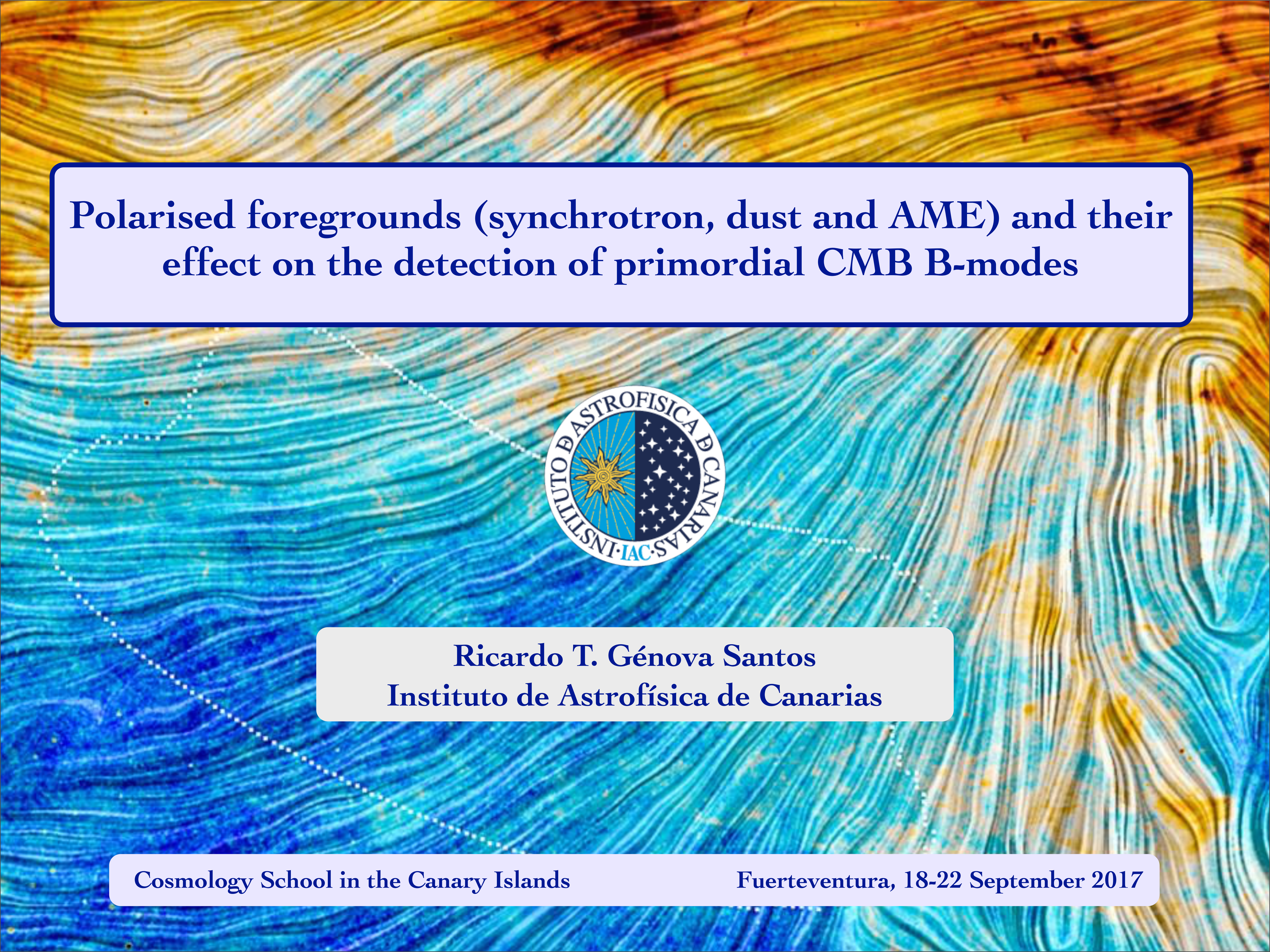

Polarised foregrounds (synchrotron, dust and AME) and their effect on the detection of primordial CMB B-modes

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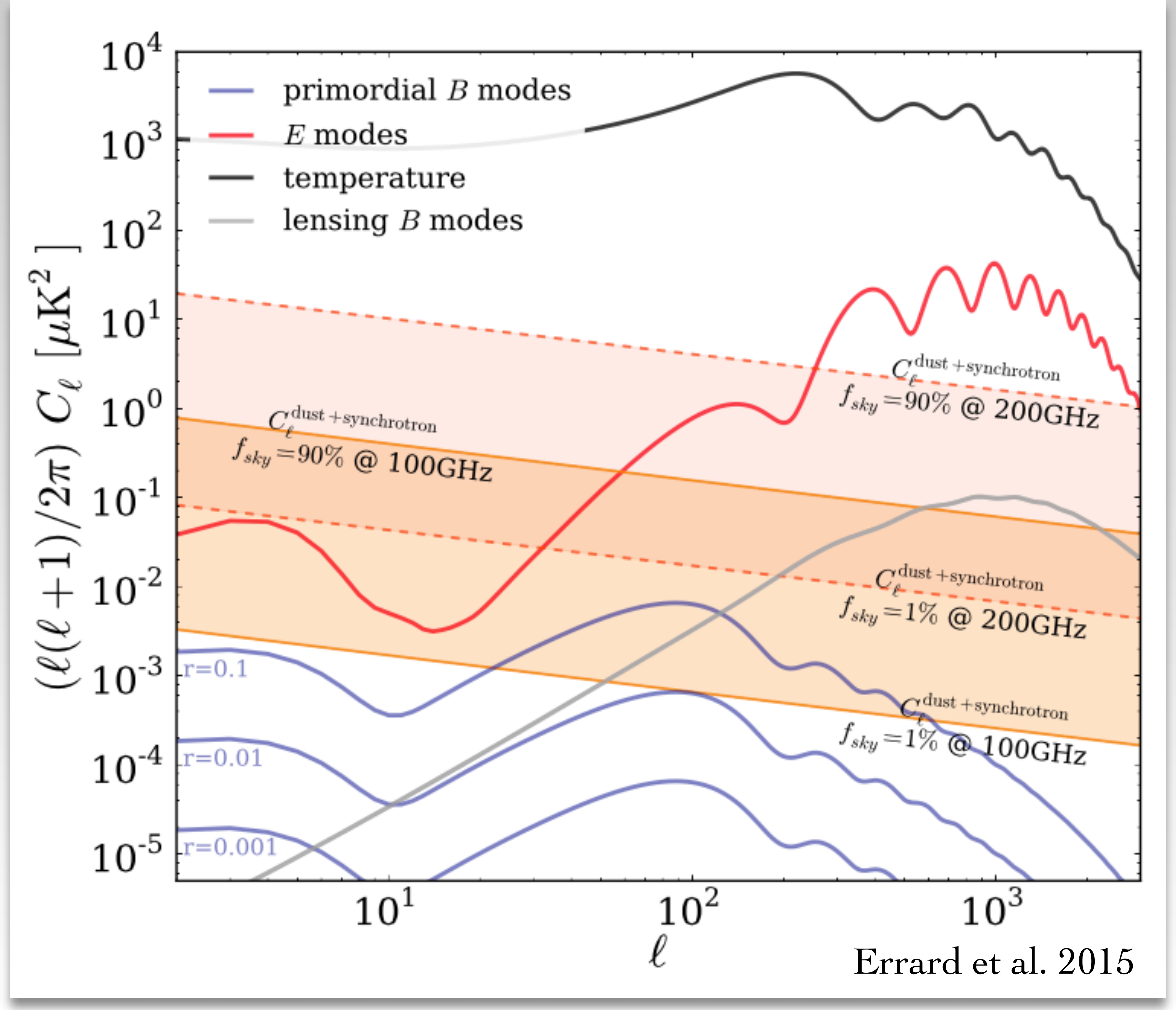
Cosmology School in the Canary Islands

Fuerteventura, 18-22 September 2017

Impact of foregrounds on the CMB

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



Errard et al. 2015

Foreground types

★ Foregrounds: 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
Cosmological	Cosmic Infrared background	Low	Small to intermediate
	Secondary anisotropies	Low	All
	Lensing	High	Small scales

Need to understand foregrounds!

★ Definitely must worry about polarised foregrounds, but...

★ Even unpolarised foregrounds are harmful, as they increase the white noise

$$\Delta T_{\rm RMS} = \frac{T_{\rm sys}}{\sqrt{\Delta\nu t}}$$

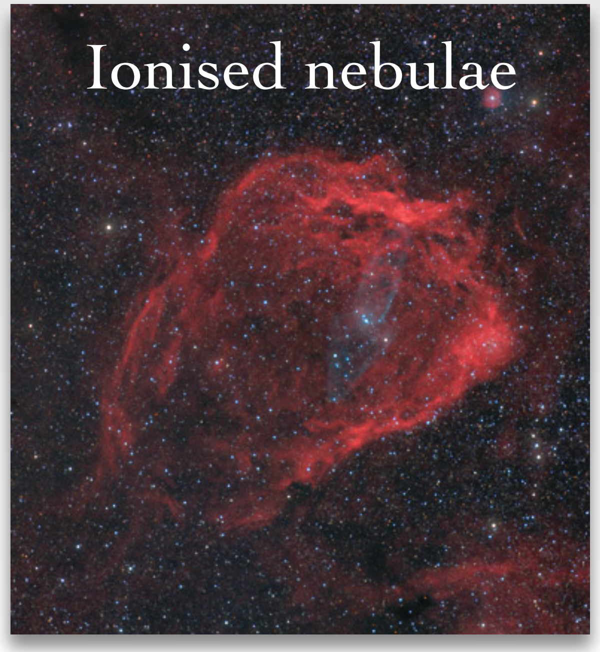
Radiometer ideal equation

$$T_{\rm sys} = T_{\rm gal} + T_{\rm atm} + T_{\rm rfi} + T_{\rm spill} + T_{\rm rec} + T_{\rm cmb} \ldots$$

Global system temperature

★ In addition, instrumental effects can lead to I→P leakage, i.e. unpolarised signals are seen as polarised by the instrument

- Need accurate modelling of the spectrum and of the spatial distribution of all possible foregrounds, both in intensity and in polarisation
- They are of astrophysical interest in their own right!



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
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Galactic	**Galactic synchrotron radiation**	**~ 10-40 %**	**Large scales**
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	Galactic electric dipole emission	**<1 %**	**Large scales**
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	Lensing	High	Small scales

Synchrotron emission

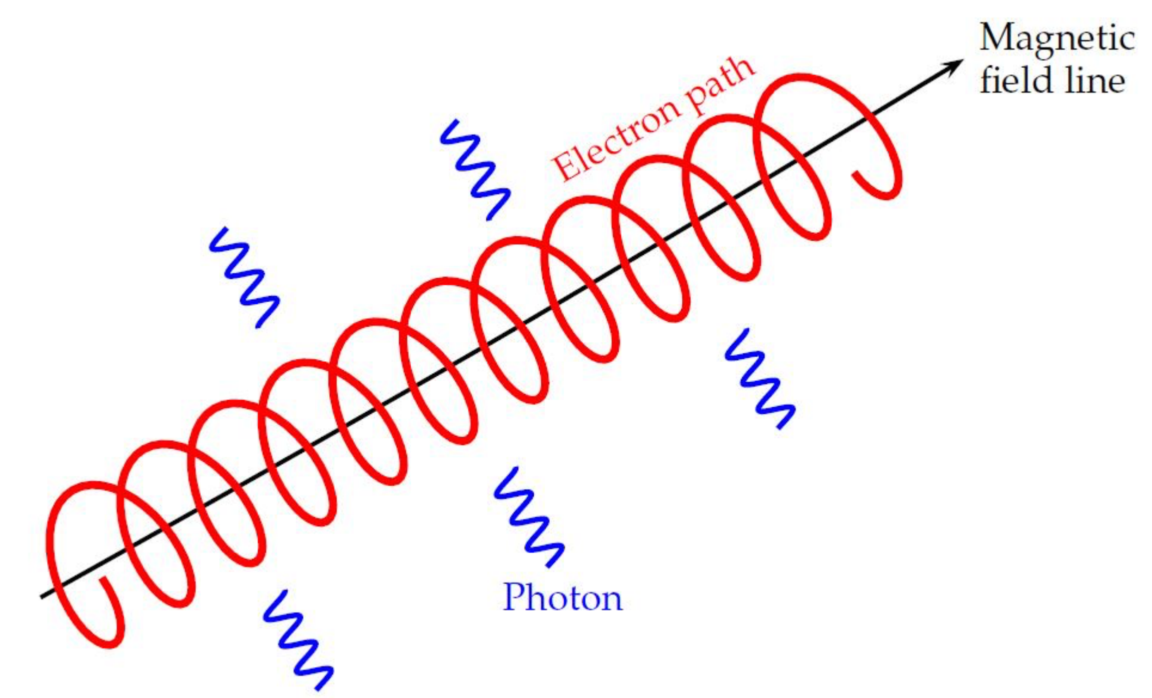
★ Magnetic bremsstrahlung from cosmic-ray relativistic (high-energy) electrons spiriling and accelerated by the strong magnetic fields

★ SNRs, radio galaxies, QSOs

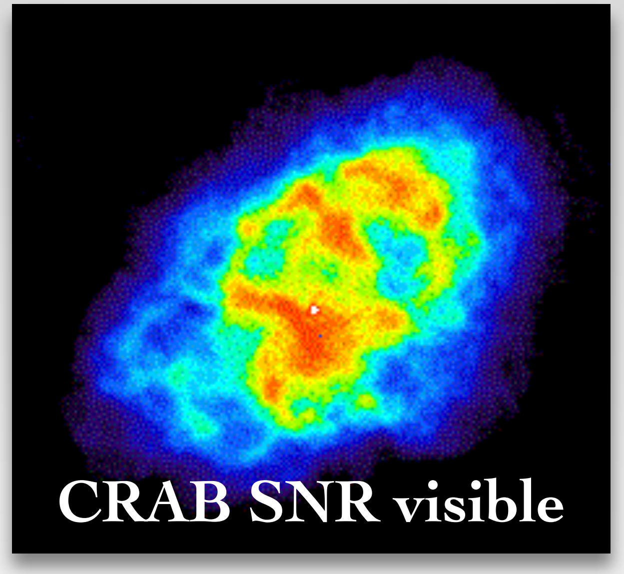
★ For a power-law distribution of electron energies $N(E) \propto E^{-p}$

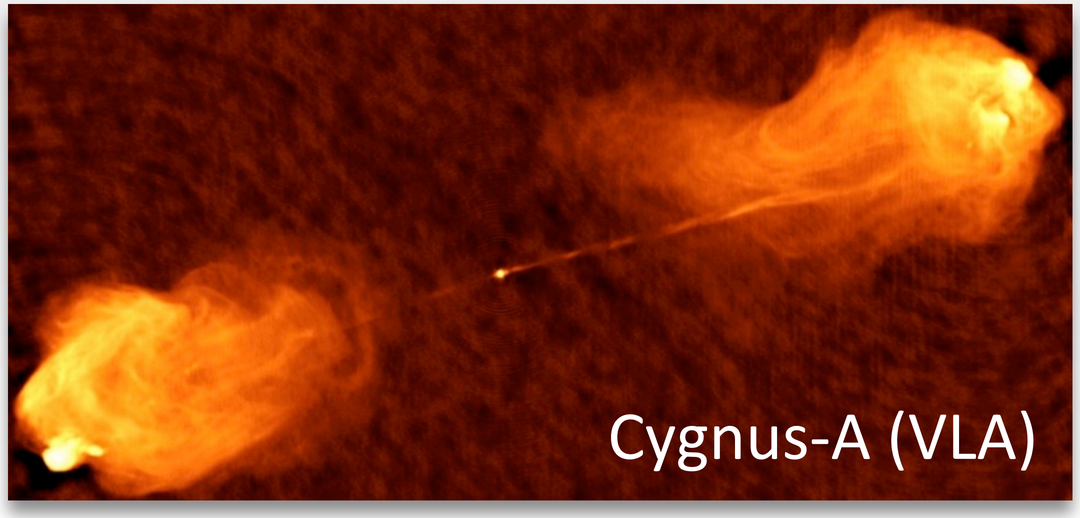
- Spectral index: $\beta = -\dfrac{p+3}{2}$
- Polarisaton fraction: $\dfrac{P}{I} = \dfrac{p+1}{p+7/3}$

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



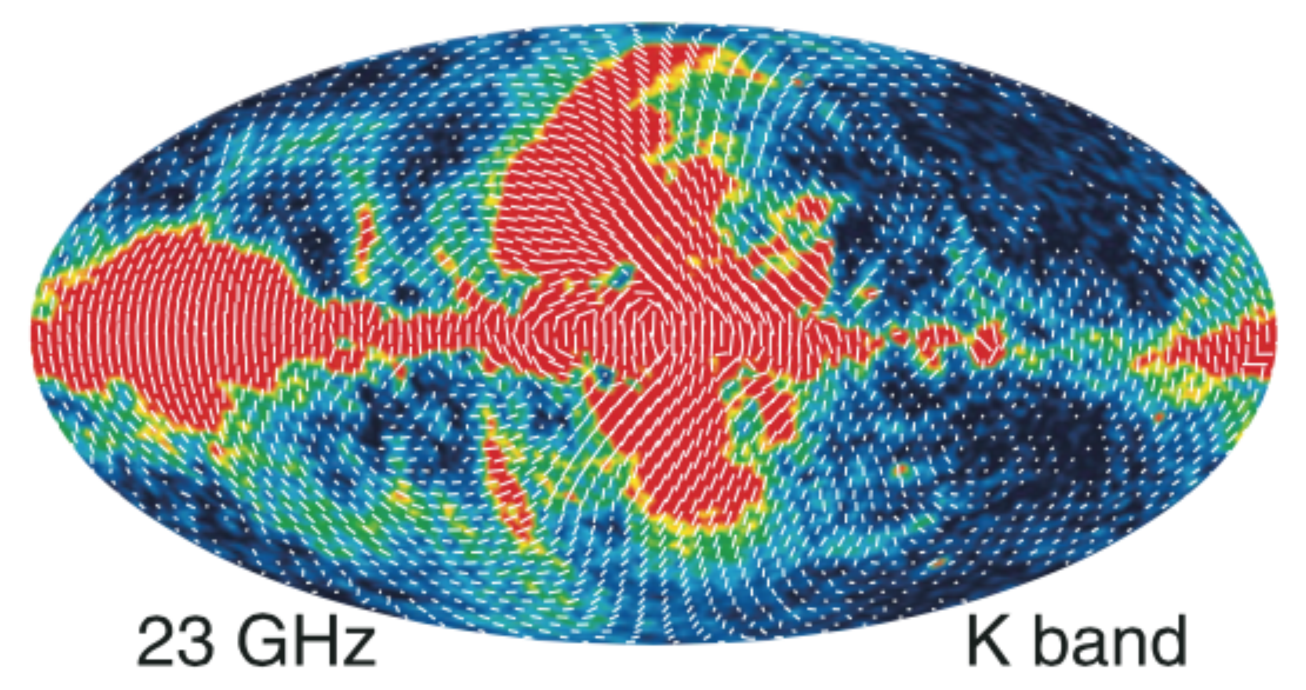

CRAB SNR radio


CRAB SNR visible


Cygnus-A (VLA)

