The Planck Sky Model

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with
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Outline

- Introduction
- "Full Focal Plane" simulations
- Polarised diffuse foregrounds
  - ✓ Thermal dust
  - ✓ Synchrotron
- Lensing and the CIB
- The monopole
- Summary

The PSM in a nutshell

- The "Planck Sky Model" is a parametric multicomponent model of sky emission originally developed for and by the Planck collaboration

- It is constituted of data and software, and is distributed as a single code that can be run to generate
  a) A complete parametric model of multicomponent sky emission (maps of diffuse components, catalogues of point sources, emission law parameters, power spectra, number counts;
  b) Observations of this model sky in a number of channels specified each by a frequency band, a (gaussian) symmetric beam, and noise properties;

- The simulation uses HEALPix maps at a given *nside*, up to a given *lmax*, both user-defined;

- Everything is automated, including "on the fly" downloading of the data needed to run the code. One single command line produces all the output.

PSM implementation

- Components are modelled as sums of (parametric) emission laws.
- For diffuse components, we use maps:

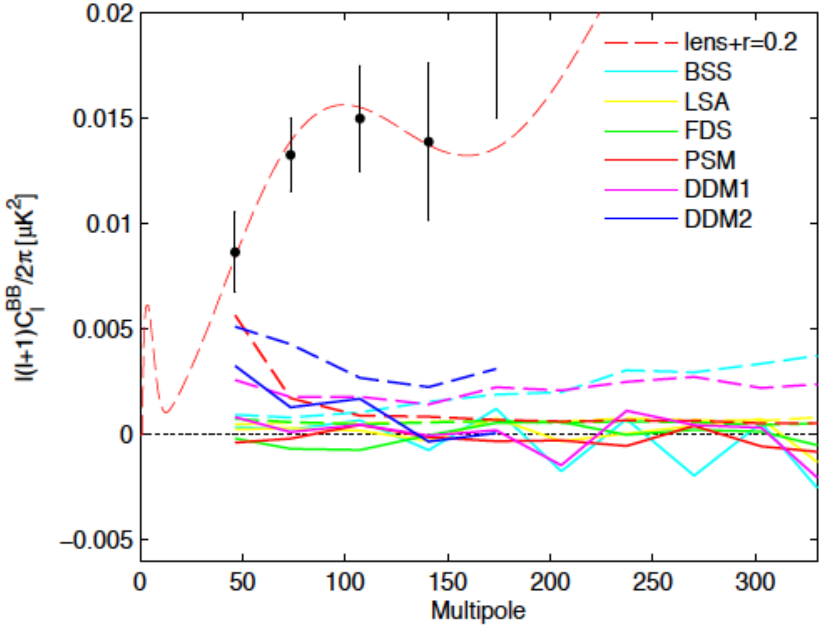
$$I_{\text{comp}}(\vec{p},\nu) = \sum_k \underbrace{I_k(\vec{p},\nu_0)}_{\text{Template map at some reference frequency}} \underbrace{\left[\frac{f_k(\vec{p},\nu)}{f_k(\vec{p},\nu_0)}\right]}_{\text{Normalised emission law}}$$

- For compact objects, we use catalogues, in which each object is modelled as a superposition of such emission laws, and may also be assigned a profile (galaxy clusters).

- Once generated, all the parameters and meta-parameters of a modelled sky are stored in specific subdirectories of the output directory. They can be "observed" and "re-observed" a posteriori with (simple) models of instruments for band-integration.

Objectives of a sky model

- **PREDICT** the emission of the real sky components in a given frequency band – using everything we know, theoretically or observationally…
  - *Example: Estimate the dust contamination in the BICEP2 observation*
  - *However, the (publicly released) PSM at that time was too poorly constrained by observations.*
  - *Most of its 150 GHz polarisation was random on degree scales.*
  - *In addition, it had too little power on average, because of low early estimates of the dust polarisation fraction, - and possibly also specifically in BICEP2 patch…*



Objectives of a sky model

- **SIMULATE** fake, plausible sky emission with properties close to the real ones, to investigate the performance of future experiments or of data processing pipelines
  - *Example: Can we simulate CMB B-modes for r=0.002 (yes!)*
  - *Can we simulate e.g. synchrotron B-modes to that level of accuracy?*
  - *Can we capture the sky complexity at the appropriate level?*

Delabrouille et al. 2013, A&A 553, 96

- **RECENT SIMULATION** with improvements w.r.t. the "pre-launch" PSM for the generation of "Full Focal Plane" simulations (FFP8) – *Planck 2015 results. XII.*
  - Used for the Planck analysis (test, validation, error estimates, …)

Planck 2015 results. XII. arXiv:1509.06348

Objectives for COrE / LiteCOrE / LiteBIRD

- **CAN WE DETECT PRIMORDIAL B-Modes ?**
- The sky model is a tool to investigate the de-contamination of observed B-modes from polarized foreground emission and from CMB lensing.

- **Requirements**
  - *Investigate possible / plausible foreground emission complexity;*
  - *Learn component separation and de-lensing on mock data sets;*
  - *Evaluate possible residuals* ***and their uncertainties****.*

- **Most important**
  - ***Polarised galactic emission*** *on large scale*
  - ***CMB lensing reconstruction*** *: Polarised foregrounds on small scale, usefulness of CIB emission observations for de-lensing.*

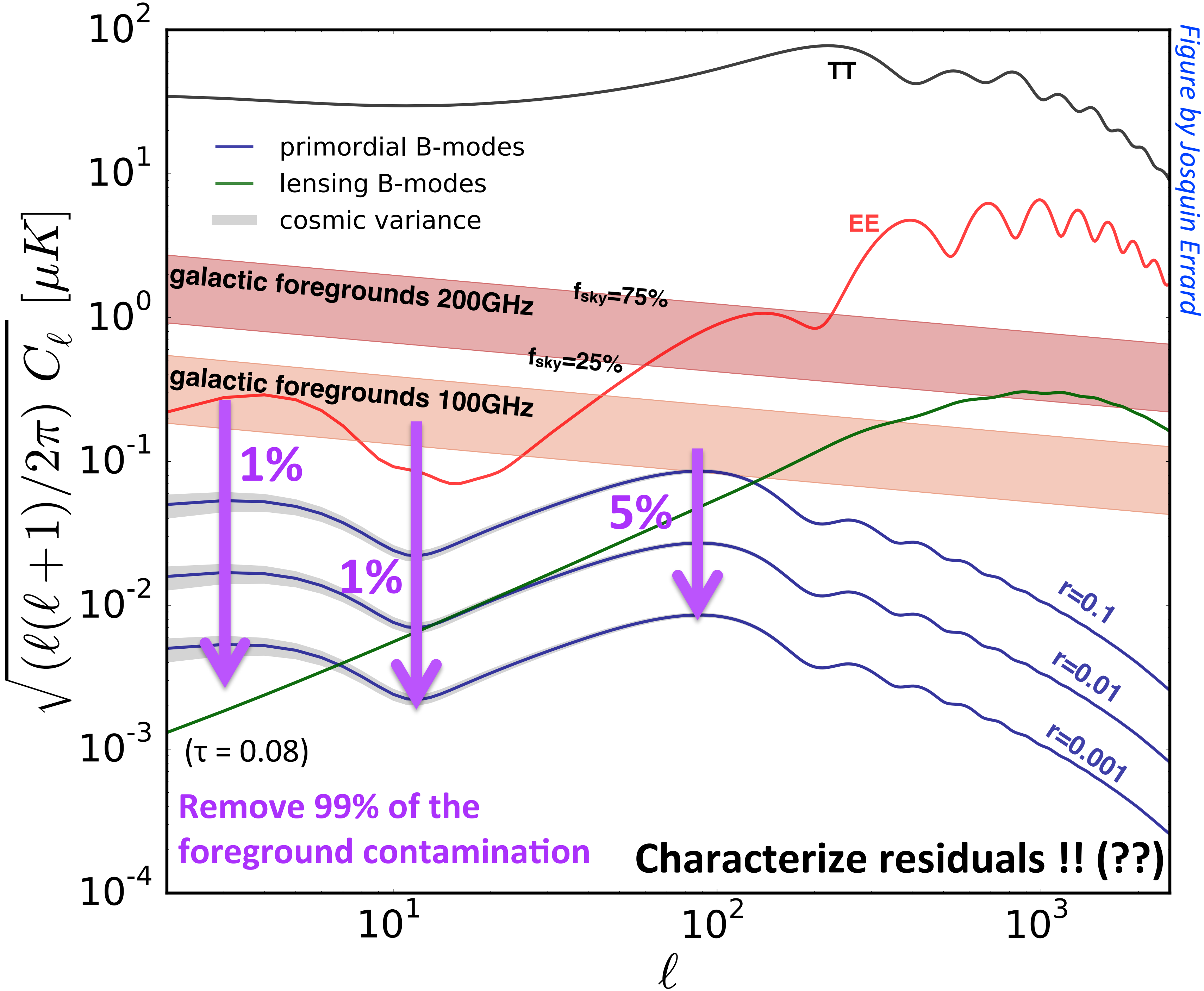


Figure by Josquin Errard
TT
EE
primordial B-modes
lensing B-modes
cosmic variance
galactic foregrounds 200GHz
galactic foregrounds 100GHz
f_{sky}=75%
f_{sky}=25%
1%
1%
5%
r=0.1
r=0.01
r=0.001
(τ = 0.08)
Remove 99% of the foreground contamination
Characterize residuals !! (??)
$\sqrt{\ell(\ell+1)/2\pi)\ C_\ell}\ [\mu K]$
ℓ

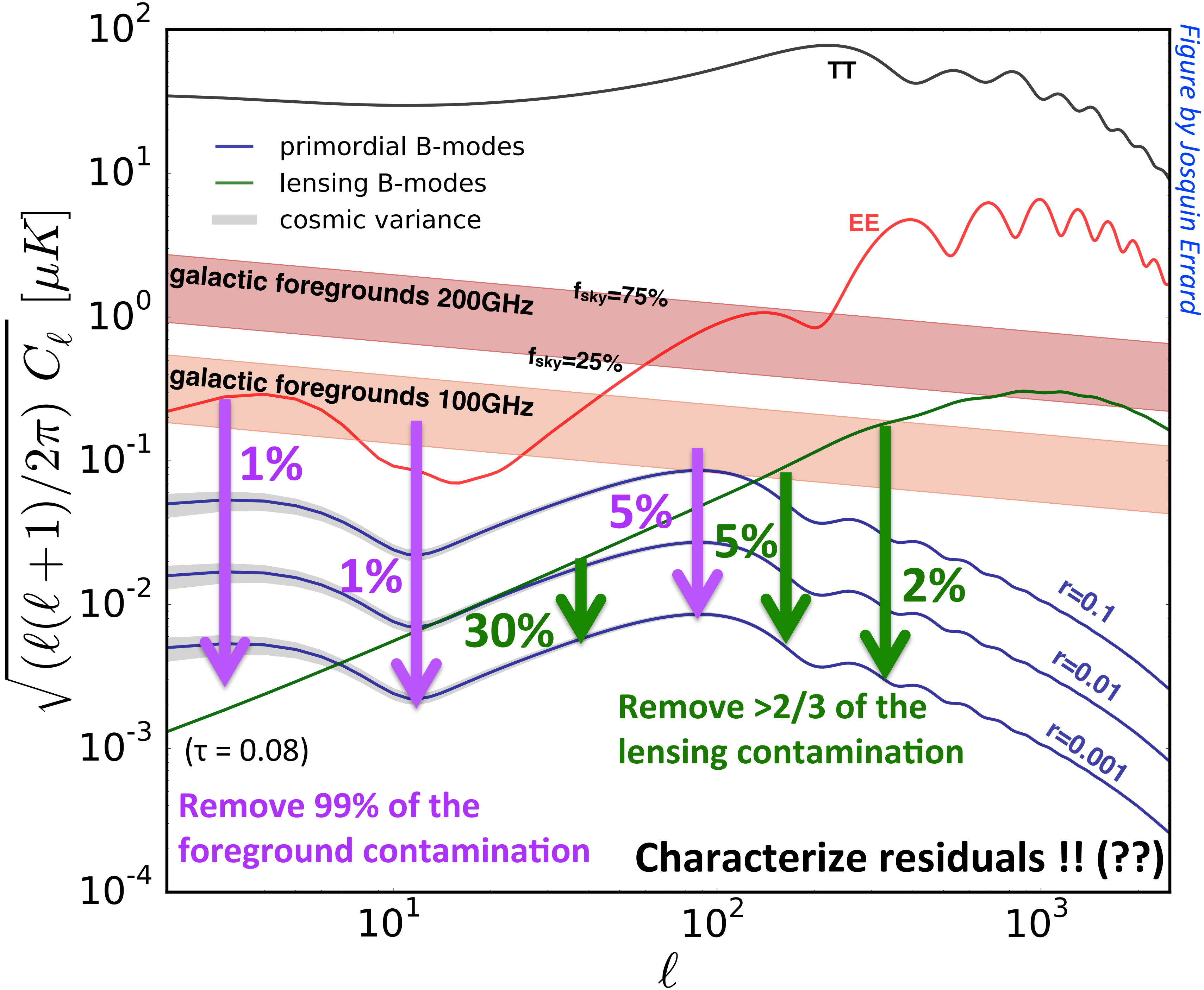


Figure by Josquin Errard
TT
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primordial B-modes
lensing B-modes
cosmic variance
galactic foregrounds 200GHz
galactic foregrounds 100GHz
f_sky=75%
f_sky=25%
1%
1%
5%
5%
30%
2%
r=0.1
r=0.01
r=0.001
(τ = 0.08)
Remove >2/3 of the lensing contamination
Remove 99% of the foreground contamination
Characterize residuals !! (??)
$\sqrt{\ell(\ell+1)/2\pi)\ C_\ell}\ [\mu K]$
ℓ

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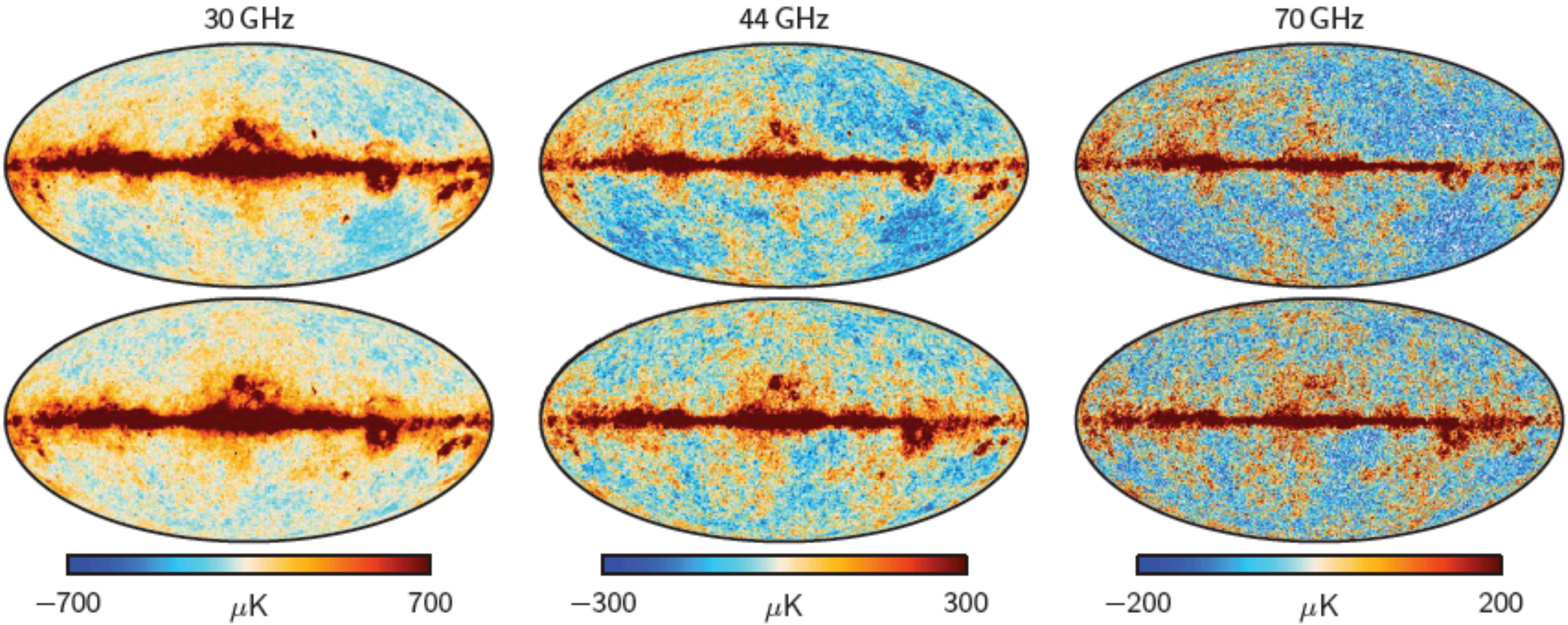
Full Focal Plane simulations



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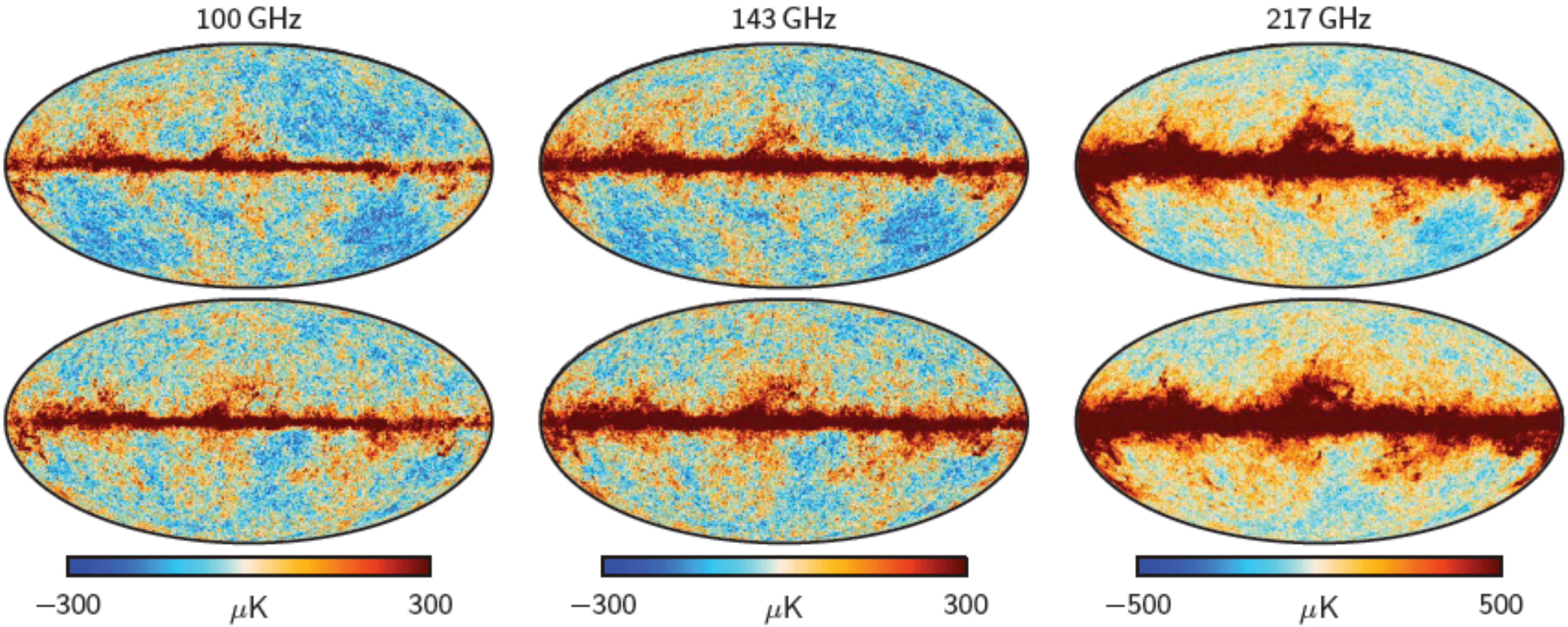
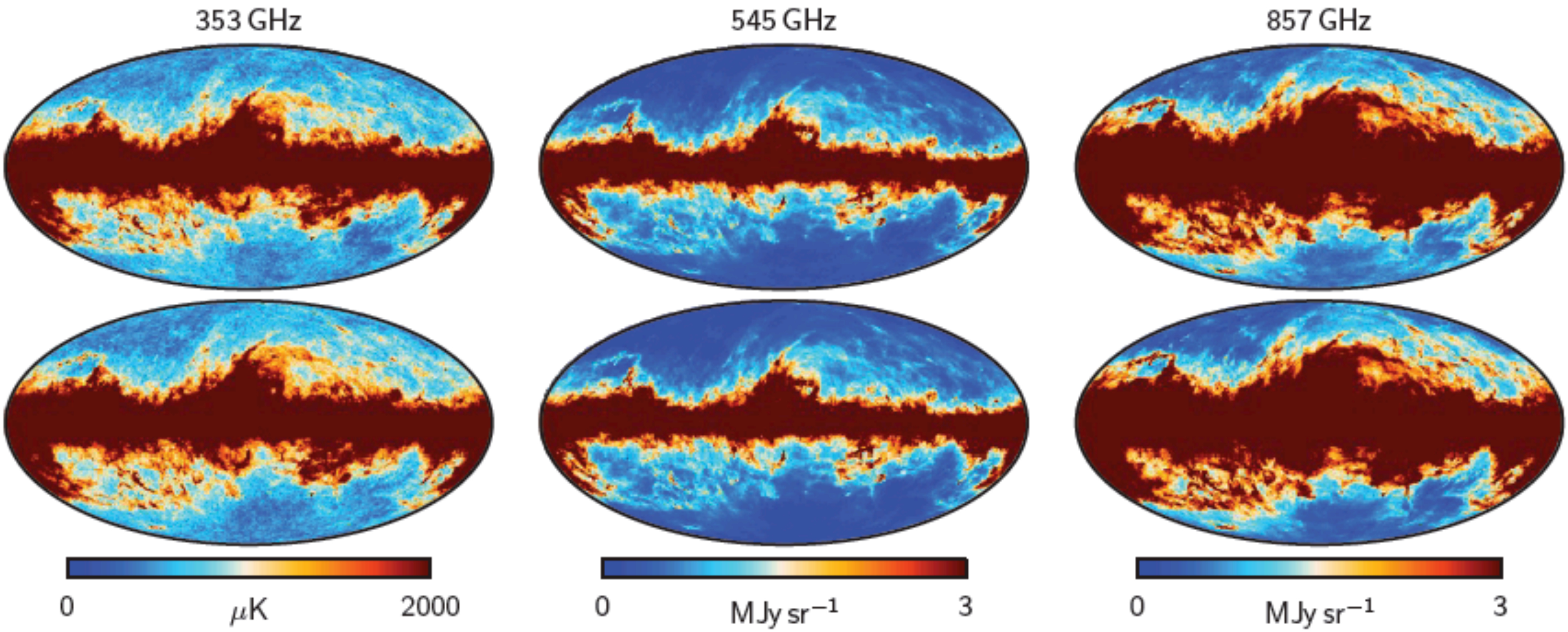
Full Focal Plane simulations



Full Focal Plane simulations



The current "state of the art"...

