Deep Cosmostat Days - 13/02/2026

📍 Paris, France

"Foreground removal in HI 21 cm intensity mapping under frequency-dependent beam distortions"

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FORTH INSTITUTE OF COMPUTER SCIENCE

TITAN ARTIFICIAL INTELLIGENCE IN ASTROPHYSICS

Signal Processing Laboratory

Funded by the European Union

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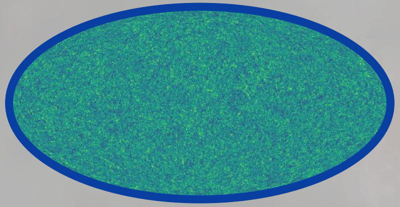
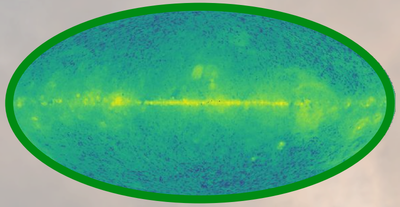
Foregrounds of the HI 21 cm signal

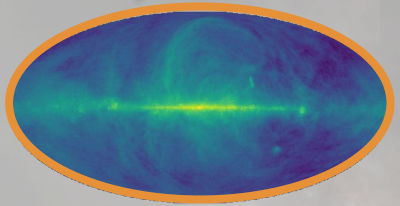
HI 21cm



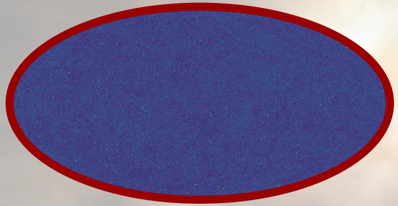
free-free



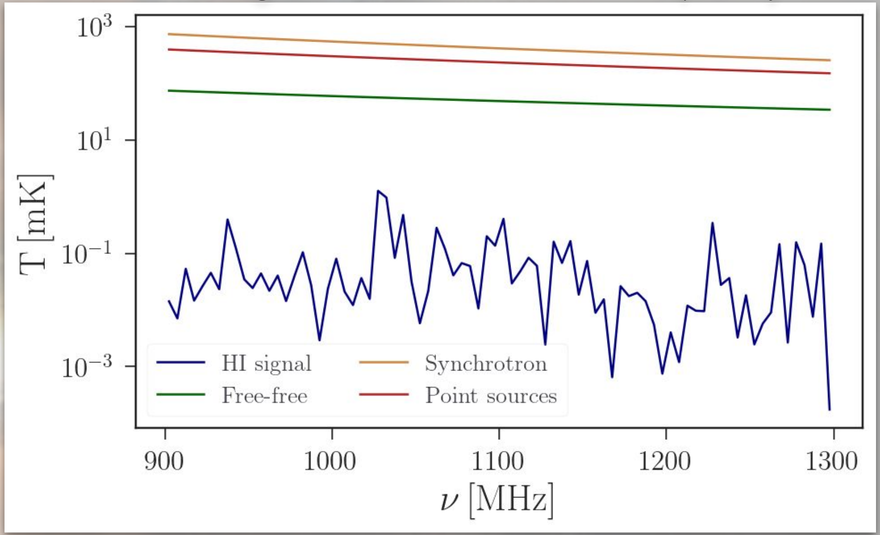
synchrotron



point sources



Foregrounds are smooth in frequency

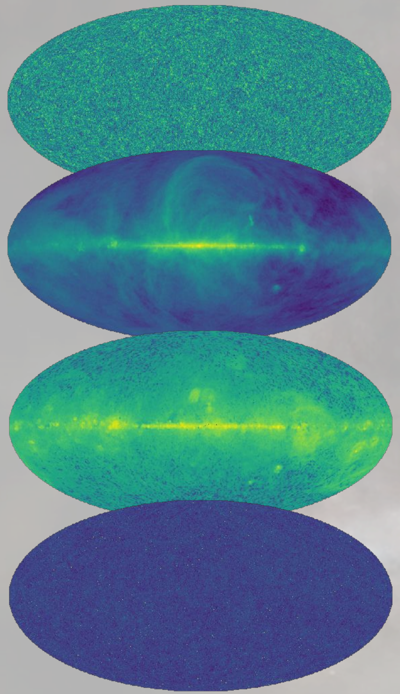


Biggest challenges in extracting HI signal:

