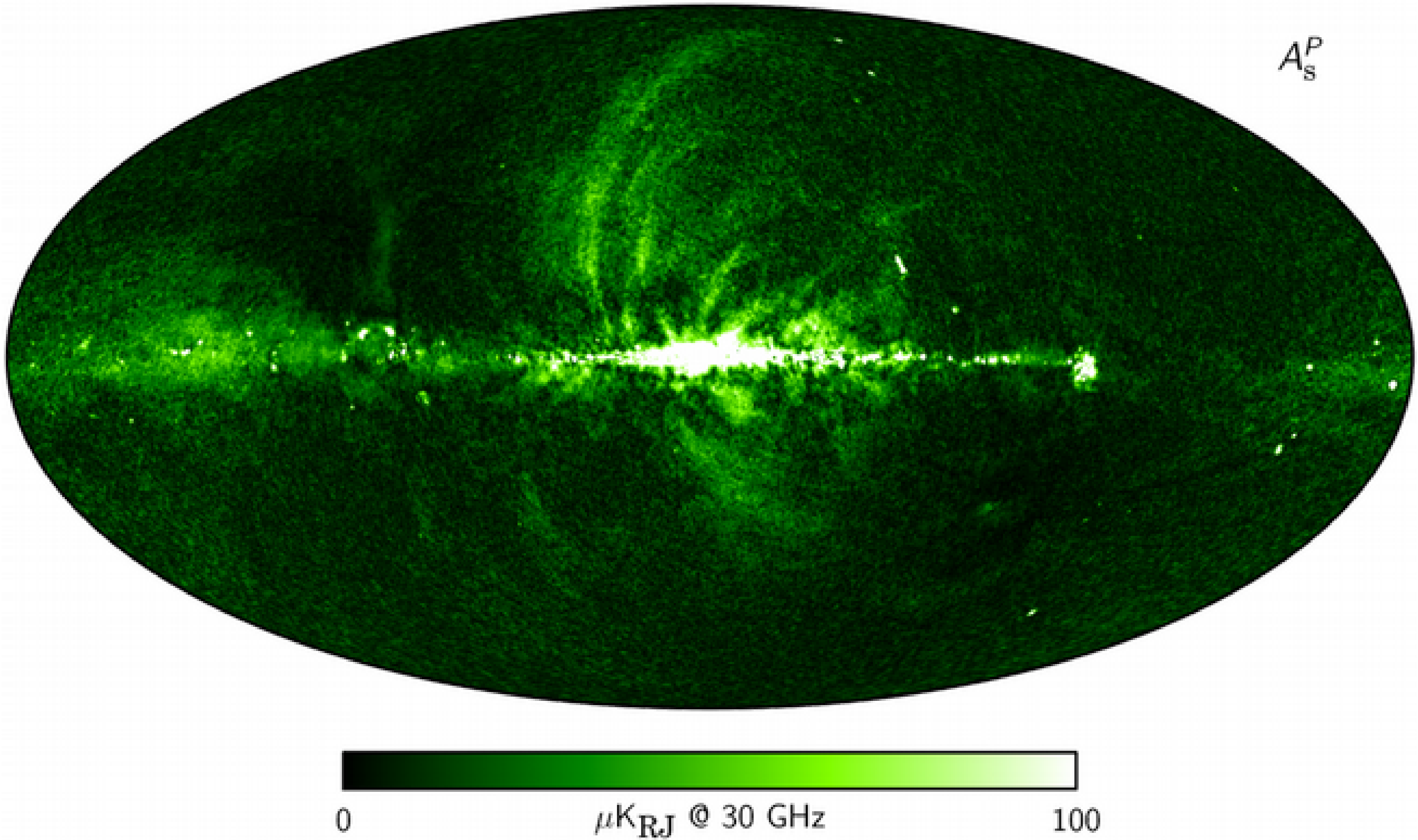
Topic: Foregrounds

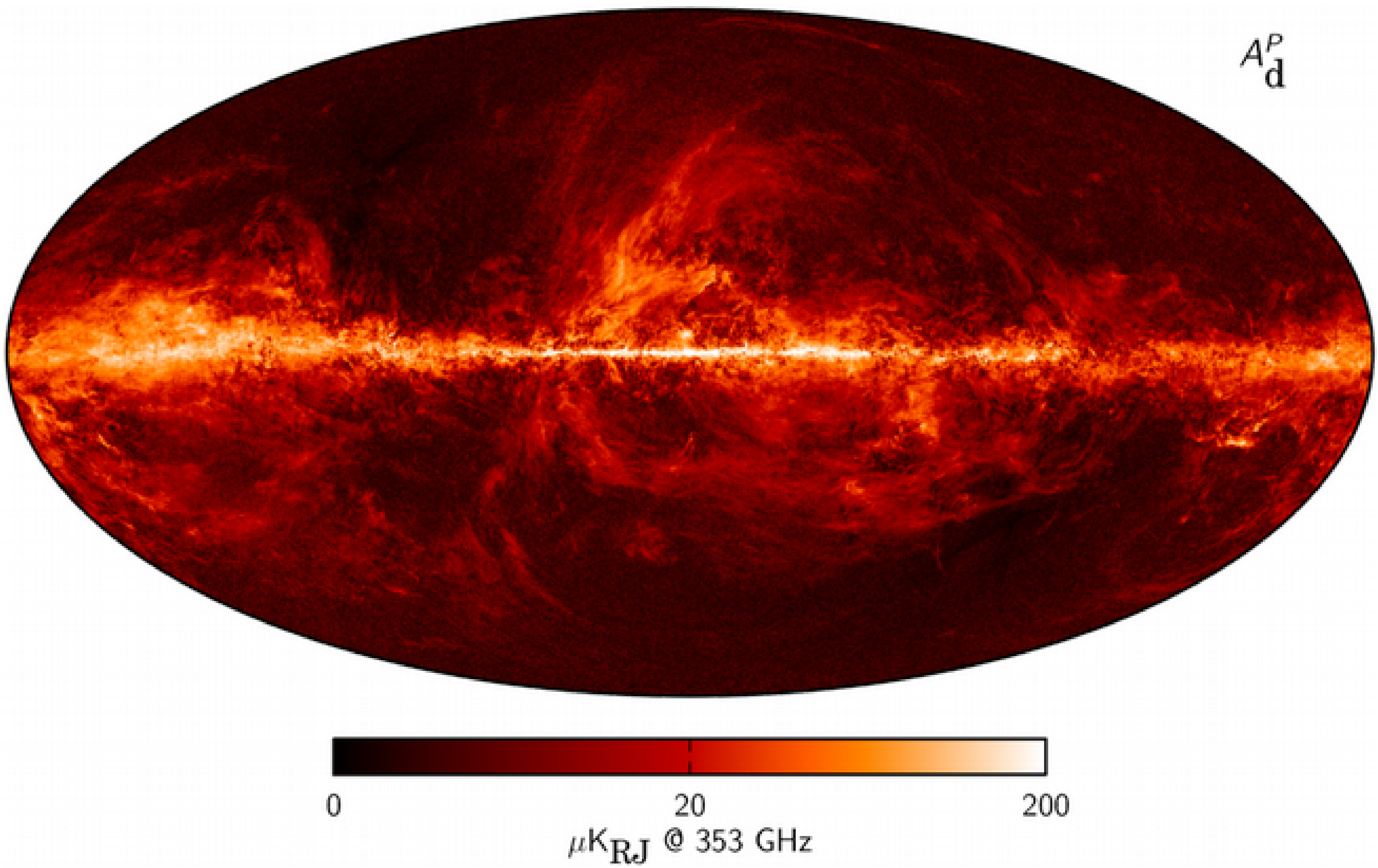
Designing future CMB Experiments Workshop

Polarized foreground overview



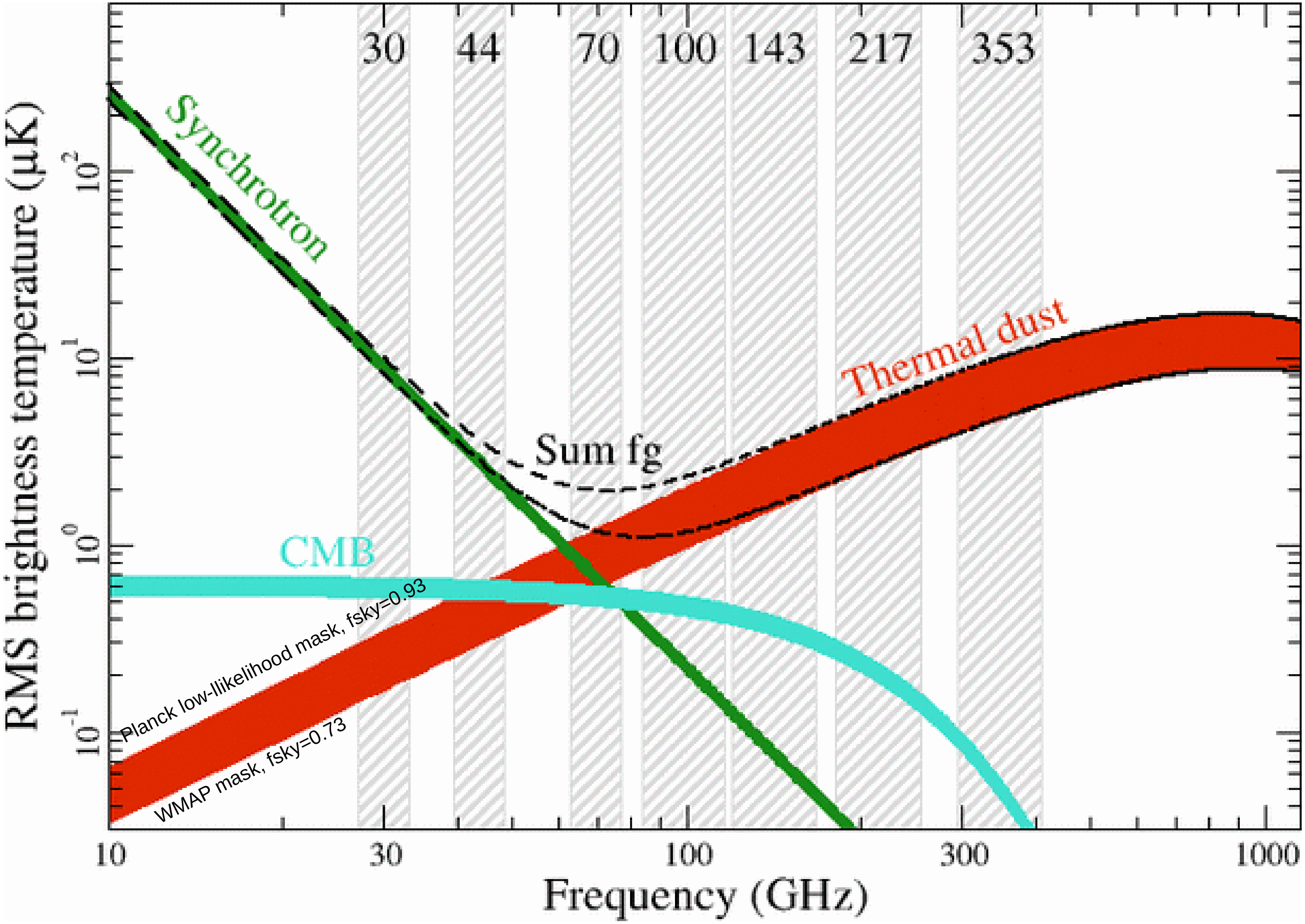
Synchrotron polarization amplitude at 30 GHz

Polarized foreground overview



Thermal dust polarization amplitude at 353 GHz

Polarized foreground overview



Foregrounds

Must consider SED variations and spatial variations

- SED Variations
  - How much intrinsic variability in the SED?
  - How many parameters needed to characterize it?
- Spatial Variations
  - How much variability as a function of multipole?
- Both!
  - How much does a map of a foreground at one frequency look like a map of that foreground at a different frequency?