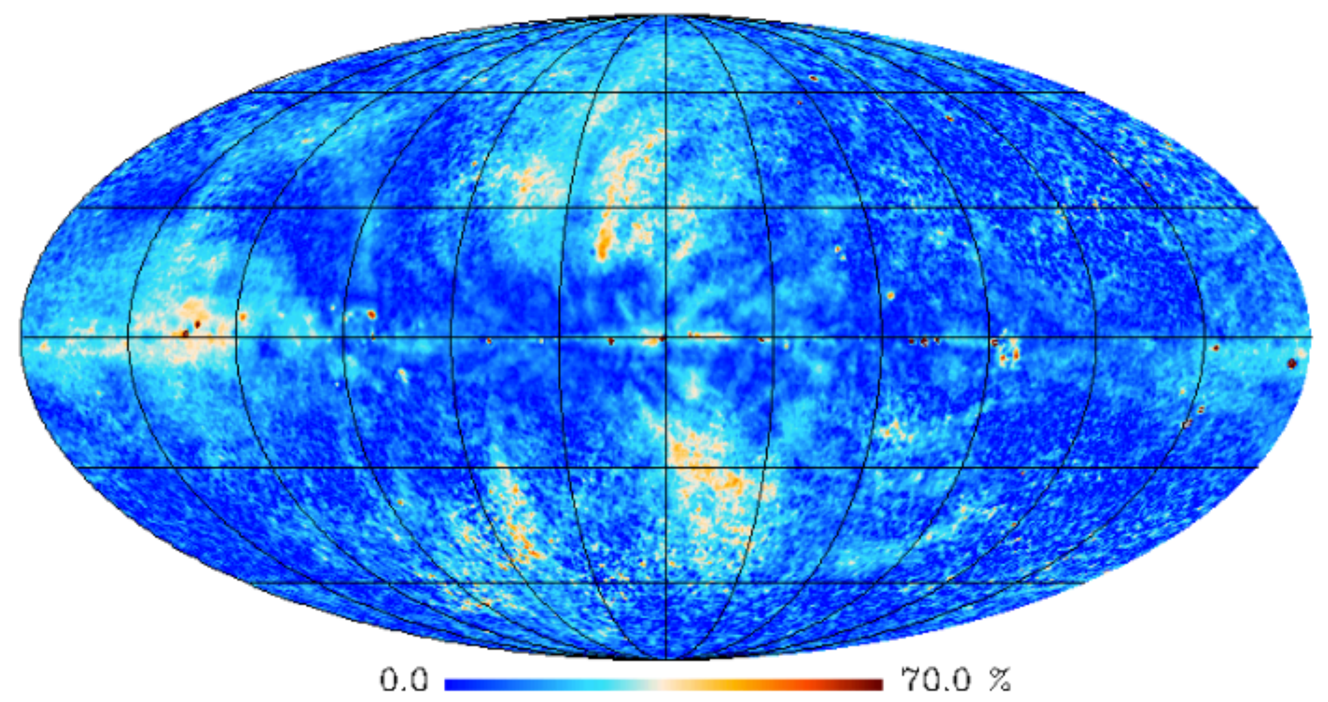
Synchrotron emission

P at 23 GHz, WMAP9



Bennet et al. (2013)

P/I at 23 GHz, from Commander/Planck



Planck 2015 results, XXV

- Maximum polarisation fractions of the order of 50%, on average **≈10-40%**
- Decrease at lower frequencies ($\lesssim$ 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)

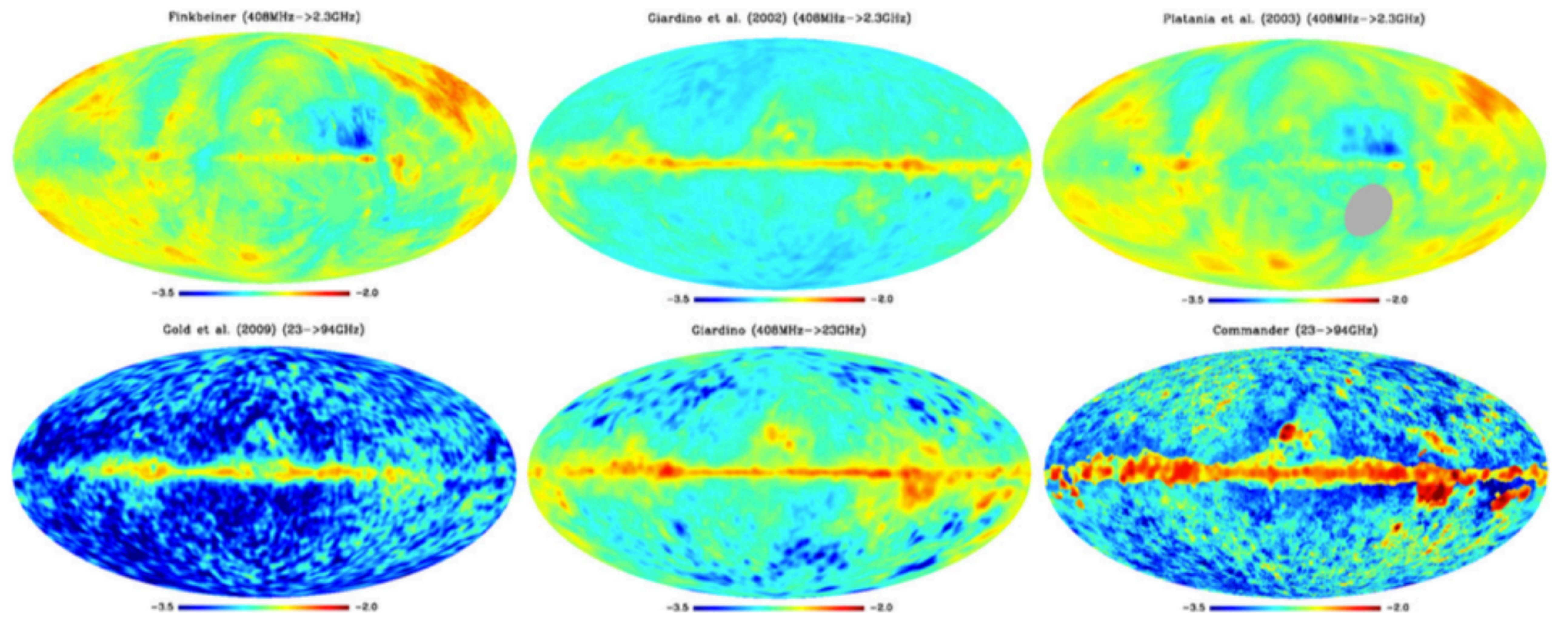
Synchrotron emission

★ Normally modelled with two parameters (*A*, β)

★ Typical spectral indices **β~ -3.2 to -2.5** (important at low frequencies, ≲ 10 GHz)

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

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



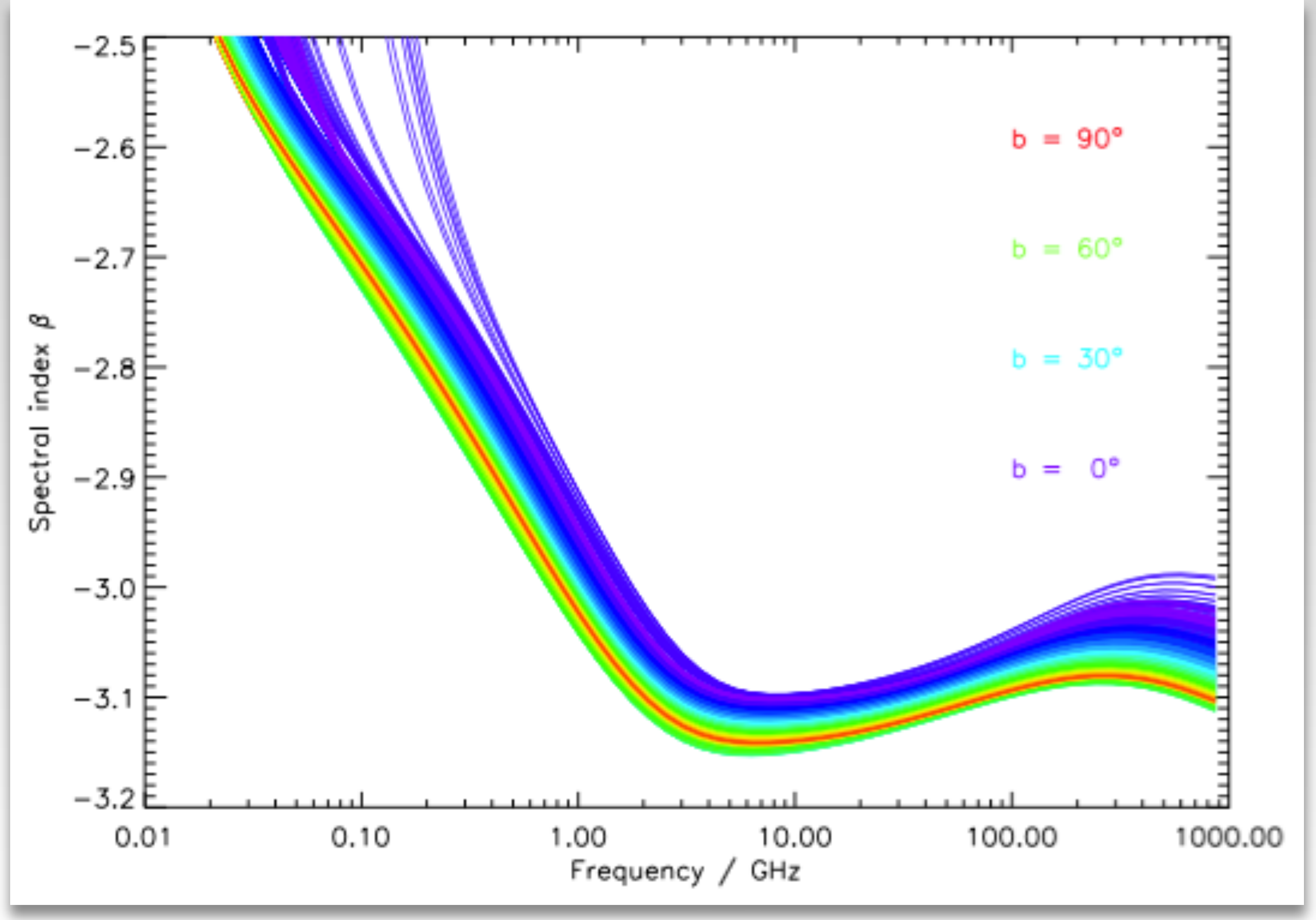
(Dickinson et al. 2009)

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)



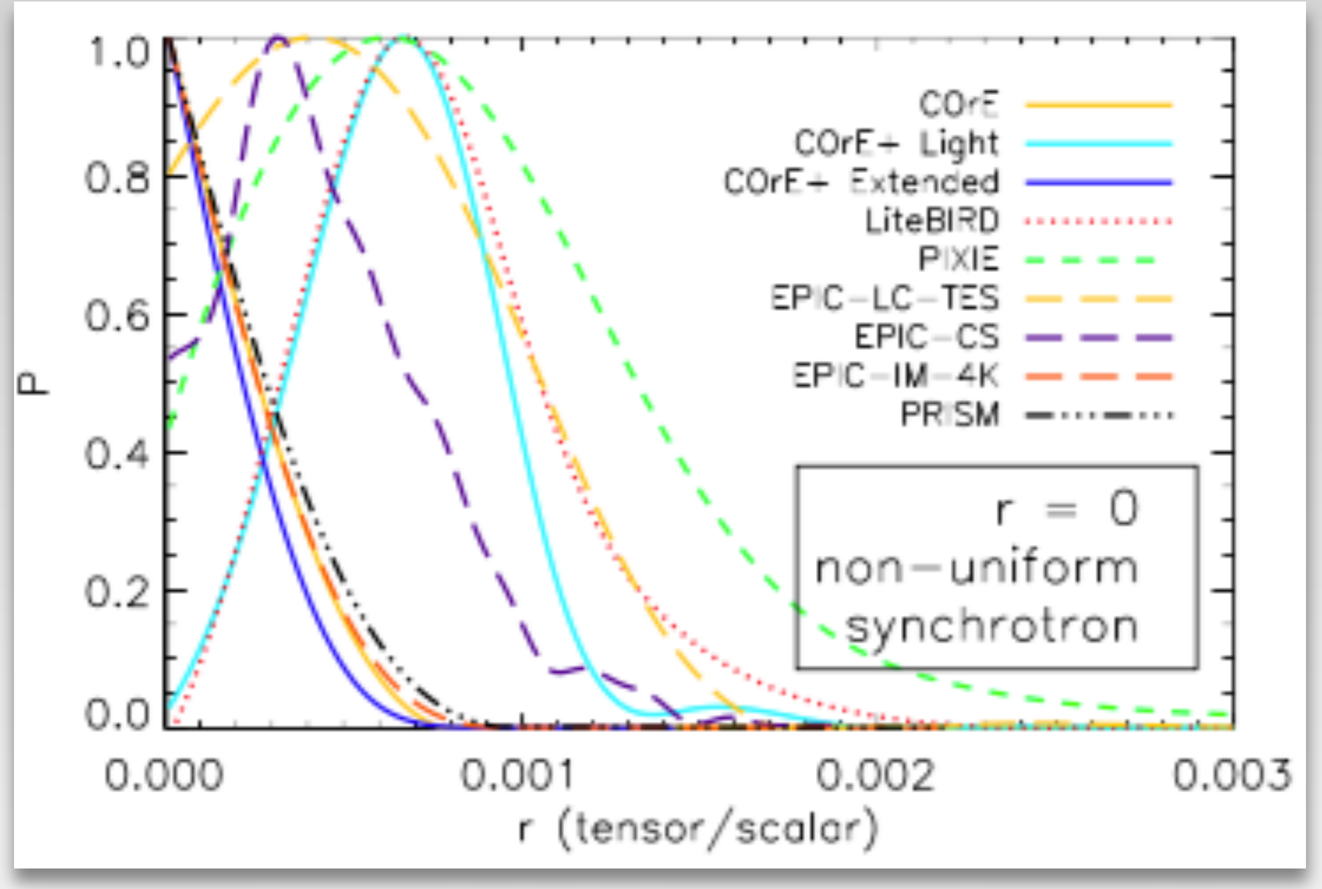
★ Maybe fitting a single power law will not be enough

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

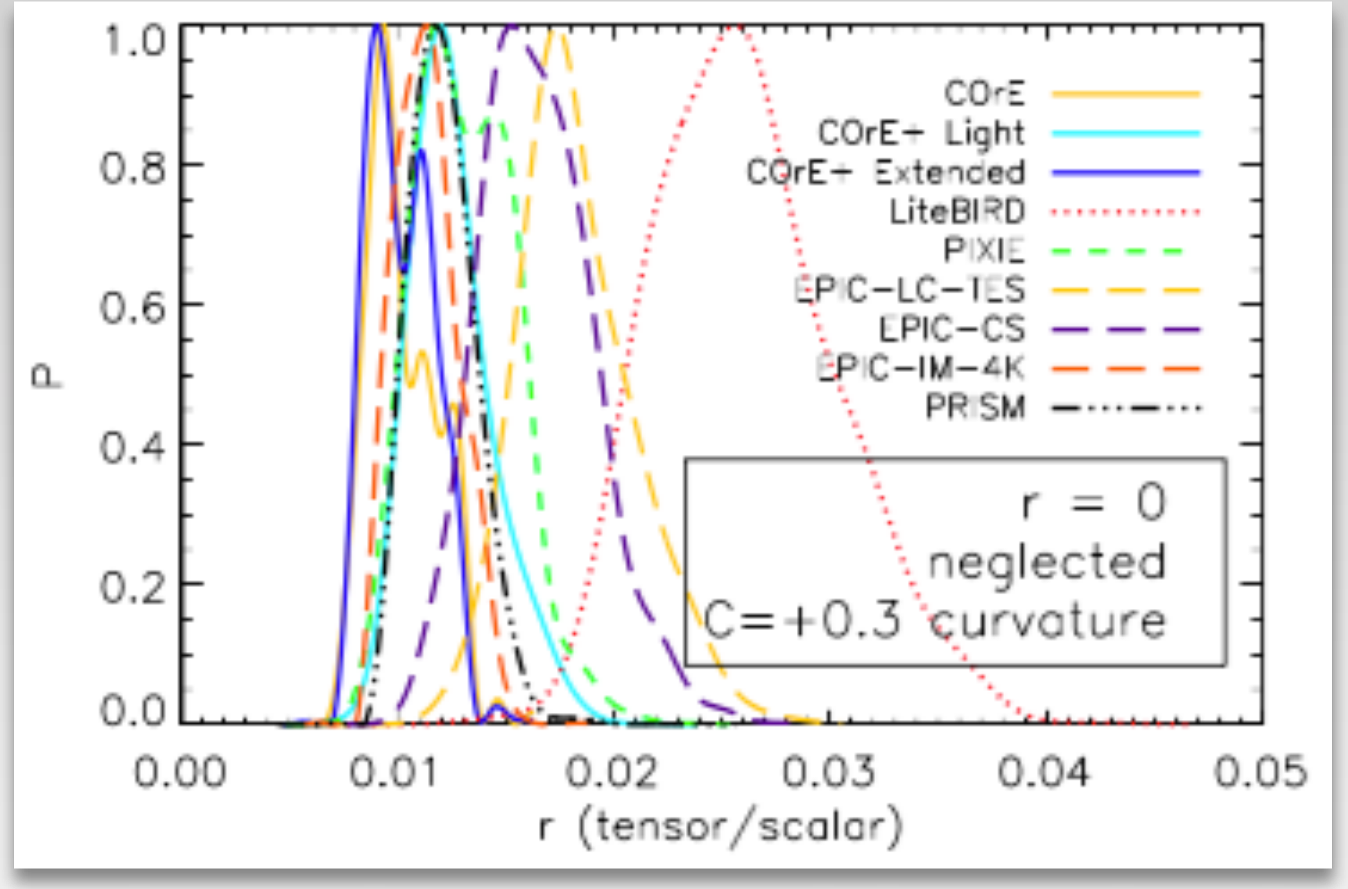
(Planck 2015 results XXV)

