Thermal Dust Fitting: with the Dust Temperature Ladder Model

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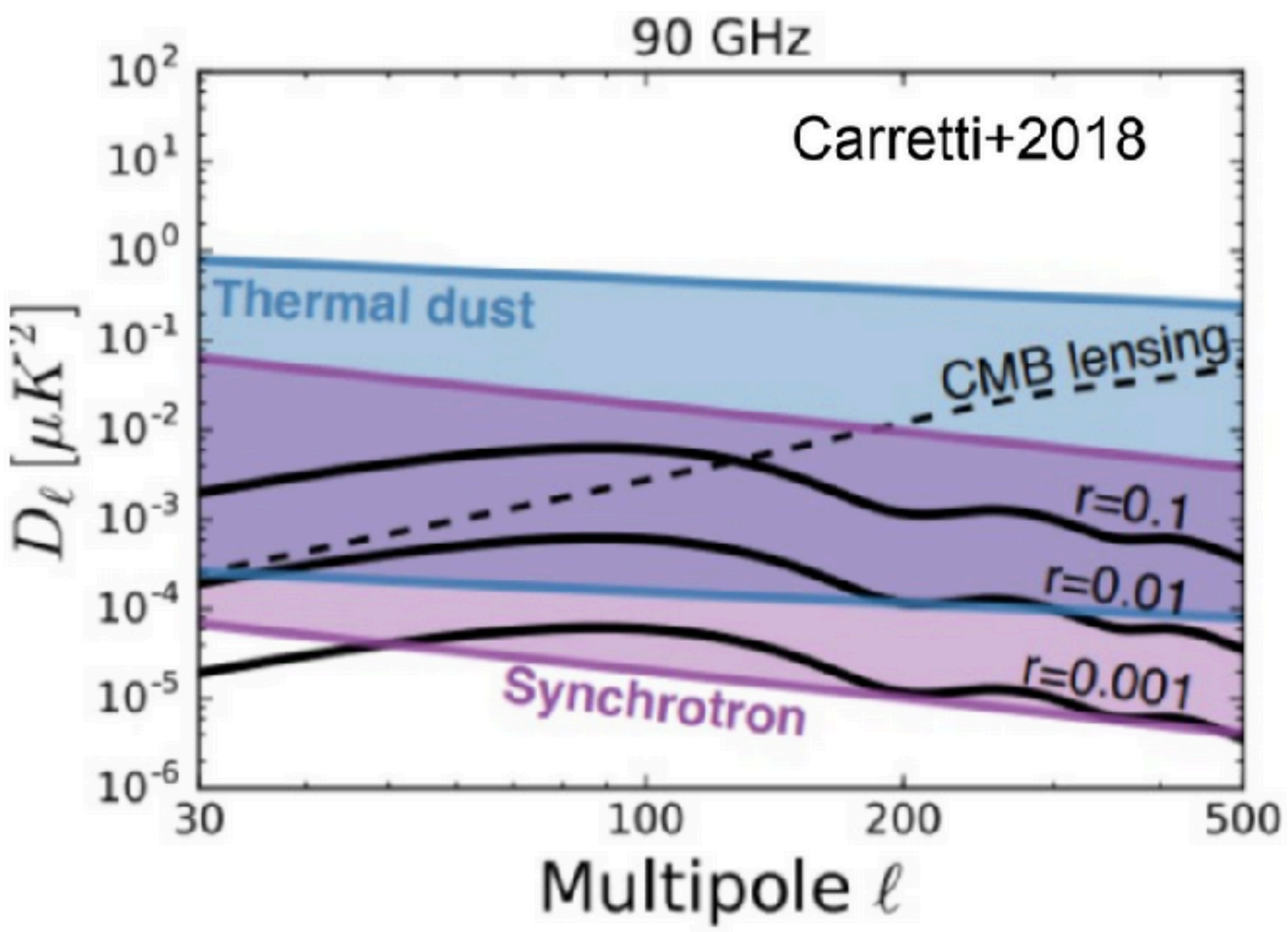
RADIO FOREGROUNDS+

HORIZON-CL4-2023-SPACE-01, GA 101135036

Objective: Modelling Dust Complexities

- Thermal dust emission is one of the dominant foreground for CMB B-mode searches, especially at large angular scales.
- Standard analyses model dust with a single modified blackbody (1MBB) for each pixel, assuming uniform temperature and spectral index along the LOS [Planck Collaboration XI 2014].
- However, interstellar dust resides in complex environments, leading to spatial and line-of-sight variations in dust temperature and spectral properties.
- Such variations distort the effective dust SED, producing deviations from a pure 1MBB description.
- This can have an impact B-mode measurements, because inaccurate modeling of such effects can bias component separation.
- In this work, we model the temperature variation in the thermal dust environments at different temperatures.



The Dust Temperature Ladder Model (TLM)

F-Xavier Desert (A&A 2022)

GRENOBLE | MODANE

- Consider a small temperature range around T with a log-normal distribution

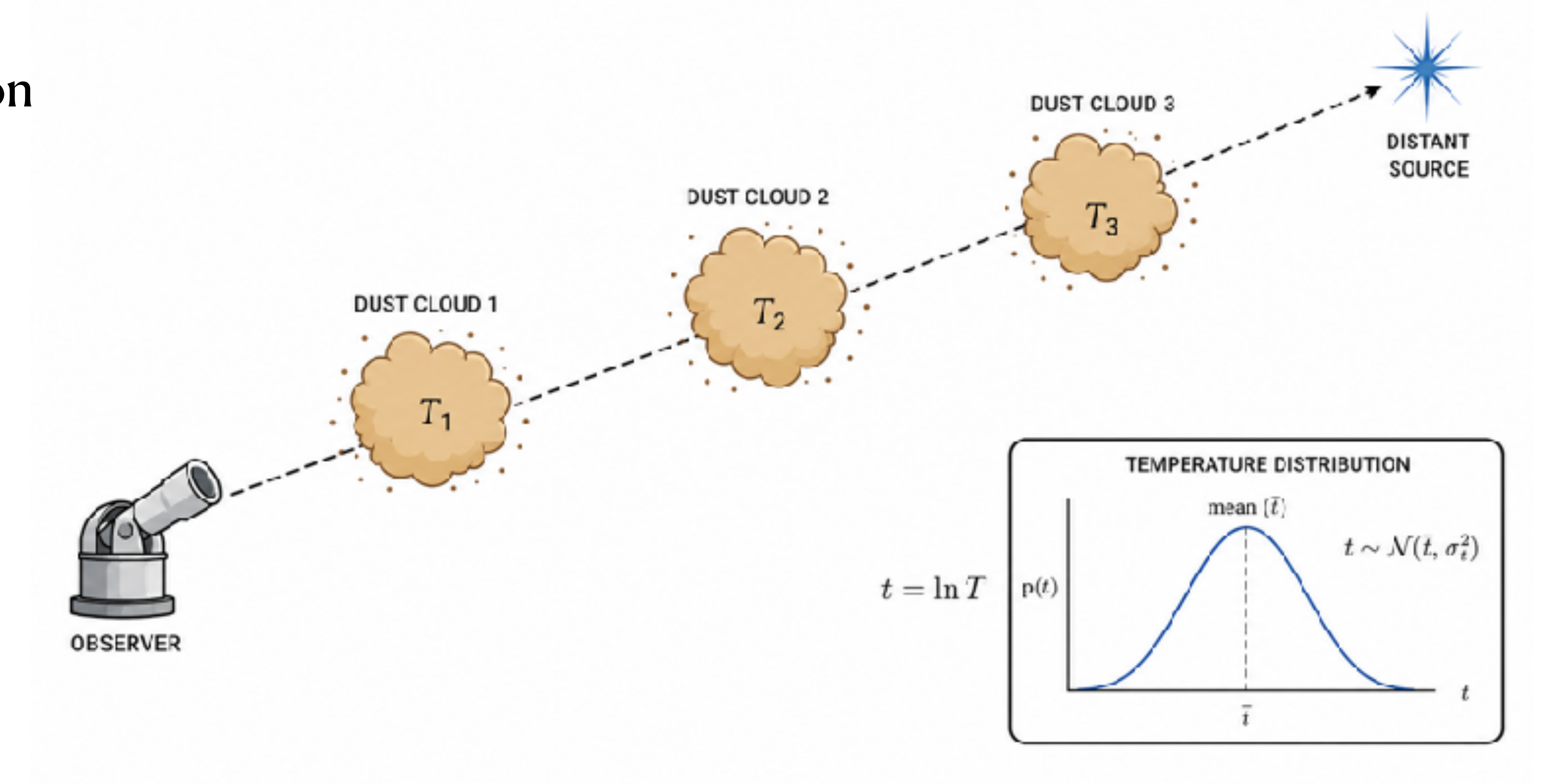
$$p(t)dt = \frac{1}{\sigma\sqrt{2\pi}} exp\left(-\frac{(t-t_m)^2}{2\sigma^2}\right)dt,$$

- The proposed dust emission spectrum over the LOS:

$$I_\nu = \tau_\nu \int dt p(t) B_\nu(T)$$

$$\tau_\nu = \tau_{dust}\left(\frac{\nu}{\nu_0}\right)^\beta$$

The Planck Function

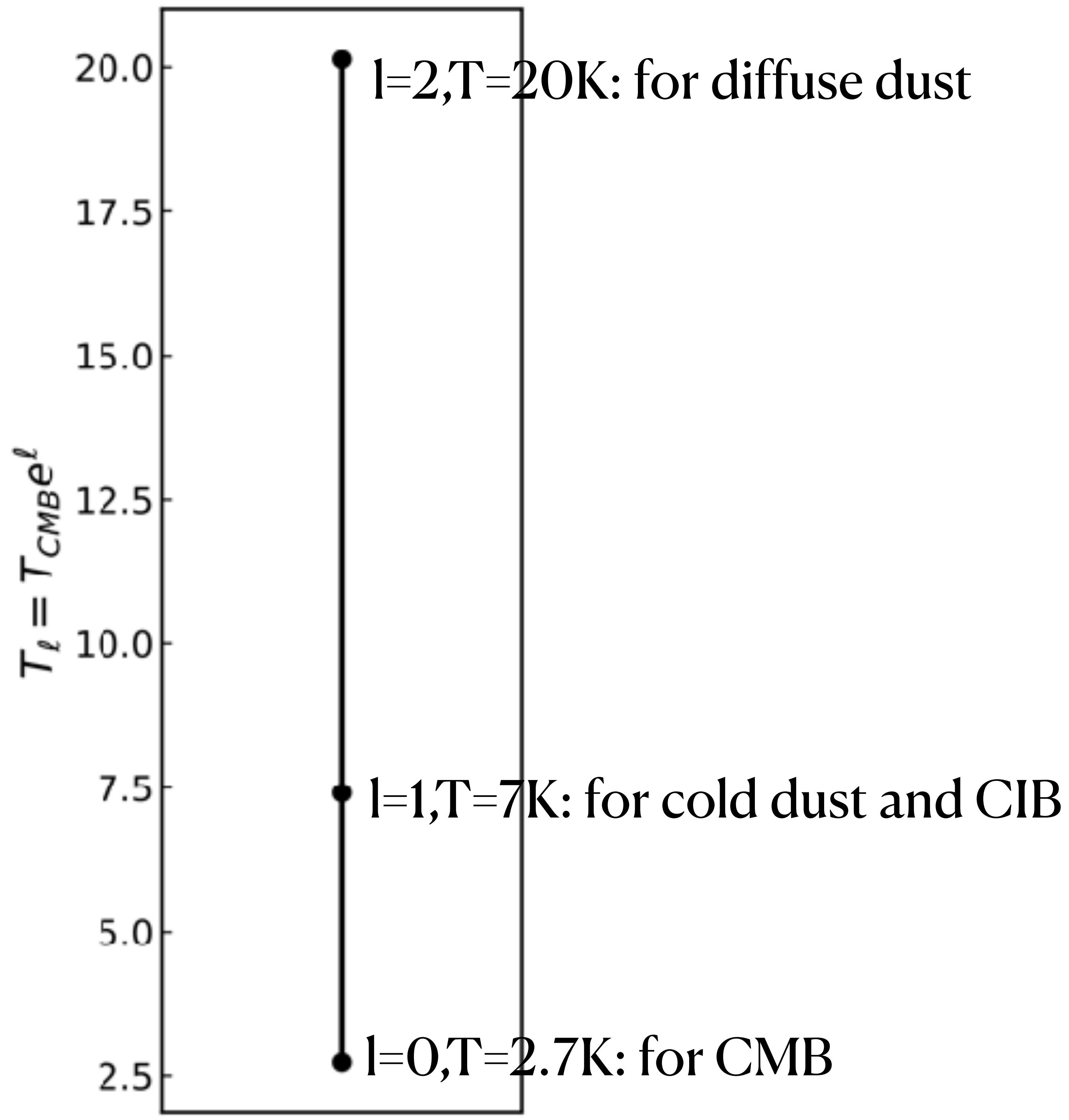


- Taylor expand $B_\nu(T)$ around a reference temperature T_0: $I_\nu = \tau_\nu \left[B_\nu(T_0) + \Delta t \frac{dB_\nu}{dt}(T_0) + \frac{1}{2}(\Delta t^2 + \sigma^2)\frac{d^2B_\nu}{dt^2}(T_0)\right]$

- Discretize and include the effect of bandpass integration in the TLM model: $I_n = \sum_{l=0} \tau_l \left[K_{0,nl} + \Delta t_l K_{1,nl} + \frac{1}{2}\left(\Delta t_l^2 + \sigma_l^2\right) K_{2,nl}\right]$

The Temperature Ladder and the TLM Coefficients

$$I_n = \sum_{l=0} \tau_l \left[K_{0,nl} + \Delta t_l K_{1,nl} + \frac{1}{2}\left(\Delta t_l^2 + \sigma_l^2\right) K_{2,nl} \right] \longrightarrow$$ Linear Model



$C_{l0} = \tau_l$ —- the dust optical depth

$C_{l1} = \tau_l \Delta t_l$ — the mean dust temperature correction from the reference temperature

$C_{l2} = \tau_l \frac{1}{2}(\Delta t_l^2 + \sigma_l^2)$ — spread of the temperature distribution along LOS

