The quest for the detection of the primordial gravitational wave background with CMB polarization

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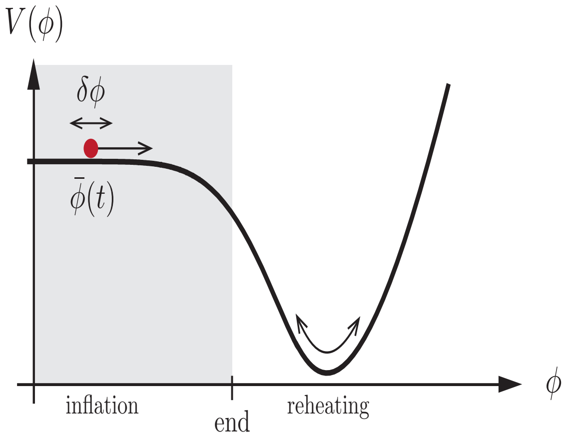
Outline

- Inflation and primordial GWs.
- The GW imprint on the CMB
- Present observational limits on r.
- Difficulties with measuring the CMB B-modes: foregrounds contamination
- Future CMB polarization experiments: the need to go to space
- Forecasts for r and other cosmological parameters
- Summary

Inflation and primordial GWs

Inflation: a scenario of accelerated expansion in the very early universe that solves the initial conditions problem of the classical Big Band theory.

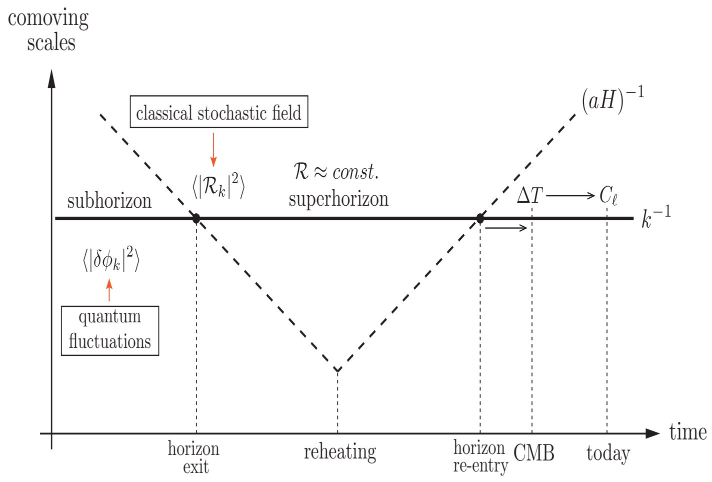


$$\frac{\ddot{a}}{a} = \dot{H} + H^2 > 0 \quad \Longrightarrow \quad \epsilon \equiv -\frac{\dot{H}}{H^2} < 1$$

Constant expansion rate: H ≈ constant

Several problems of the classical Big Bang model are naturally solved:

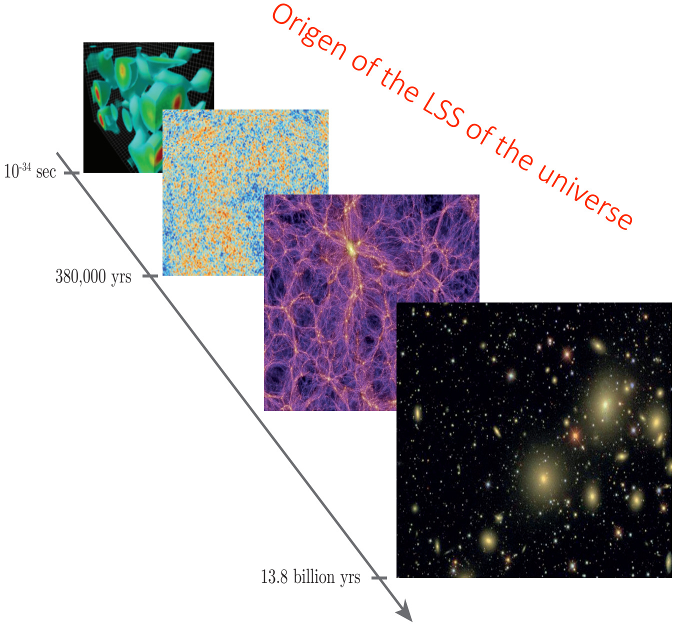
- Horizon
- Flatness
- Topological defects



Inflation and primordial GWs

Its major success is that it explains the LSS as originated from quantum fluctuations at microscopic scales that were stretched beyond the horizon.

Prize of the BBVA Foundation 2015 in basic Sciences



Origen of the LSS of the universe

Is this result a definitive evidence of inflation?

Are there definitive evidences of an accelerated expansion in the early universe?

Curvature fluctuations:

$$\zeta = \frac{(2\varepsilon c_s)^{-1/2}}{\underbrace{2\pi M_{pl}}_{\text{Time dependent}}} \times H$$

In the inflation model H is nearly constant:

Nearly scale invariant spectrum:

$$\Delta_\zeta^2(k) = A_s\left(\frac{k}{k_*}\right)^{n_s-1}, n_s \approx 0.97$$

$\zeta \propto H(t)$ but the proportionality factor depends on the matter properties present in the universe (ε, c_s) .
H(t) could vary rapidly keeping ζ nearly scale-invariant if the matter properties, ε and/or c_s, also vary compensating the H(t) variation.

A direct measurement of H(t) is needed

Primordial gravitational waves

$$h_{ij}^{prim} = \frac{e_{ij}}{\underbrace{\pi M_{pl}}_{\text{Time independent}}} \times H$$

$h \propto H$ but now the proportionality factor is constant

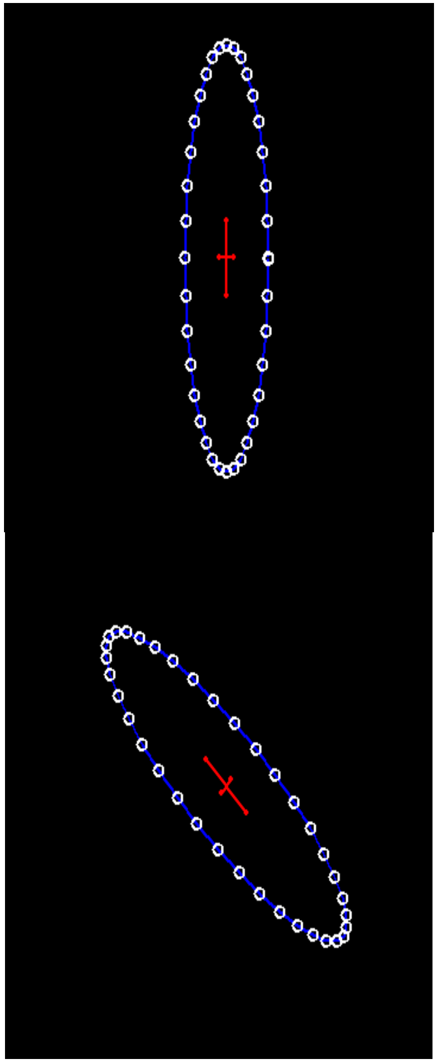
The standard inflation model predicts
a scale invariant spectrum:

$$\Delta_t^2(k) = 2\left\langle h_{ij}^{prim}(k) h_{prim}^{ij,*}(k) \right\rangle = A_t \left(\frac{k}{k_*} \right)^{n_t}, n_t \approx 0$$

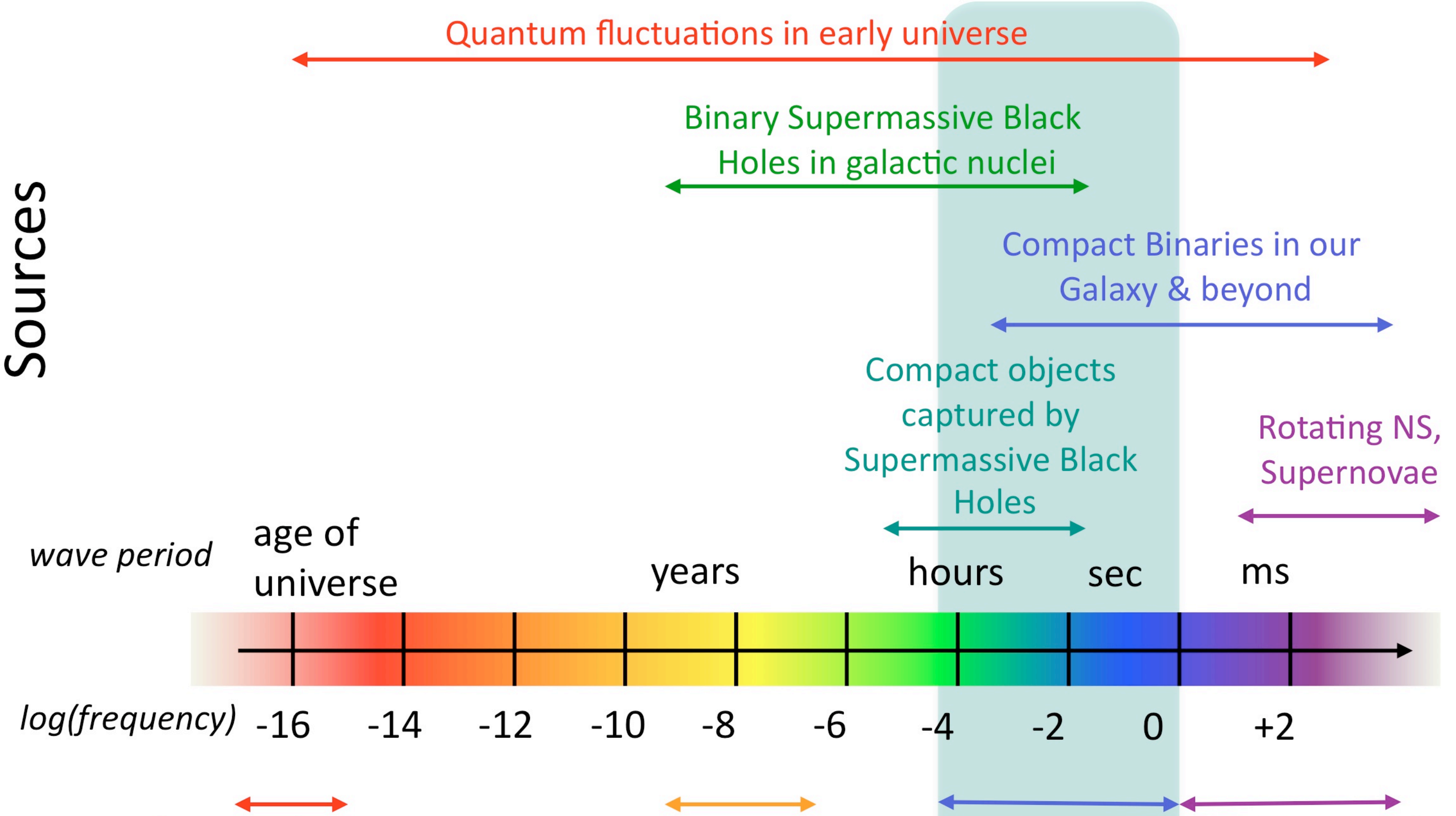
Tensor-to-scalar ratio: $r \equiv \frac{A_t}{A_s}$

Energy scale of inflation: $V(\phi)^{1/4} \approx 10^{16} \left(\frac{r}{0.1} \right)^{1/4} GeV$

A more robust and model independent prediction of inflation



The Gravitational Wave Spectrum



Sources

Quantum fluctuations in early universe

Binary Supermassive Black Holes in galactic nuclei

Compact Binaries in our Galaxy & beyond

Compact objects captured by Supermassive Black Holes

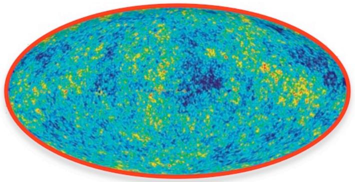
Rotating NS, Supernovae

wave period age of universe years hours sec ms

log(frequency) -16 -14 -12 -10 -8 -6 -4 -2 0 +2

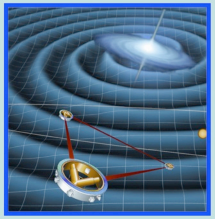
Detectors

Cosmic microwave background polarization



Pulsar Timing

Space Interferometers



Terrestrial interferometers

From NASA Goddard Space Flight Center

Primordial gravitational wave spectrum

Evolution of the relative spectral energy density $\Omega_h(\tau,k)$:

For GWs entering the horizon during the matter era:

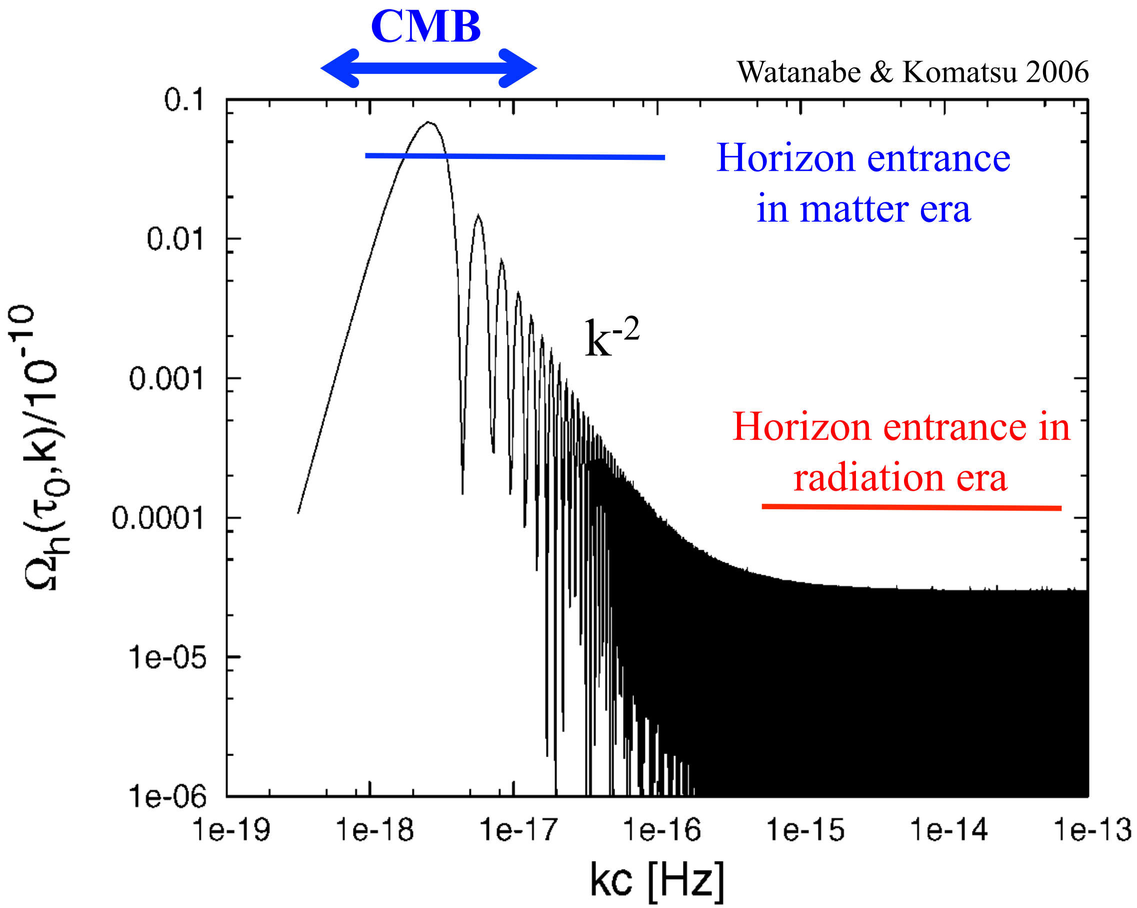
$$\Omega_h(\tau,k) \propto a^{-1}$$

This explains the rise towards lower frequencies at $k < 10^{-15}$Hz

However, for GWs entering the horizon during the radiation era there is no evolution:

$$\Omega_h(\tau,k) \propto const$$

This explains the scale-invariant spectrum at higher frequencies $k > 10^{-15}$Hz