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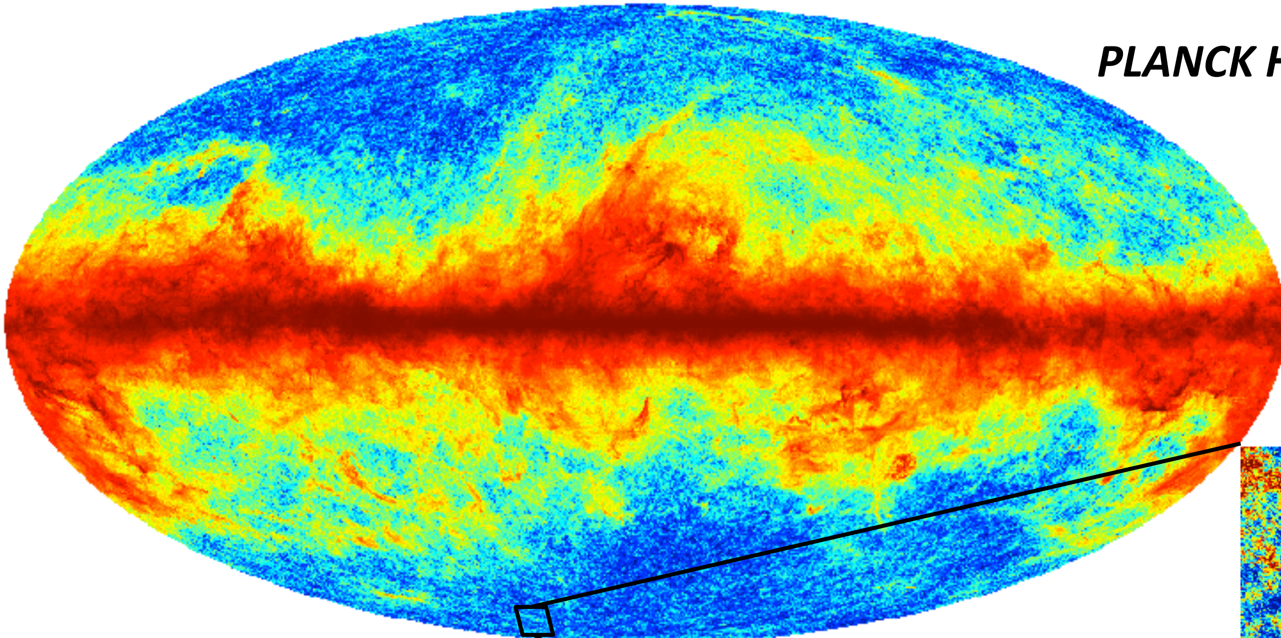
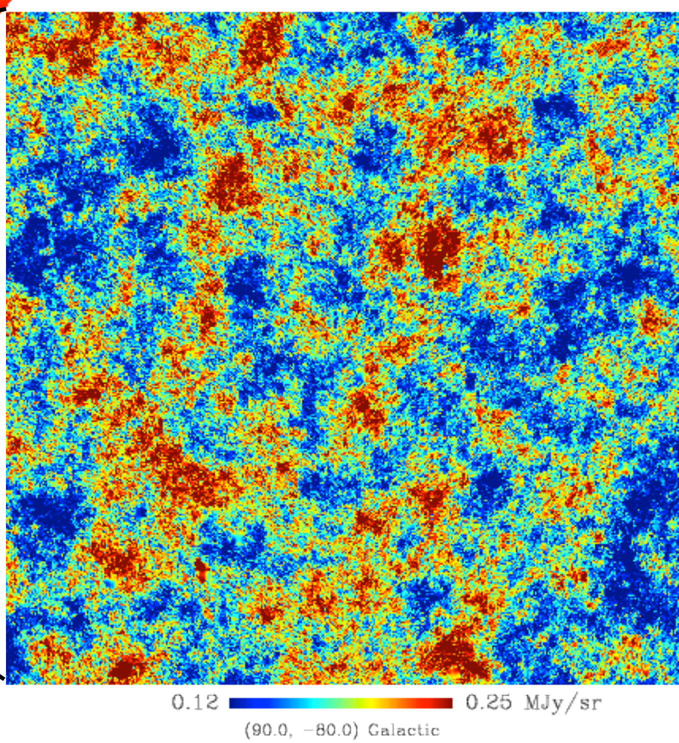
Improving dust maps



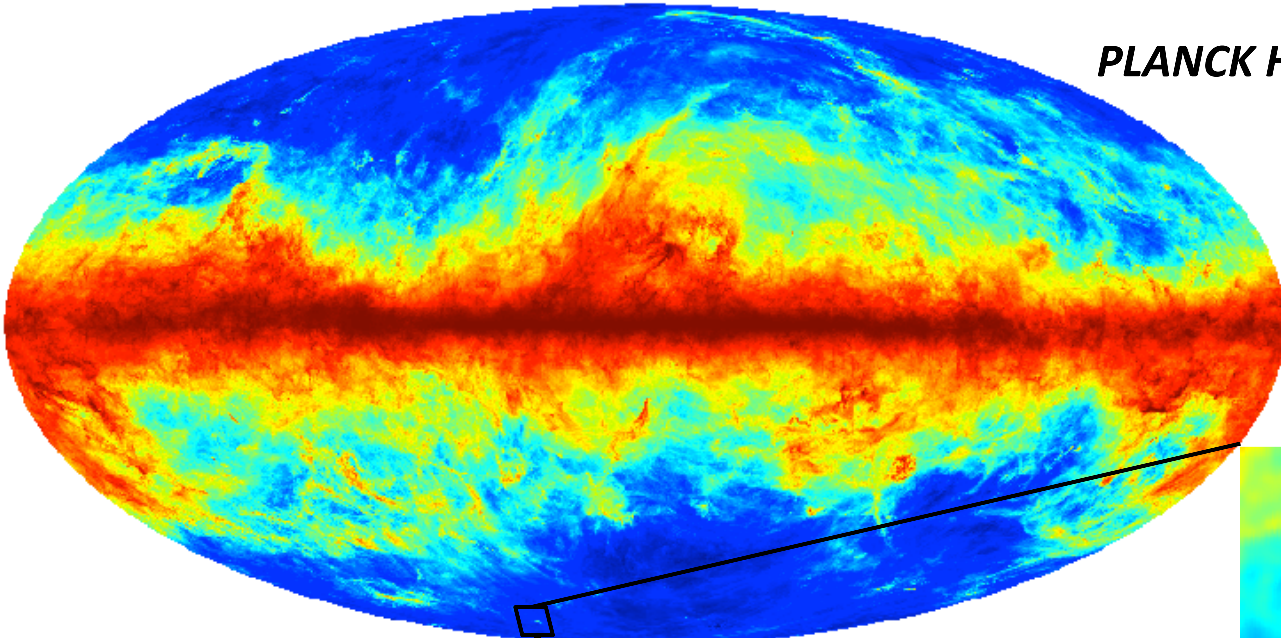


Dust maps are contaminated
by CIB, (by CMB) and by noise

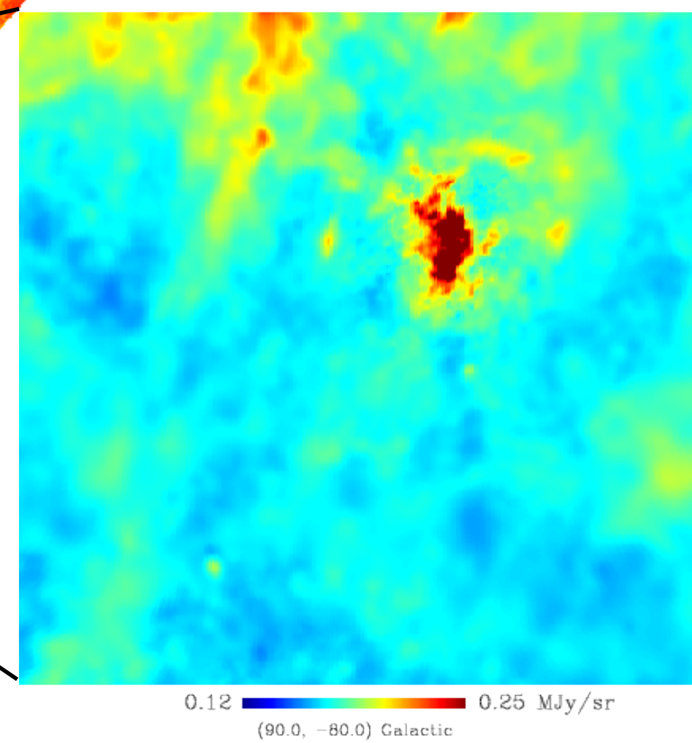
Processing of multifrequency maps with GNILC

Remazeilles, Delabrouille & Cardoso 2011, MNRAS, 418, 467

Improving dust maps



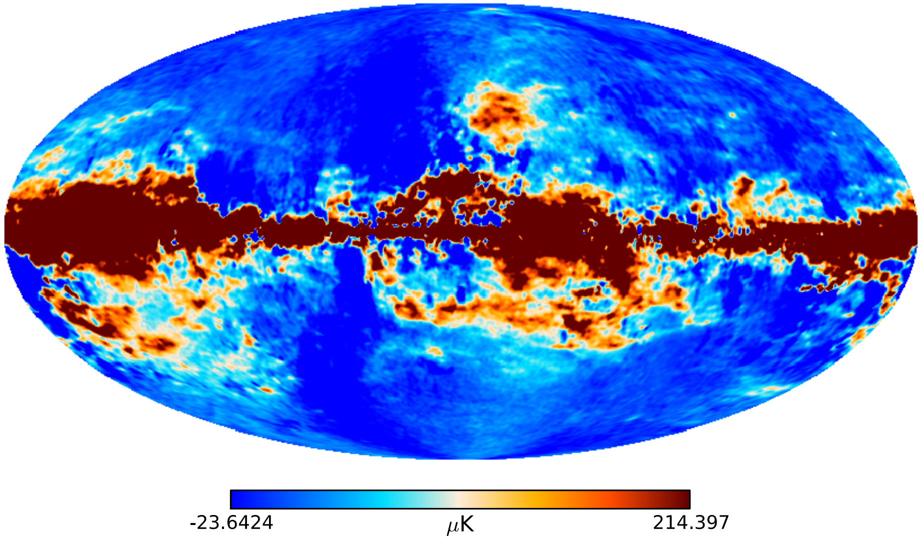
PLANCK HFI 353 GHz



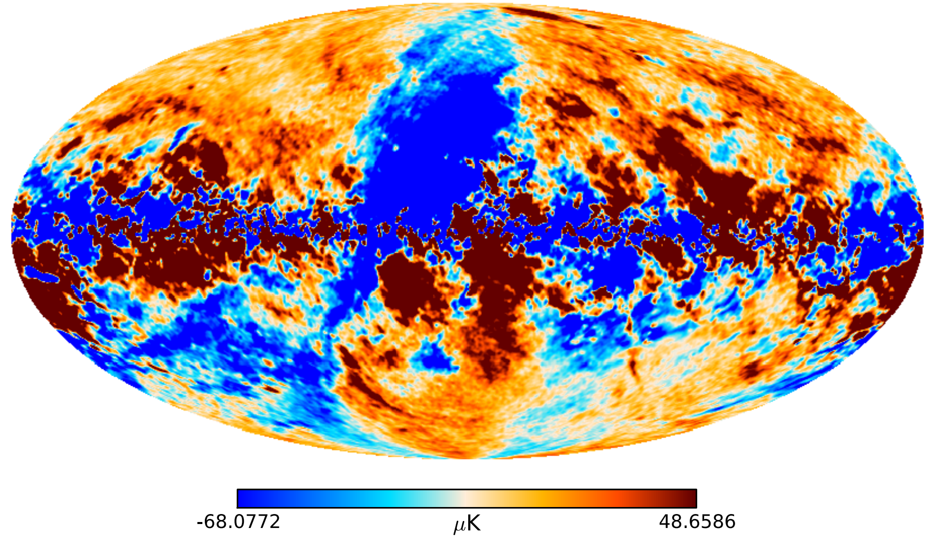
This method works best when we have many different maps available, with high-enough angular resolution

GNILC polarised dust (preliminary!)

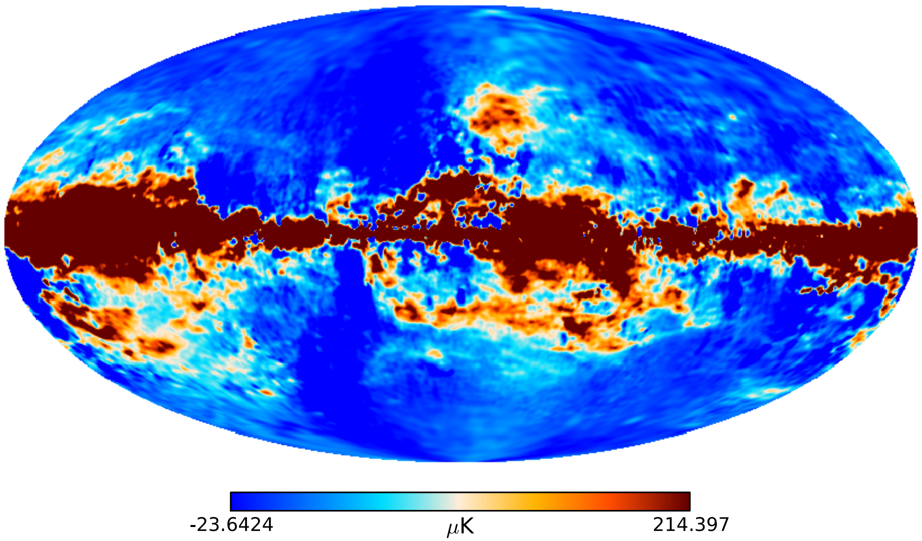
353GHz Band Data Q



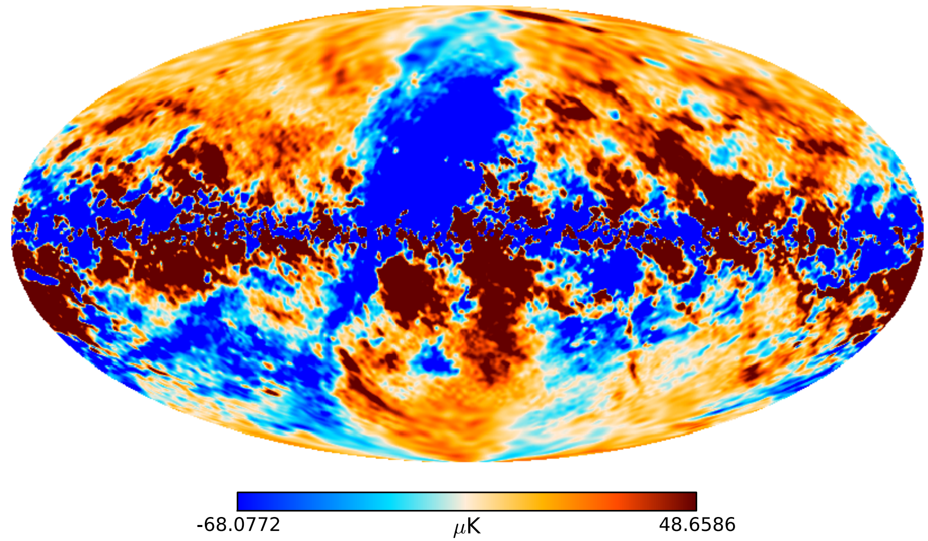
353GHz Band Data U



353GHz Band NILC Q

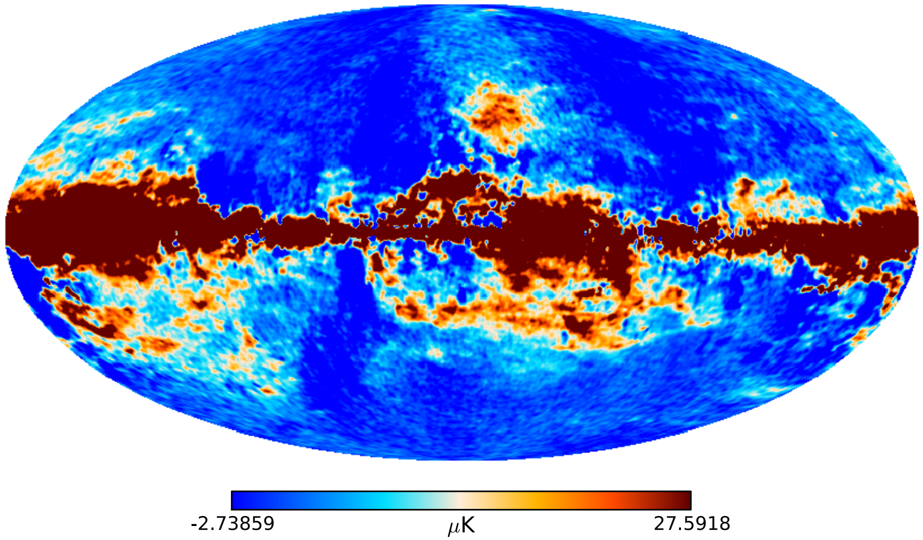


353GHz Band NILC U

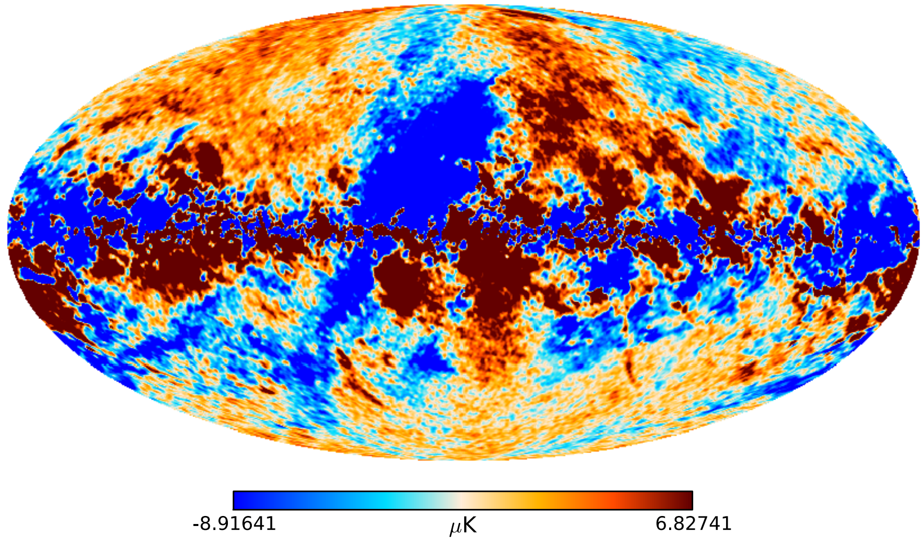


GNILC polarised dust (preliminary!)

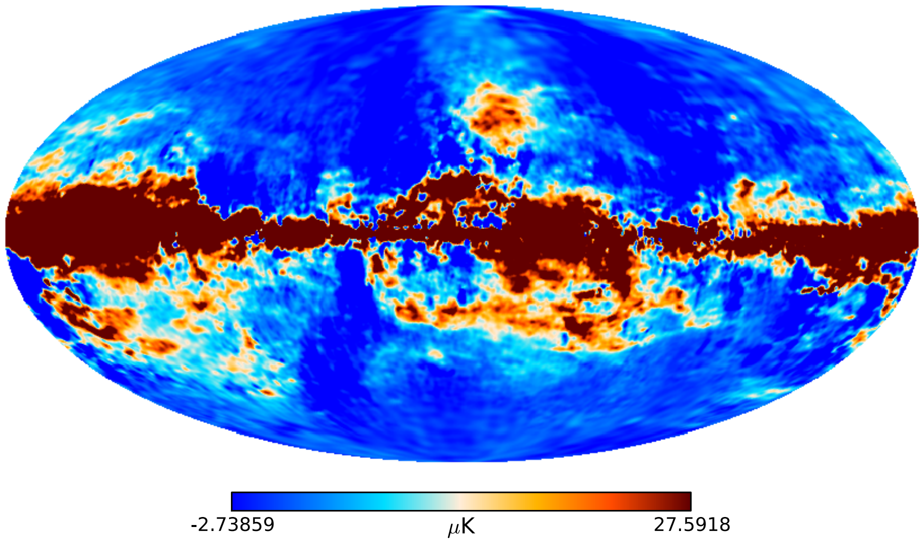
217GHz Band Data Q



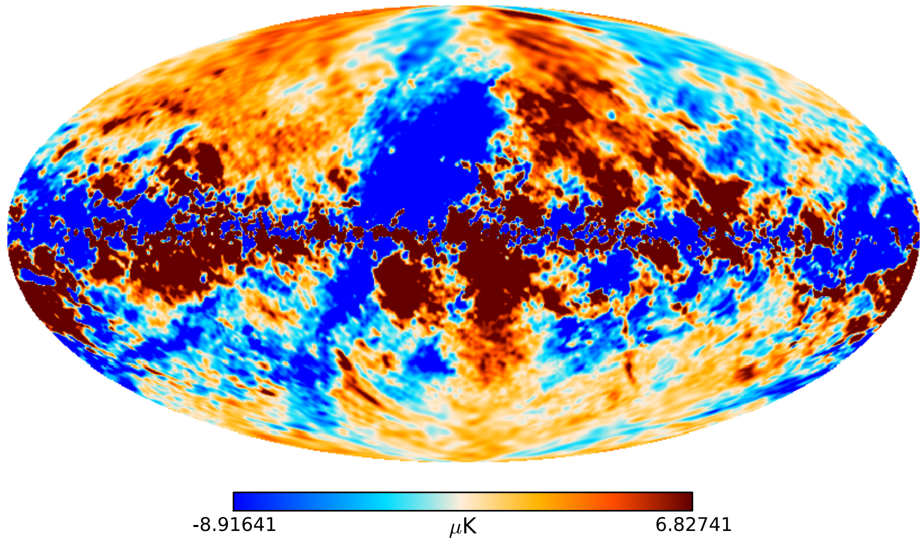
217GHz Band Data U



217GHz Band NILC Q

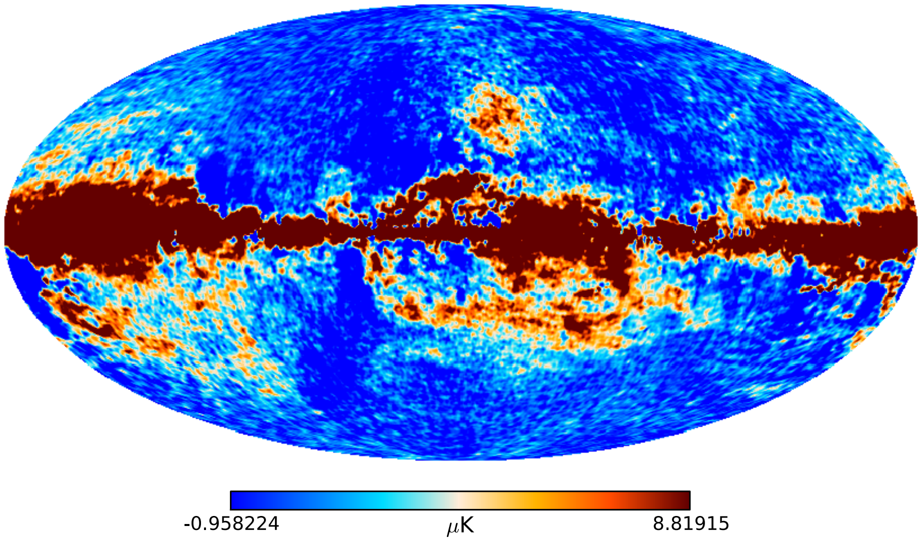


217GHz Band NILC U

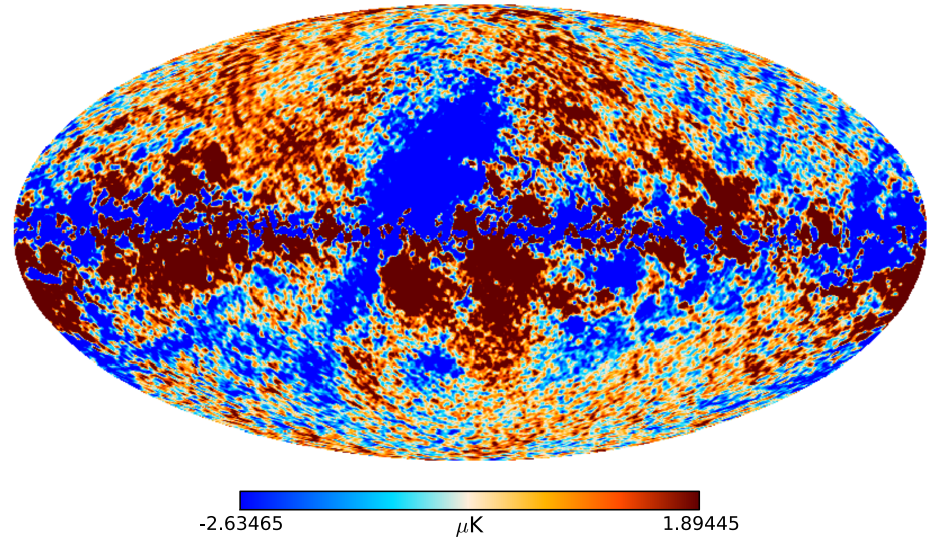


GNILC polarised dust (preliminary!)