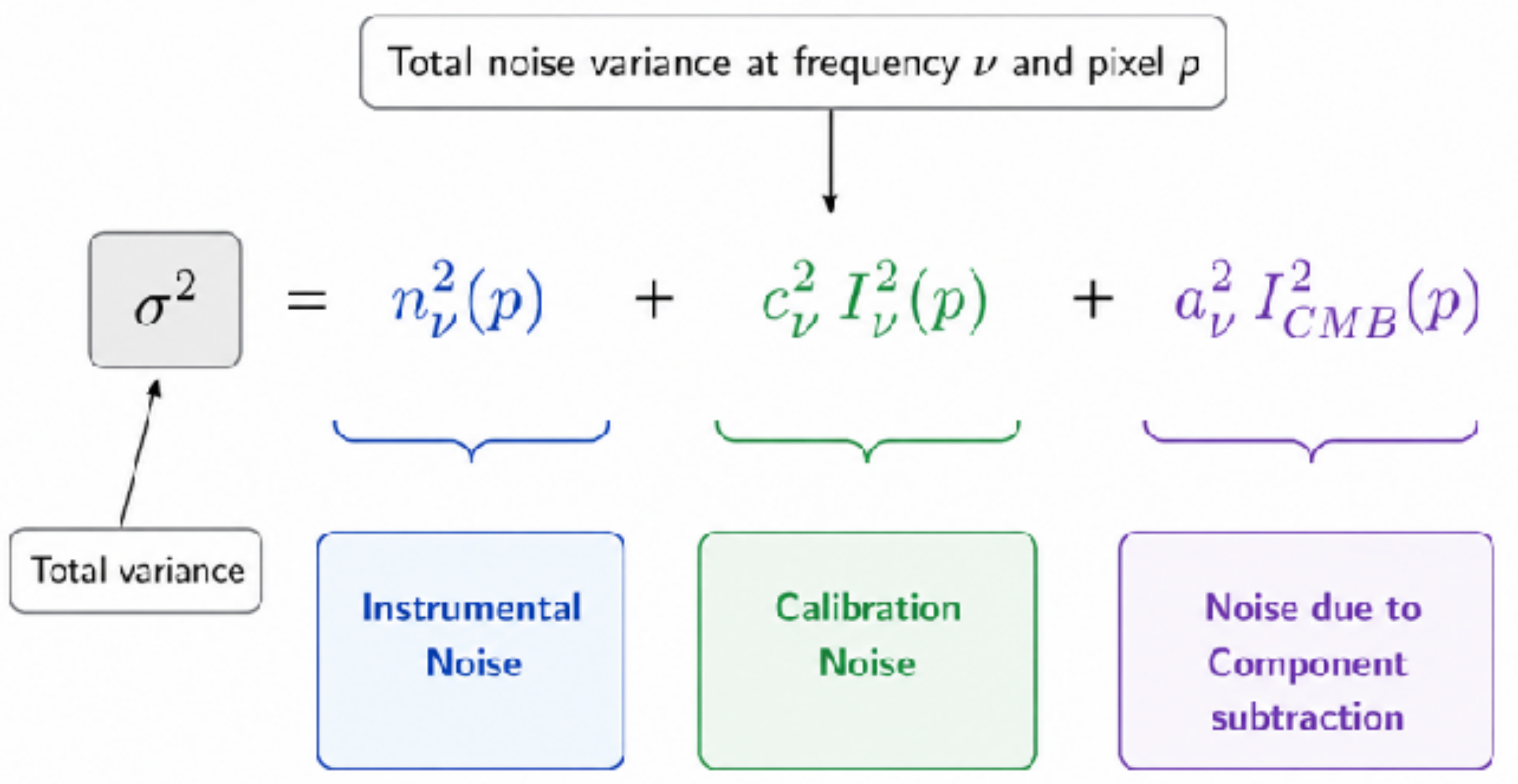
The temperature Ladder: Instrument photometric bands are regularly spaced in log(frequency);
lnT should also be regularly spaced in the discretization of temperatures.

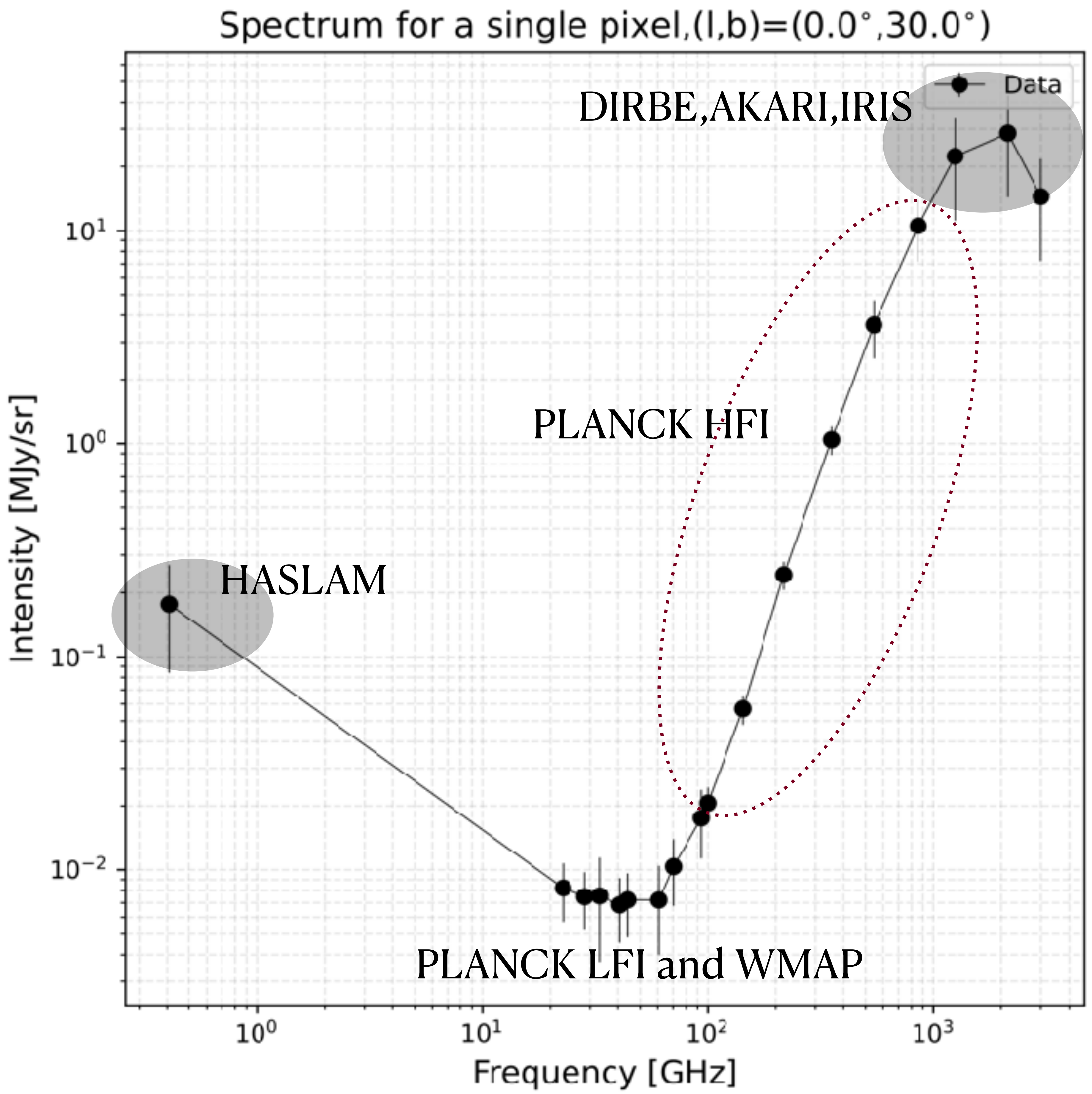
Implementation: Reference temperature fixed at 20K, and $\beta_{dust} = 1.5$

- We use 4 TLM coefficients : $C_0^{20K}, C_1^{20K}, C_0^{7K} C_1^{7K}$
- *In the future:* C_0^{50K} for hot dust in galactic plane.

The Data and the error model

- We use total of 18 Frequency bands
- Haslam (0.408 GHz), WMAP-9yr and Planck-PR3 (22-857 GHz), IRIS, DIRBE, AKARI (1200-3000 GHz)
- Maps Analyzed on HealPIX grid of $N_{SIDE} = 256$ and smoothed with FWHM= 1 degree beam.
- The error model:





Error bars scaled by a factor of 5 for visual clarity

Fitting on the data: Methodology

- **Components in the data:**
  - CMB
  - Astrophysical Diffuse components (Radio-foregrounds + Thermal-dust + CO +CIB monopole)
  - Dipole, Zodiacal light
  - Systematics: Zero level corrections, calibration errors

CMB subtracted Data

↓

SED fitting I1
dust+sync+ff+AME

→

Template Fit on Residual maps
dipole+monopole+
CO+Zodi+
calibration

→

Remove from the CMB subtracted Data
dipole+monopole+
CO+Zodi+
calibration

→

SED fitting I2
dust+sync+ff+AME

SED fit for the Radioforeground Components

We fit for three components at low frequency following [M Fernandez-Torreiro et.al 2023]:

- Synchrotron emission:

$$I_{Sync} = A_{Sync}\left(\frac{\nu}{\nu_0}\right)^{\alpha_s} + B_{Sync}\left(\frac{\nu}{\nu_0}\right)^{\alpha_s} ln\left(\frac{\nu}{\nu_0}\right)$$

- Free-Free emission:

$$I_{ff} = A_{ff}\nu^{\alpha_{ff}}$$

- AME emission:

$$I_{AME} = A_{AME}exp\left[-\frac{1}{w_{AME}}ln^2\frac{\nu}{\nu_{AME}}\right]$$

Fixed Parameters:

$$\alpha_s = -1.1, \nu_0 = 30GHz \alpha_{ff} = -0.1$$

$$w_{AME} = 0.55, \nu_{AME} = 21GHz$$

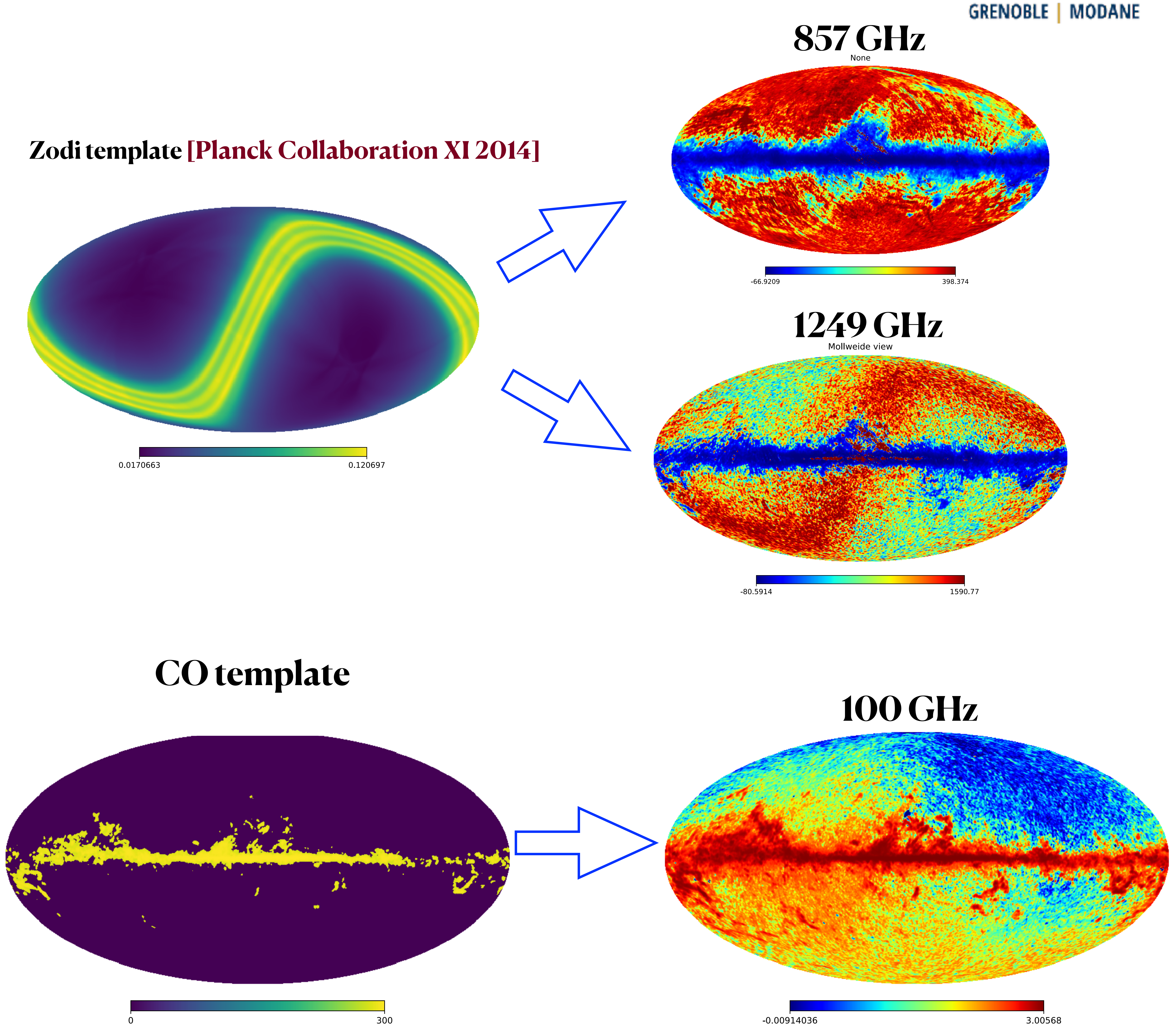
Free Parameters:

$$A_{Sync}, B_{Sync}, A_{ff} and A_{AME}$$

Using 18 frequency bands, we fit for 4+4=8 parameters in total.