Thermal Dust Emission

$$I_\nu^{\text{dust}} = A \left(\frac{\nu}{\nu_0} \right)^{\beta} B_\nu \left(T_d \right)$$

Spatial Variations

- Amplitude – Yes! Clear gradient with Galactic latitude, discrete structures, etc.
- Temperature – Yes! Radiation field heating grains is not uniform
- Beta – Probably! Evidence of change with Galactocentric radius, will vary as dust composition(s) varies

Thermal Dust Emission

$$I_\nu^{\mathrm{dust}} = A \left(\frac{\nu}{\nu_0} \right)^{\beta} B_\nu \left(T_d \right)$$

When (not if!) will the Modified Blackbody fail?

- More than one kind of dust (e.g., silicate and carbonaceous, iron grains)
- Distribution of dust temperatures, not just a single value
- Line of sight integration– sum of many MBBs!
- Opacity is not a power law, i.e., beta varies with frequency

Thermal Dust Emission

$$I_\nu^{\text{dust}} = A \left(\frac{\nu}{\nu_0} \right)^{\beta} B_\nu(T_d)$$

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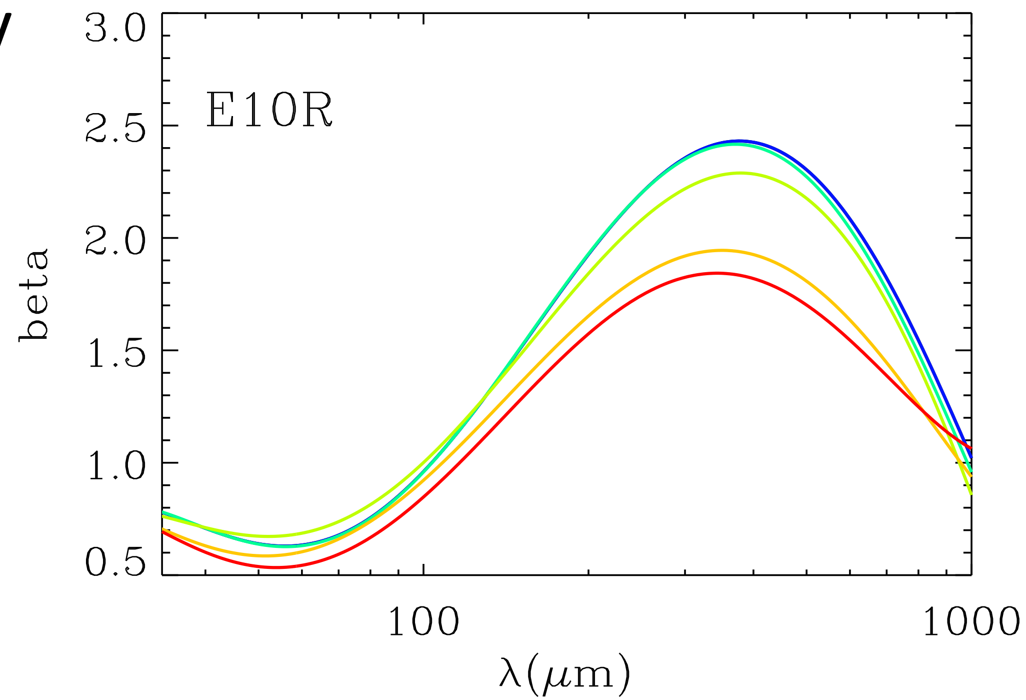


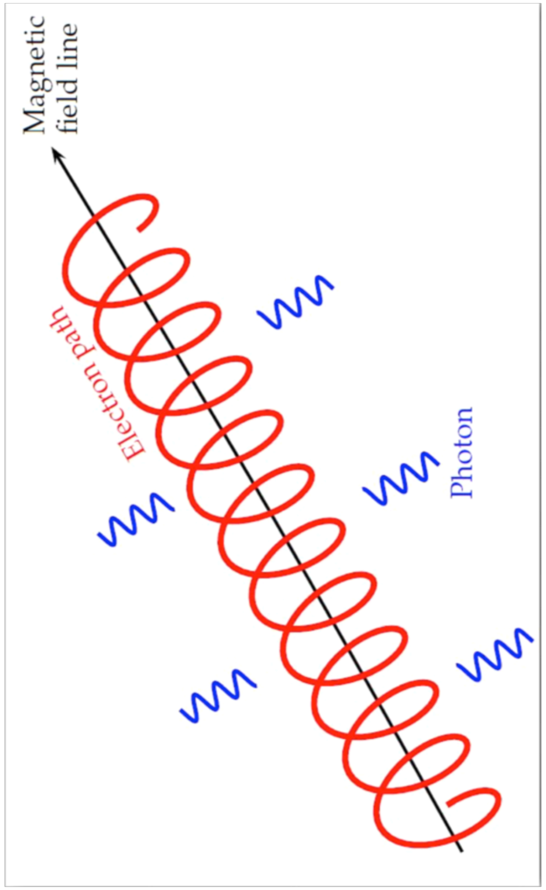
Designing future CMB Experiments: Foregrounds session

R. Belén Barreiro
Instituto de Física de Cantabria (CSIC-UC)

Synchrotron emission

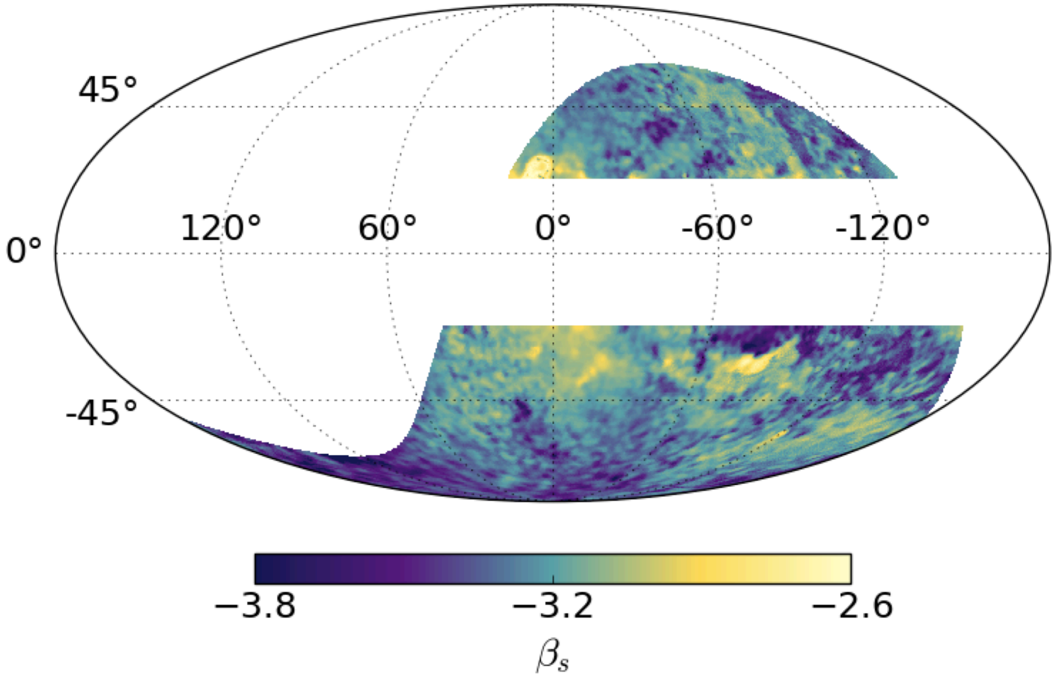
- Emission from relativistic cosmic ray electrons, which are accelerated by the Galactic magnetic field
- SED typically modelled as a power law. For a power-law distribution of electron energies $N(E) \propto E^{-p}$

  Spectral index $\beta_s = -(p+3)/2$
- Typical values of spectral index
  - $\beta_s = -2.7$ (low frequencies, ν below ~5 GHz)
  - $\beta_s = -3.0$ (above ~5 GHz)
  - But it also varies spatially
- Large uncertaintites in the determination of the spectral index
  - difficult to characterise in intensity because of mixing with free-free and AME
  - Less data at the required frequency range than at higher frequencies



Synchrotron emission: polarization

- It is polarised in the direction perpendicular to the Galactic magnetic field
- Typically P/I ~10-40%



Also find that EE spectra show more power than BB spectra:

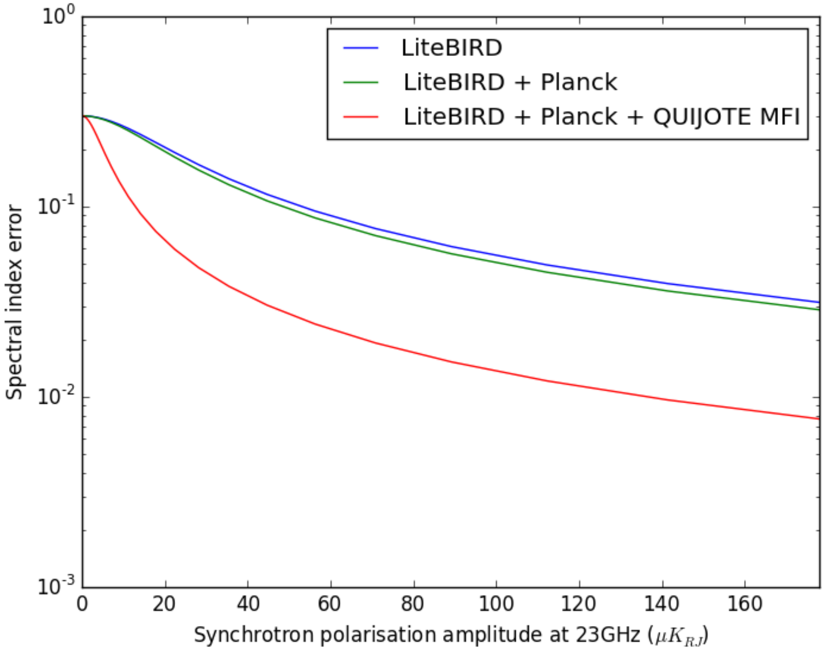
A_{BB}/A_{EE} ~0.5

Similar to asymmetry found for dust with Planck

Synchrotron spectral index from S-PASS (2.3 GHz), WMAP and Planck (Krachmalnicoff et al. 2018)

Impact of synchrotron on B-modes

- Even in the cleanest ~1% region of the sky, synchrotron emission could be as large as r_{SYN}=0.005 @ 110 GHz [Krachmalnicoff et al. 2016], so it can not be ignored
- Error $\Delta\beta_s$~ 0.02 ⇒error Δr ~ 10^{-3} when extrapolated from 23 to 145 GHz [Remazeilles et al. 2017]
- Low-frequency experiments (e.g. QUIJOTE, C-BASS) are essential to monitor the synchrotron especially for spatially varying spectral indices [Errard et al. 2015]
- When adding QUIJOTE MFI [10-20 GHz], errors in the estimation of β_s are significantly reduced with respect to use only LiteBIRD [40-400 GHz]



Forecast on the error on the estimation of β_s (figure from B. Casaponsa)

Synchrotron emission: open questions

- How to model it ?
  - Spatially varying power law may be insufficient
  - Is introducing a spatially-constant curvature enough?
  - How do we best simulate it?

- Which frequencies are necessary in order to characterise the emission
  - Too low frequencies may not be good enough due to decorrelation
  - Range between 10-30 GHz is probably optimal

- Should we observe from space or from Earth ?
  - From Earth:
    - how damaging is the atmosphere? Can we observe the largest scales?
    - How do we cover the full-sky? Which are the best sites in the Northern and Southern hemispheres?
  - From space:
    - Observing low frequencies from space requires large horns, is it worth to dedicate this space in the focal plane to low frequencies at the price of loosing sensitivity at higher frequencies?
  - Which is the best compromise between both types of observations?

