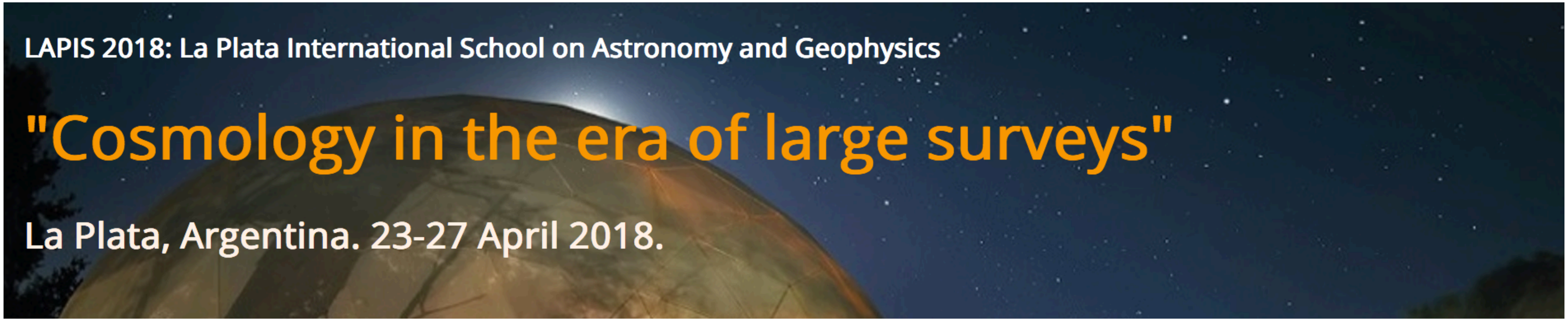
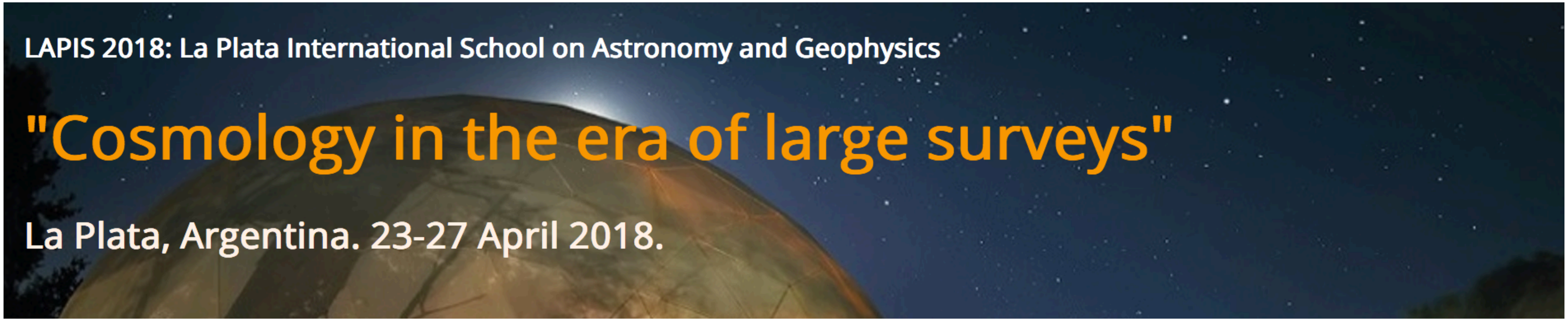


CMB foregrounds for B-mode studies

José Alberto Rubiño Martín

(@jarubinom)

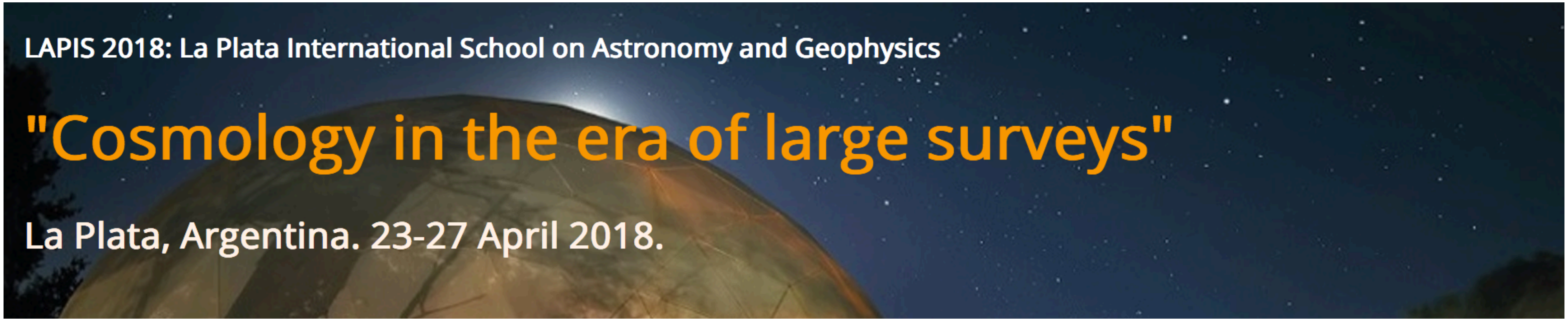
IAC, Tenerife



CMB foregrounds for B-mode studies

I. Introduction
II. Physical mechanisms producing polarised emission at large scales.
III. Component separation and impact on B-mode science

RADIO FOREGROUNDS

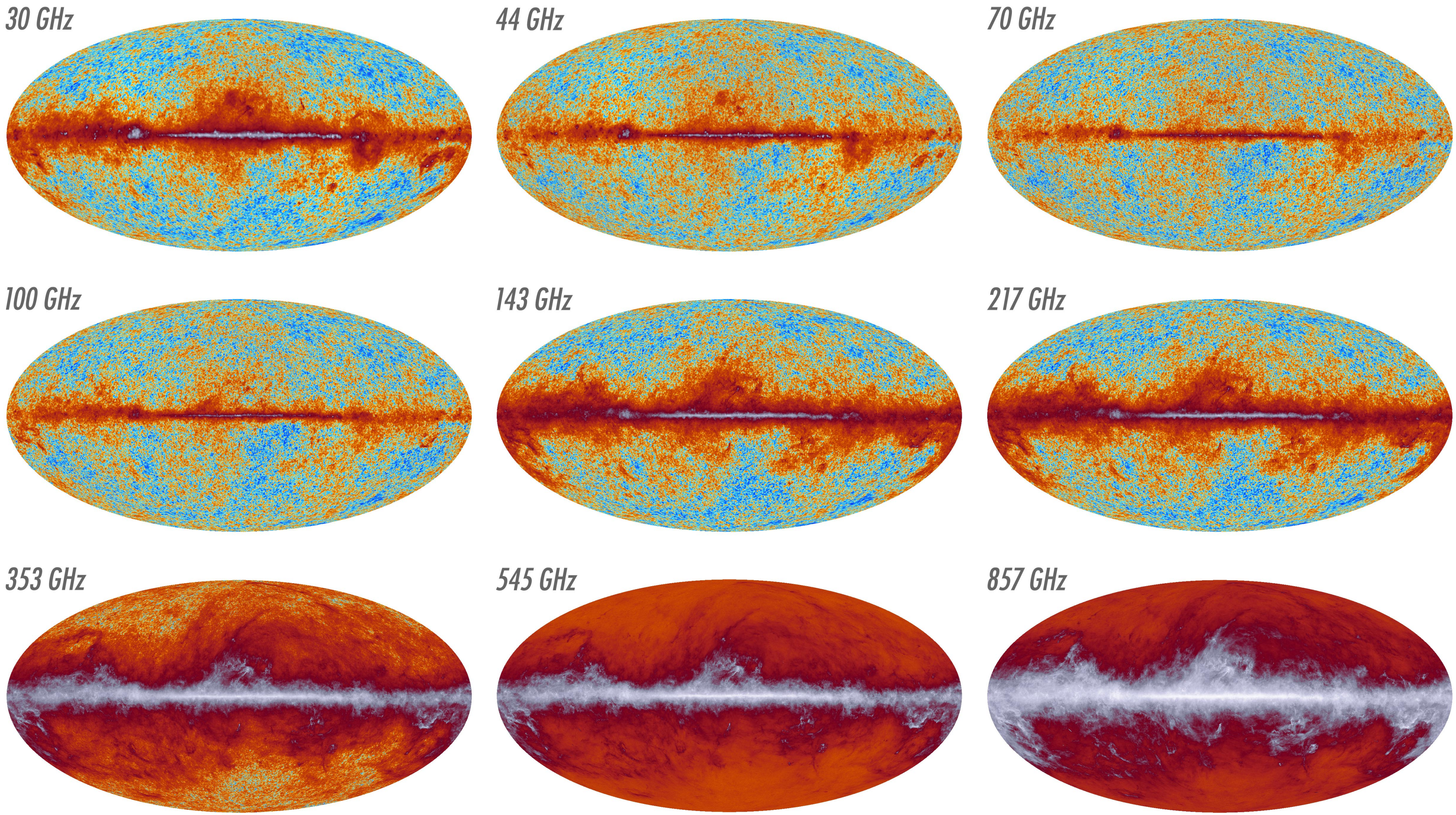


CMB foregrounds for B-mode studies

I. **Introduction**

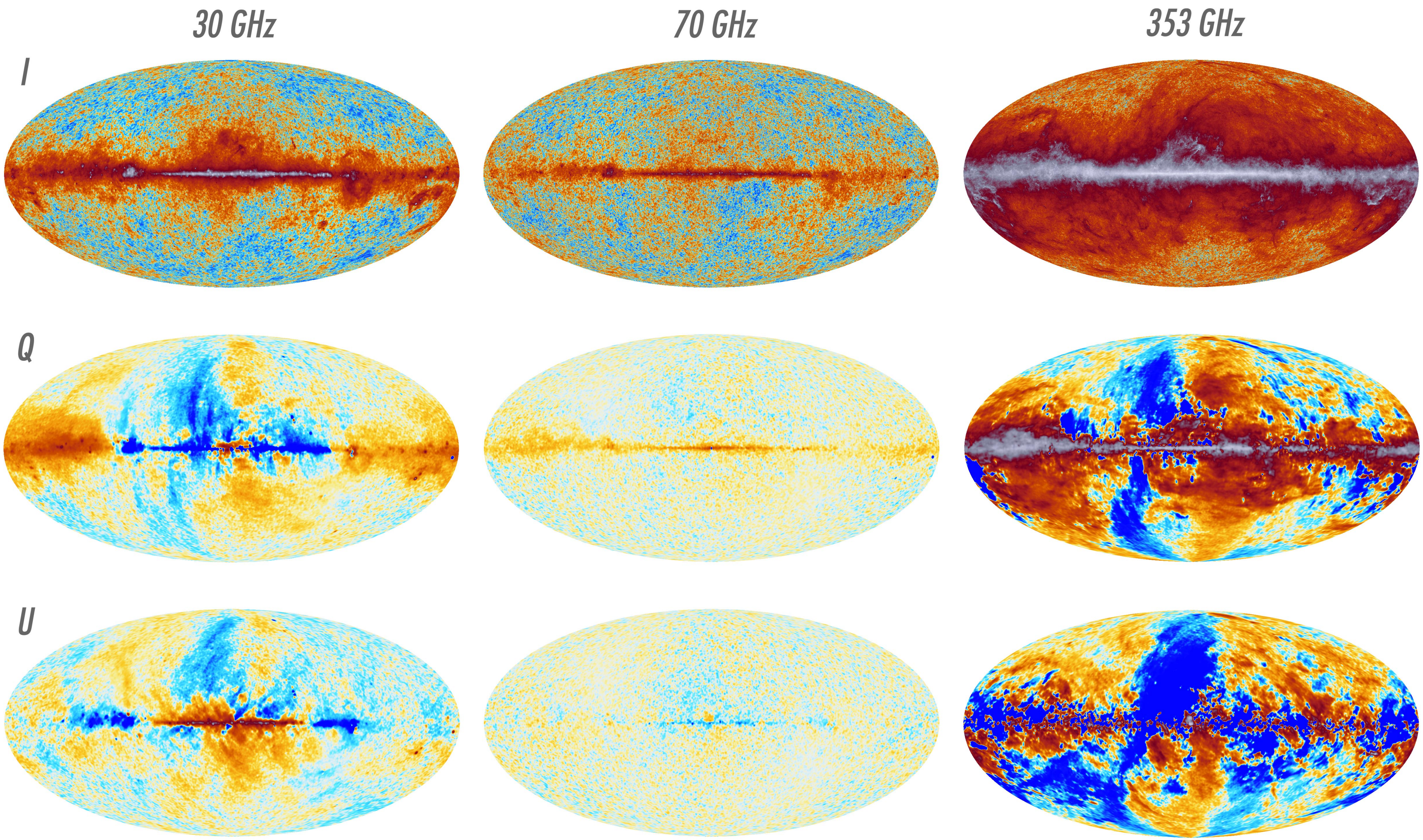
II. Physical mechanisms producing polarised emission at large scales.

III. Component separation and impact on B-mode science



PLANCK 2015

The microwave sky in intensity



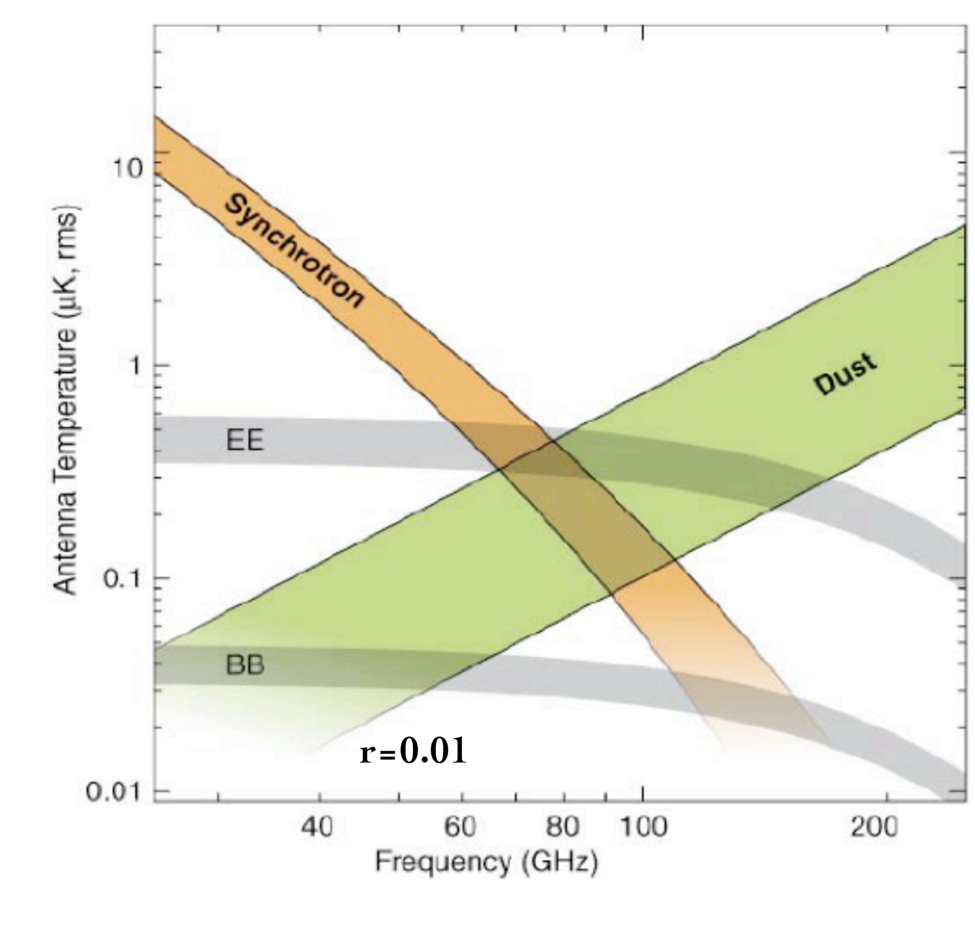
PLANCK 2015

The microwave sky in polarization

Observability of B-modes

❖**Signals are extremely small** ⇒ large number of receivers with large bandwidths are required.

- Accurate **control of systematics** (cross-pol, spillover,...) is mandatory.
- **Foregrounds**. B-mode signal is subdominant over Galactic foregrounds
  - Free-free, low-freq, not polarized
  - Synchrotron, low-freq, pol ~10%
  - Thermal dust, high-freq, pol ~10%
  - Anomalous emission, 20-60 GHz, pol ~3%?
  - Point sources, low-freq, pol ~5%



(Bock et al. 2006, arXiv:0604101)

Foreground types

★ **Foregrounds. Definition**: any physical mechanism intervening between the LSS and us and producing radiation in the same frequencies of interest for CMB observations.

	Foreground	Polarization	Angular scales
Local	Atmosphere	~ 0 %	Large scales
	Ground spill over	Varies	Large scales
	Radio Frequency Interference	0-100 %	All
Solar system	Sun/Moon	Low	All
	Planets / Solar system objects	Low	Small scales
	Zodiacal light	Low	Large scales
Galactic	Galactic synchrotron radiation	~ 10-40 %	Large scales
	Galactic free-free radiation	Low	Large scales
	Galactic electric dipole emission	<1 %	Large scales
	Galactic magnetic dipole emission	0-35 %	Large scales
	Galactic thermal dust radiation	~2-20 %	Large scales
	Galactic light emission (CO)	Low	Large scales
Extra galact	Radio galaxies	Few %	Small scales
	Sub-mm IR galaxies	Low	Small scales
Cosmolog ical	Cosmic Infrared background	Low	Small to intermediate
	Secondary anisotropies	Low	All
	Lensing	High	Small scales

A few definitions

★ **Flux density.** S_ν [W m^{-2} Hz^{-1}] related to "brightness temperature" T_b via simple equation involving solid angle Ω and λ.

★ T_b often defined in the Rayleigh-Jeans (R-J) limit i.e. hν << kT (not to be confused with "thermodynamic temperature" TCMB which is defined relative to a blackbody at T=2.725 K).

$$\frac{S_\nu}{\Omega} = \frac{2k_B}{\lambda^2} T_b$$

★ **Optical depth** τ related to T_b via the effective temperature T.

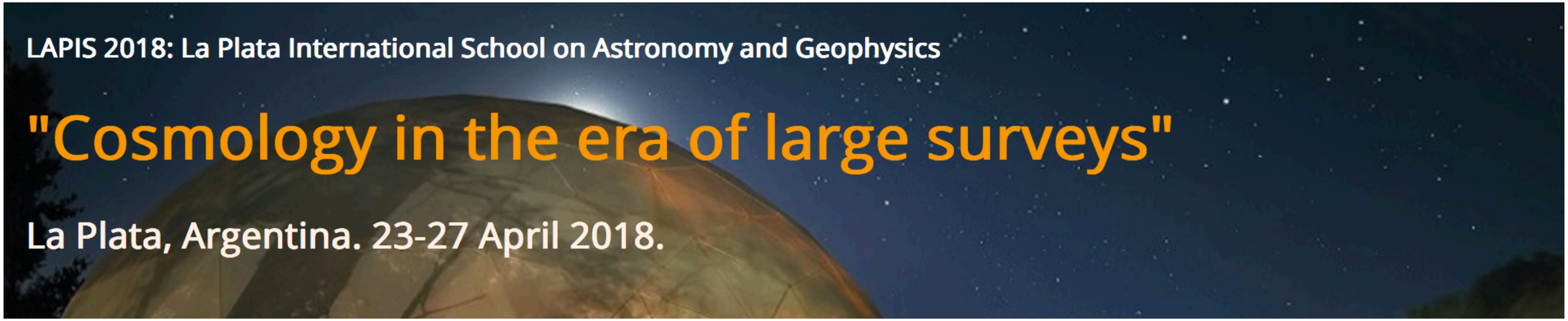
- Optically thin (tau <<1).
- Optically thick (tau >>1).

$$T_b = T(1 - e^{-\tau})$$

★ **Spectral index** is the slope of the spectrum between two frequencies in log-space

$$\alpha = \frac{\ln(S_1/S_2)}{\ln(\nu_1/\nu_2)}$$

$$S_\nu \propto \nu^\alpha \qquad (T \propto \nu^\beta; \qquad \alpha = \beta + 2)$$



CMB foregrounds for B-mode studies

I. Introduction

II. Physical mechanisms producing polarised emission at large scales.

III. Component separation and impact on B-mode science

RADIO FOREGROUNDS

Foreground types

★ Let’s focus in the large-scale Galactic foregounds covering wide frequency ranges.

	Foreground	Polarization	Angular scales
Local	Atmosphere	~ 0 %	Large scales
	Ground spill over	Varies	Large scales
	Radio Frequency Interference	0-100 %	All
Solar system	Sun/Moon	Low	All
	Planets / Solar system objects	Low	Small scales
	Zodiacal light	Low	Large scales
Galactic	**Galactic synchrotron radiation**	**~ 10-40 %**	**Large scales**
	Galactic free-free radiation	Low	Large scales
	Galactic electric dipole emission	**<1 %**	**Large scales**
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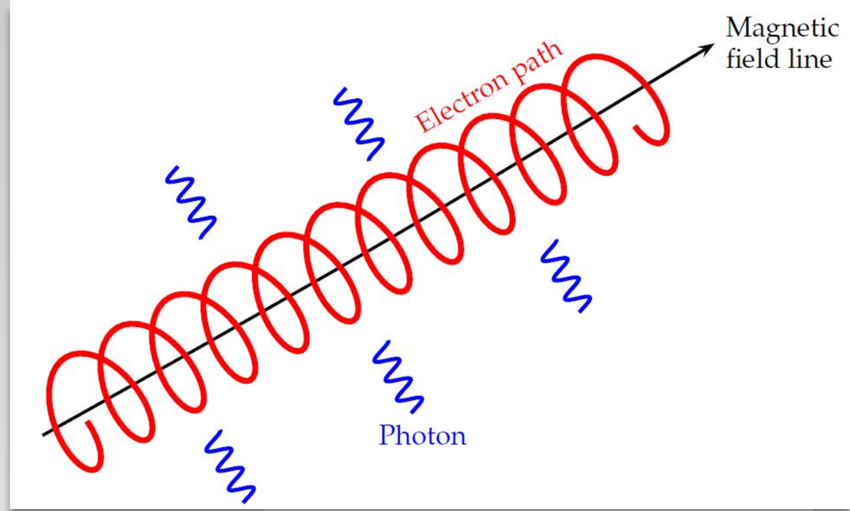
	Sub-mm IR galaxies	Low	Small scales
Cosmolog ical	Cosmic Infrared background	Low	Small to intermediate
	Secondary anisotropies	Low	All
	Lensing	High	Small scales

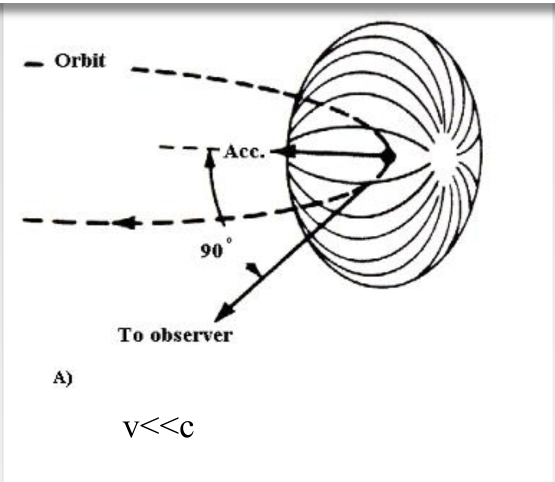
Synchrotron emission (I)

★ **Relativistic** (high-energy) cosmic rays (e.g. electrons) accelerated by magnetic fields



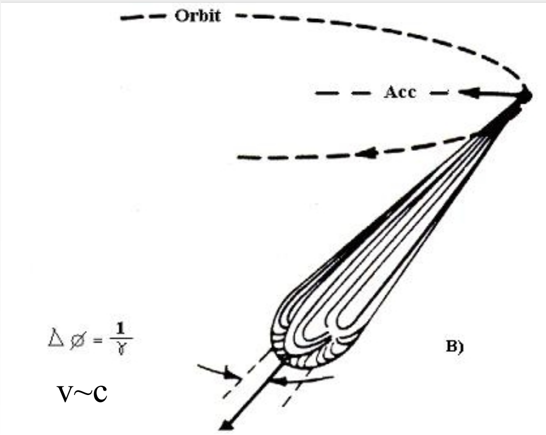
★ At non-relativistic velocities, we have the classical cyclotron emission, at the Larmor frequency:

$$\nu_L = 2.8\left(\frac{B}{1Gauss}\right)MHz$$



★ How to generate a continuum spectrum extending up to GHz frequencies??

- **Relativistic beaming effect.** → highly polarised
- Relativistic Doppler shift.



★ Spectrum extends up to:

$$\nu_C = \frac{3}{4\pi}\gamma^2\nu_L \sin\alpha \qquad \gamma = \frac{1}{\sqrt{1-\frac{v^2}{c^2}}}$$

Synchrotron emission (II)

★ **Power radiated by a single electron:**

broad function peaked around $\nu_C = \frac{3}{4\pi}\gamma^2 \nu_L \sin\alpha$

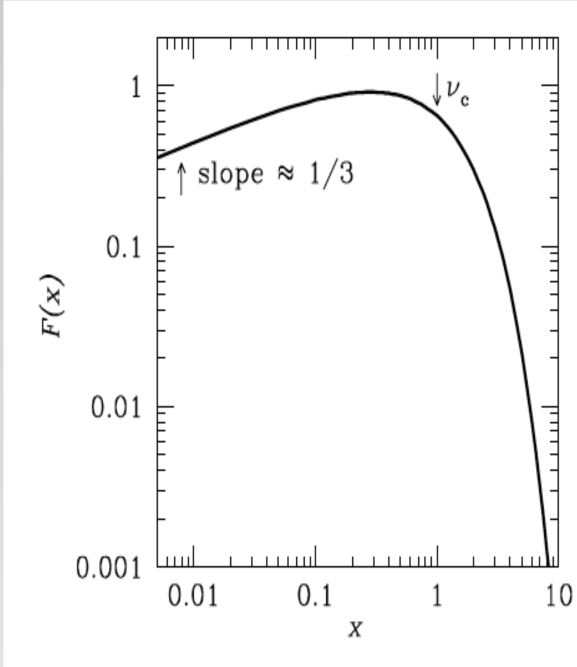
★ **For a power-law distribution of electron energies $N(E) \propto E^{-p}$**

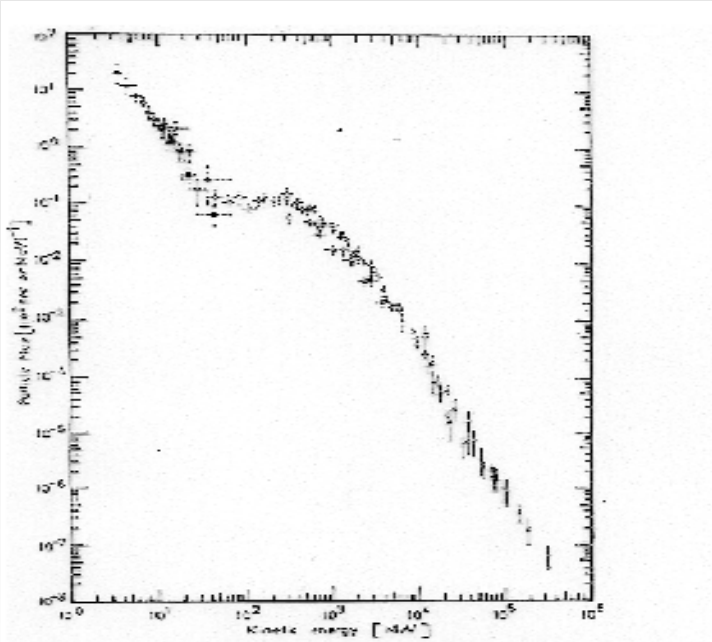
$$\boxed{j_\nu \propto B^{\frac{p+1}{2}} \nu^{-\frac{p-1}{2}}}$$

- Spectral index: $\beta = -\frac{p+3}{2}$

- Polarisaton fraction (for regular B): $\frac{P}{I} = \frac{p+1}{p+7/3}$

- However, due to incoherence of the magnetic field, and beam depolarisation, the observed polarisation fractions are typically much lower
- Typically P/I < 40%



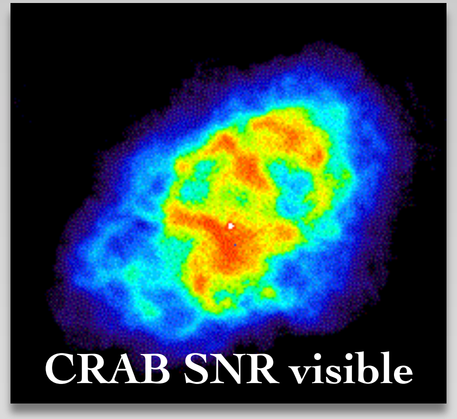


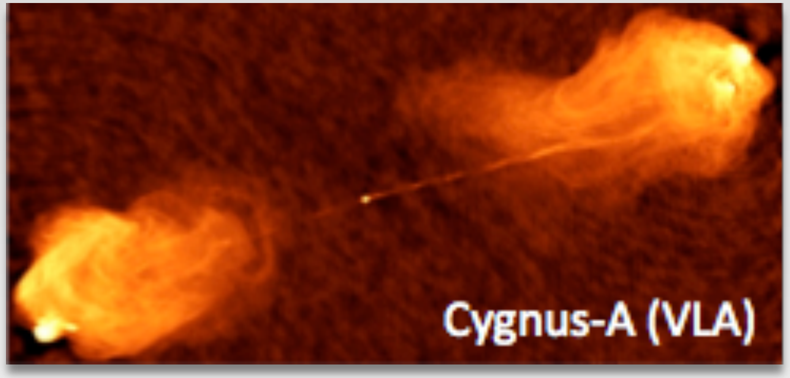
Synchrotron emission (III)

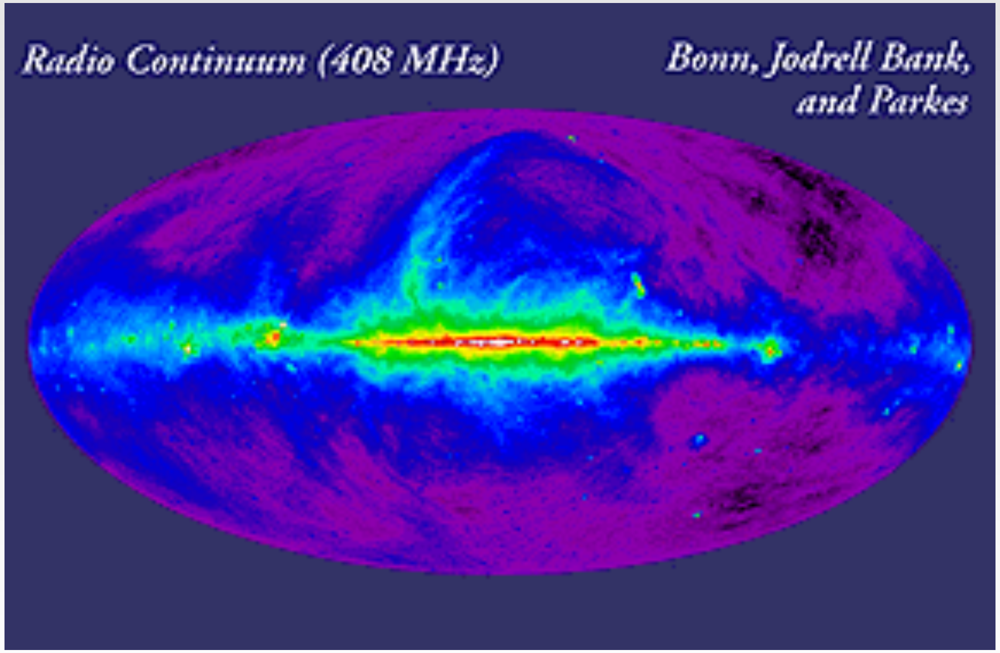
★ SNRs, radio galaxies, QSOs.

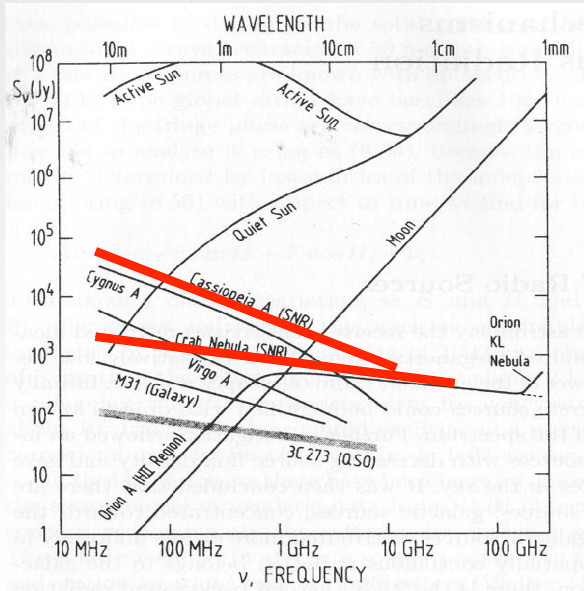
★ Responsible for the main part of the continuum emission of our galaxy in radio wavelengths.

★ Dominates at low frequencies. Typical dependence of beta=-2.7. (Non-thermal emission).



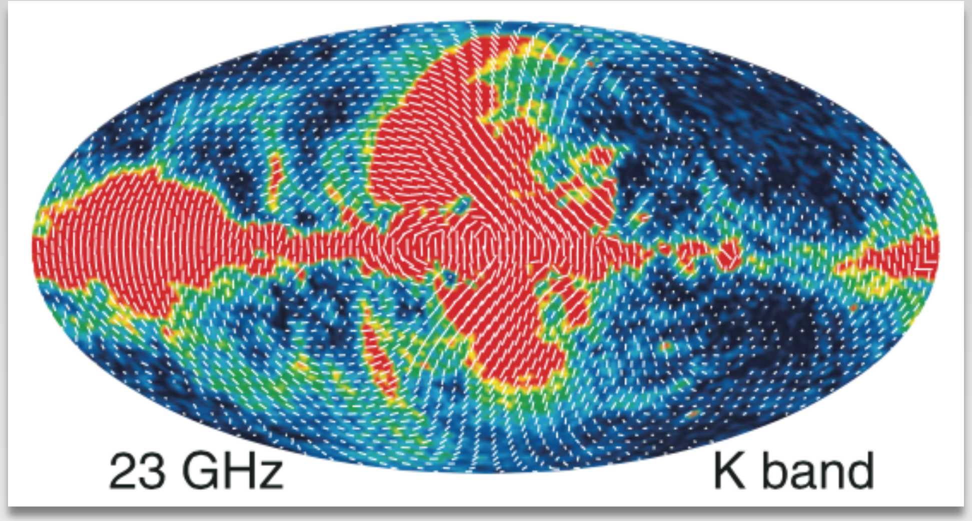




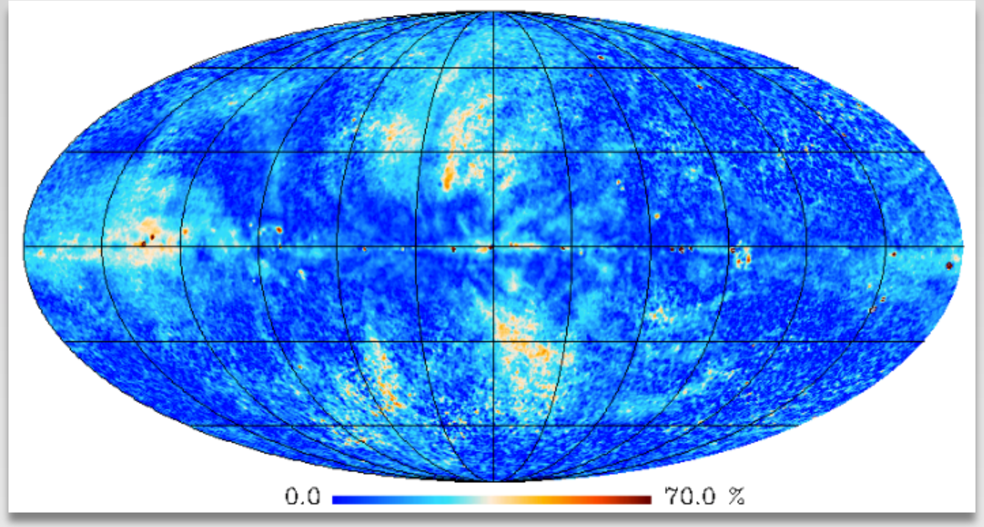


Synchrotron emission (IV)

P at 23 GHz, WMAP9



P/I at 23 GHz, from Commander/Planck



Bennet et al. (2013)

Planck 2015 results, XXV

- Maximum polarisation fractions of the order of 50%, on average **≈10-40%**
- Decrease at lower frequencies (≲ 5 GHz) due to Faraday depolarisation
- Difficult to measure at higher frequencies due to the presence of free-free and AME
- Higher polarisation fractions in the high-b filaments
- Masking the Galactic plane should not be enough for B-modes! Need also to mask the filamentes, or to correct the synchrotron (Vidal et al. 2015)

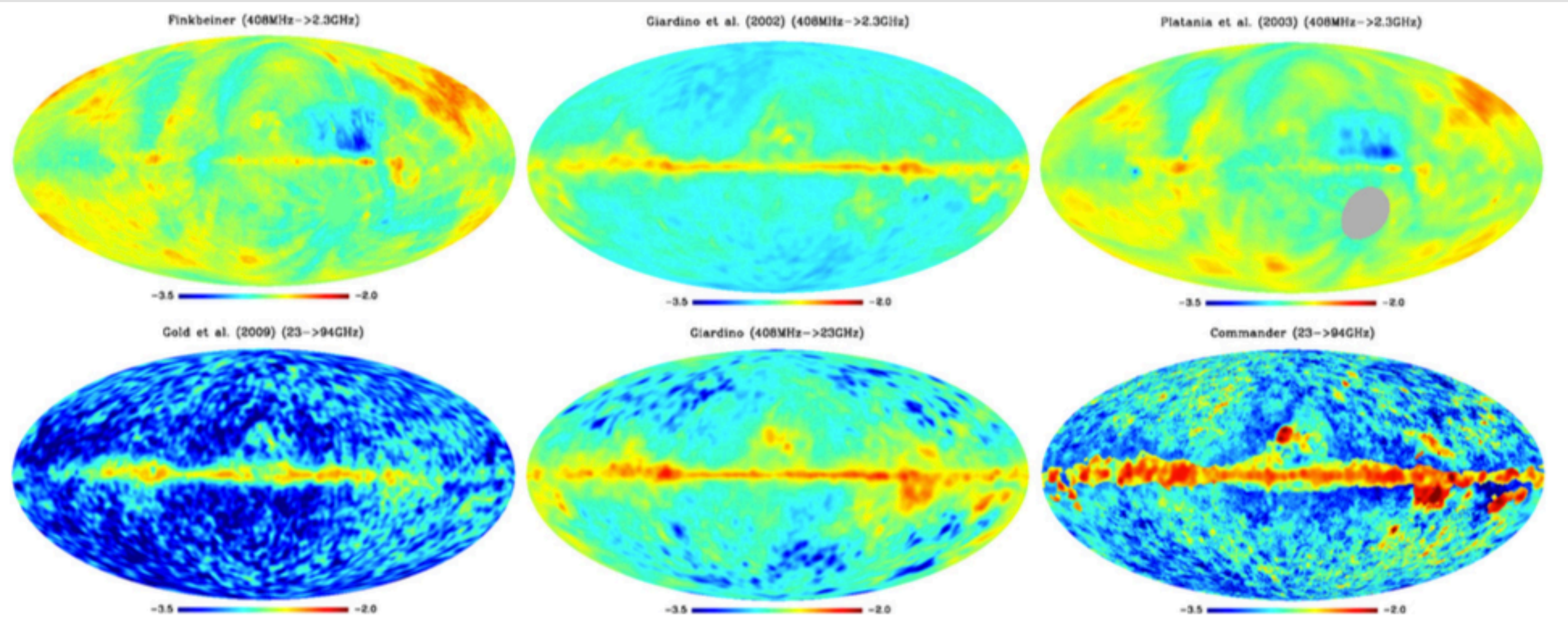
Modelling the synchrotron emission

★ Normally modelled with two parameters (A, β)

