Untangling dust and CIB emission in Planck 353 GHz observation with Scattering Coefficients

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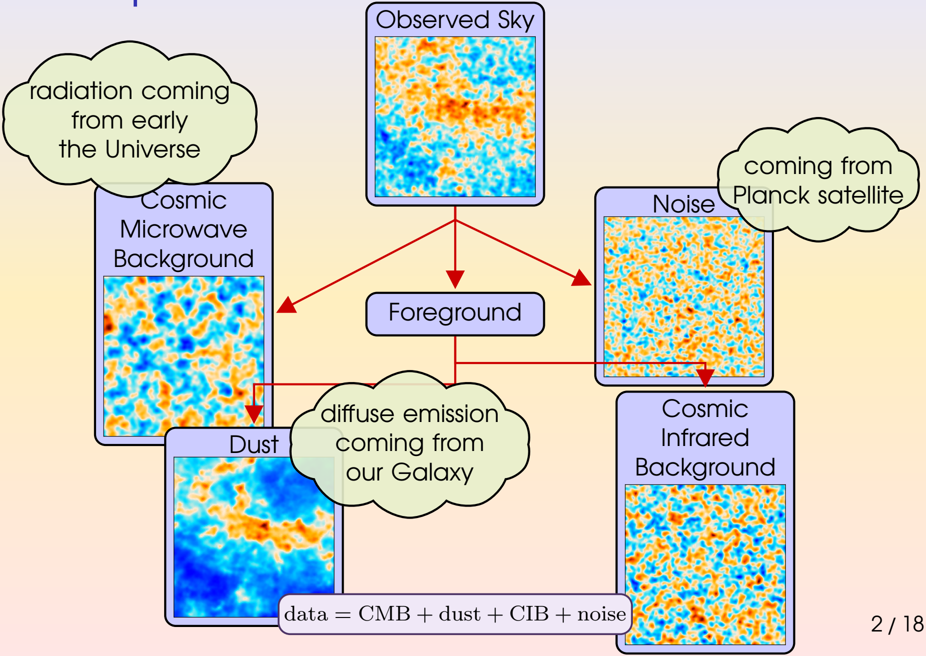
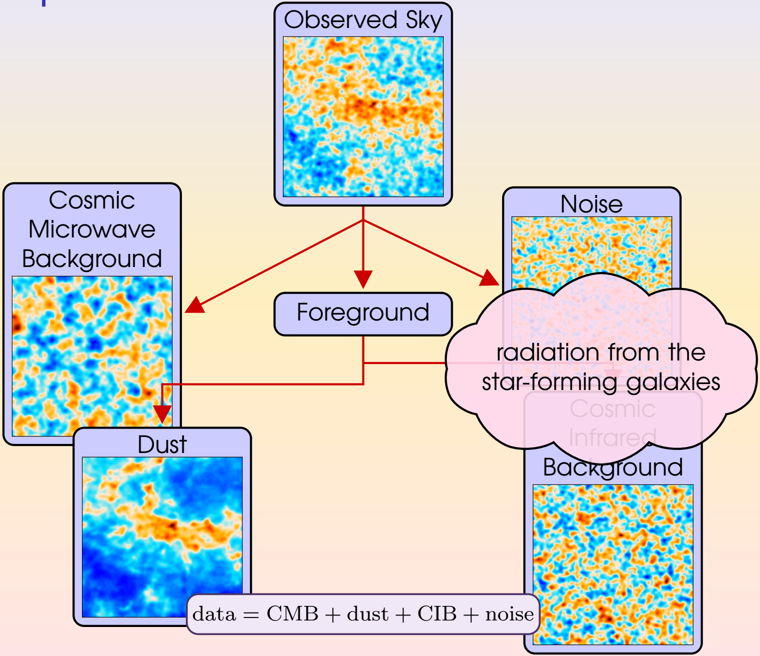
Components at 353 GHz