Template Fit on the residual Maps

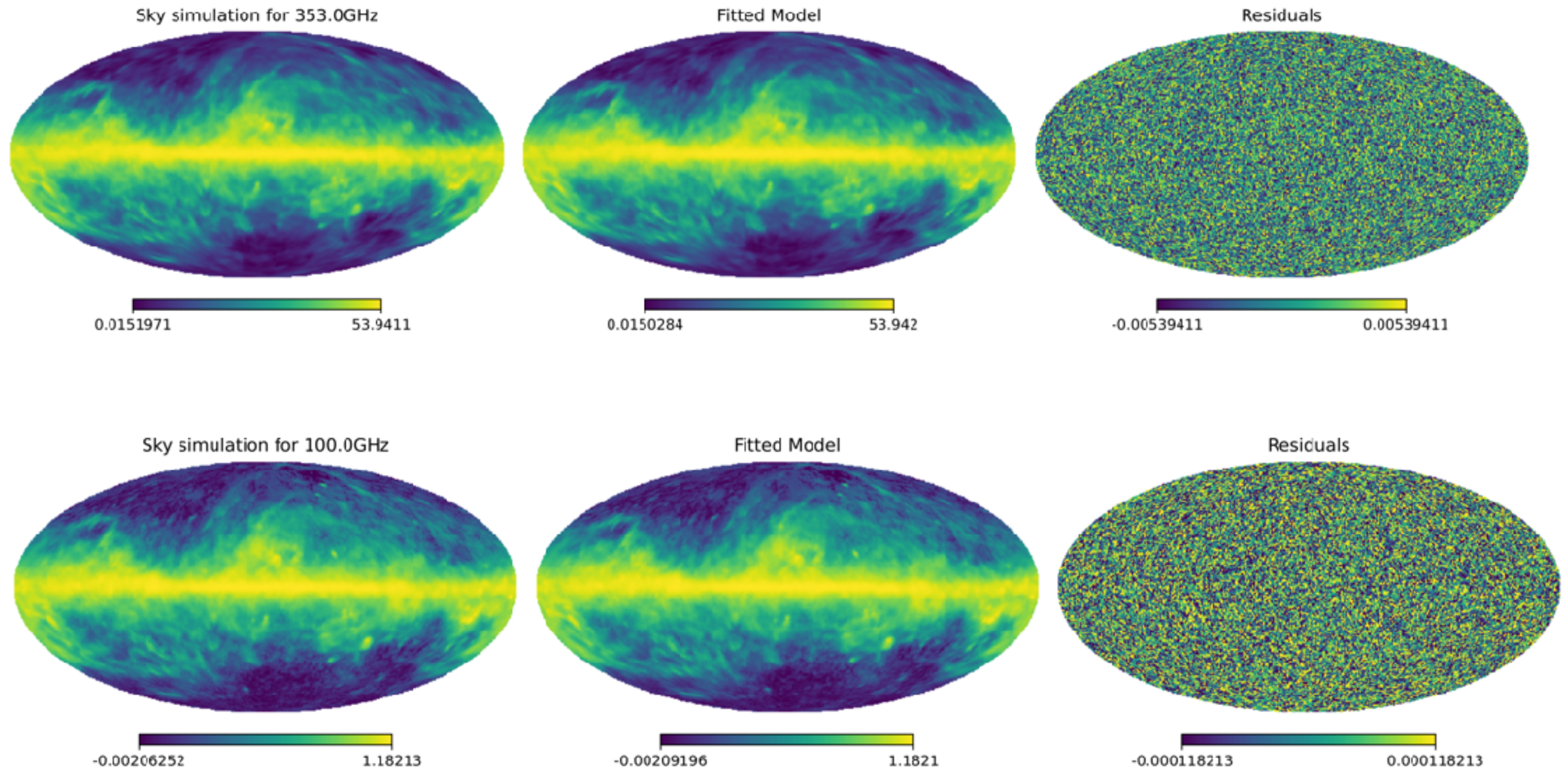
- Regression fit for 7 parameters on each frequency map :
  - m_ν for zero level
  - $d_\nu^X, d_\nu^Y, d_\nu^Z$ for cmb dipole [*in frequencies below 143 GHz*]
  - z_ν for Zodiacal light, fitted over ZL template [*in frequencies above 100 GHz*]
  - co_ν component for CO emission [Ghosh, Remazeilles et.al 2023]
  - ϵ_ν component for calibration error



Validating the DTLM method on simulations

Simulations
model[SED fit parameters]+noise

→ **SED fitting** → **Fitted Model**



Range of validity of the DTLM approach

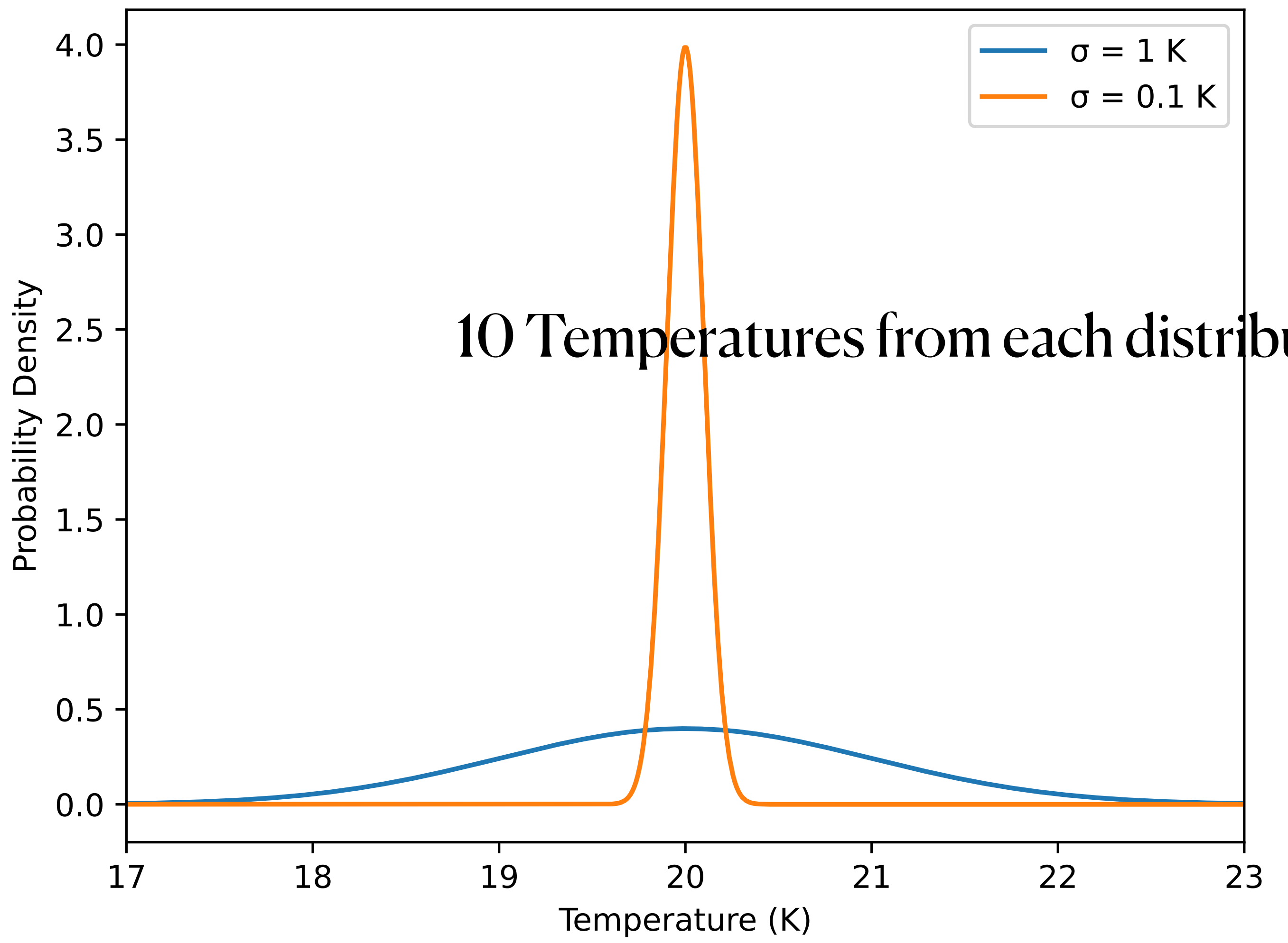
Simulations
Thermal dust 10MBB distribution+ Noise
[distribution of 10 Temperatures along LOS, centered at 20K, with spread of σ]

→

TLM fit

→

Fitted Model and TLM coefficients



10 Temperatures from each distributions

Increase σ to add more complexity to the simulated thermal dust model.

The DTLM model is flexible enough for different levels of complexity considered this dust model and provides good quality fits in all cases.

Range of validity of the DTLM approach

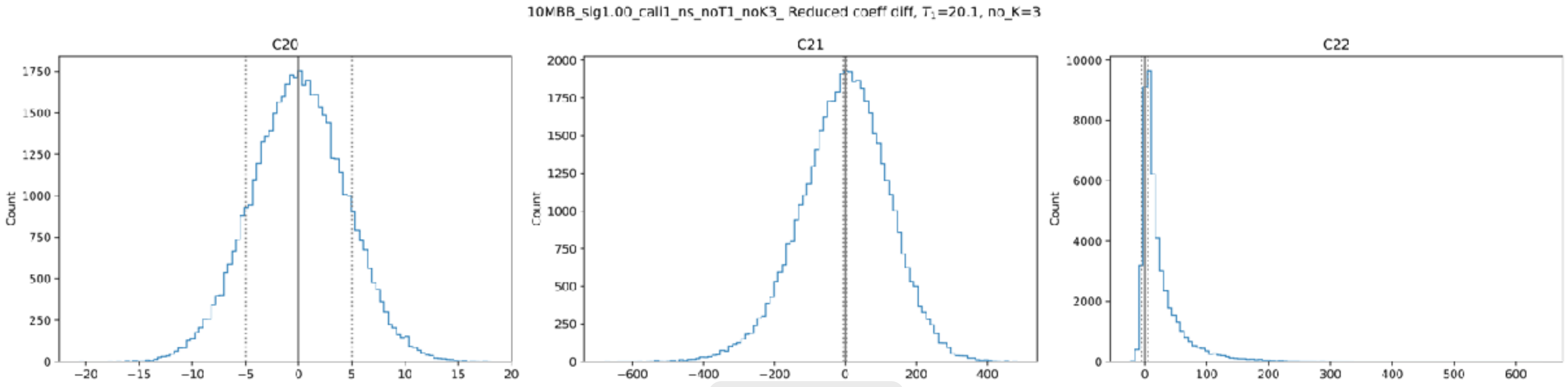
Are we able to recover the input parameters

of the thermal dust simulation model?

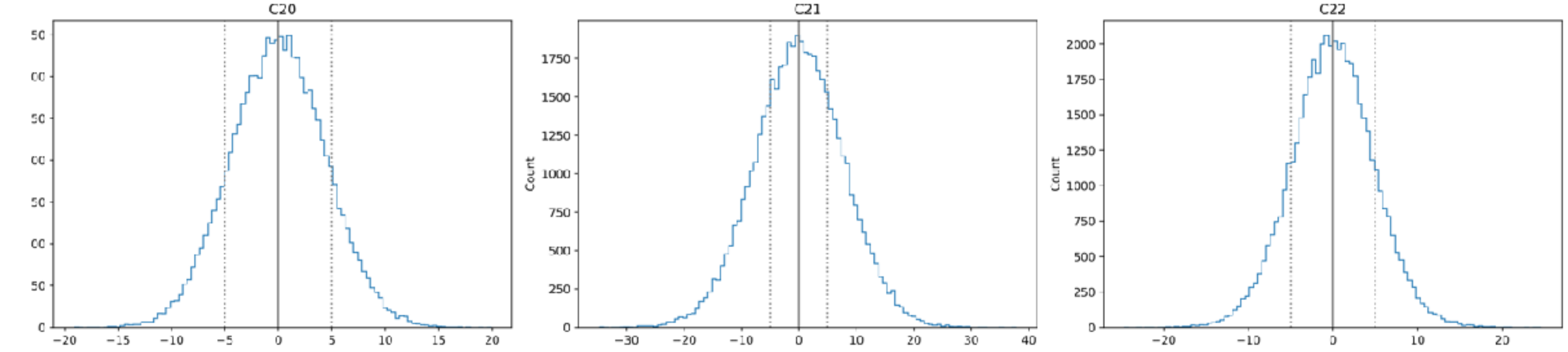
$$ReducedCoeff = \frac{InputCoeff - RecoveredCoeff}{Error}$$

The accuracy in the recovery first and second order coefficients depend upon the level of complexity in our simulations.

