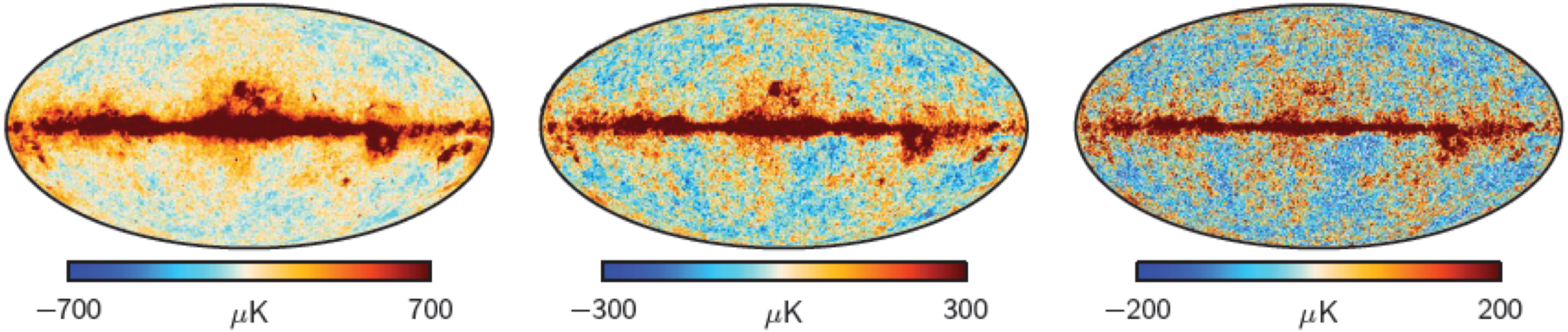
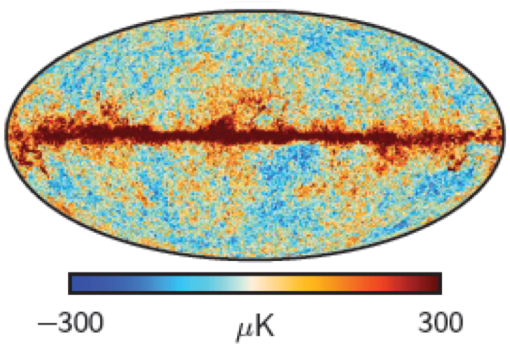


The Planck Sky Model

and simulations for future CMB experiments

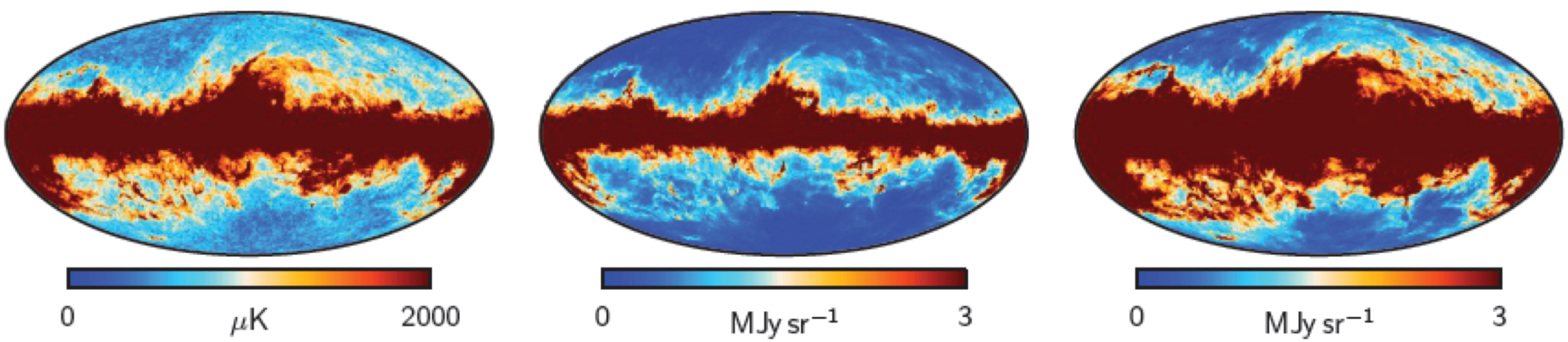


Jacques Delabrouille, APC Paris

& Marcos Lopez-Caniego, Gines Martinez-Solaeche,

Jean-Baptiste Melin, Mathieu Remazeilles,

On behalf of the PSM team



The PSM team

Global coordination and scientific responsibility

- Jacques Delabrouille and Gianfranco de Zotti.

Main developers and contributors

The following additional people have contributed to the PSM project so far:

- Mark Ashdown, Jonathan Aumont, Carlo Baccigalupi, Anthony Banday, Soumen Basak, Jean-Philippe Bernard, Marc Betoule, François Bouchet, François Boulanger, Guillaume Castex, Dave Clements, Antonio Da Silva, Clive Dickinson, Fabrice Dodu, Klaus Dolag, Franz Elsner, Hans-Kristian Eriksen, Lauranne Fauvet, Gilles Faÿ, Tuhin Ghosh, Giovanna Giardino, Joaquin Gonzalez-Nuevo, Ata Karakci, Guilaine Lagache, Maude le Jeune, Samuel Leach, Julien Lesgourgues, Michele Liguori, Marcos Lopez-Caniego, Juan Macias-Perez, Gines Martinez-Solaeche, Marcella Massardi, Sabino Matarrese, Pasquale Mazzotta, Jean-Baptiste Melin, Marc-Antoine Miville-Deschênes, Ludovic Montier, Sylvain Mottet, Roberta Paladini, Bruce Partridge, Rocco Piffaretti, Gary Prézeau, Simon Prunet, Mathieu Remazeilles, Sara Ricciardi, Matthieu Roman, Bjorn Schaefer, Jan Tauber, Sybille Téchéné, Luigi Toffolatti, Flavien Vansyngel, Ingunn Wehus, Niraj Welikala.

… and the Planck collaboration

Contributors present here at the workshop

Outline

- Introduction to the PSM
- PSM components & modelling strategy
- Multilayer dust emission
- Dust in galaxy clusters
- Summary and perspective

Introduction to the PSM

- The PSM is a software tool for investigating/modelling astrophysical emissions at millimetre wavelengths.

- Originally designed for the Planck data analysis, it is also widely used for a range of scientific investigations and for planning future experiments.

- It comprises a data base of observations of those astrophysical emissions which contribute to the total sky emission from ≈400 MHz (Haslam 408 GHz map) to. ≈ 5 THz (IRAS 60μm).

- It encompasses a library of programs of general use for CMB data analysis and for modelling astrophysical emissions and their observation in that frequency range.

- A single main program can be run to generate full-sky healpix maps of sky emission that includes any subset of all known astrophysical components in the Planck mission frequency range.

PSM specifications (1/2)

- Provide a tool to answer the following questions / requirements:
  - What is the current best estimate of the emission of component x at frequency ν ? (prediction)
  - What is a plausible emission for component x at frequency ν ? (simulation, with some random part that differs from the real sky)
  - What kind of sky should/will my planned experiment see ? (generate simulated data sets "observed" by ongoing/future experiments)
  - What kind of uncertainties should I expect? (capability to generate modelled emission for various plausible assumptions)

PSM specifications (2/2)

- The sky model must be consistent
  - Internally
    - Same cosmological parameters for CMB and clusters
    - Same magnetic field for synchrotron and dust simulations
    - Avoid randomly generated maps with the same seed…
    - …
  - With the existing data (at some level)
    - Statistically (power spectra, source number counts, …)
    - At the map level (sum of components = observation)
- Simulations of sky emission must be
  - Easy to run (push a button)
  - Traceable (store all the meta data in an organised output directory, don't forget headers in fits files, etc.)
  - Easily "re-observable" later with additionnal frequency bands

PSM status (1/2)

- Currently evolving from "Pre-launch" to "Planck Legacy".

  - Pre-launch based (mostly) on
    - WMAP
    - IRAS
    - Radiosource counts and catalogues from NVSS, SUMSS, GB6, …
    - X-ray observations of galaxy clusters
    - 408 MHz synchrotron map from Haslam et al.
    - Hα emission from WHAM and SHASSA (for free-free)
    - CO emission from Dame et al.

  - Legacy version
    - Planck observations replace previous observation at 30-850 GHz
    - Refinements in the model based on the Planck legacy publications.

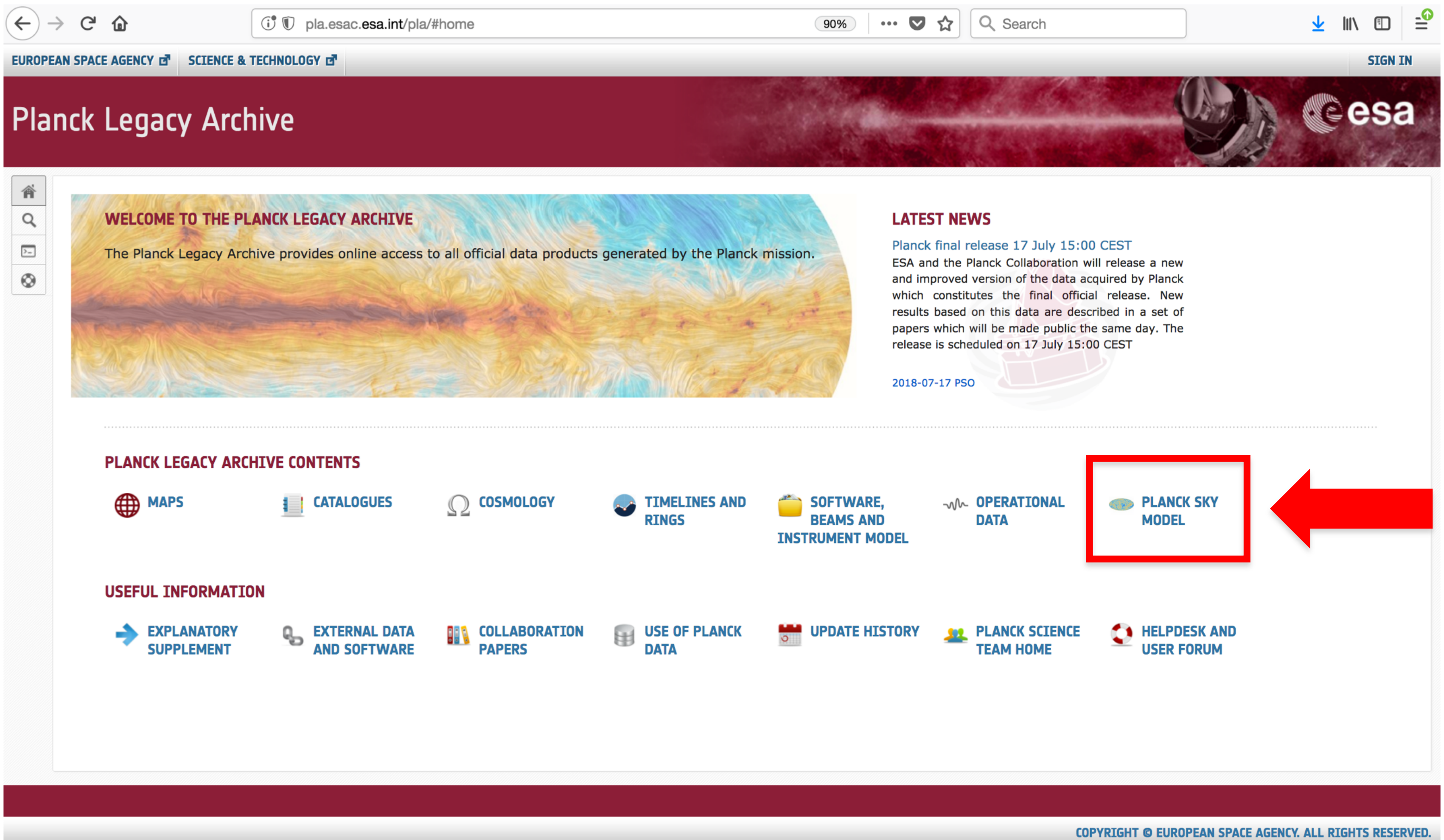
PSM status (2/2)

http://www.apc.univ-paris7.fr/~delabrou/PSM/psm.html

Date	Release page	Comments	Download user manual in pdf format	Status
09 Jan 2017	v2.0.2	Preliminary post-launch version. Many major updates, new models, makes use of Planck data from public releases 1 and 2. Compatible with FFP10 simulations. Not fully tested yet.	No user manual available yet...	RESTRICTED
26 Jun 2014	v1.9.0	Version used to generate FFP8 simulations.	PSM_user_manual_v1_9_0.pdf	RESTRICTED
27 Feb 2014	v1.8.0	Major update after FFP7 simulations (snapshot before new major update for FFP8).	PSM_user_manual_v1_8_0.pdf	RESTRICTED
31 May 2013	v1.7.8	This is the public release that goes with the PSM Pre-Launch publication.	PSM_user_manual_v1_7_8.pdf	PUBLIC
24 September 2012	v1.7.7	This is a minor update of v1.7.6. The documentation has been expanded, and some details have been fixed in various places (nothing critical).	PSM_user_manual_v1_7_7.pdf	RESTRICTED
18 September 2012	v1.7.6	This is a major update of the PSM software. See the release page for details.	PSM_user_manual_v1_7_6.pdf	RESTRICTED
⋮		⋮		⋮

