Results from the Planck Satellite

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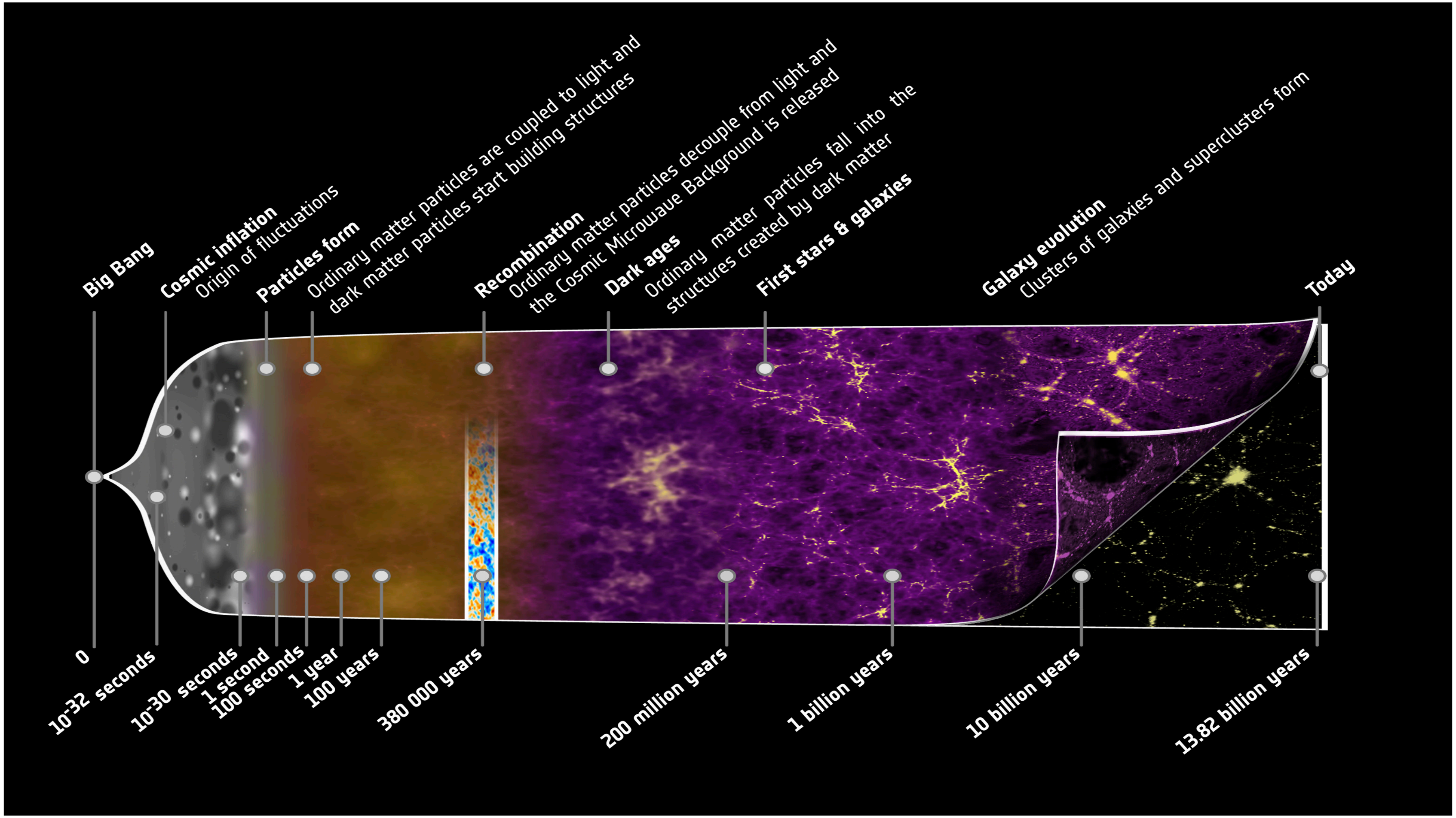
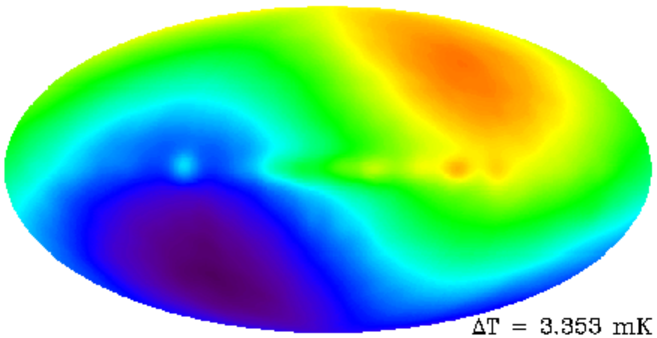
History of our Universe

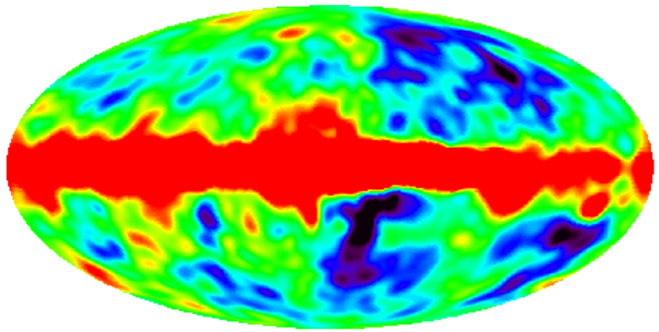


Cosmic Microwave Background

- Discovered by Penzias & Wilson (1964)

- Perfect Black Body spectrum (to the limit of the instruments) at 2.725 K measured by the COBE satellite

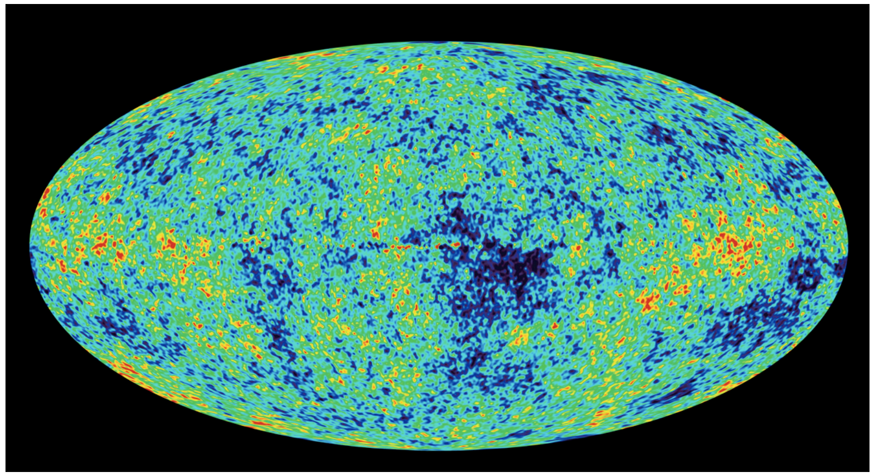




- Small temperature fluctuations ~ 100 μK

- Several ground-based and balloon experiments measured the CMB since.

WMAP satellite (2003) :



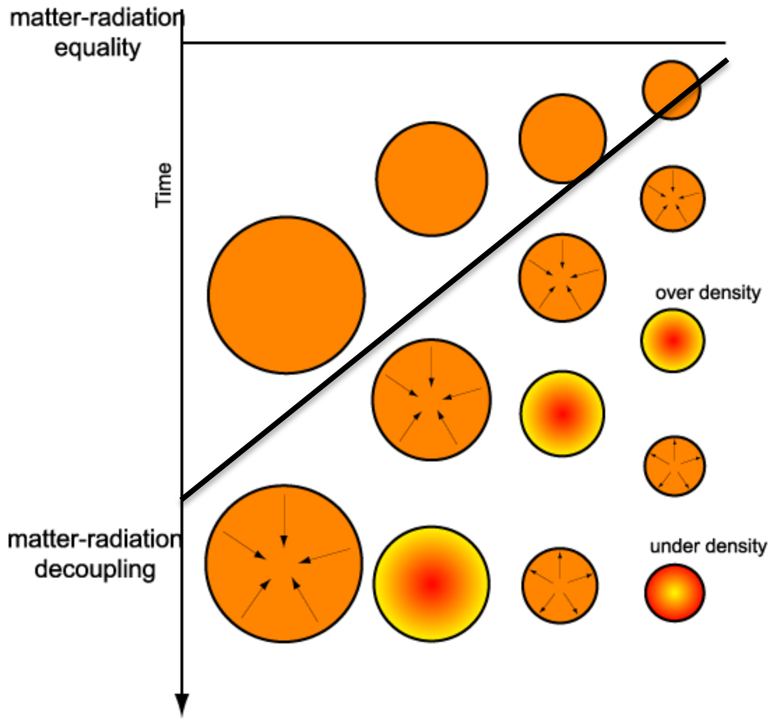
CMB fluctuations

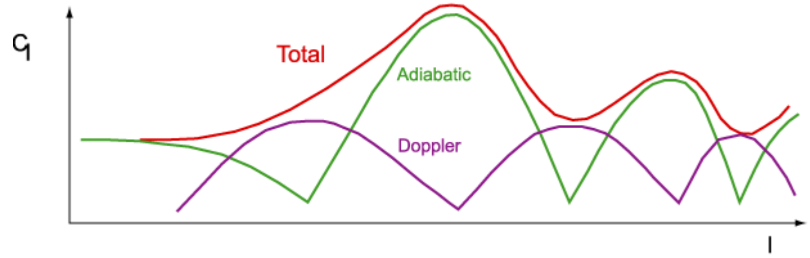
- CMB fluctuations are the consequence of metric fluctuations (scalar and tensor) in the primordial Universe. In the standard picture, primordial fluctuations result from quantum fluctuations growing to cosmological scales during inflation.

- While the horizon grows, fluctuations are entering the horizon and start to oscillate under the effect of radiation pressure and gravitation.

Some scales are at their maxima after decoupling → Acoustic peaks

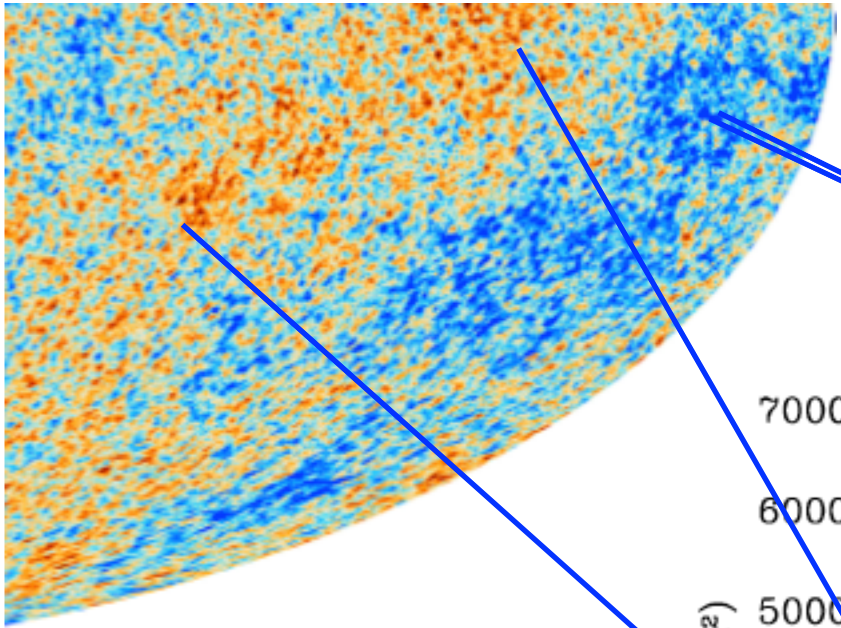
Dark matter fluctuations grow: no radiation pressure.





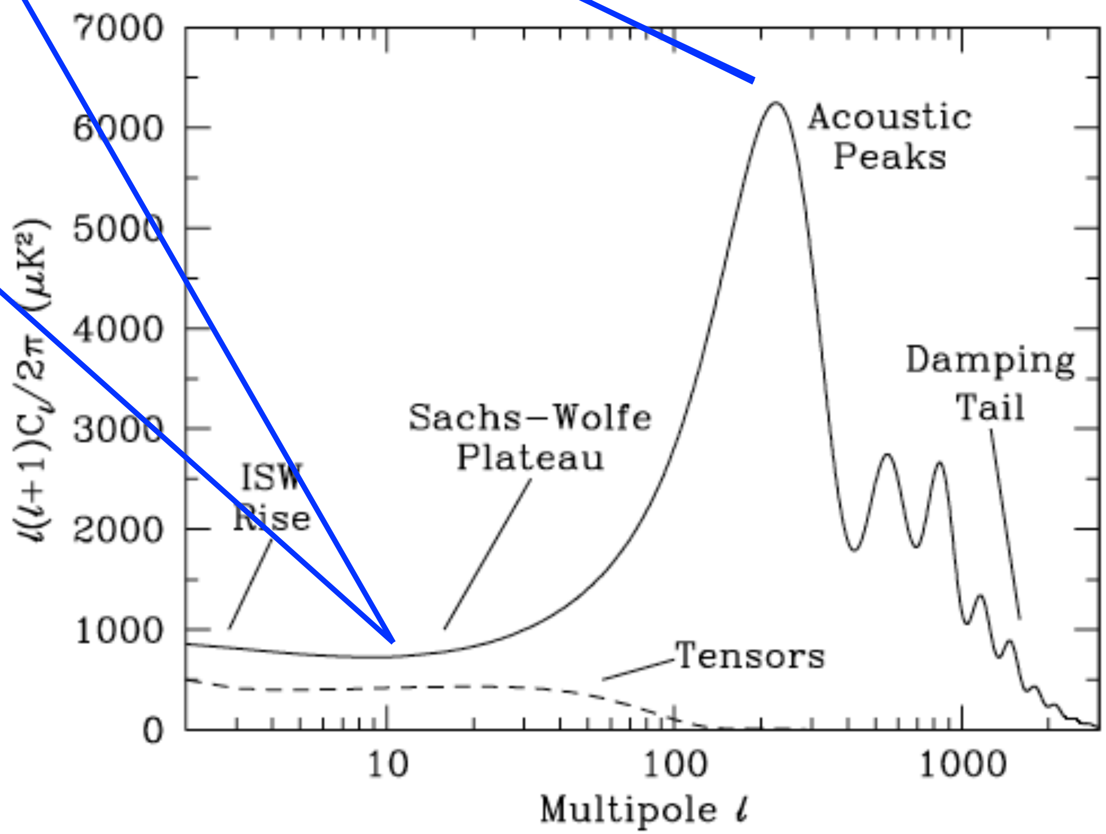
Adapted from Lineweaver (1998)

Power spectrum



$$\frac{\delta T}{T} = \sum_{\ell=0}^{\infty} \sum_{m=-\ell}^{\ell} a_{\ell m} Y_{\ell m}(\theta, \phi)$$

$$C_\ell = < a_{\ell m} >$$



Gaussian fluctuations:
All physical information is contained in the power spectrum.

