High Precision Foreground Modeling Using Current And Future Multi-frequency Microwave Maps

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Motivation:

- **Conventional methods** rely on **simple parametrizations** of different **foreground** components or are **blind (variance minimization).**
- For B-mode and spectral distortions measurements we are entering a “new era” : No signal dominated channels! Will these methods work as well?
  - **Yes! Are we sure? Are we using sufficiently realistic simulations for foregrounds? How might we generate more realistic simulations?**
  - **No! We need new techniques for modeling foregrounds !**

Outline:

- What are moments? **J. Chluba, J. C. Hill & M. H. Abitbol, MNRAS, Vol. 472, Iss. 1, 1195-1213**
- An example demonstrating bias in inferred cosmology.
- How well in-principle can we do with moment expansions?
- Measuring moments from Planck maps.

Scope

Moments are new observables

Signals

Foregrounds

Separations methods

Parametric

Non-Parametric

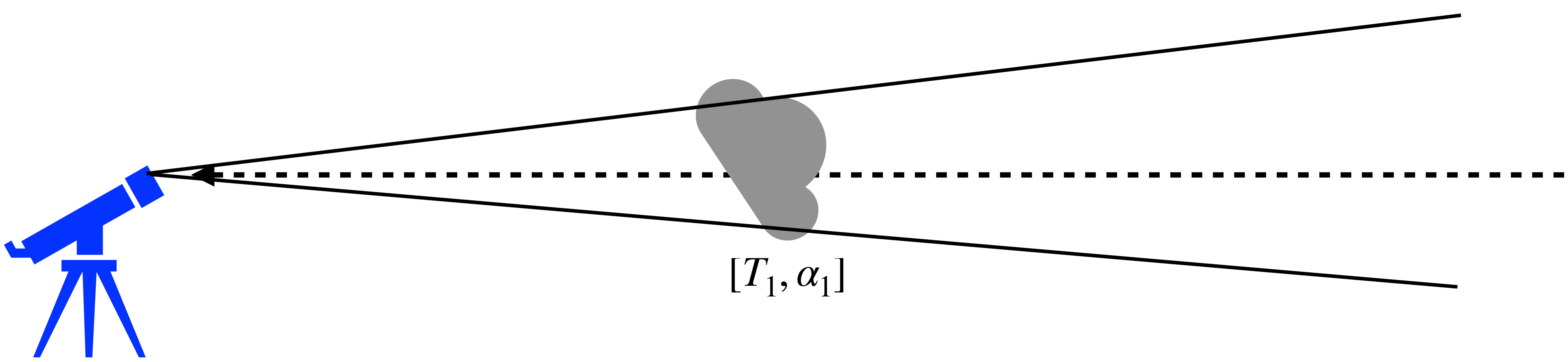
New foreground cleaning method

Connection between parametric and non-parametric methods?

Observers assumption
(current)

Each cloud emits a modified black body spectrum.

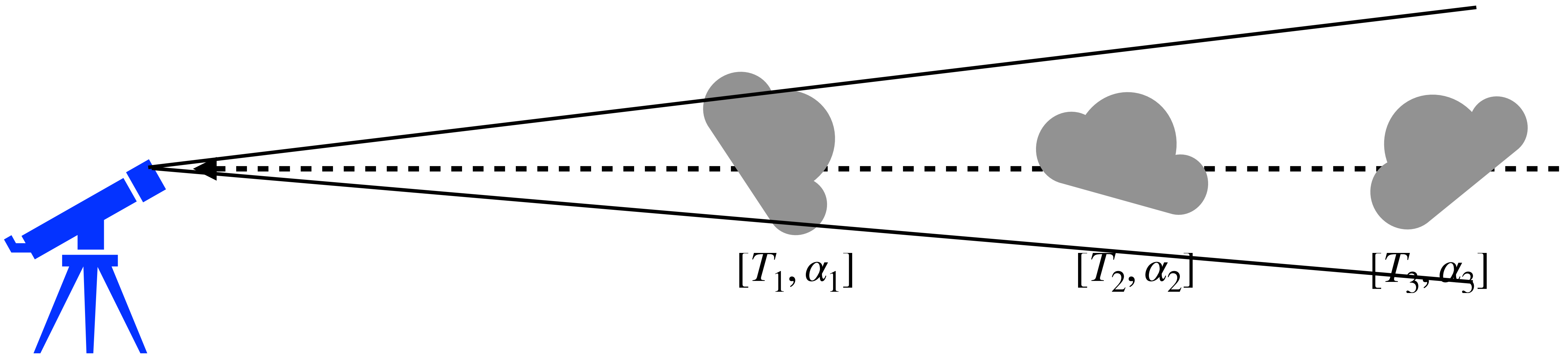
$$B_\nu(\alpha, T) = A\frac{2h\nu^3}{c^2}\left(\frac{\nu}{\nu_0}\right)^\alpha \frac{1}{e^{\frac{h\nu}{kT}} - 1}$$



