EXTRACTING HI INFORMATION FROM THE SKY MAPS WITH BINGO TELESCOPE

11TH AEGEAN SUMMER SCHOOL

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BINGO TELESCOPE BUILDER

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TALK OUTLINE

- 21cm cosmology
- 21 cm through Intensity mapping
- Components observed from the sky
- Modelling the observation
- Algorithms
- Spherical Wavelet Transforms
- Reconstruction of the Contaminants
- Reconstruction of the HI information

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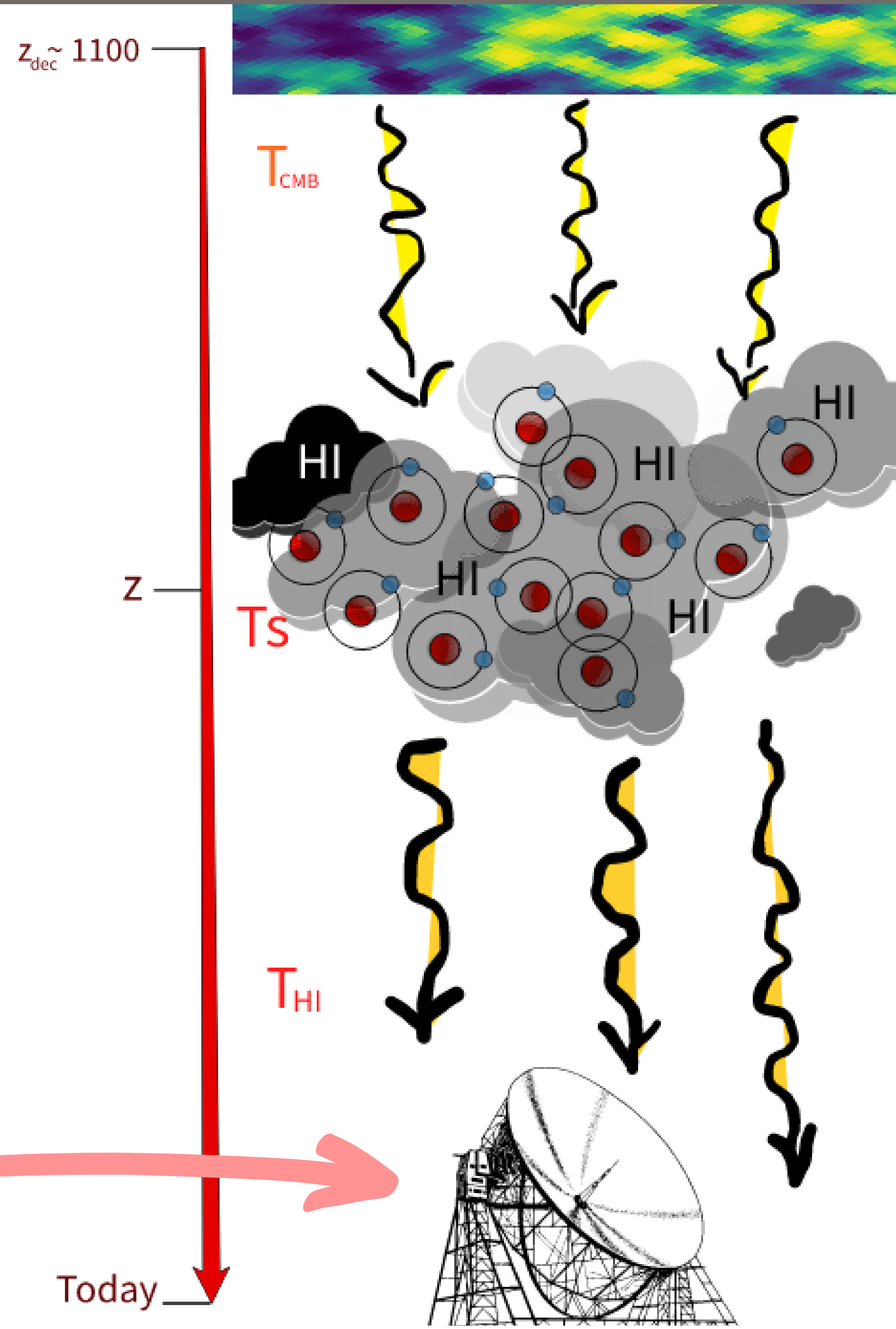
21cm Cosmology

- Used to trace the distribution of matter at radiofrequency
- Gives information between CMB and the Local Universe
- Informs about several astrophysical process at high-z
- Sensitive to the dynamics of the Universe
- Informs about the ionization state of hydrogen

HI Brightness Temperature

$$T_{\rm HI}(z) = \left(\frac{9hc^3A_{10}}{256\pi^2 G k_{\rm B}\nu_{10}^2 m_{\rm HI}}\right)\frac{\Omega_{\rm HI}(z)}{(1+z)^2}\frac{H_0^2}{\|dv_{\|}/d\chi\|}$$

$$\delta T_{\rm HI}(z,\hat{n}) = \delta_{\rm n} - \frac{1}{\mathcal{H}}\hat{\mathbf{n}}\cdot(\hat{\mathbf{n}}\cdot\nabla\hat{\mathbf{v}}) + \left(\frac{\rm d}{{\rm d}\eta}\ln\left(a^3\bar{n}_{\rm HI}\right) - \frac{\dot{\mathcal{H}}}{\mathcal{H}} - 2\mathcal{H}\right)\delta\eta + \frac{1}{\mathcal{H}}\dot{\Phi} + \Psi$$



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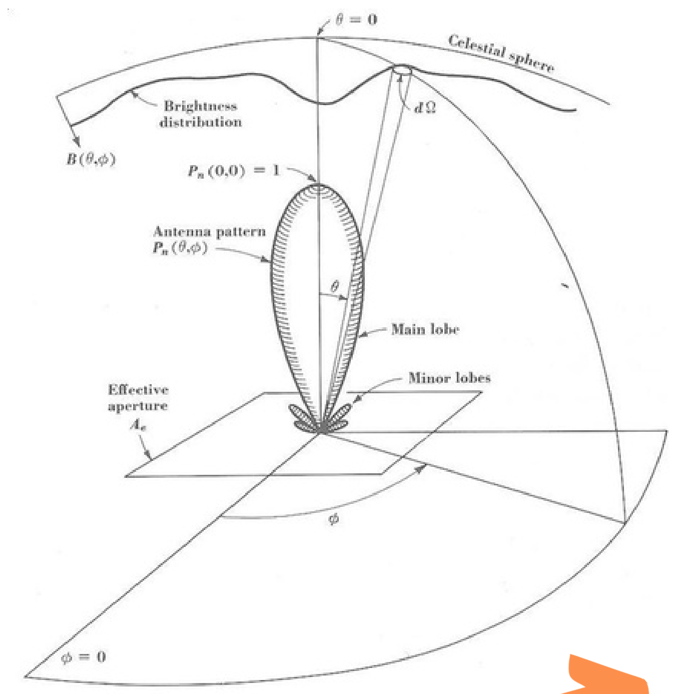
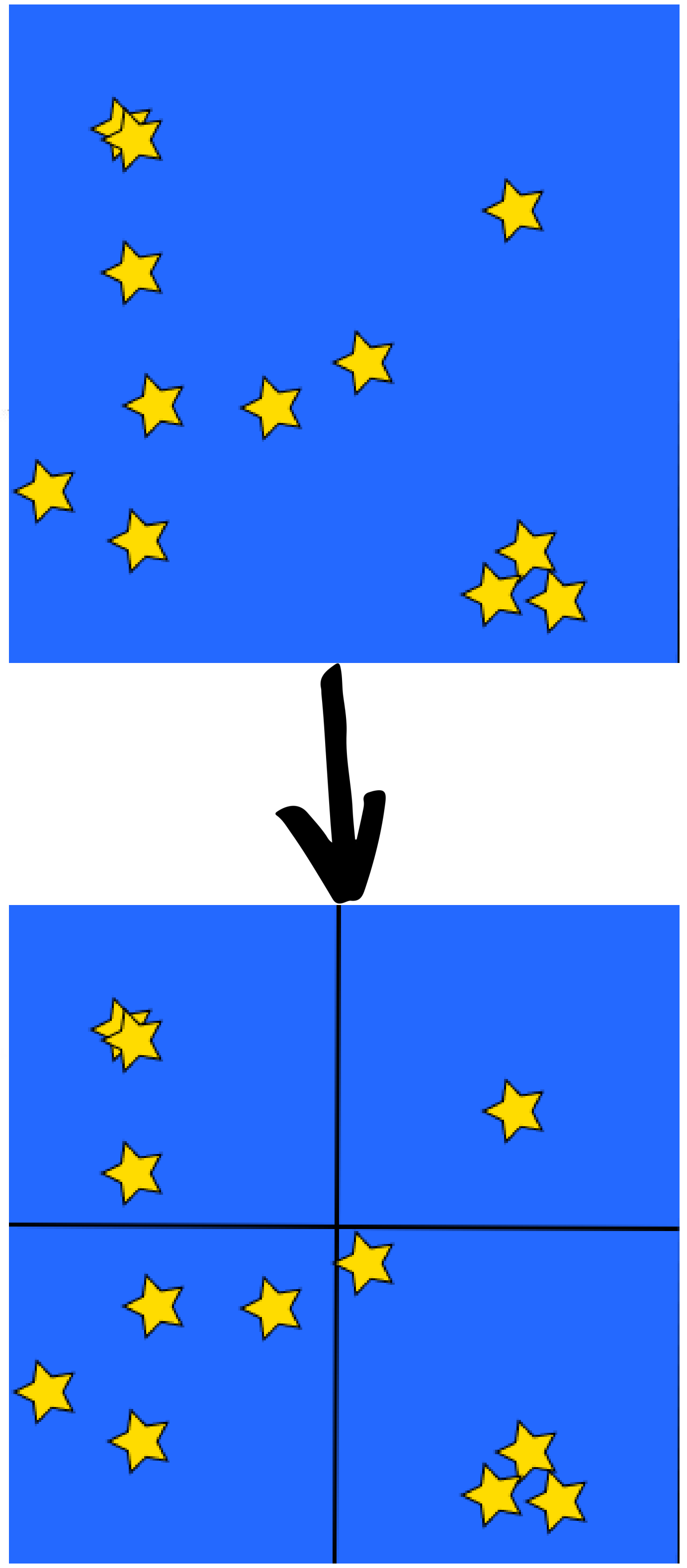
21 cm through Intensity Mapping