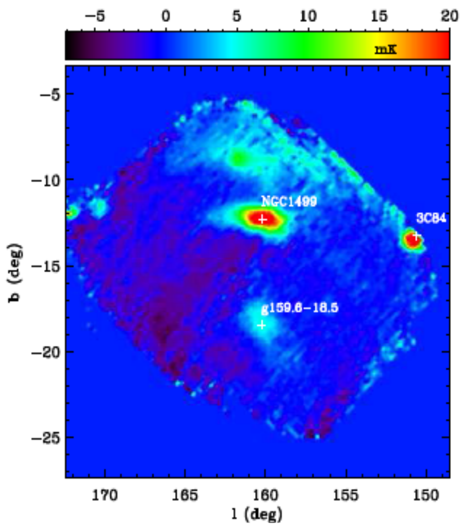
Anomalous microwave emission

- Dust correlated emission, first detected in COBE data (Kogut et al. 1996)
- Proposed models of the emission:
  - Electric dipole emission (spinning dust) (Draine & Lazarian 1998)
    - Polarization typically predicted to be very low (<1 %), with a polarization fraction that decreases with frequency
  - Magnetic dipole emission (Draine & Lazarian 1999)
    - Magnetic dust polarization expected to be higher (<5% at 10-20 GHz, Draine & Hensley 2013)
  - Difficult to make predictions about these models due to many free parameteres

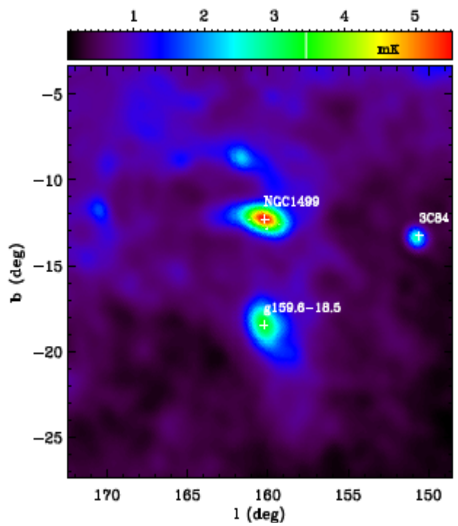
Anomalous microwave emission : Perseus molecular region from QUIJOTE

- Large observation program (~200 hours), on an area covering ~250 deg^2 around the Perseus molecular complex.
- One of the brightest AME regions on the sky
- Final map sensitivity of ≈30 μK/beam

Quijote 11 GHz

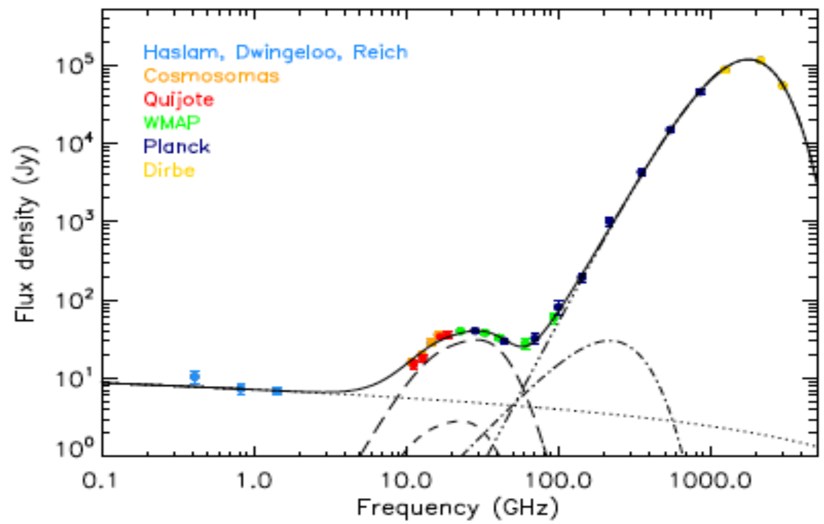


WMAP 23 GHz



Génova-Santos et al. (2015)

SED modelling on G159.6-18.5 in intensity



Well fitted by a combination of free-free, CMB, spinning dust and thermal dust, and two spinning dust components associated to a high-density molecular phase and to a low-density atomic phase.

Anomalous microwave emission: polarization constraints

- Diffuse emission
  - Π < 5% at 22.8 GHz with WMAP (Macellari et al. 2011)
  - Π = 0.6 +/- 0.5 % (Planck 2015 results, XXV)
- Individual regions (from QUIJOTE data)
- Perseus molecular complex

  Π < 6.3% at 12GHz and < 2.8% at 18 GHz (95% C.L.) (Génova-Santos et al. 2015)

- W43 molecular complex

  Π < 0.39% at 18.7 GHz and < 0.22% at 40.6 GHz (95% C.L.) (Génova-Santos et al. 2017)

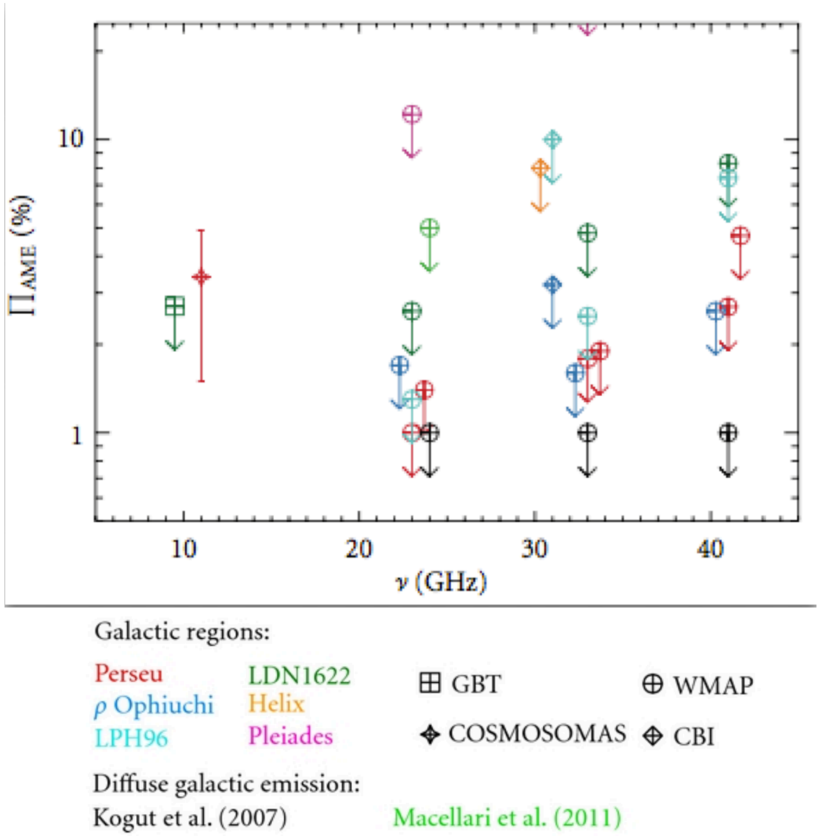
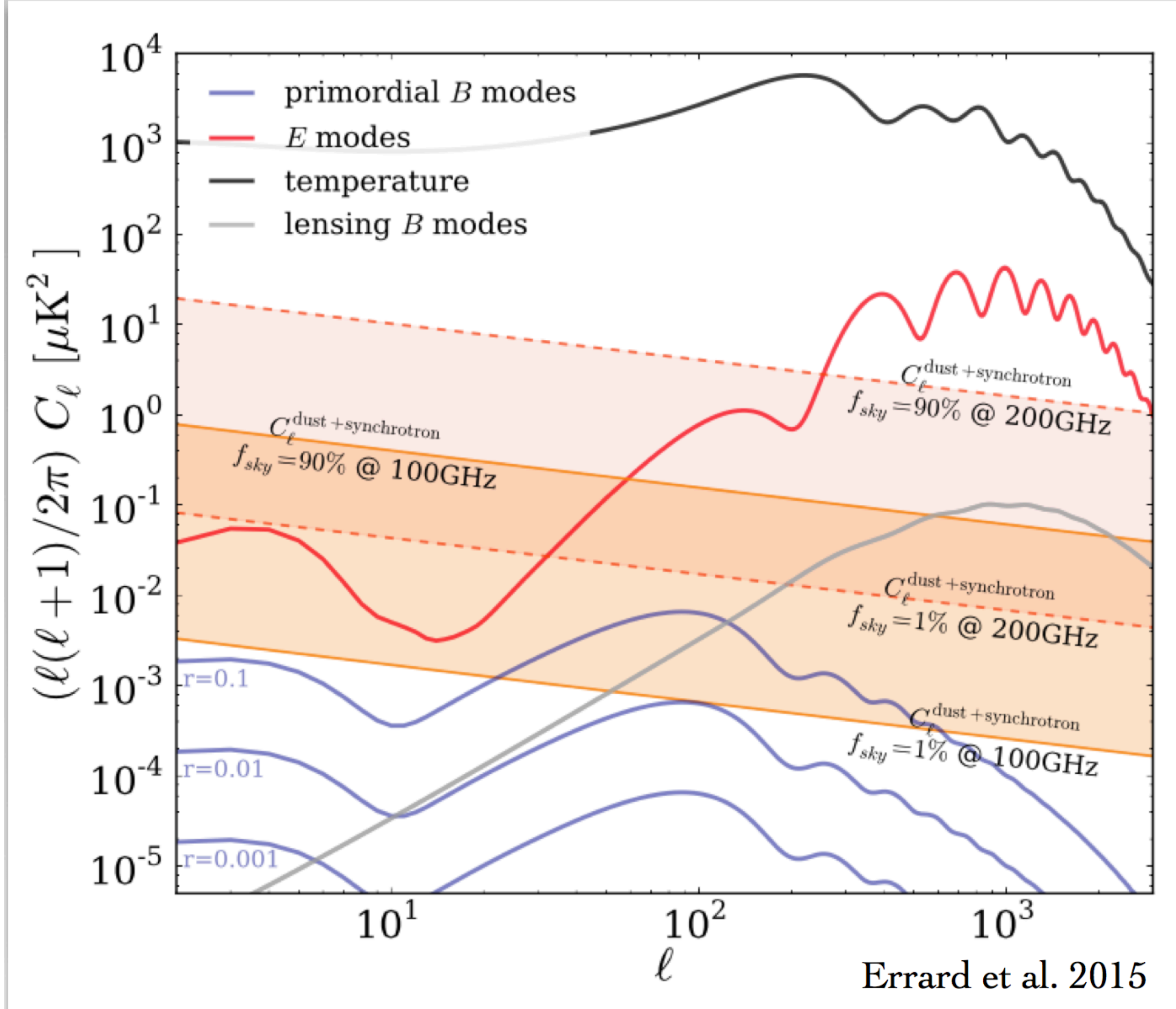


Figure from Rubiño-Martín (2012)

Which is the impact of AME polarization on detecting B-modes?

