Making the Next Generation of 3D Interstellar Medium Dust Temperature Maps

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UNIVERSITY OF TORONTO | CITA ICAT Canadian Institute for Theoretical Astrophysics / L'institut Canadien d'astrophysique théorique | DUNLAP INSTITUTE for ASTRONOMY & ASTROPHYSICS

Background

- Dust is a significant part of the Milky Way's Interstellar Medium, known to absorb and scatter UV and visible light and re-radiate in the infrared frequency range.

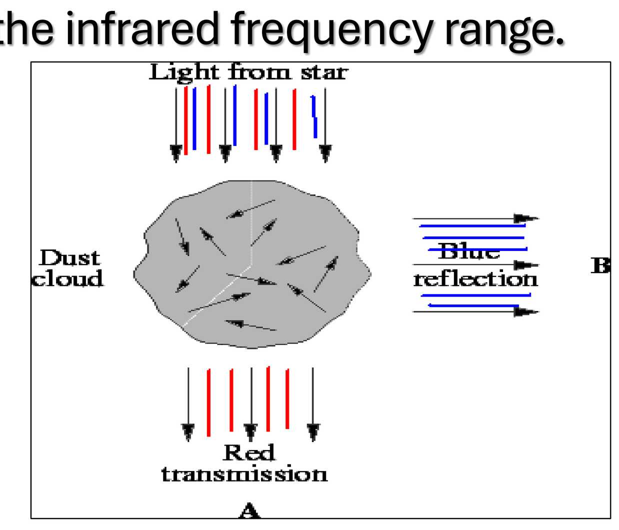


Fig 1: Brief description of how dust clouds interact

- Inferring ISM dust's radiative properties has many potential applications in
  - Cosmological measurements,
  - Identifying milky way star formation regions,
  - Analyzing ISM magnetic field structure,
  - Characterizing the Interstellar Radiation field
  - Investigating gamma-ray diffused emission for dark matter annihilation surveys.

All these applications significantly benefit from increasing angular resolution of the temperature map as much as possible

Problem: 3D Dust Temperature Map Resolution Limit

- Previous work by Zelko et al [1], combines information from 2D dust emission maps (Planck & IRAS/DIRBE satellites) and 3D dust extinction maps (Bayestar19 [2]) to infer temperature values along line-of-sight.

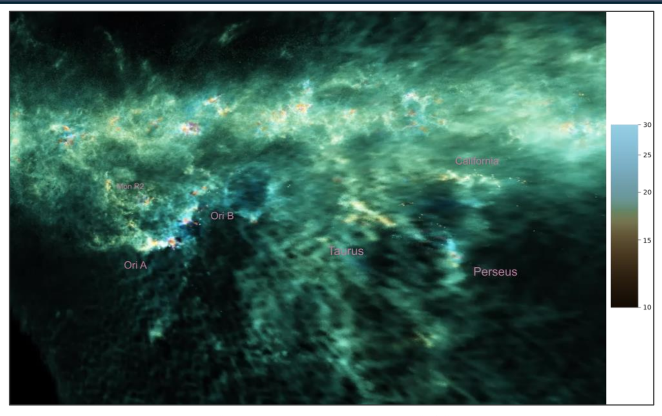


Fig 2: 3D dust temperature map (Zelko et al 2022) at the galactic anticenter (l,b=180,0), with some star-forming regions identified