$\sigma = 1.0$



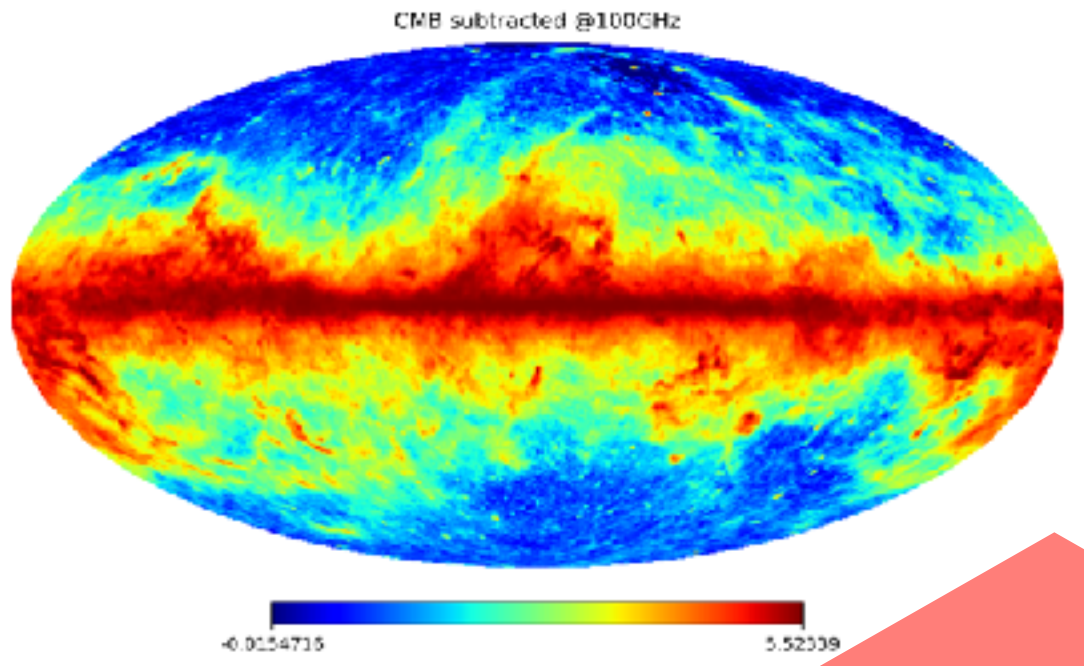
$\sigma = 0.1$



Results from data

Methodology Recap

CMB subtracted Data

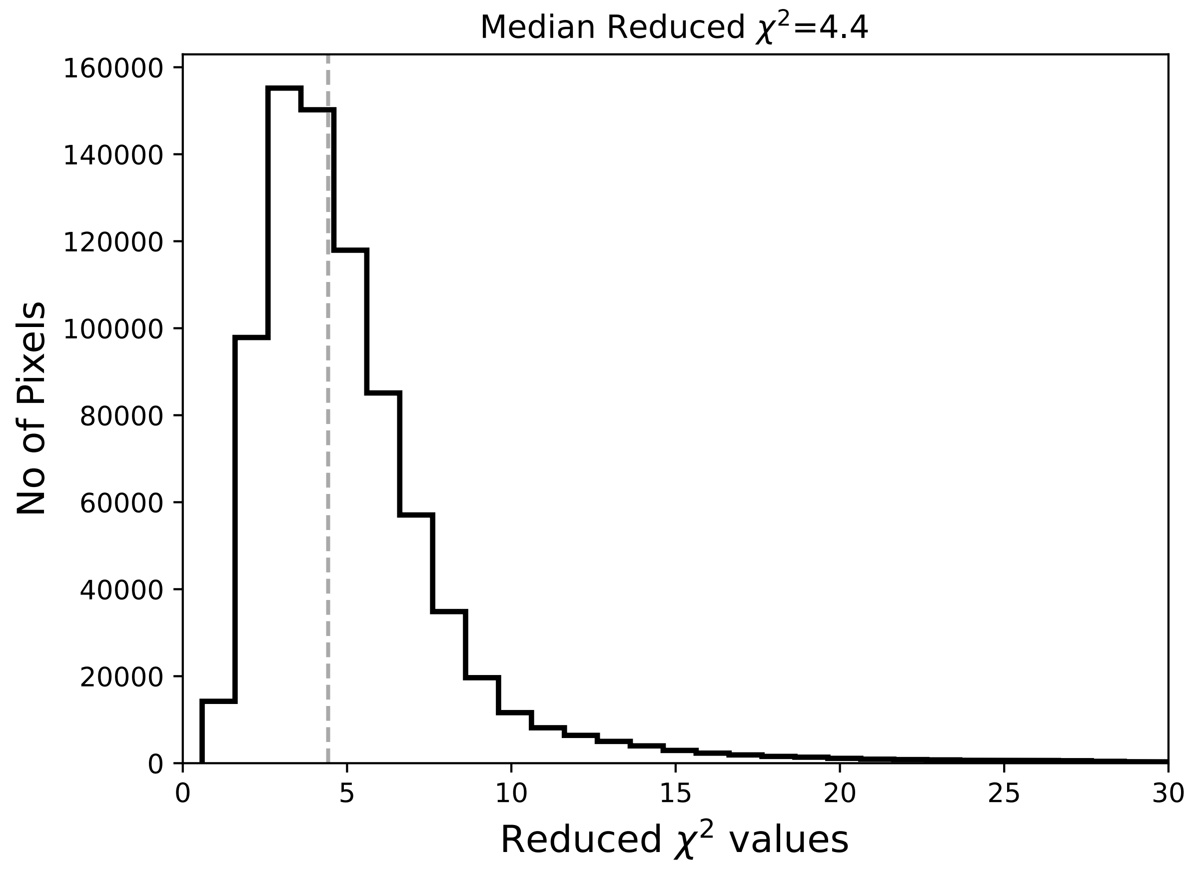


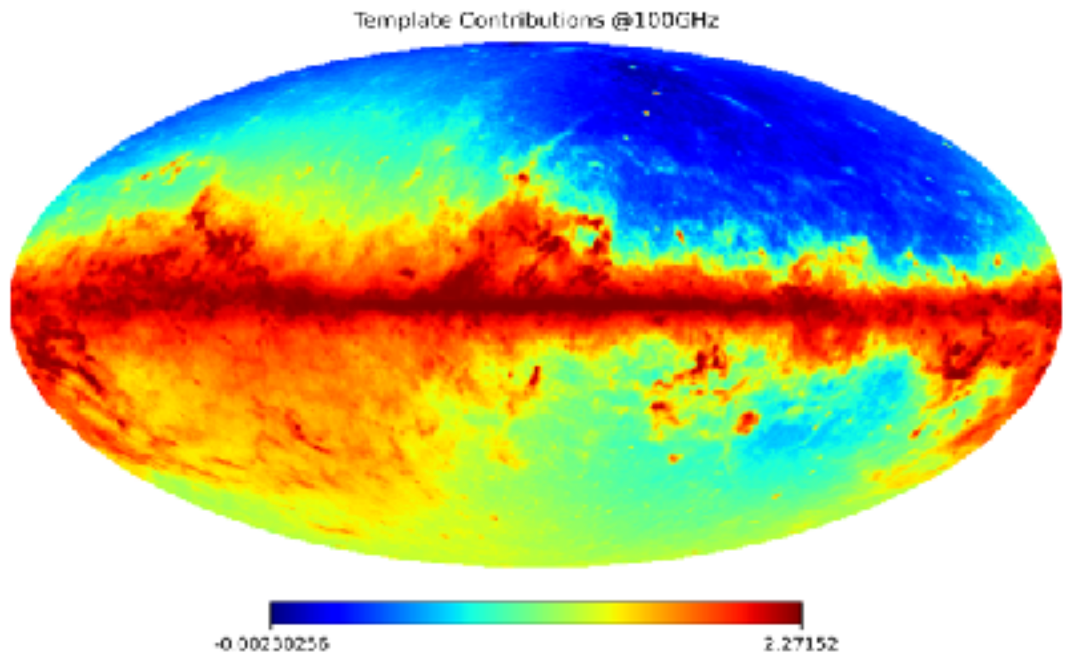
SED fitting I1
dust+sync+ff+AME

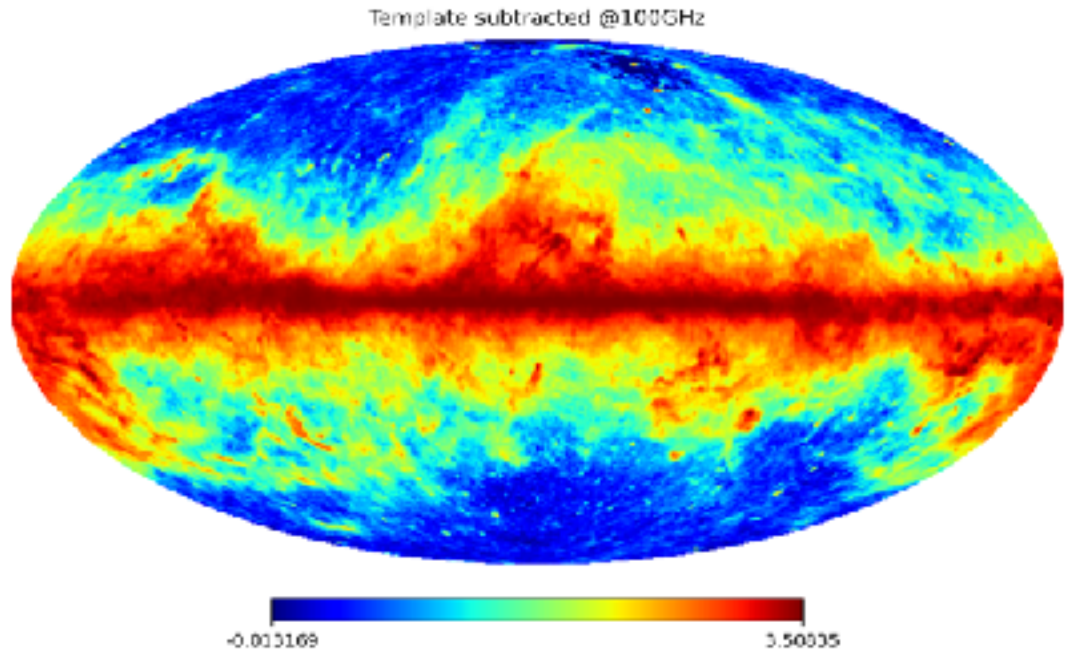
Template Fit on Residual maps
dipole+monopole+
Zodi

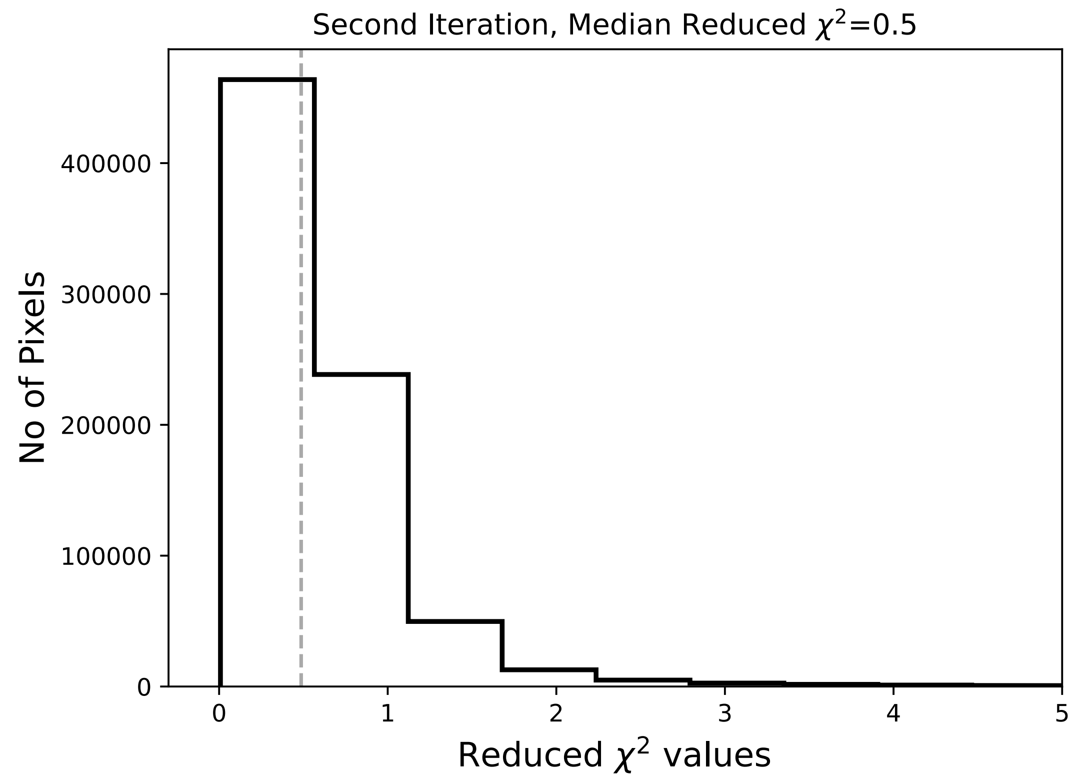
Remove from the CMB subtracted Data
dipole+monopole+
CO+Zodi+
calibration