Spectrum depends on cosmological parameters

Cosmological parameters

Parameter	
$\Omega_b h^2$	Baryon density today
$\Omega_c h^2$	Dark matter density today
$100\theta_{MC}$	Acoustic horizon size at decoupling
τ	Reionization optical depth
n_s	Primordial scalar spectrum index
$\ln(10^{10} A_s)$	Primordial scalar spectrum amplitude

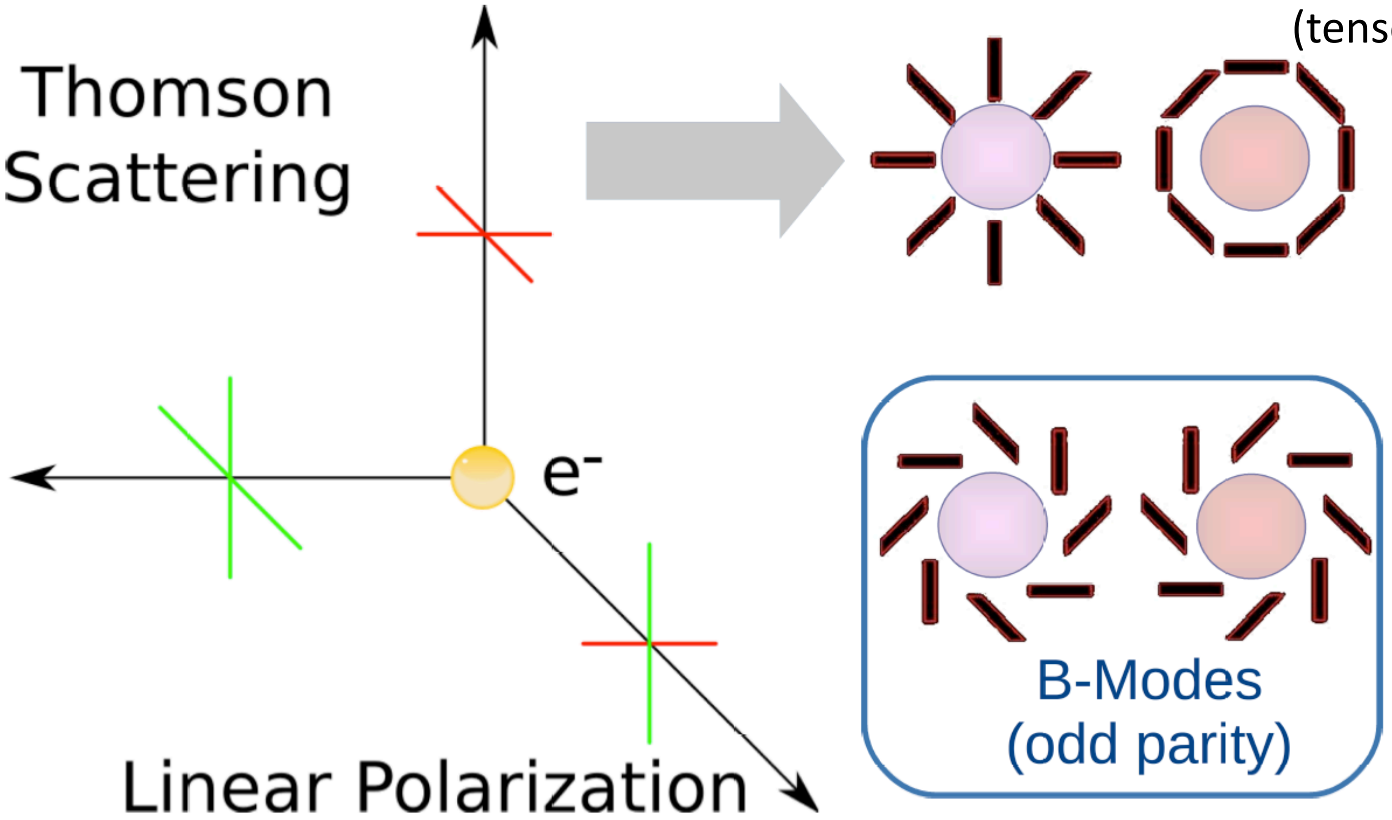
Derived parameters:

Ω_Λ	Dark energy density
H_0	Hubble constant today
Age/Gyr	Age of the Universe

⋮

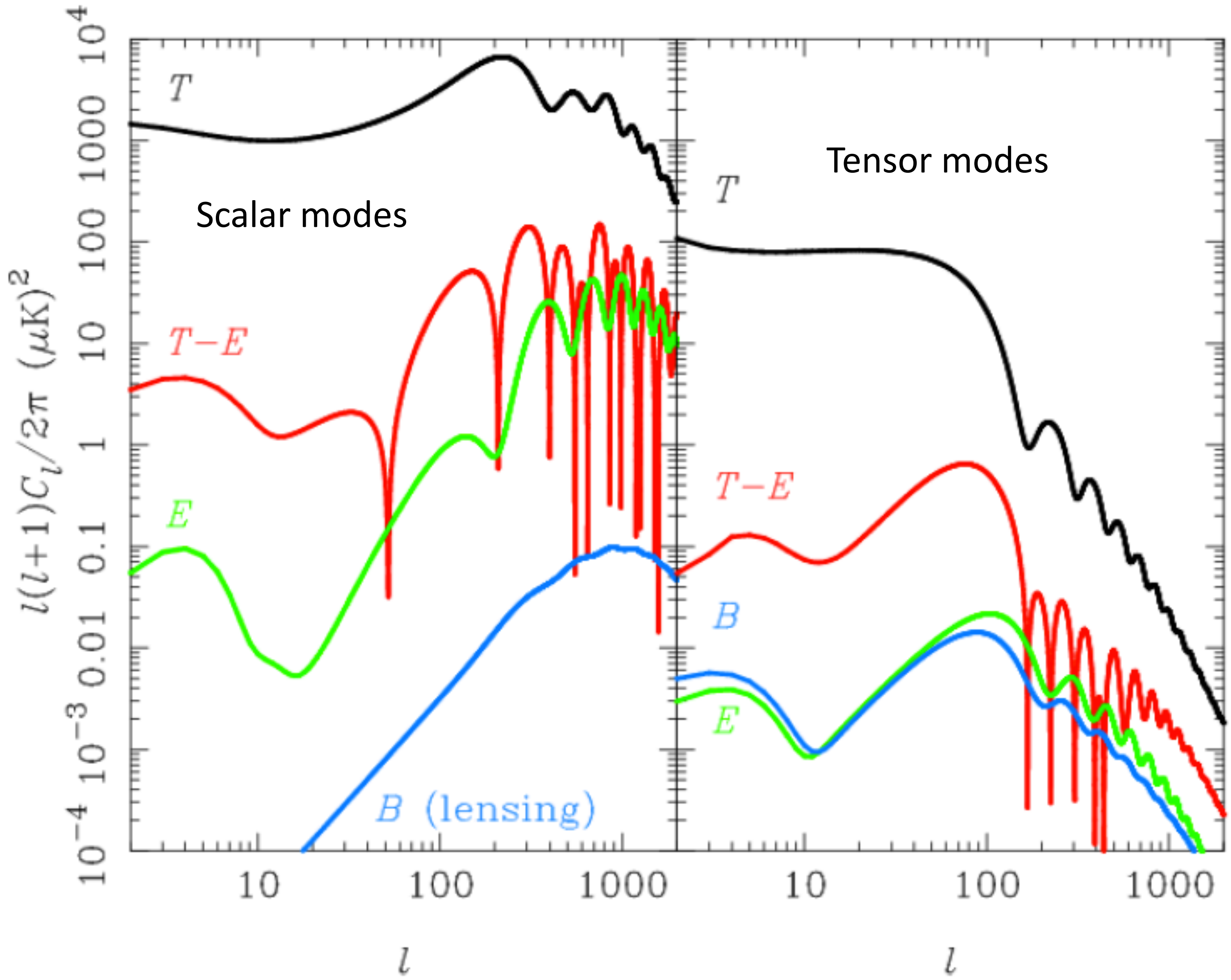
Polarization

E modes are produced by density perturbations and gravitational perturbations (tensor modes)



Produced by gravitational waves only

Polarization power spectra



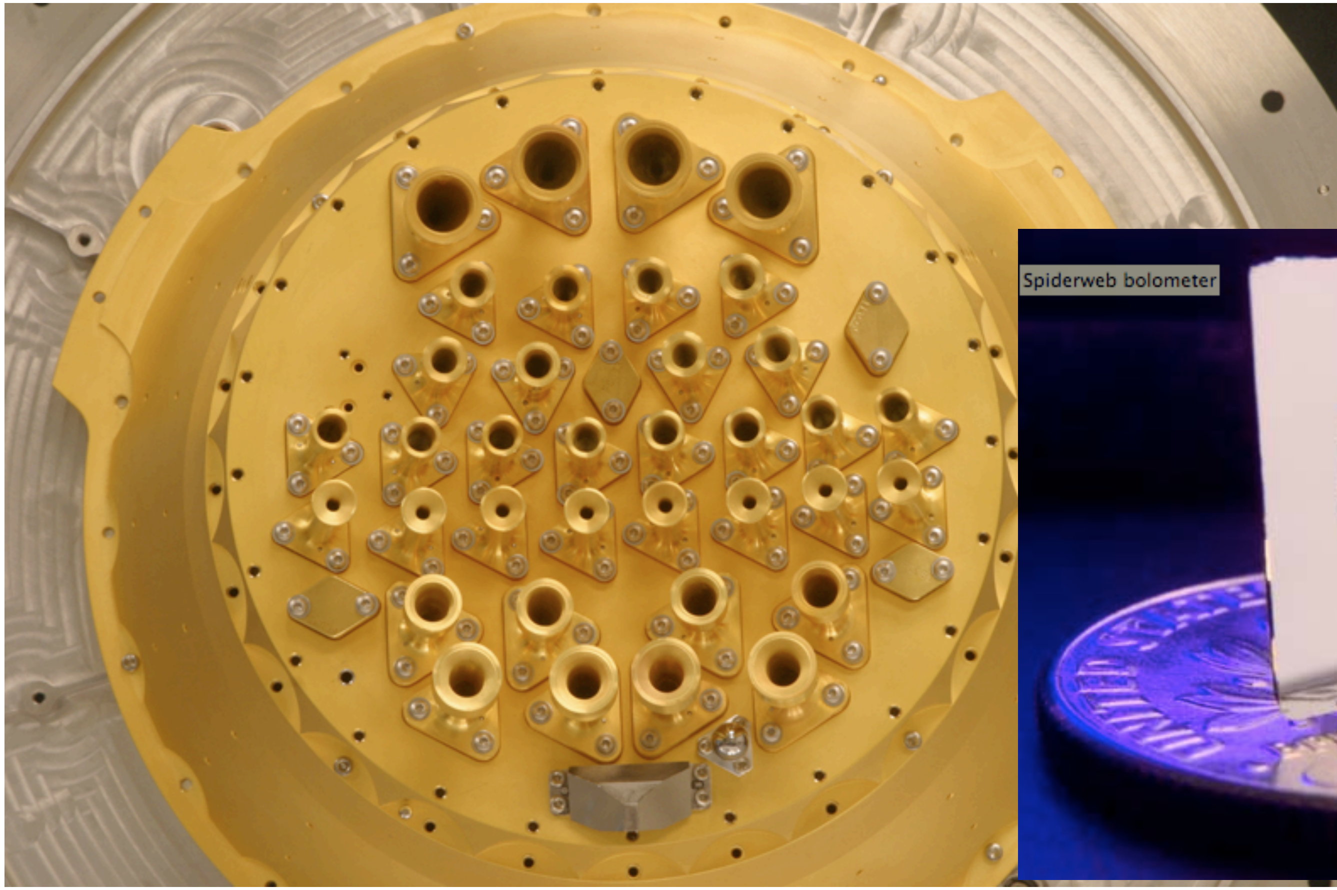
The Planck satellite

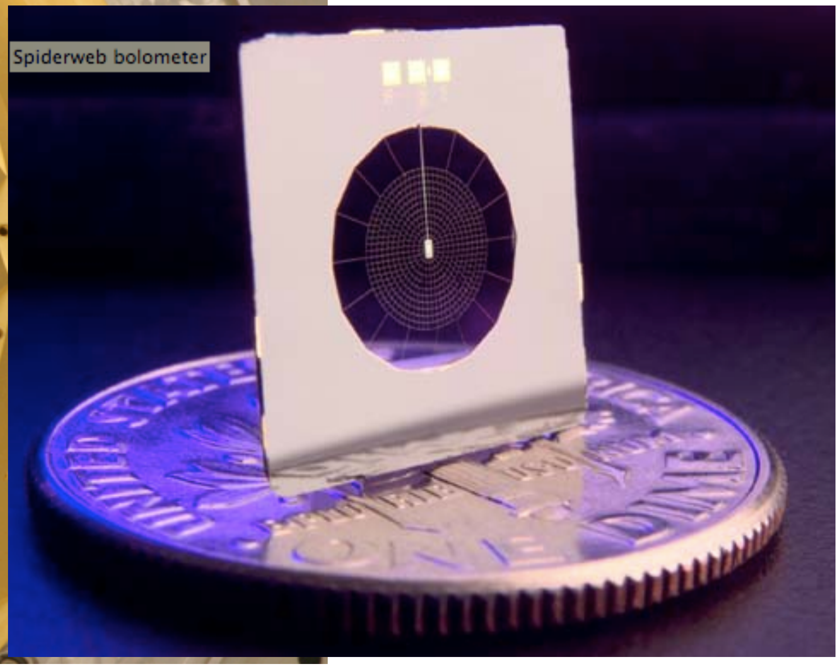
Planck

- 1.5 m off-axis Gregorian telescope
- 2 instruments:
- LFI (20K)
- HFI (0.1K)
- Angular resolution : 30’ to 5’
- 650 M€, 600 scientists, 29 laboratories, 14 countries (Europe, USA, Canada)

The Planck detectors

- LFI instrument: HEMT antennas, 3 bands between 33 et 70 GHz
- HFI instrument: bolometers cooled down to 100 mK, 6 bands between 100 et 857 GHz