- Foregrounds order of magnitudes brighter than HI
- Telescope beam: frequency-dependent

Foreground removal pipeline

900–1400 MHz



Simulation

Beam convolution

HI-bright sources masked

PCA

FastICA

GMCA

Polinomial Fit

Parametric fit

SDecGMCA

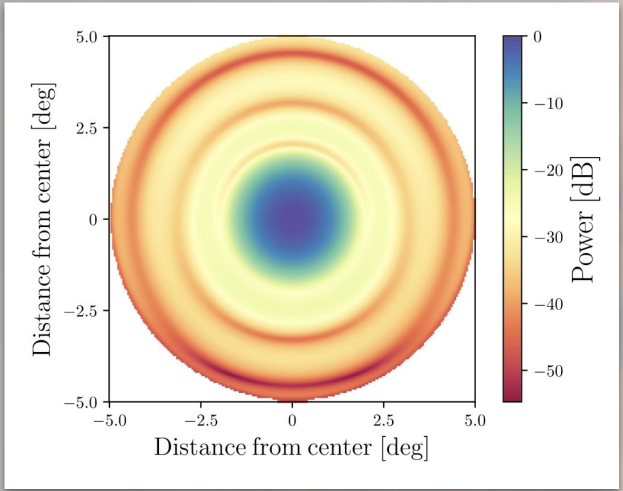
Methods

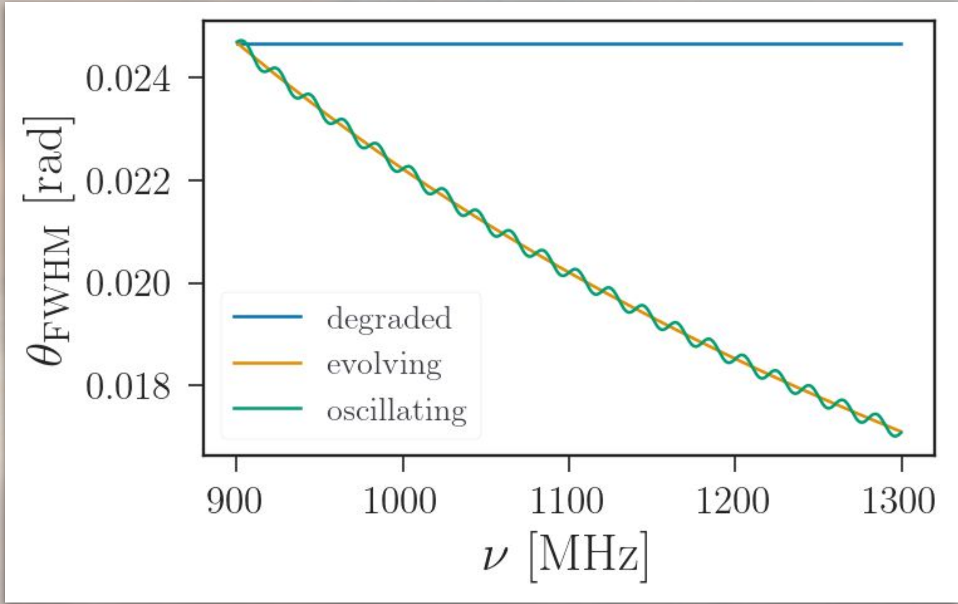
Radial (frequency) power spectrum $P(k_\nu)$

Angular power spectrum C_ℓ

Validation

Telescope Beam (e.g., MeerKAT)

