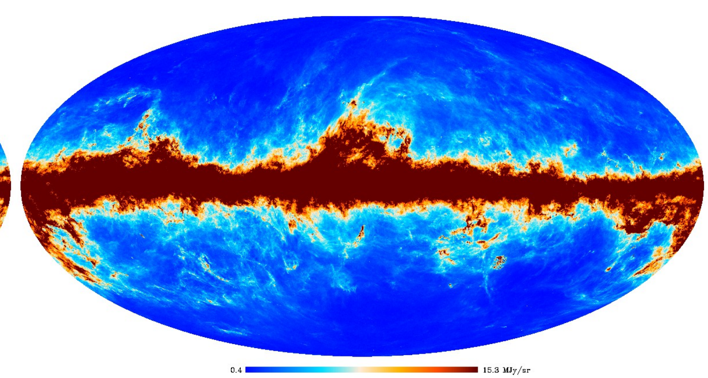
353 GHz



545 GHz



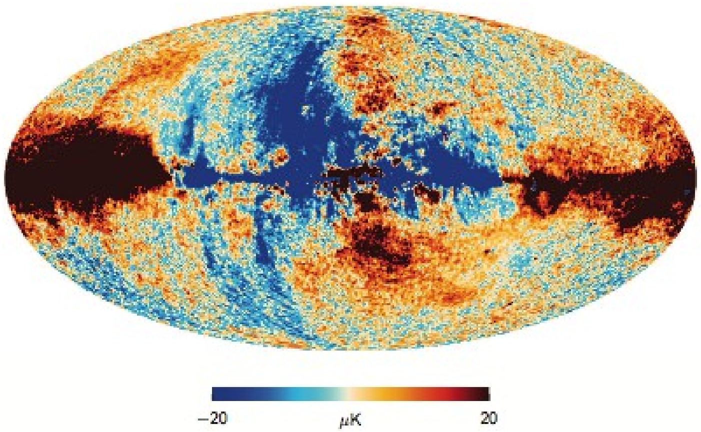
857 GHz



4 Planck Q maps [Feb. 2015]

[Planck 2015 results. VI, VIII]

30 GHz



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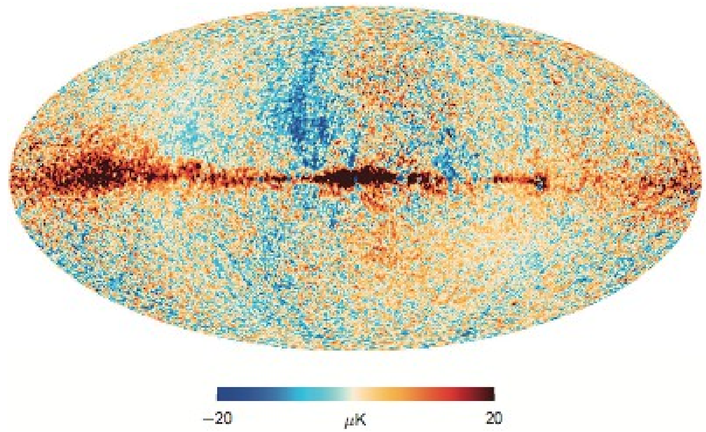
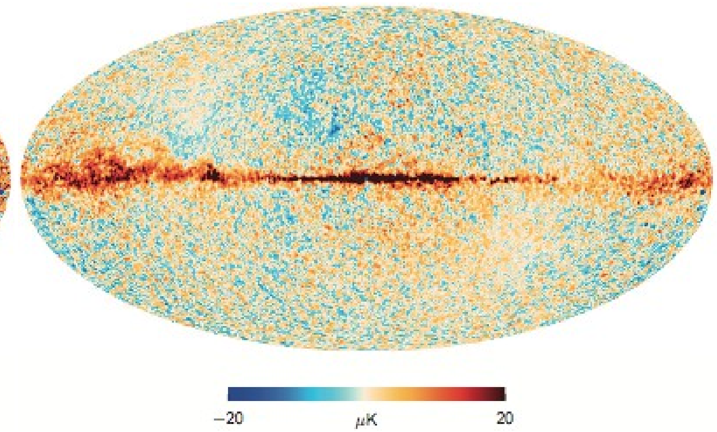


70 GHz

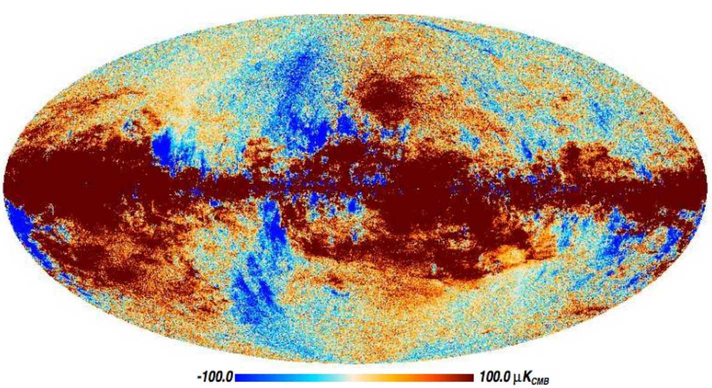


100 Q
coming june 2015...

143 Q
coming june 2015...

217 Q
coming june 2015...

353 GHz



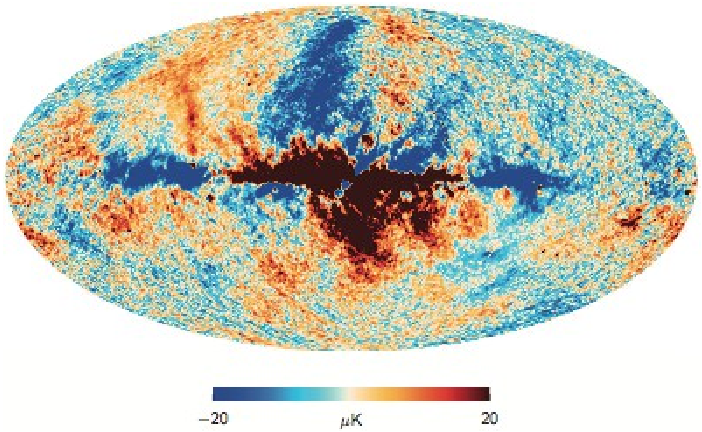
At 100, 143 and 217, large scale systematics due to intensity-to-polarisation leakage

→ map release postponed

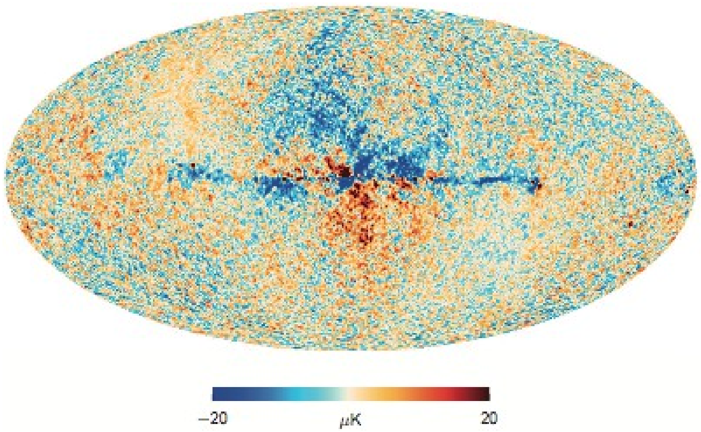
4 Planck U maps [Feb. 2015]

[Planck 2015 results. VI, VIII]

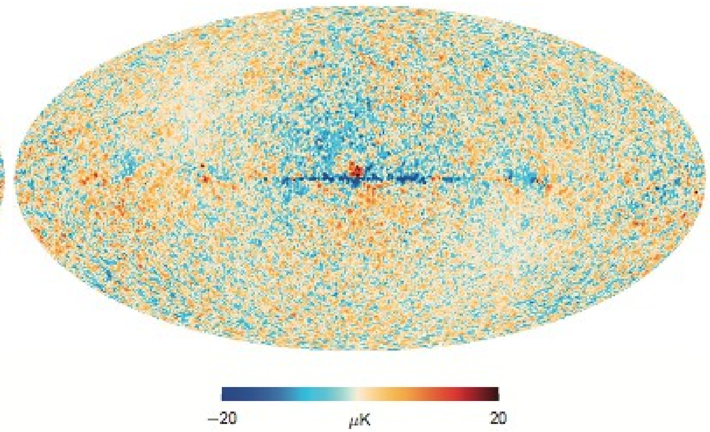
30 GHz



44 GHz



70 GHz

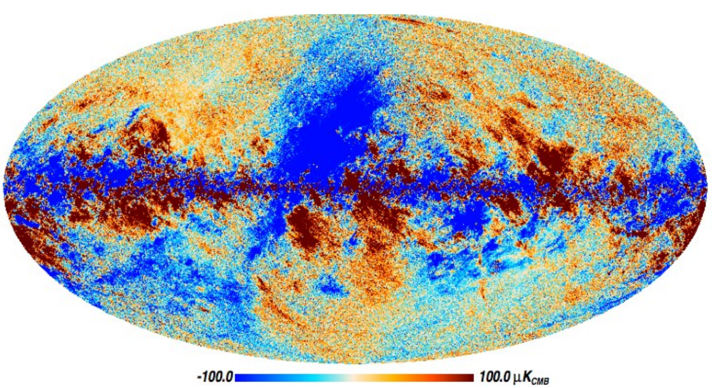


100 U
coming june 2015...

143 U
coming june 2015...

217 U
coming june 2015...

353 GHz



At 100, 143 and 217, large scale systematics due to intensity-to-polarisation leakage

→ map release postponed

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4. Conclusions

Planck's 2015 papers (as of April)

I. Overview of products and results (*this paper*)
II. Low Frequency Instrument data processing
III. LFI systematic uncertainties
IV. LFI beams and window functions
V. LFI calibration
VI. LFI maps
VII. High Frequency Instrument data processing: Time-ordered information and beam processing
VIII. High Frequency Instrument data processing: Calibration and maps
IX. Diffuse component separation: CMB maps
X. Diffuse component separation: Foreground maps
XI. CMB power spectra, likelihood, and consistency of cosmological parameters
XII. Simulations
XIII. Cosmological parameters
XIV. Dark energy and modified gravity
XV. Gravitational lensing
XVI. Isotropy and statistics of the CMB
XVII. Primordial non-Gaussianity
XVIII. Background geometry and topology of the Universe
XIX. Constraints on primordial magnetic fields
XX. Constraints on inflation
XXI. The integrated Sachs-Wolfe effect
XXII. A map of the thermal Sunyaev-Zeldovich effect
XXIII. The thermal Sunyaev-Zeldovich effect–cosmic infrared background correlation
XXIV. Cosmology from Sunyaev-Zeldovich cluster counts
XXV. Diffuse, low-frequency Galactic foregrounds
XXVI. The Second Planck Catalogue of Compact Sources
XXVII. The Second Planck Catalogue of Sunyaev-Zeldovich Sources
XXVIII. The Planck Catalogue of Galactic Cold Clumps

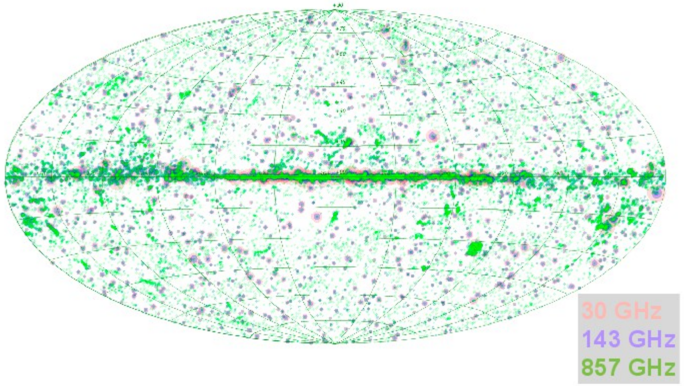
BICEP2/Planck joint analysis

What's in the maps?