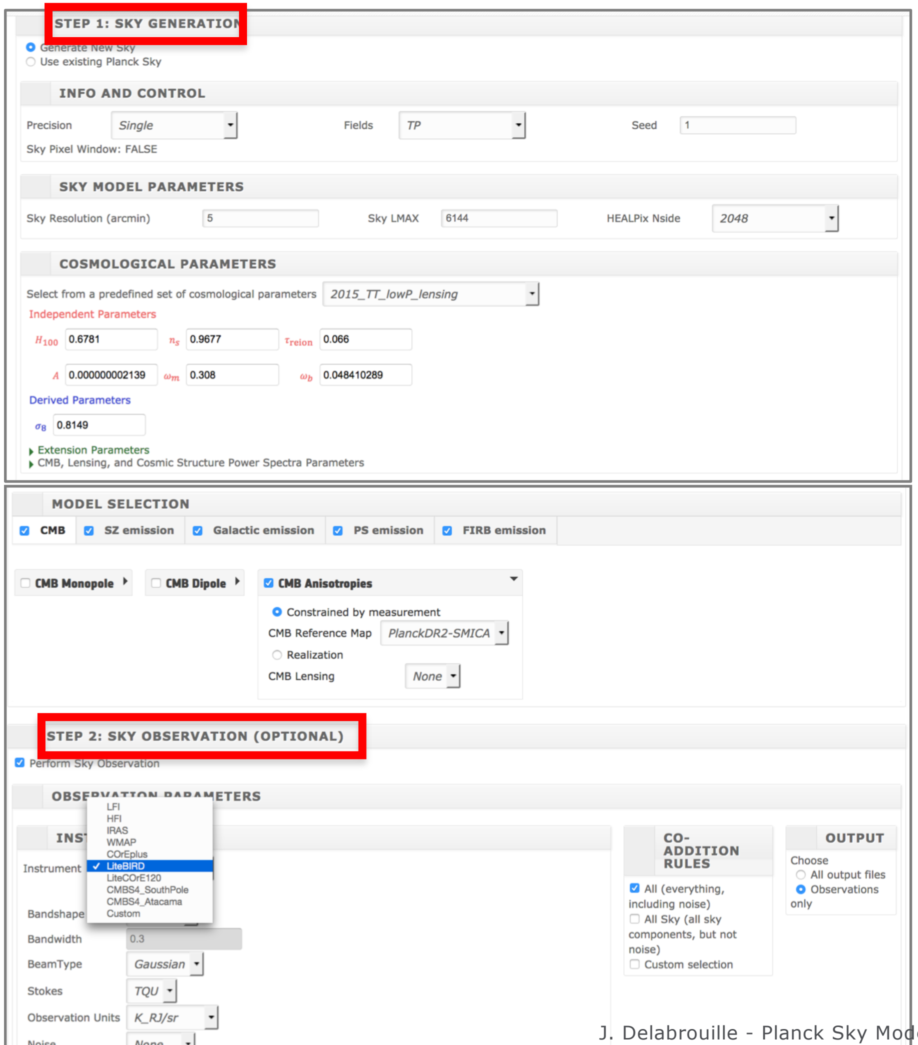
Interface on the Planck Legacy Archive implemented at ESA (Marcos Lopez-Caniego). This is not the final "Legacy" version yet (the current version at the PLA is v2.0.7).

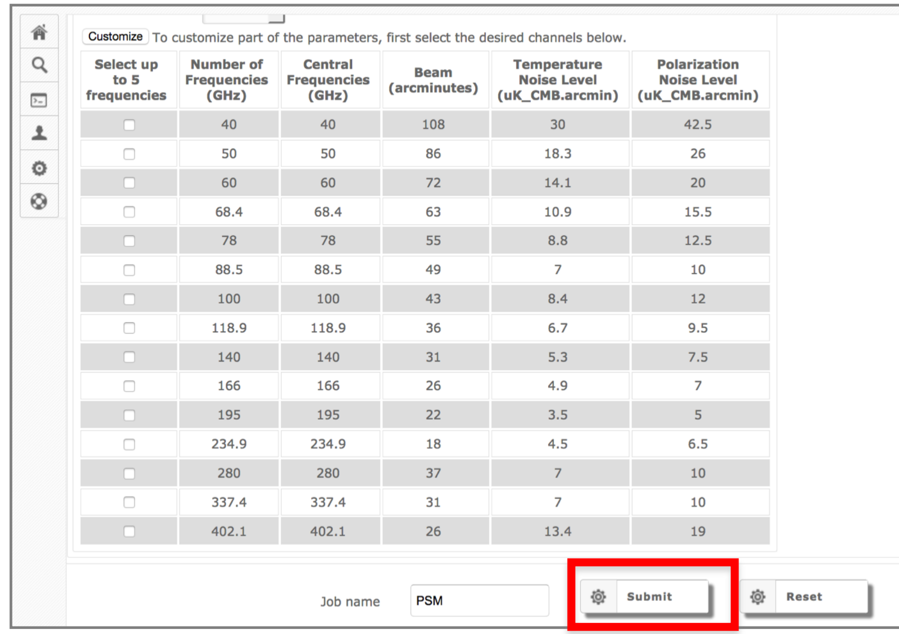
The Planck Sky Model interface in the PLA



Slides from M. Lopez-Caniego

The Planck Sky Model interface in the PLA





Customize To customize part of the parameters, first select the desired channels below.

Select up to 5 frequencies	Number of Frequencies (GHz)	Central Frequencies (GHz)	Beam (arcminutes)	Temperature Noise Level (uK_CMB.arcmin)	Polarization Noise Level (uK_CMB.arcmin)
☐	40	40	108	30	42.5
☐	50	50	86	18.3	26
☐	60	60	72	14.1	20
☐	68.4	68.4	63	10.9	15.5
☐	78	78	55	8.8	12.5
☐	88.5	88.5	49	7	10
☐	100	100	43	8.4	12
☐	118.9	118.9	36	6.7	9.5
☐	140	140	31	5.3	7.5
☐	166	166	26	4.9	7
☐	195	195	22	3.5	5
☐	234.9	234.9	18	4.5	6.5
☐	280	280	37	7	10
☐	337.4	337.4	31	7	10
☐	402.1	402.1	26	13.4	19

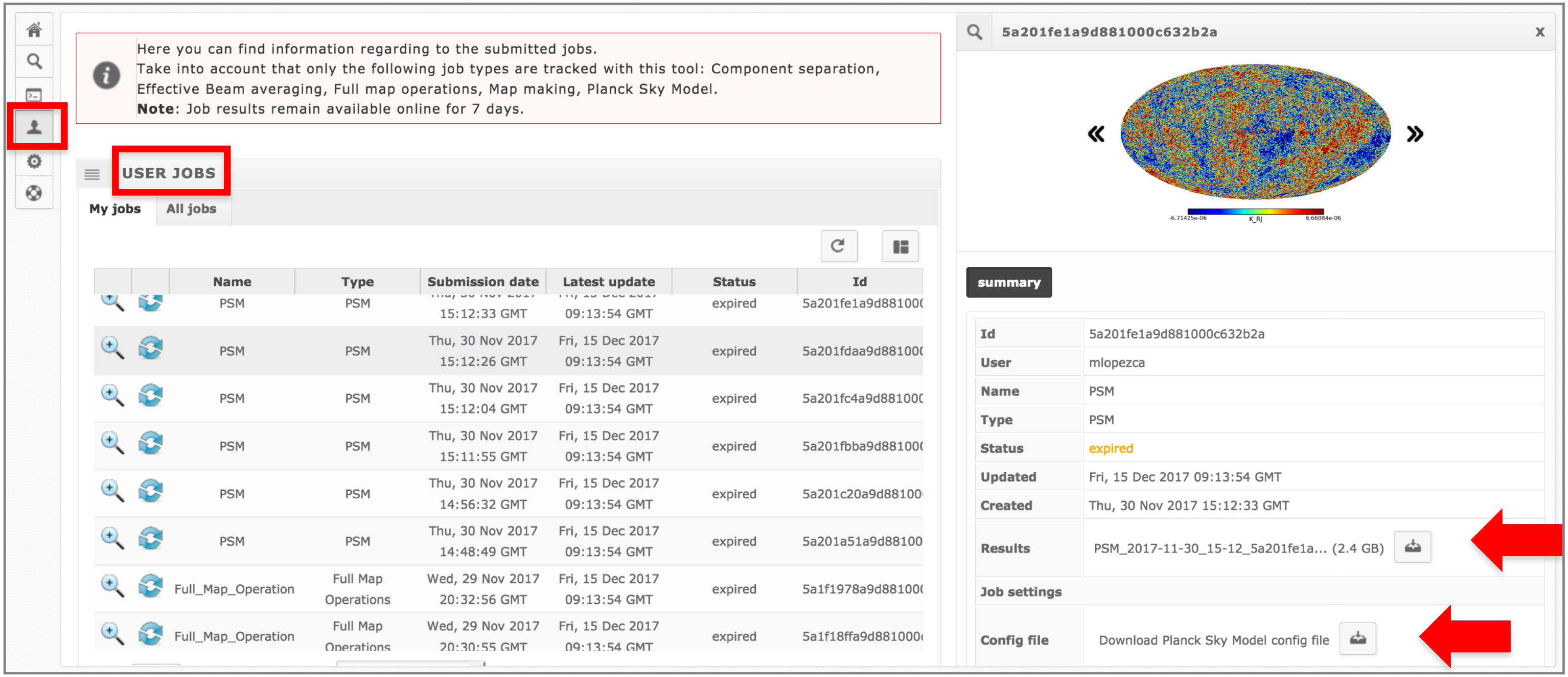
Job name PSM Submit Reset

Step 1: sky generation
Step 2 (optional) sky observation
Submit asynchronous job
Monitor the status of the job in User Job panel.
Retreive the results

The user receives an email with the results.

The Planck Sky Model interface in the PLA

After submitting the job to the cluster, the status can be monitored from the user jobs panel. An email is sent when the job has finished with a link to download the results



Preview images are generated in the user jobs panel, and the results can be downloaded from this panel too.

Please send feedback to the Planck Helpdesk: **https://support.cosmos.esa.int/pla/**

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PSM components

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

$$I_{\mathrm{comp}}(\vec{p},\nu) = \sum_k I_k(\vec{p},\nu_0) \left[\frac{f_k(\vec{p},\nu)}{f_k(\vec{p},\nu_0)} \right]$$

Template map at some reference frequency

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.

PSM key ingredients and components

- A cosmological model (parameters) + interface to CAMB and CLASS Boltzmann codes to compute C_l's, LSS-CMB correlations

- CMB
  - Monopole, dipole (prediction or simulation)
  - Spectral distortion: y and μ
  - Anisotropies (gaussian, non-gaussian, with lensing, correlated with CIB and galaxy clusters)

- Galactic ISM
  - Thermal dust (sum of modified blackbody emissions)
  - Synchrotron (sum of power laws or of power laws with running)
  - Spinning dust (with rigid scaling)
  - Free-free (with rigid scaling)
  - CO line emission (only first three lines for the moment)

PSM key ingredients and components

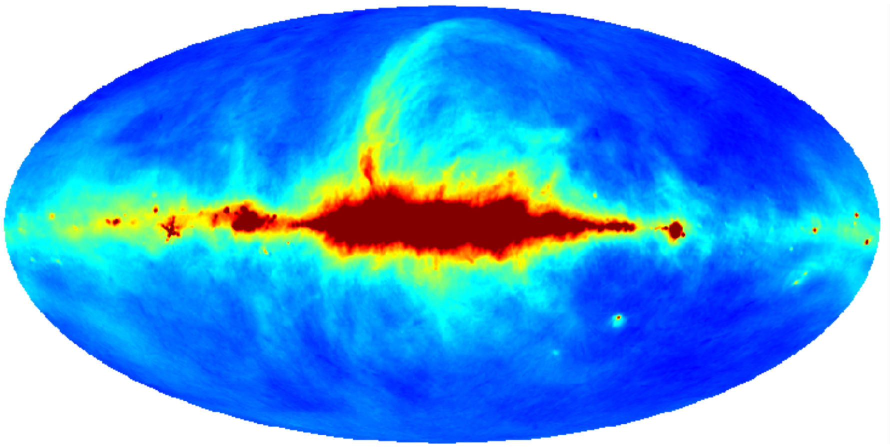
- SZ clusters
  - Thermal SZ, with relativistic corrections up to 4^{th} order
  - Kinematic SZ effect (without bulk motions at this stage)
  - Polarized SZ effect
  - Contamination of clusters by IR sources (radiosource part obsolete as of now)

- Point sources
  - Radio: each source is modelled with 5 power laws in 5 ranges of frequencies. Uses real sources + random sources to homogeneize the number counts
  - Infrared local sources: IRAS + random sources to homogeneize the number counts
  - CIB from three types of extragalactic IR galaxies (starburst, spiral, spheroids)

- Observation
  - Extrapolation to any frequency
  - Band-integration
  - Convolution with beam
  - Instrumental noise