★ Typical spectral indices $\beta \sim -3.2$ to -2.5 (important at low frequencies, $\lesssim 10$ GHz)

★ However, there are big uncertainties in the determination of the spectral index

- Low frequency data: low quality (systematics)
- High frequencies: component separation



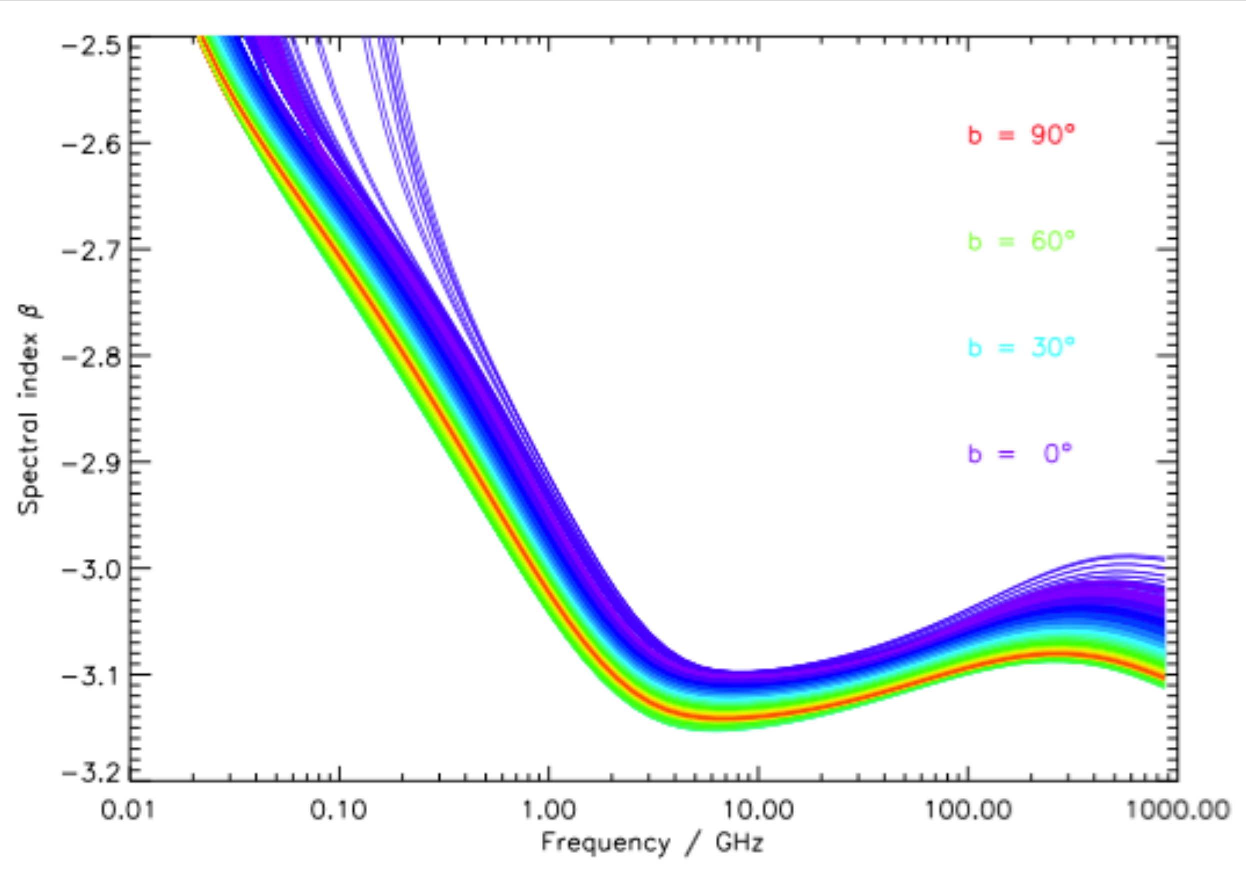
(Dickinson et al. 2009)

Modelling the synchrotron emission

★ Curvature (steepening) of the synchrotron spectrum

★ Energy loses from cosmic-ray propagation steepens the cosmic-ray spectrum

★ Predicted to change from β ~ -2.8 at 1 GHz to β ~ -3.1 at 100 GHz (Strong et al. 2007)



(Planck 2015 results XXV)

★ Fitting a single power law will not be enough

★ Need to fit for the curvature, or at least two power laws

Free-free emission (I)

★ Thermal bremsstrahlung ("braking radiation") arising from the interaction (withoug capture) between free electrons and ions (proton or alpha particle)

★ Inevitably produced in warm (~10^4 K) ionised gas (HII regions, molecular clouds)

★ Can be mostly explained by classical electromagnetistm, with small quantum mechanical corrections at high frequencies (Gaunt factor) - see Oster 1960

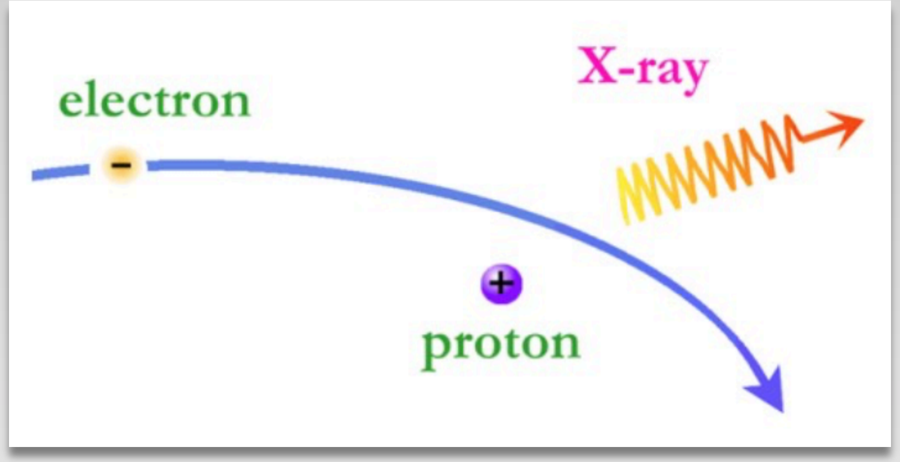
Volume emission coefficient

$$j_\nu = 5.444 \times 10^{-41}\; n_e n_i Z_i^2 T_4^{1/2} g_{\mathrm{ff,i}}\; e^{-\frac{h\nu}{kT}}$$

Gaunt coefficient

$$g_{\mathrm{ff}} = \ln\left(\exp\left[5.960 - \frac{\sqrt{3}}{\pi}\ln\left(Z_i \nu_9 T_4^{-3/2}\right)\right] + e\right)$$

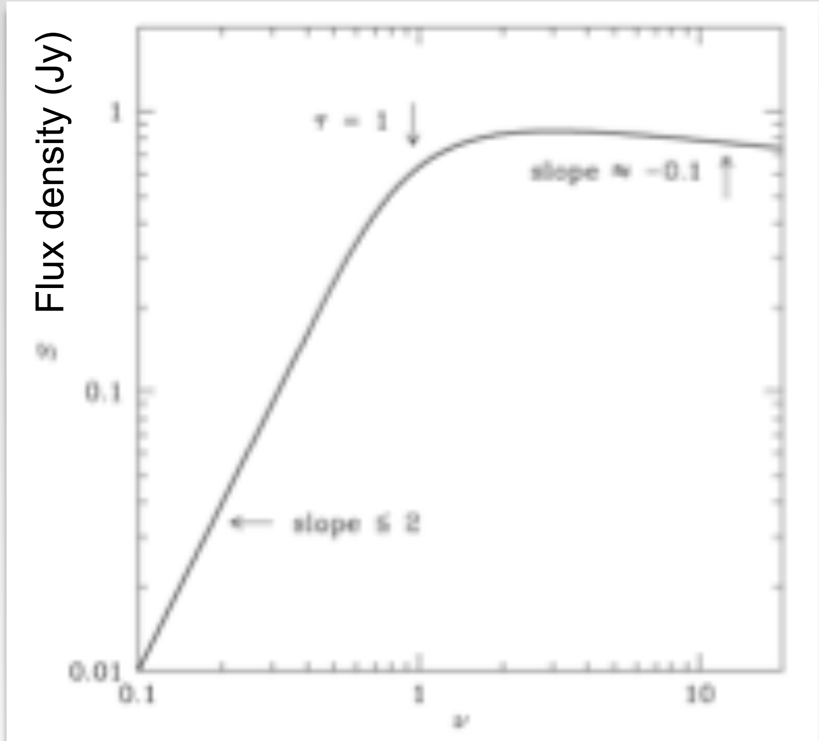
(Draine 2011)

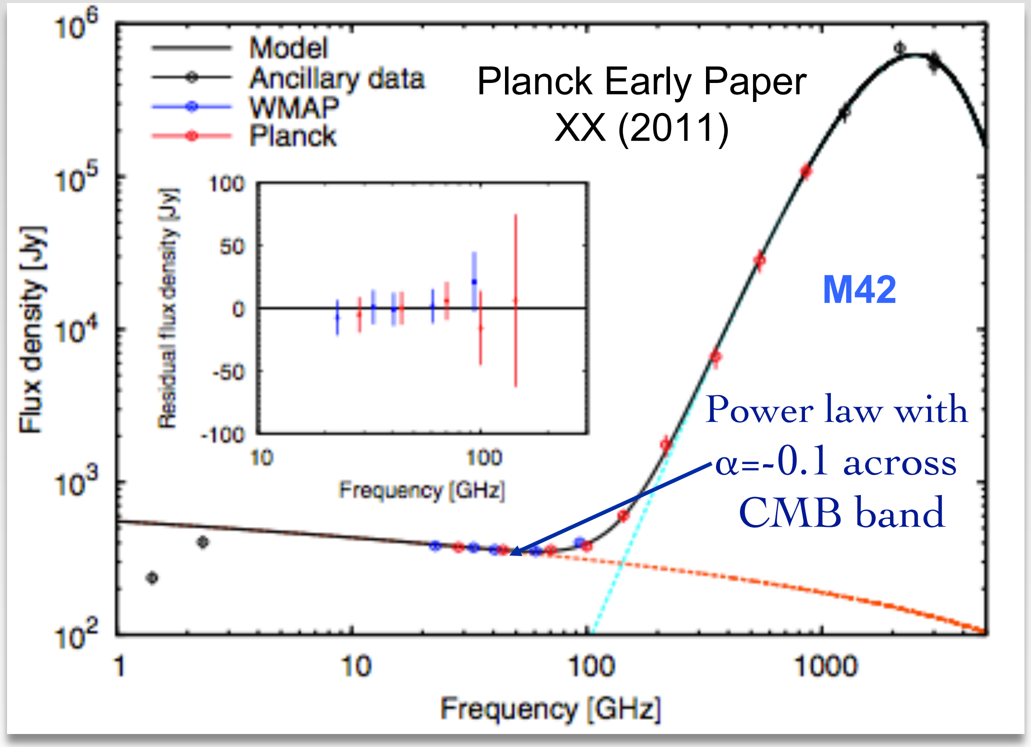


Free-free emission (II)

★ Spectrum:

- Low frequencies, $\tau>1$, to give RJ spectrum, $\propto \nu^2$, fixed by the plasma temperature (T_e).
- At high microwave frequencies, $\tau<<1$, spectrum close to β=-2.10 (α=-0.10), steppening to β=-2.15 at 100 GHz.
- Over the relevant range for CMB studies, is a power law
- Need to fit only one parameter (EM)



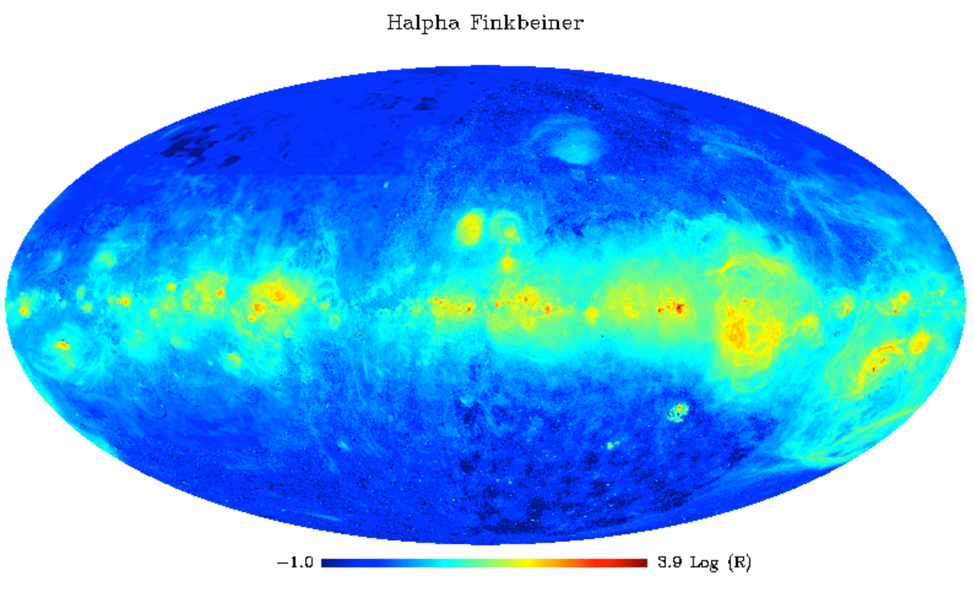


- Important at low frequencies, typically dominant at 10-100 GHz. Could be the dominant foreground at ≈70 GHz.

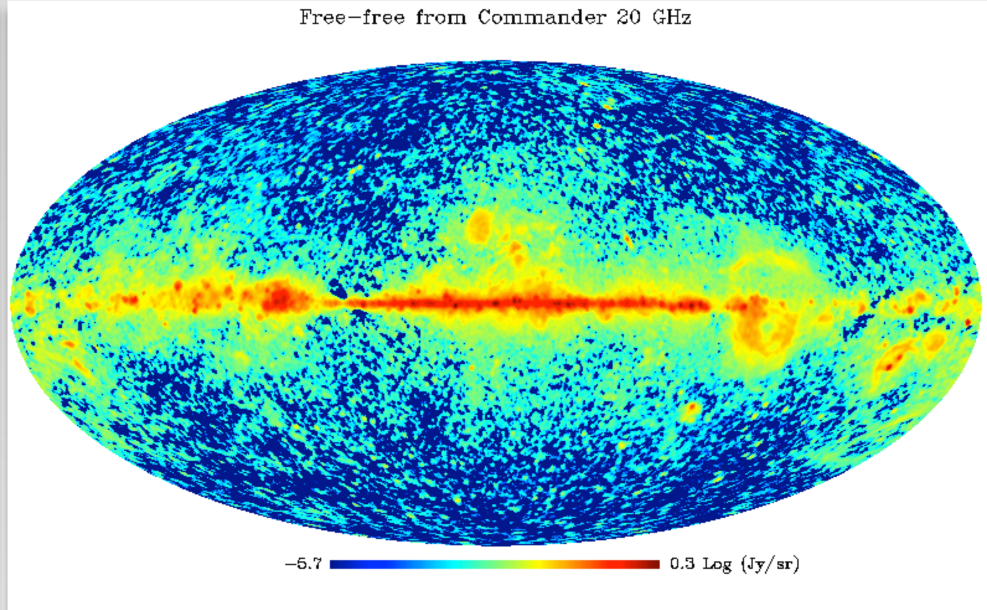
Free-free emission (III)

- Mostly concentrated in the Galactic plane
- Correlated with Hα emission (~EM) → used to predict free-free (Dickinson et al. 2003)

Hα emission (Finkbeiner 2003)



Free-free solution from Commander, at 20 GHz (Planck 2015 results)



- Free-free emission is practically unpolarised, as in a Maxwellian distribution of electrons the scattering directions are random
- Residual polarisation (up to ~10%) at the borders of HII regions due to Thomson scattering could occur
- However, HII regions are soft, and beam effects make them softer, so in practice we expect P/I<1%

Anomalous Microwave Emission (AME)

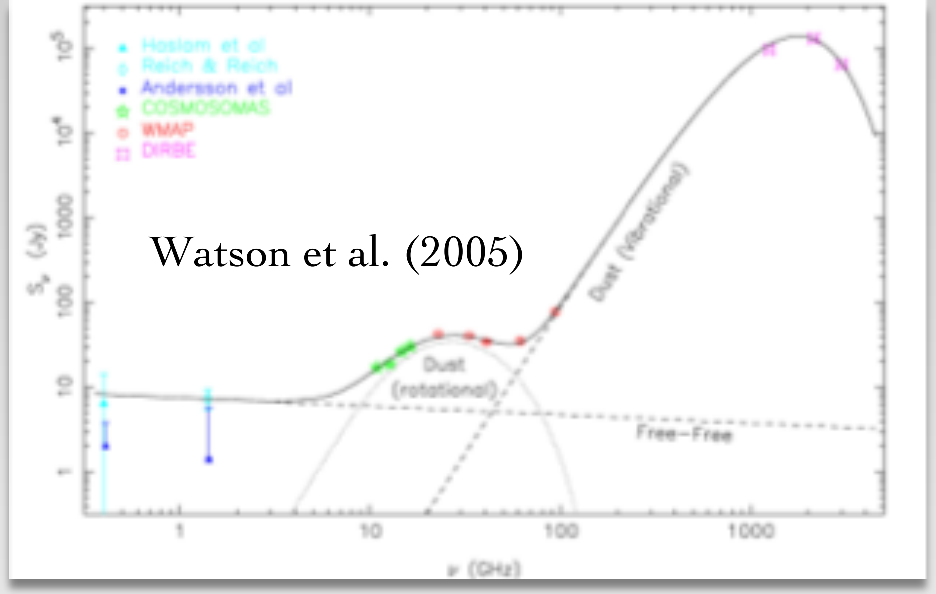
★ Dust correlated emission, first detected in COBE data at 30-90 GHz (Kogut et al. 1996)

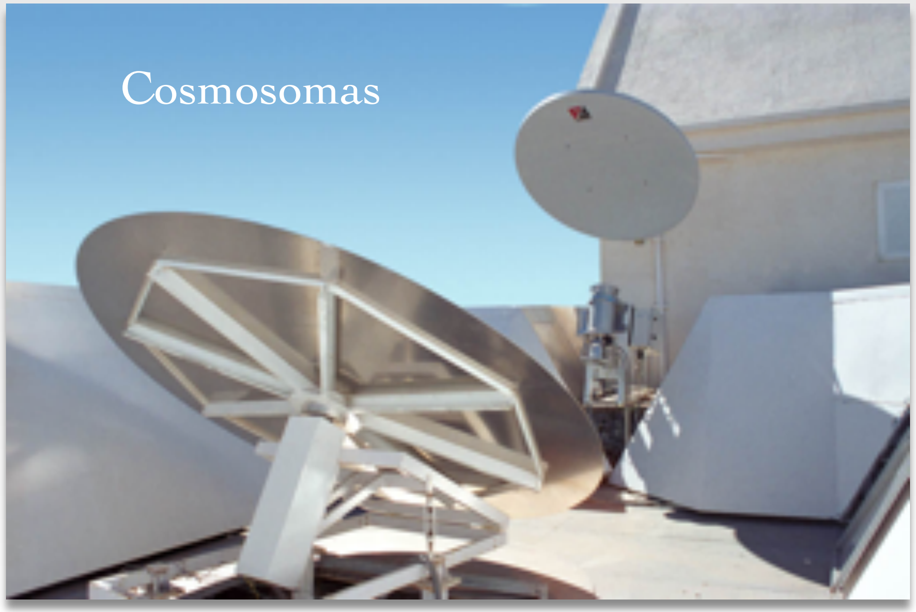
★ Right aftewards by other experiments: OVRO at 14.5 and 32 GHz (Leitch et al. 1997), Saskatoon at 30 GHz (de Oliveira-Costa et al. 1997), 19 GHz experiment (de Oliveira-Costa et al. 1998), Tenerife at 10 and 15 GHz (de Oliveira-Costa et al. 1999, 2002, 2004)

★ Later, characterisation of the I-spectrum:

- LDN1622 (Finkbeiner et al. 2002) with GBT
- Perseus molecular complex (Watson et al. 2005), with Cosmosomas.
- LDN1622 (Casassus et al. 2006) and ρ-Ophiuchus (Casassus et al. 2008) with CBI
- LDN1111 with AMI (Scaife et al. 2009)
- Pleiades RN with WMAP (Génova-Santos et al. 2011)

SED Perseus molecular complex



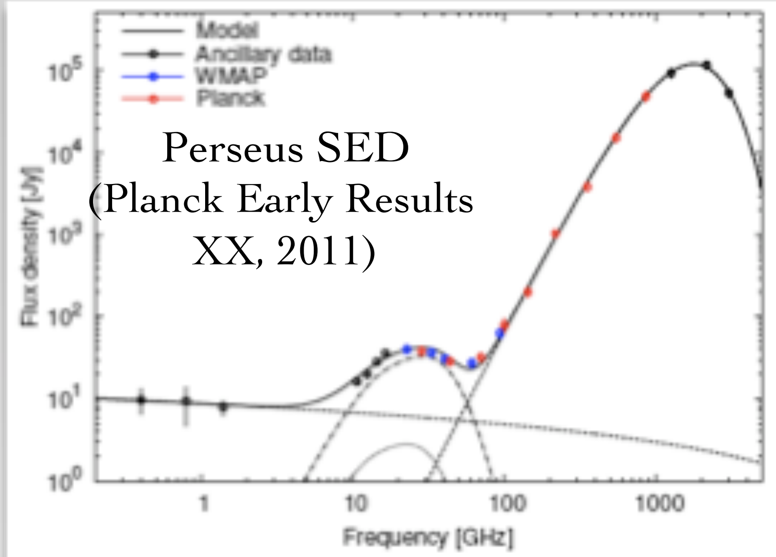


AME – Planck results

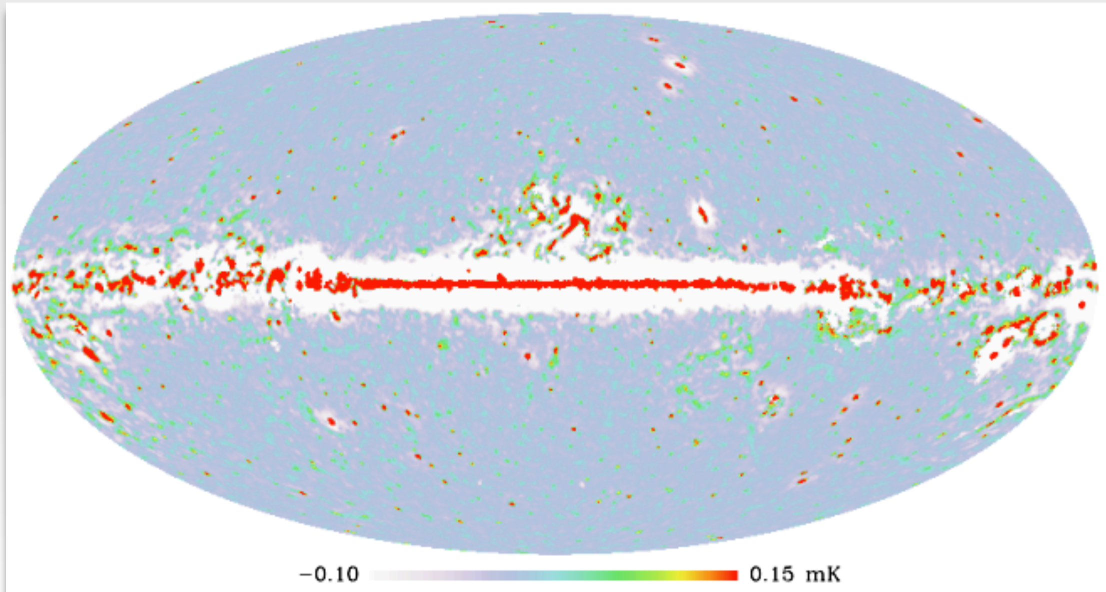
★ First systematic search of AME in the full sky.

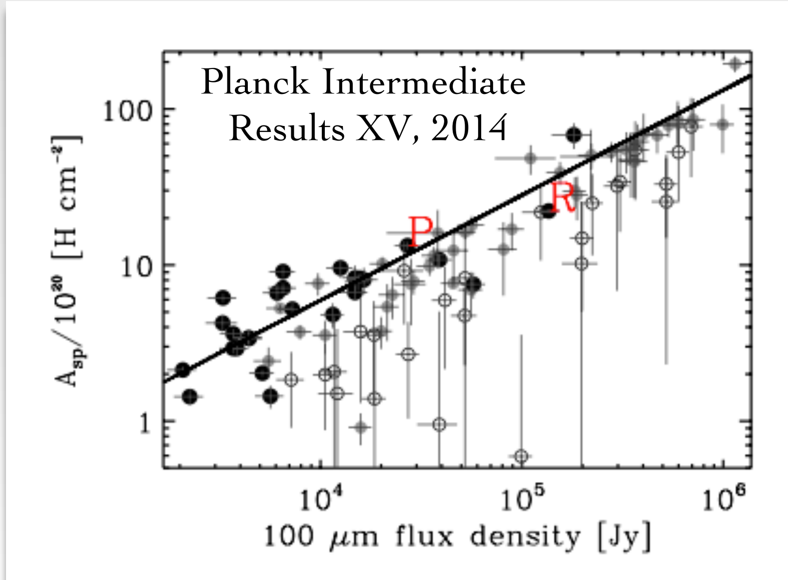
★ Confirmed early detections in Perseus and ρ-Ophiuchus, and identified ≈50 new candidates (Planck Early Results XX, 2011).

★ Presented a study of AME in 98 regions, and studied physical properties of these regions in an statistical way (Planck Int. Results XV, 2014).



Full sky AME map (Planck Intermediate Results XV, 2014)





AME - models

★ Initial proposals (hard synchrotron, free-free) not able to explain the observed spectrum and turn-over at low frequencies

★ **Electric dipole emission** (spinning dust). Most likely explanation.

- Originated in ultra-small dust gains with high rotation speeds (due to interactions with the ISM), containing a residual electric dipole moment

- First suggested by Erickson (1957), later revisited by Draine & Lazarian (1998). Power radiated by a spinning ED moment:

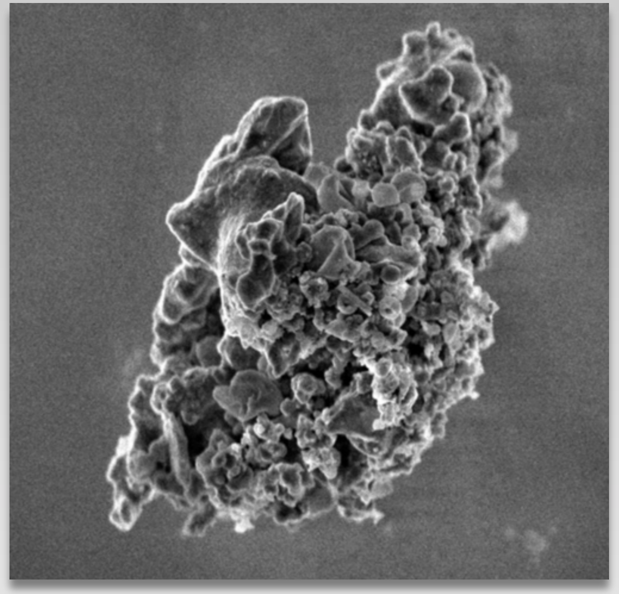
$$P = \frac{2}{3}\frac{\omega^4 \mu^2 \sin^2\theta}{c^3}$$

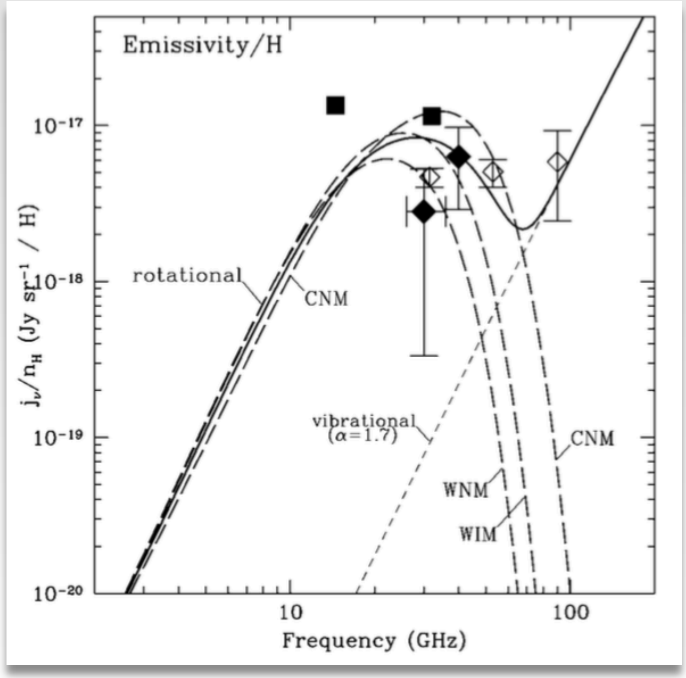
$$\frac{j_\nu}{n_\mathrm{H}} = \frac{1}{4\pi}\int_{a_\mathrm{min}}^{a_\mathrm{max}} \mathrm{d}a \frac{1}{n_\mathrm{H}}\frac{\mathrm{d}n_\mathrm{gr}}{\mathrm{d}a} 4\pi\omega^2 f_a(\omega) 2\pi \frac{2}{3}\frac{\mu_{a\perp}^2 \omega^4}{c^3}$$

- Very complicated physics! Many free parameters (grain size distribution, electric dipole moments, angular velocity distribution function, total hydrogen number density, gas temperature, intensity of the radiation field...)

- Usually fix the model spectrum and fit only one parameter (N_H)

Typical interstellar dust grain

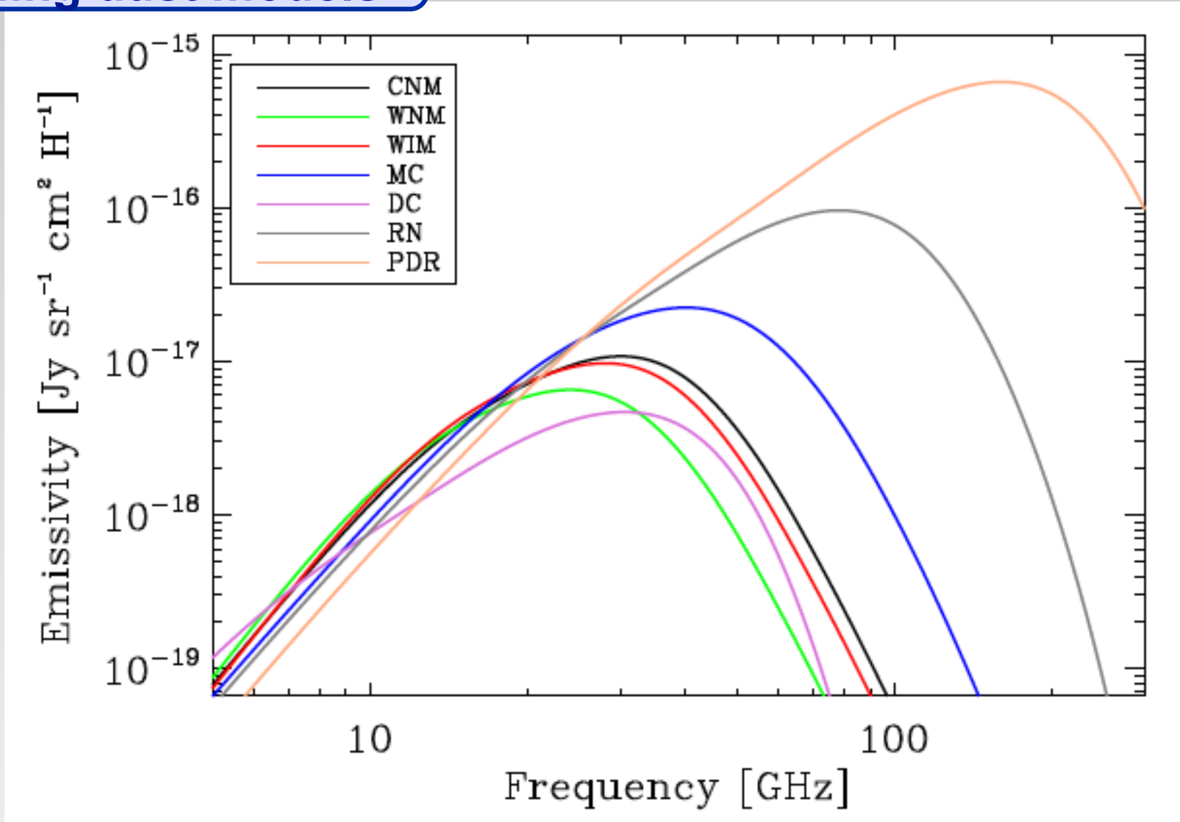




Spinning dust models (Draine & Lazarian 1998)

AME – spinning dust models

(Dickinson et al. 2018; New Astr. Reviews)



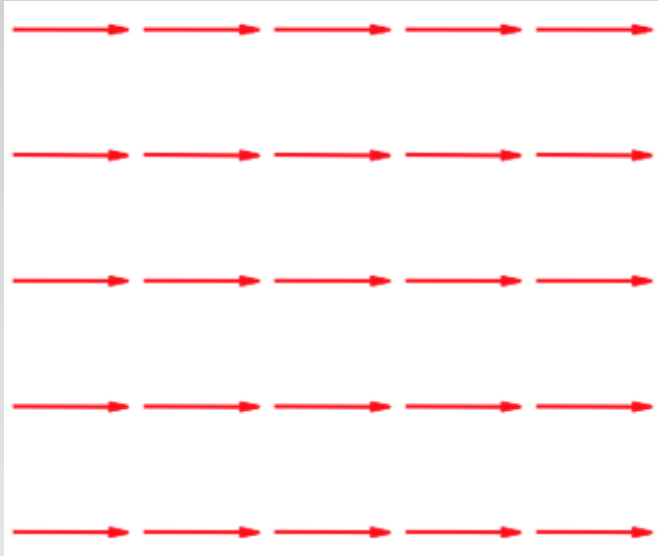
Parameter	Phase						
	DC	MC	CNM	WNM	WIM	RN	PDR
n_H (cm^{-3})	10^4	300	30	0.4	0.1	10^3	10^5
T (K)	10	20	100	6000	8000	100	300
T_d (K)	10	20	20	20	20	40	50
χ	0.0001	0.01	1	1	1	1000	3000
$y \equiv 2n(H_2)/n_H$	0.999	0.99	0	0	0	0.5	0.5
$x_H \equiv n(H^+)/n_H$	0	0	0.0012	0.1	0.99	0.001	0.0001
$x_M \equiv n(M^+)/n_H$	10^{-6}	0.0001	0.0003	0.0003	0.001	0.0002	0.0002

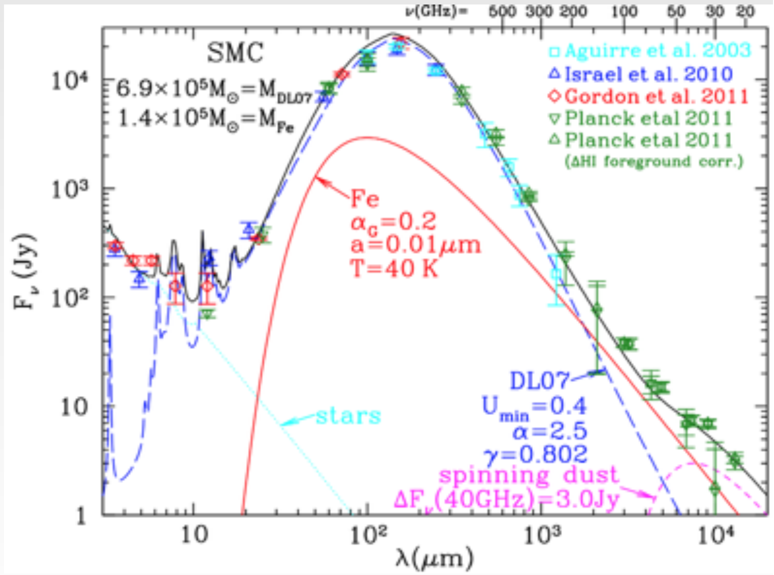
AME – models (II)

★ **Magnetic dipole emission**

- Thermal fluctuations in the magnetization of the grains (Draine & Lazarian 1999; Draine & Hensley 2013). Much of Fe could be in magnetic material (metallic Fe, magnetite, maghemite etc.)
- Lowest energy state of metallic Fe: Spins are parallel (magnetized). Magnetization M is aligned with one of the crystal axes.
- Excited state: spins parallel, but oriented away from crystal axis. Oscillations in magnetization -> magnetic dipole radiation
- No strong evidence, but there are hints (Draine & Hensley 2013): excess emission at 30-300GHz in SMC.
- Black-body like spectrum at 70-100 GHz ⇒ potentially a killer for CMB component separation.

