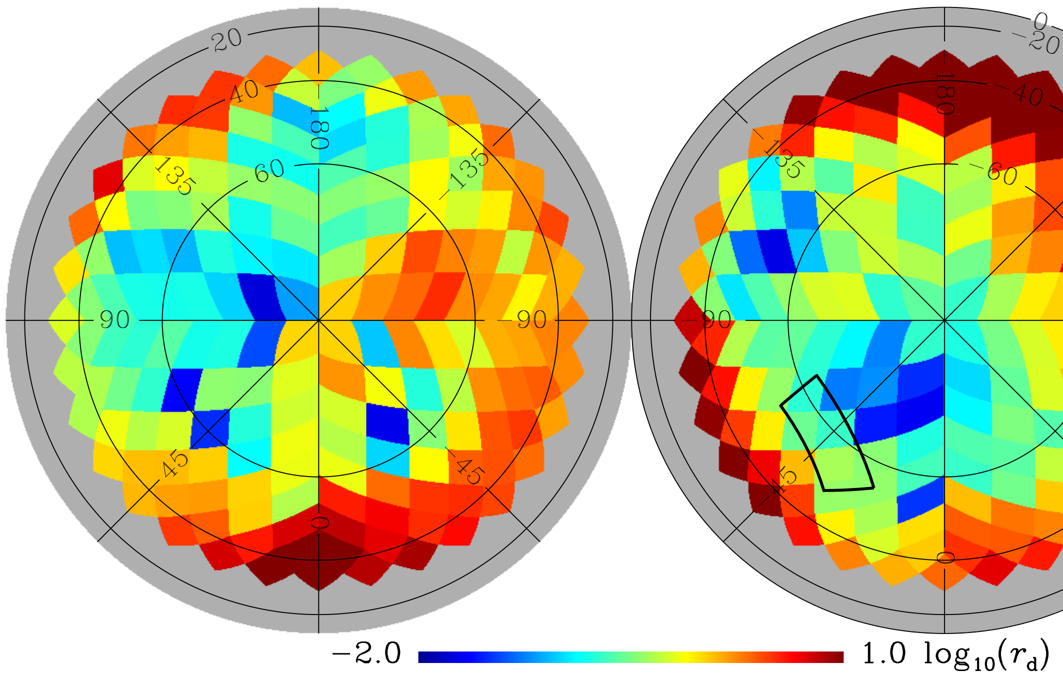
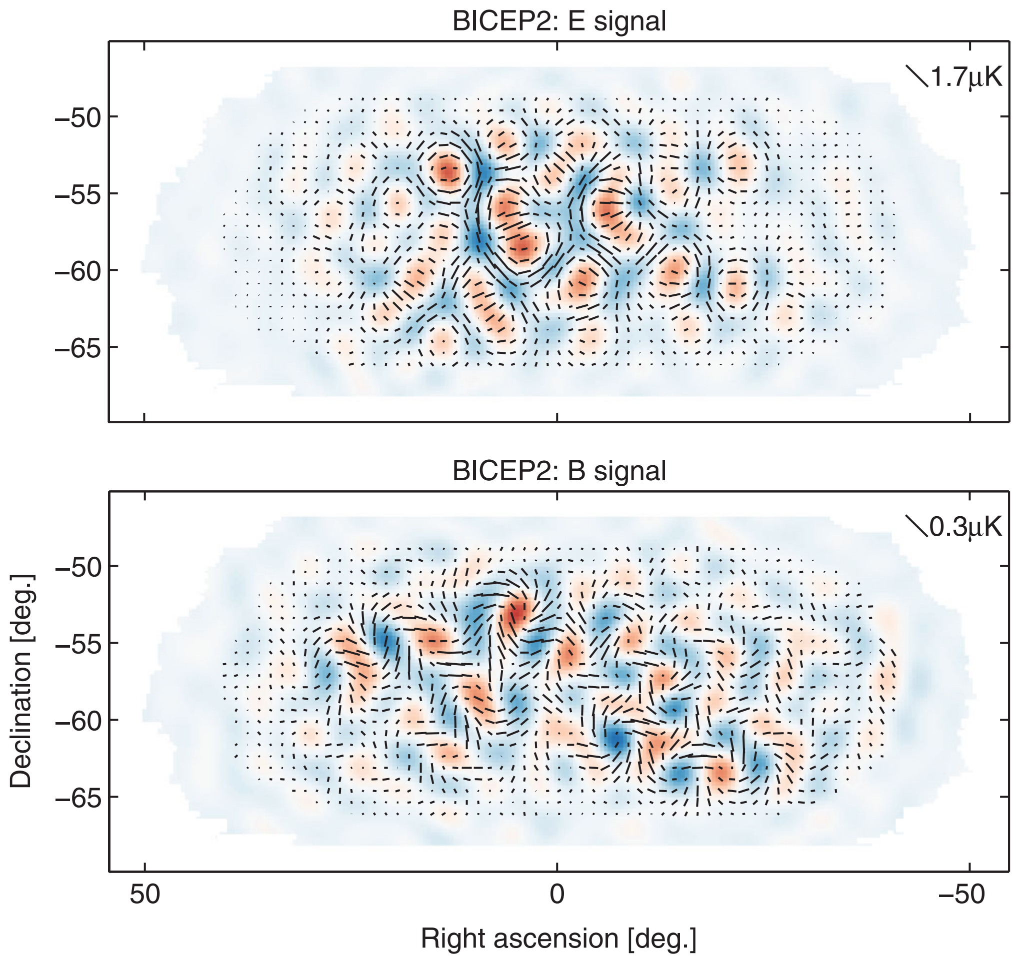
Inflation, B-modes and dust:
Planck's view on BICEP2 results.

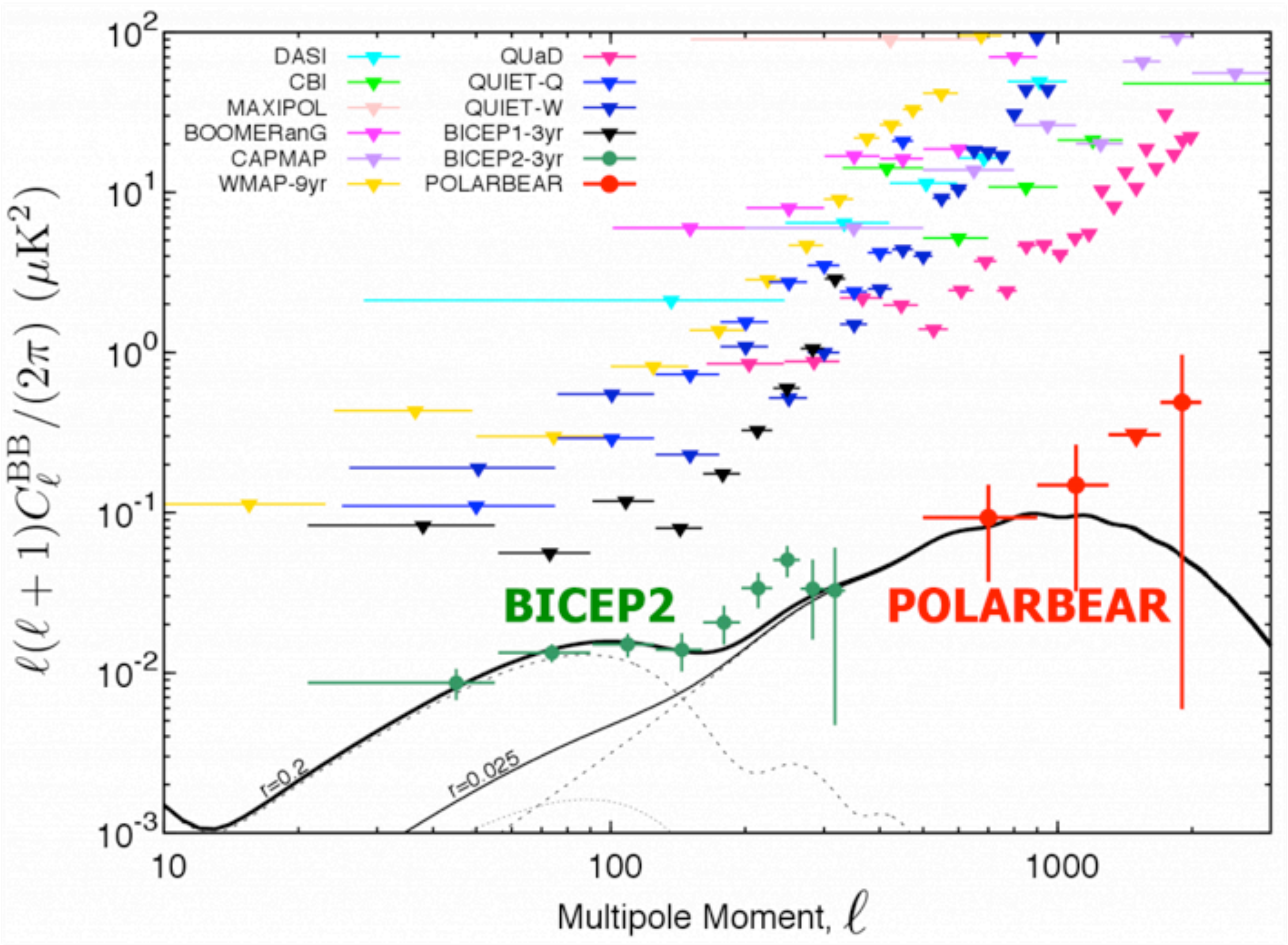




A. Benoit-Lévy

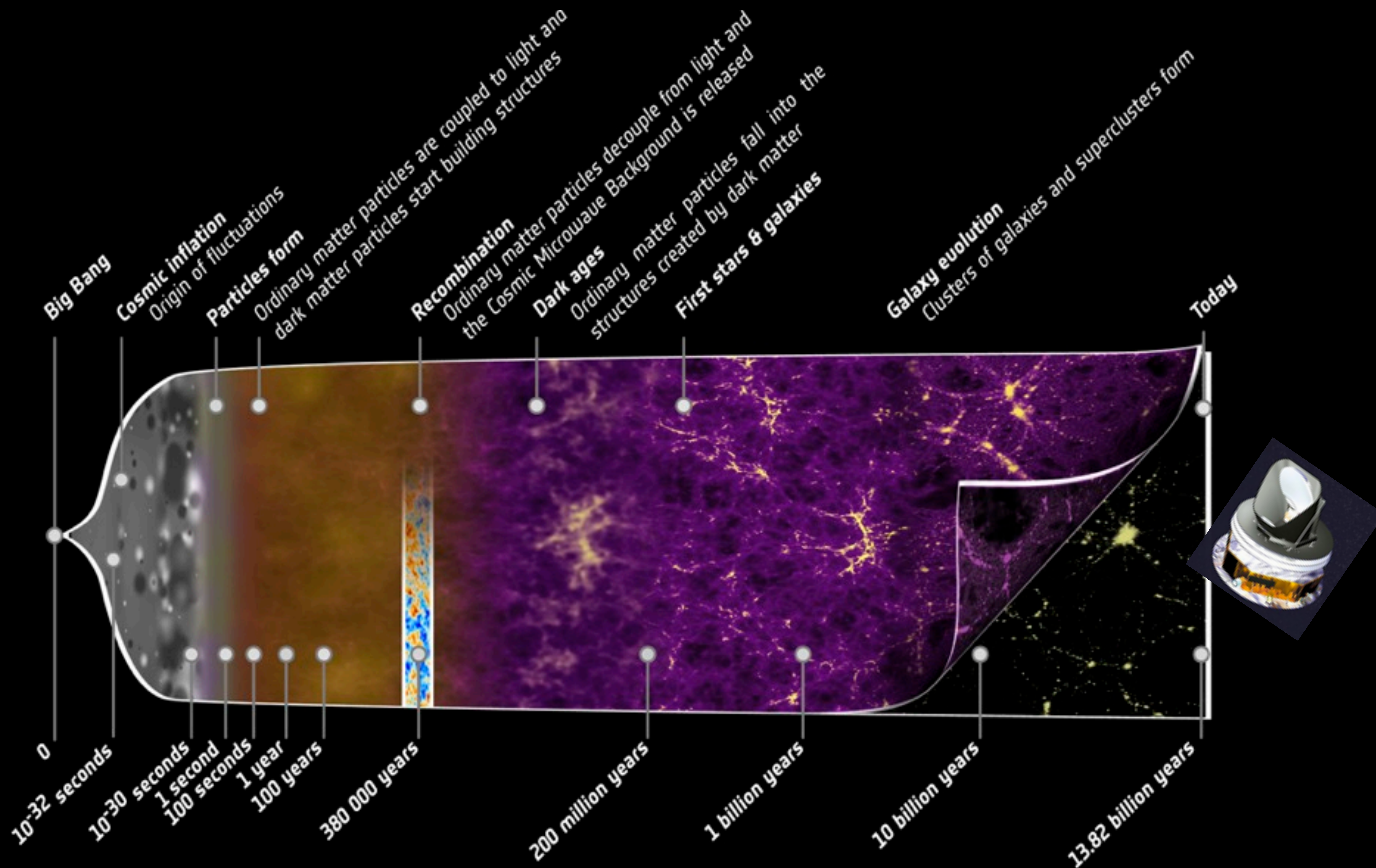
University College London

The Question: What precisely has been measured??

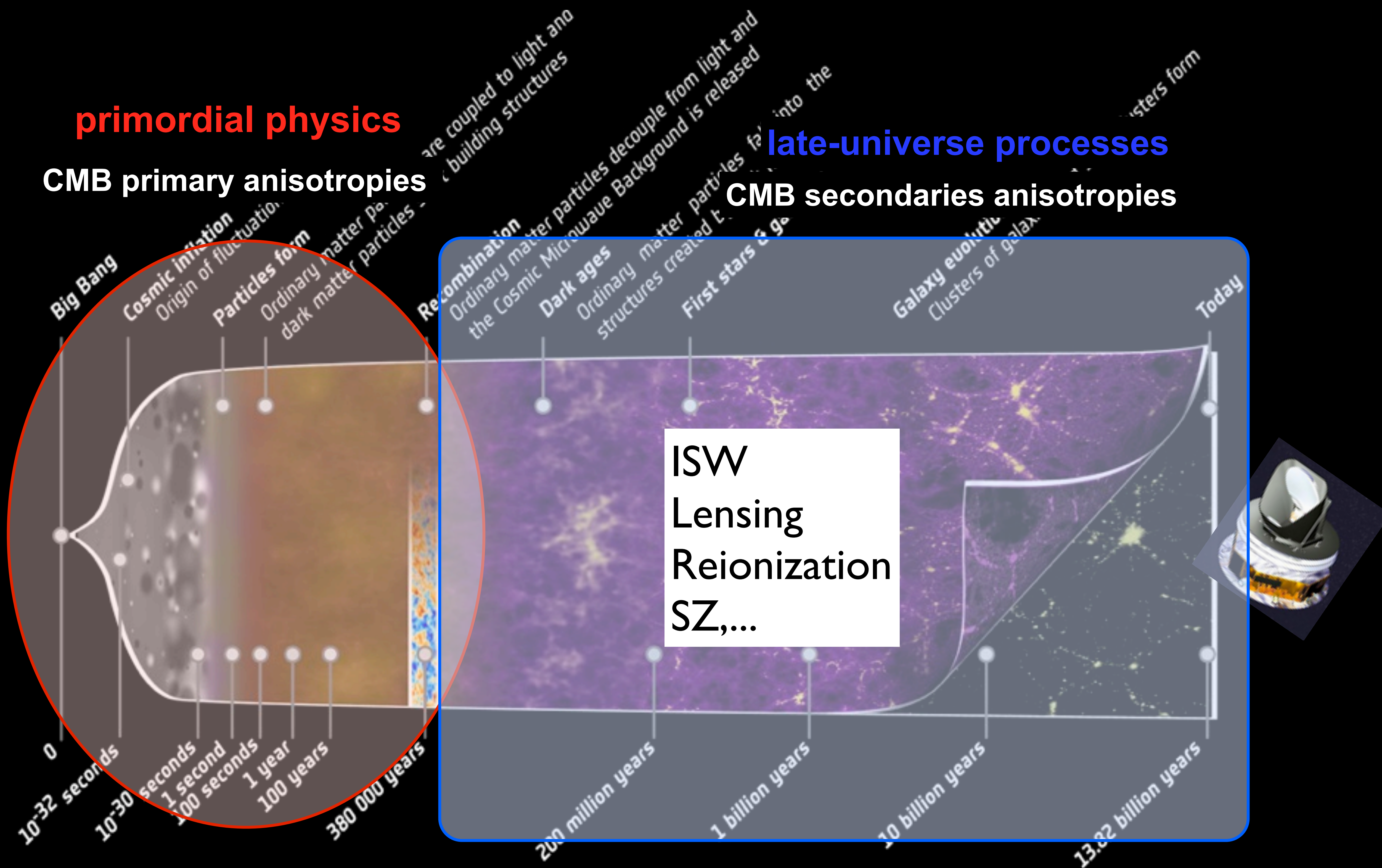


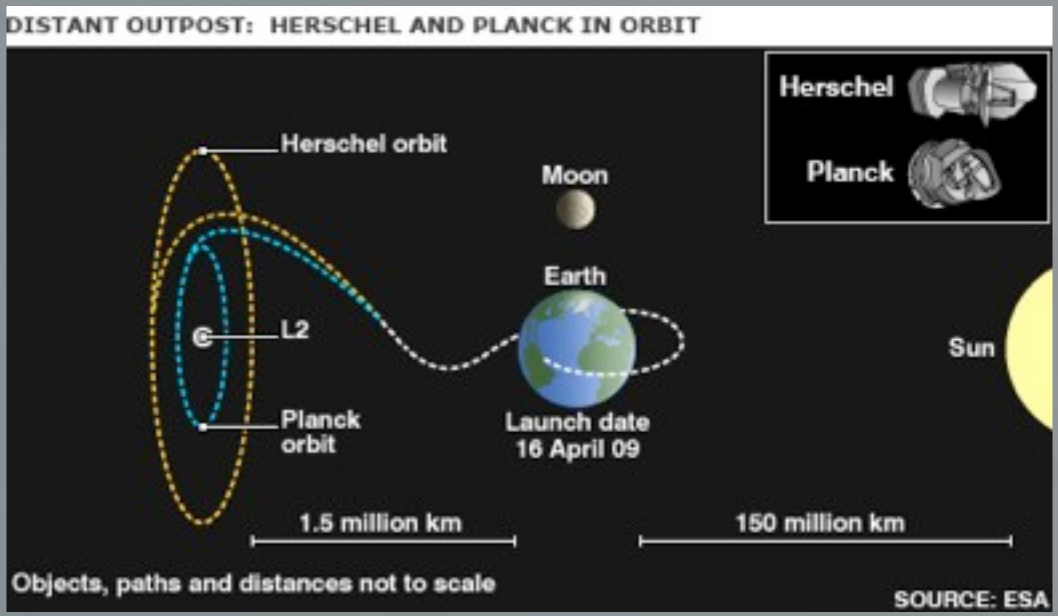
http://bolo.berkeley.edu/polarbear/newsfeed/31114