Point sources

- Galactic cold cores (star forming regions)
- Radio galaxies (quasars)
- Infrared galaxies (dusty, star forming galaxies)

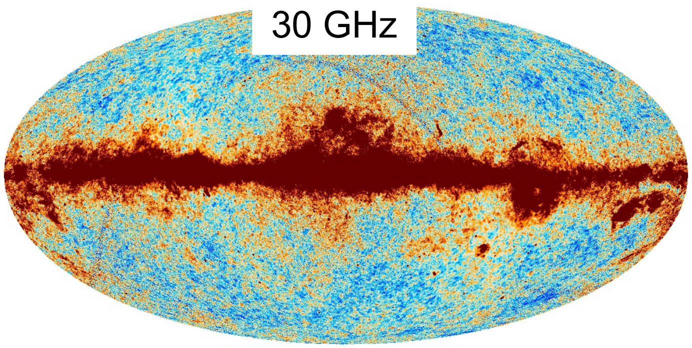
  → 25000 sources *[Planck 2013 results. XXVIII]*



Extragalactic diffuse emission → Cosmic Infrared Background

Galactic diffuse emissions *[Planck 2015 results. X]*

- Synchrotron (e- in Galactic B field)
- Free-free (Bremmstrahlung, e- + p → e- + p + hv)
- Galactic dust (thermal emission + spinning dust)
- Carbon monoxyde (CO, galactic molecular clouds)



CMB

- primary anisotropies *[Planck 2015 results. IX]*
- secondary anisotropies

  - Sunyaev Zel'dovich galaxy clusters *[Planck 2015 results. XXII, XXIV, XXVII]*

  - Lensing *[Planck 2015 results. XV]*

What's in the maps?

Point sources

- Galactic cold cores (star forming regions)
- Radio galaxies (quasars)
- Infrared galaxies (dusty, star forming galaxies)

→ 25000 sources *[Planck 2013 results. XXVIII]*

Dedicated point-source finding algorithm

Extragalactic diffuse emission → Cosmic Infrared Background

Galactic diffuse emissions *[Planck 2015 results. X]*

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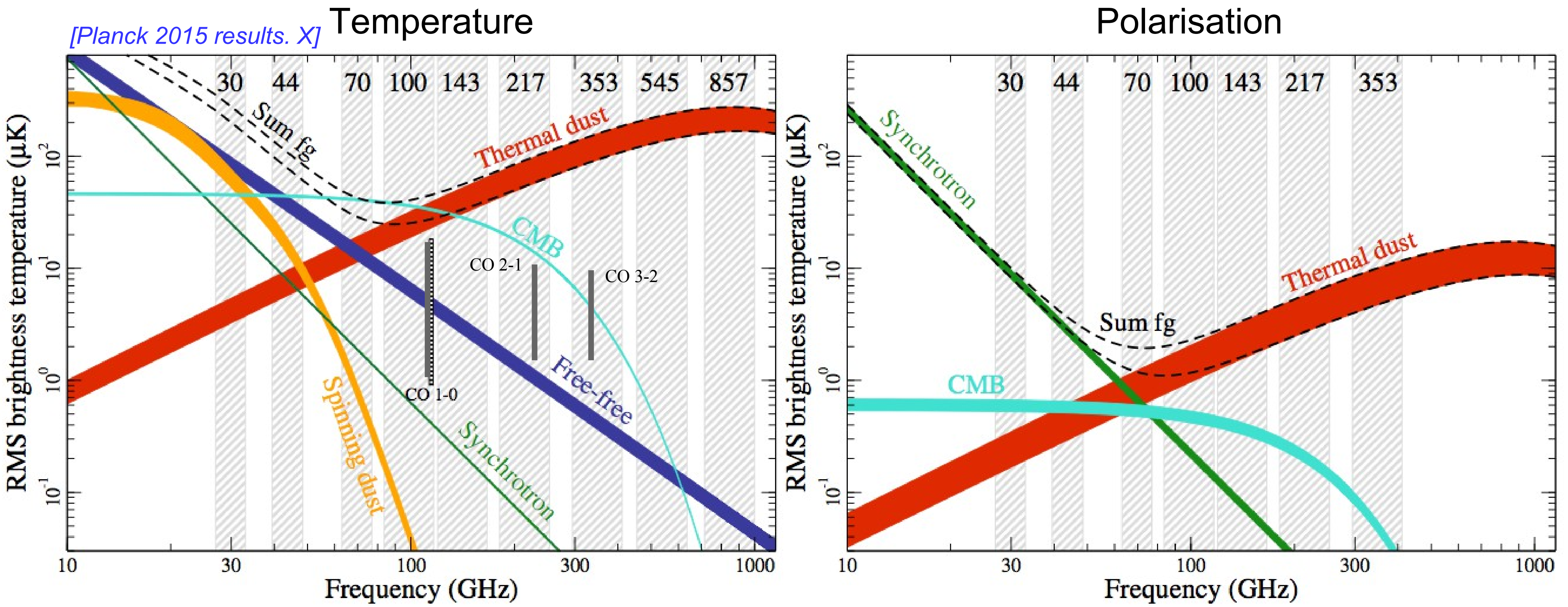
CMB

- primary anisotropies *[Planck 2015 results. IX]*
- secondary anisotropies
  - *Sunyaev Zel'dovich galaxy clusters* *[Planck 2015 results. XXII, XXIV, XXVII]*
  - *Lensing* *[Planck 2015 results. XV]*

component separation

Component separation

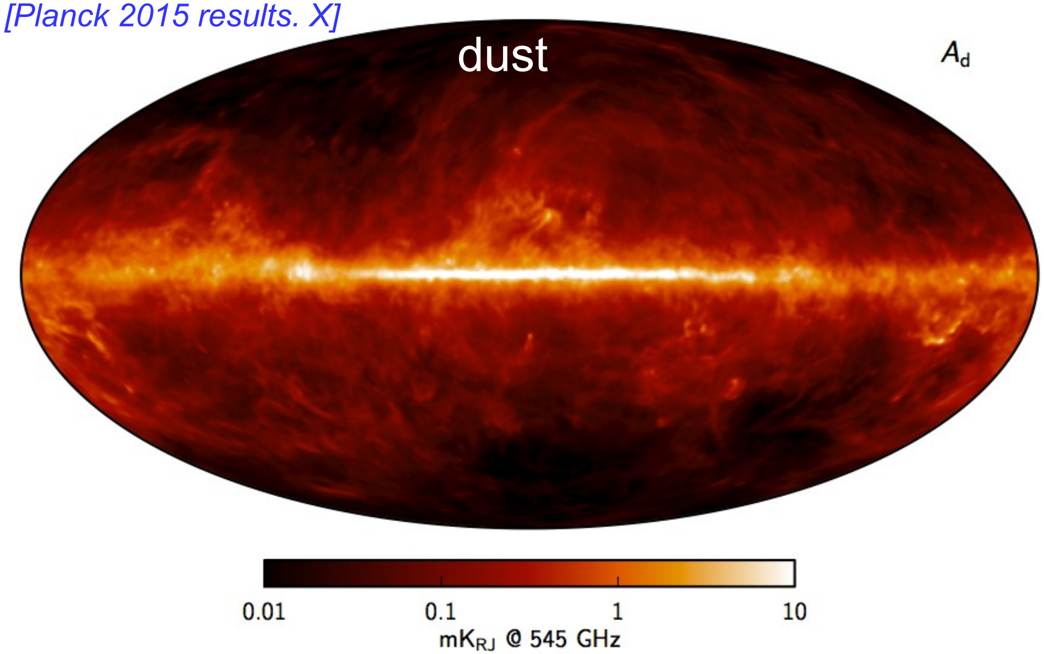


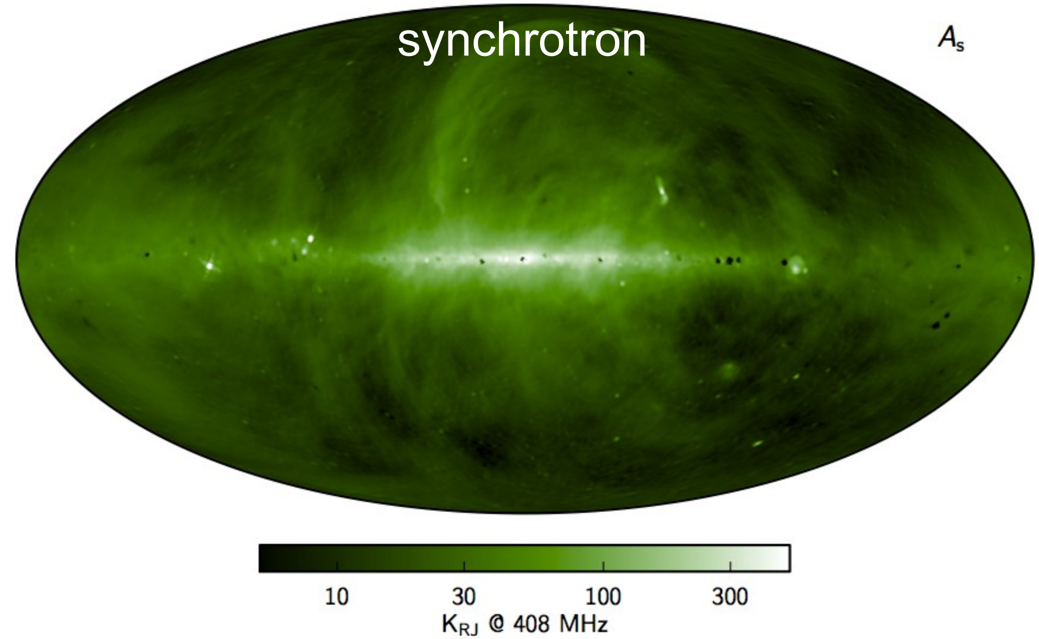
- Many components in temperature:
  → main approach: solve all at once using Planck + external datasets
  → for some components, e.g. CO, also use tailored approach