Ferromagnetic lattice with spins aligned
Thermal fluctuations will move them away producing dipole radiation





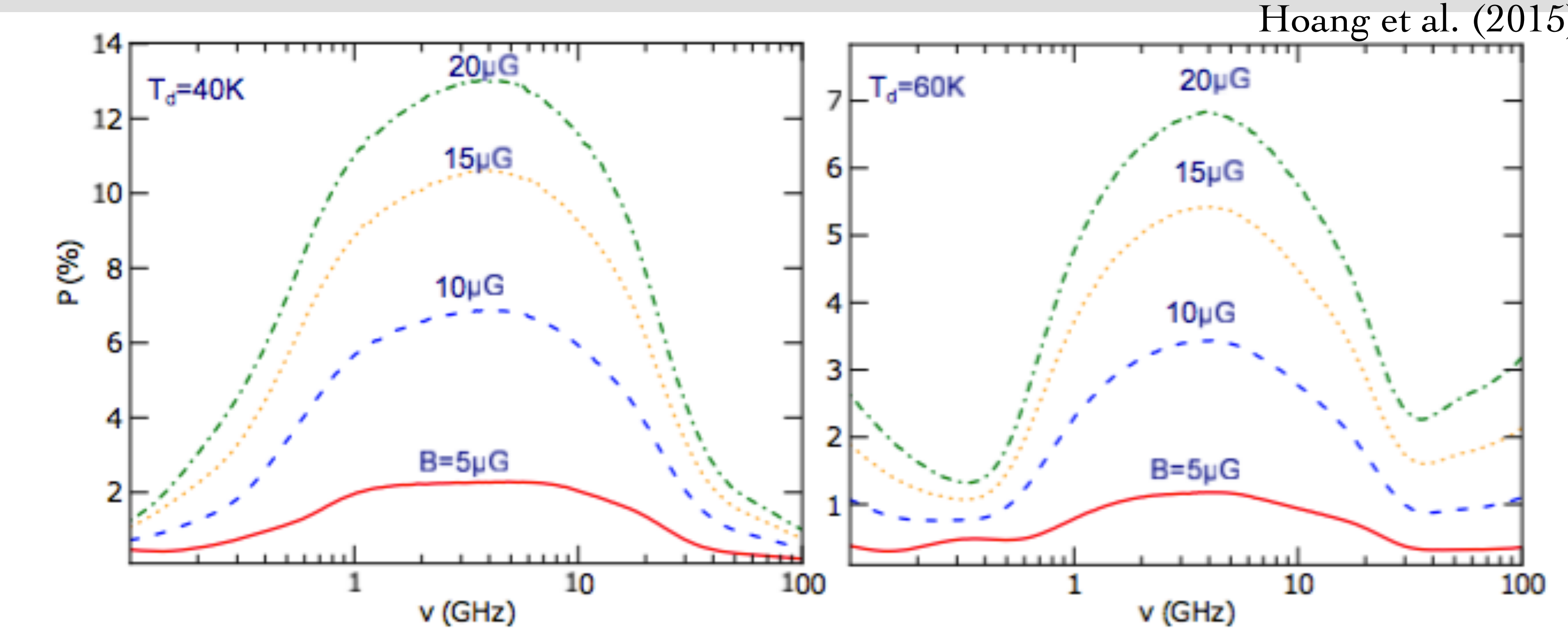
(Draine & Hensley 2013)

AME in polarization – models

★ Models of AME in polarisation:

- Spinning dust polarisation typically predicted to be very low
- Lazarian & Draine (2000): 6-7% at 2-3 GHz, 4-5% at 10 GHz
- Hoang et al. (2013): peak of **1.5% at 3 GHz**, dropping at higher frequencies. Slightly higher values for strong magnetic fields (Hoang et al. 2015)

Hoang et al. (2015)



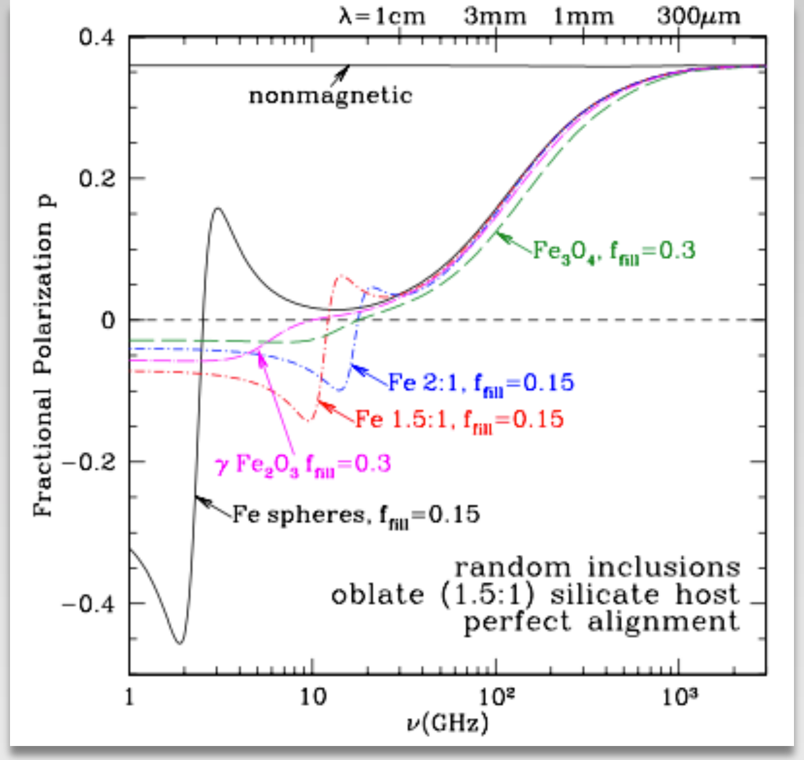
- Difficult to predict. Many free parameters!
- Also: Draine & Hensley (2016) have recently suggested that quantum dissipation of alignment will lead to practically zero polarisation

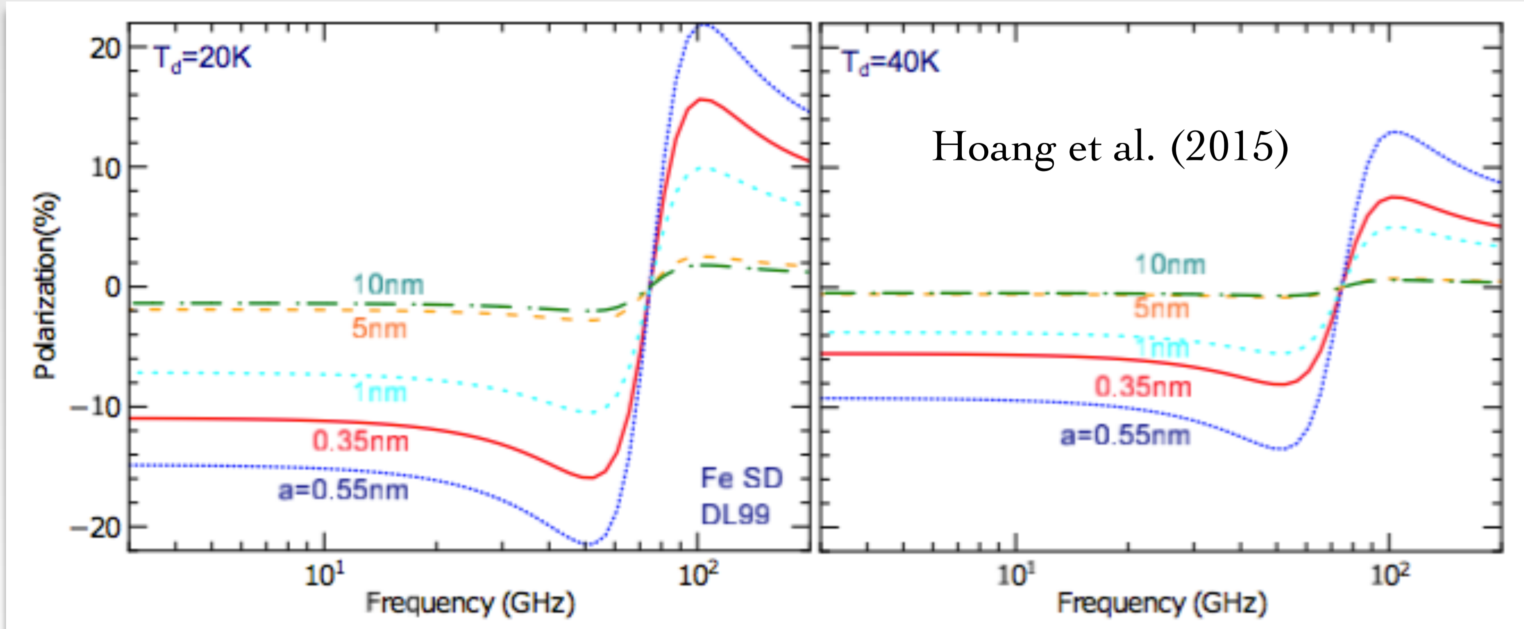
AME in polarization – models

★ Models of AME in polarisation:

- Magnetic dust polarisation expected to be higher
- Up to 40 % if grains are oriented in a single magnetic domain (Draine & Lazarian 1999)
- More realistic model with randomly oriented magnetic inclusions predict lower levels, **<5%** at 10-20 GHz (Draine & Hensley 2013)
- Also lower levels found by Hoang et al. (2015)

Draine & Hensley (2013)





- Again, difficult to predict! These models contain many underlying assumptions

AME - Polarisation constraints

★ Compact sources:

- Battistelli et al. (2006) found marginal polarisaiton with Π = 3.4±1.7 % at 11 GHz, using COSMOSOMAS
- Upper limits from, Π < 1% (95% CL) from WMAP 23 GHz (López-Caraballo et al. 2011, Dickinson et al. 2011)

★ Diffuse:

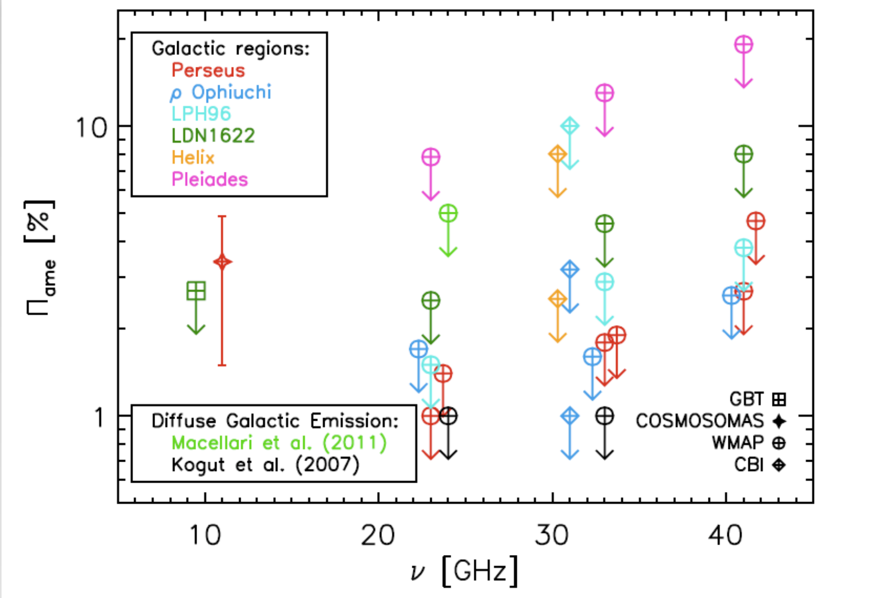
- Π < 5% (Macellari et al. 2011), at 22.8 GHz with WMAP
- Π = 0.6 ±0.5 % (Planck 2015 results, XXV)

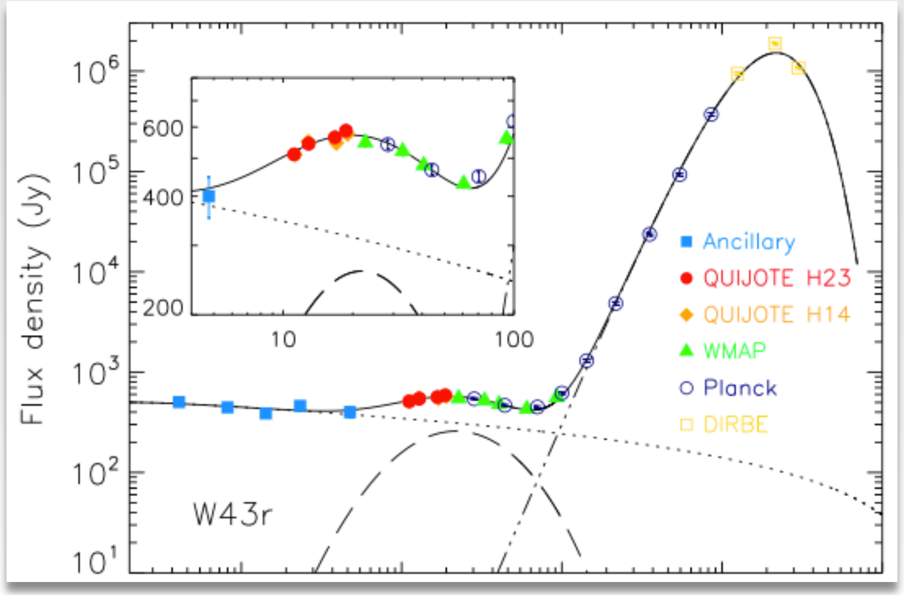
★ QUIJOTE:

- Perseus molecular complex: Π_{AME} < 6.3% at 12 GHz and Π_{AME} < 2.8% at 18 GHz (Génova-Santos et al. 2015)
- W43 molecular complex: **Π_{AME} < 0.39%** at 18.7 GHz and **<0.22%** at 40.6 GHz (Génova-Santos et al. 2017)

Best constraints to date! improving previous constraints by a factor 5

Rubiño-Martín et al. (2012)

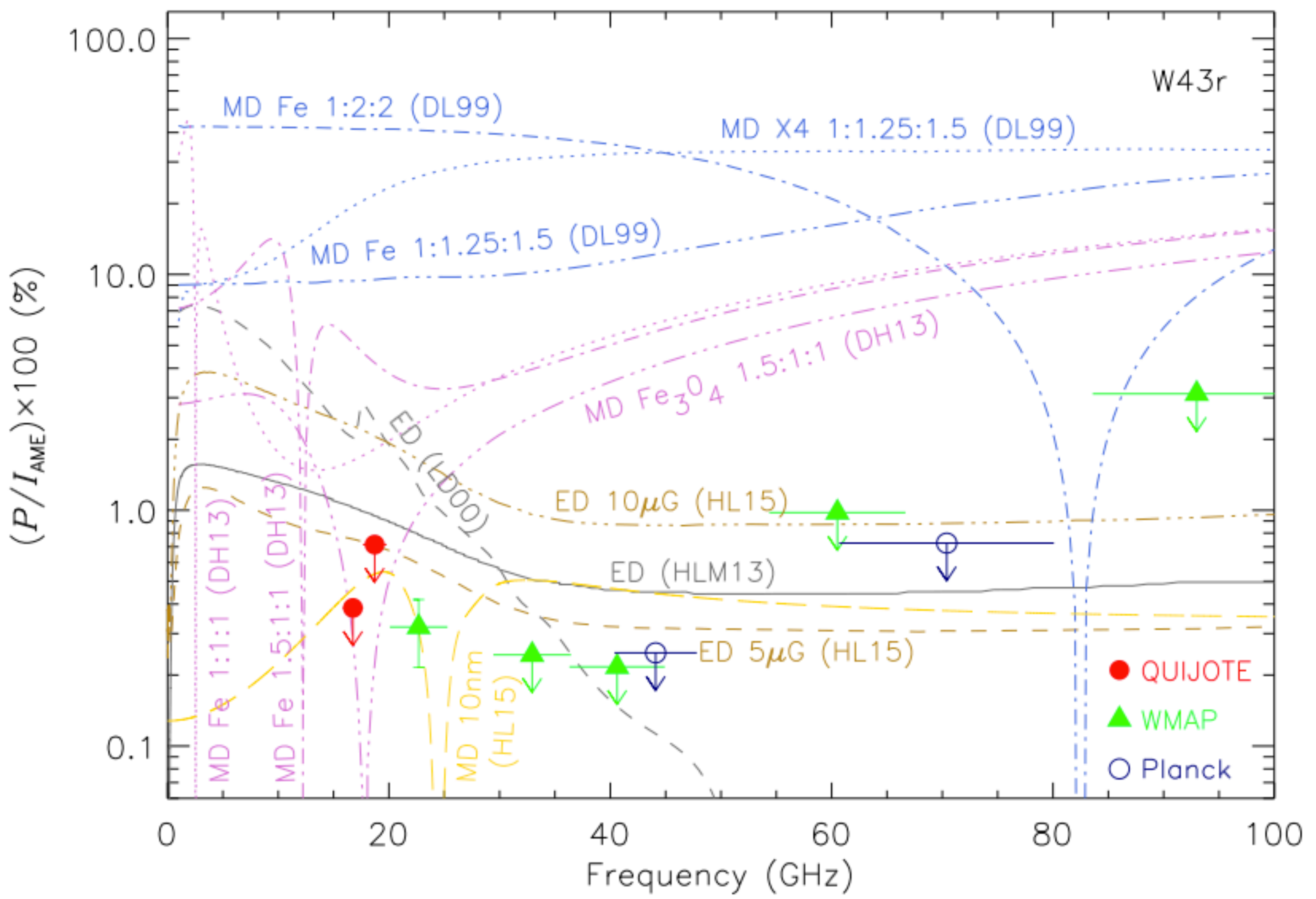




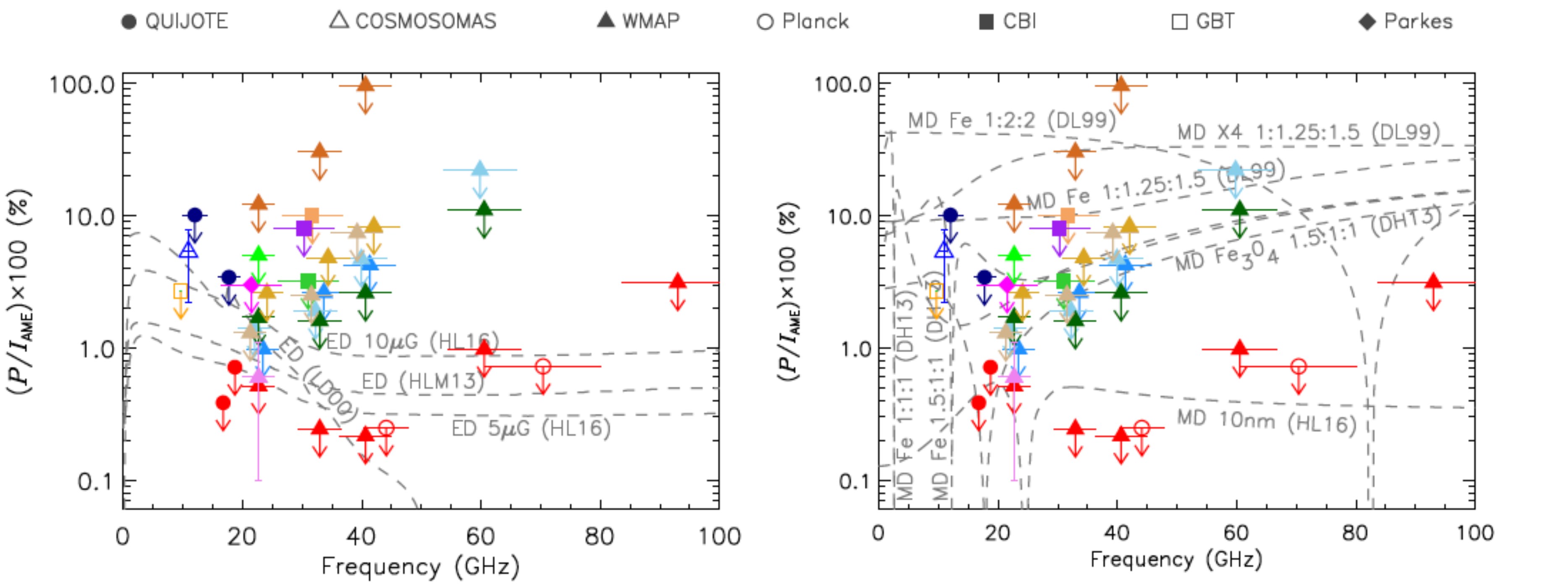
Génova-Santos et al. (2017)

AME - Polarisation constraints

Genova-Santos et al. (2017)



AME - Polarisation constraints



Dickinson et al. (2018)

Thermal dust emission

★ Thermal IR vibrational emission from different ISM dust grain populations, heated up (T_d~20 K) by UV radiation

★ Dominant foreground at >100 GHz

★ Black-body spectrum, but with opacity effects

➡ Modelled as a modified black-body (grey-body) spectrum at the relevant frequencies

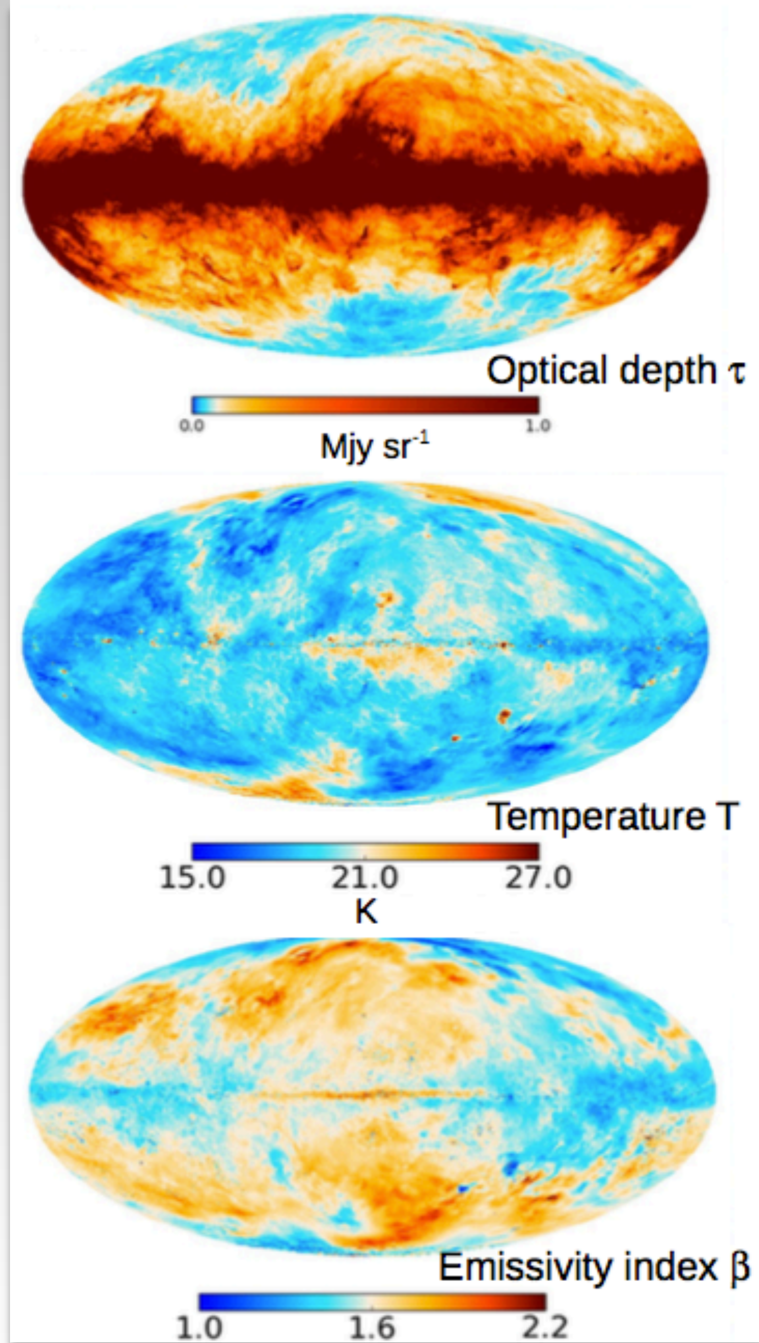
$$I_\nu = \tau_{\nu 0} \left(\frac{\nu}{\nu_0} \right)^{\beta_d} B_\nu(T_d)$$

➡ 3 free parameters

- Average values from Planck: $T_d \approx 19$ K, $\beta_d \approx 1.6$

★ Complications:

- How many dust components we need to fit?
- Significant variation of the emissivity index over the sky



Planck dust model (Planck intermediate results XLVIII, 2016)

Thermal dust emission - Polarisation

Planck results

★ Dust intensity map at 353 GHz, showing the magnetic field directions, derived from Planck component separation

★ Polarisation fraction **up to 20%** in some areas

★ **On average ≈10%** at high Galactic latitudes, inferred from Planck. Higher than previous measurements (Archeops)

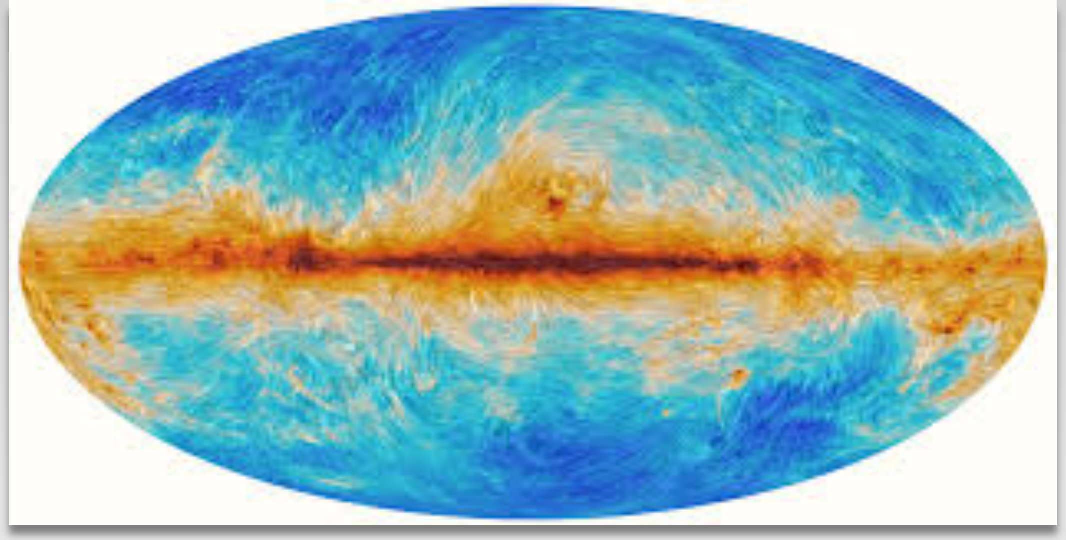
★ Lower column density lines of sight (high Galactic latitudes) have higher polarisation fractions!

- Bad for CMB studies!

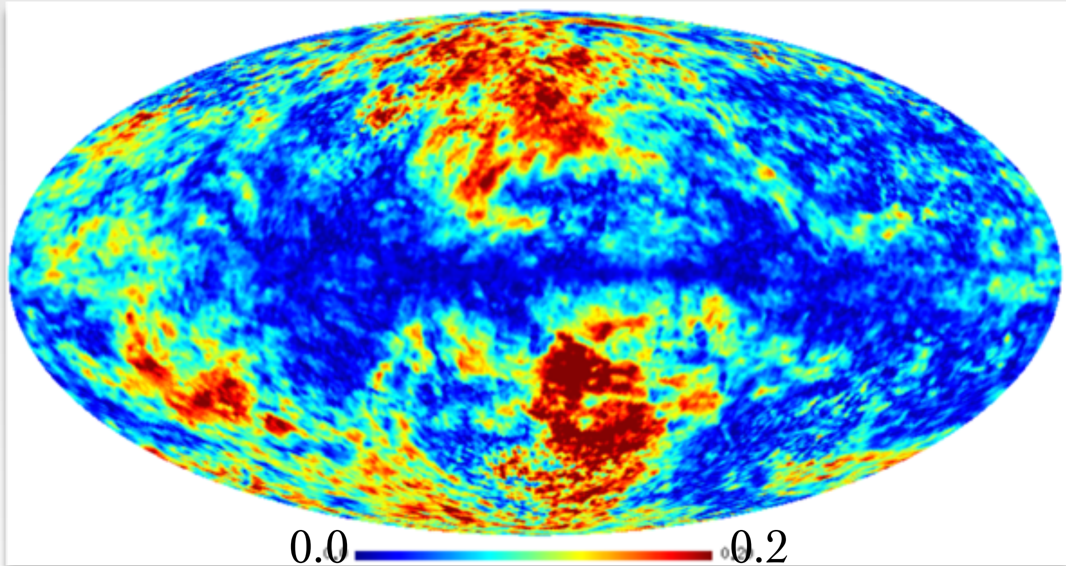
★ Very complicated modelling of the polarisation (magnetic field, turbulence,...)

★ Power spectrum $\propto l^{-2.42}$ (Planck Intermediate Results XXX, 2016)

Planck dust emission 353 GHz



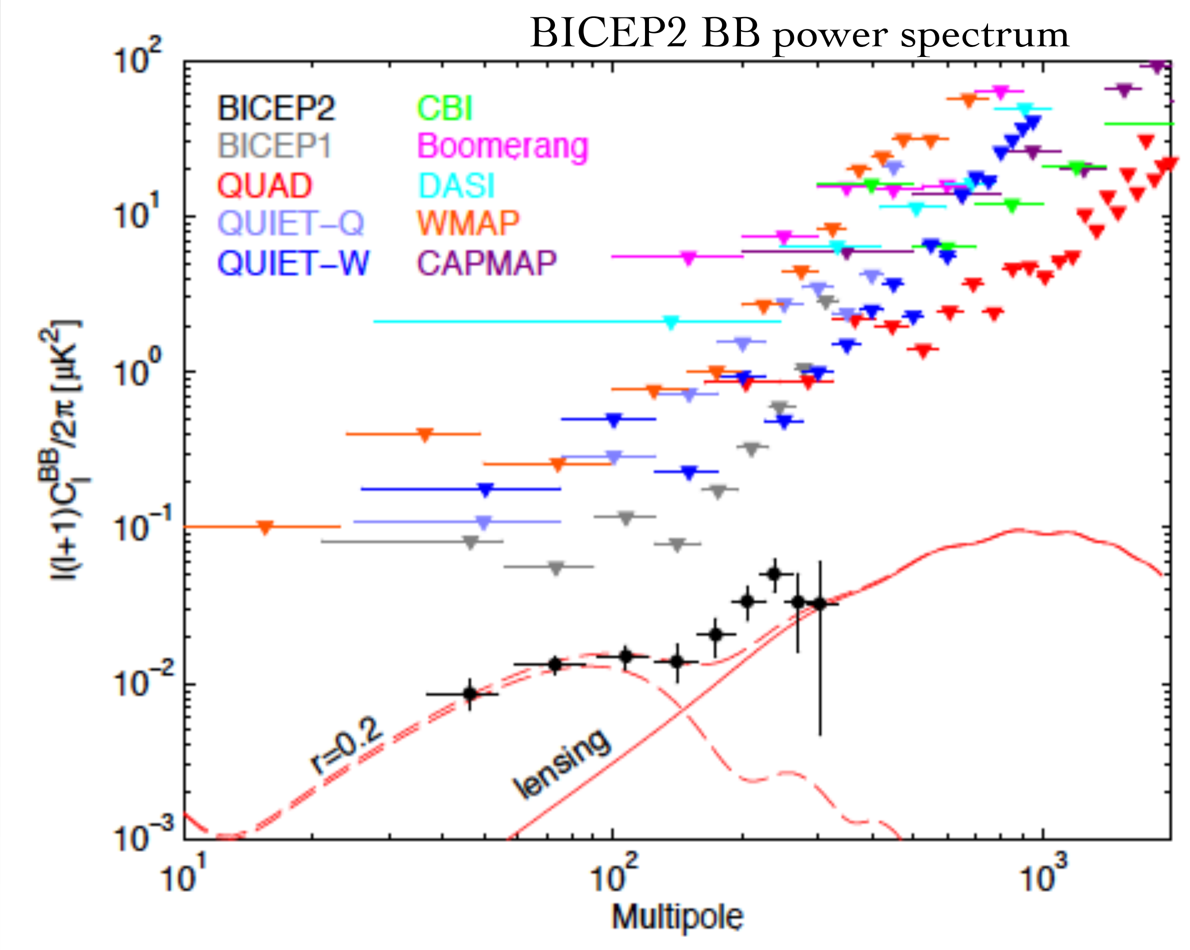
Planck polarisation fraction at 353 GHz



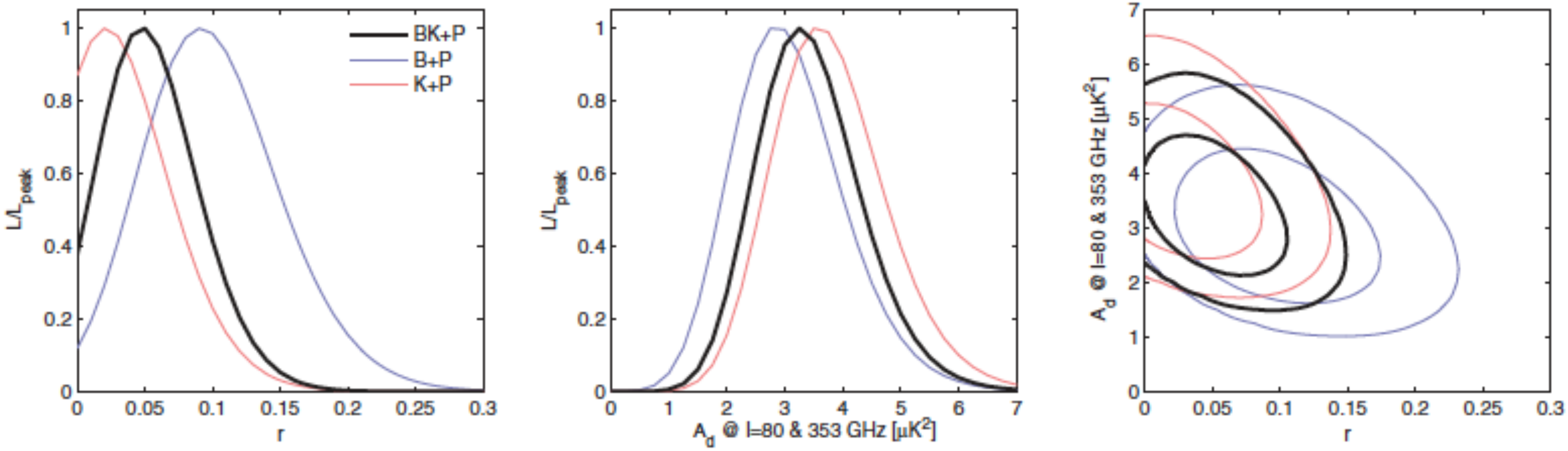
(Planck Intermediate Results IXX, 2015)

Thermal dust contamination in BICEP2

- Initially claimed a detection of primordial B-modes with **$r = 0.20^{+0.07}_{-0.05}$**
- Their estimate of the foreground contributions to their detection:
  - Dust: $r = 0.02$
  - Synchrotron: $r < 0.003$
  - Point sources: $r = 0.001$



Joint analysis of BICEP2/Keck and PLANCK

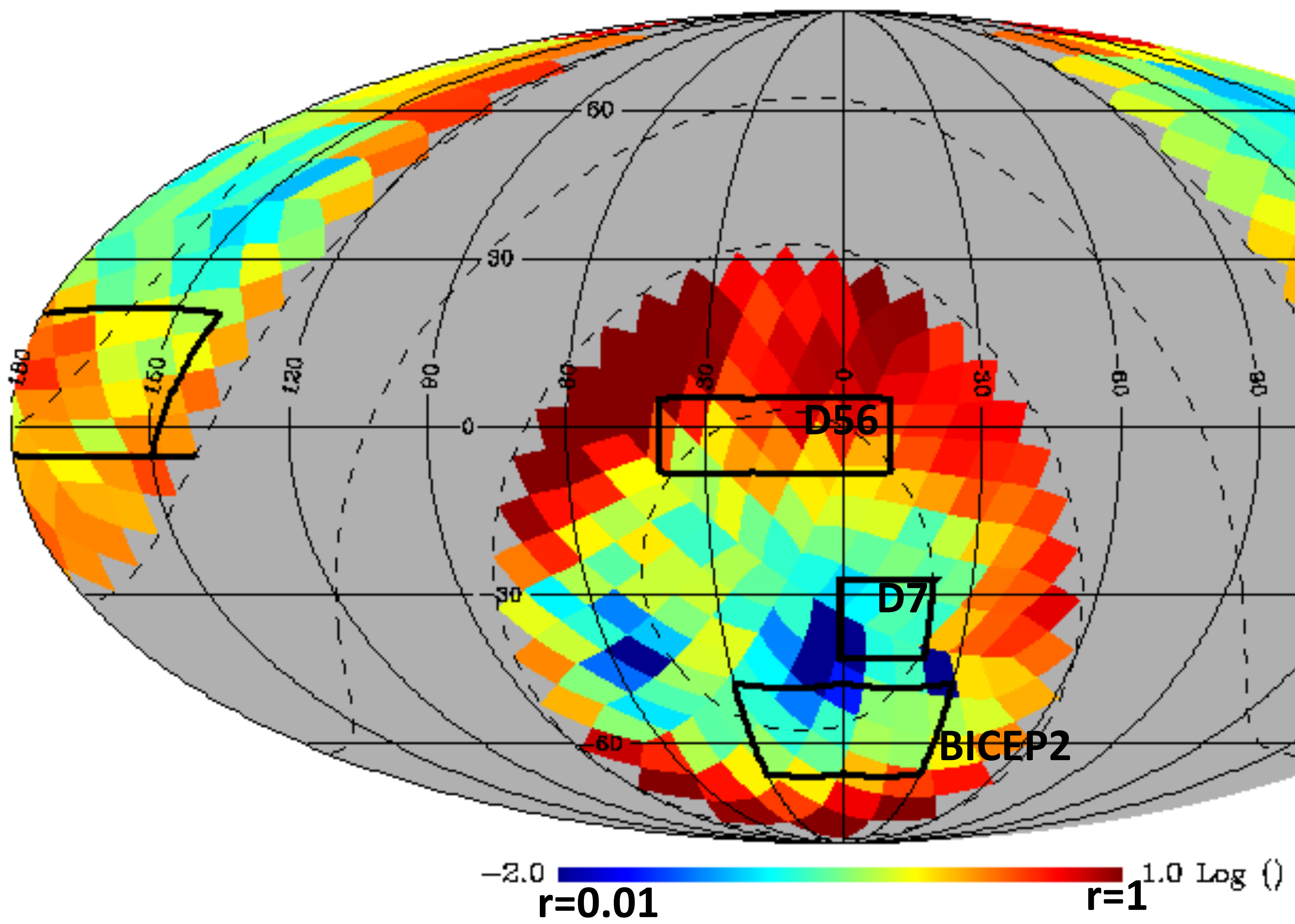


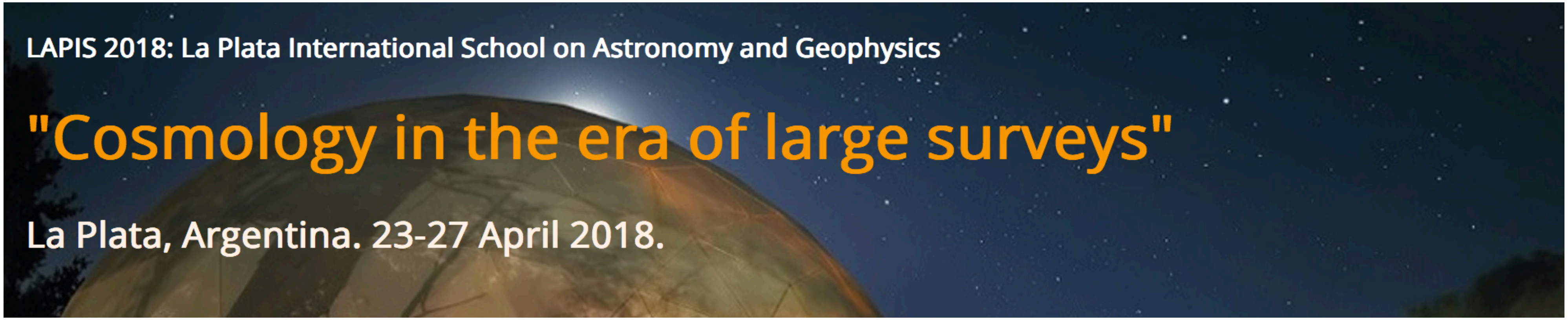
- r=0.048 +-0.035 → r<0.12 at 95% C.L.
- 5.1 sigma detection of dust power.
- Other lines: BICEP alone, Keck alone.

- Other results: 7 sigma detection of lensing B modes.

BICEP2 Keck and Planck Collaborations (2015), PRL 114, 101301.

Planck guide to low dust polarization level in effective r





CMB foregrounds for B-mode studies

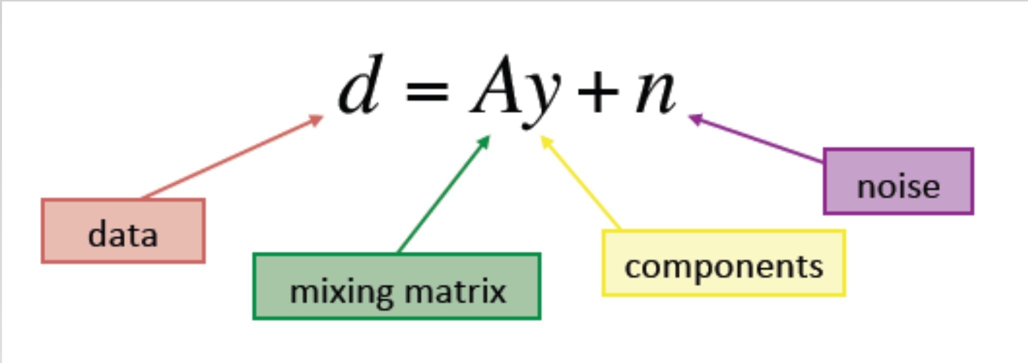
I. Introduction

II. Physical mechanisms producing polarised emission at large scales.

III. Component separation and impact on B-mode science

RADIO FOREGROUNDS

Component separation methods



- The mixing matrix encodes frequency dependence of the components. Generally unknown(at least partially).