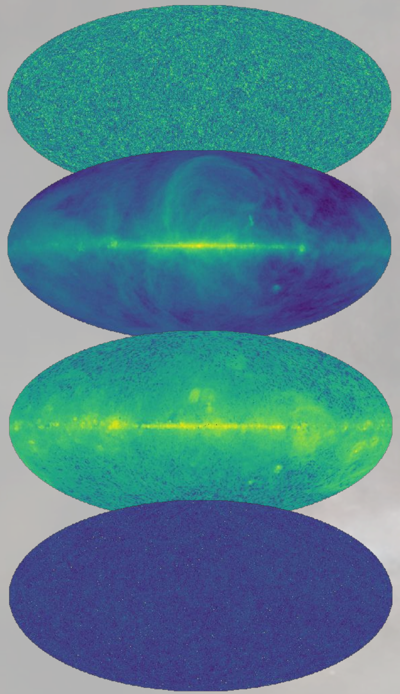




$$\theta = \frac{\lambda}{D} \longrightarrow \theta = \frac{\lambda}{D} \times A \sin\left(\frac{2\pi\nu}{T}\right)$$

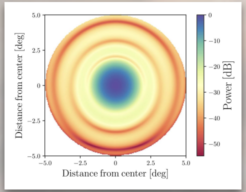
Foreground removal pipeline

900–1400 MHz



Simulation

Beam convolution



HI-bright sources masked

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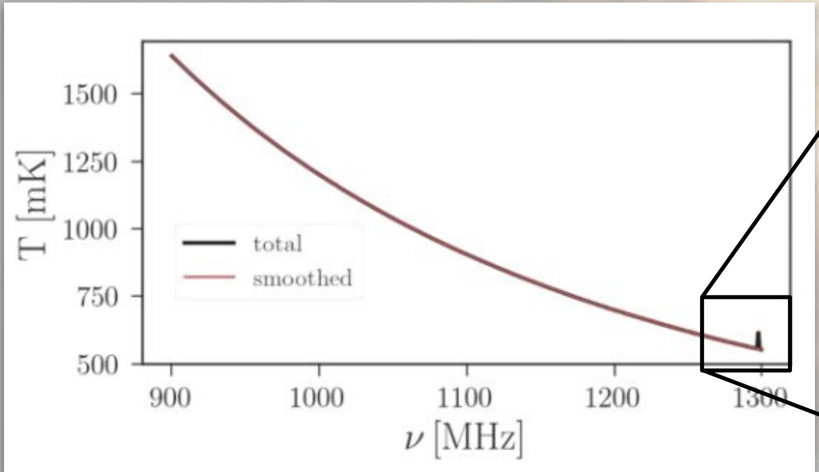
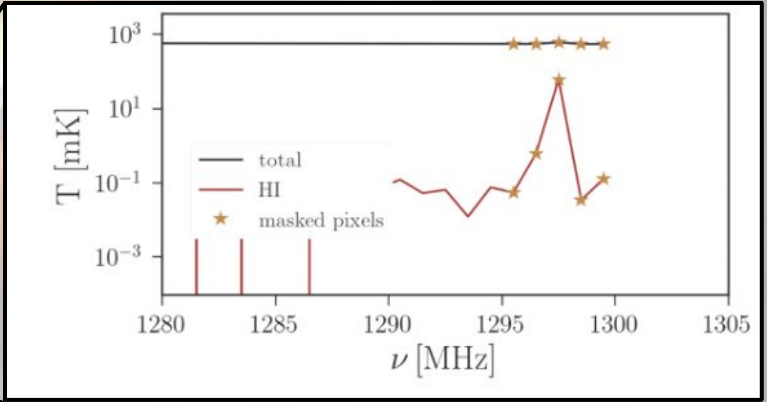
Masking the extremely bright HI sources