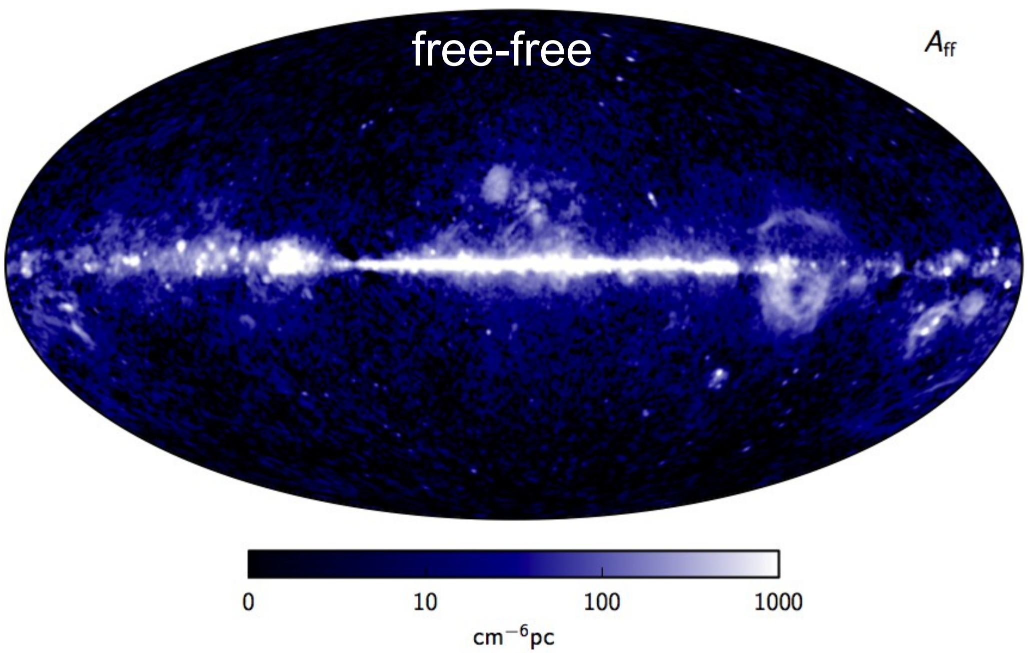
- In polarisation, only 2 main foregrounds but they dominate CMB emission in all channels

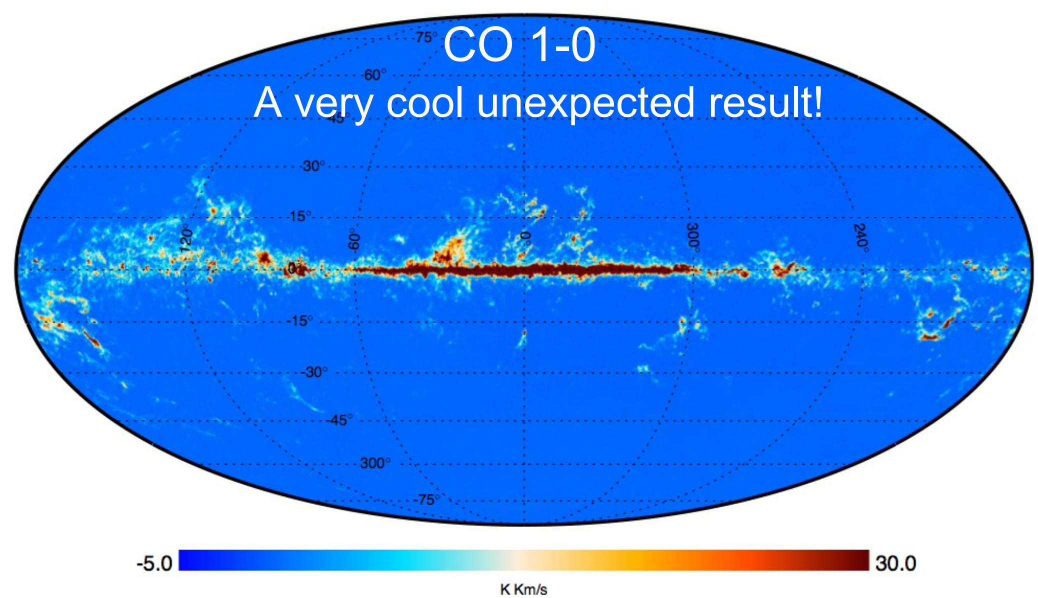
Foregrounds in temperature

[Planck 2015 results. X]



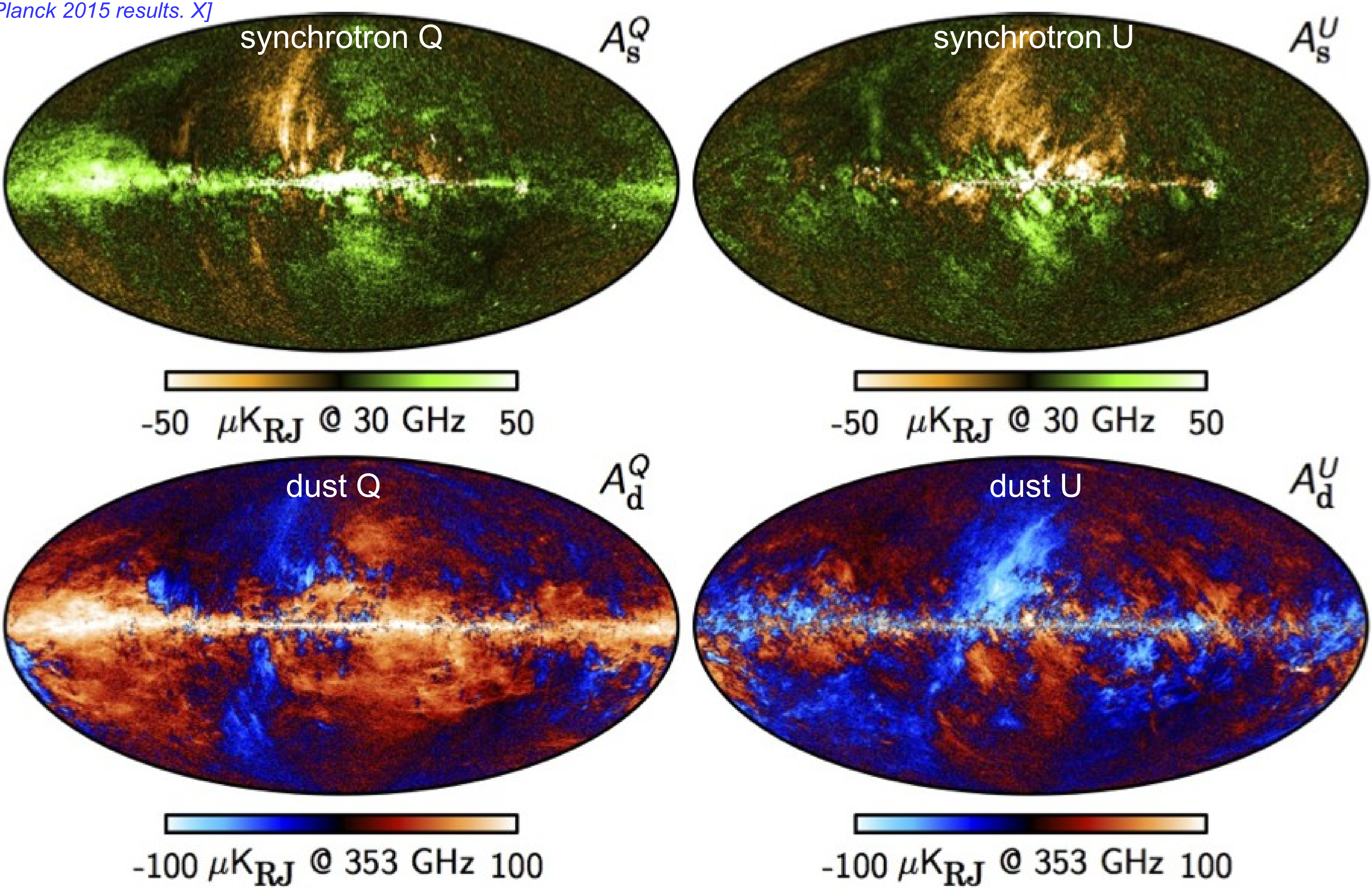






Foregrounds in polarisation

[Planck 2015 results. X]



CMB component separation

Several component separation methods are used to extract CMB maps

Minimal foreground assumptions, just look for CMB

Characteristic	Commander-Ruler	NILC	SEVEM	SMICA
Method	Bayesian parameter estimation	Internal linear combination	Internal template fitting	Spectral parameter estimation
Domain	Pixel	Needlet	Pixel	Spherical harmonic
Channels [GHz]	30–353	44–857	30–857	30–857
Effective beam FWHM [arcmin]	~7.4	5.0	5.0	5.0
ℓ_{max}	none	3200	3100	4000

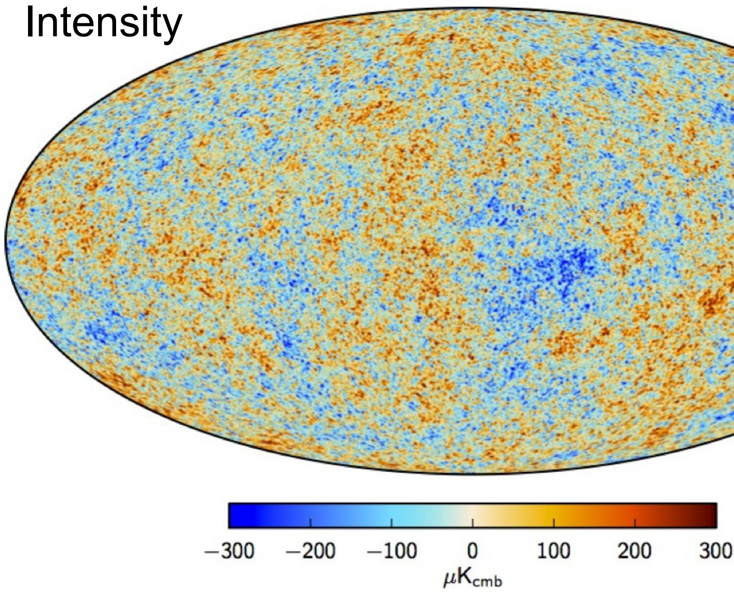
NB: Commander-Ruler also used to produced foreground maps