- Different approaches:
  - To recover all components at the same time → **foreground modelling.**
  - Focus on extracting one component (e.g. CMB, point sources).
  - Blind methods (make minimal assumptions about the components). E.g. ILC.
  - Non-blind methods (require a parametric model of the components).
  - Make work in real, harmonic or wavelet space
  - …

Foreground separation

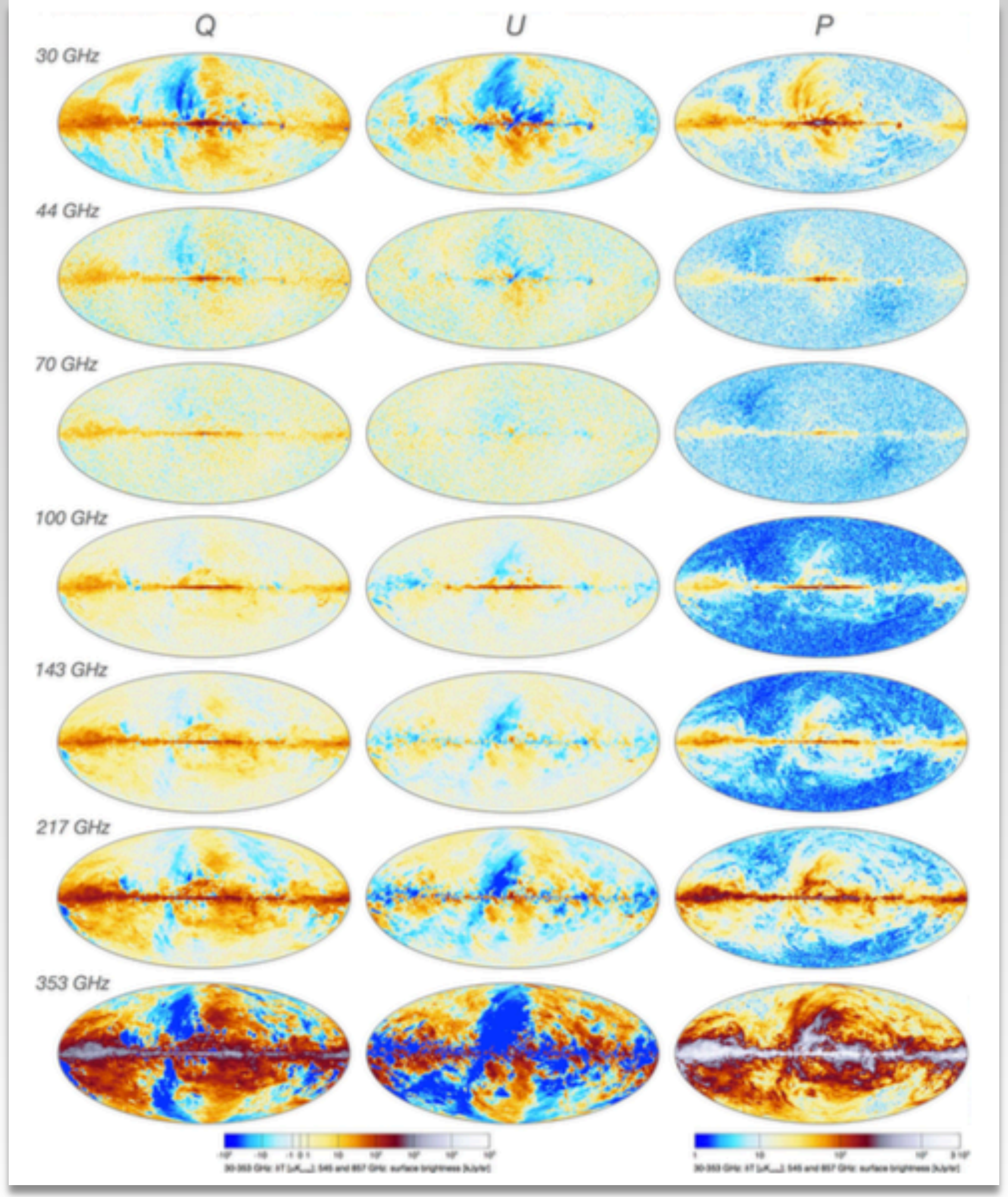
★ **Parametric methods**. Need different frequencies, and knowledge of the foregrounds physics in order to set some priors to the fitted parameters

★ Total number of parameters to be fitted in each pixel of the sky:

- Synchrotron: 2 parameters (A, β)
- Free-free: 1 parameter (EM)
- AME: at least 3 parameters (N_H, ν_{peak}, width)
- Thermal dust: 3 parameters (τ, β_d, T_d)

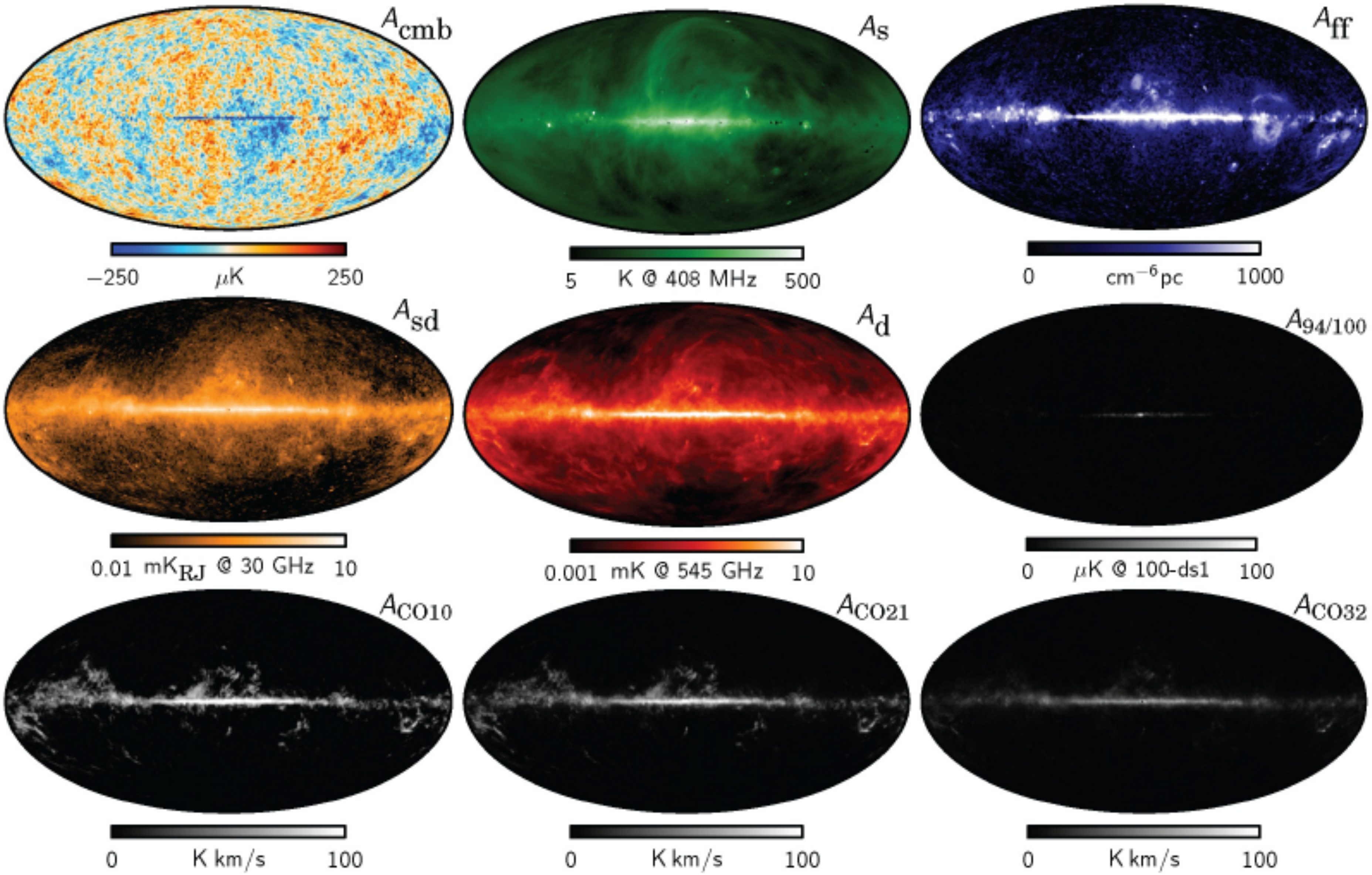
9 parameters in total for I
Maybe 5 could be sufficient in P, but need to get Q,U separately

Planck 2015 polarisation maps



Planck 2015 results I, 2016

Foreground separation

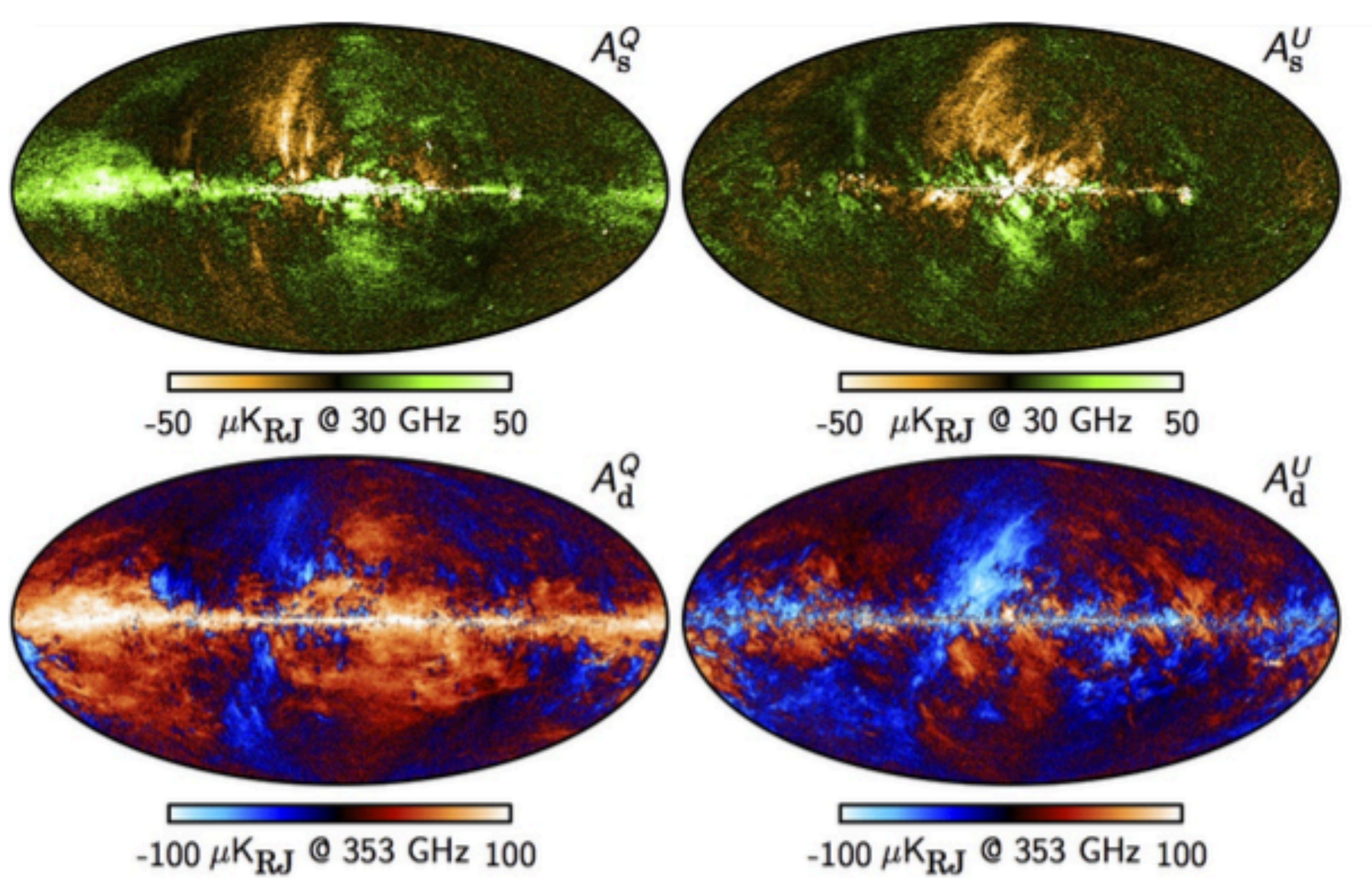


PLANCK 2015

Components in the microwave sky in intensity

Foreground separation

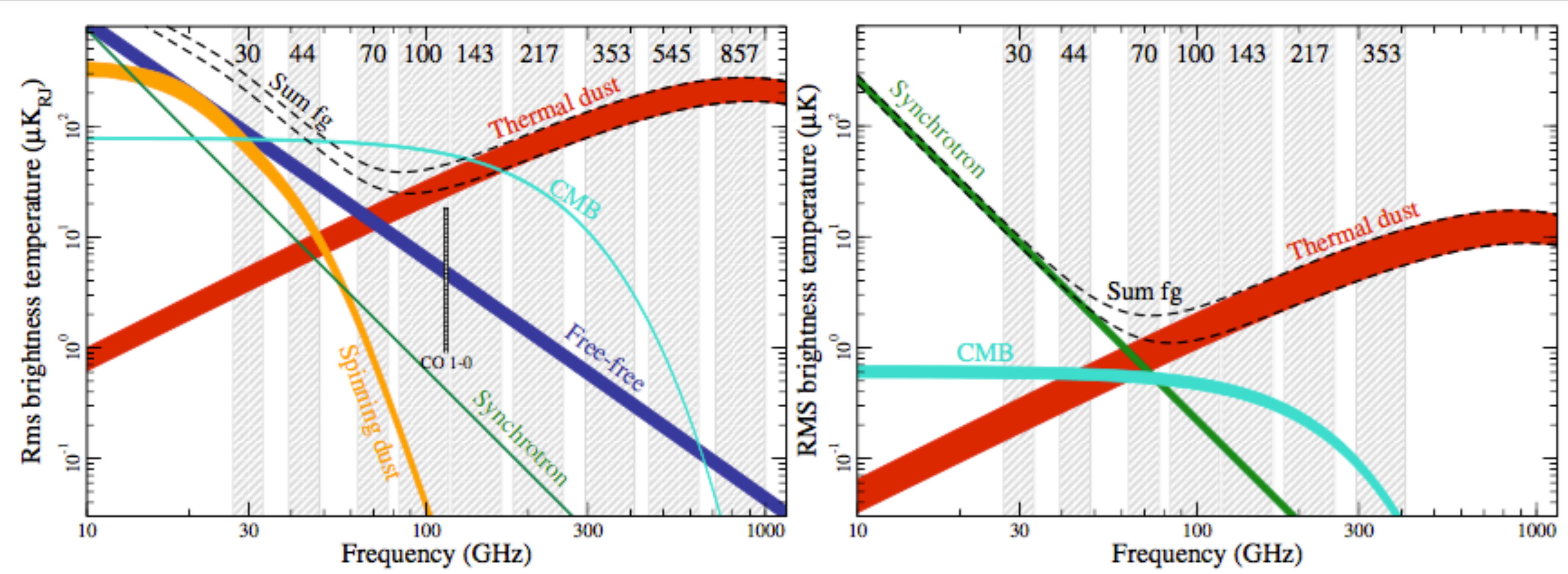
★ Planck wide frequency coverage made this possibe, and allowed to separate the synchrotron and thermal dust polarisations:



Planck 2015 results X, 2016

Foreground separation

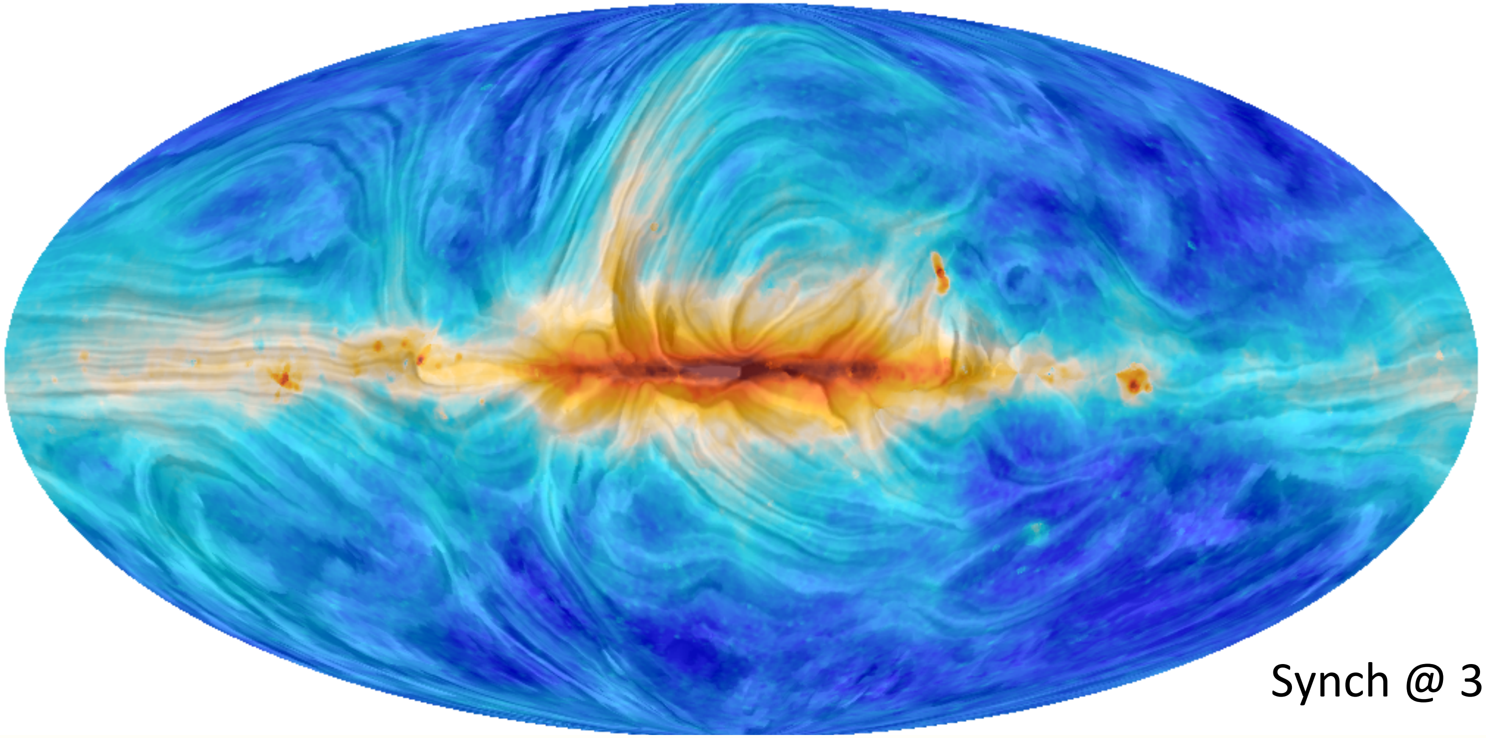
★ Average foreground contributions in the full sky, extracted from Planck data:



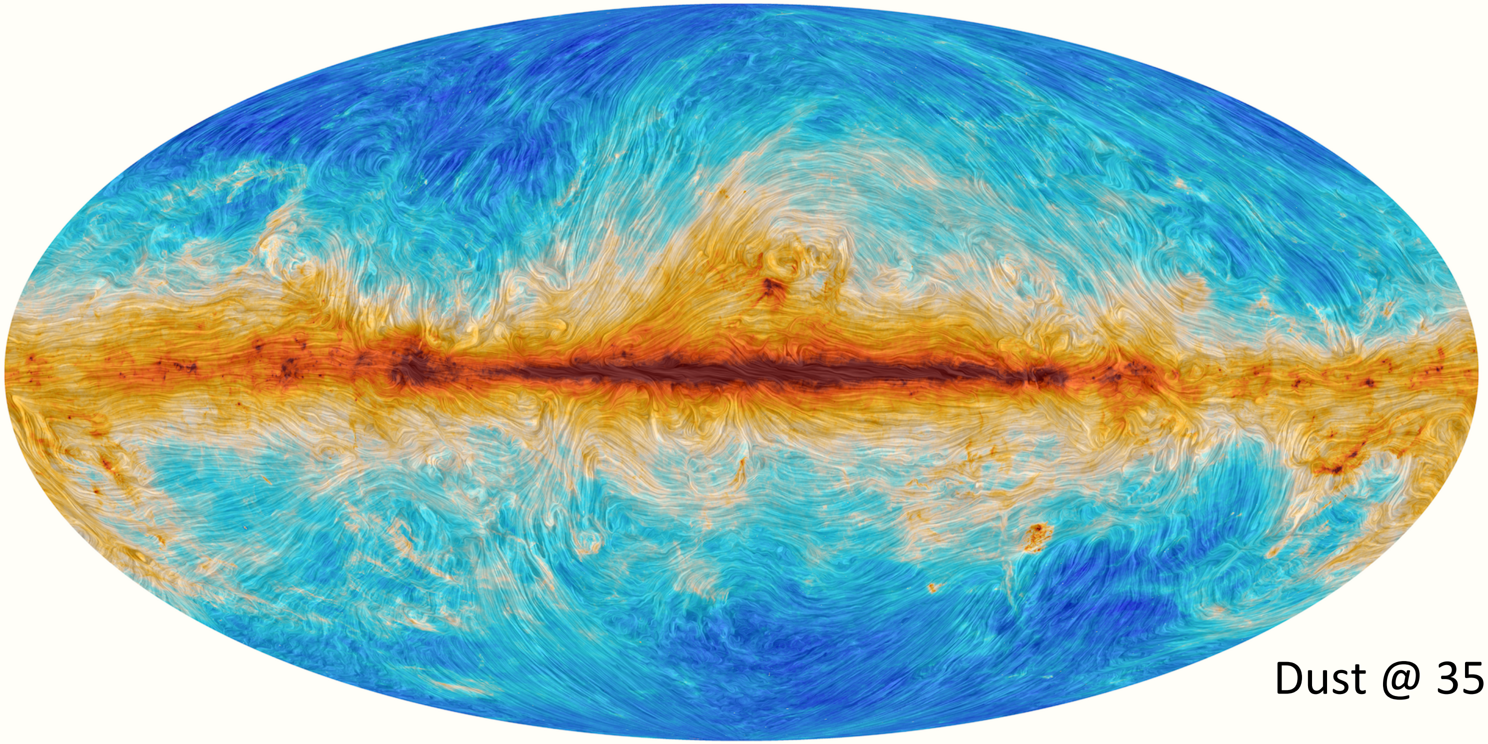
FWHM=1º
Sky fraction: 81-93%

FWHM=40'
Sky fraction: 73-93%

Planck 2015 results X, 2016

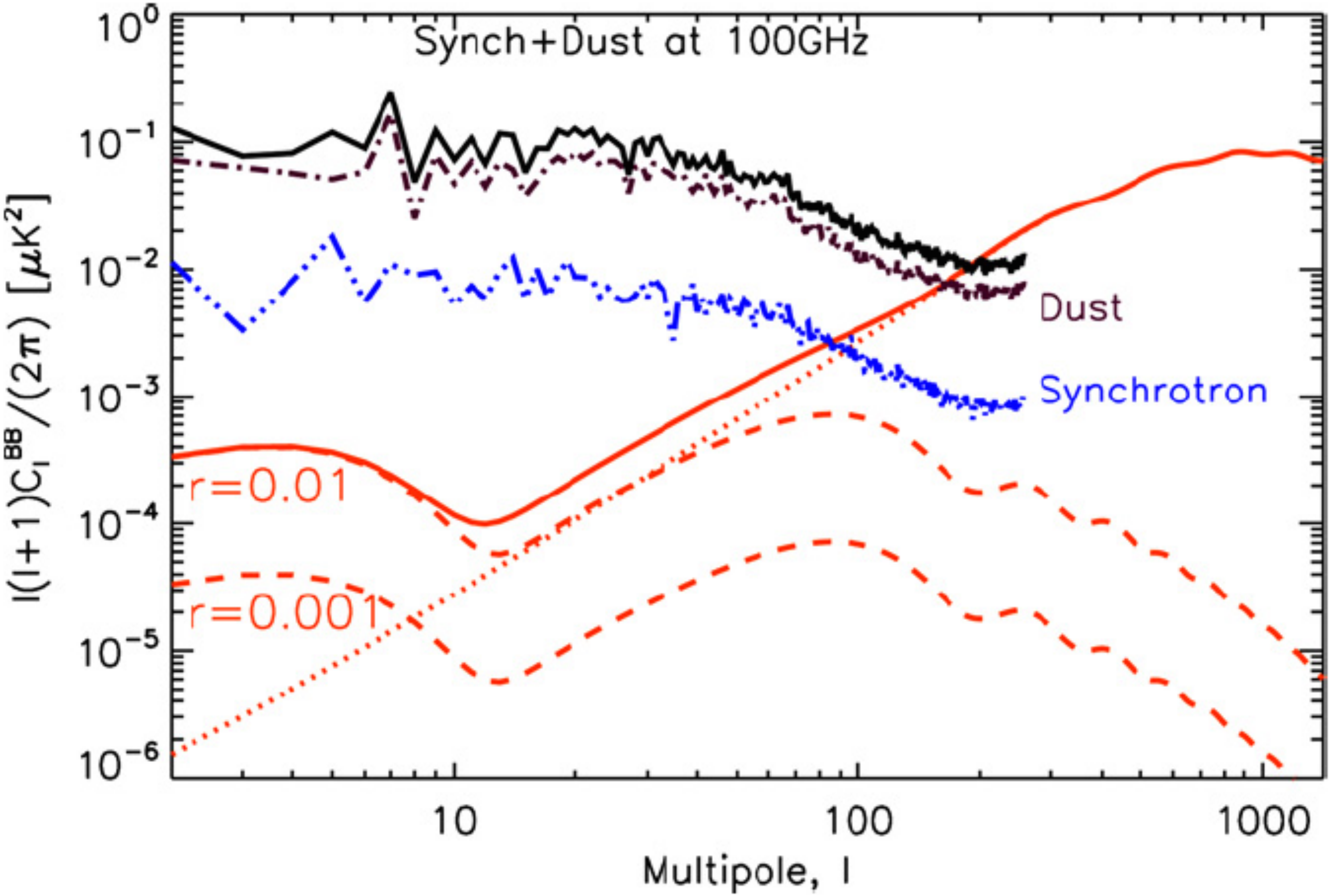


Synch @ 30GHz



Dust @ 353 GHz

Impact of foregrounds on the polarised CMB power spesctra



Katayama & Komatsu (2011)

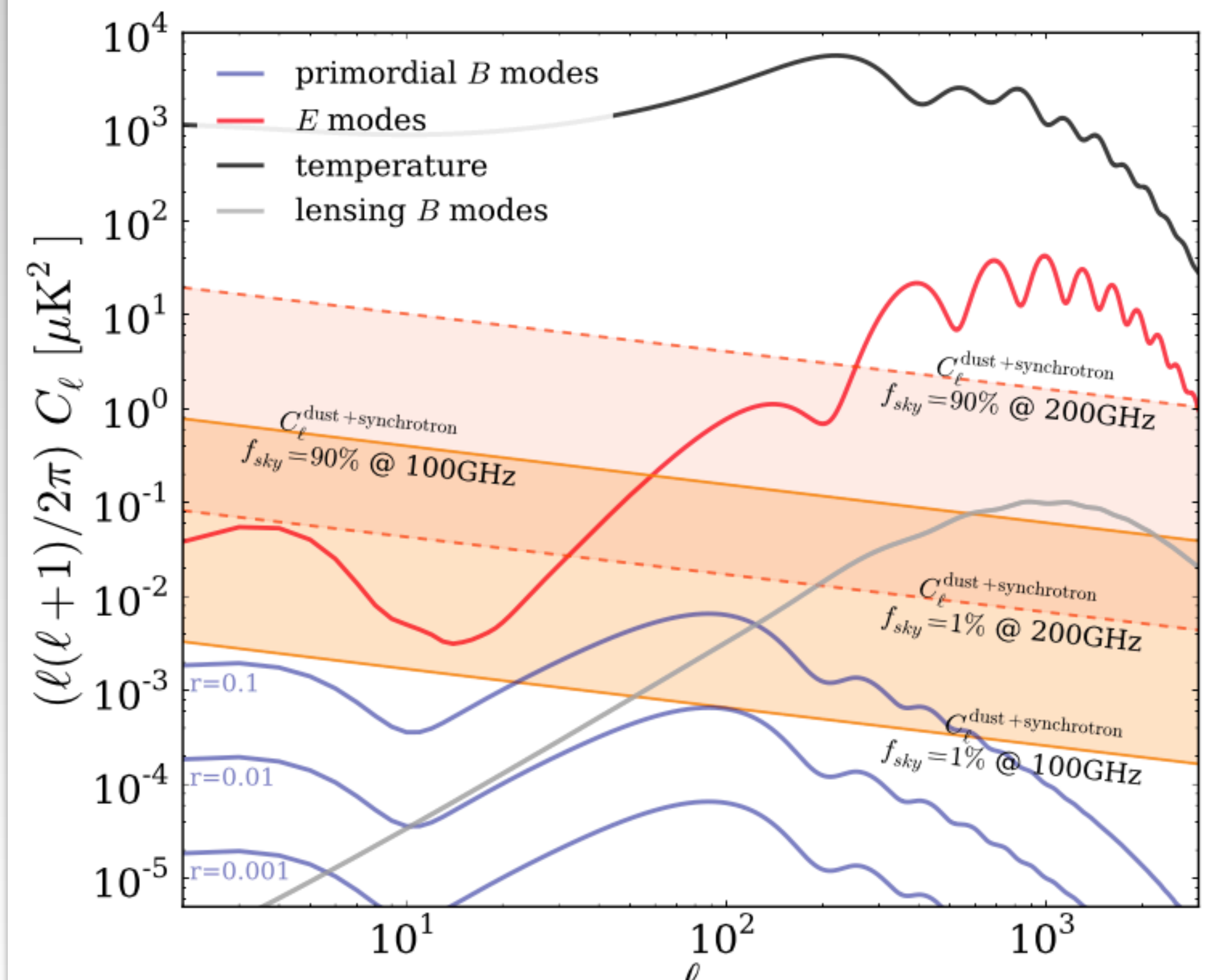
Impact of foregrounds on the polarised CMB power spesctra

★ Synchrotron+dust power spectra compared to EE power spectra and BB power spectra for different r.

★ It is critical to clean foregrounds in order to detect the B-mode polarization signal.

★ Synchrotron and thermal dust are the main contaminants at large scales.

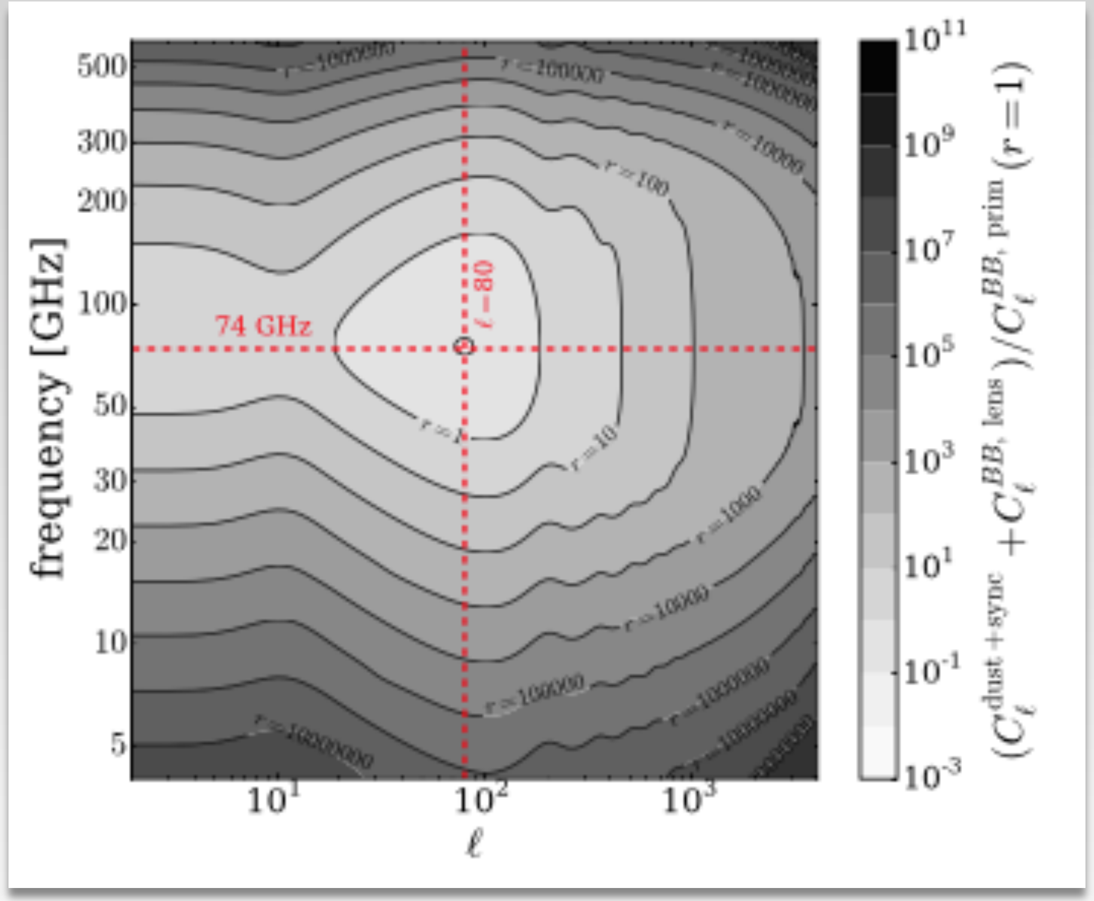
★Point sources important at Intermediate and small scales



Errard et al. 2015

What are the best frequency and angular scales?

f_{sky} = 0.5



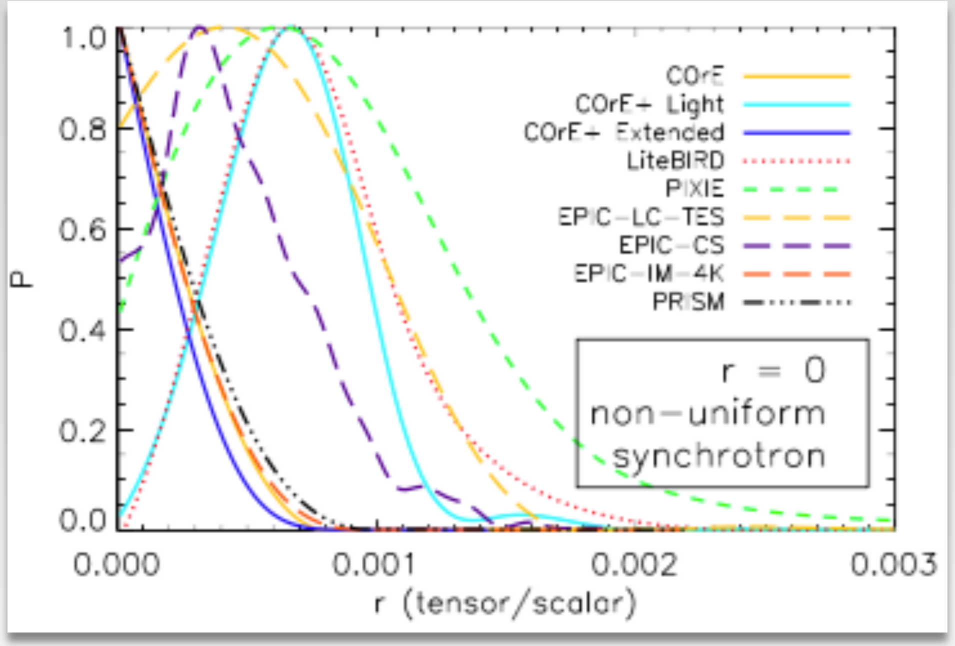
Errard et al. (2015)

★ Minimun contamination is maybe located around 60-90 GHz, and *l* ~ 80 (recombination peak).

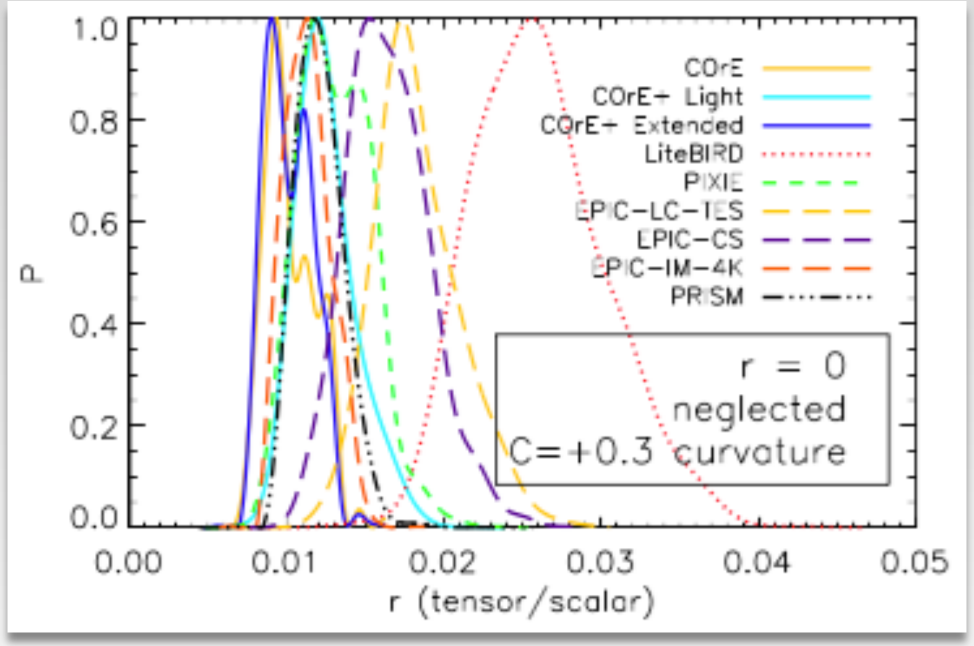
★ However, the B-mode signal is always subdominant.

Impact of incorrect synchrotron subtraction

Ignoring spatial variations of β



Ignoring synchrotron curvature

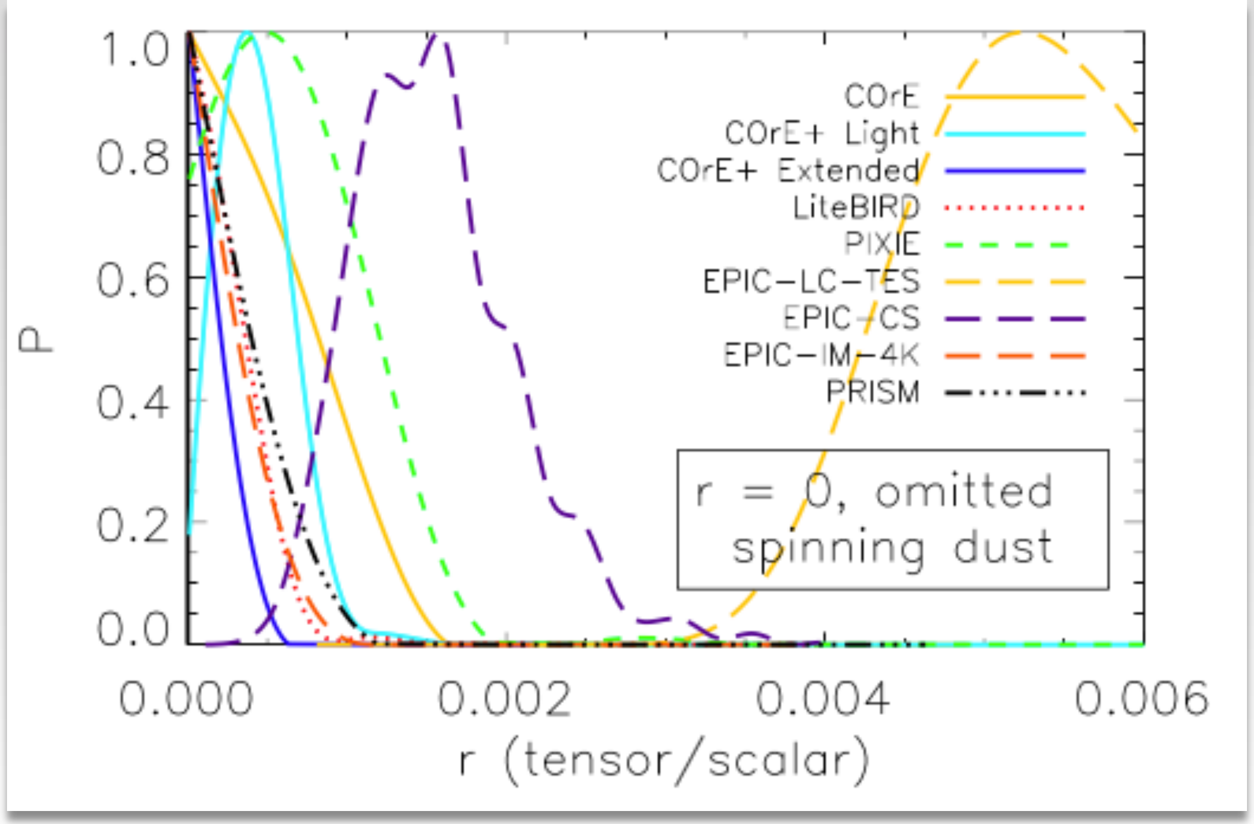


(Remazeilles et al. 2016)

Impact of ignoring the AME

★ We may not have to worry about AME in polarisation. But:

- Previous upper limits have been obtained in individual regions
- Ignoring a AME component with Π=1% may lead to significant biases in r (Remazeilles et al. 2016)



(Remazeilles et al. 2016)

Forecast for CORE. Results

★ The different methods are able to detect r> 0.005. for current foreground models (but still large uncertainties).