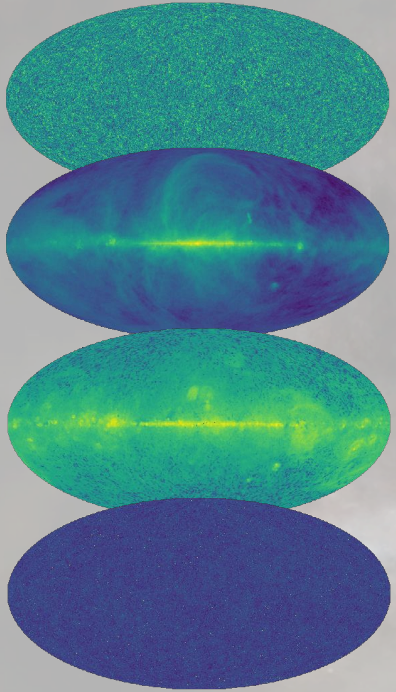
- Detecting lines of sight with peaks (extremely bright HI-sources)
- Assigning a the baseline value to this pixel





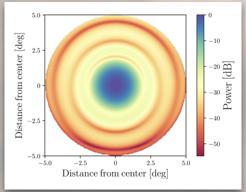
Foreground removal pipeline

900–1400 MHz

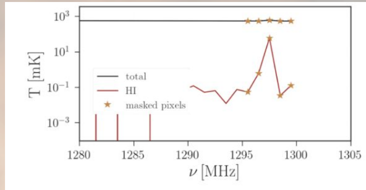


Simulation

→ Beam convolution



→ HI-bright sources masked



→

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→

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SDecGMCA: joint component separation and deconvolution on the sphere

beam model

$$\mathbf{X} = \mathbf{A}\mathbf{S} + \mathbf{N} \xrightarrow{\text{DecGMCA}} \mathbf{X}_\nu = (\mathbf{A}_\nu \mathbf{S}) * \boxed{\mathbf{H}_\nu} + \mathbf{N}_\nu \xrightarrow{\text{spherical harmonic domain}} \hat{\mathbf{X}}_\nu^{\ell,\mathbf{m}} = \hat{\mathbf{H}}_\nu^{\ell} \mathbf{A}_\nu \hat{\mathbf{S}}^{\ell,\mathbf{m}} + \hat{\mathbf{N}}_\nu^{\ell,\mathbf{m}}$$

$$\min_{\mathbf{A},\hat{\mathbf{S}}} \|\mathbf{\Lambda} \odot (\hat{\mathbf{S}}\mathcal{F}^\dagger \mathbf{\Phi}^\top)\|_1 + \sum_{(\ell,m)\in\mathcal{D}} \|\hat{\mathbf{X}}^{\ell,m} - \mathrm{diag}(\hat{\mathbf{H}}^\ell)\mathbf{A}\hat{\mathbf{S}}^{\ell,m}\|_2^2$$

sparsity
in wavelet space

data fidelity
in SH domain

algorithm

(i) *Update* $\hat{\mathbf{S}}$: Solved using a Tikhonov-regularized least-squares solution for each (ℓ, m), with $\epsilon_{n\ell}$ the regularization coefficients

(ii) *Enforce sparsity*: After the inverse harmonic transform, $\hat{\mathbf{S}}$ is projected onto the wavelet basis and sparsity is enforced via a soft-thresholding procedure

(iii) *Update* $\mathbf{A}$: The mixing matrix is estimated via least squares over all spherical harmonics

$$\mathbf{M}[l] = \mathbf{A}^\top \mathrm{diag}\left(\hat{\mathbf{H}}^l\right)^2 \mathbf{A}$$