Synchrotron

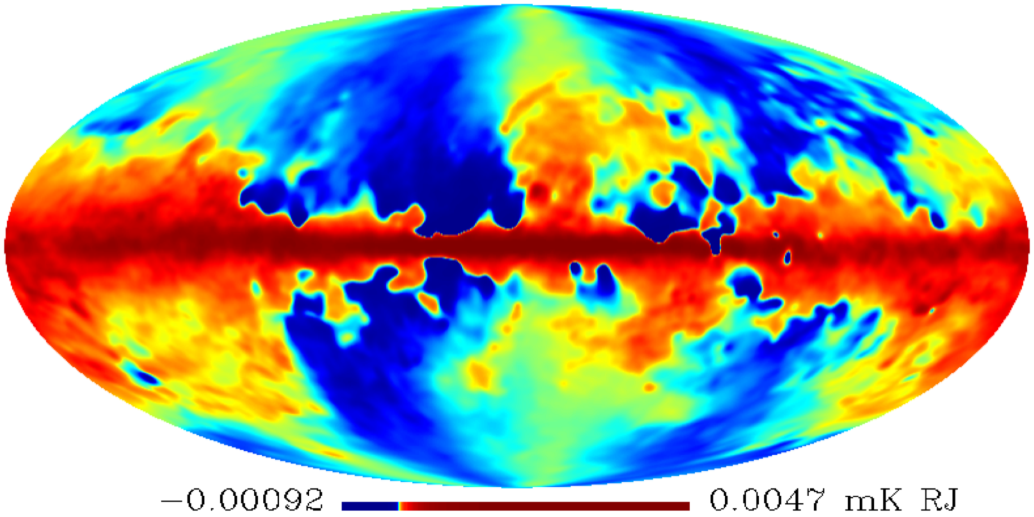
- One of the major foregrounds for CMB observations.
- Strongly polarised (up to 75%).
- Synchrotron-dominated full-sky map at 408 MHz (Haslam et al. 1982), at 51' angular resolution.
- ***408 MHz reference***: Map reprocessed to remove striping and point sources by Remazeilles et al. (2015). Angular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



Remazeilles et al. 2015, MNRAS 451, 4311

Polarized AME

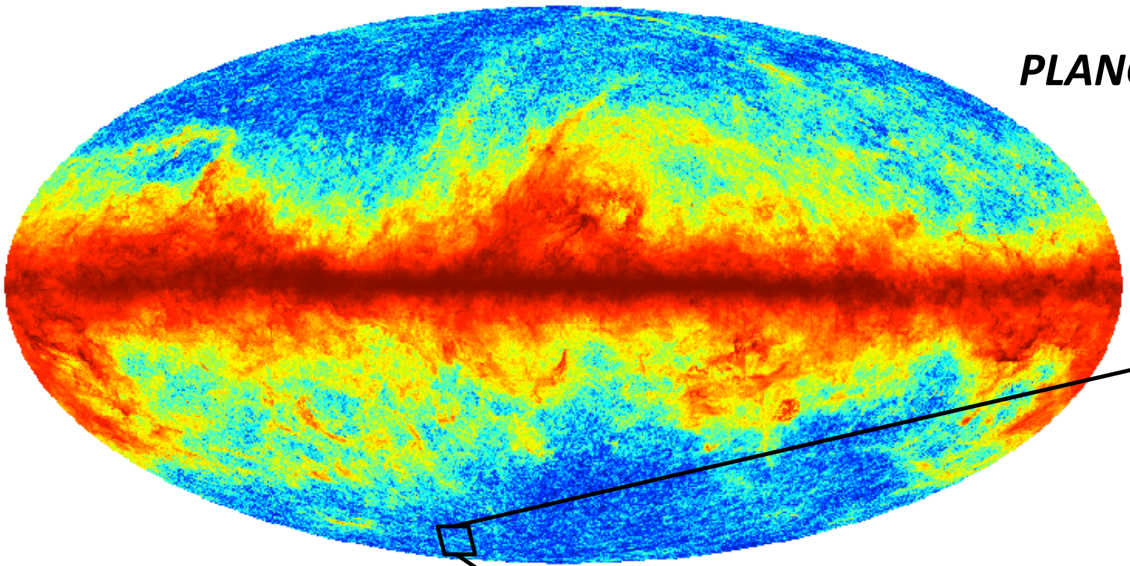
M. Remazeilles



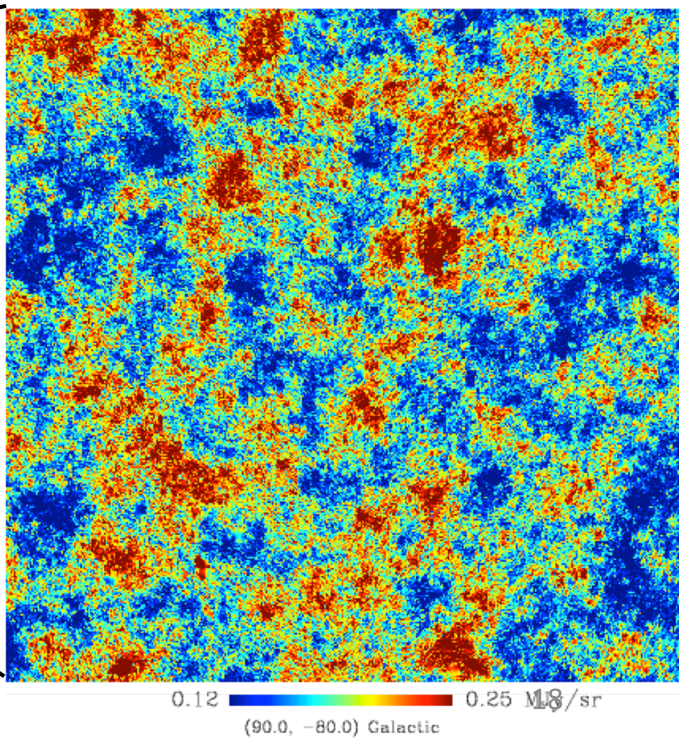
- Thermal dust intensity map rescaled at 23 GHz by 0.91 K/K (Dust-AME correlation -- *Planck 2015 results. XXV*)
- Uniform 1% polarization fraction (for CORE simulations, scalable in PSM)
- Same polarization angles as thermal dust
- Scaled across frequencies through CNM model (*Draine & Lazarian 1998*)

Slide from M. Remazeilles

Improved dust templates



PLANCK HFI 353 GHz

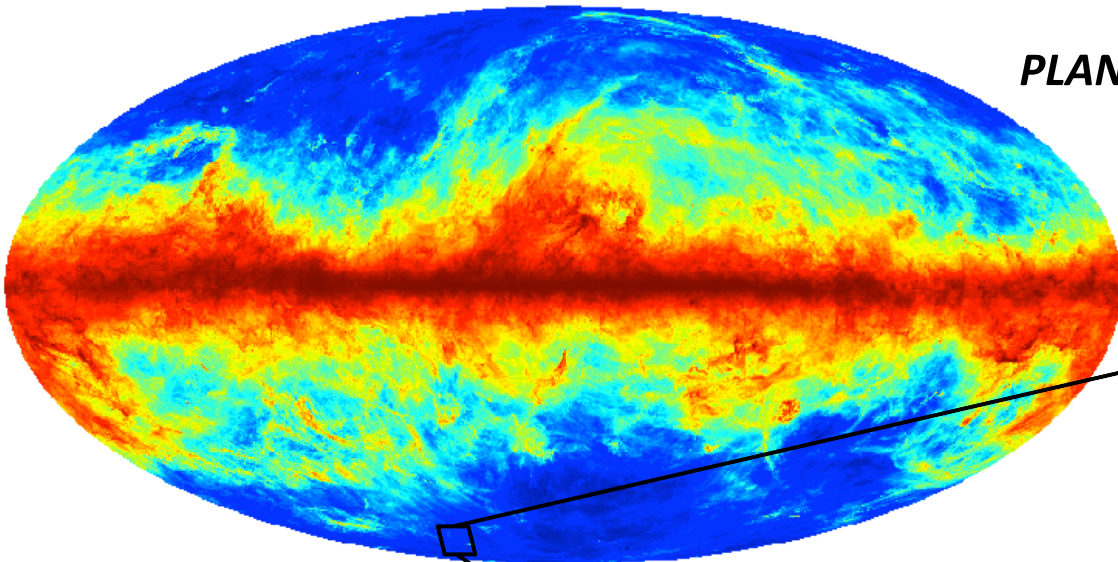


Dust maps are contaminated
by CIB, (by CMB) and by noise

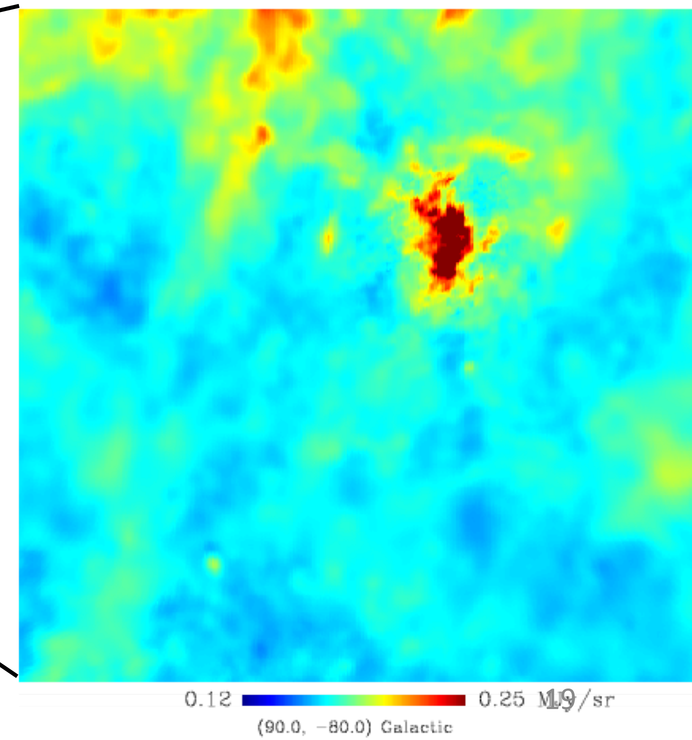
Processing of multifrequency maps with GNILC

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

Improved dust templates



PLANCK HFI 353 GHz



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

Outline

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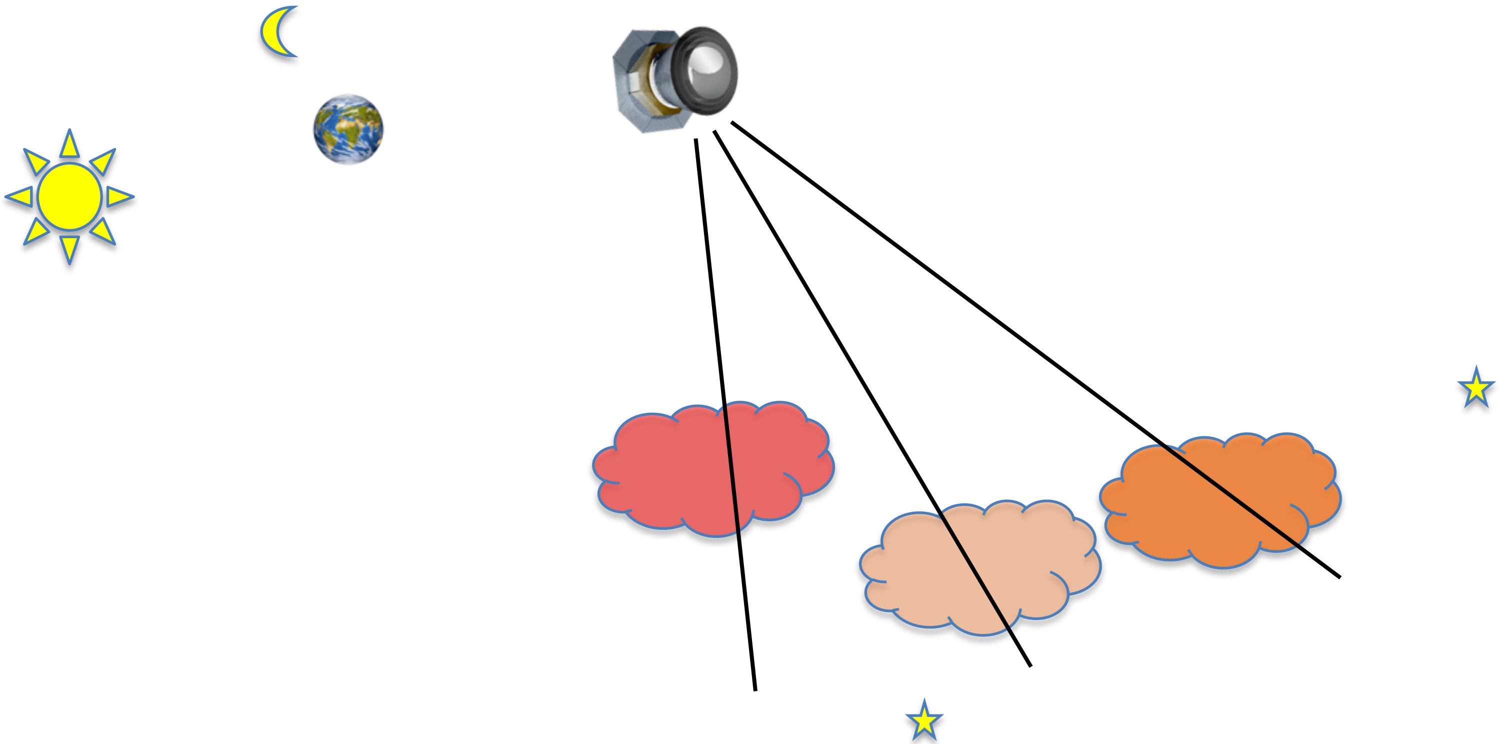
Variability of frequency scaling

- There is evidence for fluctuations of dust scaling properties
- This must be due to different local conditions in dust clouds