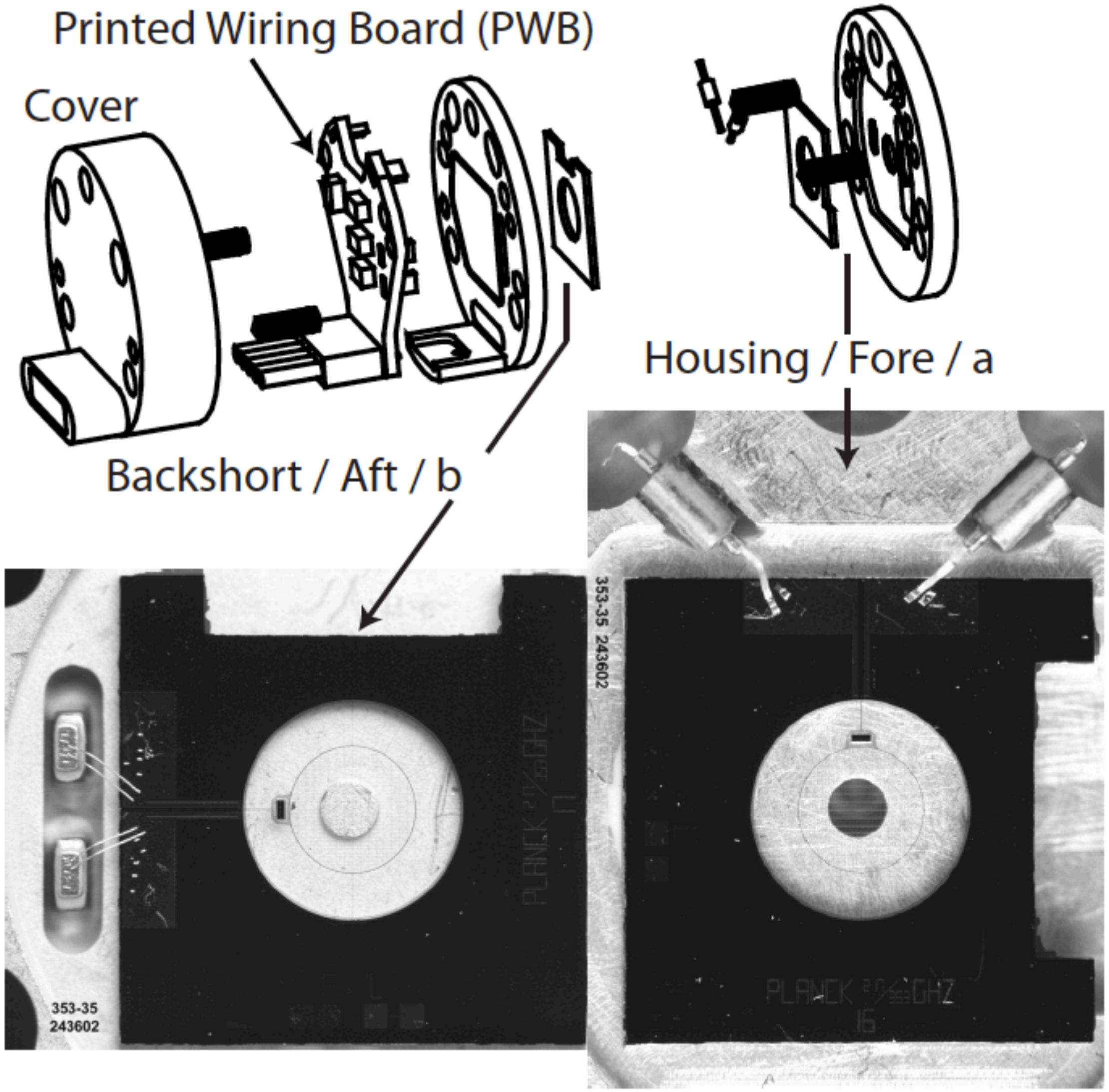




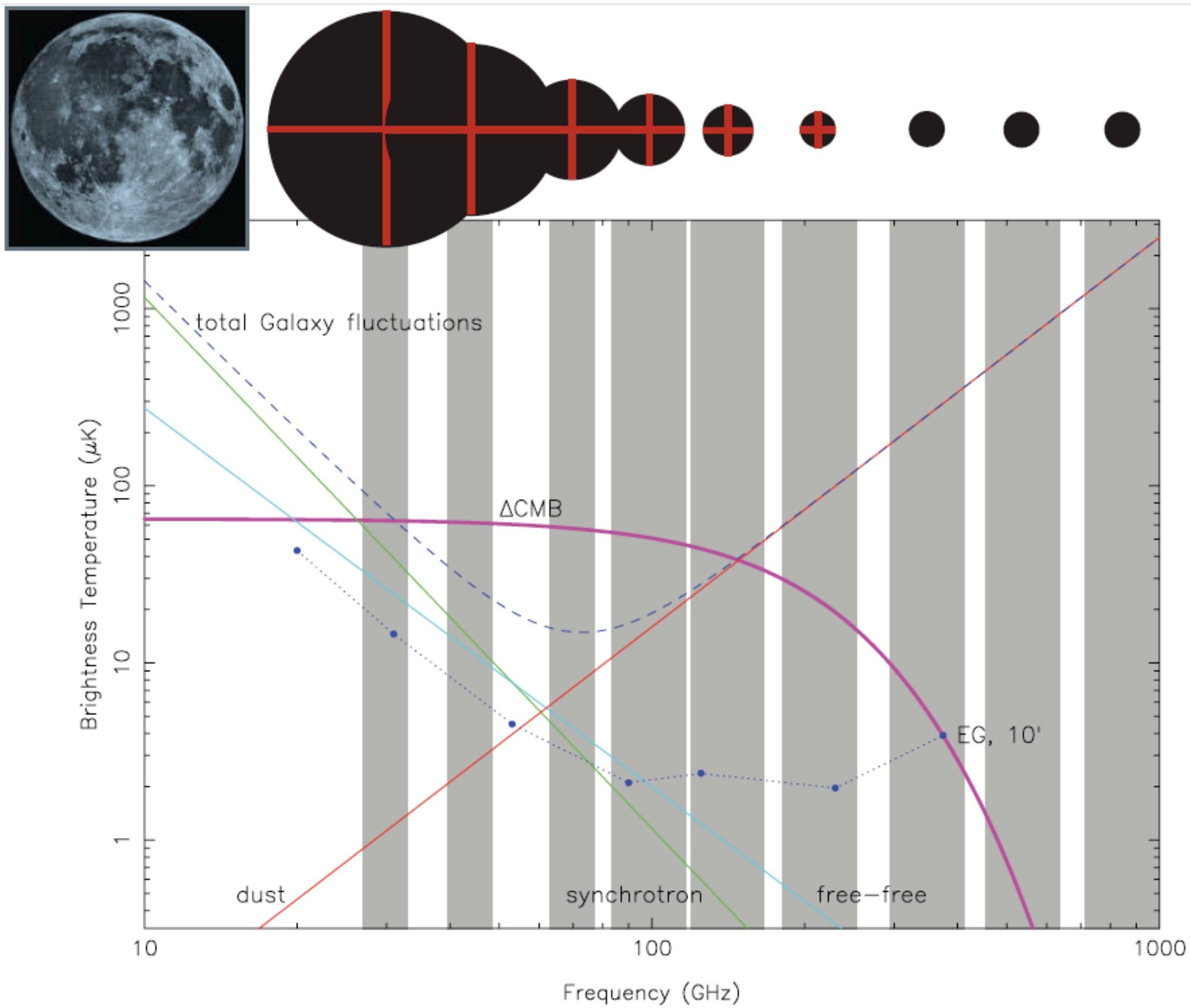
Polarization Sensitive Bolometers

2 superimposed bolometers, sensitive to the two perpendicular linear polarizations

Combinations of PSB oriented at 45 degrees from each other allow to measure I, Q and U Stokes parameters

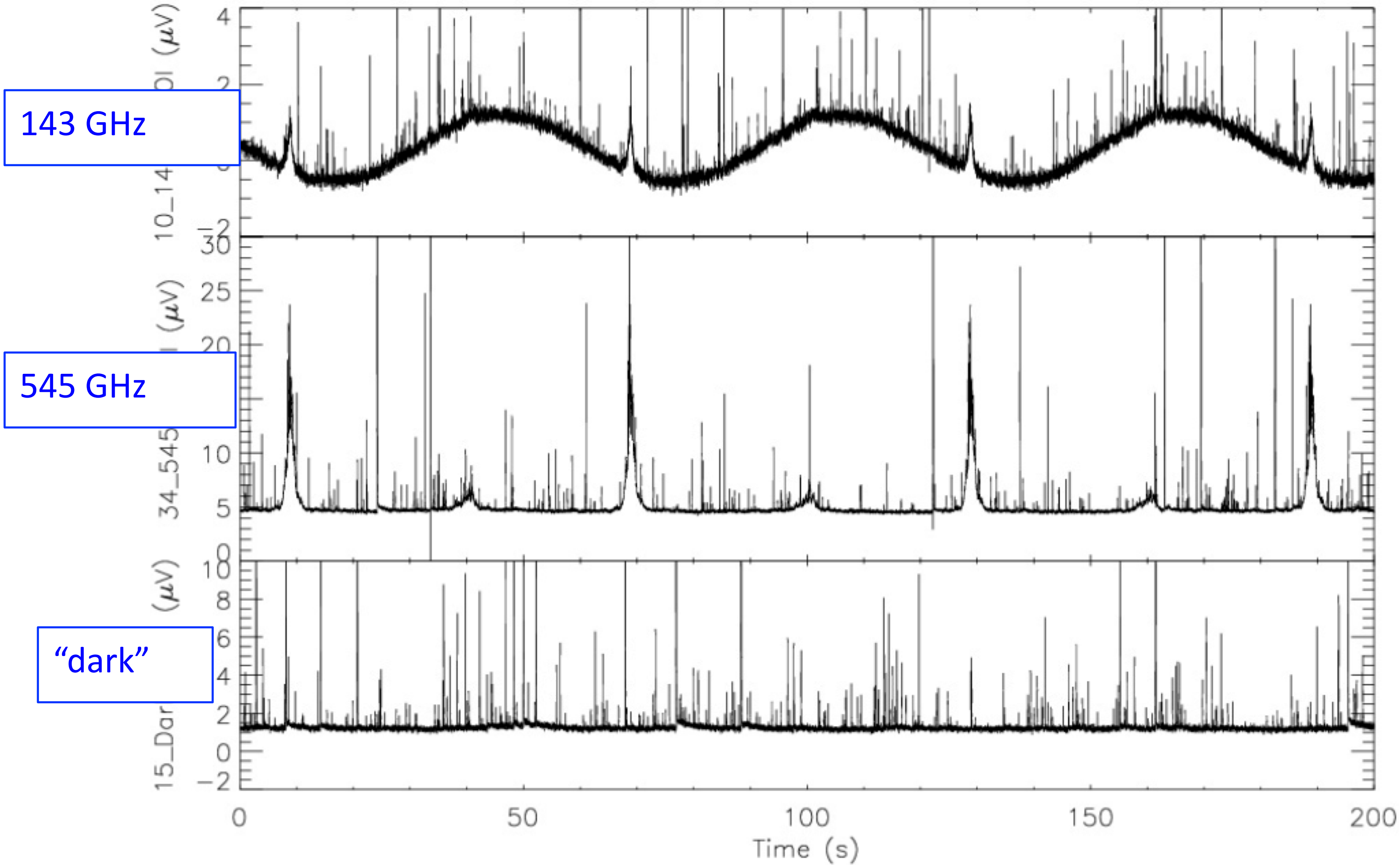


Observation frequencies

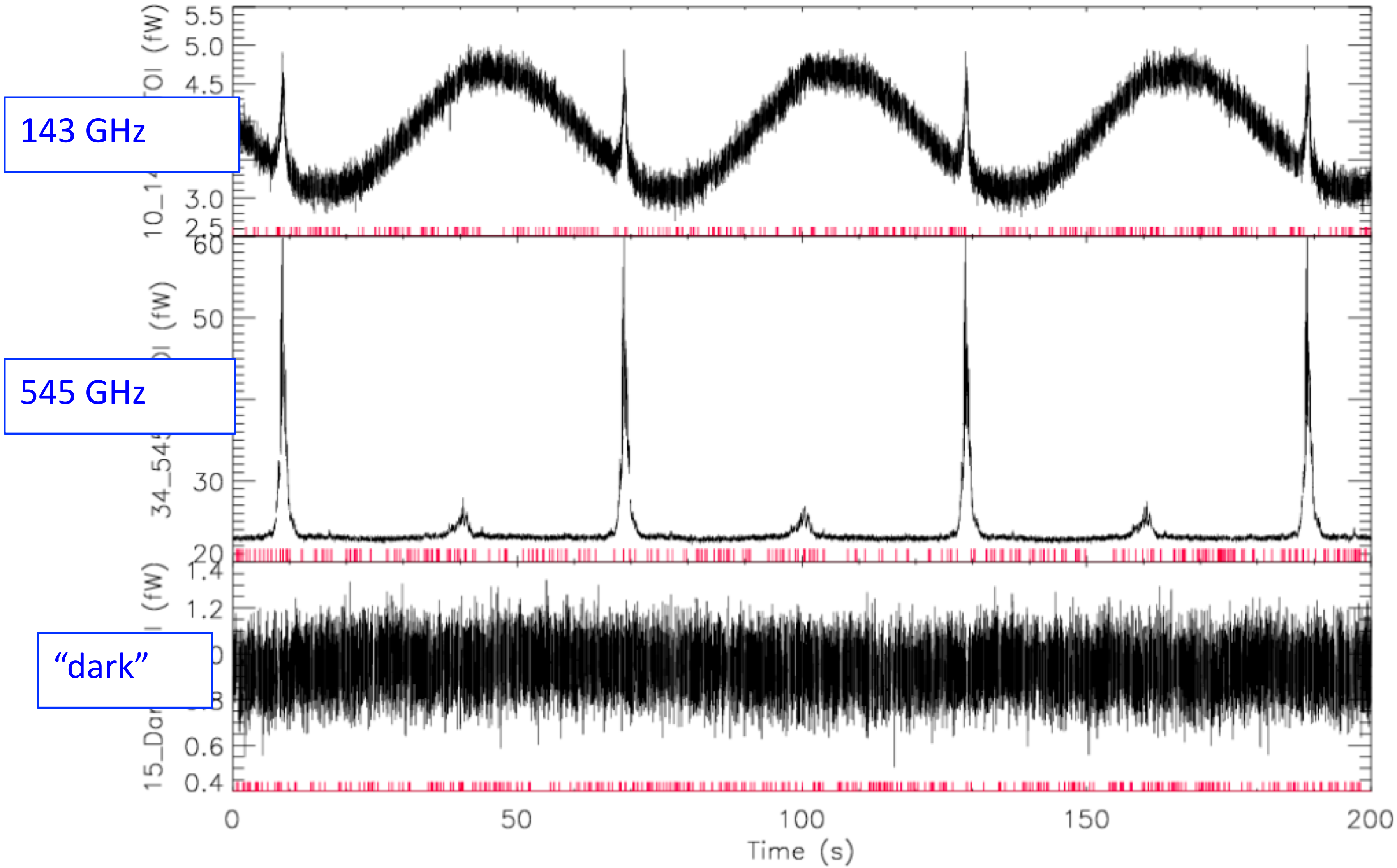


- Large frequency covering: 9 bands
  Better subtraction of foreground emissions
- Measurement of the polarisation of light

