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Combining CMB Observations with Extinction Data to Create a 3D Dust Temperature Map

CMB-S4 Summer Collaboration Meeting

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Outline

Combining CMB Observations with Extinction Data:

- Create a 3D Dust Temperature Map
- Test and explain correlation between emission and extinction properties

Uses for a 3-D dust temperature map:

If we know where the stars are, we could estimate the radiation field

As a probe to study dust properties

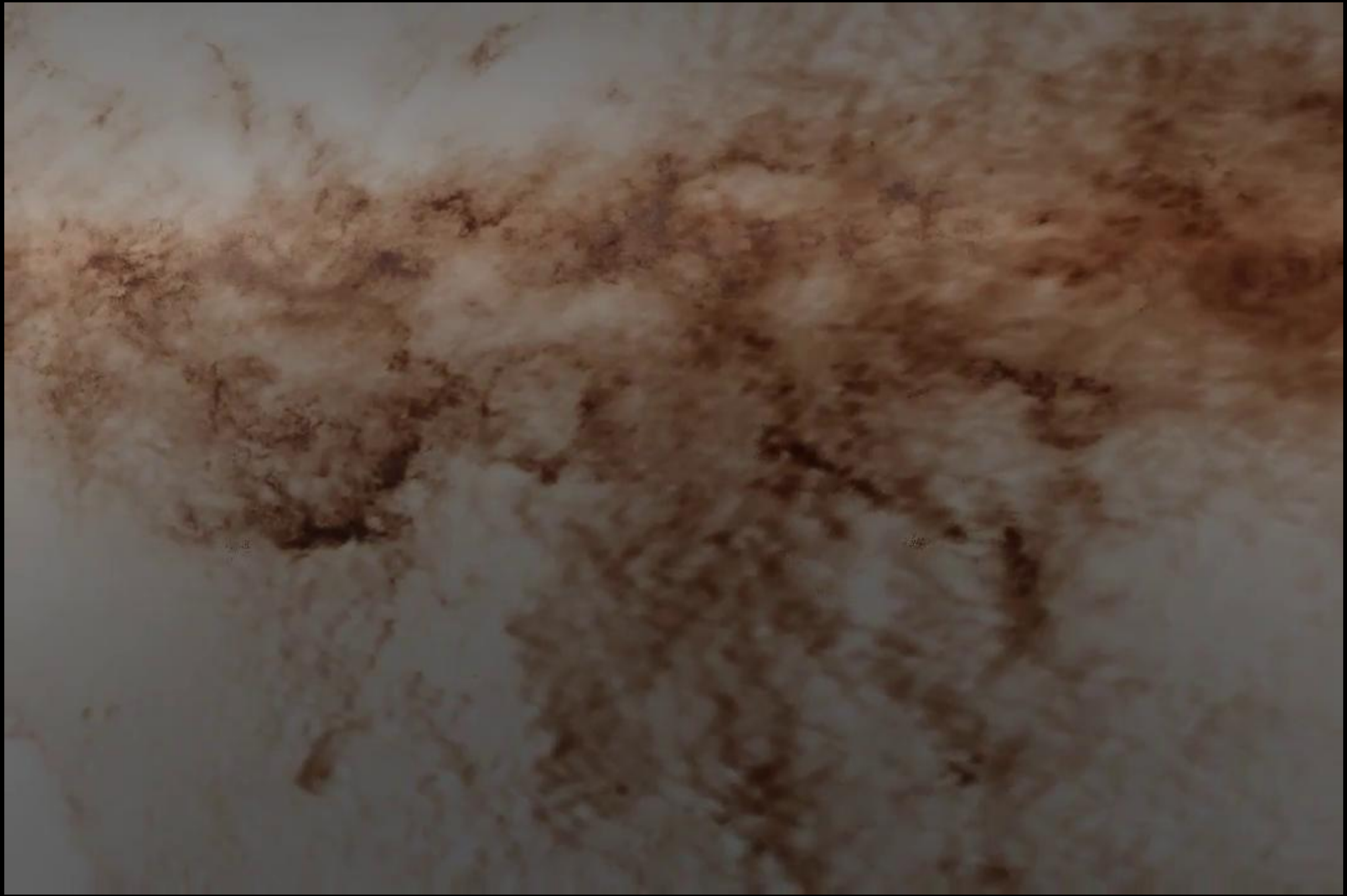
For foreground removal

Reconstruct polarized Planck maps using a B-field model, radiation field.

We have already: 3D Dust Reddening Map

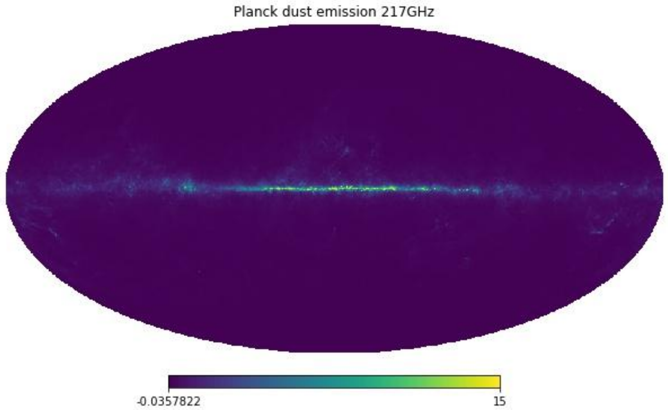
Green, Zucker, Speagel, Schlafly
(Green et al., 2019) have created a 3D maps of dust reddening

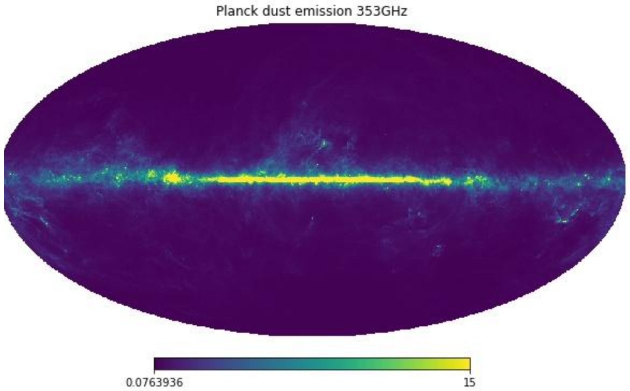
My goal: make a 3D Dust Temperature map

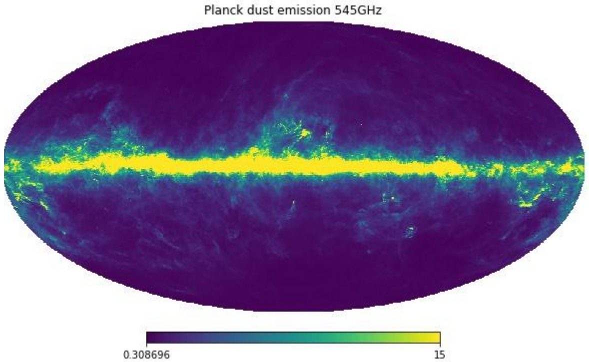


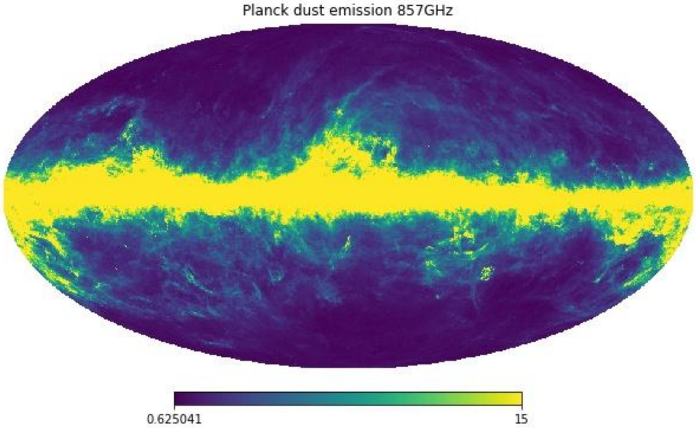
Credit: Greg Green, http://argonaut.skymaps.info/

Planck 217, 353, 545, 857GHz and SFD 3000 GHz.

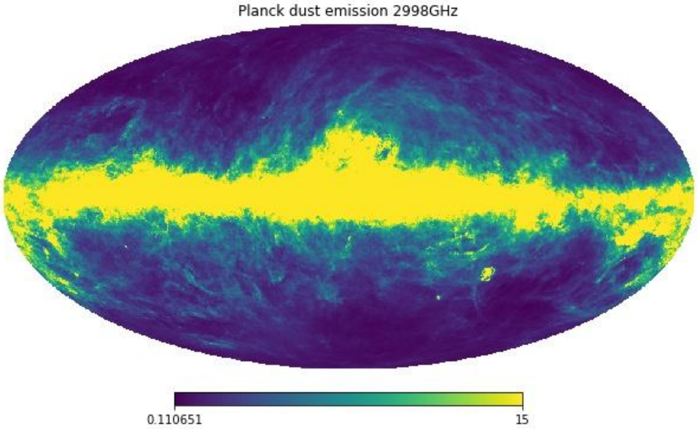


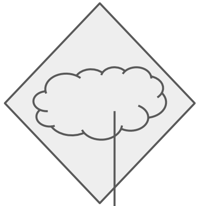






SFD/IRAS+DIRBE



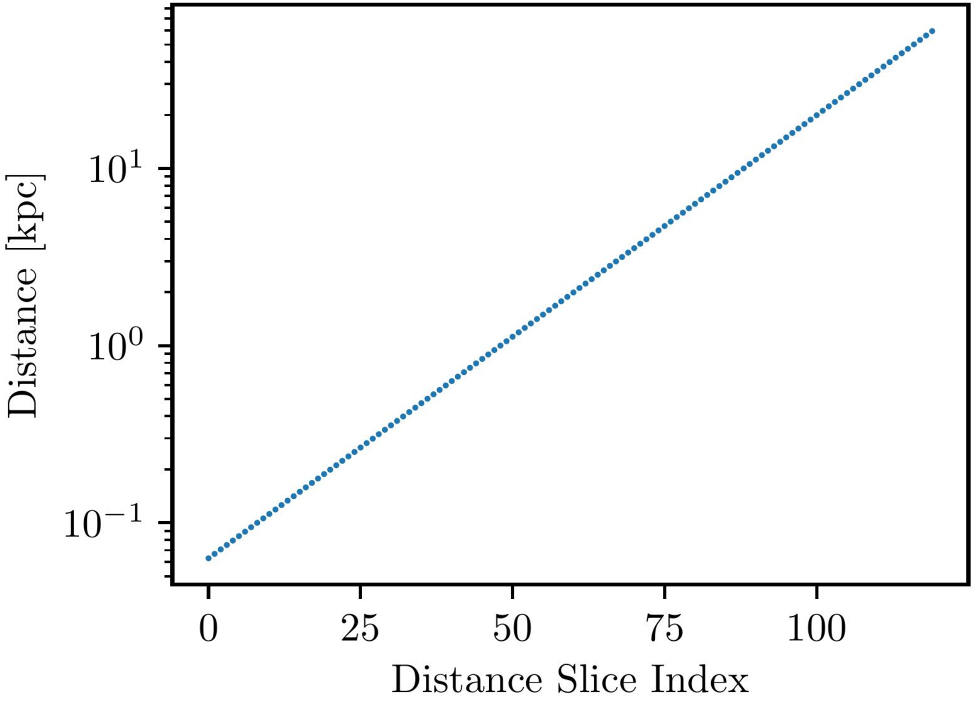


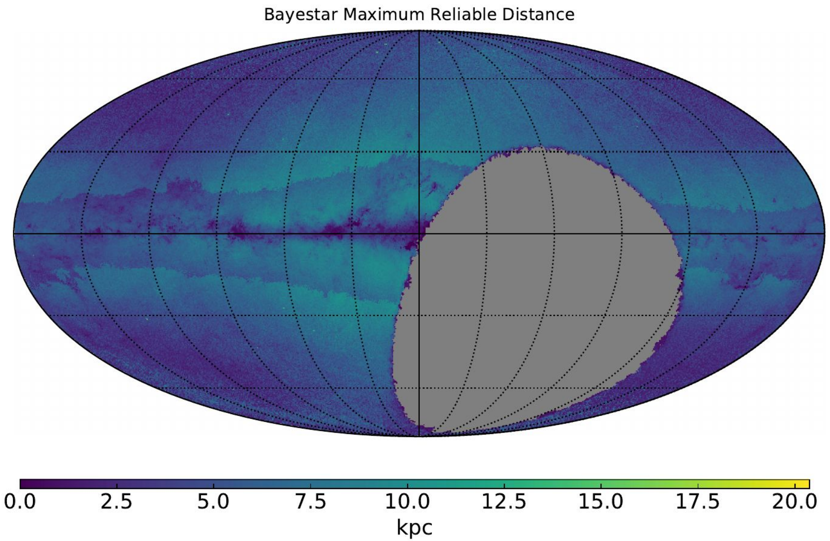
Bayestar $\Delta E^{n,k}_{\text{B-V}}$

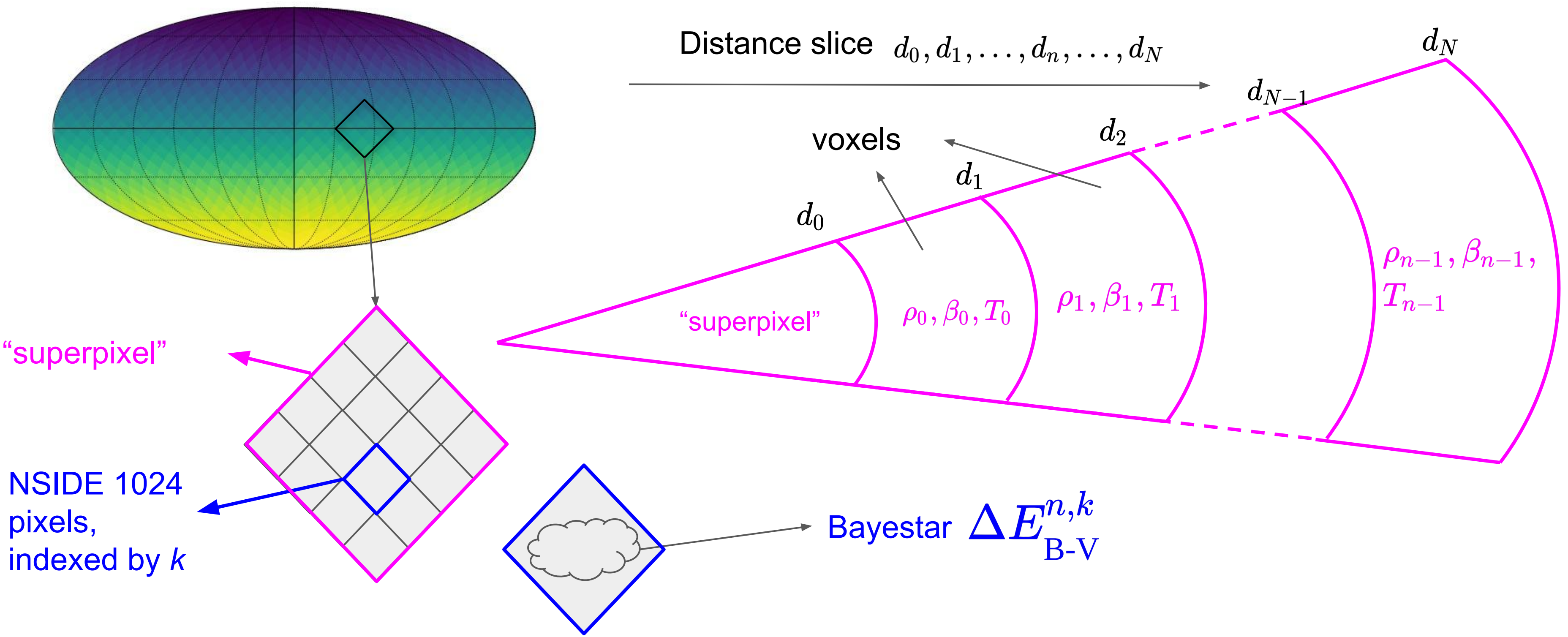
$$\tau^{n,k}_{353} = \rho^{n}_{353} \Delta E^{n,k}_{\text{B-V}}$$