Variability of frequency scaling

- There is evidence for fluctuations of dust scaling properties
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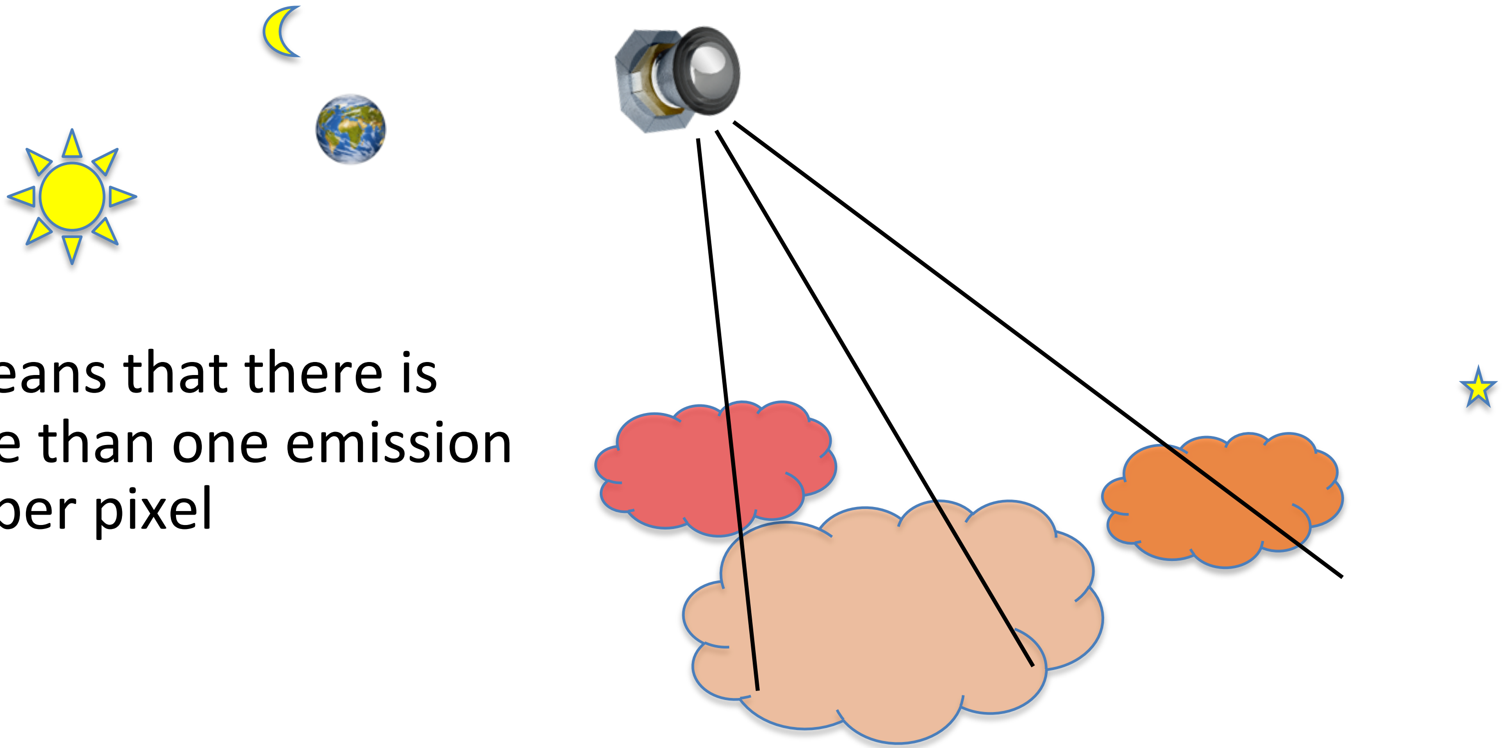
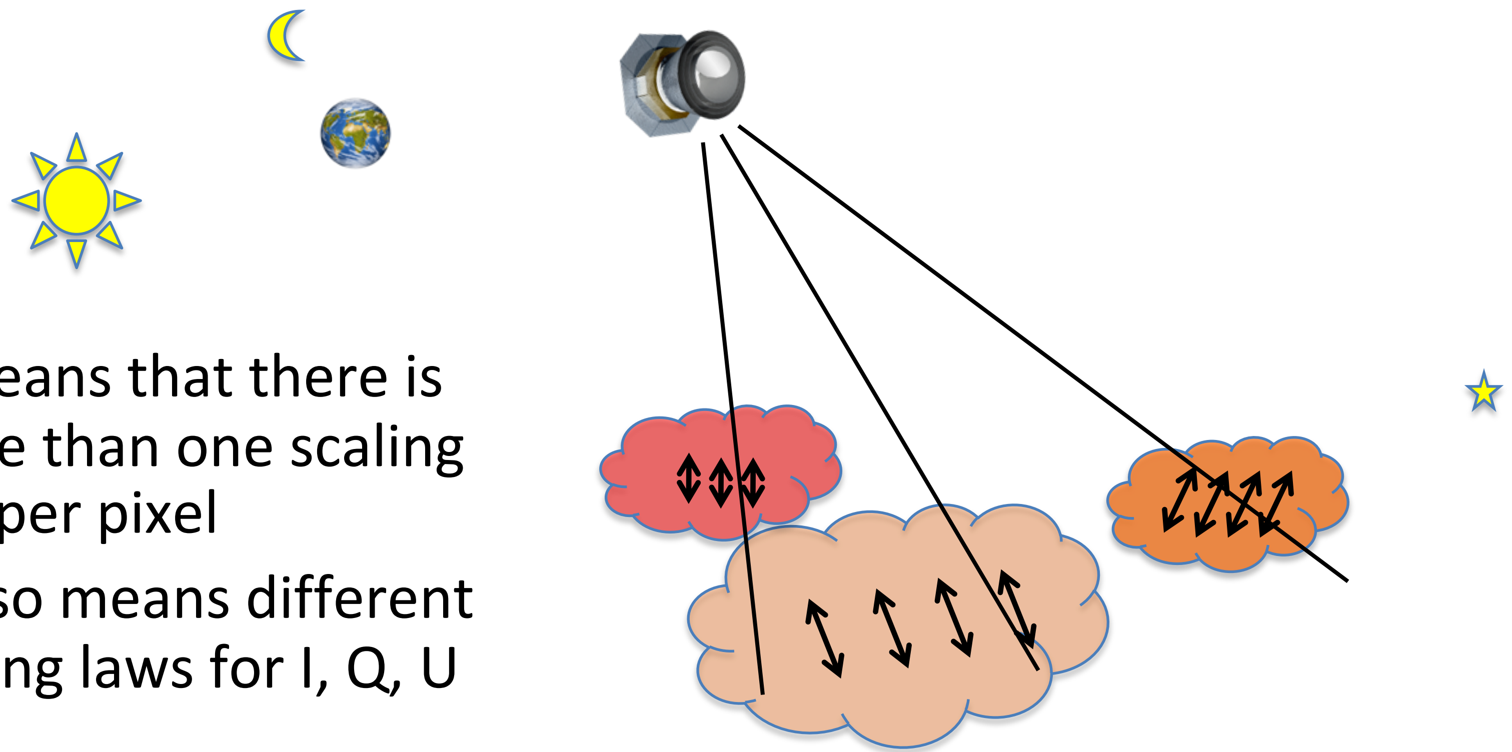


- It means that there is more than one emission law per pixel

Variability of frequency scaling

- There is evidence for fluctuations of dust scaling properties
- This must be due to different local conditions in dust clouds

See Tassis and Pavlidou 2015



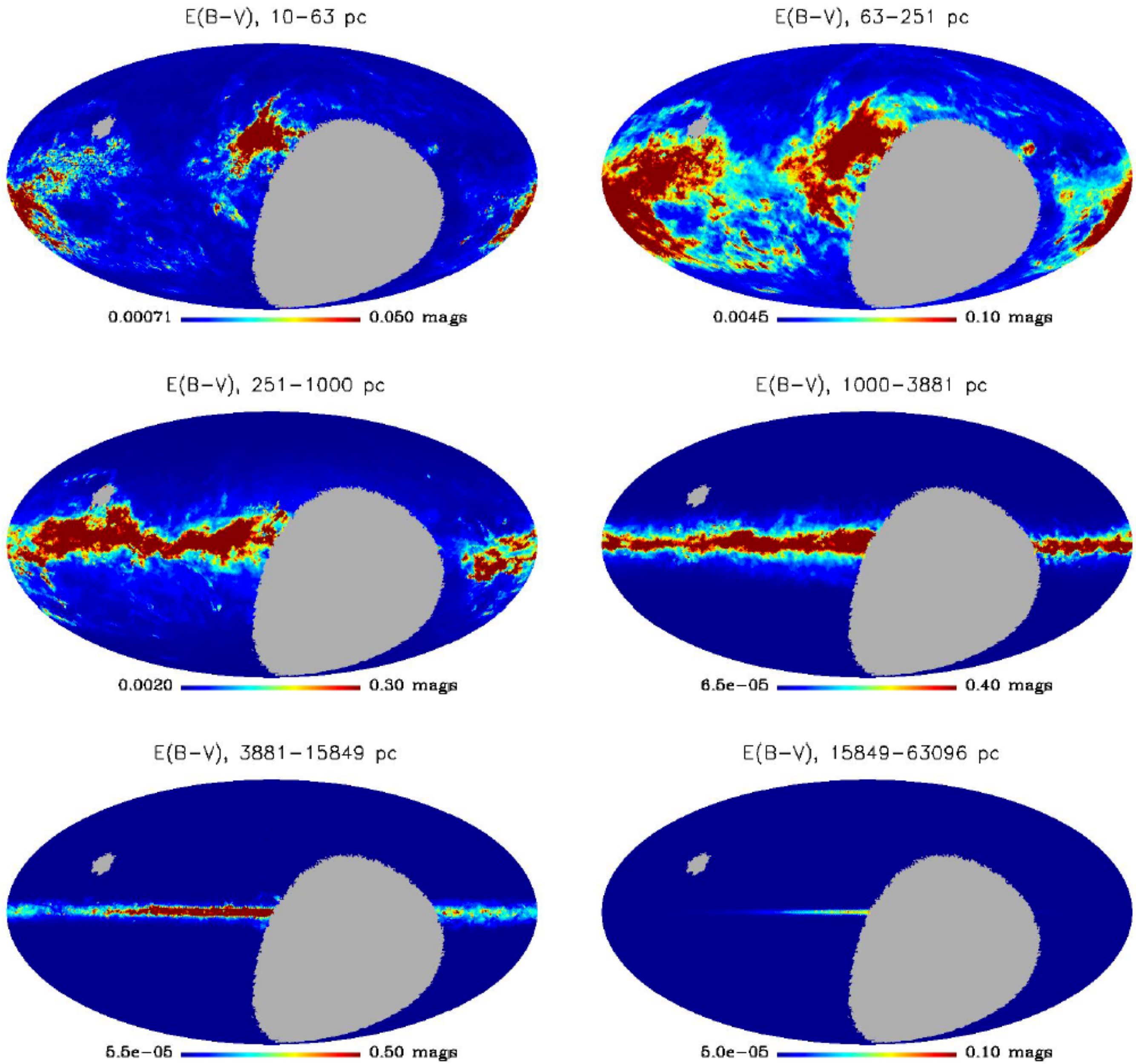
- It means that there is more than one scaling law per pixel
- It also means different scaling laws for I, Q, U

A *multilayer* dust model

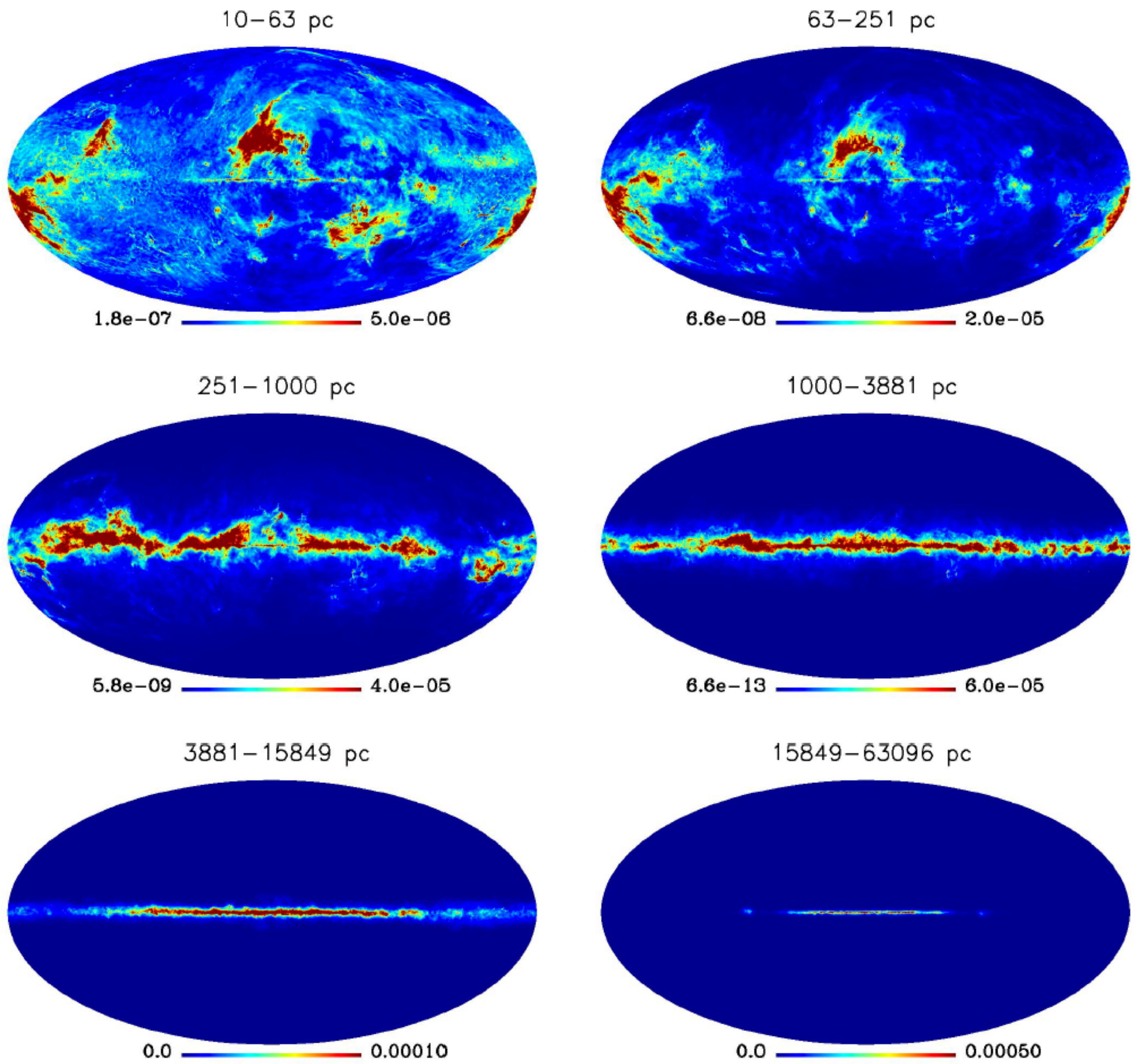
- A realistic dust model must be 3D (+ same for synchrotron)
- We need a 3D model of dust column density, emission laws, and galactic magnetic field ! Tough !