Impact of incorrect synchrotron subtraction

Ignoring spatial variations of β



Ignoring synchrotron curvature



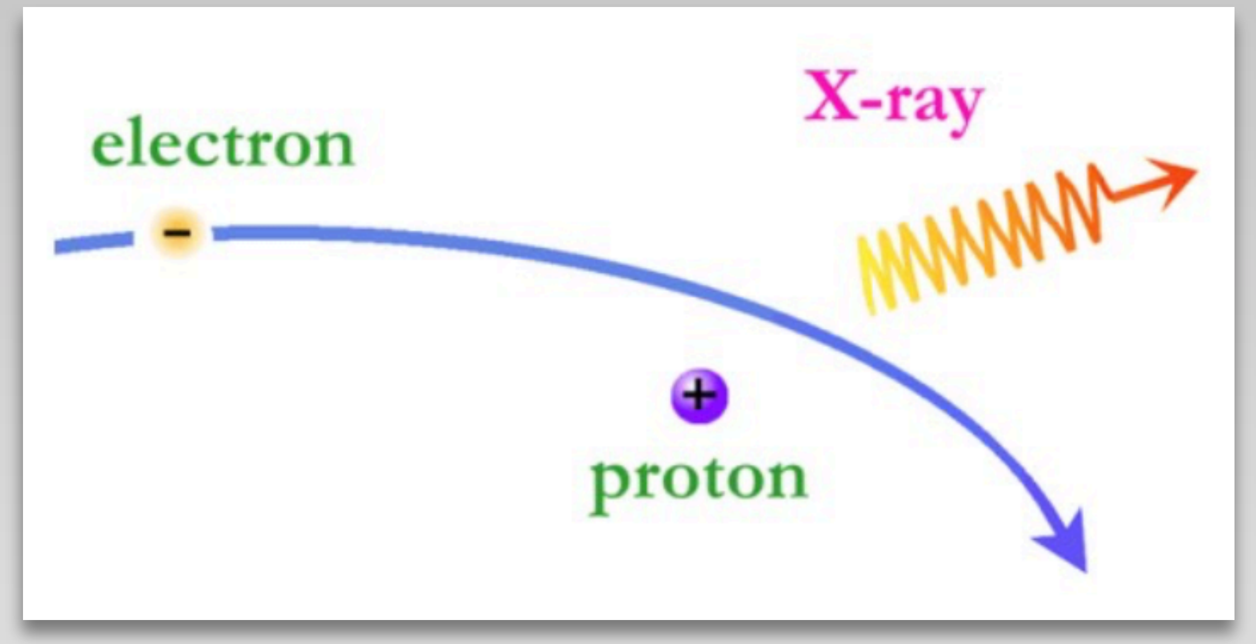
(Remazeilles et al. 2016)

Free-free emission

★ 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)

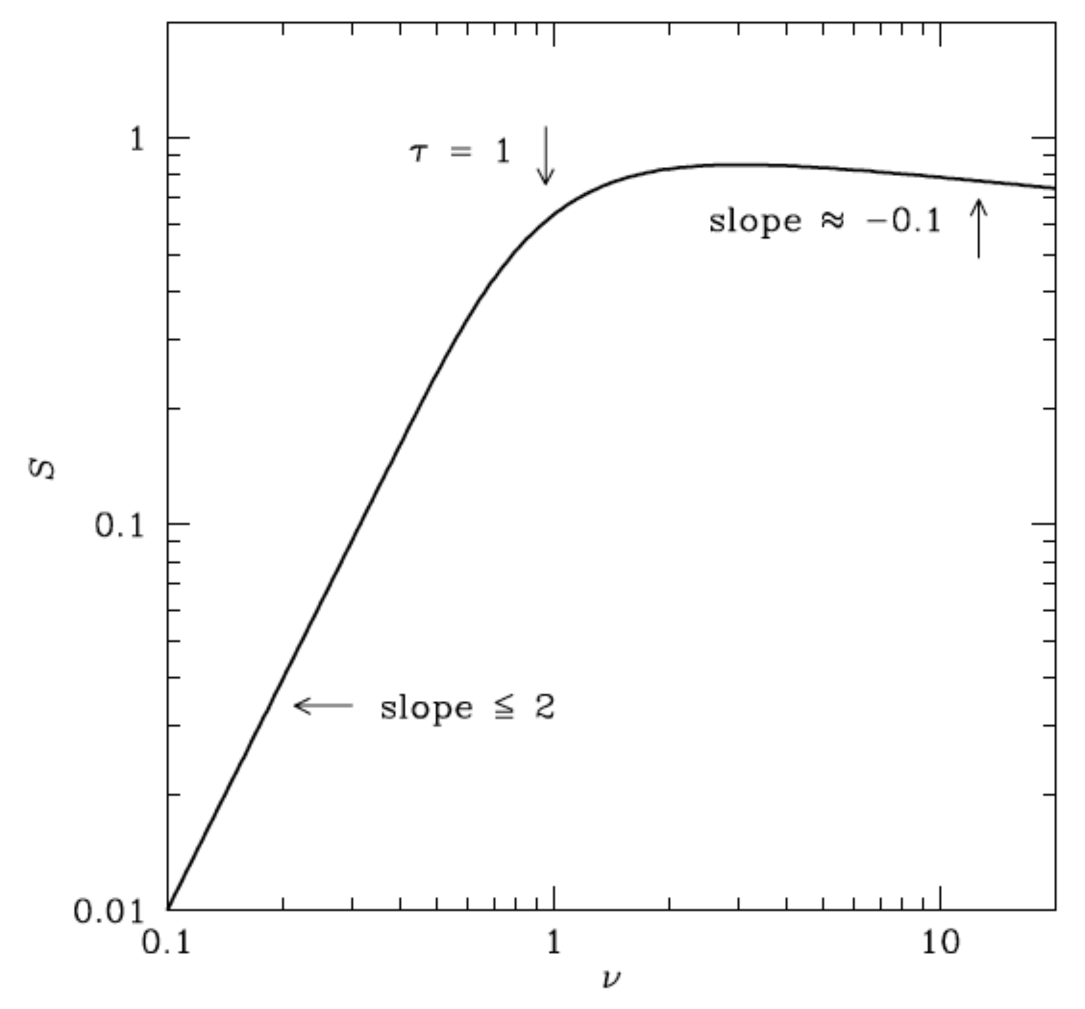

Orion nebula

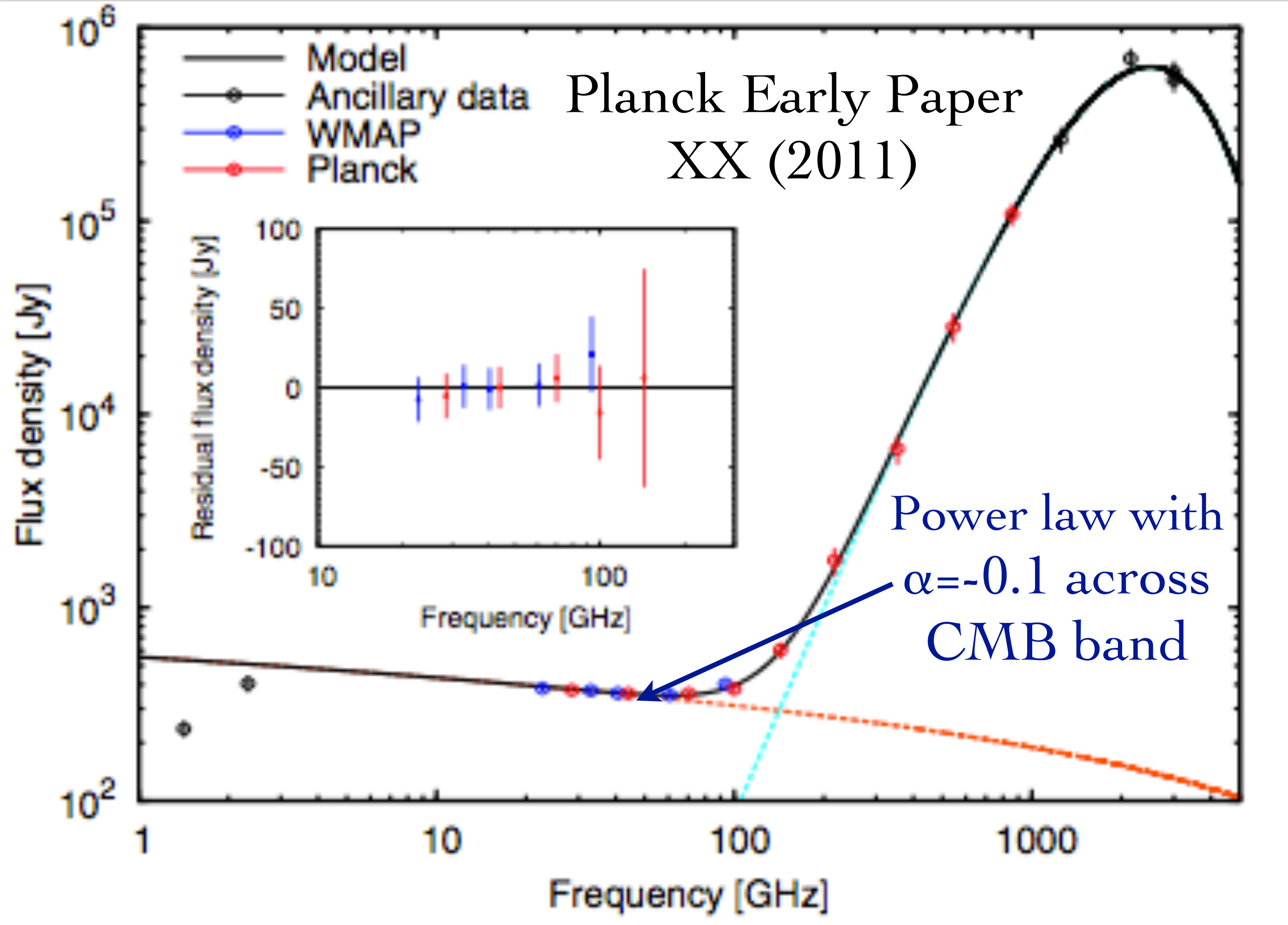
© Anglo-Australian Observatory

Free-free emission

★ Spectrum:

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





Planck Early Paper XX (2011)

Power law with α=-0.1 across CMB band

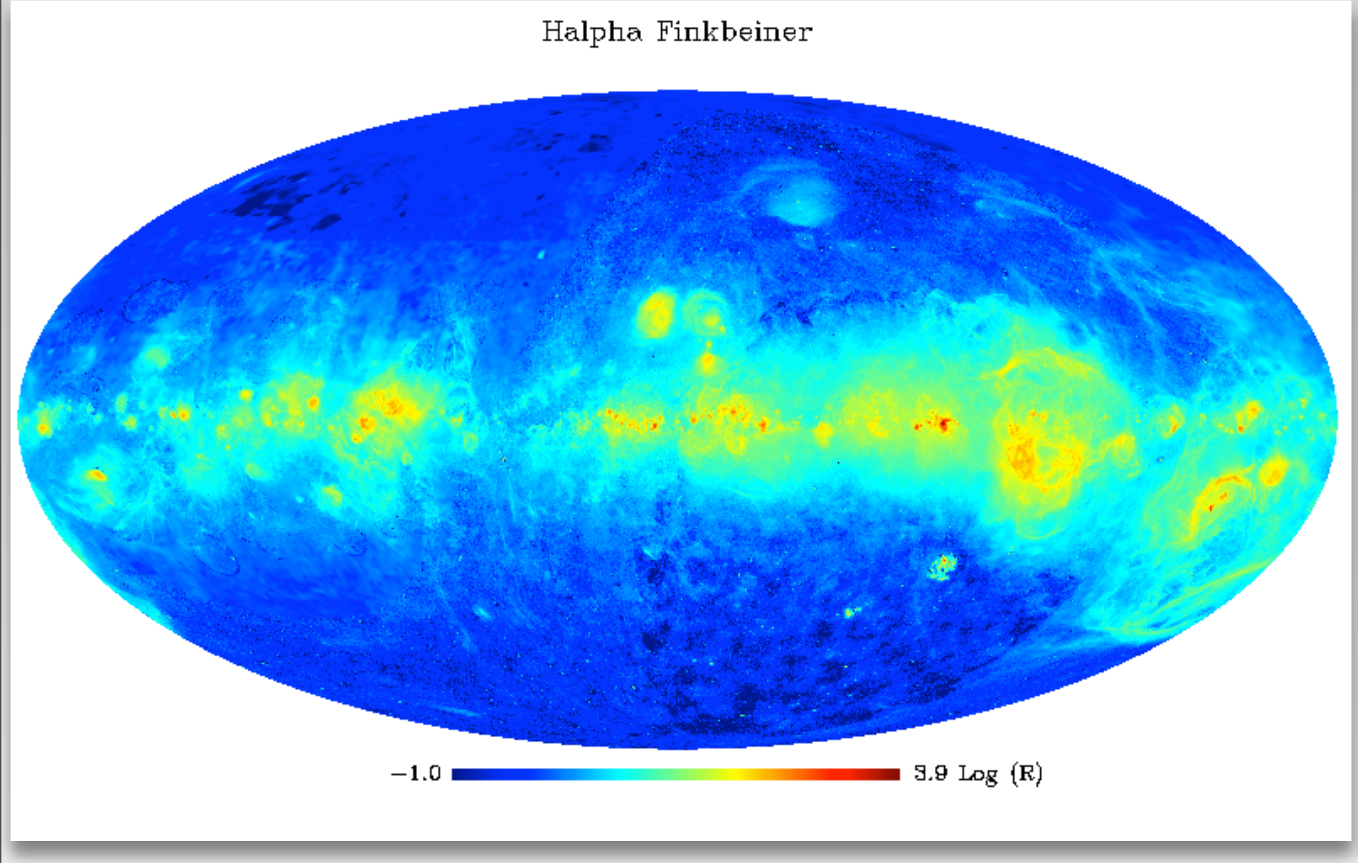
- Important at low frequencies, typically dominant at 10-100 GHz. Could be the dominant foreground at ≈70 GHz