Planck HFI data

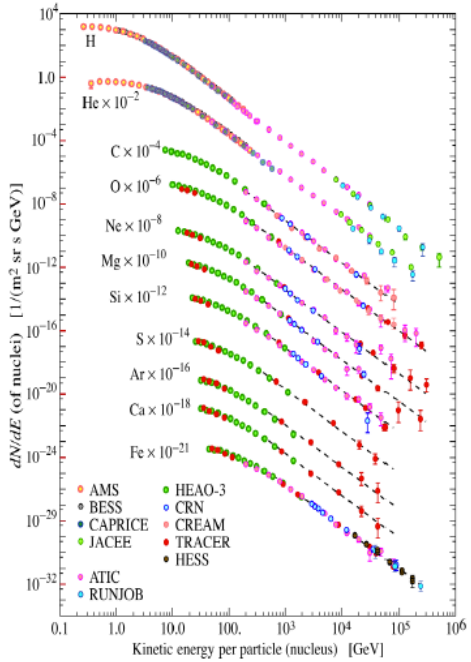


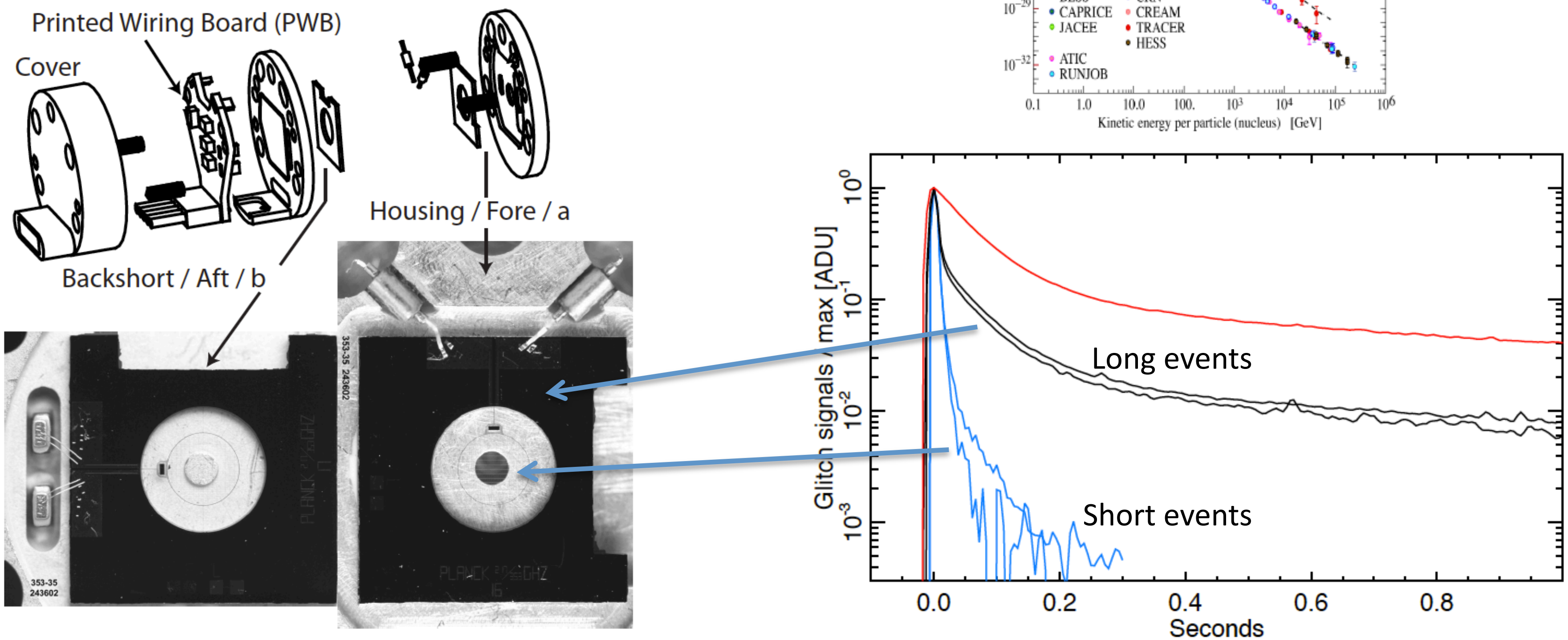
Planck HFI “cleaned” data



Interaction of cosmic rays with detectors

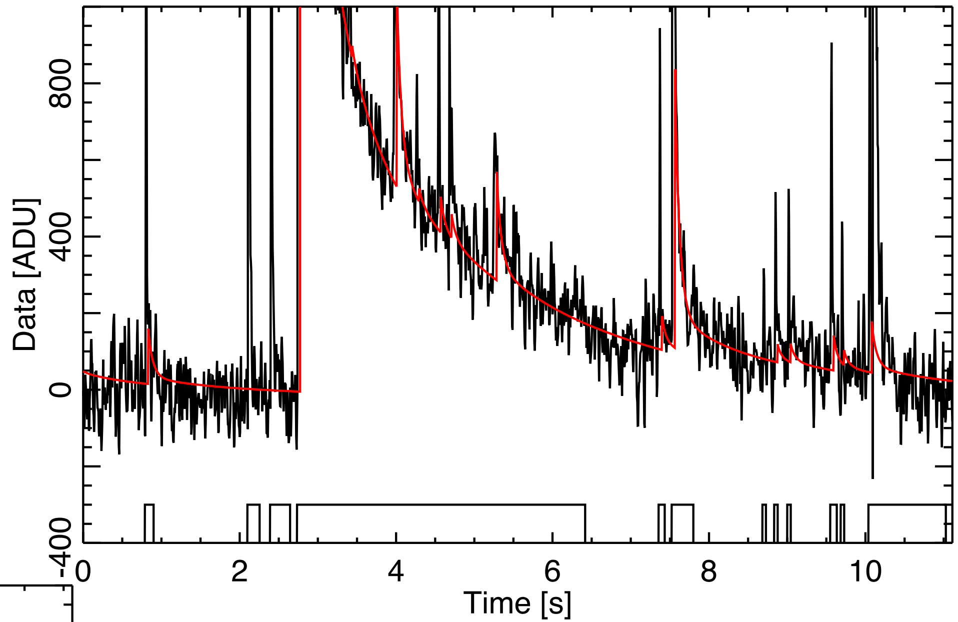
Galactic cosmic rays interact with Planck detectors and leave a strong signal in data.

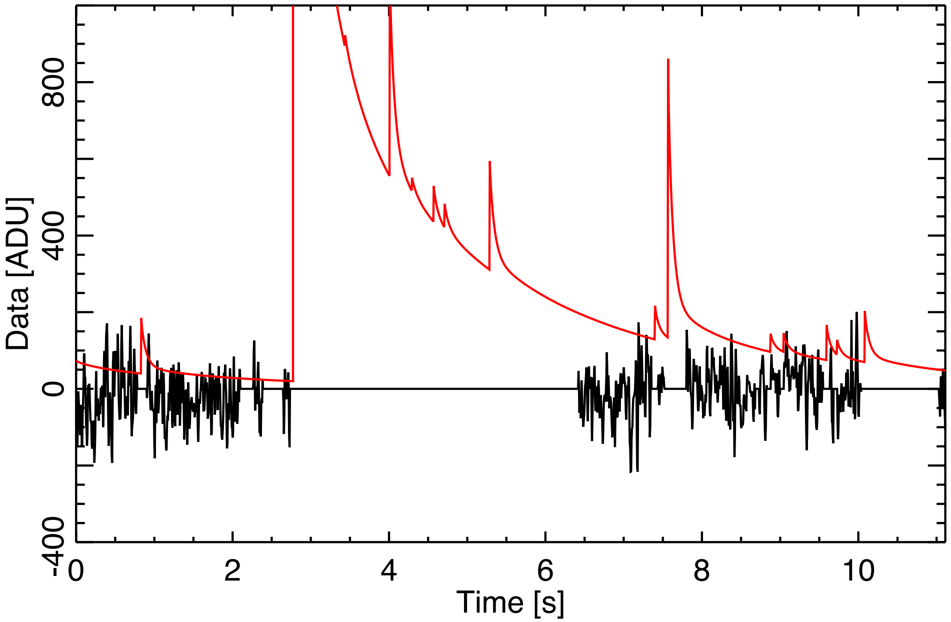




Intensive data processing

Cosmic ray signal removal:





- ADC non-linearity correction
- Deglitching, CR signal removal
- 4K line subtraction
- Gain correction
- Bolometer transfer function correction including long time constants
- Map-making and large scale noise removal

Foregrounds

Astrophysical components emit at the same wavelength than the CMB:

Galactic components:

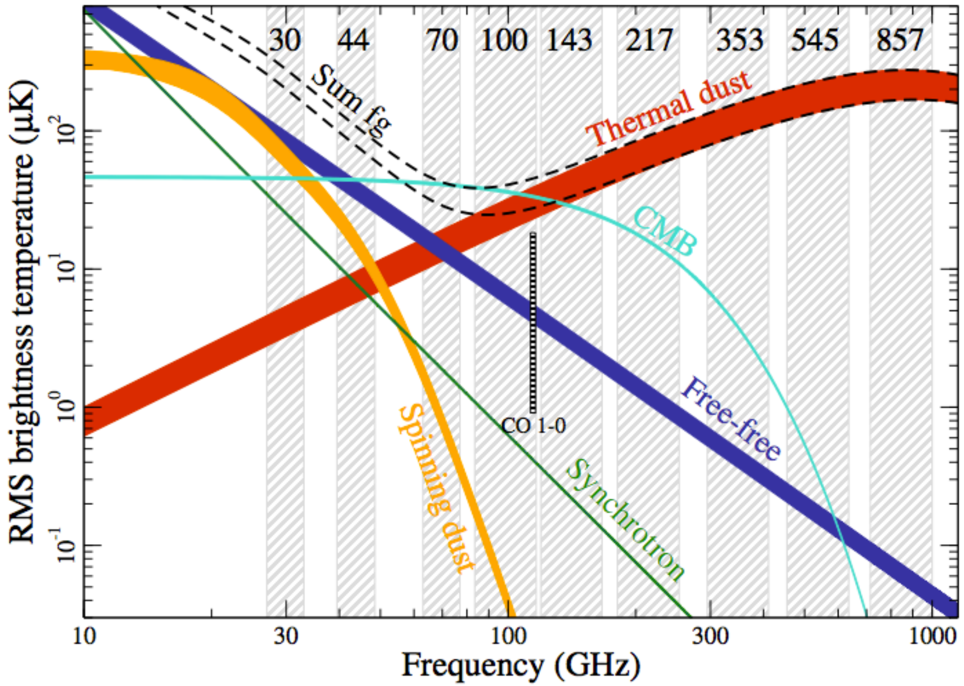
- Thermal dust
- Synchrotron emission
- free-free emission
- spinning-dust emission
- CO emission

Solar system:

- Zodiacal light

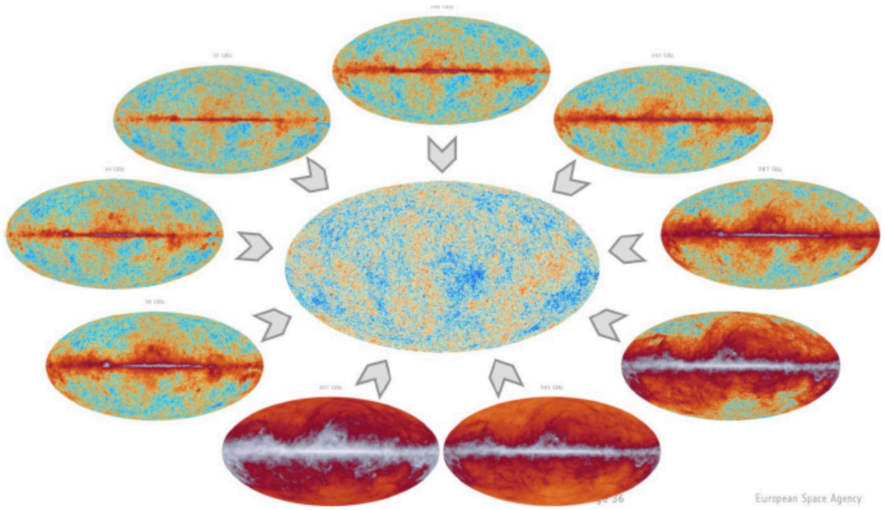
Extragalactic:

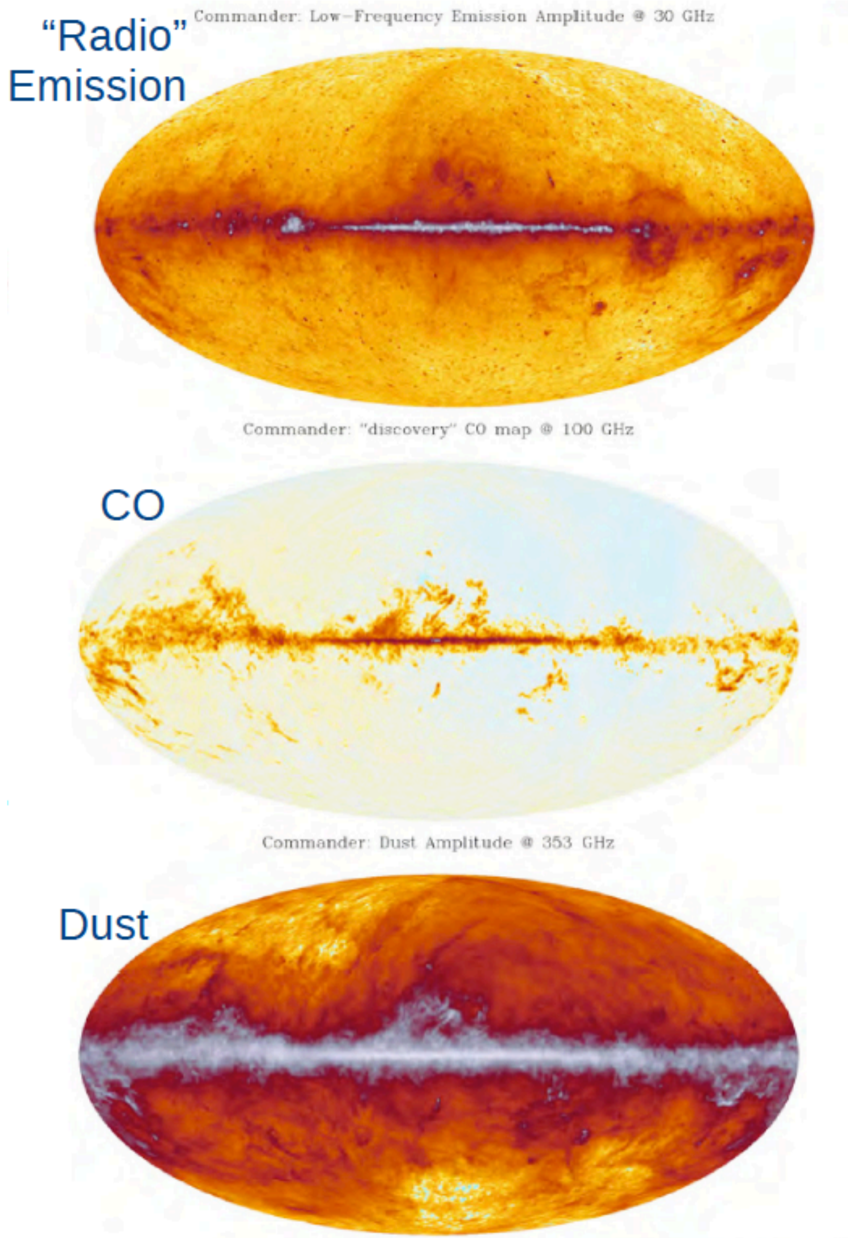
- Radio and submm sources
- Sunyaev-Zeldovich effect