SED fitting I2
dust+sync+ff+AME







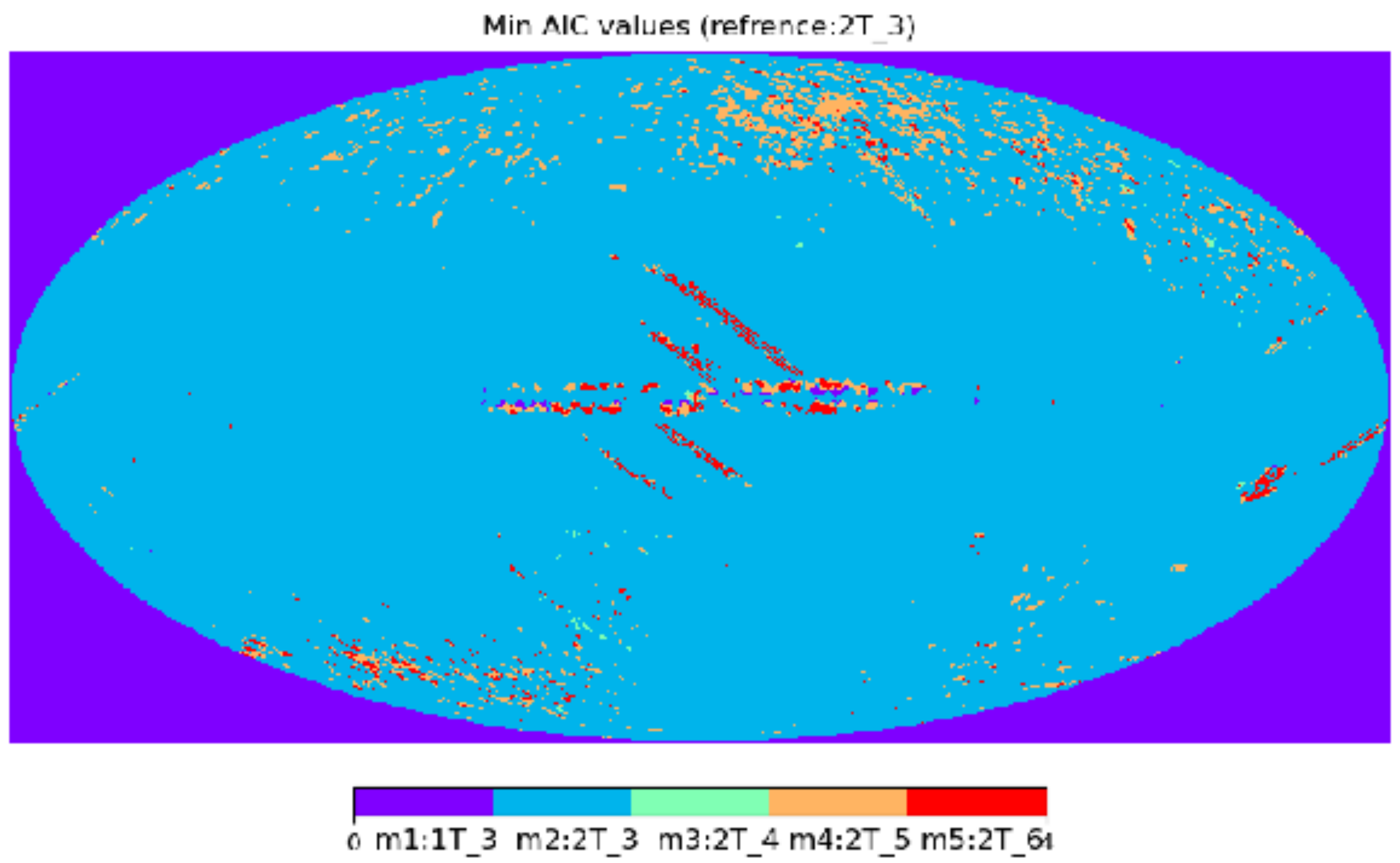


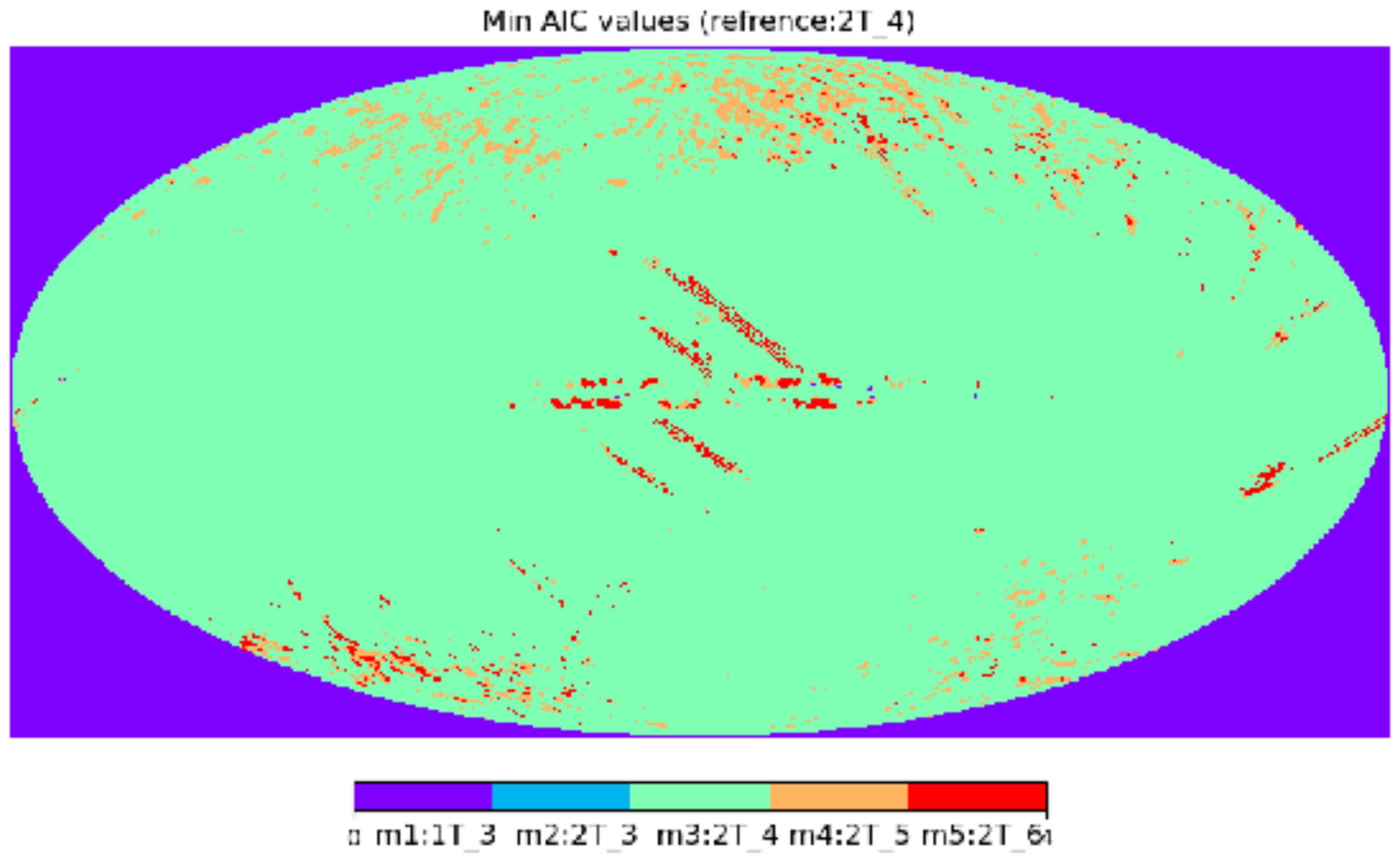
Model Selection

We consider five permutation of DTLM coefficients : Achieve good quality of fit

1T_3	2T_3	2T_4	2T_5	2T_6
$C_0^{20K}, C_1^{20K}, C_2^{20K}$	$C_0^{20K}, C_0^{7K}, C_1^{20K}$	$C_0^{20K}, C_0^{7K}, C_1^{20K}, C_1^{7K}$	$C_0^{20K}, C_0^{7K}, C_1^{20K}, C_1^{7K}, C_2^{20K}$	$C_{0,1,2}^{20K}, \quad C_{0,1,2}^{7K}$

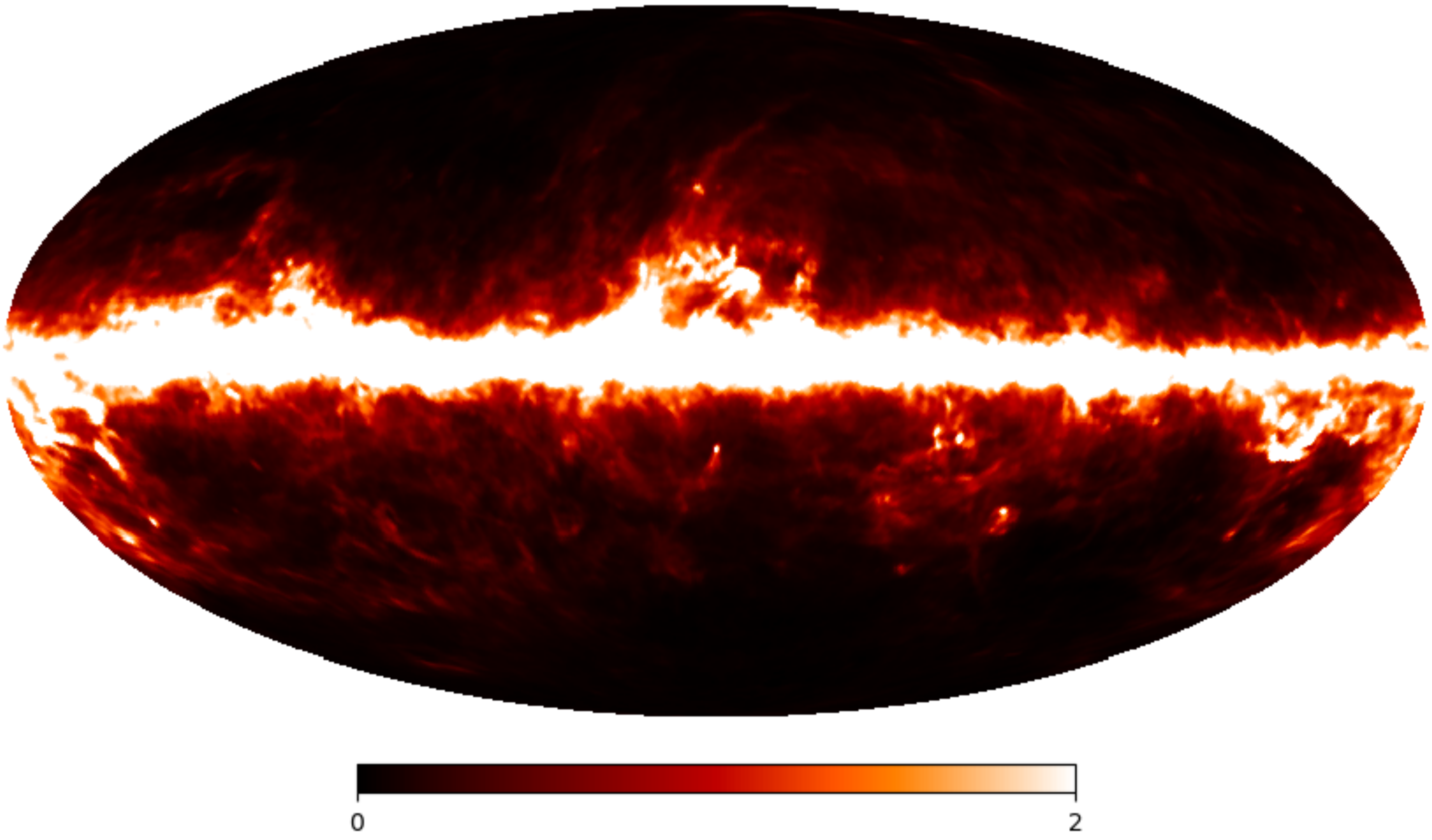
AIC criteria check: $AIC = 2k - 2ln\left(\hat{L}\right), \quad k = No \quad of \quad parameters$