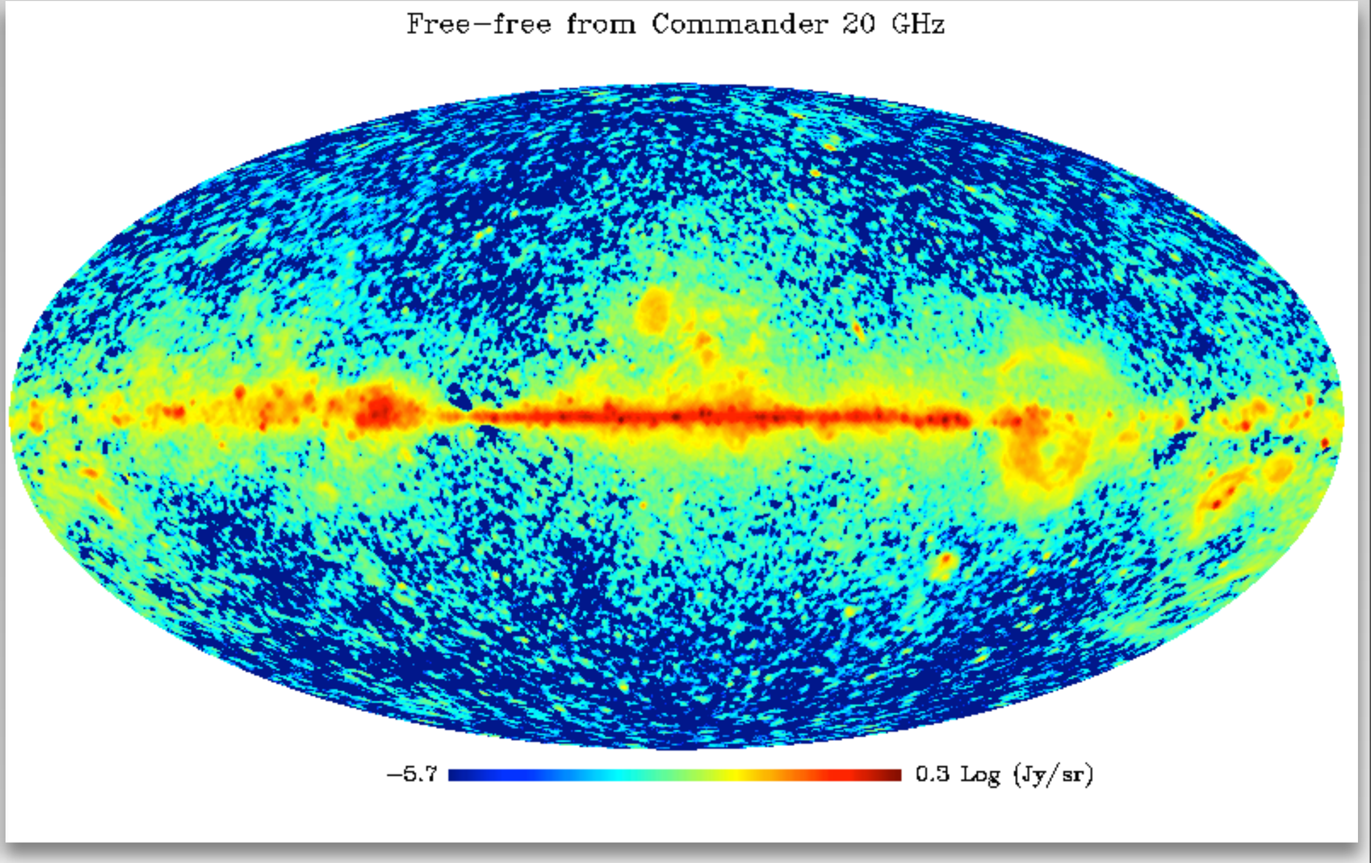
Free-free emission

- Mostly concentrated in the Galactic plane
- Well correlated with Hα emission

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

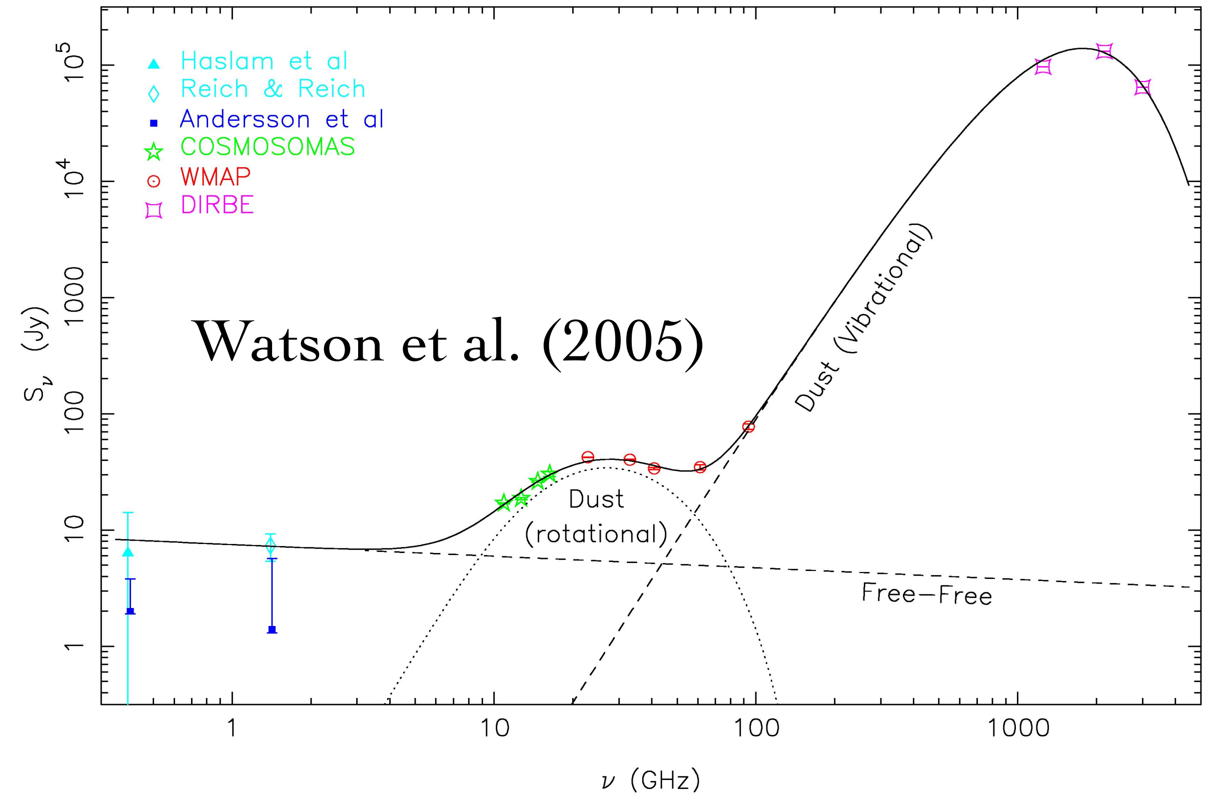
★ Dust correlated emission, first detected in COBE data at 30-90 GHz (Kogut et al. 1996)

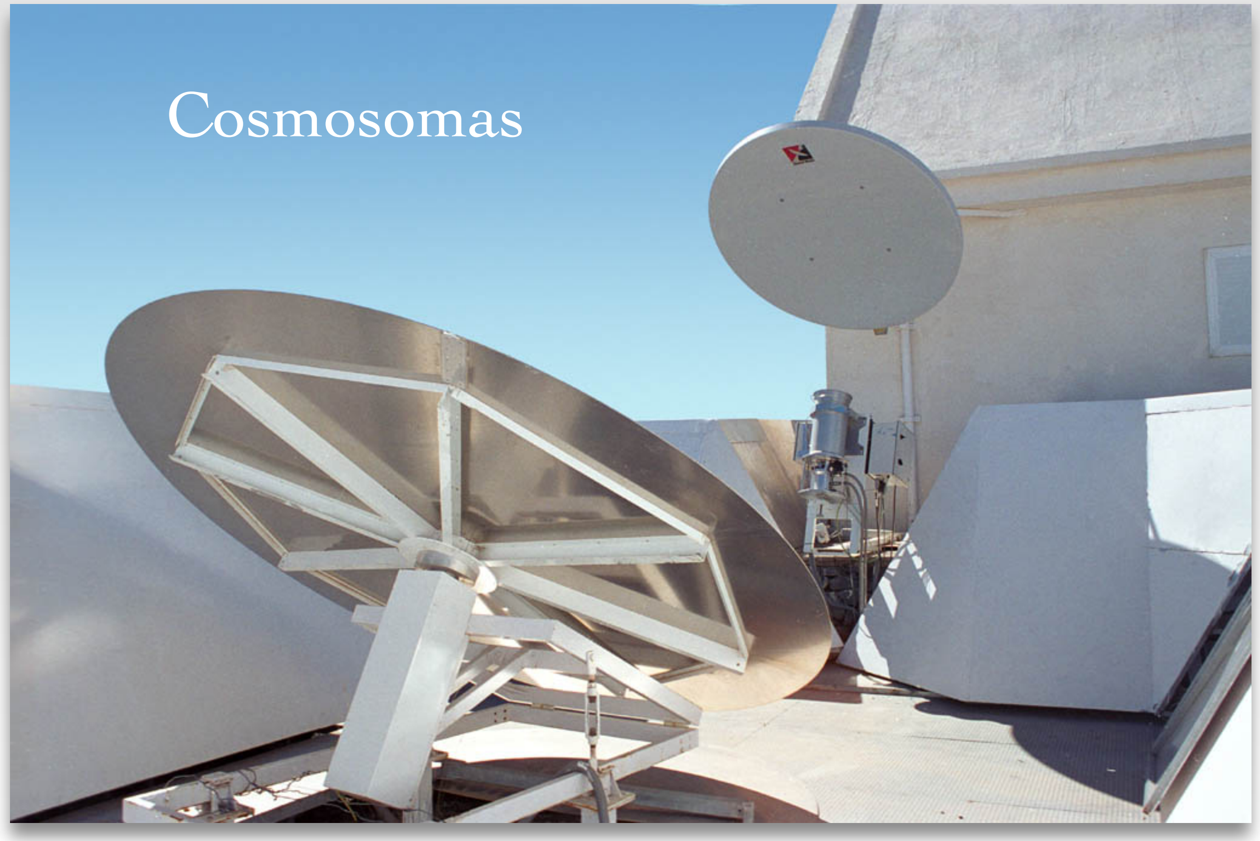
★ Right afterwards by other experiments: OVRO at 14.5 and 32 GHz (Leitch et al. 1997), Saskatoon at 30 GHz (de Oliveira-Costa et al. 1997), 19 GHz experiment (de Oliveira-Costa et al. 1998), Tenerife at 10 and 15 GHz (de Oliveira-Costa et al. 1999, 2002, 2004)

★ Later, characterisation of the 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)

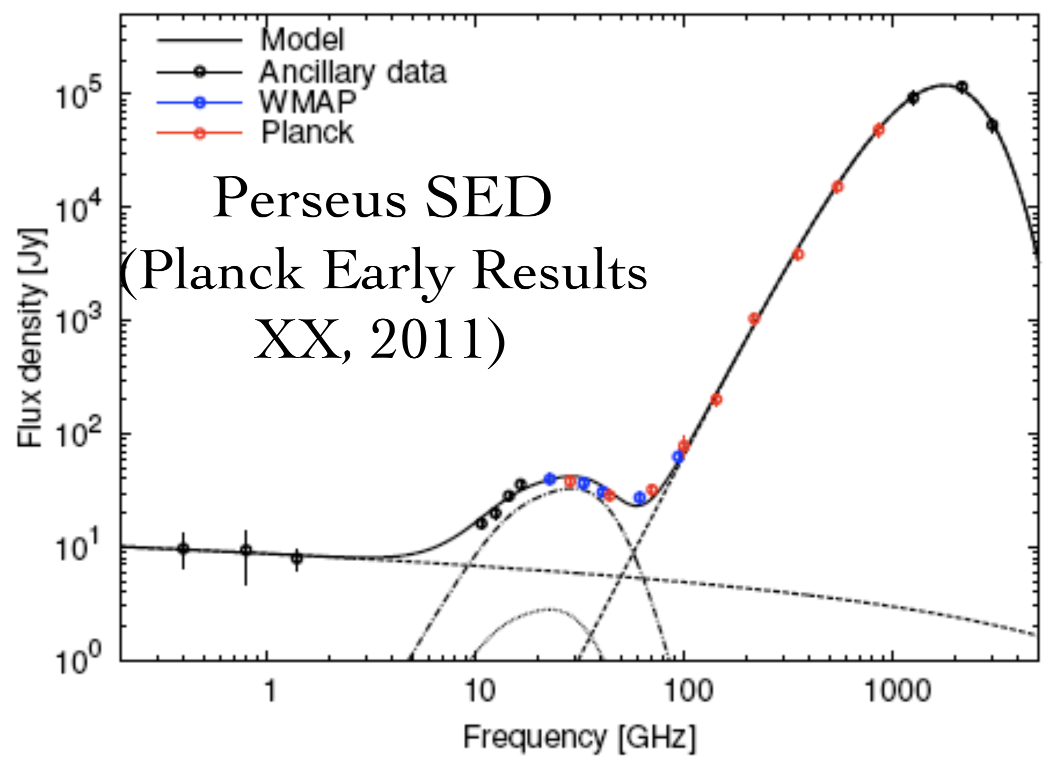
SED Perseus molecular complex





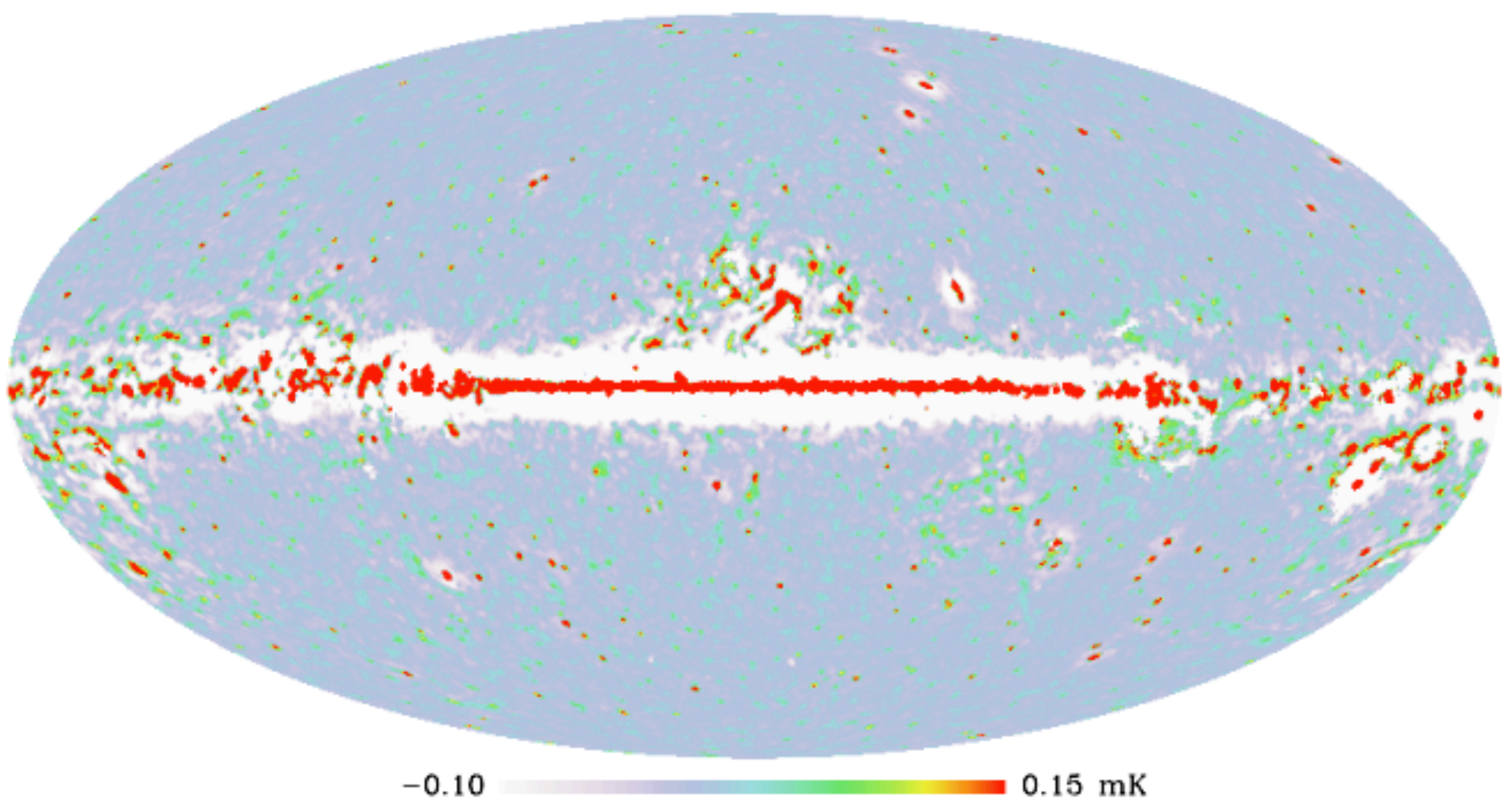
Anomalous Microwave Emission - Planck results

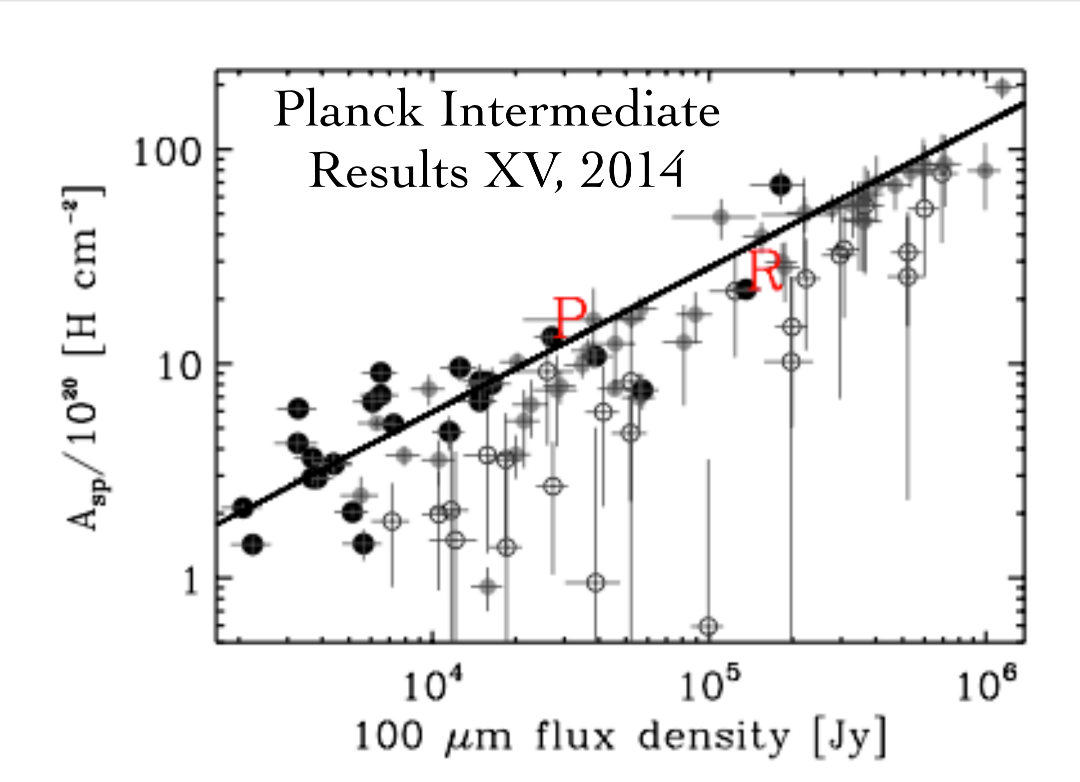
- ★ First systematic search of AME in the full sky
- ★ Confirmed early detections in Perseus and ρ-Ophiuchus, and identified ≈50 new candidates (PER XX, 2011)
- ★ Presented a study of AME in 98 regions, and studied physical properties of these regions in an statistical way (PIR XV, 2014)



Perseus SED (Planck Early Results XX, 2011)

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





Planck Intermediate Results XV, 2014

Anomalous Microwave Emission - Models

★ Initial proposals (hard synchrotron, free-free emission) not able to explain the observed spectrum