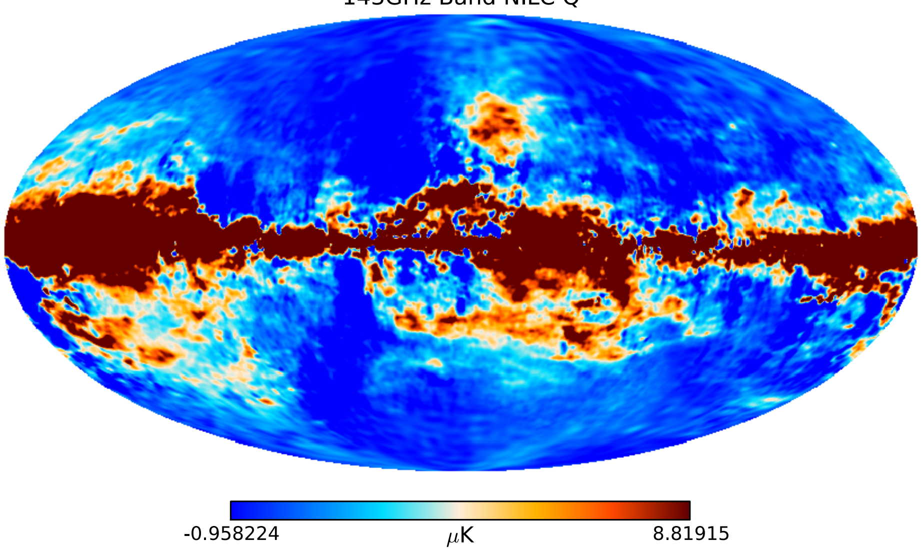
143GHz Band Data Q



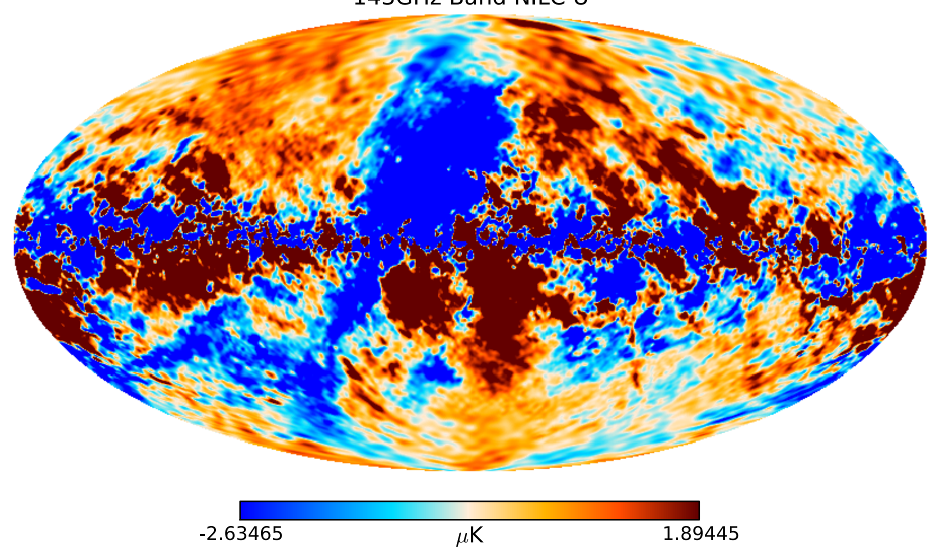
143GHz Band Data U



143GHz Band NILC Q



143GHz Band NILC U



Generating polarisation templates

- Polarisation templates from real data are at poor angular resolution
- Use them to generate (low-resolution) maps of polarisation fraction and polarisation angle, and get smaller scale polarisation by applying that to high-resolution I templates.
- There is however a limitation to this…

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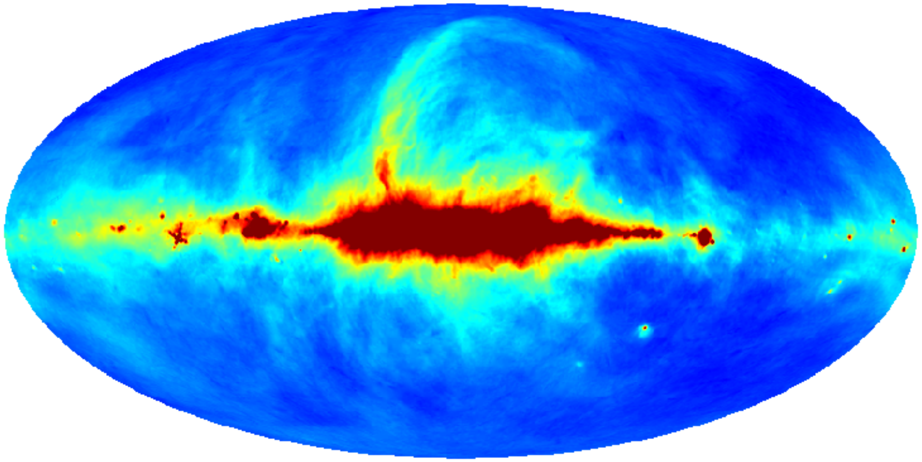
Synchrotron

- One of the major foregrounds for CMB observations.
- Strongly polarised (up to 75%).
- Synchrotron-dominated full-sky map at 408 MHz (Haslam et al. 1982), at 51' angular resolution.
- ***New 408 MHz reference***: Map reprocessed to remove striping and point sources by Remazeilles et al. (2015). Angular resolution re-assessed to 56'.



Remazeilles et al. 2015, MNRAS 451, 4311

Frequency scaling of synchrotron

For electron density following a power law,

$$n_e(E) \propto E^{-p}$$

the synchrotron emission law also follows a power law

$$T_{\mathrm{RJ}} \propto \nu^{\beta}$$

with $$\beta = -(p+3)/2$$

typical value : $\beta \simeq -3$

Frequency scaling of synchrotron

- There is evidence for fluctuations of the spectral index around a mean value of -3 (in K_{RJ} units).
- However, there is at present no good measurement of the synchrotron scaling.
- Good-enough full-sky maps of synchrotron (only) at an other frequency than 408 MHz are not available!

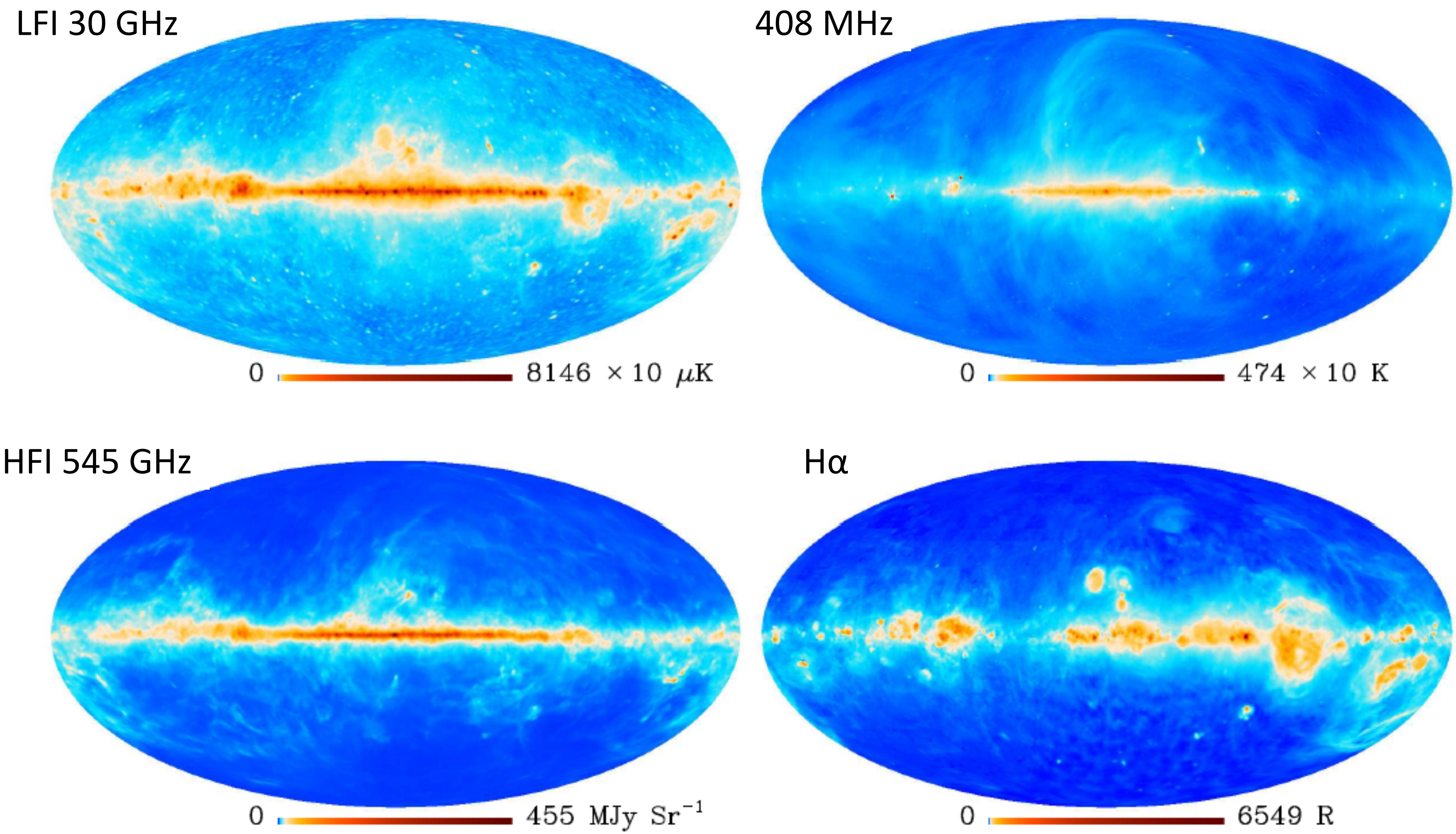
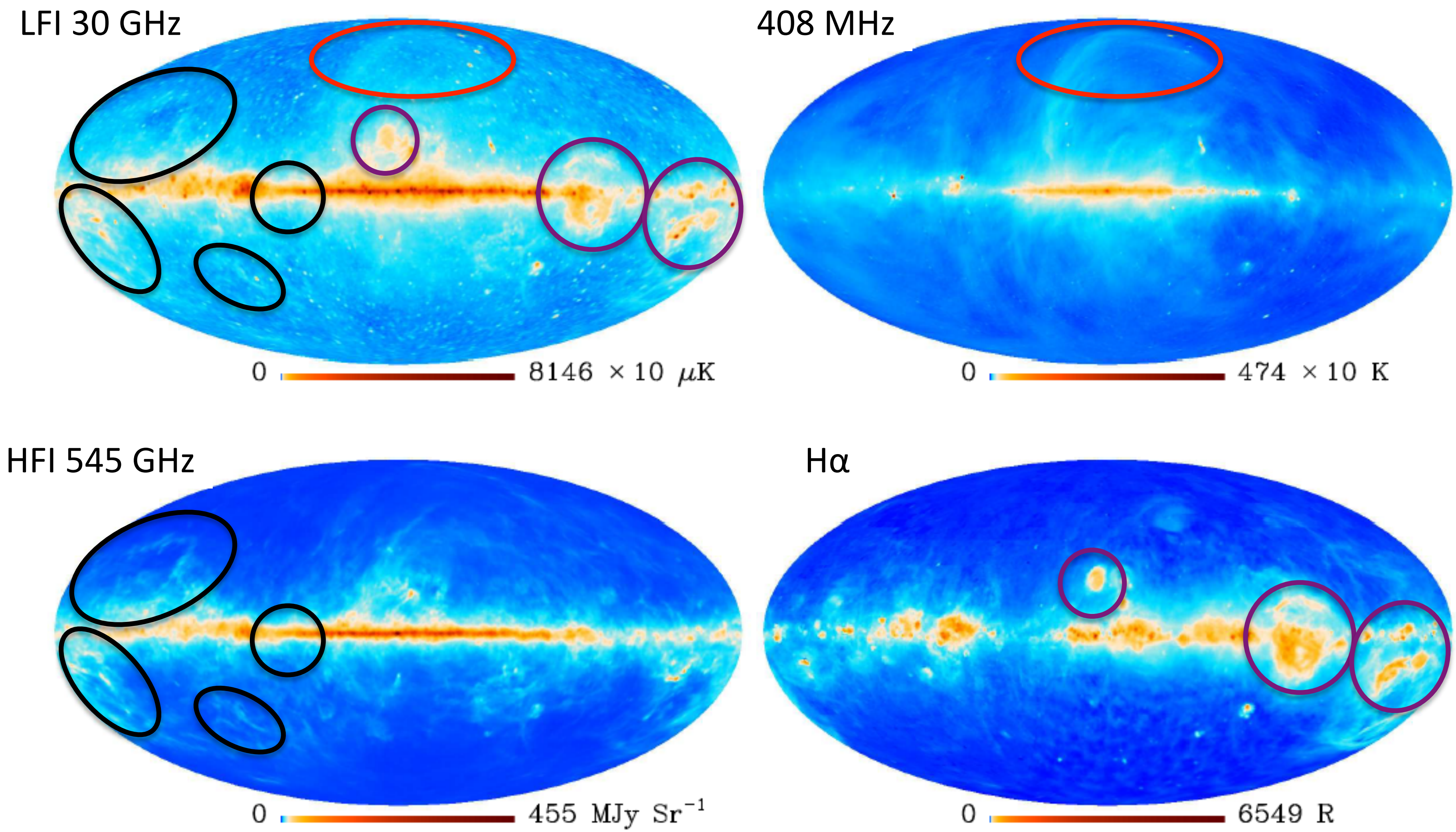


Fig. 1. (a) CMB-nulled map at 28.4 GHz, constructed using the ILC method (see text), where in this map, $\beta = -3$ emission is unchanged by construction; (b) 408 MHz map (Remazeilles et al. 2014), strongly dominated by synchrotron emission; (c) 545 GHz *Planck* map, strongly dominated by thermal dust emission; and (d) Hα map (Dickinson et al. 2003). An asinh(I) colour scale is used for all images, where I is the intensity in the units indicated. The coordinate along the colour bar is linear in I near zero and becomes logarithmic (ln(2I)) at high intensity. All maps are at 1° resolution.



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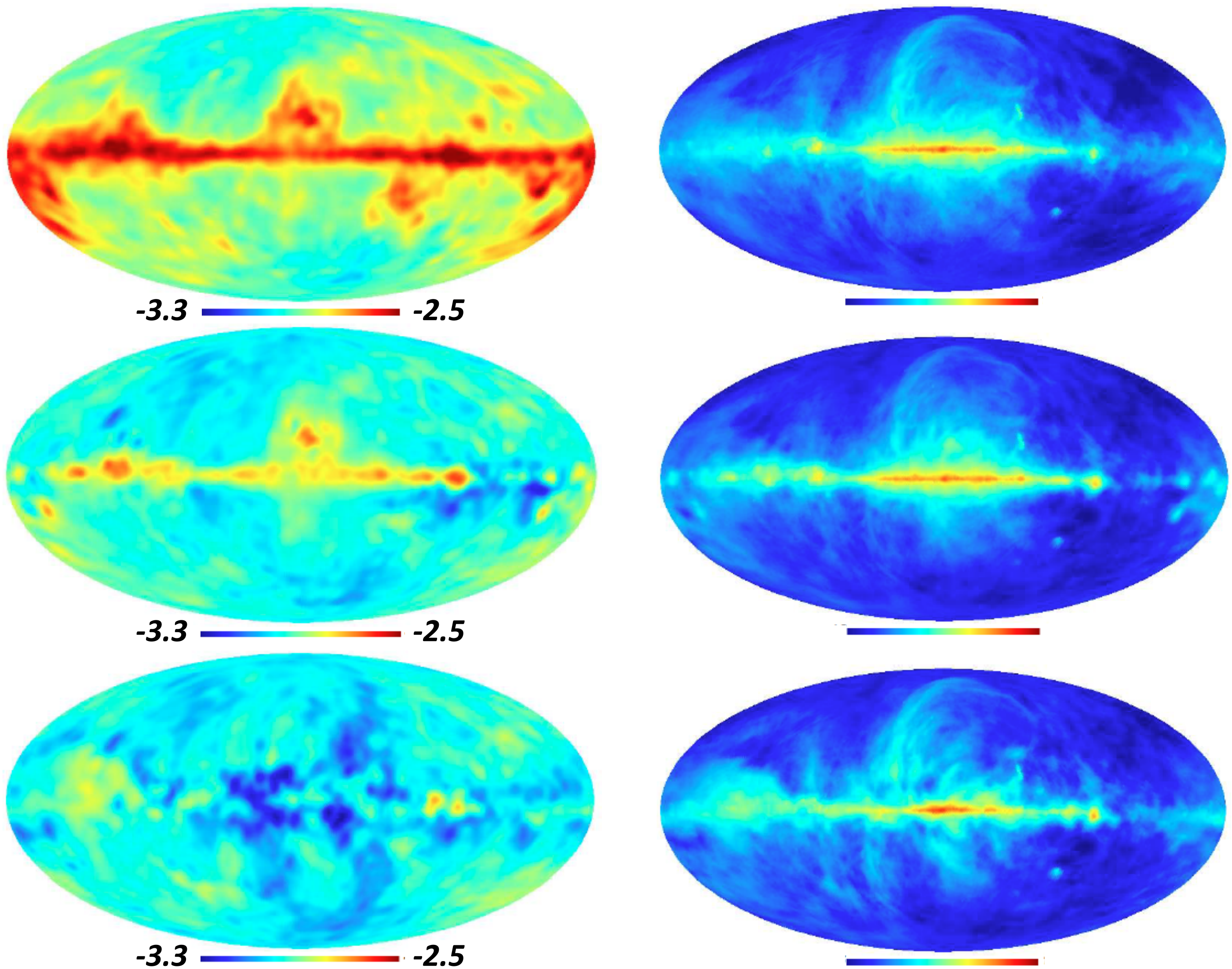
Pre-launch Planck Sky Model

Spectral index map | Synchrotron at 23 GHz

Assuming no spinning dust at 23 GHz

Spinning dust proportionnal to E(B_V)

23 GHz intensity from model of polarisation



Miville-Deschênes et al., 2008 A&A 490, 1093

Frequency scaling of synchrotron

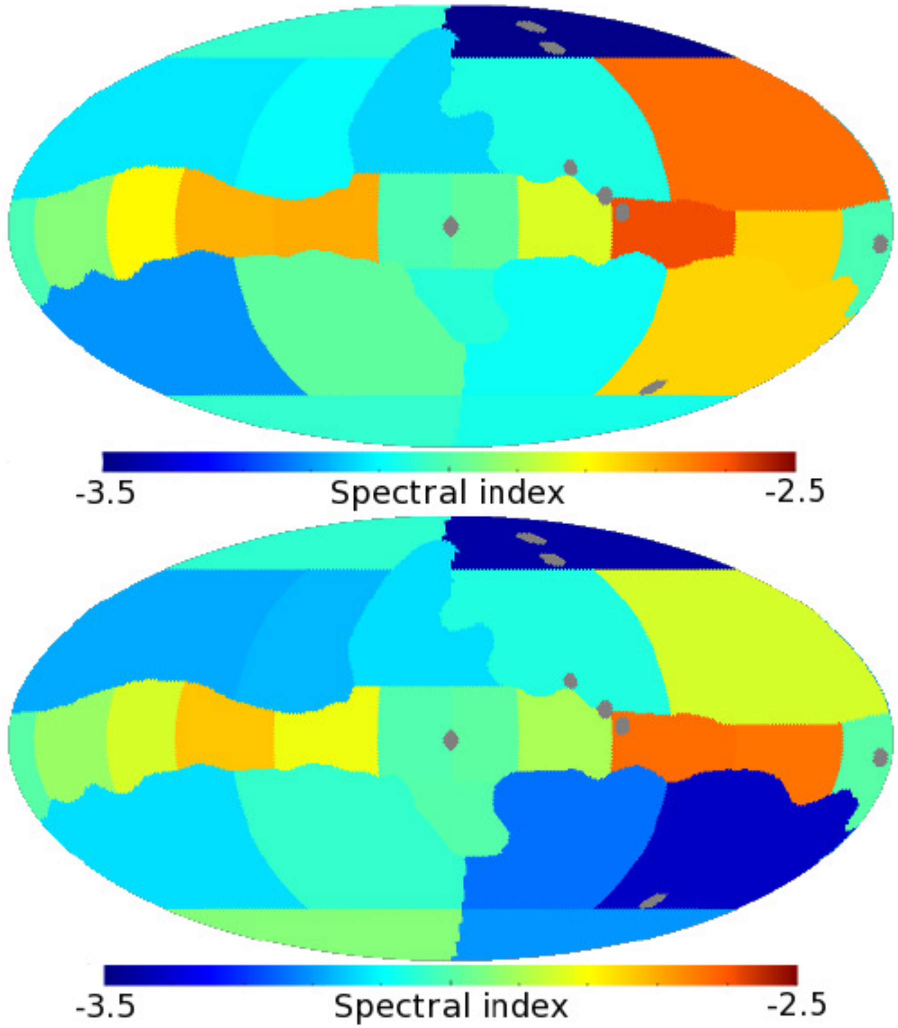
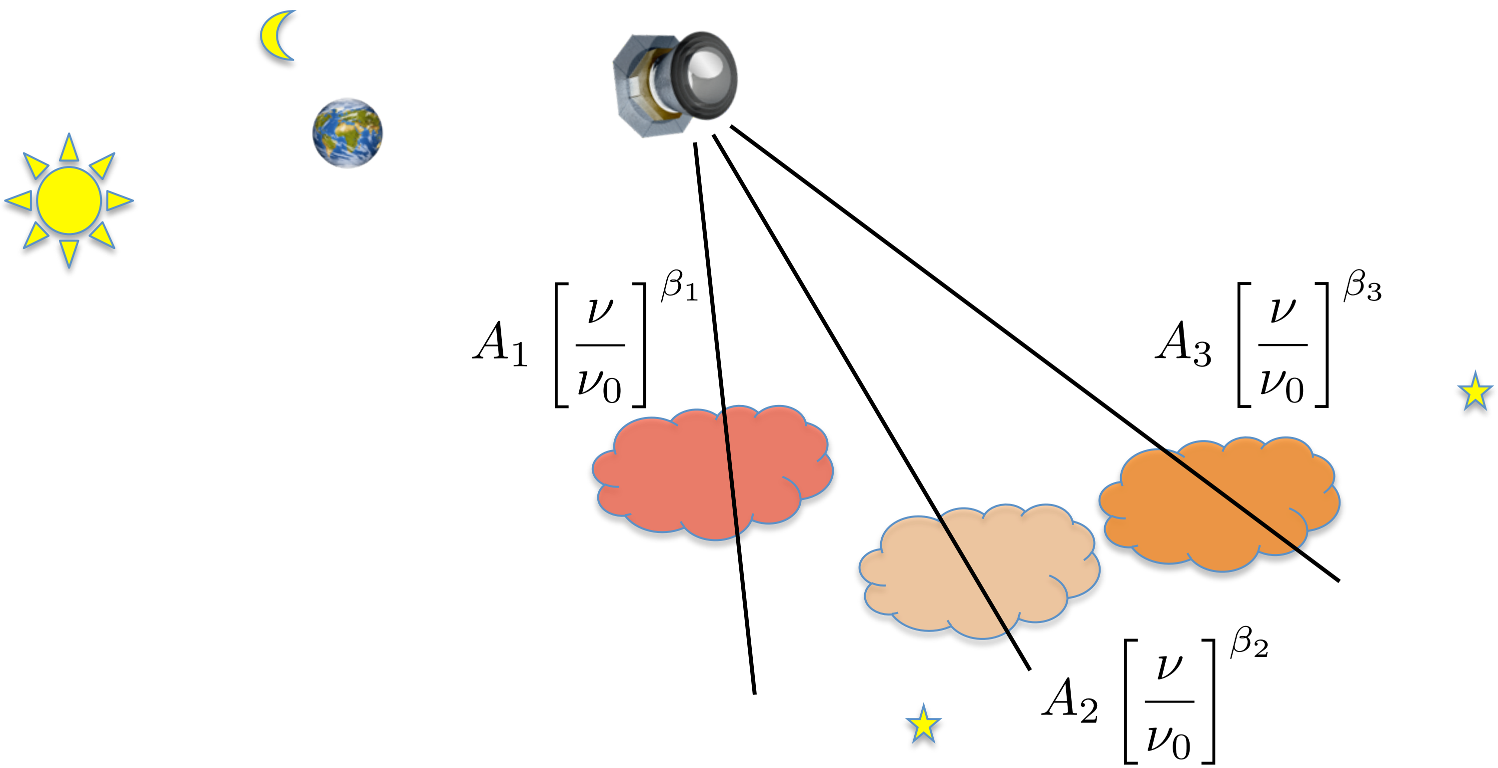


FIG. 6.— Synchrotron spectral index derived with the maximum likelihood (top panel) and T–T plot (bottom panel) methods from the 9 yr *WMAP* K- and Ka-band polarization sky maps.