- Measures spatial fluctuations of emission lines from many unresolved sources within the same beam
- Very high z coverage in tomographic analysis
- Despite the low resolution, it has a higher coverage of the sky in shorter time than conventional surveys
- However, in the same (band of) frequency, we observed many other signal sources than just HI.





All signal sources within the same beam contribute to the observation

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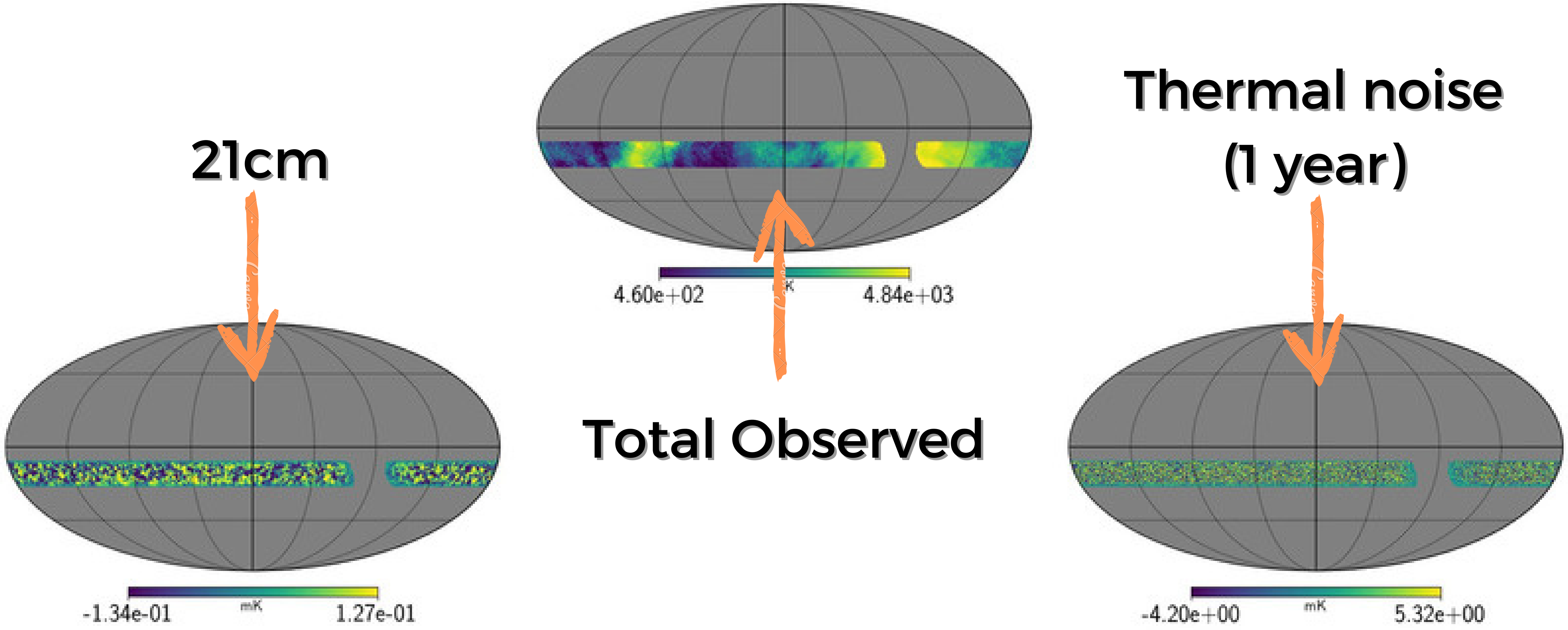
BINGO: General Information

- Fixed transit telescope covering a region in the sky by drift scanning due to the Earth's rotation
- Southern celestial hemisphere
- Operating frequency: 980-1260 MHz
- Declination region: ~ from -25^0 to -10^0
- Better resolution (center of FP, at 1.1GHz): 40 arcmin
- System Temperature: 70 K
- Total sky area covered (square deg; Phase I): ~ 5324



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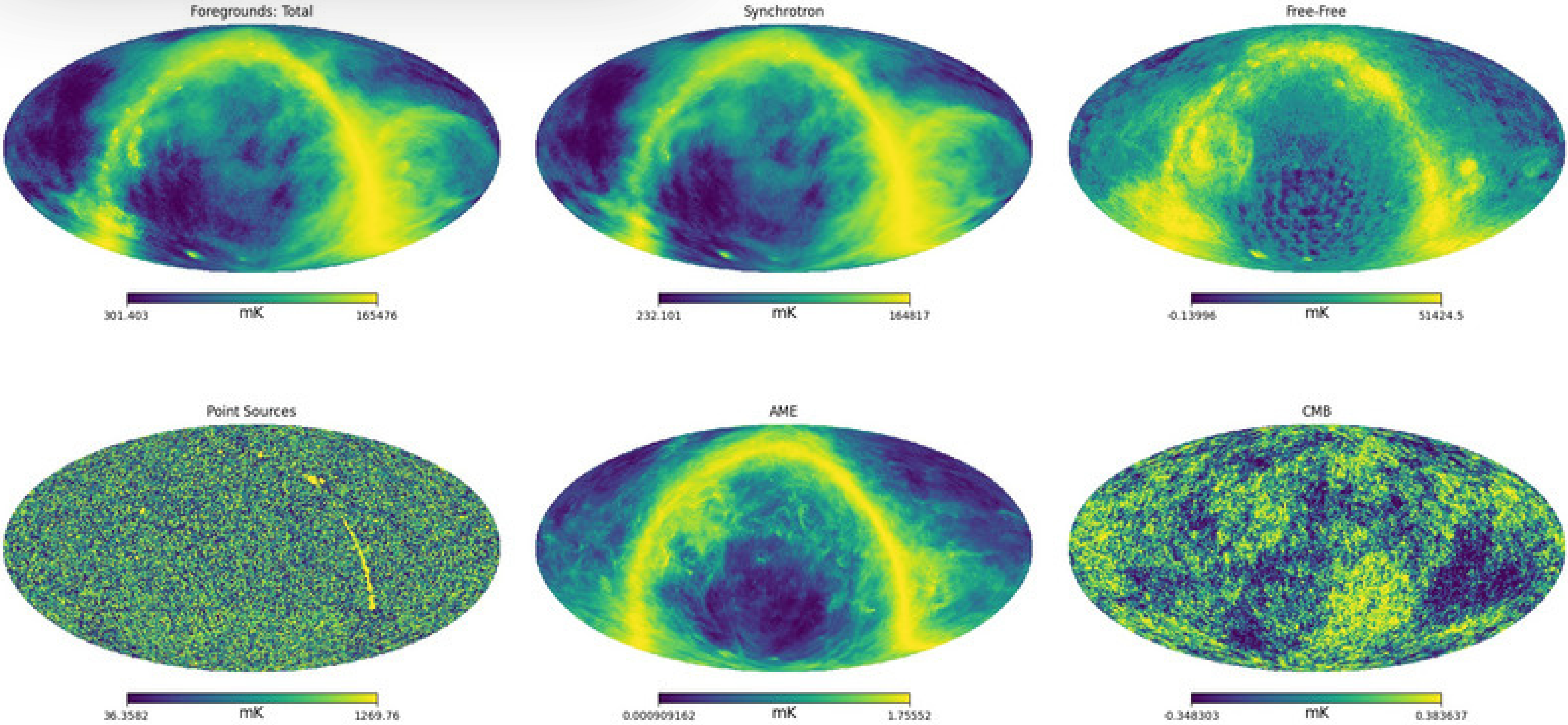
Astrophysical Contaminants