- Spinning dust polarization expected to be very low
- However, it may not be negligible if AME arising from other physical mechanisms
- Most stringent constraints have been obtained in individual regions, but what about diffuse AME?
- Ignoring an AME component with Π=1% may lead to biases on r ~10^{-3}(Remazailles et al. 2016)
- More ancillary observations are needed to make sure that we do not need to worry

Impact of Galactic foregrounds on B-mode detection



Component separation: Planck methodology

- Four conceptually different approaches
  - Commander : parametric method
  - NILC : internal lineal combination in needlet space
  - Sevem : internal template fitting
  - SMICA: spectral matching independent component analysis

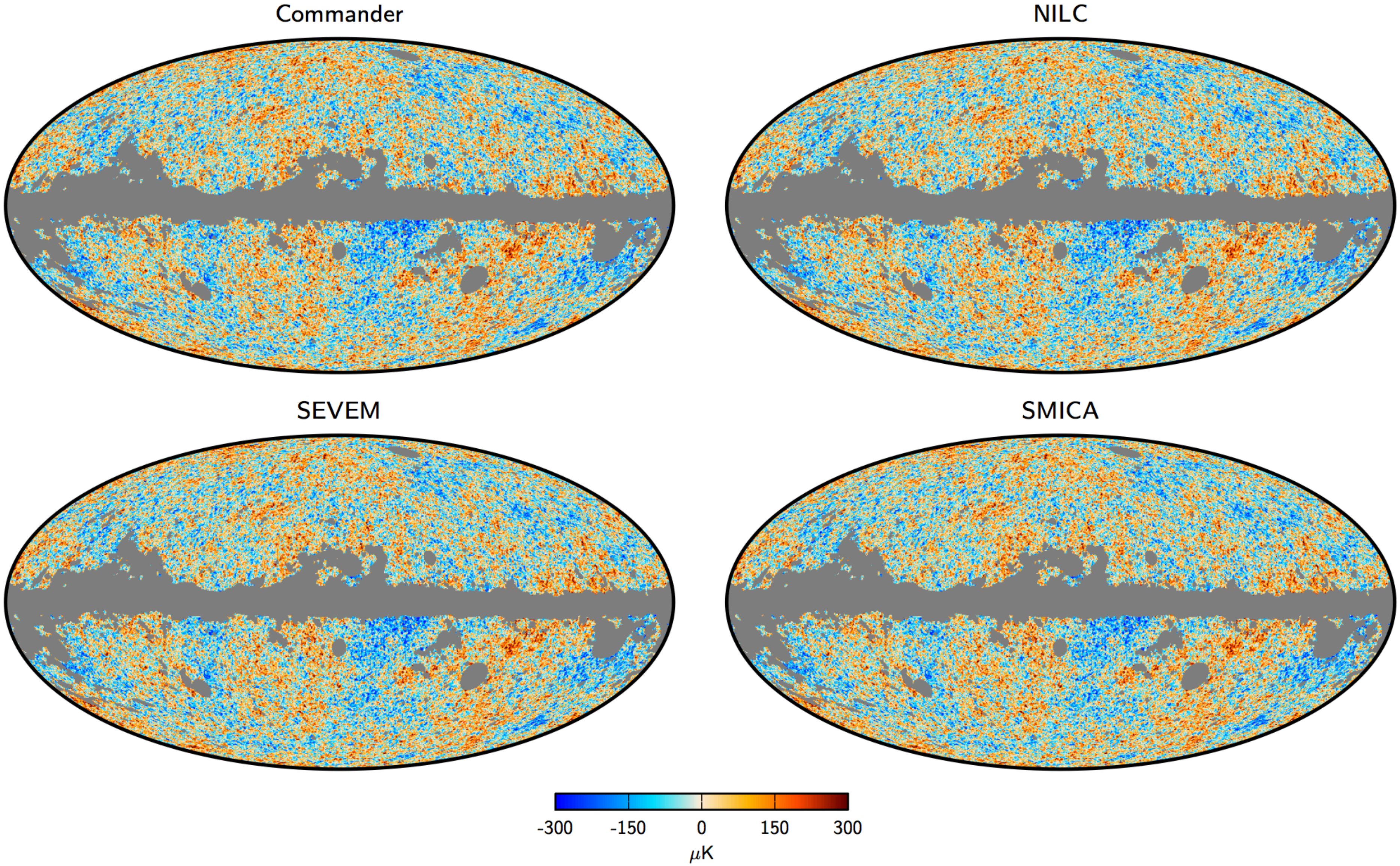
  } Blind methods

- Consistent results between methods
- Provides robustness

Component separation: parametric versus blind

- Blind methods that make minimal assumptions
  - More robust but less powerful
  - Usually faster
  - Usually focused on CMB recovery
- Parametric methods
  - The foreground components are assumed to follow a given model
  - In many cases they are implemented within a Bayesian framework, including prior information on the components or the parameters
  - Usually quite complex but very powerful, since they can recover all the foreground components
  - but they are also less robust than simpler methods, since errors in the modelling can propagate to the final recovered maps
- Complementary methods that provide consistency tests
  - Useful to have both types

Comparison between recovered CMB (T)



Generalizations to polarization

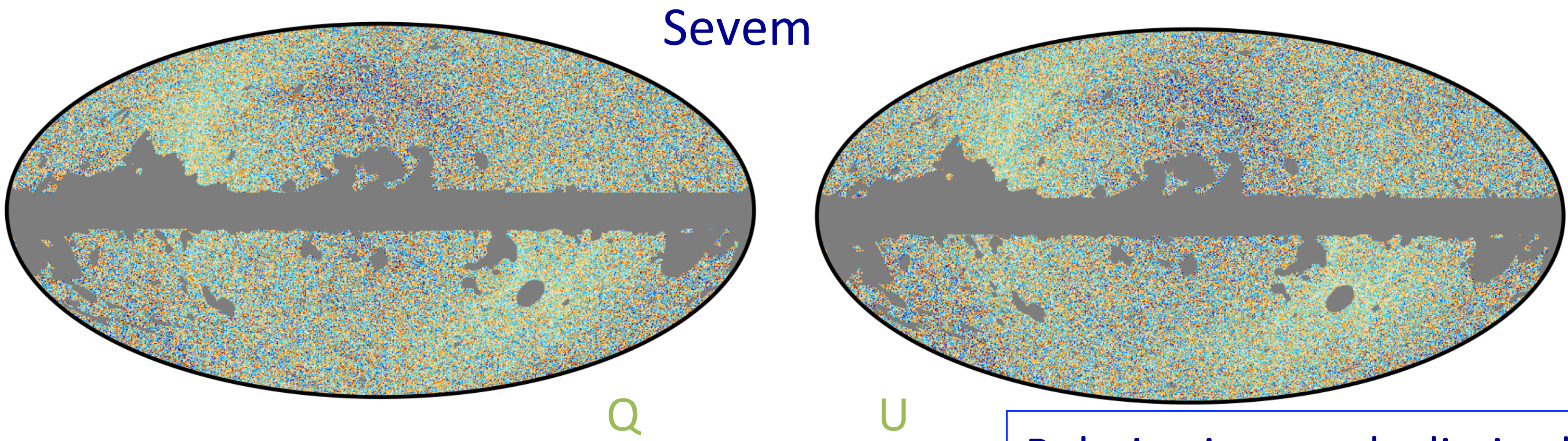
- Historically these methods have been developed for intensity and then simply adapted to polarization.
- In principle one could think of working in Q/U or E/B either independently or jointly with both maps
- For Planck, this did not seem to be critical and different choices have been done for different methods
  - Sevem, NILC: works with Q/U independently
  - Commander: fits Q/U simultaneously
  - SMICA: fits E/B simultaneously

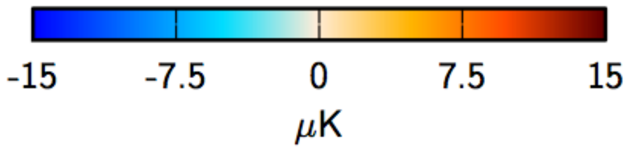
- A way to take into account the physical properties of polarization is to work with the following combination (Fernández-Cobos et al. 2016)

$$\hat{Q}(x)+i\hat{U}(x)=\sum_{j=1}^{N_\nu}\left[w_j^{(R)}+iw_j^{(I)}\right]\left[Q_j(x)+iU_j(x)\right]$$

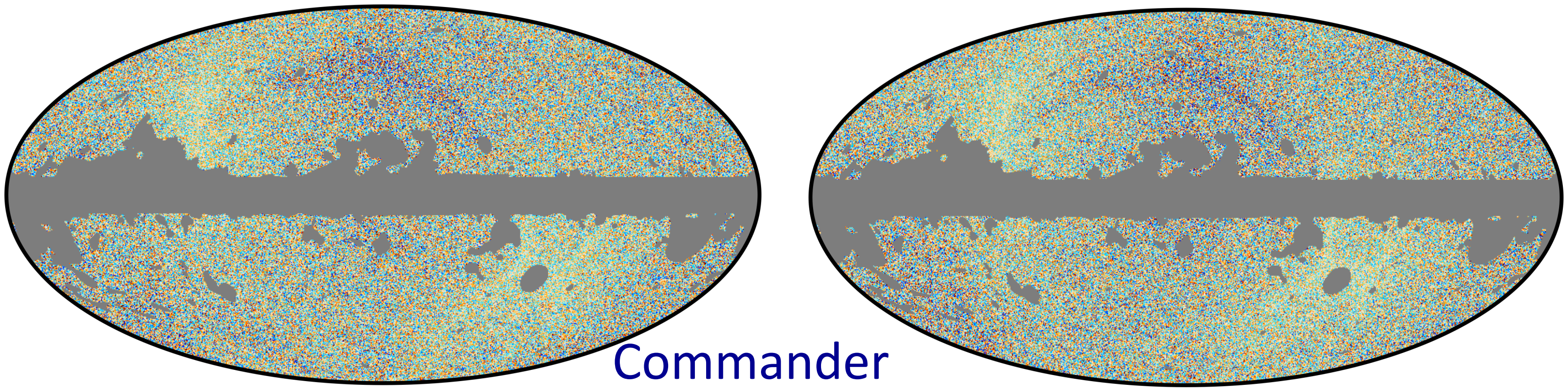
- How important is for future experiments to perform the cleaning coherently in polarization?

Planck CMB polarization





Polarization results limited in the 2015 release by systematics (they will be improved in the next release)
⇨ large scales were removed



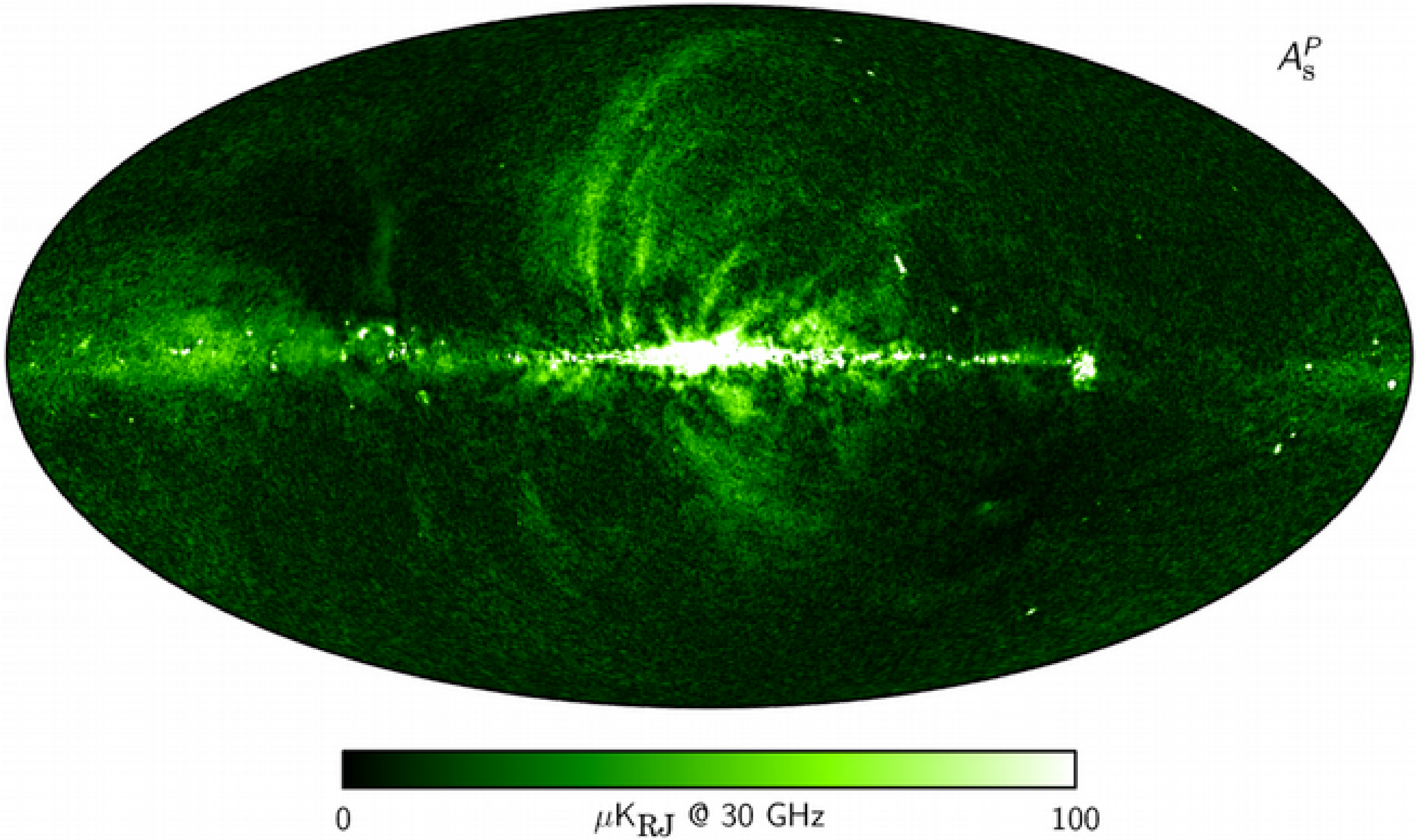
Component separation: open questions

- How do we know that our results are correct or if one output is better than other? In general, this is not trivial !
  - Definition of quality measurements

- How do we construct a confidence mask defining a region where our results are reliable?