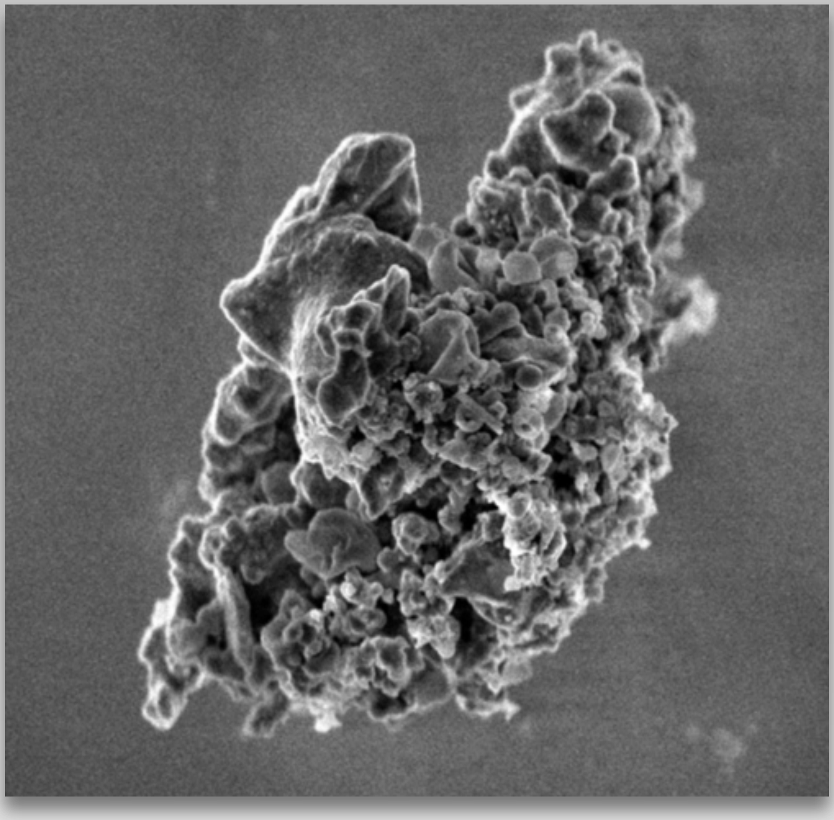
★ **Electric dipole emission** (spinning dust)

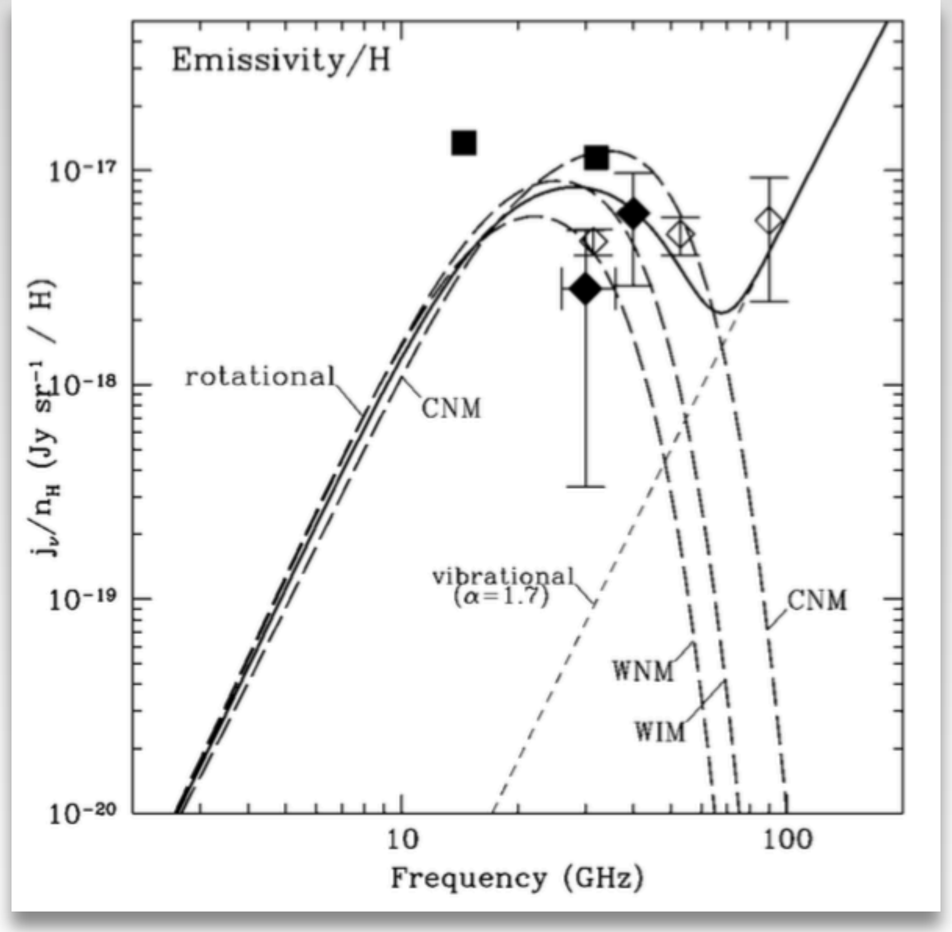
- Originated in dust gains with high rotation speeds (due to interactions with the ISM), containing a residual electric dipole moment
- First suggested by Erickson (1957), later revisited by Draine & Lazarian (1998)
- Very complicated physics! Many free parameters (grain size distribution, electric dipole 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})

★ **Magnetic dipole emission**

- Thermal fluctuations in the magnetization of the grains (Draine & Lazarian 1999)
- Black-body like spectrum at 70-100 GHz ⇒ potentially a killer for CMB component separation

Typical interstellar dust grain





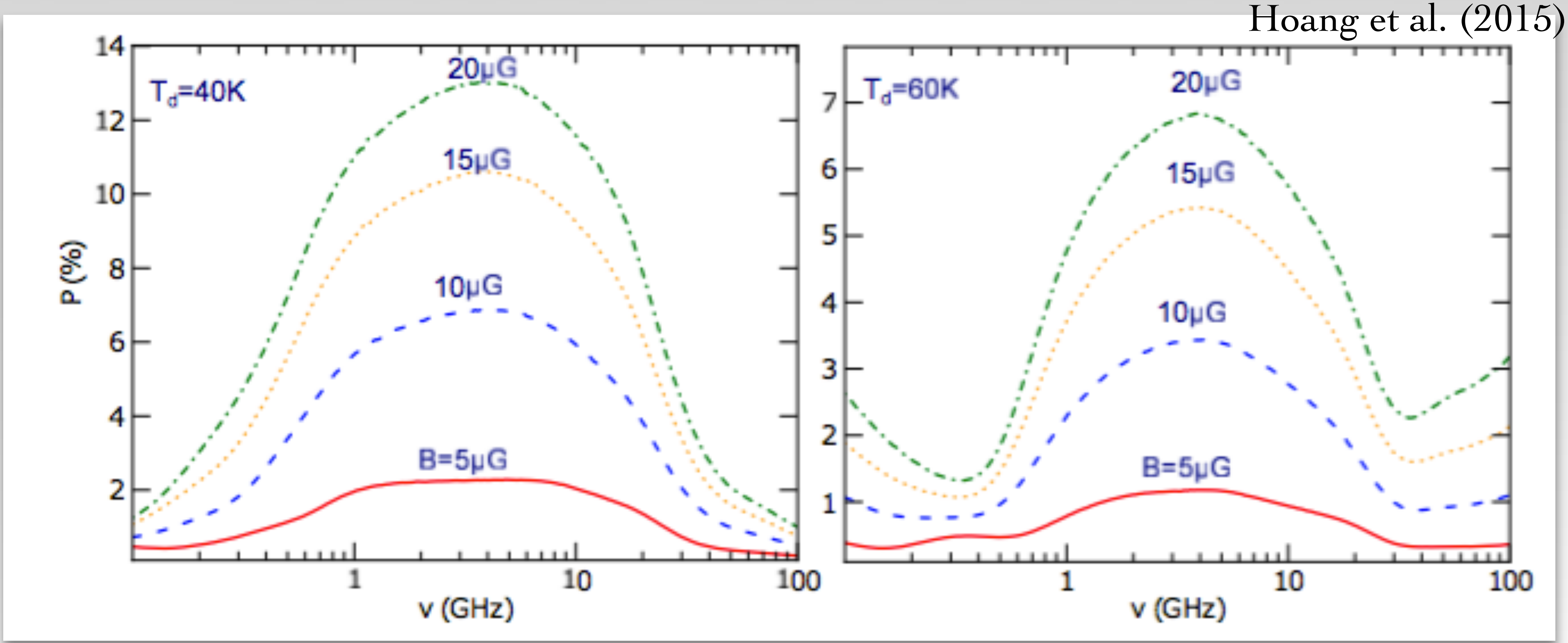
Spinning dust models (Draine & Lazarian 1998)

Anomalous Microwave Emission - 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)

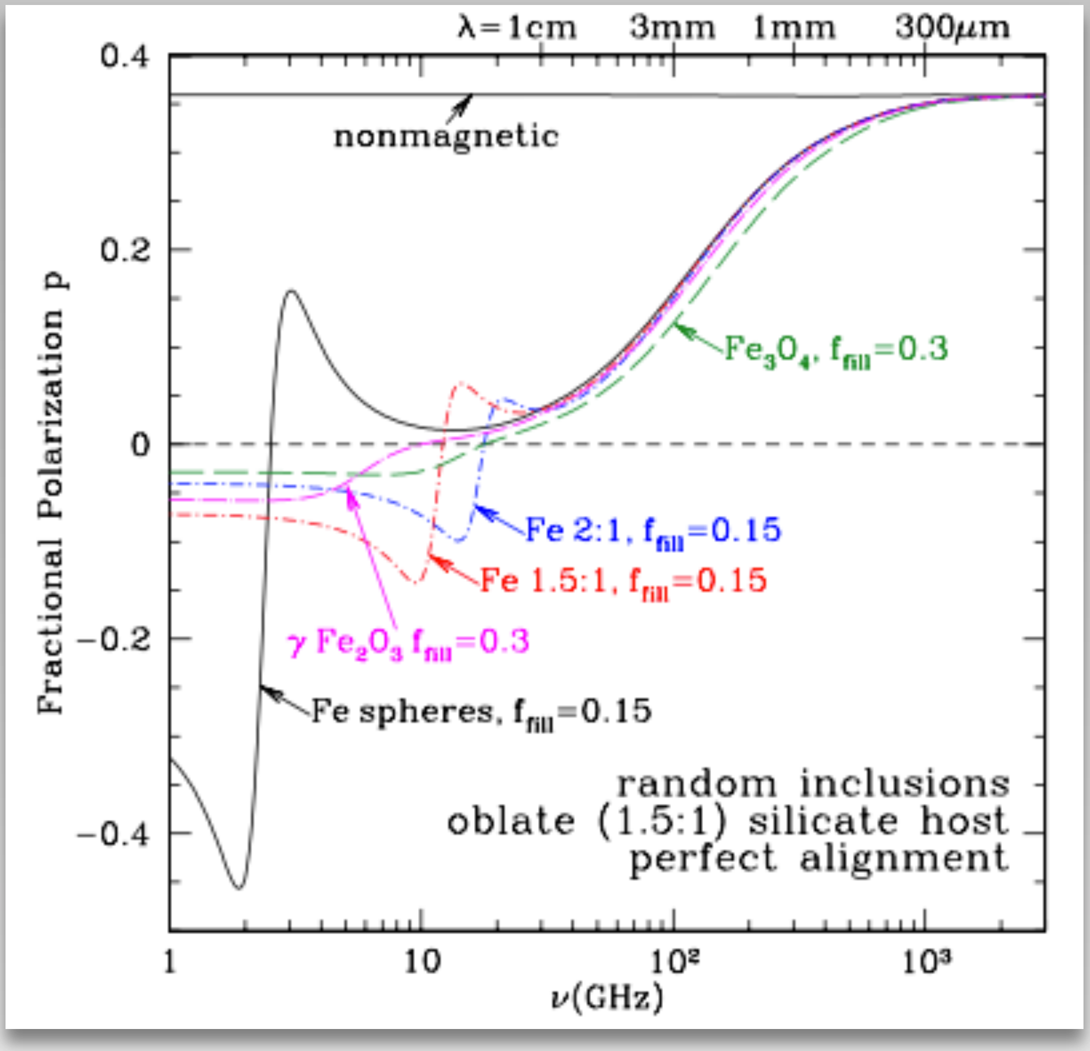
Hoang et al. (2015)



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

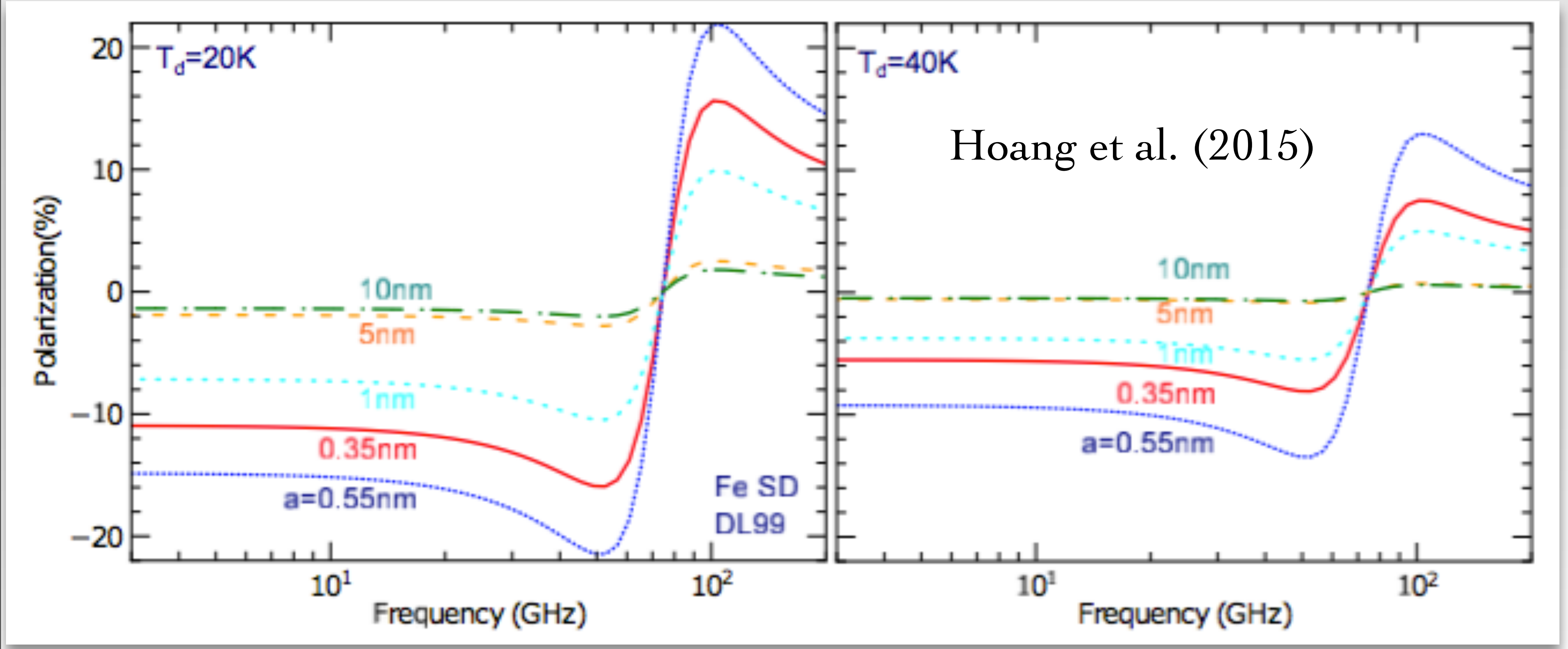
Anomalous Microwave Emission - Models

Draine & Hensley (2013)



★ 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)



Hoang et al. (2015)

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

Anomalous Microwave Emission - Polarisation constraints

★ Compact sources:

- Battistelli et al. (2006) found marginal polarisaiton with $\Pi = 3.4\pm1.7$ % at 11 GHz, using COSMOSOMAS
- Upper limits from, $\Pi < 1\%$ (95% CL) from WMAP 23 GHz (López-Caraballo et al. 2011, Dickinson et al. 2011)

★ Diffuse:

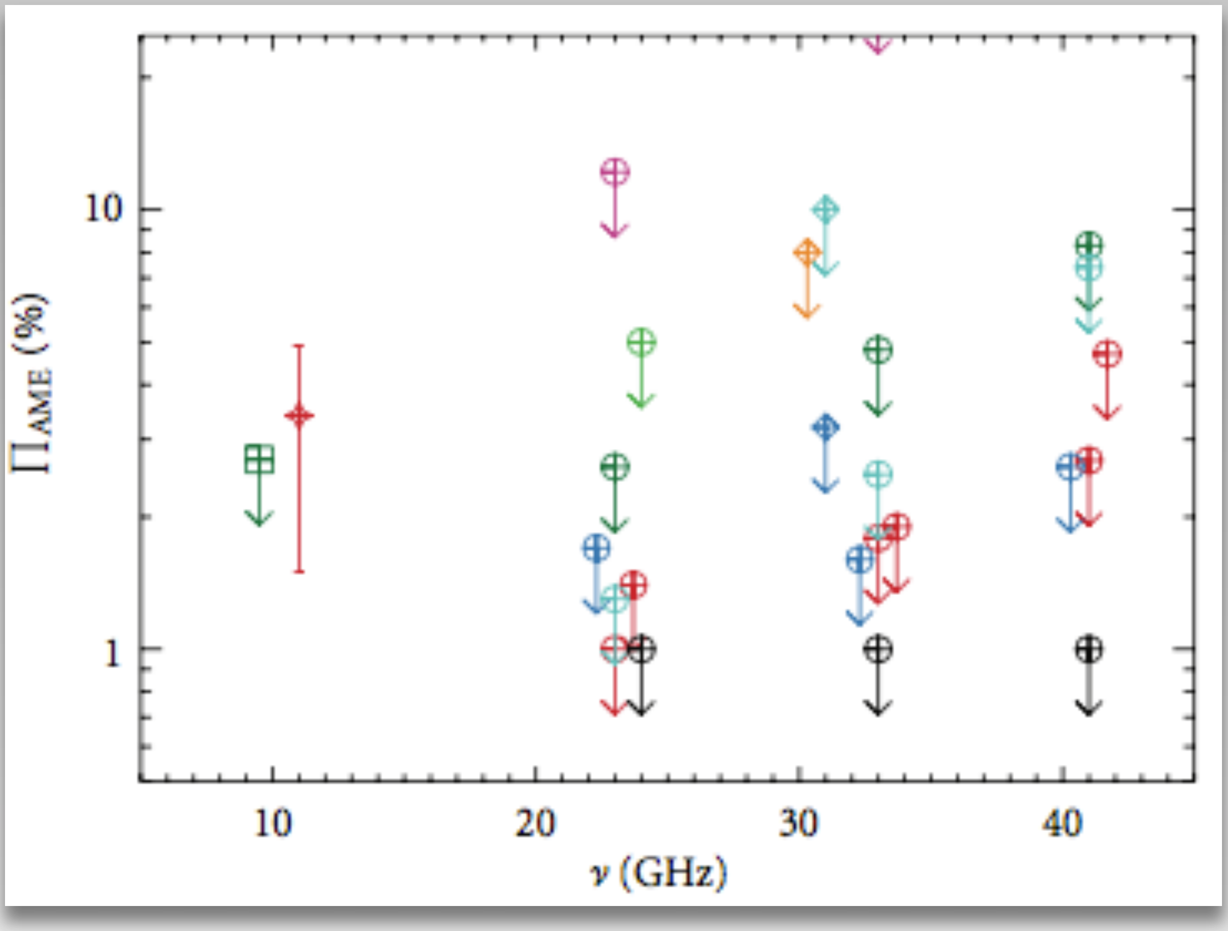
- $\Pi < 5\%$ (Macellari et al. 2011), at 22.8 GHz with WMAP
- $\Pi = 0.6 \pm 0.5$ % (Planck 2015 results, XXV)