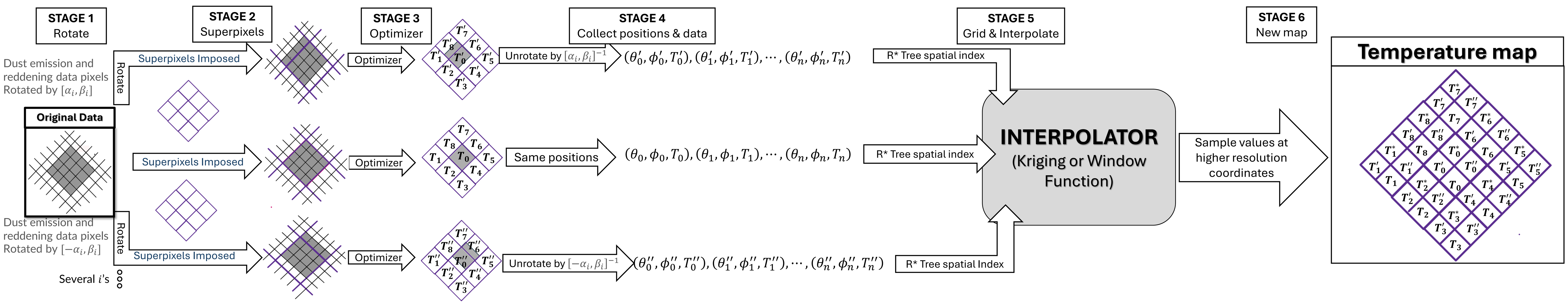
- It does this by modelling the dust emission as a single modified blackbody; the total dust emission (I_ν) from each 2D pixel is a function of cumulating 3D reddening (ΔE_{B-V}) in each distance bin along the line-of-sight.

$$I_\nu^{\mathrm{total},k} = O_\nu + \sum_n \zeta_{353}^n \Delta E_{\mathrm{B\text{-}V}}^{n,k} \left(\frac{\nu}{\nu_0}\right)^{\beta^n} B_\nu(T^n)$$

- The parameters of this model ζ_{353}^n, β^n and T^n are obtained using Bayesian Inference, with temperature T^n allowed to vary along the line of sight.

The current temperature map achieved only 27' angular resolution (from 5' data) because original data pixels need to be grouped into 'superpixels' to be able to infer temperature along the line of sight

Methods: How do we Utilize Different Tessellations of the Sky to Create New Versions of the Temperature Map?



STAGES SUMMARIZED

- **Stage 0:** Start with dust emission datasets and dust reddening datasets smoothed to matching 5' resolutions (Smoothed HEALPix Nside 1024)
- **Stage 1:** All the data pixels are rotated by the same Euler angle $[\alpha_i, \beta_i]$. This is repeated for several calculated rotation angles that give unique groupings.
- **Stage 2:** Data pixels are grouped into larger pixels called 'superpixels' (in blue). Note that the same superpixel contains different data points for each rotated map.
- **Stage 3:** Each pair of datasets (emission and reddening) is loaded into the optimiser, which carries out the Bayesian inference to obtain the Temperature values for each superpixel at each distance slice. Notice that there is one temperature value per superpixel, thus these maps are lower resolution.
- **Stage 4:** For the rotated maps, we carry out the inverse rotation on the coordinates of the temperature superpixels, to account for the initial rotation. For each new map, we collect the new latitude θ and longitude ϕ and temperature T values for each superpixel.
- **Stage 5:** At each distance slice, the coordinates and corresponding temperature values are inserted into an R* Tree spatial unstructured grid. Temperature values are inferred in between known points by interpolating with a kriging covariance function or a window function.
- **Stage 6:** By sampling temperature values at the desired coordinates for a higher resolution map, the new map is constructed.

UNCERTAINTIES AND LIMITATIONS

- **Uncertainties in rotations:** The HEALPix pixelization of the sky is not always evenly spaced in latitude, thus rotations across latitudes are not exact everywhere on the map. This is further affected by uneven distributions of neighbouring pixels in polar regions.