Martinez-Solaeche, Karakci, Delabrouille 2018, MNRAS 476, 1310

- Get (approximate) 3D dust extinction from Green et al. (2015) obtained using PanSTARRS and 2MASS data, and use those to compute the 353GHz dust optical depth from 6 shells centred on the Sun;
- Layers loosely associated to distance (but we don't care so much)
- Fill-in missing data using symmetry arguments;



Obtained from Green et al. 2015, ApJ 810, 25



10−63 pc
1.8e−07
5.0e−06
63−251 pc
6.6e−08
2.0e−05
251−1000 pc
5.8e−09
4.0e−05
1000−3881 pc
6.6e−13
6.0e−05
3881−15849 pc
0.0
0.00010
15849−63096 pc
0.0
0.00050

Lallement et al, 2018, A&A, 616, 132

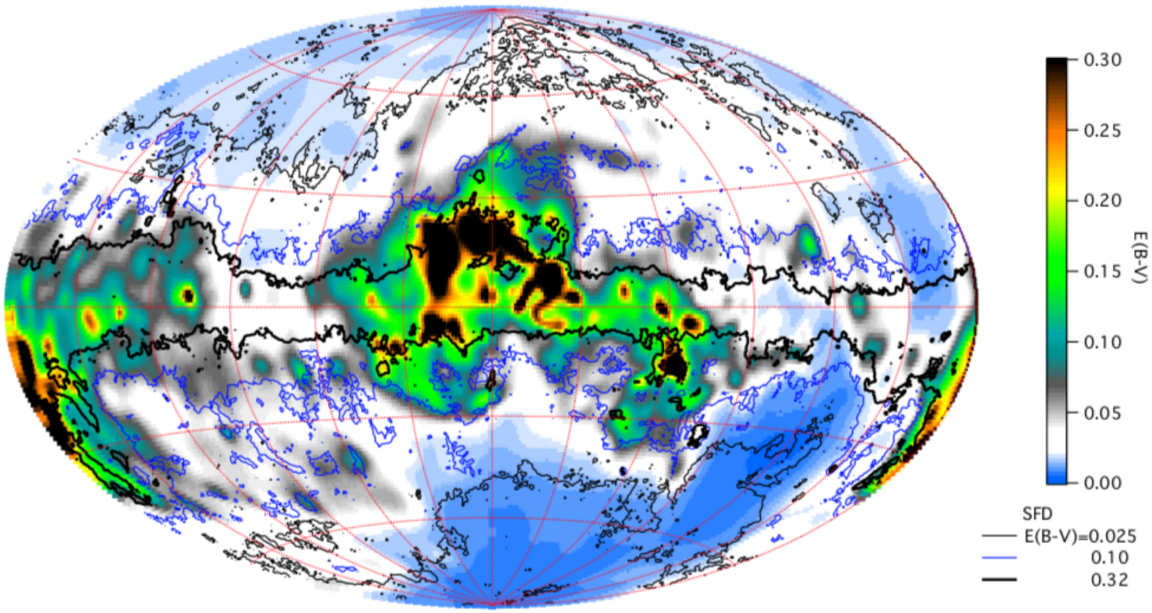


Fig. 4. Cumulative color excess E(B-V) computed by integration of the differential color excess along radial directions, from the Sun up to a distance of 300 pc. Iso-contours derived from the SFD98 reddening map are superimposed. The comparison shows that all northern high-latitude arches seen at longitudes $-150 \leq l \leq +40°$ and with E(B-V)$\geq$0.025 mag are closer than 300 pc (see text).

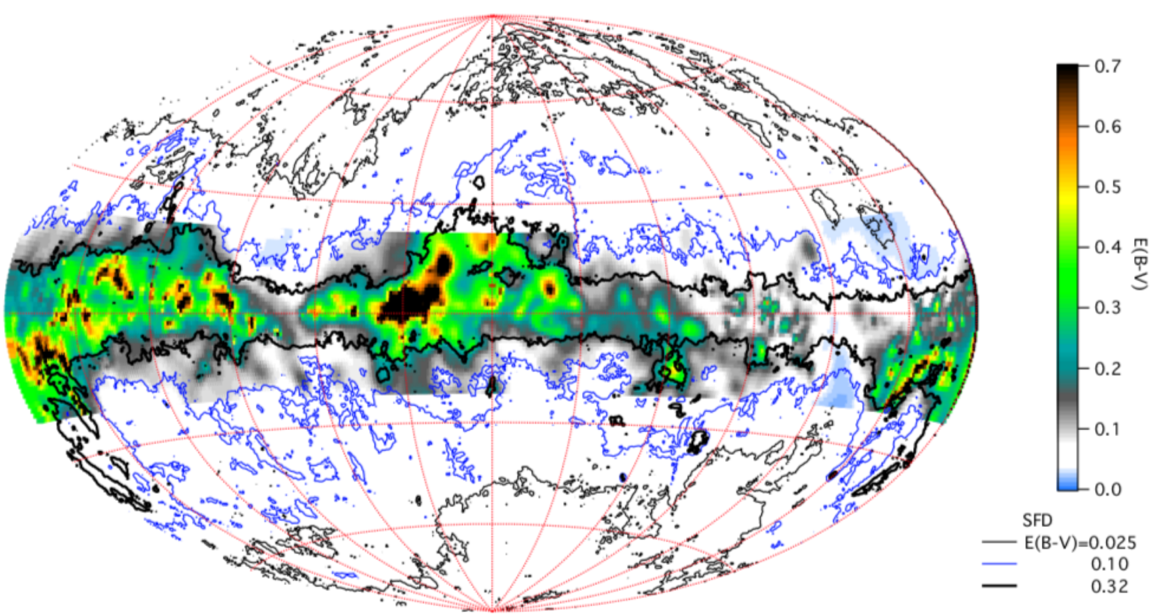


Fig. 5. Same as Fig 4, for sightlines 800 pc long. Grid points are left blank at high Galactic latitudes (abs(b)>≃25°), since for such sightlines 800 pc distant sightline extremities are out of our 4000x4000x600 pc^3 computational volume. In the second quadrant ($90 \leq l \leq 180°$) there is a good agreement between SFD98 iso-contours for E(B-V)=0.32 mag and locations corresponding to about the same value of our integrated color excess. This shows that most of the structures in these areas are within 800pc. On the contrary, for a large fraction of the third and fourth quadrants ($180 \leq l \leq 270°$ and $270 \leq l \leq 360°$ respectively) most of the dust seen in emission is beyond 800 pc.

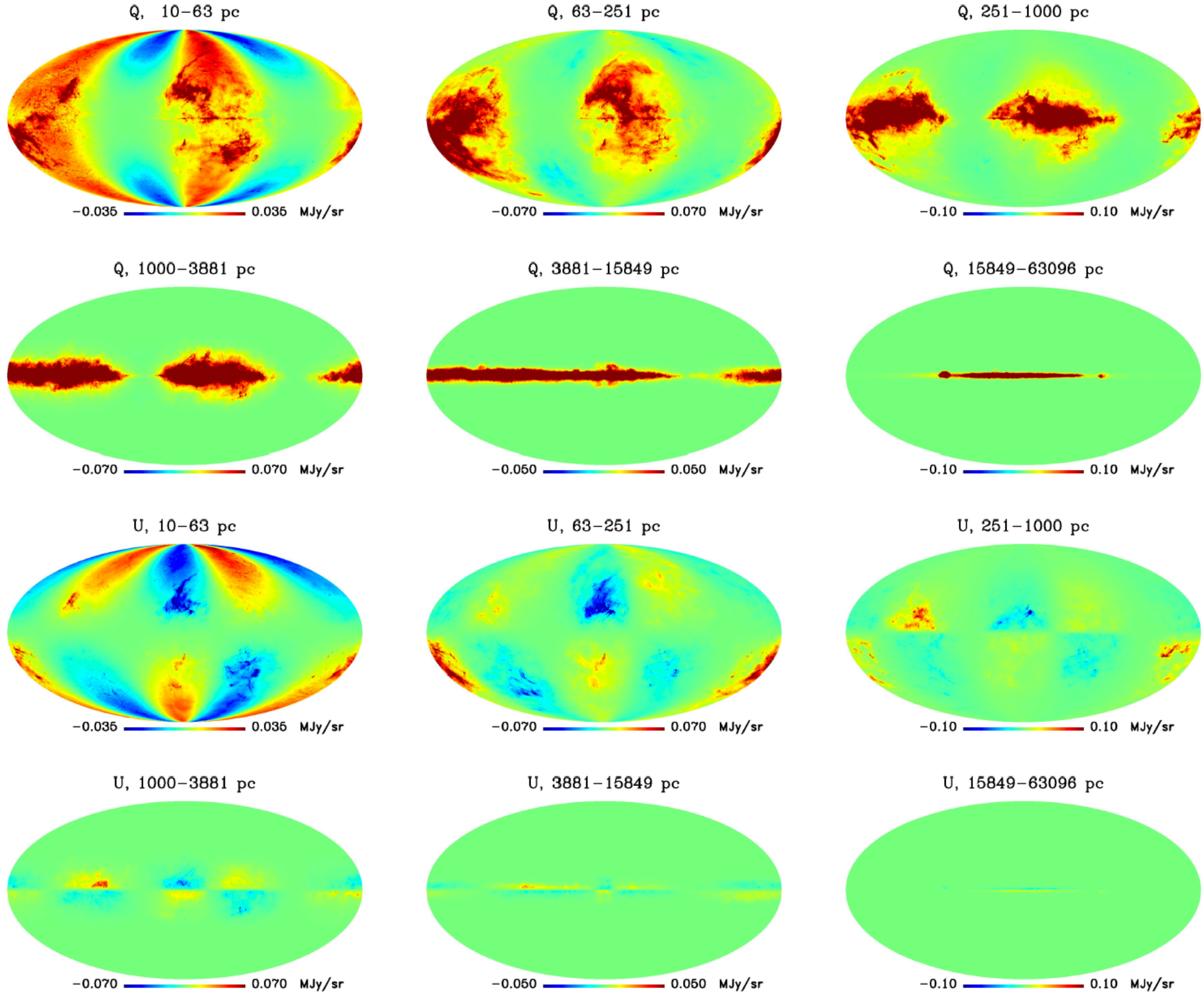
A multilayer *polarized* dust model

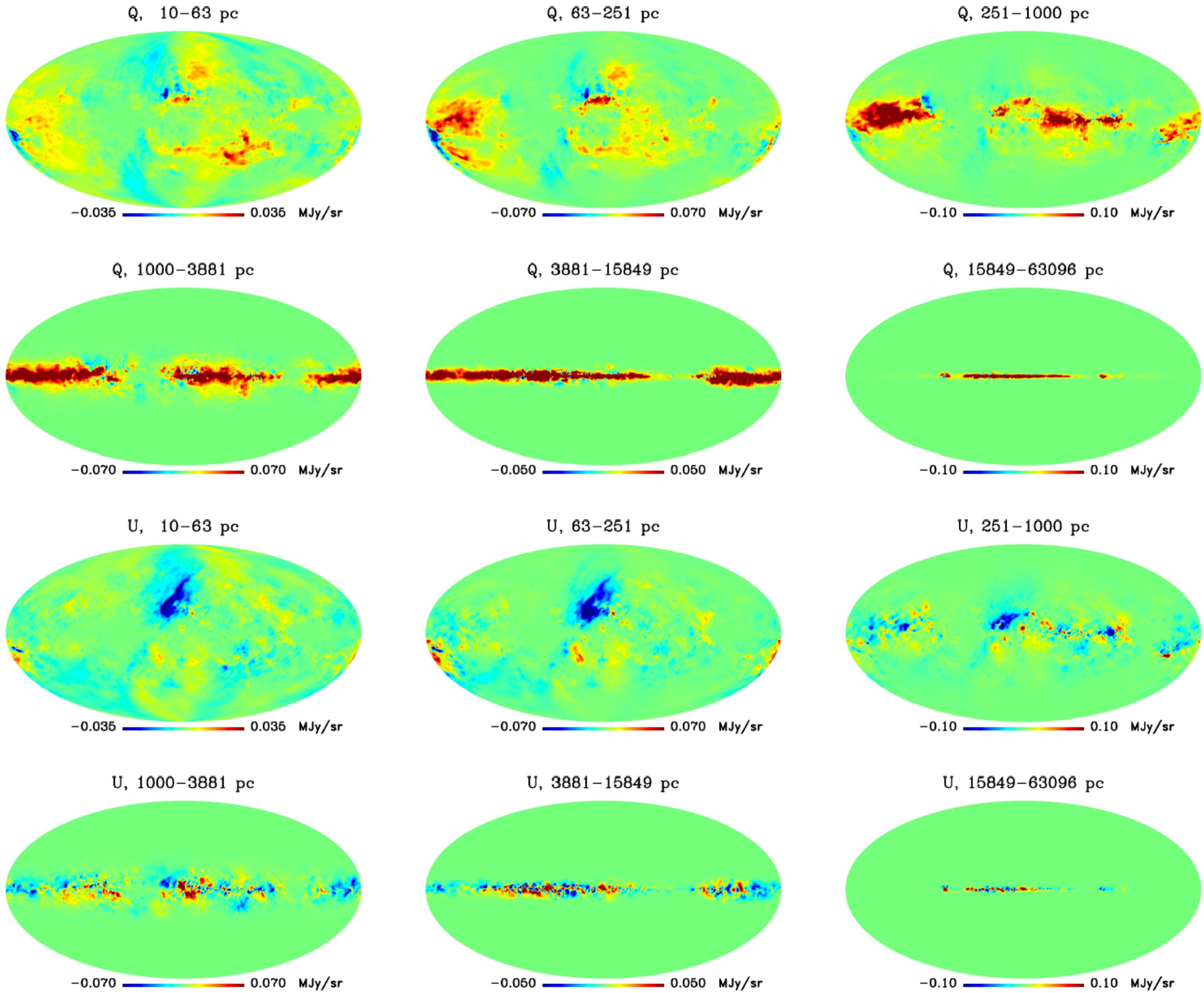
- Use a Bisymmetric Spiral model of the regular galactic magnetic field to infer a first guess of polarisation from each layer, assuming 25% intrinsic polarisation (+ projection effects); (Following Fauvet et al. 2011)
- The sum does not match the Planck polarisation observation (of course!)
- We compute the total residual and redistribute it in the layers