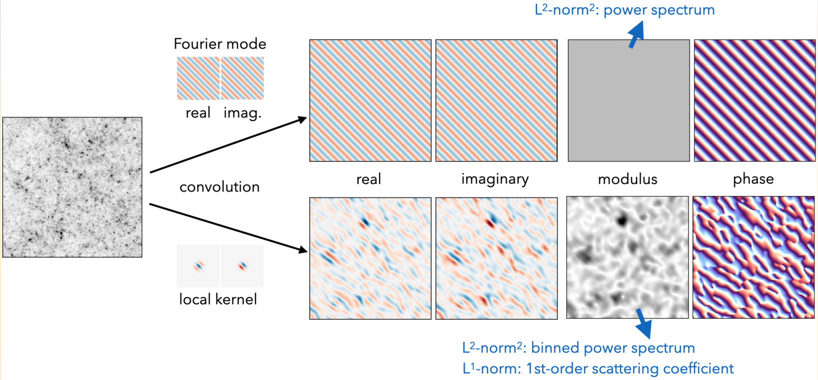
Components at 353 GHz



$$\text{data} = \text{CMB} + \text{dust} + \text{CIB} + \text{noise}$$

Scattering Transform

(S. Mallat 2012)



Goal: From a CMB-subtracted data separate dust & CIB+noise using Scattering Transform

Image credit: Sihao Cheng, Thesis, 2021

Scattering Coefficients

(S. Cheng *et al.*, PNAS Nexus 2024, L. Mousset *et al.*, A&A 2024)

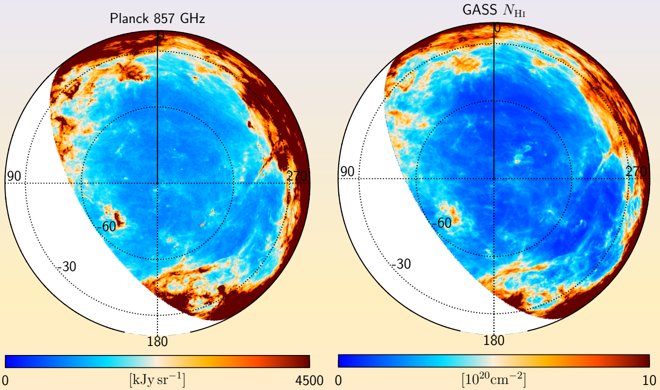
The scattering coefficients are computed with a non-linear operations on a random field (X) with a set of pre-computed wavelet filters ($\psi^{j,\gamma}$) at different scales and orientations $\lambda = (j, \gamma)$

- $S_1^{\lambda_1} = \langle |X * \psi^{\lambda_1}| \rangle \Rightarrow$ interactions at same scale
- $S_2^{\lambda_1} = \left\langle |X * \psi^{\lambda_1}|^2 \right\rangle \Rightarrow$ interactions at same scale
- $S_3^{\lambda_1,\lambda_2} = \mathrm{Cov}\left(X * \psi^{\lambda_1}, |X * \psi^{\lambda_2}| * \psi^{\lambda_1}\right) \Rightarrow$ interactions between scales
- $S_4^{\lambda_1,\lambda_2,\lambda_3} = \mathrm{Cov}\left(|X * \psi_3^{\lambda}| * \psi_1^{\lambda}, |X * \psi_2^{\lambda}| * \psi_1^{\lambda}\right) \Rightarrow$ interactions between scales
- Summary statistics $\Rightarrow \Phi \equiv (S_1, S_2, S_3, S_4)$

Methodology

- CIB is statistically isotropic $\rightarrow$ learn the statistical properties of CIB and use that to separate the dust and CIB
- Take a data patch at high neutral atomic hydrogen (HI) column density region (N_{HI})
- Define a some loss functions $\mathcal{L}$ defining the statistical correlation between the componenets
- Minimising the loss function arrive at the dust map

Dust-Gas correlation



- Dust map correlates closely with N_{HI} at high Galactic latitudes (F. Boulanger *et al.*, A&A 1996)
- We used the low-velocity (LV, $|v_{LSR}| < 30\,\mathrm{kms}^{-1}$) and intermediate-velocity (IV, $30\,\mathrm{kms}^{-1} < |v_{LSR}| < 90\,\mathrm{kms}^{-1}$) HI maps as the tracer for dust at low column density regions

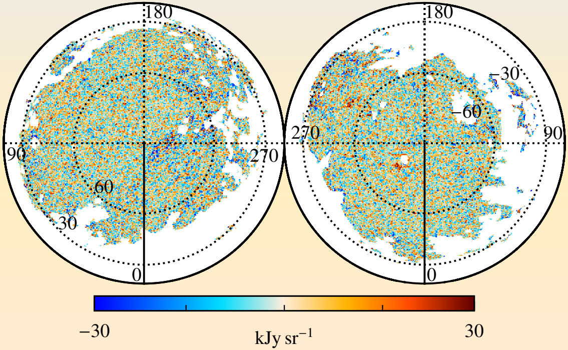
How to obtain clean CIB map?