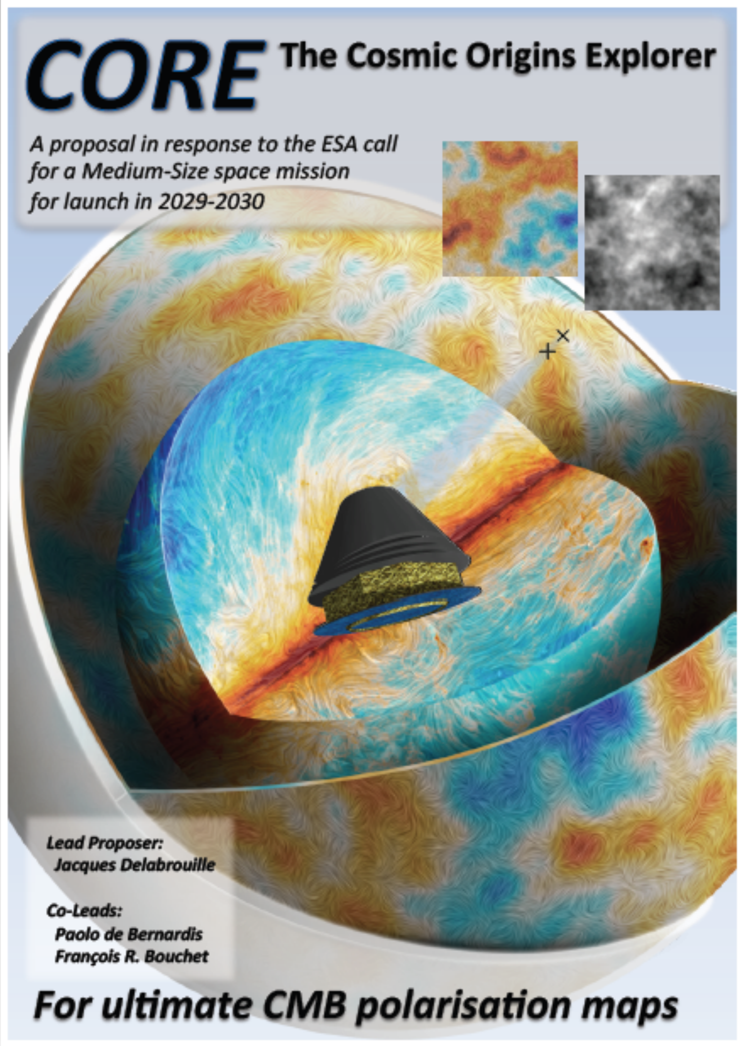
★ Detecting r=0.001 is very challenging, even assuming that 60% of the lensing signal is removed.

★ Uncertainties in the foregrounds will bias the results.

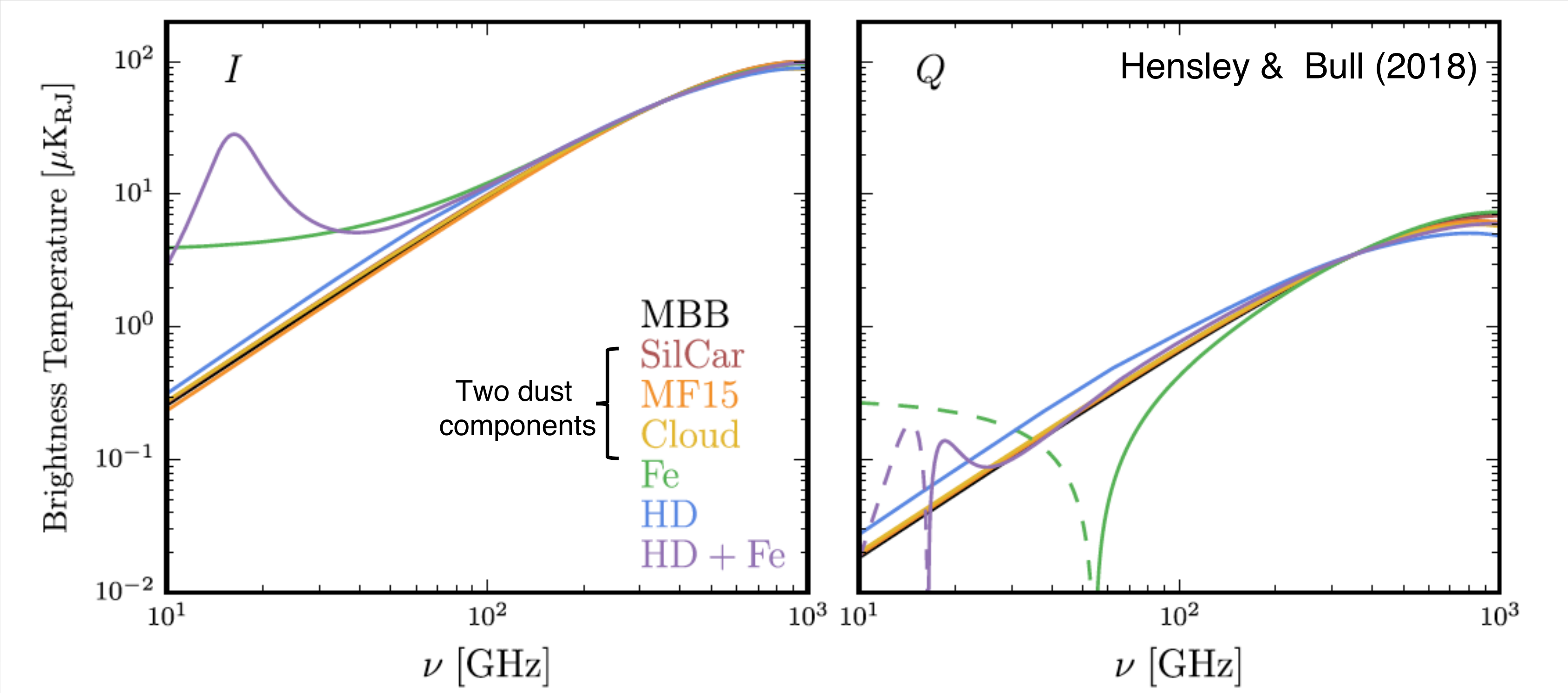
- Synchrotron modelling is more difficult due to the lack of information at low frequencies.

RADIO FOREGROUNDS

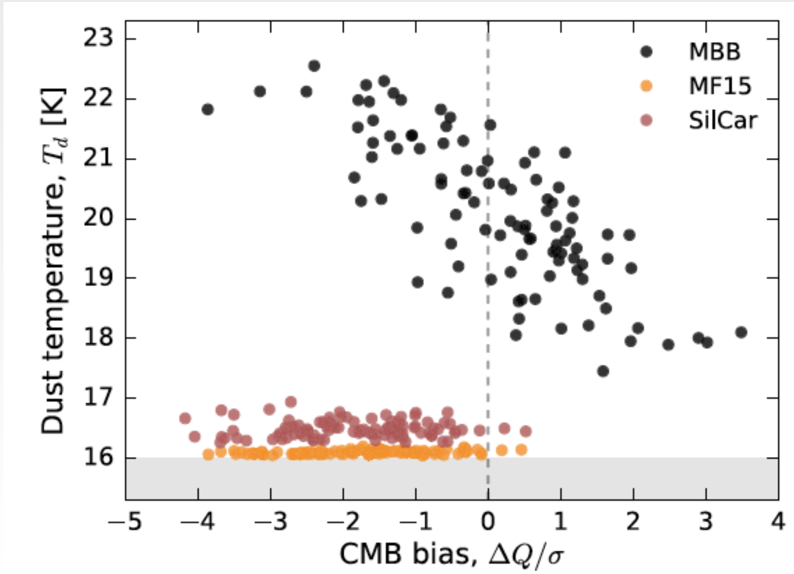
★ **Cleaning foregrounds is unavoidable to detect r.**



Modelling the complexity of foregrounds (I)

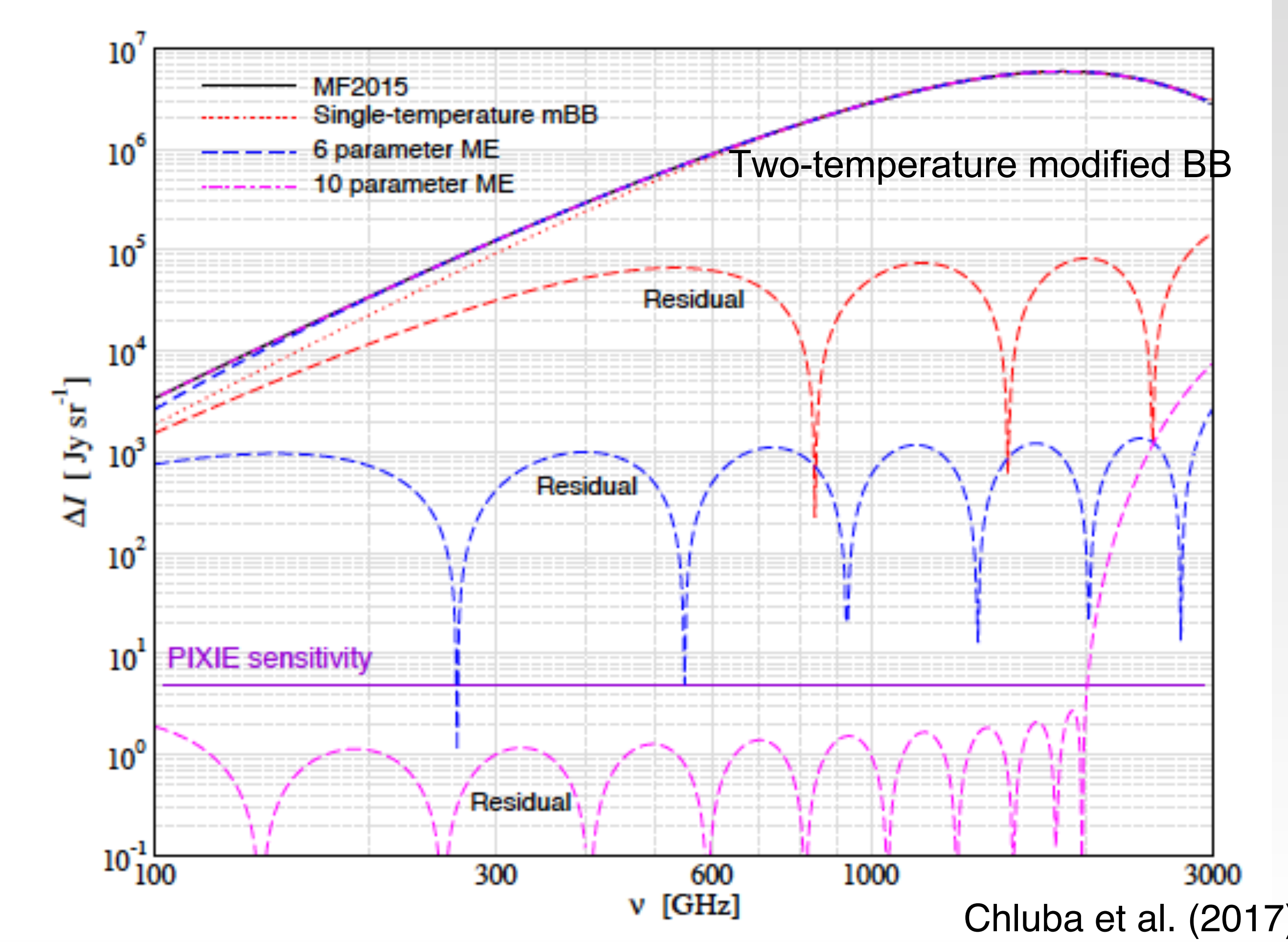


- Physically motivated dust models are complex.
- Fits employing a two-parameter modified BB (MBB) dust model have significant bias.
- Generalized MBB models with 3 additional parameters reduce this bias in most cases, but non-negligible biases can remain.
- line-of-sight effects, and the presence of iron grains are the most problematic complexities.



Modelling the complexity of foregrounds (II)

- Spatially varying foreground signals across the sky:
  - Introduces new spectral shapes (superposition of power-laws, mBBs, etc.)
  - Scale-dependent SED
- **New foreground parametrization** required.
  - **Moment expansion** (Chluba, Hill & Abitbol, 2017)



Chluba et al. (2017)

Where to look and at what frequency?

Krachmalnicoff et al. (2016)

★ Krachmalnicoff et al. (2016) estimated the frequency and the amplitude of the foreground (dust+synchrotron) minumum in individual regions of the sky

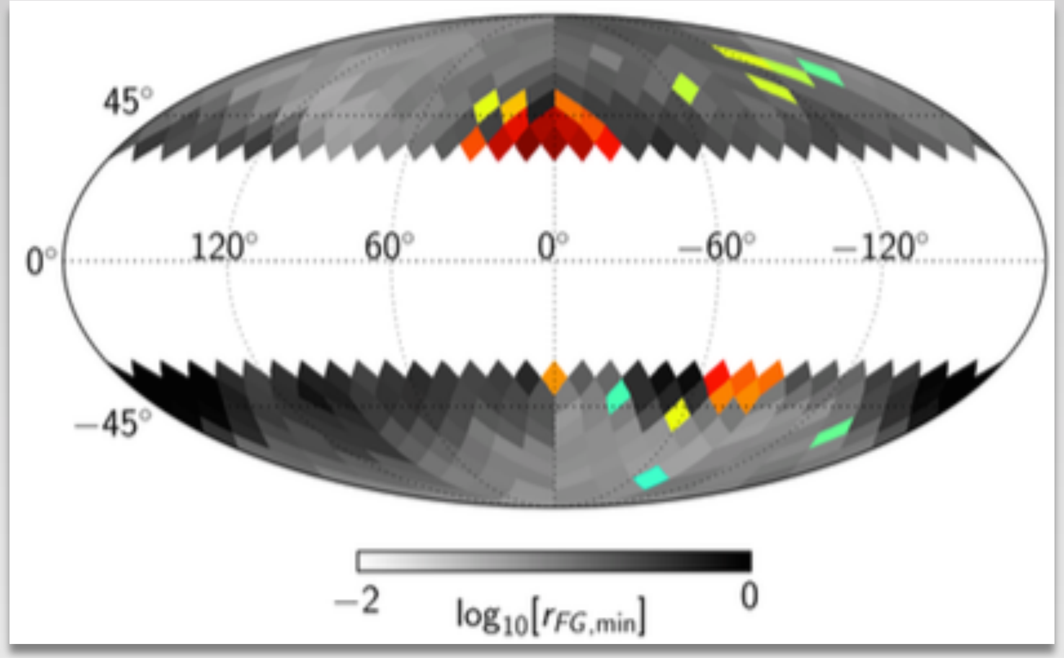
★ Detected the foreground minimum at 60-100 GHz, with an amplitude r ~ 0.06-1

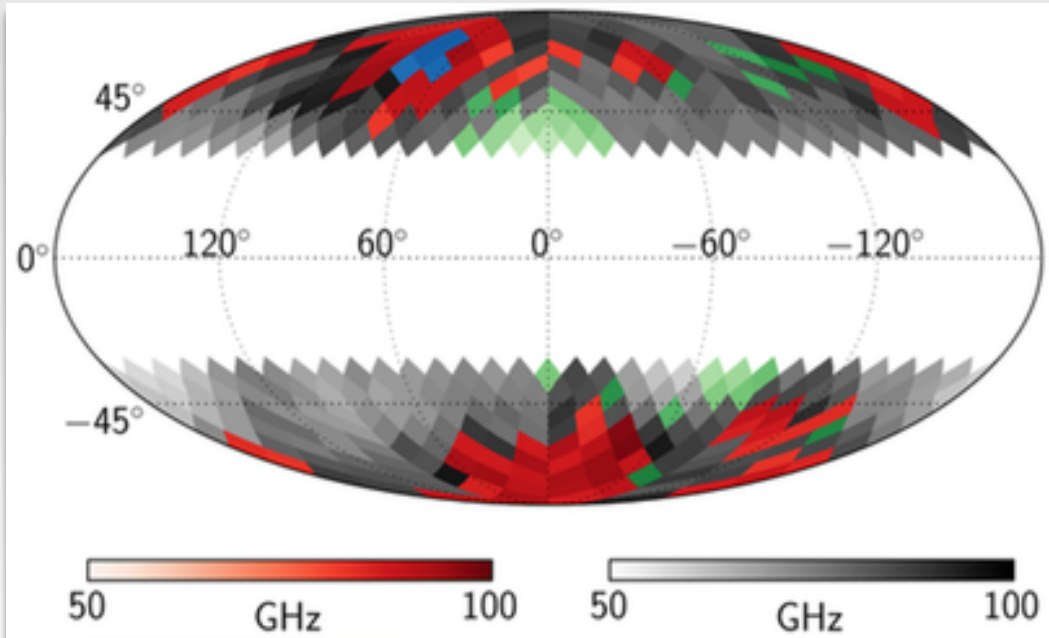
★ Set upper limits of r <0.05-1.5 between 60 and 90 GHz in other regions

★ They concluded that

- there is no region in the sky with foreground contamination r < 0.05
- synchrotron correction is needed to measure r~0.01 in any region of the sky at ν < 100 GHz

Need to jointly characterise dust +synchrotron





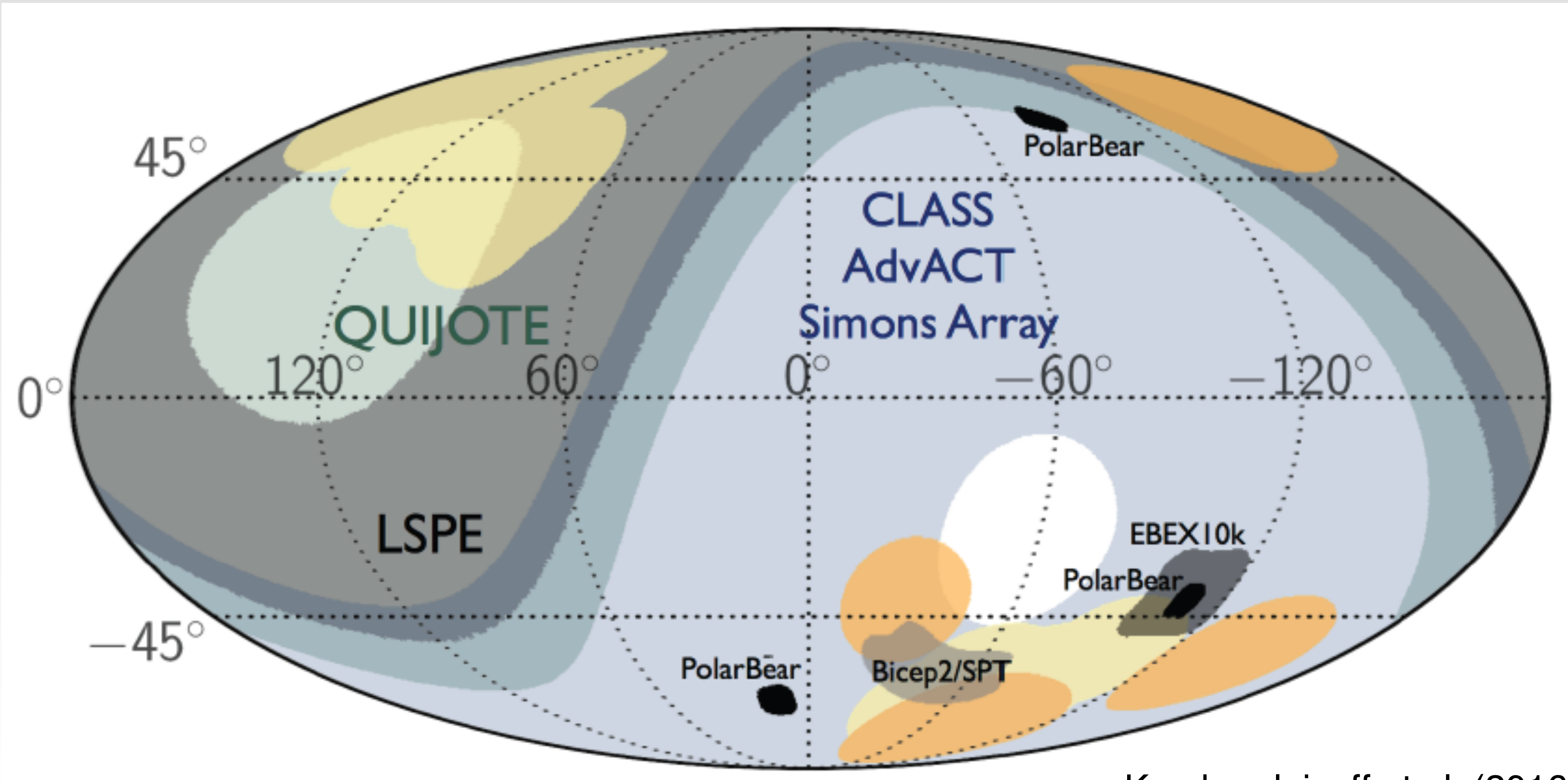
Low-frequency foregrounds. Observations planned till 2020

Southern hemisphere

- CLASS, Simons Array, Simons Observatory
- C-BASS (5 GHz). S-PASS (2.3GHz)

Northern hemisphere

- QUIJOTE (10-40GHz), C-BASS (5GHz)
- LSPE-STRIP 40-90GHz (deployed in Tenerife).



Krachmalnicoff et al. (2016).

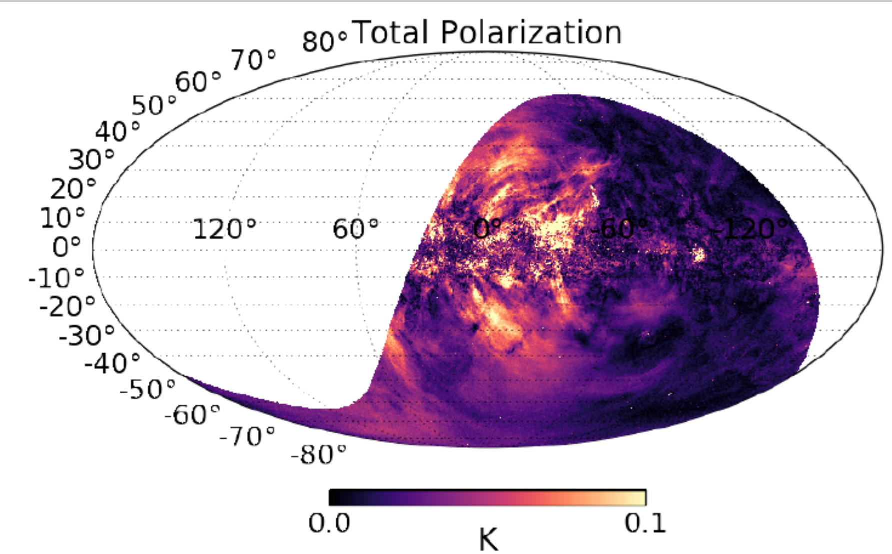
S-PASS

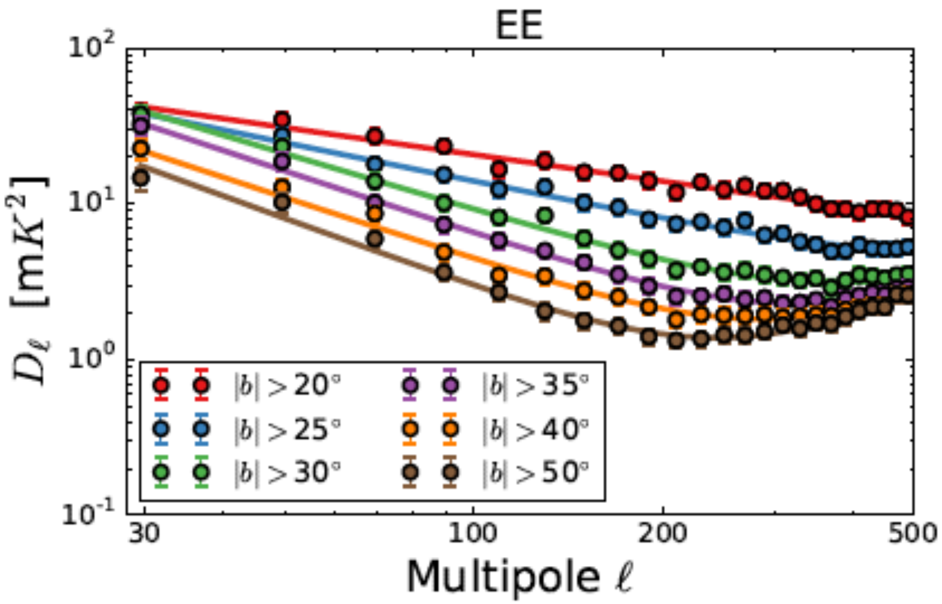
Linear polarization at **2.3 GHz** as observed by the S-band Polarization All Sky Survey (S-PASS).

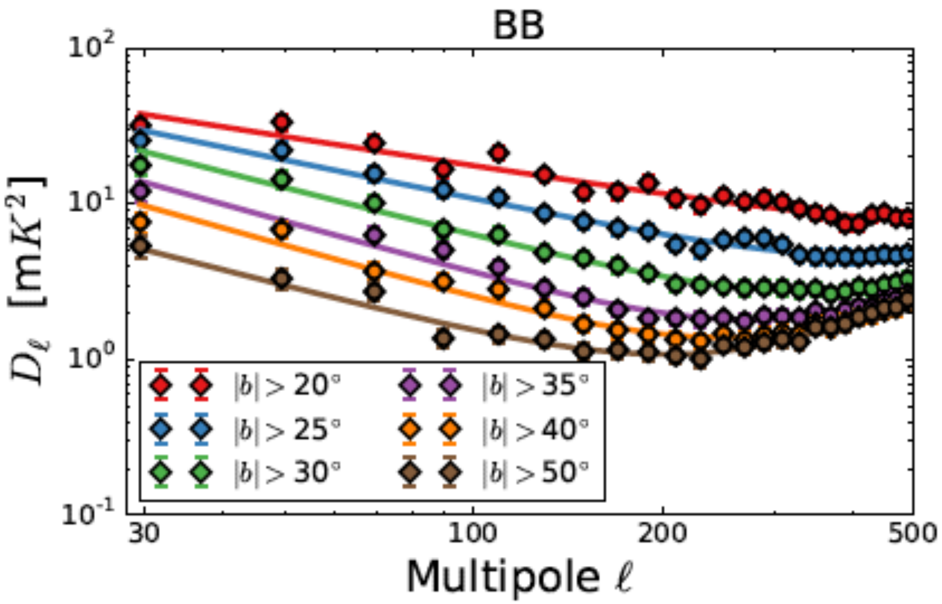
Power spectra show a decay of the amplitude as a function of multipole for l<200, typical of the diffuse emission.

The recovered SED, in the frequency range 2.3-33 GHz, is compatible with a power law with index **-3.22 ± 0.08.**

Dividing the sky in small patches (with fsky=1%), the minimal contamination at 90GHz, in the cleanest regions of the sky, is at the level of equivalent tensor-to-scalar ratio $\mathbf{r_{synch}=10^{-3}}$.







Krachmalnicoff et al. (2018), arXiv: 1802.01145.

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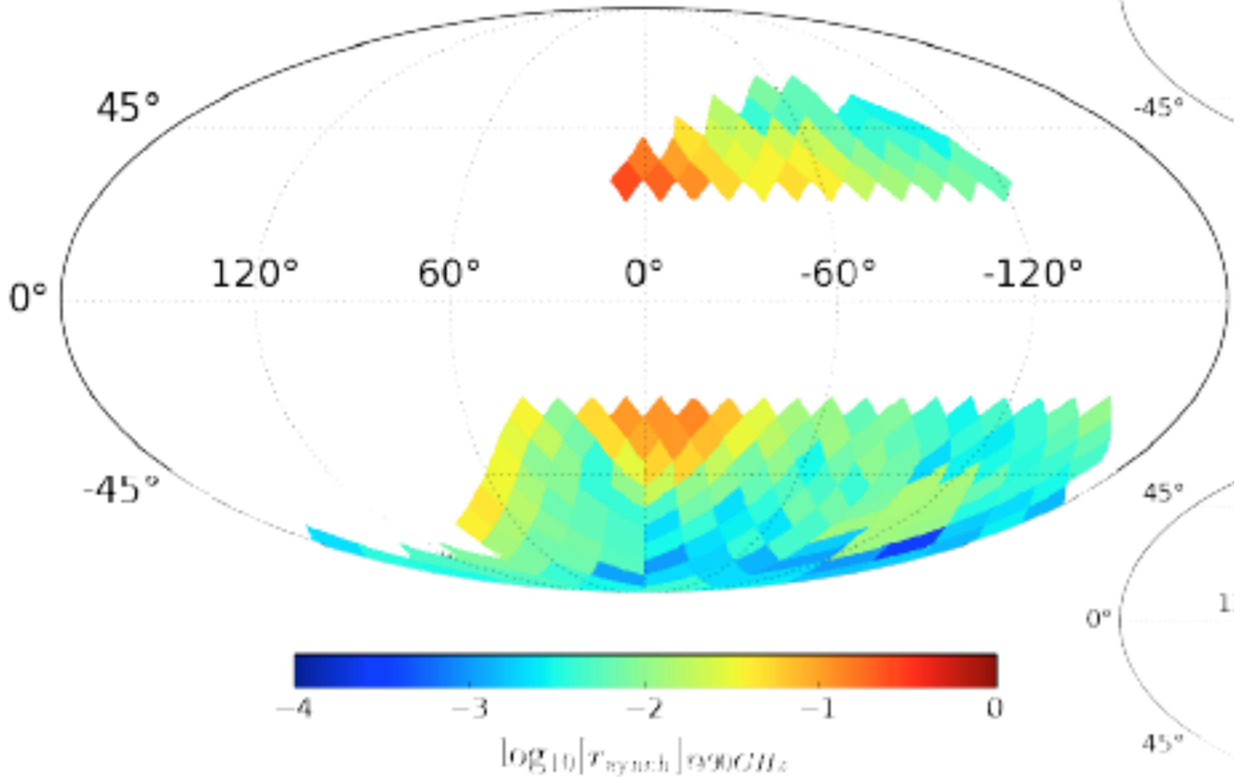
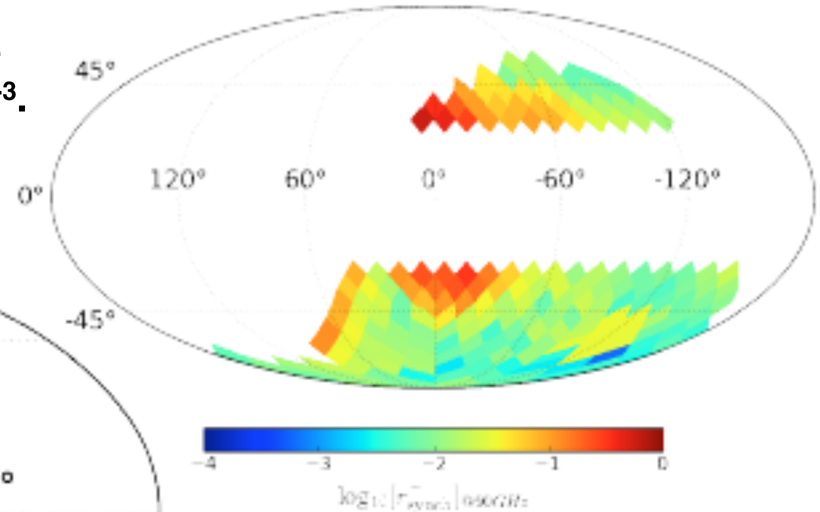
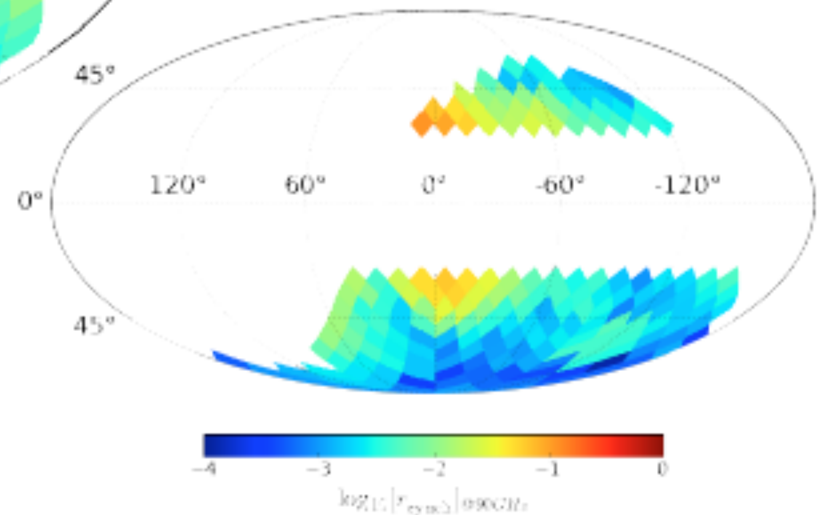


$\mathbf{Log_{10}(|r_{synch}|)}$ @ 90GHz





Krachmalnicoff et al. (2018), arXiv: 1802.01145.