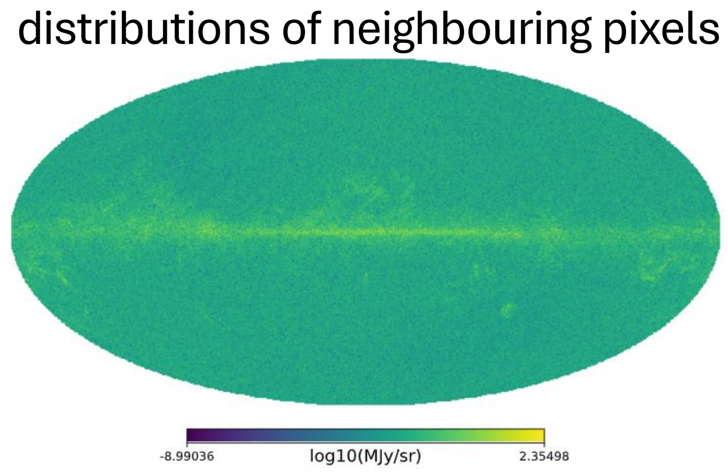
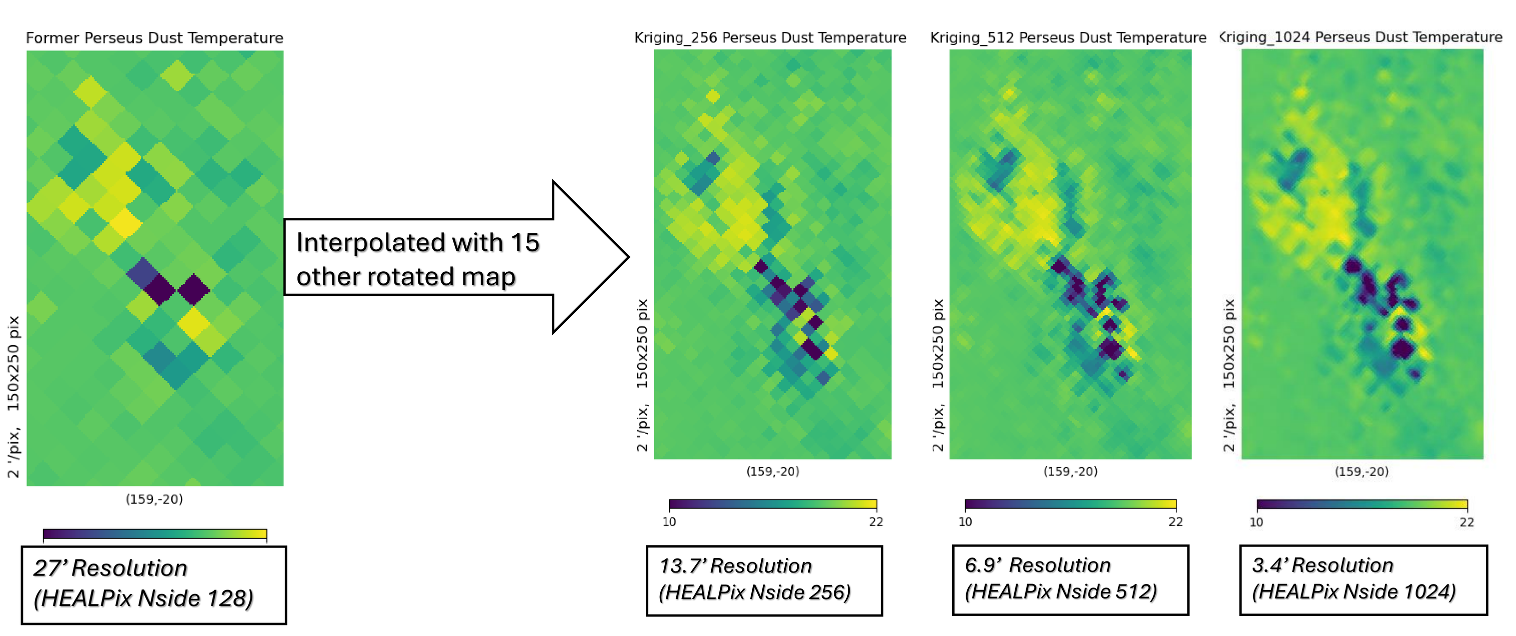