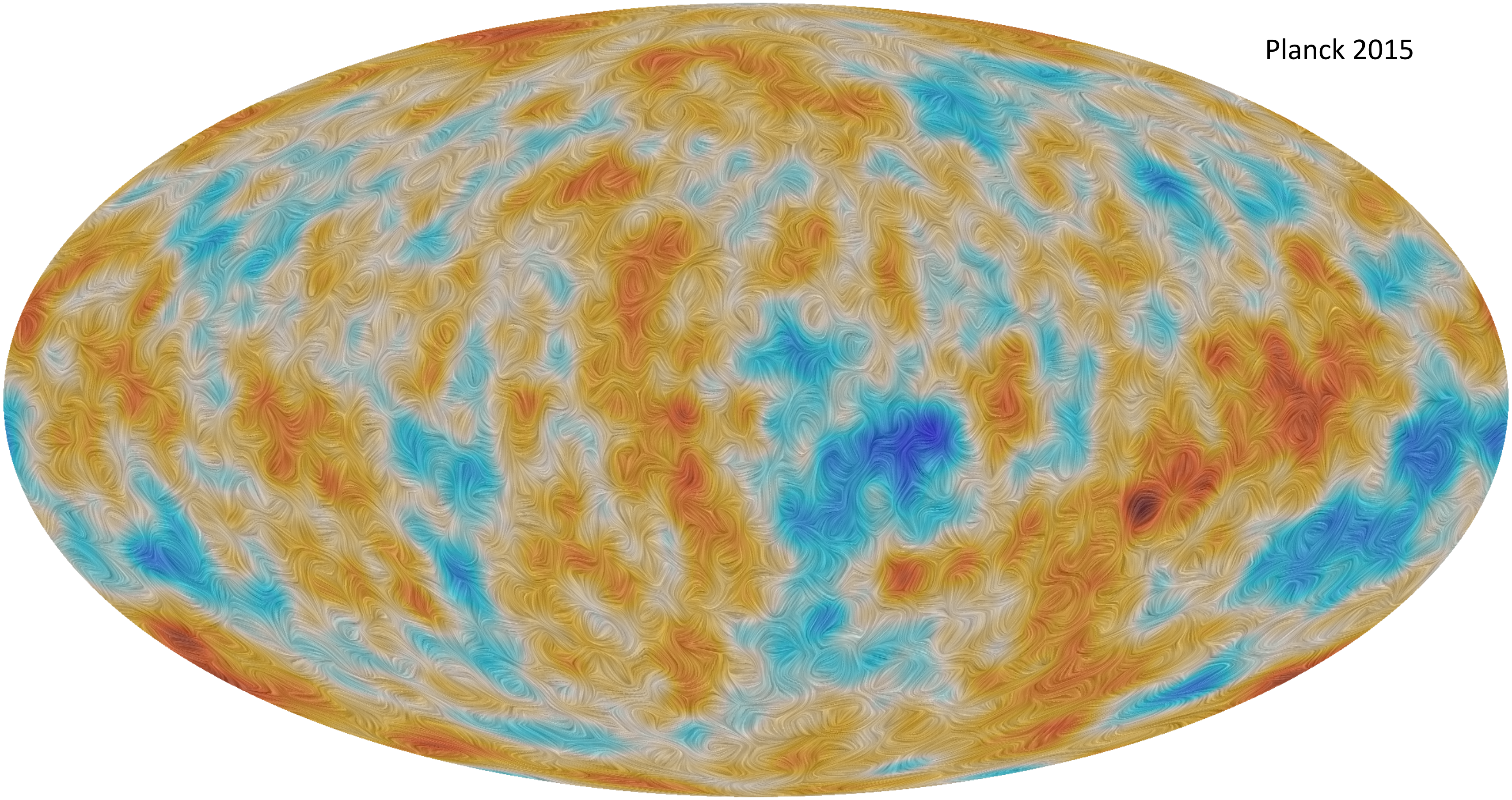


Watanabe & Komatsu 2006

Frequency of GWs observed today: $f_0 = \dfrac{kc}{2\pi}$

The best strategy to detect the PGW

Both matter and gravitational waves leave its imprint in the CMB

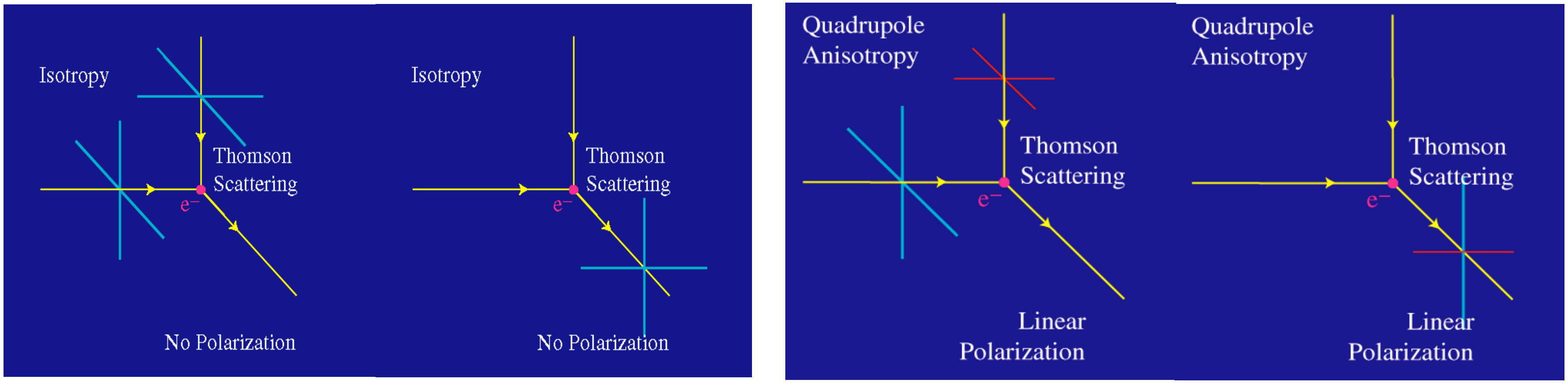


Planck 2015

CMB polarization

Polarization is only generated through photon-matter interaction

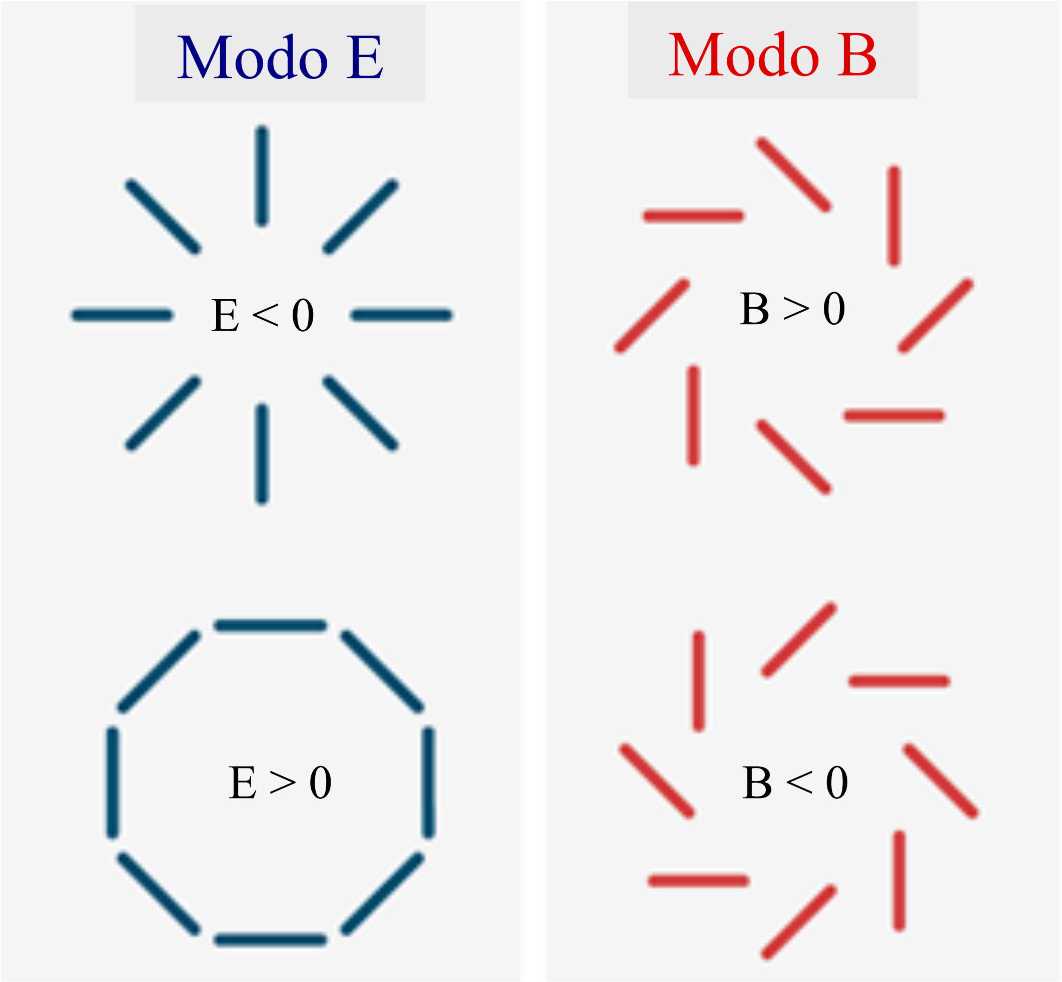
Two epochs in the universe: recombination and reionization



From Wayne Hu

Both scalar and tensor perturbations produce a quadrupole at the end of decoupling/reionization causing the polarization of the CMB photons.

CMB polarization

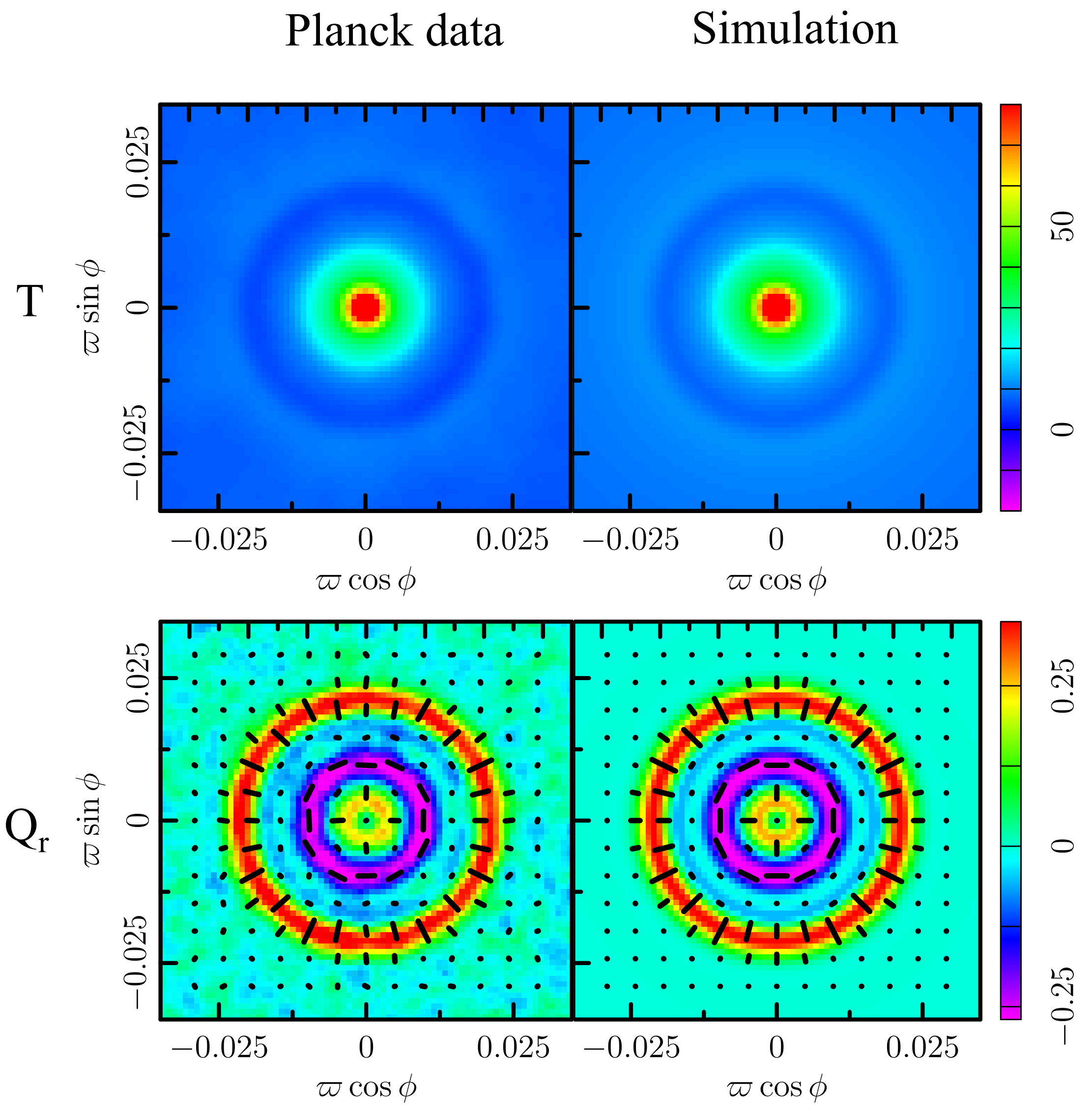


Perturbations in the matter density can only generate E mode.

However GWs can generate both E and B modes.

Planck data

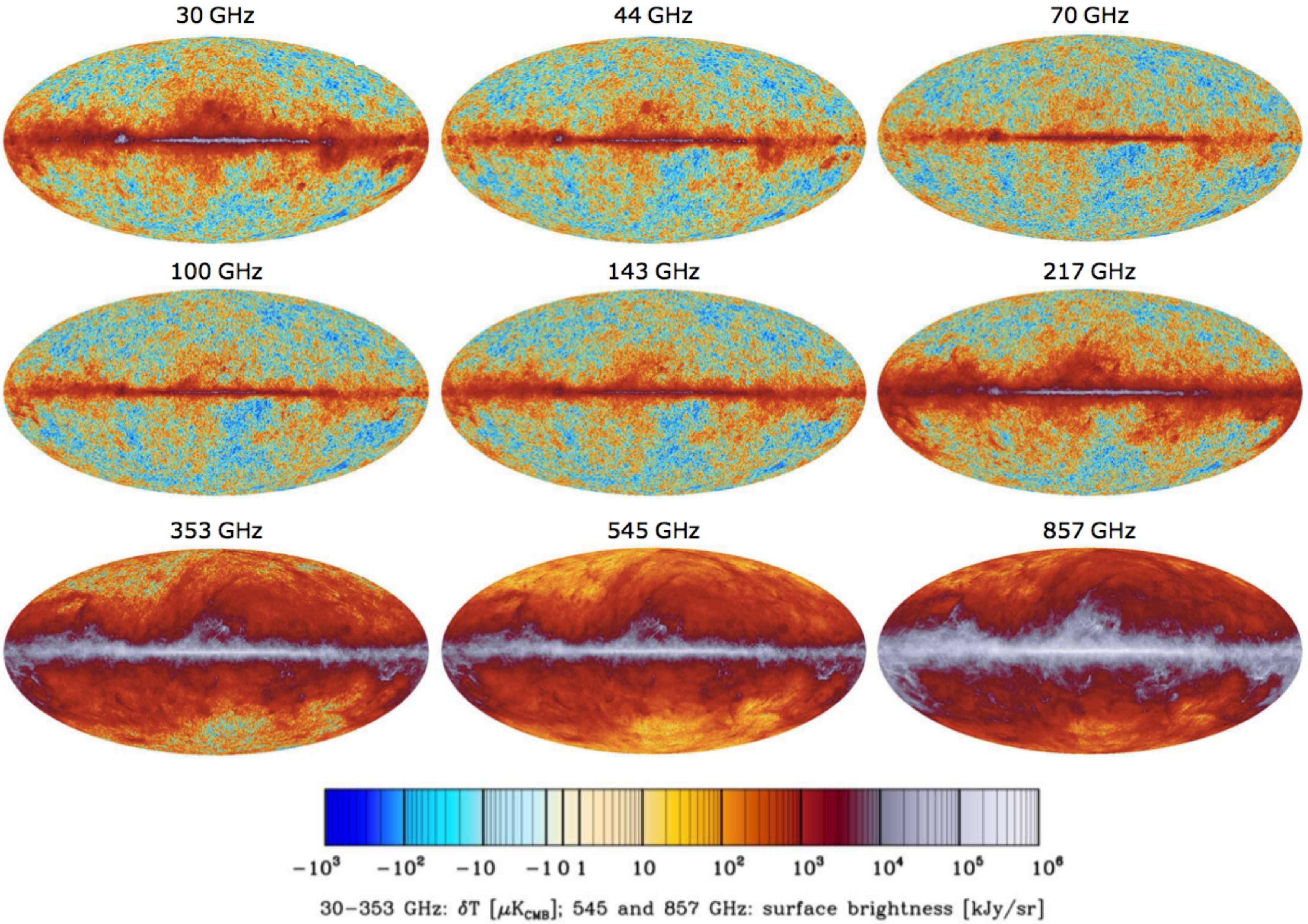
Planck Col. XVI 2016



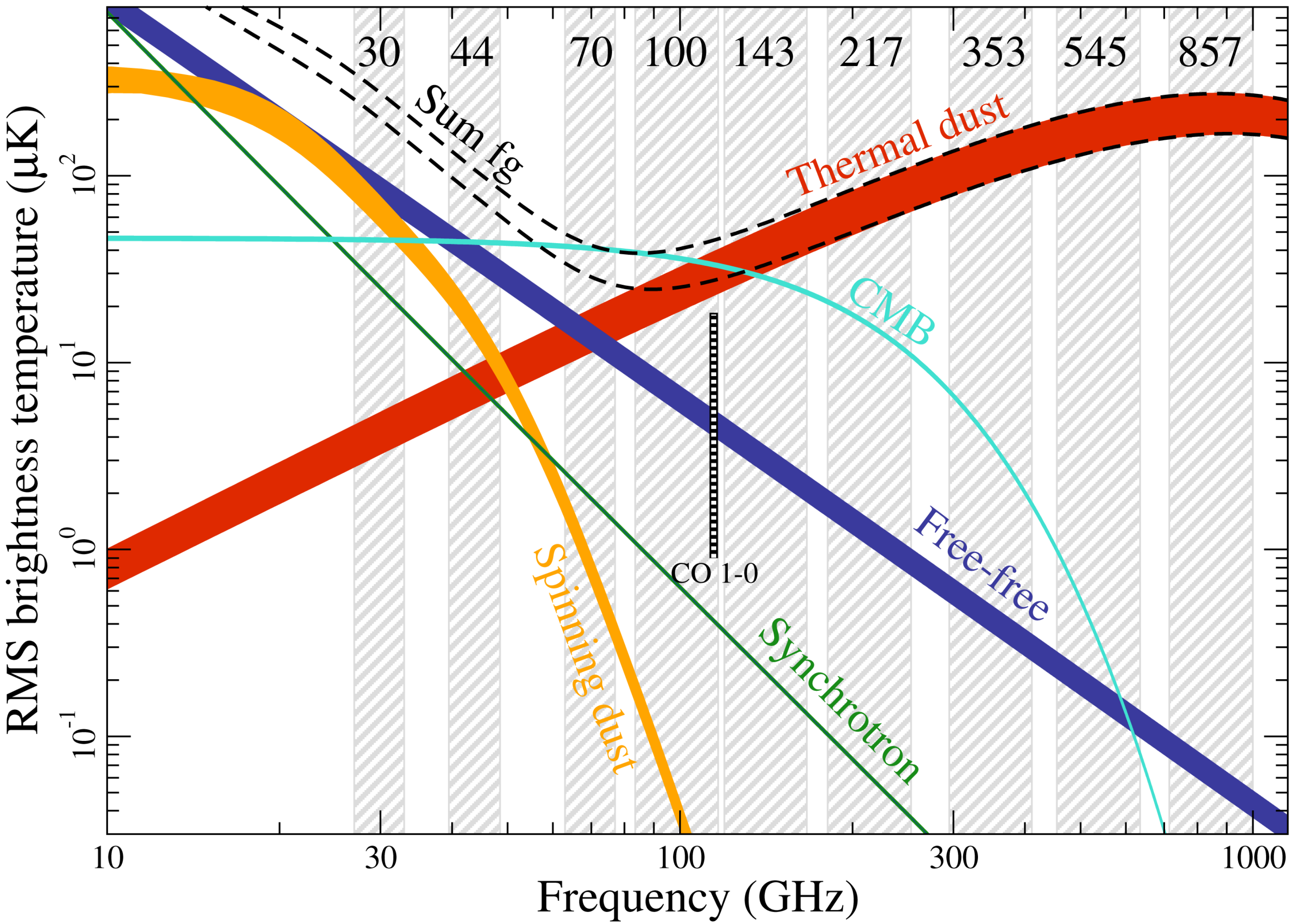
Stacking of polarization patches at temperature peak positions (T>0)