The Teide Observatory

★ Geography:

- Lat. 28º18’ N, Long. 16º30’ S
- Sky visibility: full northern hemisphere and part of the south
- Far from tropical storms

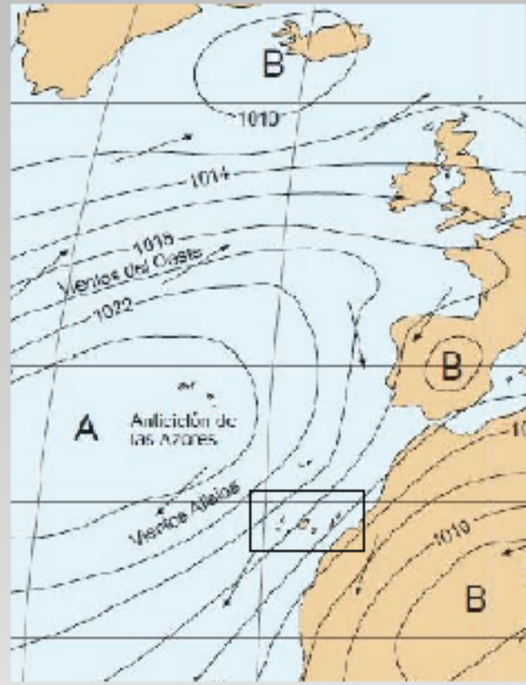
★ Climate:

- Dominated by a persistent area of high pressure in the North Atlantic (Azores anticyclone or the Bermuda High)
- Persistent inversion temperature layer at 1500 m

★ Altitude:

- 2400m
- Above the cloud layer
- Transparent and very stable atmosphere

★ Median PWV= 3.8 mm (García-Lorenzo et al. 2010)



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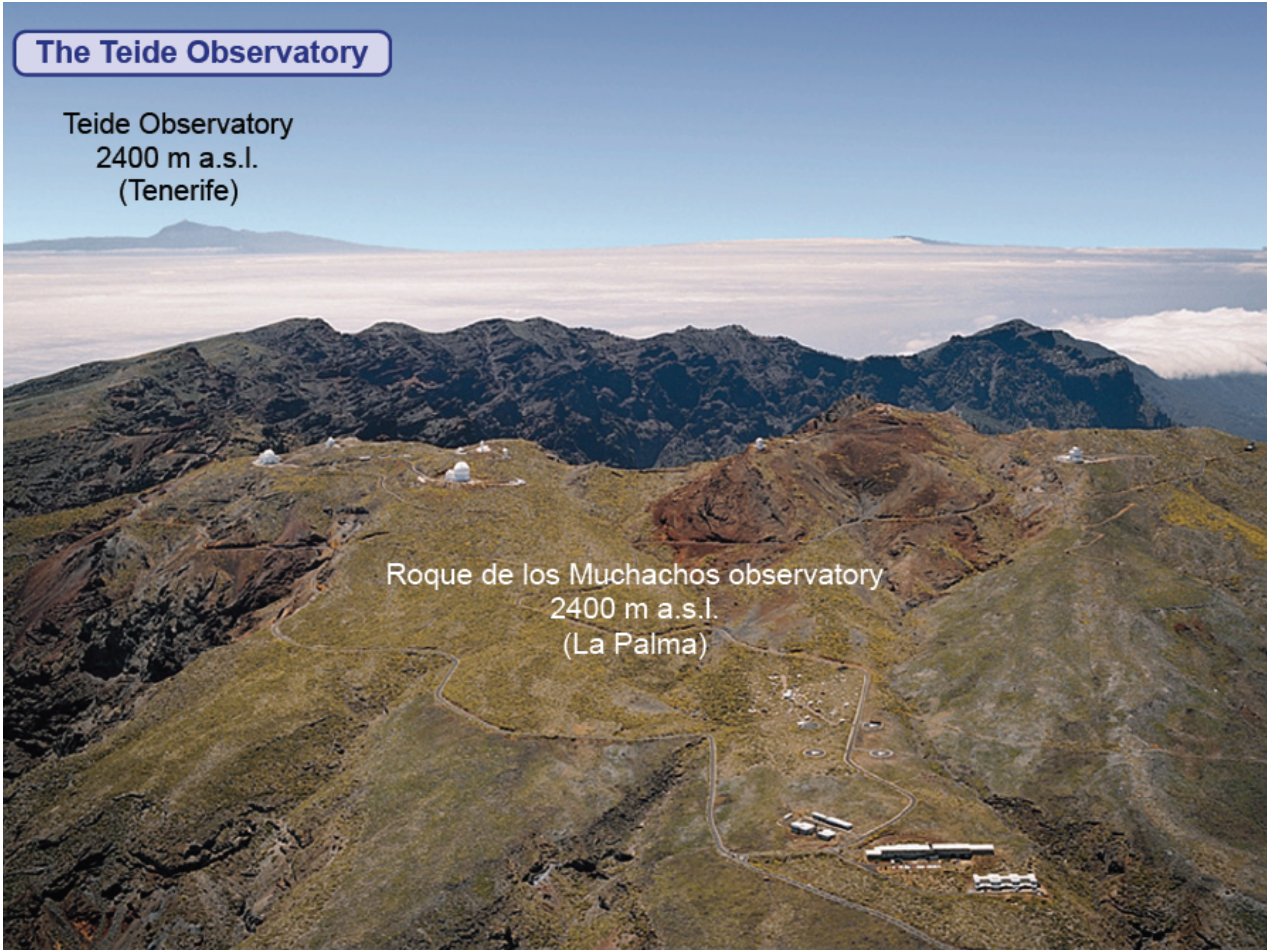
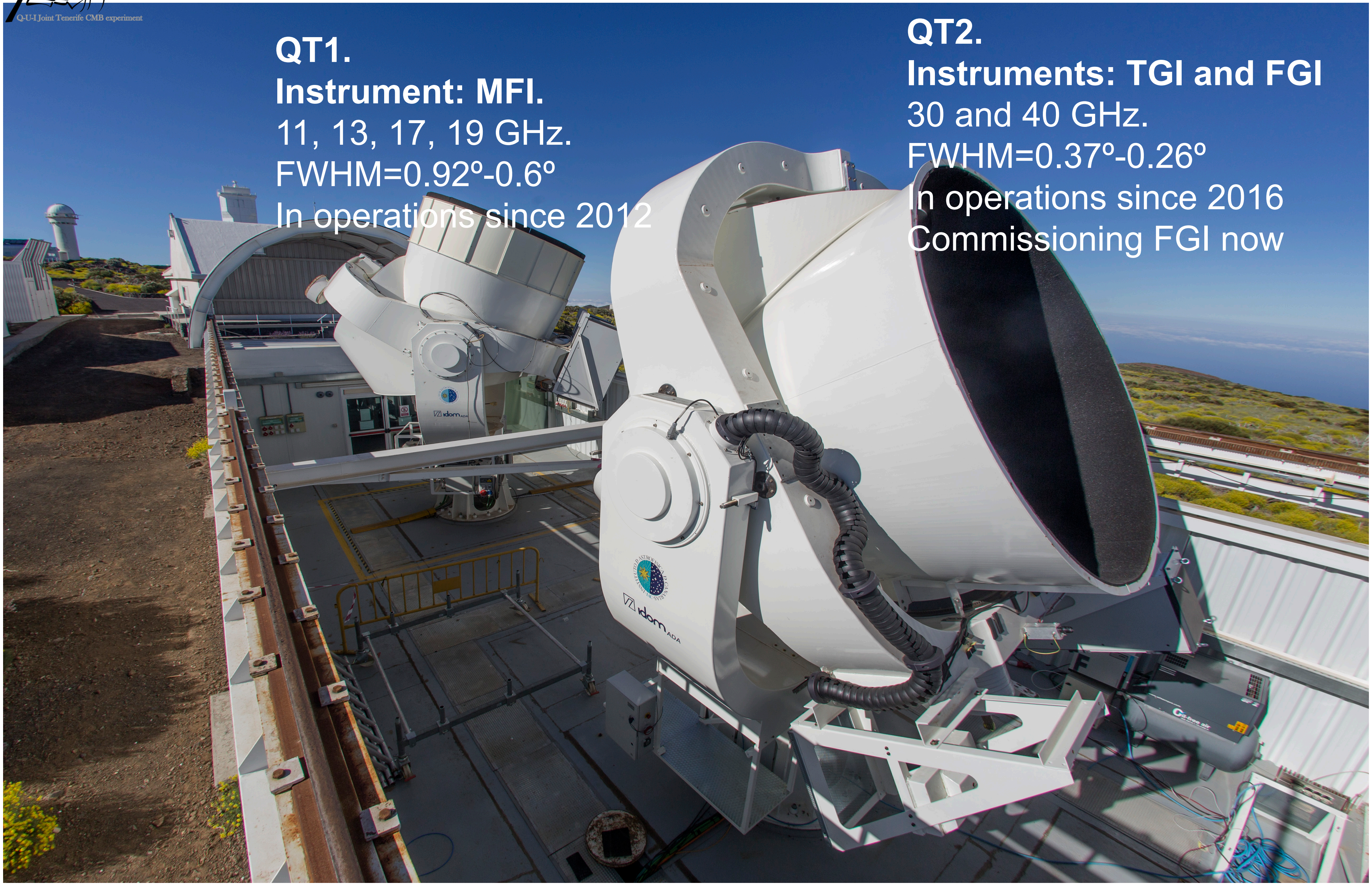


The QUIJOTE experiment

(http://www.iac.es/project/cmb/quijote)

IFCA Instituto de Física de Cantabria · DICOM · UNIVERSITY OF CAMBRIDGE · MANCHESTER 1824 The University of Manchester · idom

The QUIJOTE experiment



QT1.
Instrument: MFI.
11, 13, 17, 19 GHz.
FWHM=0.92º-0.6º
In operations since 2012

QT2.
Instruments: TGI and FGI
30 and 40 GHz.
FWHM=0.37º-0.26º
In operations since 2016
Commissioning FGI now

RADIOFOREGROUNDS project

http://www.radioforegrounds.eu

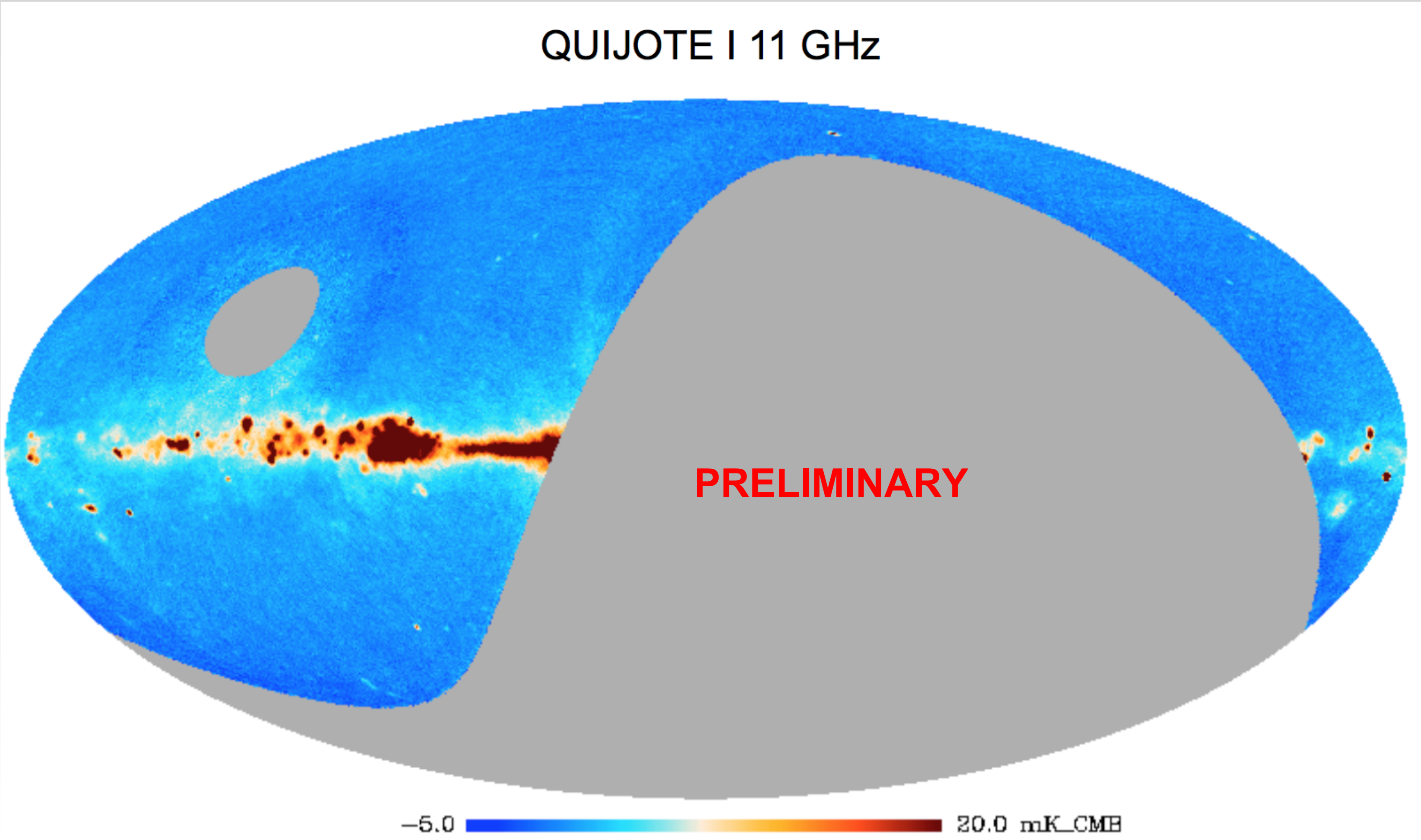
H2020-COMPET-2015. Grant agreement **687312:** "Ultimate modelling of Radio Foregrounds" (RADIOFOREGROUNDS).
3-year grant (IAC; IFCA; Cambridge; Manchester; SISSA; Grenoble; TREELOGIC).

This project will provide specific products:

a) state-of-the-art legacy maps of the synchrotron and the anomalous microwave emission (AME) in the Northern sky;
b) a detailed characterization of the synchrotron spectral index, and the implications for cosmic-rays electron physics;
c) a model of the large-scale properties of the Galactic magnetic field;
d) a detailed characterization of the AME, including its contribution in polarization; and
e) a complete and statistically significant multi-frequency catalogue of radio sources in both temperature and polarization.
f) specific (open source) software tools for data processing, data visualization and public information.

MFI wide survery

- 8,700 hrs on a region of 20,000 deg2 in the northern sky with MFI (11,13,17,19GHz)
- Still on-going (will reach ~10000 hrs).
- Goal: **~30 μK/beam** in Q,U and, **~100 μK/beam** in I.
- Example of QUIJOTE maps. Current sensitivity (Q,U) : **~60 μK/beam in Q/U.**



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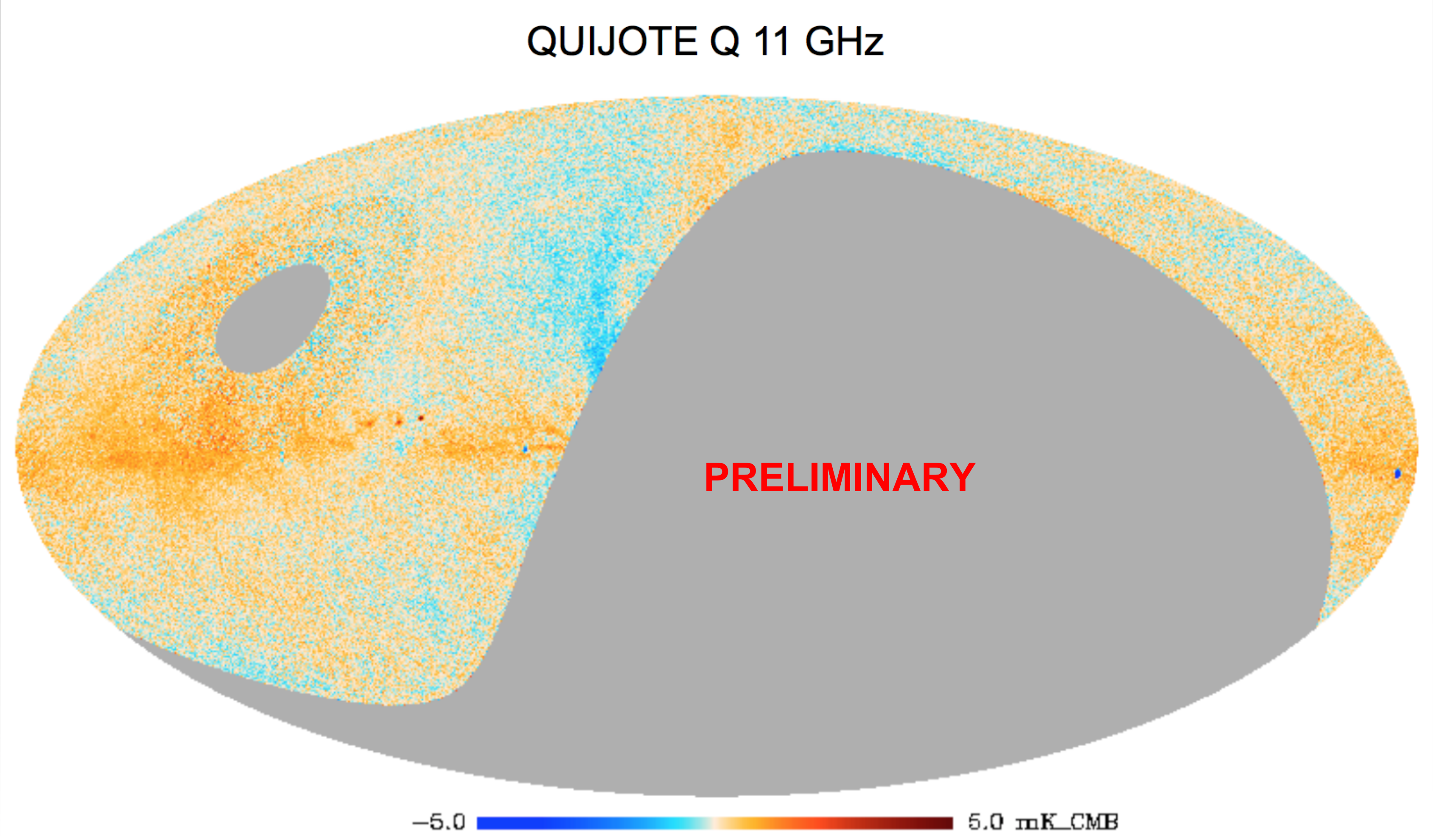

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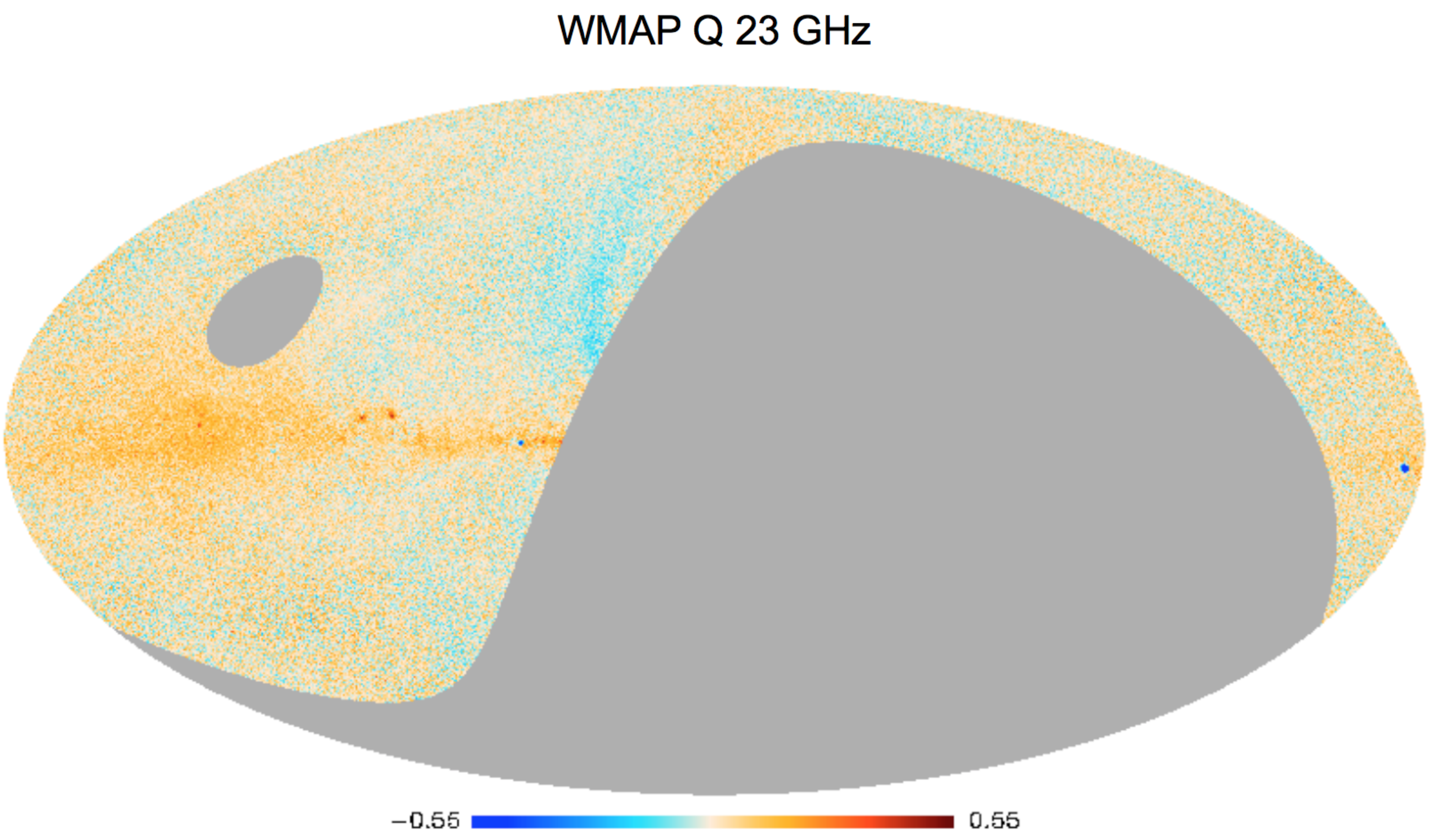

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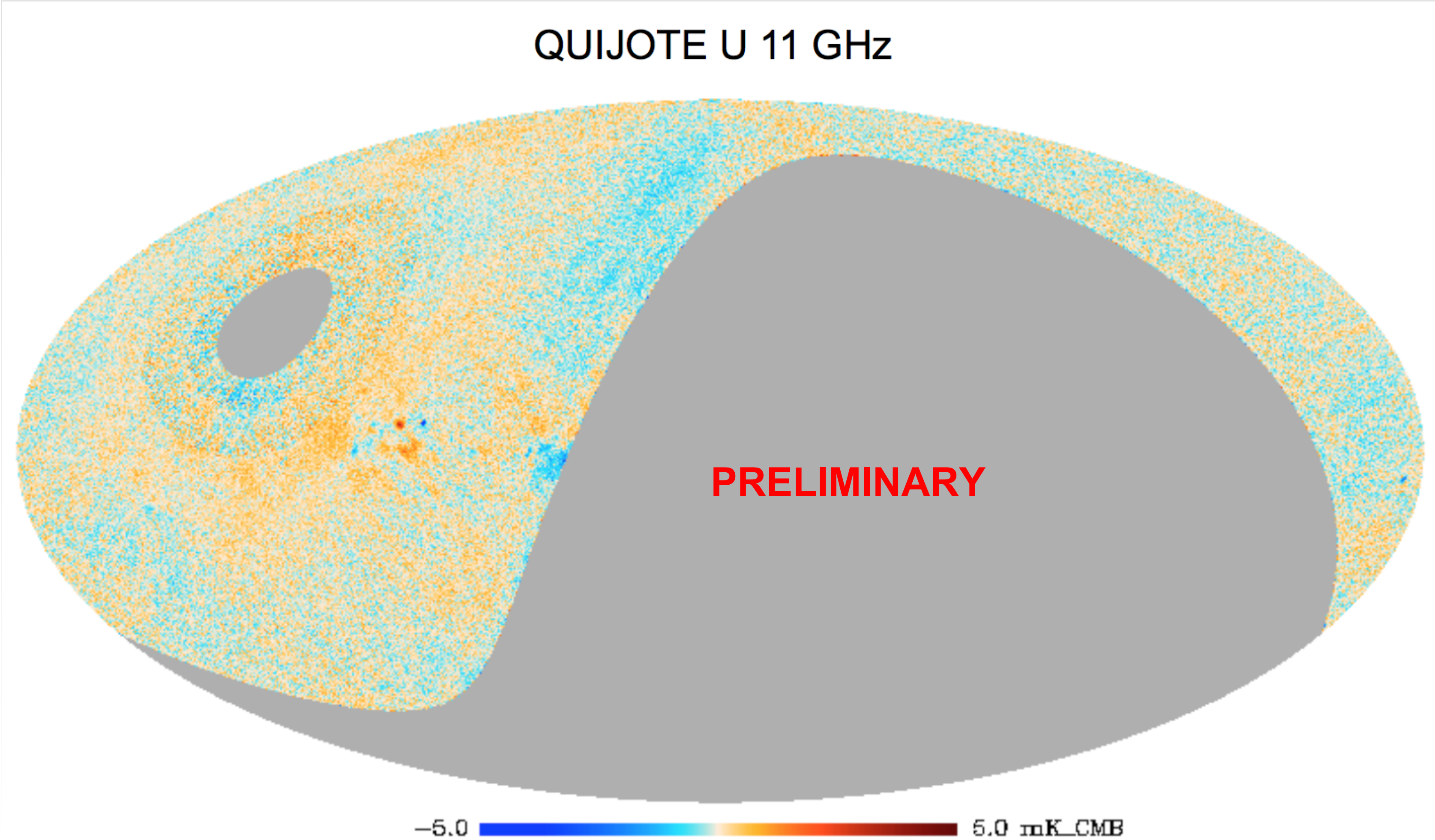

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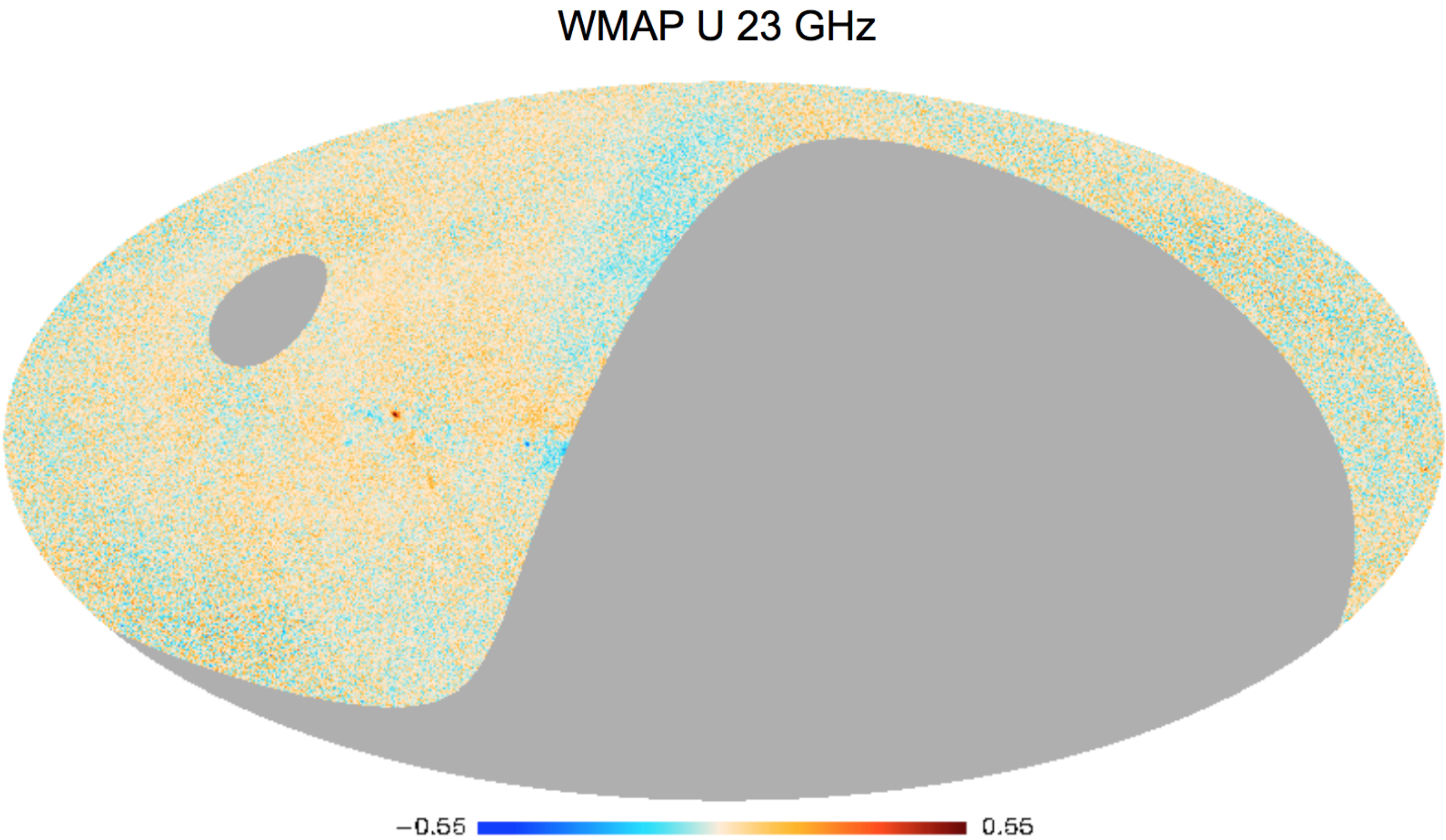
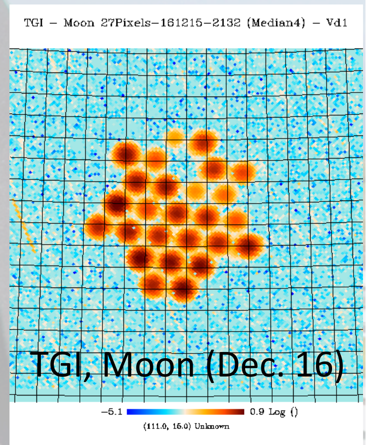
- Goal: **~30 μK/beam** in Q,U and, **~100 μK/beam** in I.
- Example of QUIJOTE maps. Current sensitivity (Q,U) : **~60 μK/beam in Q/U.**



QUIJOTE project: current status

MFI (10-20 GHz). In operations since Nov 2012.

- 4 horns, 32 chan, 4 bands: 11, 13, 17, 19 GHz, 400-600 μK $s^{1/2}$ per channel.
- Observations (> 21,000 hrs completed): COSMO fields (> 5,200 h), Wide survey (>8,500 h), galactic fields (Taurus, W49, IC443, W63, FAN, galactic center). Results published in Perseus and W43 (Genova-Santos et al. 2015; 2017). Best upper limit to date on AME pol fraction (0.2%).
- **MFI upgrade**. Funds secured. Aim: to increase the speed by at least a factor of 3. Two-years for development.
- **RADIOFOREGROUNDS** project (public results during 2018).



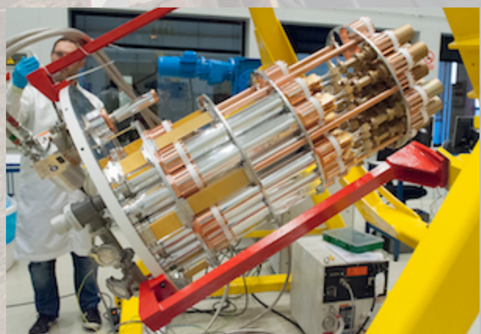
TGI, Moon (Dec. 16)

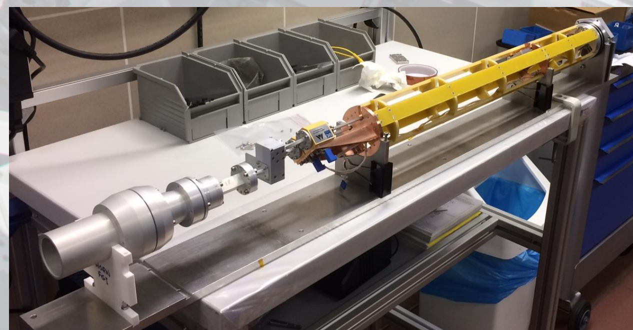
TGI (30 GHz).

- All 30 receivers integrated during 2016.
- Commissioning of 27 pixels started early 2017.

FGI (40 GHz).

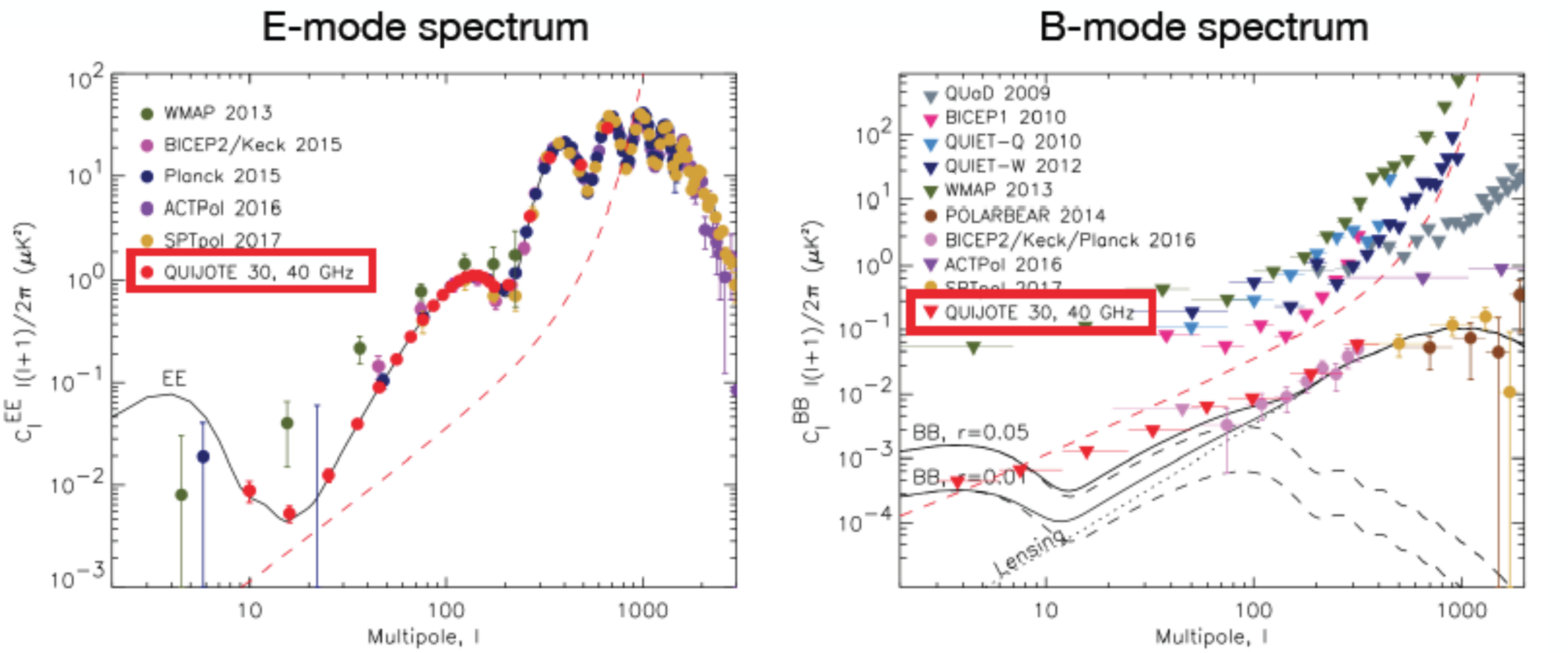
- All pixels integrated.
- In comissioning phase of TGI and FGI (sharing same cryostat).
- Observing plan for TGI/FGI science phase: cosmo survey in 3 effective years.





QUIJOTE project: science with TGI/FGI

Forecasted sensitivity after 3 years of operations:



- Combination of 3 years of observation with TGI and FGI with a 70 % efficiency and perfect removal of foregrounds.
- The B-modes are shown for the two cases **r = 0.05** and **r = 0.01**


Teide Observatory
(Tenerife, Canary Islands)
Same sky area (>20% sky, North Hemisphere)
10 frequencies from 10 to 240 GHz
Redundancy, cross-correlation
145 GHz
145 GHz
145 GHz
220 GHz
145 GHz
145 GHz
145 GHz
Pulse Tube Cooler
1st Stage
2nd Stage
GroundBIRD
145-220 GHz
LSPE/SWIPE
140-220-240GHz
LSPE horns & bolo holders (INFN-RM1)
QUIJOTE
6 frequencies in 10-40 GHz range
Large scale survey, deep fields
LSPE/STRIP
43 + 90 GHz channels
Large scale surveys, deep fields

Conclusions

★ The two main foregrounds, that may hinder the detections of polarised B-modes, are synchrotron and thermal dust emissions

★ AME seems to be polarised below 1%

★ Need physical understaning and modelling of the these componets, for which we need to combine high-frequency (e.g. Planck) with low-frequency (e.g. Quijote) surveys in large regions of the sky

★ However, physics is usually difficult:

- Number of parameters usually high (e.g. AME)
- Spatial variations of parameters
- Incomplete models: curvature of the synchrotron spectrum, multiple components along the same line of sight, and in the beam.

★ Care also be taken with missing any unexpected polarised foregrond (e.g. AME, Haze/Fermi bubbles...)

★ Need joint correction of the synchrotron and thermal dust in any region of the sky, and almost at any frequency range, if we want to push r below 0.01

CONFERENCE ANNOUNCEMENT – OCT 15-18 2018

CMB foregrounds for B-mode studies

Tenerife, Spain, October 15-18, 2018

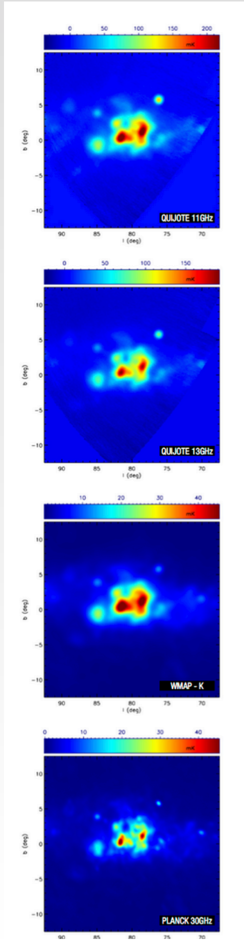
Sessions in the meeting will cover these topics:

- Current observational status - CMB polarization experiments.
- Galactic modeling I: thermal dust.
- Galactic modeling II: synchrotron and anomalous microwave emission.
- Extragalactic modeling.
- Component separation methods.
- Sky models and forecast for future missions.

Confirmed speakers:

- François Boulanger
- Masashi Hazumi
- Brandon Hensley
- Paddy Leahy
- Tobias Marriage
- Marcella Massardi
- Clem Pryke
- Osamu Tajima

RADIO FOREGROUNDS



El Experimento QUIJOTE

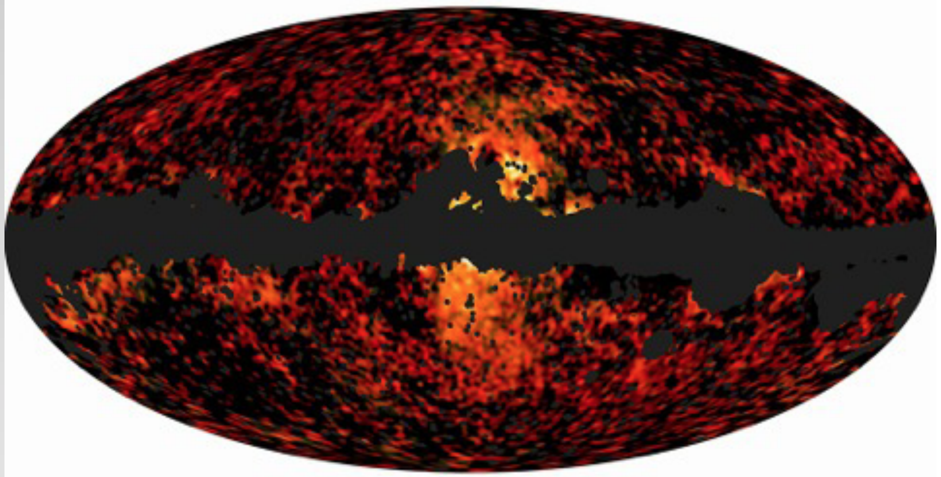
(@QuijoteCMB)

Extra slides

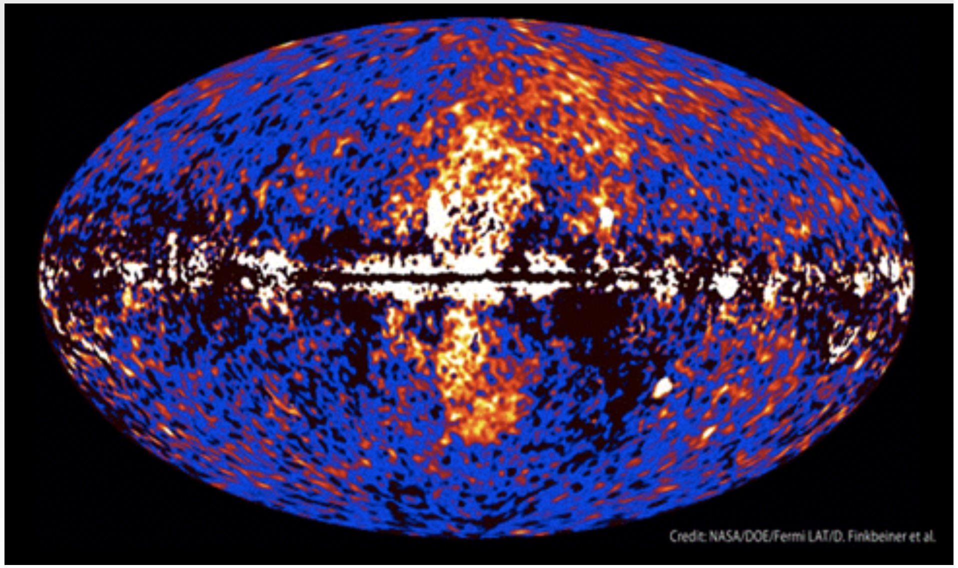
Galactic Haze
Point sources
CMB polarization experiments
Lensing
Faraday rotation

WMAP/Planck Galactic Haze

- Mysterious new component discovered in microwave data (Finkbeiner et al. 2004). Confirmed by Planck Collaboration (2013).
- Residual "haze" emission around the Galactic centre after subtraction of soft synchrotron, free-free, AME, CMB and thermal dust.
- **Spectrum appears to be hard (flatter than normal) β=-2.5!**
- Thought to be hard synchrotron from a different population of CR electrons. DM annihilation? Aparently correlated to the Fermi bubbles.
- Several ideas about origin of these. Most plausible is starburst period ~10^5-10^6 years ago providing energy injection ~10^{54}+ ergs! (Carretti et al. 2003)



WMAP/Planck Haze (Planck Collaboration 2013)



Fermi bubles (Fermi Collaboration)

Point sources

★ Affect only the small scales

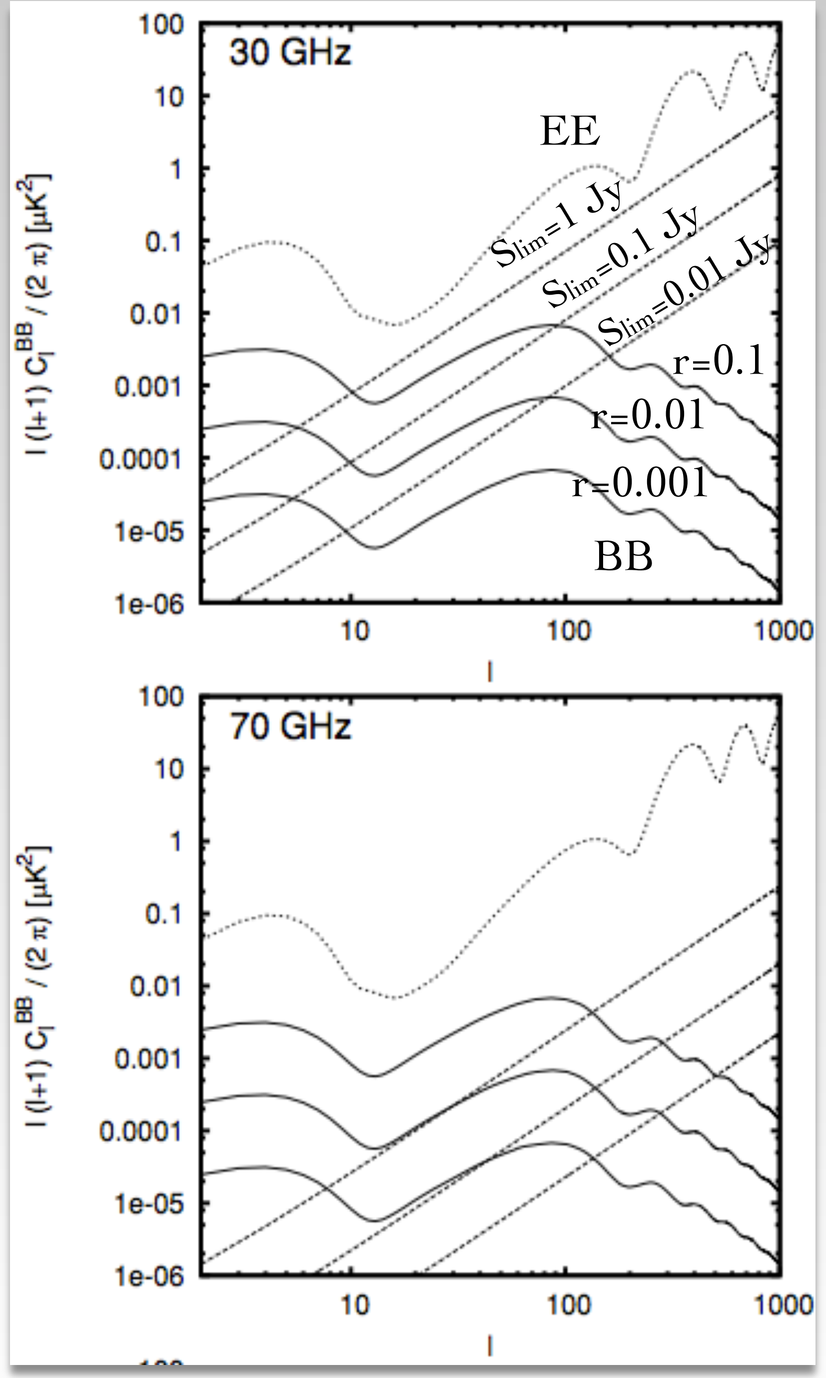
★ Difficulties:

- Good knowledge of radio sources properties in intensity, however there is insufficient information in polarisation.
- Could rely on I, but then it would be difficult to estimate the residual confusion noise
- Variability of sources ⇒ ideally need simultaneous monitoring of the polarised fluxes

★ Based on the measured statistical properties of the polarisation of a sample of 107 radio sources, Battye et al. (2011) concluded that:

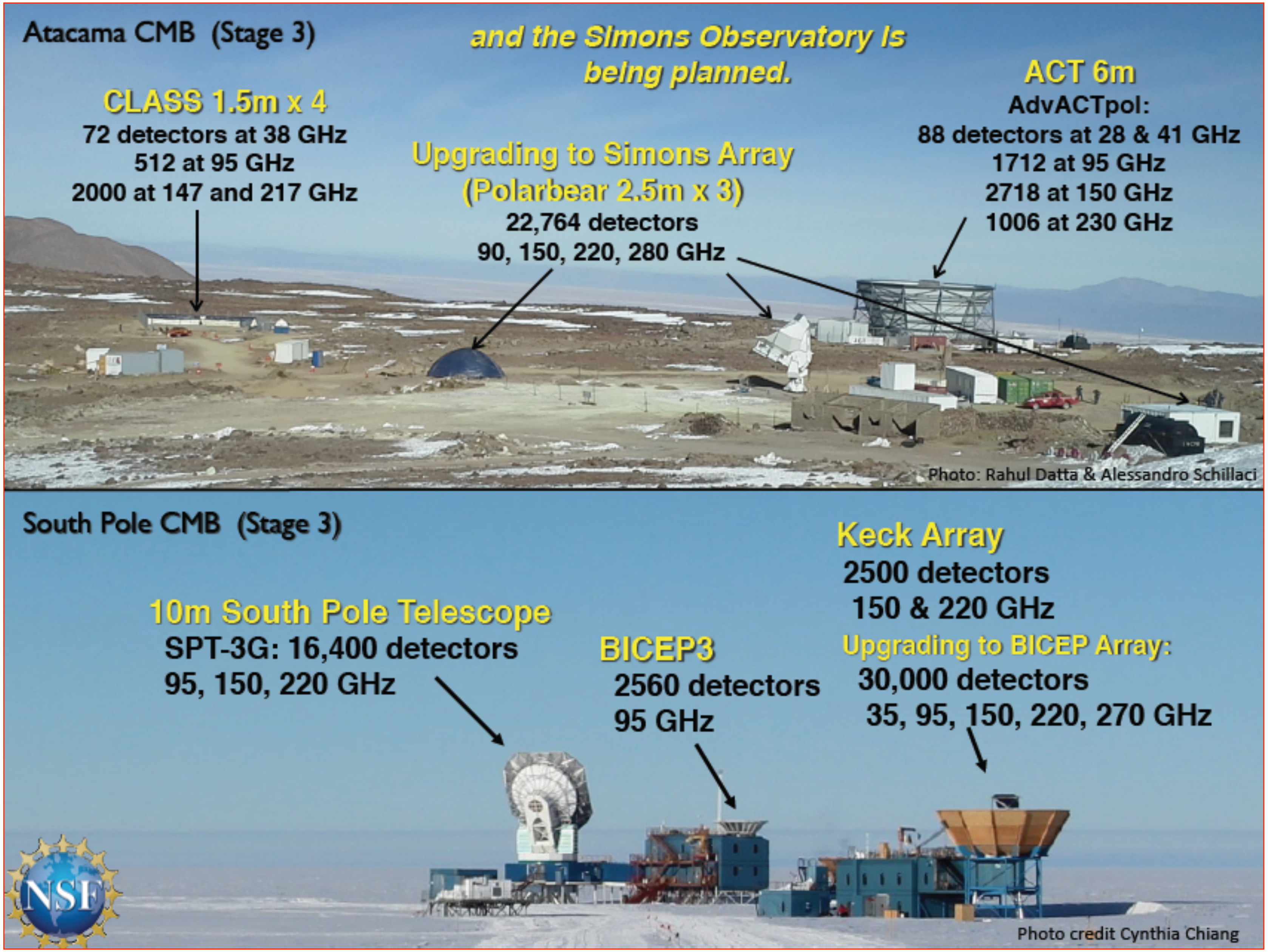
- Some level of source subtraction will be necessary to detect r~0.1 below 100 GHz, and at all frequencies to detect r~0.01

★ A possible solution is to mask. But needs to know positions!