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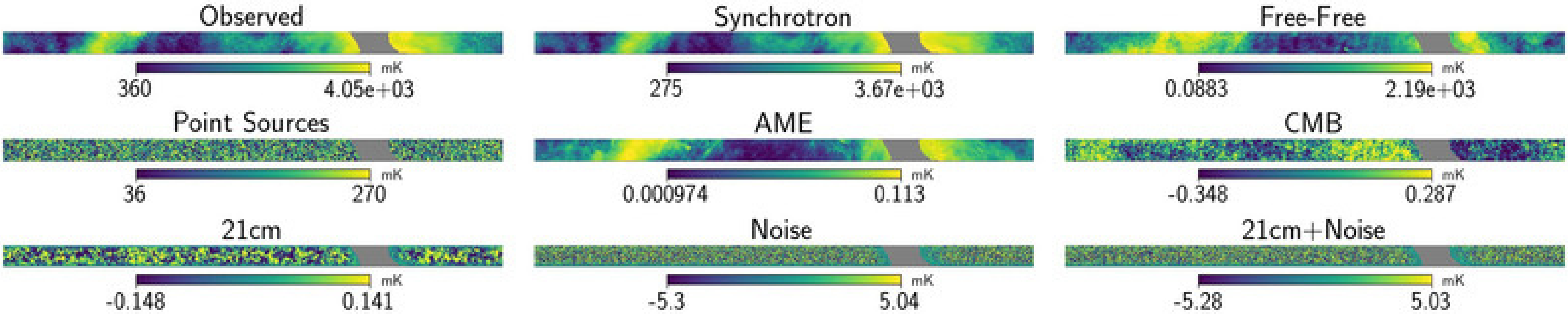
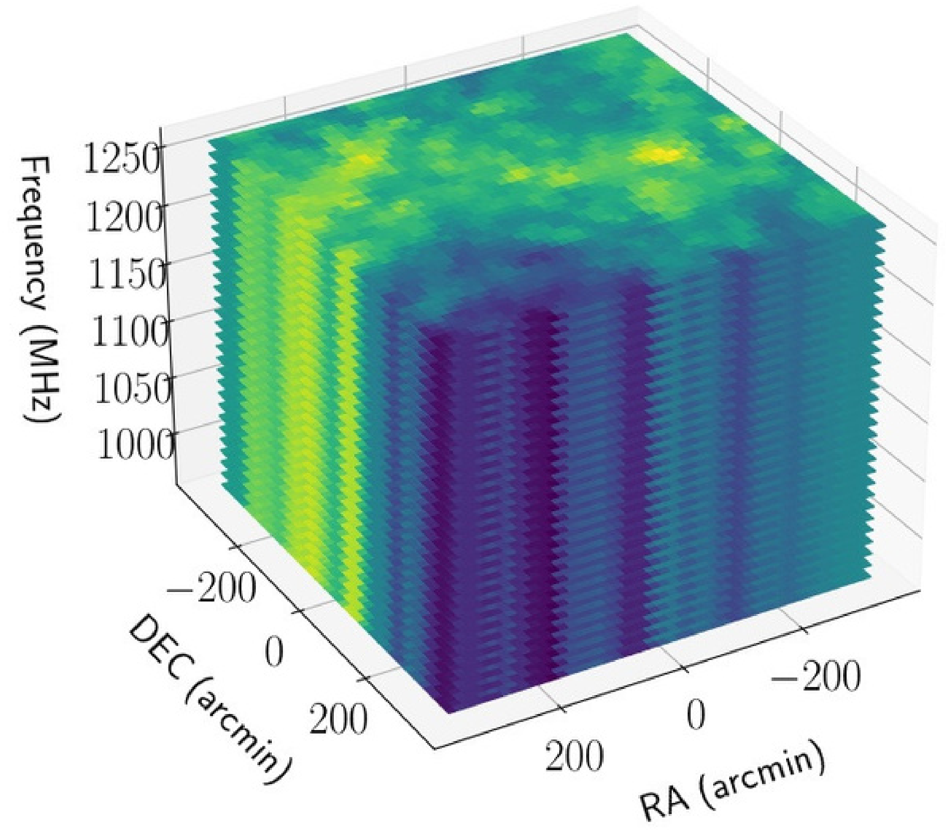
Contributions of the observed signals



All foregrounds components



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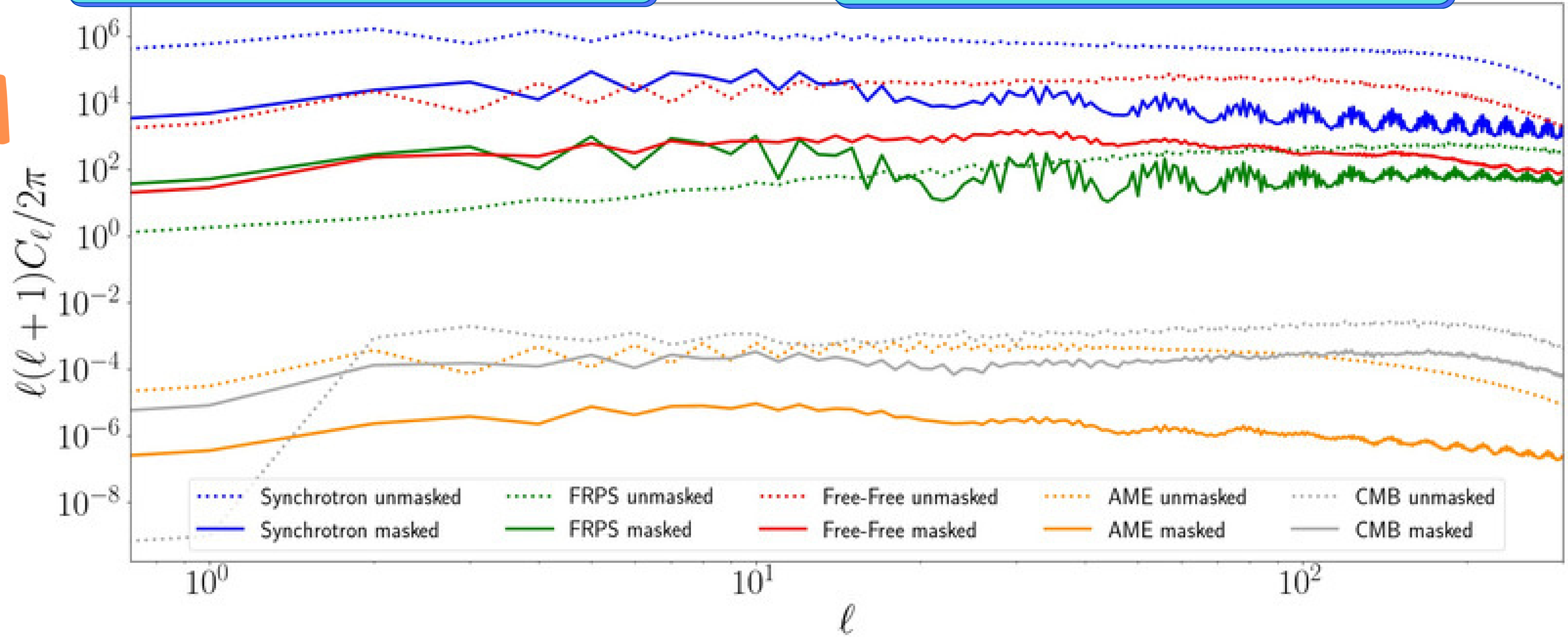
Contributions of the observed signals

$$C_\ell^{(F)} = \frac{1}{2\ell+1}\sum_{m=-\ell}^{\ell} a_{\ell m}^{(F)\dagger} a_{\ell m}^{(F)}$$

$$a_{\ell m}^{(F)} = \int \mathrm{d}\Omega\, \mathcal{Y}_{\ell m}^{\dagger}(\hat{\mathbf{r}}) F(\hat{\mathbf{r}})$$