Signature of the scalar mode fluctuations in polarization, E-mode

Planck frequency maps: intensity

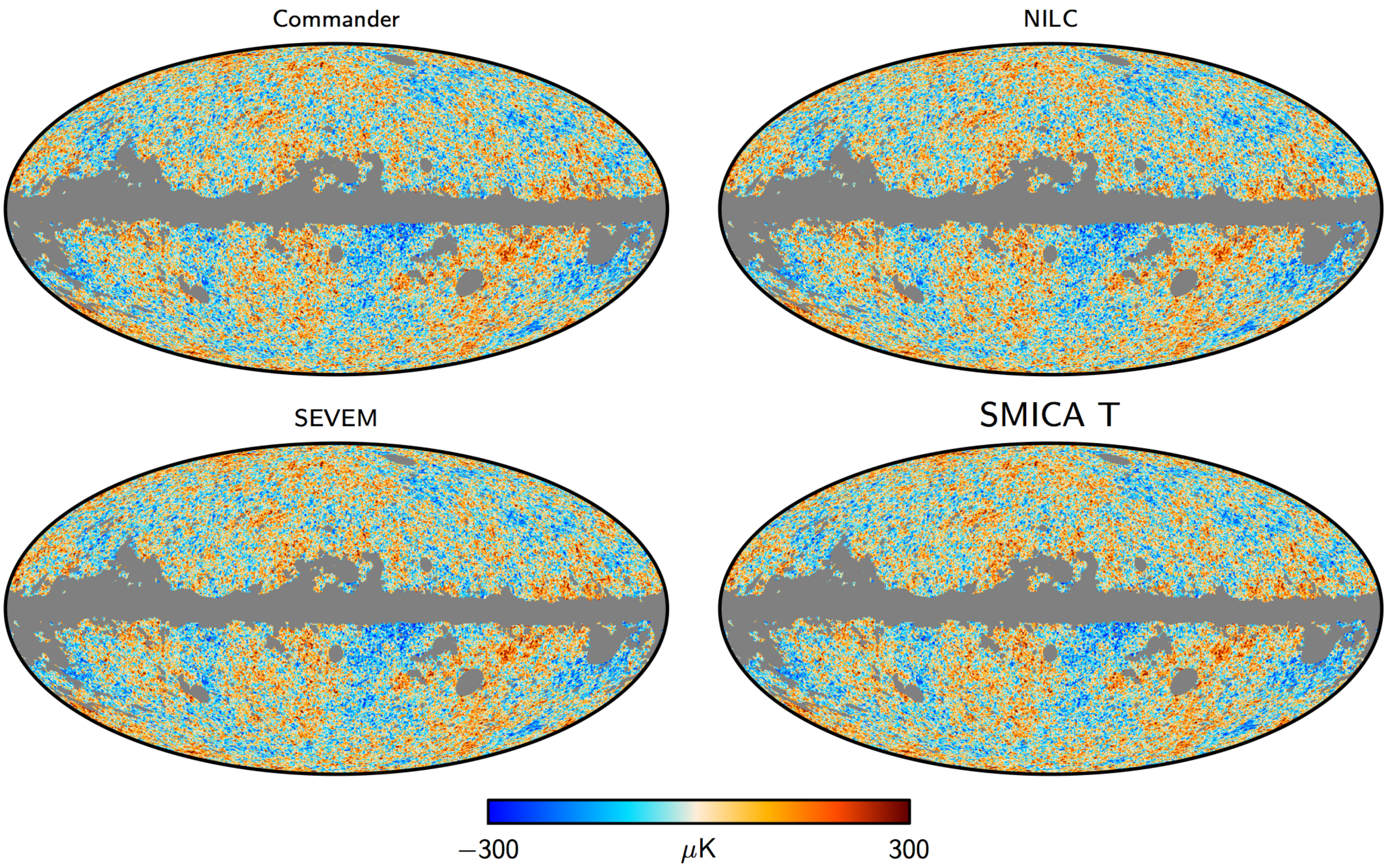


Diffuse components: intensity



CMB temperature reconstruction with four methods

Planck Col. X 2016

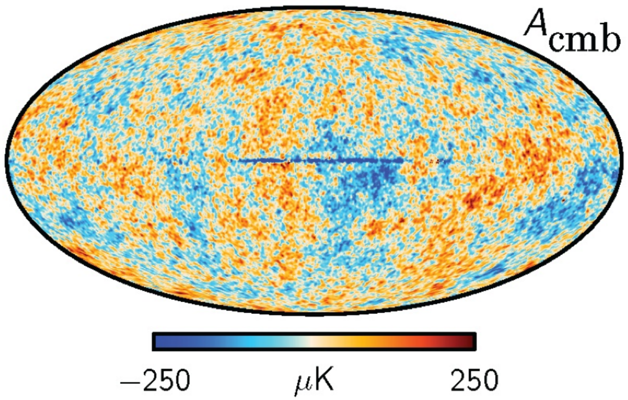


The sky seen by Planck: Intensity

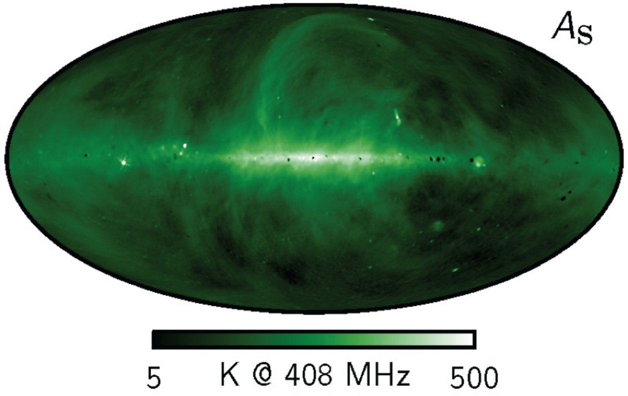
Planck Col. IX & X 2016

Maps derived from the joint analysis of Planck, WMAP and 408MHz observations

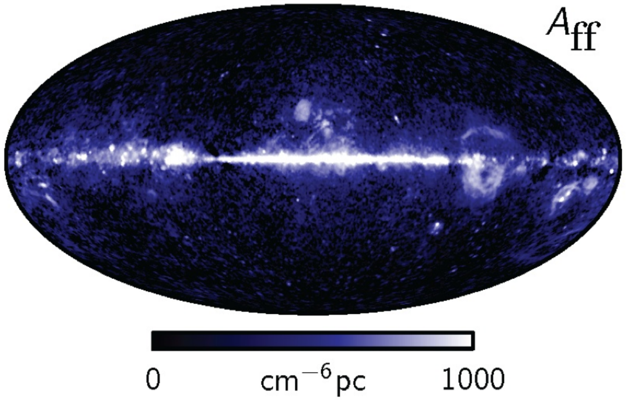
CMB

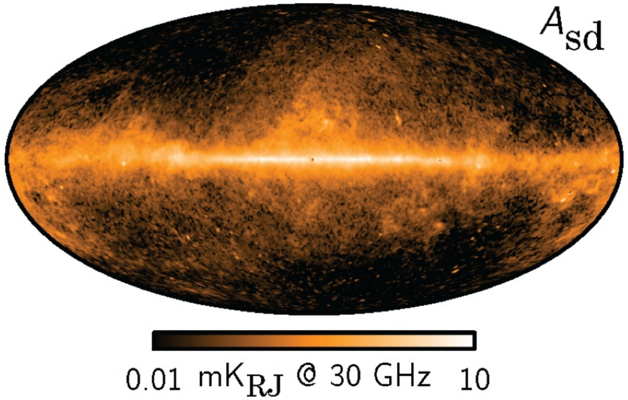


Synchrotron

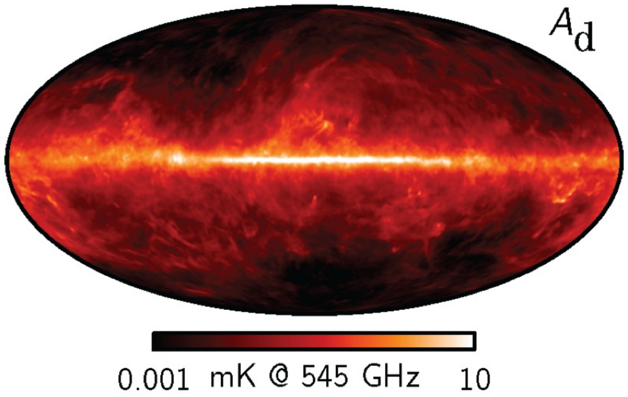


Free - free

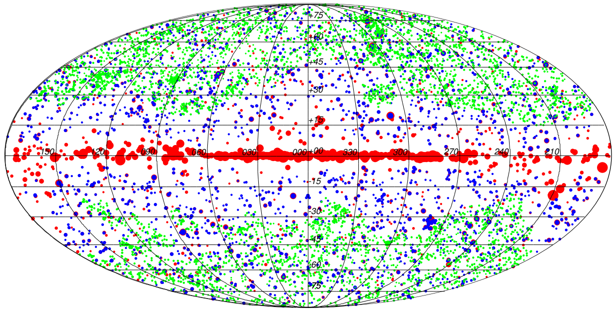




Spinning dust

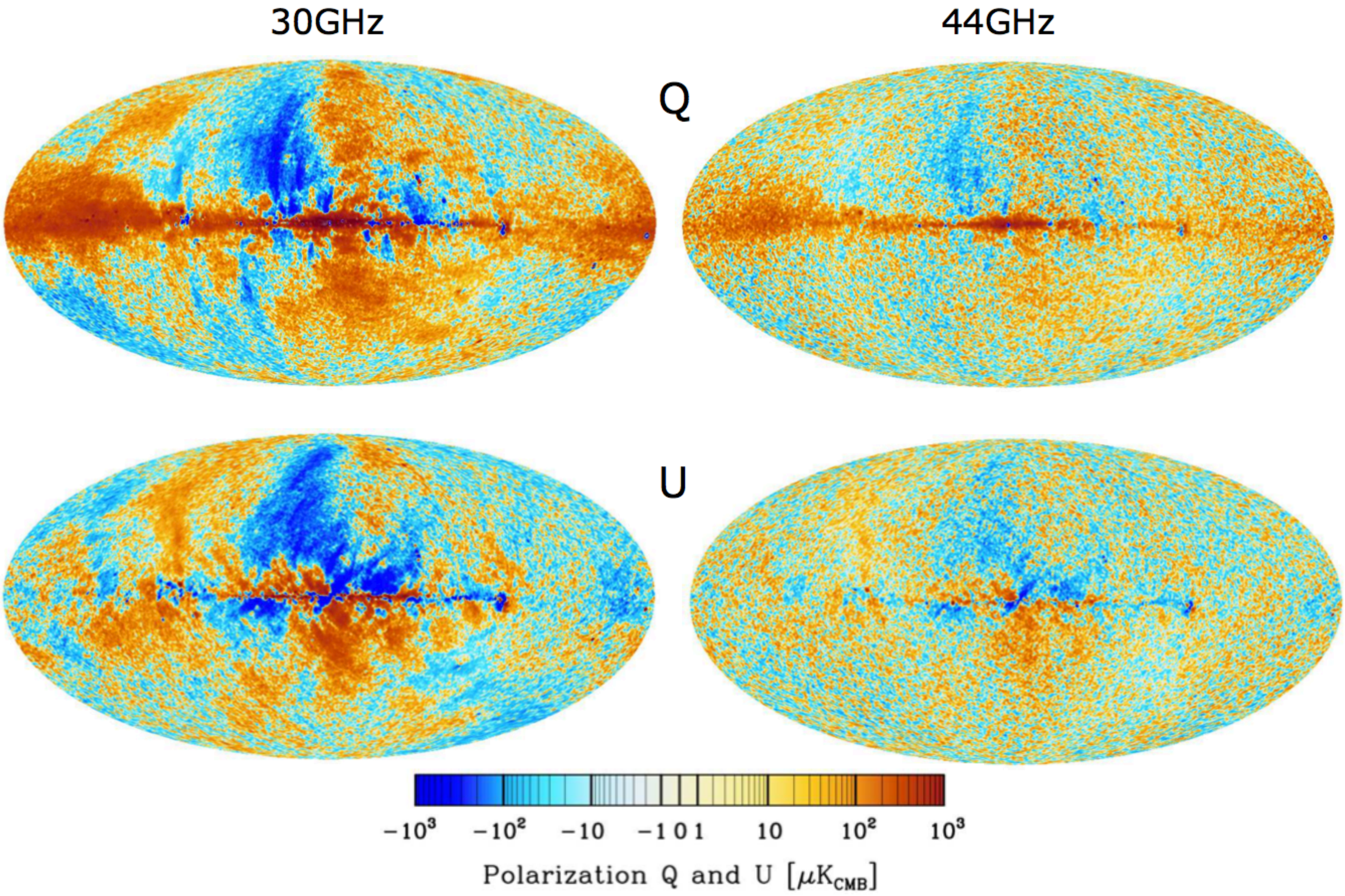


Thermal dust

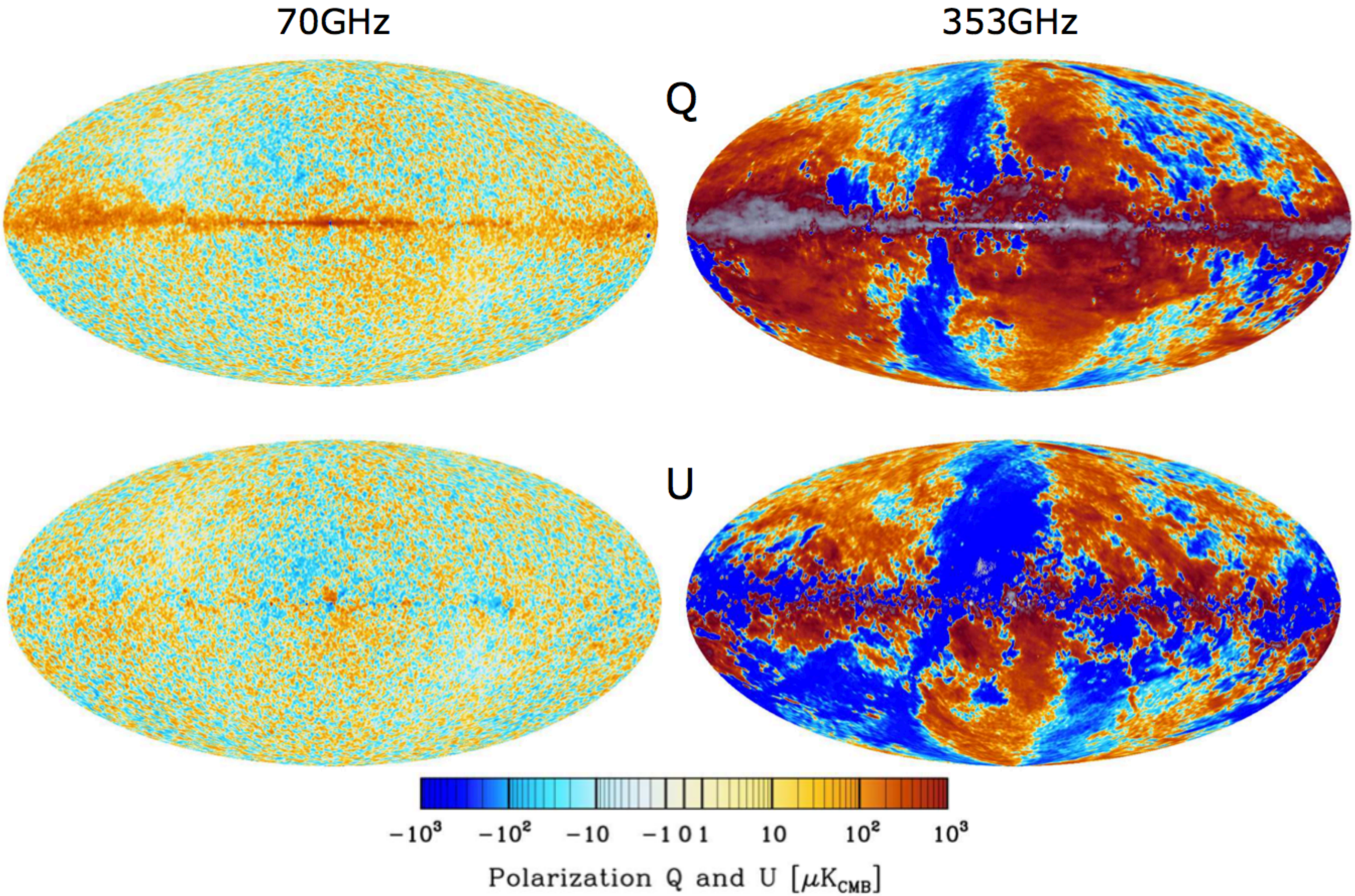


Positions of detected point sources (30,143 and 857 GHz)