Nature

Each cloud emits a modified black body spectrum.

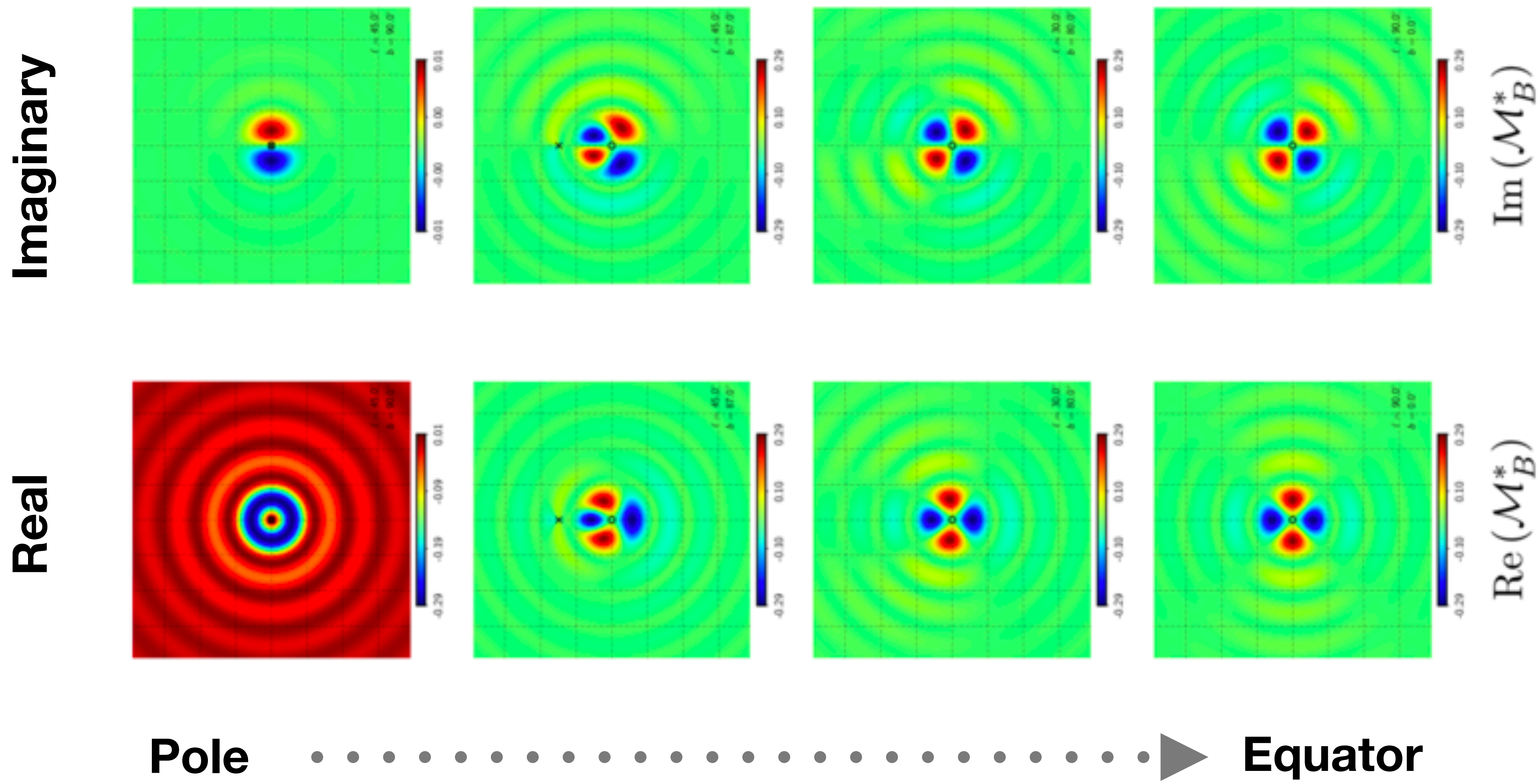
$$B_\nu(\alpha, T) = \frac{2h\nu^3}{c^2}\left(\frac{\nu}{\nu_0}\right)^\alpha \frac{1}{e^{\frac{h\nu}{kT}} - 1}$$