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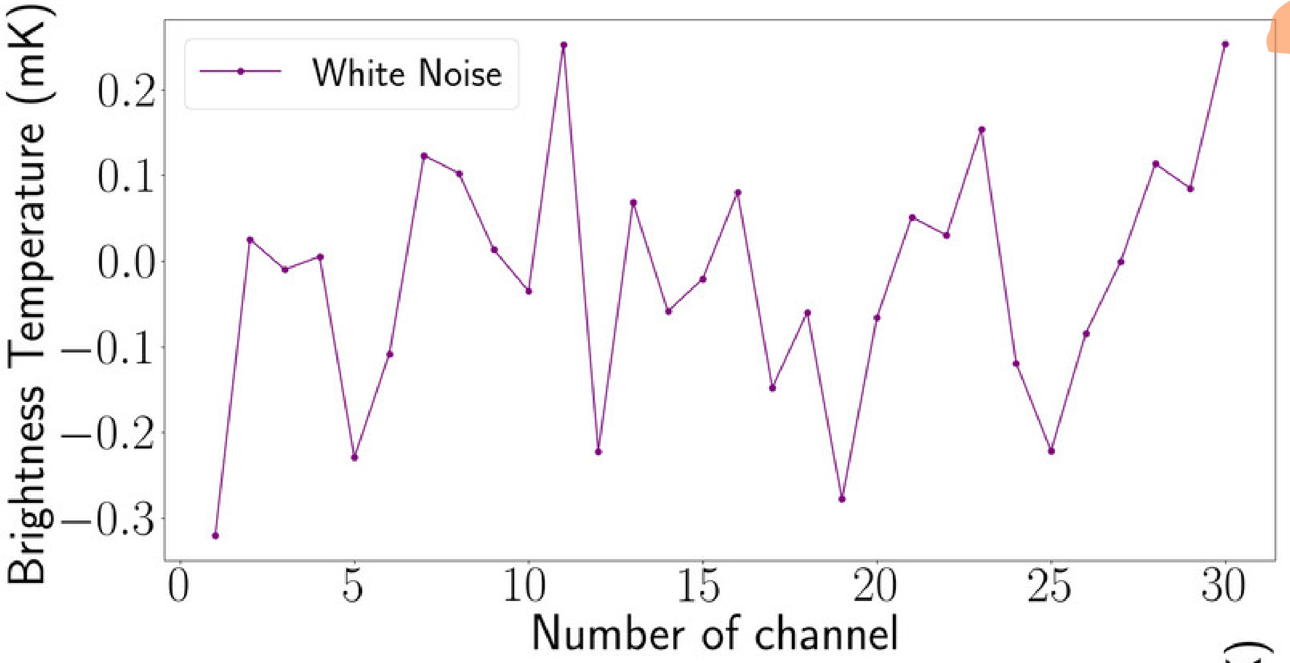
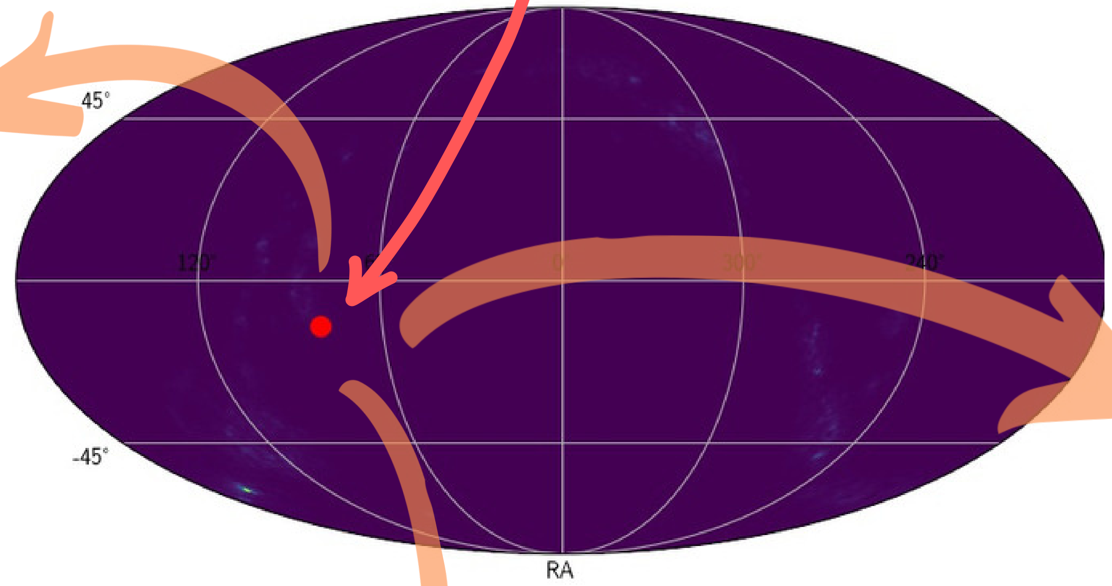
Observation modeling

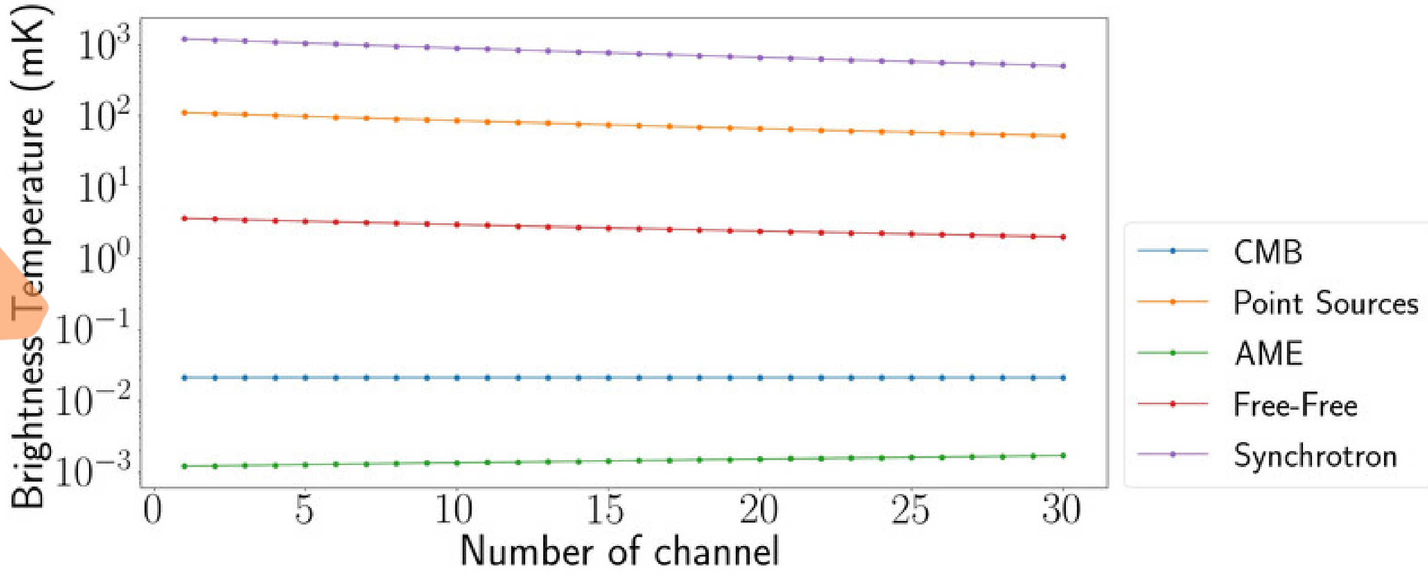
$$x\left(\nu_i, p\right) = \sum_{j=1}^{N_s} a_j\left(\nu_i\right) s_j(p) + n\left(\nu_i, p\right)$$