Fuskeland et al. arXiv:1404.5323

Frequency scaling of synchrotron

- There is evidence for fluctuations of the spectral index around a mean value of -3 (in K_{RJ} units)
- This must be due to different populations of electrons



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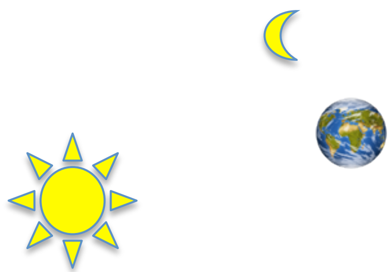
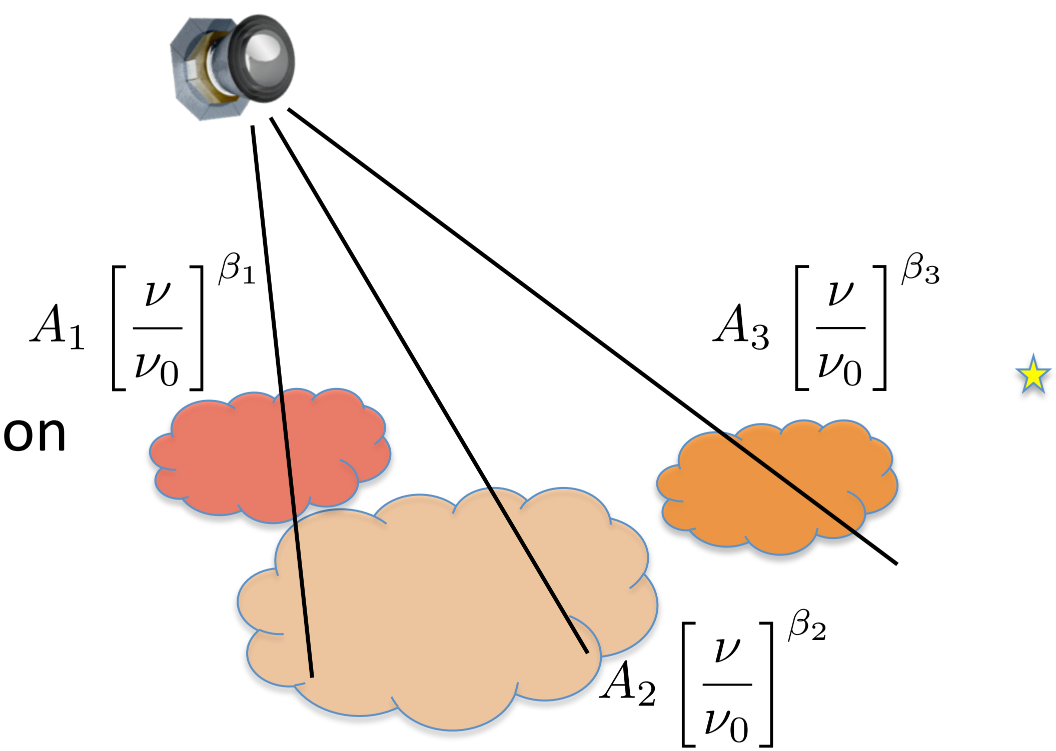


- It means that there is more than one emission law per pixel



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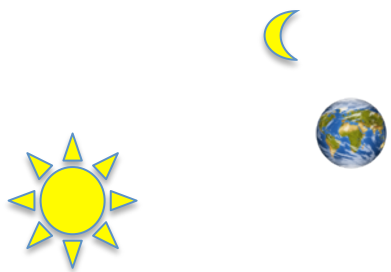
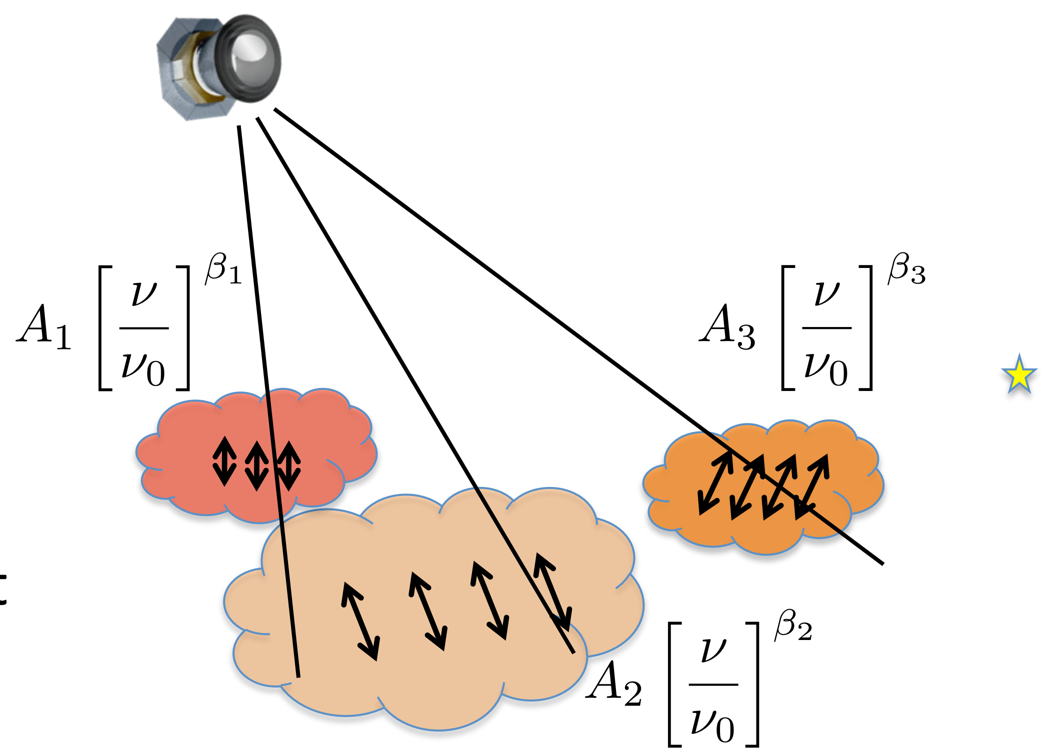
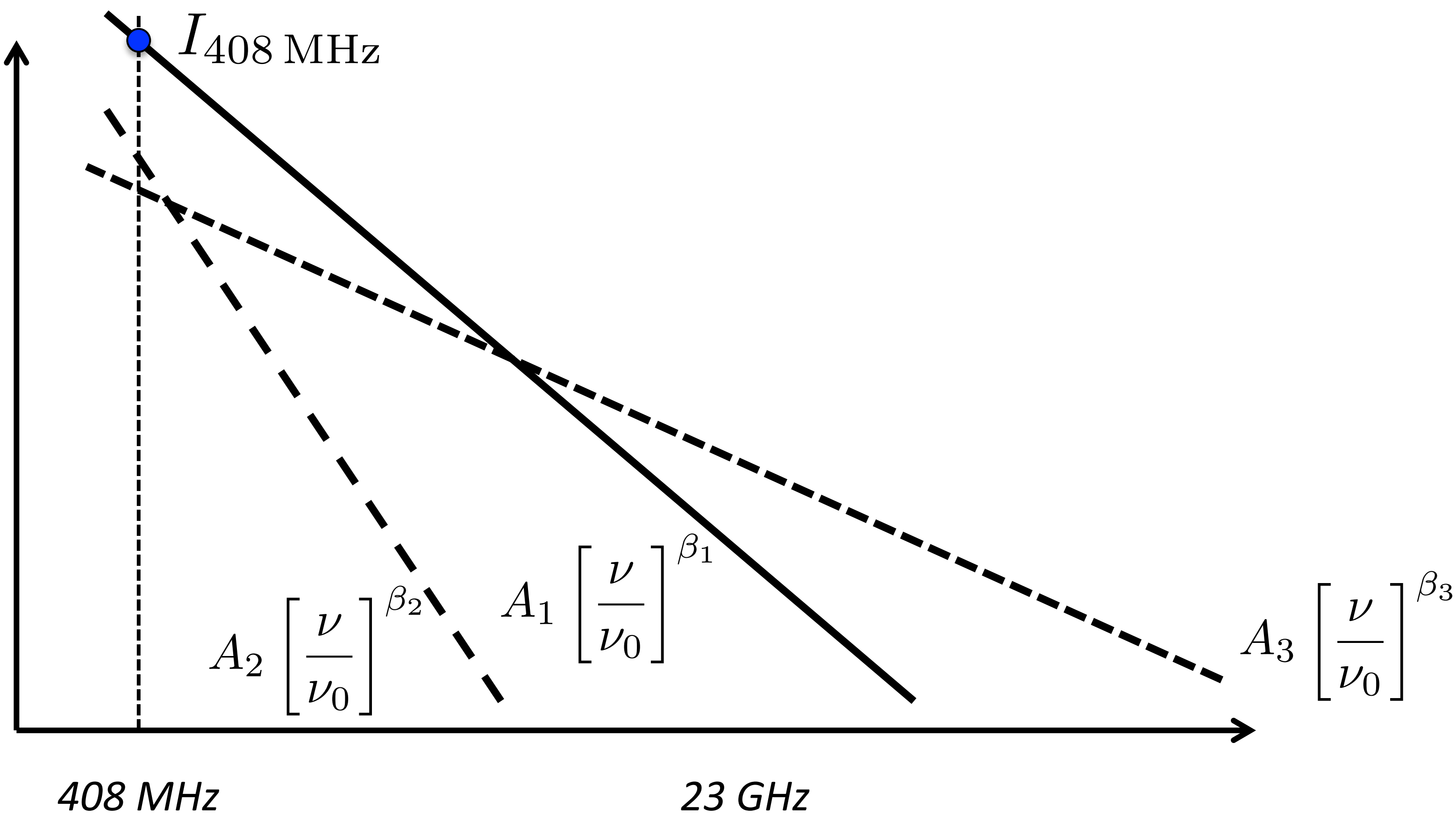




- It means that there is more than one scaling law per pixel
- It also means different scaling laws for I, Q, U

Frequency scaling of synchrotron

- A sum of power laws is not a power law…



Frequency scaling of synchrotron

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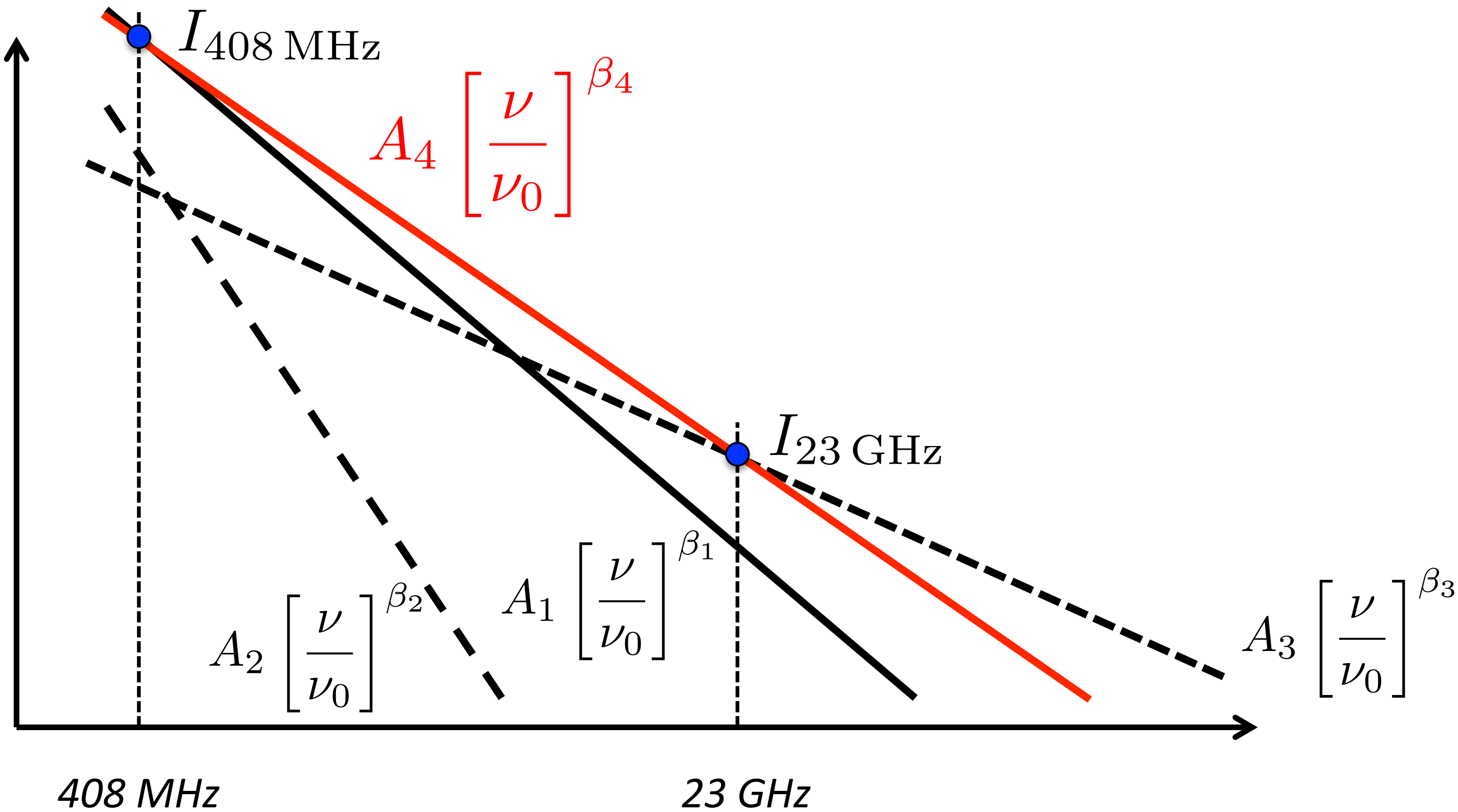

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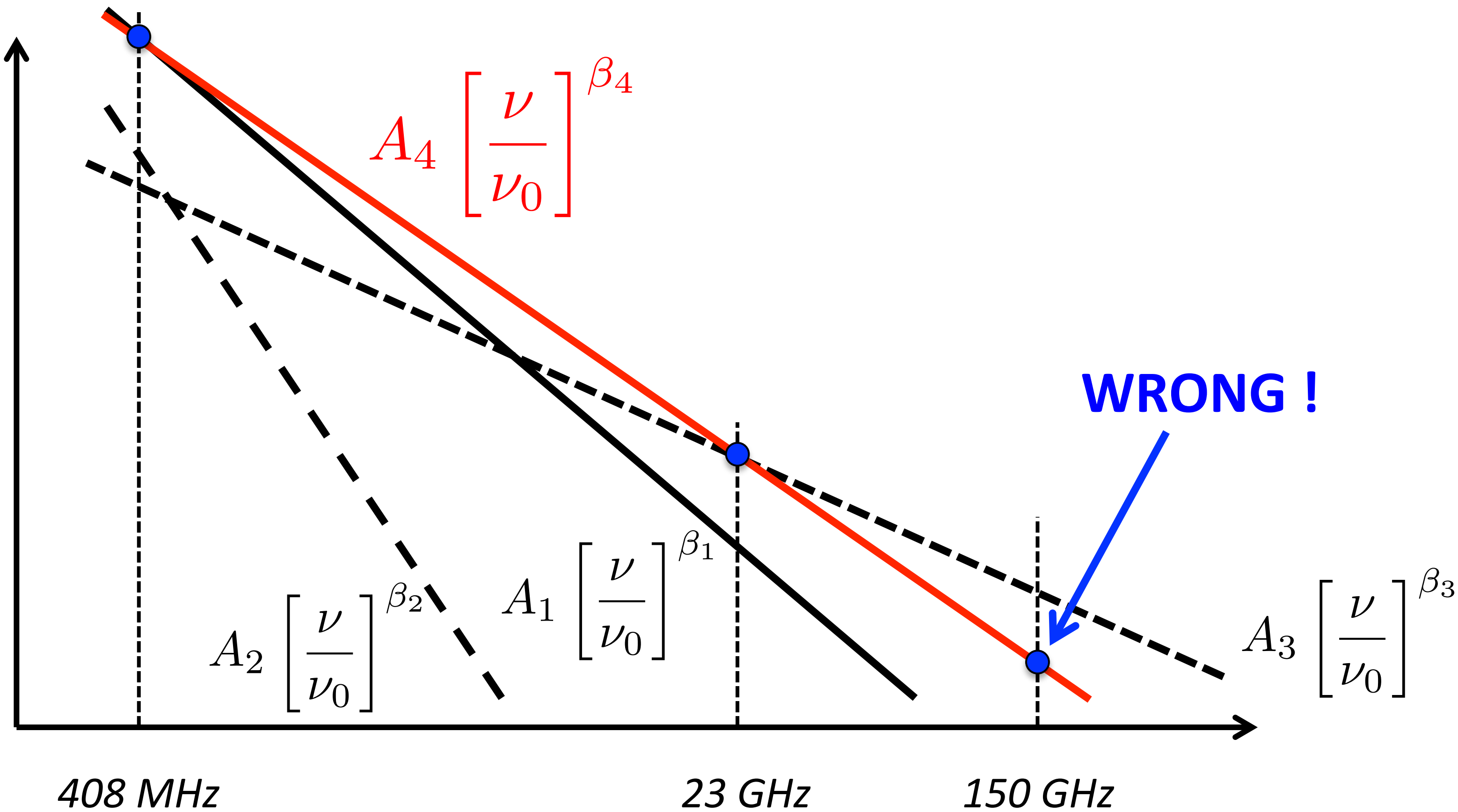
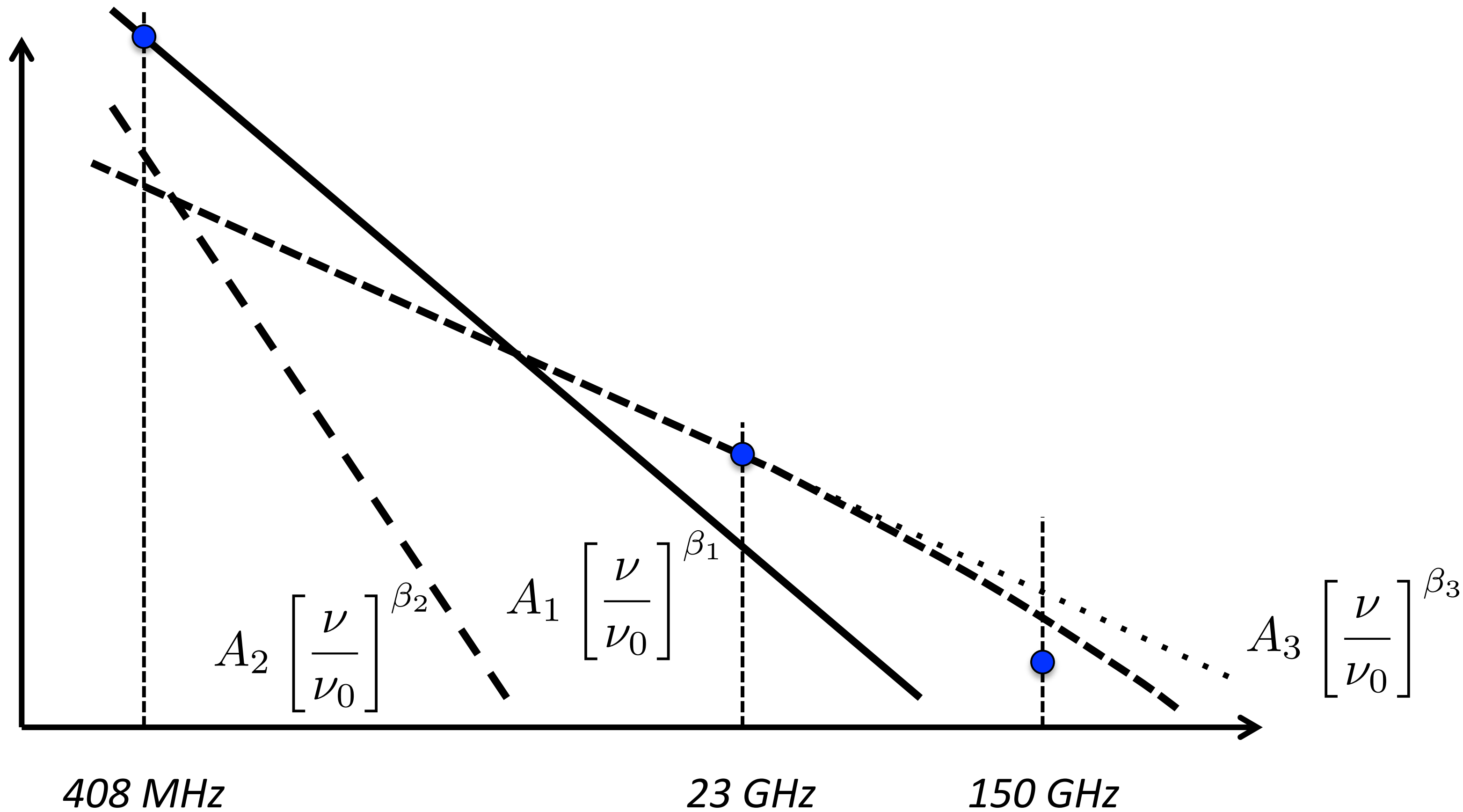


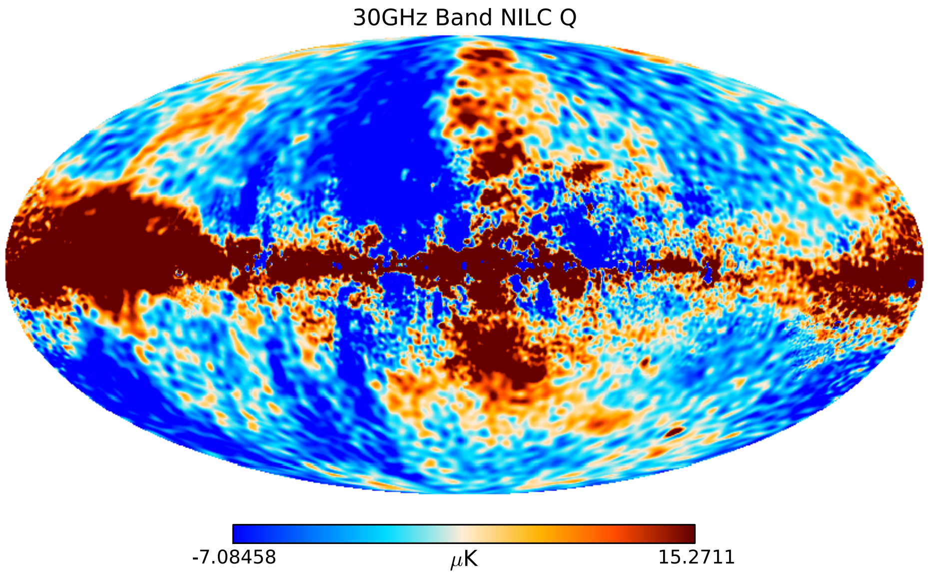
Frequency scaling of synchrotron

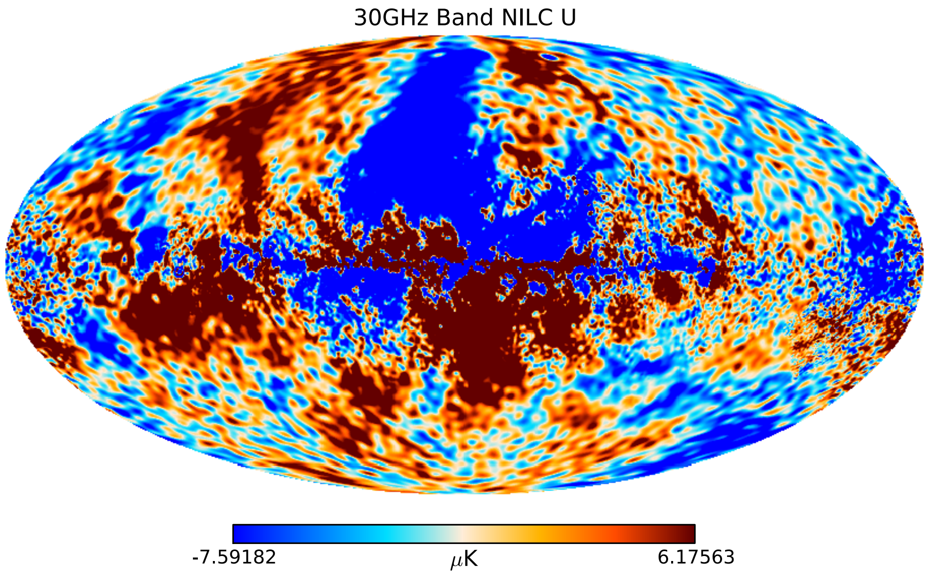
- There also is evidence for steepening of the synchrotron spectral index above 20 GHz ("aging" of CR electrons).