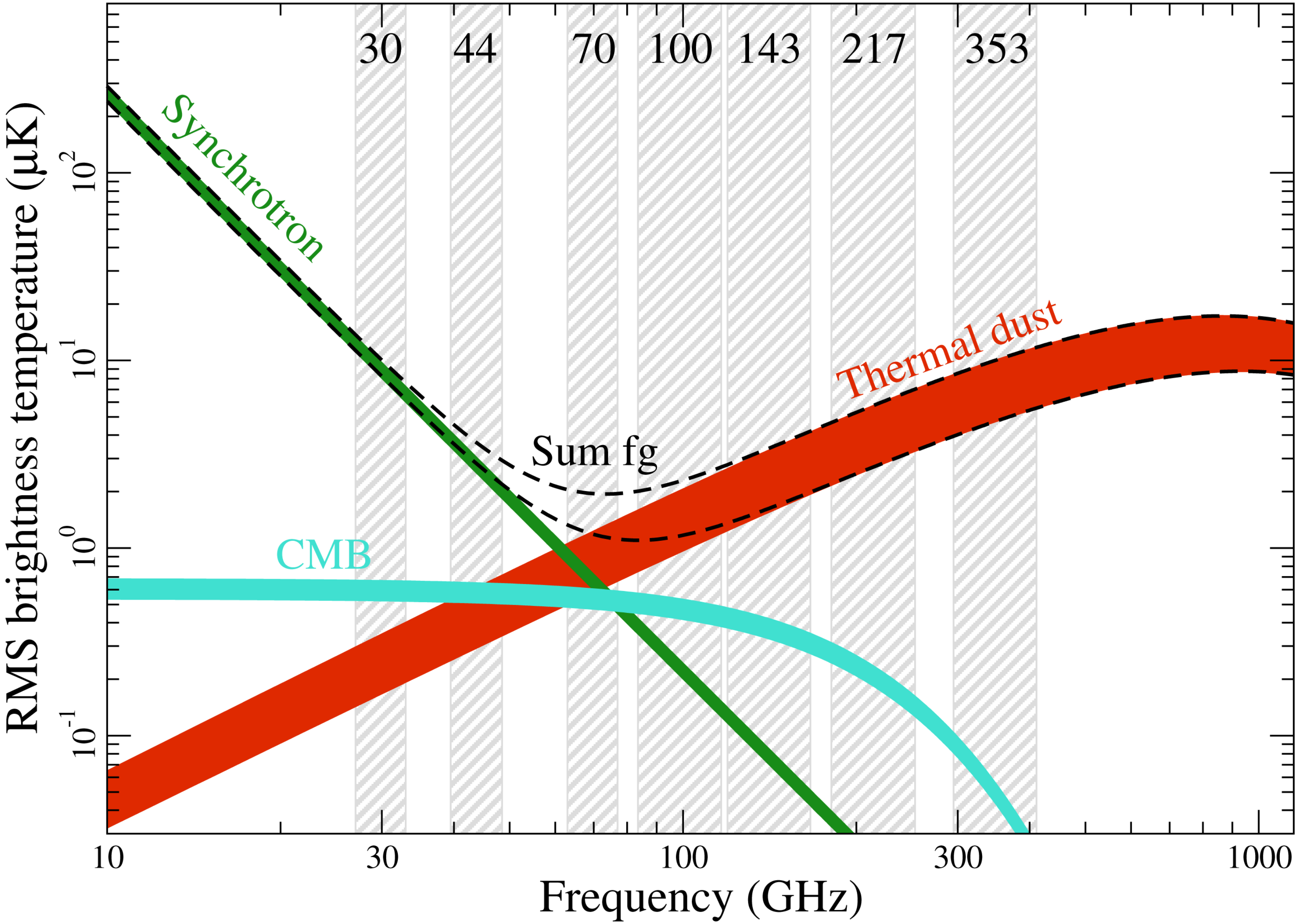
Planck frequency maps: polarization



Planck frequency maps: polarization

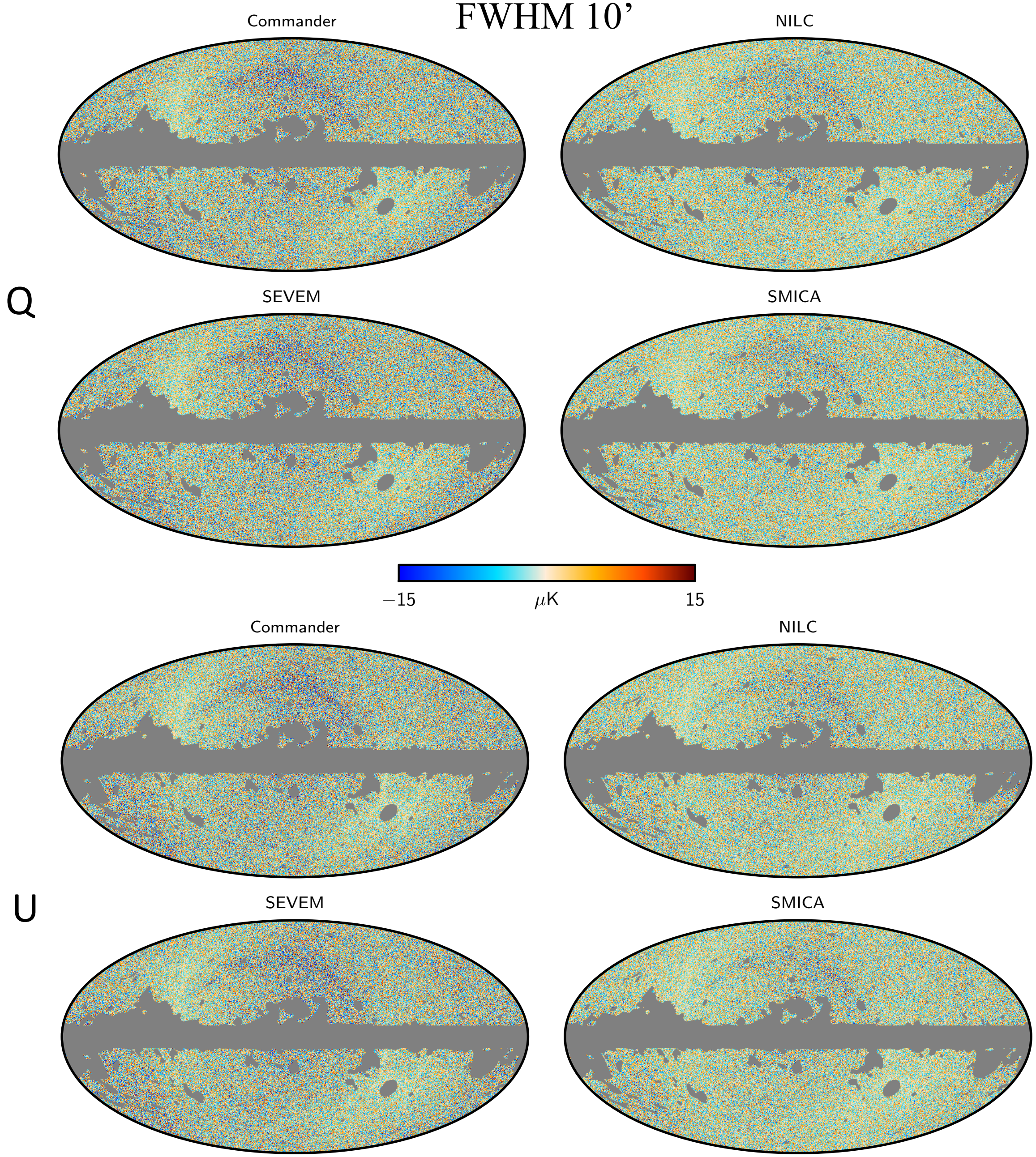


Diffuse components: polarization



The CMB polarization reconstruction

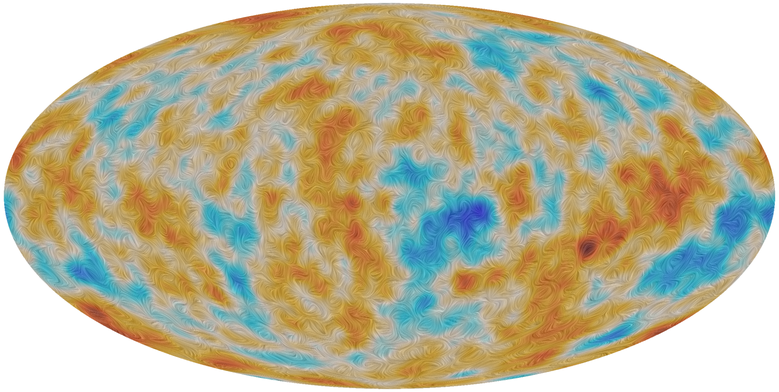
FWHM 10’



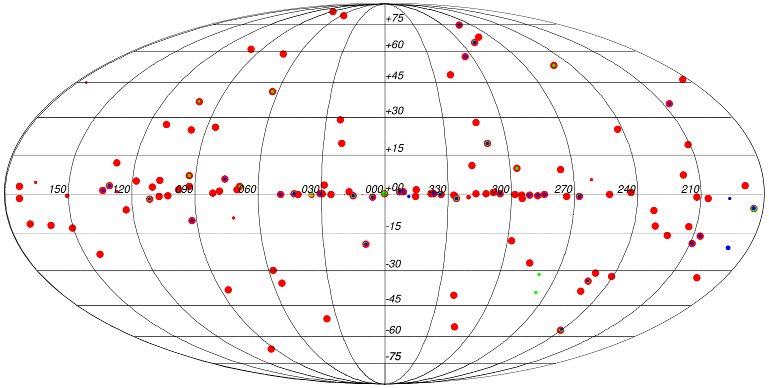
Due to the presence of systematics a high-pass filtered has been applied to remove multipoles l < 40.

The situation is expected to improve for the Planck Legacy papers (second half of 2017).

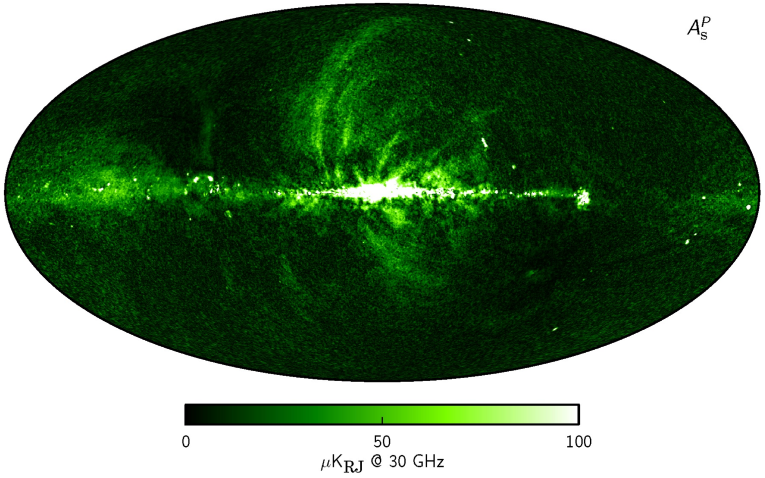
The sky seen by Planck: polarization



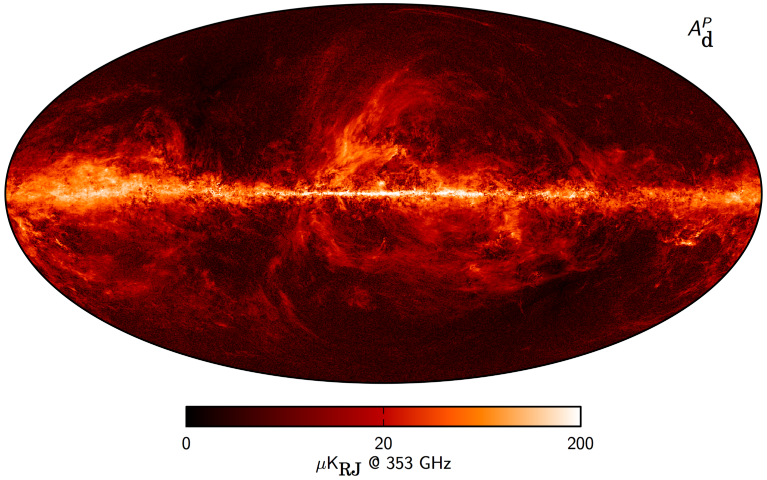
CMB intensity overlaid with polarization direction (5 degrees resolution)



Position of detected point sources (30, 44, 70 GHz)

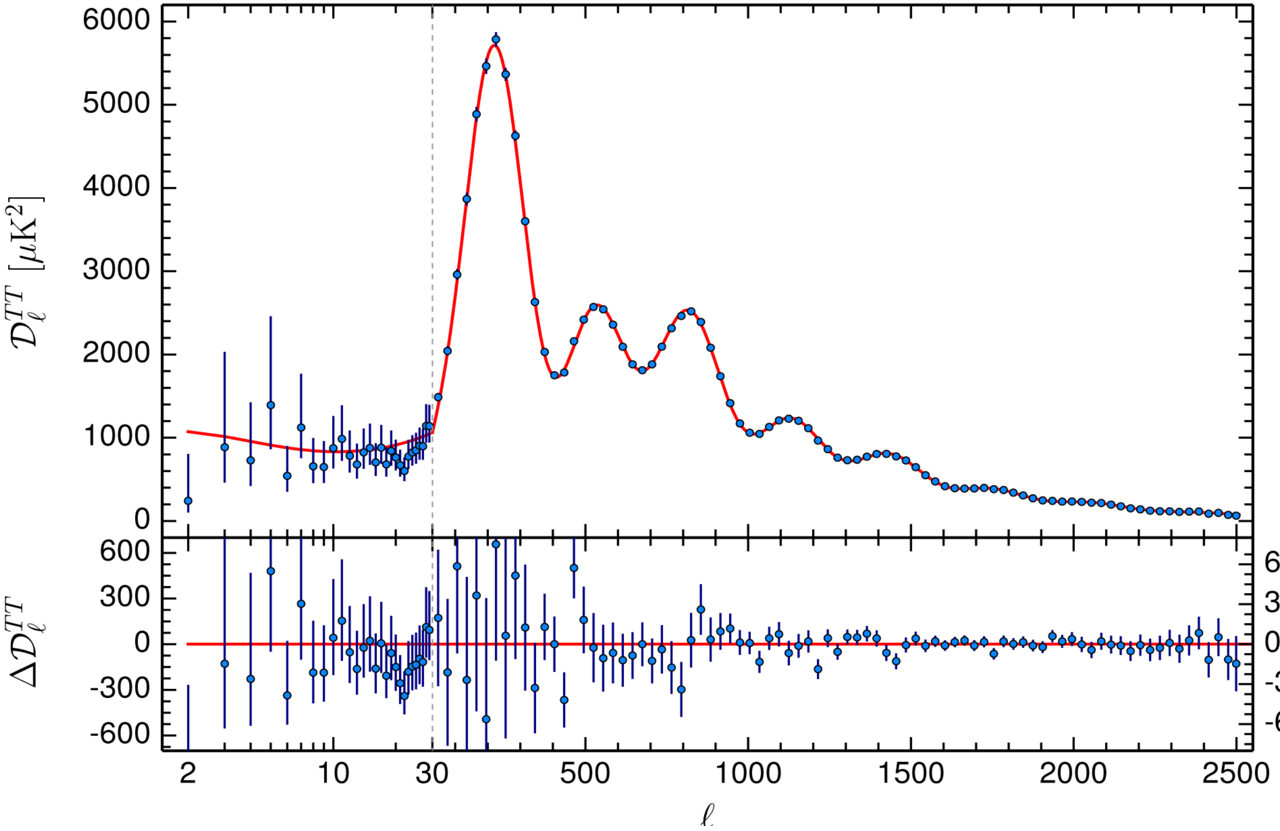


Synchrotron polarization amplitude map P ($P^2=Q^2+U^2$)



Dust polarization amplitude map P ($P^2=Q^2+U^2$)

CMB power spectrum: temperature

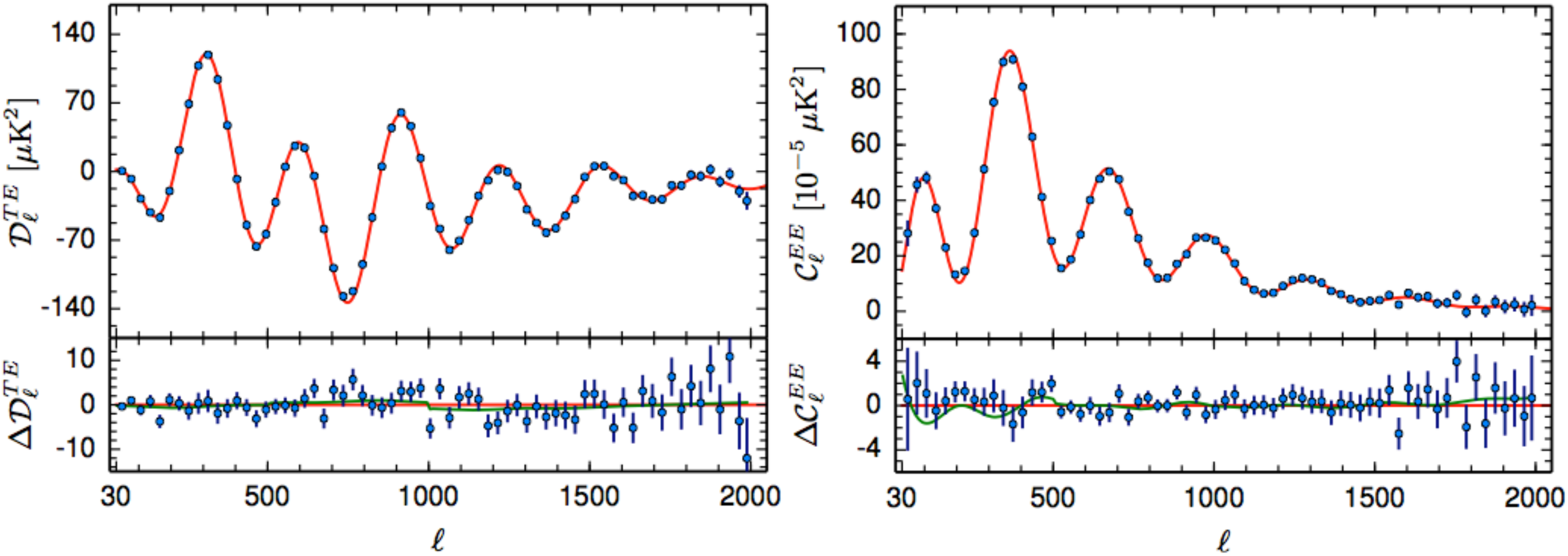


Planck Collaboration XIII 2016

Excellent agreement with the standard spatially-flat six-parameter ΛCDM model!

CMB power spectrum: polarization

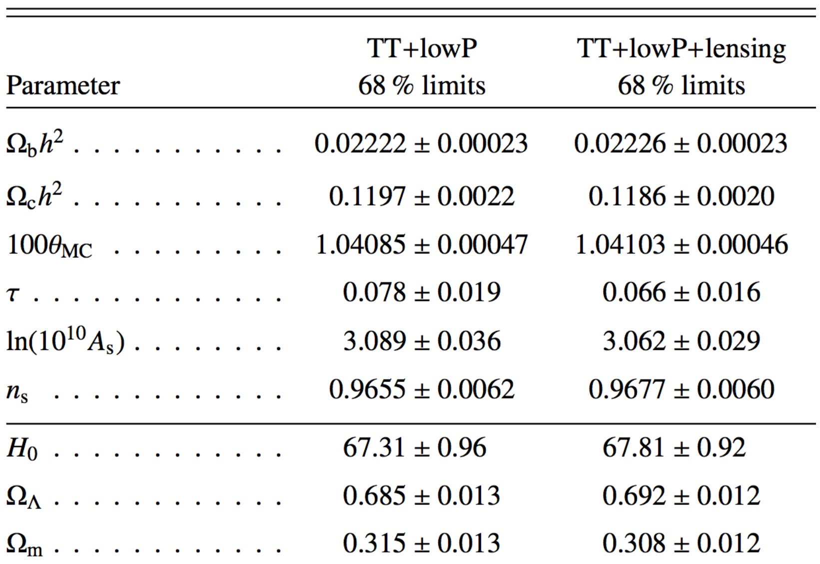
Planck Collaboration XIII 2016



- Red line: best fit model from TT+lowP
- HFI systematics in polarization not well understood at low multipoles, < 30
- Constraints using polarization should be taken with caution

Base ΛCDM 6 parameters (Planck alone)

Planck Collaboration XIII 2016



Parameter	TT+lowP 68 % limits	TT+lowP+lensing 68 % limits
$\Omega_b h^2$	0.02222 ± 0.00023	0.02226 ± 0.00023
$\Omega_c h^2$	0.1197 ± 0.0022	0.1186 ± 0.0020
$100\theta_{MC}$	1.04085 ± 0.00047	1.04103 ± 0.00046
τ	0.078 ± 0.019	0.066 ± 0.016
$\ln(10^{10} A_s)$	3.089 ± 0.036	3.062 ± 0.029
n_s	0.9655 ± 0.0062	0.9677 ± 0.0060
H_0	67.31 ± 0.96	67.81 ± 0.92
Ω_Λ	0.685 ± 0.013	0.692 ± 0.012
Ω_m	0.315 ± 0.013	0.308 ± 0.012

- Planck data are extremely well described by the standard spatially-flat ΛCDM model
- The angular scale of the sound horizon at recombination is the best determined parameter (0.05%)
- Scale invariant is ruled out at high significance (6σ) and the result is robust to changes in the model (e.g. running spectral index, tensor fluctuations)
- A significantly lower value of τ is found: reionization is pushed to later times.
- Tension with some astrophysical measurements:
  - A low value of the Hubble constant
  - A high value of the matter density fluctuations parameter

Other extensions to the base ΛCDM model

- No evidence for tensor modes
  - $r < 0.11$ (95%) Planck TT + lowP + lensing + ext
- No evidence of running of the spectral index of primordial fluctuations
- Isocurvature modes strongly constrained
  - Less than ~3% of the adiabatic modes
- Dark energy
  - Consistent with a cosmological constant ($w=p/r=-1$)
- No evidence of modified gravity
- No detection of topological defects

None of the considered extensions can alleviate the tensions found with certain astrophysical data.