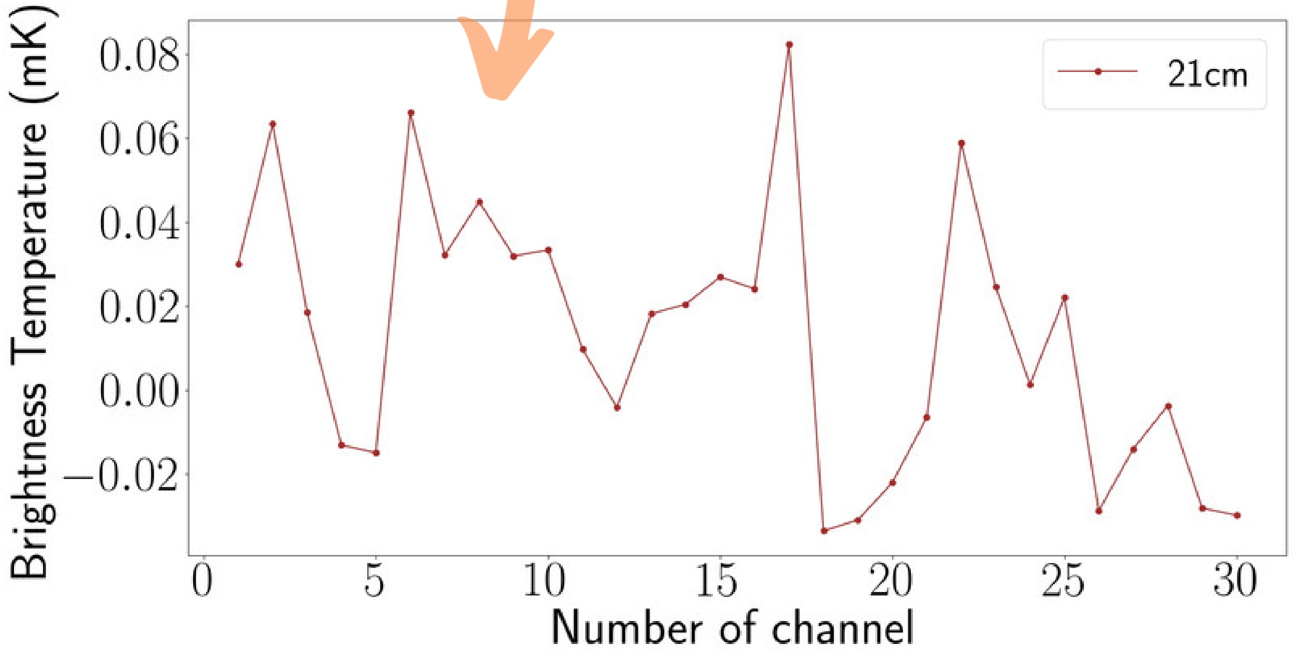
(RA,DEC)=(−20.91º, 12.33º)

$$\mathbb{X} = \mathbb{A}\mathbb{S} + \mathbb{N}$$









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Observation modeling

$$\mathbb{X} = \mathbb{A}\mathbb{S} + \mathbb{N}$$

$$\nabla_{\mathbb{S}}\Big|_{\hat{\mathbb{A}},\hat{\mathbb{S}}}\left(\frac{1}{2}\|\mathbb{N}\|^2_{\mathbb{Q}}\right) = 0$$

21cm + N + modeling error

Observation

Foreground estimated

$$\mathbb{R} = \mathbb{X} - \left[\hat{\mathbb{A}}\left(\hat{\mathbb{A}}^T\hat{\mathbb{A}}\right)^{-1}\hat{\mathbb{A}}^T\right]\mathbb{X}$$

Moore-Penrose pseudoinverse

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Algorithms

FastICA

$$\{\mathbb{W}\} = \underset{\mathbb{W}}{\operatorname{argmax}}\left\{ J\left(\mathbb{W}^{\mathrm{T}}\mathbb{X}\right) + \lambda\|\mathbb{W}\mathbb{W}^{\mathrm{T}} - \mathbb{I}\| \right\}$$

GMCA

$$\{\hat{\mathbb{A}}, \hat{\alpha}\} = \underset{\mathbb{A},\alpha}{\operatorname{argmin}}\left\{ \|\mathbb{X}\mathcal{D}^{\mathrm{T}} - \mathbb{A}\alpha\|^2_{\mathrm{F},\mathbb{C}_{\mathbb{N}}^{-1}} + 2\lambda\|\alpha\|_{\ell_1} \right\}$$

GNILC

$$\{\hat{\mathbb{A}}, \hat{\mathbb{S}}\} = \underset{\mathbb{A},\mathbb{S}}{\operatorname{argmin}}\left\{ \|\mathbb{W}\|^2_{\mathrm{F},\mathbb{R}_{\mathbb{X}}^{-1}} + \|\Lambda^{\mathrm{T}}\left(\mathbb{A} - \mathbb{W}\mathbb{A}\right)\|_{\mathrm{F}} \right\}$$

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Algorithms

FastICA

$$\{\mathbb{W}\} = \underset{\mathbb{W}}{\text{argmax}}\left\{ J\left(\mathbb{W}^{\mathrm{T}}\mathbb{X}\right) + \lambda \|\mathbb{W}\mathbb{W}^{\mathrm{T}} - \mathbb{I}\| \right\}$$

- Assumes that astrophysical sources are statistically independent;
- Searching for independent components is equivalent to searching for maximally non-Gaussian components;
- Aims to describe the observation in N independent components;
- Measures non-Gaussianity by *Negentropy:* $J\left(\xi\right) = H\left(\xi_{\mathrm{G}}\right) - H\left(\xi\right)$
- *Hyvärinen Negentropy:* $J\left(\xi\right) \sim \left[\mathrm{E}\{g(\xi)\} - \mathrm{E}\{g(\nu_{\mathrm{G}})\}\right]^2$

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Algorithms

- **Sparsity:** A signal is said to be sparse in a dictionary if a few dictionary elements can represent it: $y = \alpha\Phi = \sum_{\gamma\in\Gamma} \alpha_\gamma \phi_\gamma$
- **Morphological Diversity:** It is the characteristic of representing a signal by some *morphological components* from one or more dictionaries $s_j = \sum_{k=1}^{D} \phi_{jk} = \sum_{k=1}^{D} \alpha_j{}^k \boldsymbol{\Phi}_k$

GMCA

$$\{\hat{\mathbb{A}}, \hat{\alpha}\} = \underset{\mathbb{A},\alpha}{\operatorname{argmin}} \left\{ \|\mathbb{X}\mathcal{D}^{\mathrm{T}} - \mathbb{A}\alpha\|^2_{\mathrm{F},\mathbb{C}_{\mathbb{N}}^{-1}} + 2\lambda\|\alpha\|_{\ell_1} \right\}$$

$$\mathcal{D} = [\boldsymbol{\Phi}_1^{\mathrm{T}}, \ldots, \boldsymbol{\Phi}_D^{\mathrm{T}}]^{\mathrm{T}}$$

- The algorithm searches for the sparsest solution among all possible solution
- It is important that at least one of the dictionaries be some kind of *wavelet transform*

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Algorithms

- Estimates the foreground contributions in the Needlet space (a kind of spherical wavelet),
- The estimation is made for each needlet band in a specific multipole range;
- Uses a residual template to estimate the foreground dimension;
- The template only serves to get the signal-to-noise ratio and then estimates the degree of freedom of the foregrounds.

$$\hat{\mathbb{R}}_{\mathrm{prior}}^{-1/2}\mathbb{R}_{\mathbb{X}}\hat{\mathbb{R}}_{\mathrm{prior}}^{-1/2} = \hat{\mathbb{U}}\hat{\mathbb{D}}\hat{\mathbb{U}}^{\dagger} \rightarrow \hat{\mathbb{U}} = \left[\hat{\mathbb{U}}_{\mathrm{FG}}, \hat{\mathbb{U}}_{21\mathrm{cm+N}}\right] \rightarrow \hat{\mathbb{A}} = \hat{\mathbb{R}}_{\mathrm{prior}}\hat{\mathbb{U}}_{21\mathrm{cm+N}}$$

GNILC

$$\{\hat{\mathbb{A}}, \hat{\mathbb{S}}\} = \underset{\mathbb{A},\mathbb{S}}{\operatorname{argmin}}\left\{ \|\mathbb{W}\|^2_{\mathrm{F},\mathbb{R}_{\mathbb{X}}^{-1}} + \|\Lambda^{\mathrm{T}}(\mathbb{A} - \mathbb{W}\mathbb{A})\|_{\mathrm{F}} \right\}$$