Polarisation at 30 GHz (LFI)

- Polarisation maps from Planck LFI (30, 44 GHz) and WMAP (<40 GHz) are dominated by synchrotron.
- 30 GHz polarisation maps obtained from Planck using GNILC

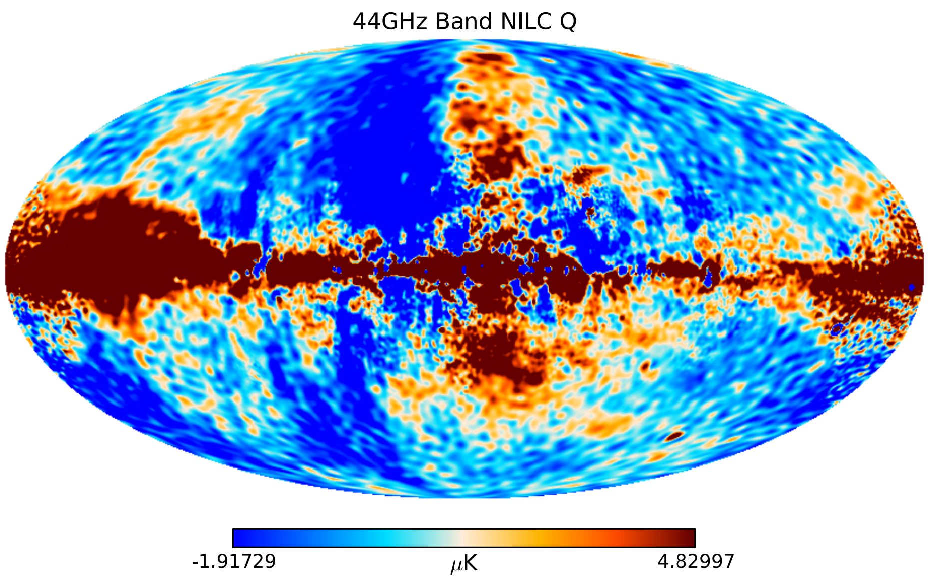


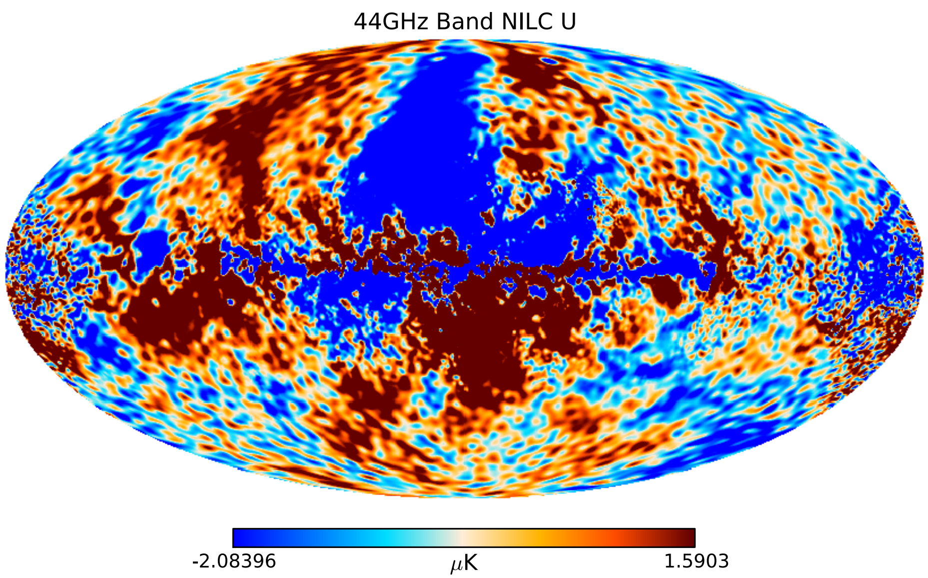


Signal-dominated at scales larger than 2-3 degrees

Polarisation at 44 GHz (LFI)

- Polarisation maps from Planck LFI (30, 44 GHz) and WMAP (<40 GHz) are dominated by synchrotron.
- 44 GHz polarisation maps obtained from Planck using GNILC





Polarised GNILC maps by Ata Karakci (ongoing work)

Spectral index for polarisation

- Polarisation maps from Planck LFI (30, 44 GHz) and WMAP (<40 GHz) are dominated by synchrotron.
- Best-fit spectral index of -3.275 for Q and -3.274 for U at galactic latitudes > 10° (very good agreement)

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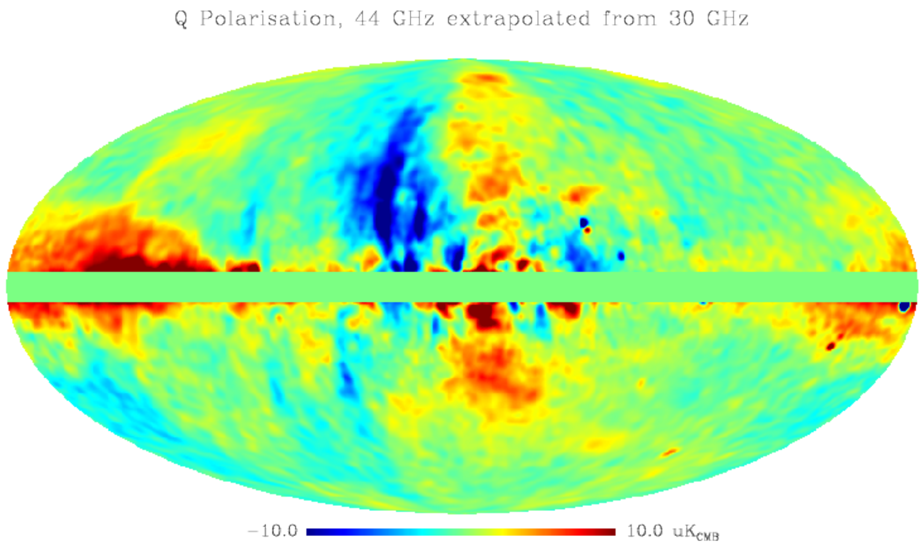

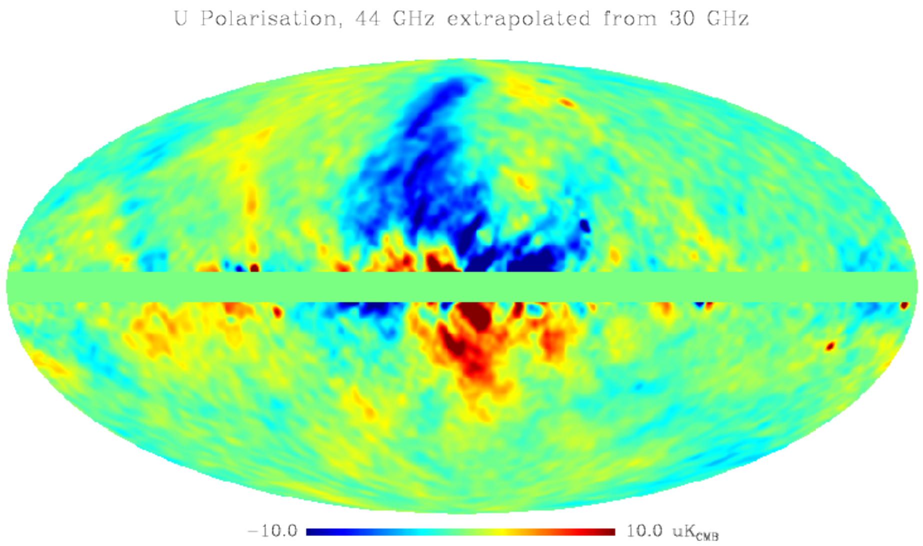

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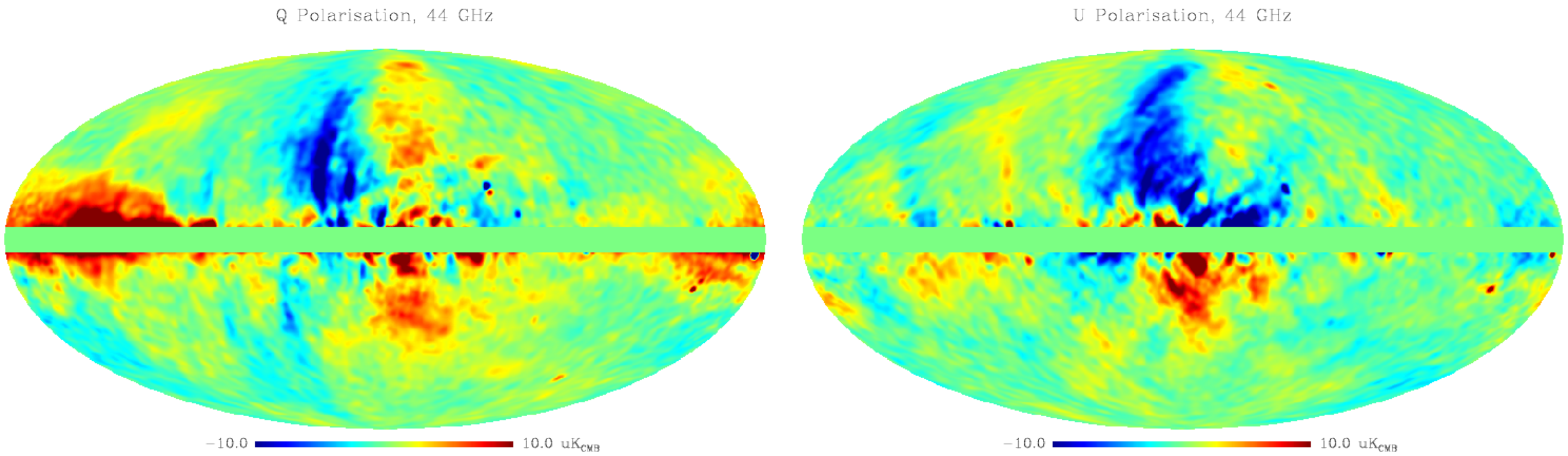
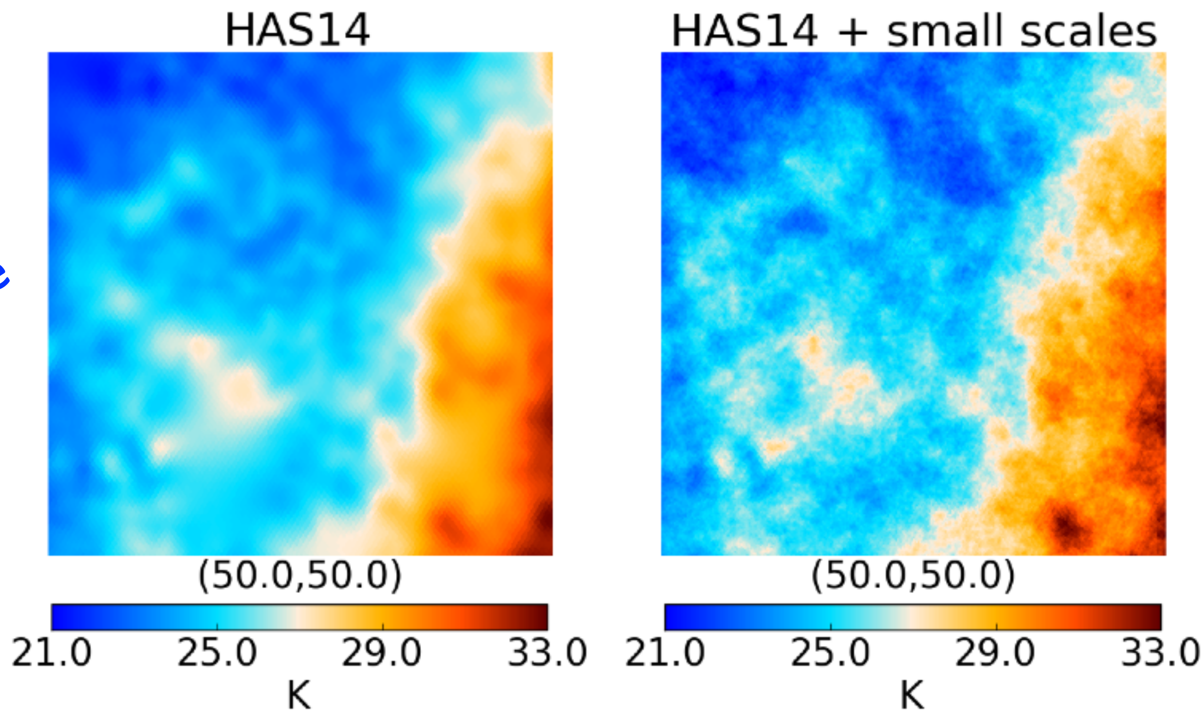


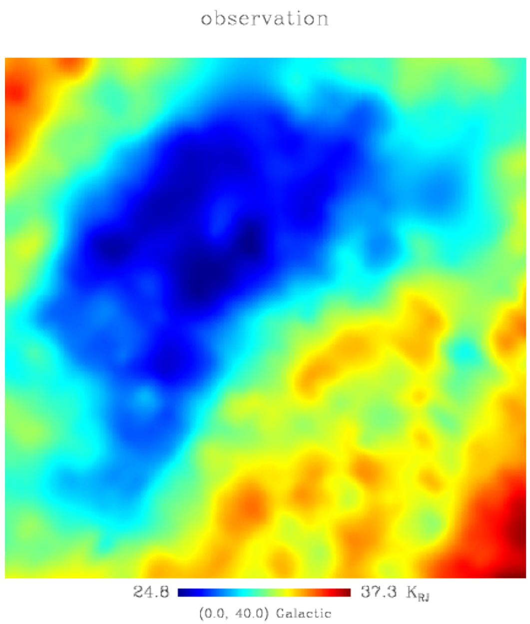
Synchrotron: small scales

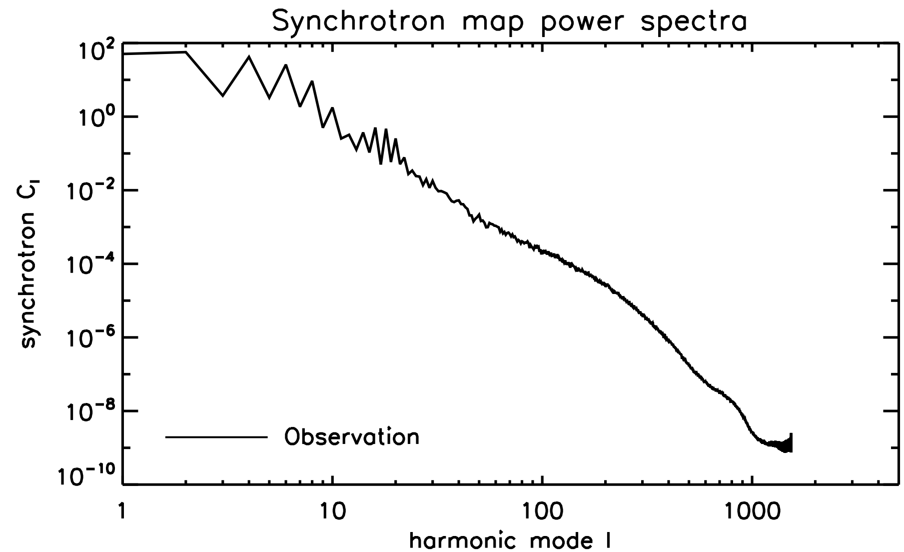
Angular resolution ~ 1 degree

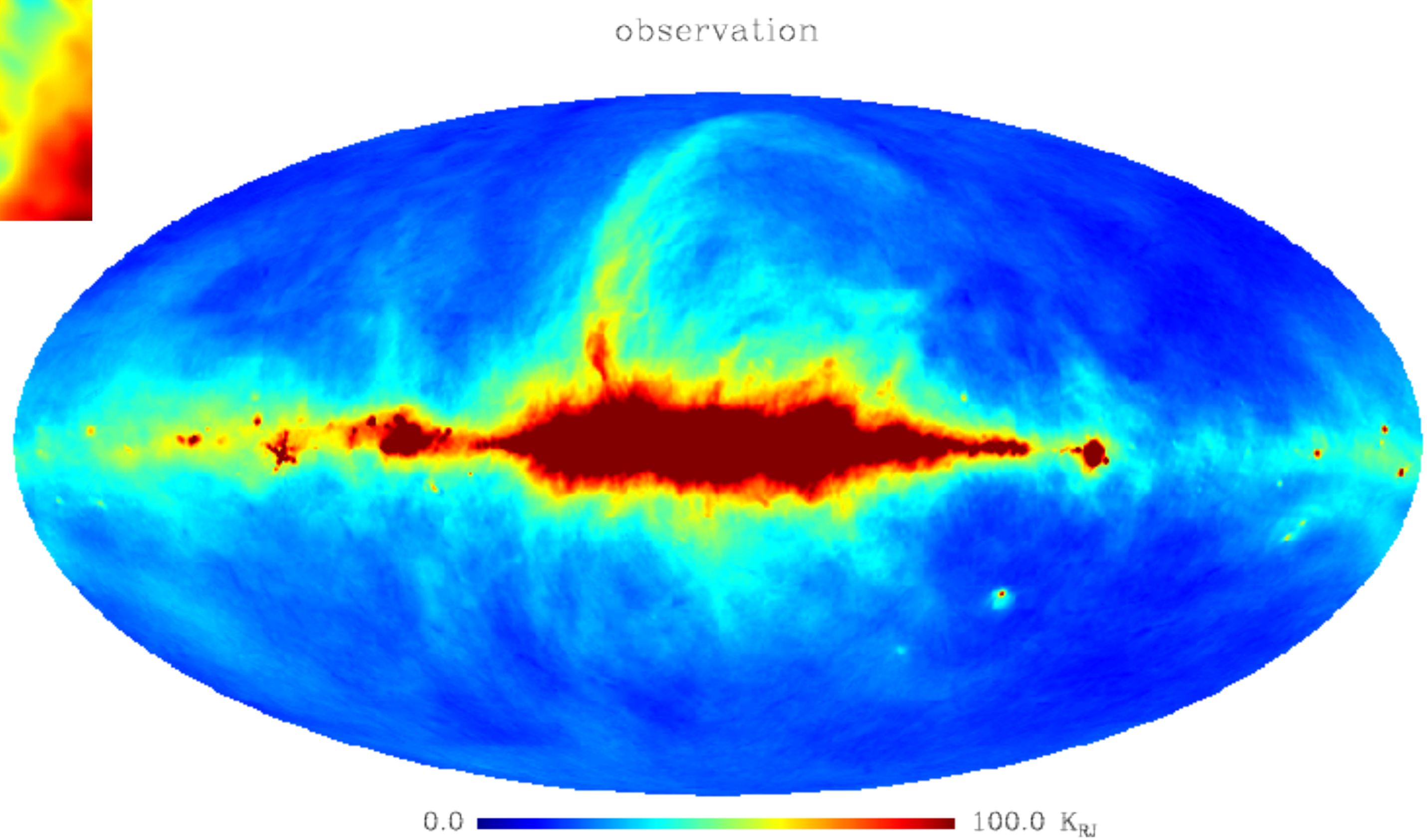


- **SMALL SCALES MISSING IN 408 MHz MAP**
- One single map with small scales added has been made available by Remazeilles et al. at nside=2048 (pixel size = 1.7'). Small scales are generated as Gaussian fluctuations, following the prescription implemented in the pre-launch PSM.