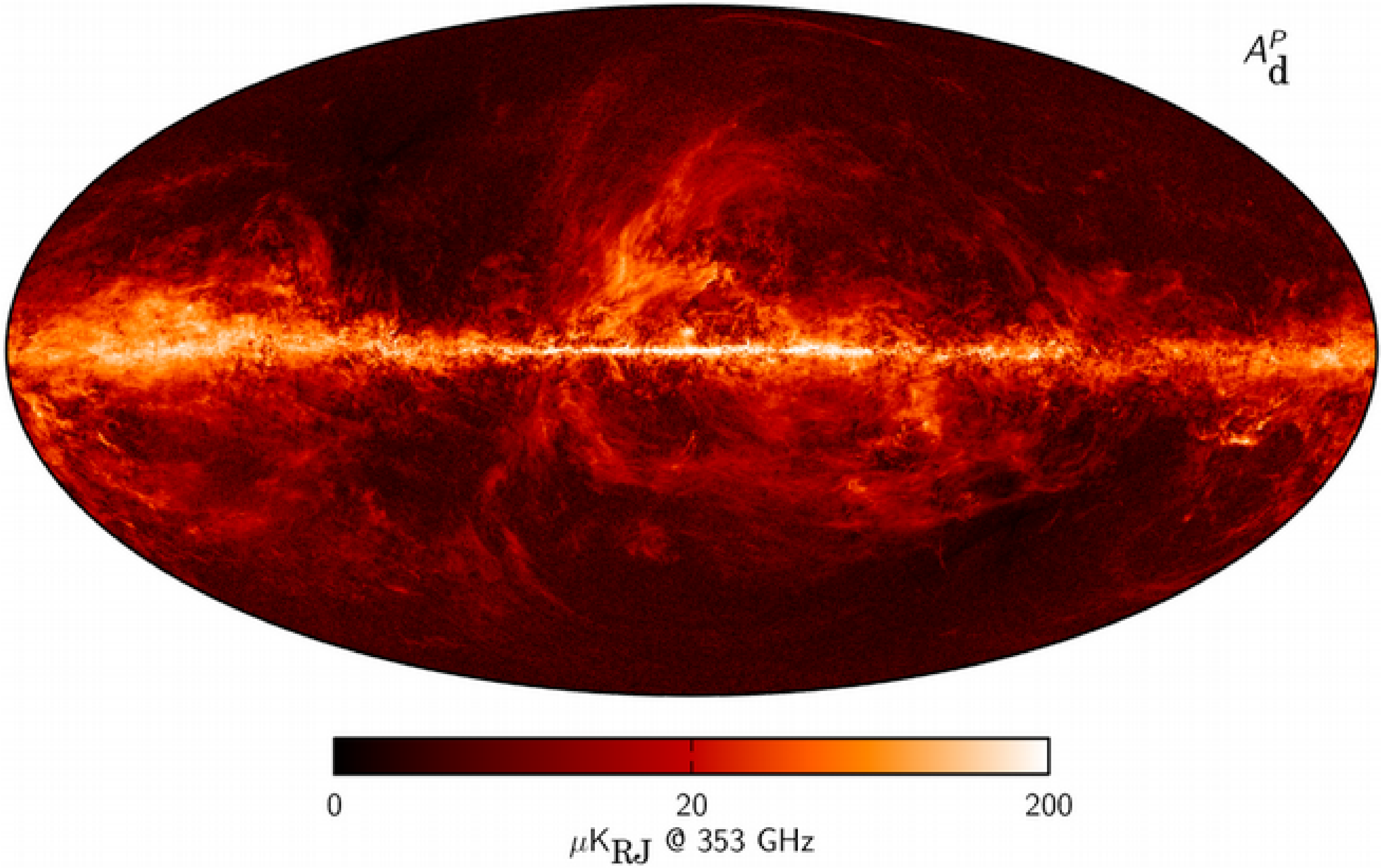
- How to control errors introduced by a wrong modelisation of the foregrounds
  - Could be useful the test of generic models (e.g. Taylor expansion)?

Polarized foreground overview



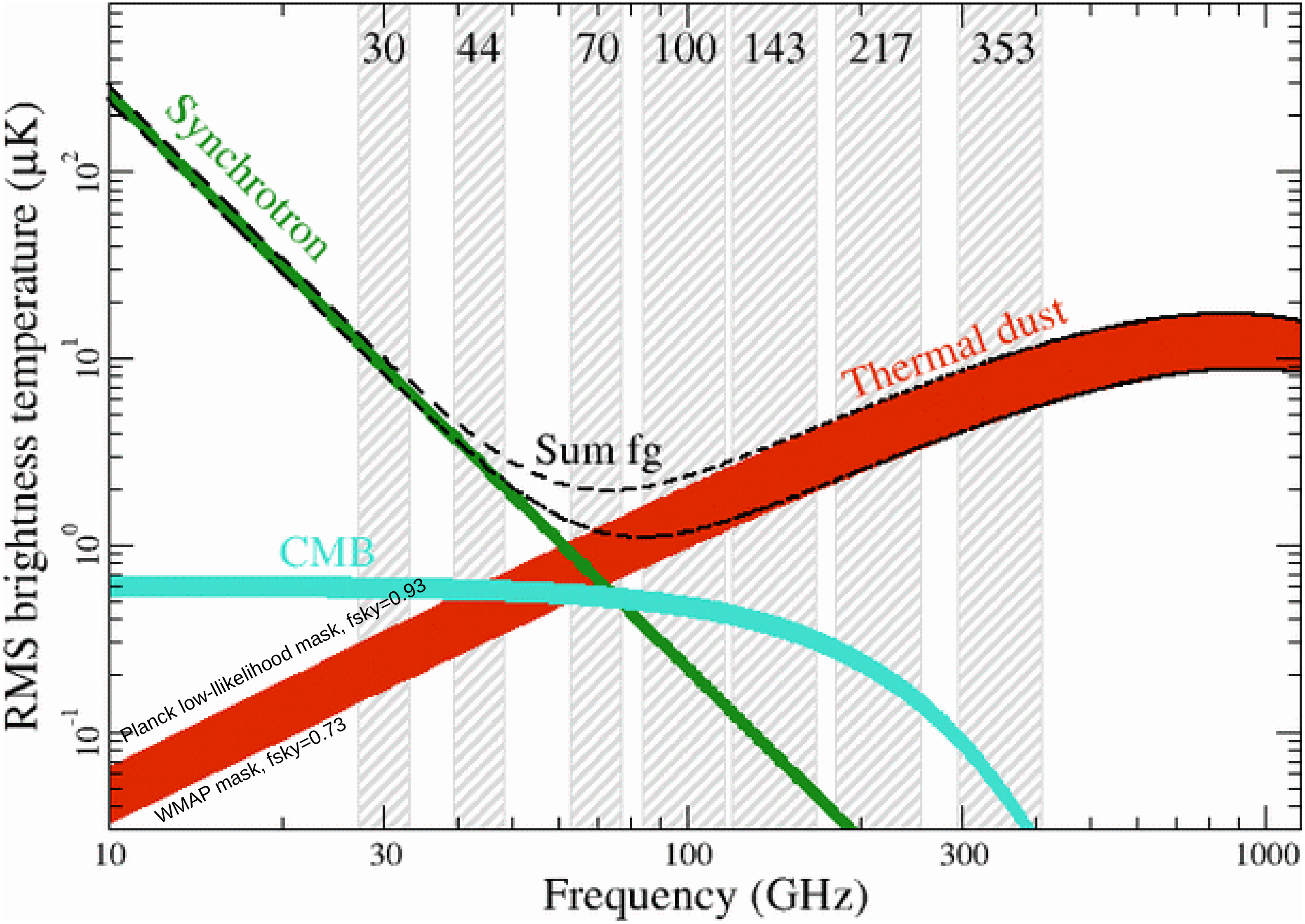
Synchrotron polarization amplitude at 30 GHz

Polarized foreground overview



Thermal dust polarization amplitude at 353 GHz

Polarized foreground overview



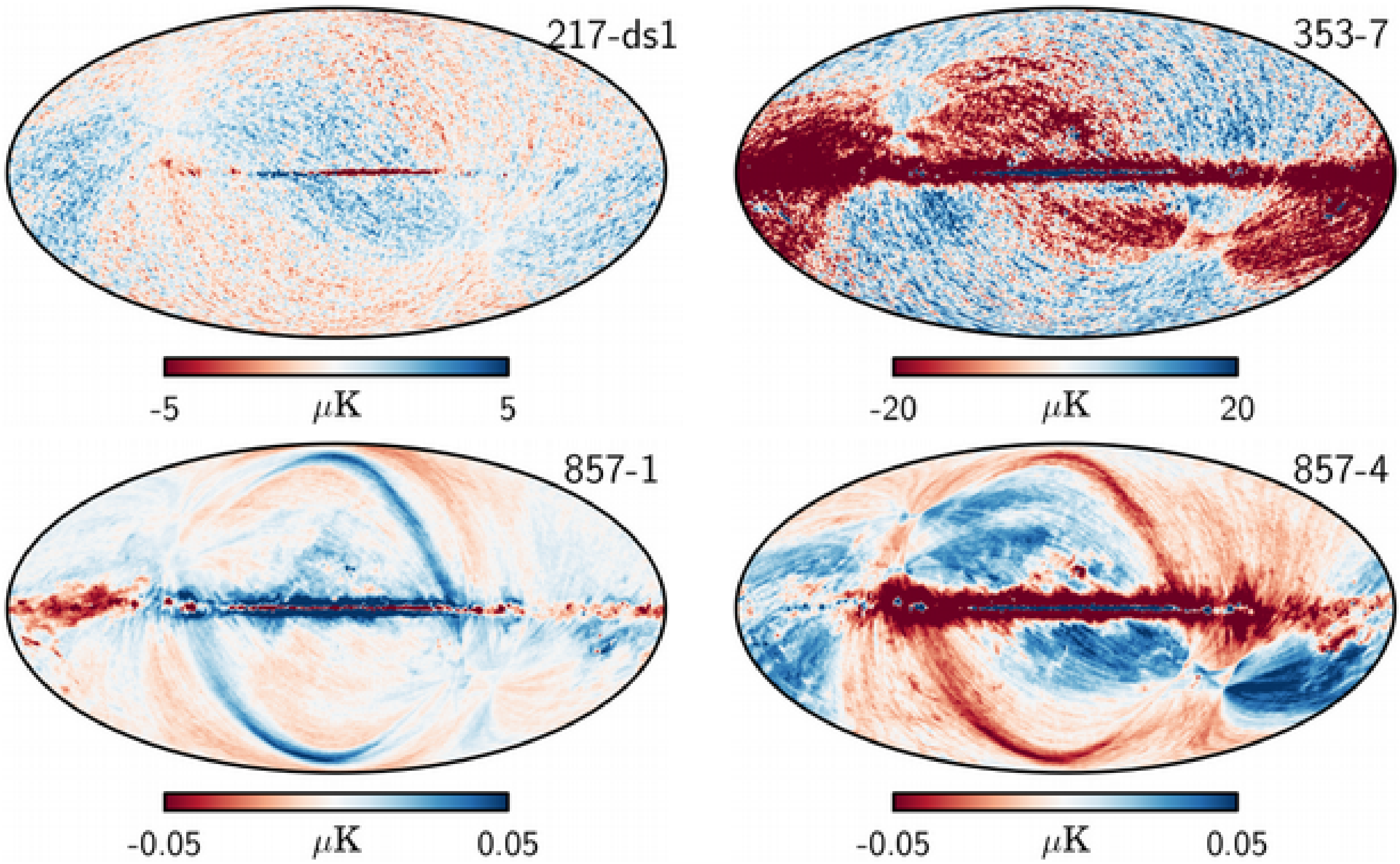
Foregrounds versus systematics

- For Planck, the most difficult problem was not to remove synchrotron or thermal dust, but to disentangle instrumental systematics from foregrounds
  - The calibration process is “disturbed” by the presence of foregrounds
  - To calibrate the instrument, one needs to know what the sky is, but in order to know what the sky is, one needs well calibrated data
-
- Should assume that the same will be true for any future experiment as well
  - If one is lucky, and the systematics are low, then that is good, but one shouldn’t count on it
-
- If that is the case, one is likely to need a detailed and realistic astrophysical model in order to derive accurate leakage models
  - For a true polarimeter-based experiment, this may only require estimation of synchrotron and thermal dust (and possibly polarized AME++) => moderate frequency range
  - For total-power experiments, one also needs to decompose the temperature sky into free-free, AME, CIB, zodi etc… => wider frequency range