Component separation is needed

Component separation

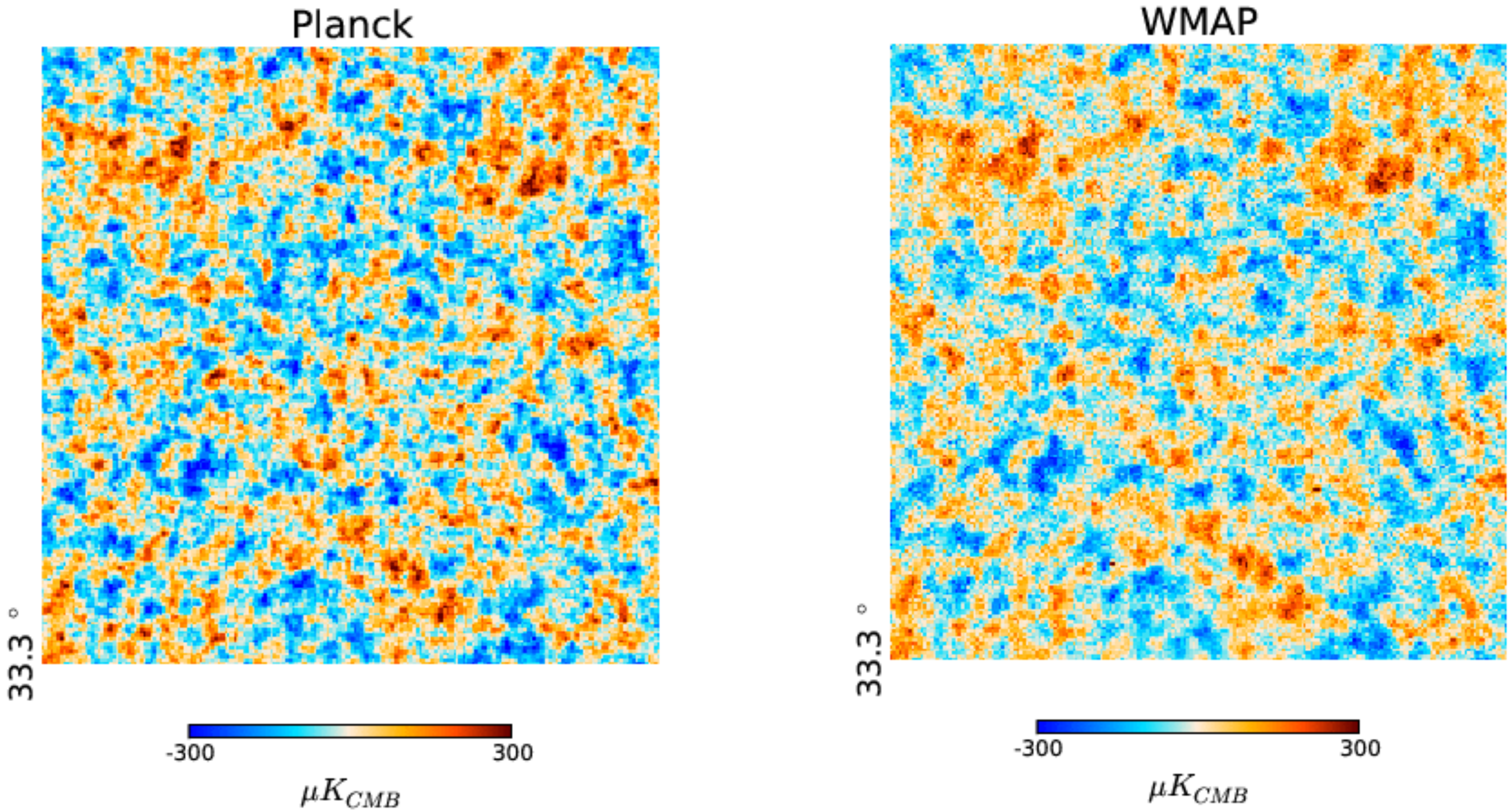


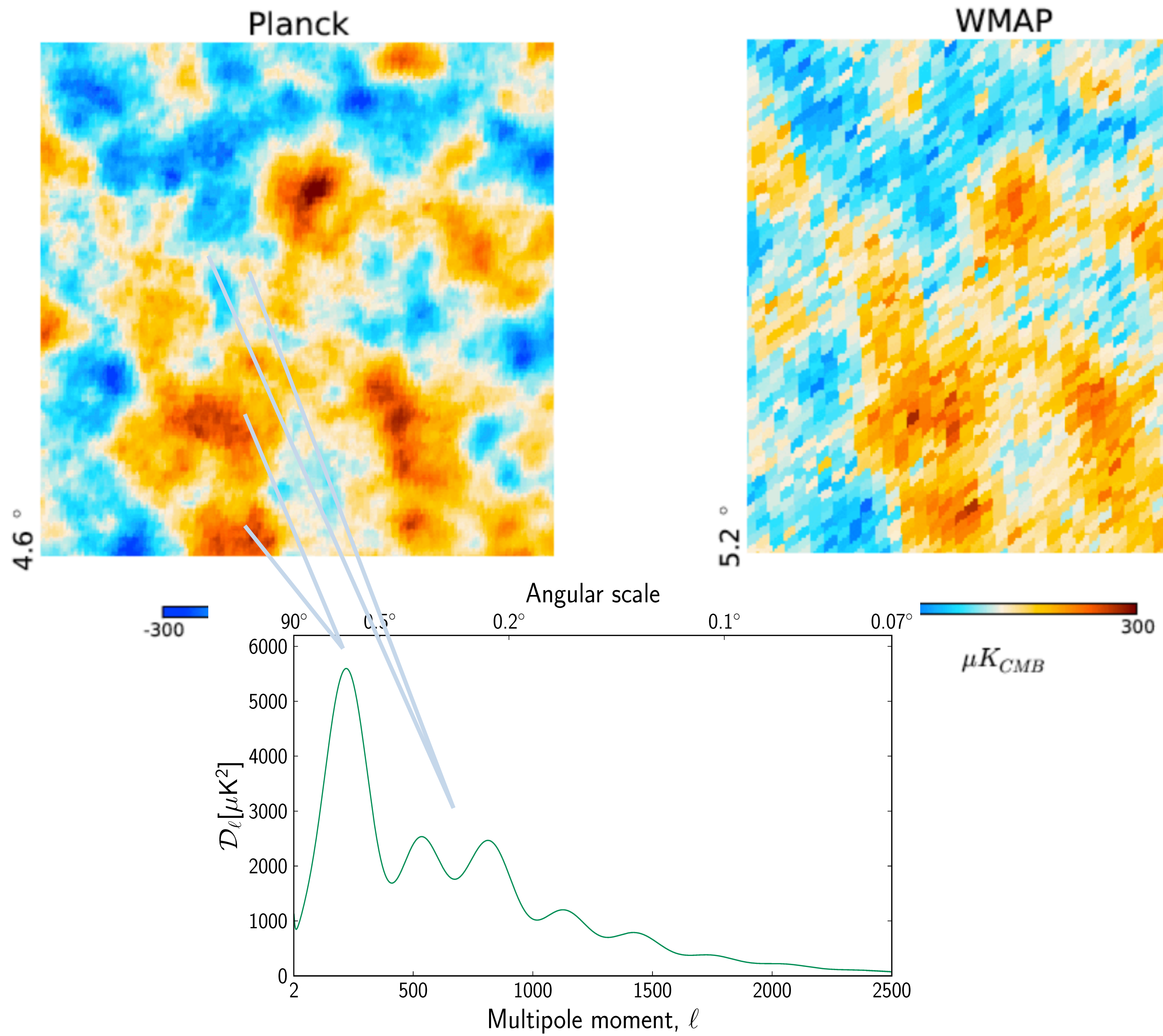


Combination of 9 frequency channels allows to separate the different components.

Basic assumption: Observations are a linear superposition of components

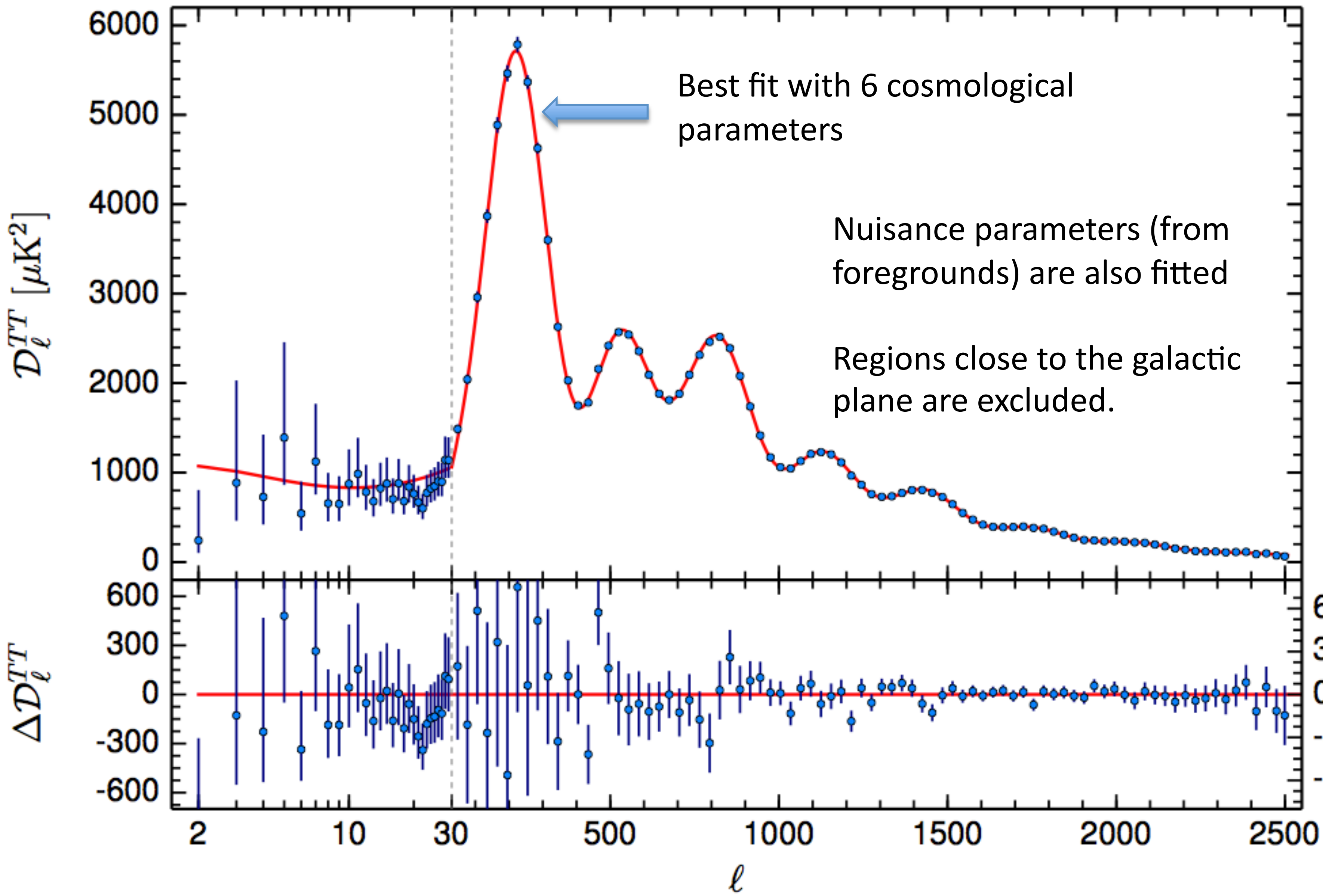
Comparison Planck - WMAP



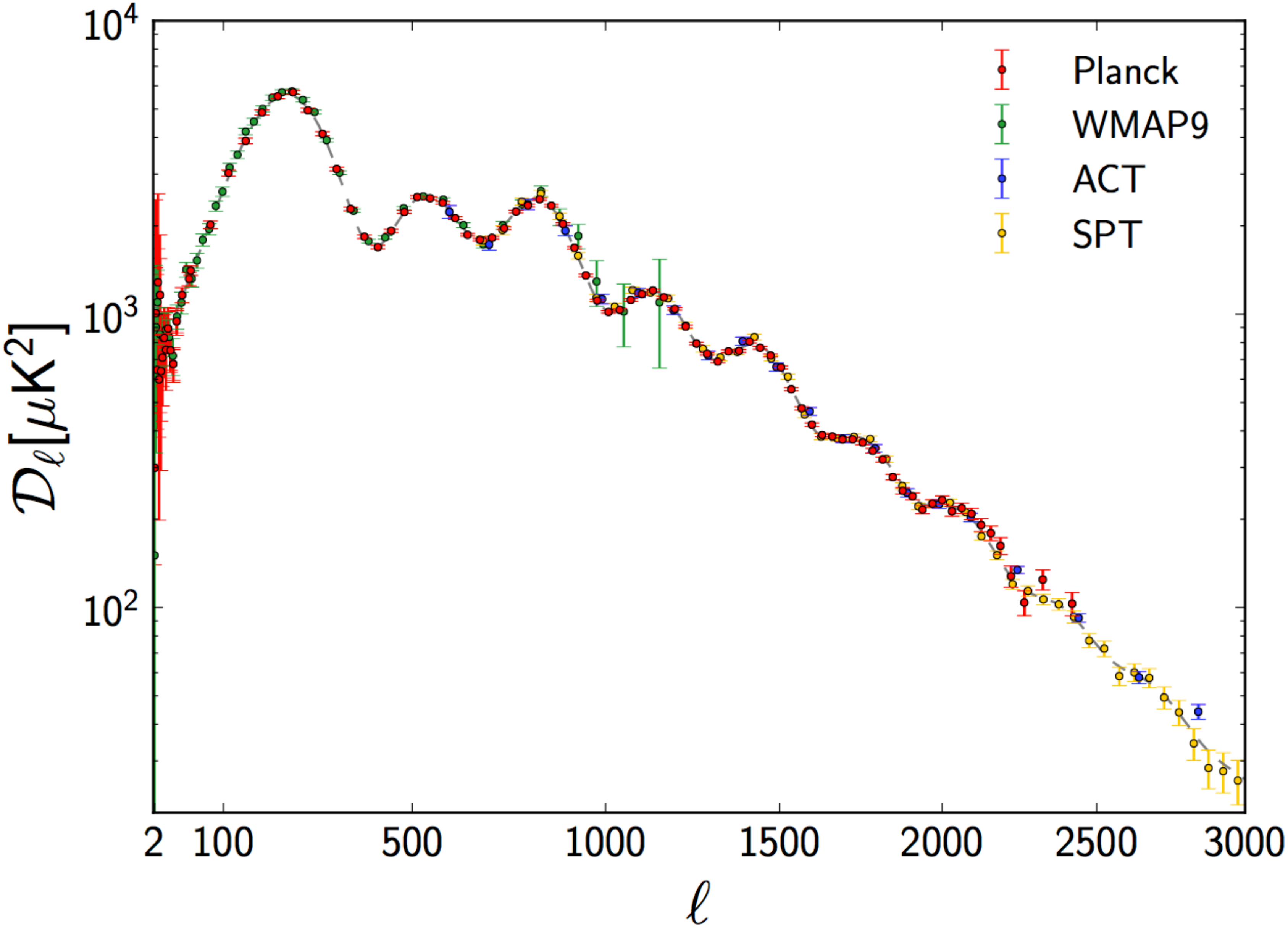

Planck
WMAP
4.6 °
5.2 °
Angular scale
90°
0.5°
0.2°
0.1°
0.07°
-300
300
μK_{CMB}
$\mathcal{D}_\ell [\mu K^2]$
6000
5000
4000
3000
2000
1000
0
2
500
1000
1500
2000
2500
Multipole moment, ℓ