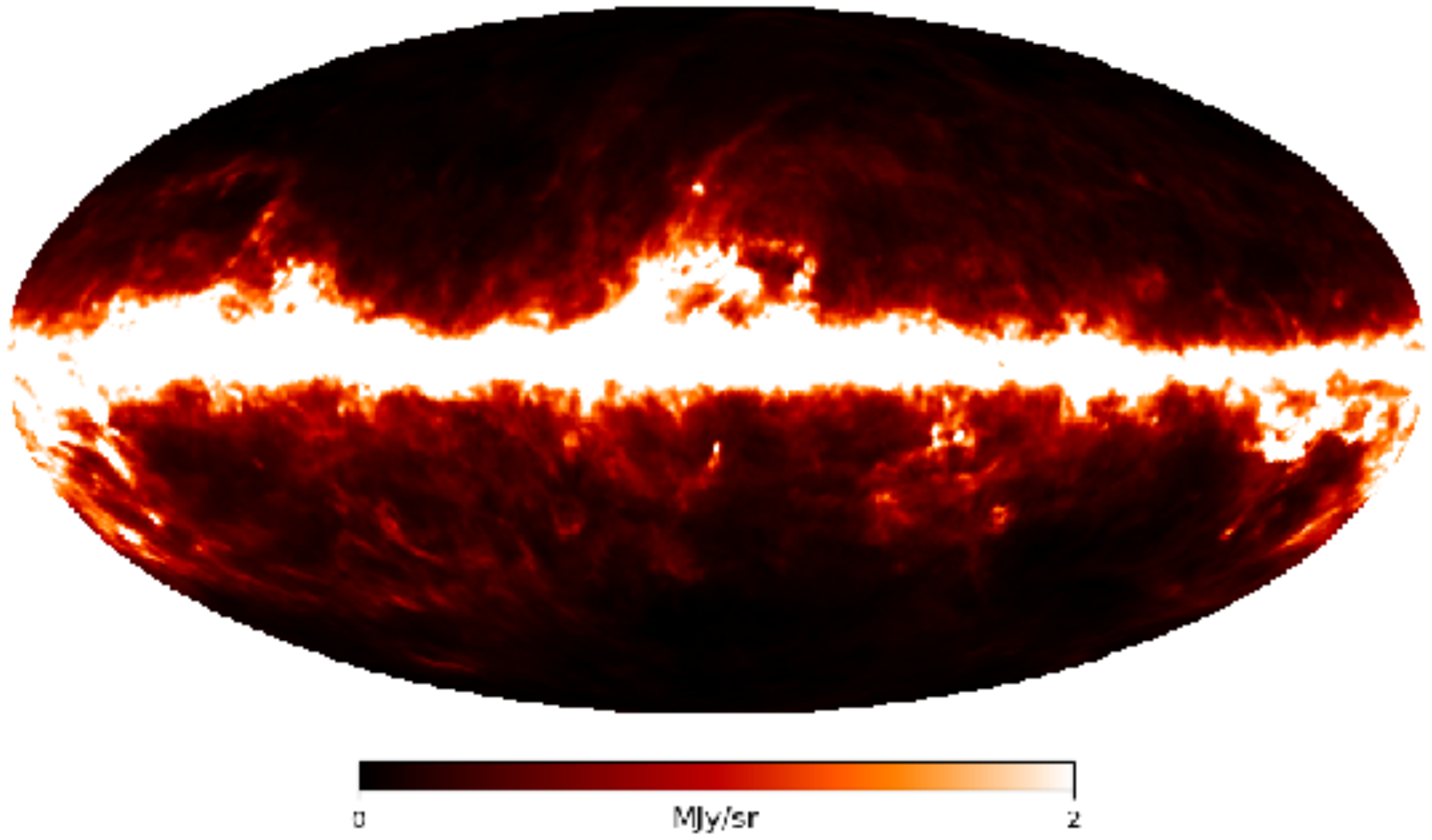


Recovered dust Map @353 GHz

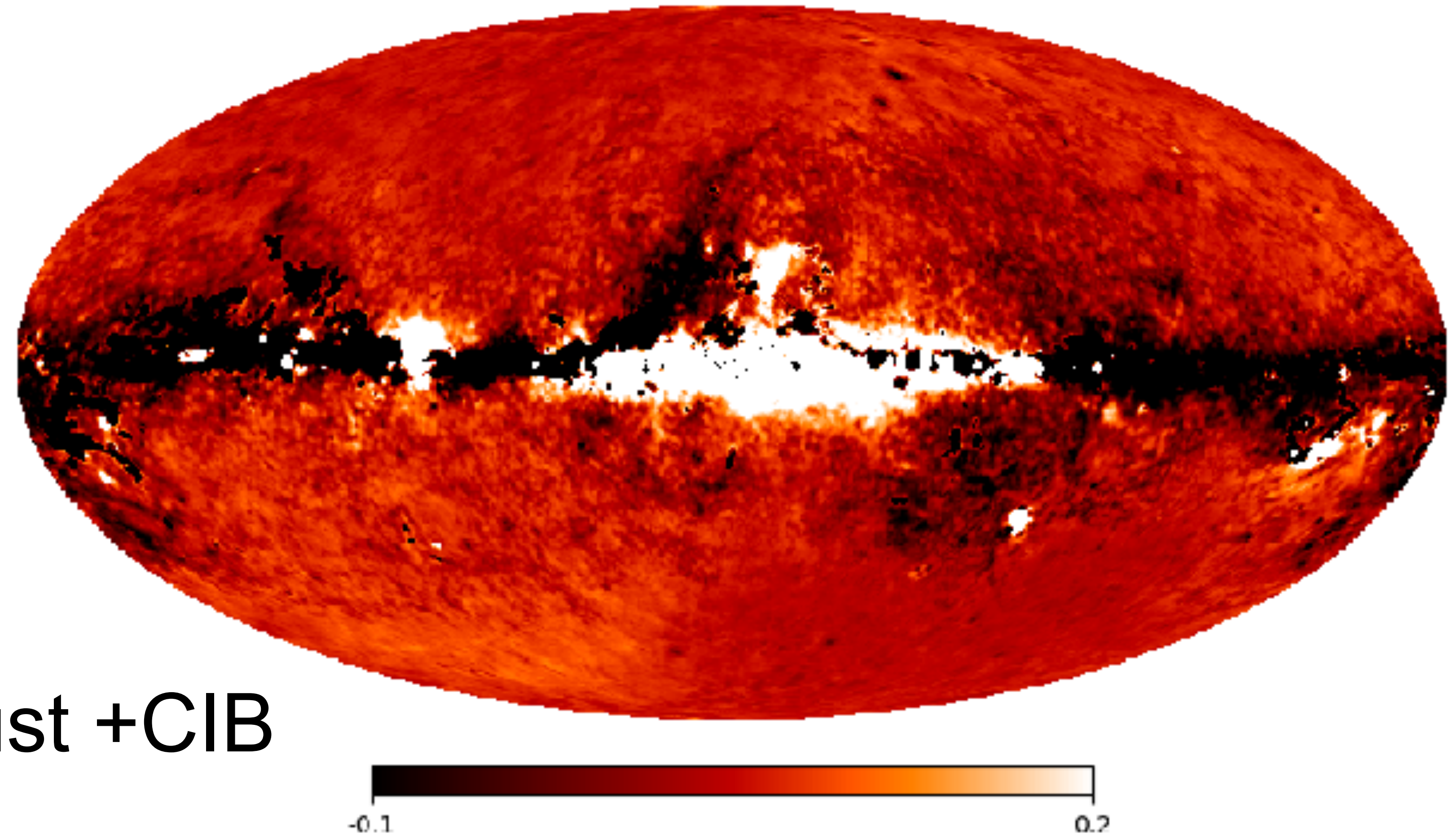
Model: 2T-4



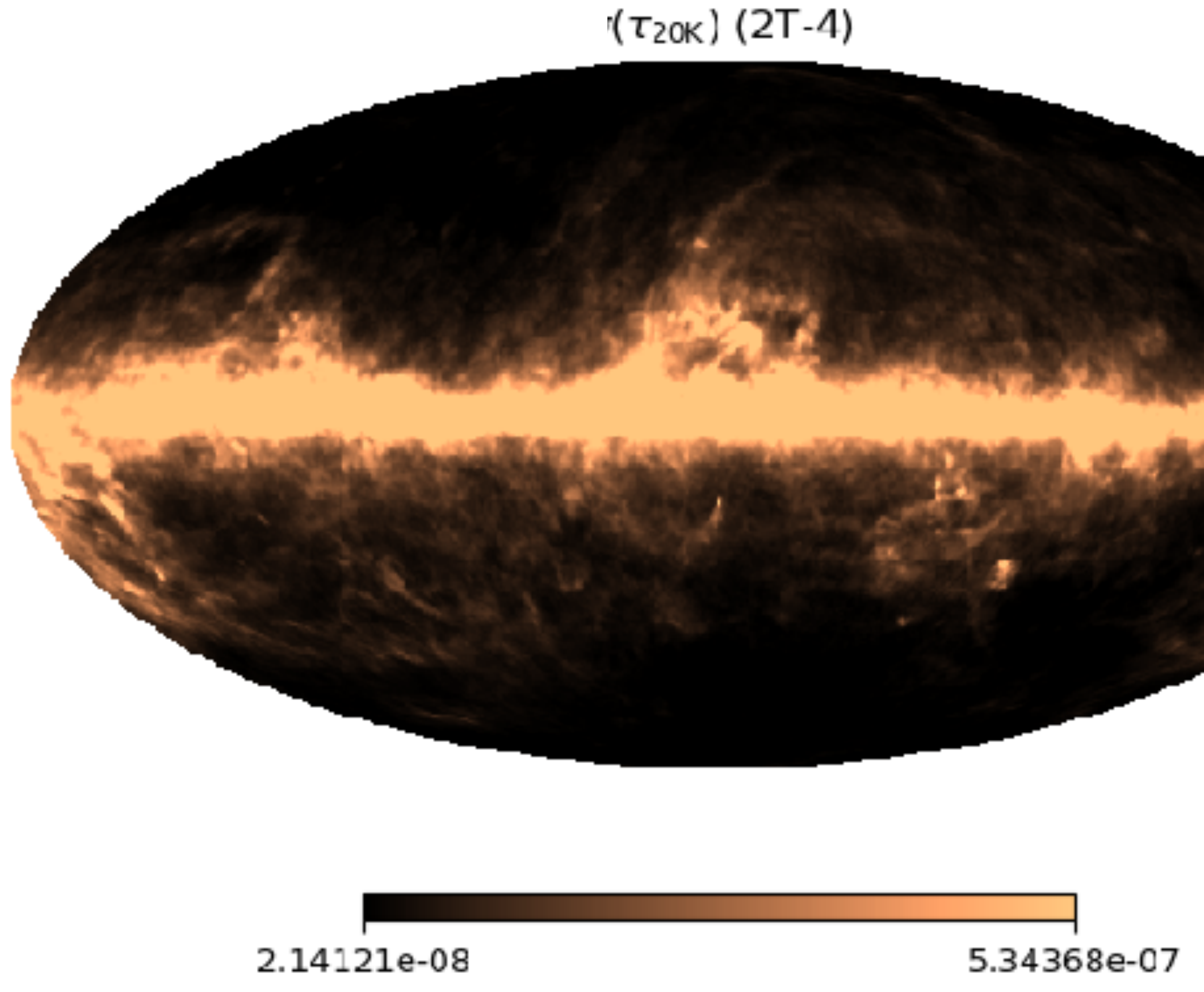
Hot Dust

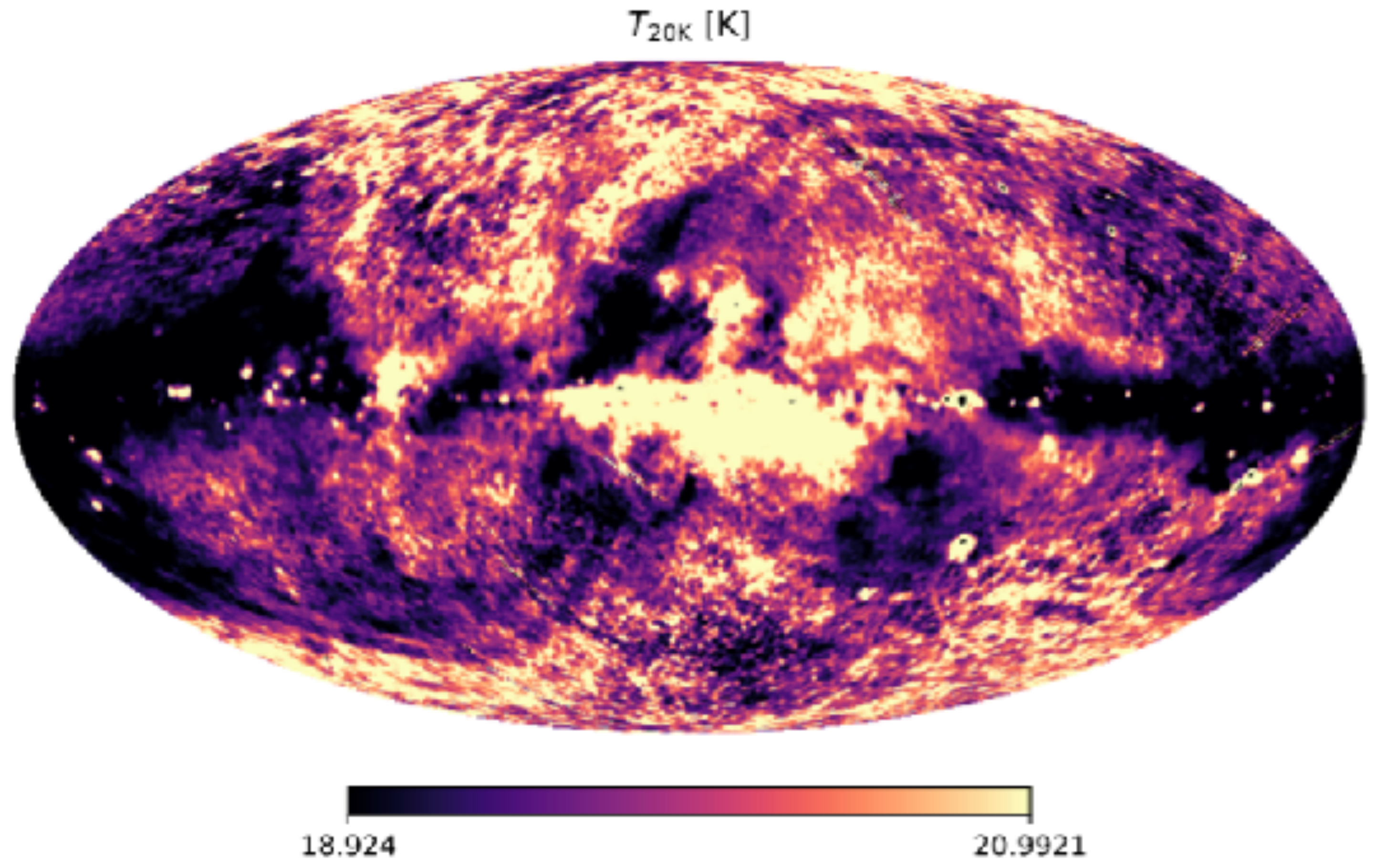


Cold Dust +CIB



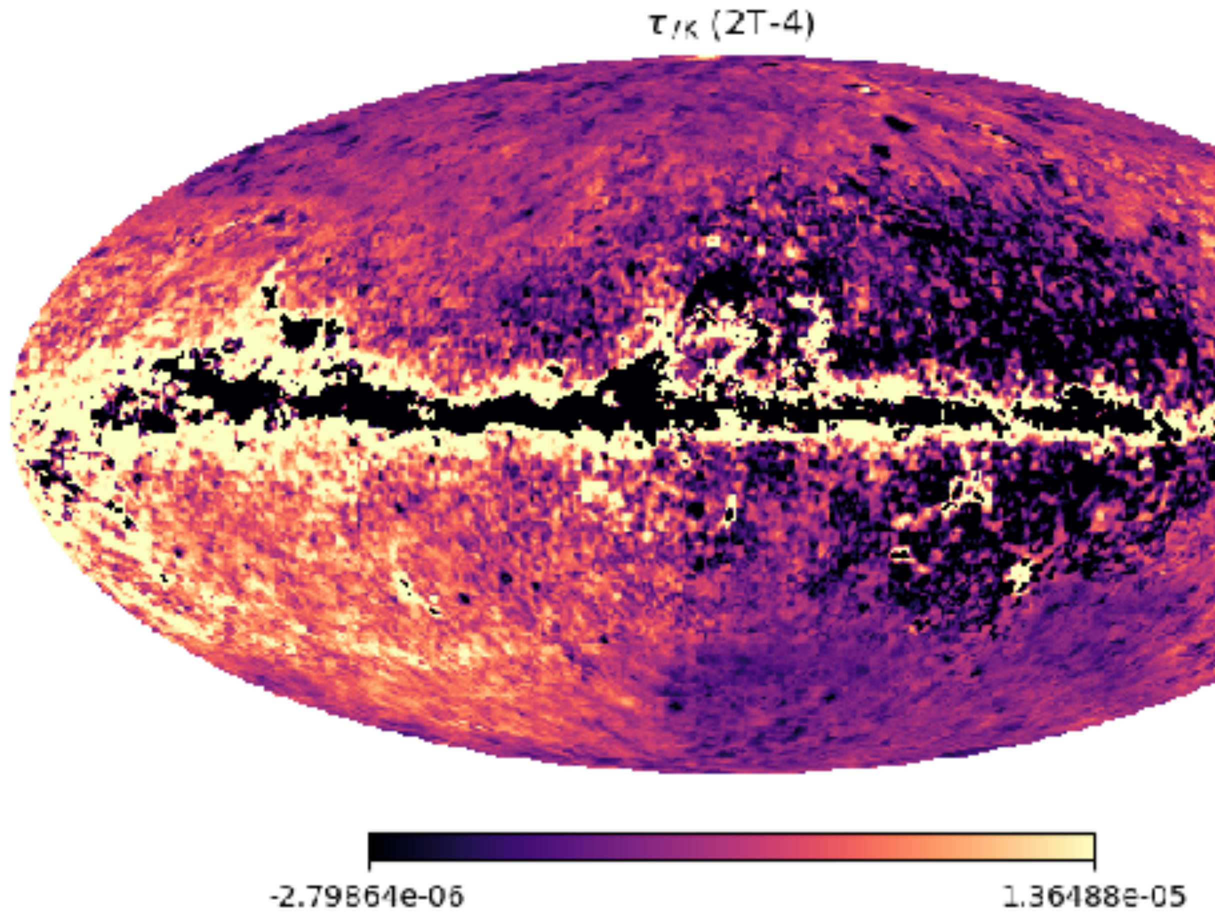
Constraints on Dust Physics

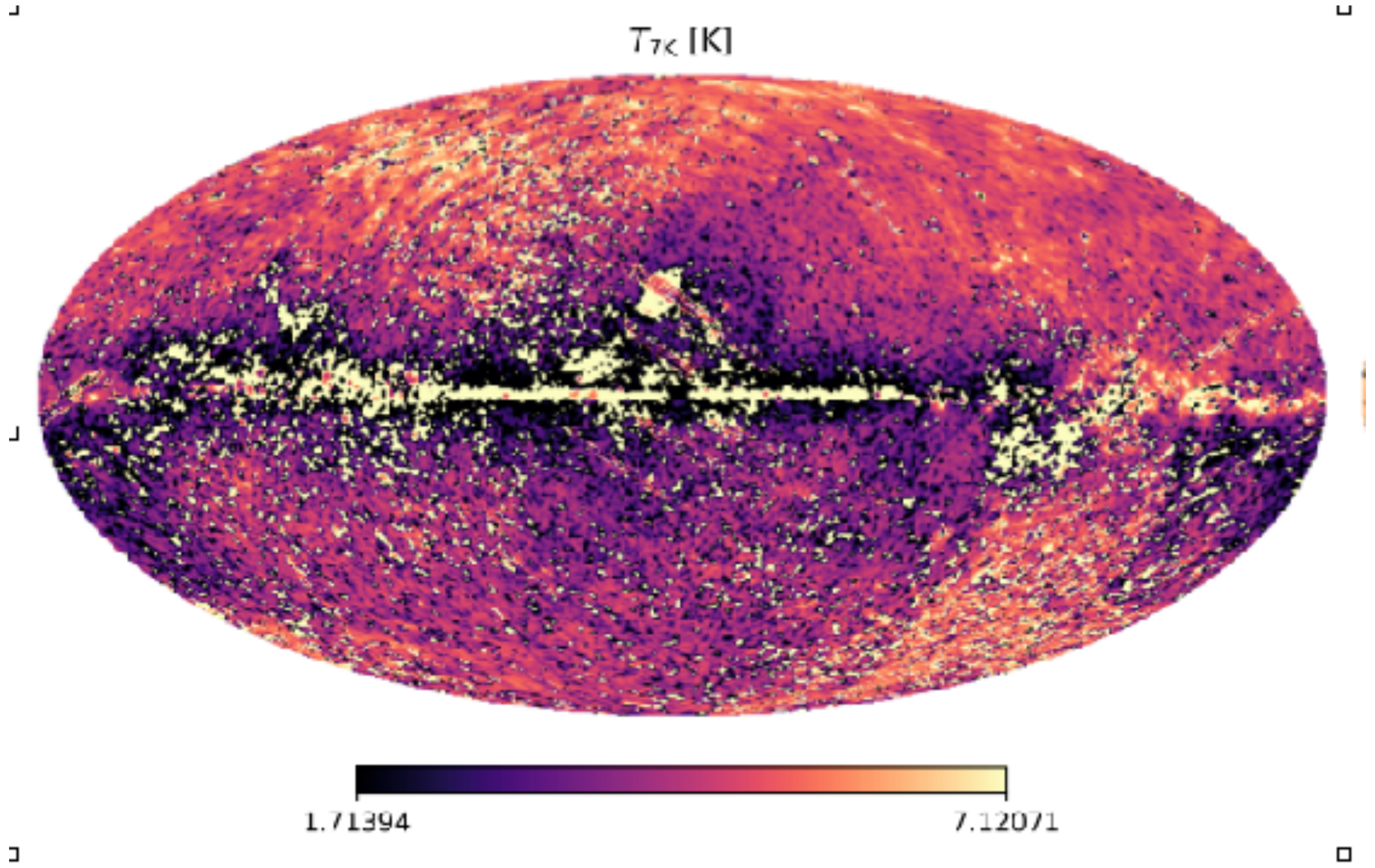




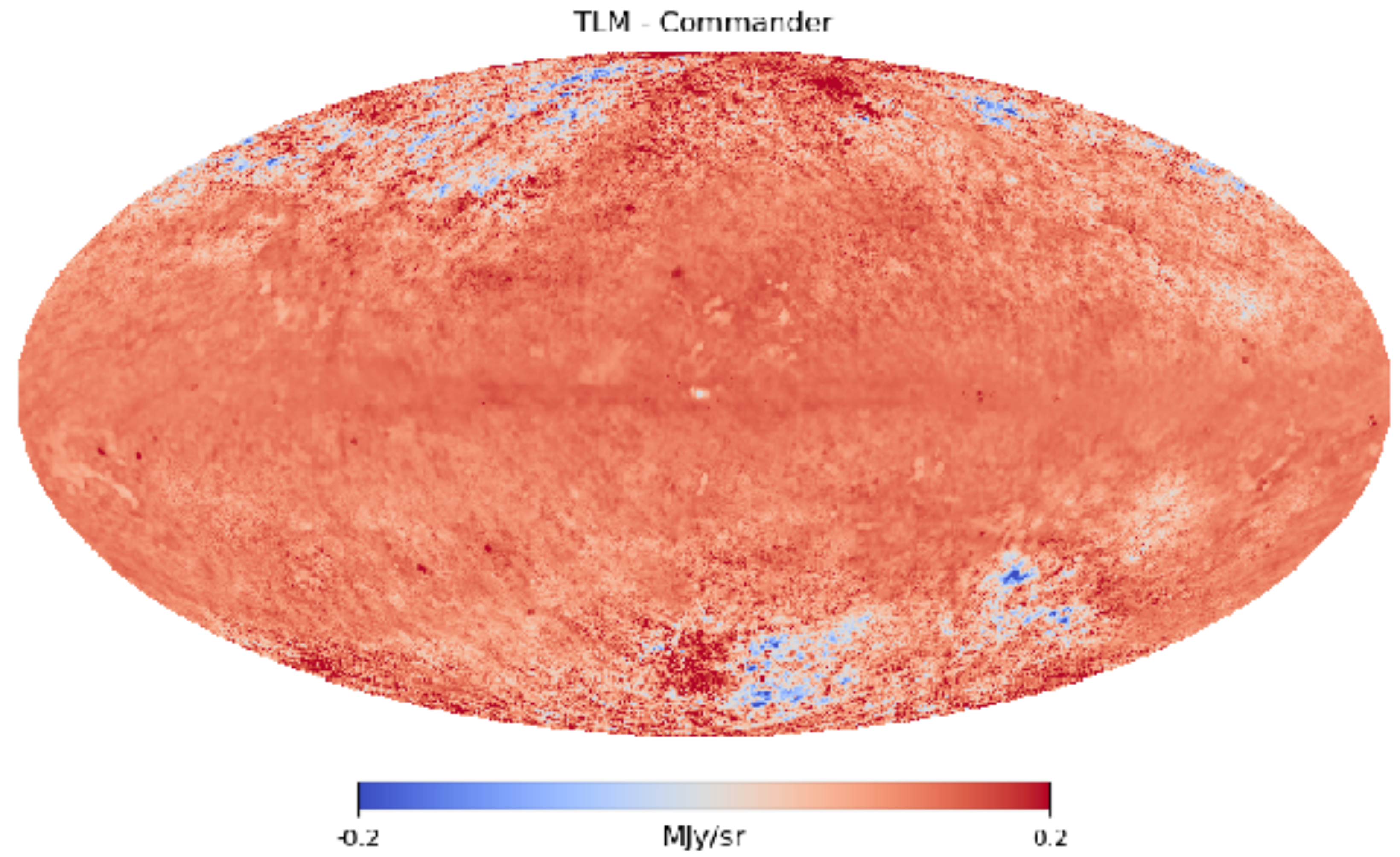
Optical depth maps

Dust Temperature distribution

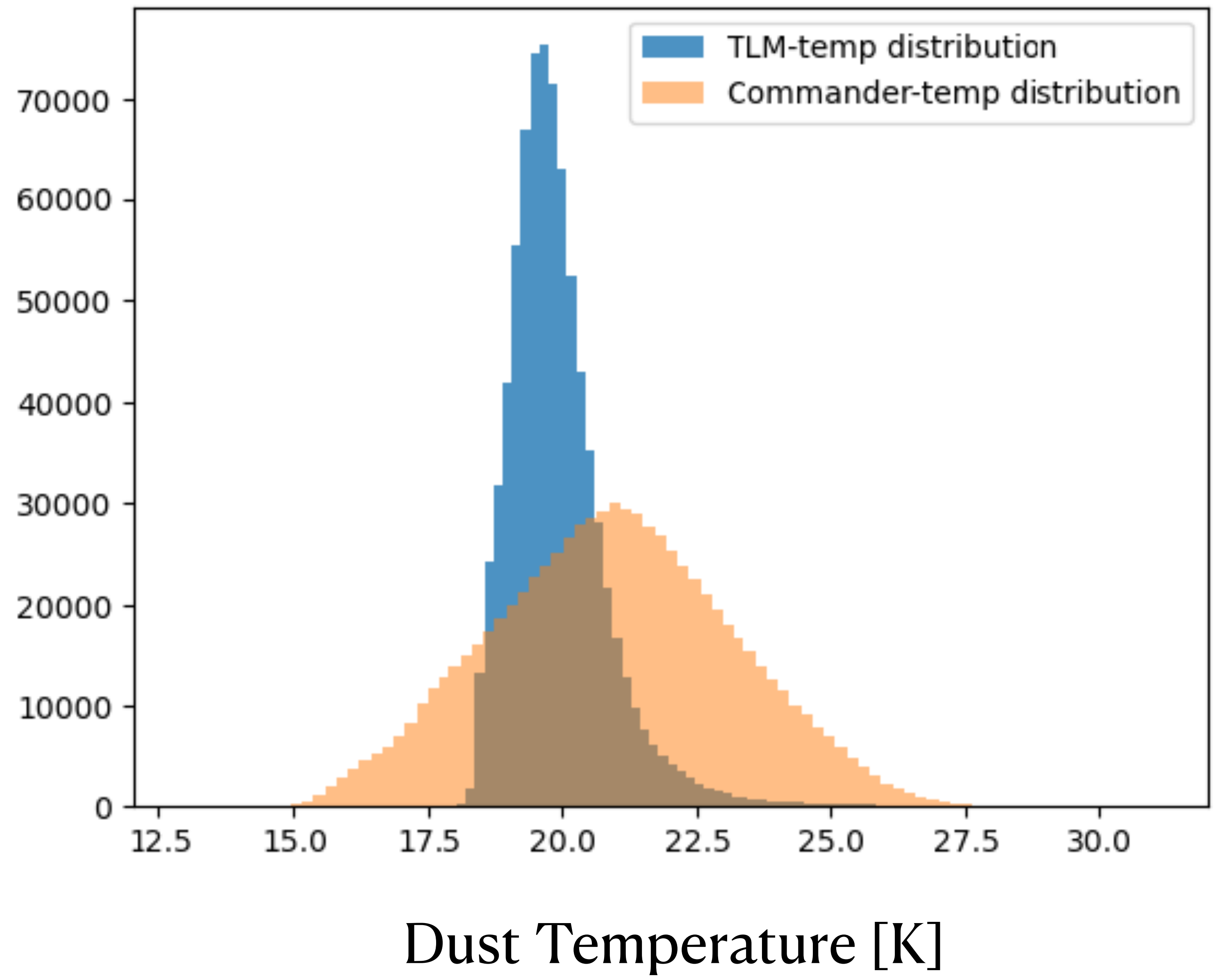




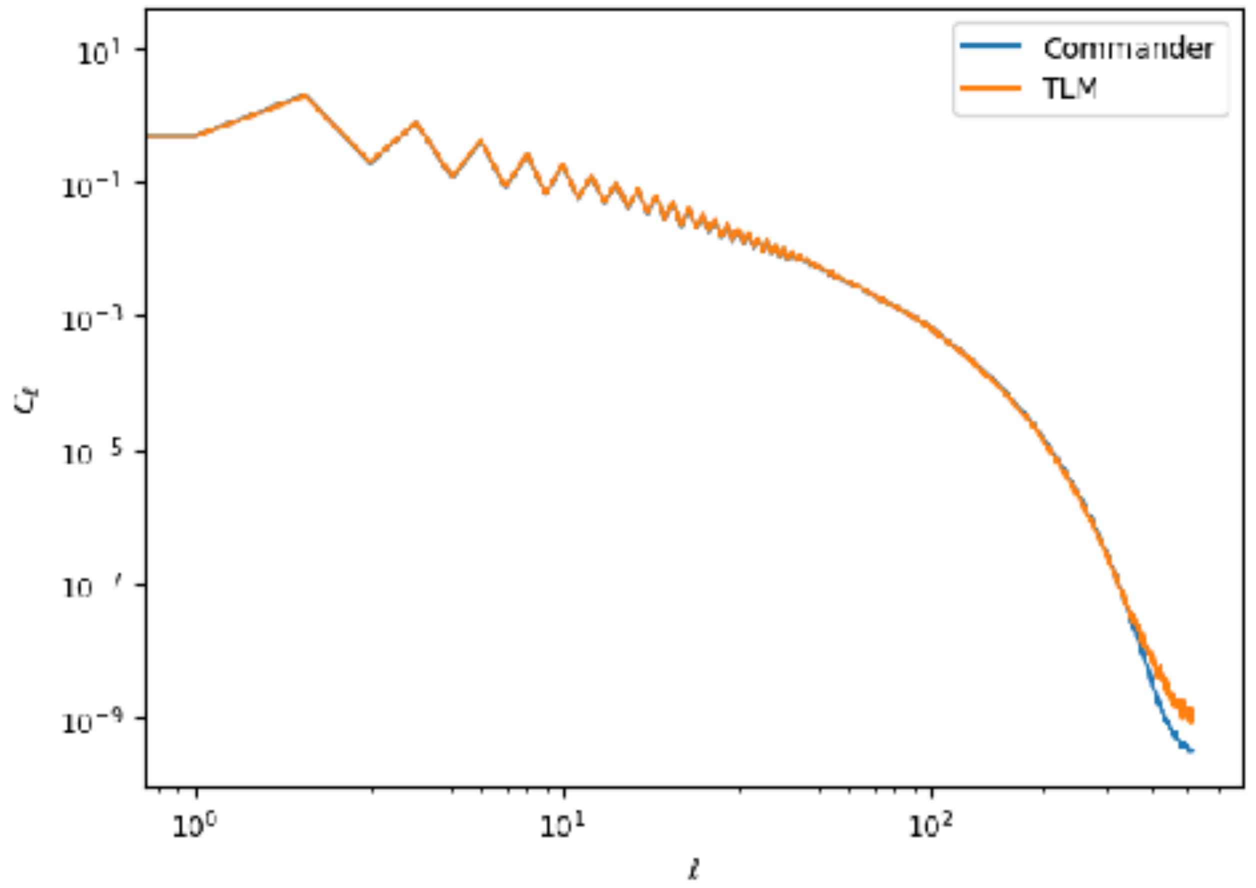
Comparison with Commander Dust Maps



Difference Map= $\frac{D_1 - D2}{(D_1 + D_2)/2}$

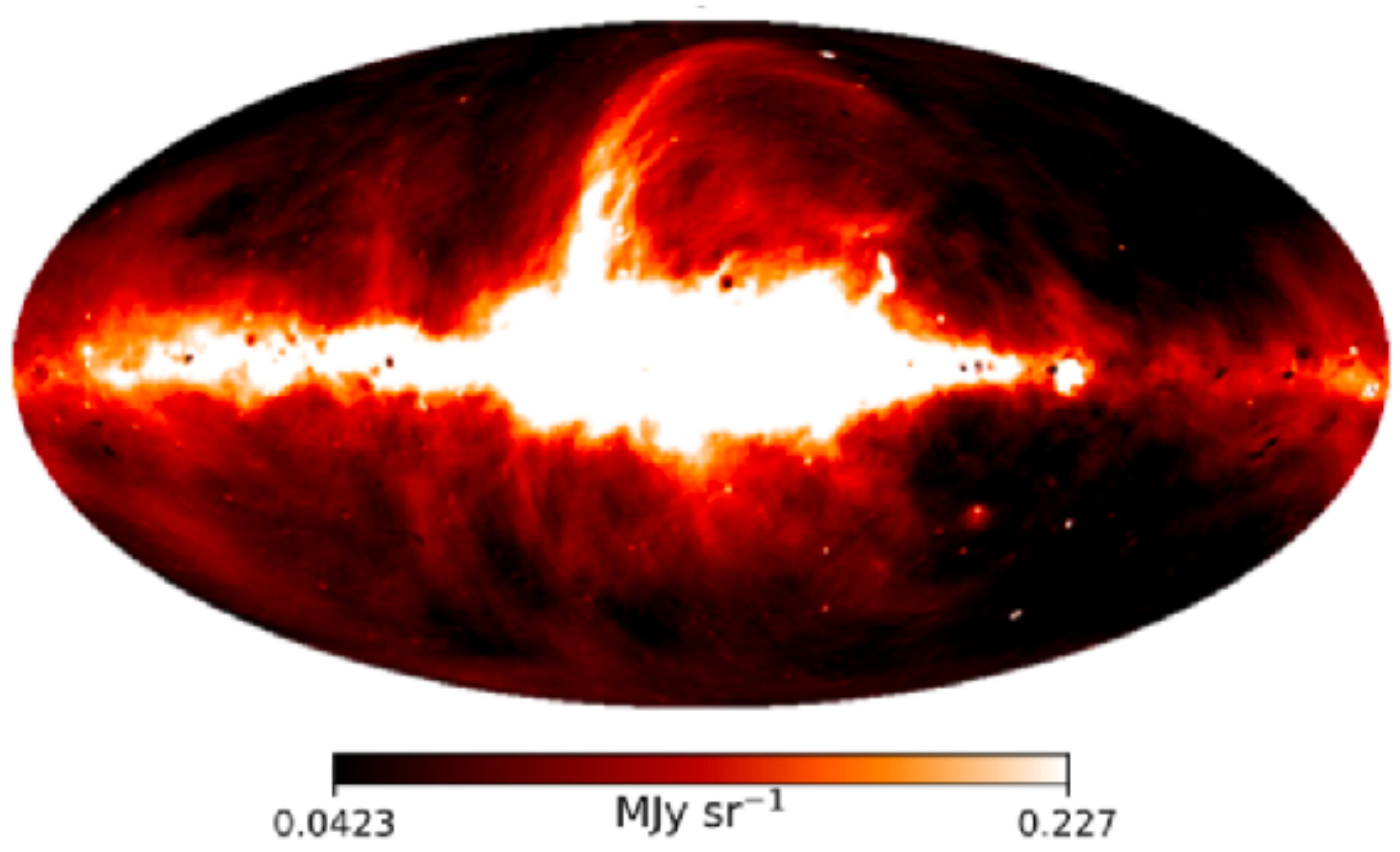


Angular Power Spectrum