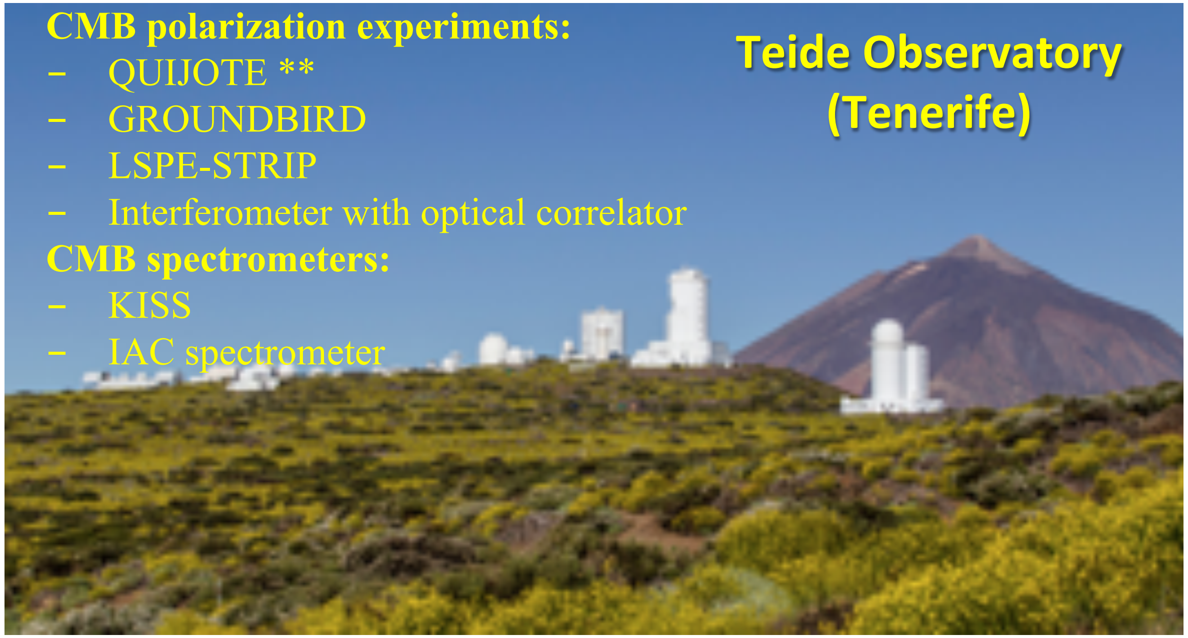
Battye et al. (2011)

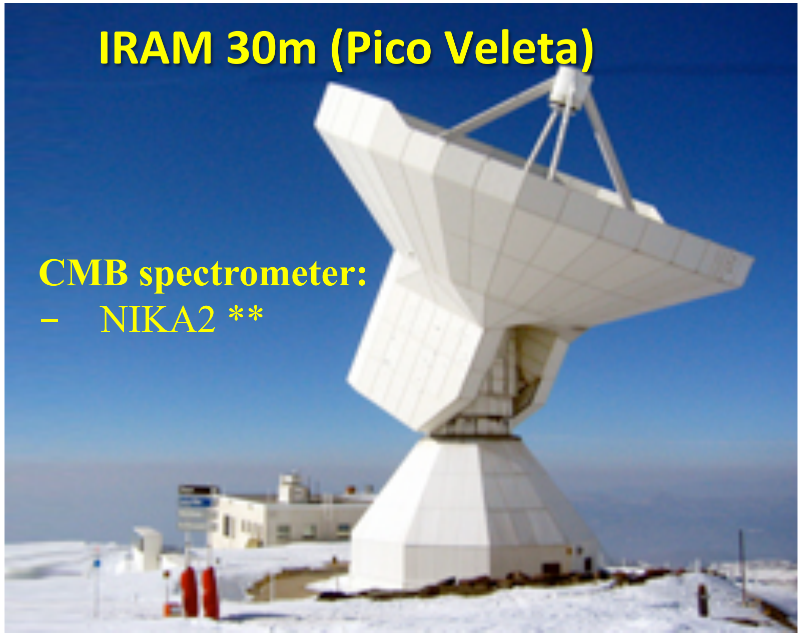
US CMB Stage 3 experiments

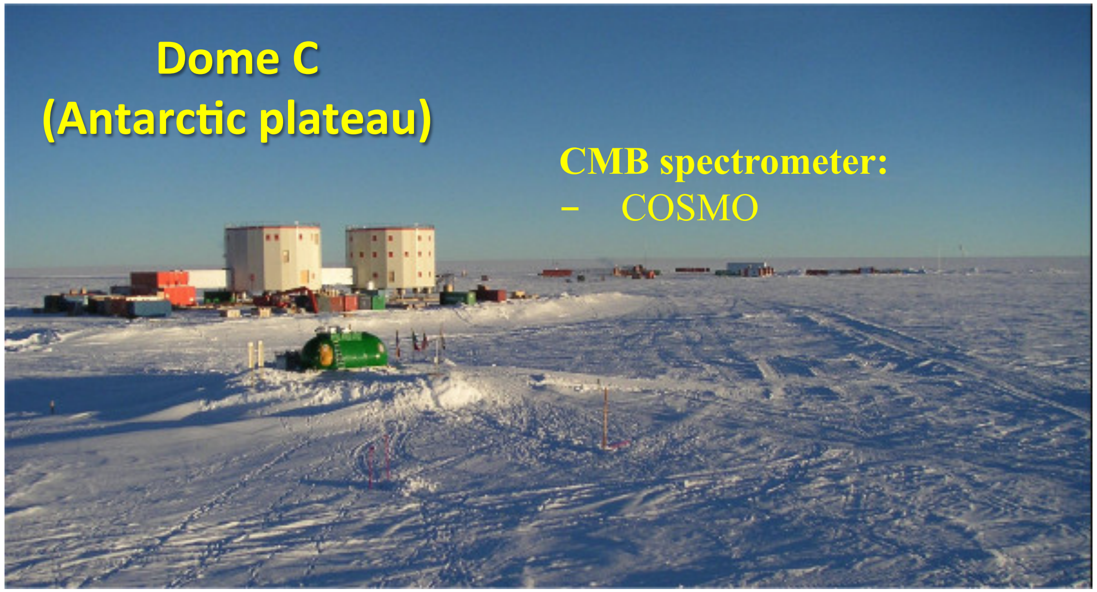


(Slide from J. Carlstrom. Florence 2017. https://indico.in2p3.fr/event/14661/timetable)

European CMB experiments







(** = in operation)

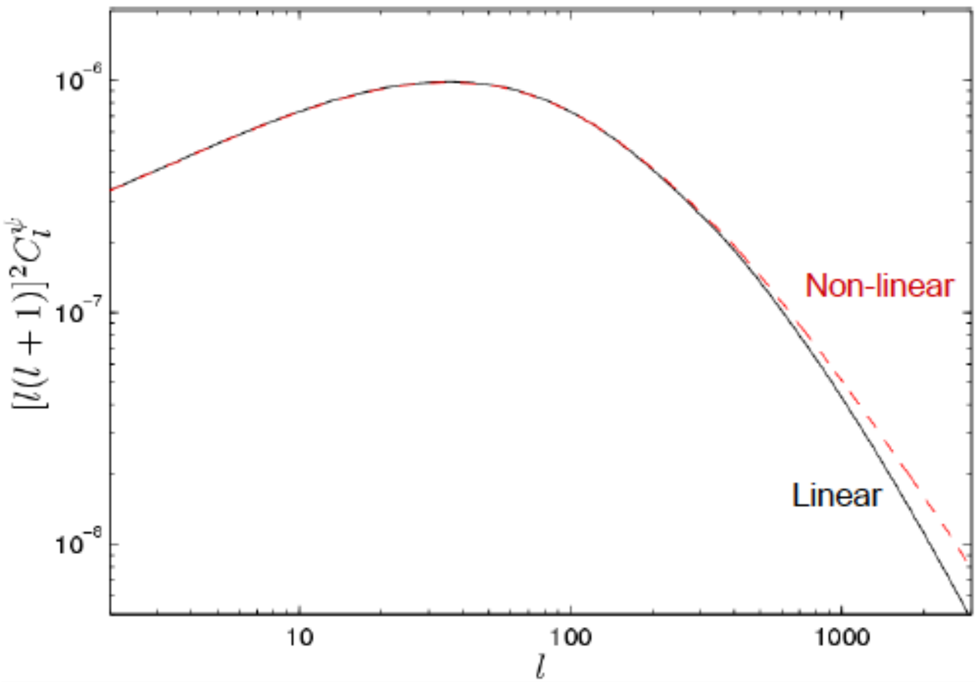
(J.A. Rubiño. https://indico.in2p3.fr/event/14661/timetable)

Gravitational lensing

Deflection angle power spectrum

Large-scale lenses: potentials nearly linear, clean physics

$$\boldsymbol{\alpha} = \nabla\psi$$

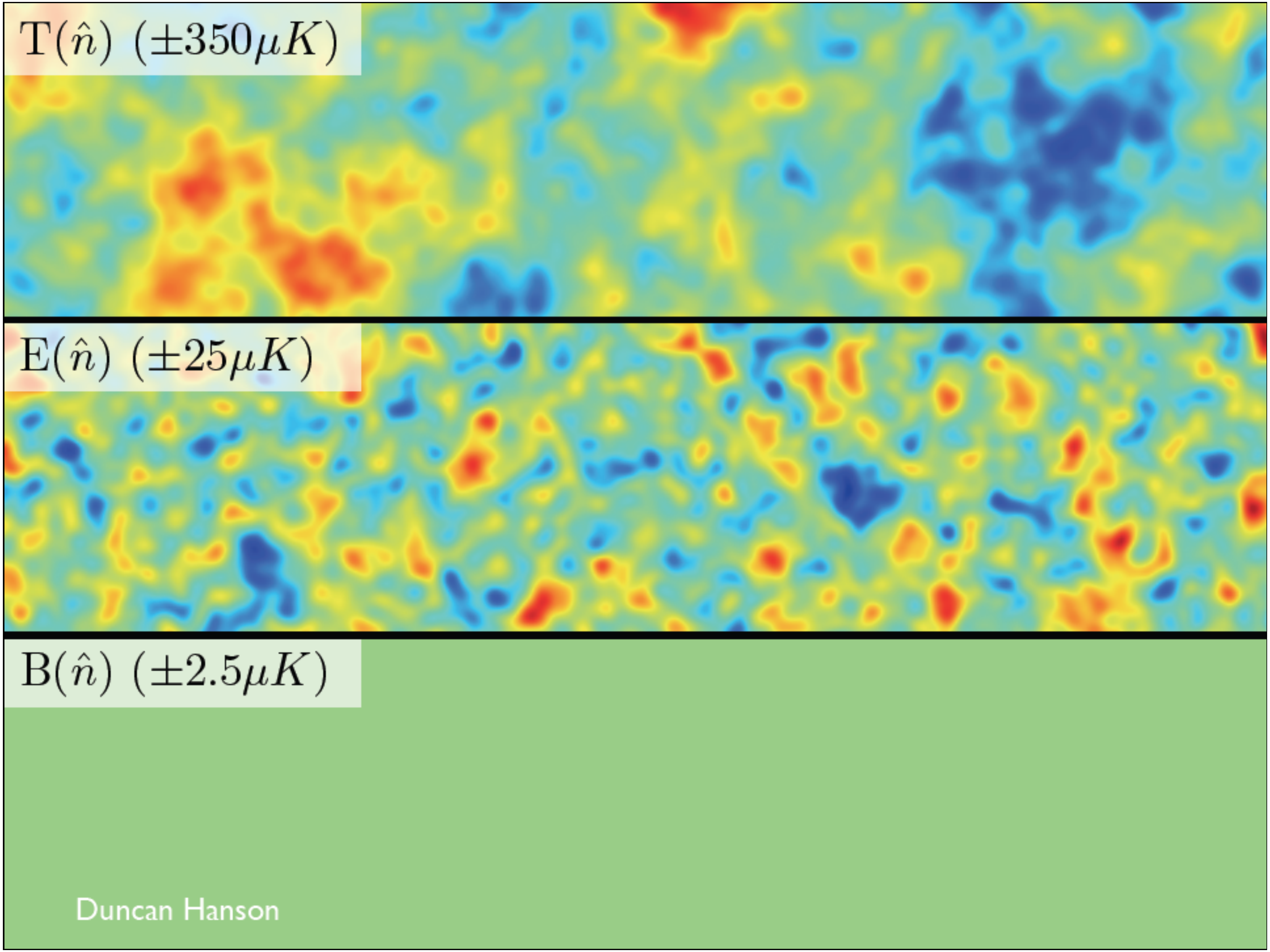


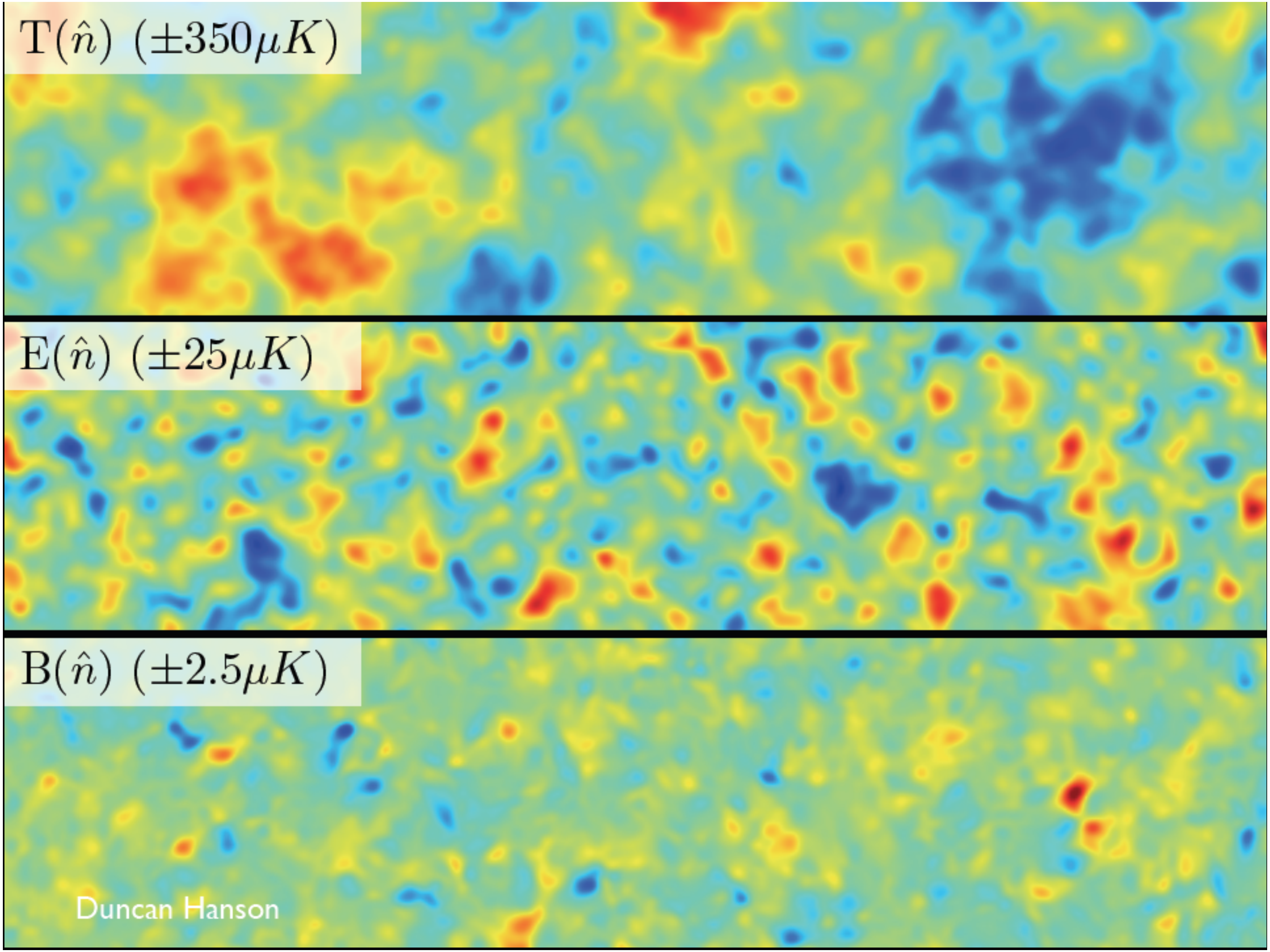
Deflections O(10^{-3}) , but coherent on degree scales

Probes matter distribution at roughly $0.5 < z < 6$ depending on l

Non-linear structure growth effects not a major headache

(Slide from A. Lewis, https://indico.in2p3.fr/event/14661/timetable/#all)


$T(\hat{n})$ $(\pm 350\mu K)$
$E(\hat{n})$ $(\pm 25\mu K)$
$B(\hat{n})$ $(\pm 2.5\mu K)$
Duncan Hanson


$T(\hat{n})$ $(\pm 350\mu K)$
$E(\hat{n})$ $(\pm 25\mu K)$
$B(\hat{n})$ $(\pm 2.5\mu K)$
Duncan Hanson

Detectability of B-modes. Delensing

- Gravitational lensing induced by Large Scale Structure generates B-modes.
- **Delensing** is necessary in order to reduce this additonal source of confusion.

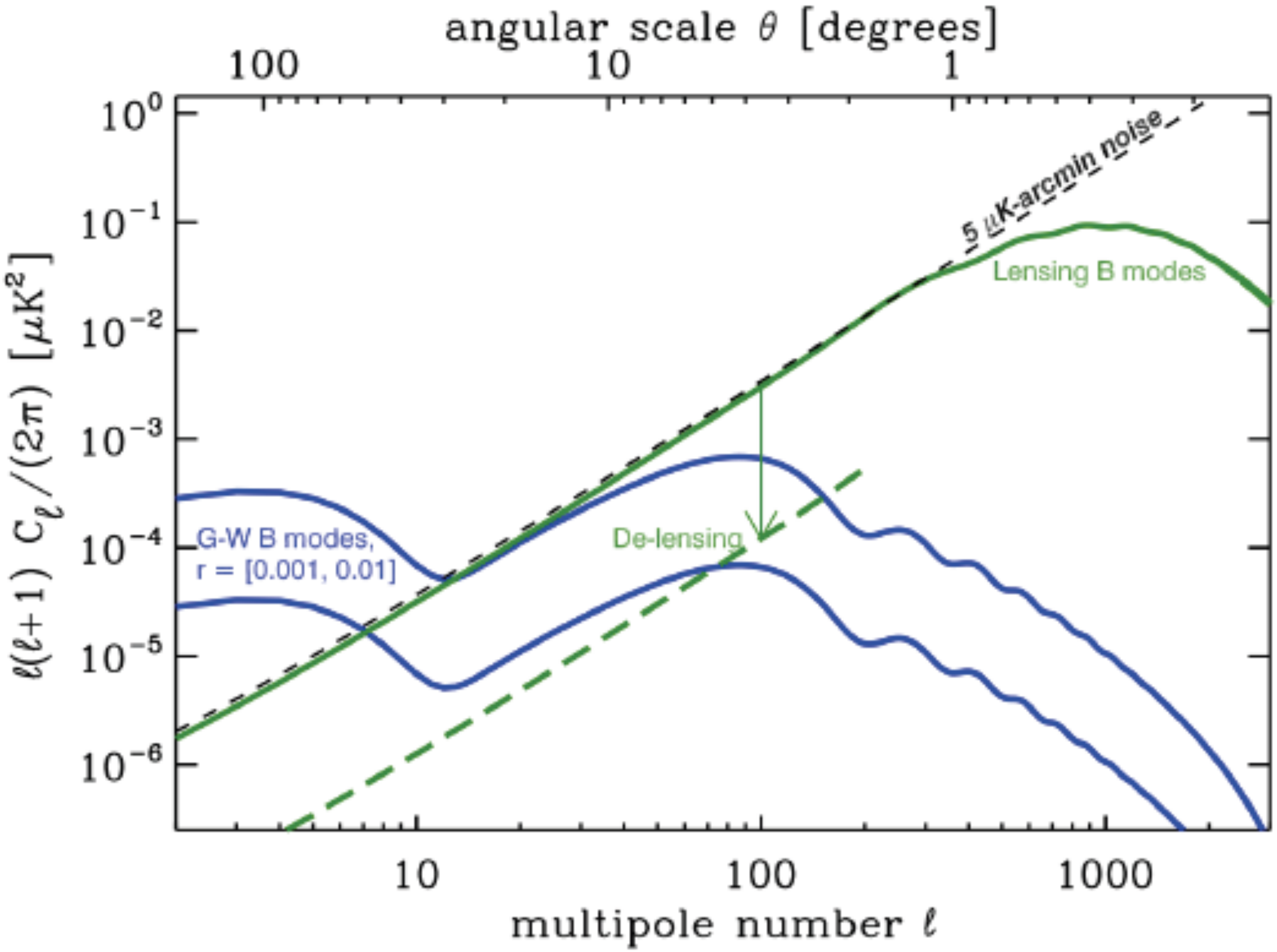


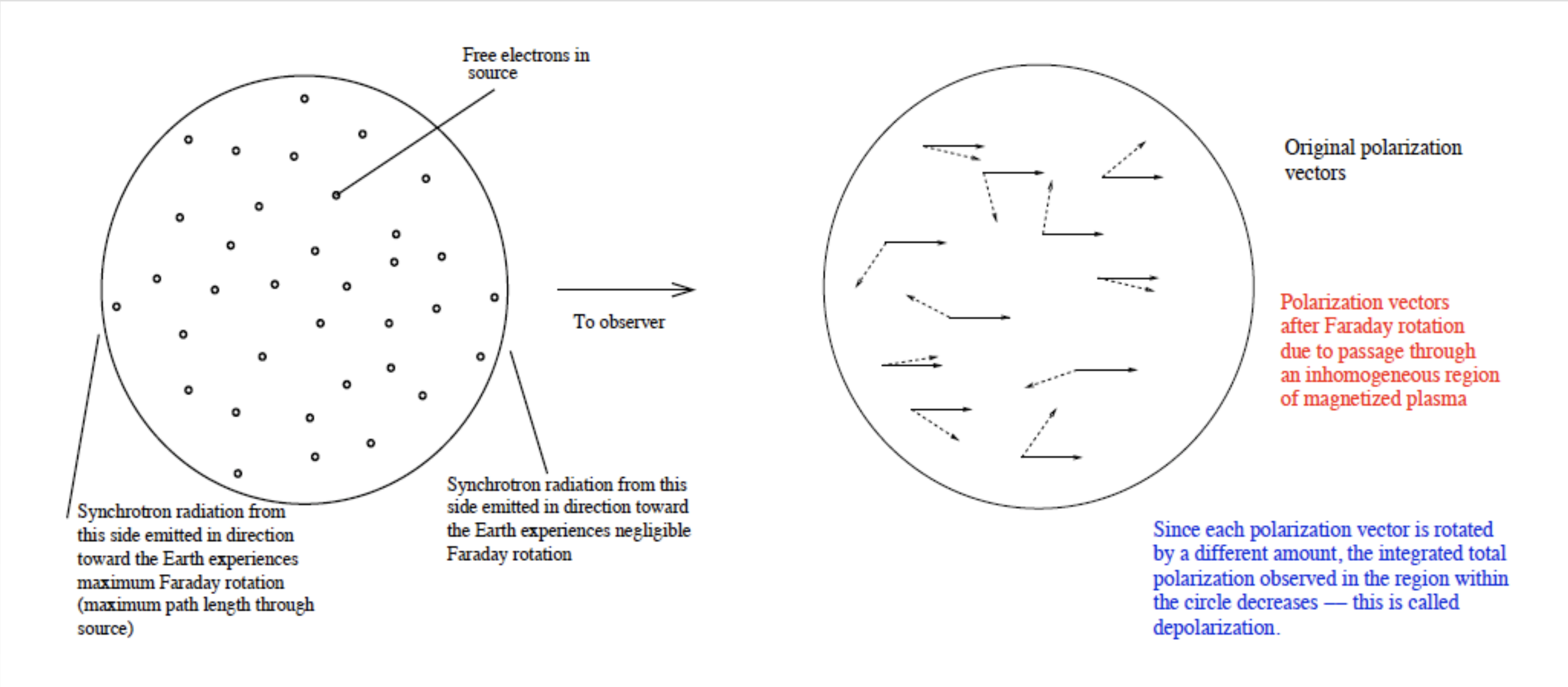
Figure from CMB-S4 Science Book

Synchrotron emission: propagation effects

A) Faraday Rotation. A rotation of the plane of polarization of an EM wave that occurs if it passes through a region with free electrons and magnetic field.

$$\Delta\theta = (RM)\lambda^2 \qquad RM \propto \int B_{\parallel} n_e dl$$

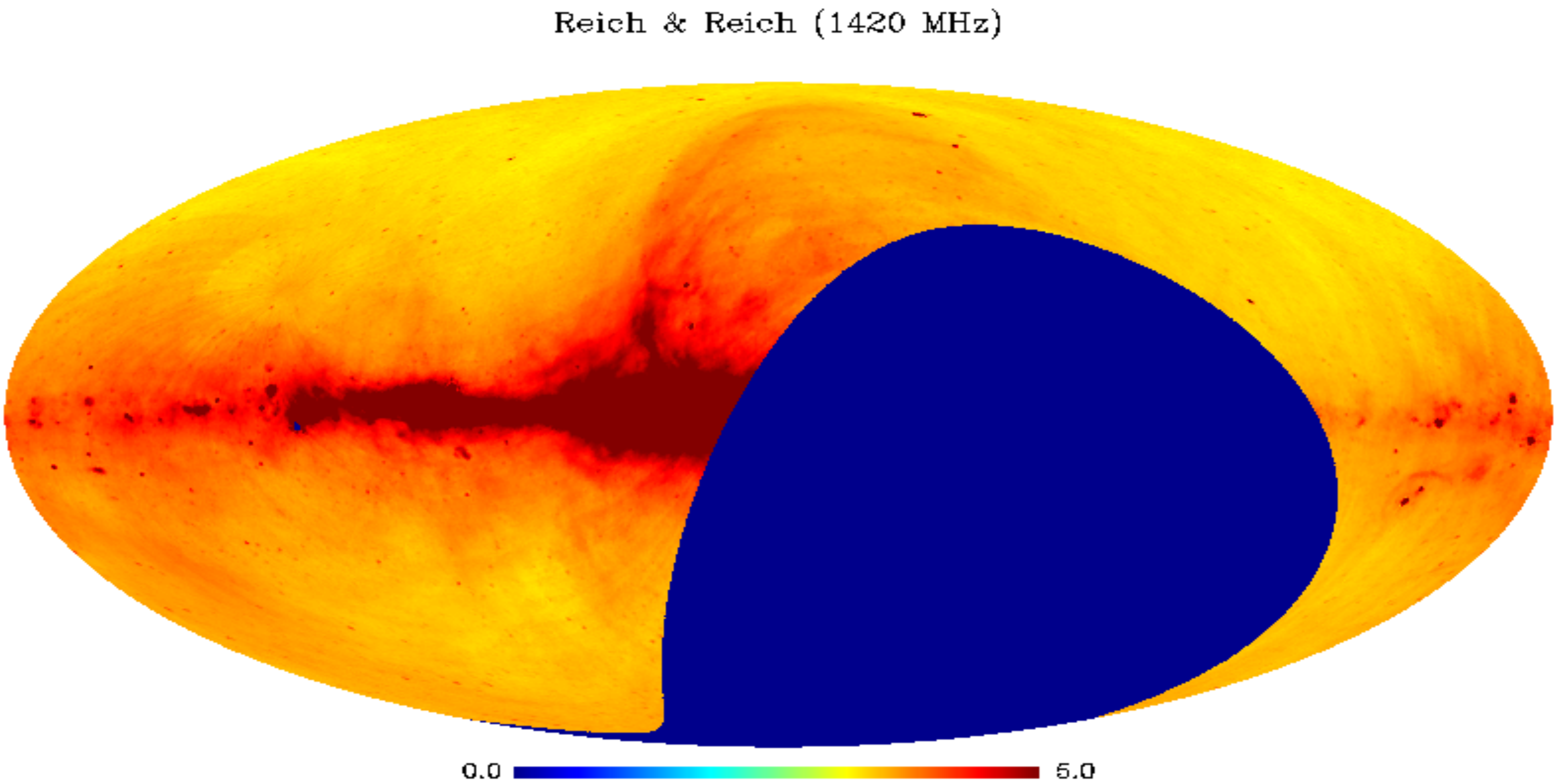
B) Depolarization. Faraday Rotation can "depolarize" due to two effects.



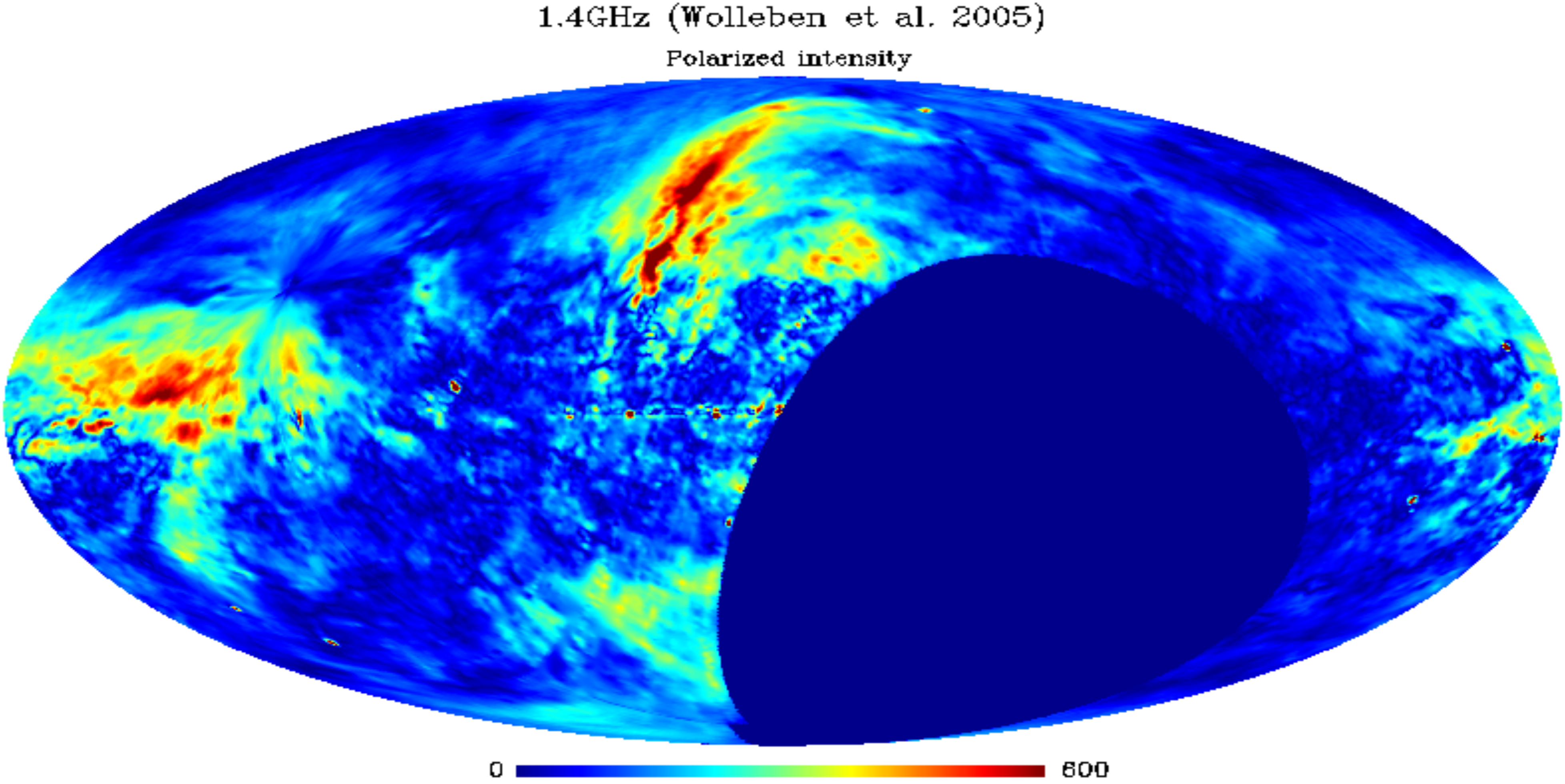
Front-back depolarization

Beam depolarization

Galactic radio-continuum. 21 cm.

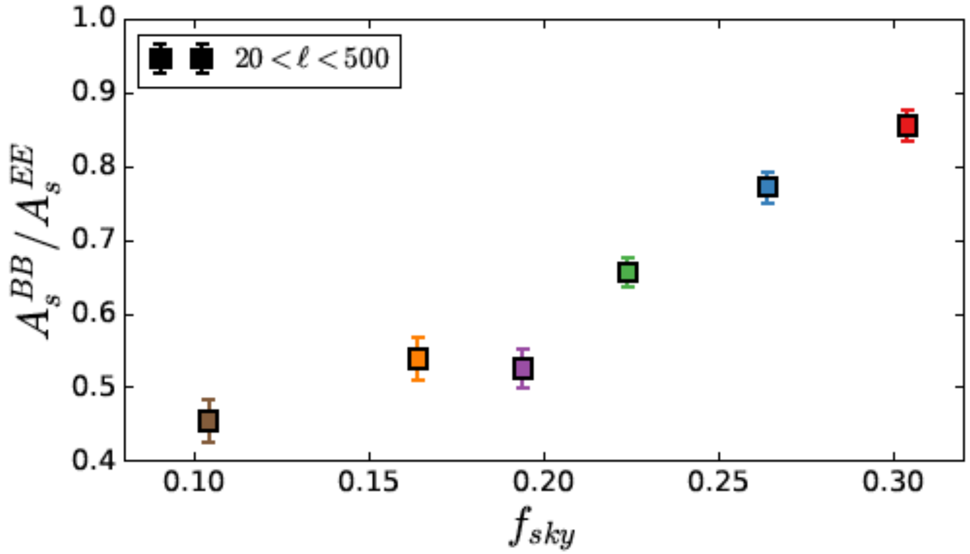


Galactic radio-continuum. 21 cm.