CMB power spectrum

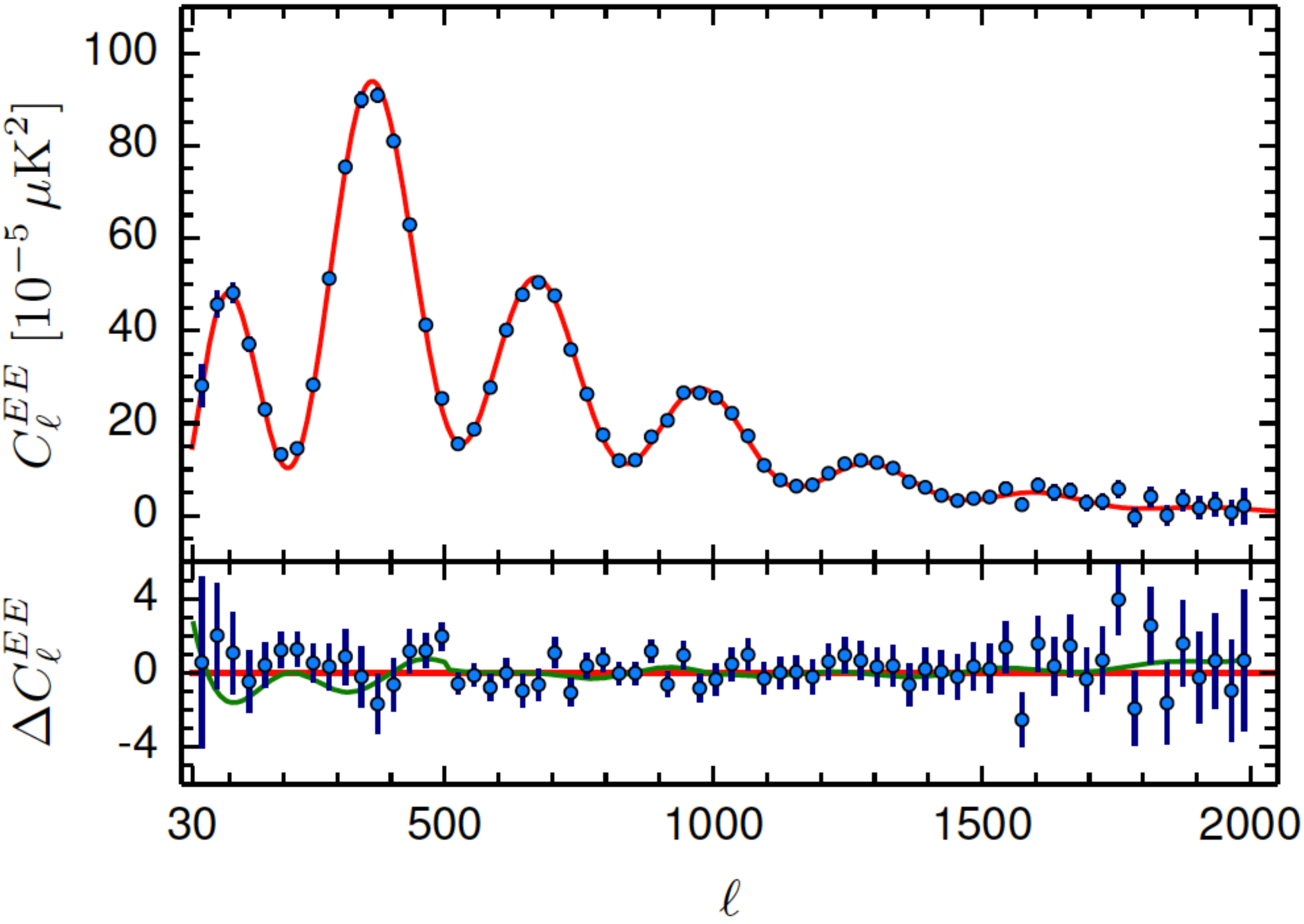
Planck Collaboration: The *Planck* mission



Best CMB spectrum including other measurements



EE power spectrum



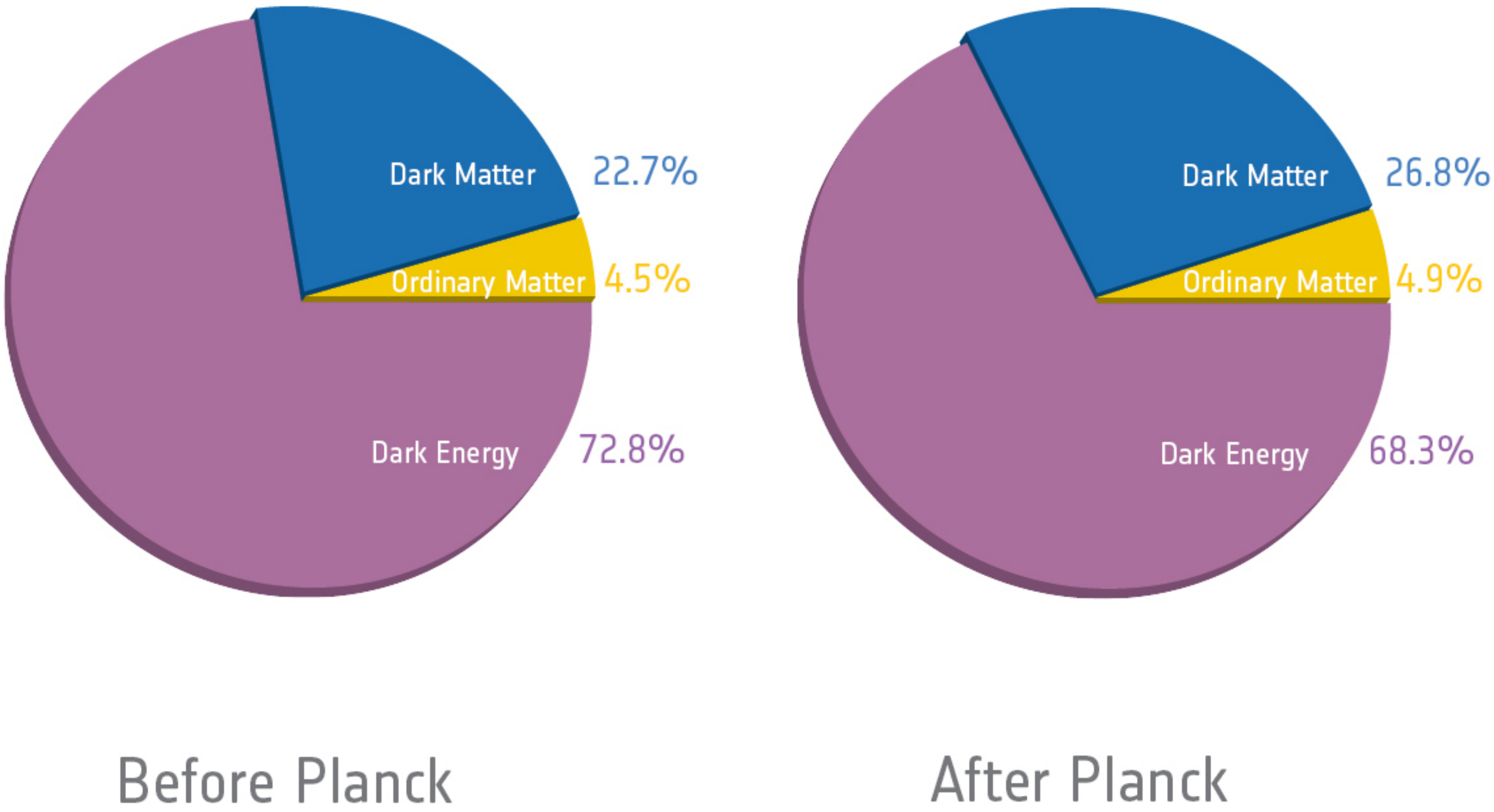
Cosmological parameters

Parameter	TT,TE,EE+lowP+lensing 68 % limits
$\Omega_b h^2$	0.02226 ± 0.00016
$\Omega_c h^2$	0.1193 ± 0.0014
$100\theta_{MC}$	1.04087 ± 0.00032
τ	0.063 ± 0.014
$\ln(10^{10} A_s)$	3.059 ± 0.025
n_s	0.9653 ± 0.0048
H_0	67.51 ± 0.64
Ω_Λ	0.6879 ± 0.0087
Ω_m	0.3121 ± 0.0087
$\Omega_m h^2$	0.1422 ± 0.0013
$\Omega_m h^3$	0.09596 ± 0.00030
σ_8	0.8150 ± 0.0087
$\sigma_8 \Omega_m^{0.5}$	0.4553 ± 0.0068
$\sigma_8 \Omega_m^{0.25}$	0.6091 ± 0.0067
z_{re}	$8.5^{+1.4}_{-1.2}$

LFI polarization at large scale.
Low reionisation optical depth as compared to previous measurements

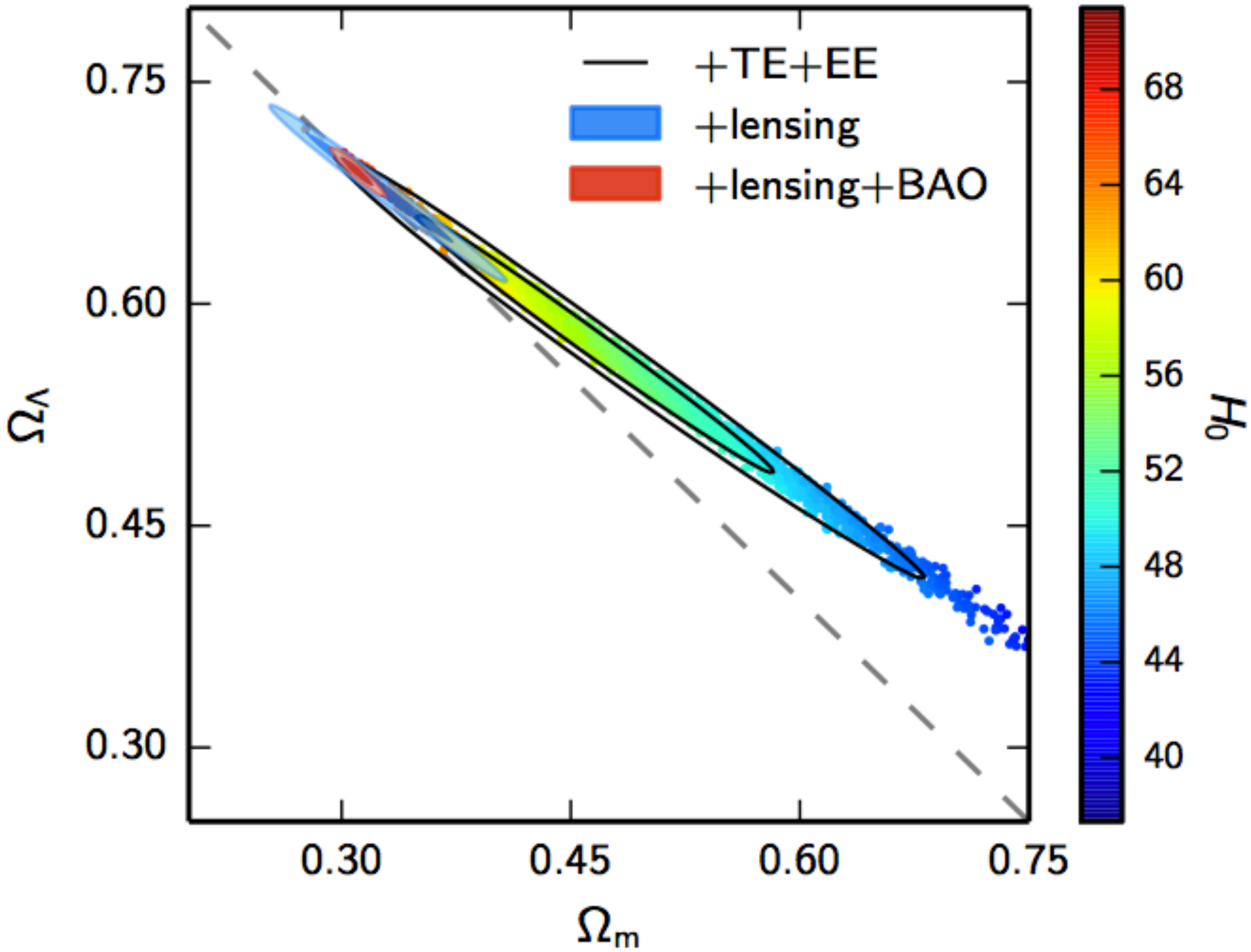
Scale invariant spectrum is excluded at many sigmas

Universe components



Adding other observations

Data at different z break the geometrical degeneracy



Beyond the 6-parameter model

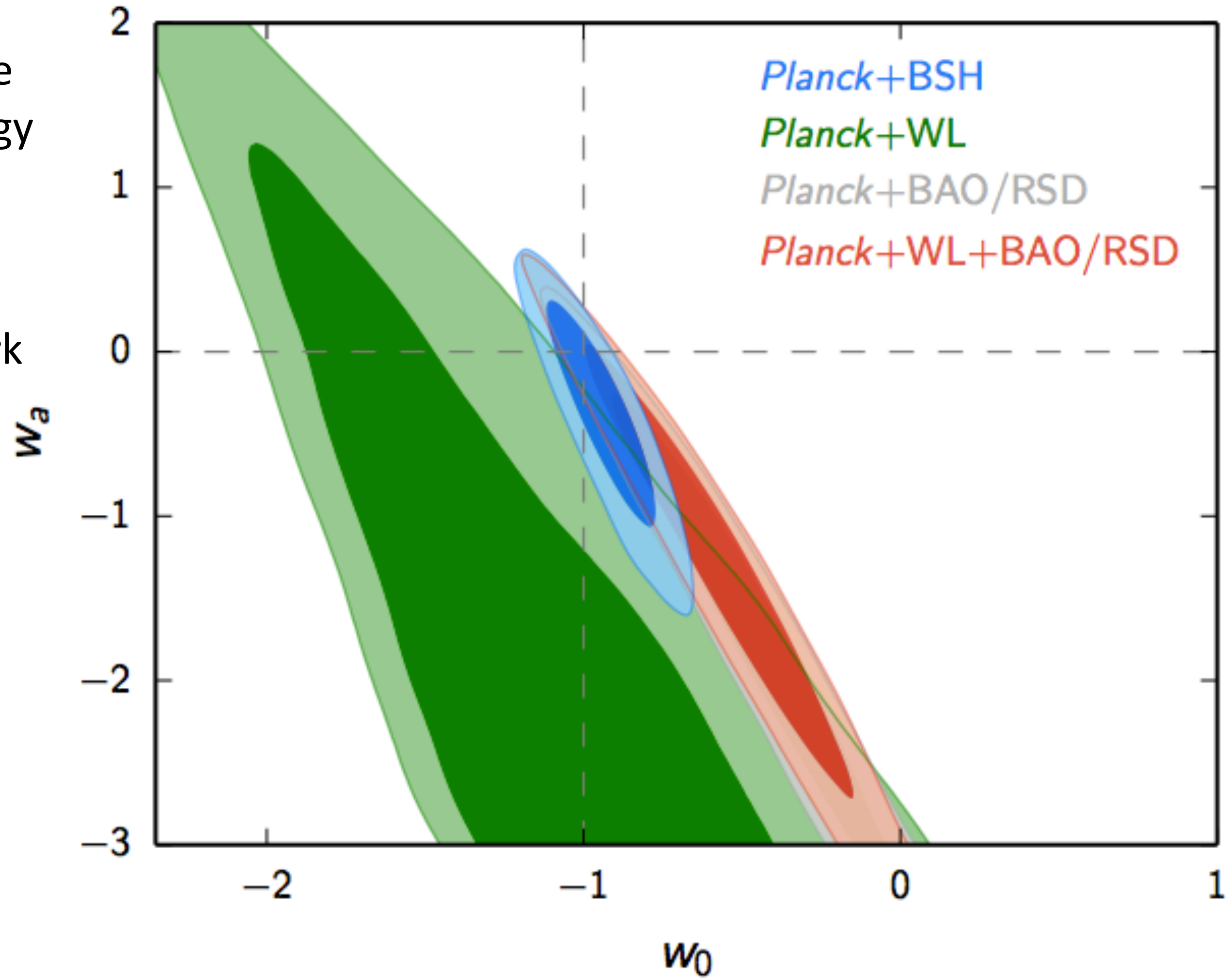
Best constraints on the neutrino masses.
If m ~ 1 eV, neutrinos start becoming less relativistic at recombination.
Effect on late ISW and free-streaming on structure formation