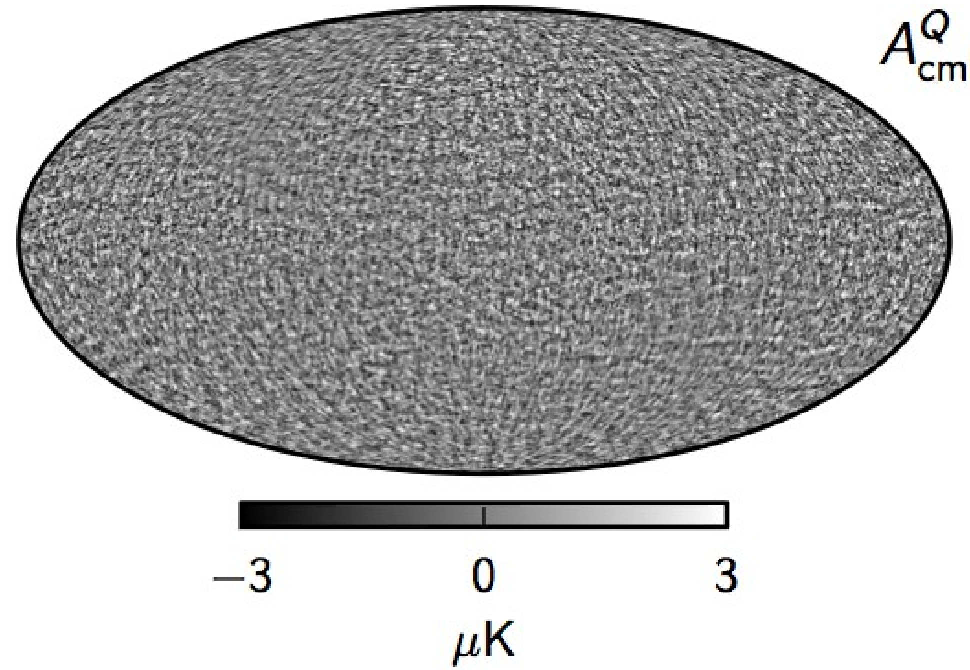
CMB + Foreground fitting

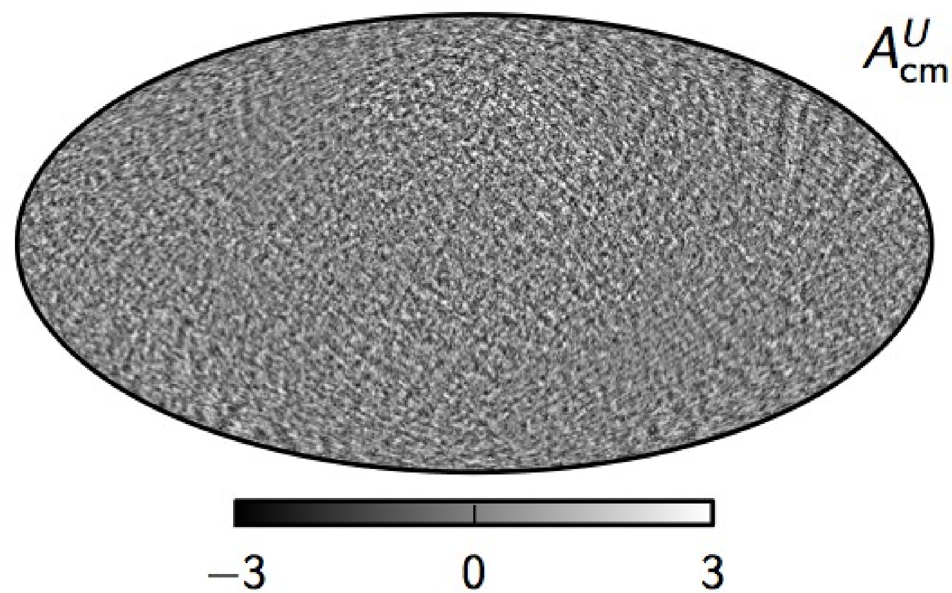
- Dispersion between results gives estimate of uncertainty in CMB recovery

CMB component separation

Intensity







- CMB maps mainly used for non-Gaussianity analyses and lensing
- CMB polarisation maps suffers from large-angular scales systematics

  → large-scales have been filtered out

[Planck 2015 results. I, IX]

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MCMC parameter estimation

DATA

Planck temperature only

Planck T likelihood
[HFI TT spectra]

Planck T likelihood +
lensing likelihood
[TT and ΦΦ spectra]

Planck temperature + polar.

- $l > 30$ – HFI TE and EE spectra
- Use LFI 70 GHz polarisation data for low-l polar likelihood (lowP) [breaks the (A_s –) degeneracy]

Other observables

Baryon acoustic oscillations
Supernovae Ia
Direct H_0 measurements

MODELS

Base 6-parameter   CDM model

Primordial perturb. spectrum $P(k) = \underline{A_s}\left(\frac{k}{k_0}\right)^{\underline{n_s}-1}$

Matter densities $\underline{\Omega_b h^2}, \underline{\Omega_c h^2}$

Angular size of sound horizon $\underline{\theta_\star}$

Optical depth to reionisation _

→ Derived parameters: $H_0,\ \Omega_\Lambda,\ \Omega_m,\ \sigma_8, \ldots$

To be varied in model extensions

No running $dn_s/d\ln k = 0$

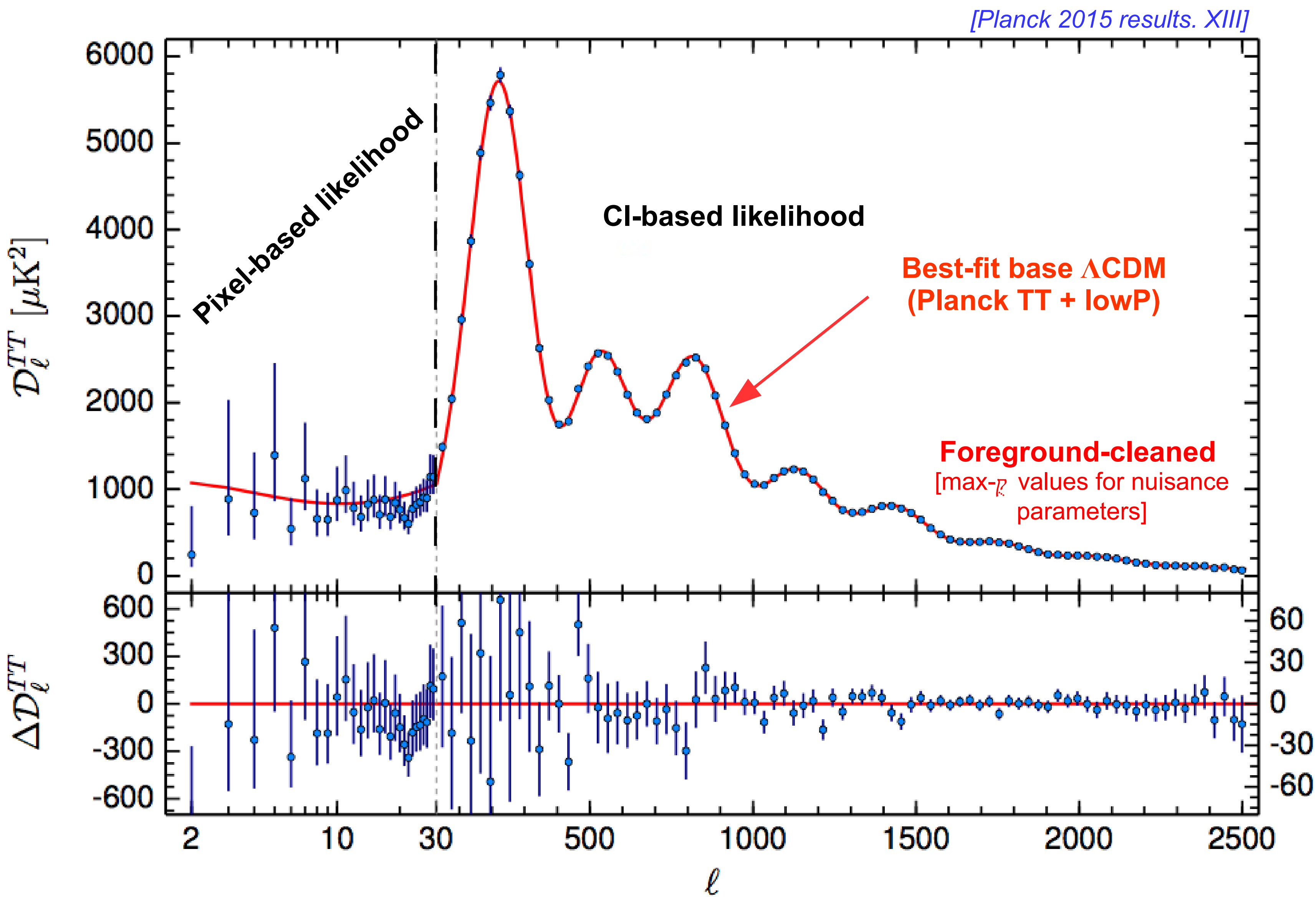
No tensor perturbations $r = 0$

Flat universe $\Omega_\kappa = 0$

Neutrinos $\begin{cases} N_{\rm eff} = 3.046 \\ \sum m_\nu = 0.06\ \text{eV} \end{cases}$

+ more....