$$Q_{353}^i = \left(\frac{Q_m^i}{I_m^i}\right) I_{353}^i + F_i \left[Q_{353}^{\rm obs} - \sum_{j=1}^{N} \left(\frac{Q_m^j}{I_m^j}\right) I_{353}^j\right]$$

$$F_i = P_i \,/\, \sum_j P_j$$

Martinez-Solaeche, Karakci, Delabrouille 2018, MNRAS 476, 1310


Q, 10−63 pc
−0.035 0.035 MJy/sr
Q, 63−251 pc
−0.070 0.070 MJy/sr
Q, 251−1000 pc
−0.10 0.10 MJy/sr
Q, 1000−3881 pc
−0.070 0.070 MJy/sr
Q, 3881−15849 pc
−0.050 0.050 MJy/sr
Q, 15849−63096 pc
−0.10 0.10 MJy/sr
U, 10−63 pc
−0.035 0.035 MJy/sr
U, 63−251 pc
−0.070 0.070 MJy/sr
U, 251−1000 pc
−0.10 0.10 MJy/sr
U, 1000−3881 pc
−0.070 0.070 MJy/sr
U, 3881−15849 pc
−0.050 0.050 MJy/sr
U, 15849−63096 pc
−0.10 0.10 MJy/sr


Q, 10−63 pc
−0.035 0.035 MJy/sr
Q, 63−251 pc
−0.070 0.070 MJy/sr
Q, 251−1000 pc
−0.10 0.10 MJy/sr
Q, 1000−3881 pc
−0.070 0.070 MJy/sr
Q, 3881−15849 pc
−0.050 0.050 MJy/sr
Q, 15849−63096 pc
−0.10 0.10 MJy/sr
U, 10−63 pc
−0.035 0.035 MJy/sr
U, 63−251 pc
−0.070 0.070 MJy/sr
U, 251−1000 pc
−0.10 0.10 MJy/sr
U, 1000−3881 pc
−0.070 0.070 MJy/sr
U, 3881−15849 pc
−0.050 0.050 MJy/sr
U, 15849−63096 pc
−0.10 0.10 MJy/sr

A multilayer polarized dust model

- We add small scales (lognormal distribution for intensity, Gaussian for polarisation, modulated in pixel space by the local dust intensity)
- We generate *for each layer* maps of temperature and spectral index that match the statistical properties observed on Planck data
- However, when we add everything-up and make a MBB fit for each pixel it does not quite work:
  - The average temperature is too high (by about 2%)
  - The average spectral index is too low
  - The standard deviations are too small (by a factor close to 2)
- We readjust the statistics in individual layers to match the observed statistics for the sum.

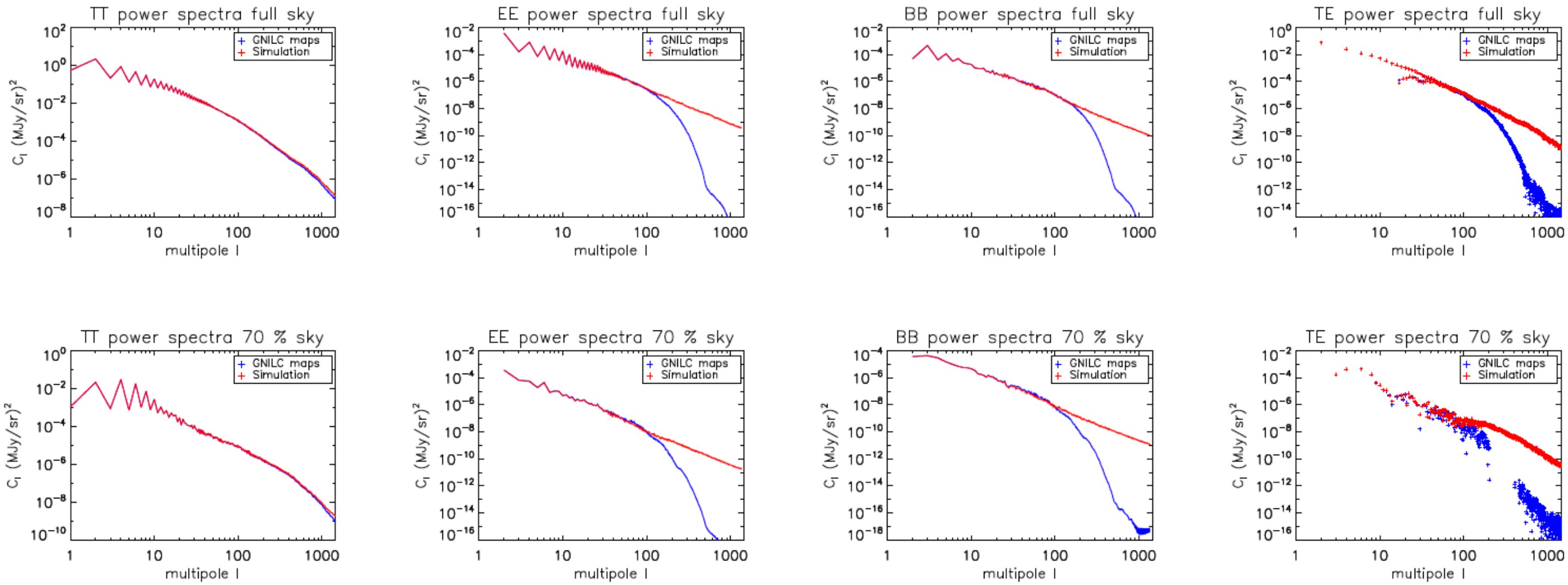


Figure 11. *TT*, *EE*, *BB*, *TE* power spectra of both GNILC maps and of simulated maps including small scale fluctuations.

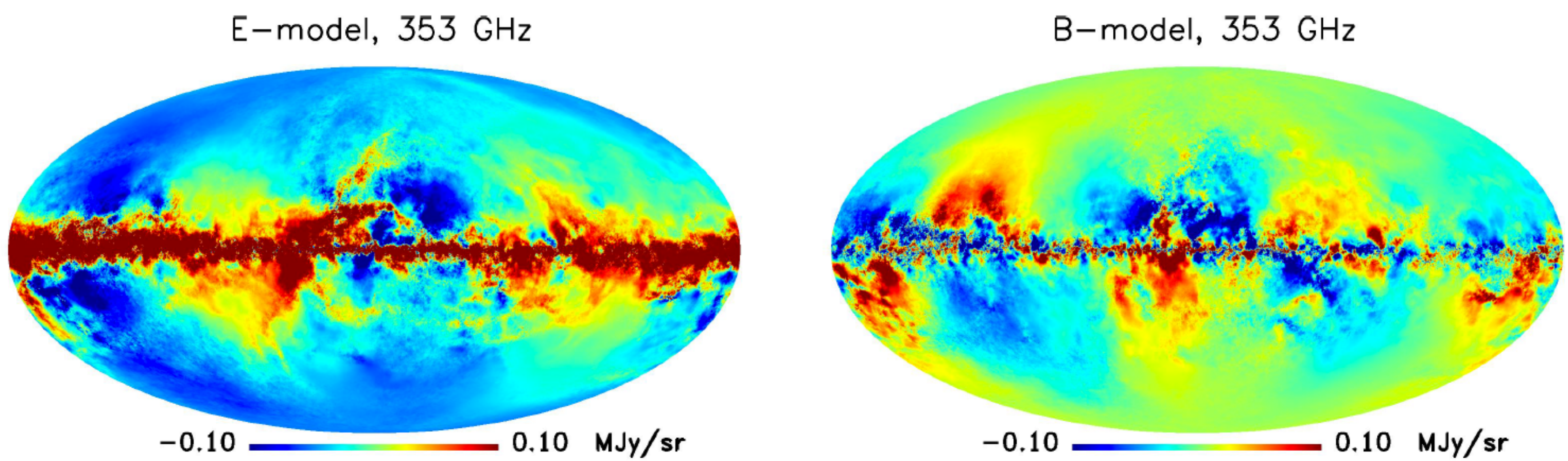


Figure 12. Modelled *E* and *B* modes maps at 353 GHz, after adding small scale fluctuations, adding-up six layers of emission (see text).

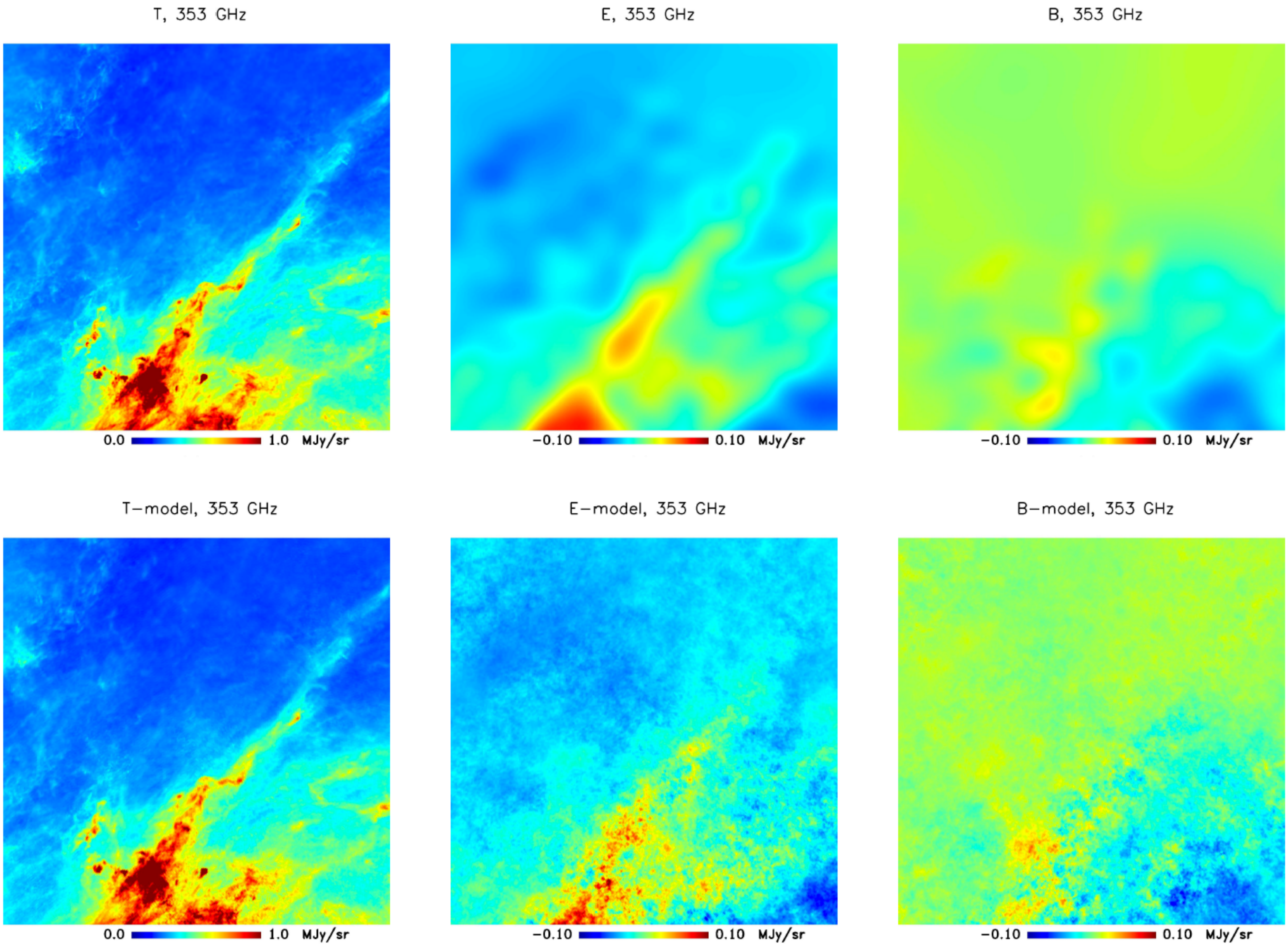


Figure 13. Observed and modelled E and B modes maps at 353 GHz – detail around $(l, b) = (0^\circ, 50^\circ)$. *Top row:* T, E and B modes, observed with Planck after GNILC processing; *Bottom row:* modelled T, E and B modes at NSIDE=512, after adding small scale fluctuations, adding-up six layers of emission.