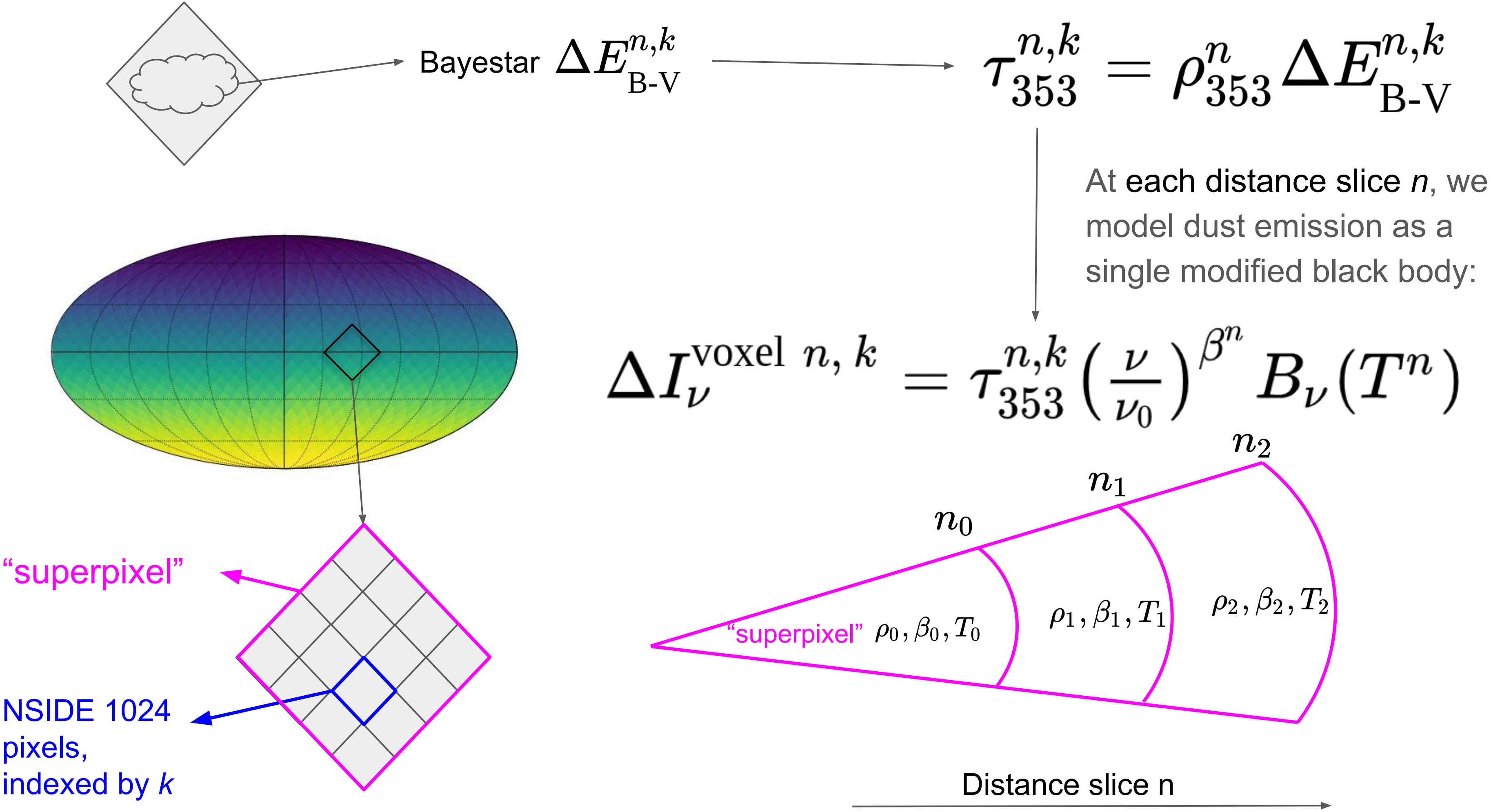
Extra: Testing the variance of ρ across the sky. ρ is the conversion factor used in SFD to move between extinction and emission maps.

Bayestar gives us the reddening at 120 distance bins






Distance slice $d_0, d_1, \ldots, d_n, \ldots, d_N$
voxels
d_0
d_1
d_2
d_{N-1}
d_N
"superpixel"
ρ_0, β_0, T_0
ρ_1, β_1, T_1
$\rho_{n-1}, \beta_{n-1}, T_{n-1}$
"superpixel"
NSIDE 1024 pixels, indexed by *k*
Bayestar $\Delta E_{\text{B-V}}^{n,k}$



Bayestar $\Delta E_{\text{B-V}}^{n,k}$
$\tau_{353}^{n,k} = \rho_{353}^{n} \Delta E_{\text{B-V}}^{n,k}$
At each distance slice *n*, we model dust emission as a single modified black body:
$\Delta I_{\nu}^{\text{voxel } n,\, k} = \tau_{353}^{n,k} \left(\frac{\nu}{\nu_0}\right)^{\beta^n} B_{\nu}(T^n)$
"superpixel"
NSIDE 1024 pixels, indexed by *k*
n_0
n_1
n_2
"superpixel"
ρ_0, β_0, T_0
ρ_1, β_1, T_1
ρ_2, β_2, T_2
Distance slice n

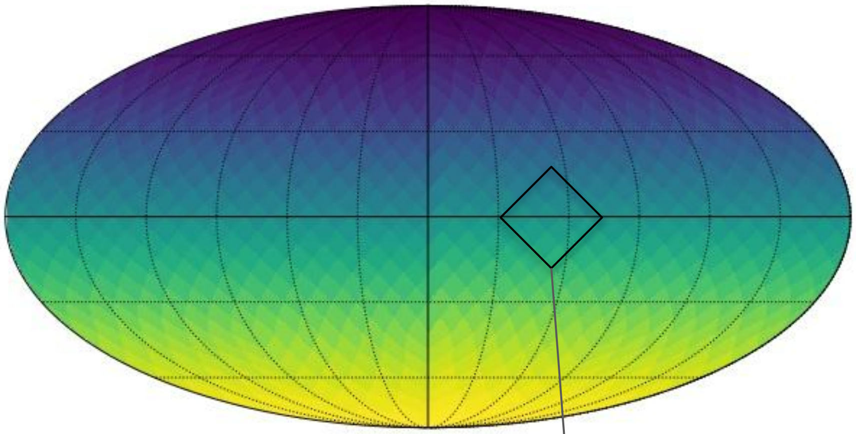
Calculating emission for a pixel within a "superpixel"

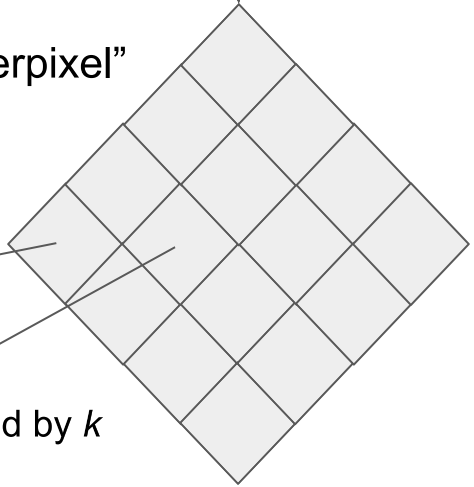
$$\tau_{353}^{n,k} = \rho_{353}^{n} \Delta E_{\text{B-V}}^{n,k}$$

At each distance slice *n*, we model dust emission as a single modified black body:

$$\Delta I_{\nu}^{\text{voxel } n,\, k} = \tau_{353}^{n,k} \left(\frac{\nu}{\nu_0}\right)^{\beta^n} B_{\nu}(T^n)$$

$$I_{\nu}^{\text{total}\,,k} = O_{\nu} + \sum_n \Delta I_{\nu}^{\text{voxel } n,\, k}$$





Model Analysis for Each Superpixel

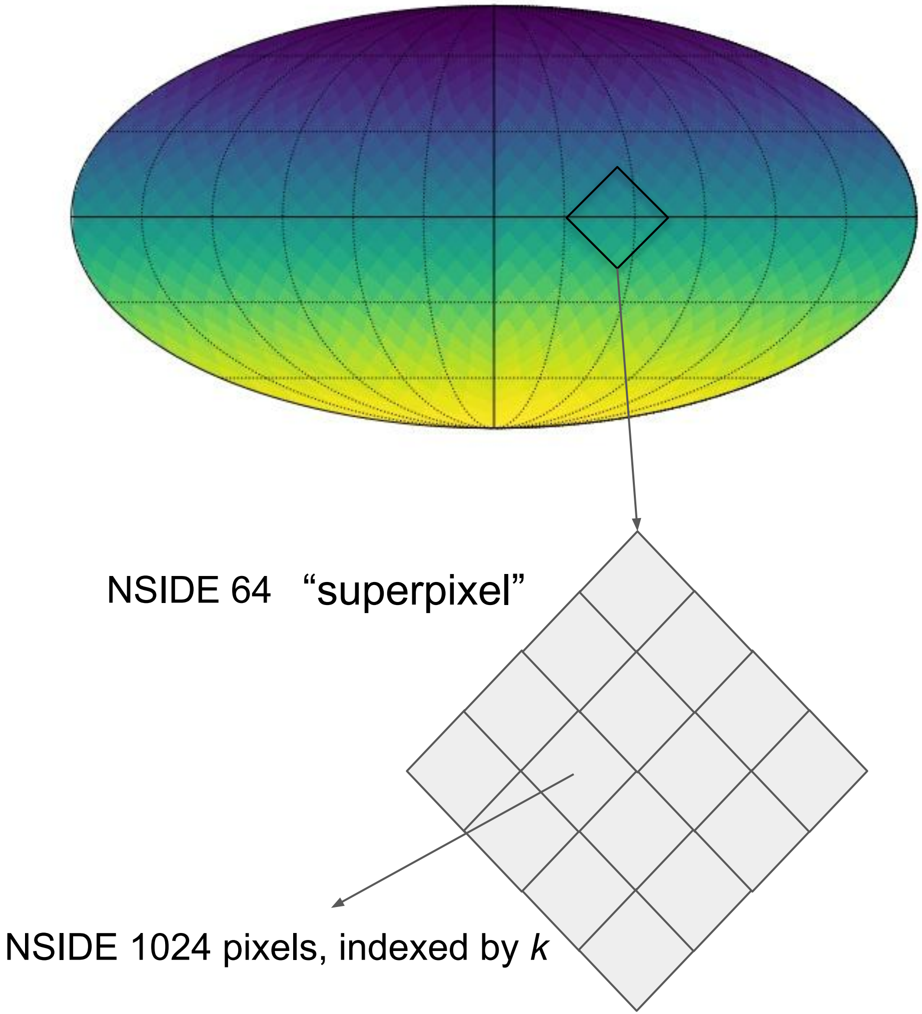
$$p(\theta|\mathrm{D}) = \frac{p(\mathrm{D}|\theta)p(\theta)}{p(\mathrm{D})}$$

Our data are:

$$\{I_\nu^{\mathrm{D},k}\}, \{\sigma_\nu^{\mathrm{D}}\}, \{\Delta E_{\text{B-V}}^{k,n}\}$$

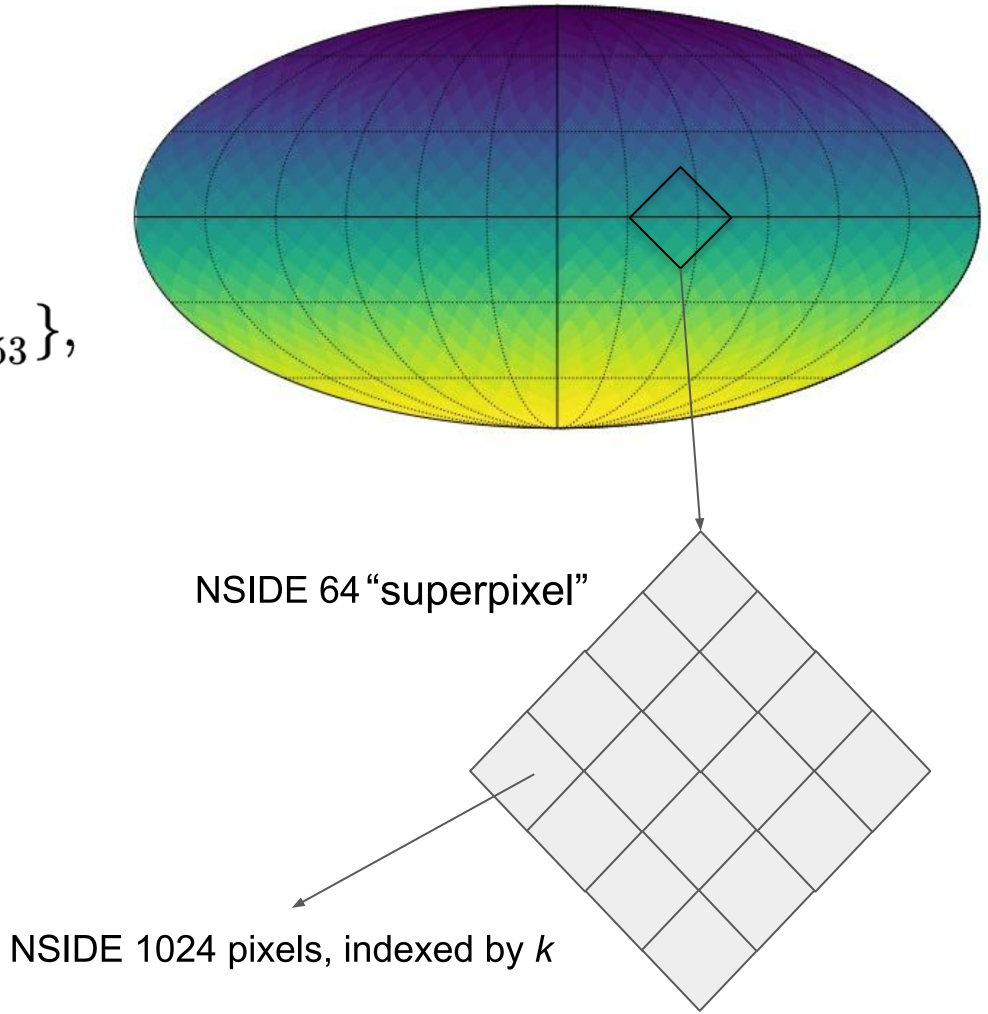
The model parameters are:

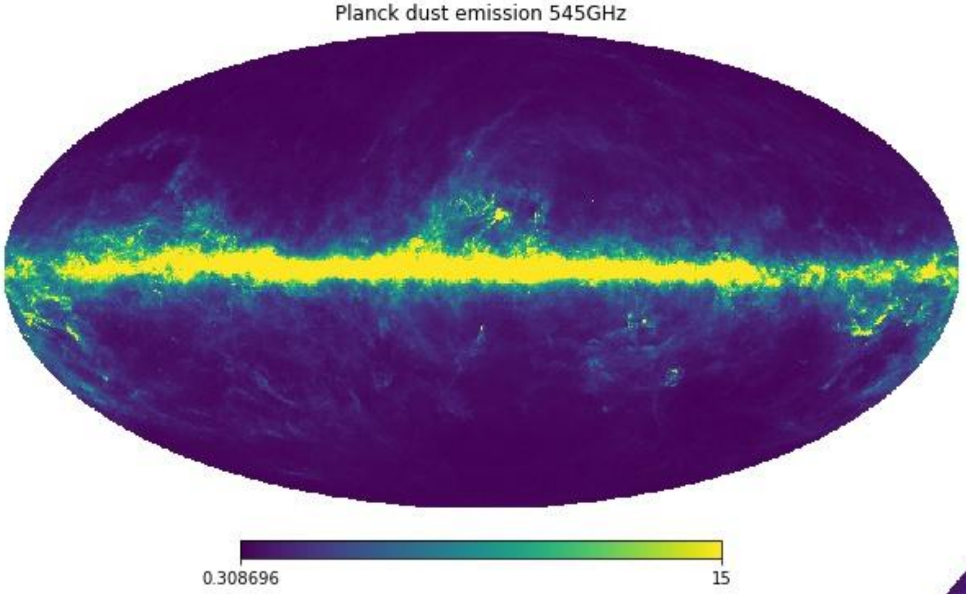
$$\{\rho_{353}^n\}, \{\beta^n\}, \{T^n\}, \{O_\nu\}$$

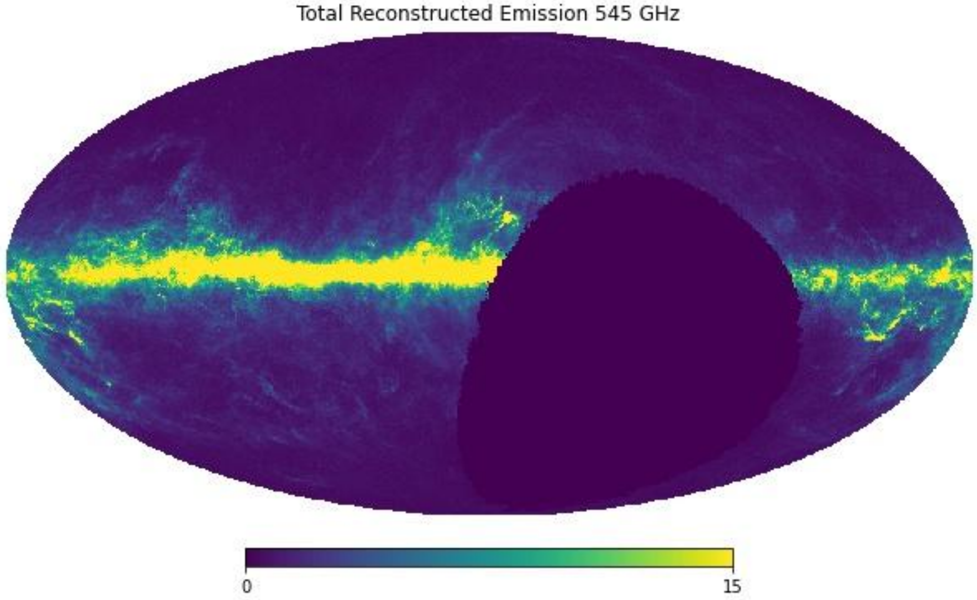


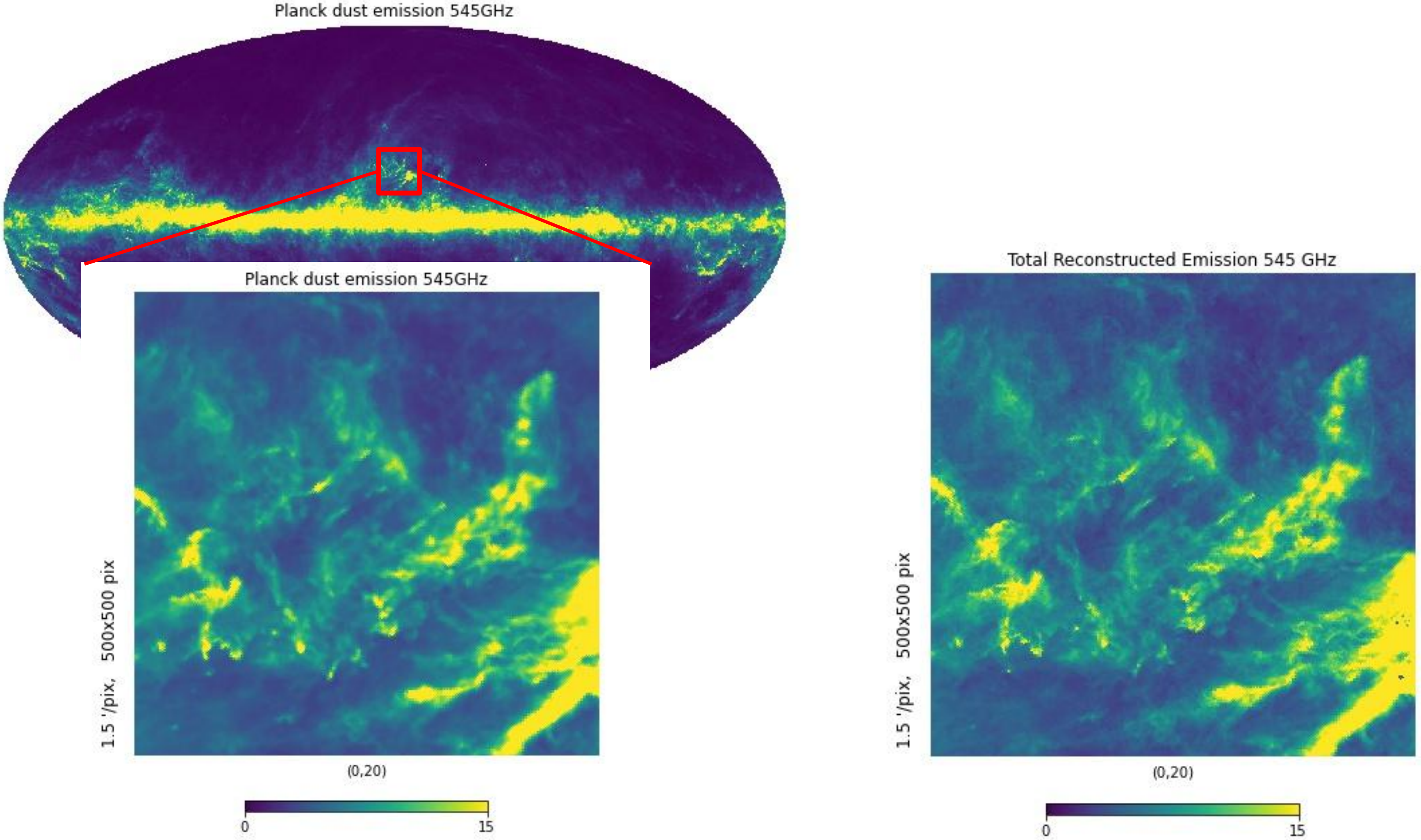
Model Analysis for Each Superpixel

$$
\begin{aligned}
\mathcal{L} &= p(\mathrm{D}|\theta) \\
&= p(\{I_\nu^{\mathrm{D},k}\}, \{\sigma_\nu^{\mathrm{D}}\}, \{\Delta E_{\text{B-V}}^{k,n}\} | \{\rho_{353}^n\}, \\
&\qquad \{\beta^n\}, \{T^n\}) \\
&= \prod_k \prod_\nu \frac{1}{\sqrt{2\pi {\sigma_\nu^{\mathrm{D}}}^2}} \exp \\
&\quad -(I_\nu^{\mathrm{total},k} - I_\nu^{\mathrm{D},k})^2 / 2{\sigma_\nu^{\mathrm{D}}}^2
\end{aligned}
$$