The 6-parameter ΛCDM model provides an excellent match to the Planck data

Present observational limits on r

Planck Collaboration XIII 2016 based on an analysis of the data TT+lowP+lensing+ext constrained $r_{0.002} < 0.11$ ($r_{0.05} < 0.12$).

The best constraint based on B-modes has been imposed by the BICEP2/Keck col. 2016 PRL (including the Keck 95 GHz data) $r_{0.05} < 0.09$.

Combining the previous BICEP2/Keck B-modes data with the Planck TT+lowP+lensing+ext data provides the strongest constraint $r_{0.05}<0.07$.

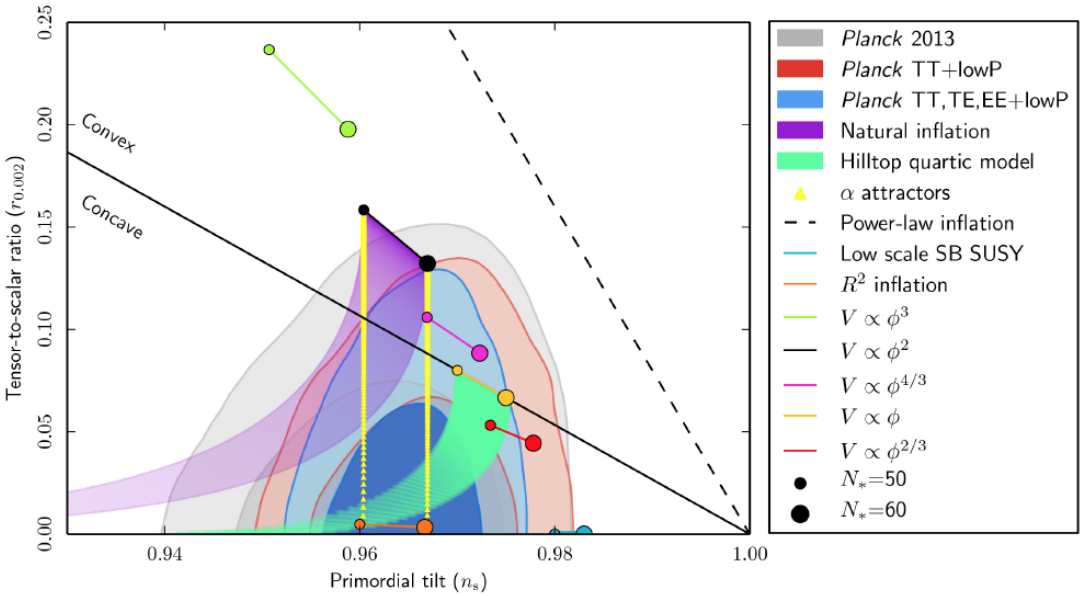
Inflation and Planck

Predictions from the simplest models of inflation	Planck measurements
Spatially flat Universe	$\Omega_K = 0 \pm 0.0025$
Nearly scale-invariant spectrum	$n_s = 0.968 \pm 0.006$
Almost a power-law	$dn_s/d\ln k = -0.0065 \pm 0.0076$
Dominated by scalar perturbations	$r_{0.002} < 0.09$ (95%)
Gaussian	$f_{NL} = 2.5 \pm 5.7$
Adiabatic	$\beta_{iso} < 3\%$ (95%)
Negligible topological defects	$f_{10} < 0.04$ ($G\mu/c^2 < 10^{-7} – 10^{-6}$)

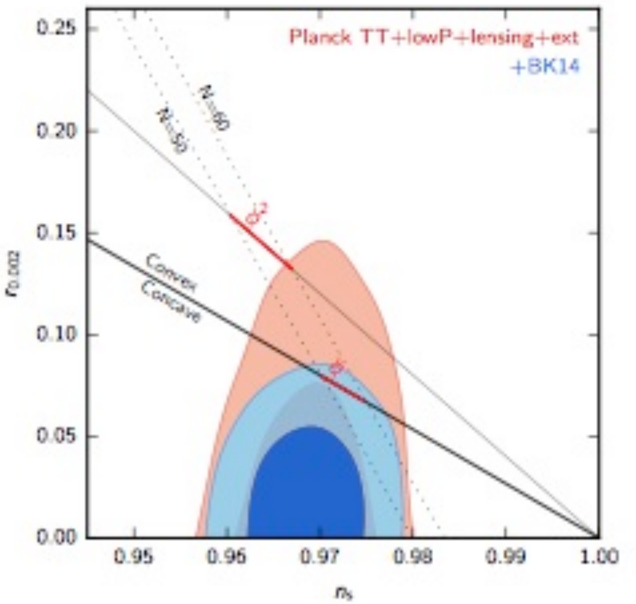
And a gravitational wave background with undetermined amplitude…

Constraints on inflationary models

Planck Col. XX 2016



Keck+BICEP2 collaborations 2016 PRL



$r_{0.002} < 0.11$, *Planck* TT+lowP+lensing+ext,

$r_{0.002} < 0.09$, *Planck* TT+lowP+lensing+ext+BKP.

$r_{0.05} < 0.07$ Planck TT+lowP +lensing+ext +BK14

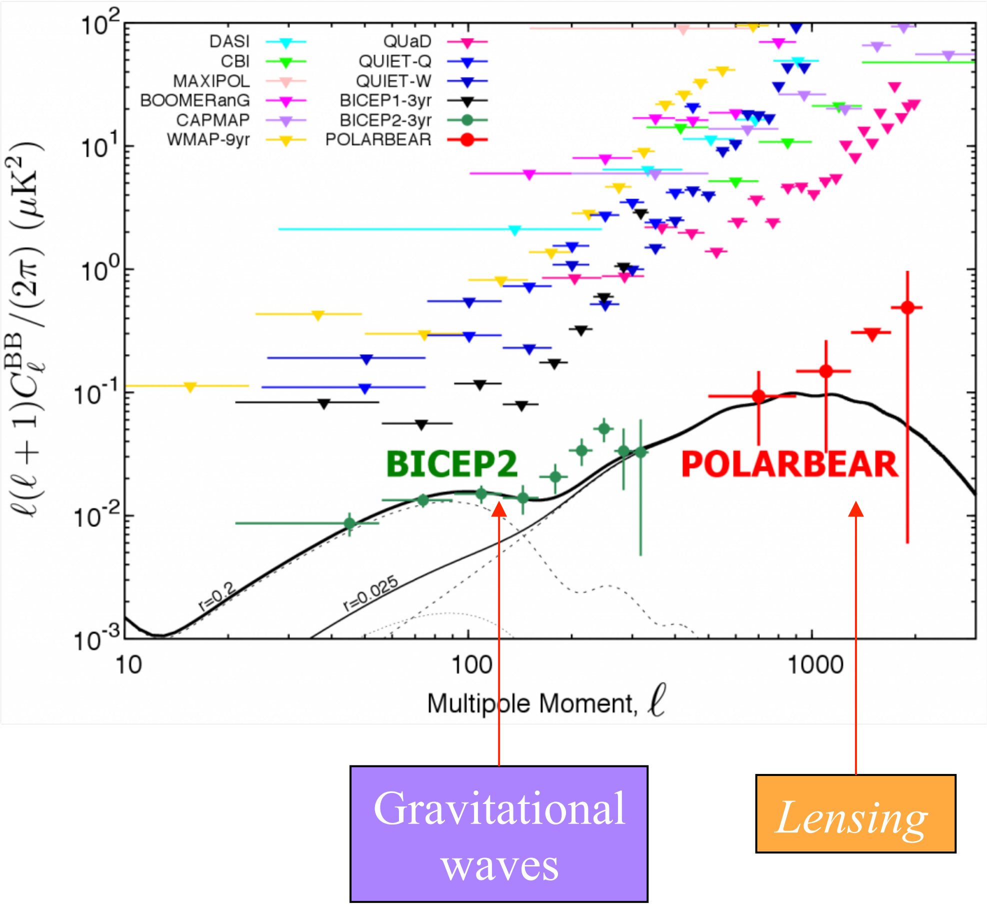
R^2 inflation (Starobinsky 1980) has the strongest evidence.

Monomial potentials with n>2 are strongly disfavored.

CMB B-modes experiments

Name	Platform	Area (deg^2)	FWHM	Freq (GHz)	Detectors	r_{lim}	Start
BICEP/KECK	Ground	800	~1°	100,150,220	Bolom	0.01	✓
QUIJOTE	Ground	5000	~1°	10-50	HEMTs	0.05	✓
PolarBear	Ground	1200	3’-7’	90,150,220	Bolom	0.01	✓
QUBIC	Ground	800	~0.5°	90,150,220	Bol/inter	0.01	
AdvACTpol	Ground	4000	~1’	28,41,95,150,230	Bolom	0.03	
SPT-3G	Ground	500	1’-1.6’	100,150,220	Bolom	0.03	
CLASS	Ground	70% sky	~0.5°	40,90,150,220	Bolom	0.01	
Simons Array	Ground	70% sky	3’.5	90,150,220	Bolom	0.01	
S4	Ground	Full sky	1’	30-300	Bolom	0.001	
PIPER	Balloon	80% sky	0°.6	200,270,350,800	Bolom	0.007	
EBEX	Balloon	350	8’	150,250,350,450	Bolom	0.03	
SPIDER	Balloon	24000	17’-50’	90,145,280	Bolom	0.03	✓
LSPE	Balloon		30’	40-250	Bolom/HEMT	0.03	
Planck	Satellite	Full sky	5’-33’	30-353	Bolom/HEMT	0.05	✓
LiteBIRD	Satellite	Full sky	30’	40-400	Bolom	0.001	>2025
PIXIE	Satellite	Full sky	1°.6	30-6000	Bolom	0.001	?
CORE	Satellite	Full sky	5’	60’-600’	KIDs	0.001	?

The quest for the primordial GWB: BICEP2 B-mode results



Gravitational waves

Lensing

BICEP2 Collaboration 2014, PRL

BICEP2 (March 2014)

It observes a region of the sky of 380 squared degrees @ 150 GHz with high-sensitivity

$r=0.20^{+0.07}_{-0.05}$ (68% CL)

Constraint from Planck 2013 + other CMB experiments (flat LCDM)

$r < 0.11$ (95% CL)

¿Was the B-mode really detected?

- Galactic contamination?

- Only one frequency available

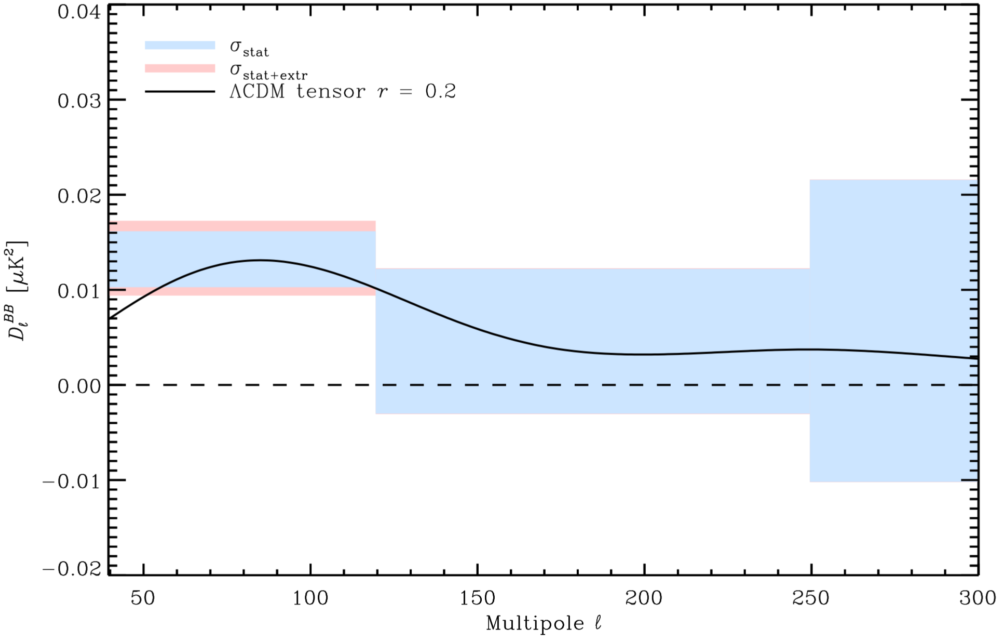
- Large uncertainty in level of foreground contamination

- Extensions of LCDM?

$r<0.26$ (95% CL) Planck

Dust polarization from Planck

- Using Planck multifrequency observations, it is found that the dust polarised emission follows a modified blackbody spectrum with T_d=19.6 and b_d=1.59
- The Planck 353 GHz channel is dominated by dust, extrapolating to BICEP2 frequency → find a contribution from dust similar to the BICEP2 signal
- However, uncertainties are large → needs joint Planck+BICEP2 analysis

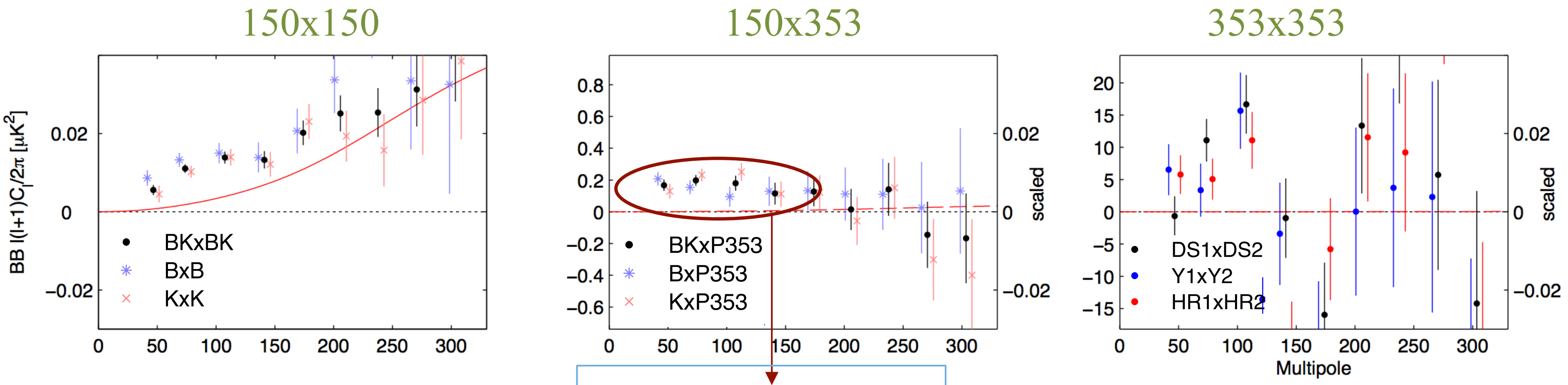


Planck coll. Int. XXX 2016, A&A

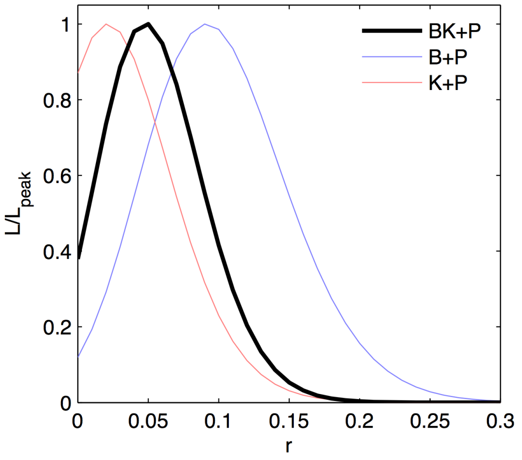
Planck prediction of dust contribution at 150 GHz in a region similar to BICEP2

BICEP2/Keck Array/Planck combined analysis

(BICEP2/Keck & Planck coll. 2015 PRL)



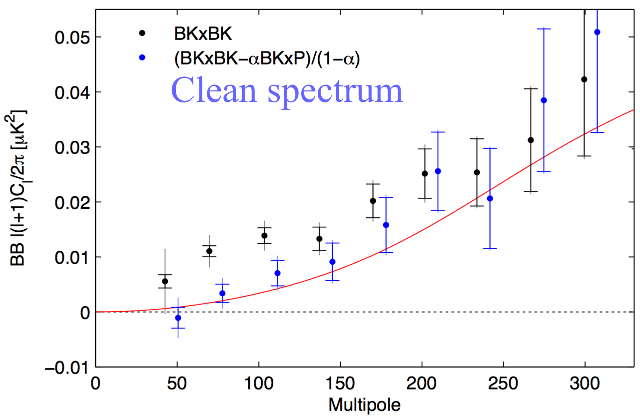
Significant cross-correlation detected



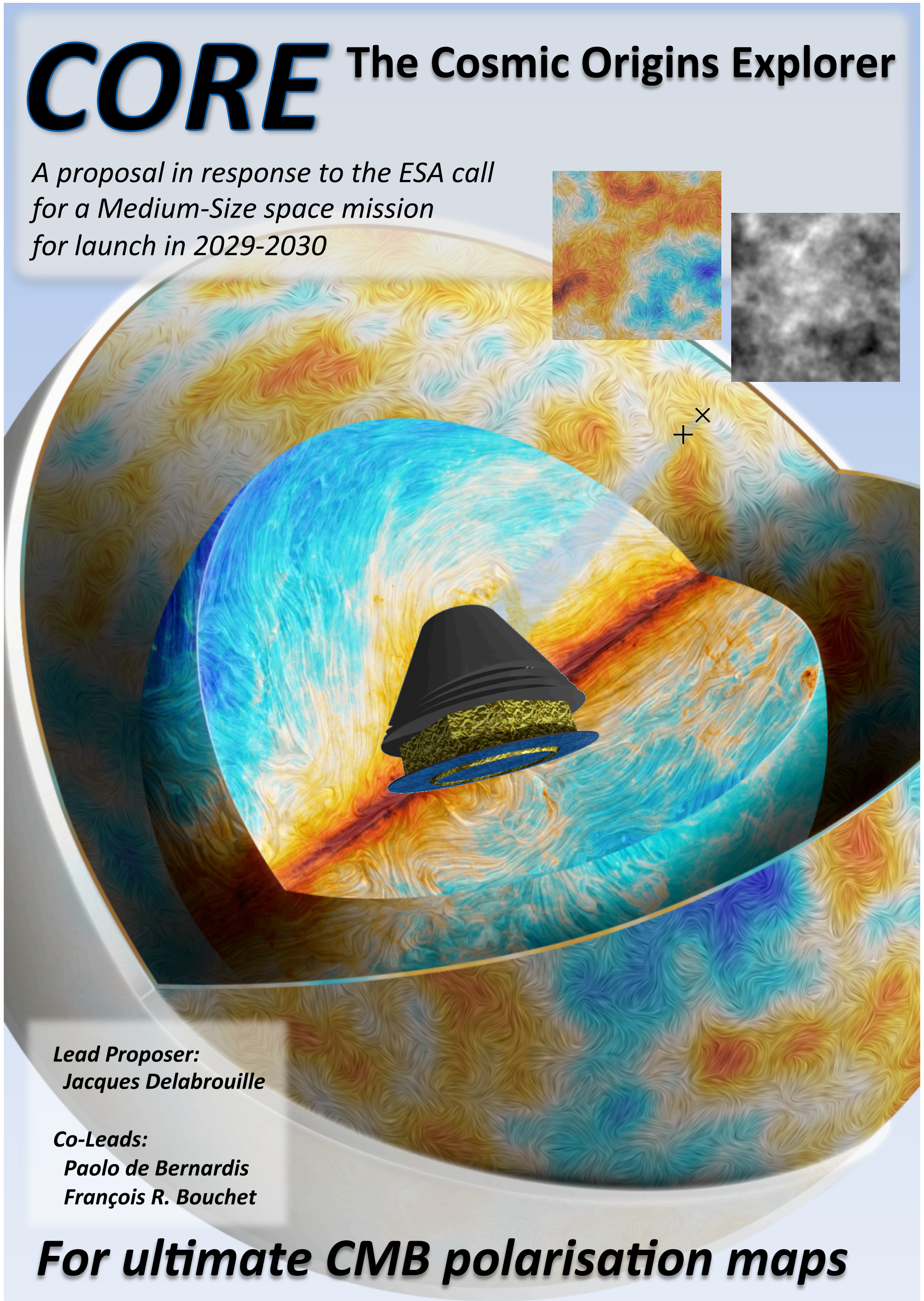
No GWB detection !!