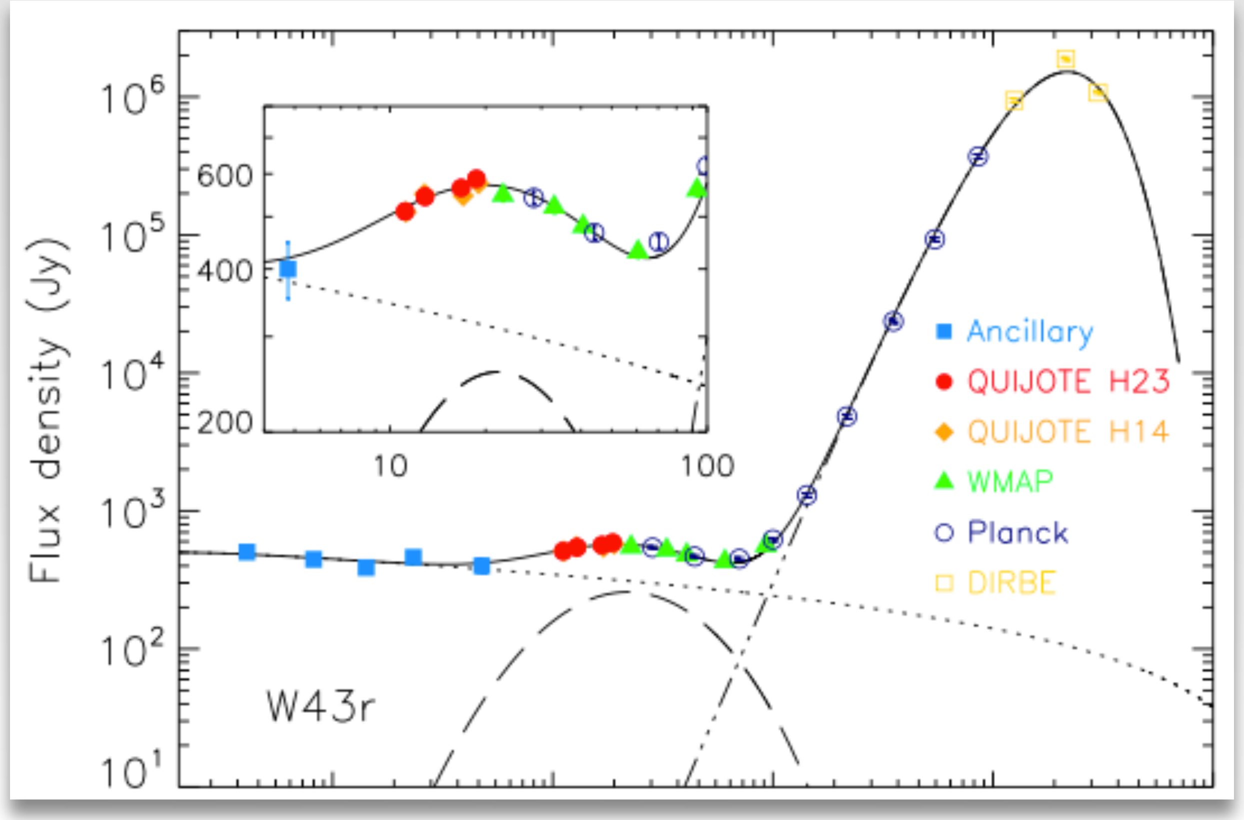
★ QUIJOTE:

- Perseus molecular complex: $\Pi_{\rm AME} < 6.3\%$ at 12 GHz and $\Pi_{\rm AME} < 2.8\%$ at 18 GHz (Génova-Santos et al. 2015)
- W43 molecular complex: **$\Pi_{\rm AME} < 0.39\%$** 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)

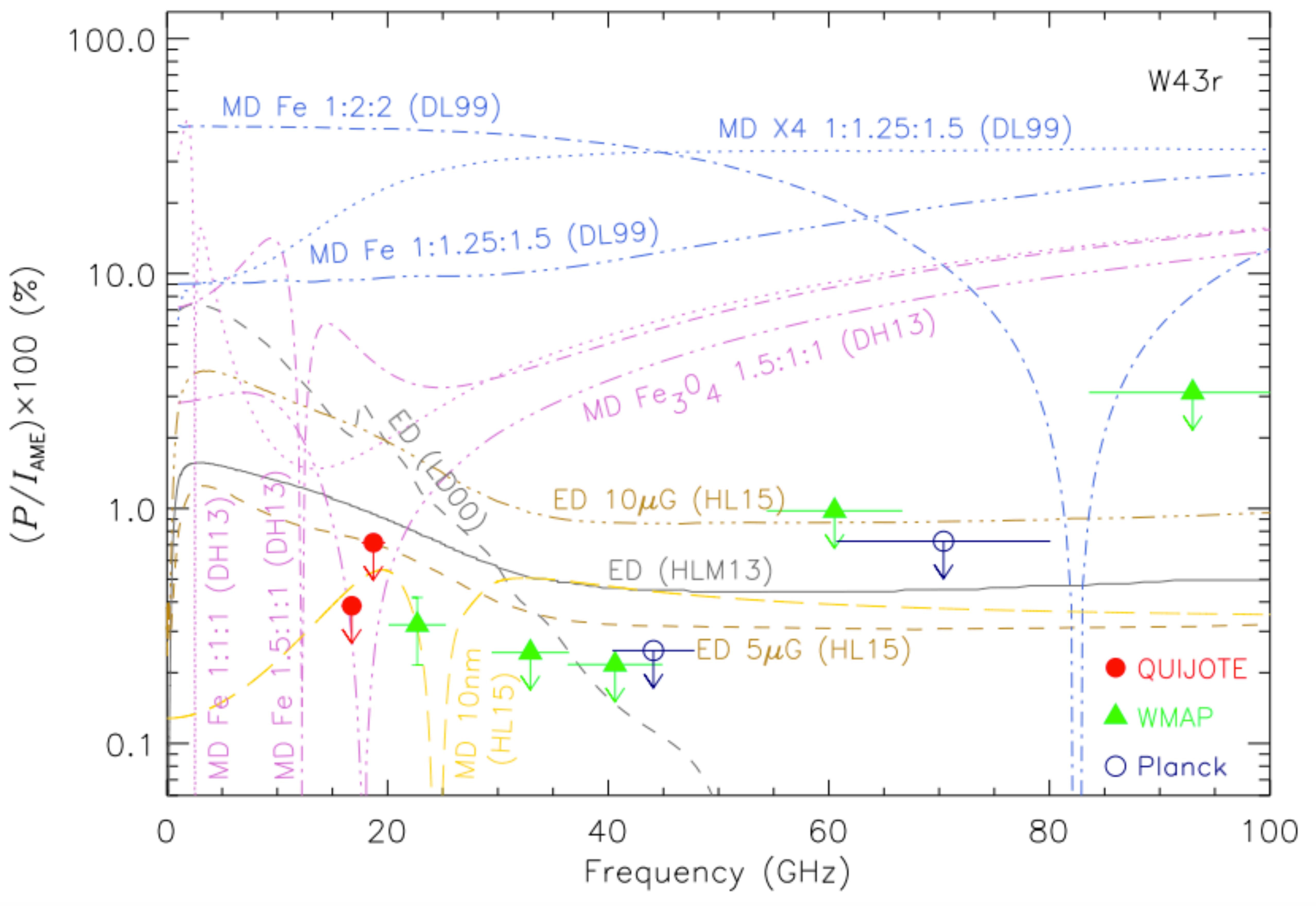




Génova-Santos et al. (2017)

Anomalous Microwave Emission - Polarisation constraints

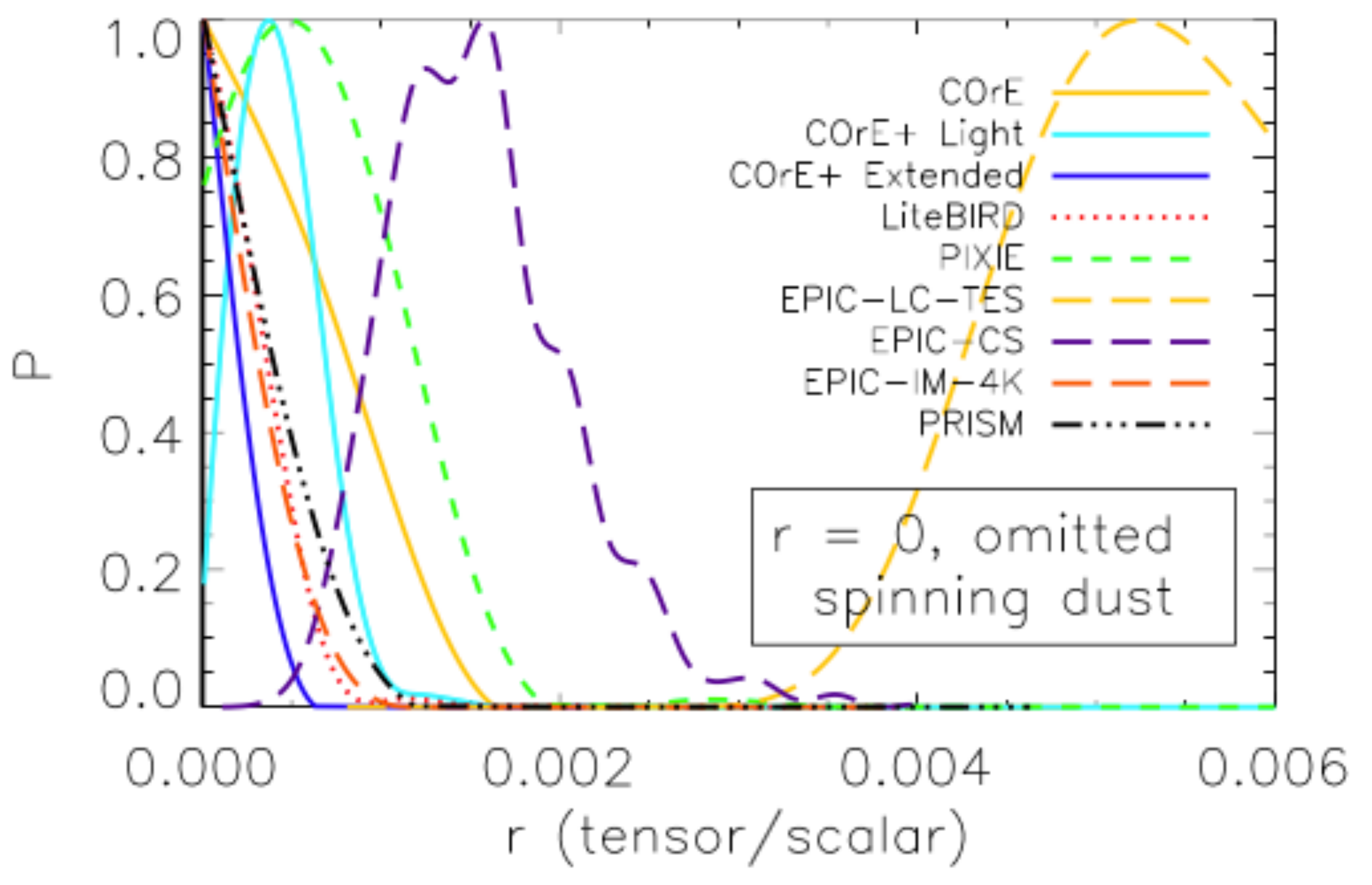
Genova-Santos et al. (2017)



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)

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

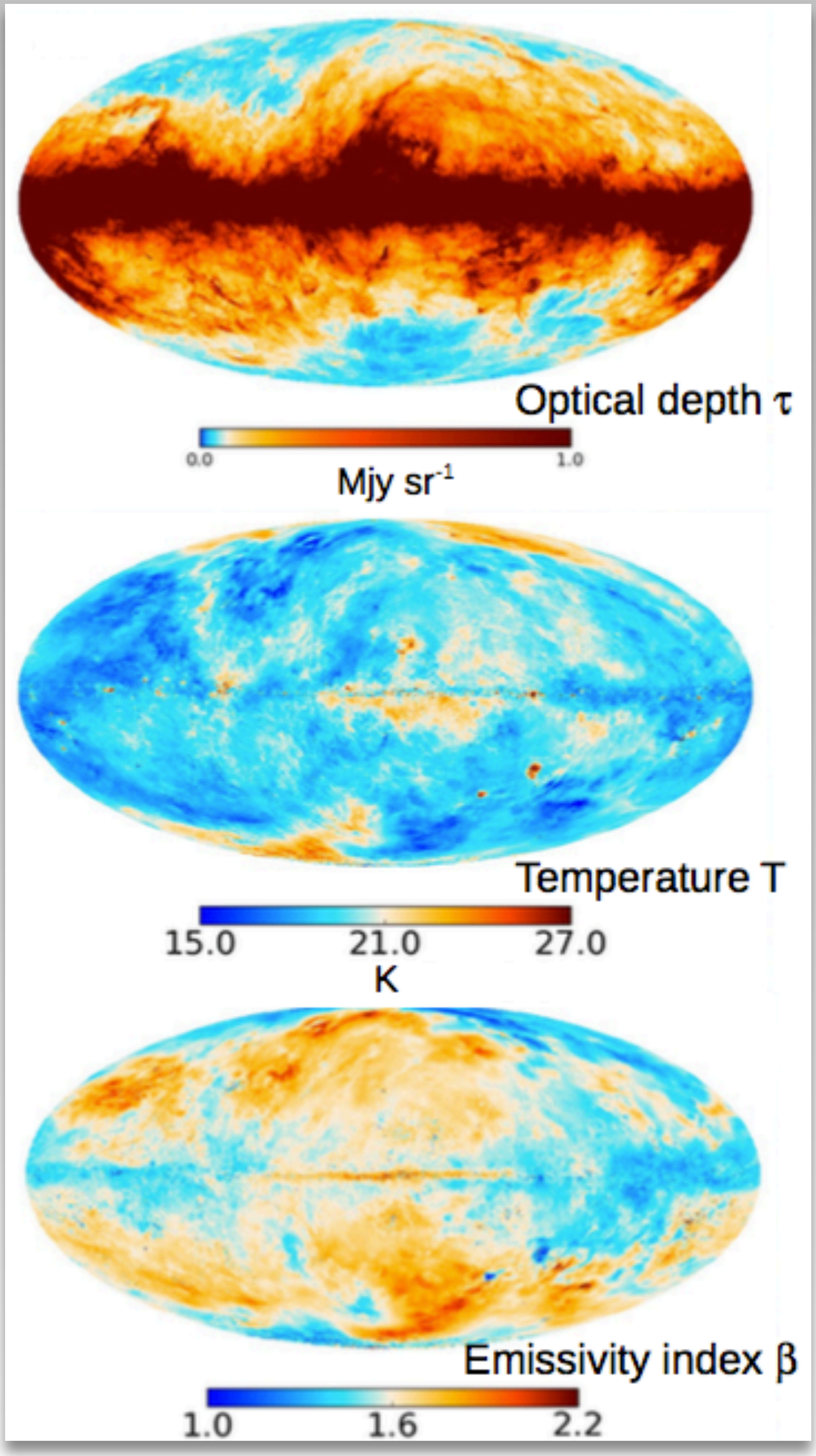
$$I_\nu = \tau_{\nu 0} \left(\frac{\nu}{\nu_0}\right)^{\beta_\mathrm{d}} B_\nu(T_\mathrm{d})$$

➡ 3 free parameters

- Average values from Planck: $T_\mathrm{d} \approx 19$ K, $\beta_\mathrm{d} \approx 1.6$

★ Complications:

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



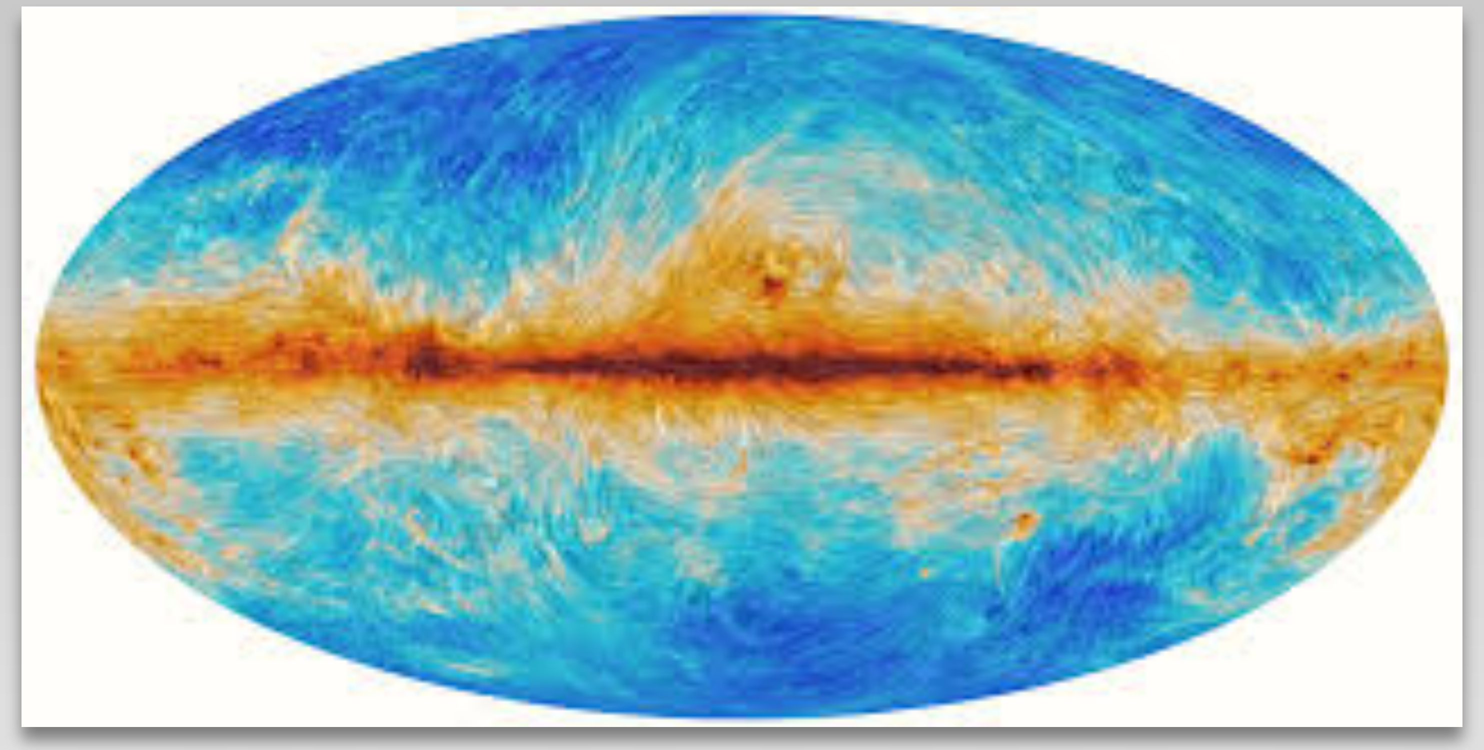
Planck dust model (Planck intermediate results XLVIII, 2016)

Thermal dust emission - Polarisation

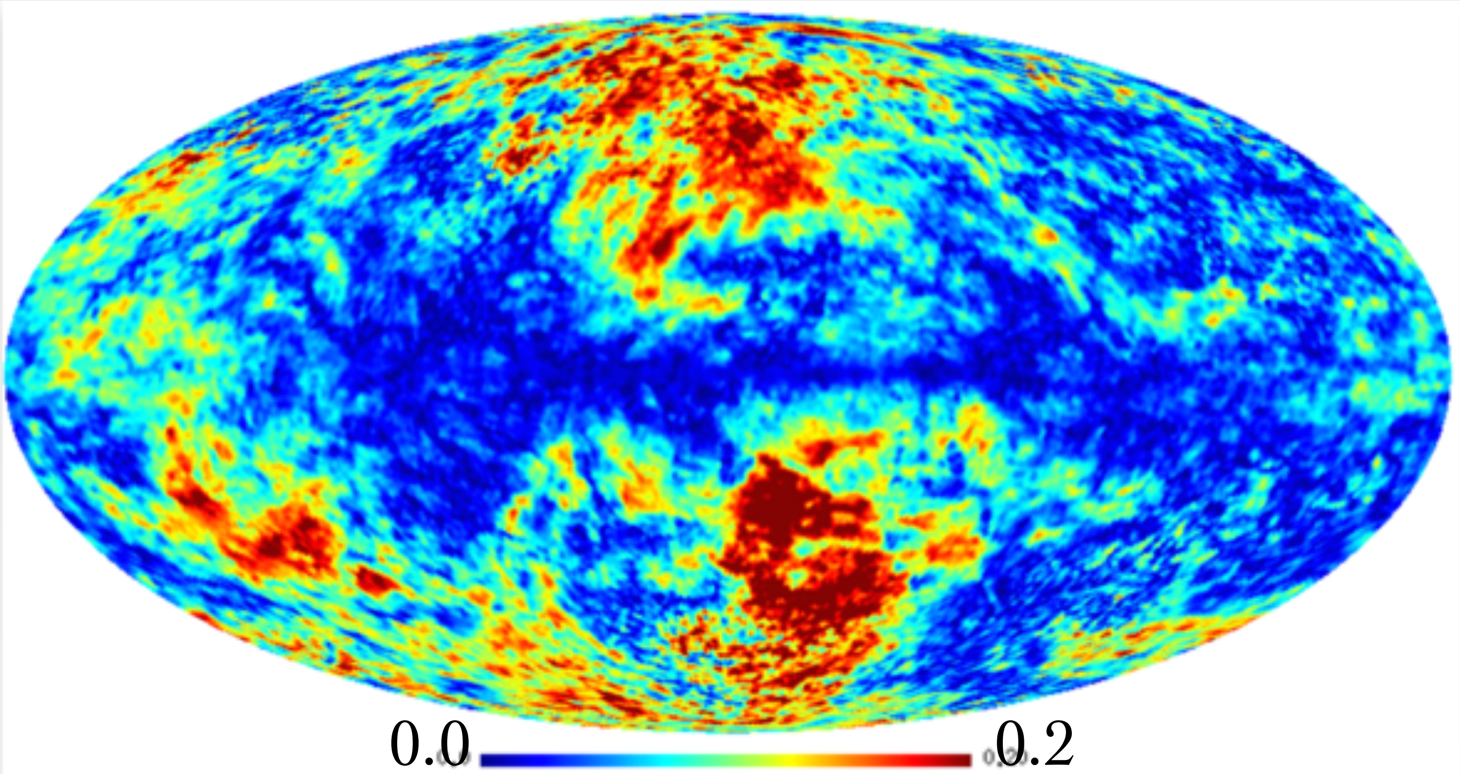
Planck results

- ★ 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 ∝ $\ell^{-2.42}$ (Planck Intermediate Results XXX, 2016)

Planck dust emission 353 GHz



Planck polarisation fraction at 353 GHz

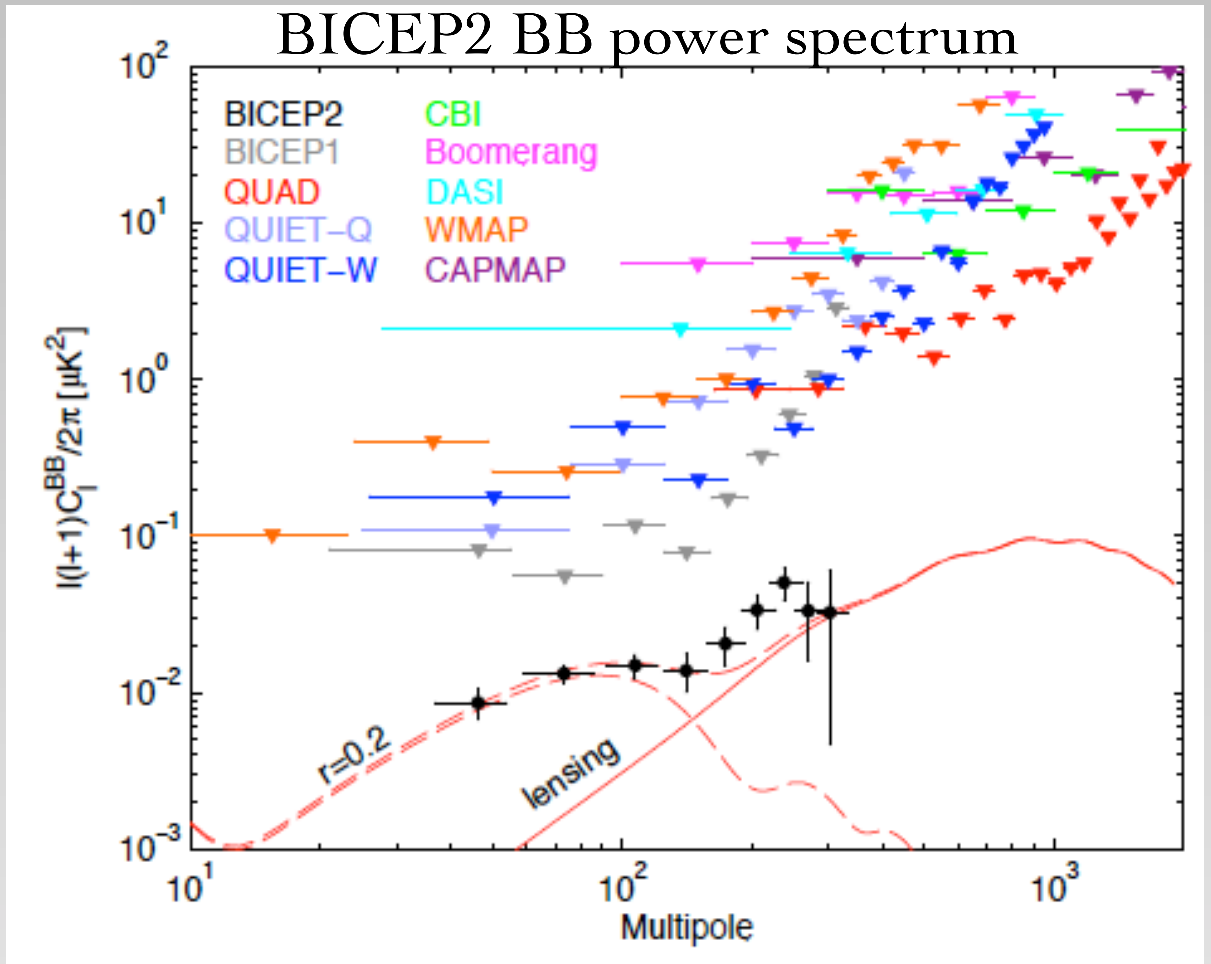


(Planck Intermediate Results IXX, 2015)

Thermal dust contamination in BICEP2

★ BICEP2 results:

- 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: $r = 0.001$

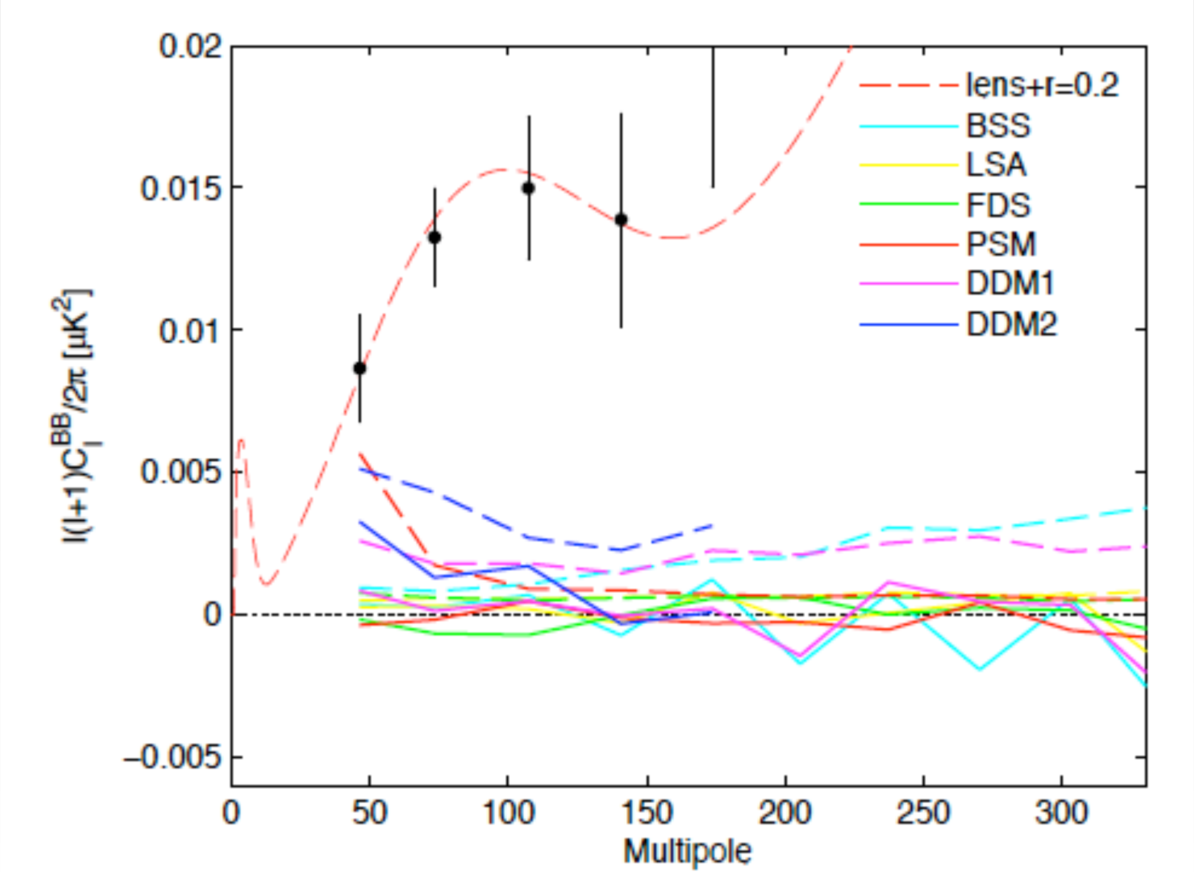


BICEP2 BB power spectrum

★ Too simplistic modelling and assumptions of foreground components. Some cases assumed constant P/I=5% in the full sky for the dust

★ Planck 353 GHz polarisation demonstrated that the dust contamination was rather higher

★ Joint Planck/BICEP2 reanalysis: **$r < 0.07$** (BICEP2/Keck/Planck collaborations, 2015)



Dust residuals in the BICEP2 field

Point sources

★ Affect only the small scales

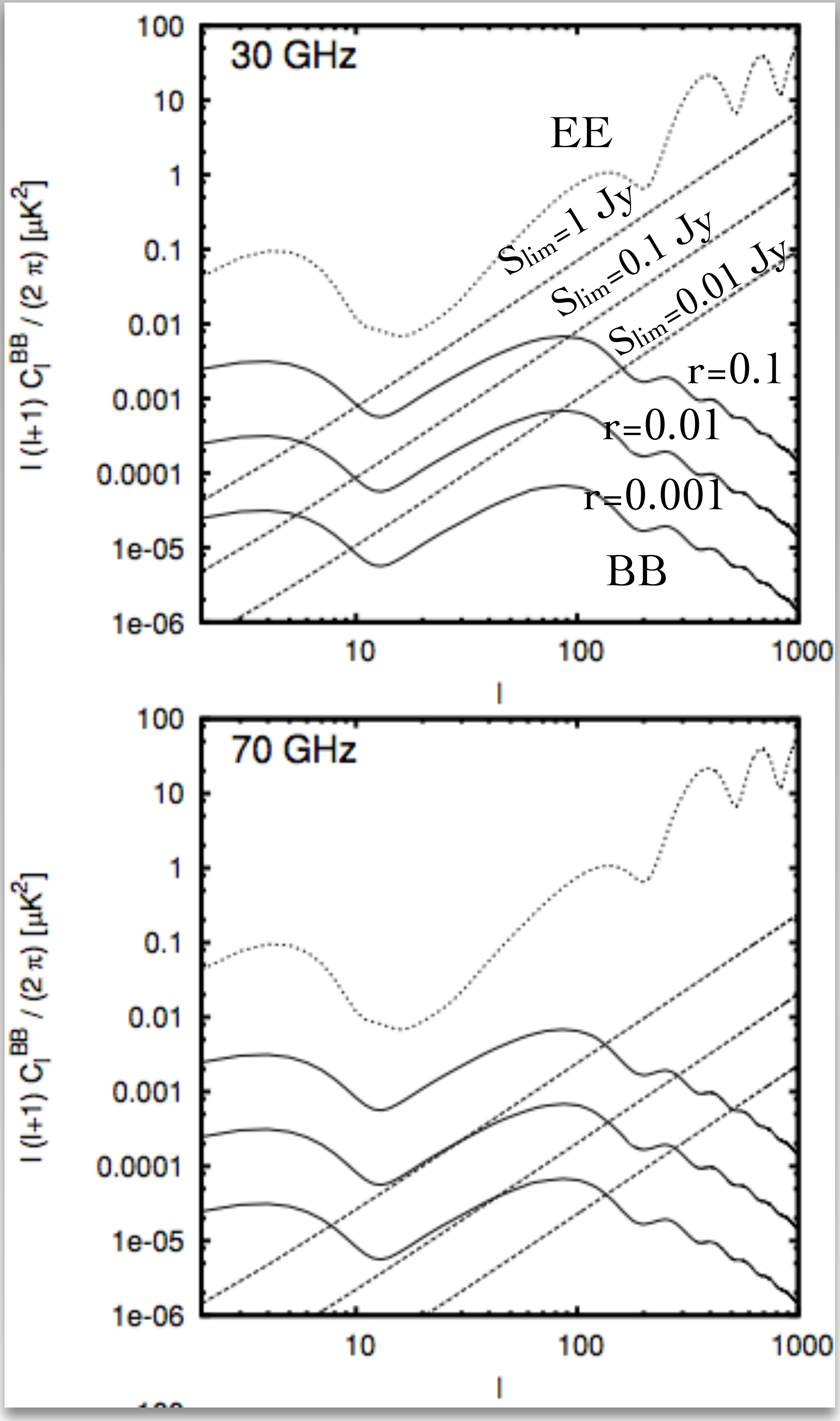
★ Difficulties:

- 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)