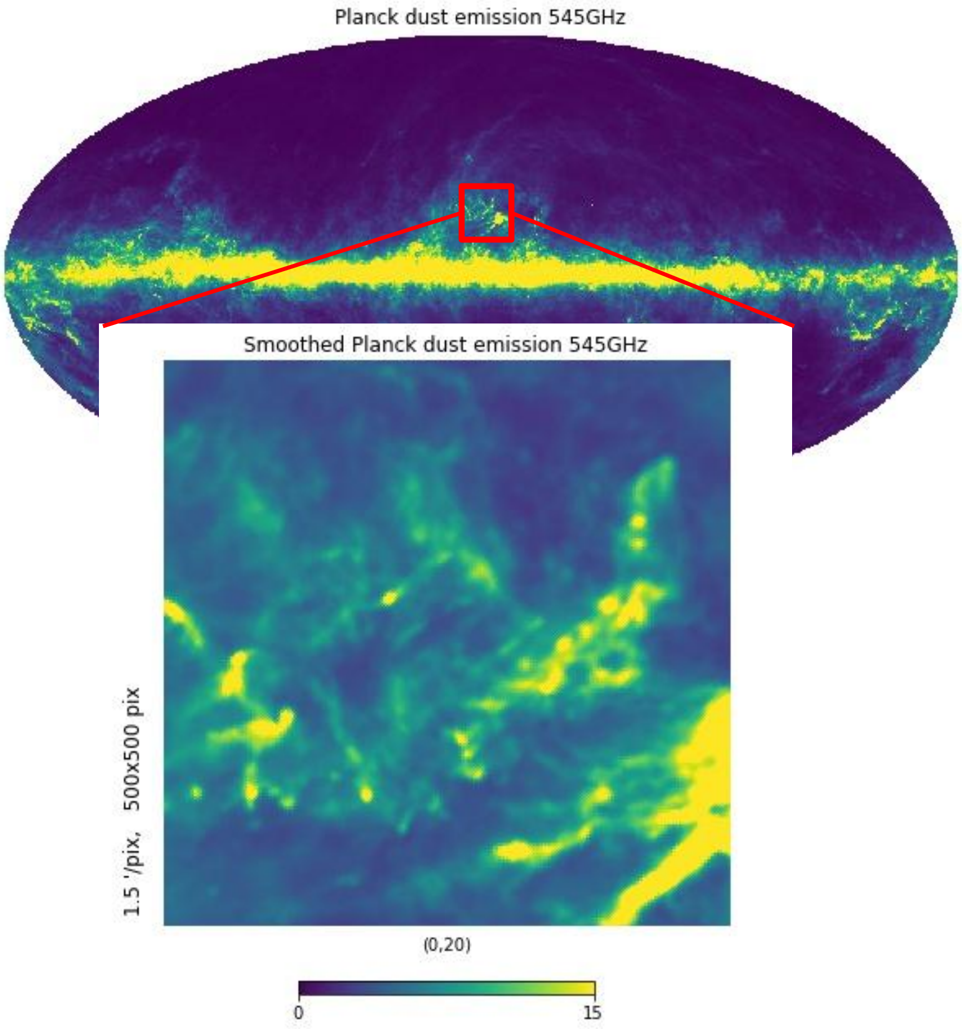


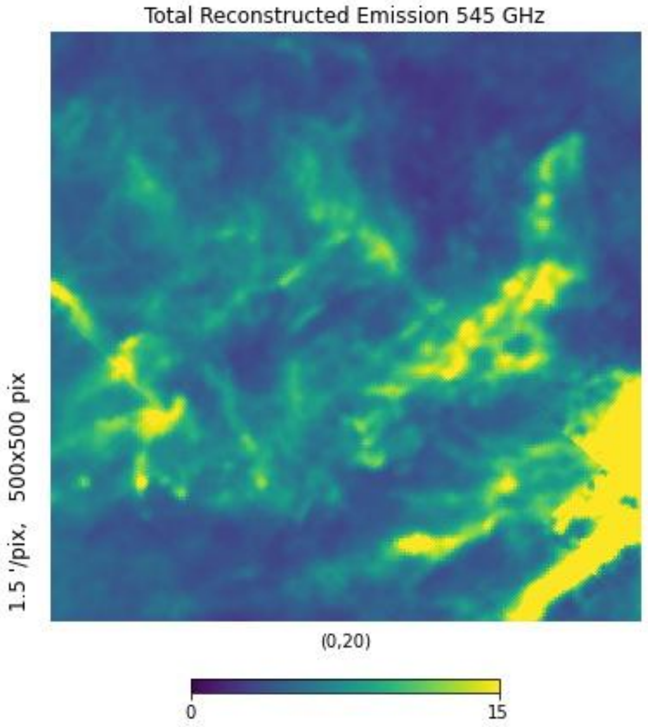

Planck dust emission 545GHz
0.308696
15

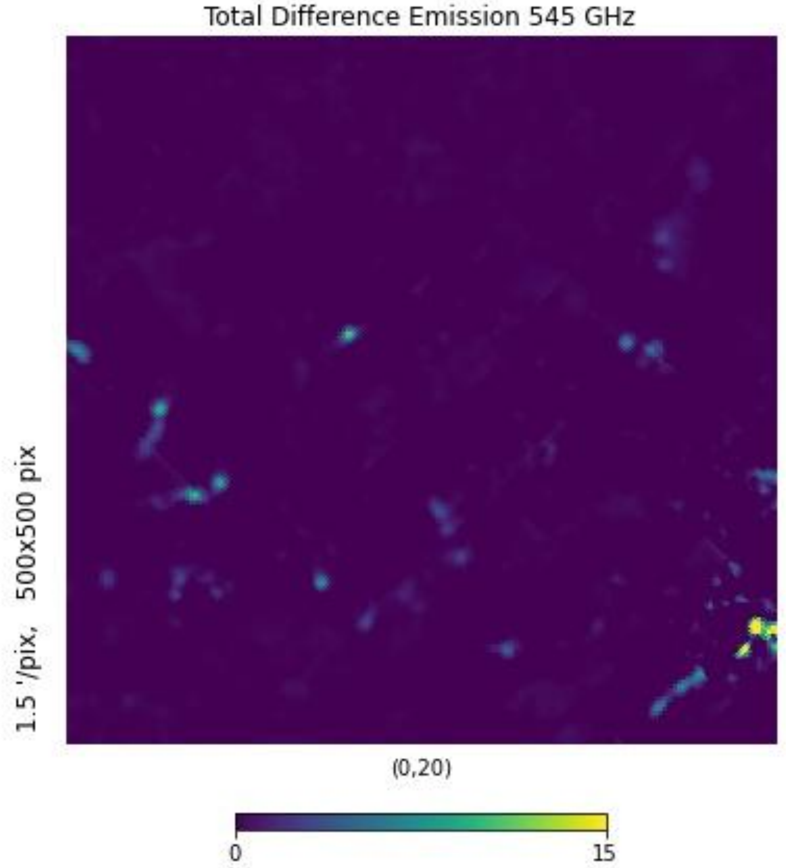

Total Reconstructed Emission 545 GHz
0
15


Planck dust emission 545GHz
Planck dust emission 545GHz
1.5 '/pix, 500x500 pix
(0,20)
0
15
Total Reconstructed Emission 545 GHz
1.5 '/pix, 500x500 pix
(0,20)
0
15

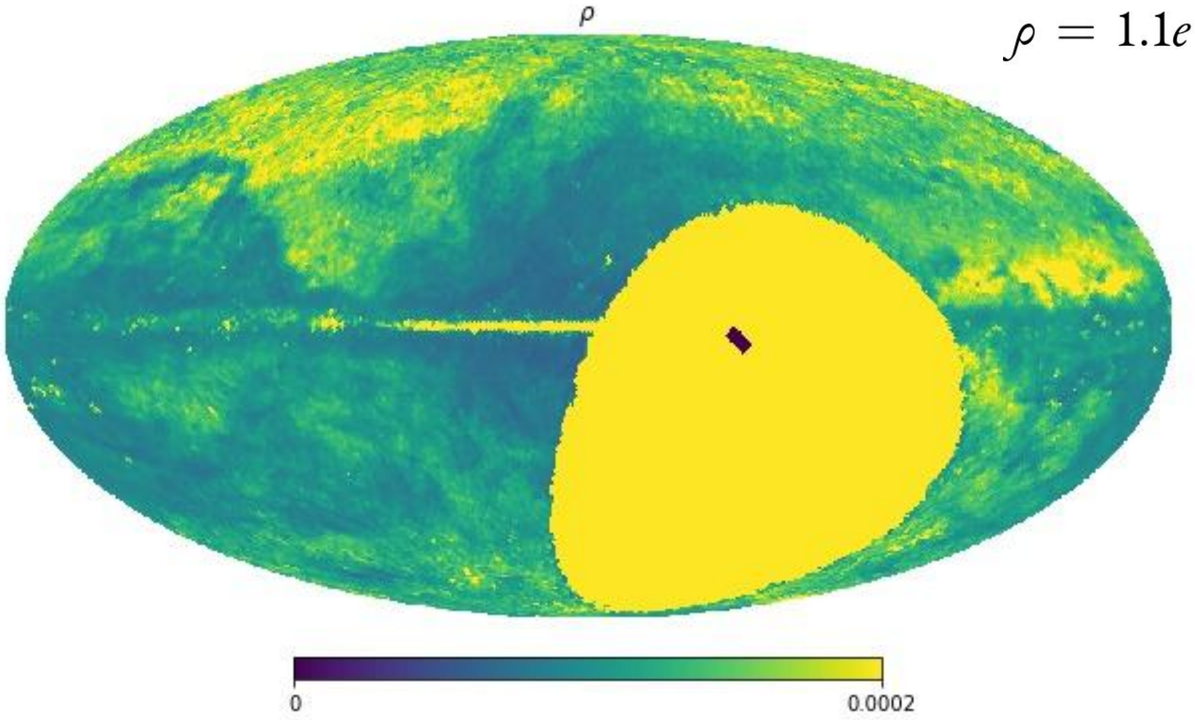
Matching the “PSF”