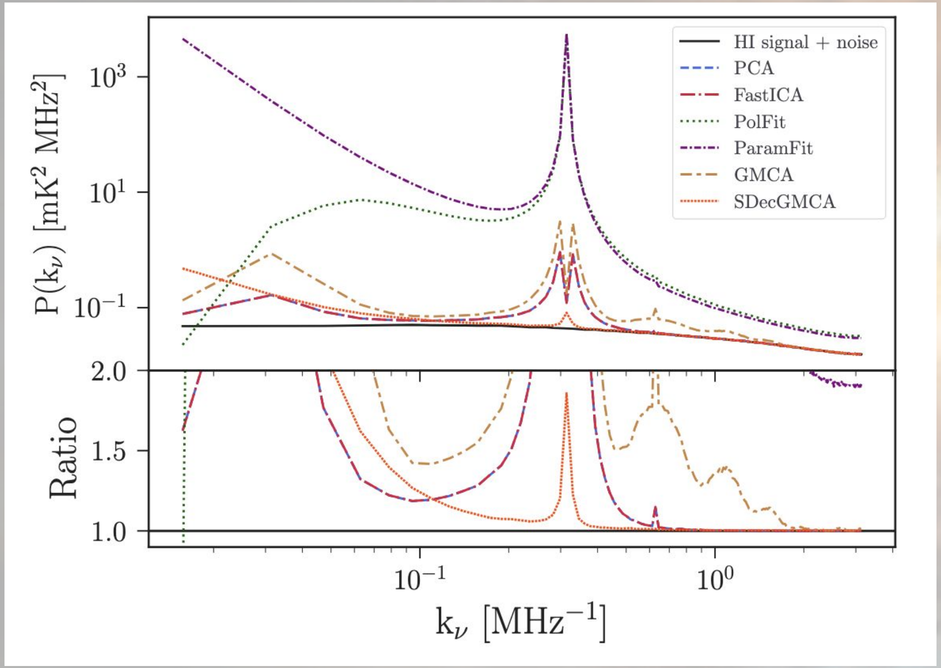
$$\hat{\mathbf{S}}^{l,m} \leftarrow \left(\boxed{\mathbf{M}[l]} + \mathop{\mathrm{diag}}_{n\in[1,N_s]} (\varepsilon_{n,l})\right)^{-1} \mathbf{A}^\top \mathrm{diag}\left(\hat{\mathbf{H}}^l\right) \hat{\mathbf{X}}^{l,m}$$

$$\mathbf{A}_\nu \leftarrow \left(\sum_{(l,m)\in\mathcal{D}} \hat{\mathbf{X}}_\nu^{l,m} \hat{\mathbf{H}}_\nu^l \hat{\mathbf{S}}^{l,m\dagger}\right) \left(\sum_{(l,m)\in\mathcal{D}} \hat{\mathbf{H}}_\nu^{l\,2} \hat{\mathbf{S}}^{l,m} \hat{\mathbf{S}}^{l,m\dagger}\right)^{-1}$$