$$S_\nu = \int \frac{dI}{ds} ds \neq B_\nu(\alpha', T')$$

An un-avoidable averaging in Polarization analysis

Complex real space beam : Q/U —> E/B



A. Rotti & K. Huffenberger arXiv:1807.11940

What are moments?

Describing SED resulting from sum of modified black bodies:

$$S_\nu = \int \frac{dI}{ds} ds = \int B_\nu(\alpha, T) P(\alpha, T) d\alpha dT$$

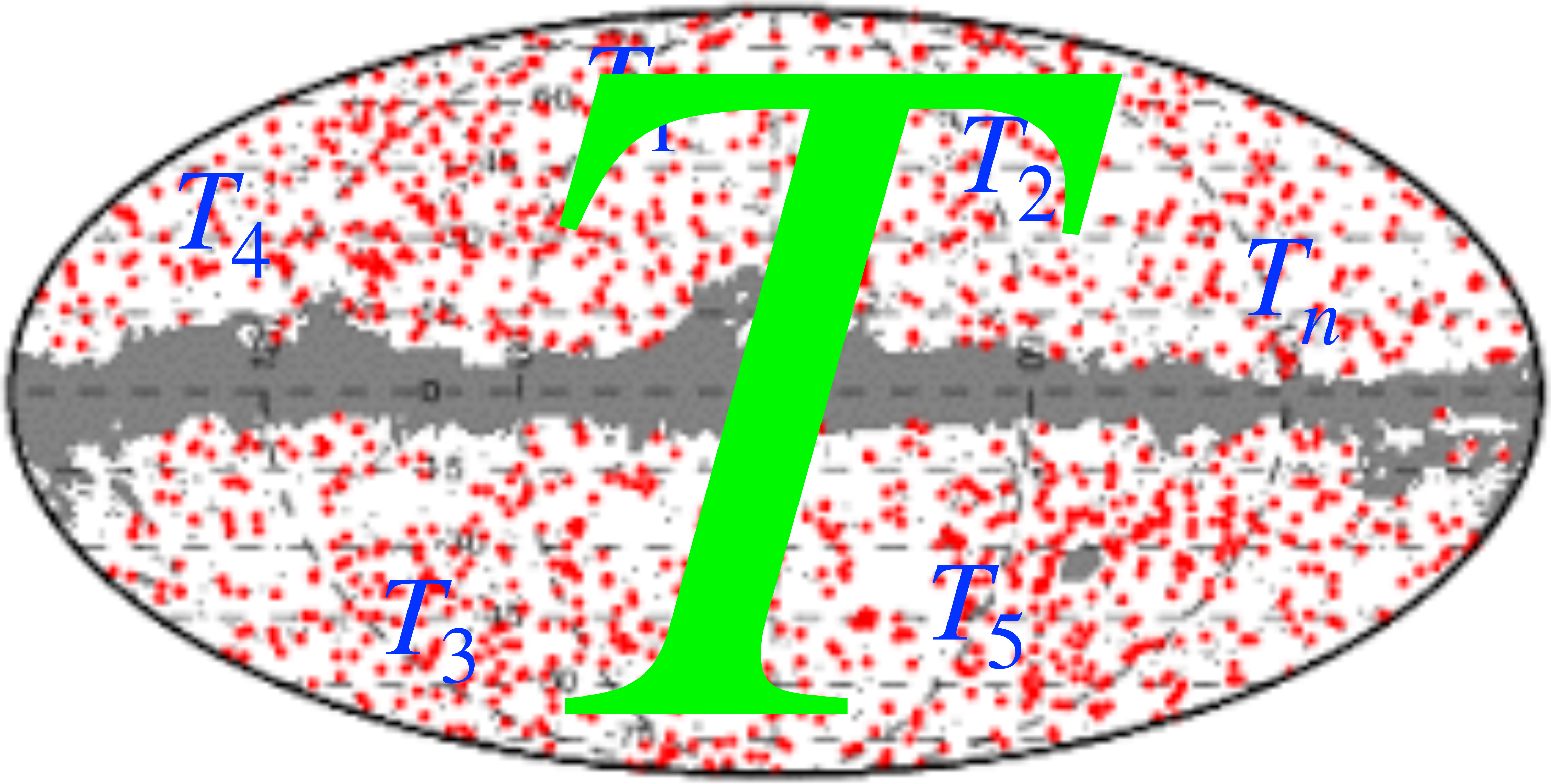
Building on top of the simple parametrization:

$$S_\nu = \sum_{m,n} \partial_\alpha^m \partial_T^n B_\nu(\alpha_0, T_0) \int (\alpha - \alpha_0)^m (T - T_0)^n P(\alpha, T) d\alpha dT$$

Moments of the distribution function

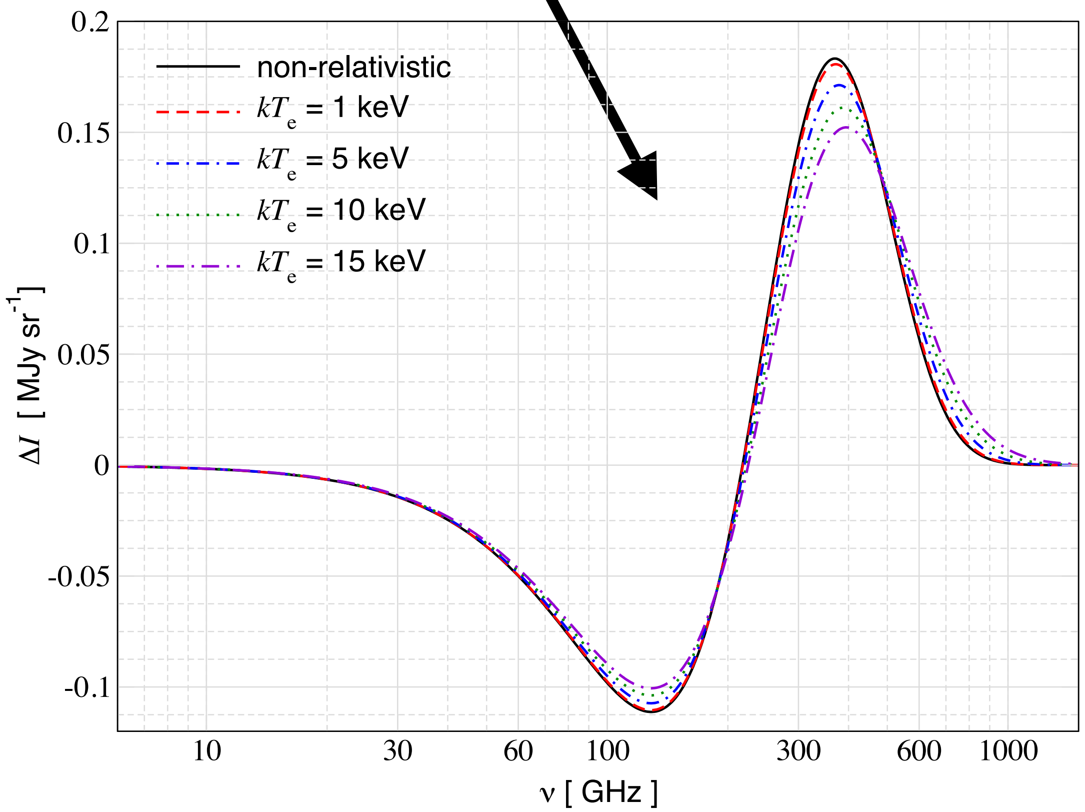
$$S_\nu(\alpha_0, T_0, A, p_\alpha, p_T, p_{\alpha\alpha}, p_{\alpha T}, p_{TT}, \cdots) \simeq AB_\nu(\alpha_0, T_0)$$
$$+ p_\alpha \partial_\alpha B_\nu(\alpha_0, T_0) + p_T \partial_T B_\nu(\alpha_0, T_0)$$
$$+ p_{\alpha\alpha} \partial_\alpha^2 B(\alpha_0, T_0) + p_{\alpha T} \partial_\alpha \partial_T B(\alpha_0, T_0) + p_{TT} \partial_T^2 B(\alpha_0, T_0)$$
$$+ \cdots$$