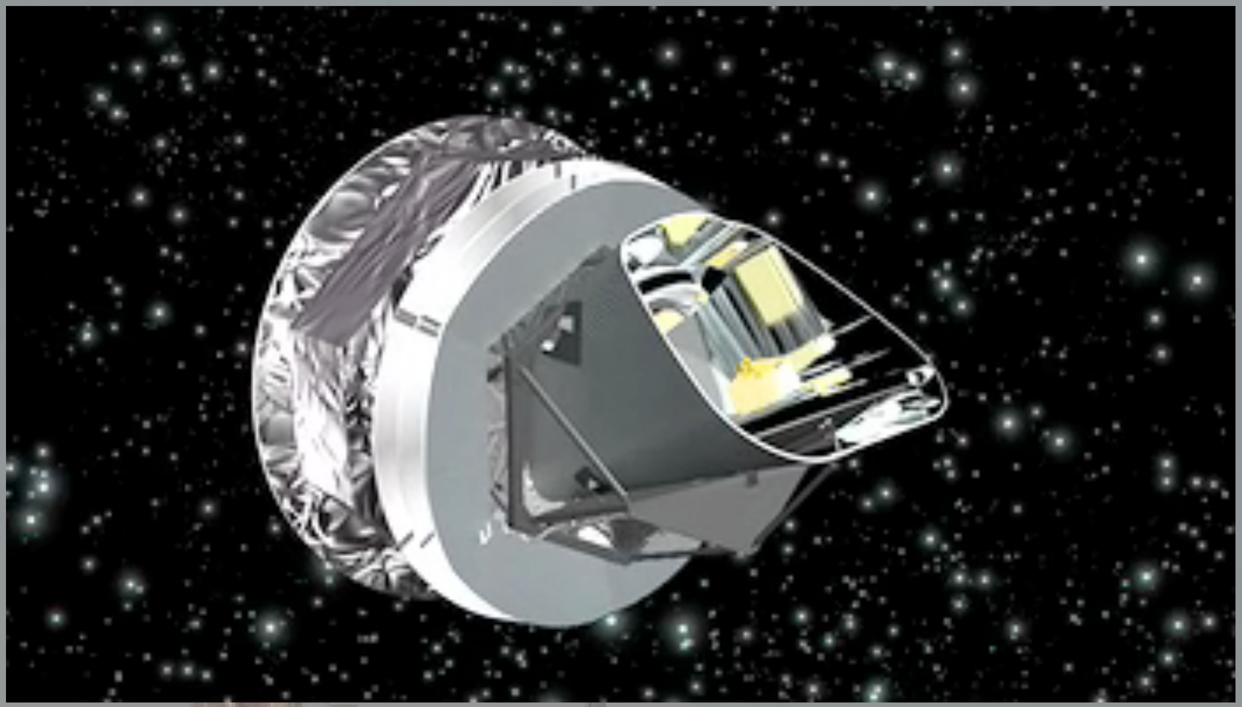
A quick summary of the current status of cosmology



CMB: central observation in cosmology



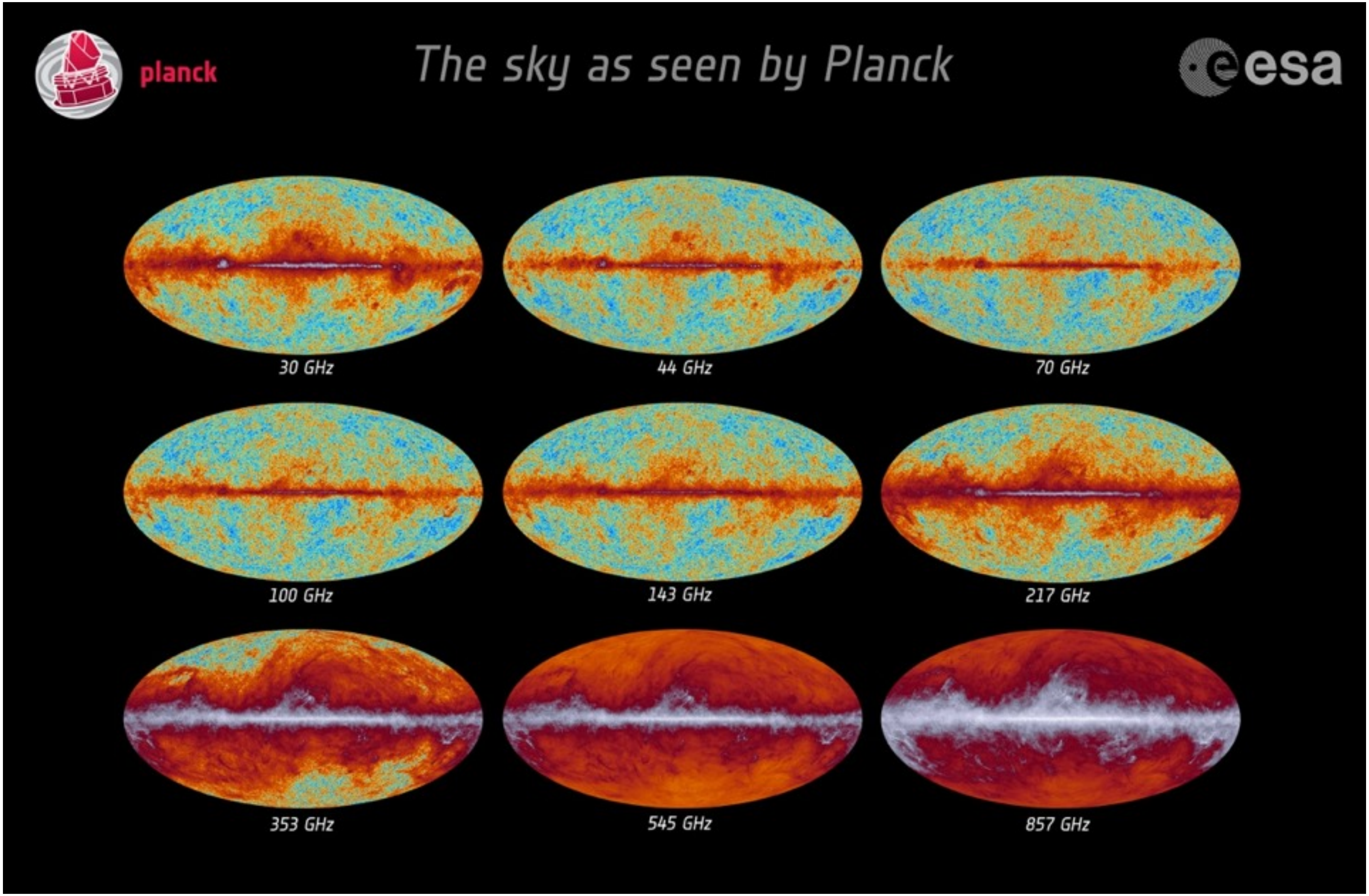




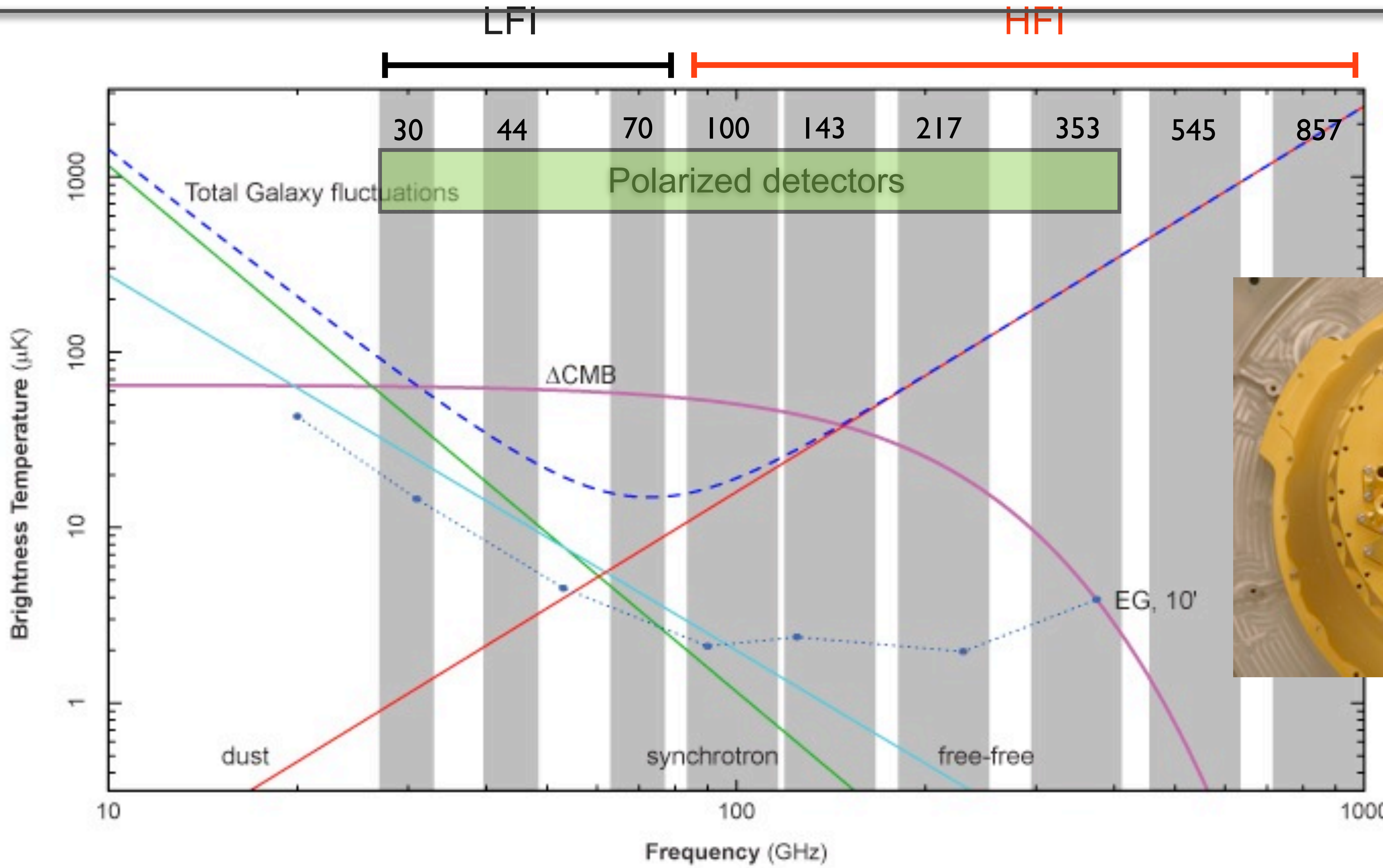
- Proposed to ESA in 1993, selected in 1996
- Launched on May 14th 2009
- First complete coverage of sky in June 2010
- Nominal mission completed in November 2010
- End of light (HFI) January 14th 2012. 32 months after launch
- March 2013: First cosmological data release
- August 2013: Departure manoeuvre from L2. 1554 days of mission. 8 LFI surveys
- Full release in 2014

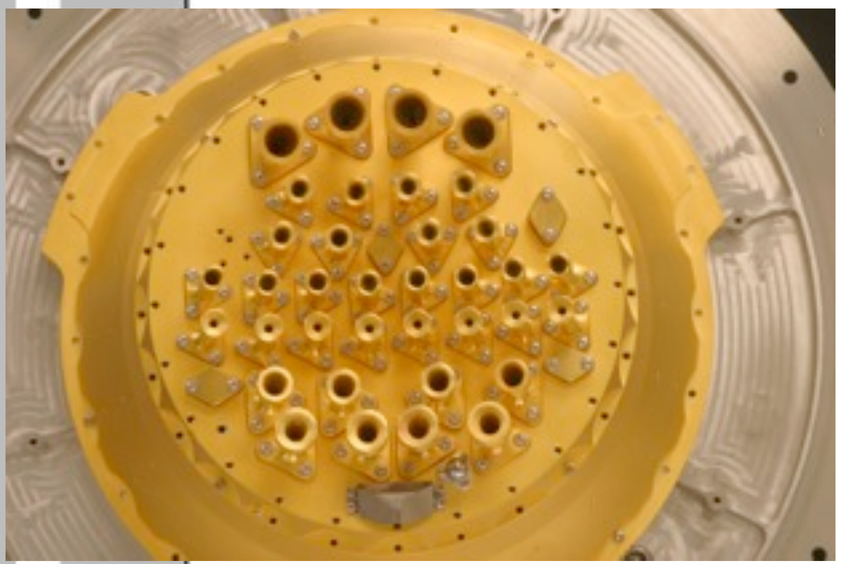
Ariane 5 ECA Launch • HERSCHEL – PLANCK - *May 14, 2009*

Planck sky maps

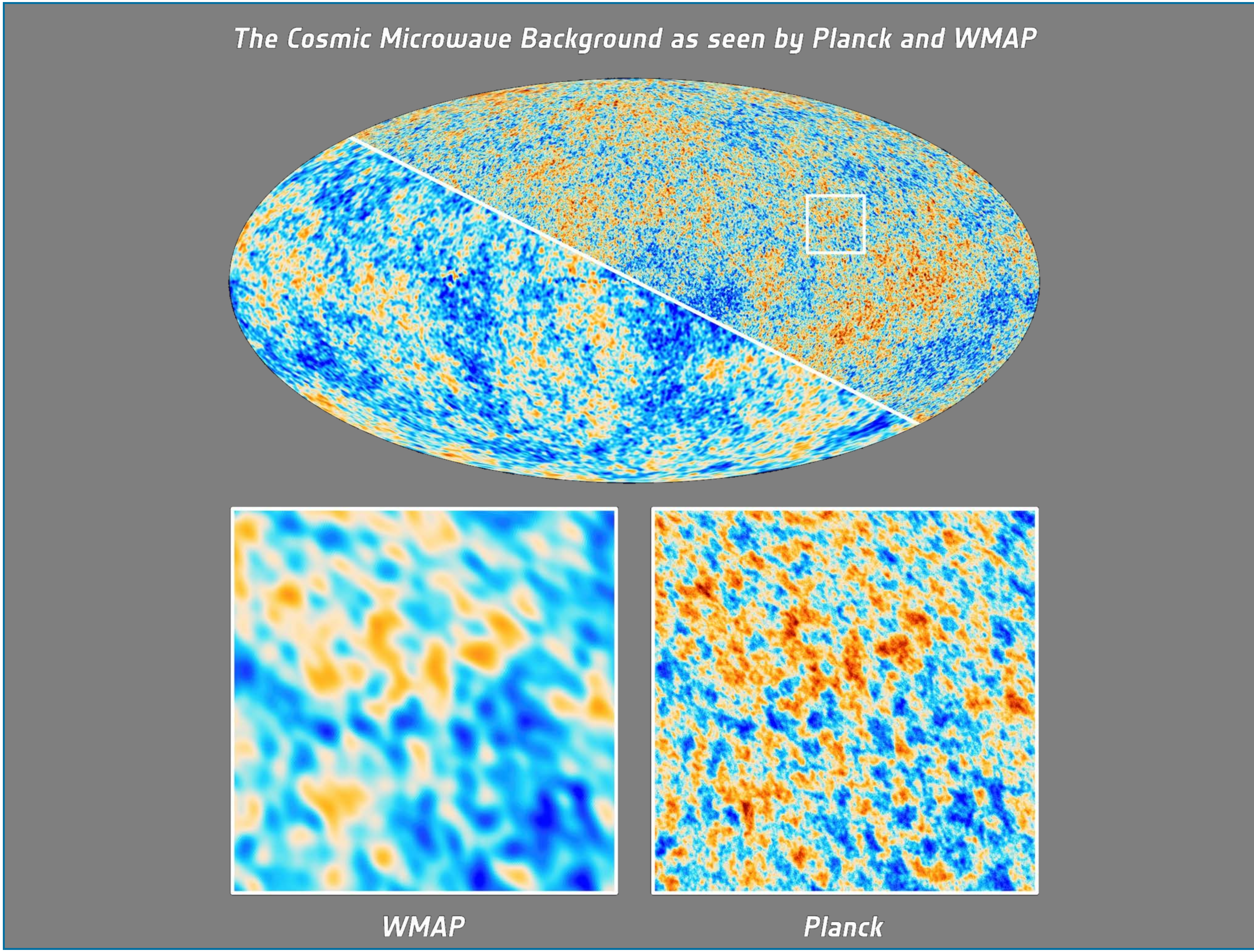


Planck concept

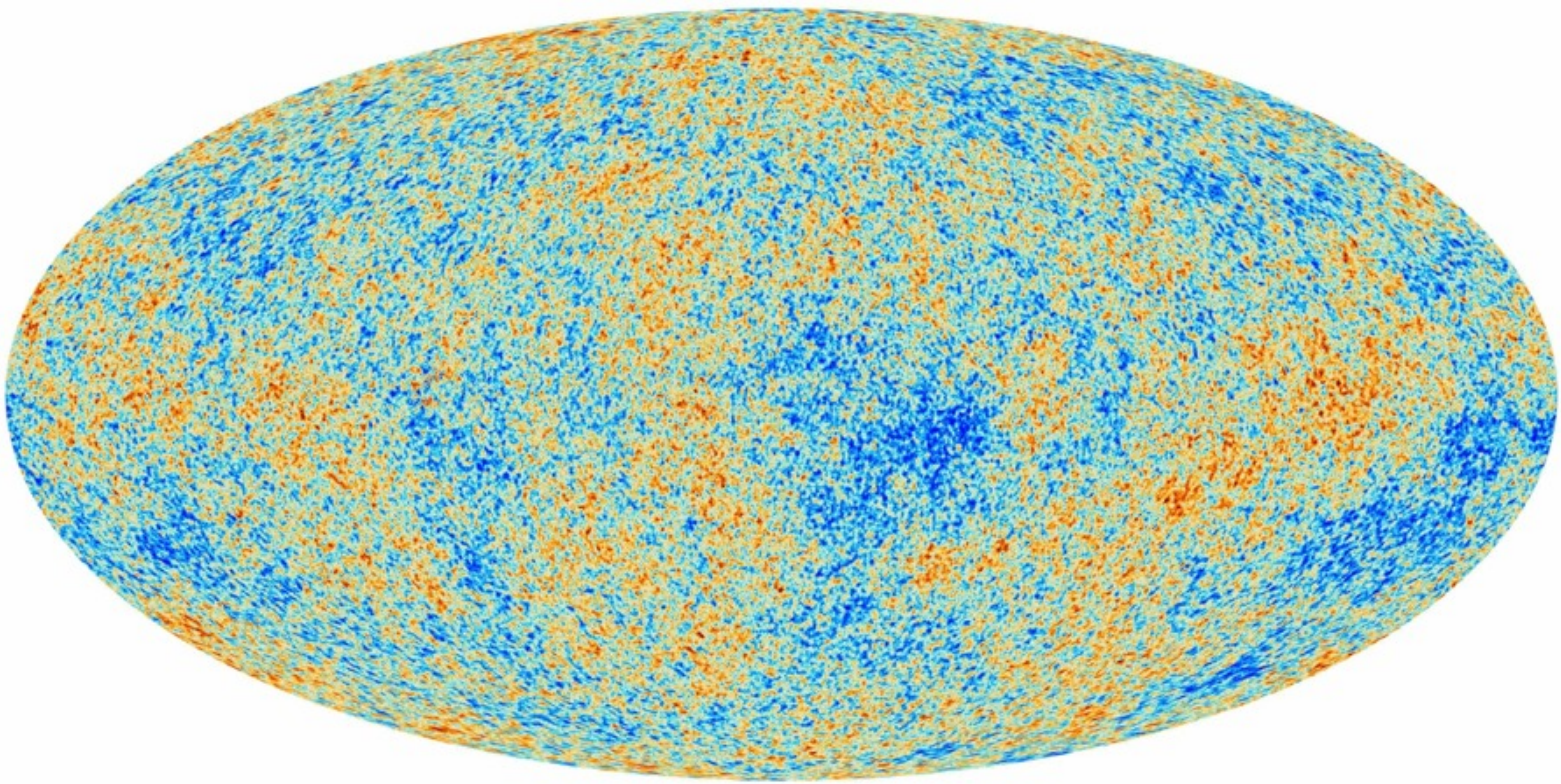




PLANCK	LFI			HFI					
Center Freq (GHz)	30	44	70	100	143	217	353	545	857
Angular resolution (FWHM arcmin)	33	24	14	10	7.1	5.0	5.0	5	5
Sensitivity in I [μK.deg] [$\sigma_{pix}\ \Omega_{pix}^{1/2}$]	3.0	3.0	3.0	1.1	0,7	1.1	3.3	33	3.0