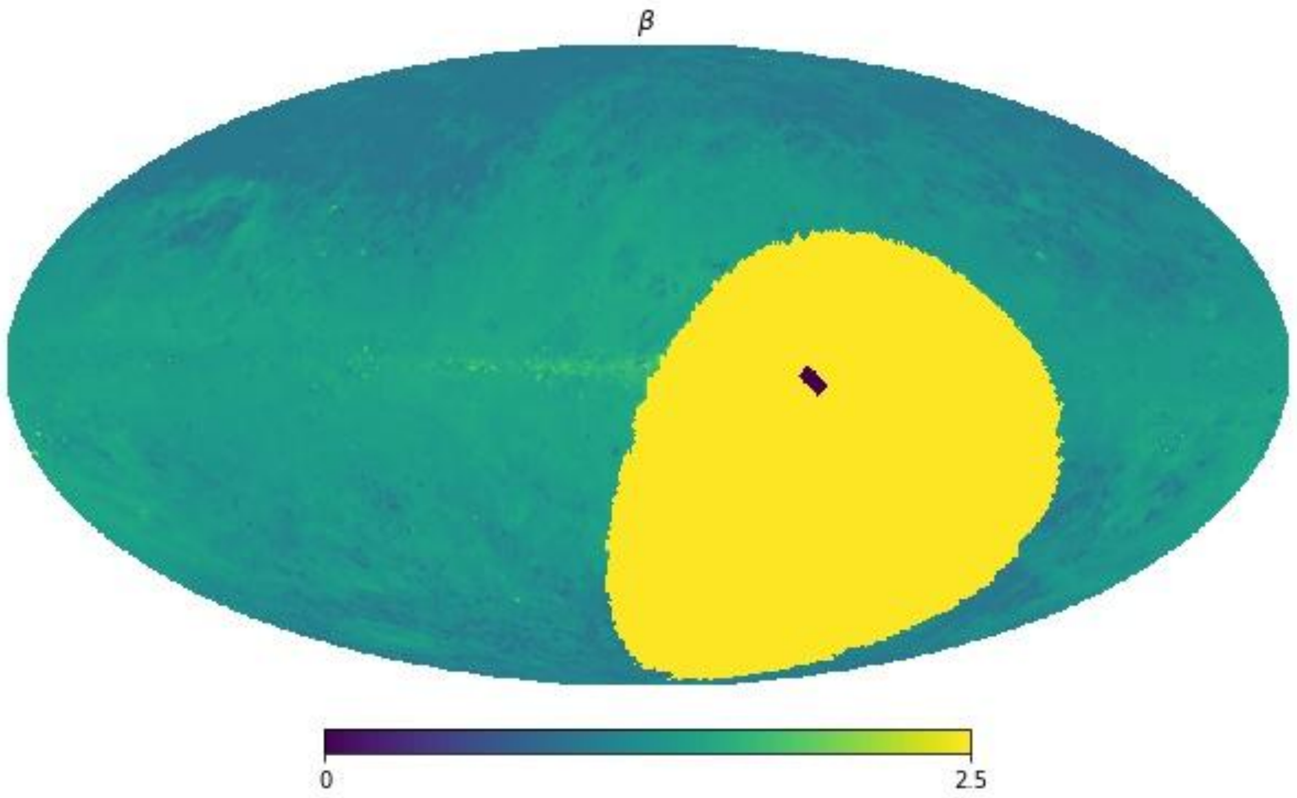



Total Difference Emission 545 GHz
1.5 '/pix,   500x500 pix
(0,20)
0
15

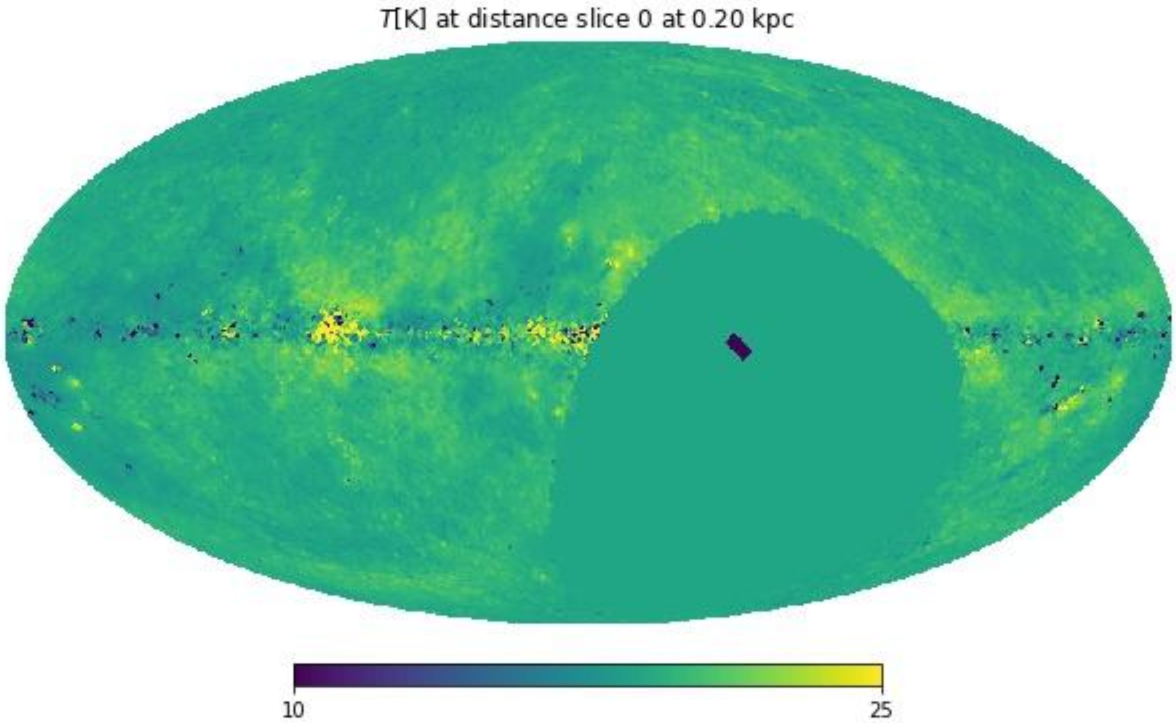
Variation of the ρ conversion factor

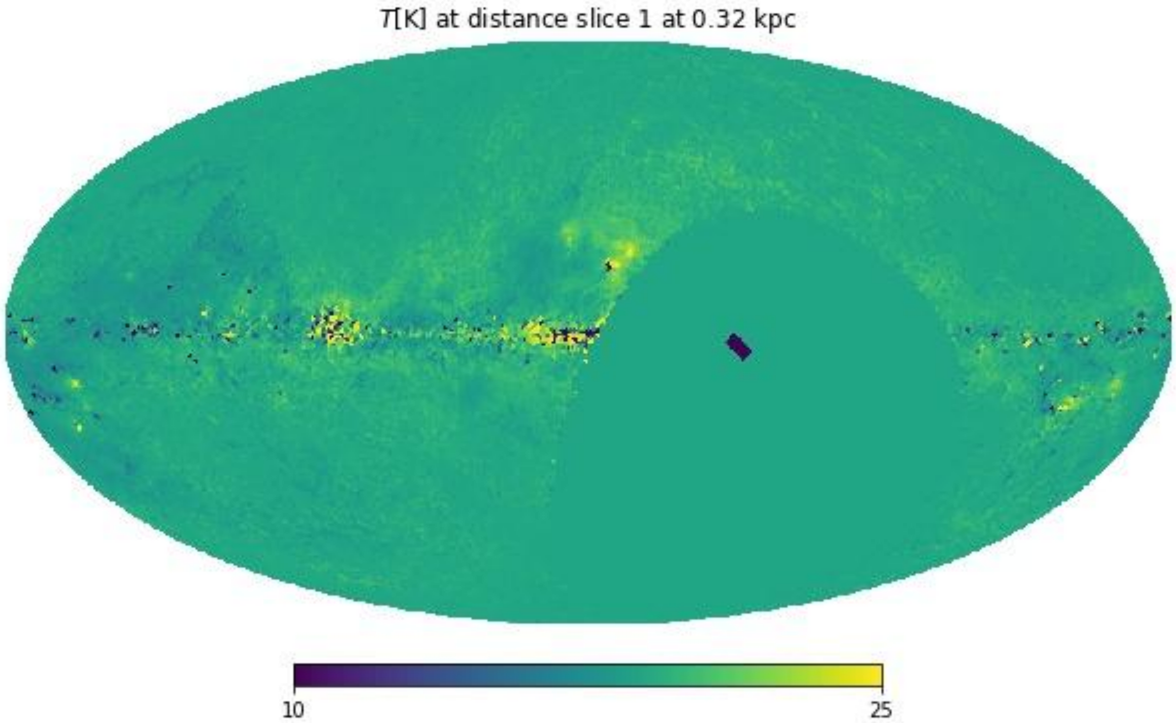


$$\rho = 1.1e - 04^{+2.5e-04}_{-3.0e-05}$$

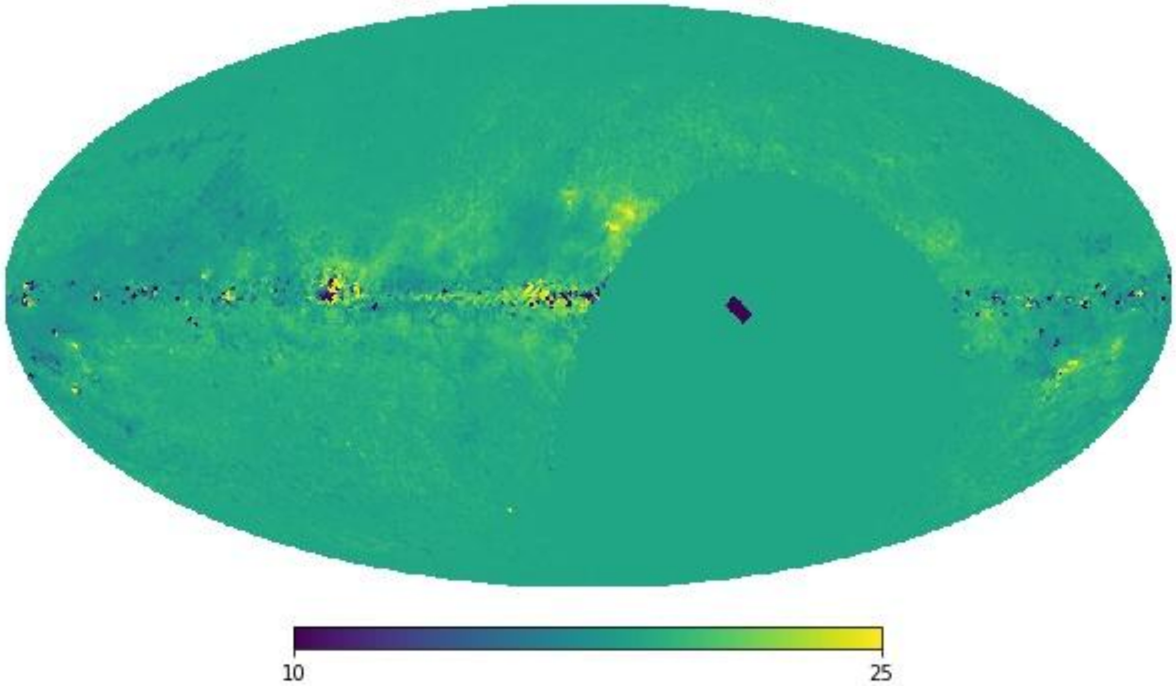


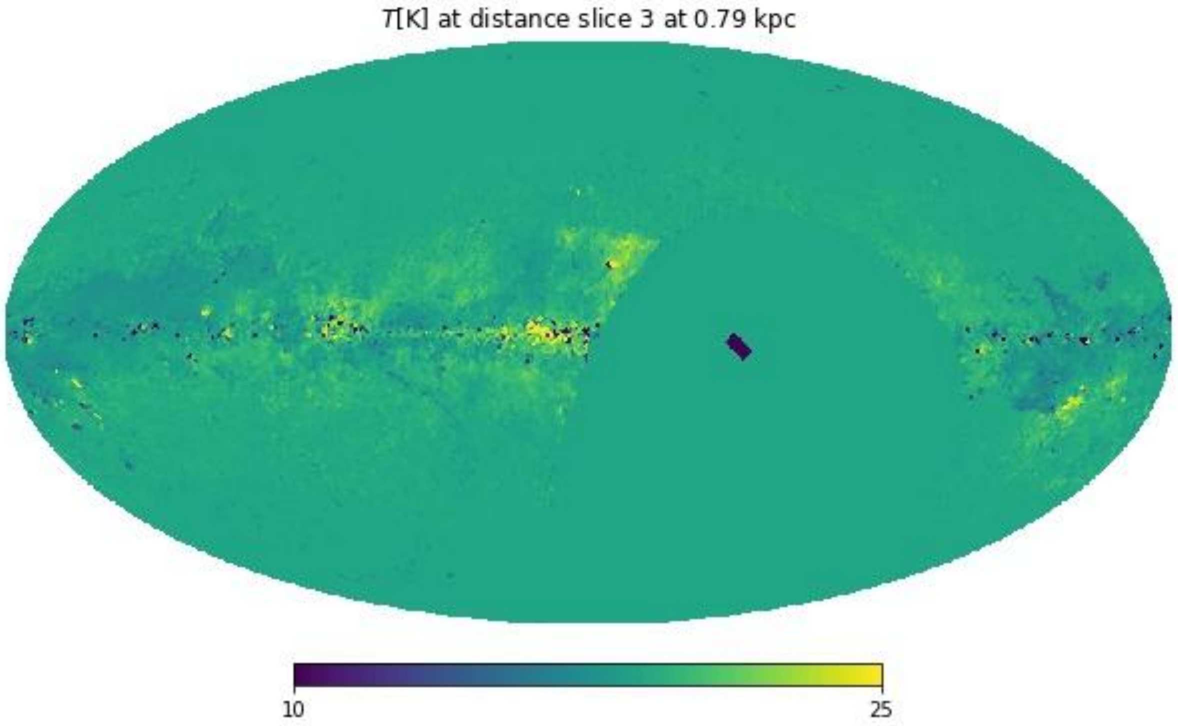
β
0
2.5


T[K] at distance slice 0 at 0.20 kpc
10
25

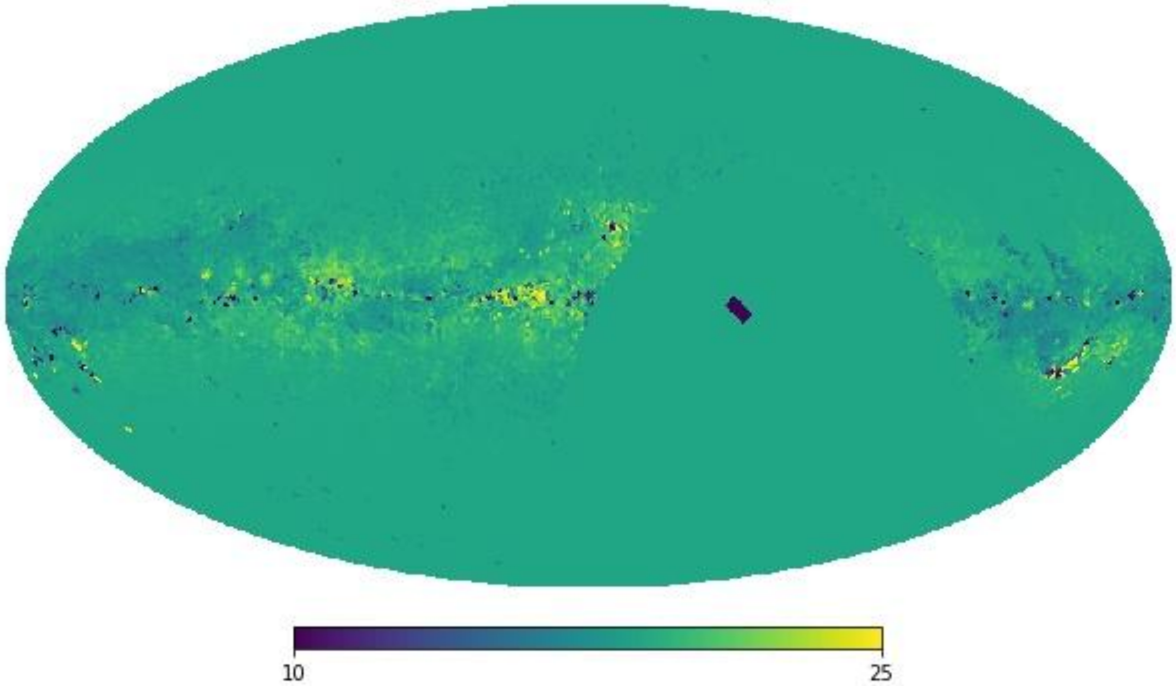

T[K] at distance slice 1 at 0.32 kpc
10
25

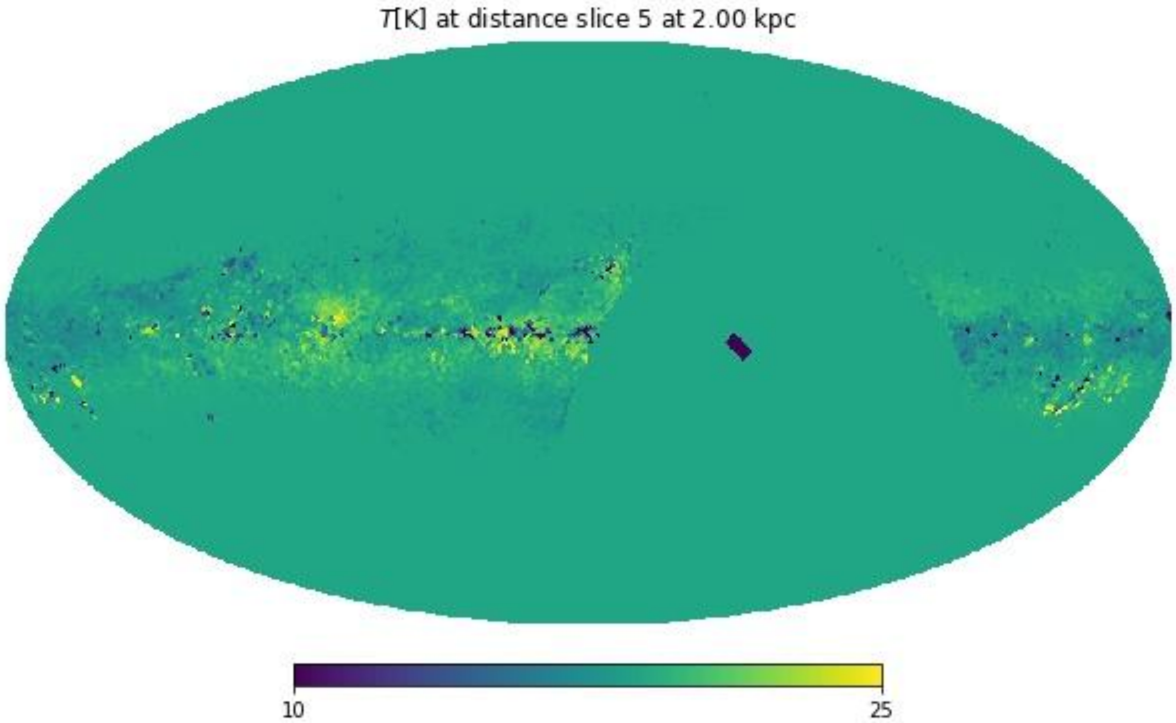
T[K] at distance slice 2 at 0.50 kpc