TT spectrum

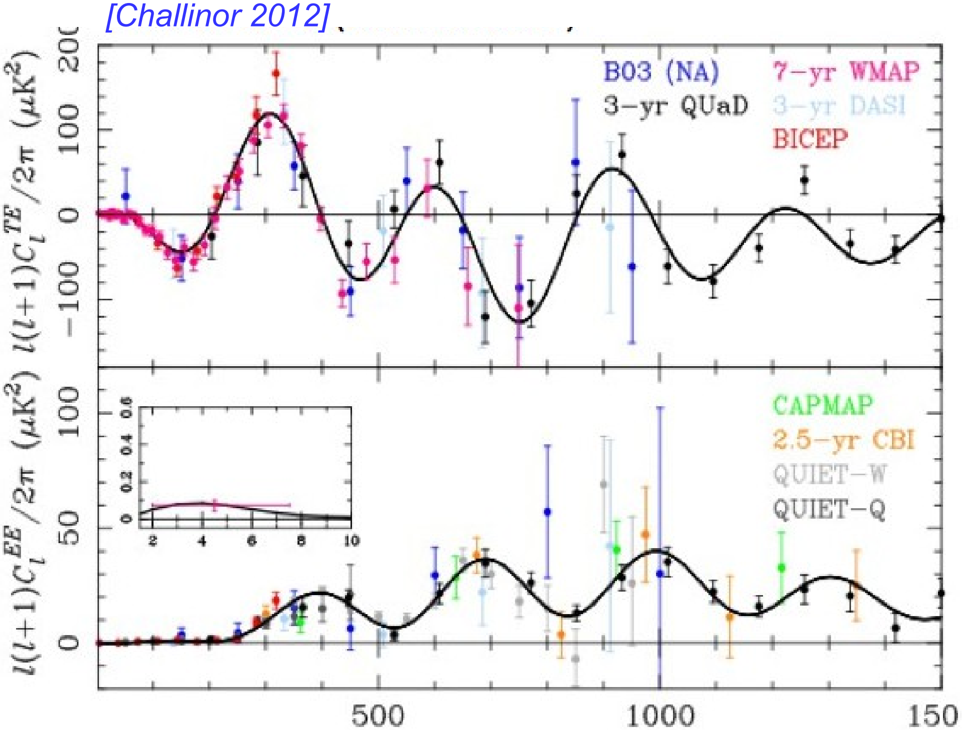


Base ΛCDM provides an excellent fit to the data

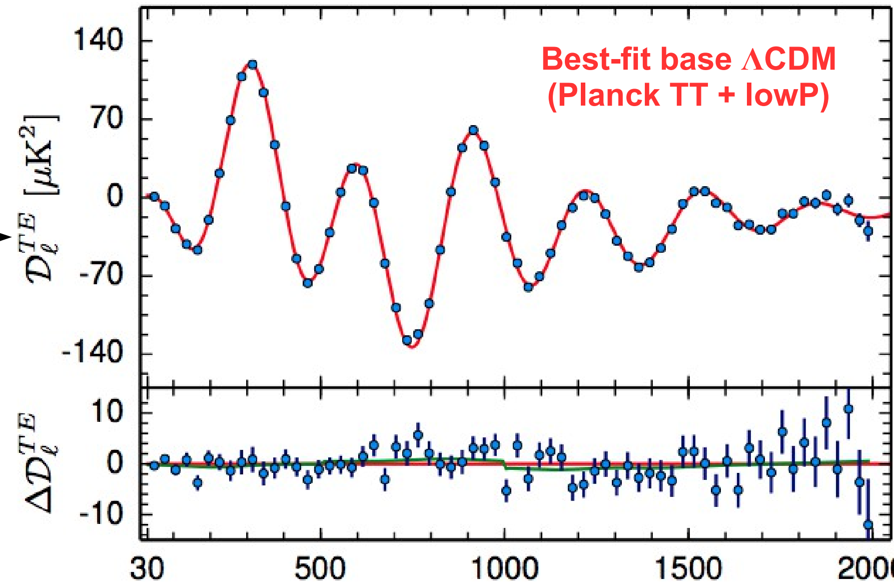
TE, EE spectra

Before Planck

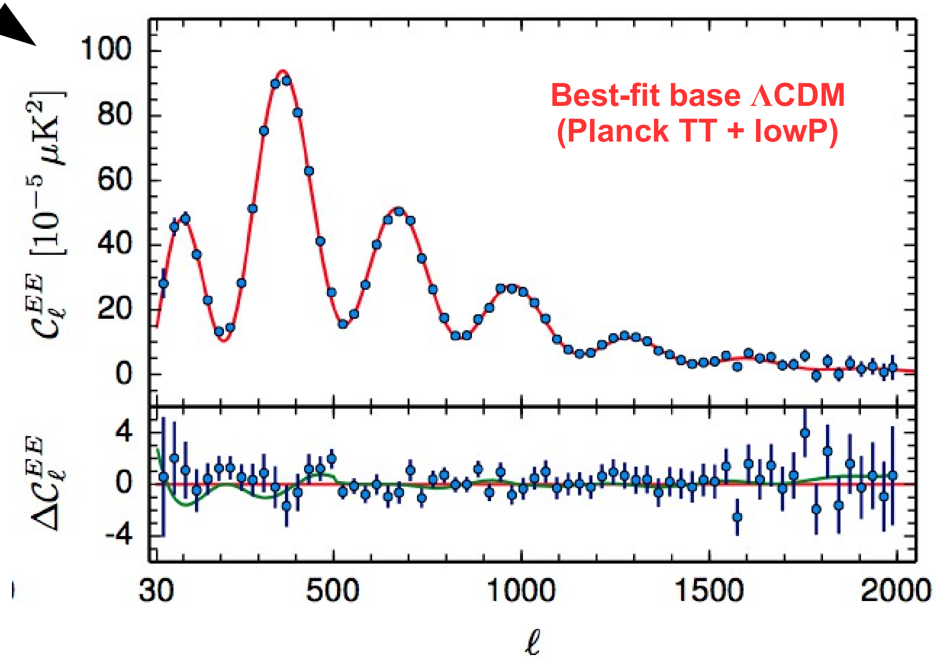
[Challinor 2012]



Planck 2015

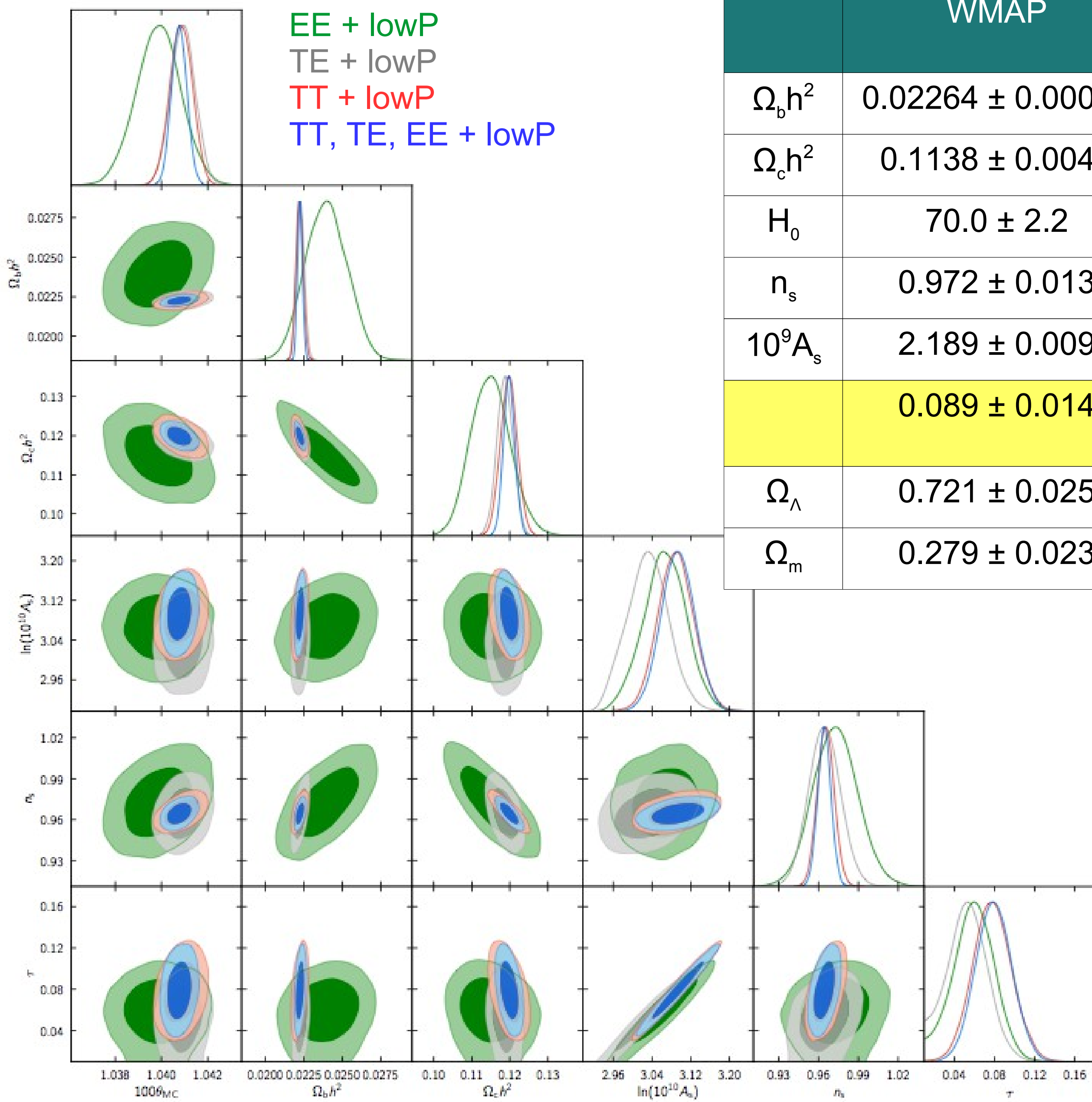


[Planck 2015 results. XIII]



- Improved sensitivity to polarisation compared to previous experiments.
- Polarisation power spectra in excellent agreement with temperature
- Polarisation spectra used in parameter estimation
- Large angular scales (ell < 30) systematics still need to be dealt with...

Base ΛCDM parameters



	WMAP	Planck + WP 2013	Planck + lowP 2015
$\Omega_b h^2$	0.02264 ± 0.00050	0.02205± 0.00028	0.02222± 0.00023
$\Omega_c h^2$	0.1138 ± 0.0045	0.1199 ± 0.0027	0.1197 ± 0.0022
H_0	70.0 ± 2.2	67.3 ± 1.2	67.31 ± 0.96
n_s	0.972 ± 0.013	0.960 ± 0.007	0.9655 ± 0.0062
$10^9 A_s$	2.189 ± 0.009	2.196 ± 0.06	2.196 ± 0.06
	0.089 ± 0.014	0.089 ± 0.014	0.078 ± 0.019 0.066 ± 0.016 (+ lens)
Ω_Λ	0.721 ± 0.025	0.685 ± 0.018	0.685 ± 0.013
Ω_m	0.279 ± 0.023	0.315 ± 0.018	0.315 ± 0.013

[Planck 2015 results. XIII]

Compared to WMAP, Planck finds

- a smaller Hubble parameter
- more matter
- less dark energy
- a smaller optical depth to reionisation

1-parameter extensions

Scalar perturb. $P_s(k) = A_s \left(\frac{k}{k_0}\right)^{n_s - 1 + \frac{1}{2}\frac{\partial n_s}{\partial \ln k}\ln(k/k_0)}$ "running"

Tensor perturb. $P_t(k) = A_t \left(\frac{k}{k_0}\right)^{n_t}$ → $r = \frac{A_t}{A_s}$

do not impose:

- $N_{\rm eff} = 3.046$
- $\sum m_\nu = 0.06\ \ {\rm eV}$
- Helium abundance
- $\Omega_k = 0$

Parameter	TT	TT+lensing	TT+lensing+ext	TT, TE, EE	TT, TE, EE+lensing	TT, TE, EE+lensing+ext
Ω_K	$-0.052^{+0.049}_{-0.055}$	$-0.005^{+0.016}_{-0.017}$	$-0.0001^{+0.0054}_{-0.0052}$	$-0.040^{+0.038}_{-0.041}$	$-0.004^{+0.015}_{-0.015}$	$0.0008^{+0.0040}_{-0.0039}$
Σm_ν [eV]	< 0.715	< 0.675	< 0.234	< 0.492	< 0.589	< 0.194
$N_{\rm eff}$	$3.13^{+0.64}_{-0.63}$	$3.13^{+0.62}_{-0.61}$	$3.15^{+0.41}_{-0.40}$	$2.99^{+0.41}_{-0.39}$	$2.94^{+0.38}_{-0.38}$	$3.04^{+0.33}_{-0.33}$
$Y_{\rm P}$	$0.252^{+0.041}_{-0.042}$	$0.251^{+0.040}_{-0.039}$	$0.251^{+0.035}_{-0.036}$	$0.250^{+0.026}_{-0.027}$	$0.247^{+0.026}_{-0.027}$	$0.249^{+0.025}_{-0.026}$
$dn_s/d\ln k$	$-0.008^{+0.016}_{-0.016}$	$-0.003^{+0.015}_{-0.015}$	$-0.003^{+0.015}_{-0.014}$	$-0.006^{+0.014}_{-0.014}$	$-0.002^{+0.013}_{-0.013}$	$-0.002^{+0.013}_{-0.013}$
$r_{0.002}$	< 0.103	< 0.114	< 0.114	< 0.0987	< 0.112	< 0.113
w	$-1.54^{+0.62}_{-0.50}$	$-1.41^{+0.64}_{-0.56}$	$-1.006^{+0.085}_{-0.091}$	$-1.55^{+0.58}_{-0.48}$	$-1.42^{+0.62}_{-0.56}$	$-1.019^{+0.075}_{-0.080}$