The Cosmic Microwave Background as seen by Planck and WMAP
WMAP
Planck

Planck full-sky CMB map



- 3% sky fraction filled with Gaussian constrained realisations

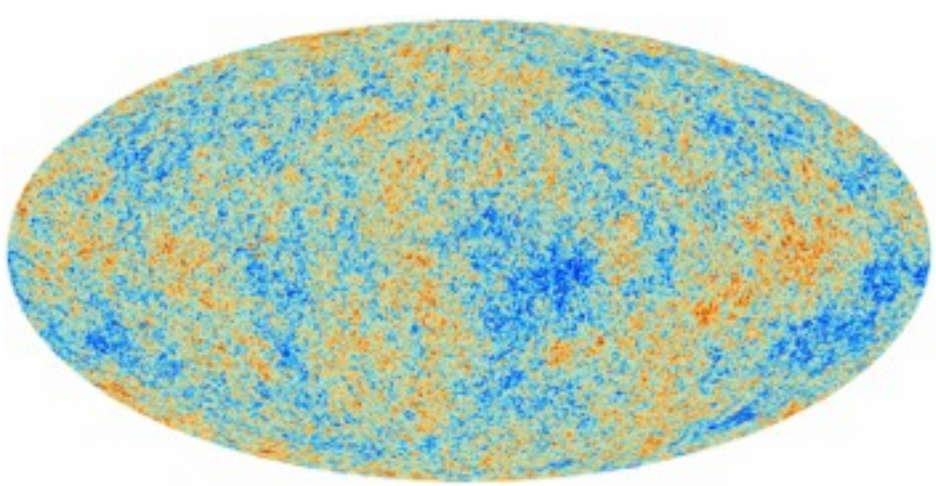
Cosmic Microwave background

- Decompose the temperature on the sphere $T(\hat{\mathbf{n}}) \longrightarrow T_{\ell m}$

Cosmic Microwave background

- Decompose the temperature on the sphere $T(\hat{\mathbf{n}}) \longrightarrow T_{\ell m}$

$T(\hat{\mathbf{n}})$



$T_{\ell m}$

```
-1.36393664e-06 +1.78900125e-07j,
 3.48160018e-07 +5.48607128e-07j,
 8.64414116e-07 +1.58062970e-06j,
 2.32962756e-07 +1.72990879e-07j,
 2.07366735e-07 -1.48637056e-06j,
 1.33636760e-06 +1.44430207e-06j,
-1.33047477e-06 +1.49222938e-06j,
 2.01588688e-07 +1.39367943e-08j,
 1.20185303e-06 -1.04105033e-06j,
-1.88960308e-06 -2.69868746e-07j,
 1.06239463e-06 +4.31127048e-07j,
 3.98739296e-07 +1.19163879e-07j,
-1.24503110e-06 -1.93401840e-06j,
 5.68052758e-07 +6.49802586e-08j,
 5.05386856e-07 -2.28955226e-07j,
-2.60272490e-07 +2.21246718e-06j,
-1.11889361e-06 +1.87312956e-06j,
 9.72080476e-07 -6.89214224e-07j,
 3.26351028e-07 +1.08530943e-06j,
 2.14977119e-06 -9.44341599e-07j,
```

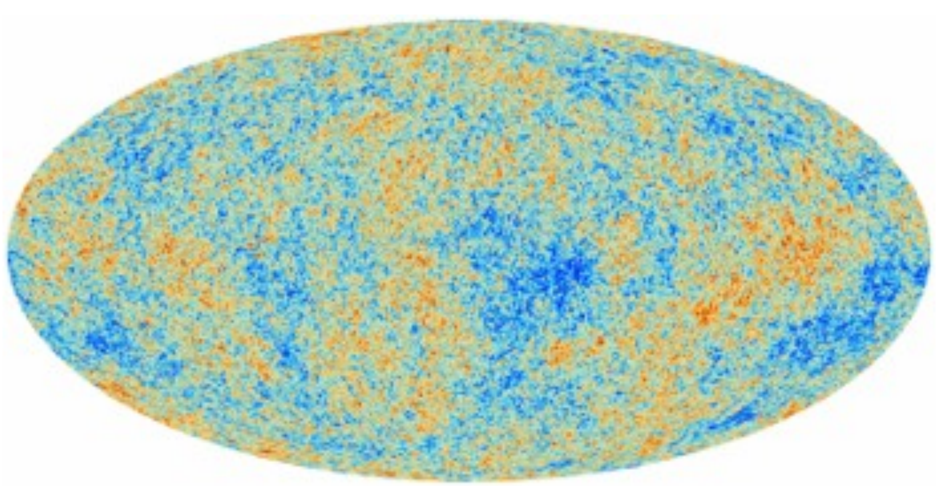
Cosmic Microwave background

- Decompose the temperature on the sphere $T(\hat{\mathbf{n}}) \longrightarrow T_{\ell m}$
- CMB is (almost) Gaussian: all the information is in the variance $\langle t_{\ell m} t^*_{\ell' m'} \rangle = C_\ell$

Power spectrum can be computed: e.g. CAMB

Can be measured from observations: e.g. pseudo-Cl's $\hat{C}_\ell = \frac{1}{2\ell+1} \sum_{m=-\ell}^{\ell} |T_{\ell m}|^2$

$T(\hat{\mathbf{n}})$



$T_{\ell m}$

```
-1.36393664e-06 +1.78900125e-07j,
 3.48160018e-07 +5.48607128e-07j,
 8.64414116e-07 +1.58062970e-06j,
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-1.33047477e-06 +1.49222938e-06j,
 2.01588688e-07 +1.39367943e-08j,
 1.20185303e-06 -1.04105033e-06j,
-1.88960308e-06 -2.69868746e-07j,
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 3.98739296e-07 +1.19163879e-07j,
-1.24503110e-06 -1.93401840e-06j,
 5.68052758e-07 +6.49802586e-08j,
 5.05386856e-07 -2.28955226e-07j,
-2.60272490e-07 +2.21246718e-06j,
-1.11889361e-06 +1.87312956e-06j,
 9.72080476e-07 -6.89214224e-07j,
 3.26351028e-07 +1.08530943e-06j,
 2.14977119e-06 -9.44341599e-07j,
```
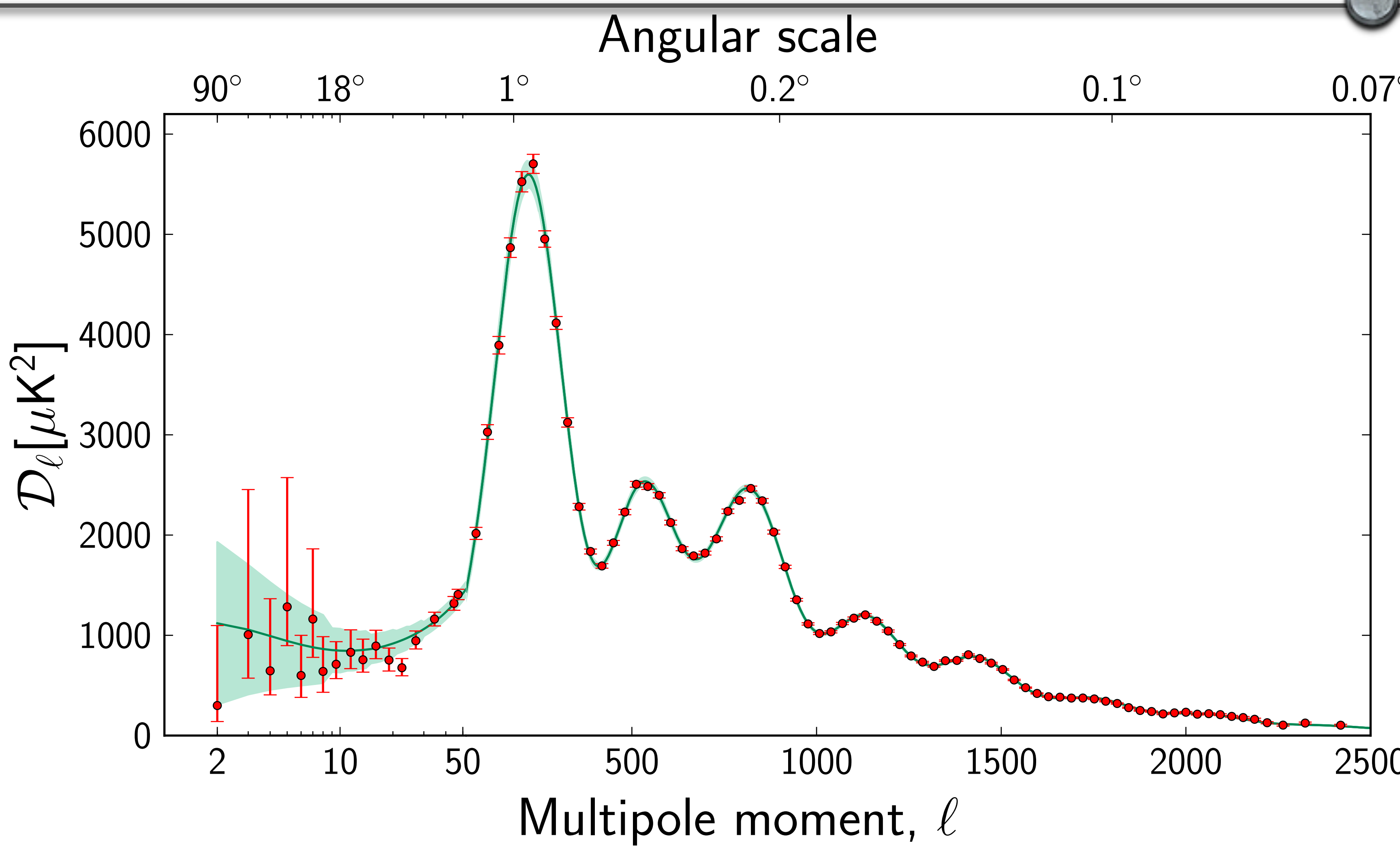
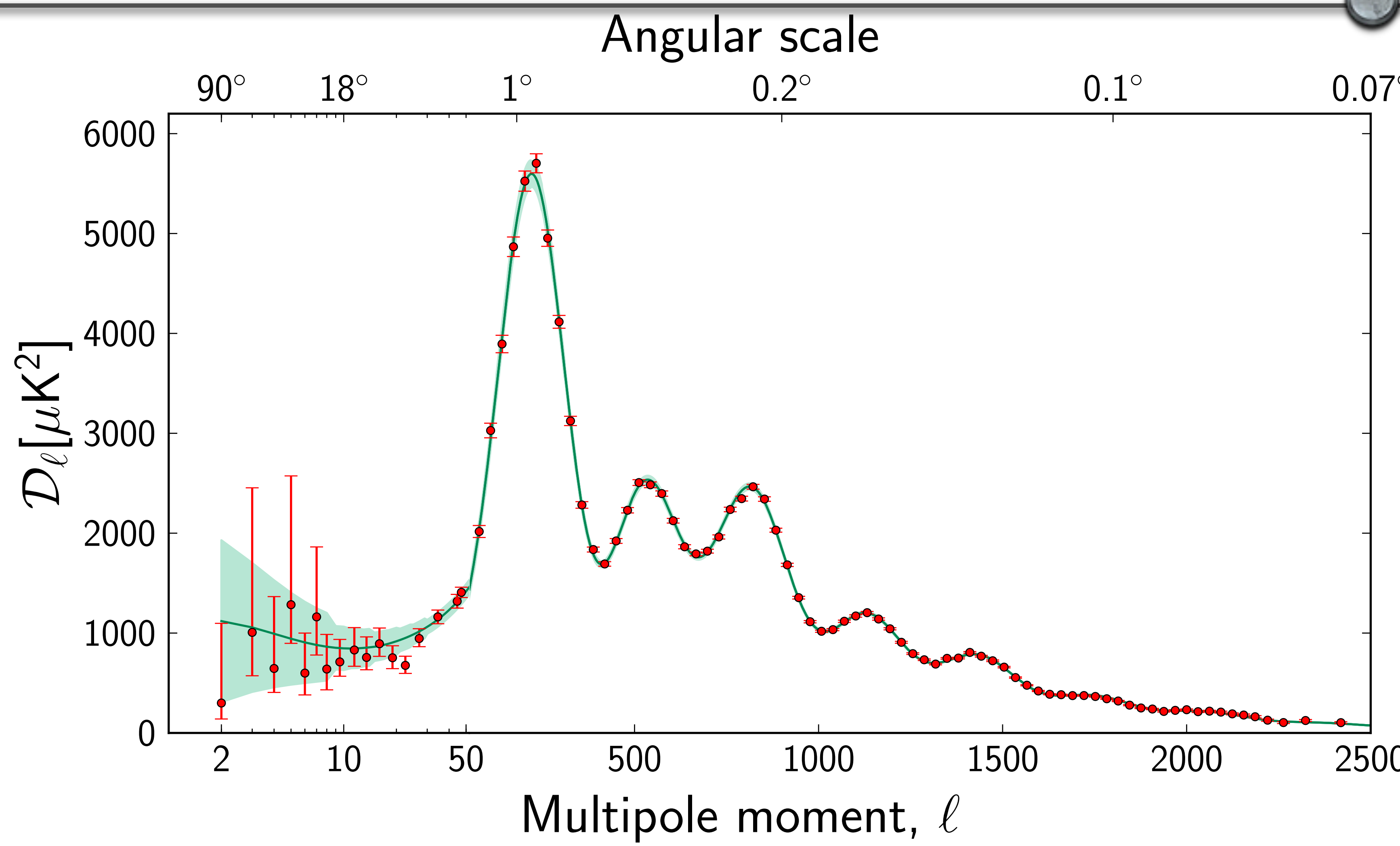
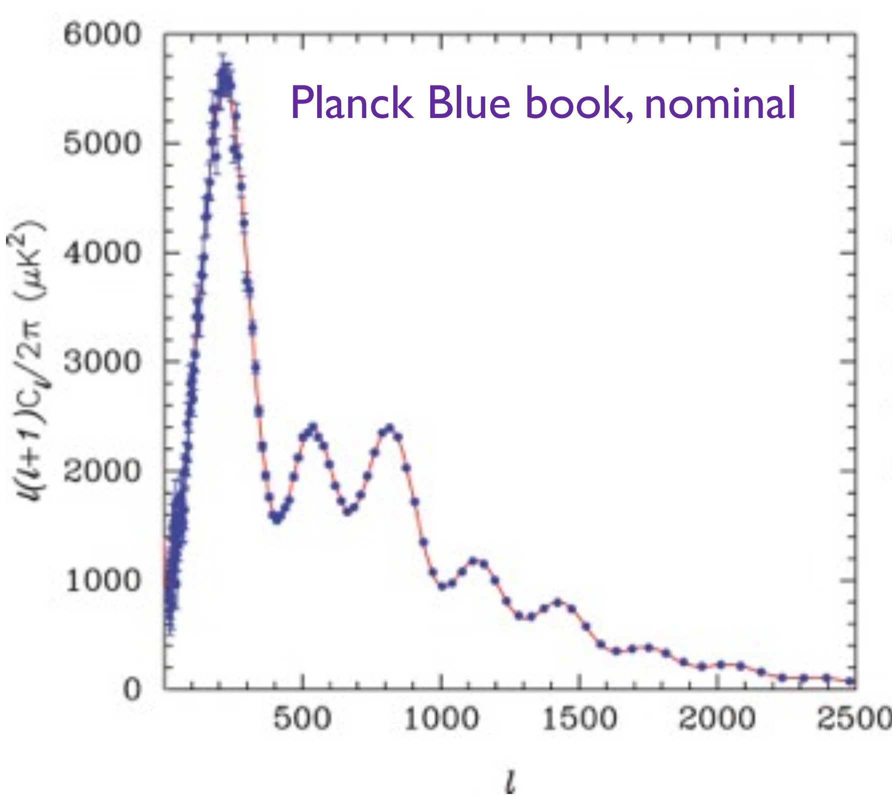
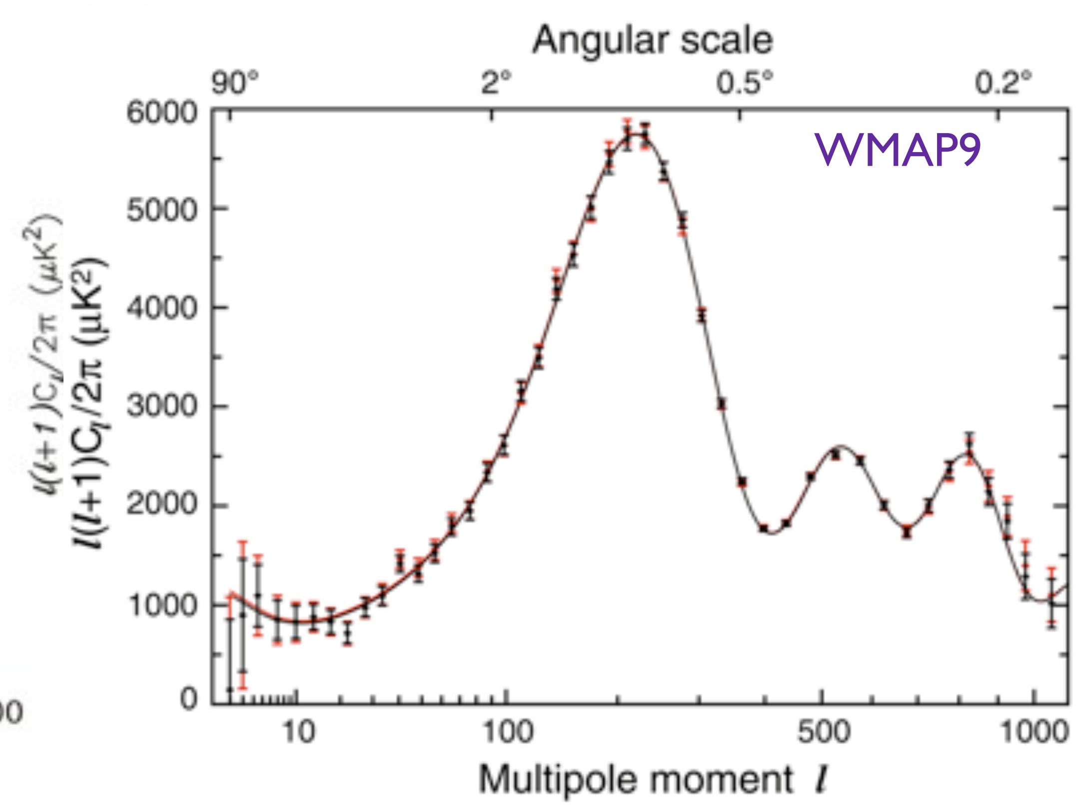