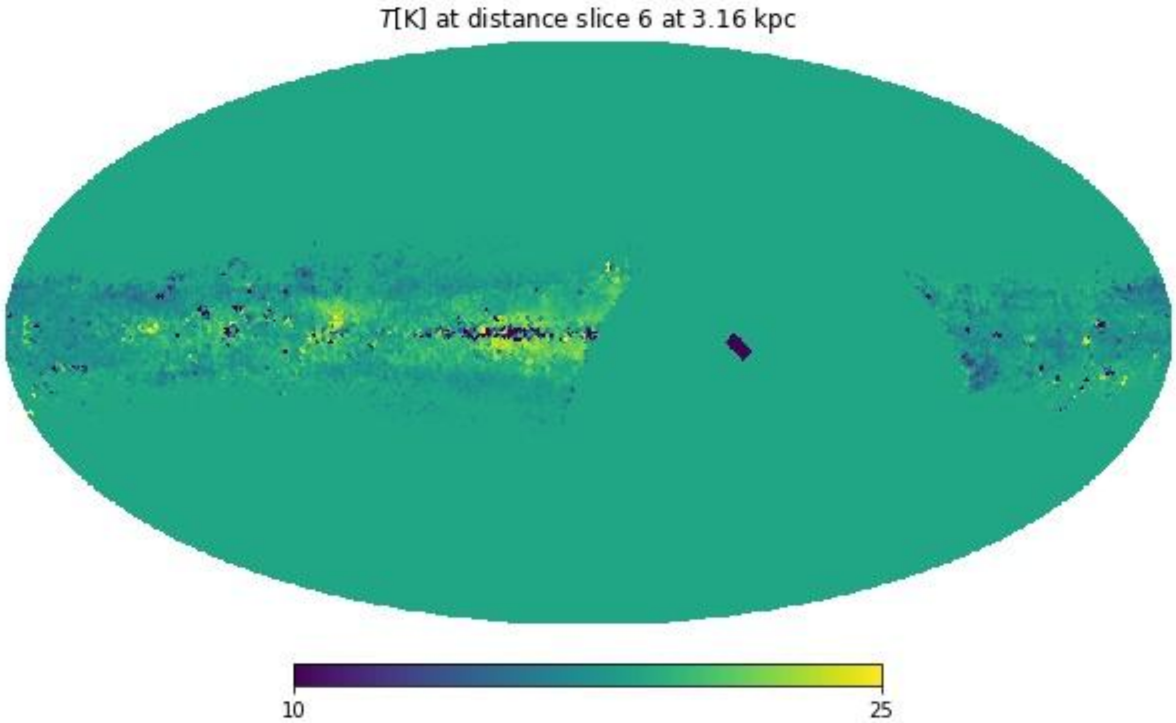


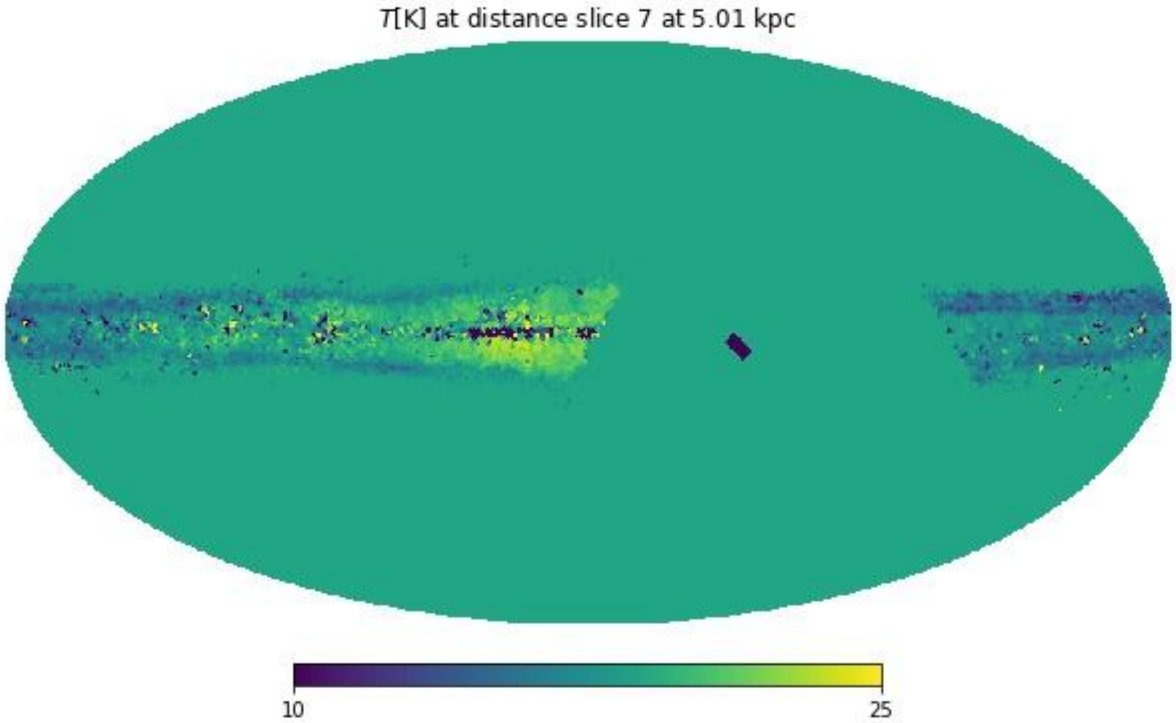

T[K] at distance slice 3 at 0.79 kpc
10
25

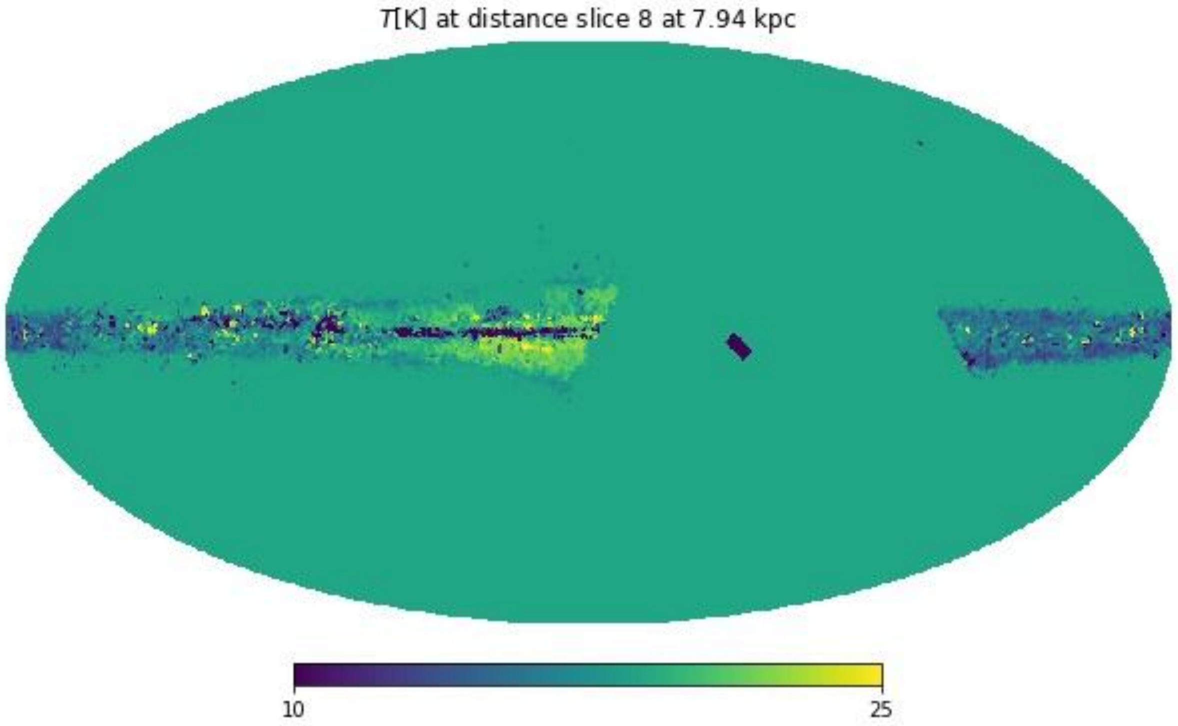
T[K] at distance slice 4 at 1.26 kpc

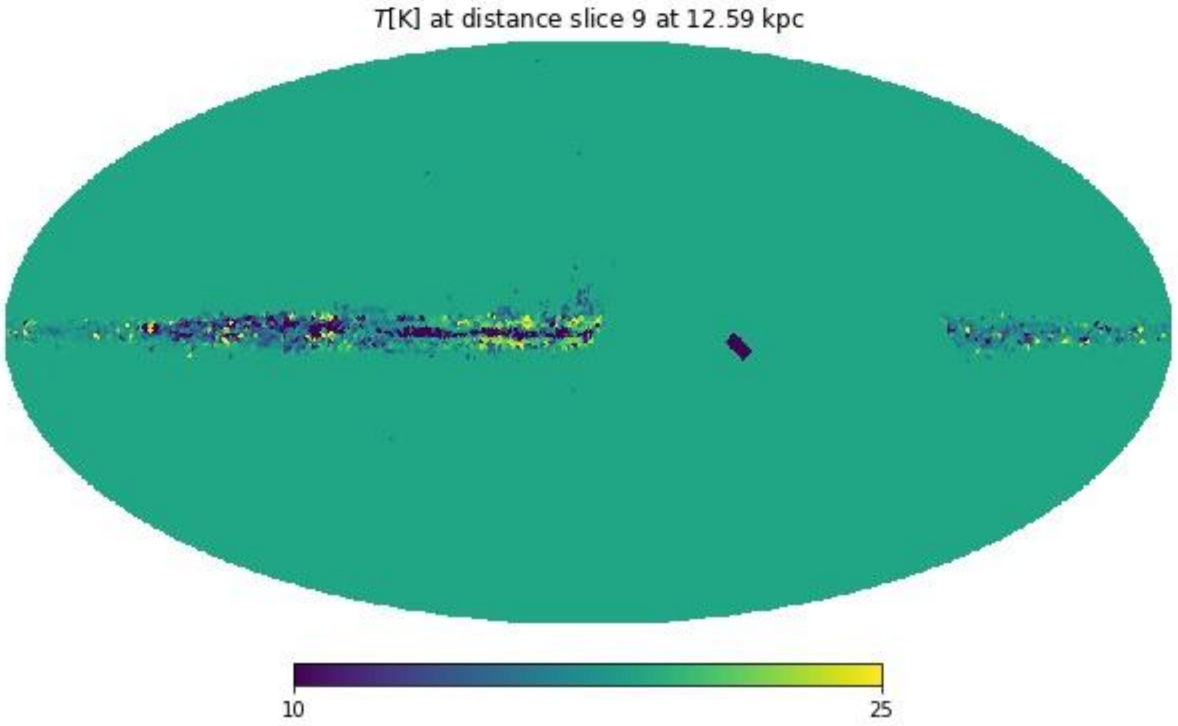



T[K] at distance slice 5 at 2.00 kpc
10
25

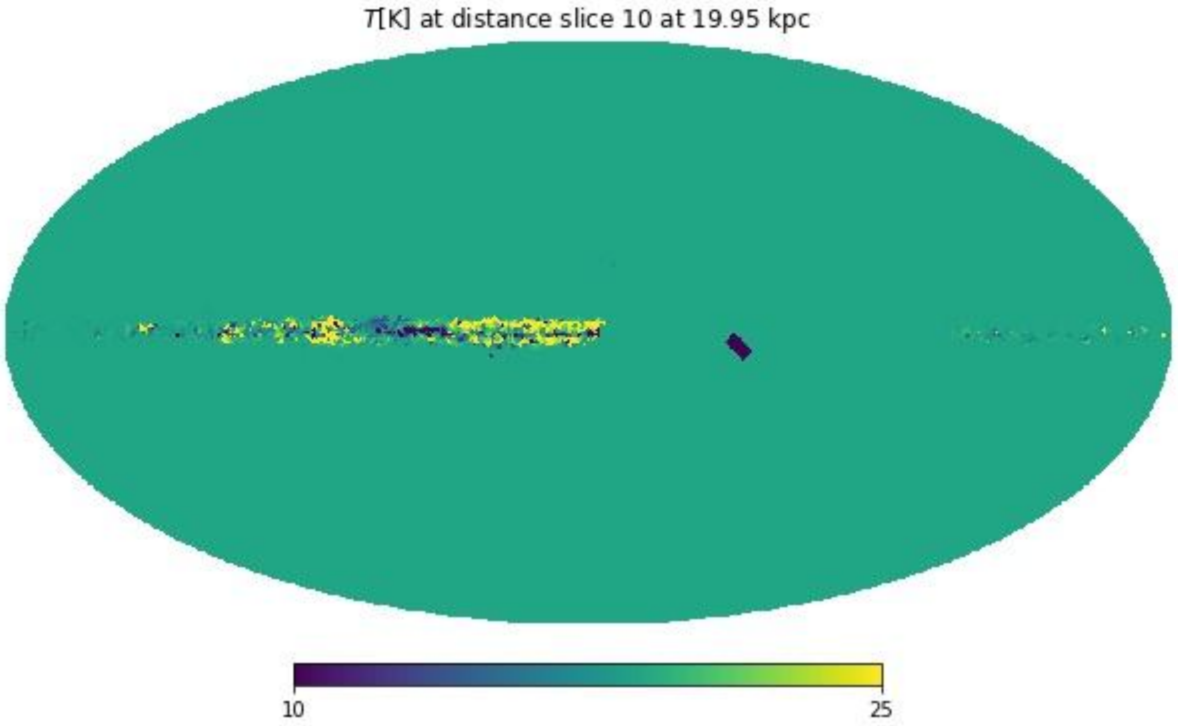

T[K] at distance slice 6 at 3.16 kpc
10
25

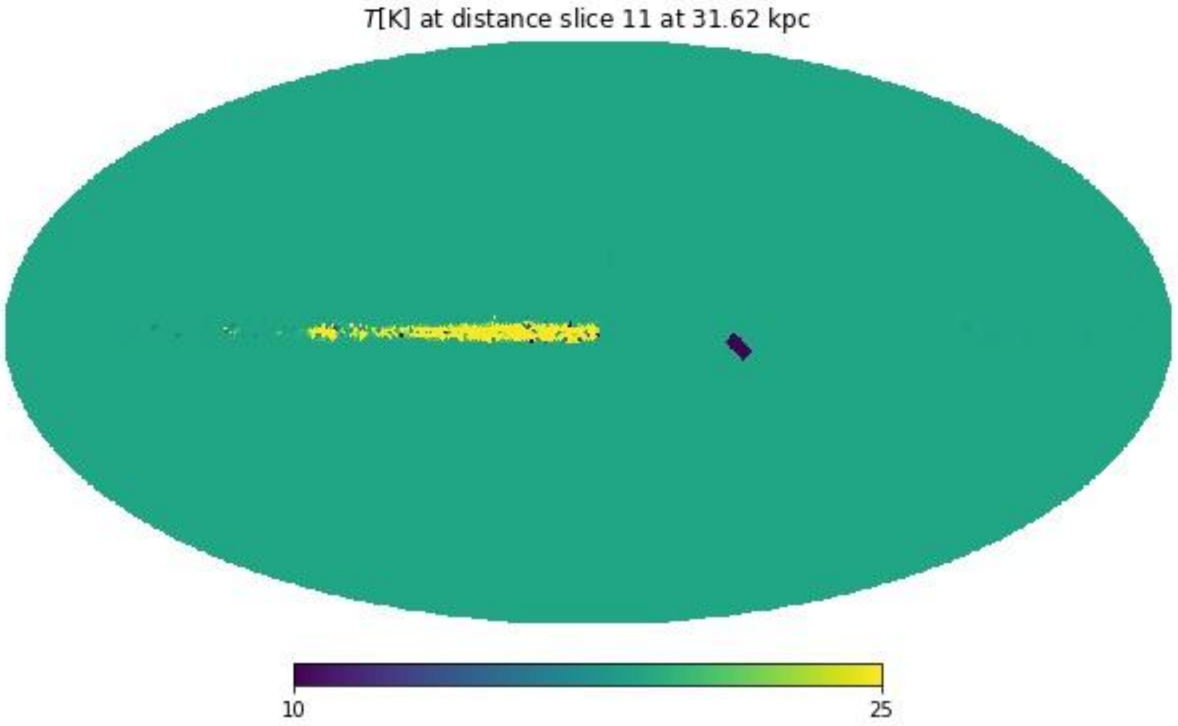

T[K] at distance slice 7 at 5.01 kpc
10
25


T[K] at distance slice 8 at 7.94 kpc
10
25

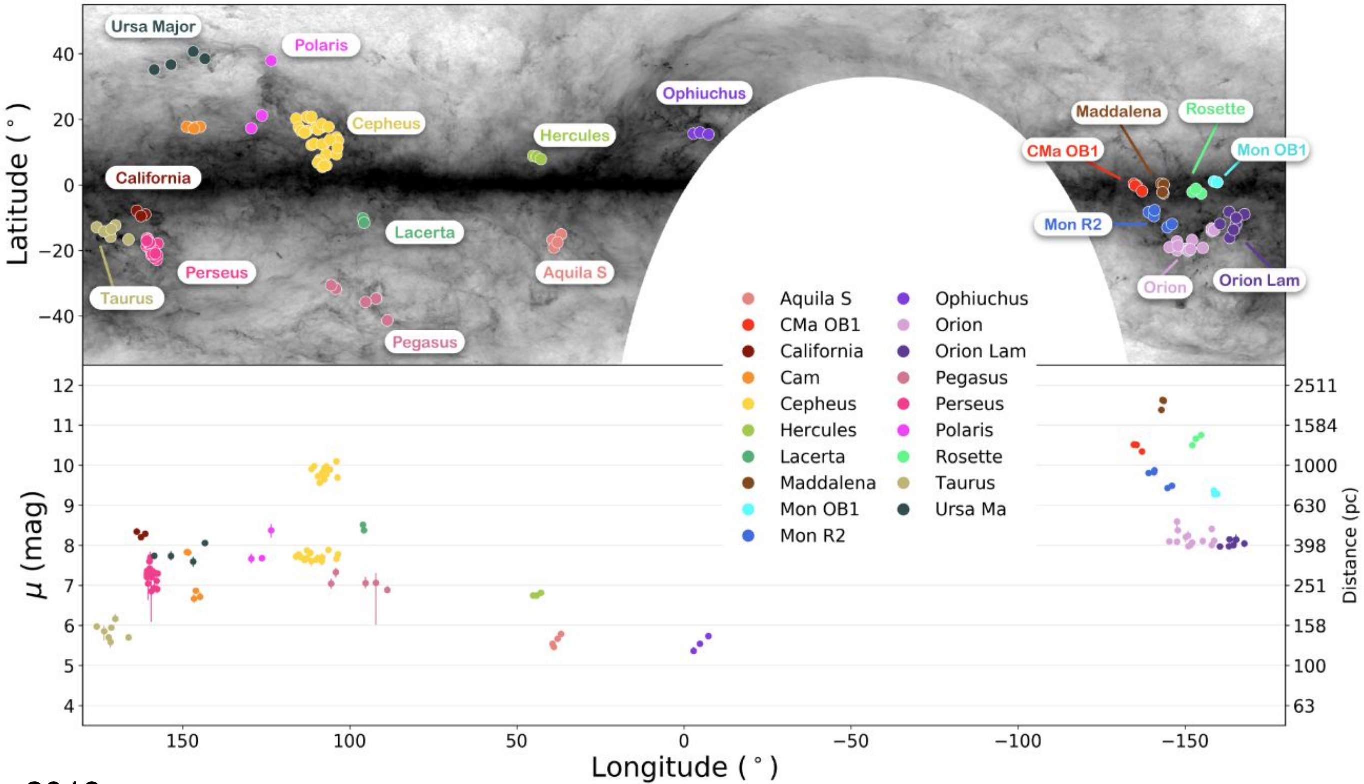