[Planck 2015 results. XIII]

- Neutrinos → No departure from base ΛCDM
- Curvature → No departure from zero
- No running of perturbation spectral index
- Dark energy equation of state consistent with cosmological constant
- Helium abundances consistent with BB nucleosynthesis

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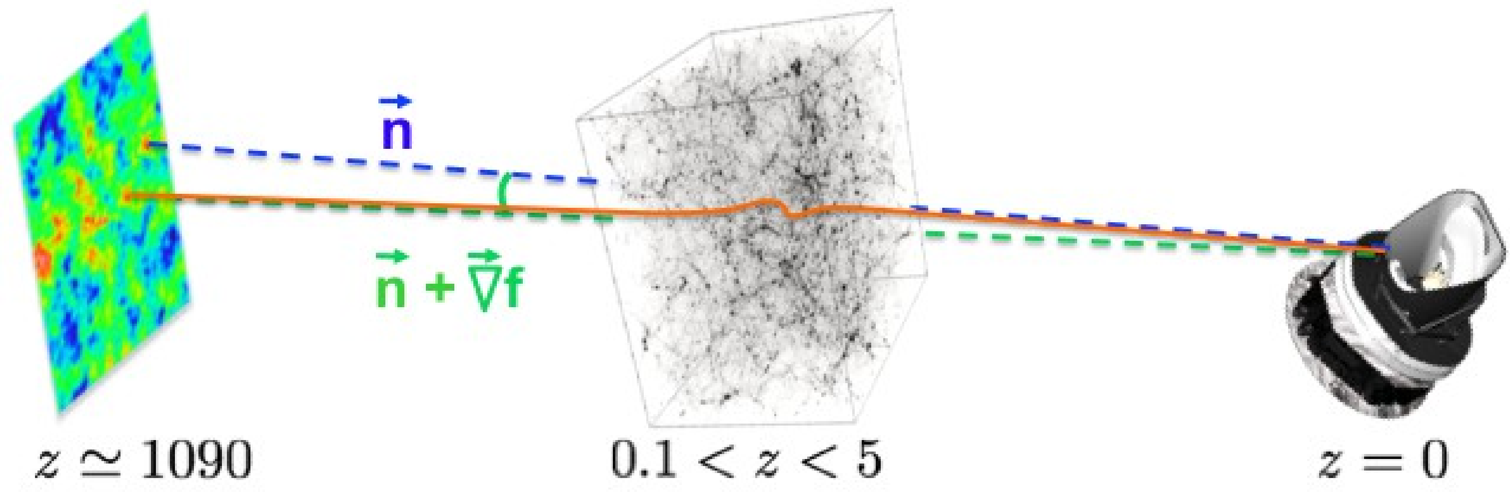
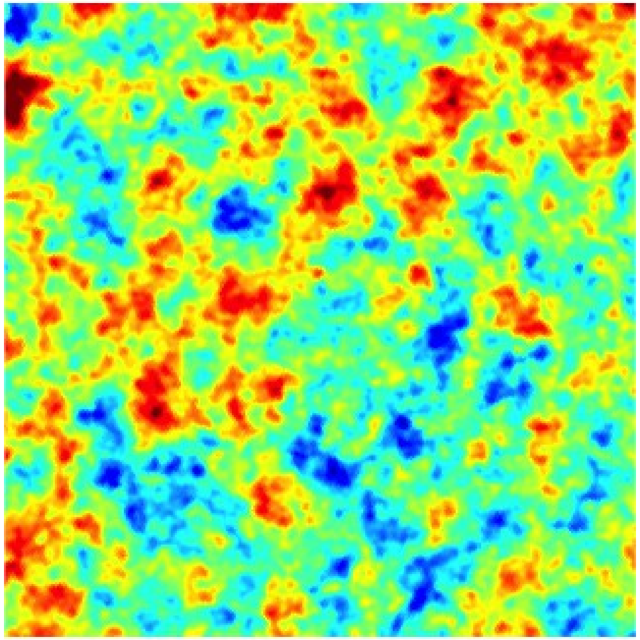
Lensing



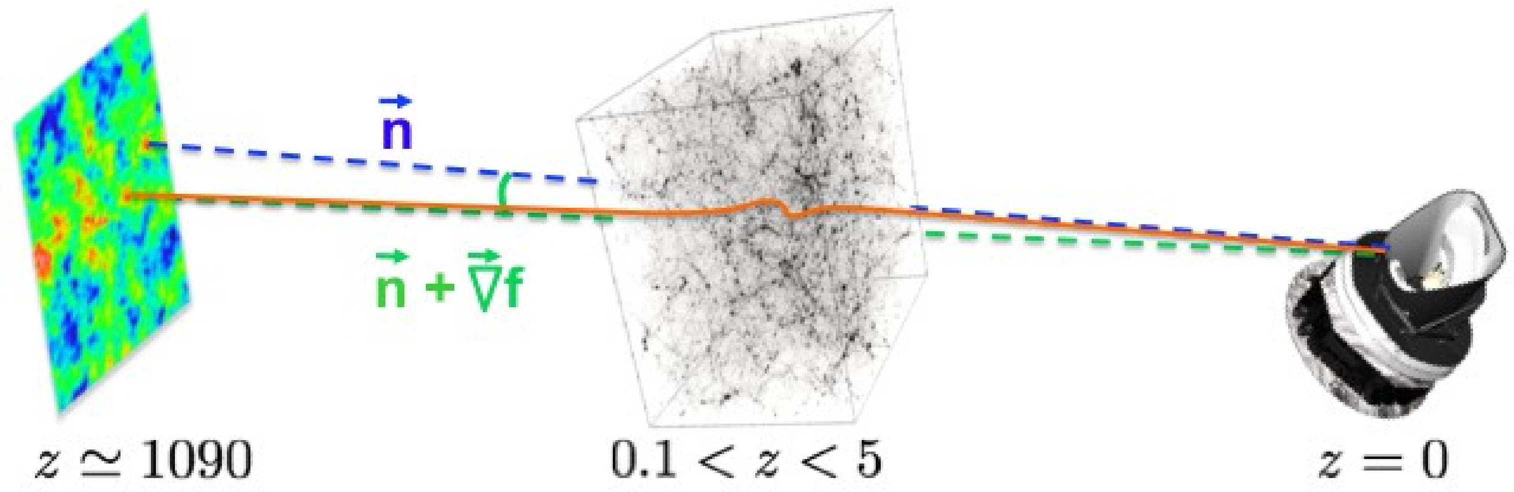
Gravitational lensing of CMB by large scale structures
=
Secondary anisotropy of the CMB

- Lensing generates non-gaussianity
- Allows to reconstruct the integrated gravitational potential between z = 1100 and z = 0
- Impacts the temperature power spectrum (smooth peaks at high-l)

Unlensed T



Lensing



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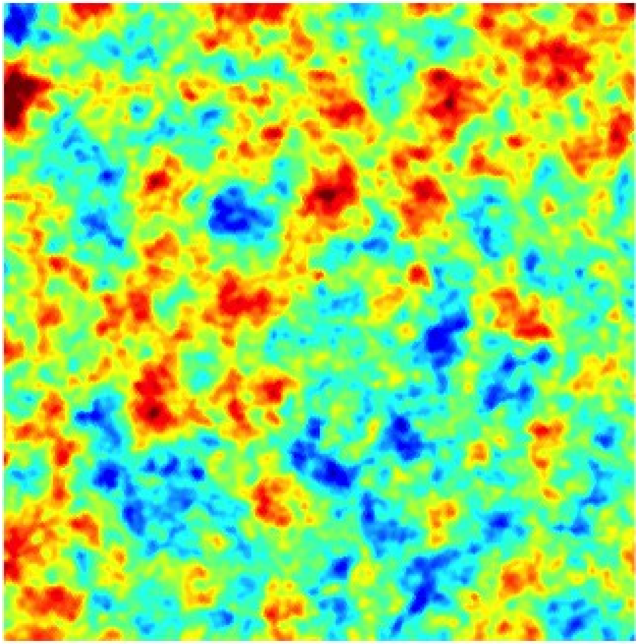
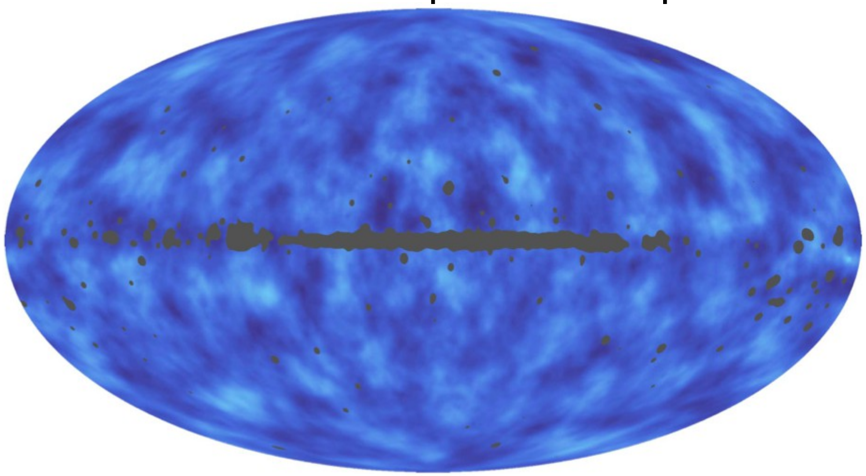
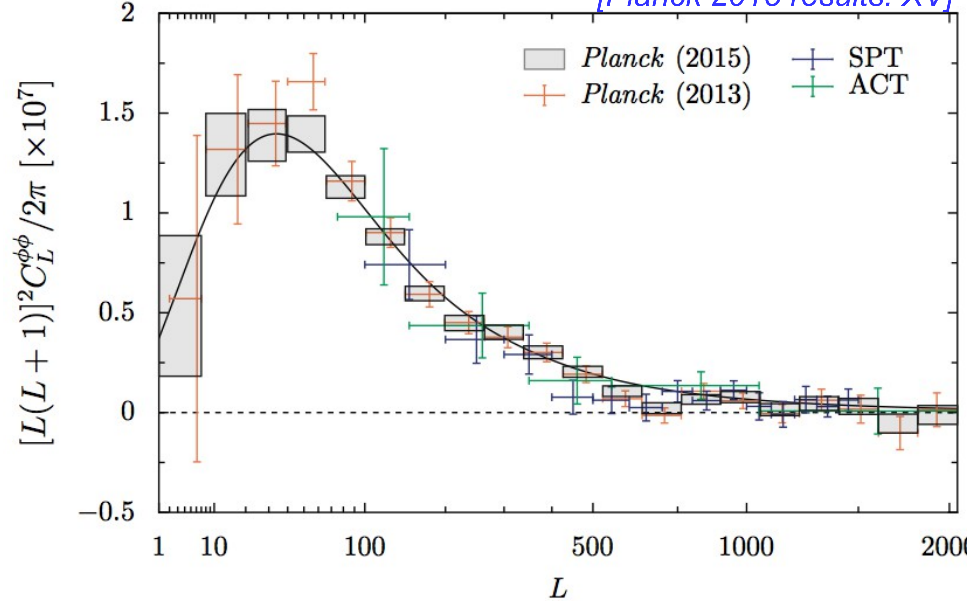