Random temperature and spectral indices

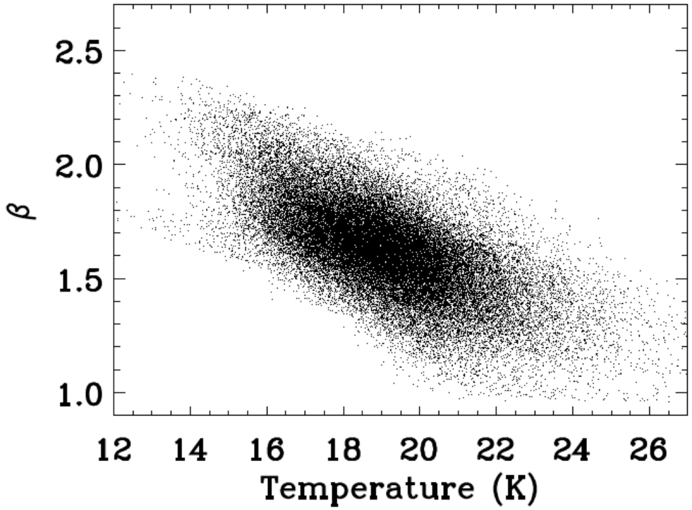


Table 1. Averages and standard deviation values of temperature and spectral index in each layer, for a simulation with 6.87′ pixels HEALPix pixels at NSIDE=512. The average and standard deviation of the resulting temperature and spectral index, as obtained from an MBB fit on the total intensity maps at 353, 545, 857 and 3000 GHz, is compared to what is obtained on Planck observations.

Layer	1	2	3	4	5	6
T_{avg}	19.10	18.96	18.98	19.35	19.23	20.05
σ_T	2.059	2.100	2.022	2.076	2.117	2.069
β_{avg}	1.627	1.628	1.598	1.538	1.513	1.689
σ_β	0.209	0.210	0.207	0.208	0.202	0.204
	$T_{\mathrm{avg}}^{\mathrm{MMB}}$	σ_T^{MMB}	$\beta_{\mathrm{avg}}^{\mathrm{MMB}}$	$\sigma_\beta^{\mathrm{MMB}}$		
Planck fit	19.396	1.247	1.598	0.126		
Simul. fit	19.389	1.253	1.598	0.135		

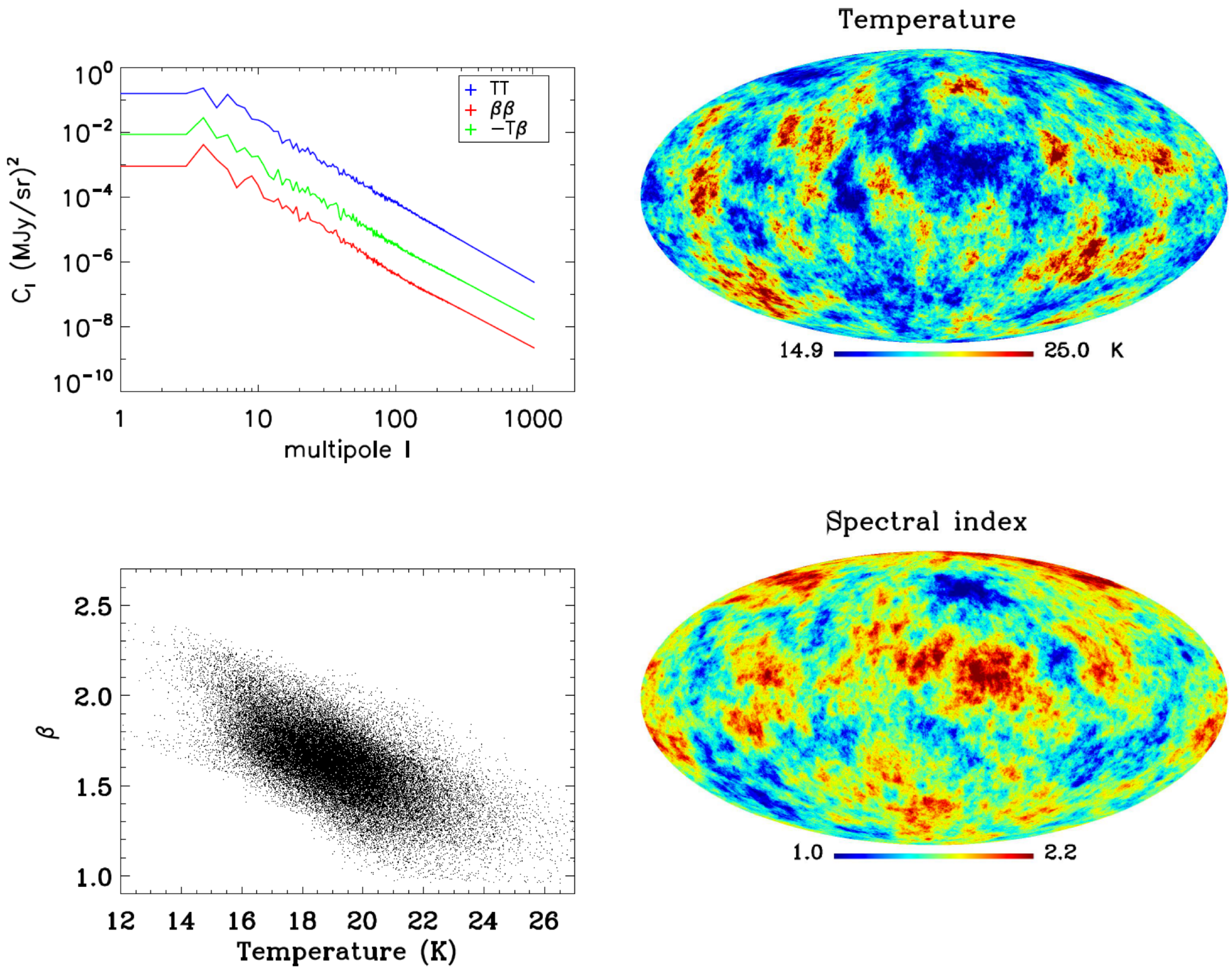
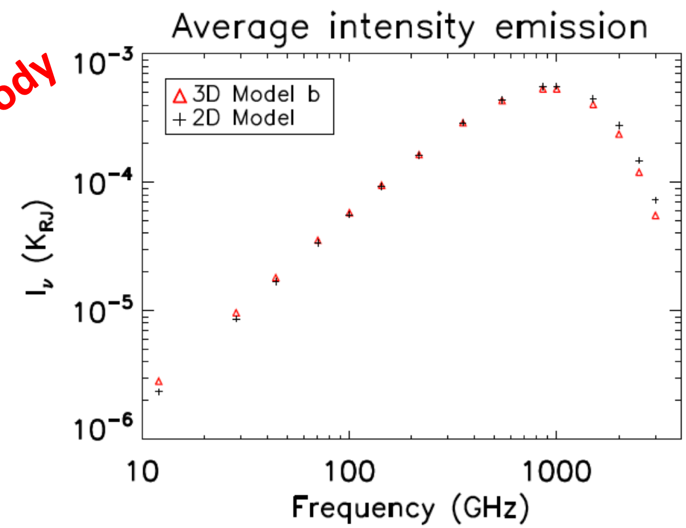
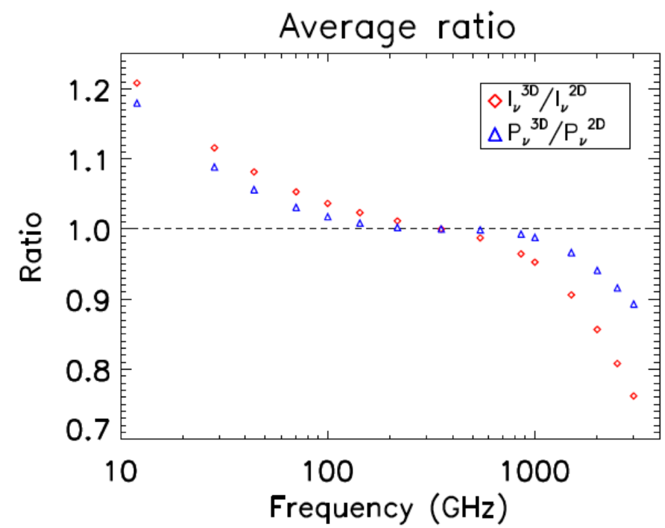


Figure 15. *Top left:* Power spectra used to draw random realisations of temperature and spectral index maps (note the negative sign of the $T\beta$ cross-spectrum). *Bottom left:* Scatter plot of T and β for a pair of random maps (right), showing an overall anticorrelation and the same general behaviour as observed by Planck Collaboration (2014) on Planck observations (see their Fig. 16). *Right:* Maps of randomly generated temperature and spectral index for the first layer, with $T_{\rm avg} = 19.10$, $\sigma_T = 2.059$ $\beta_{\rm avg} = 1.627$, $\sigma_\beta = 0.209$.

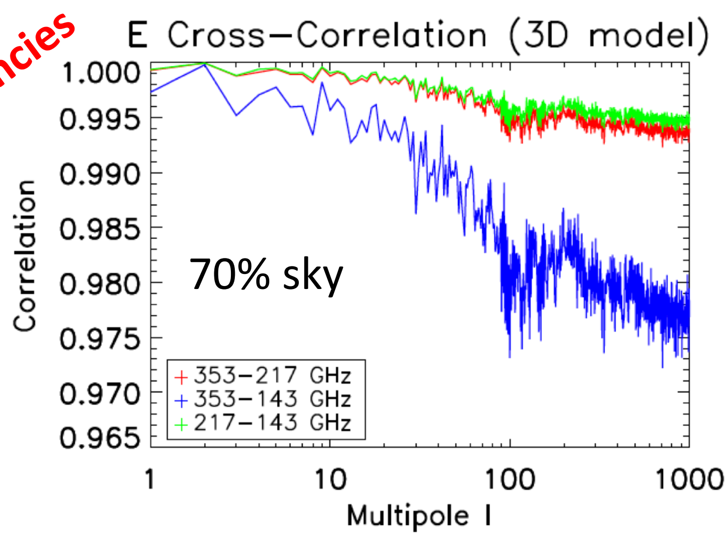
Consequences...

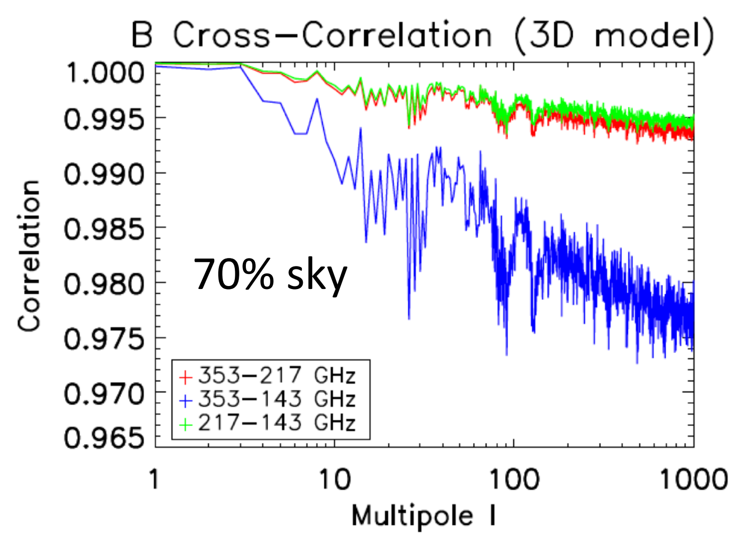
Departure from modified blackbody





Decorrelation Between frequencies





3D-ISM status and perspectives

- Piped only partially in the PSM at this stage (code not released)

- Simulations available for the community:
  - PICO model 90.98
  - Simulations for CORE, CMB-S4 and LiteBIRD made available at NERSC (nside=512) – Ask Julian where to get it, cite our paper

- New Gaia data!