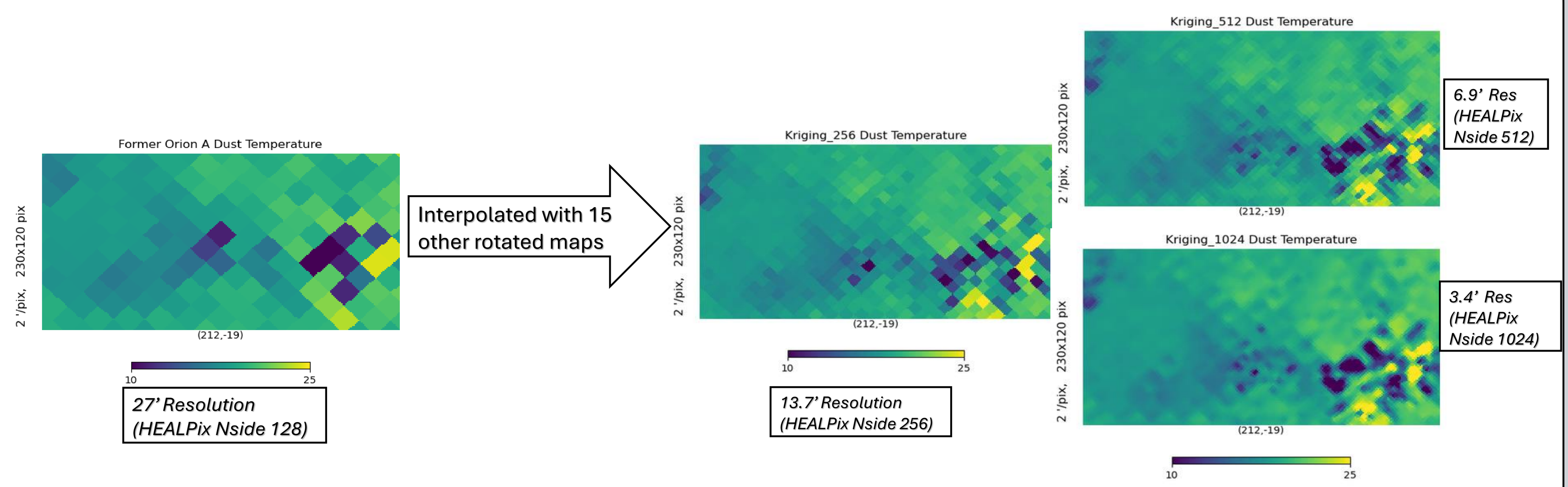
Fig 3: Residuals after rotating a Planck 353GHz dust emission map and rotating back.

- **Uncertainties in Interpolations:** Interpolations between known data coordinates are always estimates based on weights and distances between a chosen number of neighbours.

Results: New 3D Temperature Maps with 4 times Improved Resolution!! 🎉 🎉



Zoomed-in Comparison of Perseus Region



Zoomed-in Comparison of Orion-A Region

Link to 3D Visualization

Summary and Future Improvements

- We have been able to improve the angular resolution of the 3D dust temperature map using novel tessellation techniques, which can be applied anywhere superpixelization is used to infer parameters.
- Subsequently, we hope to improve distance resolution using new reddening datasets

References

[1] Zelko, I., Finkbeiner, D., & Lee, A., & Green,G. (2022). The First 3π 3D Map of ISM Dust Temperature. 10.48550/arXiv.2211.07667.

[2] Green, G. M., Schlafly, E., Zucker, C., Speagle, J. S. & Finkbeiner, D. A 3D Dust Map Based on Gaia, Pan-STARRS 1, and 2MASS. The Astrophysical Journal 887, 93 (2019). URL https://ui.adsabs.harvard.edu/abs/2019ApJ...887...93G.

Fig.1: http://burro.astr.cwru.edu/Academics/Astr221/StarProp/dust.html

Fig 3: Tijani, O., Zelko, I., Speagle J. Next generation of 3D Interstellar Medium Dust Temperature maps, In progress