Cosmic Microwave background



Cosmic Microwave background

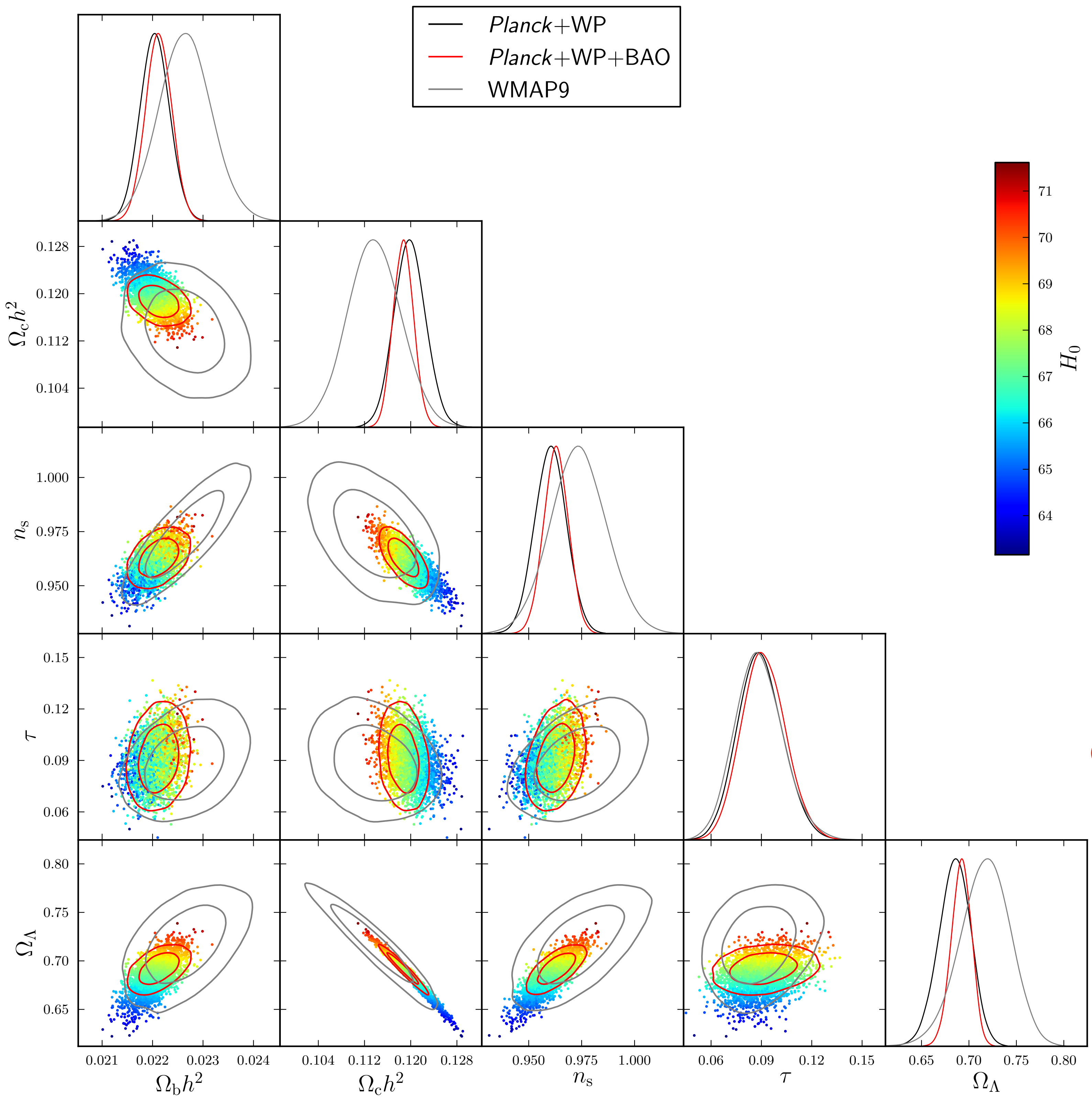


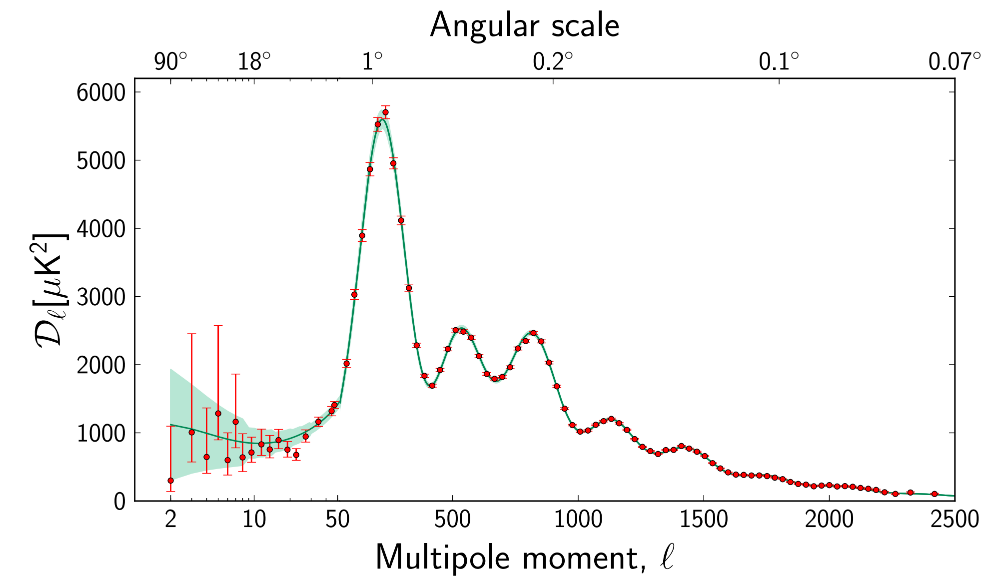




Planck cosmological parameters

A model described by only 6 parameters





- Peak scale 0.060%
- Baryon density 1.3%
- CDM density 2.3%
- Primordial amplitude 2.5%
- Primordial spectral index 0.76%
- Reionization optical depth 0.13%

Inflation

Inflation was introduced in the 80's to solve the horizon and flatness problems

Horizon problem:
size of the horizon at recombination is about 1degree. Then why is the temperature the same everywhere on the sky?

Flatness problem:
our Universe is observed today as being flat. This require unnatural fine-tuning in the initial conditions.

A period of accelerated expansion in the Early universe would solve those two problems.

Quantum fluctuation generated during inflation also provides perturbations. Seeds for large-scale structure

Linking Inflation properties to CMB

The metric describes the distances between two points in space

$$d\ell^2 = a^2(t)[1 + 2\zeta(\mathbf{x}, t)][\delta_{ij} + h_{ij}(\mathbf{x}, t)]dx^i dx^j$$

curvature perturbation (scalar)

Gravitational waves (tensor)

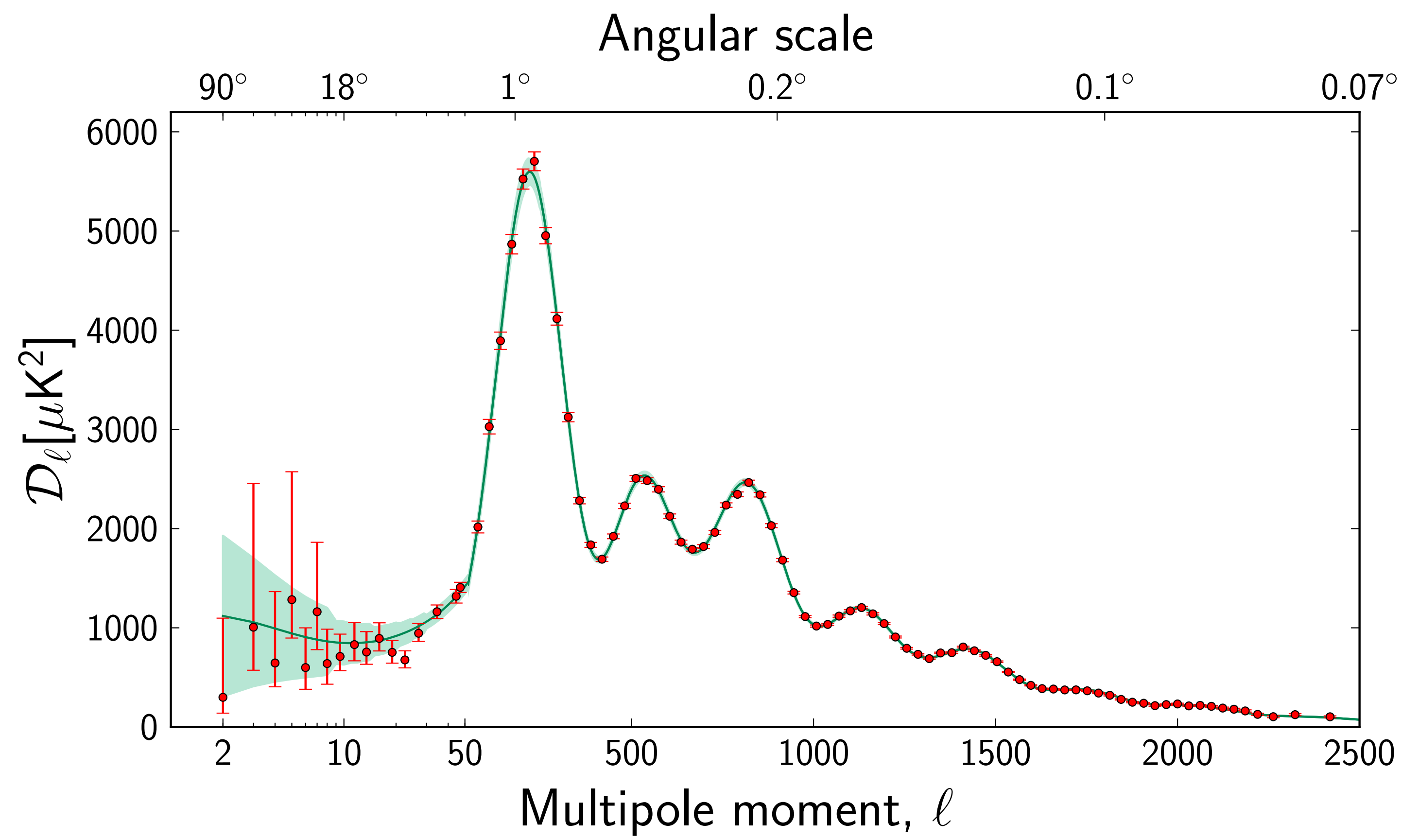
Tensor-to-scalar ratio

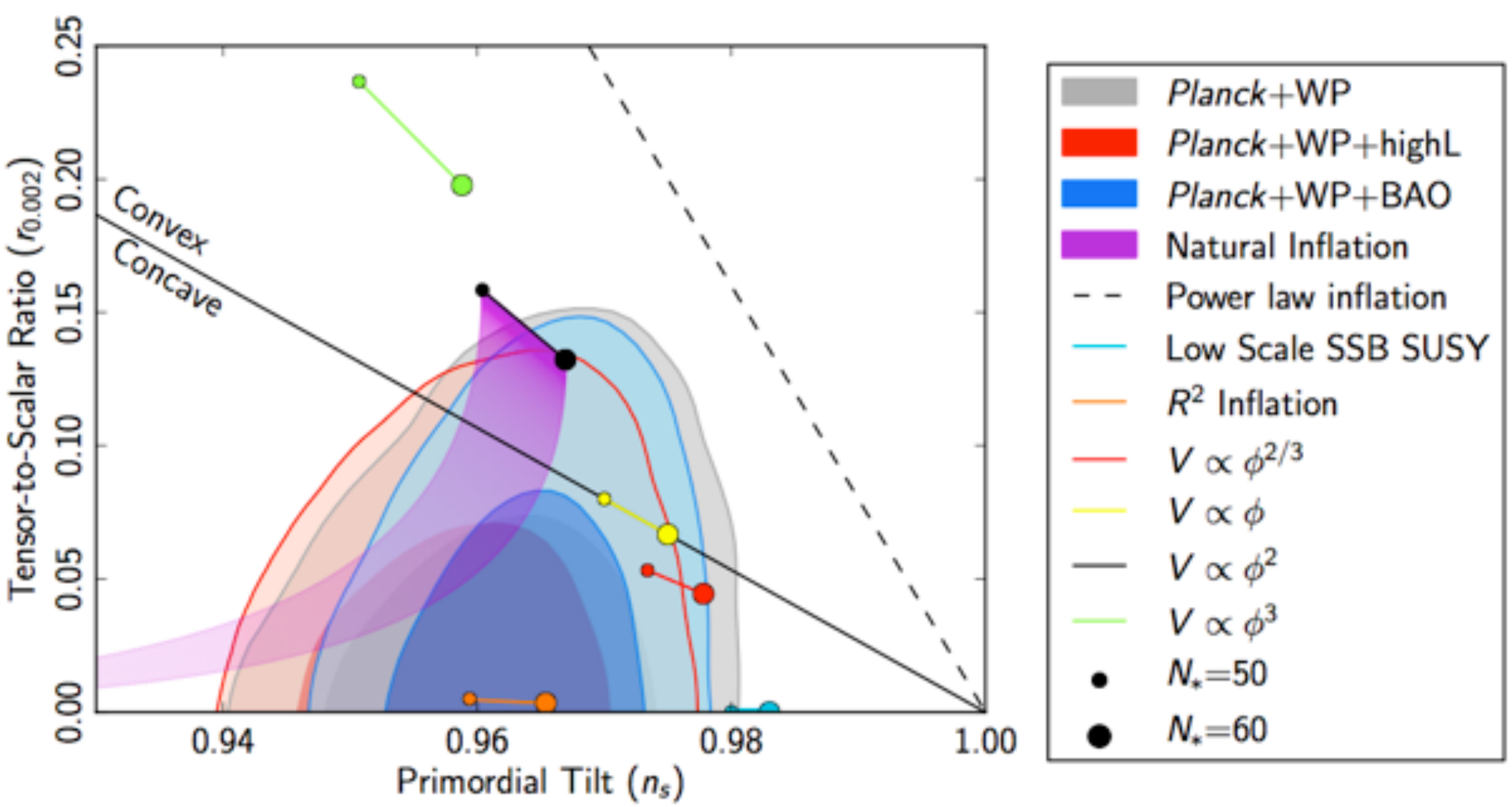
$$r \equiv \frac{\mathcal{P}_h}{\mathcal{P}_\zeta}$$

Spectral indices

$$n_\mathrm{S} - 1 \equiv \left.\frac{\mathrm{d}\ln\mathcal{P}_\zeta}{\mathrm{d}\ln k}\right|_{k_*}, \quad n_\mathrm{T} \equiv \left.\frac{\mathrm{d}\ln\mathcal{P}_h}{\mathrm{d}\ln k}\right|_{k_*}.$$

Constraints from current Planck data

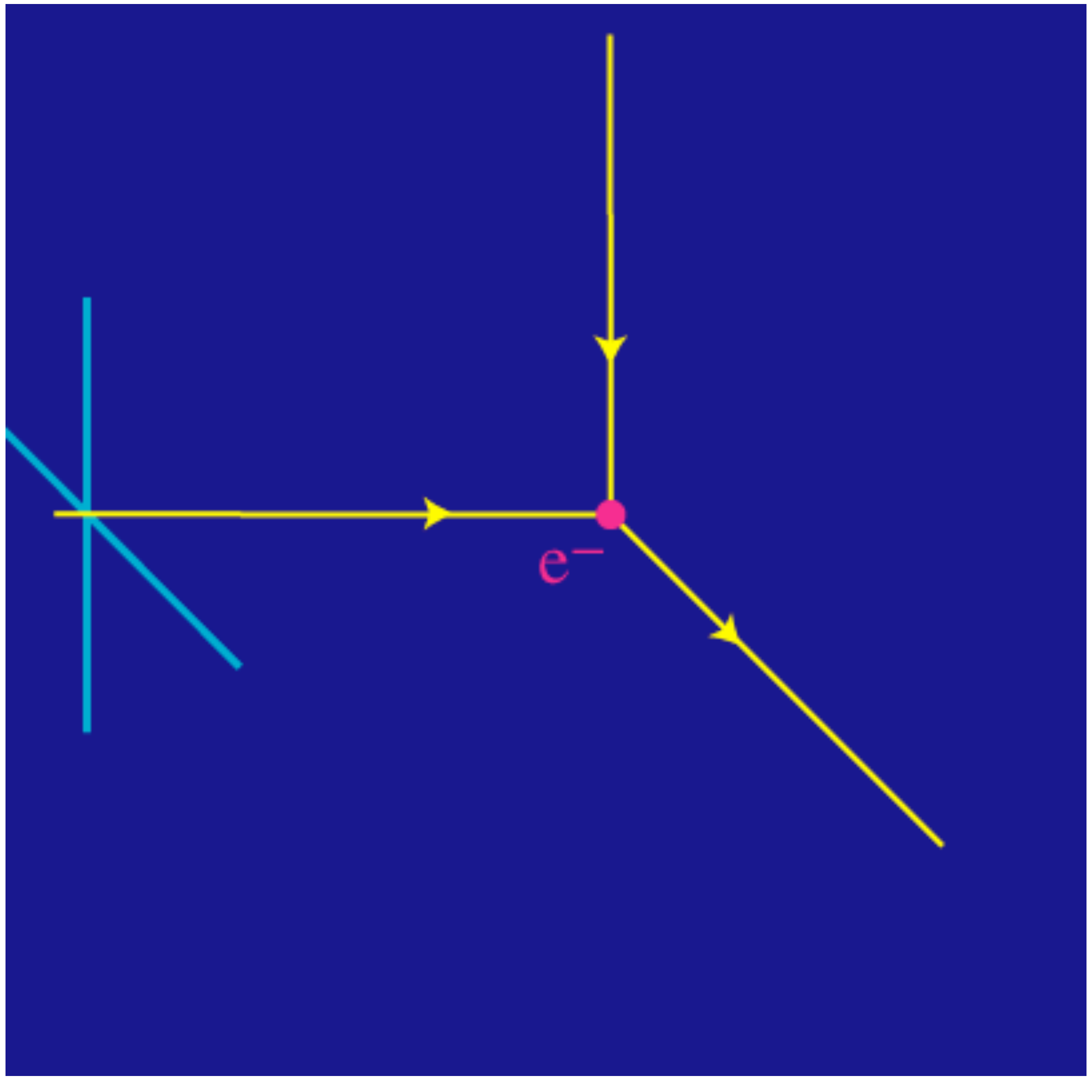




How to get better constraints on r?