Lensing

Gravitational potential map



[Planck 2015 results. XV]



- Lensing generates non-gaussianity
- Allows to reconstruct the integrated gravitational potential between z = 1100 and z = 0
- Impacts the temperature power spectrum (smooth peaks at high-l)
- Is insensitive to optical depth → breaks the (A_s –) degeneracy (but less so than low-l polar)

Lensing power spectrum C_l independent and in agreement with expectation from CMB alone

→ strong consistency check

Lensing likelihood can be added to parameter estimation

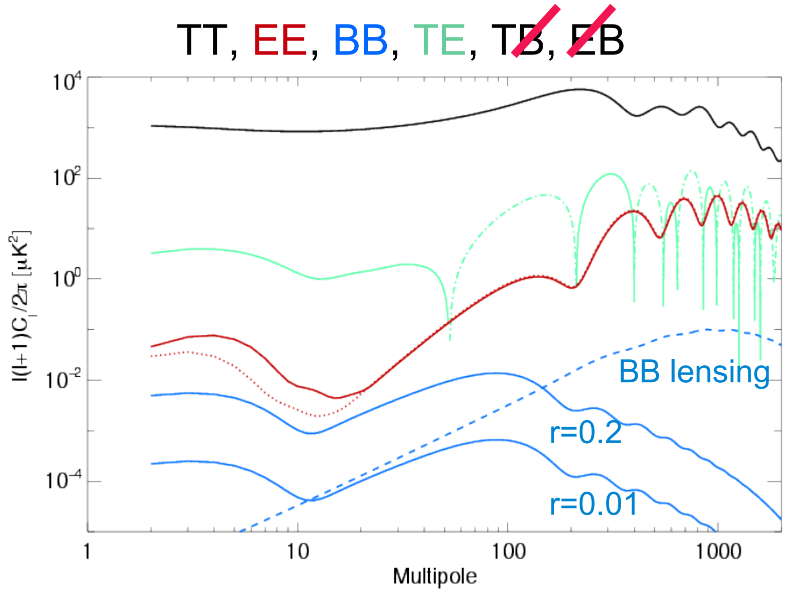
Lensing B modes

Gravitational lensing mixes E and B modes
→ generates B modes from E modes

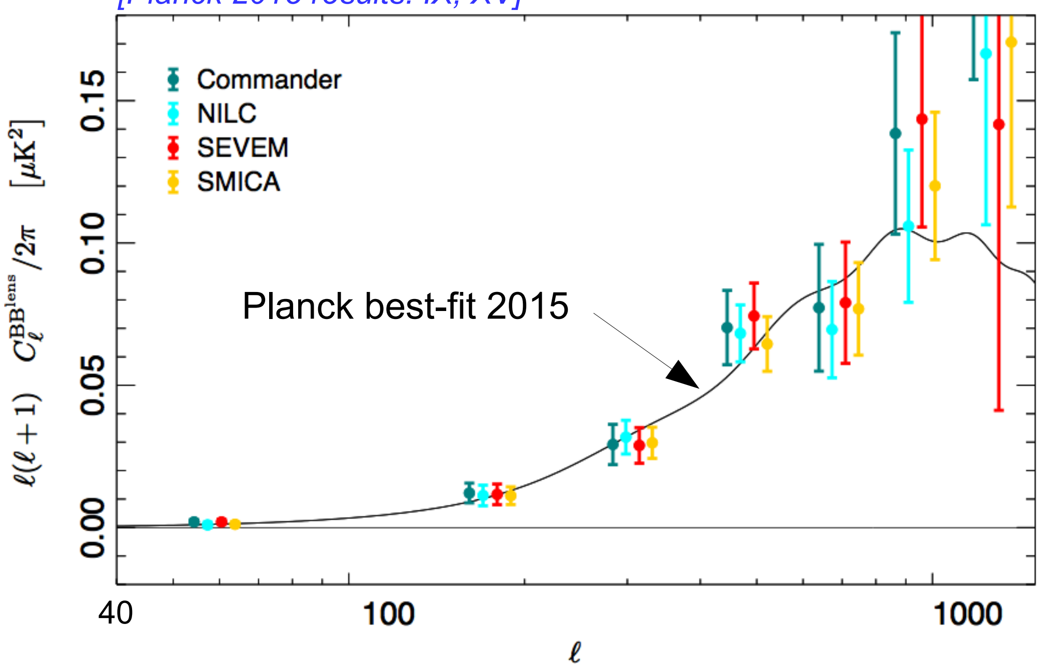
Approach:

- Given E and Φ, build estimator of B lensing
- Cross correlate the estimator with Planck B-mode sky

  → **lensing B-mode detection and spectrum**



[Planck 2015 results. IX, XV]



- 10 – 12 sigma detection of lensing B modes
- Large ell-range compared to ground-based experiments

  → Polarbear (500 < ell < 2000)

  → SPT (500 < ell < 2500)

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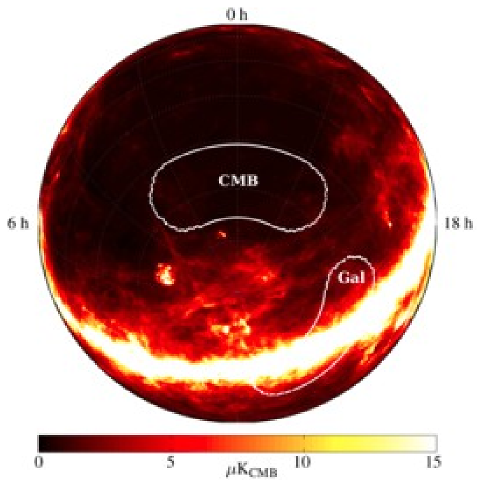
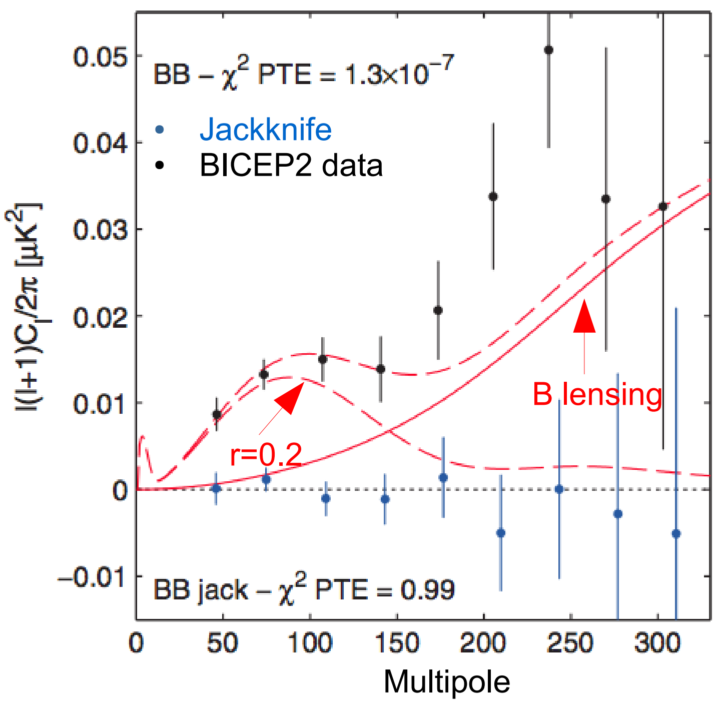
The search for primordial B modes

1. March 2014: BICEP 2 detection of B-modes *[BICEP2 collaboration, PRL, 112, 241101]*



- 512 polarised TES detectors at 150 GHz
- ~ 590 days of CMB observations at South Pole
  → extremely deep polarised observations on ~ 1% of the sky
- Extreme control of systematic effects
- **5-sigma B modes detection**



Interpretation of the B mode excess

- Need to decorrelate from polarised dust and synchrotron
- Use WMAP K-band for synchrotron → negligible
- No polarised dust template available at the time
  → use 5 models to estimate dust polarisation in this region
- **Conclusions**: primordial B modes with $r_{0.05}$ = 0.2 +/- 0.07

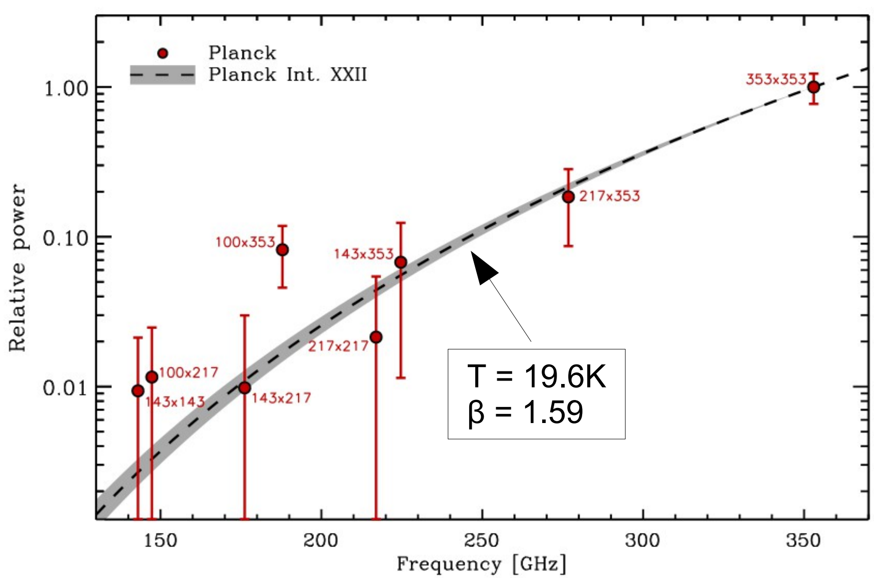
The search for primordial B modes

2. September 2014: Planck polarised dust spectrum *[Planck collaboration, arXiv:1409.5738v2]*

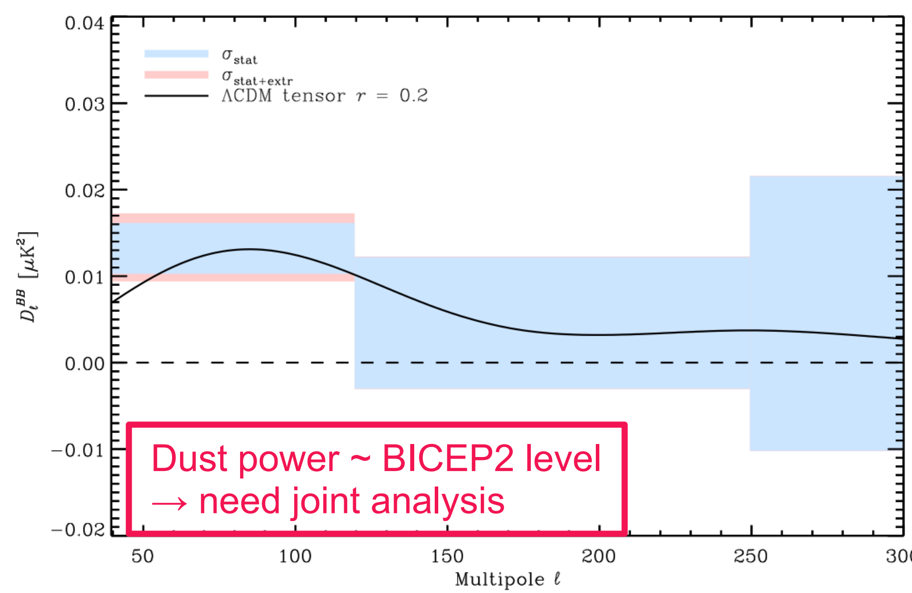
- Provides a statistical view of polarised dust properties
  → new insights into interstellar dust physics
  → determination of the **level of contamination for CMB polarised experiments**