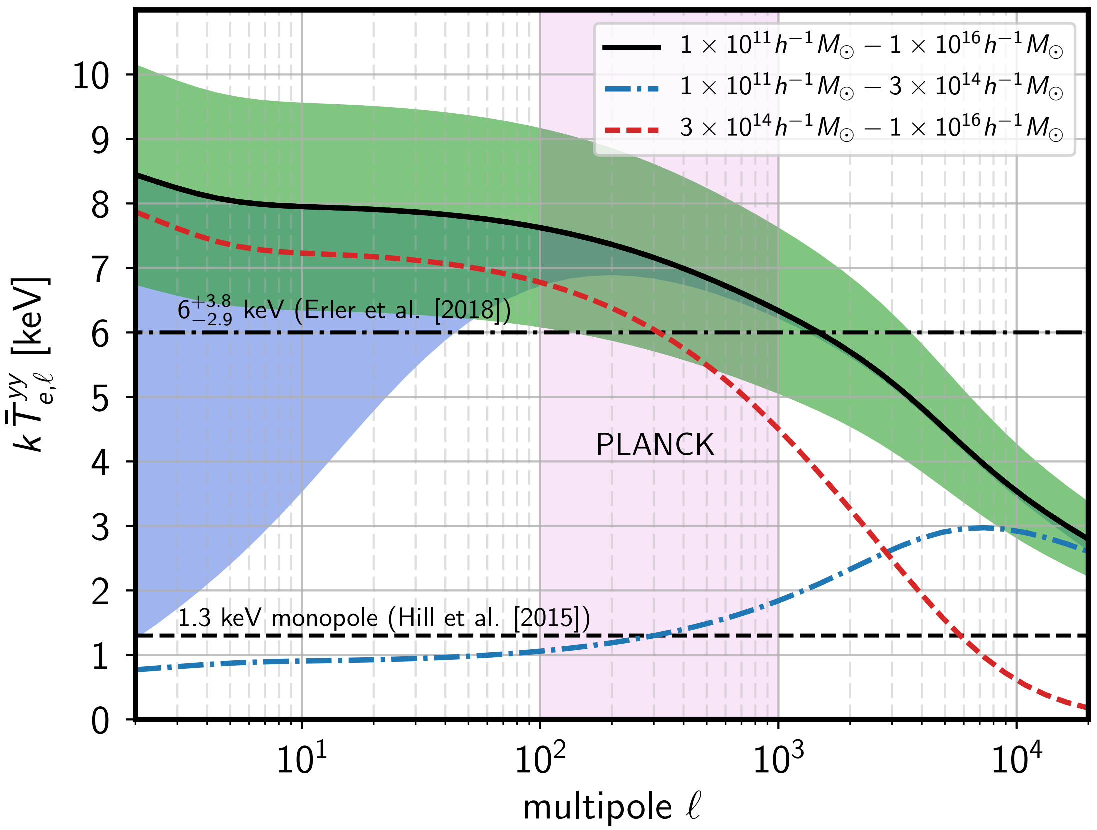
Moments in the thermal SZ analysis



Moments in the thermal SZ analysis

$$y^{tSZ}(\nu, \hat{n}) = Y_{(0)}(\