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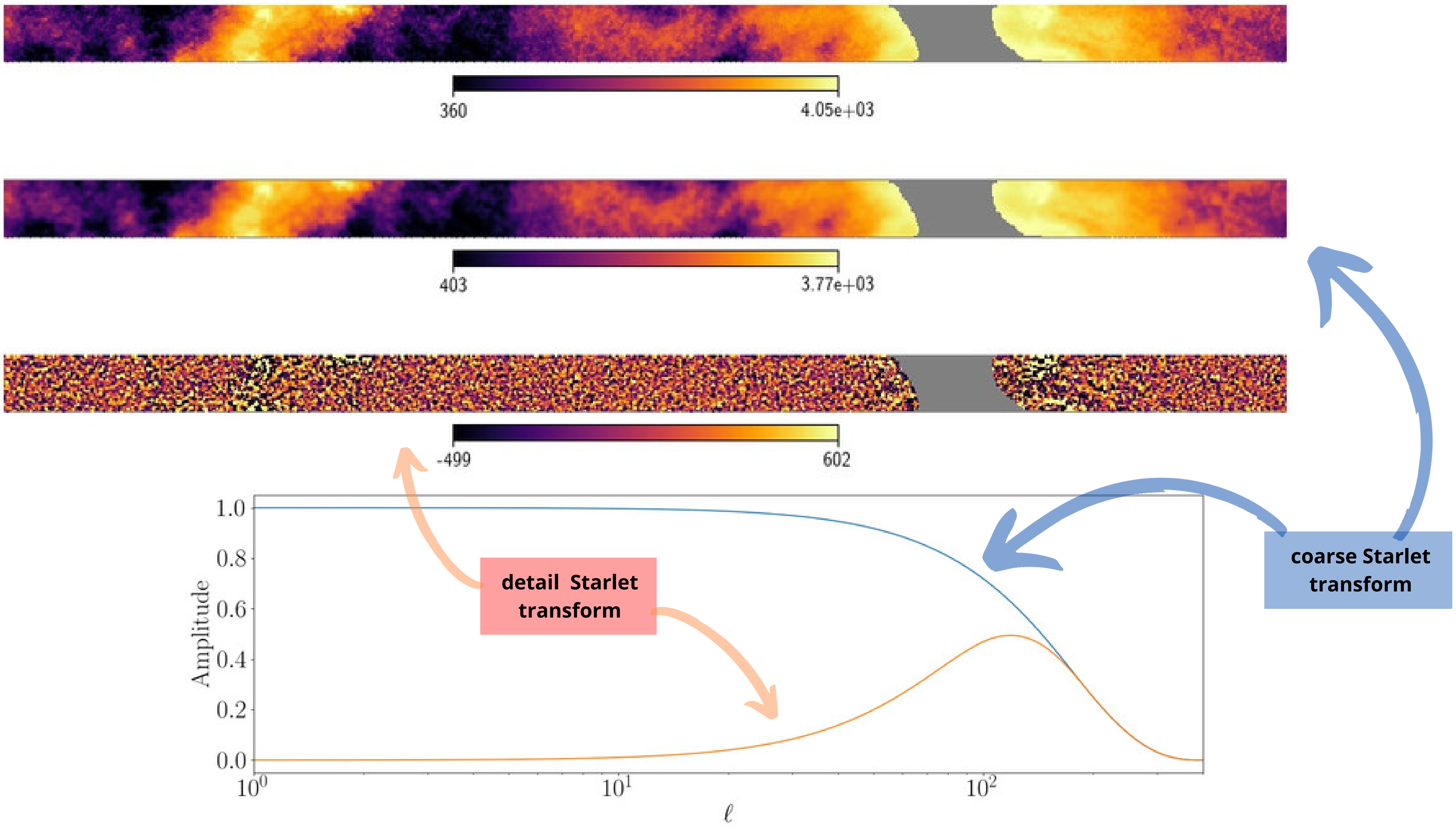
Starlet Transform



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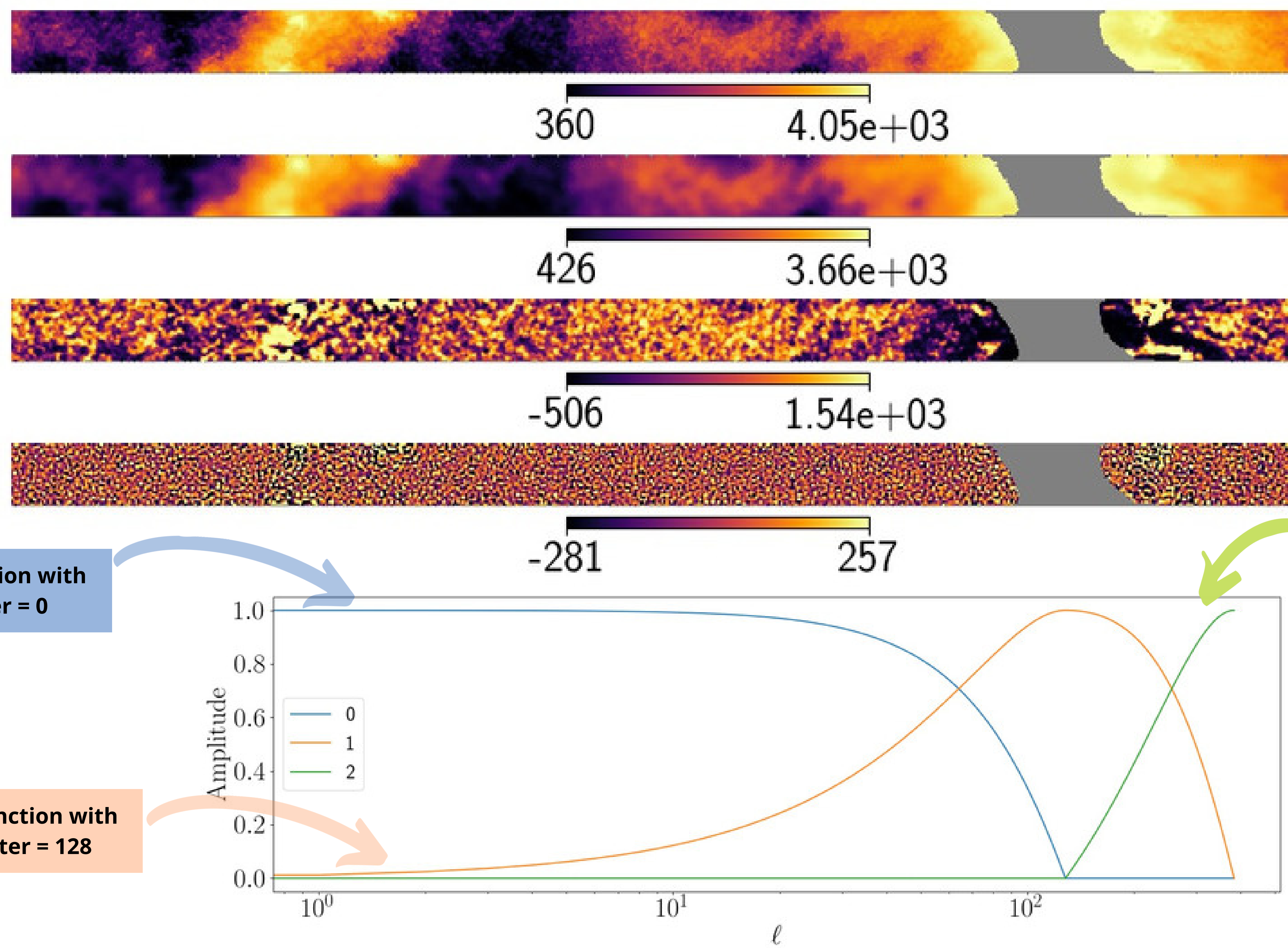
Needlet Transform