$r_{0.05} < 0.12$ (95 %)

BICEP2 signal was significantly contaminated by dust



Including all BICEP2/Keck data (adding the Keck 95 GHz data) and Planck, $r_{0.05} < 0.07$ (95 %) (Keck+BICEP2 coll. 2016 PRL)



CORE The Cosmic Origins Explorer

A proposal in response to the ESA call for a Medium-Size space mission for launch in 2029-2030

Lead Proposer:
Jacques Delabrouille

Co-Leads:
Paolo de Bernardis
François R. Bouchet

For ultimate CMB polarisation maps

Lead Proposer: Jacques Delabrouille

CNRS, Laboratoire APC, 10 Avenue Alice Domon et Léonie Duquet 75013 Paris, France
tel.: +33157276040, fax: +33157276071, mail: delabrouille@apc.in2p3.fr

The Lead Proposer will support the study activities by making available at least 70% of his time throughout the study period.

Proposal co-leads: Paolo de Bernardis (Sapienza Università di Roma); François R. Bouchet (IAP, Paris);

Executive Board:

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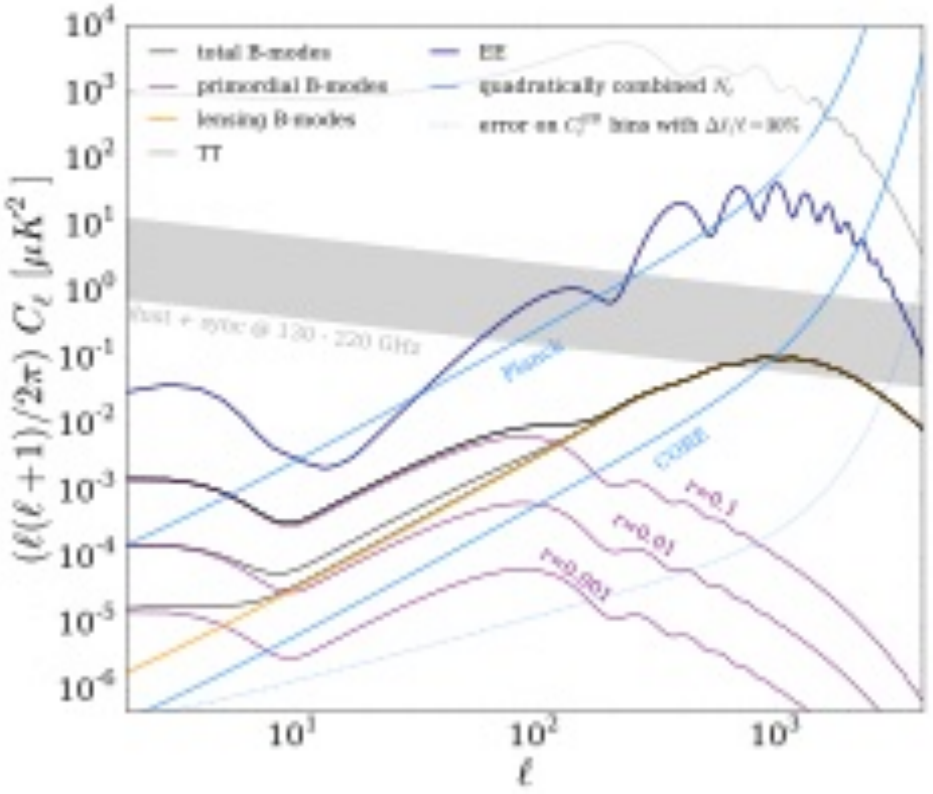
350 proposers from 15+1 countries

SCIENCE CASE

Inflation

- Primordial GWs:
  Energies 10^{12}xLHC

CORE_inflation_1612.08270.pdf

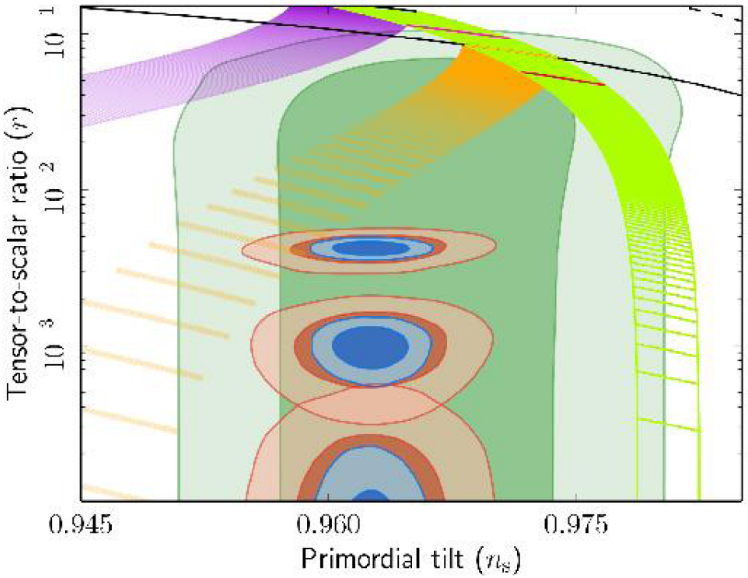


Sensitivity in r ≈ 0.001

Both Starobinsky and Higgs Inflation models can be probed.

SCIENCE CASE

Inflation



- Primordial non-Gaussianity:

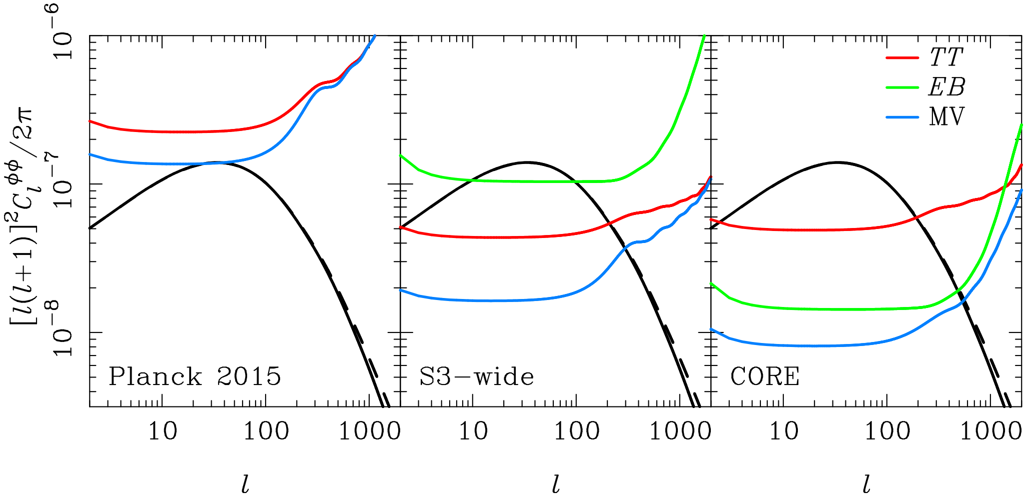
Parameter		Current results	*CORE* expected uncertainties
Ω_k	Curvature	$\Omega_k = -0.005^{+0.009}_{-0.008}$ (68 % CL) [30]	$\sigma(\Omega_k) = \mathbf{0.0018}$
$dn_s/d\ln k$	Running index	$dn_s/d\ln k = -0.003 \pm 0.007$ (68 % CL) [30]	$\sigma(dn_s/d\ln k) = \mathbf{0.0023}$
f_{NL}	Non-Gaussianity	$f_{NL}^{local} = 0.8 \pm 5.0$ (68 % CL) [13]	$\sigma(f_{NL}^{local}) = \mathbf{2.1}$
		$f_{NL}^{equil} = -3.7 \pm 43$ (68 % CL) [13]	$\sigma(f_{NL}^{equil}) = \mathbf{21}$
		$f_{NL}^{ortho} = -26 \pm 21$ (68 % CL) [13]	$\sigma\left(f_{NL}^{ortho}\right) = \mathbf{9.6}$
β_{iso}	Non-adiabaticity	$\beta_{iso} < 0.0013$ (95 % CL) [11]	$\beta_{iso} < \mathbf{0.00026}$ (95 % CL)
$G\mu$	Cosmic strings	$G\mu < 2.0 \times 10^{-7}$ (95 % CL) [31]	$G\mu < \mathbf{2.1 \times 10^{-8}}$ (95 % CL)

SCIENCE CASE

Mapping the dark matter structures

- Gravitational lensing:

Neutrino mass $\Sigma m_\nu < 44$meV
Detection at $> 2\sigma$ with CORE+BAO



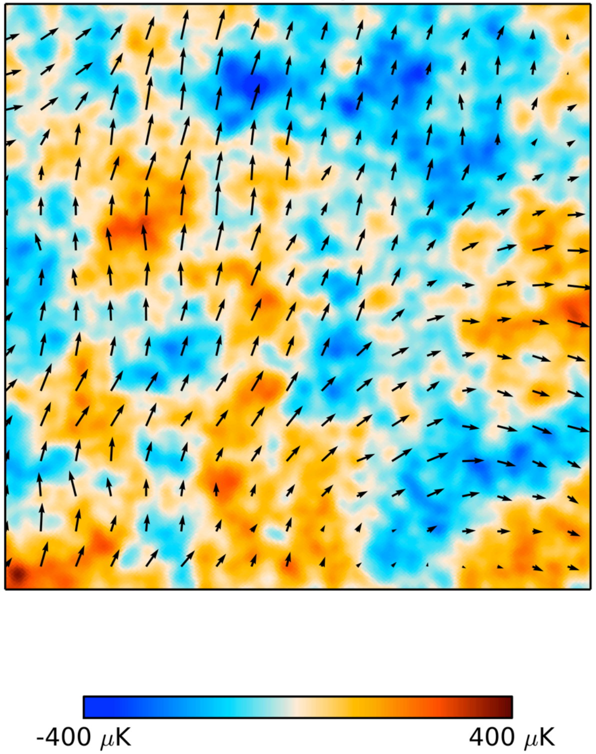
- Dark energy:

FoM(w_0,w_a) for CORE+Euclid ~ 10 x only Euclid
A robust result based on only linear scales from Euclid

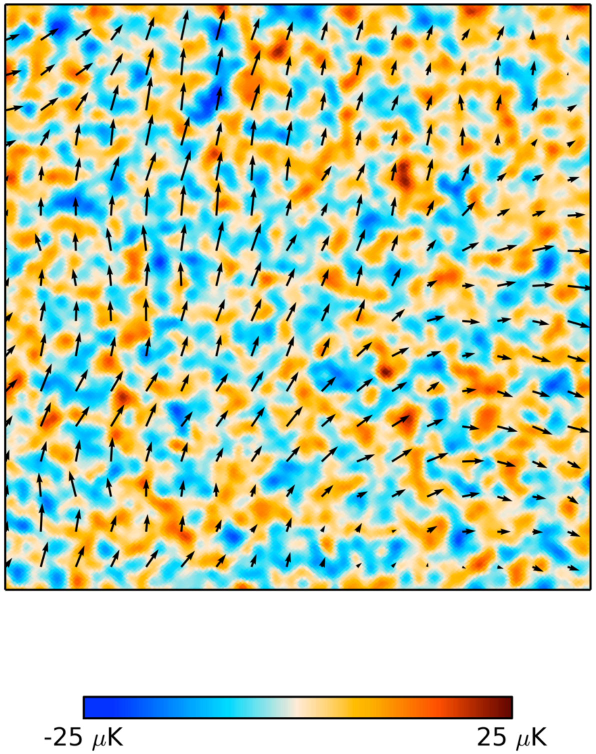
- Delensing primordial B-mode polarization:

Lensing convers E-mode into B-mode ⟷ 5 μKarcmin noise
Removal of 60% lensing B-mode power