nu, \bar{T})y(\hat{n})$$





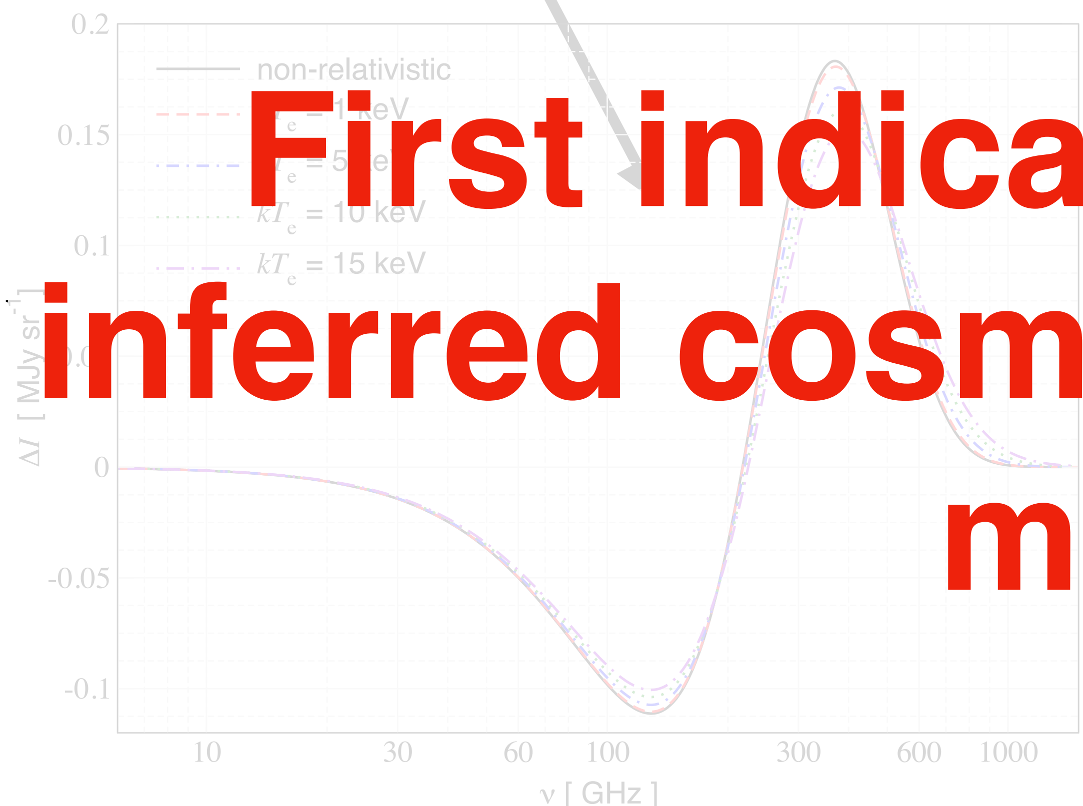
Effective change in the amplitude of the matter power spectrum for **Planck**