- CMB subtracted maps are modelled $\rightarrow m = \underbrace{s}_{\text{dust signal}} + \underbrace{r}_{\text{residual emission}}$
- Estimate the probability distribution of the parameters Θ of a model **M** for the given dataset **D**

$$p(\Theta|\mathbf{D},\mathbf{M}) = \frac{p(\mathbf{D}|\Theta,\mathbf{M})\, p(\Theta|\mathbf{M})}{p(\mathbf{D}|\mathbf{M})}$$

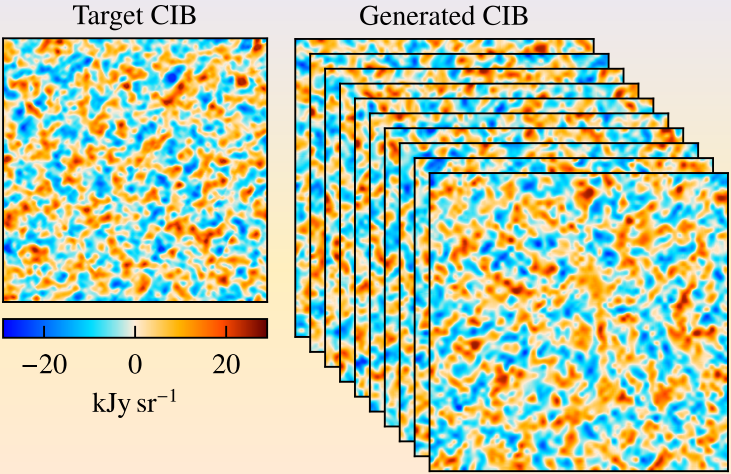
- $\mathbf{D} \equiv m$, $\Theta \equiv \{\epsilon, O\}$ and $\mathbf{M} \equiv s$
- Dust is modelled with HI map $\rightarrow$ $\boxed{s = \epsilon \text{HI} + O}$, $\epsilon \Rightarrow$ emissivity, $O \Rightarrow$ offset
- Likelihood $\longrightarrow \mathcal{L}(m|\{\epsilon, O\}) \propto e^{-\chi^2/2}$ where $\chi^2 = (m - s)^\intercal\, \Sigma^{-1}(m - s)$
- $\Sigma \equiv \Sigma^{\rm CIB} + \Sigma^N \Rightarrow$ Covariance Matrix of residual emission
- CIB anisotropies have a correlation between two pixels
- Sampled ϵ at each pixels & O globally using Hamiltonian Monte Carlo (HMC) sampling formalism (D. Adak *et al.*, MNRAS 2024)

How to obtain clean CIB map?



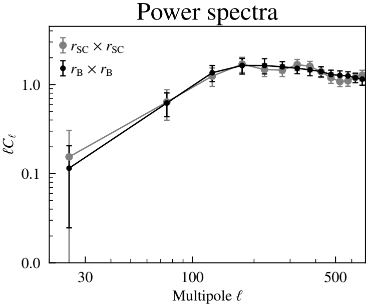
- With iterative fitting approach obtained a mask with $f_{\mathrm{sky}} = 0.33$
- From HMC we obtain the dust model s_{B} and the residual $r_{\mathrm{B}} = (m - s_{\mathrm{B}})$
- Extract 25 clean CIB square regions ($15^\circ \times 15^\circ$) from the North and South Galactic pole