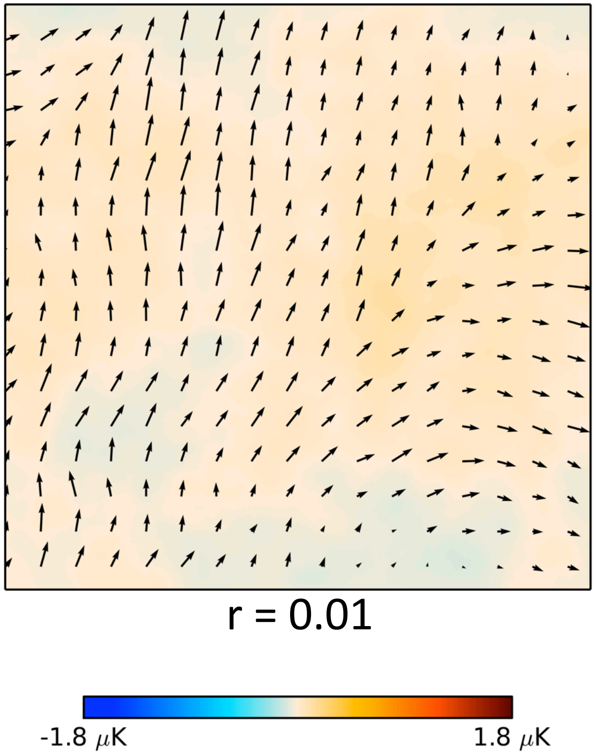
Unlensed Temperature



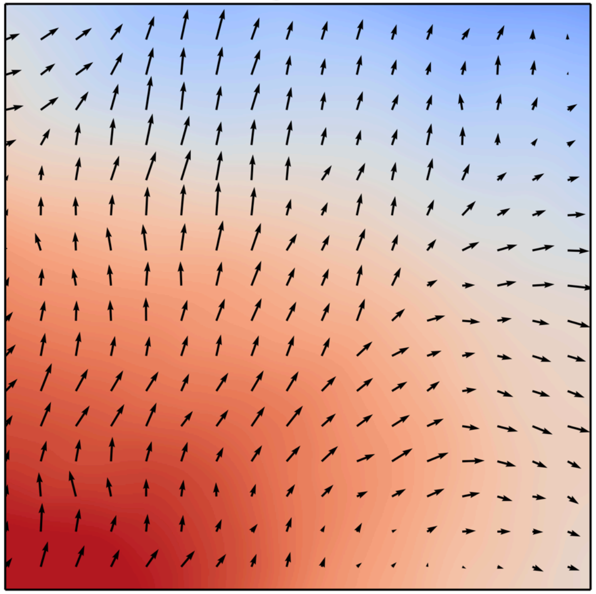
Unlensed E-Modes



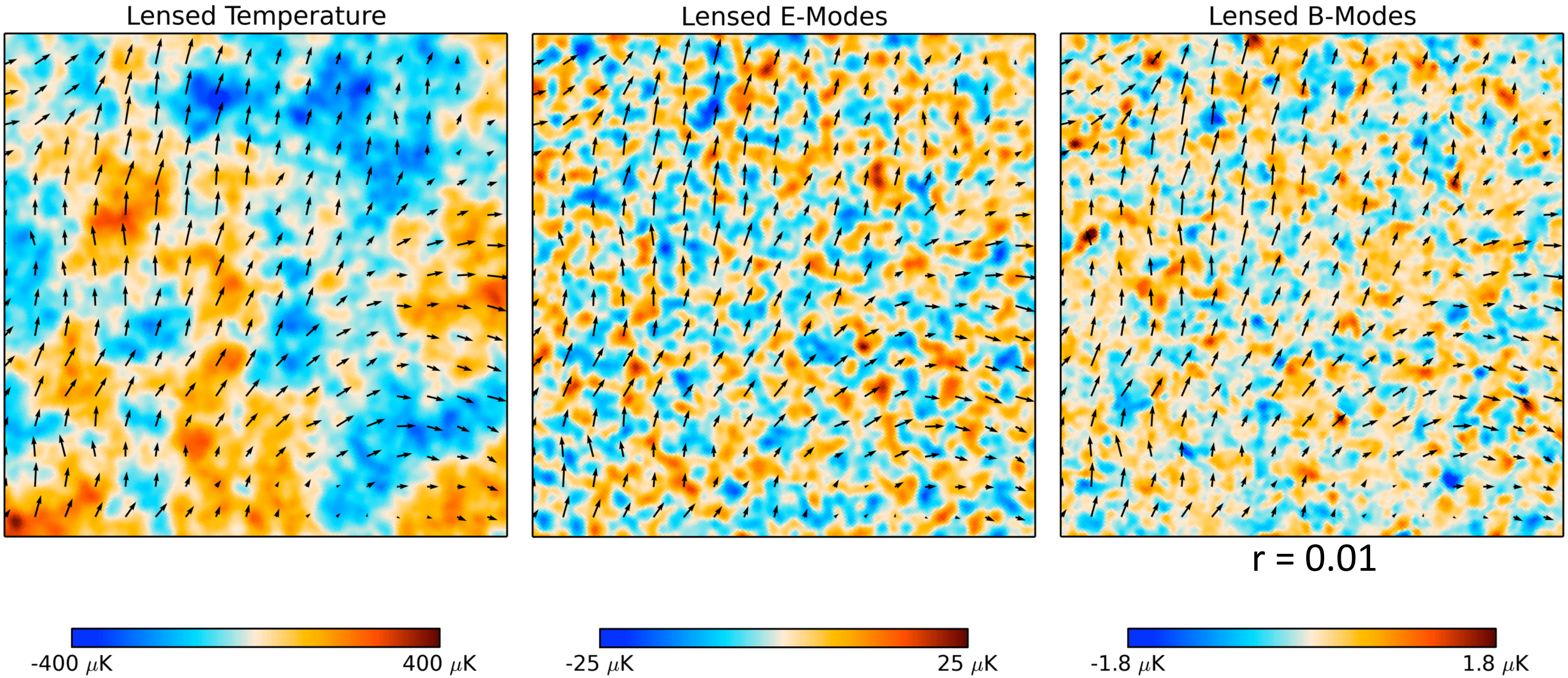
Unlensed B-Modes

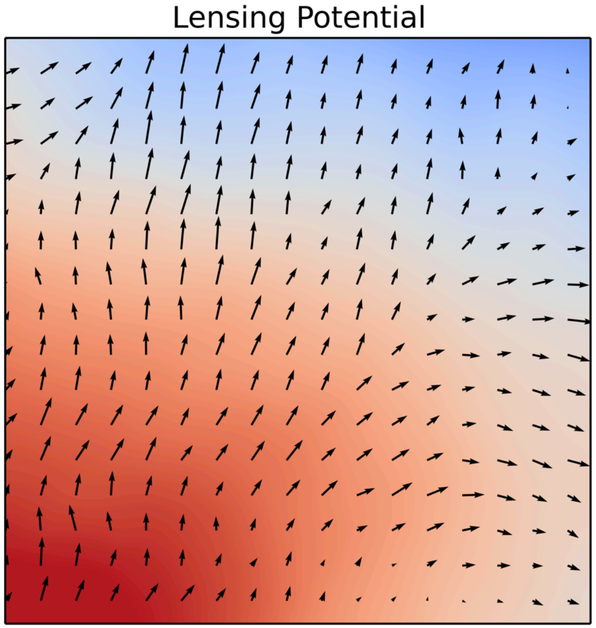


Lensing Potential



Gravitational lensing of the CMB
z ≈ 1-3





Gravitational lensing of the CMB
$z \approx 1\text{-}3$

3 unknown maps	3 observed maps
Φ	T_{OBS}
T_{LSS}	E_{OBS}
E_{LSS}	B_{OBS}

SCIENCE CASE

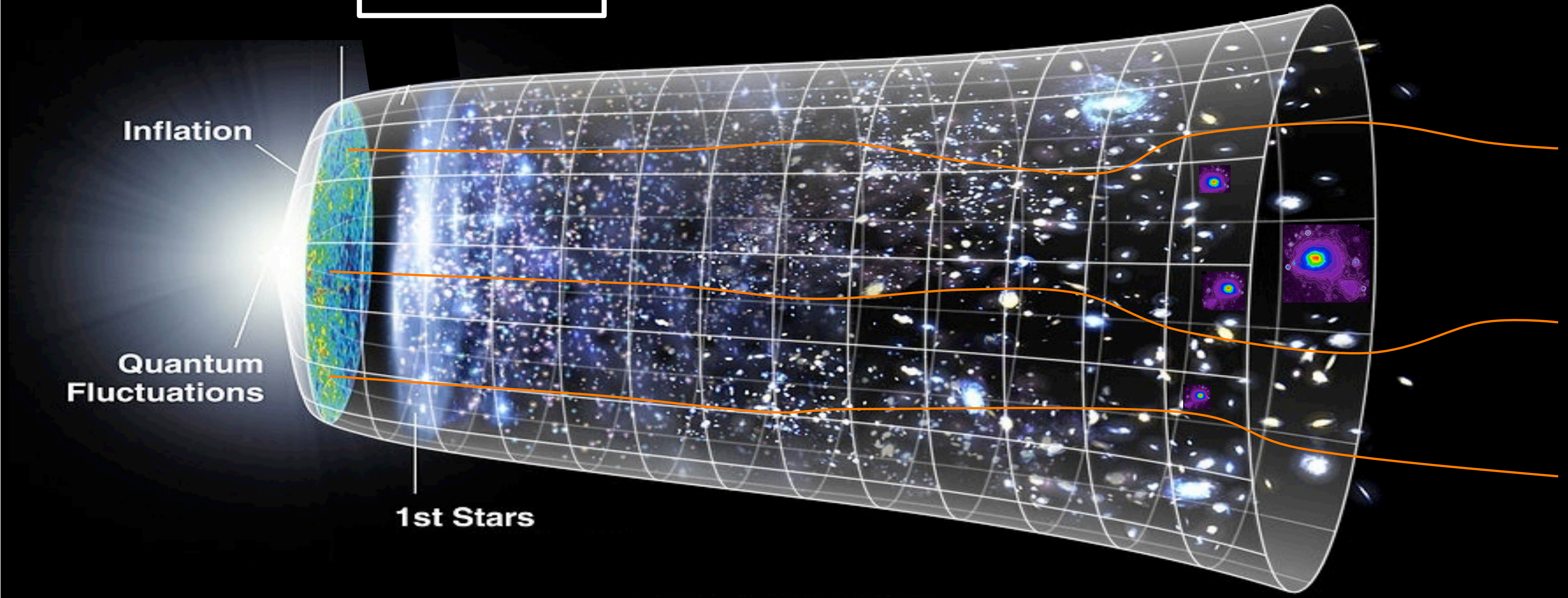
The cosmological scenario

Parameter	Description	Current results (Planck 2015+Lensing)	CORE expected uncertainties
ΛCDM			
$\Omega_\mathrm{b}h^2$	Baryon density	$\Omega_\mathrm{b}h^2 = 0.02226 \pm 0.00016$ (68 % CL) [30]	$\sigma(\Omega_\mathrm{b}h^2) = \mathbf{0.000037}$ $\{4.3\}$
$\Omega_\mathrm{c}h^2$	Cold dark matter density	$\Omega_\mathrm{c}h^2 = 0.1193 \pm 0.0014$ (68 % CL) [30]	$\sigma(\Omega_\mathrm{c}h^2) = \mathbf{0.00026}$ $\{5.4\}$
n_s	Scalar spectral index	$n_\mathrm{s} = 0.9653 \pm 0.0048$ (68 % CL) [30]	$\sigma(n_\mathrm{s}) = \mathbf{0.0014}$ $\{3.4\}$
τ	Reionization optical depth	0.063 ± 0.014 (68 % CL) [30]	$\sigma(\tau) = \mathbf{0.002}$ $\{7.0\}$
H_0	Hubble constant	$H_0 = 67.51 \pm 0.64$ (68 % CL) [30]	$\sigma(H_0) = \mathbf{0.11}$ $\{5.8\}$
σ_8	r.m.s. mass fluctuations	$\sigma_8 = 0.8150 \pm 0.0087$ (68 % CL) [30]	$\sigma(\sigma_8) = \mathbf{0.0011}$ $\{7.9\}$
Extensions			
N_eff	Relativistic degrees of freedom	$N_\mathrm{eff} = 2.94 \pm 0.20$ (68 % CL) [30]	$\sigma(N_\mathrm{eff}) = \mathbf{0.041}$ $\{4.9\}$
$\sum m_\nu$	Total neutrino mass	$\sum m_\nu < 0.315\,\mathrm{eV}$ (68 % CL) [30]	$\sigma(\sum m_\nu) = \mathbf{0.043}\,\mathrm{eV}$ $\{7.3\}$
$(m_\mathrm{s}^\mathrm{eff}, N_\mathrm{s})$	Sterile neutrino parameters	$(m_\mathrm{s}^\mathrm{eff} < 0.33\,\mathrm{eV}, N_\mathrm{s} < 3.24)$ (68 % CL) [30]	$\sigma(m_\mathrm{s}^\mathrm{eff}, N_\mathrm{s}) = (\mathbf{0.037}\,\mathrm{eV}, \mathbf{0.053})$ $\{8.9, 4.5\}$
Y_P	Primordial helium abundance	$Y_\mathrm{P} = 0.247 \pm 0.014$ (68 % CL) [30]	$\sigma(Y_\mathrm{P}) = \mathbf{0.0029}$ $\{4.8\}$
Y_P	Primordial helium (free N_eff)	$Y_\mathrm{P} = 0.259^{+0.020}_{-0.017}$ (68 % CL) [30]	$\sigma(Y_\mathrm{P}) = \mathbf{0.0056}$ $\{3.2\}$
w	Dark energy equation of state	$w = -1.42^{+0.25}_{-0.47}$ (68 % CL) [30]	$\sigma(w) = \mathbf{0.12}$ $\{3\}$
T_0	CMB temperature	Unconstrained [30]	$\sigma(T_0) = \mathbf{0.018}\,\mathrm{K}$
p_ann	Dark matter annihilation	$p_\mathrm{ann} < 3.4 \times 10^{-28}\,\mathrm{cm}^3\,\mathrm{GeV}^{-1}\,\mathrm{s}^{-1}$ (68 % CL) [30]	$\sigma(p_\mathrm{ann}) = \mathbf{5.3 \times 10^{-29}}\,\mathrm{cm}^3\,\mathrm{GeV}^{-1}\,\mathrm{s}^{-1}$ $\{6.4\}$
α/α_0	Fine-structure constant	$\alpha/\alpha_0 = 0.9990 \pm 0.0034$ (68 % CL)	$\sigma(\alpha/\alpha_0) = \mathbf{0.0007}$ $\{4.8\}$
$\Sigma_0 - 1$	Modified gravity	$\Sigma_0 - 1 = 0.10 \pm 0.11$ (68 % CL) [48]	$\sigma(\Sigma_0 - 1) = \mathbf{0.044}$ $\{2.5\}$
$A_{2s1s}/8.2206$	Recombination 2-photon rate	$A_{2s1s}/8.2206 = 0.94 \pm 0.07$ (68 % CL) [30]	$\sigma(A_{2s1s}/8.2206) = \mathbf{0.015}$ $\{4.7\}$
$\Delta(z_\mathrm{reion})$	Reionization duration	$\Delta(z_\mathrm{reion}) < 2.26$ (68 % CL) [49]	$\sigma(\Delta z_\mathrm{reion}) = \mathbf{0.58}$ $\{3.9\}$

CMB probes the entire history of the universe

$z \approx 6\text{-}11$
Reionization

$z \approx 0\text{-}1$
Integrated Sach Wolfe:
Accelerated expansion



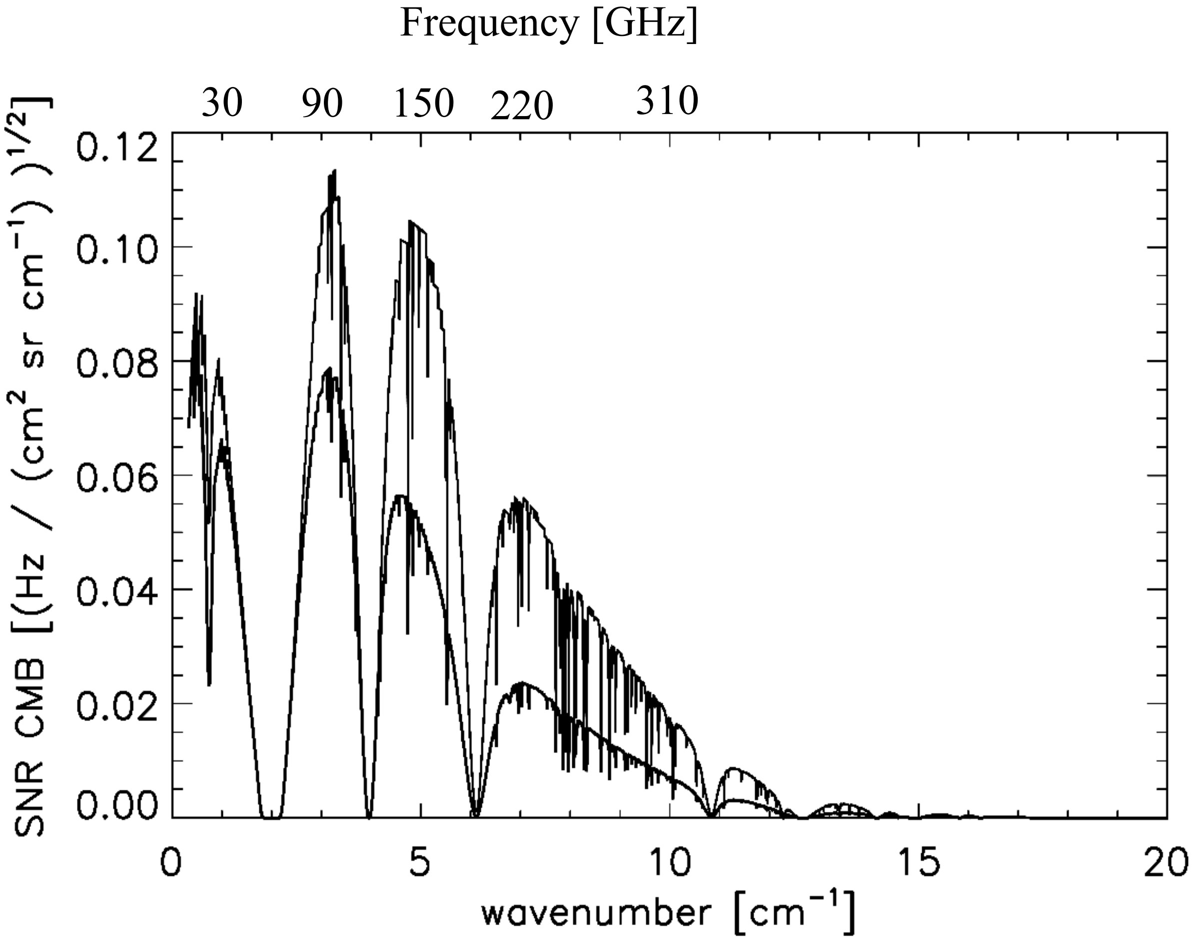
Inflation
Physics at ≈ 10^{16} GeV
$E > 10^{12} \times E_{LHC}$

$z \approx 1\text{-}3$
Gravitational lensing
Dark matter distribution

$z \approx 0\text{-}2$
Sunyaev-Zeldovich effect:
Distribution of the hot gas
and velocity field

WHY SPACE?

Atmospheric windows for 0.5 and 2 mm precipitable water vapor



From Paolo de Bernardis

WHY SPACE?

Unique observing environment

- All frequencies accessible (astrophysical foregrounds)
- Full sky coverage (large scales + cosmic variance)
- A clean and stable environment (systematics)
- Low background (better sensitivity per detector compared to ground)
- Nearly 100% observing efficiency
- Distant points in the sky can be observed in short timescales

Extracting all available information from the CMB requires a space mission.

What space mission?

There is no specific theoretical expectation for B-modes:

Finding the best strategy is complicated

Then, the requirements for the ultimate B-mode polarisation mission must be set by the lensing B-modes:

- *Map the dark matter distribution in the Universe*
- *De-lens B-modes for inflationary science*

Extracting the maximum information from the CMB (primary and secondary anisotropies) requires a comprehensive space mission

CORE in a nutshell

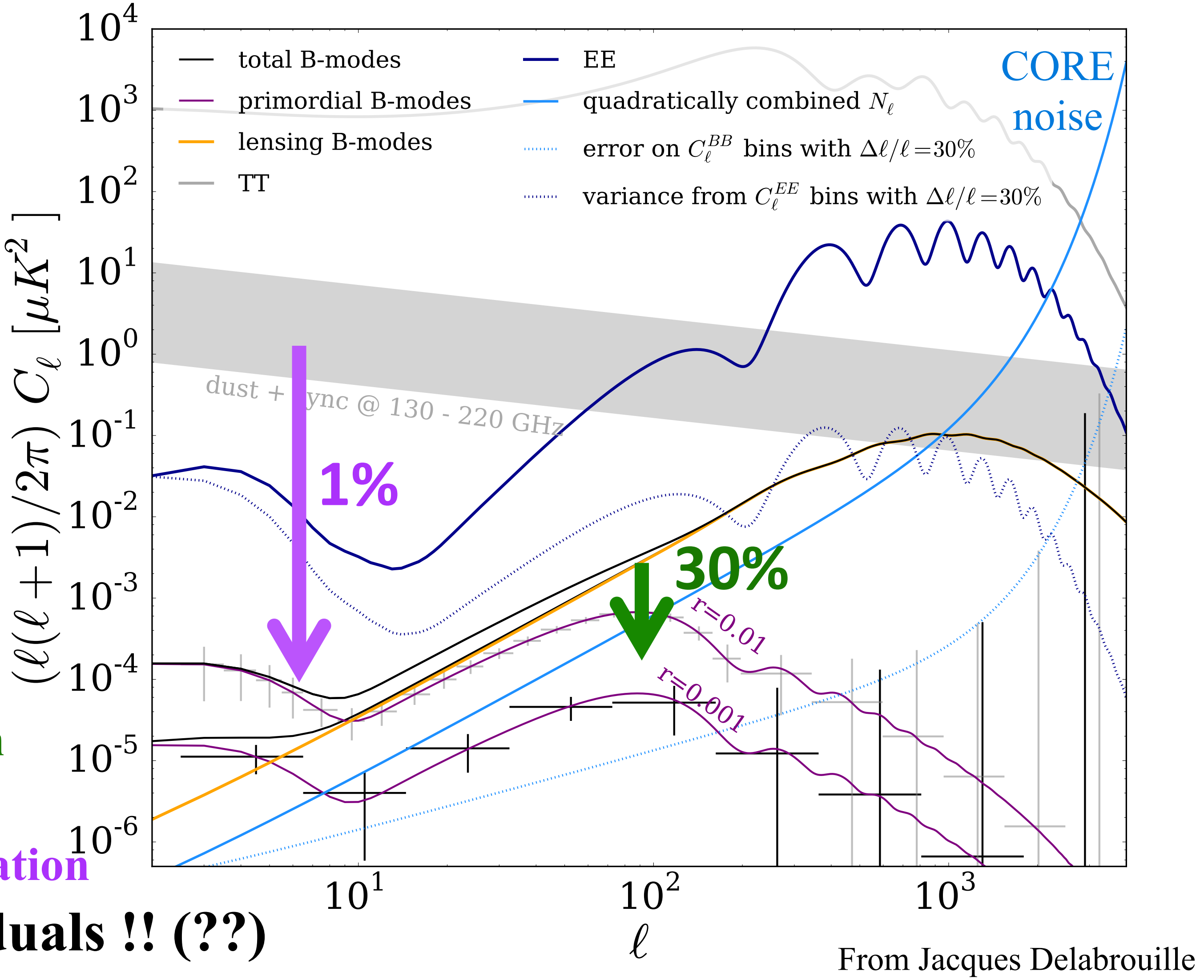
- 2 μK arcmin sensitivity
  - Allowing signal-dominated lensing maps and σ(r)=0.001

- 19 frequency channels
  - 6 for low-frequency foregrounds (synchrotron), below 115 GHz
  - 6 for the CMB, between 130 and 220 GHz
  - 7 for high-frequency foregrounds (dust), above 250 GHz

- 2 - 20 arcminute resolution
  - 5-10' in CMB channels (10' versus 30' at 100 GHz for LiteBIRD)

- Control of systematics
  - Very stable observing conditions
  - Polarisation modulation by the scan strategy

Space or ground ?



From Jacques Delabrouille

Remove >2/3 of the lensing contamination

Remove >99% of the foreground contamination

Characterize residuals !! (??)