Extended model, ΛCDM+r+	Parameter	*Planck* TT+lowP +lensing	*Planck* TT+lowP +BAO	*Planck* TT,TE,EE +lowP
+general reionization	r	$r < 0.11$	$r < 0.10$	< 0.10
	n_s	0.975 ± 0.006	0.971 ± 0.005	0.968 ± 0.005
$+N_{eff}$	r	< 0.14	< 0.12	< 0.11
	n_s	$0.977^{+0.016}_{-0.017}$	0.972 ± 0.009	0.964 ± 0.010
	N_{eff}	$3.24^{+0.30}_{-0.35}$	3.19 ± 0.24	$3.02^{+0.20}_{-0.21}$
$+Y_{He}$	r	< 0.14	< 0.12	< 0.12
	n_s	0.975 ± 0.007	0.973 ± 0.009	0.969 ± 0.008
	Y_{He}	0.258 ± 0.022	0.257 ± 0.022	0.252 ± 0.014
$+m_\nu$	r	< 0.11	< 0.11	< 0.11
	n_s	0.963 ± 0.007	0.967 ± 0.005	0.962 ± 0.005
	m_ν	< 0.67	< 0.21	< 0.58
$+\Omega_K$	r	< 0.15	$r < 0.11$	< 0.15
	n_s	0.971 ± 0.007	0.971 ± 0.007	0.969 ± 0.005
	Ω_K	$-0.008^{+0.010}_{-0.008}$	-0.001 ± 0.003	$-0.045^{+0.016}_{-0.020}$
$+w$	r	< 0.14	< 0.11	< 0.12
	n_s	0.969 ± 0.006	0.967 ± 0.006	0.966 ± 0.005
	w	$-1.46^{+0.20}_{-0.40}$	$-1.02^{+0.08}_{-0.07}$	$-1.57^{+0.17}_{-0.37}$
$+\Omega_K+dn_s/d\ln k$	r	< 0.20	< 0.18	< 0.19
	n_s	0.971 ± 0.007	0.969 ± 0.007	0.969 ± 0.005
	$dn_s/d\ln k$	-0.006 ± 0.009	-0.013 ± 0.009	-0.004 ± 0.008
	Ω_K	$-0.006^{+0.010}_{-0.009}$	-0.001 ± 0.003	$-0.043^{+0.011}_{-0.020}$
$+N_{eff}+m_{eff}$	r	$r < 0.14$	$r < 0.13$	< 0.12
	n_s	$0.980^{+0.010}_{-0.014}$	$0.978^{+0.008}_{-0.011}$	$0.968^{+0.006}_{-0.008}$
	m_{eff}	< 0.27	< 0.21	< 0.83
	N_{eff}	< 3.45	< 3.73	< 3.47

Dark energy equation of state

CMB alone is not sensitive to variations in dark energy density

Requires local measurements, when dark energy dominates



BICEP2 and Keck Array

Keck Array 2011-...

x5

Relentless observation of the CMB polarization from NSF's station at the geographic South Pole

Dry, stable atmosphere, high altitude + 24h coverage of the Southern Sky

Compact cold refractive optics optimized for the angular scales of the inflationary signal

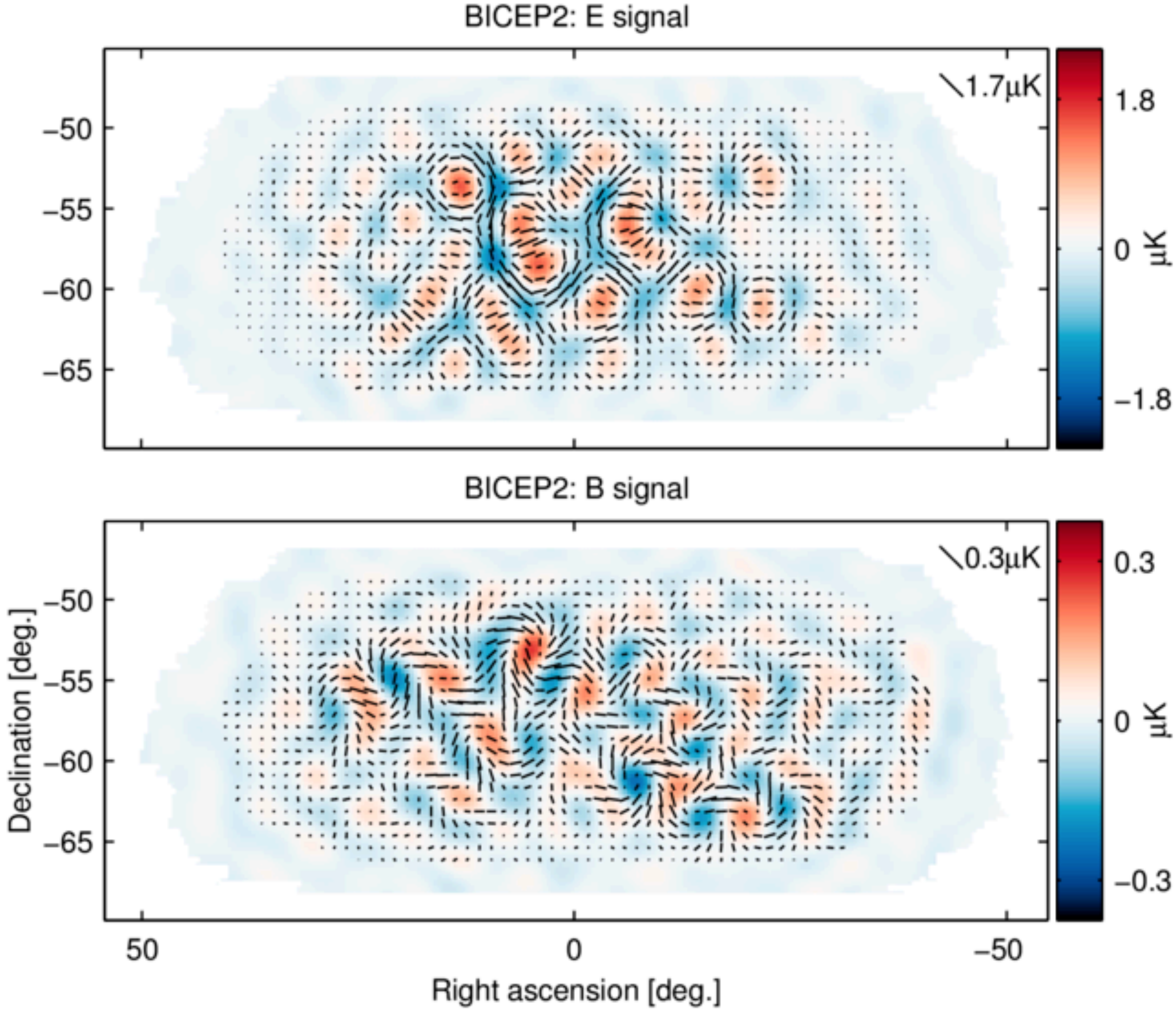
Superconducting phased antenna arrays

Observation at 150 GHz (Keck 2014 also at 95 GHz)
Focus on ~**400 deg²** patch = 1% of the sky

3yrs of BICEP2 + Keck 2012/13

→ **Final map depth: 3.4 μK arcmin / 57 nk deg** (RMS noise in sq-deg pixels

Deepest map of the CMB polarization ever made!

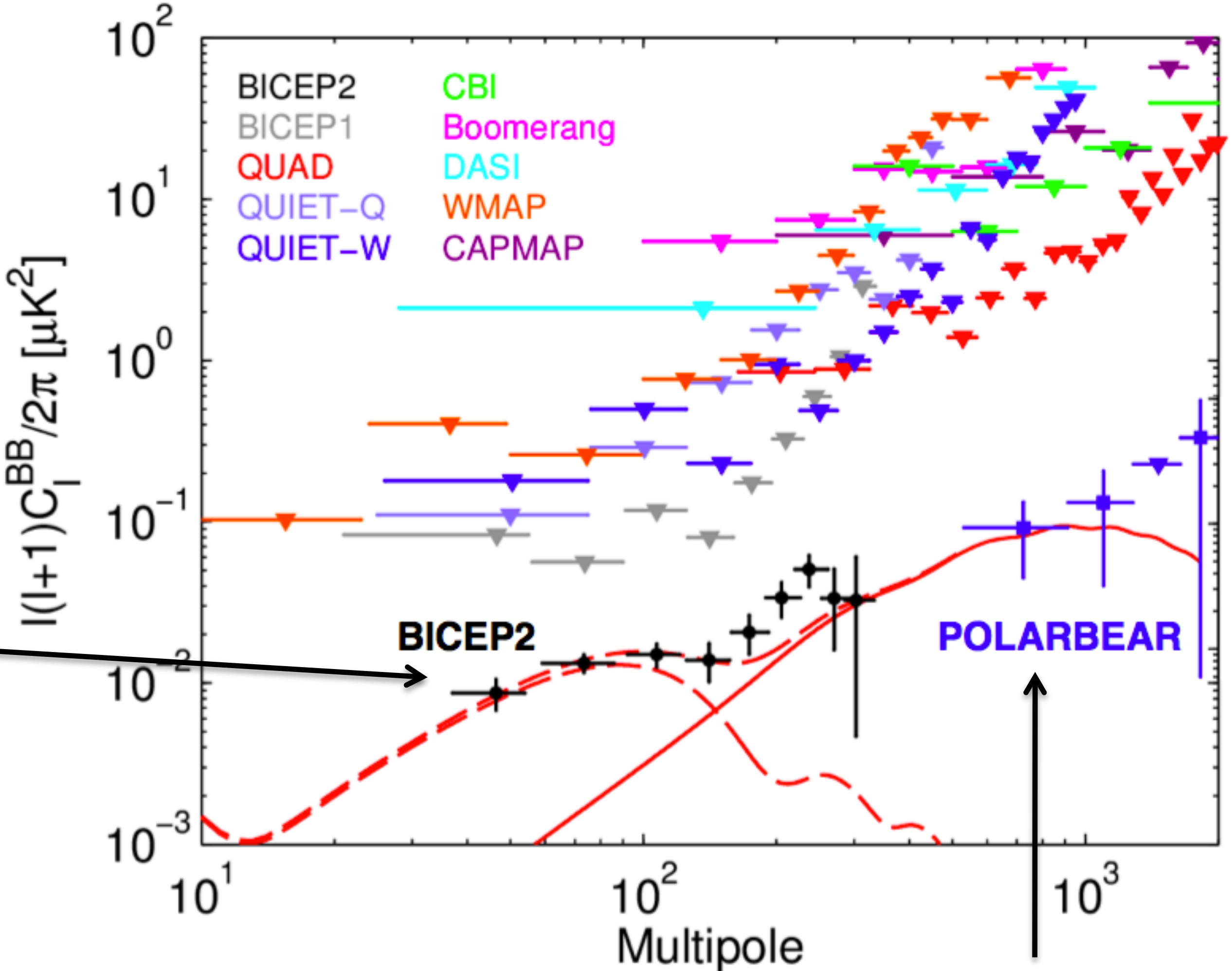

BICEP2: E signal
1.7μK
1.8
0
μK
−1.8
−50
−55
−60
−65
BICEP2: B signal
0.3μK
0.3
0
μK
−0.3
Declination [deg.]
50
0
−50
Right ascension [deg.]

B-mode detection

Significant B-mode signal at large angular scale

Best fit of primordial B-mode model gave r = 0.16

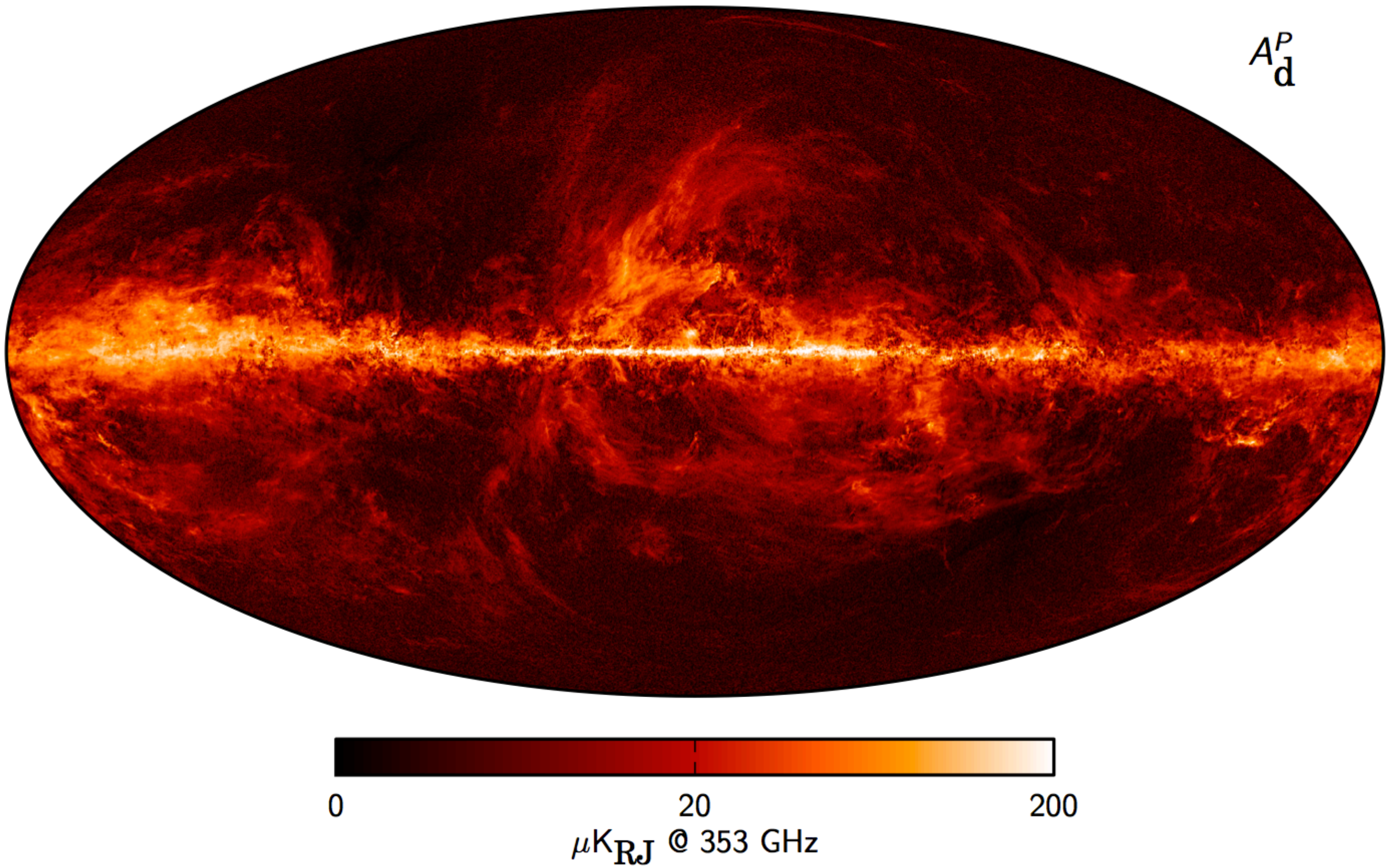
Contribution from dust polarization was underestimated