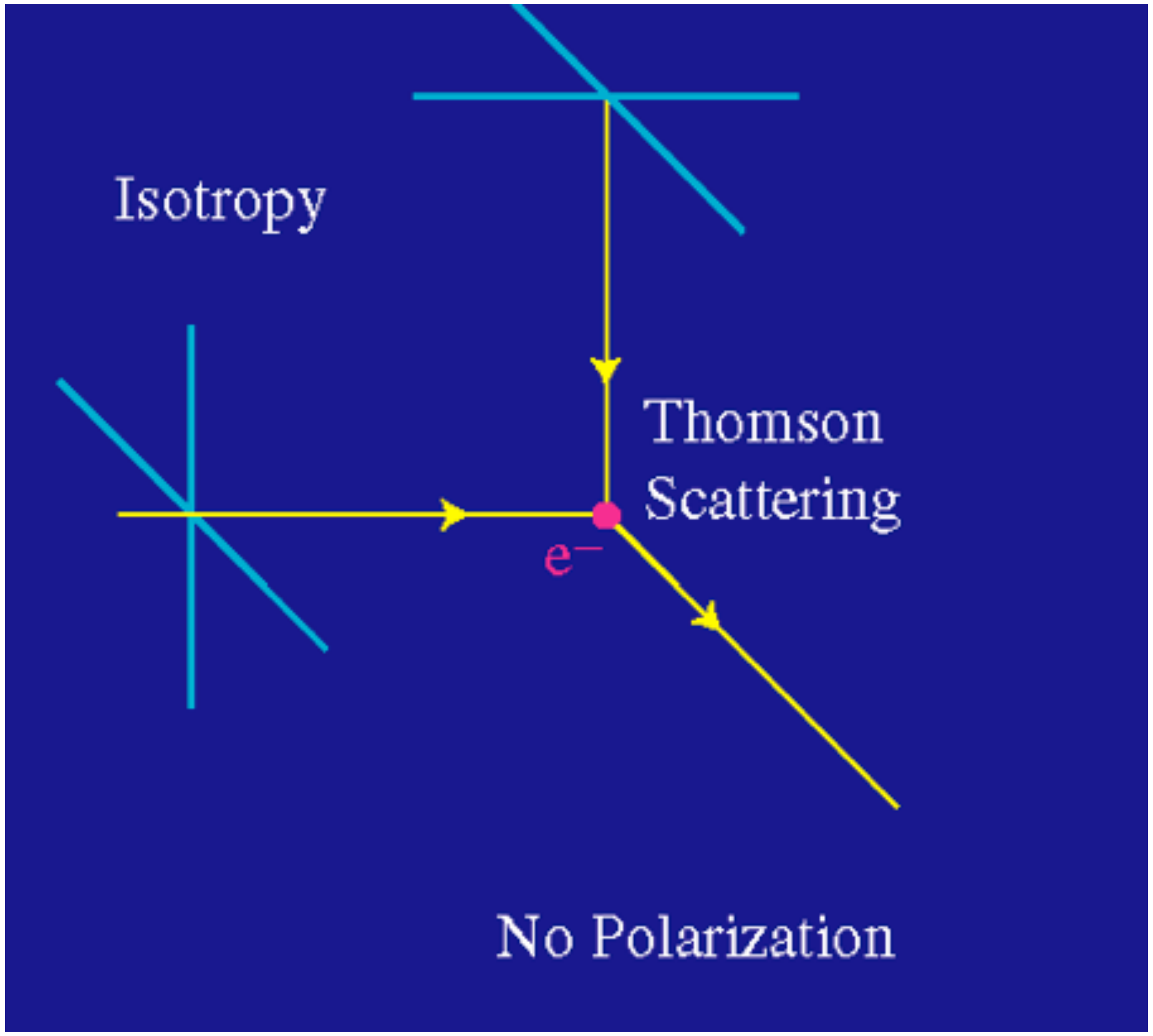
CMB polarisation

unpolarized
incoming light



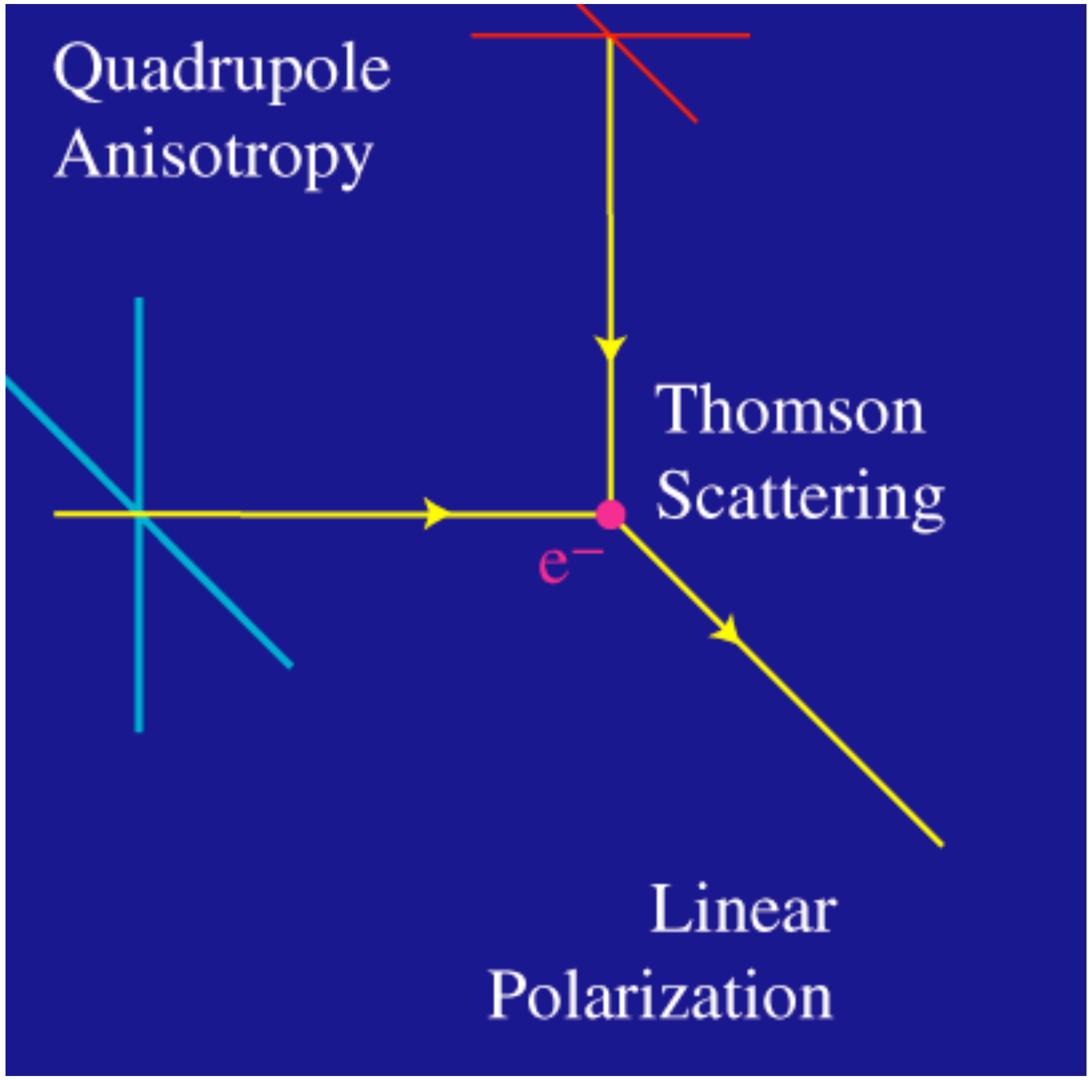
from Wayne Hu

CMB polarisation



from Wayne Hu

CMB polarisation



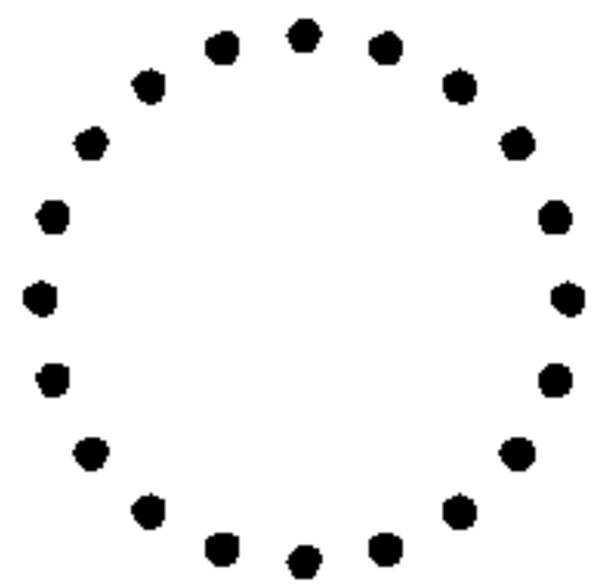
Polarization is generated from Thomson scattering if there is a quadrupole anisotropy

from Wayne Hu

Quadrupole at recombination

$$d\ell^2 = a^2(t)[1 + 2\zeta(\mathbf{x}, t)][\delta_{ij} + h_{ij}(\mathbf{x}, t)]dx^i dx^j$$

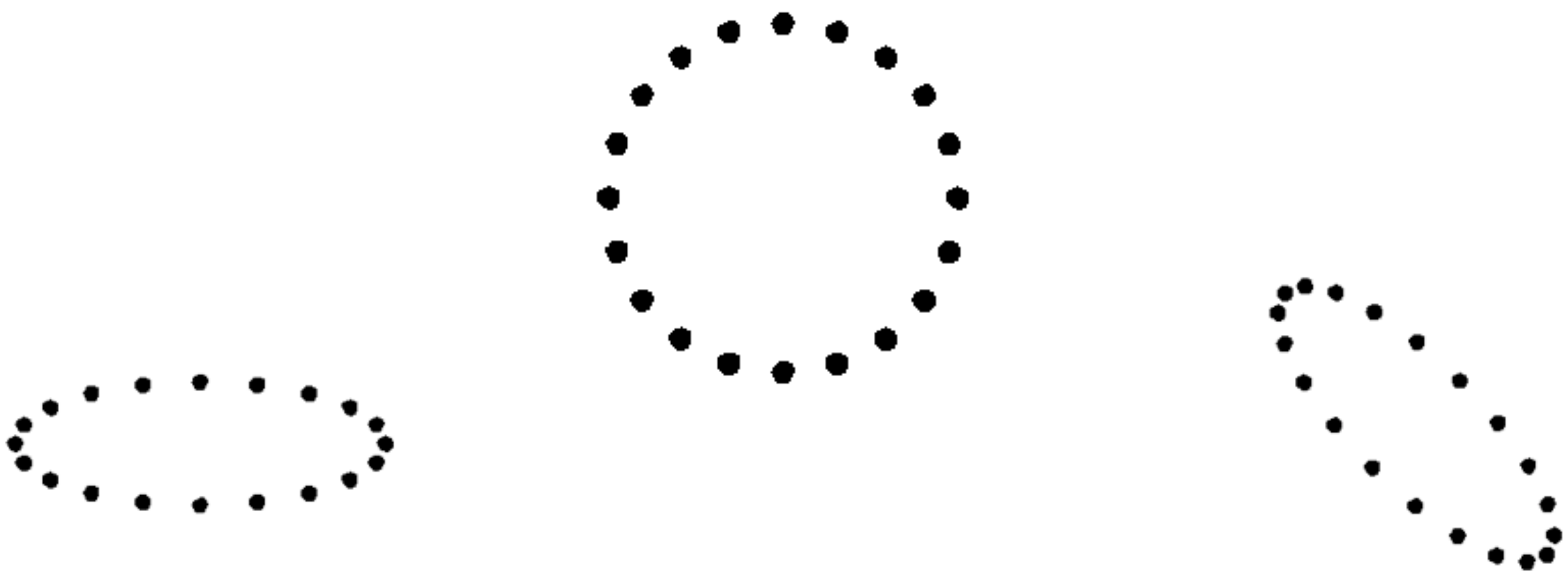
GW coming toward you



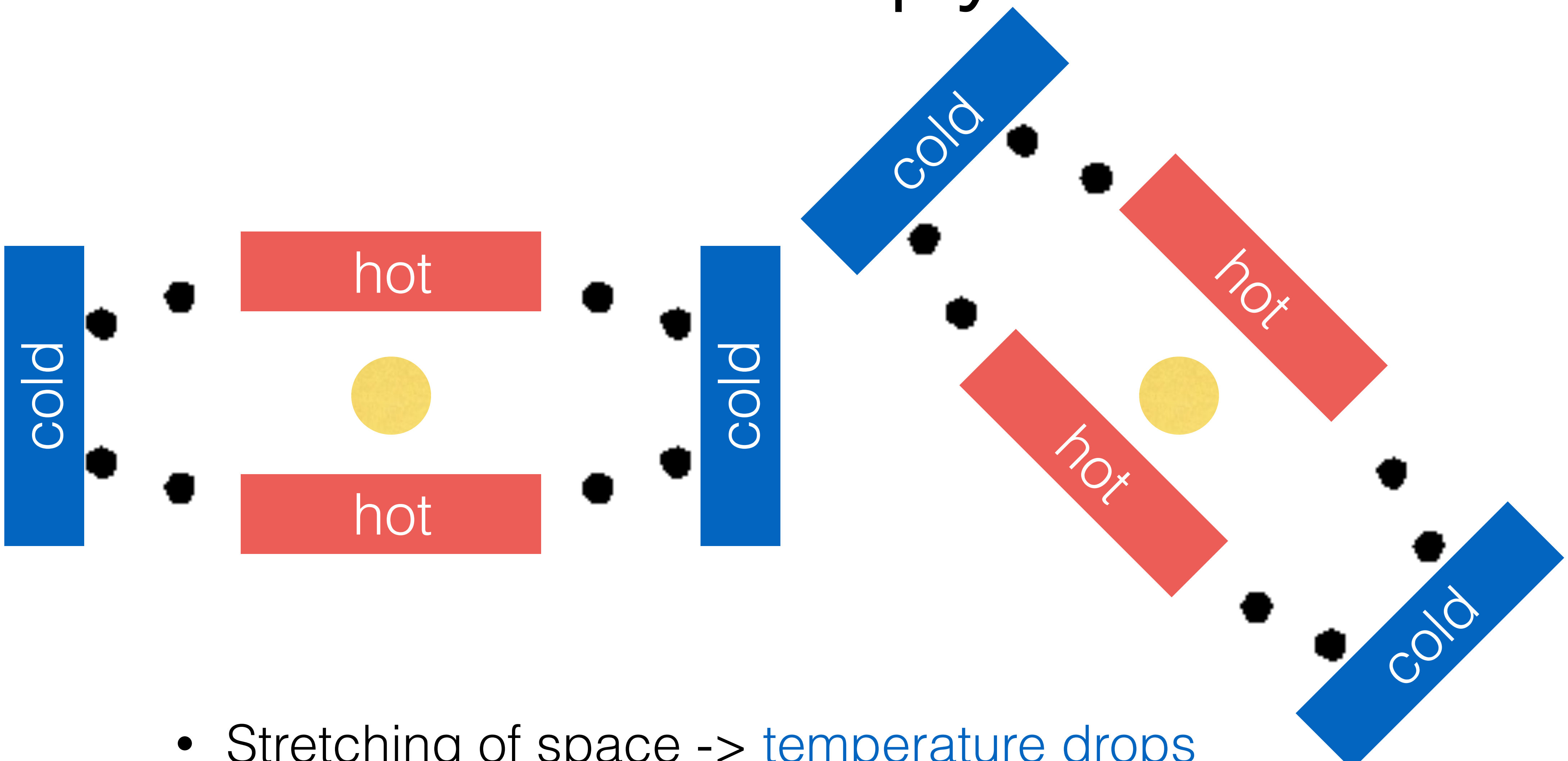
Quadrupole at recombination

$$d\ell^2 = a^2(t)[1 + 2\zeta(\mathbf{x}, t)][\delta_{ij} + h_{ij}(\mathbf{x}, t)]dx^i dx^j$$

GW coming toward you



GW to temperature anisotropy

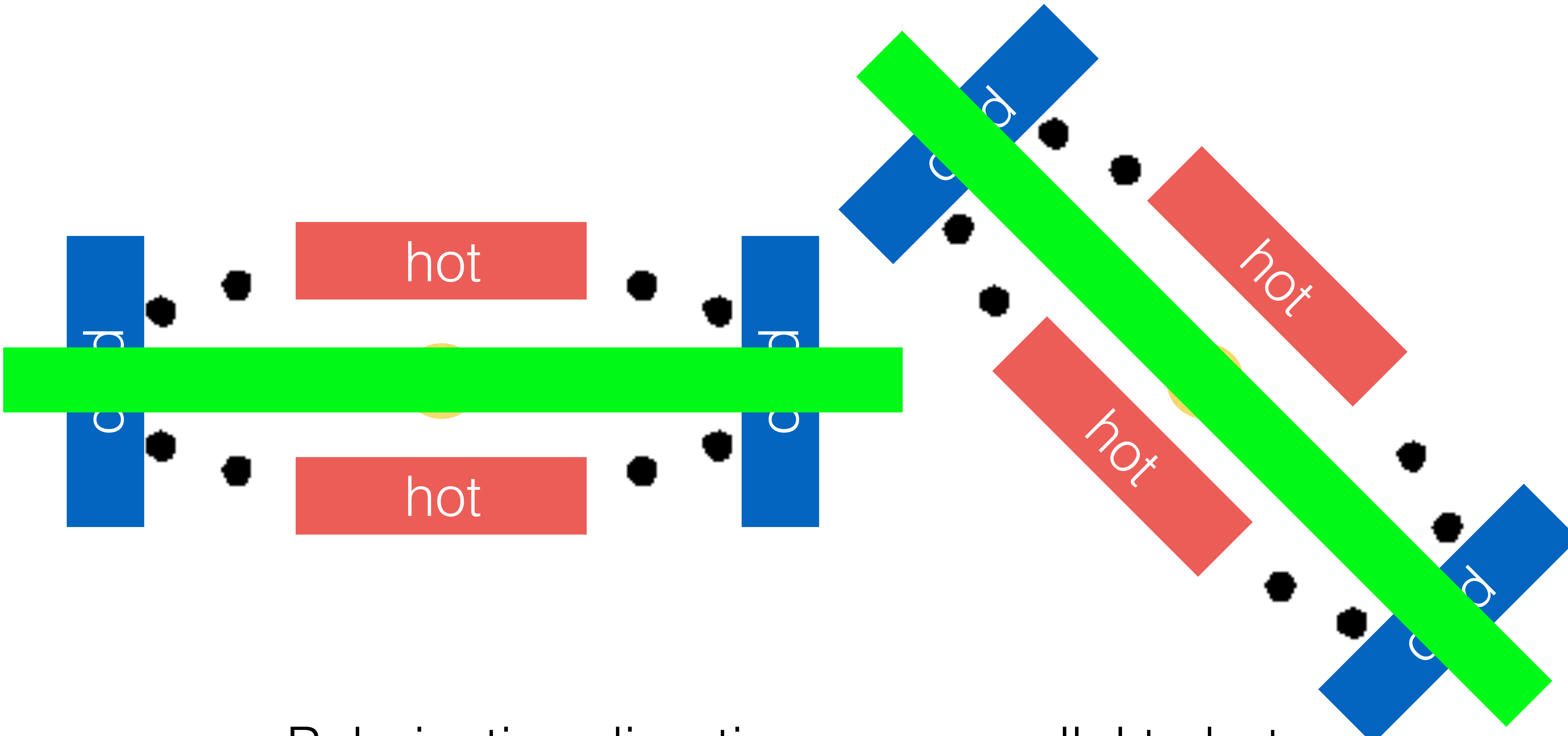


- Stretching of space -> temperature drops
- Contraction of space -> temperature rises

Temperature quadrupole anisotropy from GW

from Eiichiro Komatsu

Then to polarisation!



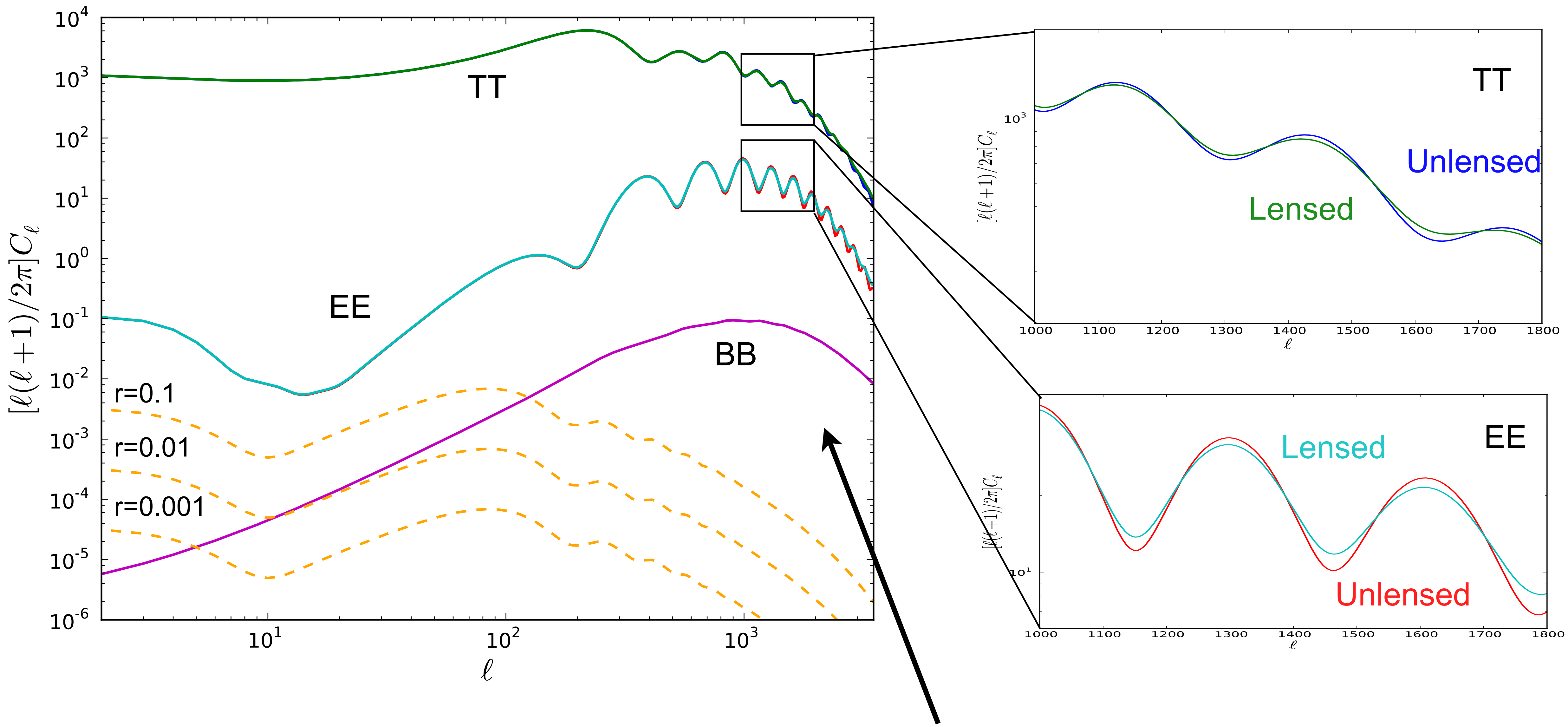
- Polarisation directions are parallel to hot regions

from Eiichiro Komatsu

Temperature and polarisation power spectra

Scalar perturbations create only E-modes

Tensor pertubations create both E and B modes



Gravitational lensing is a known source of B modes at small-scales

What is BICEP2?