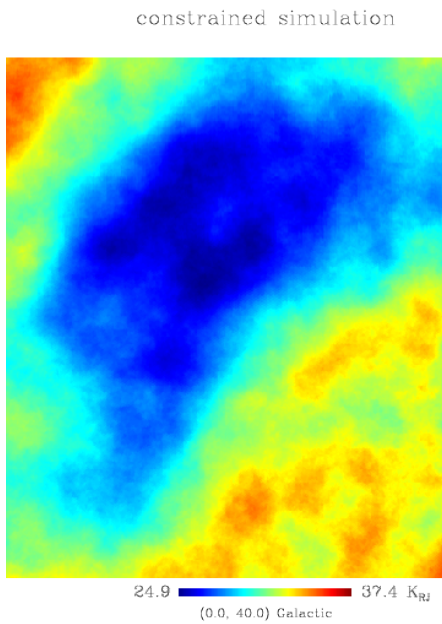
Observation

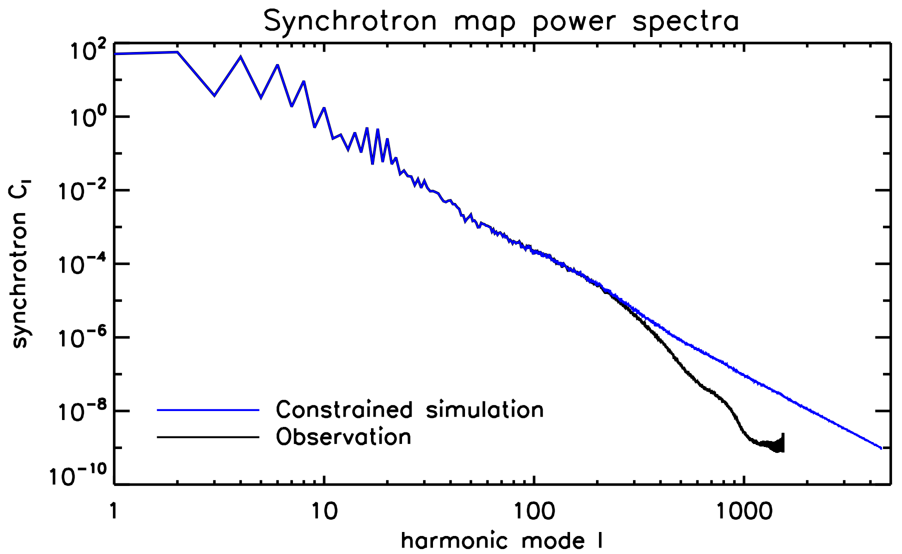


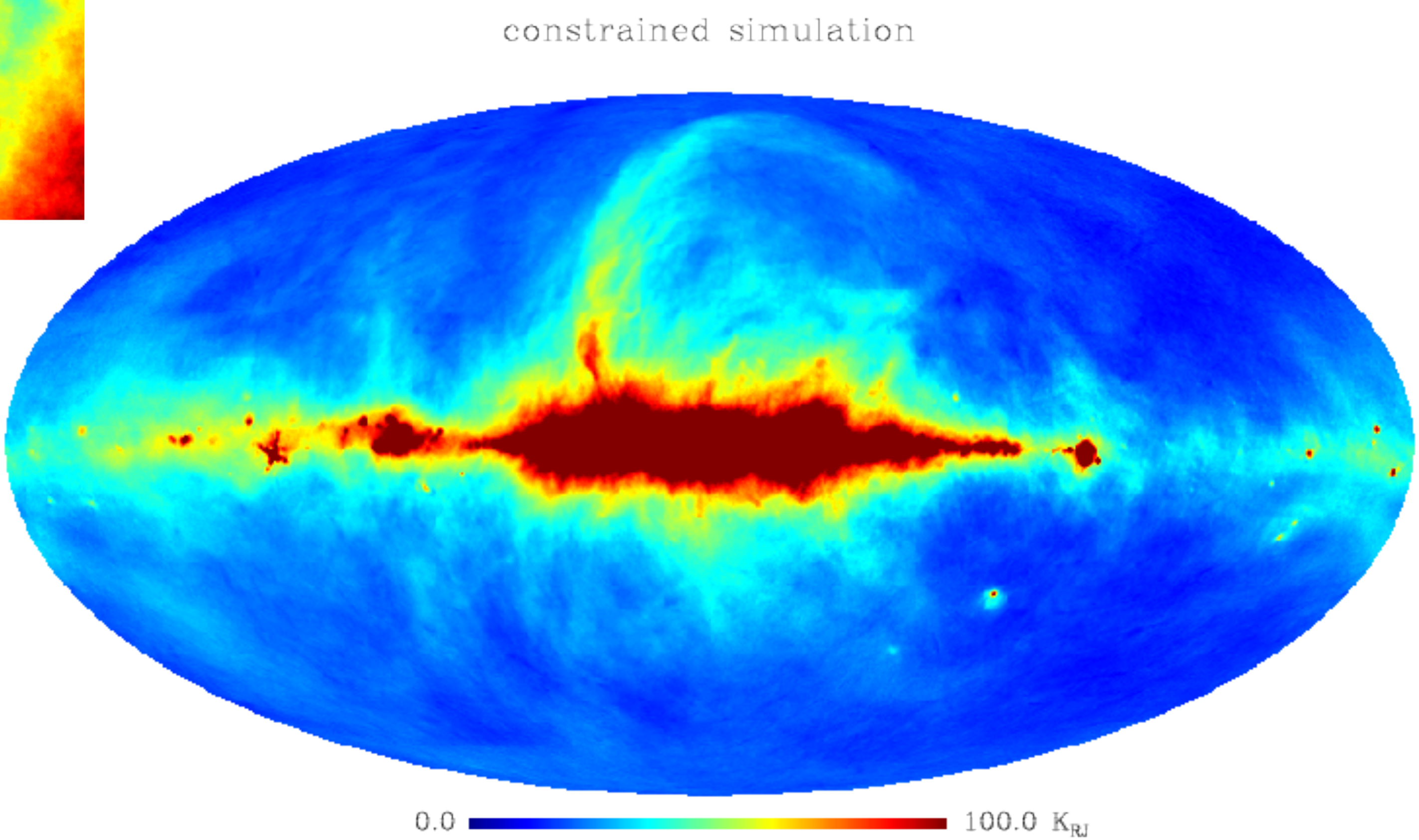




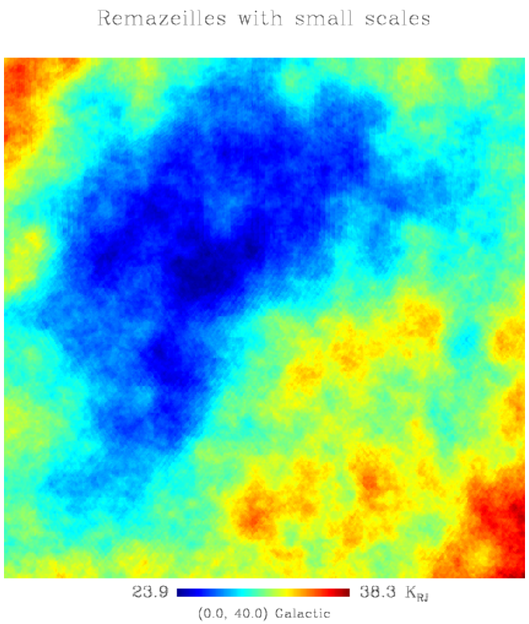
Constrained

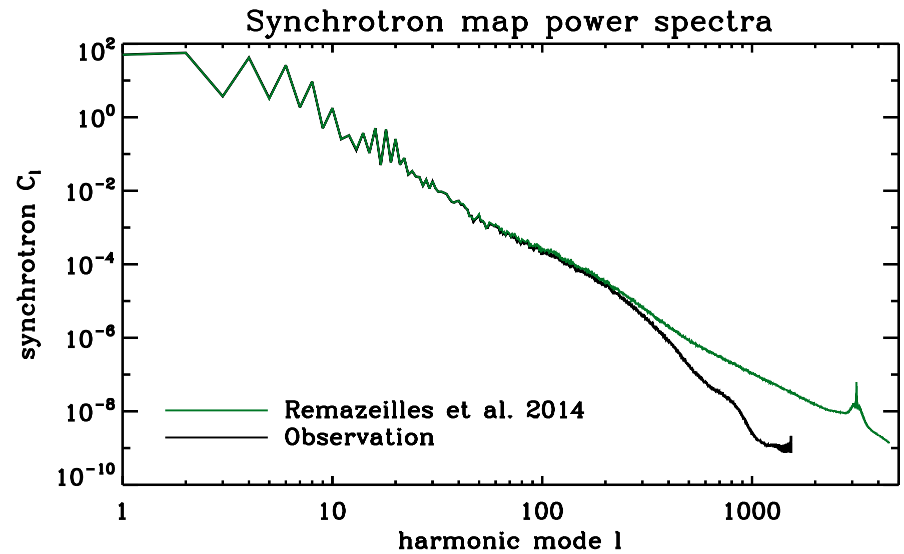


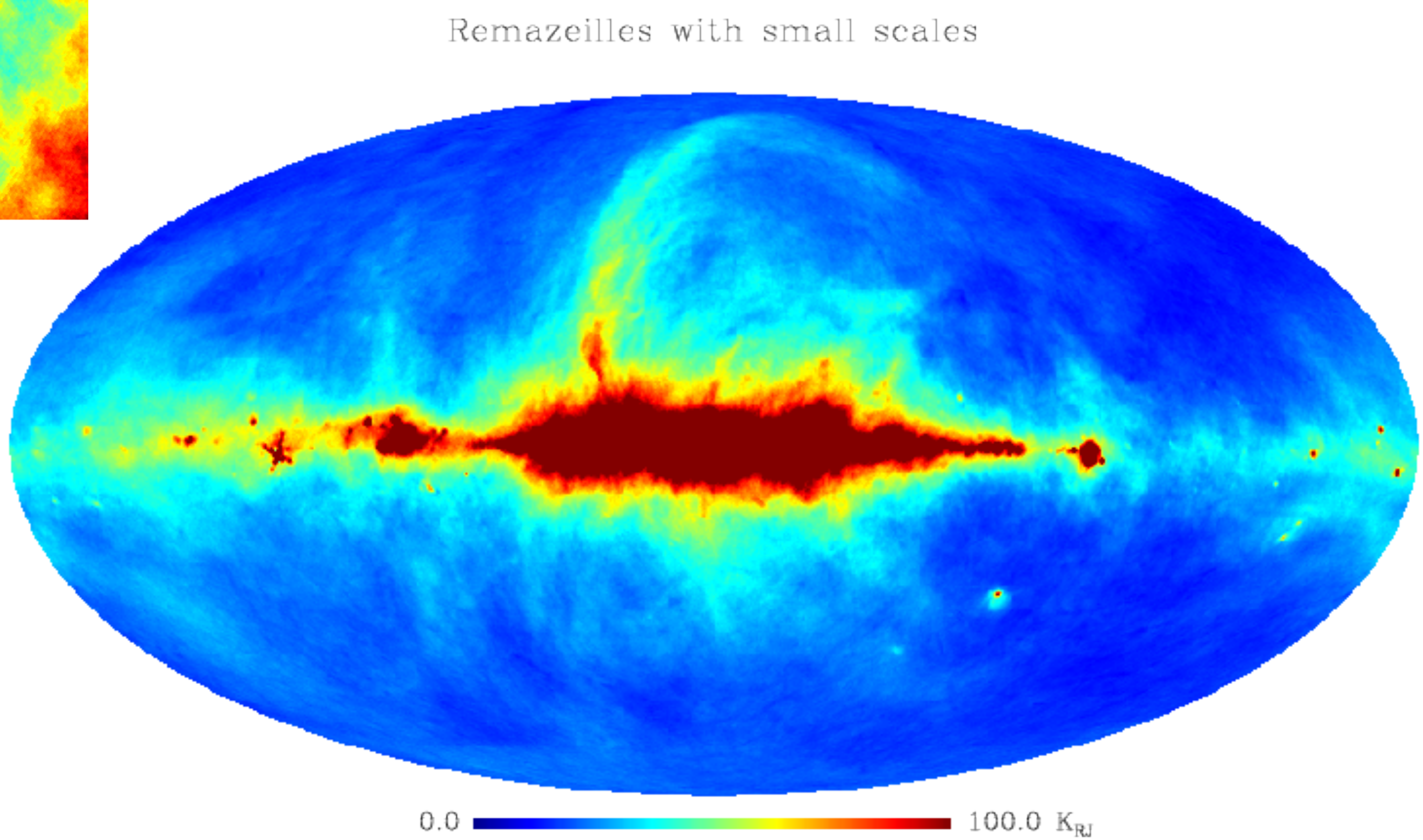




Remazeilles 2014



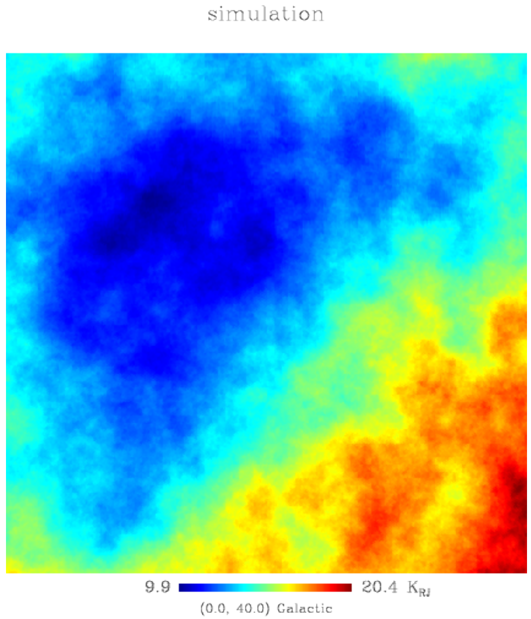


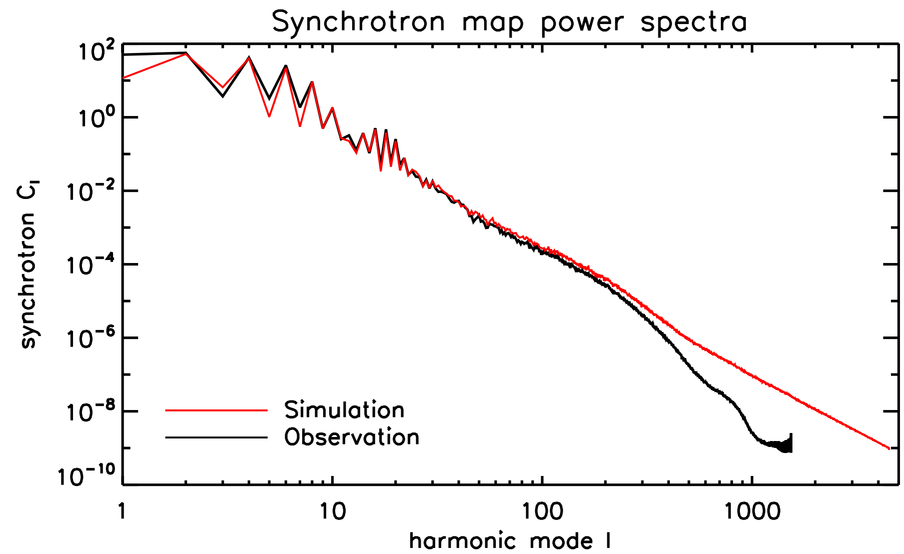


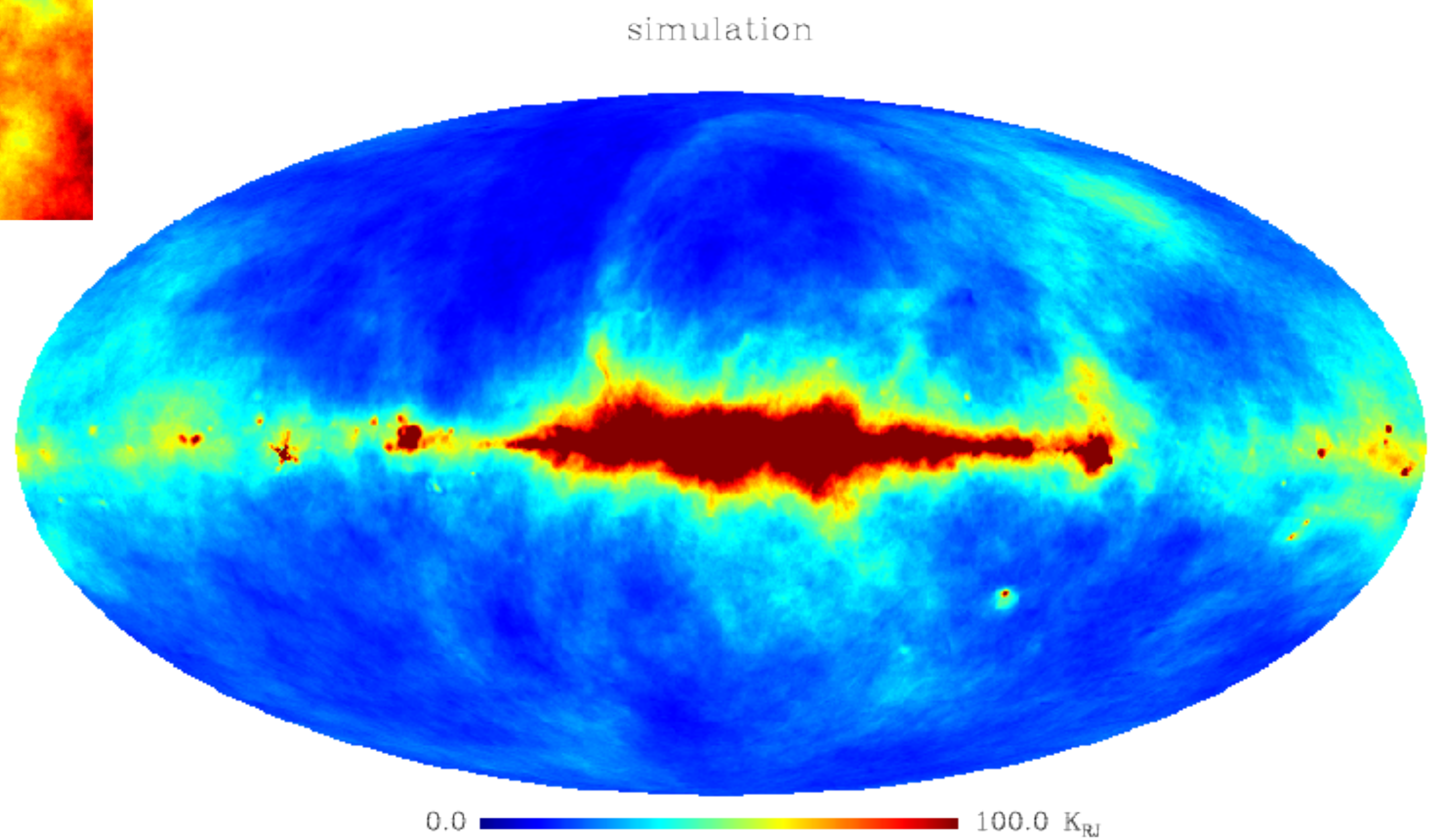
Random high resolution synchrotron ?

- ***NEW in PSM*** : We can now also generate a fully random synchrotron map with the same power spectrum (l^{-3}), with log-normal statistics in the map domain, modulated by the real synchrotron map for a similar "galactic" morphology.

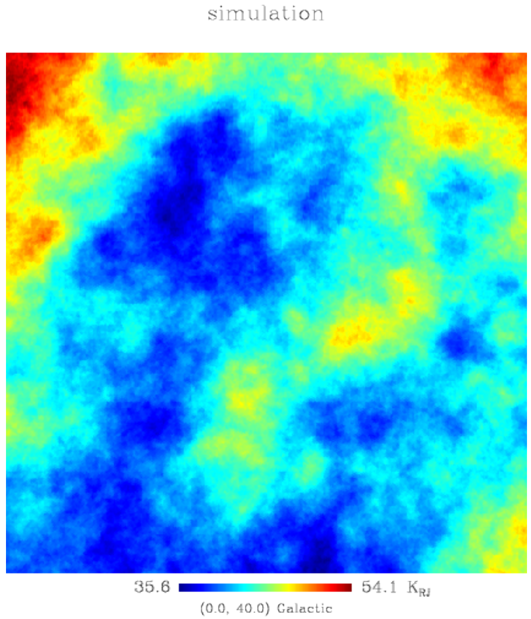
Realisation 1

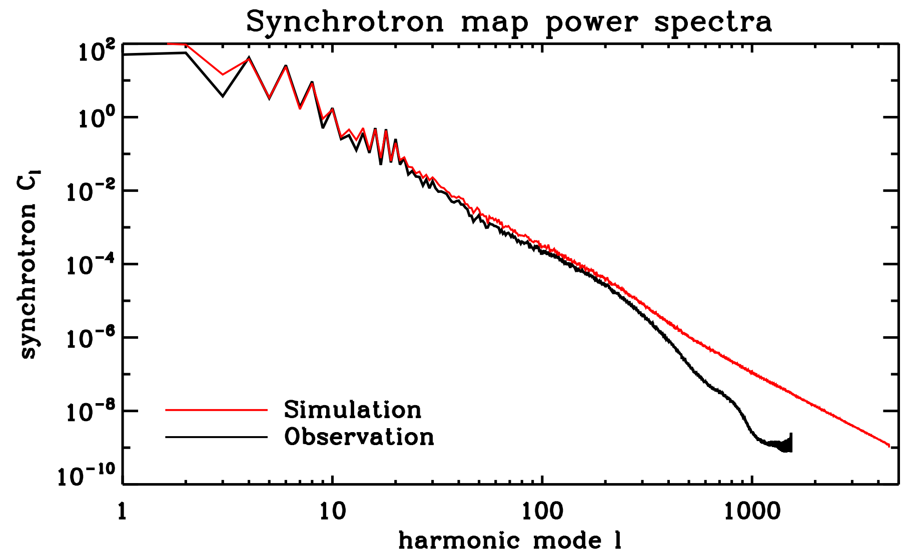


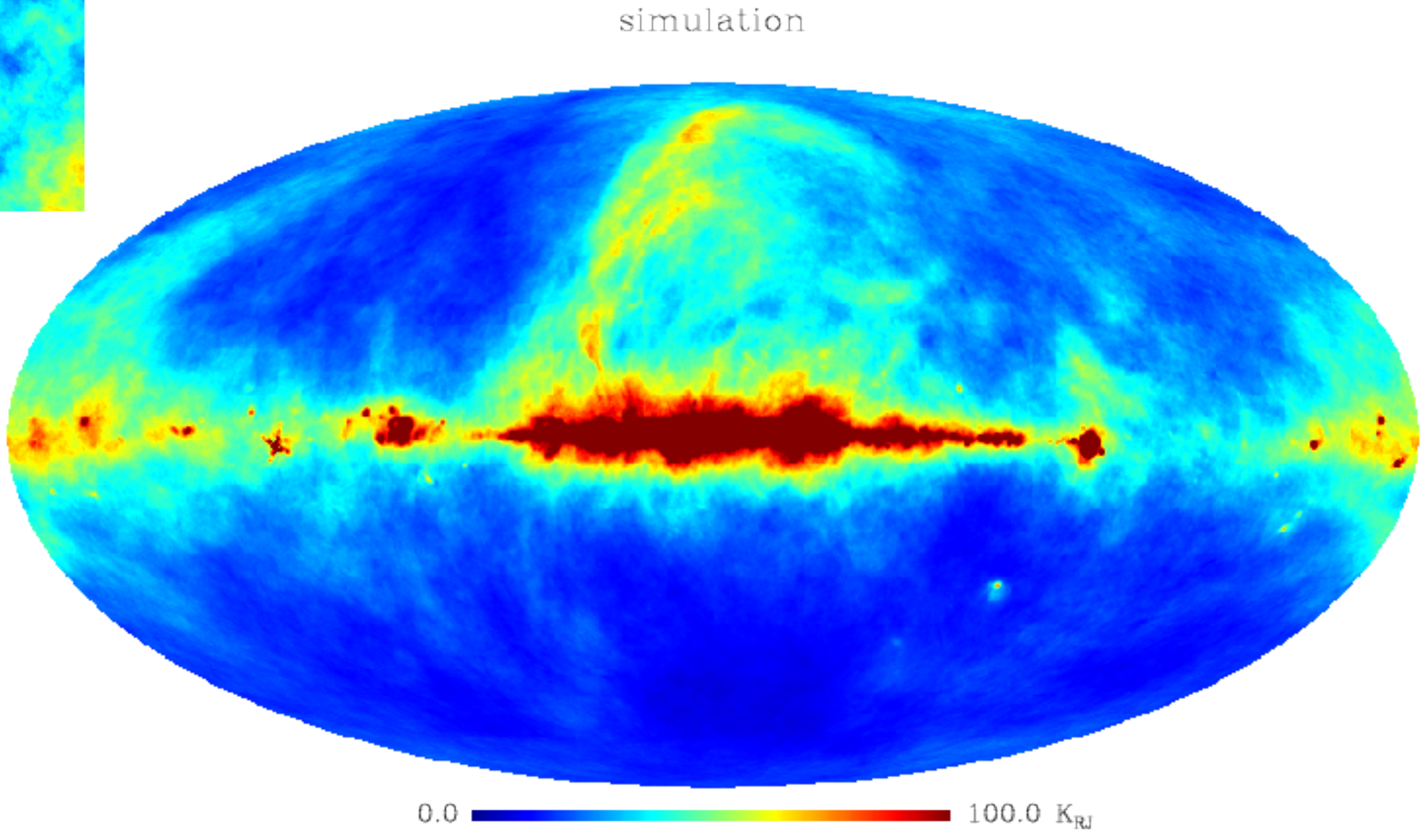




Realisation 2







Outline

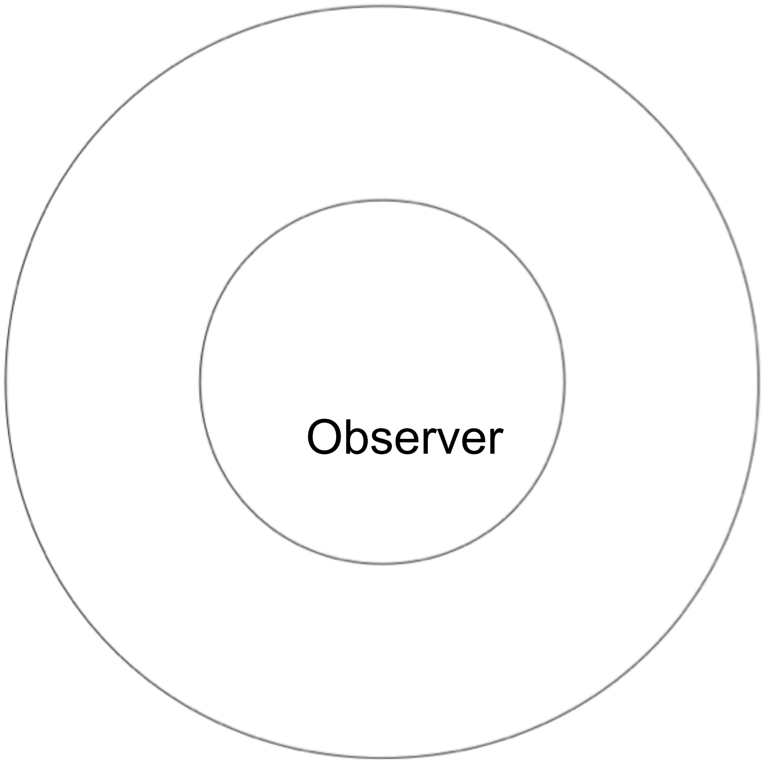
- Introduction
- "Full Focal Plane" simulations
- Polarised diffuse foregrounds
  - ✓ Thermal dust
  - ✓ Synchrotron
- Lensing and the CIB
- The monopole
- Summary

Lensing and de-lensing

- Lensing is important in CMB B-modes physics.
- For $r < 0.01$, it is the main contribution to the total B-modes
- Lensing is generated by large scale structures that are also associated to CIB and to SZ emission. The three must be modelled in a consistent way.
- Are foregrounds an issue for measuring lensing B-modes and for de-lensing ?
- How well can the CIB be used to de-lens?