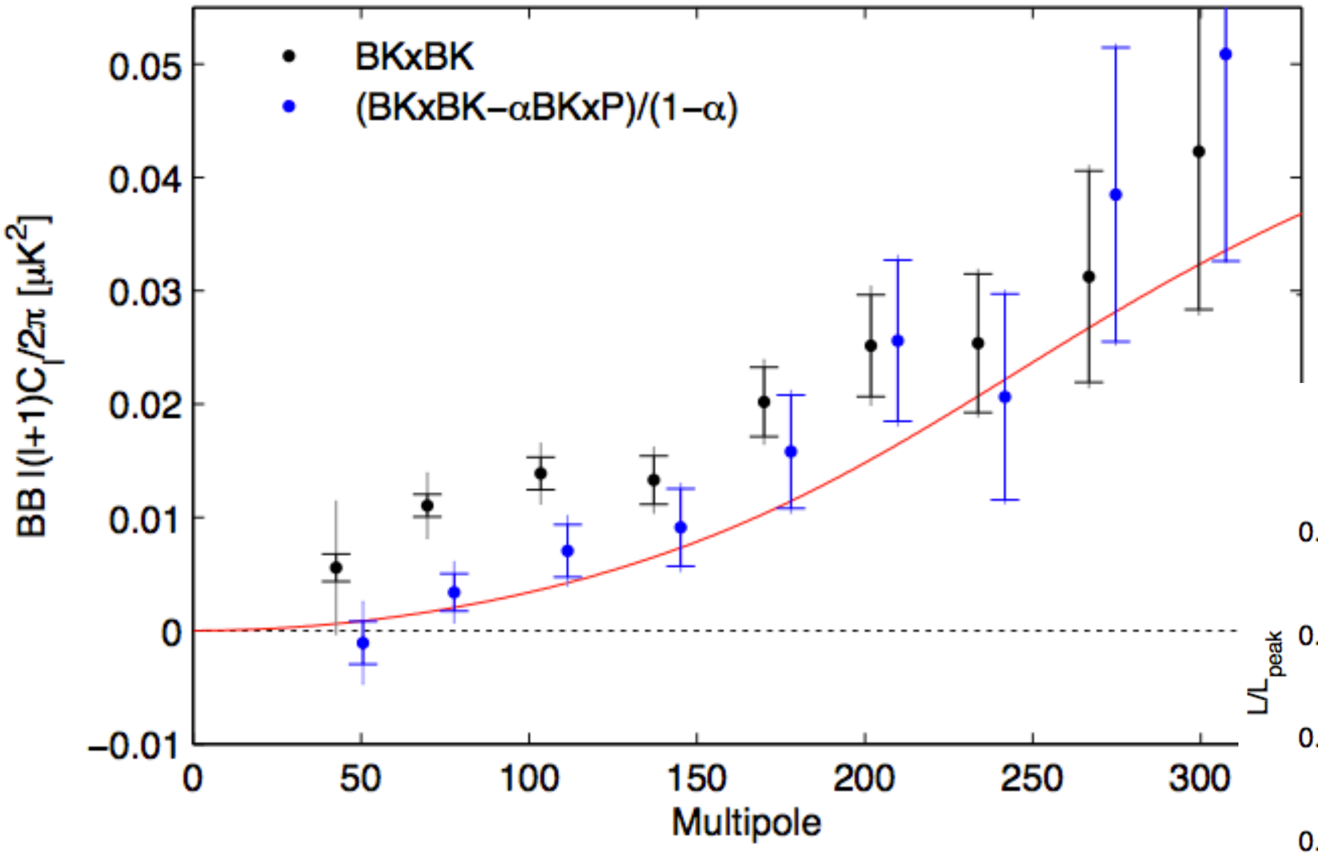
Detection of lensing B-mode

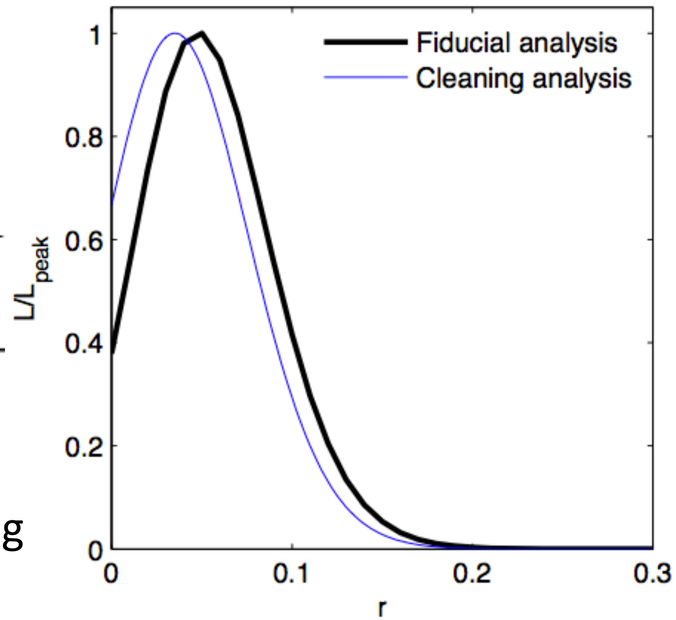
Polarization of Dust seen by Planck

Galactic dust emission is polarized.
- Dust grains are not spherical
- Alignment mechanism due to the galactic magnetic field inducing coherent polarized emission



Joint analysis Bicep2 - Planck

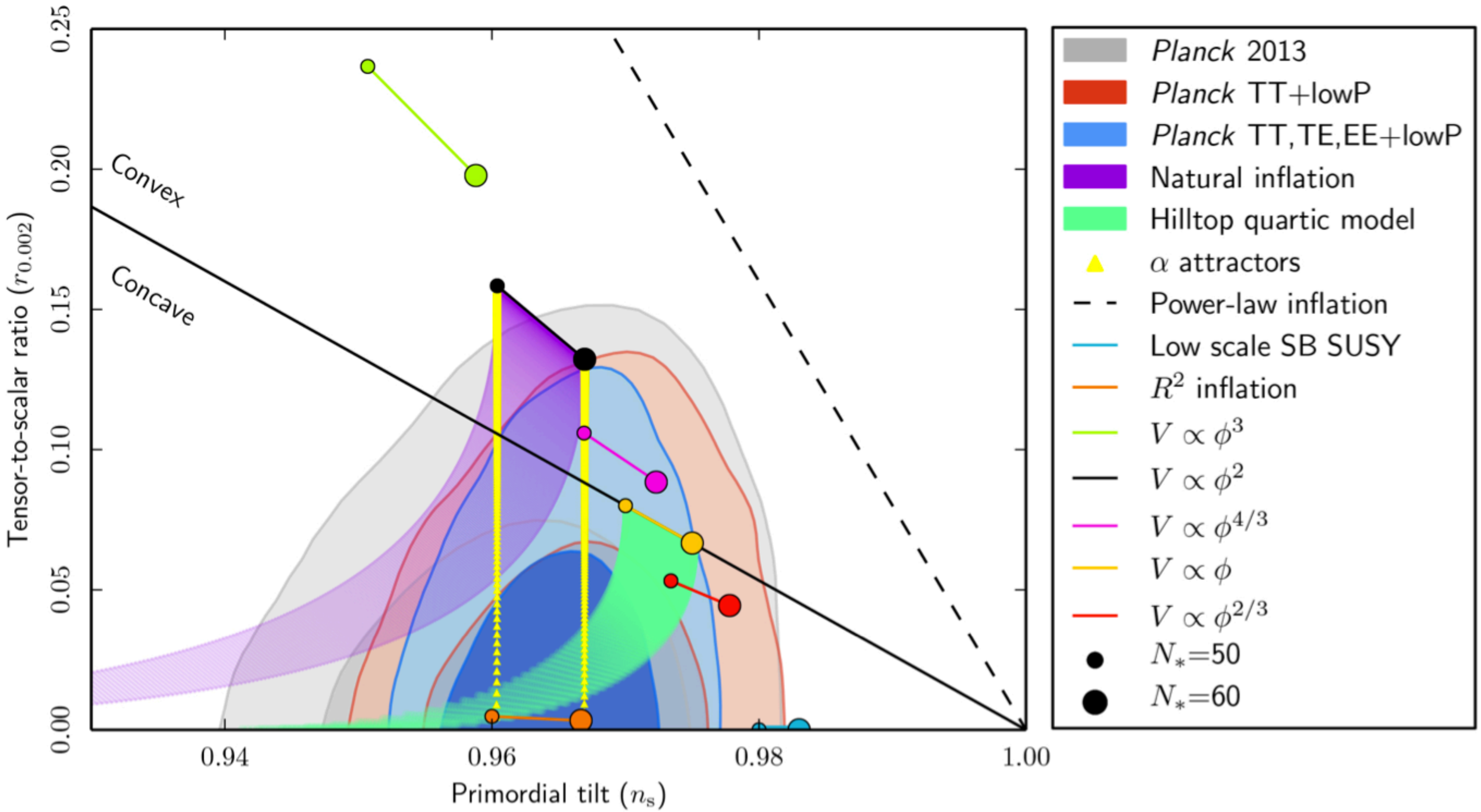




Spectrum is entirely explained by polarized dust + lensing

Best limit : r < 0.11

Constraints on inflation



Simple single field models of inflation are compatible with Planck data.

Non-gaussianity

Some inflation models can produce a significant level of non-gaussianity.

Parametric model for local non-gaussianity: $\Phi_{NG}(x) = \Phi_G(x) + f_{NL}\Phi_G(x)^2$

This can be constrained with the 3-pts correlation function in harmonic space.

$$< \Phi(k_1).\Phi(k_2).\Phi(k_3) >= f_{NL}\delta(k_1 + k_2 + k_3)F(k_1,k_2,k_3)$$

can be related to $< a_{l_1 m_1} .a_{l_2 m_2} .a_{l_3 m_3} >$

→ No detection of non-gaussianity in Planck CMB maps

$$f_{\rm NL}^{\rm local} = 0.8 \pm 5.0$$

$$f_{\rm NL}^{\rm equil} = -4 \pm 43$$

$$f_{\rm NL}^{\rm ortho} = -26 \pm 21$$

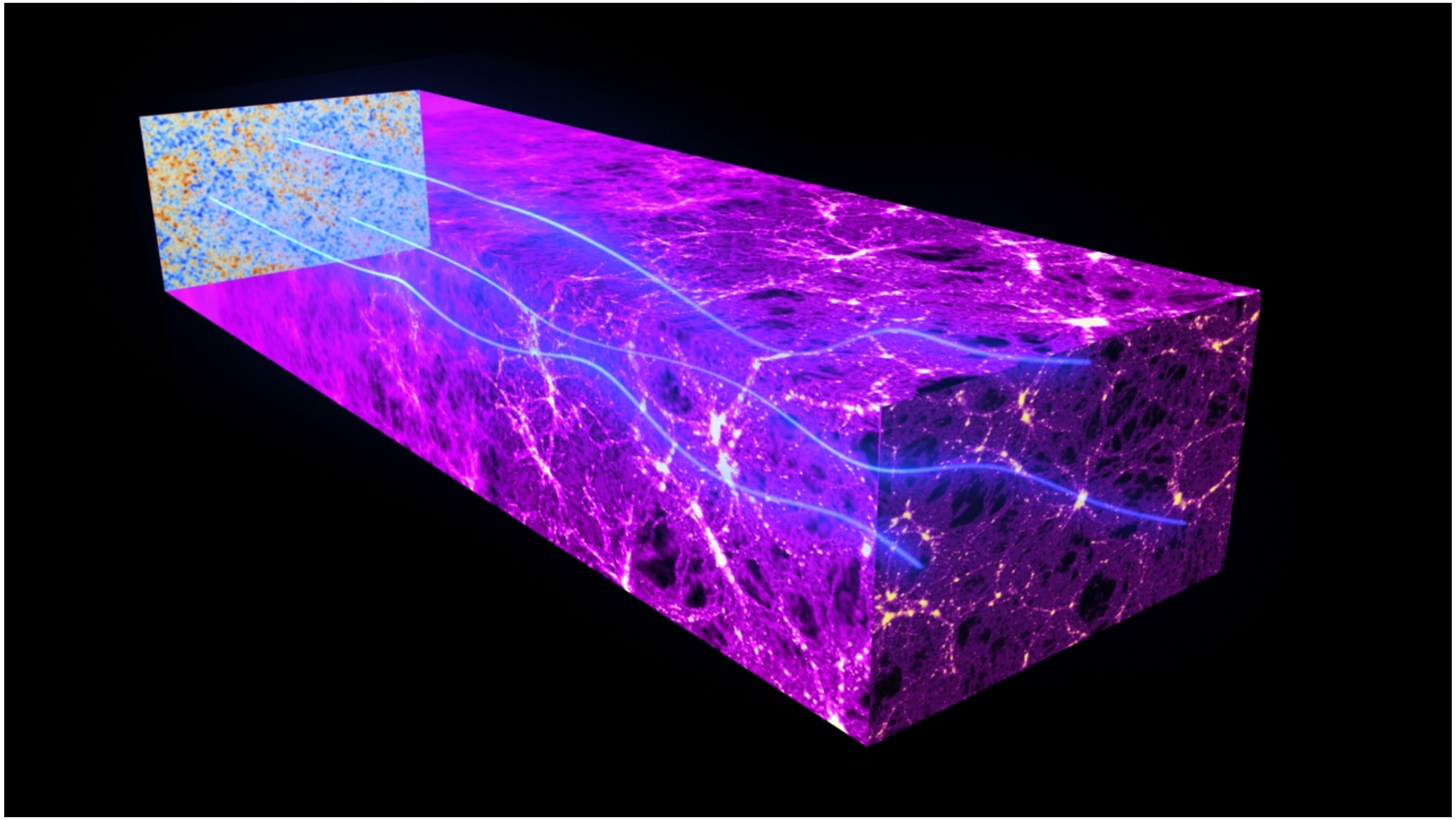
This is compatible with the simplest models of inflation

Conclusion

- LCDM standard model provides a remarkable fit to the data with only 6 parameters
- Planck data compatible with the simplest inflation models
- No detection of primordial B-mode signal from the joint analysis of Planck and Bicep2/Keck data.
- Many other cosmological results with cluster of galaxies : Sunyaev Zeldovitch effect, weak lensing of CMB, which is a probe of dark matter distribution between the CMB emission and us.
- HFI measurements of CMB polarization at large scale, still dominated by systematic effects, are not published yet and are expected for next year
- Processing of HFI data is being improved!

Gravitational lensing

Mass induces curvature of space curving the trajectory of photons passing through. Trajectory of CMB photons is affected by all the mass fluctuations between the CMB and us. This ''weak gravitational lensing'' distord the observed image of the CMB



Power spectrum of matter distribution