- Analysis based on 353 GHz Q and U maps
  → Compute BB spectrum in BICEP2 field
  → Scale the result to BICEP2 150 GHz band using greybody $I_{\rm d}(\nu) \propto \nu^{\beta_{\rm d}} B_\nu(T_{\rm d})$

Planck BB spectra in agreement with greybody

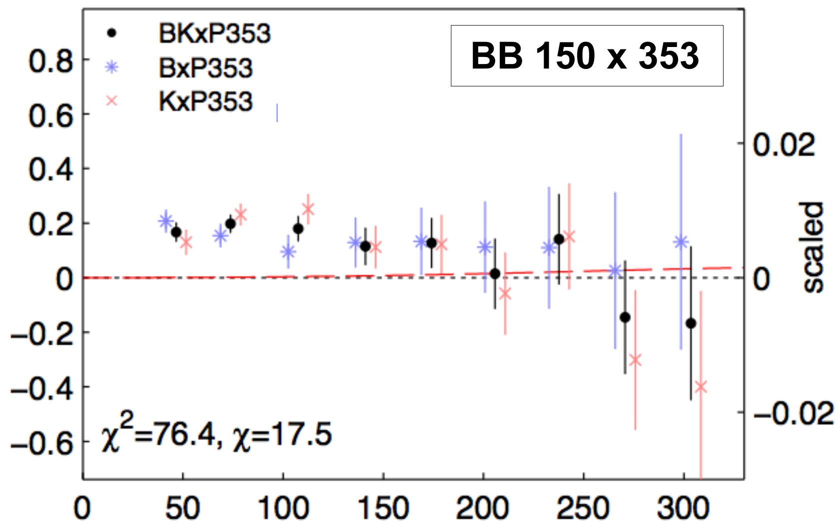


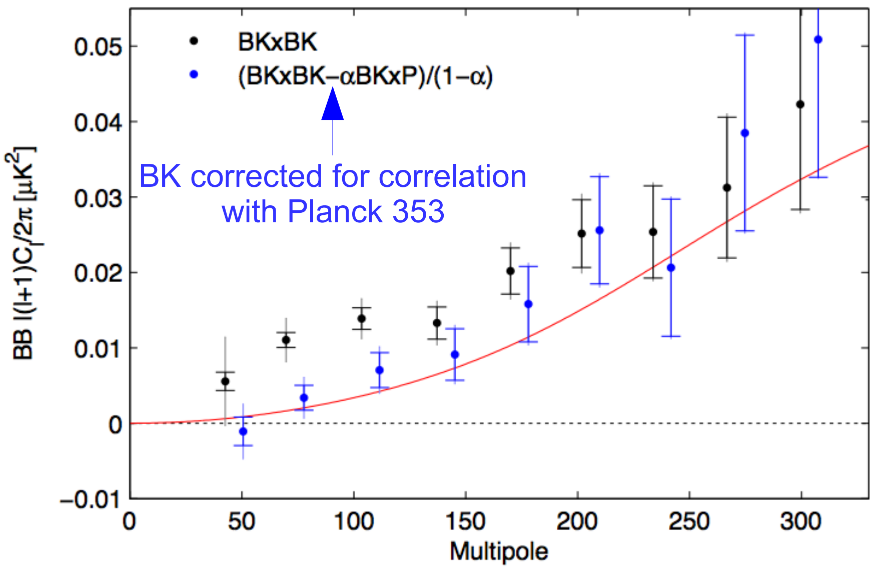
353x353 BB spectrum in B2 field, scaled to 150 GHz

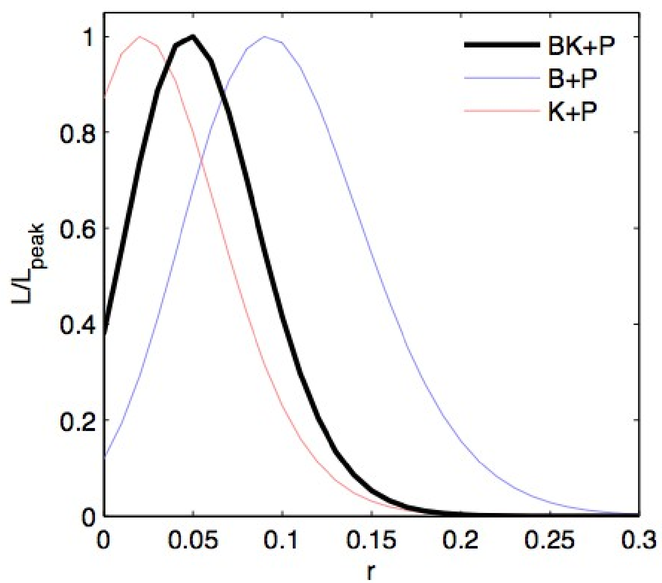


The search for primordial B modes

3. February 2015: BICEP2/Keck/Planck joint analysis *[BICEP2/Keck/Planck collaborations, PRL, 114, 101301]*







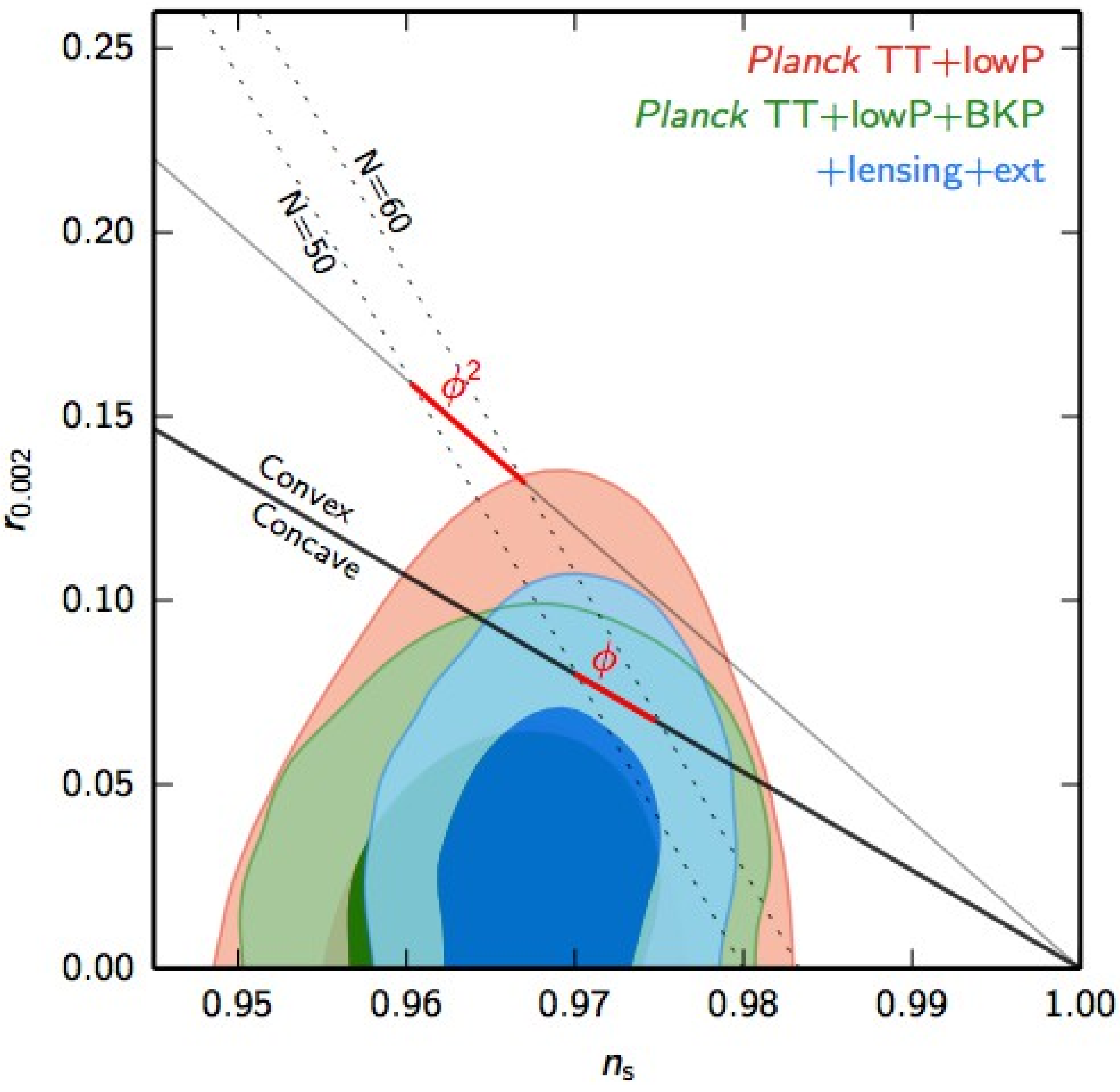
- Significant correlation between BK and Planck 353
- Fit 2-component model: tensor modes (r) + dust (A_d)
  → no detection, but upper limit

$r_{0.05} < 0.12$ at 95% CL

Soon more to come with: upcoming Planck analyses, Keck second channel at 95GHz (ongoing analysis), BICEP 3 with increased sensitivity at 95GHz

Early Universe physics

[Planck 2015 results. XIII]



- Single-field inflationary models predict $n_s < 1$
- 2013 and 2015 Planck analysis exclude $n_s = 1$
- Joint Planck + BKP likelihood $\rightarrow r_{0.002} < 0.09$ (95% CL)
- Rules out quadratic inflationary potentional $V(\phi) \propto m^2\phi^2$

More in Planck 2015 results XX.: constraints on inflation

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Conclusions

Planck products:

- 9 frequency maps in intensity
- 4 (soon 7) frequency maps in polarisation
- CMB temperature anisotropy maps, I, Q, and U (ell > 30)
- Compact source and SZ galaxy cluster catalogues
- Galactic foregrounds: free-free (intensity), CO (intensity), spinning dust, thermal dust and synchrotron (intensity and polarisation)
- Lensing deflection field map
- Likelihoods [coming soon]

Planck temperature + polarisation cosmological results

- No compelling evidence for extensions beyond 6-parameter ΛCDM (no extra neutrino, flat universe, cosmological constant, etc.)
- Optical depth smaller than that of WMAP → later reionization
- Planck + BKP → best current upper limit on tensor-to-scalar ratio
- Tightest limits to date on: primoridal non-gaussianity, primordial magnetic fields