Physical model versus “Taylor expansion”

- Recently increased interest in use of Taylor expansion approximations instead of physical parametric models
  - Assume SED can be approximated by power-law + curvature or similar
  - Can be used to partially account for 3D integration effects
- Main advantage: Only need to know the foreground spectrum accurately around the foreground minimum
- Main disadvantage: No simple support for ancillary information to break degeneracies
  - Examples: Haslam for synchrotron, recombination line surveys for free-free, Dame for CO, HI for thermal dust, PASIPHAE for 3D integration etc.
- A proper physical model can incorporate a wide range of data, and is therefore in general better suited to break degeneracies by adding more data
- Modeling errors are often raised as a particular problem for parametric methods. In practice we have experience the opposite: Chi-square and residual maps are extremely powerful tools to uncover both astrophysical modeling errors and instrumental systematics, and a direct handle on how to fix them
- Study proposal: Perform head-to-head comparison of Taylor-expansion and physical models with the same PICO and S4 simulations
  - What bias and uncertainties result for each as a function of frequency range?

Residual maps from bad Planck channels



Difficulties with parametric fitting

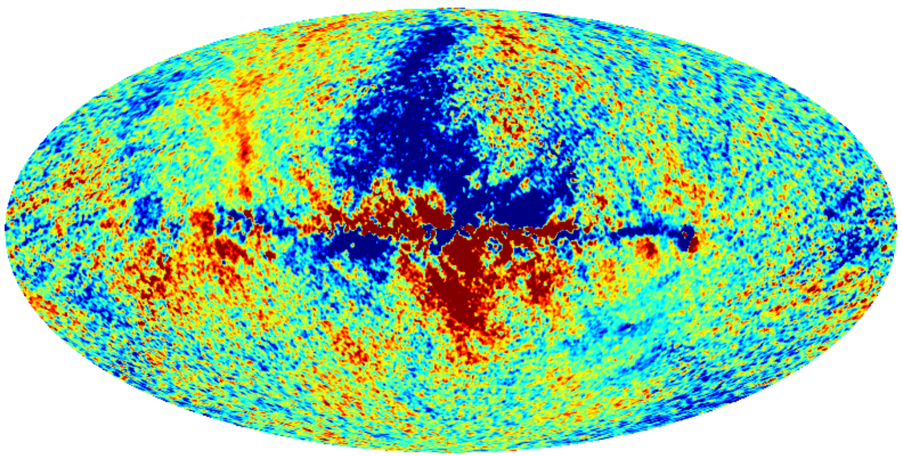
- Some of the most difficult issues with parametric fitting for Planck have been:
  - Determining accurate zero-levels for each map => degeneracies with foreground amplitudes and spectral indices
  - Accurate calibration of non-CMB dominated frequencies (545 and 857 GHz for Planck) => degeneracies with spectral indices
  - Choice of priors for low signal-to-noise parameters
    - Are the physical properties of foregrounds similar in the Galactic plane and at high latitudes?
  - Coupling between CIB and thermal dust spectral parameters at high latitudes => bias in dust SED parameters
  - Too low sensitivity at low frequencies to disentangle synchrotron, free-free and AME
  -
- The general solution to all these problems may be use of more ancillary observations.
  - What is available today, and how robust and trustworthy are these data sets?
  - Could one consider building dedicated special-purpose supporting experiments for PICO and S4, similar to C-BASS, PASIPHAE etc.?

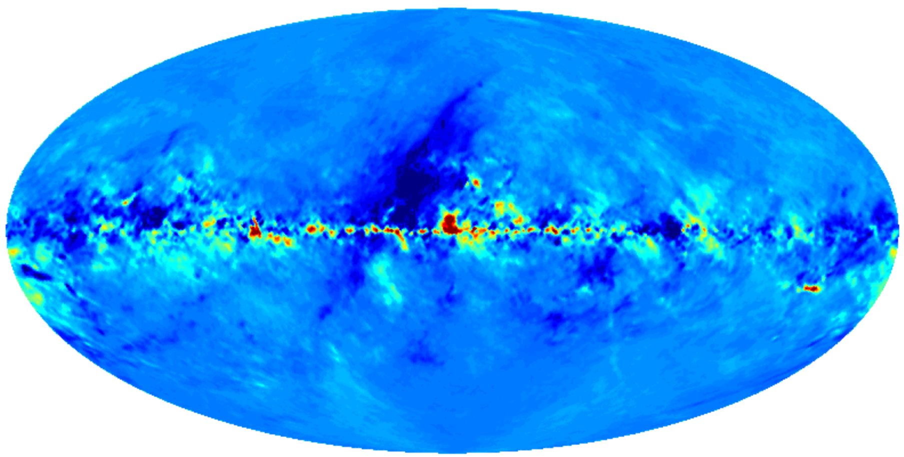
Sky modeling

Raphael Flauger

CMB-S4 Data Challenge models

Template based models 01-03

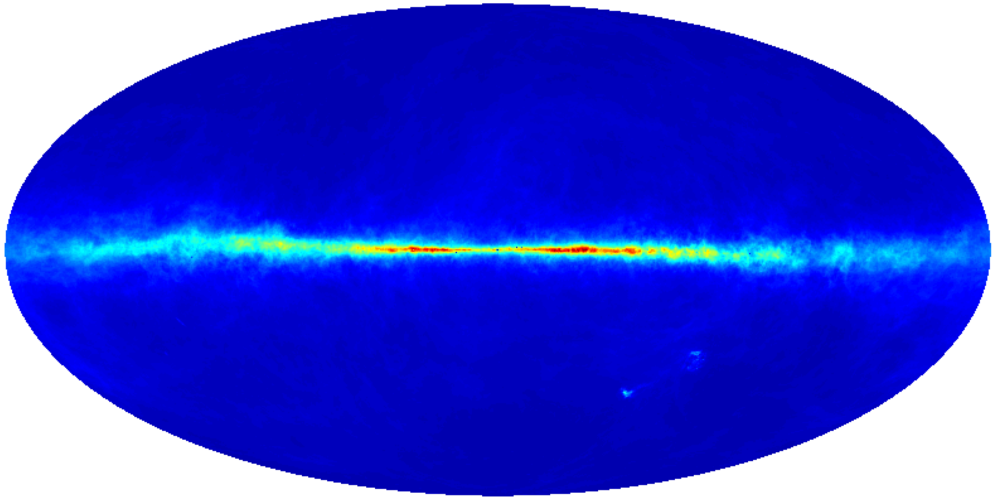




- synchrotron template from WMAP 23 GHz or LFI 30 GHz
- dust template from Planck 353 GHz
- assumed spectral dependence

CMB-S4 Data Challenge models

HI based dust models   04

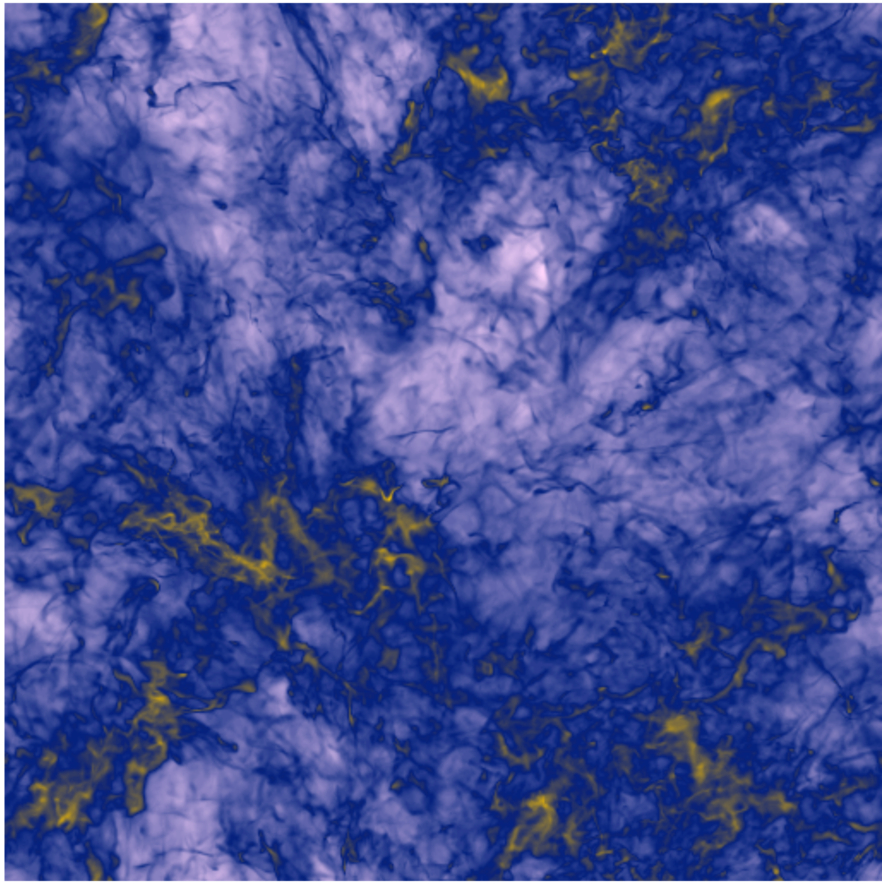


- both amplitude and polarization angles can be estimated from HI data

CMB-S4 Data Challenge models

Models based on (3d) MHD simulations   06 and 08

- assume constant dust-to-gas ratio to include dust
- assume energy spectrum of electrons to include synchrotron