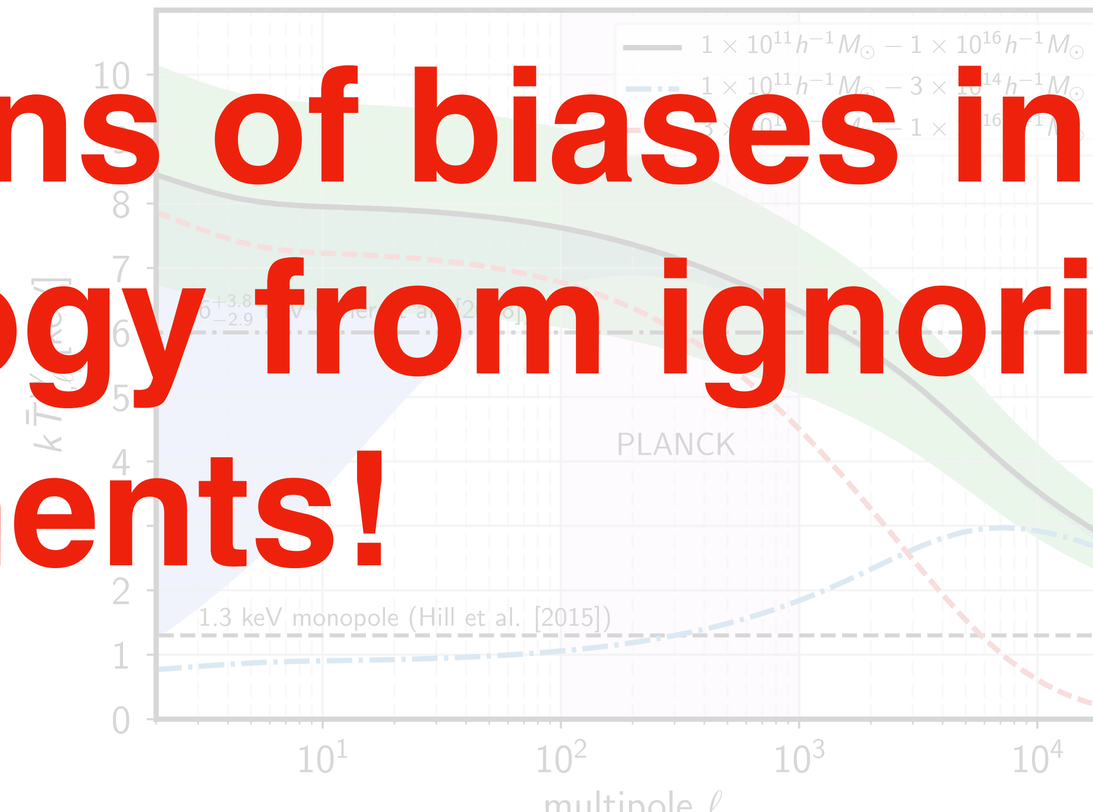
$$\Delta\sigma_8/\sigma_8^\star \simeq 0.019 \left[\frac{k\bar{T}_e}{5\,\mathrm{keV}}\right]$$

Remazeilles et. al. arXiv:1809.09666

Moments in the thermal SZ analysis

$$y^{tSZ}(\nu,\hat{n}) = Y_{(0)}(\nu,\bar{T})y(\hat{n}) + \sum_{i=1}^{N(\hat{n})} \frac{Y_{(i)}(\nu,\bar{T})(T_e(\hat{n})-\bar{T})^i}{i!} y(\hat{n}) \Rightarrow k\bar{T}^{yy}_{e,\ell} = \frac{\langle kT_e(M,z)\,|y_\ell|^2\rangle}{\langle |y_\ell|^2\rangle} = \frac{C_\ell^{T_e,yy}}{C_\ell^{yy}}$$





First indications of biases in inferred cosmology from ignoring moments!

Effective change in the amplitude of the matter power spectrum for **Planck**

$$\Delta\sigma_8/\sigma_8^\star \simeq 0.019 \left[\frac{k\bar{T}_e}{5\,\mathrm{keV}}\right]$$