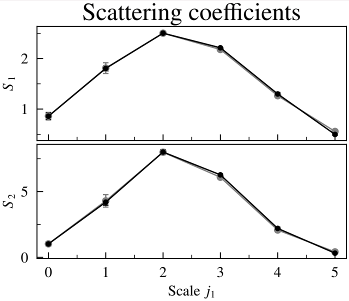
Synthesise a CIB map

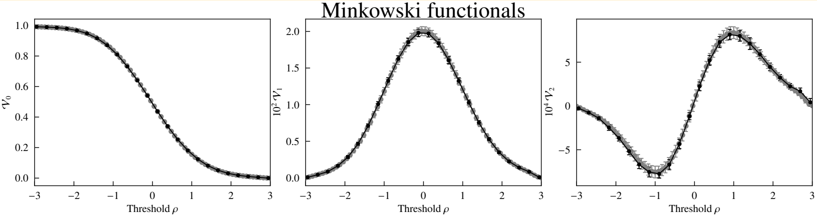


- Starting from an initial random image
- Compute the Φ and minimise the difference between target and initial image ⇒ $\mathcal{L} = \|\Phi(\text{in}) - \Phi(\text{out})\|^2$

Summary Statistics







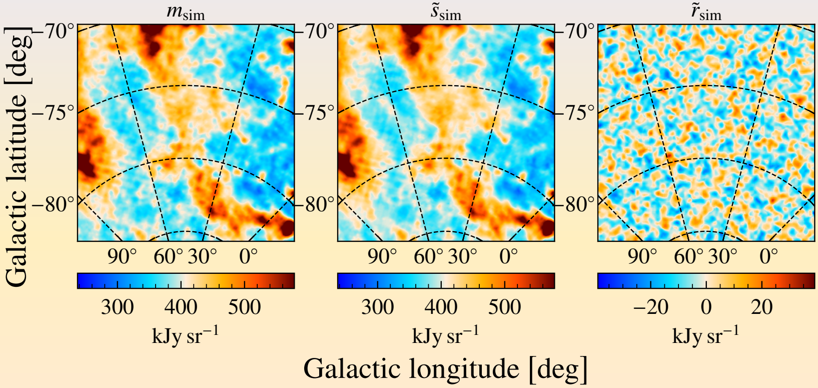
Loss definitions

- $\boxed{\Phi(m) \simeq \langle \Phi(s + c_i + n_i) \rangle_{i \in N}}$ $\Rightarrow$ statistics of dust+CIB+noise matches the total map
- $\boxed{\Phi(\text{HI}, m) \simeq \langle \Phi(\text{HI}, s + c_i + n_i) \rangle_{i \in N}}$ $\Rightarrow$ dust and HI are correlated
- $\boxed{\Phi(m - s) \simeq \langle \Phi(c_i + n_i) \rangle_{i \in N}}$ $\Rightarrow$ dust and CIB+noise are uncorrelated
- $\boxed{\Phi(\text{H}\alpha, m - s) \simeq \langle \Phi(\text{H}\alpha, c_i + n_i) \rangle_{i \in N}}$ $\Rightarrow$ CIB+noise are uncorrelated to Hα

Validation on simulation

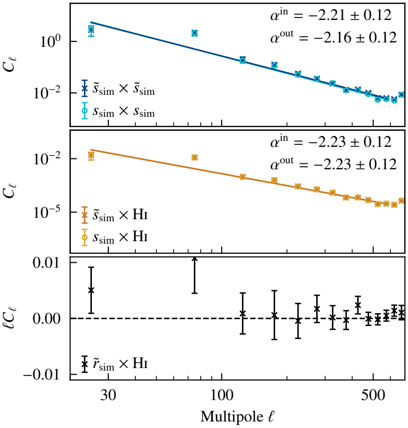
- Interstellar reddening map $E(B-V)$ at low HI column denisity (D. Lenz *et al.*, APJ 2017)
- Scale the dust with κ such that $SNR = \frac{\sigma_{\kappa E(B-V)}}{\sigma_{r_{\mathrm{sim}}}}$
- $s_{\mathrm{sim}} = \kappa E(B-V) + O$
- Made the data map $m_{\mathrm{sim}} = s_{\mathrm{sim}} + r_{\mathrm{sim}}$
- Verified the algorithm for $SNR = 3$ to 9

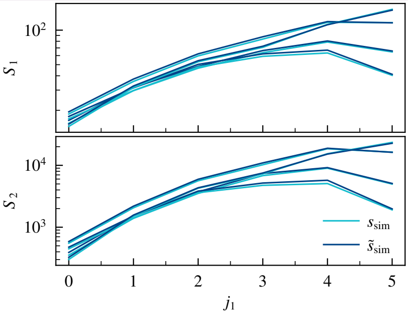
Recovered dust and CIB+noise



- Simulated map $m_{\rm sim} = \tilde{s}_{\rm sim} + \tilde{r}_{\rm sim}$, where $\tilde{s}_{\rm sim} \equiv$ recovered dust signal, $\tilde{r}_{\rm sim} = (m_{\rm sim} - \tilde{s}_{\rm sim}) \equiv$ recovered CIB+noise