- Next: do the same for synchrotron (taking care of synchrotron-dust correlation)
  - Started but progress is slow by lack of person-power

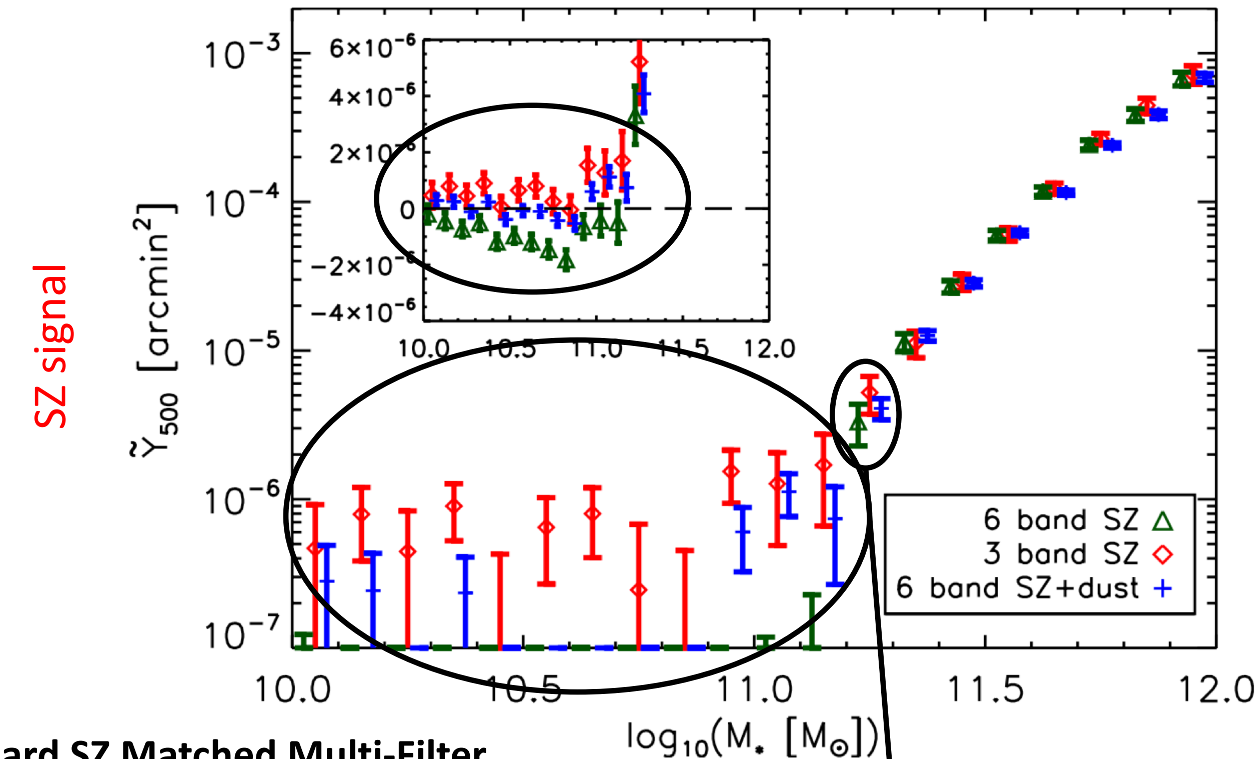
Outline

- Introduction to the PSM
- PSM components & modelling strategy
- Multilayer dust emission
- Dust in galaxy clusters
- Summary and perspective

Dust in clusters and astrophysics

Slide from J.B. Melin

Planck SZ "stacks" of ~260,000 Locally Brightest Galaxies @ z~0.1 (SDSS)



Standard SZ Matched Multi-Filter biased at low mass ➔ *dust!*

M_*~$2\times10^{11} M_\odot$
M_{500}~$2\times10^{13} M_\odot$

Planck Intermediate XI 2013

Dust in clusters: astrophysics & cosmology

Slide from J.B. Melin

Astrophysics (at mm wavelengths)

- Dust dominates over SZ emission for halos $M_{500}<2x10^{13}M_{\odot}$ (@z=0.1) Planck Intermediate XI 2013
- Dust is the major emission of the quasars (@all z) Verdier et al. 2016

⬇

Traces star formation rate

Constrains stellar feedback in the intergalactic medium

Cosmology (at mm wavelengths)

- Dust impacts SZ size and flux estimation
- Dust has (and will have) some impact on SZ survey completeness

Melin et al. 2018

⬇

Need to assess the impact on science results of SZ experiments

Dust model

Slide from J.B. Melin

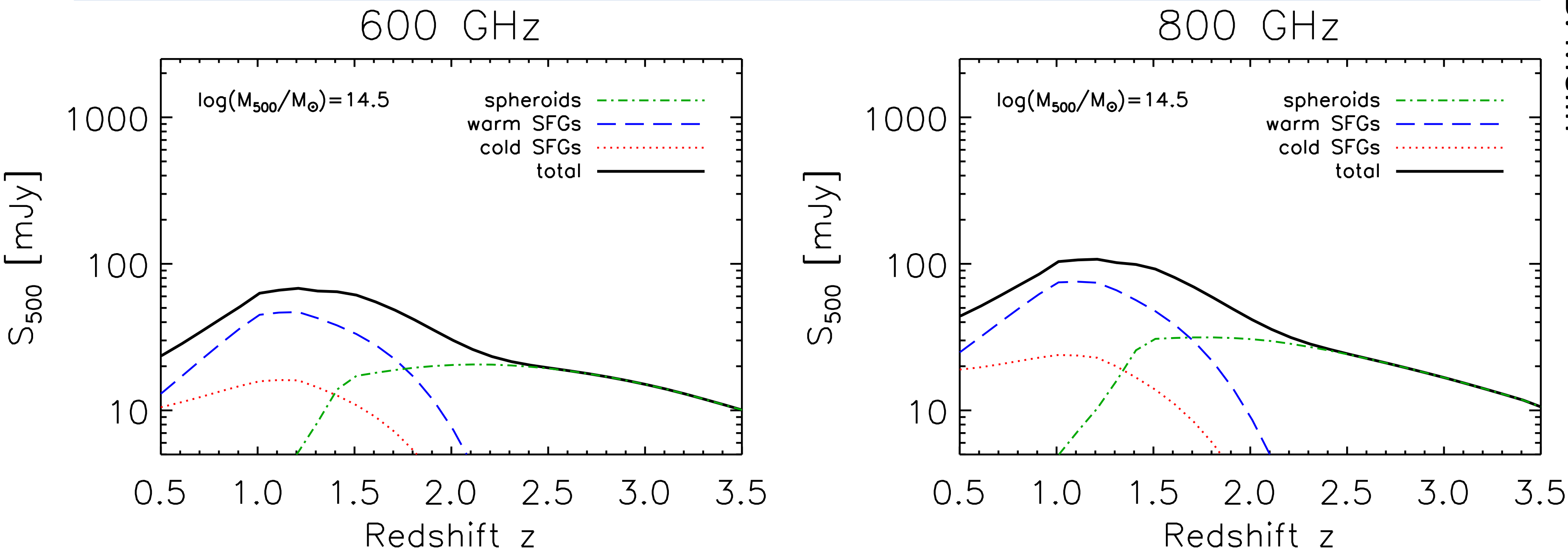


Figure adapted from De Zotti et al. 2016

De Zotti et al. 2016

➔based on *Herschel* observations (Alberts et al. 2014, 2016) and on the model from Cai et al. 2013 for the luminosity functions and spectral energy distributions

Melin et al. 2018

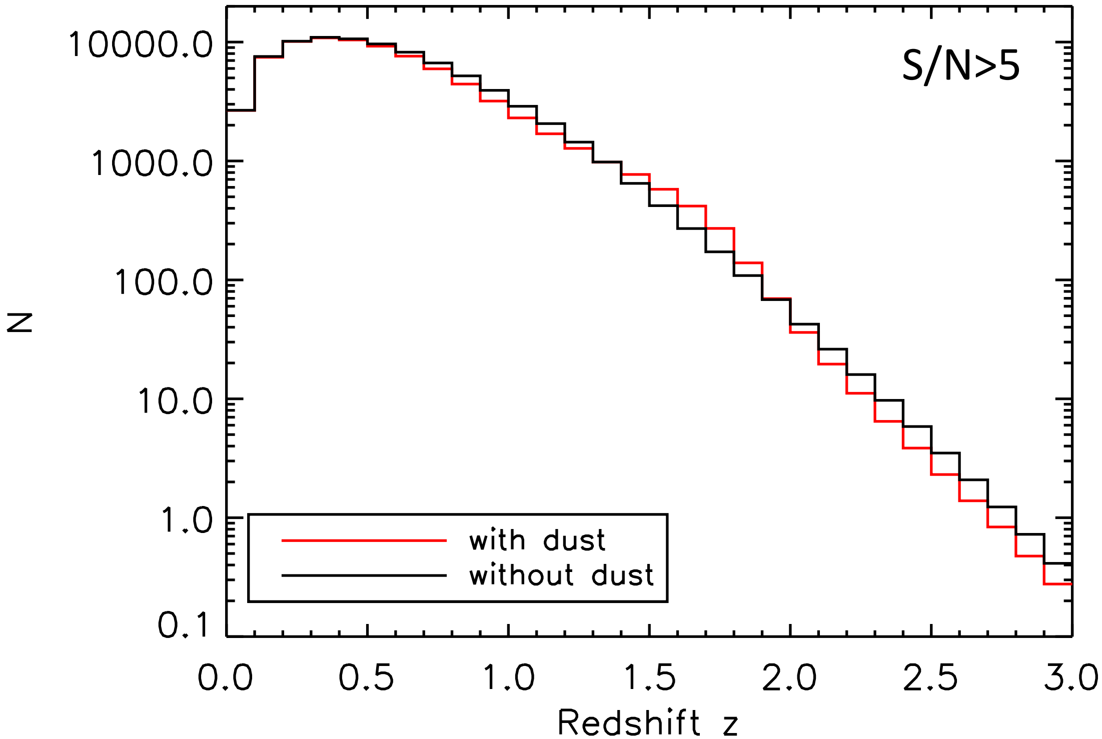
➔based on the De Zotti et al. 2016 model. The profile of dust emission and the normalisation of the luminosity-mass relation are constrained using Planck maps at PSZ2 cluster location. **➔in the PSM**

Expected cluster counts for PICO

Slide from J.B. Melin

Simulations by M. Remazeilles using the Planck Sky Model (Delabrouille et al. 2013)
Cluster extraction tool: SZ Matched Multi Filter (Melin et al. 2006, Planck Collab. 2011, 2013, 2015)

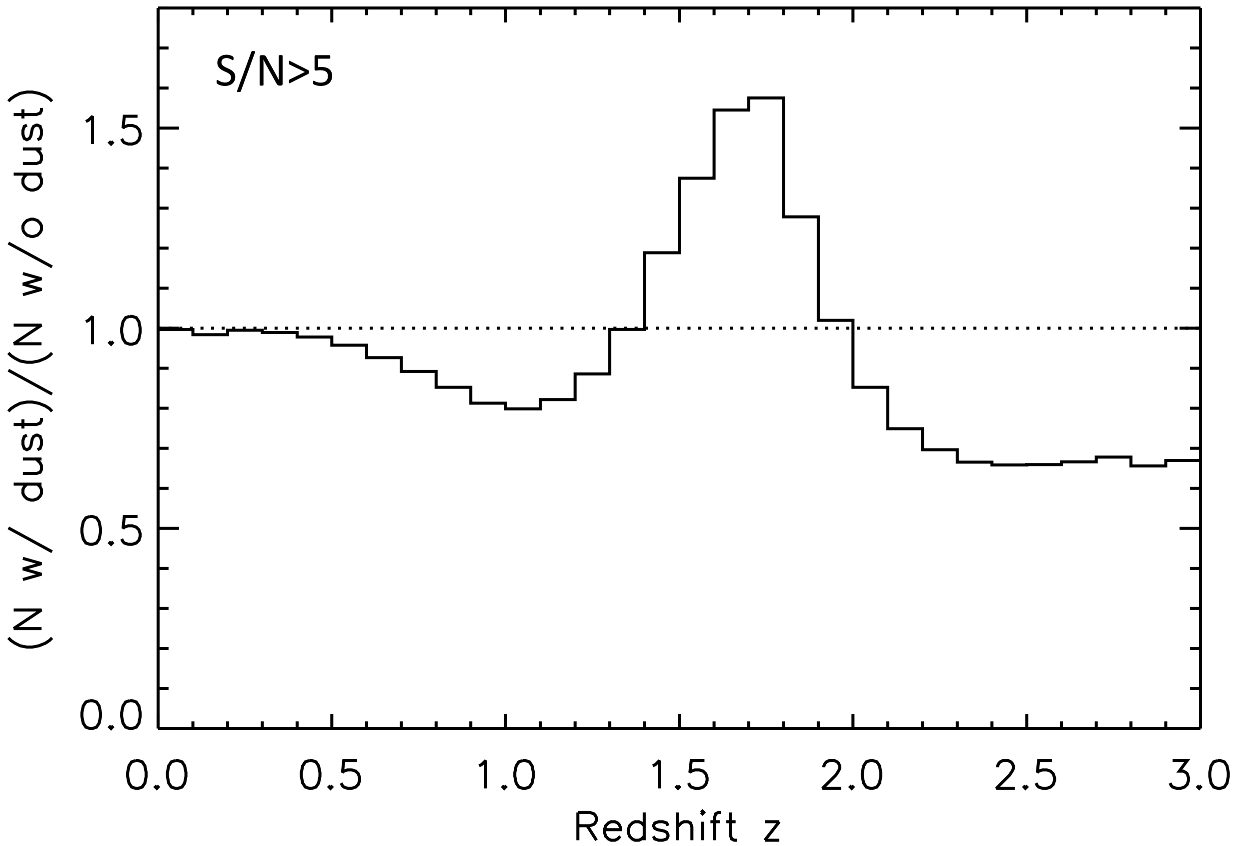
Frequencies [GHz]
21, 25, 30, 36, 43, 52, 62, 75, 90, 110, 130, 155, 185, 225, 270, 320, 385, 460, 555, 665, 800



84,900 clusters (without dust)
80,500 clusters (with dust)

Expected cluster counts for PICO

Slide from J.B. Melin



➔Up to 50% difference at a given redshift between observation (“N w/ dust”) and expectation if dust is not modelled (“N w/o dust”)

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Summary and perspective

- The mm-wave sky is complex!
- The PSM is a multi-component model informed by existing observations.
- The relevant observational data is large and growing fast – difficult to keep-up!
- You can get PSM simulations on the PLA: use the tool and give feedback!
- This is a tool for the community: send me wish lists…
- Happy to collaborate to either improve the PSM or use it to address open questions.
- A legacy post-planck version is in (slow) progress (help welcome).