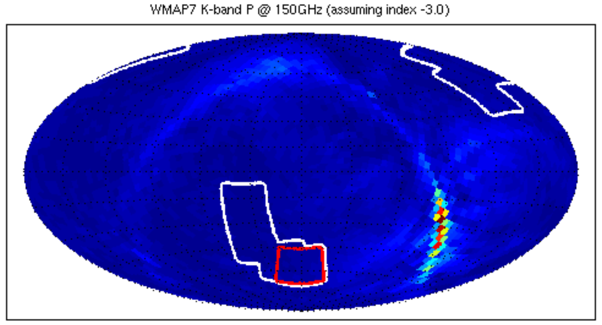
26cm telescope at the South Pole

512 detector at 150GHz

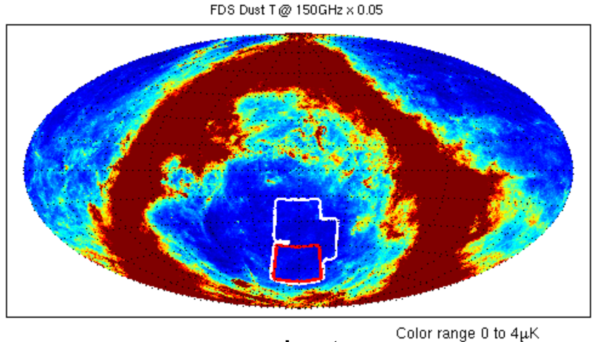
Observing strategy: go deep on a small, clean patch of the sky.

Same patch observed during 590 days

“Southern Hole”

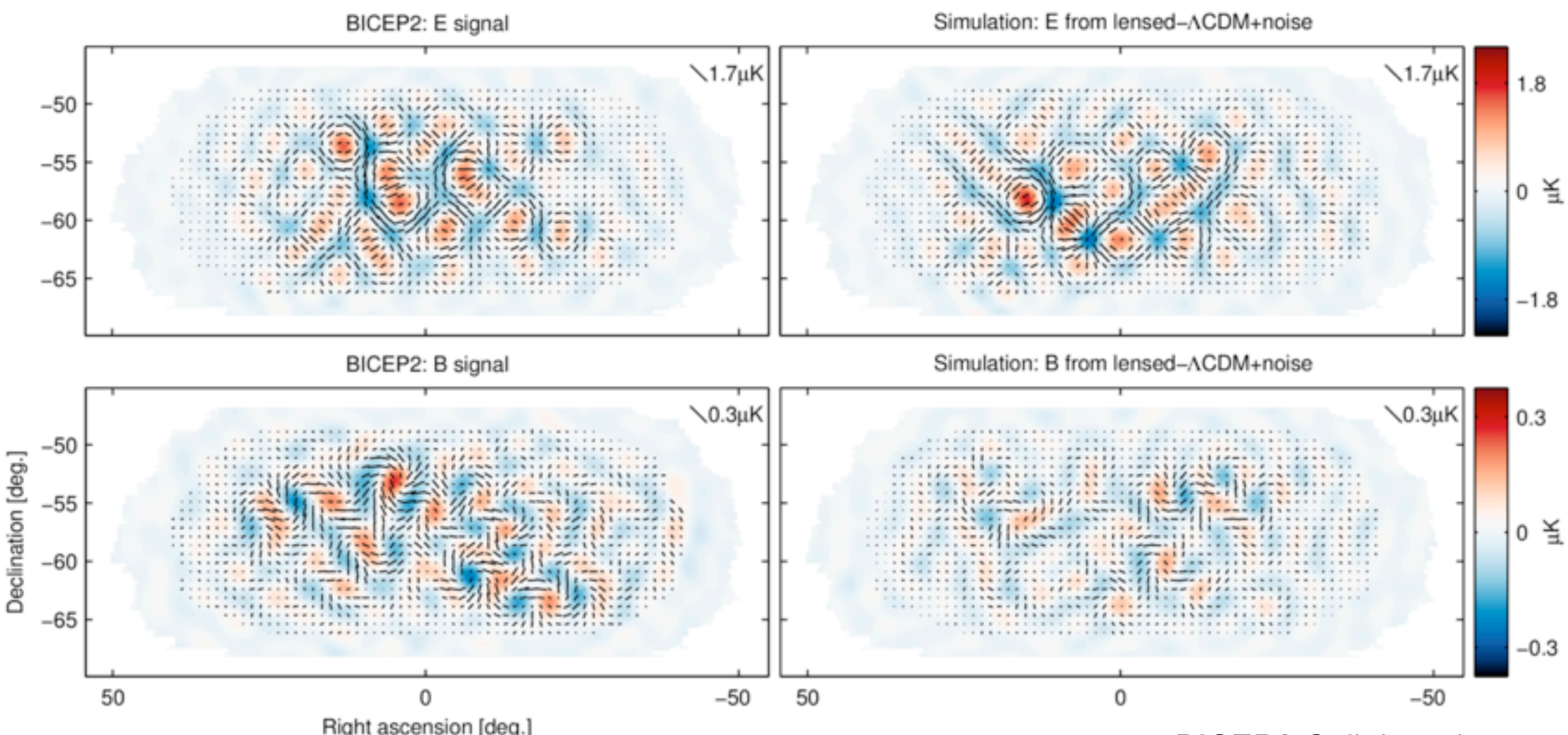


synchrotron



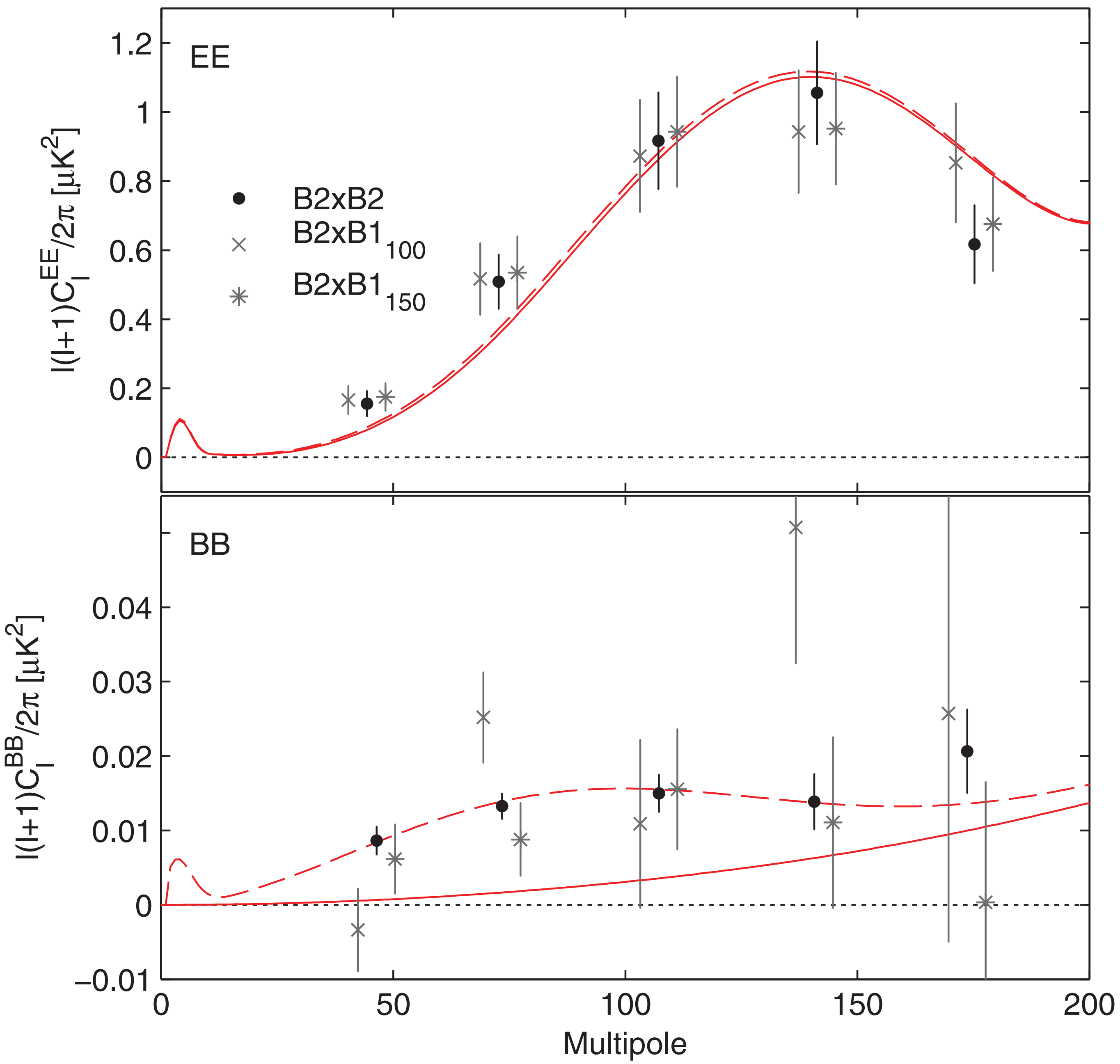
dust

BICEP2 EB maps



BICEP2 Collaboration

BICEP2 EB power spectra



r=0.2 is high, and higher than expected

Planck constraint was r <0.11

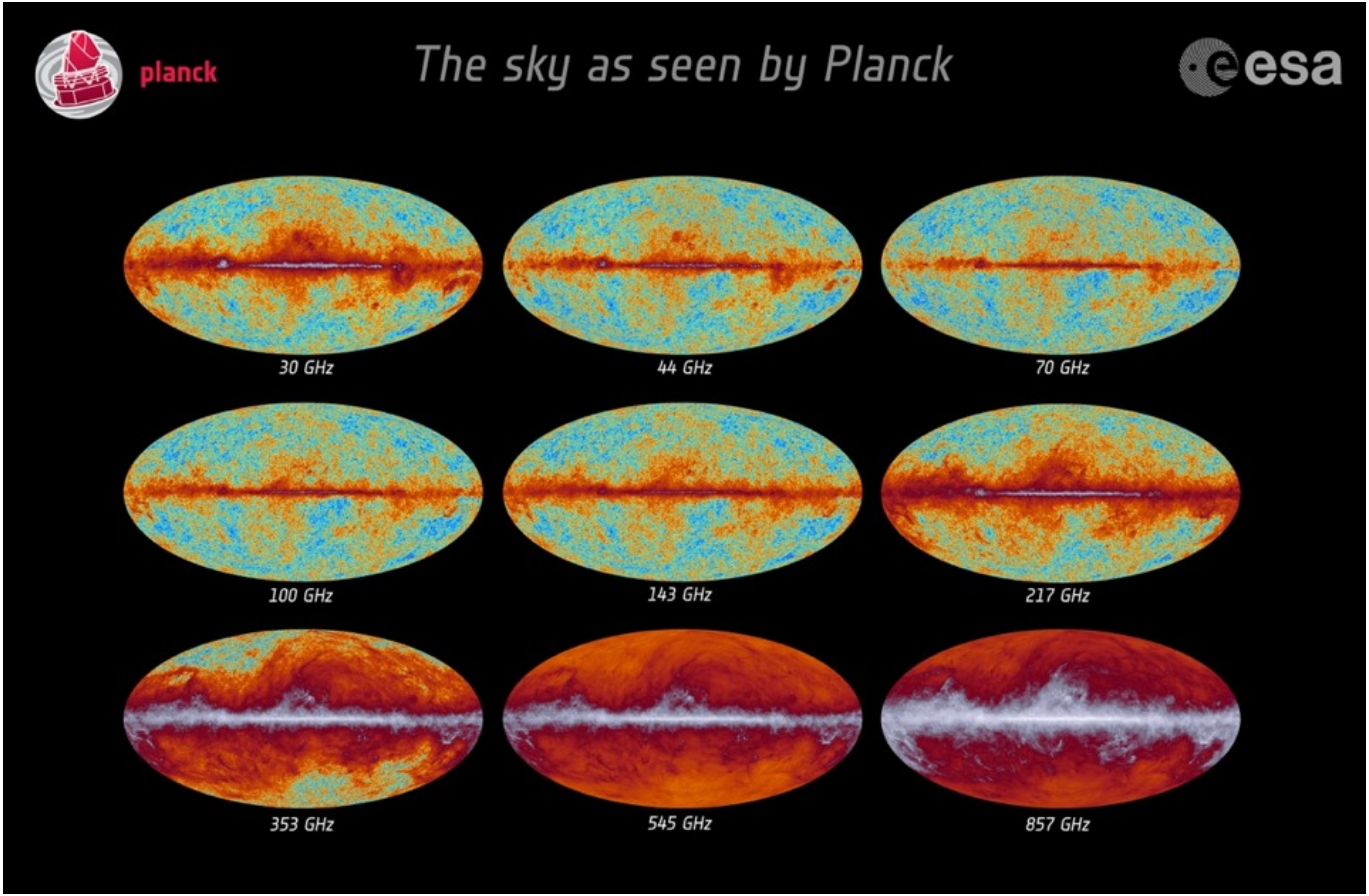
r=0.2

r=0

BICEP2 Collaboration

How are we sure that what has been measured is of cosmological origin?

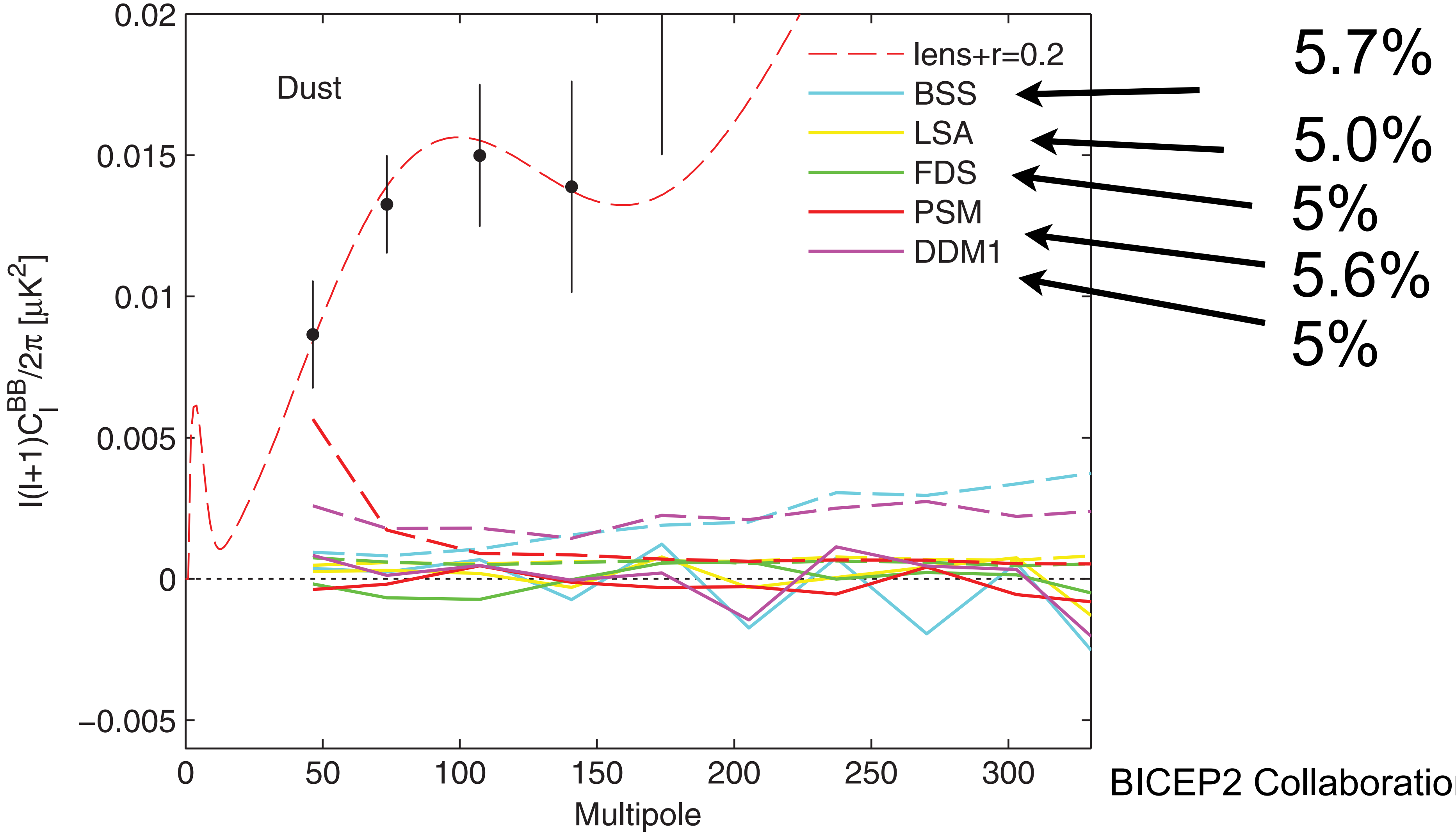
Planck sky maps



Galactic dust

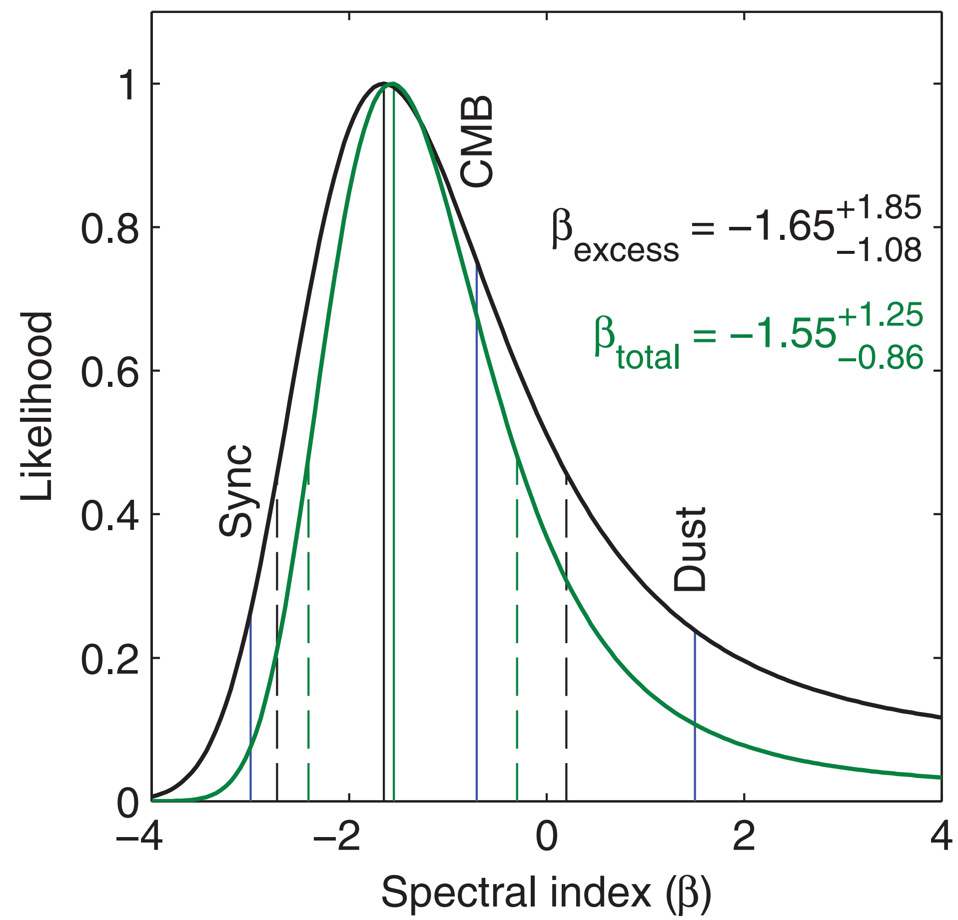
Polarized dust emission arises from the alignment of non-spherical dust grains with the interstellar magnetic field.

take a existing dust intensity map, and "convert" to polarisation assuming a polarisation fraction