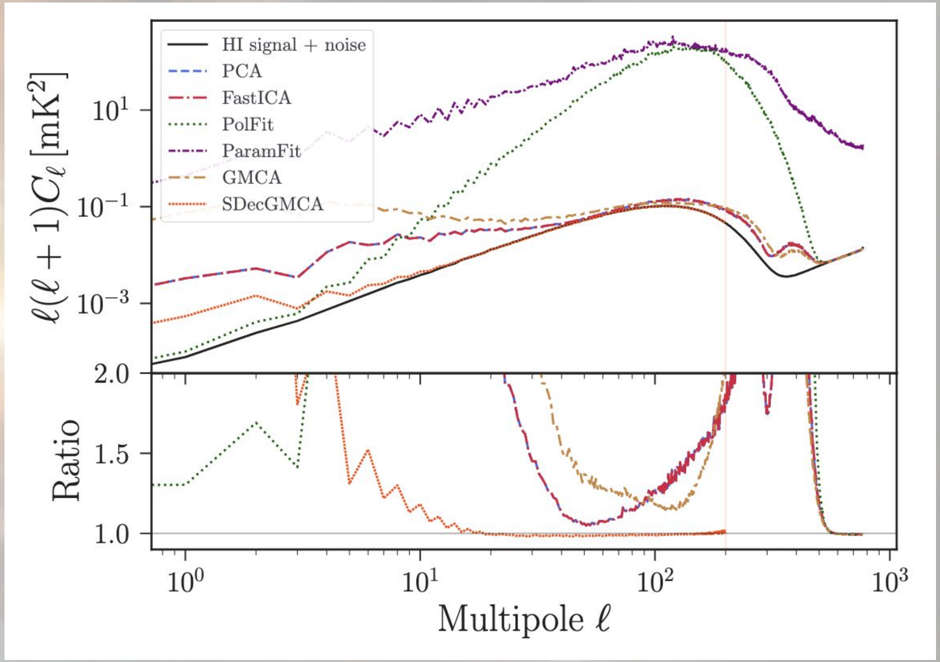
Carloni Gertosio & Bobin 2021

Gaussian oscillating beam

Frequency power spectrum



Angular power spectrum



Gkogkou+ 2026

SDecGMCA: limitations

- Bright Galactic plane
  - Masked SDecGMCA
  - Applicable to real data (footprint)

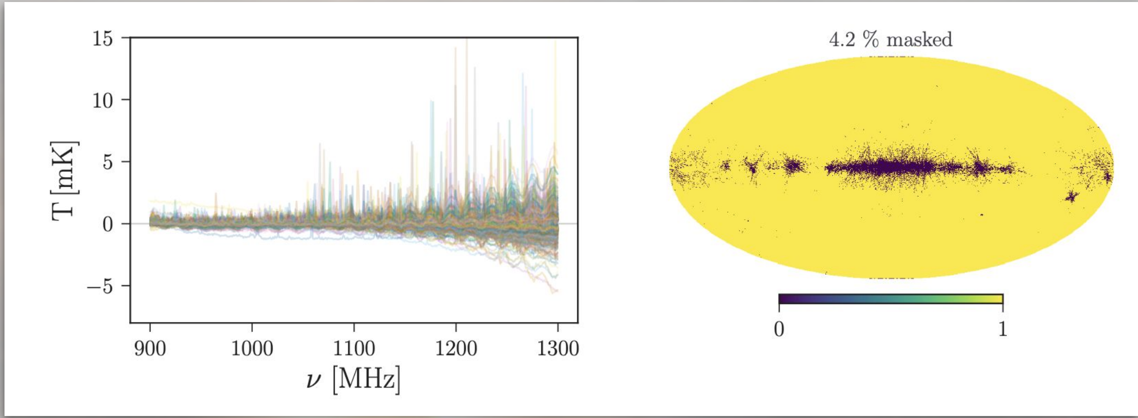
- Sensitive to thresholding hyperparameters
  - Instead of thresholding in wavelet domain
  - Use learnlets (Bonjean+26)

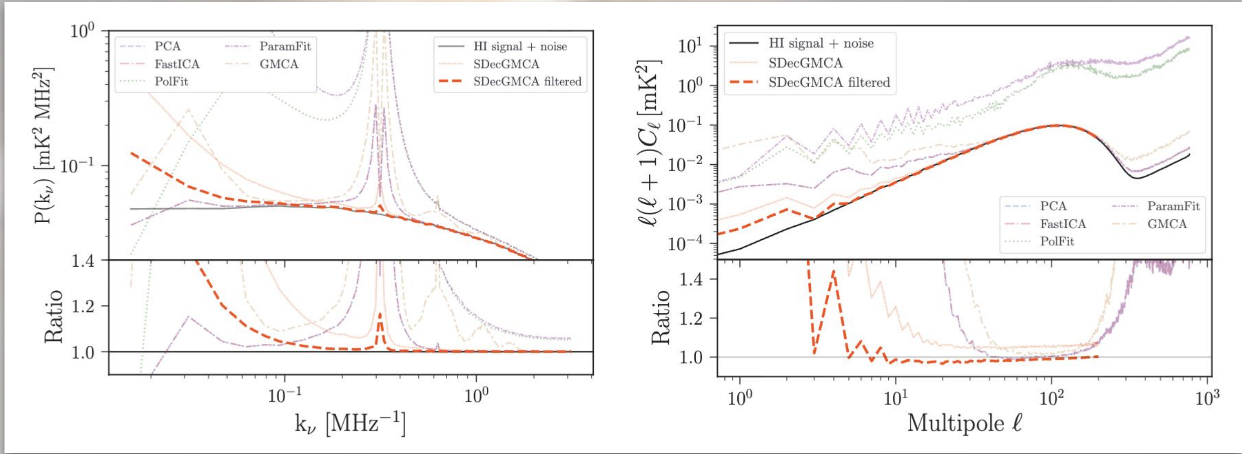
- Artificial peak in Cell
  - SDecGMCA per wavelet scale