Observed

First layer

Second layer

Third layer



Needlet function with bandcenter = 0

Needlet function with bandcenter = 383

Needlet function with bandcenter = 128

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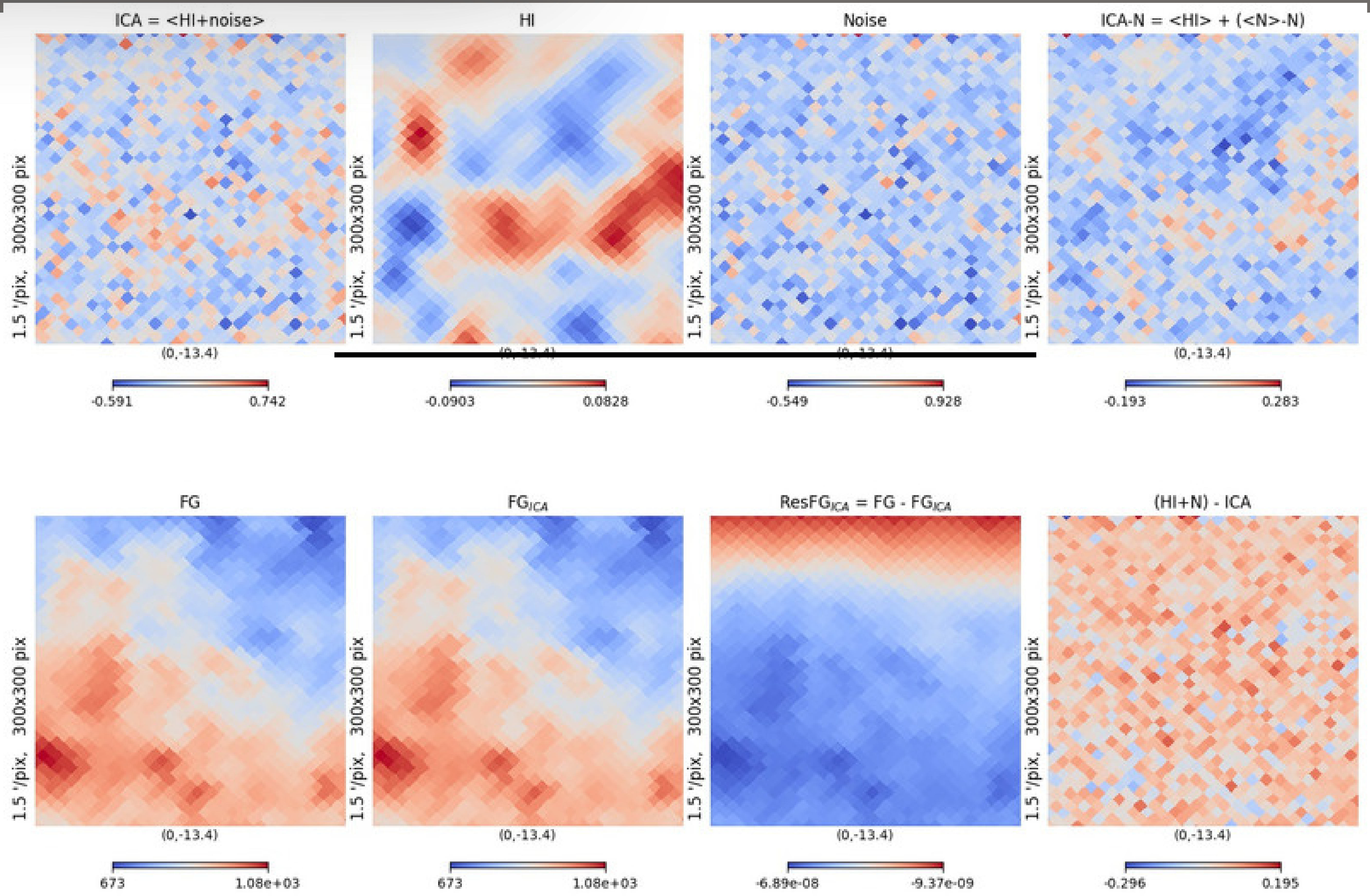
Foreground Reconstruction by FastICA



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Reconstruction of HI information

$$a_{\ell m}^{(F)} = \int \mathrm{d}\Omega \mathcal{Y}_{\ell m}^{\dagger}(\hat{\mathbf{r}}) F(\hat{\mathbf{r}})$$

$$C_\ell^{(F)} = \frac{1}{2\ell+1} \sum_{m=-\ell}^{\ell} a_{\ell m}^{(F)\dagger} a_{\ell m}^{(F)}$$

$$\hat{C}_\ell^{(21cm)} = \frac{C_\ell^{(21\mathrm{cm}\,+\,\mathrm{N})}}{S_\ell} - \left\langle C_\ell^{(\mathrm{N})} \right\rangle_{L_j}^{j \neq i}$$

Realization assumed as Universe

realization

$$S_\ell = \left\langle \frac{C_\ell^{(21\mathrm{cm}\,+\,\mathrm{N})}}{C_\ell^{(\mathrm{prior})}} \right\rangle_{L_j}^{j \neq i}$$

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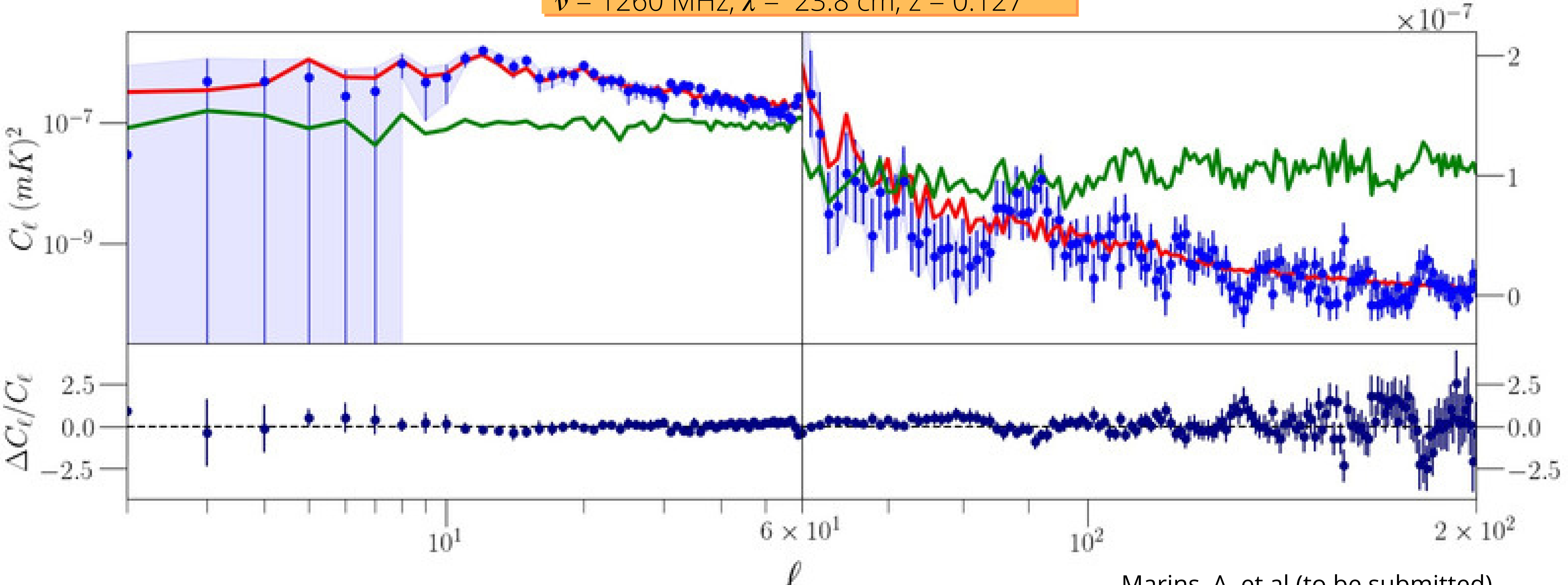
Reconstruction of HI information
FastICA

Channel 30 (1250 - 1260 MHz)
ν = 1250 MHz, λ = 24.0 cm, z = 0.136
ν = 1260 MHz, λ = 23.8 cm, z = 0.127



Marins, A. et al (to be submitted)

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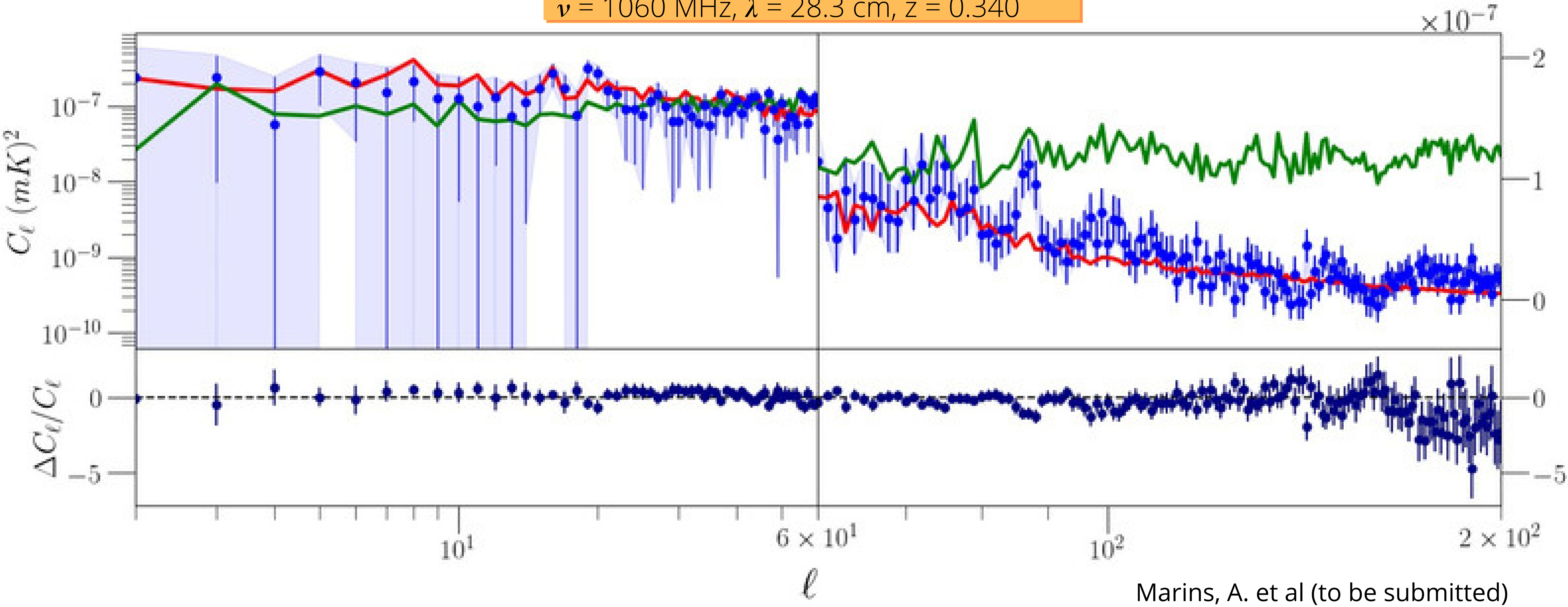
Reconstruction of HI information GNILC