BICEP2 Collaboration

Galactic dust



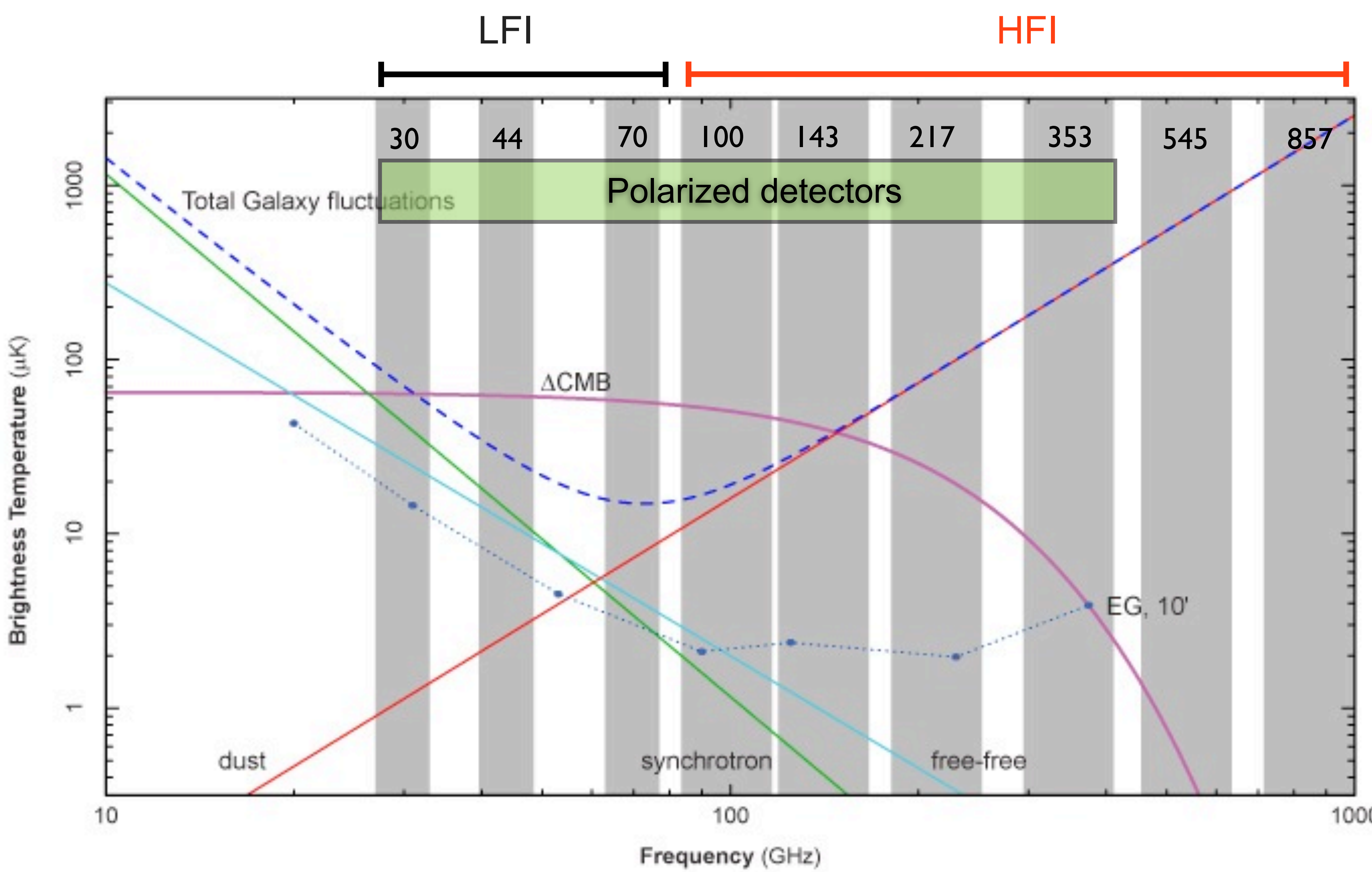
smaller than the observed signal. These foreground models possess no significant cross-correlation with our maps. Additionally, cross-correlating BICEP2 against 100 GHz maps from the BICEP1 experiment, the excess signal is confirmed with 3σ significance and its spectral index is found to be consistent with that of the CMB, disfavoring synchrotron or dust at 2.3σ and 2.2σ, respectively. The observed B-mode power spectrum is well-

From the original abstract

Even from then, no clear evidence of the cosmological origin of the signal. (Of course it is easy to say that today!!)

What happen since March?

New Planck results!

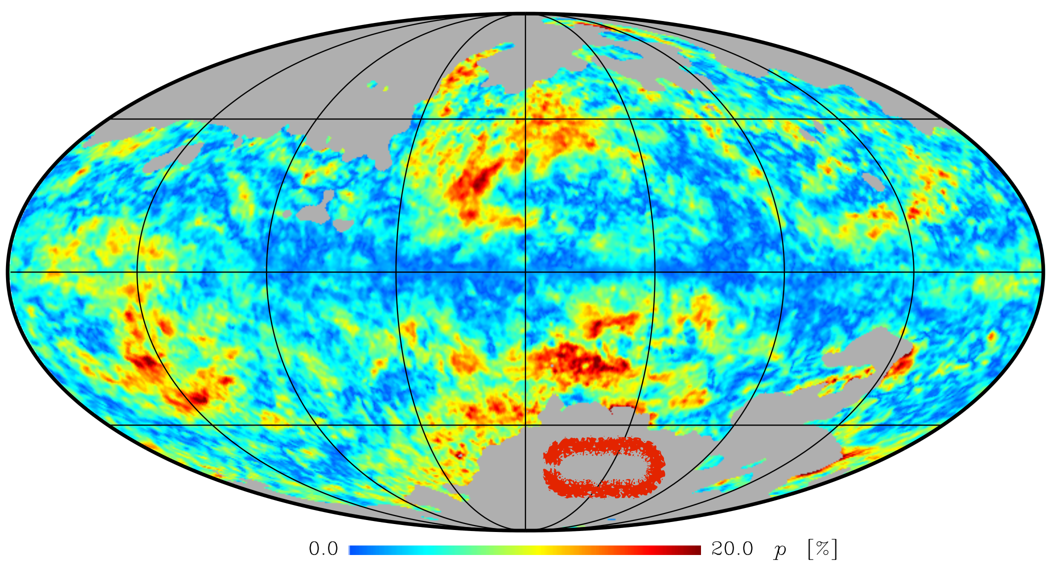


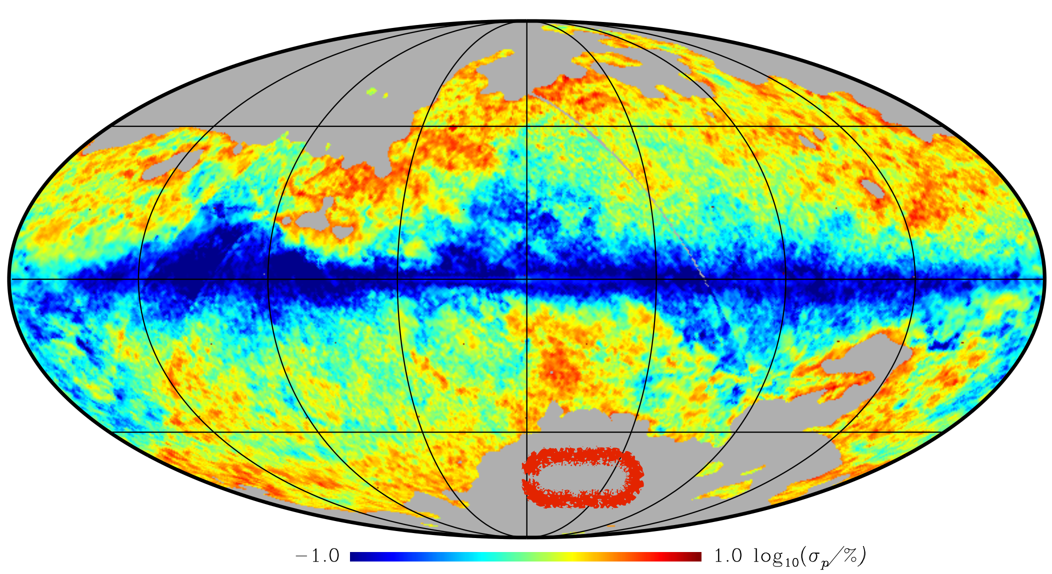
May 2014

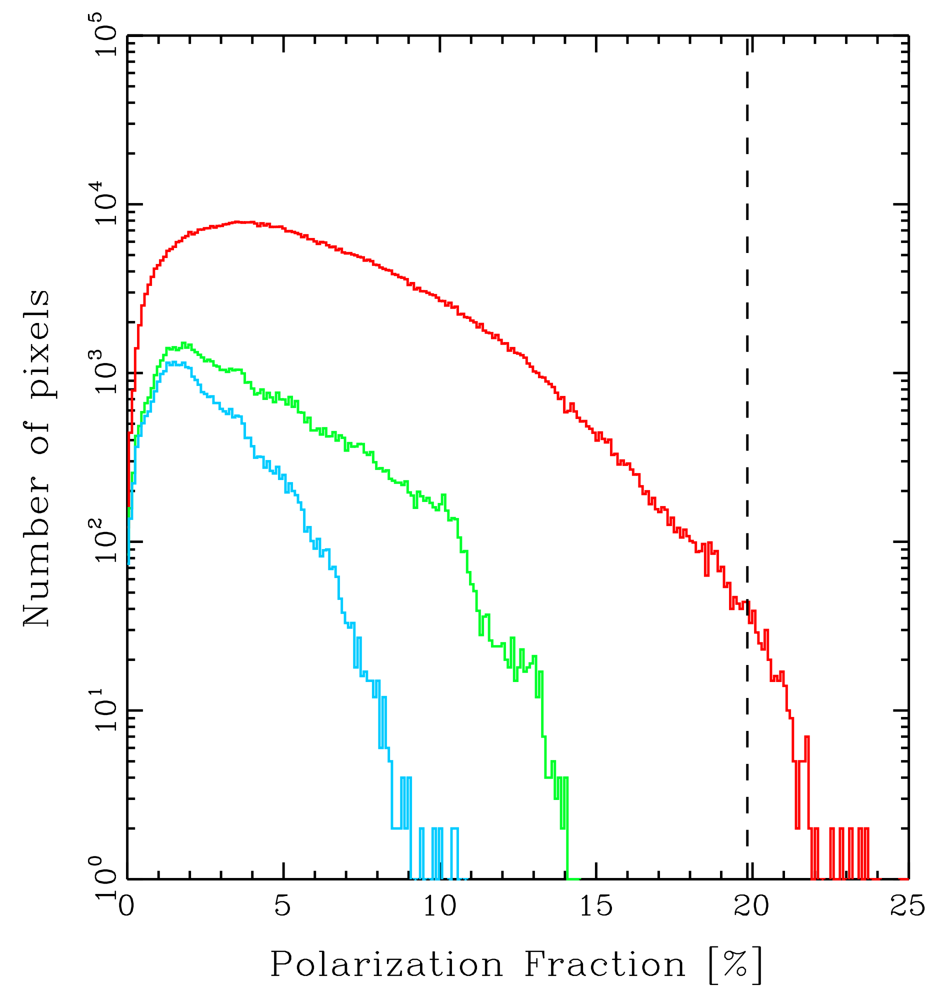
Planck intermediate results. XIX. An overview of the polarized thermal emission from Galactic dust

polarisation fraction p

$$p = \frac{\sqrt{Q^2 + U^2}}{I},$$





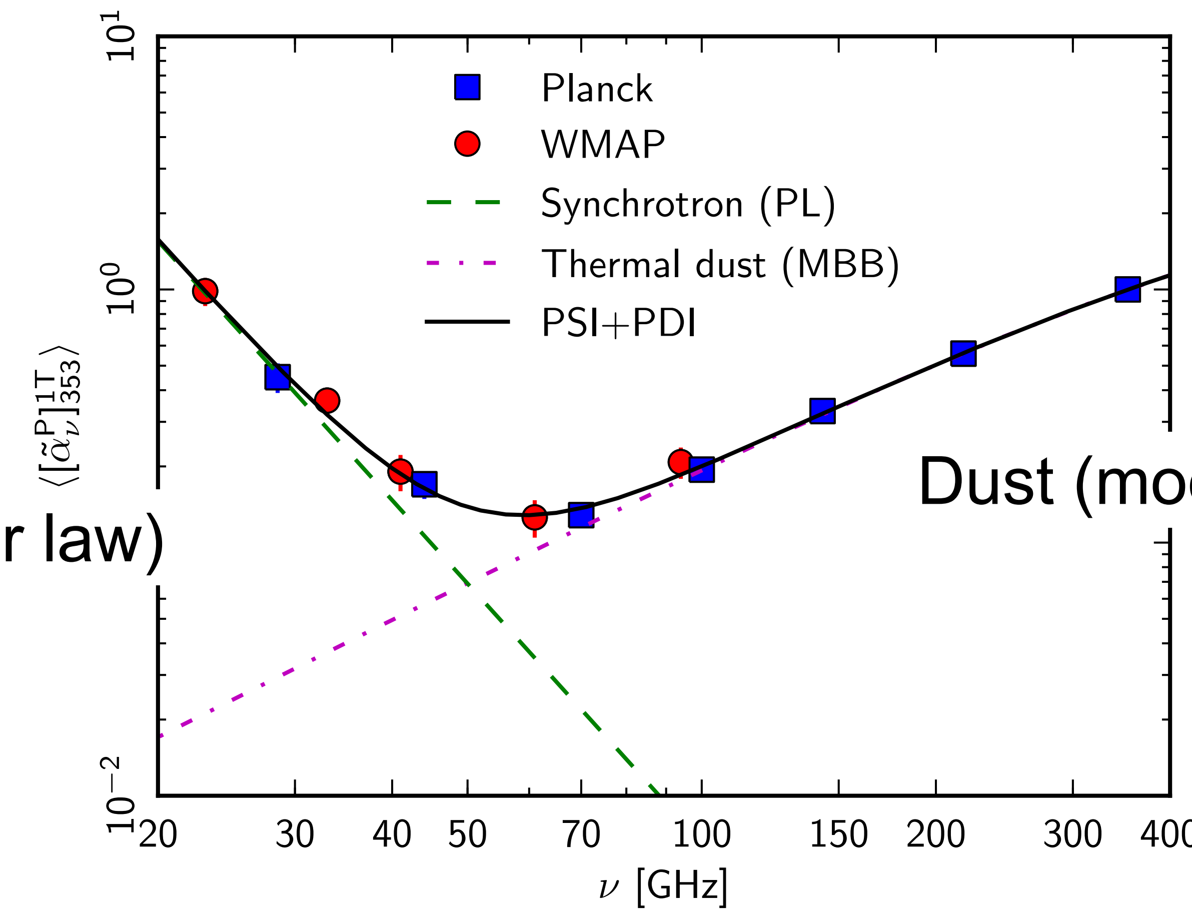


There are regions of the sky with high polarization fraction, possibly higher than what the BICEP2 team assumed.

May 2014

Planck intermediate results. XXII. Frequency dependence of thermal emission from Galactic dust in intensity and polarization

Modeling the dust SED (Spectral Energy Distribution)



Synchrotron (power law)

Dust (modified blackdody)

$$\langle[\tilde{\alpha}_\nu^{P}]_{353}^{1T}\rangle = A_s^P \left(\frac{\nu}{\nu_b}\right)^{\beta_s^P} + \left(\frac{\nu}{\nu_{ref}}\right)^{\beta_{d,mm}^P - 2} \frac{B_\nu(T_d)}{B_{\nu_{ref}}(T_d)},$$

$$\beta_{d,mm}^P = 1.59 \pm 0.02,$$

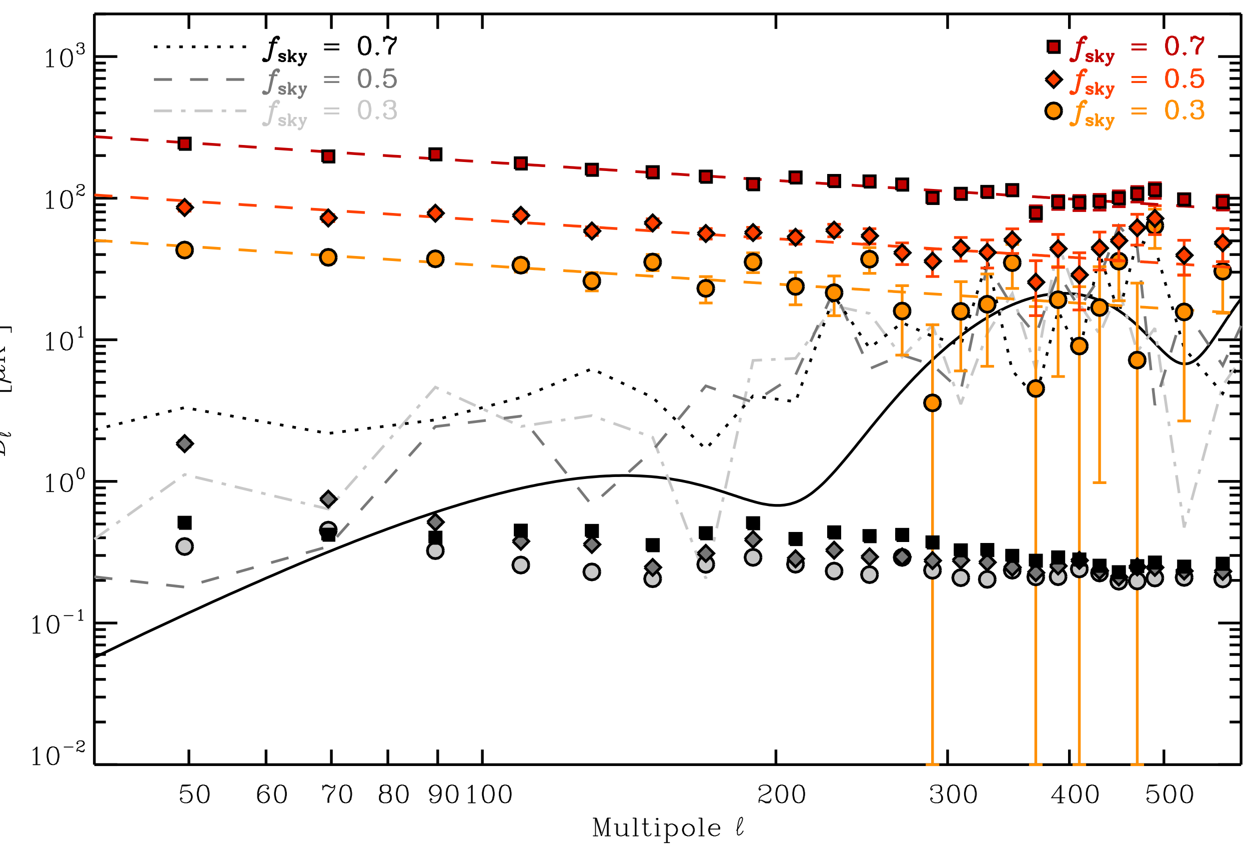
$$T_d = 19.6\,K.$$

Allow conversion/extrapolation of measurements to different frequencies

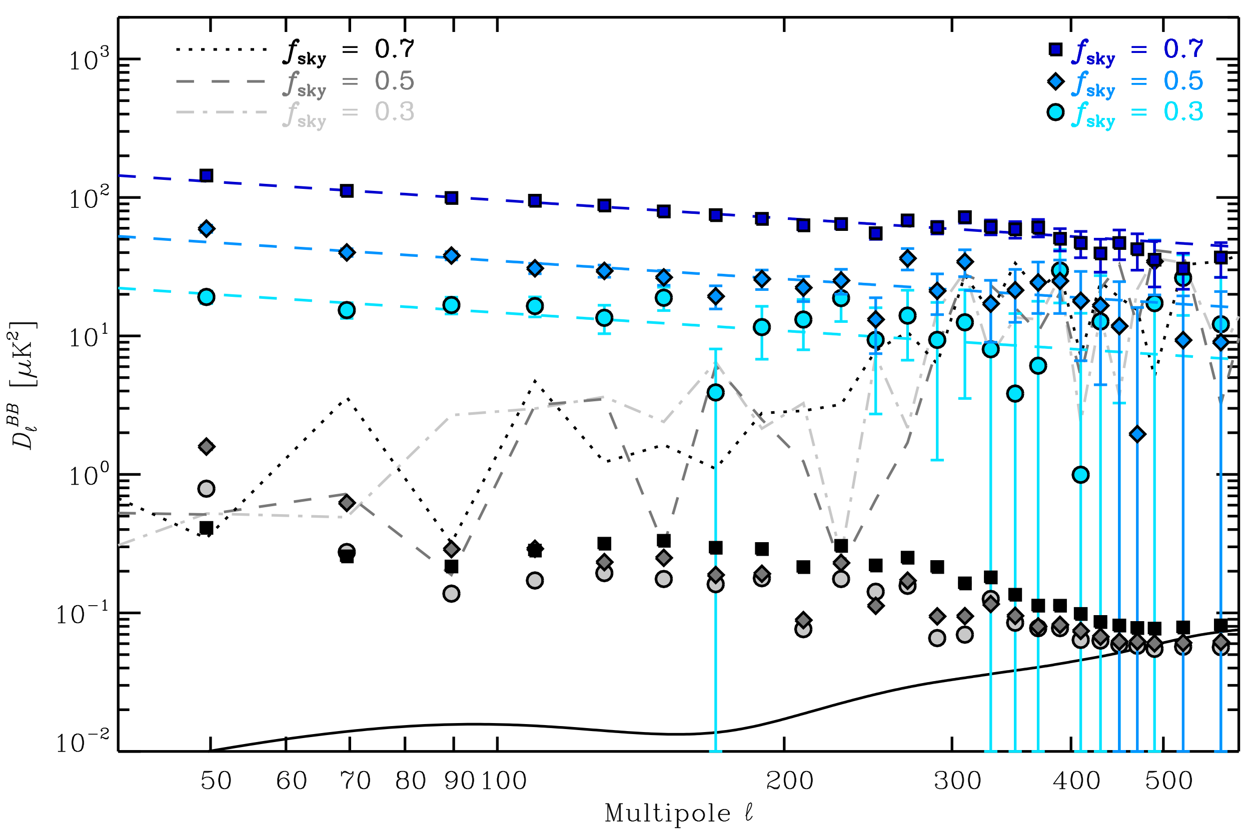
September 2014

Planck intermediate results. XXX. The angular power spectrum of polarized dust emission at intermediate and high Galactic latitudes