Bright Galactic plane

$$|\langle \mathrm{MSE}\rangle - \mathrm{MSE}_{\mathrm{los}}| > \sigma_{\mathrm{MSE}}$$

$\mathbf{HI_{rec} - HI_{true}}$
along each line of sight





Gkogkou+2026

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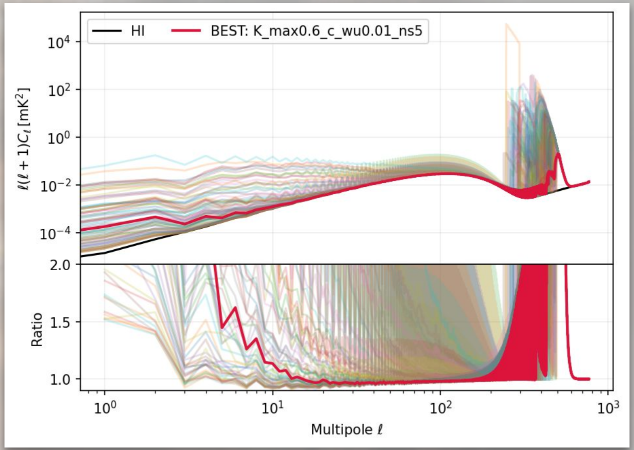

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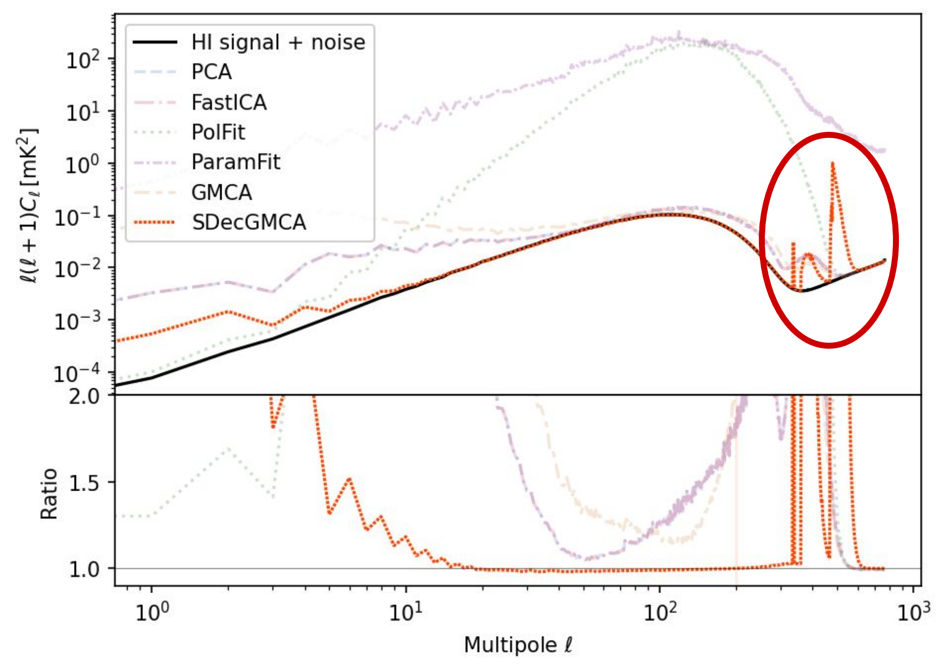