T[K] at distance slice 9 at 12.59 kpc
10
25

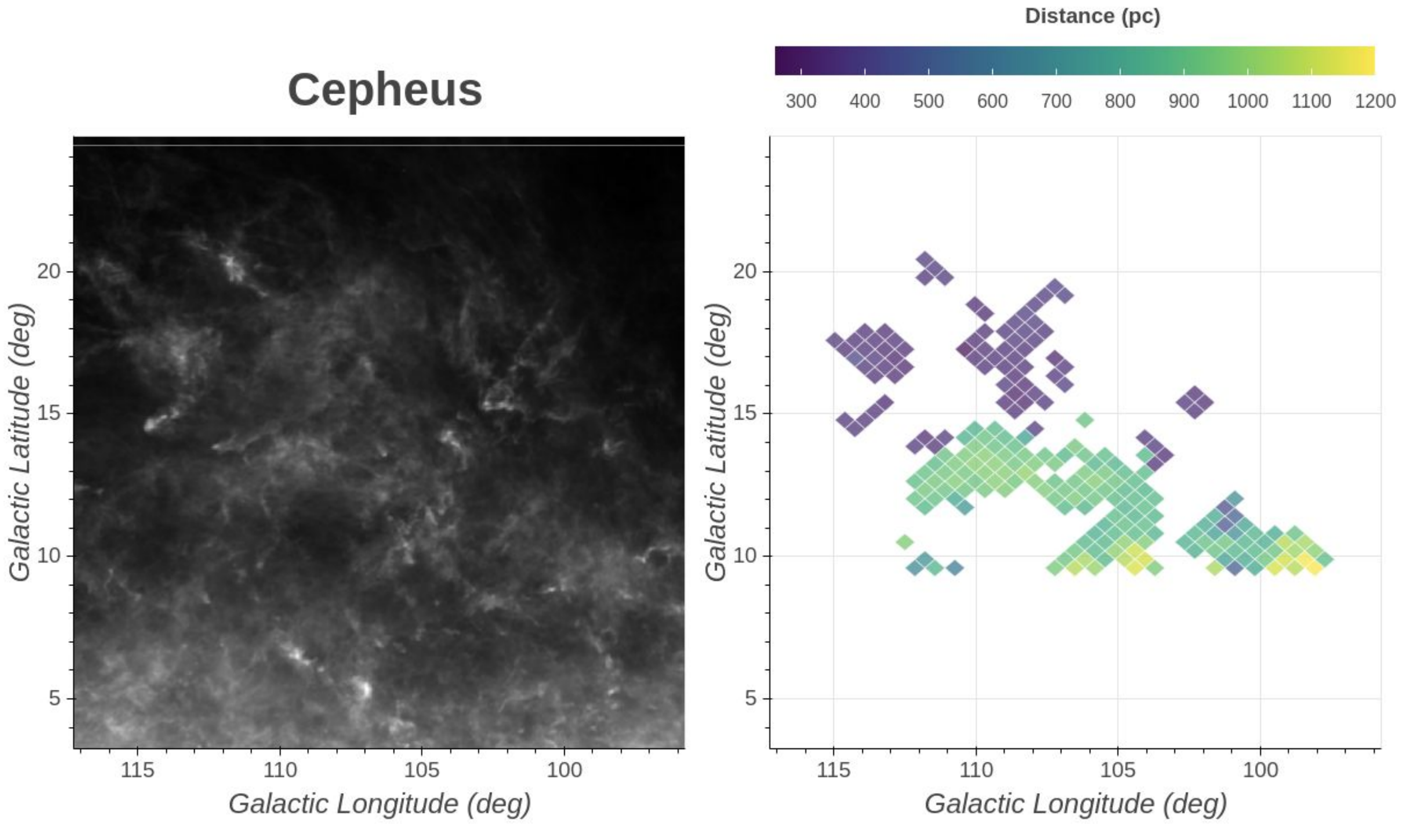

T[K] at distance slice 10 at 19.95 kpc
10
25


T[K] at distance slice 11 at 31.62 kpc
10
25

Calculating the Temperature of a Dust Cloud with Two Components

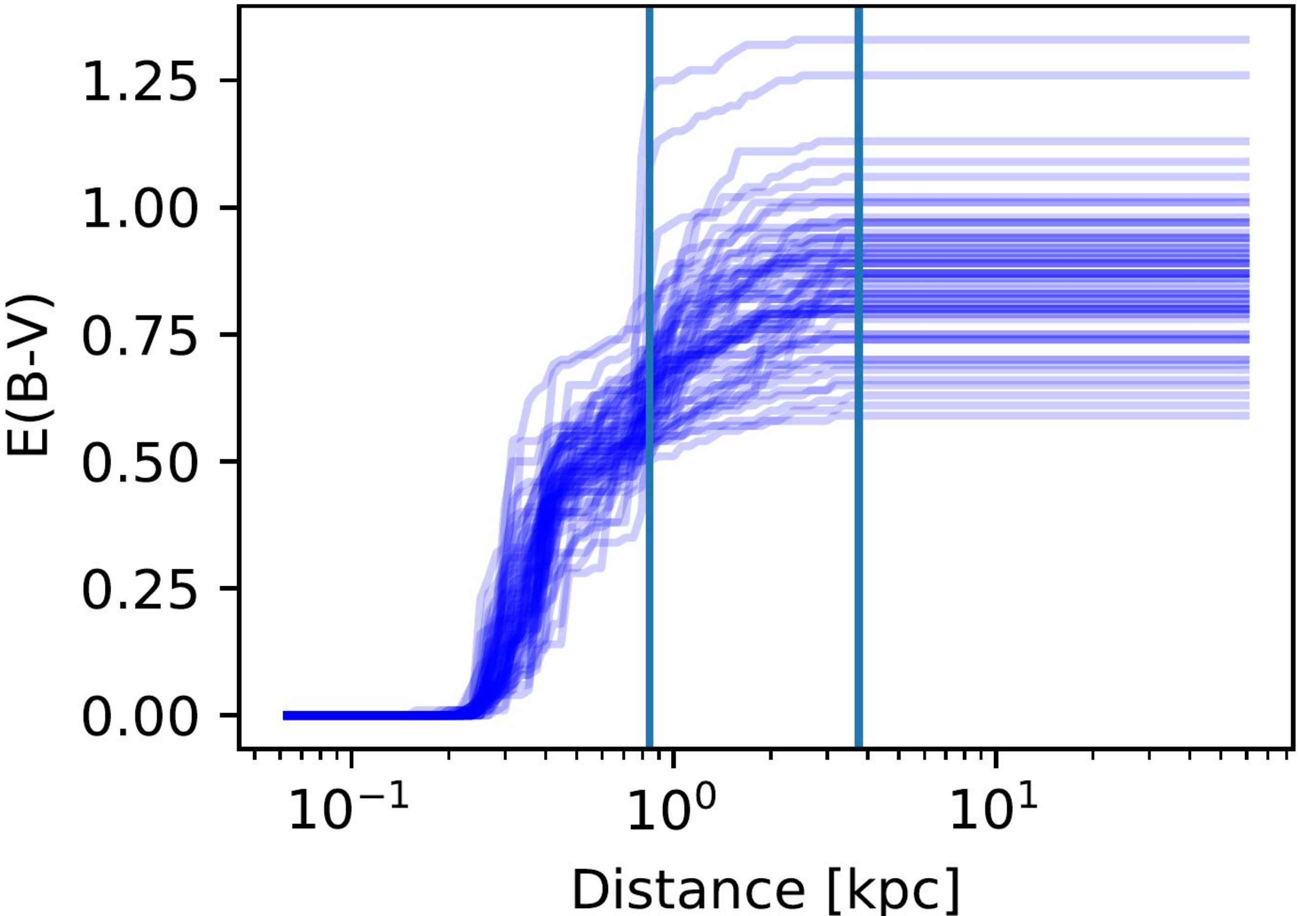


Credit: Zucker 2019

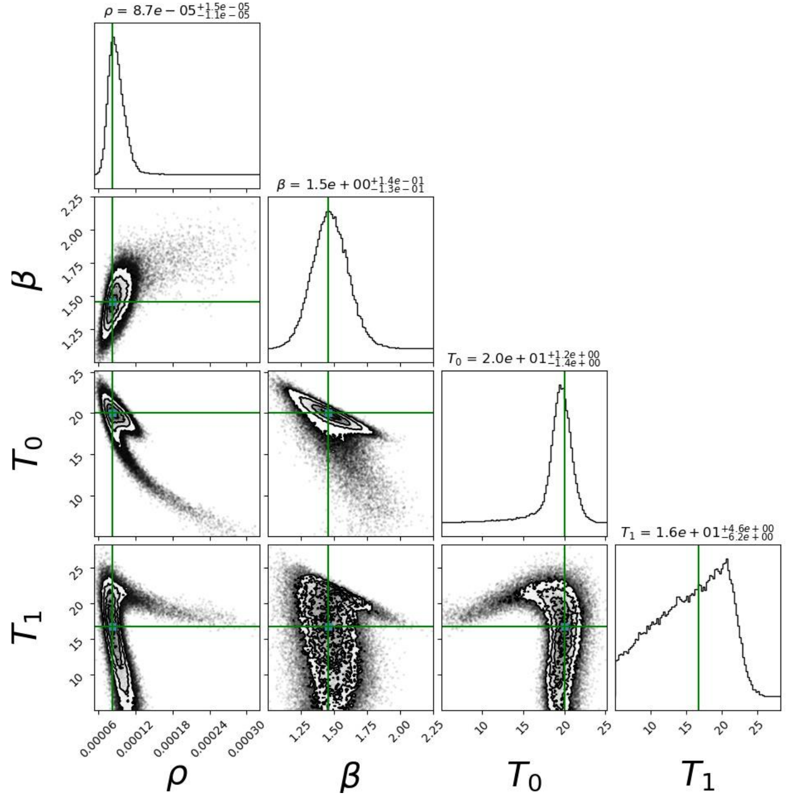


Credit: Zucker 2019

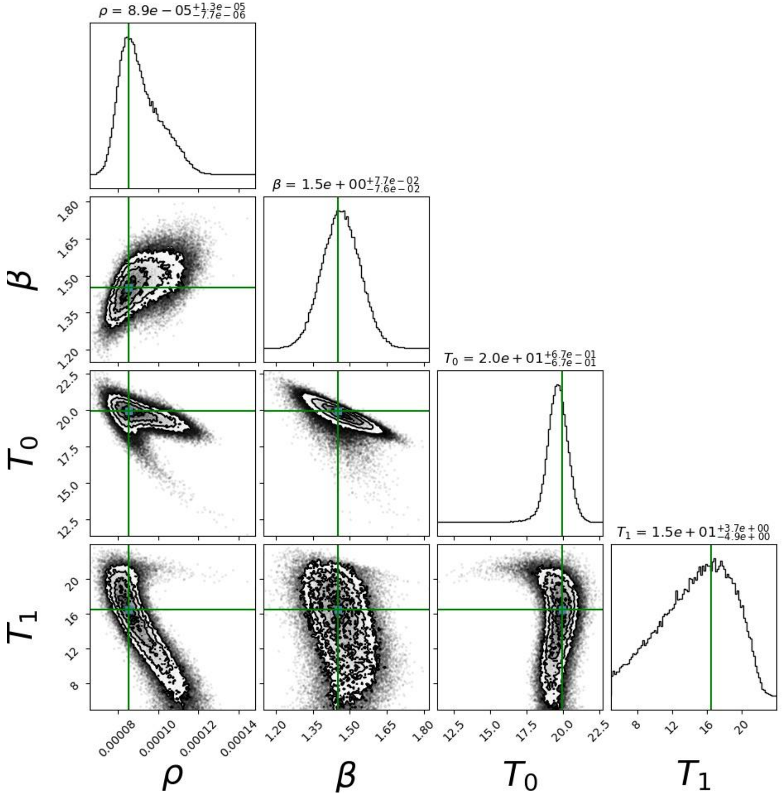
Reddening for a Cepheus cloud line of sight of nside 128



0.5× 0.5° resolution (NSIDE 128)

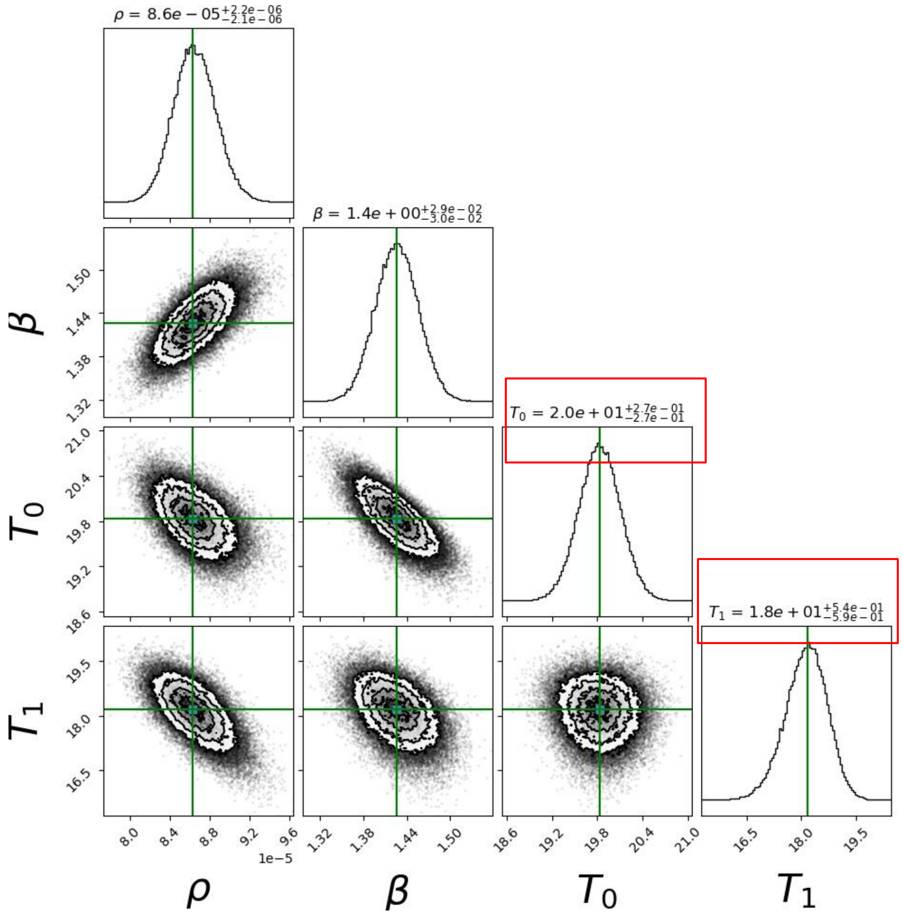


1× 1° resolution (NSIDE 64)