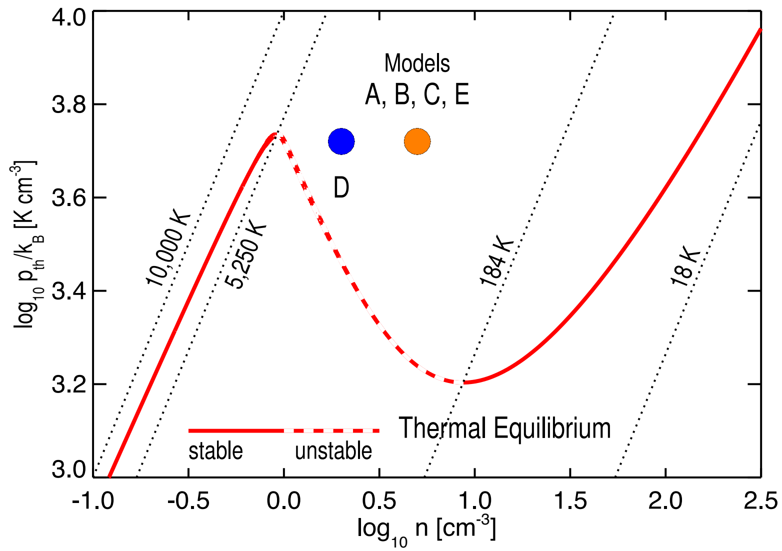
MHD simulations

Models based on (3d) MHD simulations 06 and 08

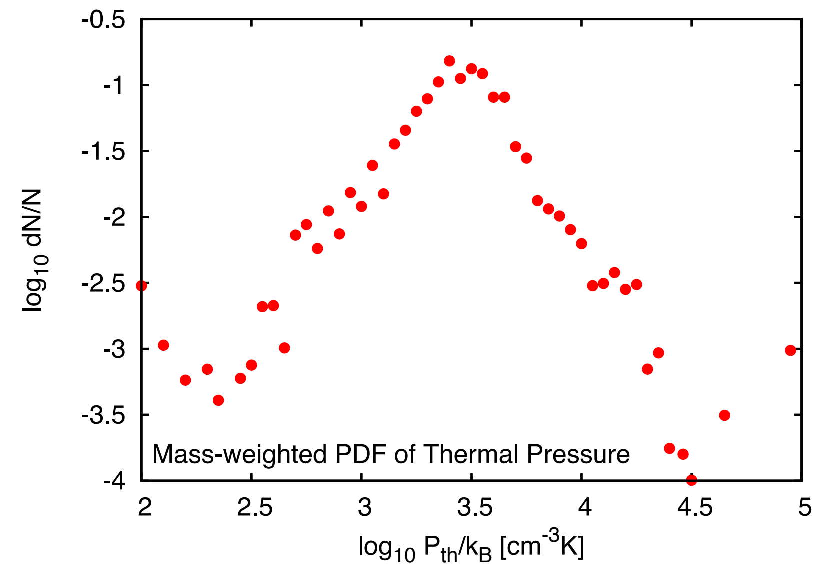
$$
\begin{aligned}
\partial_t \rho \quad &+ \boldsymbol{\nabla} \cdot (\rho \boldsymbol{u}) = 0, \\
\partial_t (\rho \boldsymbol{u}) &+ \boldsymbol{\nabla} \cdot \left[\rho \boldsymbol{u}\boldsymbol{u} - \boldsymbol{B}\boldsymbol{B} + \left(p + \frac{\boldsymbol{B}^2}{2} \right) \boldsymbol{I} \right] = \boldsymbol{f}, \\
\partial_t \boldsymbol{B} \quad &+ \boldsymbol{\nabla} \cdot (\boldsymbol{u}\boldsymbol{B} - \boldsymbol{B}\boldsymbol{u}) = 0, \\
\partial_t \mathcal{E} \quad &+ \boldsymbol{\nabla} \cdot \left[\left(\mathcal{E} + p + \frac{\boldsymbol{B}^2}{2} \right) \boldsymbol{u} - (\boldsymbol{B} \cdot \boldsymbol{u}) \, \boldsymbol{B} \right] = \boldsymbol{u} \cdot \boldsymbol{f} - \rho \mathcal{L}(\rho, T).
\end{aligned}
$$

MHD simulations

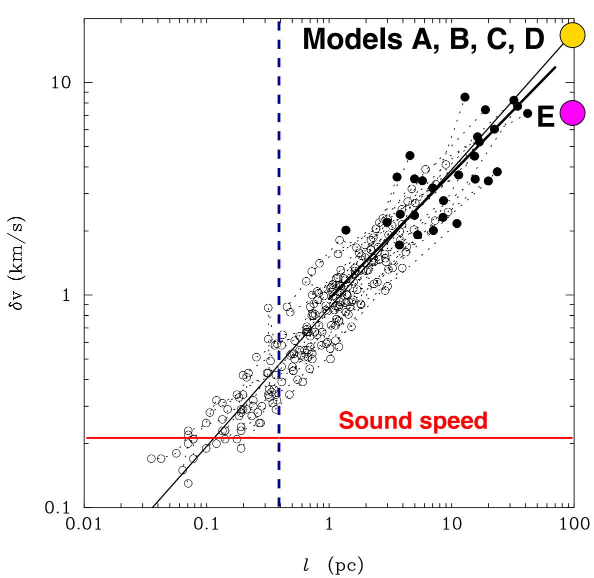
ISM thermodynamics [Wolfire et al., 2003]



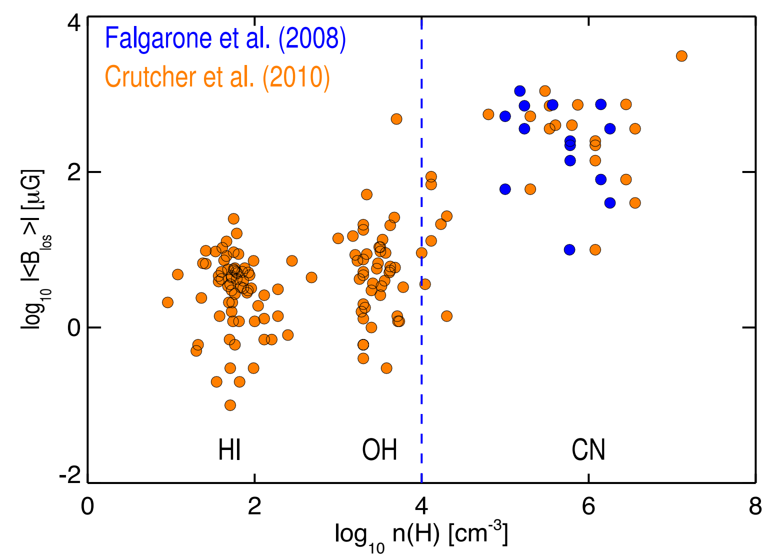
PDF of thermal pressure [Jenkins, 2010]



Linewidth-size relation [Brunt & Heyer, 2004]

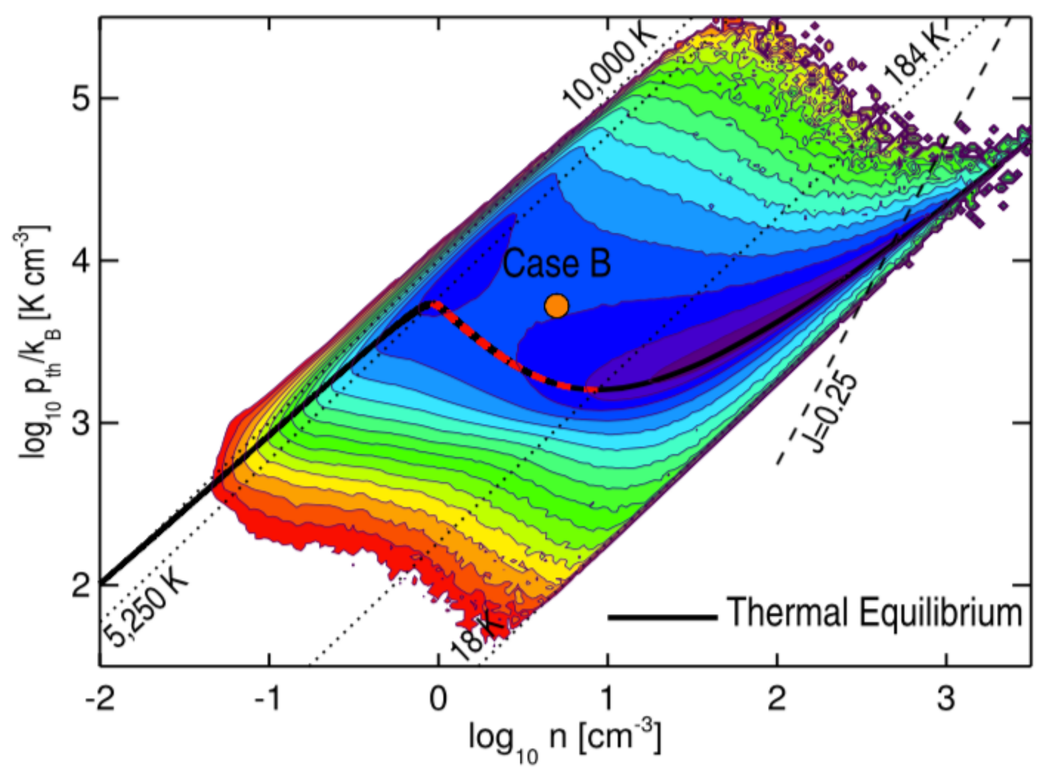


B–n relation [Crutcher et al., 2009]



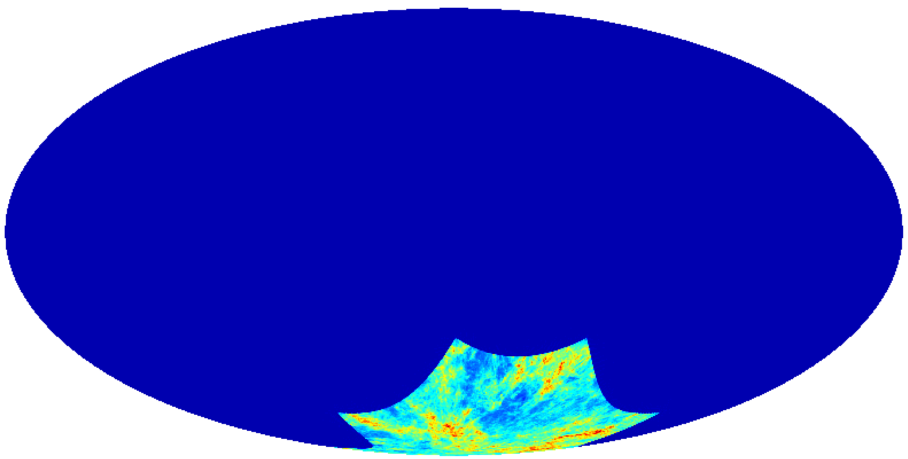
MHD simulations

Case	b_0	$b_{\rm rms}$	$b'_{\rm rms}$	$\mathcal{M}_a$	$\mathcal{M}_a^w$	$\mathcal{M}_a^u$	$\mathcal{M}_a^c$	$\mathcal{M}_s$	$\mathcal{M}_s^w$	$\mathcal{M}_s^u$	$\mathcal{M}_s^c$	$\mathcal{F}^w$	$\mathcal{F}^u$	$\mathcal{F}^c$
	μG	μG	μG									%	%	%
A	9.54	16.6	13.6	1.0	0.6	0.9	2.5	4.9	1.8	4.0	13.5	25	68	7
B	3.02	11.7	11.3	1.4	1.2	1.6	4.3	5.4	1.7	4.2	15.2	23	70	7