Channel 10 (1050. - 1060. MHz)
ν = 1050 MHz, λ = 28.6 cm, z = 0.352
ν = 1060 MHz, λ = 28.3 cm, z = 0.340



Marins, A. et al (to be submitted)

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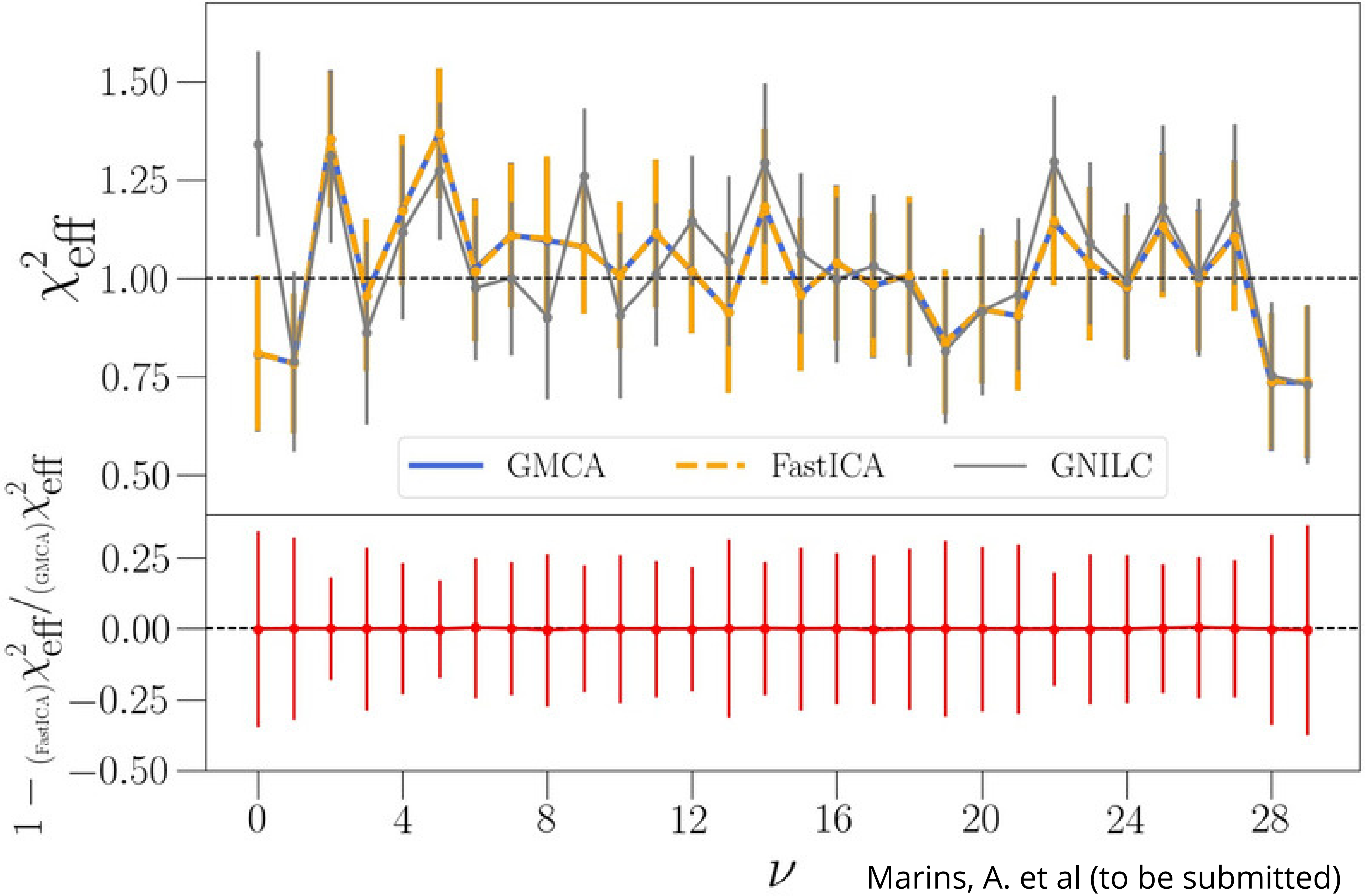
Reconstruction of HI information
GNILC

$$\chi^2(\nu,\ell) = \frac{\left(\hat{C}_\ell^{21cm}(\nu) - C_\ell^{\text{input}}(\nu)\right)^2}{\hat{\sigma}_\ell^2(\nu)}$$

$$\chi^2_{\text{eff}}(\nu) = \frac{1}{n_\ell}\sum_{\ell=\ell_{\min}}^{\ell_{\max}} \chi^2(\nu,\ell)$$



Marins, A. et al (to be submitted)

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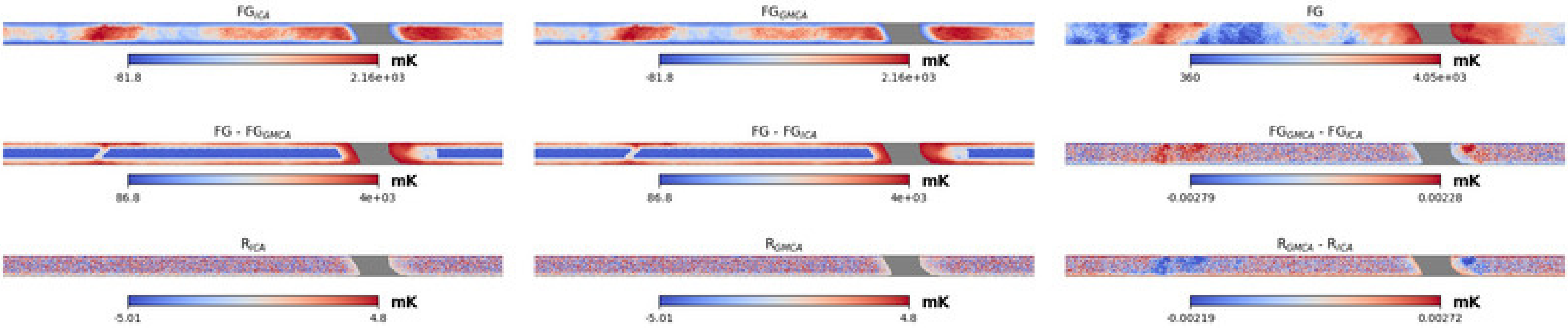
Foreground Reconstruction: Comparison FastICA x GMCA



Marins, A. et al (to be submitted)

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Final considerations

The results obtained so far assume:

- 1 year of observation;
- All horns with the same beam shape and resolution;
- No correlated noise effect (ex: 1/f);
- No maps used were pre-processed by TOD and MapMaking;

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Foreground Removal and HI reconstruction team:

- Alessandro Marins (University of Sao Paulo - Brazil)
- Larissa Santos (Yangzhou University - China)
- Mathieu Remazeilles (Inst de Fisica de Cantabria - Spain)
- Filipe Abdalla (University College London - UK)
- Giancarlo de Gaspari (University of Roma - Italy)
- Eduardo Merícia (Instituto Nacional de Pesquisas Espaciais - Brazil)
- Jacques Delabrouille (Laboratoire AstroParticule et Cosmologie - France)

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Thank you all !!