Delensing problem

Depends on sensitivity and resolution (no theoretical limit)

Kendrick Smith et al, JCAP, Issue 06, id. 014 (2012)

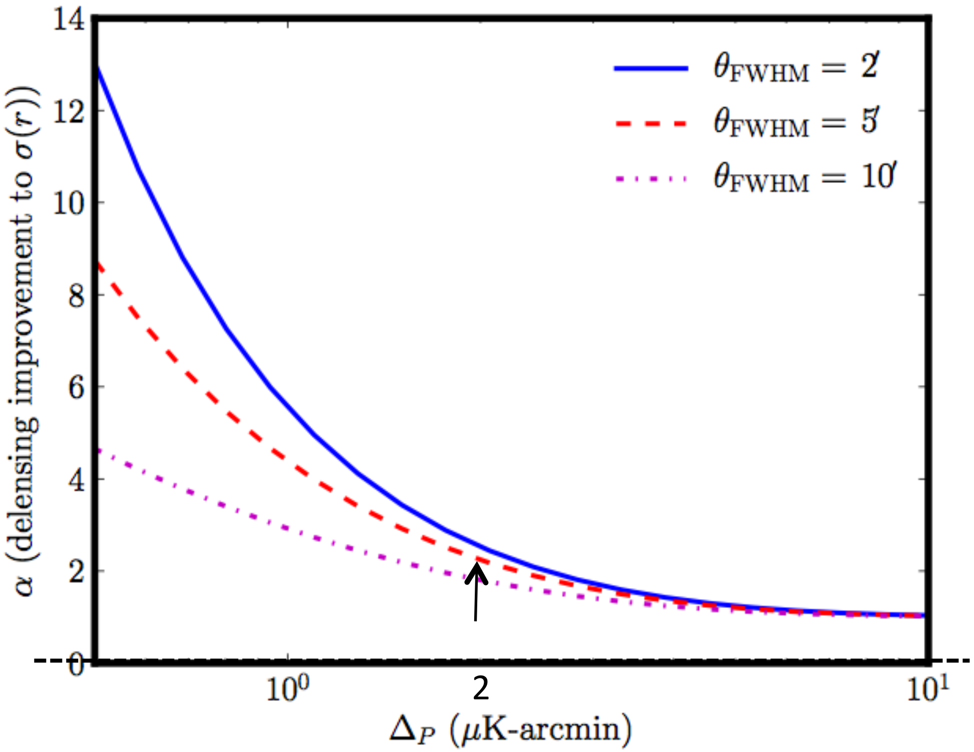


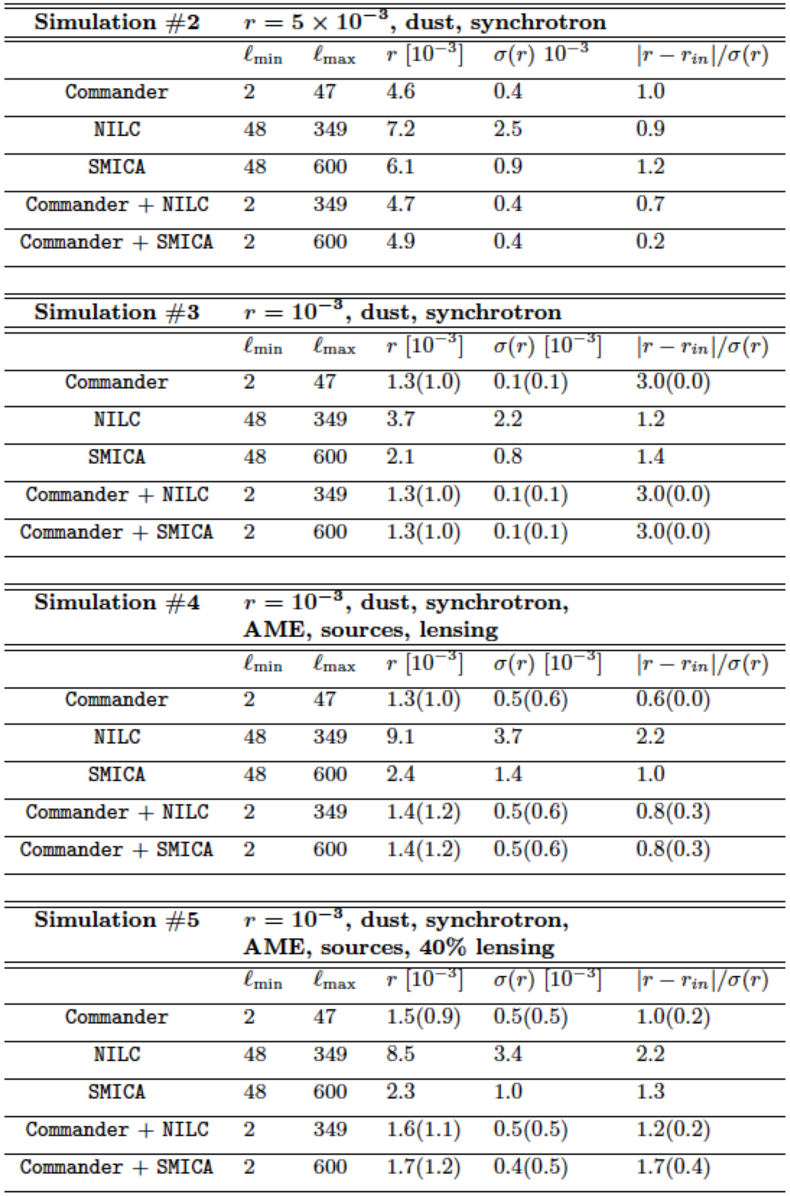
Figure 3: Forecasted improvement $\alpha = \sigma_0(r)/\sigma(r)$ in the statistical error on r due to polarization delensing, for varying noise level and beam. In the limit of low noise and high resolution, we find no limit (from delensing residuals alone) to how well r can be measured.

An alternative is to use e.g. the CIB as a tracer of mass (Sherwin & Schmittfull 2015)

Forecast on r under “realistic” conditions

CORE col. 2017 Component Separation

- Realistic simulations based on the PSM are used, including:
  - Galactic synchrotron and thermal dust with variable spectral indices over the sky
  - Polarized anomalous microwave emission (AME)
  - Polarized IR and radio sources
  - Gravitational lensing effects
- Present methods of component separation are able to accurately detect values of $r \geq 5\times10^{-3}$.
- Achieving values of $r \approx 10^{-3}$ (even assuming 60% delensing) is limited by foreground uncertainties specially at the reionization bump.
- Sources of potential bias for the detection of the primordial B-modes:
  - Incorrect foreground models
  - Averaging of spectral indices by pixelization



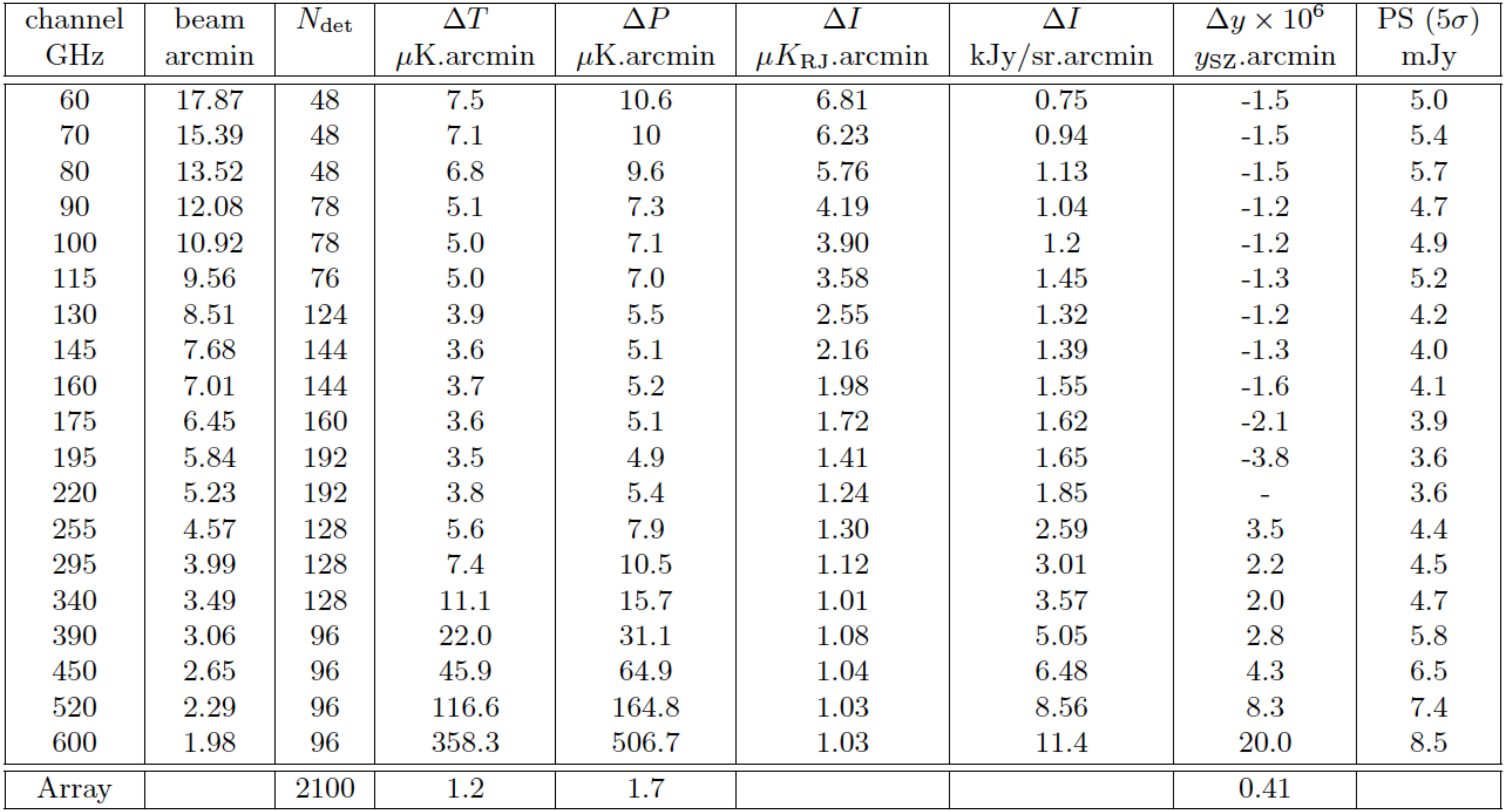
Simulation #2	**$r = 5\times10^{-3}$, dust, synchrotron**				
	$\ell_{\rm min}$	$\ell_{\rm max}$	r $[10^{-3}]$	$\sigma(r)$ 10^{-3}	$\lvert r - r_{in}\rvert/\sigma(r)$
Commander	2	47	4.6	0.4	1.0
NILC	48	349	7.2	2.5	0.9
SMICA	48	600	6.1	0.9	1.2
Commander + NILC	2	349	4.7	0.4	0.7
Commander + SMICA	2	600	4.9	0.4	0.2

Simulation #3	**$r = 10^{-3}$, dust, synchrotron**				
	$\ell_{\rm min}$	$\ell_{\rm max}$	r $[10^{-3}]$	$\sigma(r)$ $[10^{-3}]$	$\lvert r - r_{in}\rvert/\sigma(r)$
Commander	2	47	1.3(1.0)	0.1(0.1)	3.0(0.0)
NILC	48	349	3.7	2.2	1.2
SMICA	48	600	2.1	0.8	1.4
Commander + NILC	2	349	1.3(1.0)	0.1(0.1)	3.0(0.0)
Commander + SMICA	2	600	1.3(1.0)	0.1(0.1)	3.0(0.0)

Simulation #4	**$r = 10^{-3}$, dust, synchrotron, AME, sources, lensing**				
	$\ell_{\rm min}$	$\ell_{\rm max}$	r $[10^{-3}]$	$\sigma(r)$ $[10^{-3}]$	$\lvert r - r_{in}\rvert/\sigma(r)$
Commander	2	47	1.3(1.0)	0.5(0.6)	0.6(0.0)
NILC	48	349	9.1	3.7	2.2
SMICA	48	600	2.4	1.4	1.0
Commander + NILC	2	349	1.4(1.2)	0.5(0.6)	0.8(0.3)
Commander + SMICA	2	600	1.4(1.2)	0.5(0.6)	0.8(0.3)

Simulation #5	**$r = 10^{-3}$, dust, synchrotron, AME, sources, 40% lensing**				
	$\ell_{\rm min}$	$\ell_{\rm max}$	r $[10^{-3}]$	$\sigma(r)$ $[10^{-3}]$	$\lvert r - r_{in}\rvert/\sigma(r)$
Commander	2	47	1.5(0.9)	0.5(0.5)	1.0(0.2)
NILC	48	349	8.5	3.4	2.2
SMICA	48	600	2.3	1.0	1.3
Commander + NILC	2	349	1.6(1.1)	0.5(0.5)	1.2(0.2)
Commander + SMICA	2	600	1.7(1.2)	0.4(0.5)	1.7(0.4)

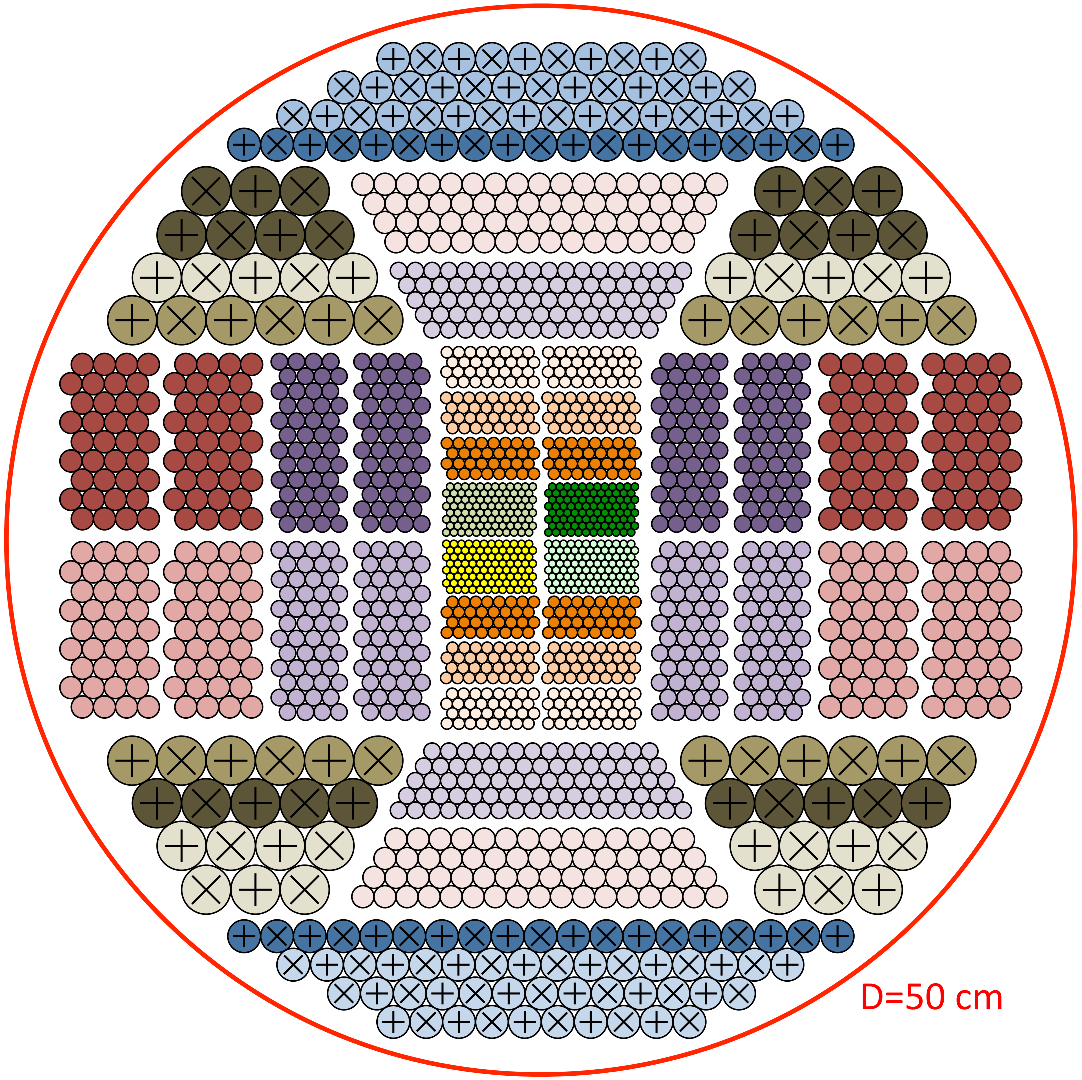
CORE channels



channel GHz	beam arcmin	N_{det}	ΔT μK.arcmin	ΔP μK.arcmin	ΔI μK_{RJ}.arcmin	ΔI kJy/sr.arcmin	$\Delta y \times 10^6$ y_{SZ}.arcmin	PS (5σ) mJy
60	17.87	48	7.5	10.6	6.81	0.75	-1.5	5.0
70	15.39	48	7.1	10	6.23	0.94	-1.5	5.4
80	13.52	48	6.8	9.6	5.76	1.13	-1.5	5.7
90	12.08	78	5.1	7.3	4.19	1.04	-1.2	4.7
100	10.92	78	5.0	7.1	3.90	1.2	-1.2	4.9
115	9.56	76	5.0	7.0	3.58	1.45	-1.3	5.2
130	8.51	124	3.9	5.5	2.55	1.32	-1.2	4.2
145	7.68	144	3.6	5.1	2.16	1.39	-1.3	4.0
160	7.01	144	3.7	5.2	1.98	1.55	-1.6	4.1
175	6.45	160	3.6	5.1	1.72	1.62	-2.1	3.9
195	5.84	192	3.5	4.9	1.41	1.65	-3.8	3.6
220	5.23	192	3.8	5.4	1.24	1.85	-	3.6
255	4.57	128	5.6	7.9	1.30	2.59	3.5	4.4
295	3.99	128	7.4	10.5	1.12	3.01	2.2	4.5
340	3.49	128	11.1	15.7	1.01	3.57	2.0	4.7
390	3.06	96	22.0	31.1	1.08	5.05	2.8	5.8
450	2.65	96	45.9	64.9	1.04	6.48	4.3	6.5
520	2.29	96	116.6	164.8	1.03	8.56	8.3	7.4
600	1.98	96	358.3	506.7	1.03	11.4	20.0	8.5
Array		2100	1.2	1.7			0.41	

Focal plane

	GHz	N_{det}
●	60	24×2
●	70	24×2
●	80	24×2
●	90	39×2
●	100	39×2
●	115	38×2
●	130	124
●	145	144
●	160	144
●	175	160
●	195	192
●	220	192
●	255	128
●	295	128
●	340	128
●	390	96
●	450	96
●	520	96
●	600	96
	TOTAL	2100



Summary

- Only (primary) CMB temperature anisotropies have been measured so far with high S/N.
- E-modes well detected at a statistical level (spectrum) but the best full-sky map still has S/N ≈ 1 per pixel (on all scales larger than about 15')
- B-modes (lensing) just barely detected statistically. Their precise mapping is the key to both inflationary tensor modes, and to precise direct observation of (dark) matter structures in the Hubble volume.
- CMB science is well understood and there is the necessary expertise to run ground/balloon/space-borne experiments to measure the B-modes.
- A space mission is needed to extract the maximum information from the CMB.