EE



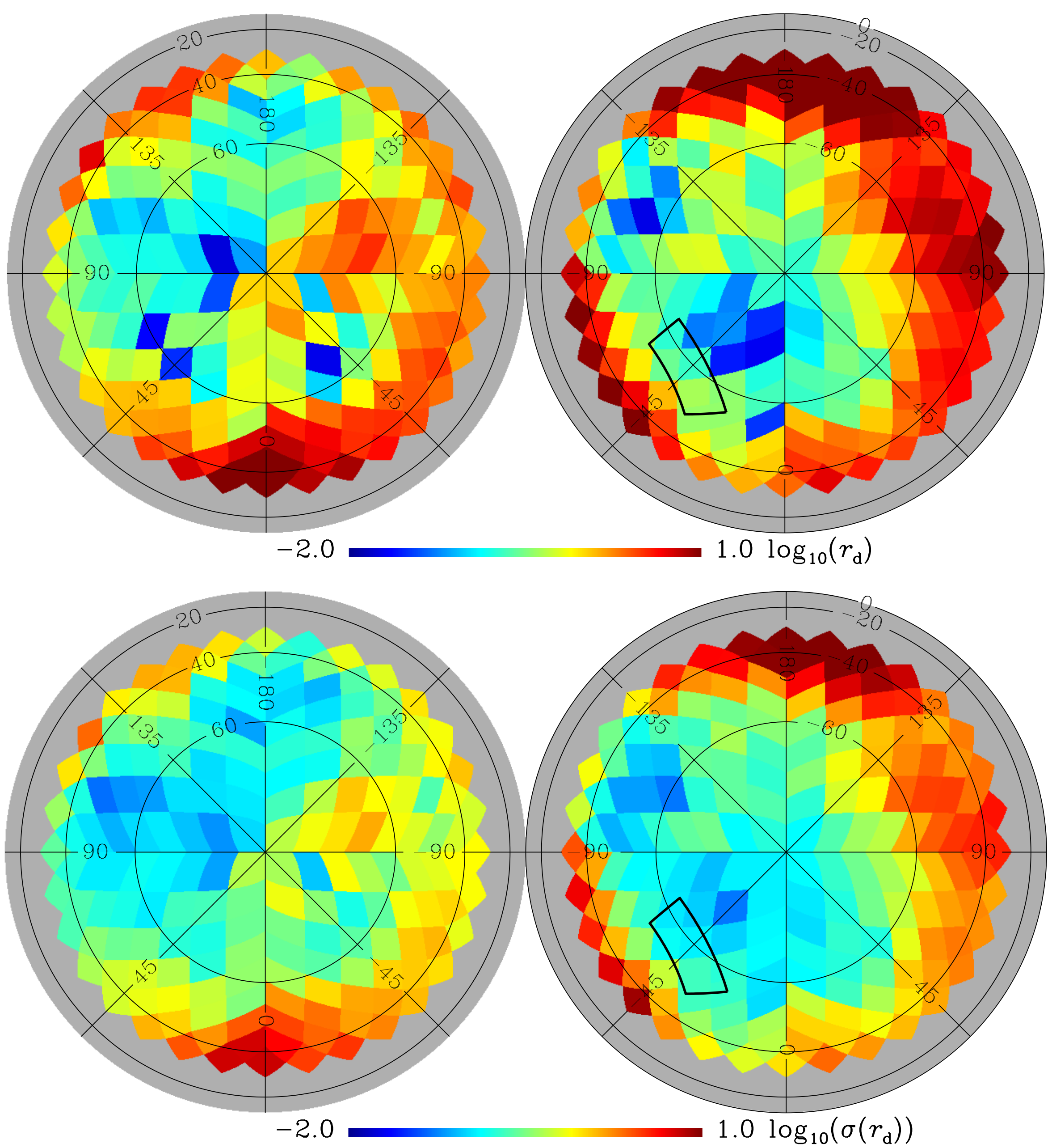
BB



Those are measurements on large fraction of sky.
What can Planck say on small patches?

Planck intermediate results. XXX.
The angular power spectrum of polarized dust emission at intermediate and high Galactic latitudes

Consider 352 circular 400 deg^2 patches centered at the Nside=8 Healpix pixels



$$r_d = \frac{D_\ell^{BB,350\rightarrow150}}{D_\ell^{BB,th,r=1}}$$

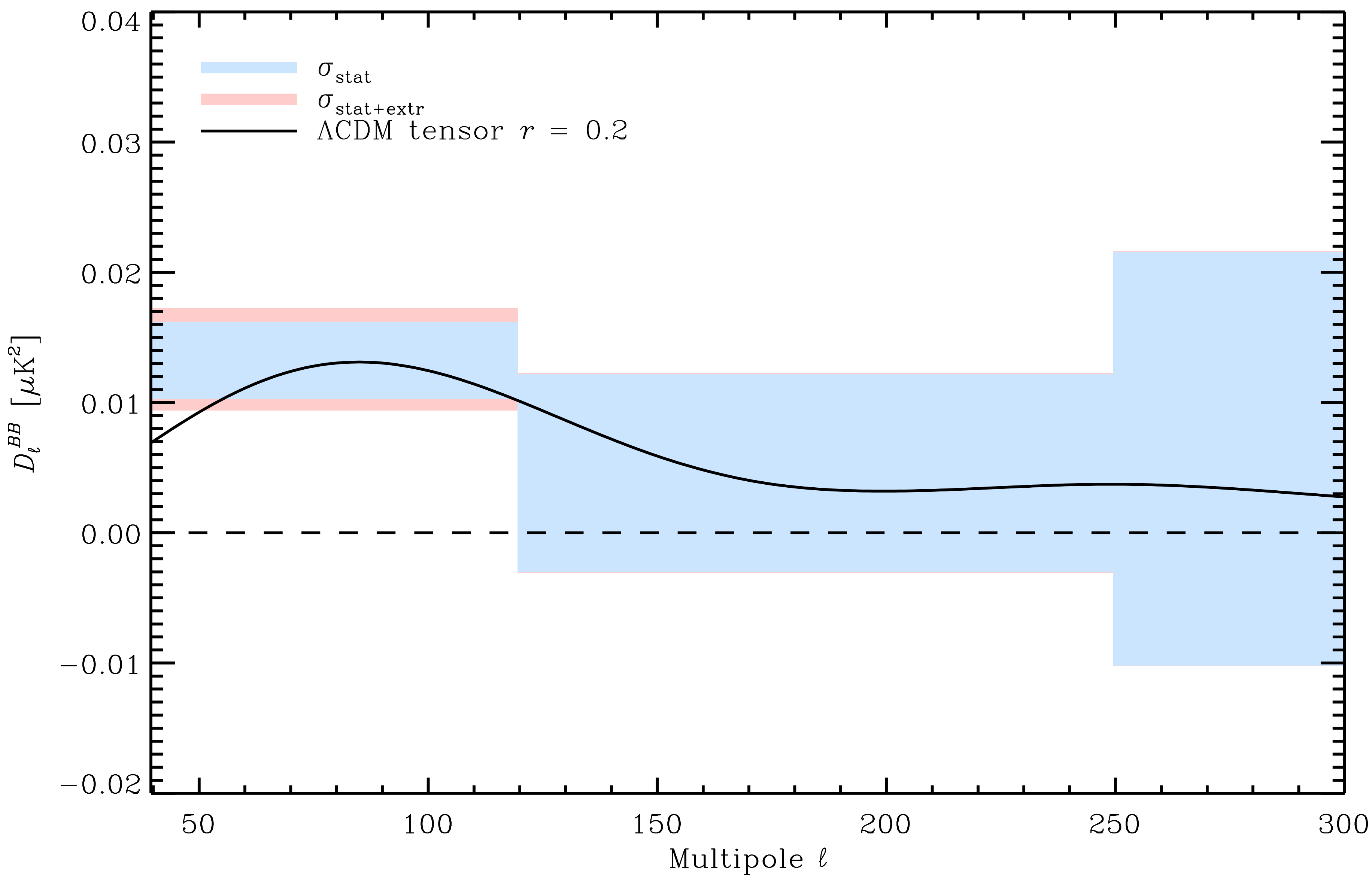
r_d =0.1 means that dust contamination is equal to the amplitude of primordial r=0.1 BB spectrum

Minimun uncertainty on r_d : 0.17 (3σ)

BICEP2 field is not the cleanest part of the southern sky

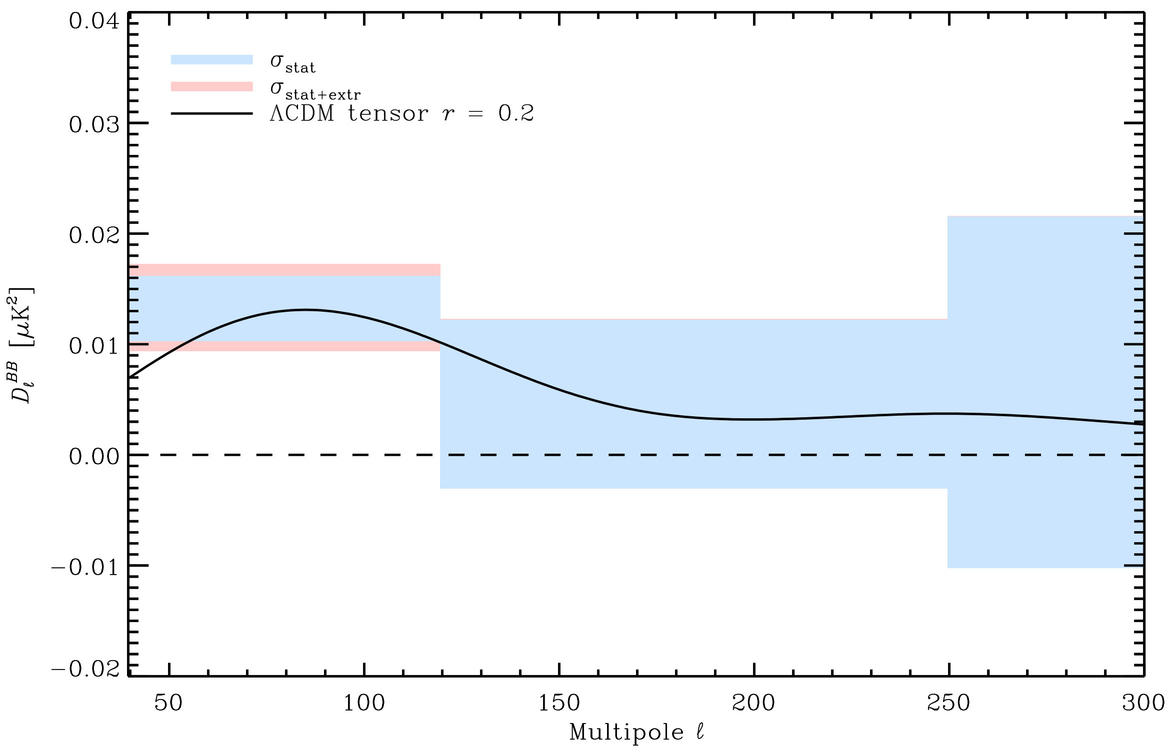
There are cleaner patches on the sky

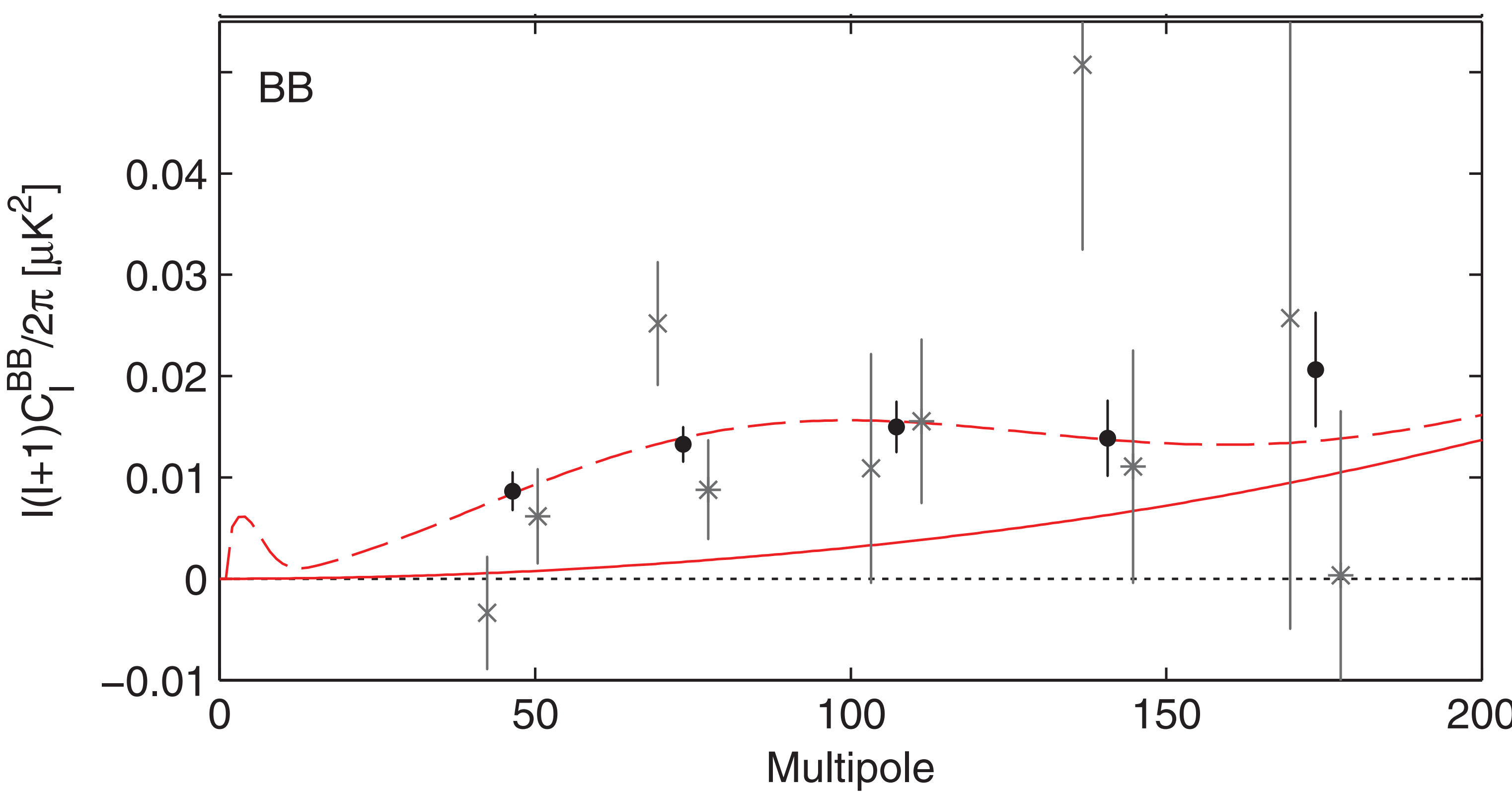
Planck intermediate results. XXX. The angular power spectrum of polarized dust emission at intermediate and high Galactic latitudes



Measurements made at 353GHz map and then extrapolated to 150GHz

Planck intermediate results. XXX.
The angular power spectrum of polarized dust emission at intermediate and high Galactic latitudes

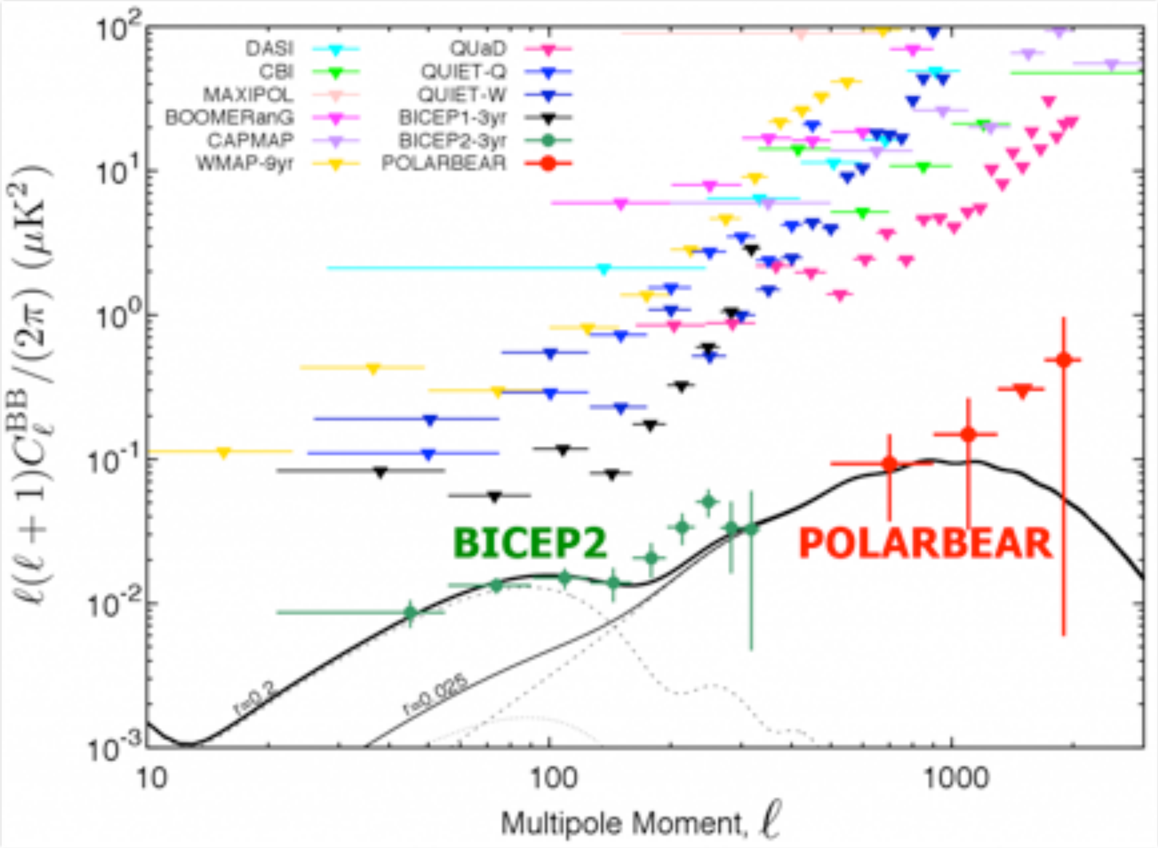




We estimated the dust contribution at 150 GHz to be comparable in magnitude to the BICEP2 measurements

Conclusions

BICEP2 has measured B-mode polarization at 150GHz!



Interpretation is under question: Is it GW B-modes or dust B-modes?

Using polarisation measurements at 353GHz, and multi-frequency coverage to estimate dust SED, Planck find significant amount of dust polarisation in the BICEP2 field

It does not mean that there are no primordial B-modes. Joint analysis Planck-BICEP2 required and on-going.

There are cleaner regions than the BICEP2 field that can be investigated

The scientific results that we present today are a product of the Planck Collaboration, including individuals from more than 100 scientific institutes in Europe, the USA and Canada

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