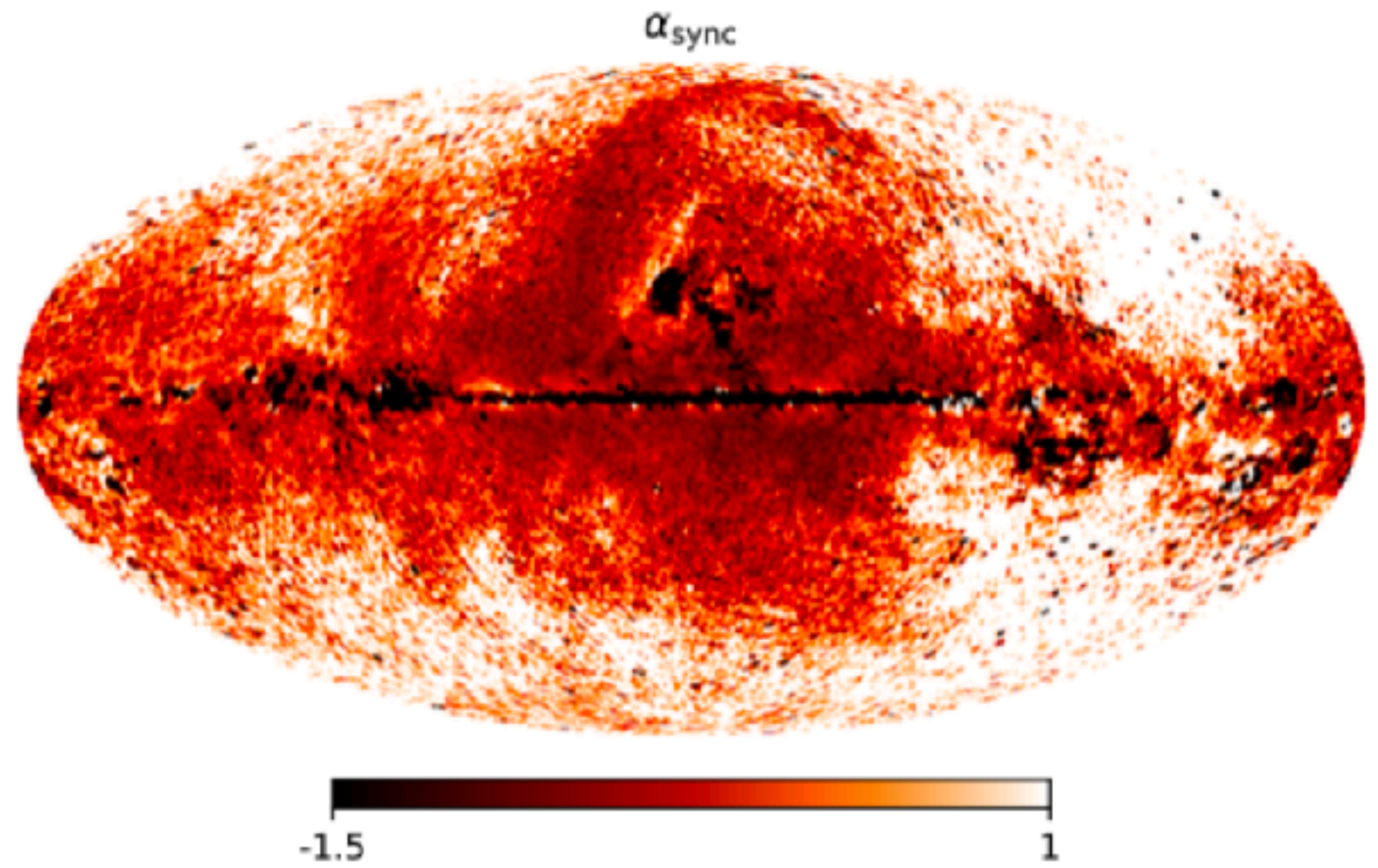


The Recovered Radio-Foregrounds: Synchrotron

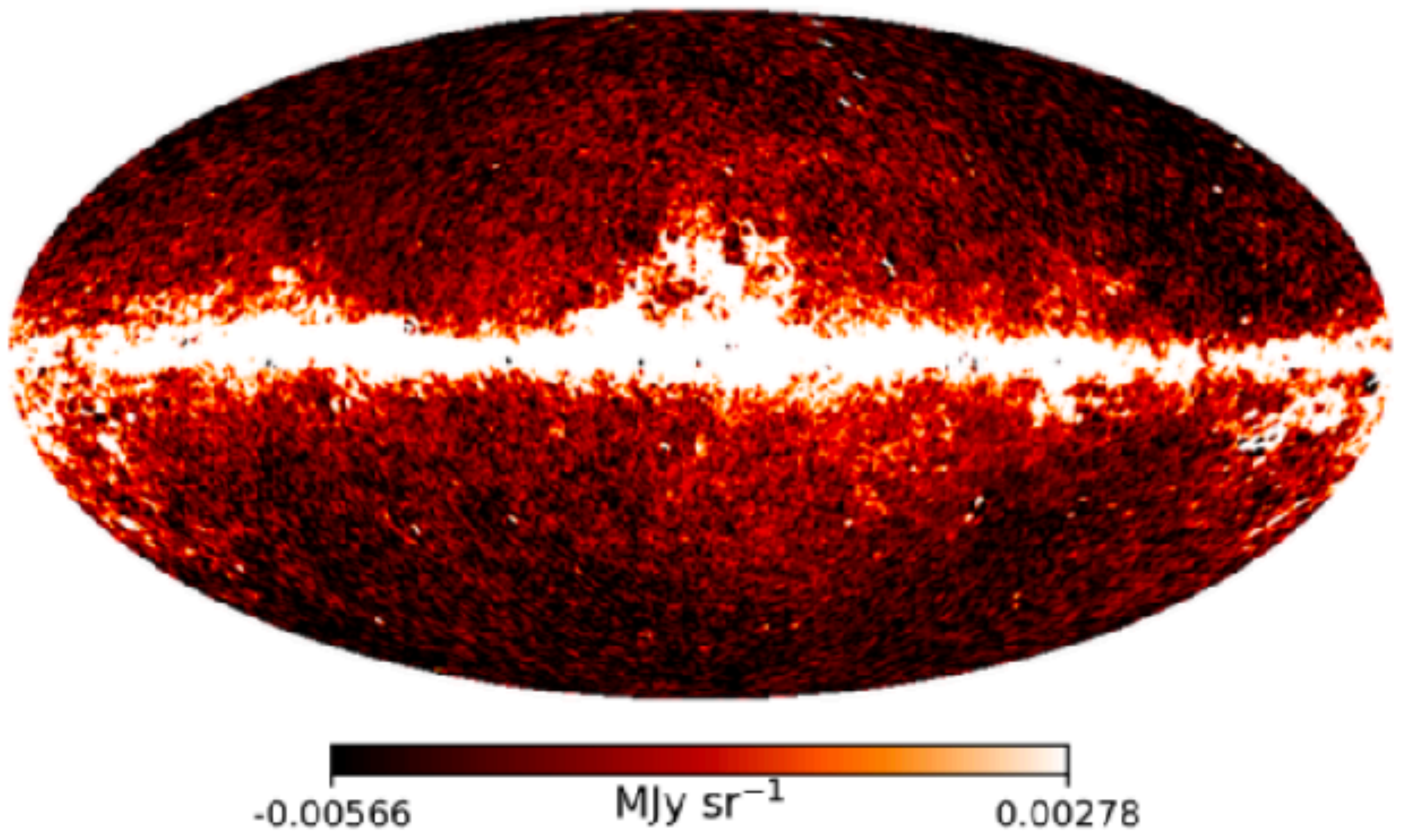
Synchrotron



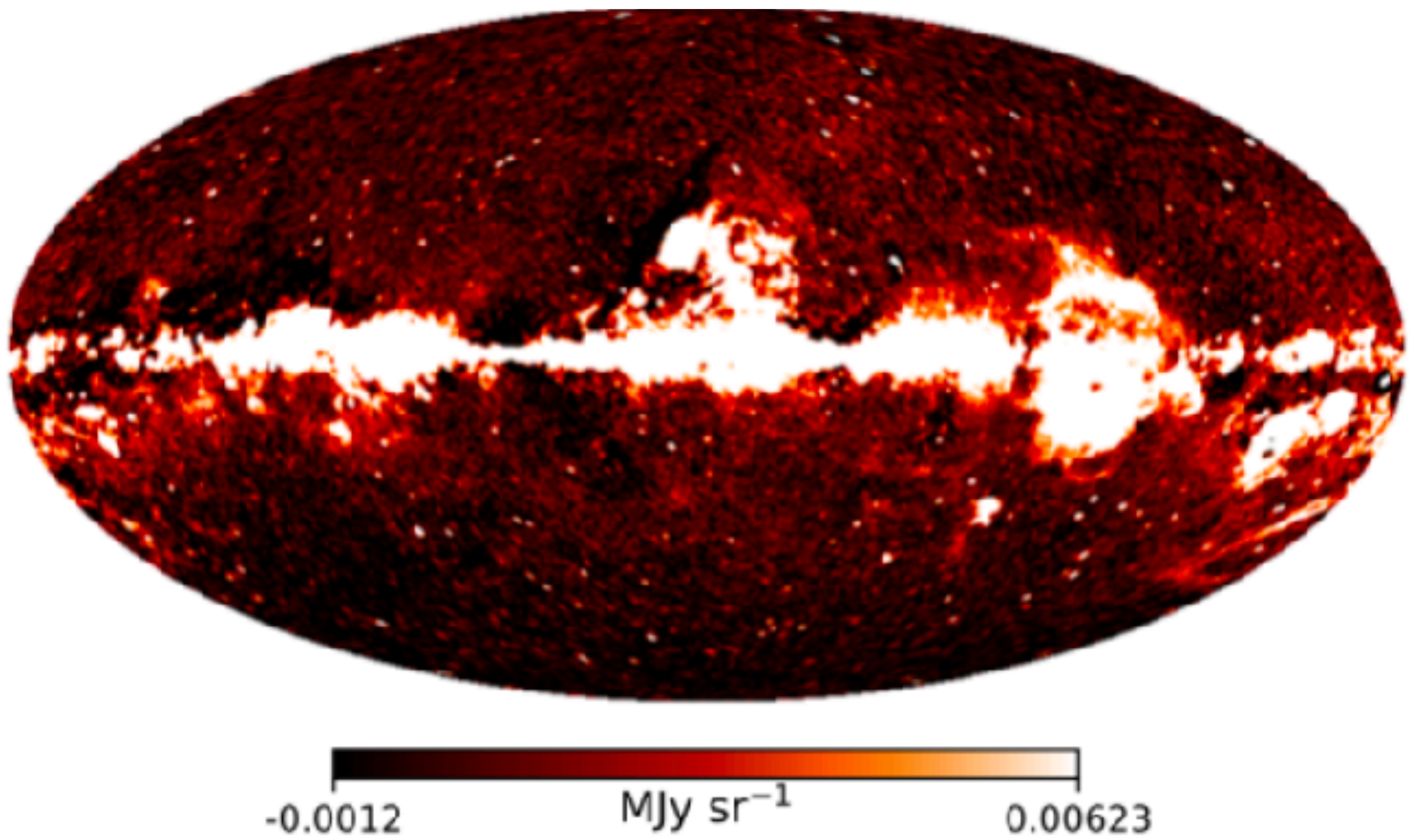
Synchrotron Spectral Index



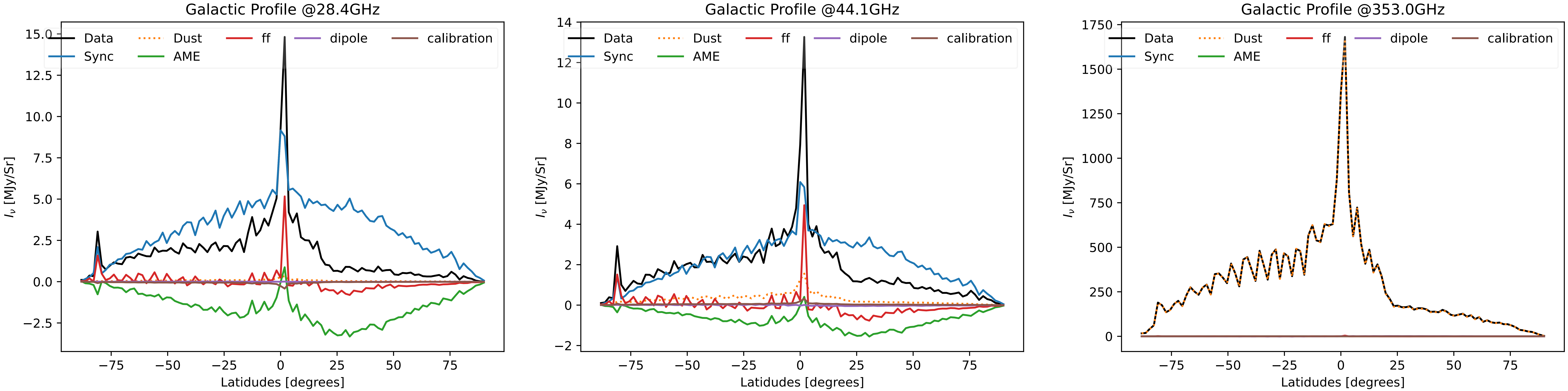
AME



Free-Free



Galactic Profiles of the Recovered Components



Summary and the next Steps

- In order to model the thermal dust emission, we implement a global fit with 8 parameters on a very wide range of frequencies. (408MHz-3000GHz).
- We achieve a good quality of fit on the data and recover the maps for dust optical depth and the mean temperature of the dust environments at both hot and cold temperatures.
- We recover the Thermal dust emissions with high level of accuracy and also compare the dust parameters with the standard Commander dust products.
- The galactic plane is very complex and may need additional TLM coefficients for a more accurate modeling.
- Our model is linear and hence the fit is computationally "cheap".
- We will explore the effect of changing the dust spectral parameter and its correlation with temperature.
- In the future, we plan to extend our analysis to the Polarized Planck data and propose models for polarized dust maps, derived using prior information from the temperature maps.

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Thank You