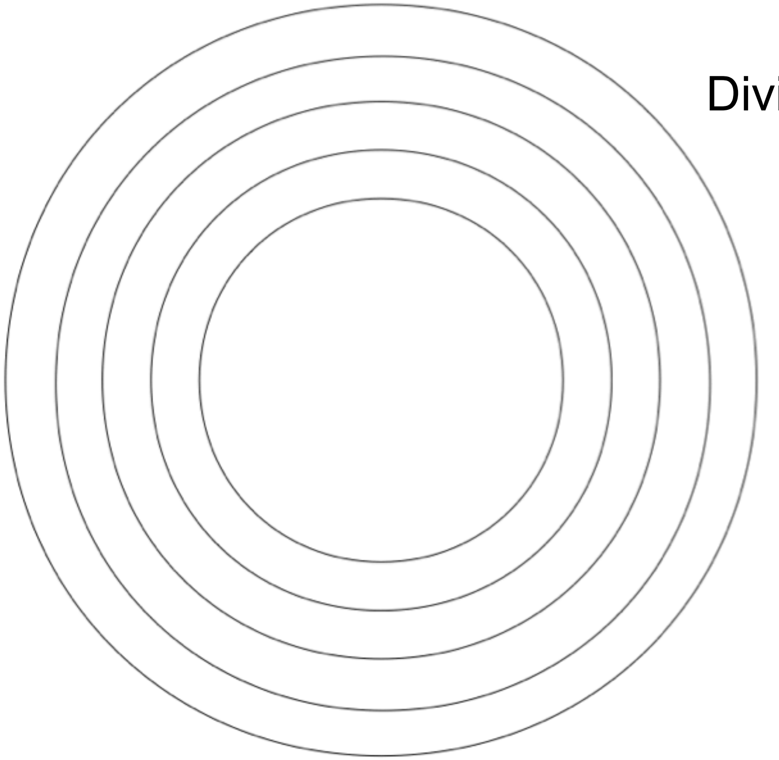
Simulating the CIB

Infrared galaxies from z = zmin to z = zmax



Simulating the CIB

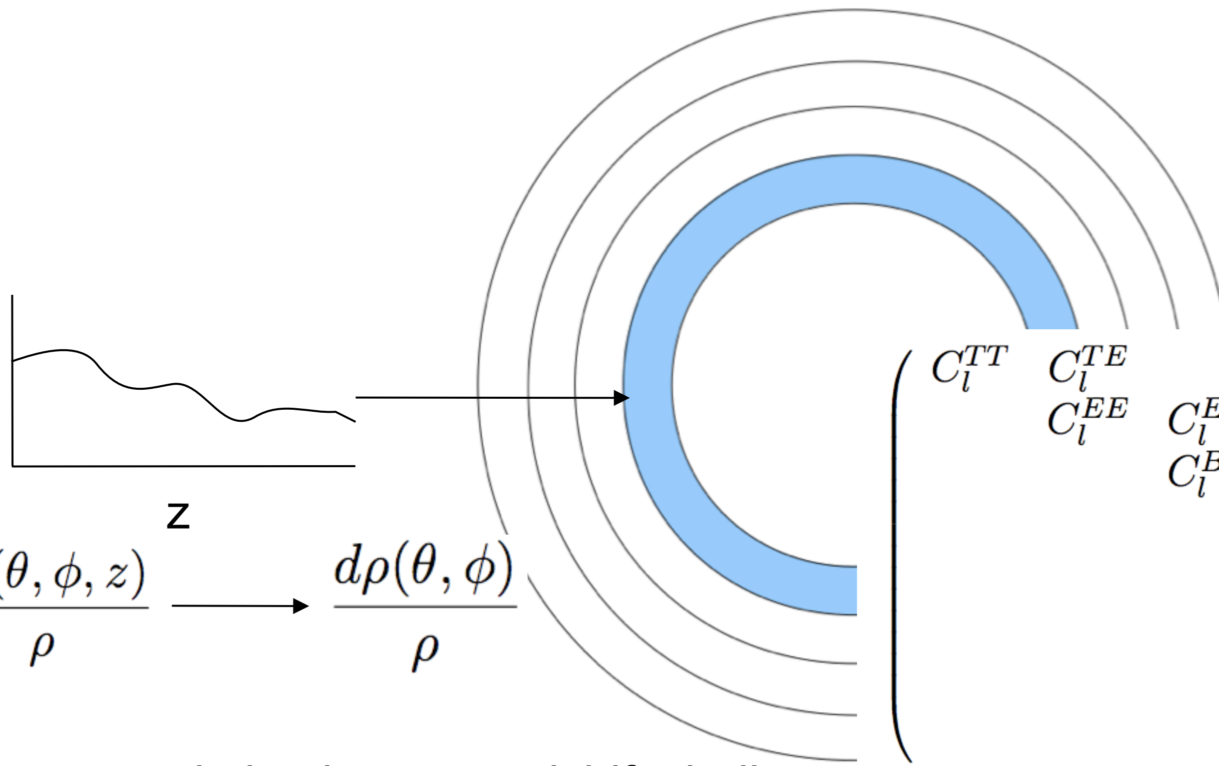
Infrared galaxies from z = zmin to z = zmax



Divide into shells

The CLASS software computes matter distribution Cl coefficients for given cosmological parameters

Integration of matter distribution over a redshift shell of thickness Δz



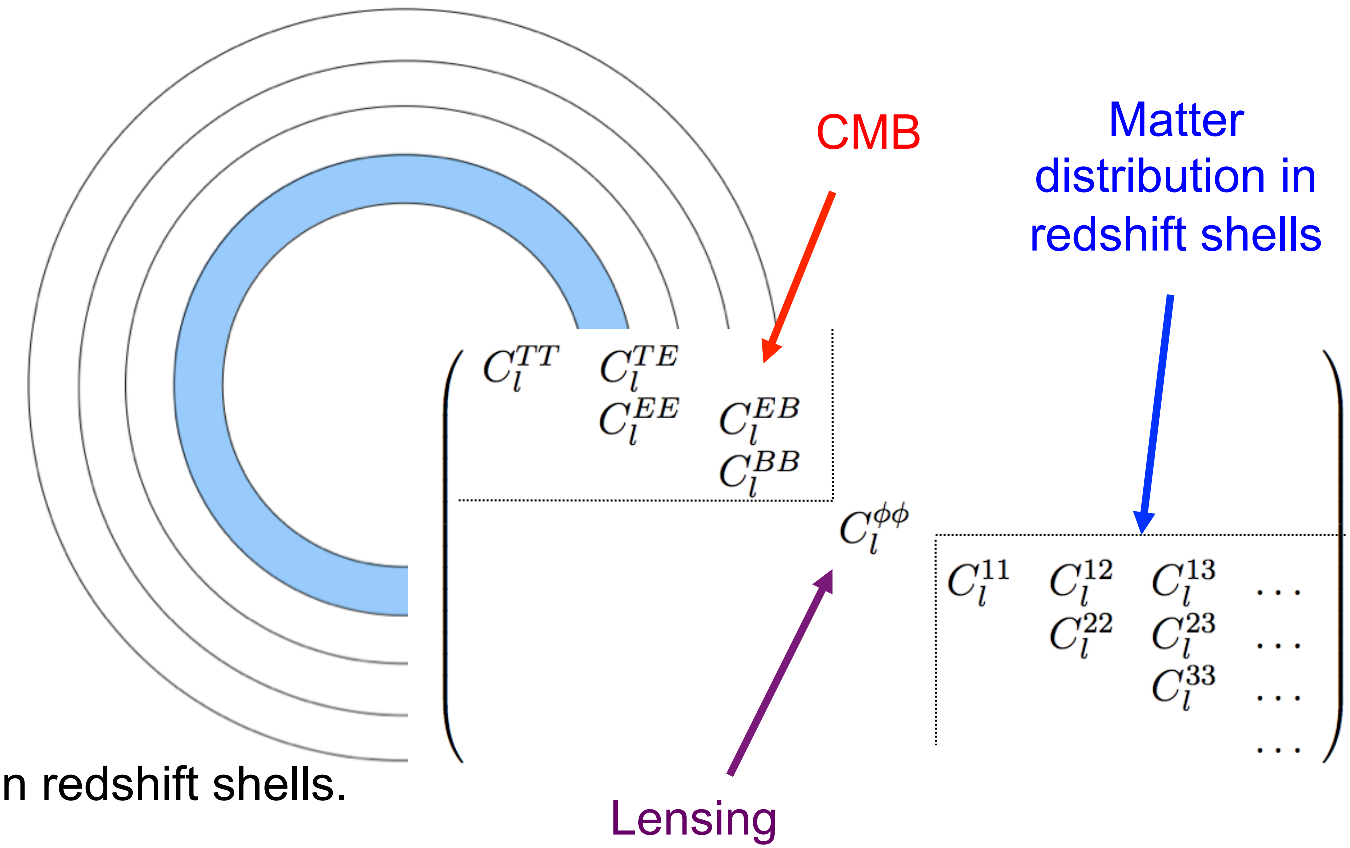
$$\frac{d\rho(\theta,\phi,z)}{\rho} \longrightarrow \frac{d\rho(\theta,\phi)}{\rho}$$

$$\begin{pmatrix}
C_l^{TT} & C_l^{TE} & & & & & & \\
& C_l^{EE} & C_l^{EB} & & & & & \\
& & C_l^{BB} & & & & & \\
& & & C_l^{\phi\phi} & & & & \\
& & & & C_l^{11} & C_l^{12} & C_l^{13} & \dots \\
& & & & & C_l^{22} & C_l^{23} & \dots \\
& & & & & & C_l^{33} & \dots \\
& & & & & & & \dots
\end{pmatrix}$$

-Cross-correlation betwen redshift shells.

The CLASS software computes matter distribution Cl coefficients for given cosmological parameters

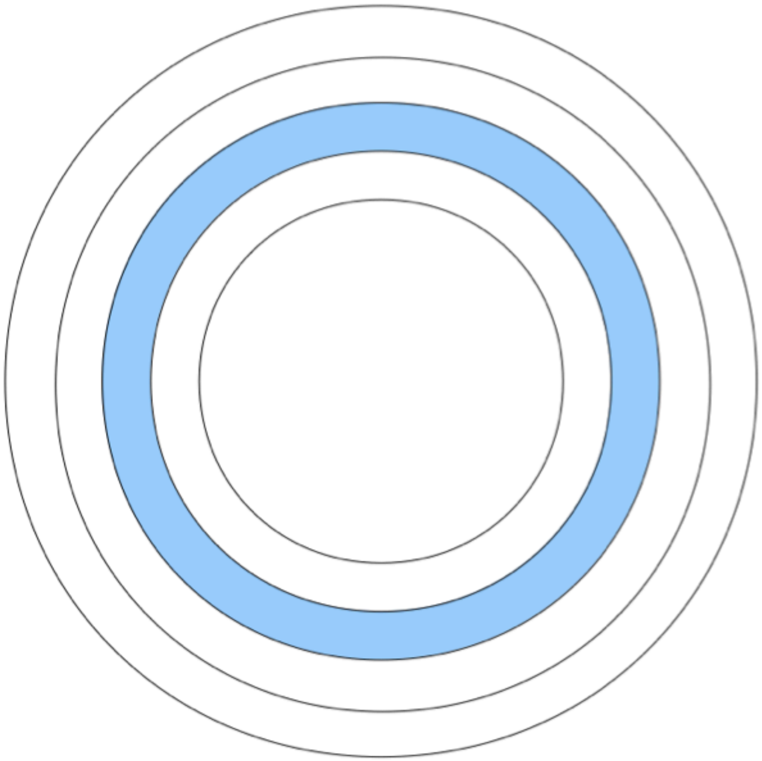
Integration of matter distribution over a redshift shell of thickness Δz



-Cross-correlation betwen redshift shells.

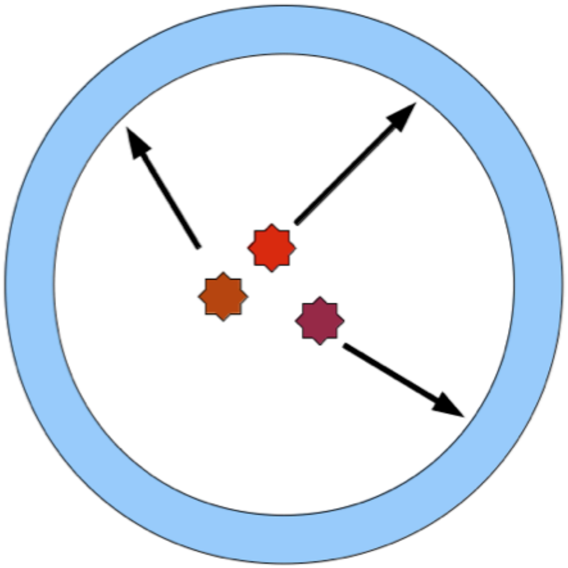
For each matter shell

Matter distribution map



For each matter shell

Distribution of galaxies

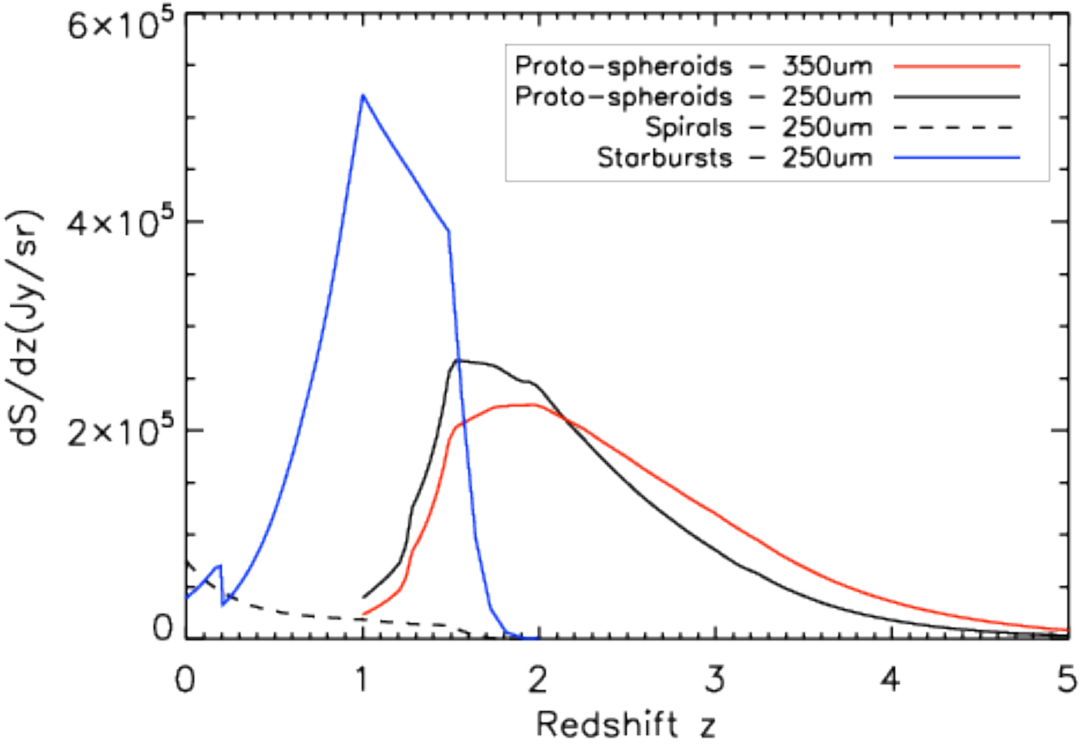


For each matter shell

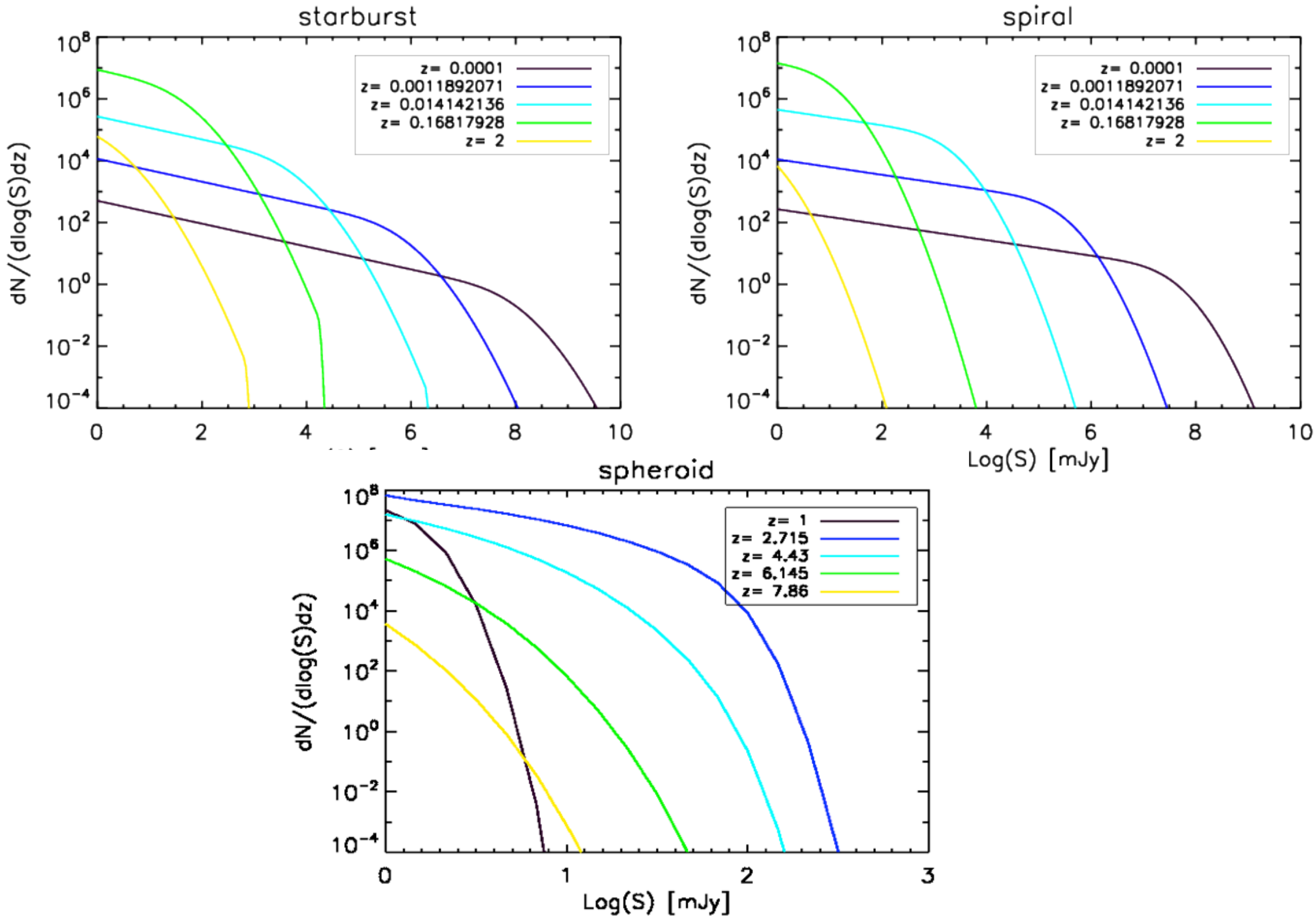
3 populations of galaxies :

- -Spirals
- -Starburst
- -Proto-Spheroids

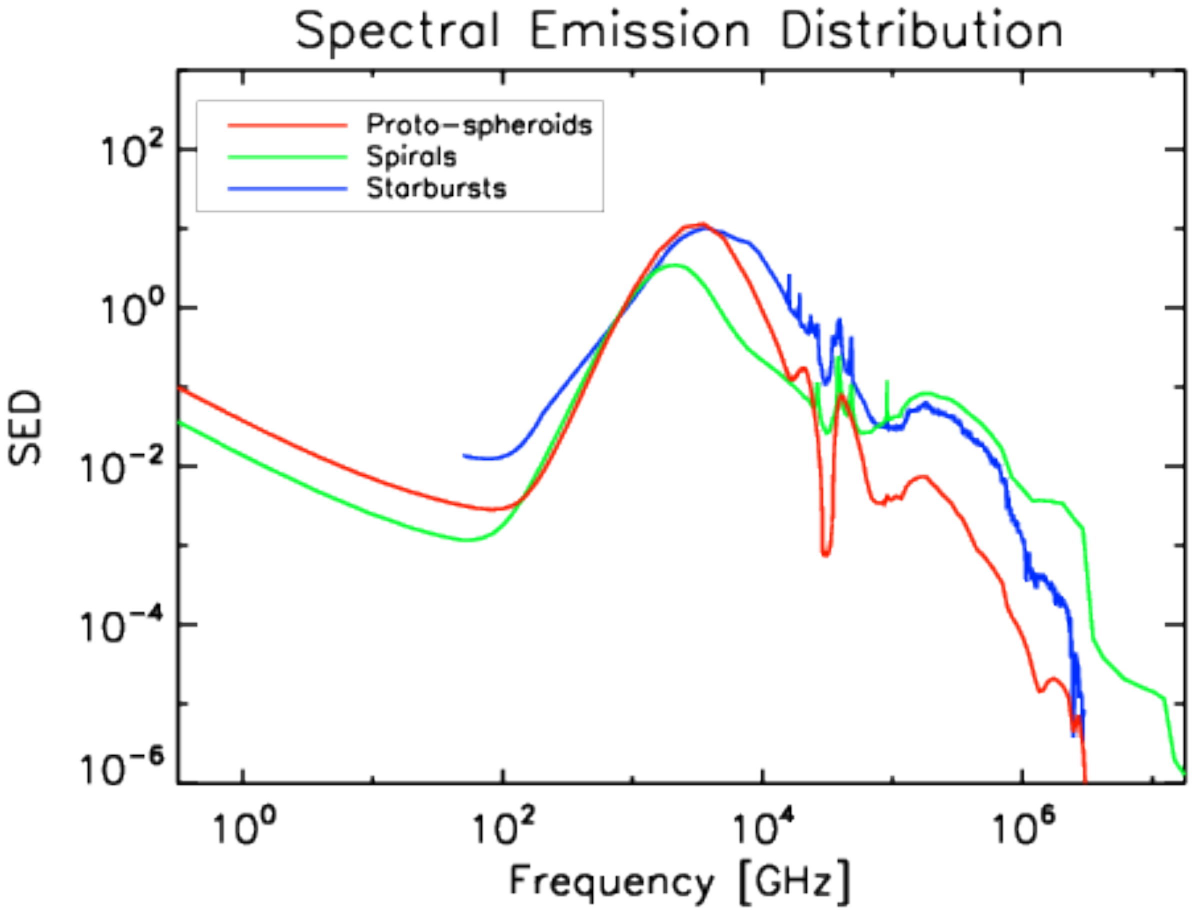
Spirals+Starburst = Late-Type



Number counts



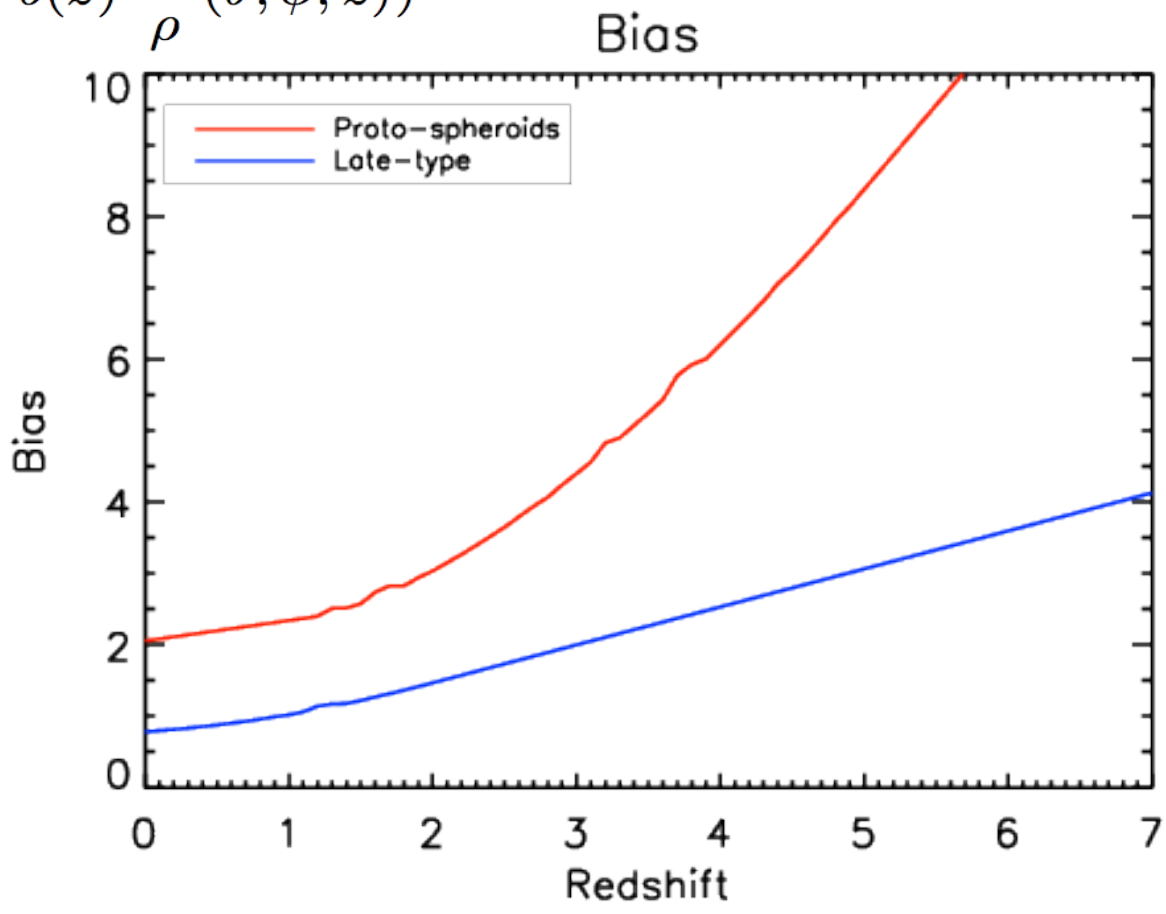
SEDs


Spectral Emission Distribution
Proto−spheroids
Spirals
Starbursts
SED
10^2
10^0
10^{-2}
10^{-4}
10^{-6}
10^0
10^2
10^4
10^6
Frequency [GHz]