Foreground cleaning

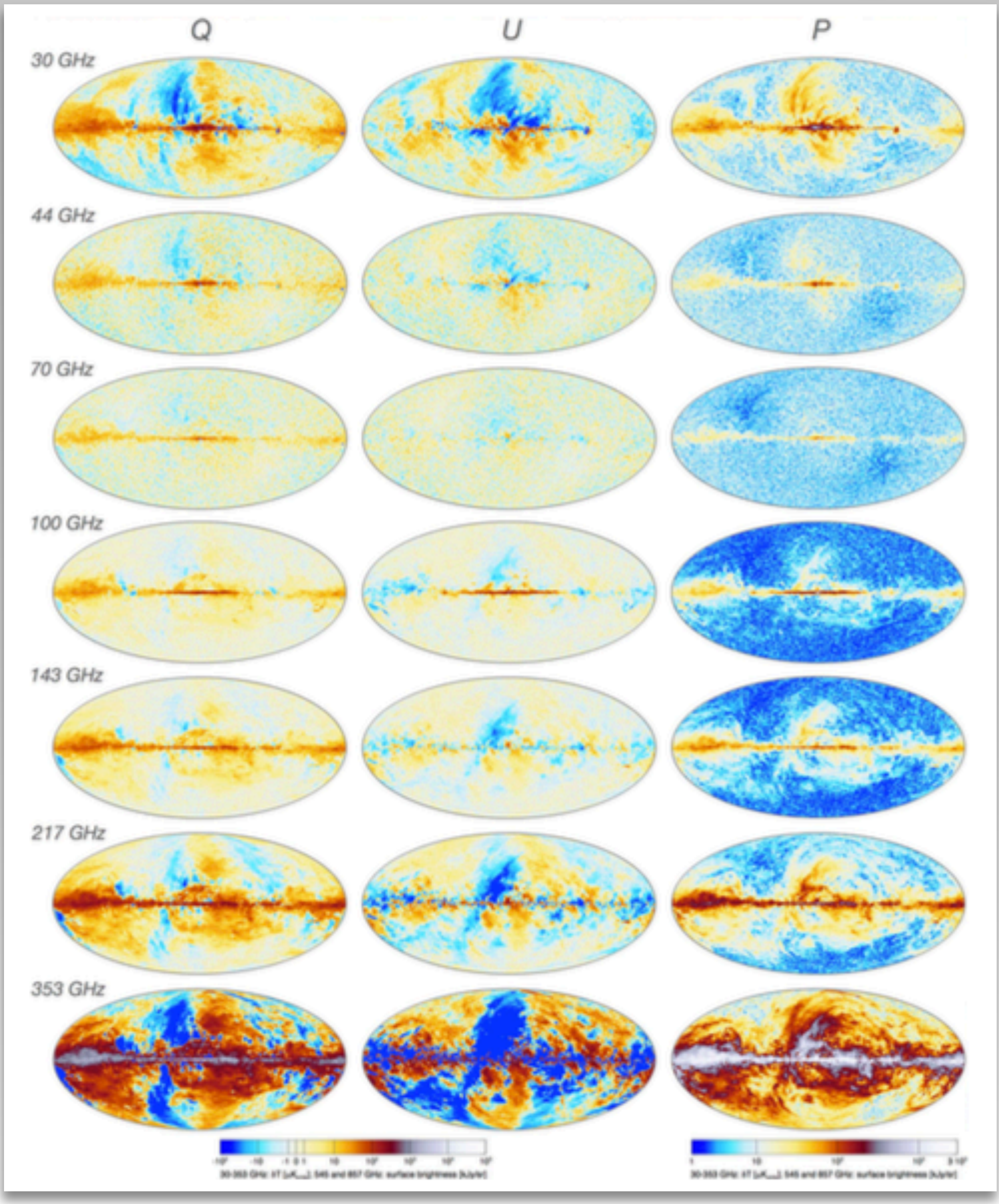
★ Need different frequencies, and knowledge of the foregrounds physics in order to set some priors to the fitted parameters

★ 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

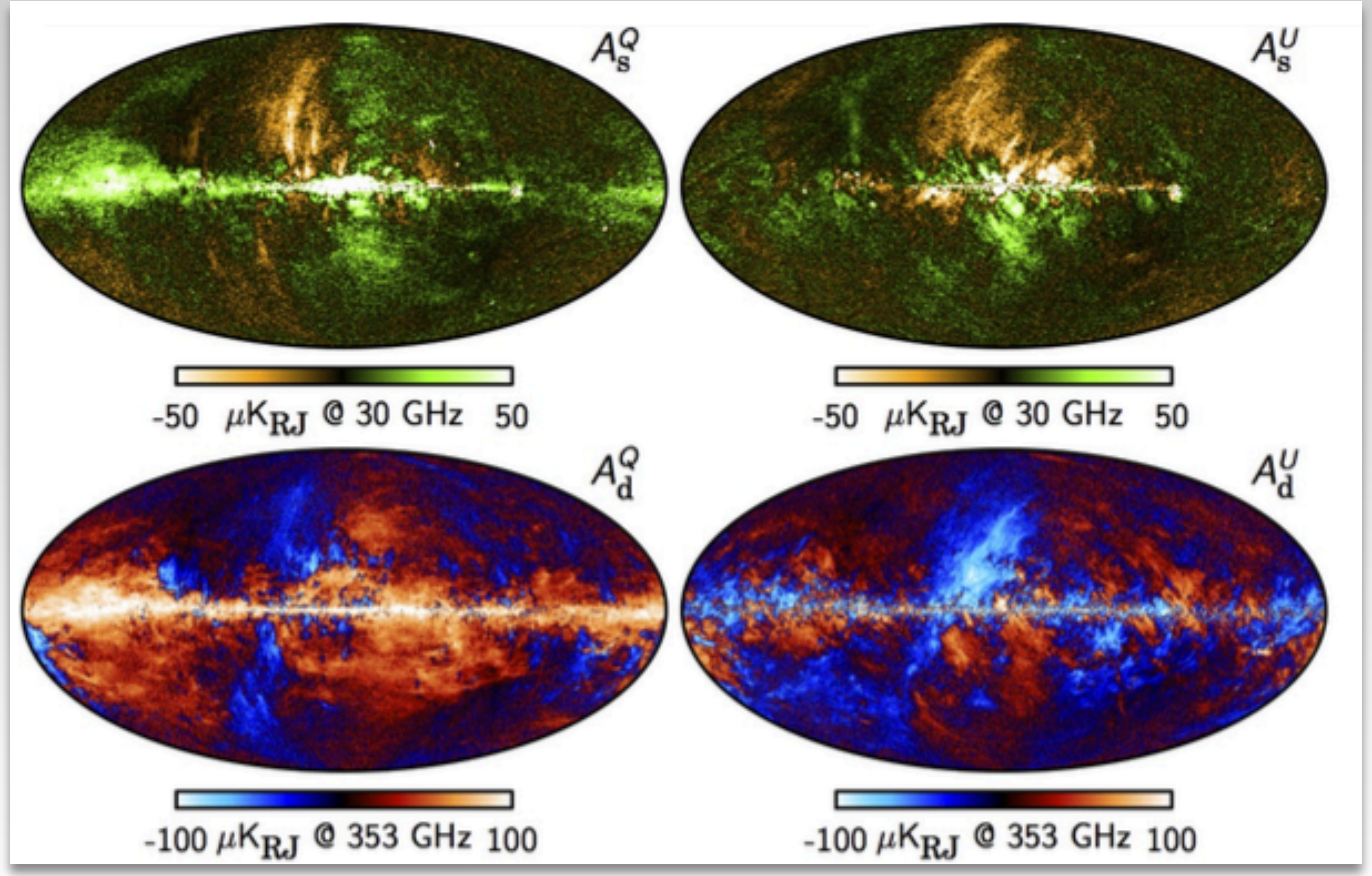
Planck 2015 polarisation maps



Planck 2015 results I, 2016

Foreground cleaning

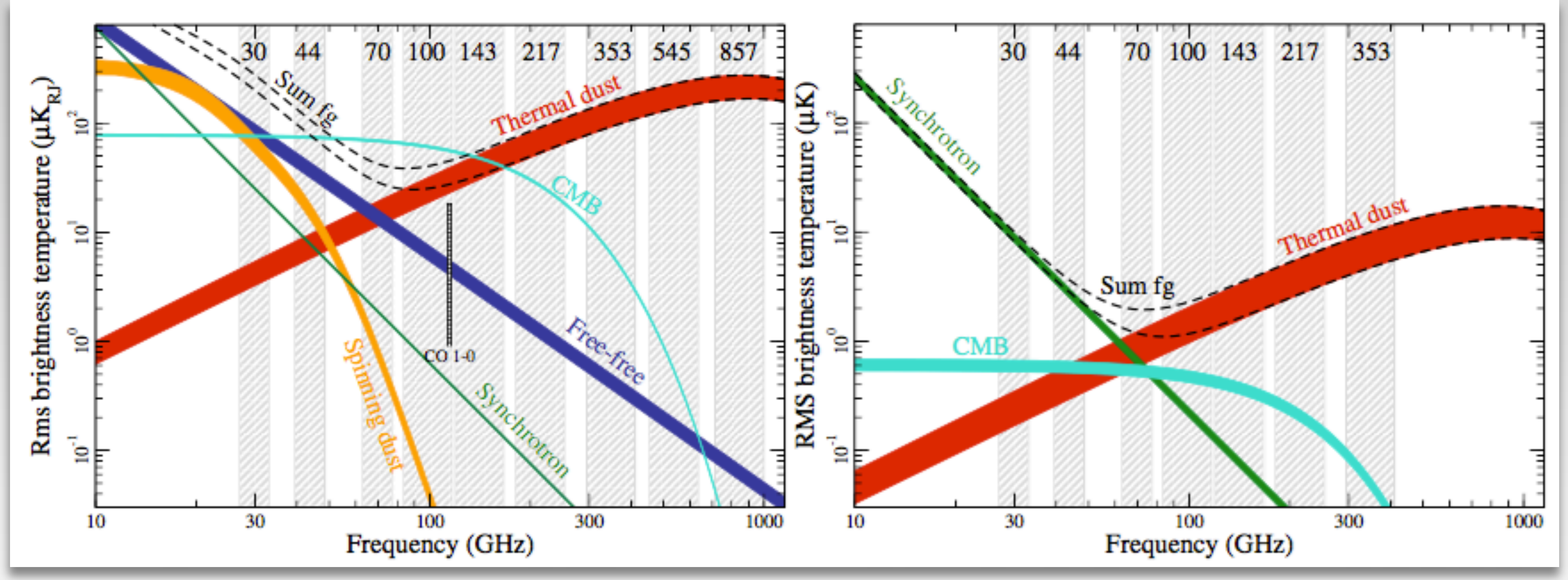
★ Planck wide frequency coverage made this possibe, and allowed to separate the synchrotron and thermal dust polarisations:



Planck 2015 results X, 2016

Foreground cleaning

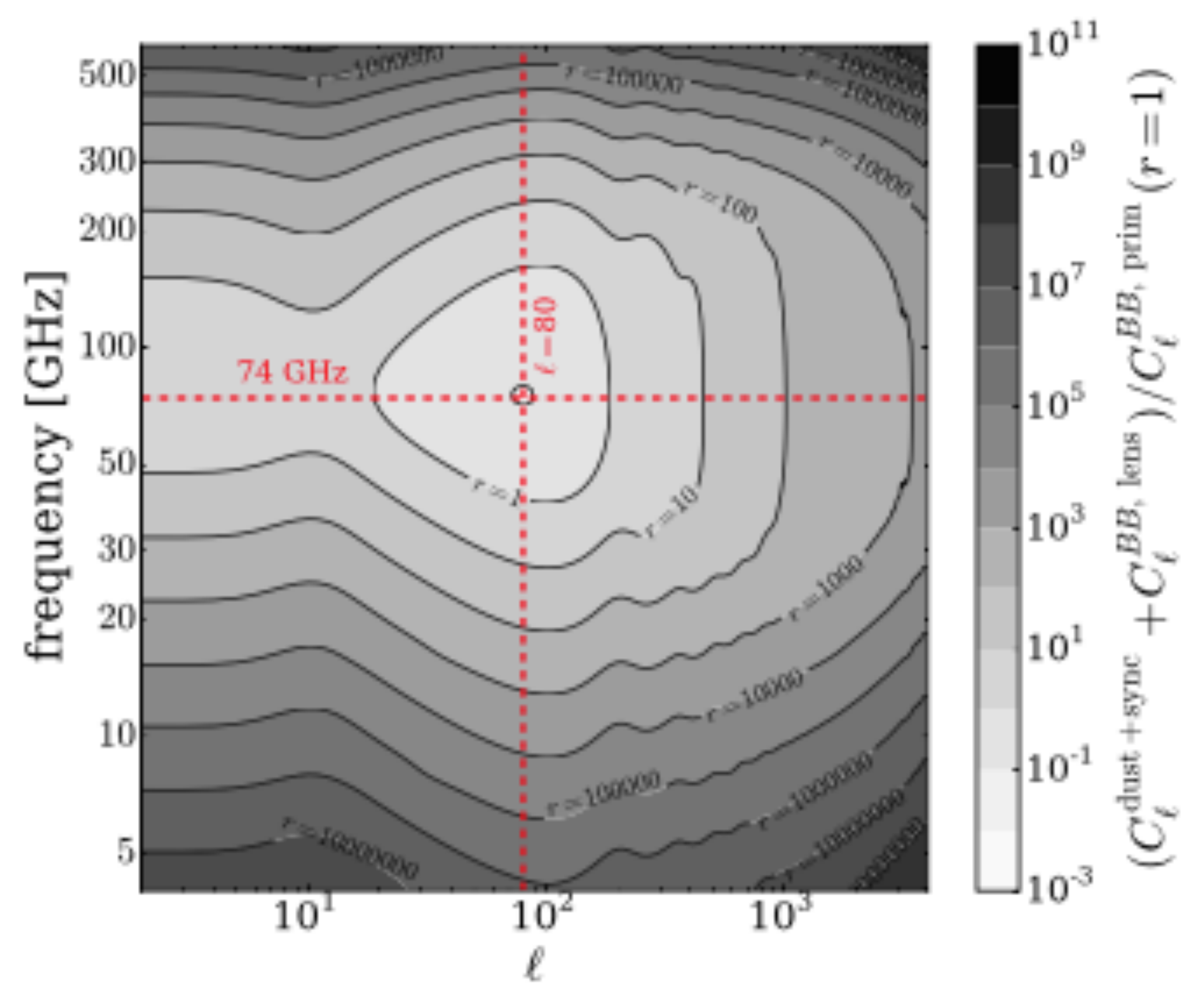
★ Average foreground contributions in the full sky, extracted from Planck data:



Planck 2015 results X, 2016

What are the best frequency and angular scale?

$f_{sky} = 0.5$



Errard et al. (2015)

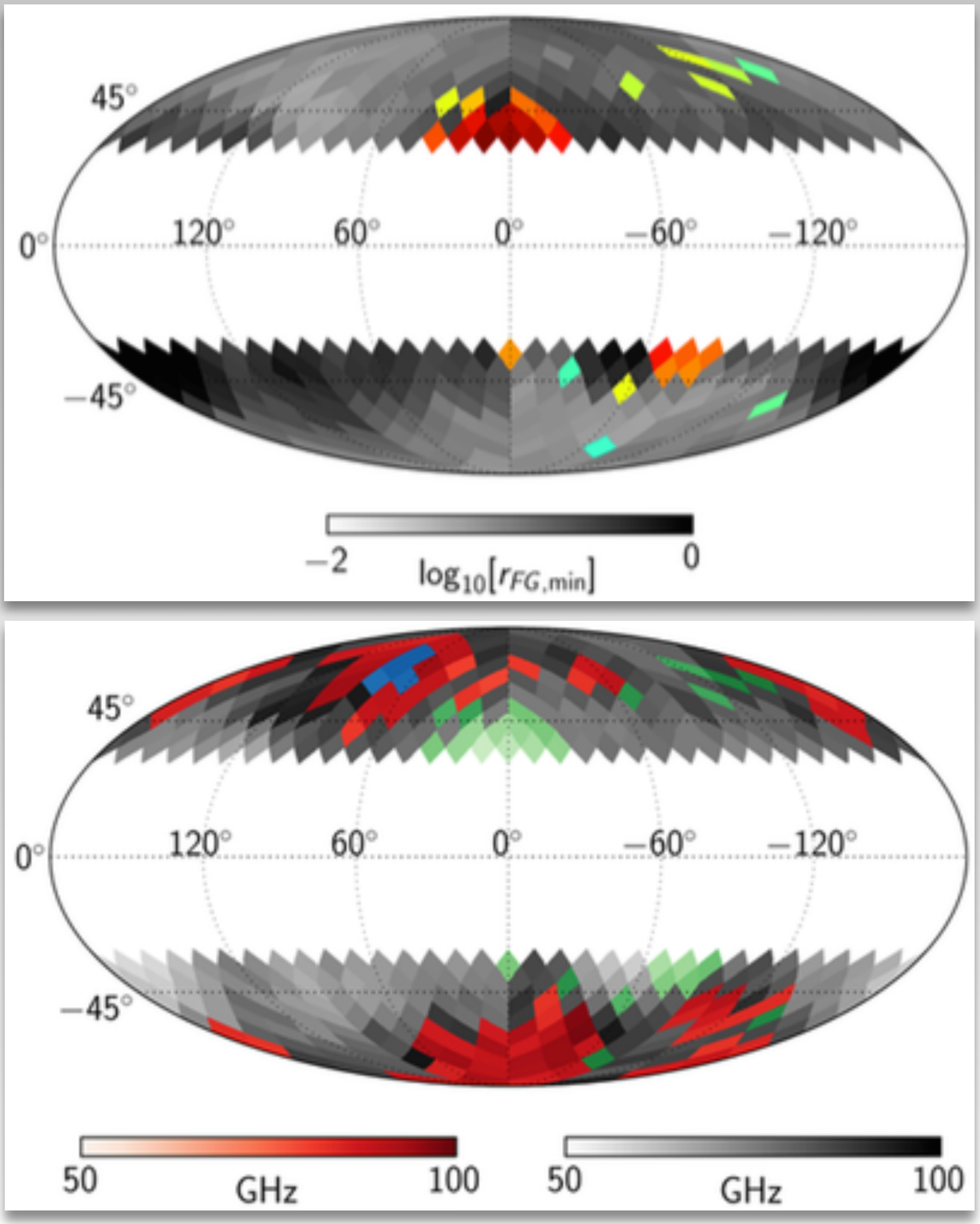
★ Maybe around 60-90 GHz, and $l \sim 80$ (around the recombination peak)

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 $r \sim 0.06-1$
- ★ 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 $r \sim 0.01$ in any region of the sky at $\nu < 100$ GHz

Need to jointly characterise dust +synchrotron



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

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 (alternatives: see Chluba et al. 2017)

★ 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