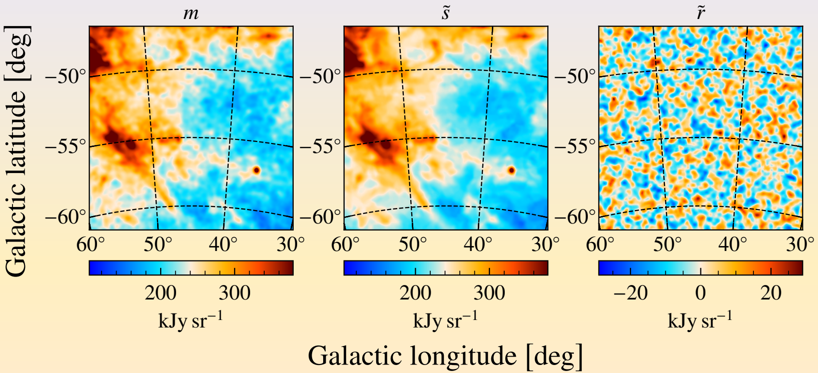
Recovered statistics





- Recovered the dust map ($\tilde{s}_{\rm sim}$)
- Recovered the dust-HI correlation
- Recovered the scattering statistics

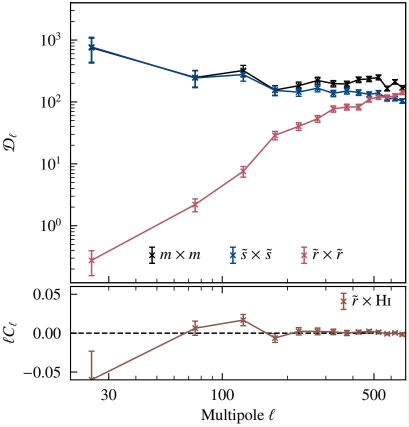
From Planck 353 GHz



- Centered around the Galactic longitude and latitude $(l, b) = (45^\circ, -54.3^\circ)$ with $SNR \approx 5$, and mean Hɪ column density $\langle N_{\mathrm{HI}}^{\mathrm{IV+LV}} \rangle = 3.3 \times 10^{20}\,\mathrm{cm}^{-2}$
- Data map $m = \tilde{s} + \tilde{r}$, where $\tilde{s} \equiv$ recovered dust signal, $\tilde{r} \equiv$ recovered CIB+noise

Results**

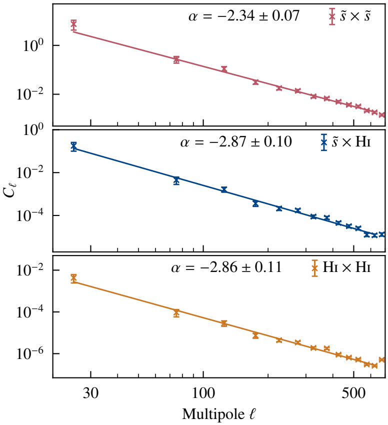
- $\tilde{s}$ at large scales is recovered
- $\tilde{r}$ at small scales is recovered
- $\tilde{r}$ is uncorrelated with HI



**S. S, T. Ghosh, E. Allys, F. Boulanger, JM. Delouis, 2025, under preparation).

Results**

- The difference in the power-law exponent value between $\alpha_{\tilde{s}\times\tilde{s}}$ and $\alpha_{\mathrm{HI}\times\mathrm{HI}}$ indicates that the dust ϵ is not constant and varies with a power-law exponent which is different from the HI auto spectrum
- We tried in other column density regions and obtain that a constant emissivity cannot explain this in all regions



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Summarise

- SC recovers the dust map where the dust intensity is higher than the CIB and noise
- At low column density, dust-HI tight correlation holds, and both template-fitting and SC gives consistent results
- At regions with other Galactic emissions in addition to the 21 cm HI, the SC can recover the dust emission
- A variable emissivity can explain the difference in exponent in the dust-HI correlation
- Obtaining a full maps are the next target

Thank You