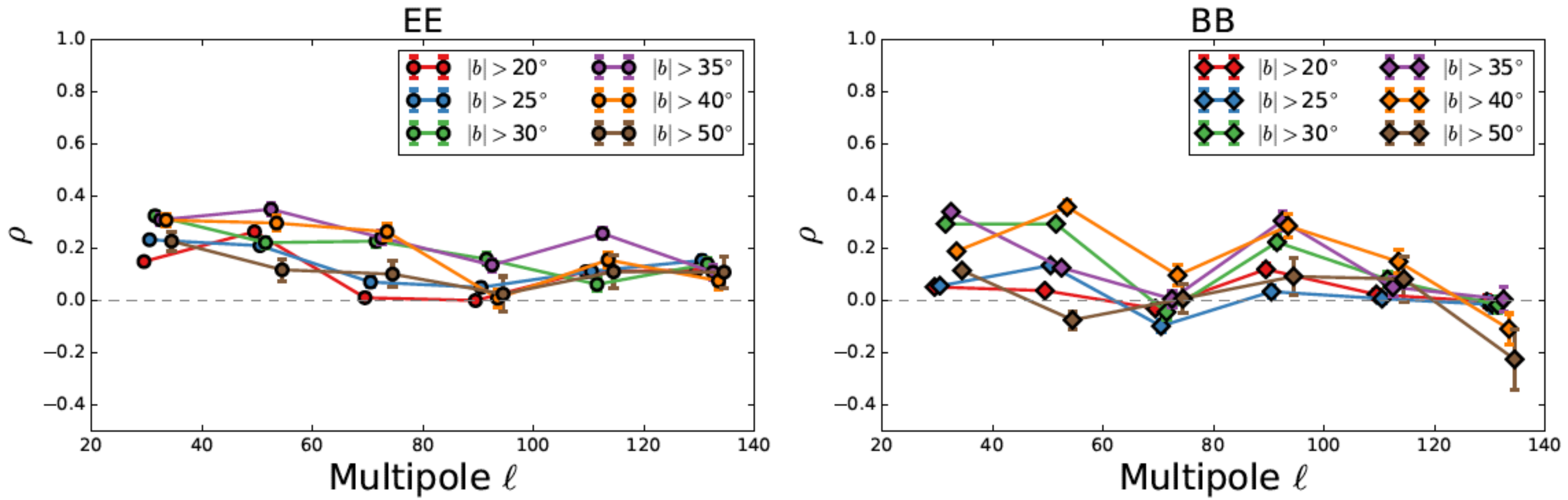


S-PASS

Dependence of the ratio BB/EE with the sky region



Correlation coefficient for thermal dust and synchrotron, using S-PASS and Planck 353 GHz maps.



Krachmalnicoff et al. (2018), arXiv: 1802.01145.

Low-frequency polarisaton surveys needed!

Q-U-I JOint Tenerife Experiment (QUIJOTE)

11, 13 ,17, 19, 30 and 40 GHz

Two telescopes at Tenerife

I,Q,U

Full northern sky

1 deg angular resolution

Target sensitivity ≈ 4 - 25 μK/deg^2

1 - 5 ≈ μK/deg^2

Capable of charterising the synchrotron (including curvature) and AME spectra in polarisation, by its own

C-Band All Sky Survey (C-BASS)

5 GHz

One telescope in California, other in ZA

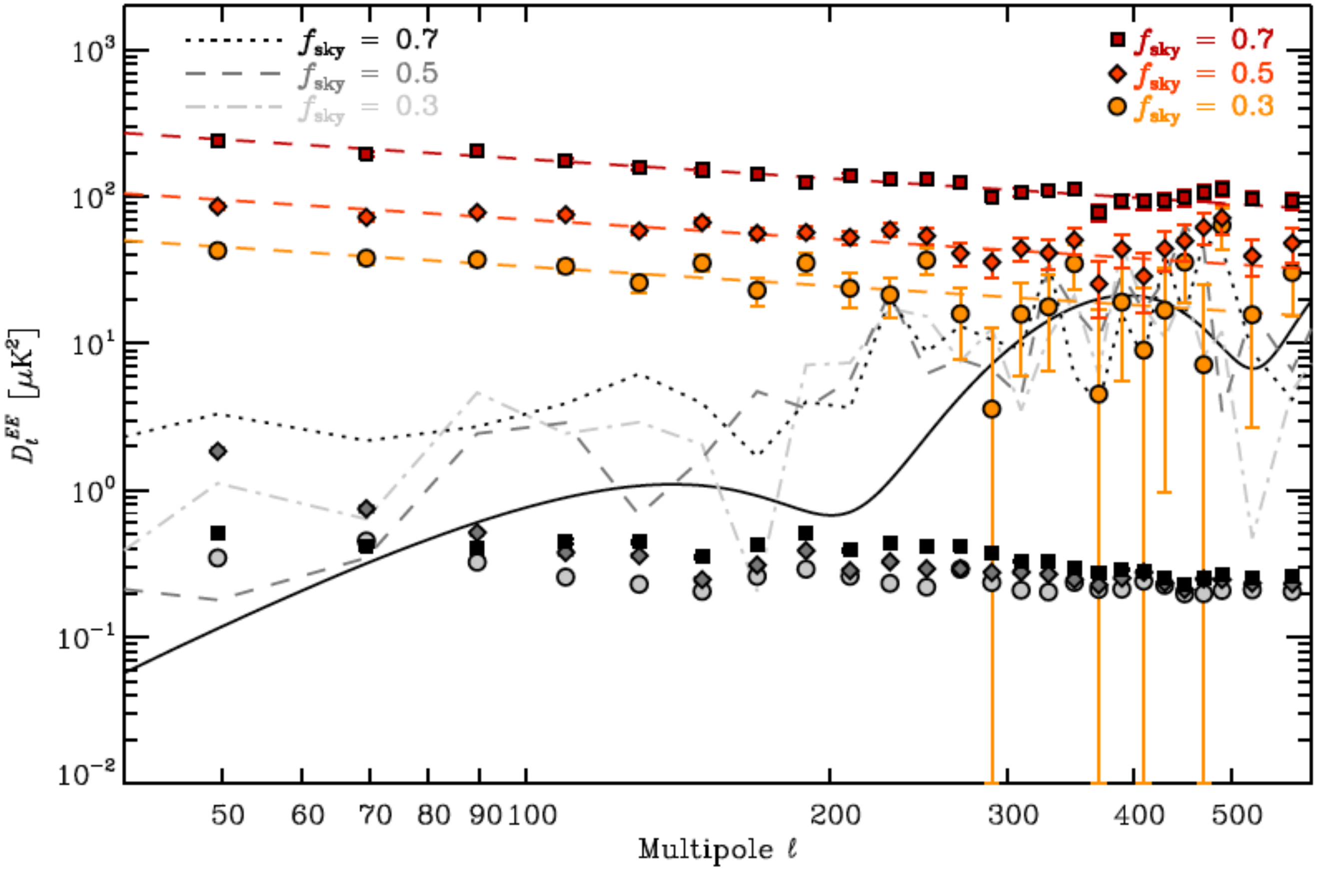
I,Q,U

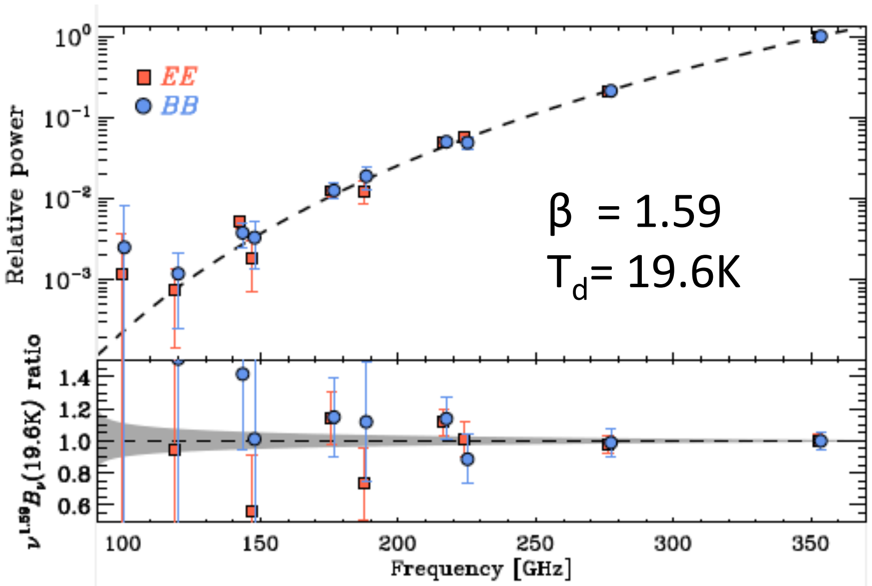
Full sky

45 arcmin angular resolution

Will help to determine the synchtrotron amplitude, and spectral index, in combination with others

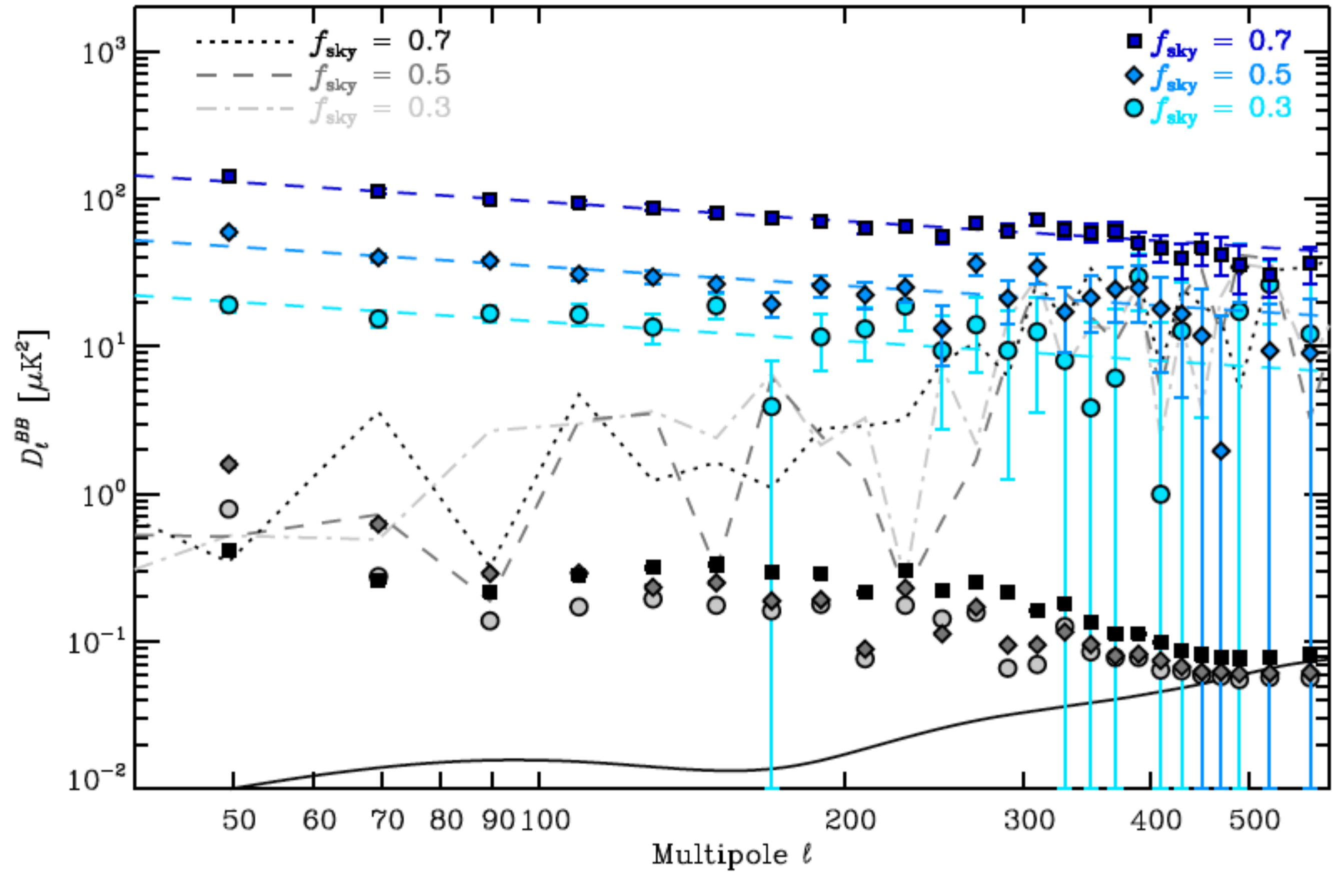
E-mode contribution from dust emission

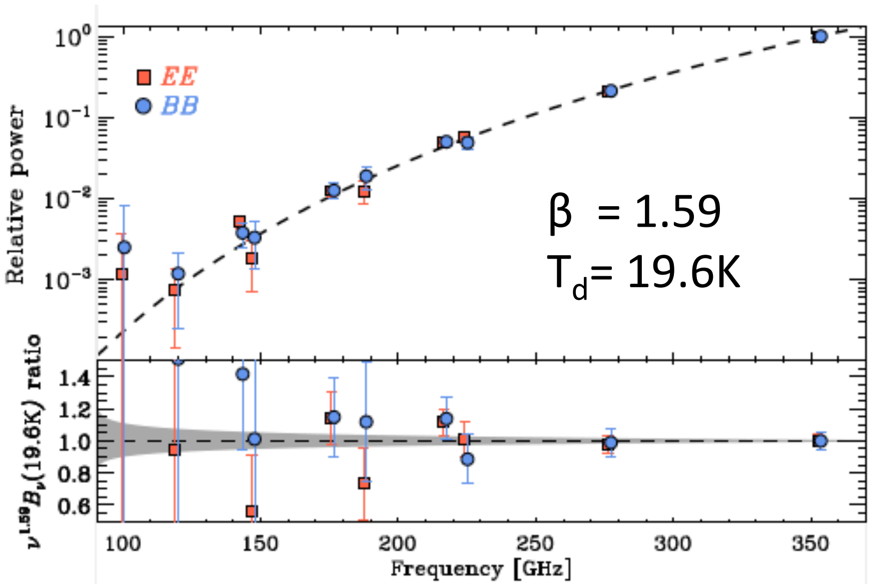




Planck Collaboration Int. XXX, 2014

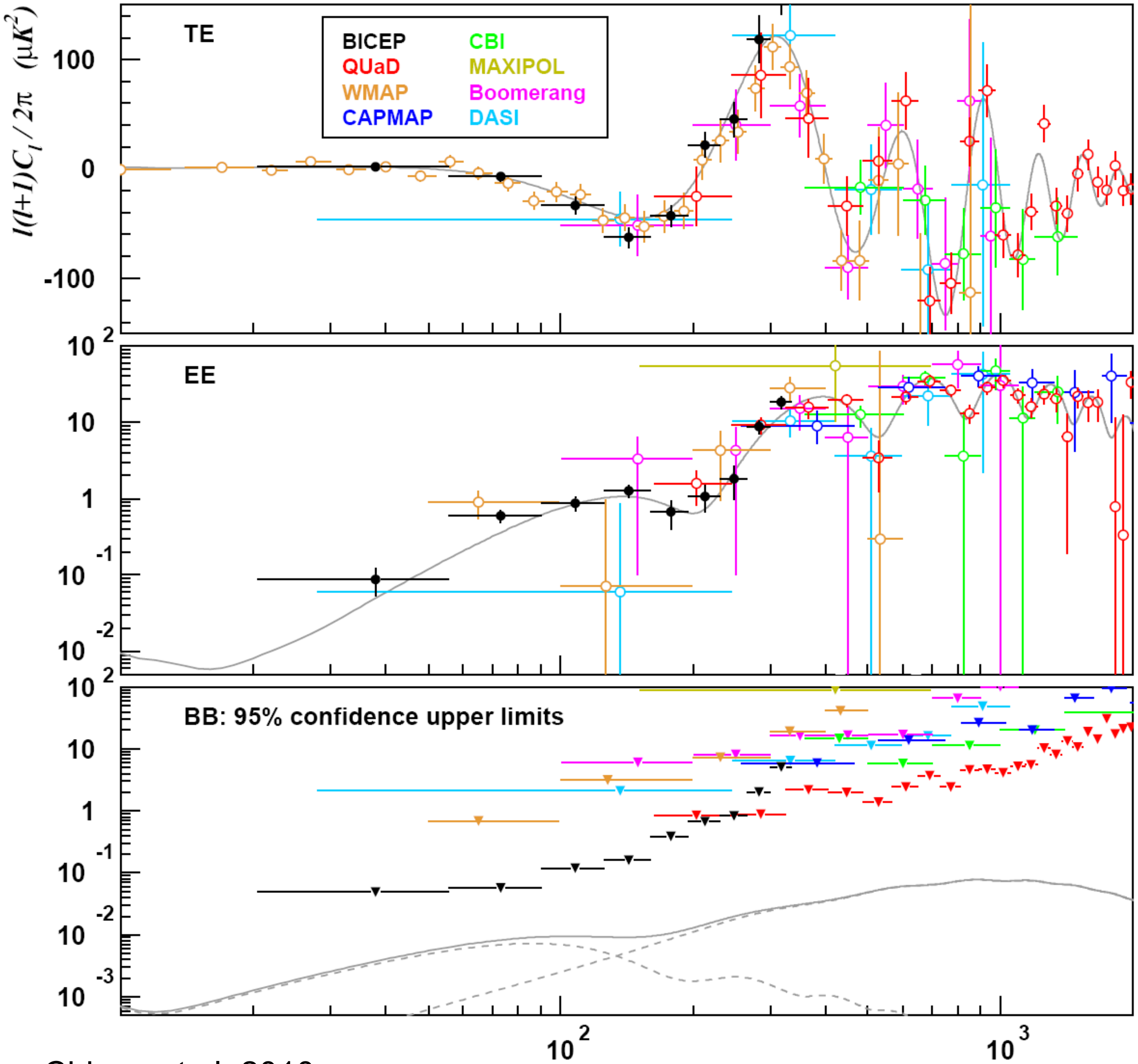
B-mode contribution from dust emission





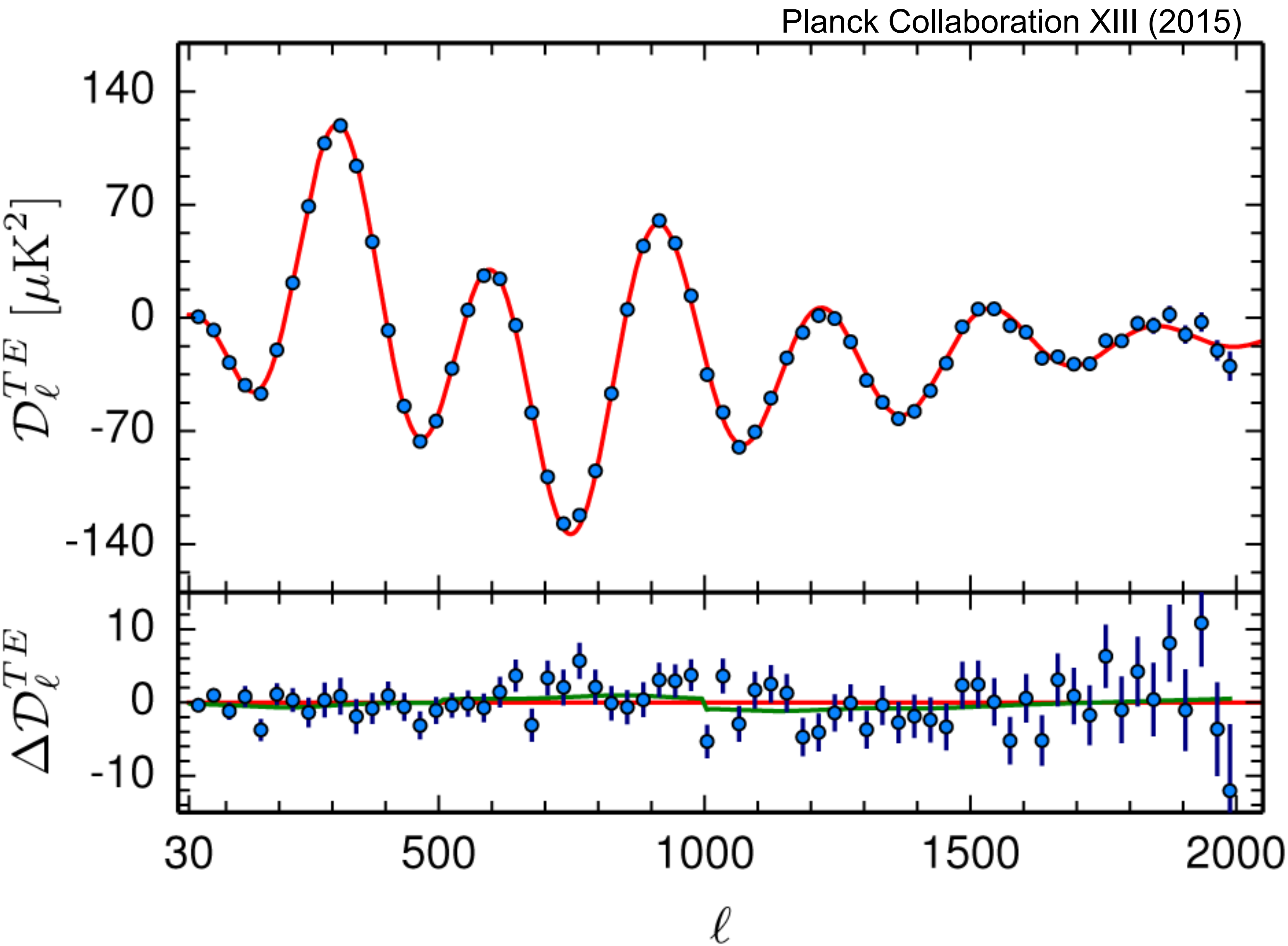
Planck Collaboration Int. XXX, 2014

CMB polarization: observational status

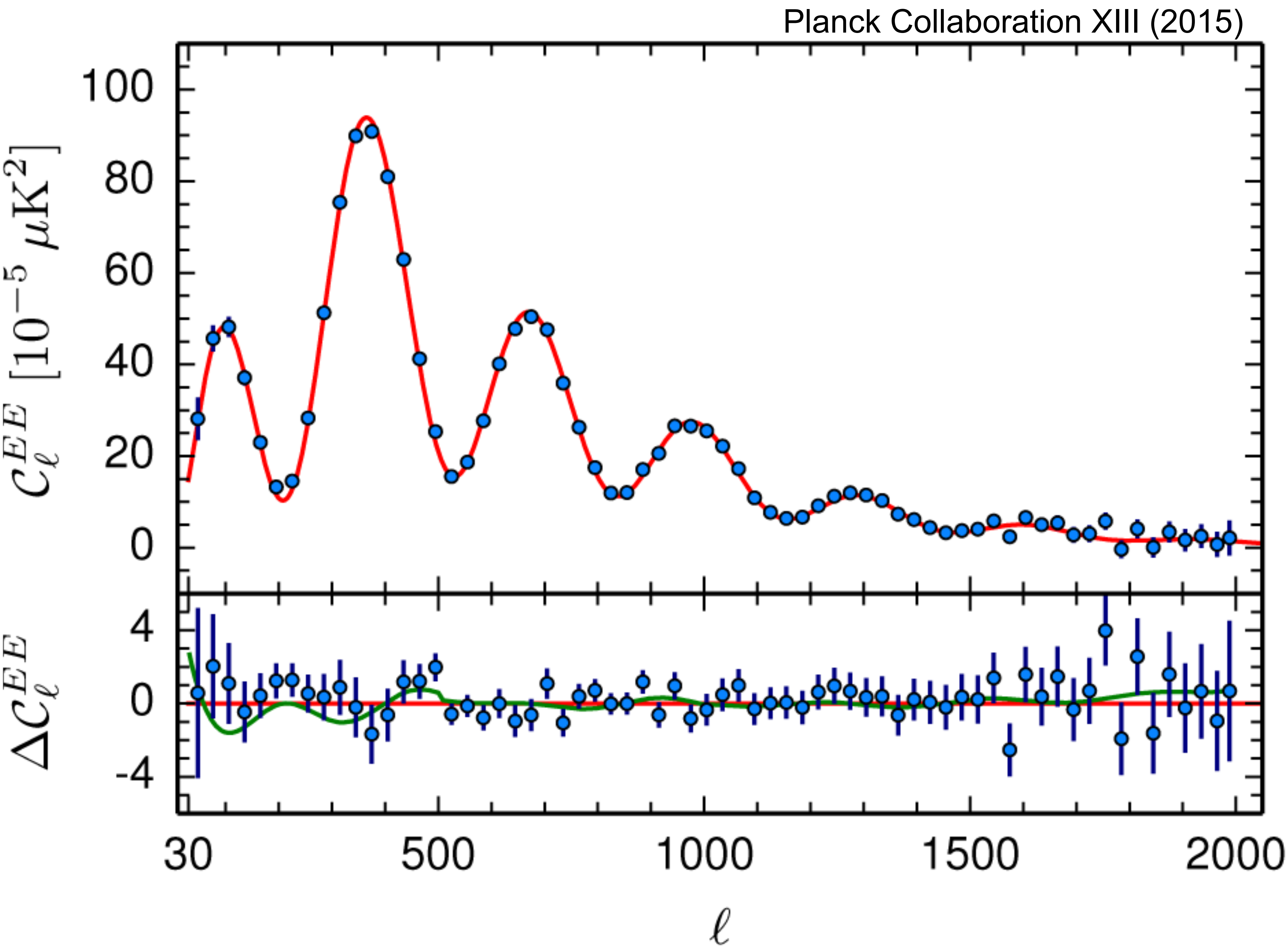


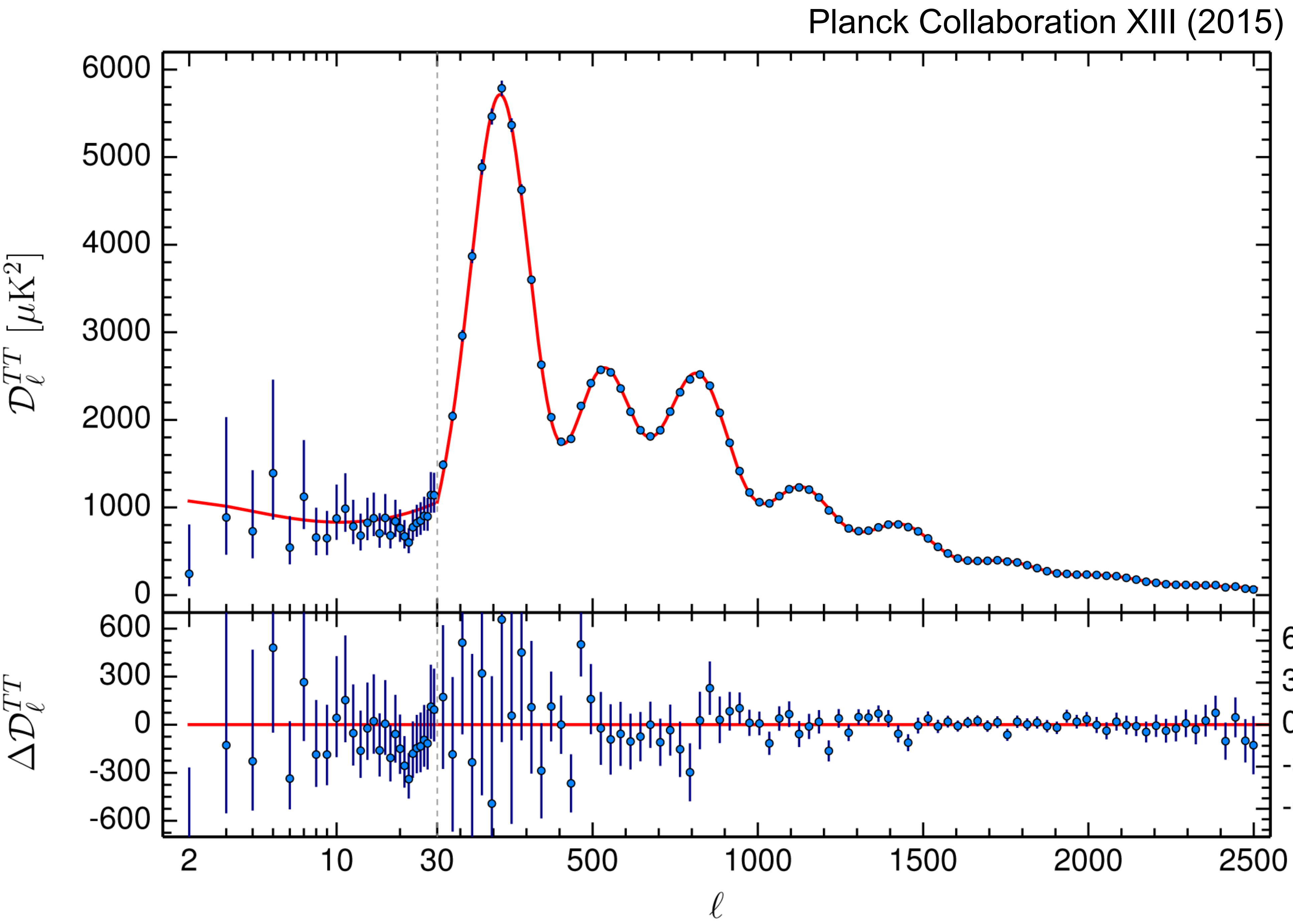
Chiang et al. 2010

- Several E-mode detections: DASI, CBI, CAPMAP, Boomerang, WMAP, QUAD, BICEP, QUIET, etc.
- WMAP7 gives r<0.93 at 95% using TE/EE/BB, and r<2.1 at 95% with BB alone.
- WMAP7+BAO+SN gives r<0.2 (Komatsu et al. 2010).
- BICEP: r<0.72 at 95% with BB only (Chiang et al. 2010).
- QUIET: $r=0.35^{+1.06}_{-0.87}$ with BB only (Bischoff et al. 2010)

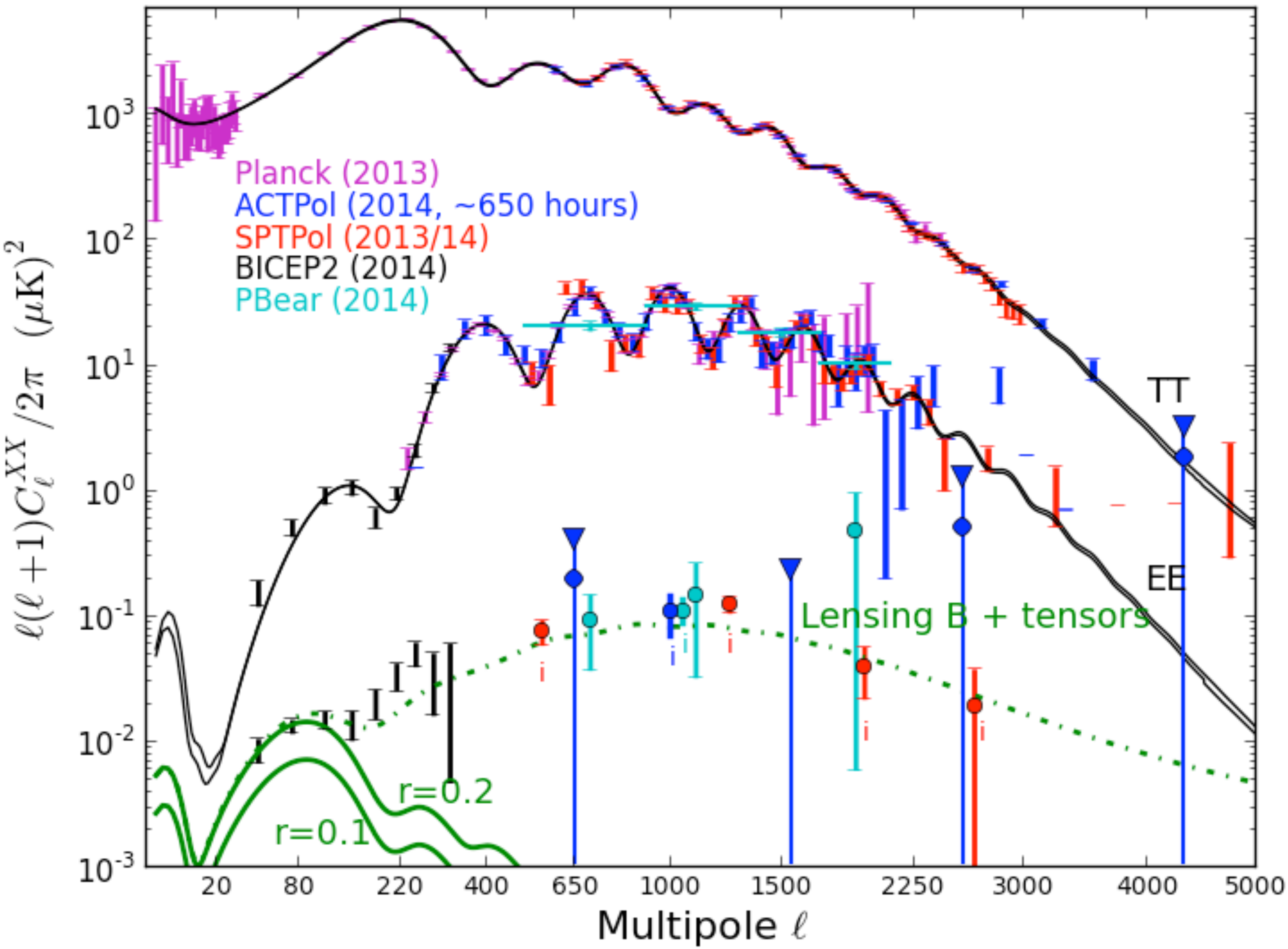


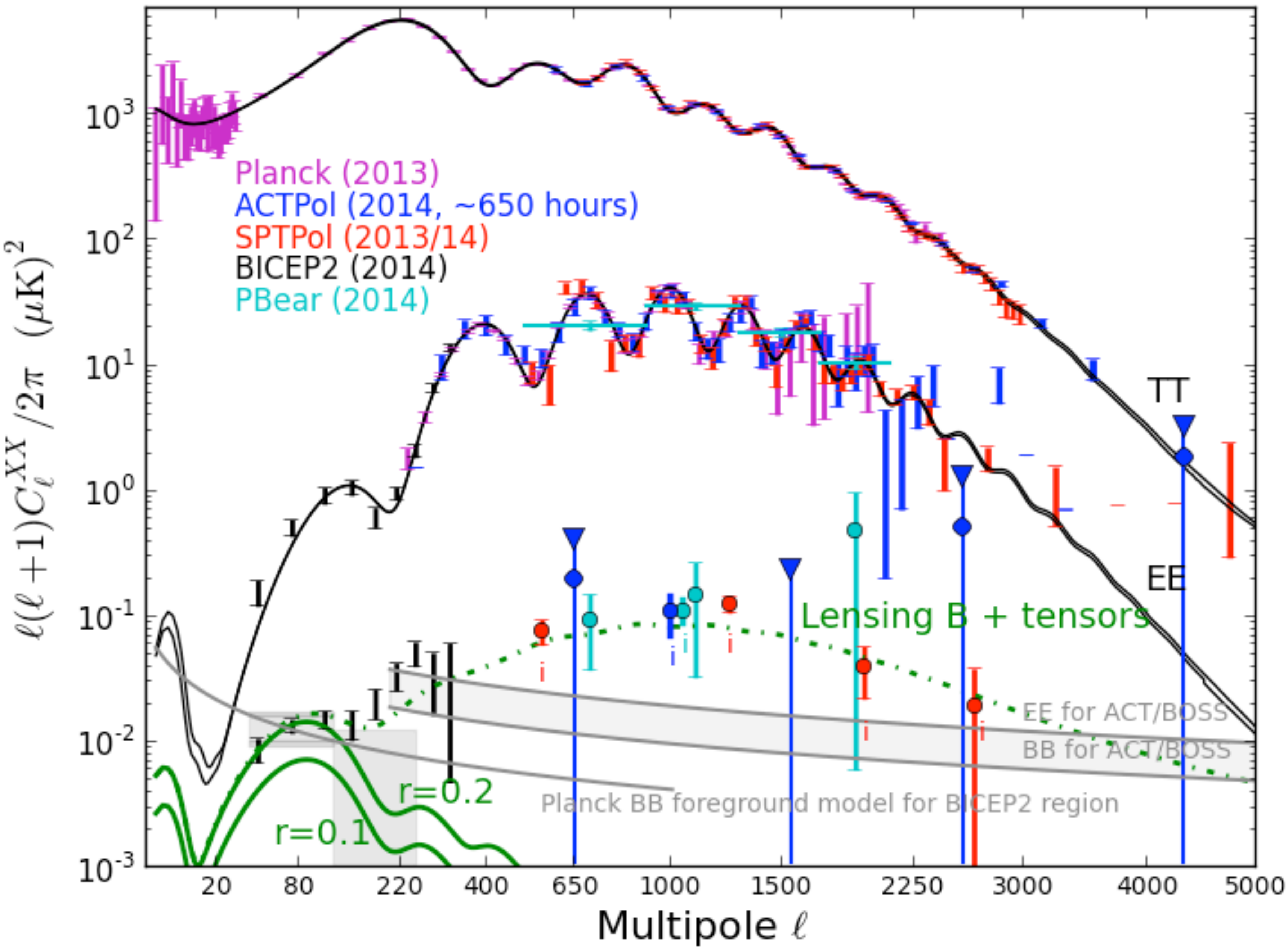
Planck Collaboration XIII (2015)
140
70
0
-70
-140
$\mathcal{D}_\ell^{TE}$ [μK^2]
10
0
-10
$\Delta\mathcal{D}_\ell^{TE}$
30
500
1000
1500
2000
ℓ


Planck Collaboration XIII (2015)
100
80
60
40
20
0
4
0
-4
30
500
1000
1500
2000
$C_\ell^{EE}\ [10^{-5}\ \mu\mathrm{K}^2]$
ΔC_ℓ^{EE}
ℓ


Planck Collaboration XIII (2015)
$\mathcal{D}_\ell^{TT}$ [μK^2]
6000
5000
4000
3000
2000
1000
0
$\Delta\mathcal{D}_\ell^{TT}$
600
300
0
-300
-600
60
30
0
-30
-60
2
10
30
500
1000
1500
2000
2500
ℓ

State of TT, EE, BB – early 2015





Planck (2013)
ACTPol (2014, ~650 hours)
SPTPol (2013/14)
BICEP2 (2014)
PBear (2014)
TT
EE
Lensing B + tensors
EE for ACT/BOSS
BB for ACT/BOSS
Planck BB foreground model for BICEP2 region
r=0.2
r=0.1
$\ell(\ell+1)C_\ell^{XX}/2\pi\ \ (\mu\mathrm{K})^2$
Multipole ℓ

Systematic effects

Parameter	Effect	Goal	Method
Cross-Polar Beam response	E →B	< 0.003	Rotate Instrument, Wave Plate
Main lobe ellipticity (0.5° beam)	dT → B	$< 10^{-4}$	Rotate Instrument, Wave Plate
Polarized sidelobes (response at Galaxy)	dT → B	$< 10^{-6}$	Baffles/shielding/measure
Instrumental polarization	dT → B	$< 10^{-4}$	Rotate Instrument, Wave Plate
Polarization angle	E → B	< 0.2 °	Measure
Relative pointing (of differenced samples)	dT → B	< 0.1″	Dual-polarization pixels
Relative calibration	dT → B	$< 10^{-5}$	Modulators
Relative calibration drift (scan synchronous)	T → B	$< 10^{-9}$	Modulators
Lyot Stop Temperature (10% spill, scan synch.)	$dT_{opt} \rightarrow B$	$dT_{opt} < 30$ nK	Measure
Cold stage T drifts (scan synch.)	$dT_{CS} \rightarrow B$	$dT_{CS} < 1$ nK	Improve uniformity, measure

TABLE 6.1 *Performance goals for a CMB* **B**-*mode measurement. The first eight parameters describe instrumental effects that transform various sky signals into false* **B**-*mode signals; here we use* **T** *to indicate intensity,* **E** *to indicate the* **E**-*mode polarization signal, and* **dT** *to indicate CMB temperature anisotropies. The listed "Goal" is the level at which an individual instrumental effect will begin to cause a 10% contamination (in units of temperature) of an* **r** = *0.01* **B**-*mode signal in the most naïve experimental design. Clever scan strategies and partial correction of known levels of contamination can relax these requirements. See the text for more details.*

(Bock et al. 2006, arXiv:0604101)