Bias

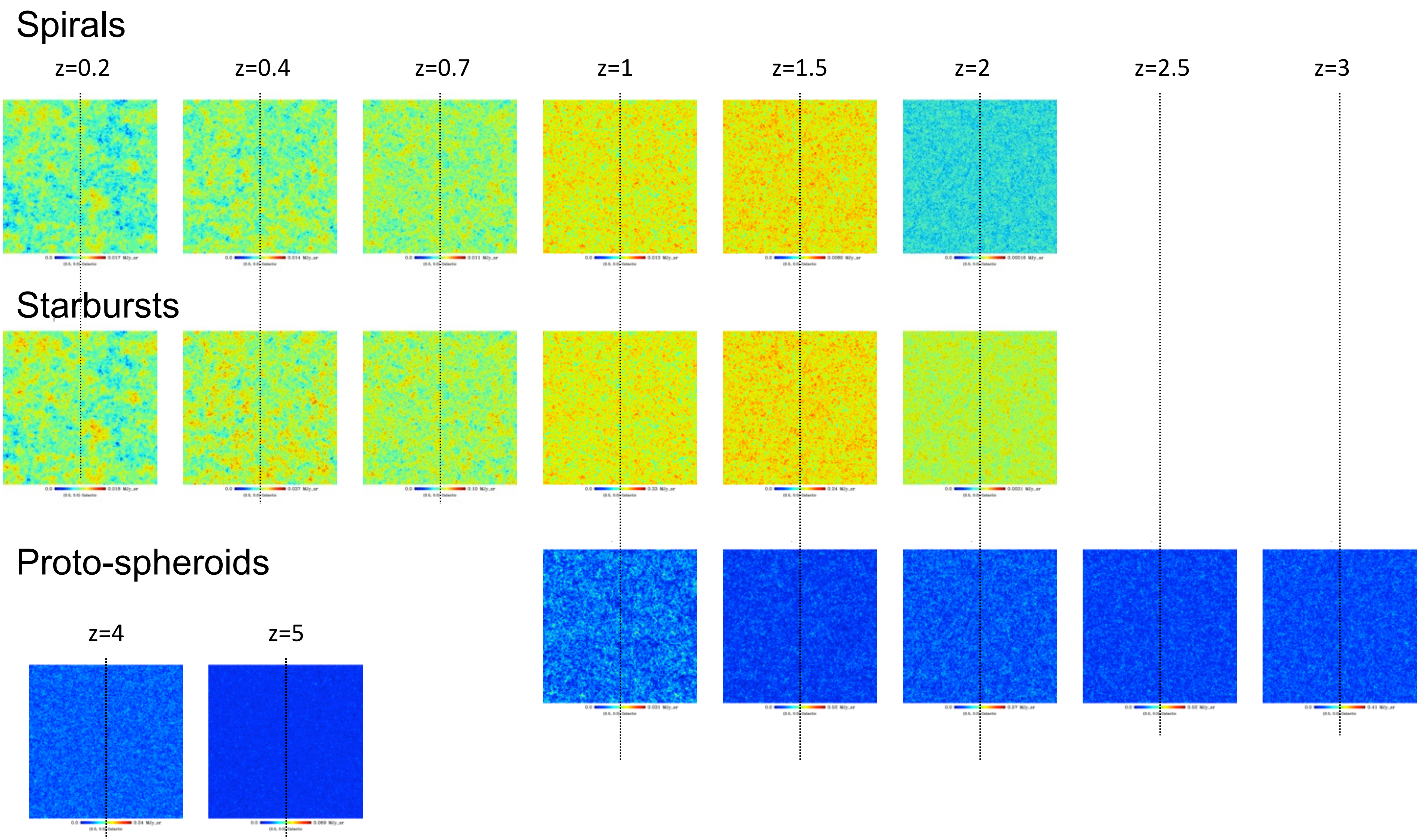
Galaxies distribution

$$p(\theta,\phi,z)\ \alpha\ (1+b(z)\,\frac{\delta\rho}{\rho}(\theta,\phi,z))$$

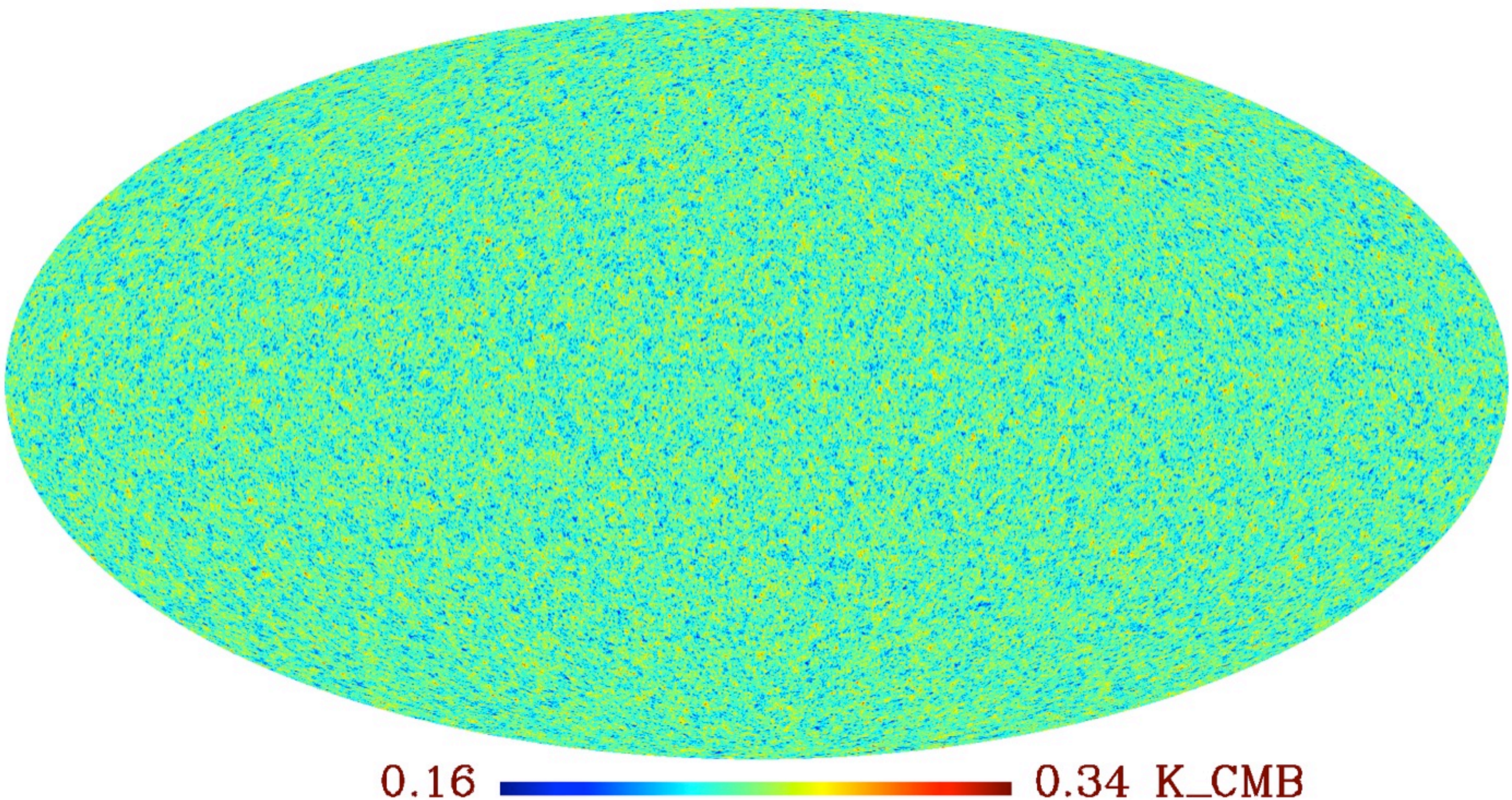


Scale independent
or scale-dependent
bias

Maps of each type for each shell



Total CIB map (857 GHz)



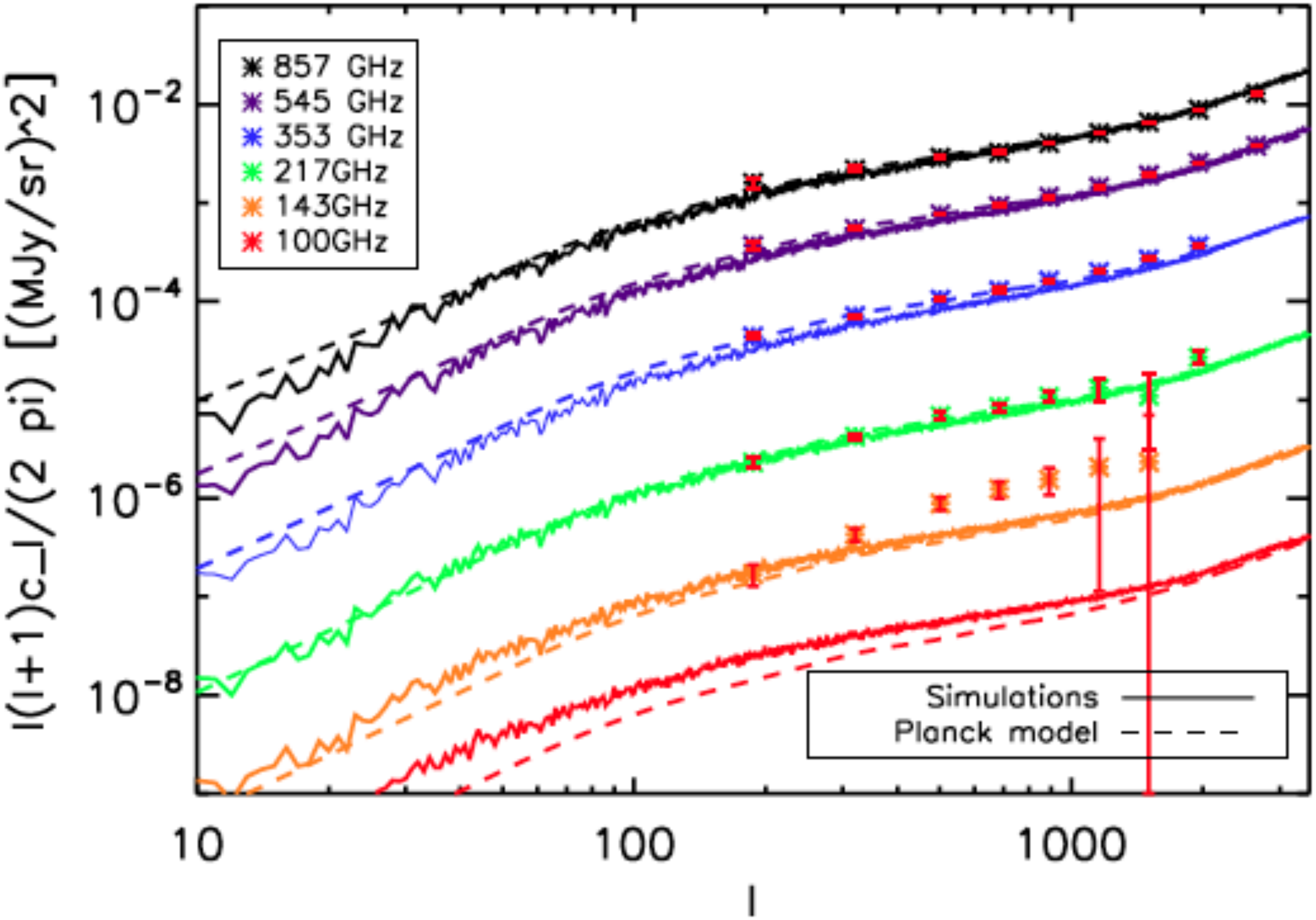
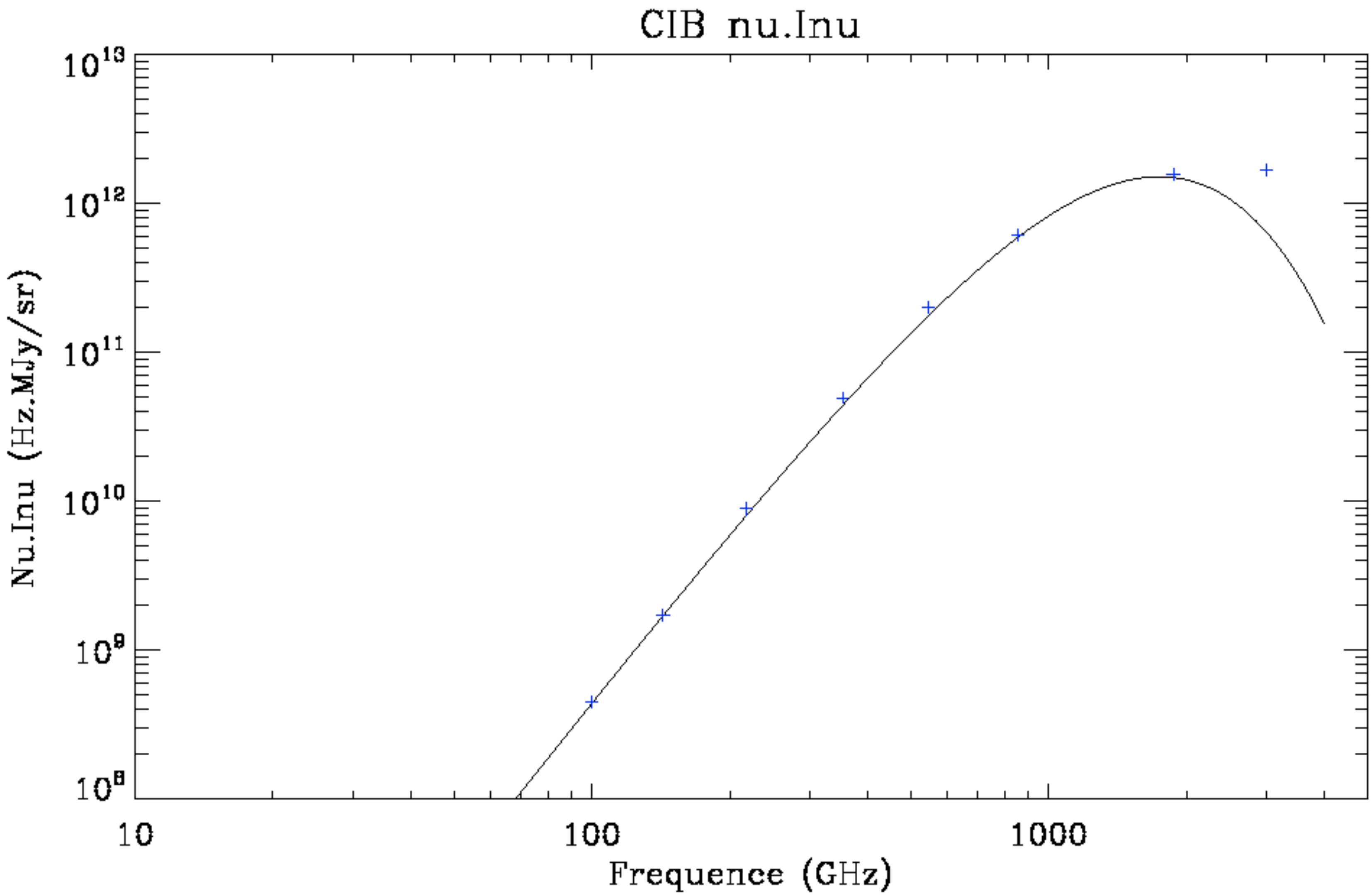


Fig. 9. Simulated and observed cosmic infrared background power spectra. Solid lines are from the PSM simulations; dashed lines are the *Planck* "extended halo model" which includes the correlated and Poisson contributions to the CIB power spectrum from dusty galaxies. Data points are *Planck* observations, corrected for the contribution of radio sources, all from Planck Collaboration XXX (2014).

Monopole



CIB nu.Inu
Nu.Inu (Hz.MJy/sr)
Frequence (GHz)
10
100
1000
10^{13}
10^{12}
10^{11}
10^{10}
10^{9}
10^{8}

New simulations

- High-ell, many redshift shells simulations
- Use CLASS to compute spectra at high ell (>6000) for CMB, lensing, and 64 redshift shells up to z>5
- NEW: log-normal statistics for density contrast in shells
- Populate shells with CIB galaxies and also galaxy clusters to have proper correlations between all those components
- Investigate how well can the CIB be extracted from observed maps (Planck HFI, COrE, …) and used to de-lens.

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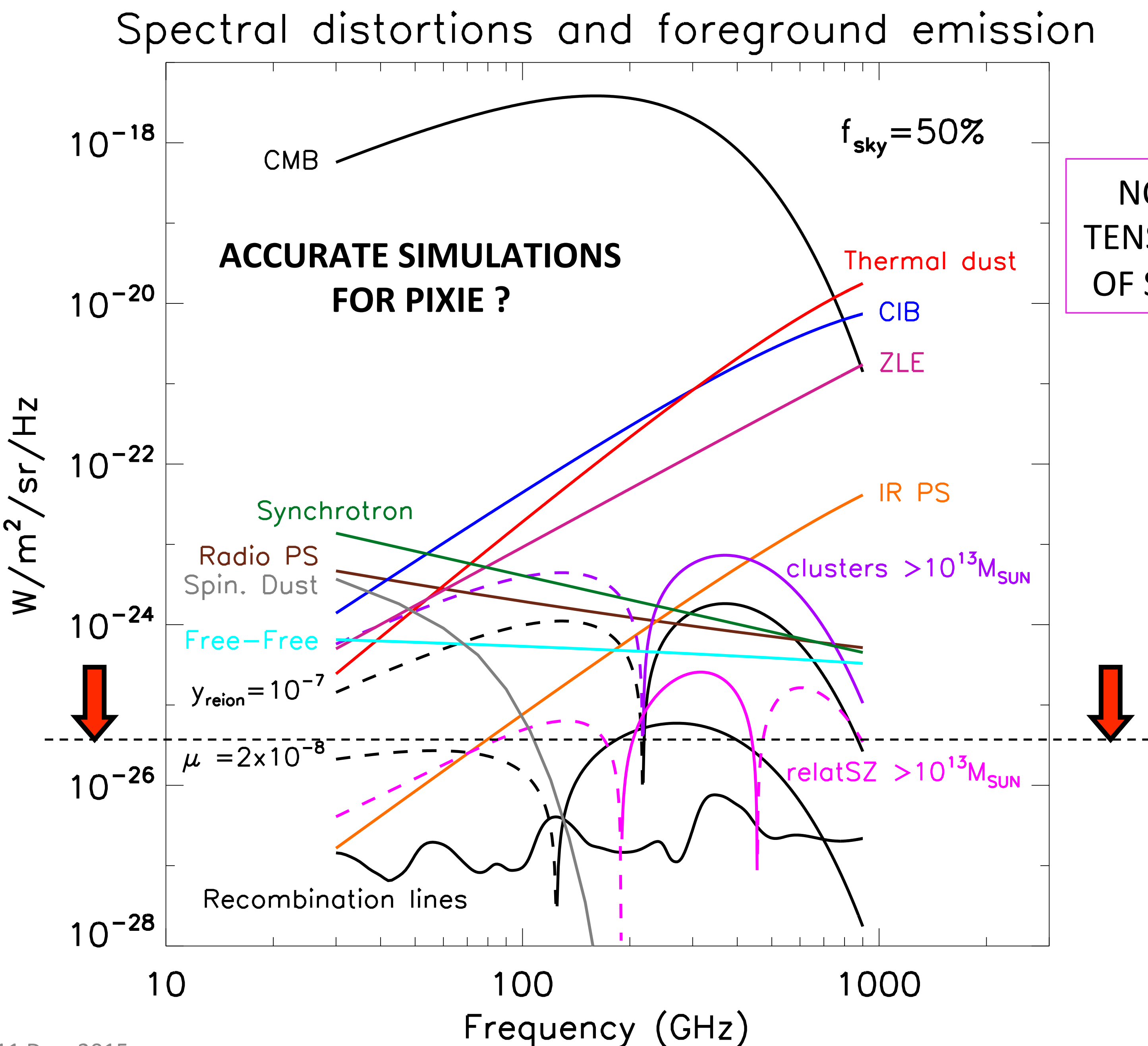
The monopole

- So far, the PSM did not implement the monopole of the various components (at least, not carefully)
- The CMB monopole (temperature = 2.726… K) is ignored
- Spectral distortions (y, μ, homogeneous part) are ignored
- The CIB, radio sources, thermal SZ effect have zero-levels that depend on a flux cut. The requirement on this flux-cut is not the same for anisotropies and for zero-level
- The zero-levels of galactic components and zodiacal light are not well known (best measurement = FIRAS) but is relevant for understanding the polarisation fraction on large scales.



NOT INCLUDED:
TENS TO HUNDREDS
OF SPECTRAL LINES

PIXIE 4 years
50% sky used
$\delta I \approx 3\times10^{-26}$

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Summary

- The PSM is in a quick development phase for generating simulations for future experiments.
- A tool for the CMB community (but person-power limited…)
- NEW features since "pre-launch" model
  - New templates for temperature and polarisation
  - Several emission laws for synchrotron and dust
  - New random galactic emission
  - New CMB x CIB x Lensing (x SZ)
  - Monopole emission with CMB spectral distortions
- Send-in your wish-list, give a hand if you can, and stay tuned !