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Gkogkou+ 2026

SDecGMCA: limitations -> improvements

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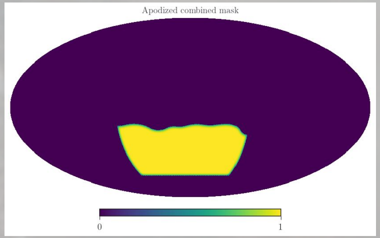

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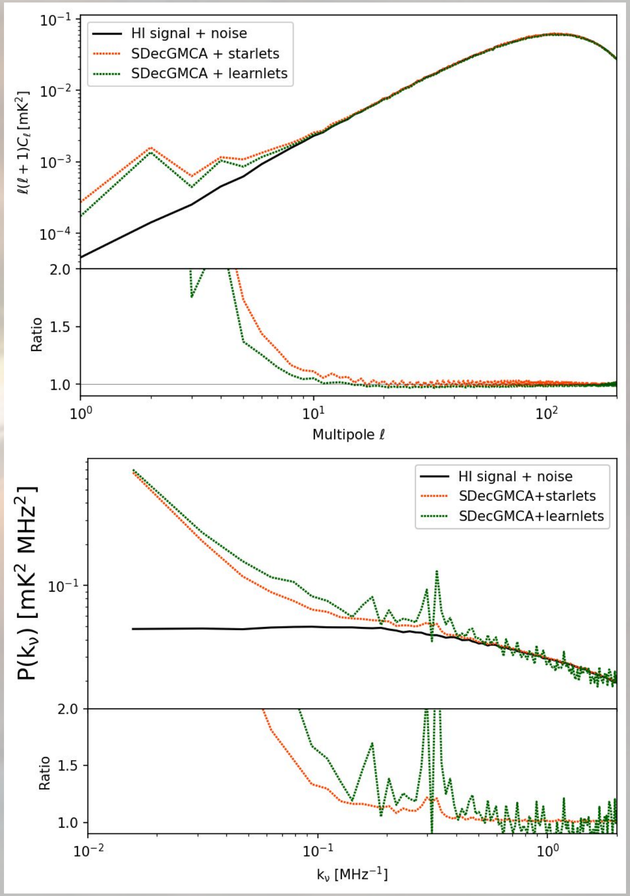
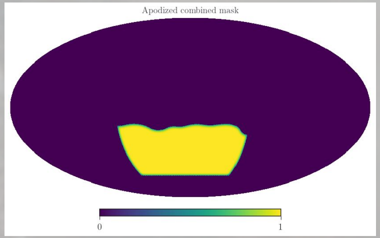


SDecGMCA: limitations -> improvements



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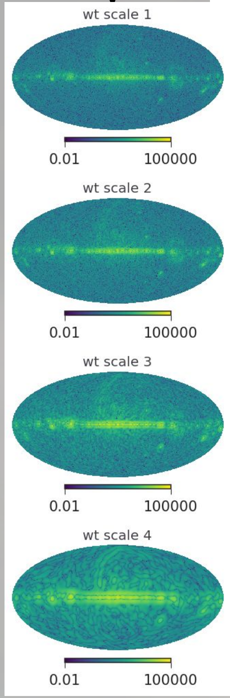
SDecGMCA: limitations -> improvements

wavelet decomposition

$$B_i^{(j)}(\ell) = \boxed{\psi_j(\ell)} B_i(\ell)$$



SDecGMCA per scale j

Residuals (HI reconstruction)

$(A, S)_j \rightarrow R_j$

$(A, S)_j \rightarrow R_j$

$(A, S)_j \rightarrow R_j$

$(A, S)_j \rightarrow R_j$

combine all scales back together for the final residual

$$\hat{R}_i = \sum_j \hat{R}_i^{(j)}$$

Summary & Conclusions

- SDecGMCA works the best in the realistic beam scenario on full sky

- Improvements that will lead to the application of the method on real data
  - Run the method in a footprint (masked version)
  - Using trained learnlets instead of starlets

- Artificial peak mitigation -> SDecGMCA per scale (?)