2× 2° resolution (NSIDE 32)

The posteriors become much more constrained as the resolution decreases



We can see a difference between the dust temperatures in the two voxels

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Summary

Successfully reconstructed the 2D emission maps from the 3D reddening maps

Created Proof-of-concept 3D dust temperature map

Tested the variation of the ρ conversion factor

3D Temperature of the Cepheus cloud

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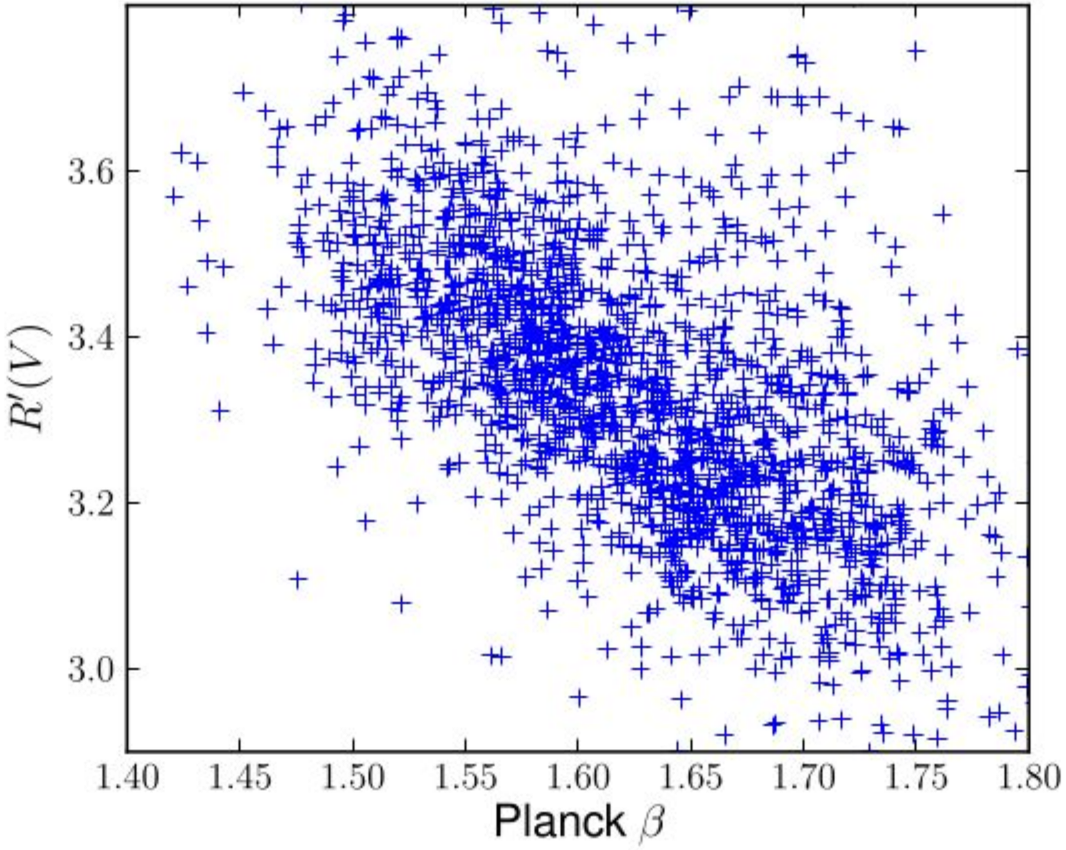
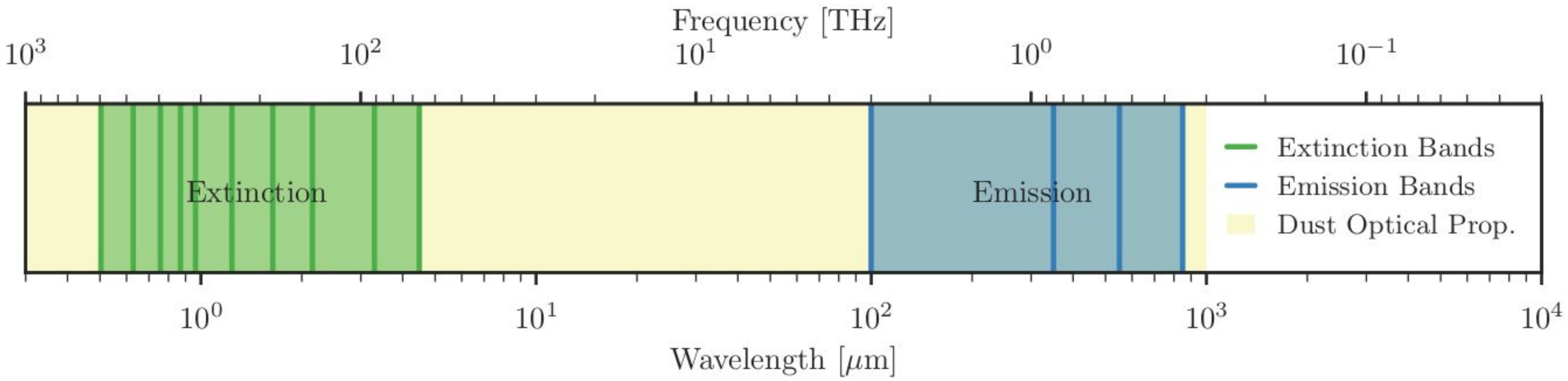
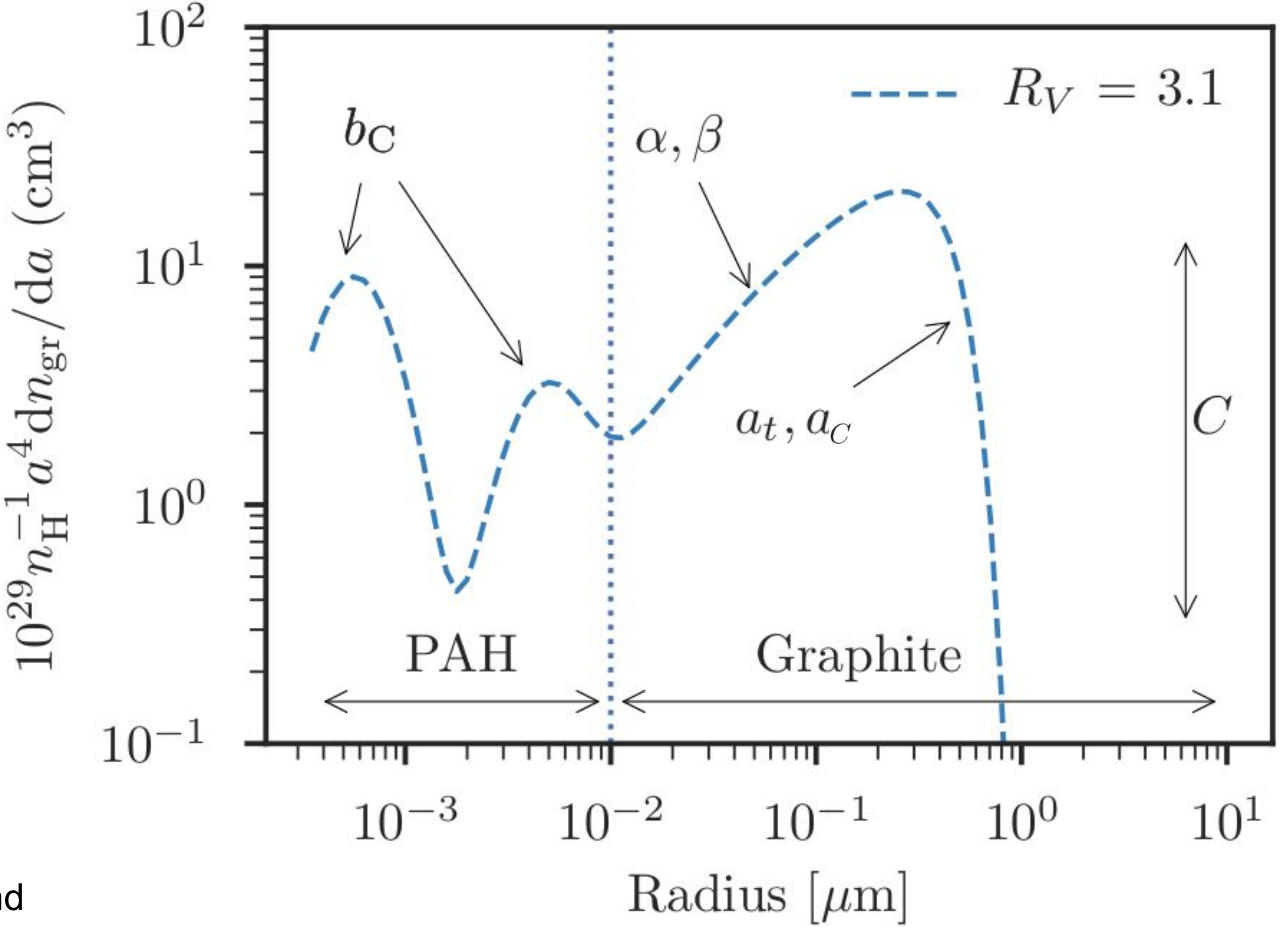
The Correlation between Dust Extinction and Emissivity (Rv - β) parameters

Schlafly et al 2016 observed a correlation between R_V and β, but it is not theoretically explained.



Schlafly2016


Frequency [THz]
10^3
10^2
10^1
10^0
10^{-1}
Extinction
Emission
Extinction Bands
Emission Bands
Dust Optical Prop.
10^0
10^1
10^2
10^3
10^4
Wavelength [μm]



Weingarder and
Draine 2001

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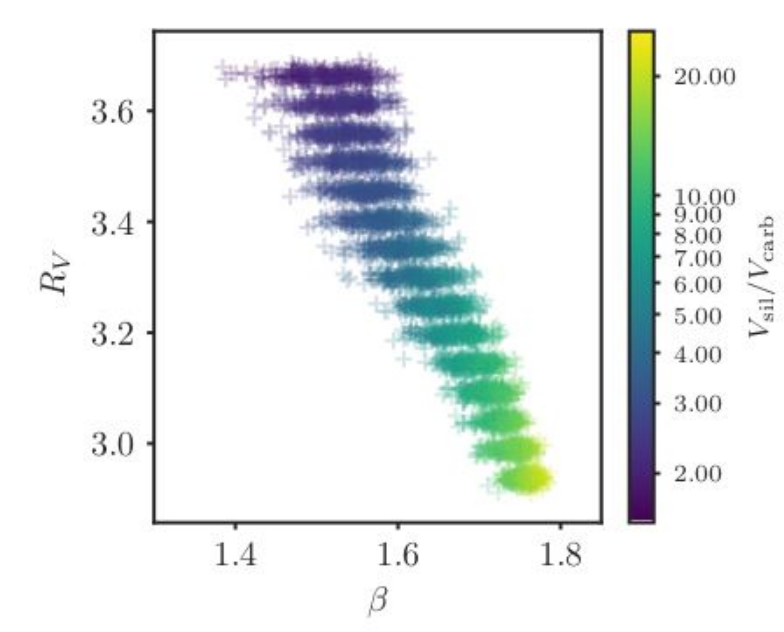

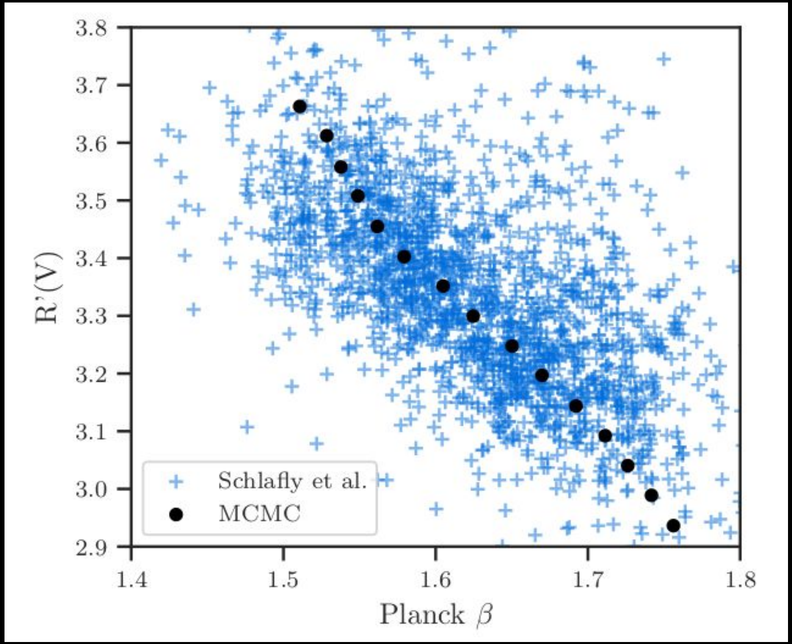

Zelko & Finkbeiner 2020

ApJ 904, 38

Thank you!

Future Directions

3D Dust Temperature Maps:

Next Generation Reddening Maps that have higher resolution,

combined with

Improved Multi-frequency Emission Data: CMB-S4, PIXIE

The Correlation between Dust Extinction and Emissivity (Rv - β) parameters:

For polarization:

This work had assumed grains are spherical. Analysis can be redone for spheroids/ellipsoids.

Ex: B. T. Draine and Brandon S. Hensley 2021 ApJ 910 47

Testing the correlation in 3D

Thinking of new dust emission model fit