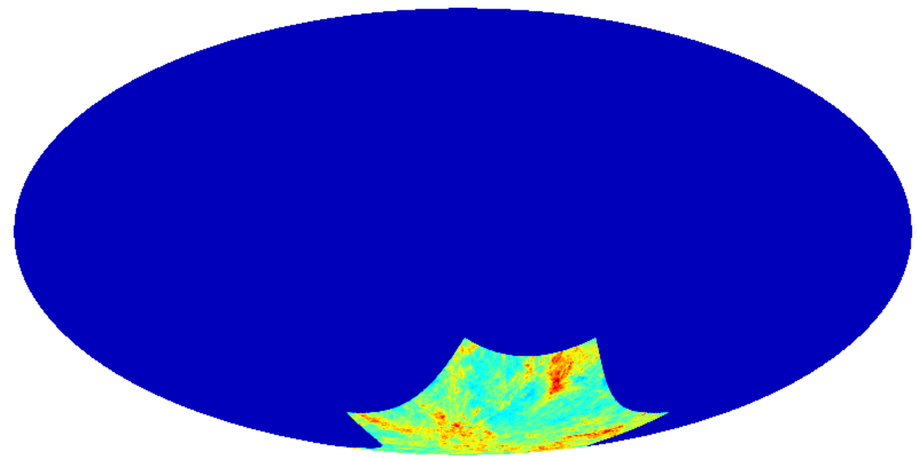


CMB-S4 Data Challenge models

Models based on (3d) MHD simulations 06 and 08



155 GHz

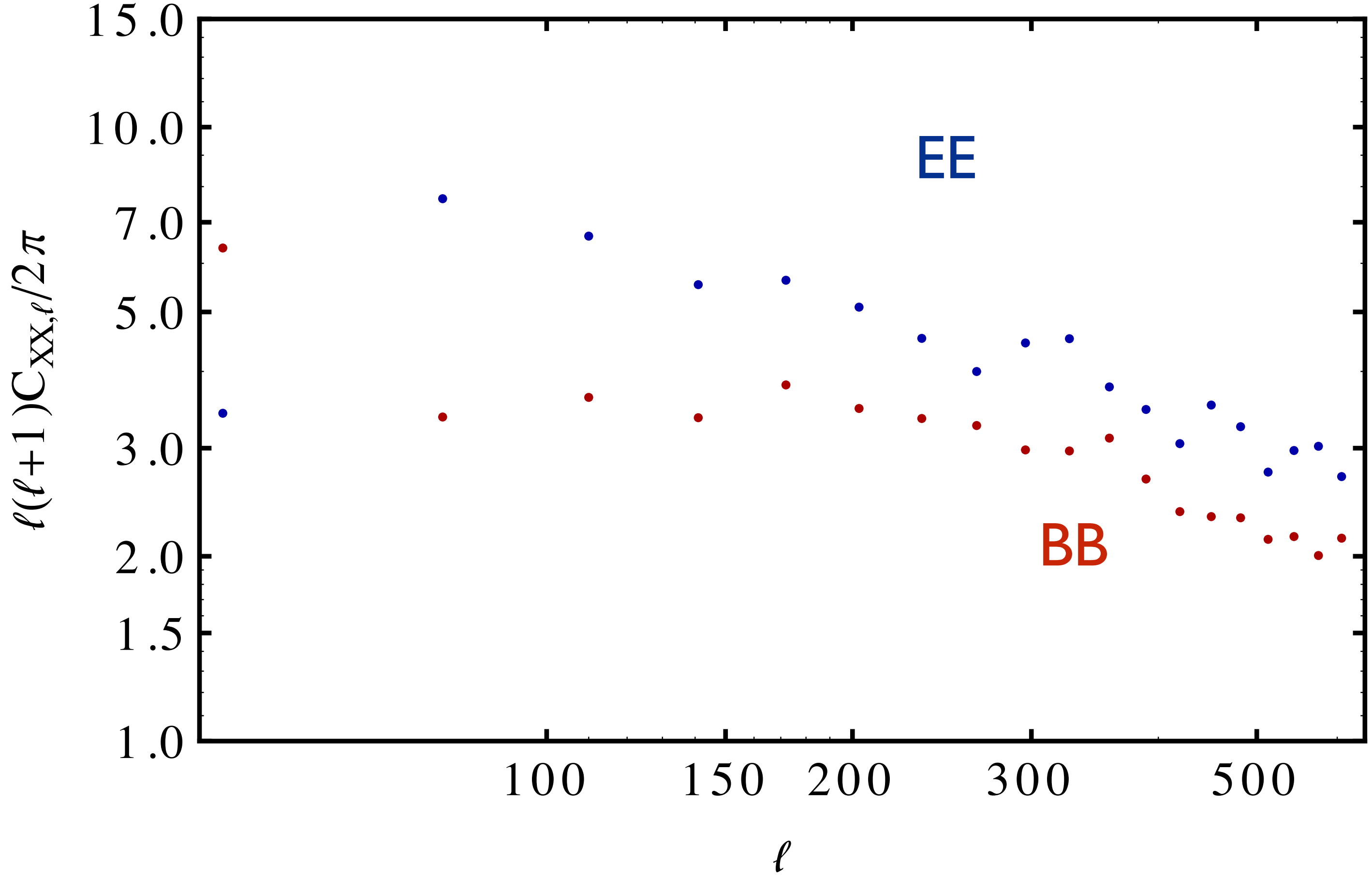


95 GHz

- Currently limited to small patches at this resolution, lower resolution available on full sky

CMB-S4 Data Challenge models

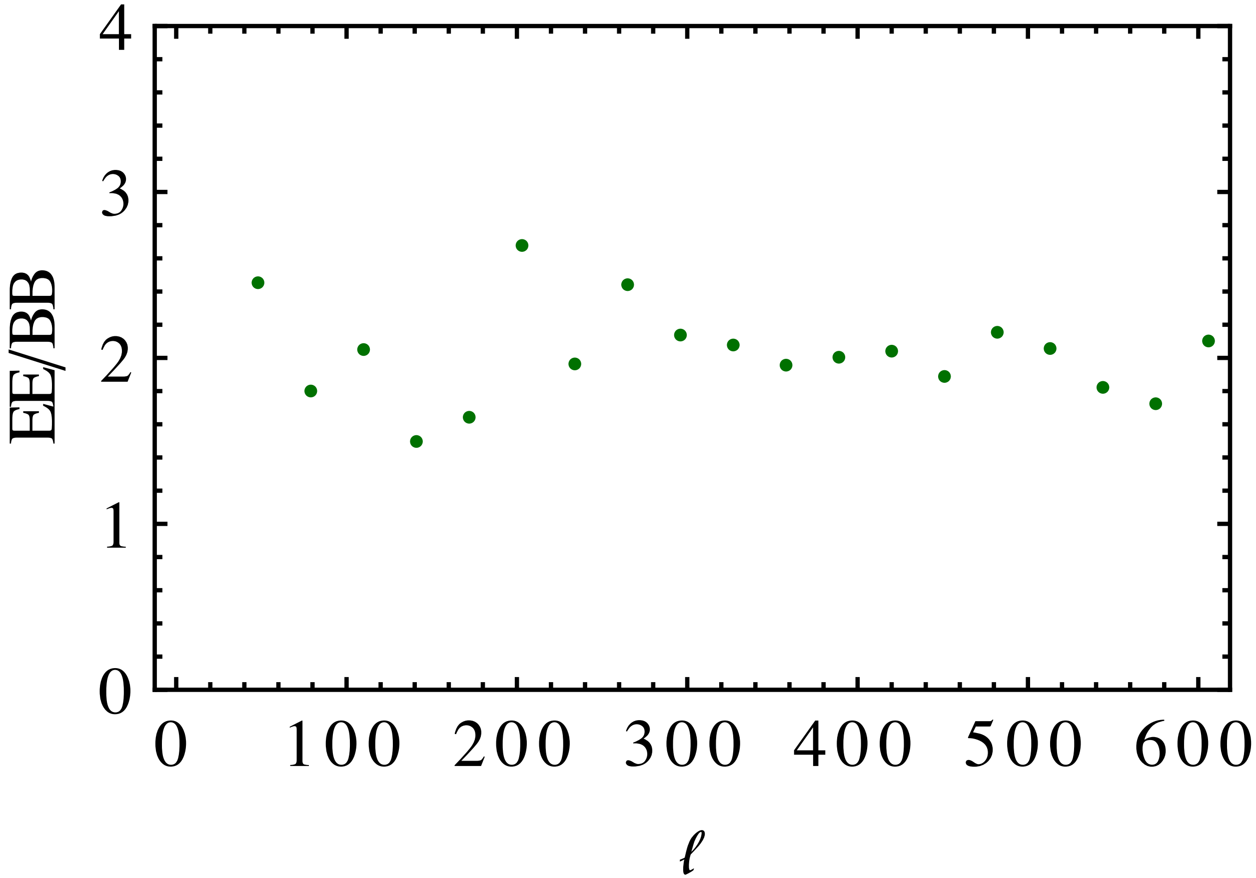
Models based on (3d) MHD simulations   06 and 08



scale dependence and E-B ratio broadly consistent with Planck

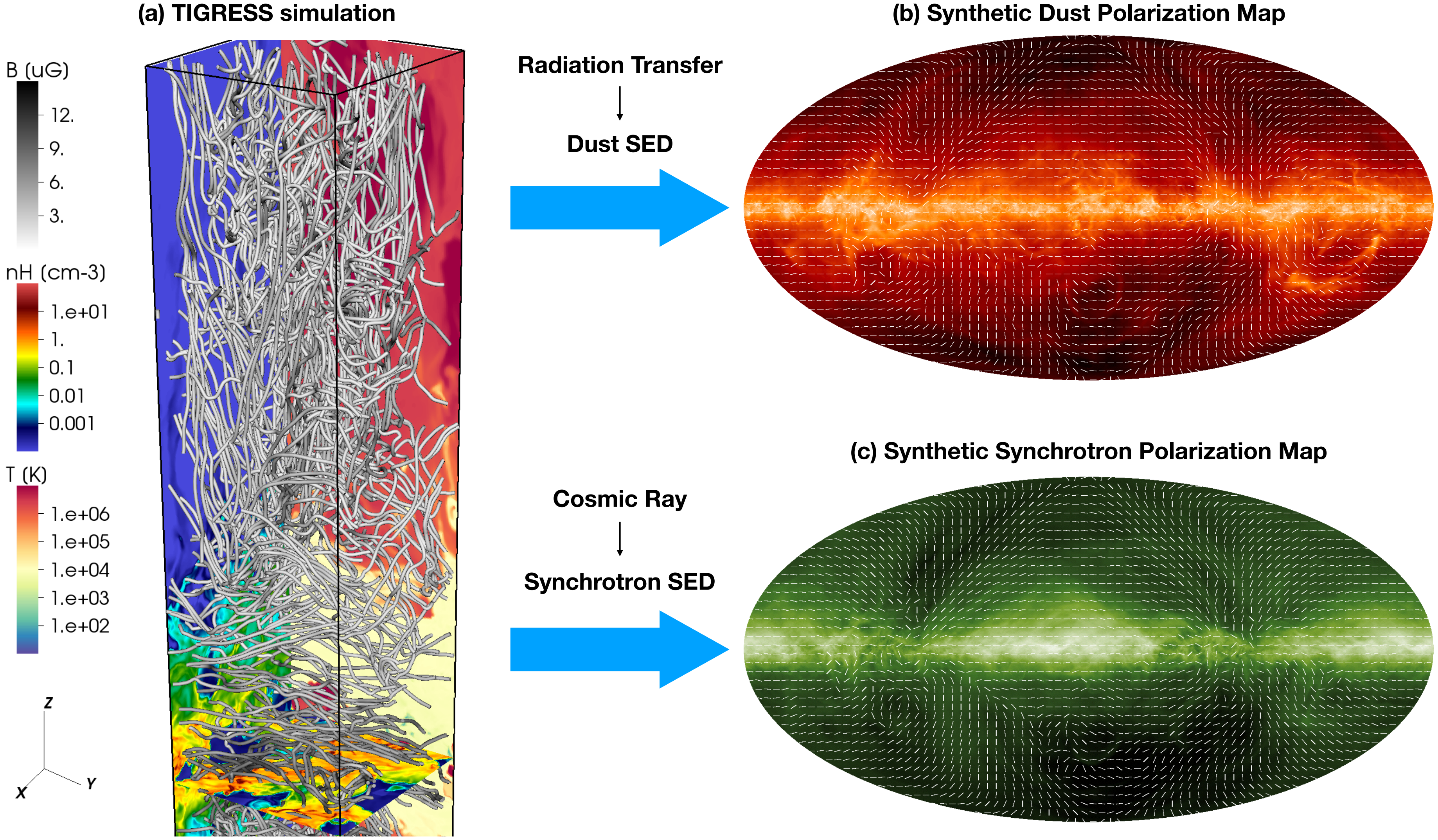
CMB-S4 Data Challenge models

MHD simulations - WNM only



scale dependence consistent with dust

Sky Maps from MHD Sims



Path forward

- Models must be improved on all scales
- Dust on degree scales is perhaps best understood. (although that does not say much…)
- MHD simulations provide some realism for synchrotron as well, but they must be improved (using data and improving simulations)
- Need models that capture the statistical properties of foregrounds beyond power spectrum and on small scales to study effect of foregrounds on delensing
- Start with existing models, and in parallel work on improved foreground models