Remazeilles et. al. arXiv:1809.09666

Measuring moments

Spectro-Spatial

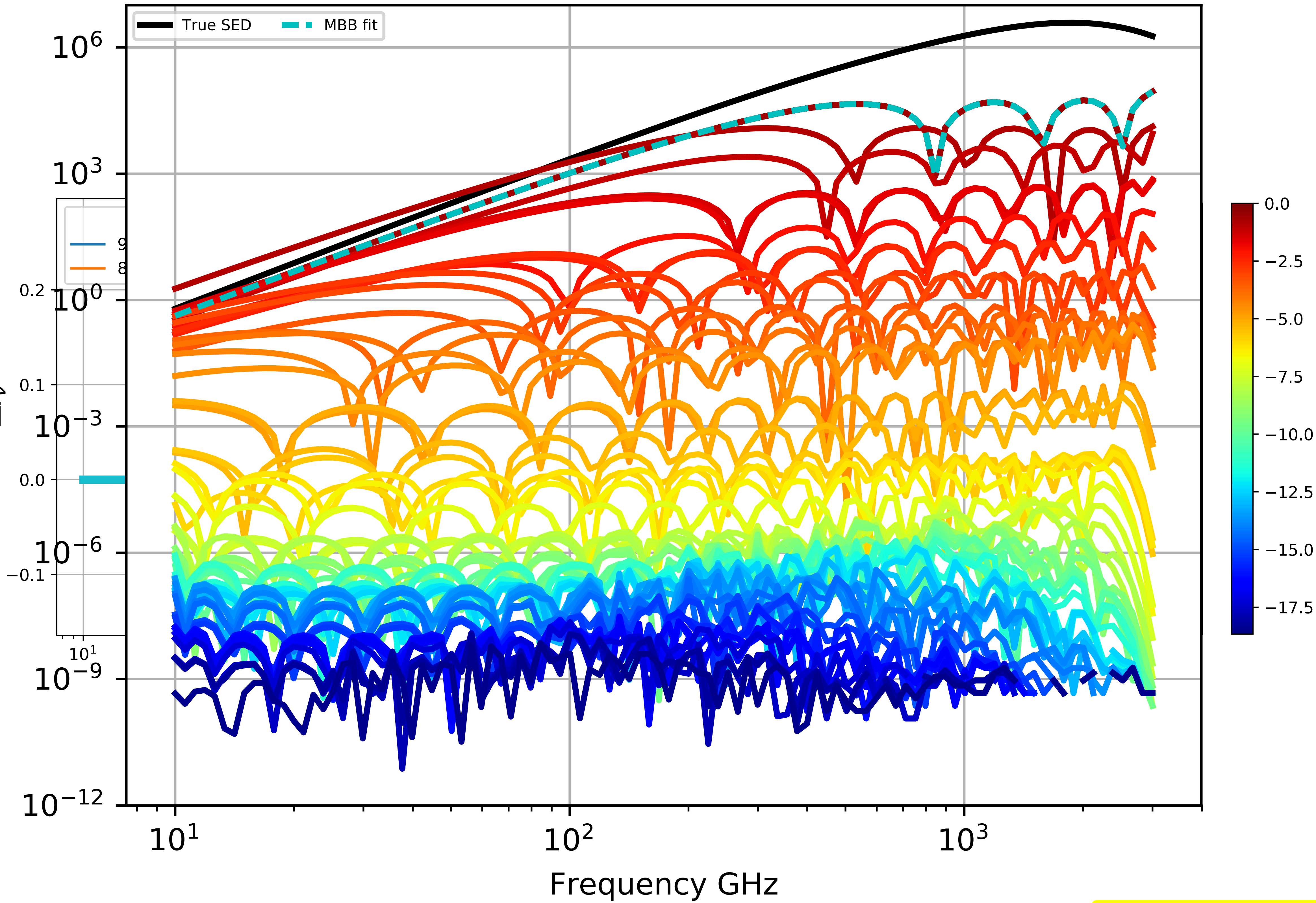
$$S_\nu(\alpha_0, T_0, A, p_\alpha, p_T, p_{\alpha\alpha}, p_{\alpha T}, p_{TT}, \cdots) = \overrightarrow{B}_{\nu i}(\alpha_0, T_0)\mathscr{M}_i + \epsilon_i$$

Think of this as a multi-parameter function: **optimize for the best fit parameters** given some measured SED!

Gram - Schmidt orthogonalize and find coefficients of these vectors. Those are related to moment maps

Maximum likelihood methods: inverting the matrix equation taking into account the error in the measured SED.

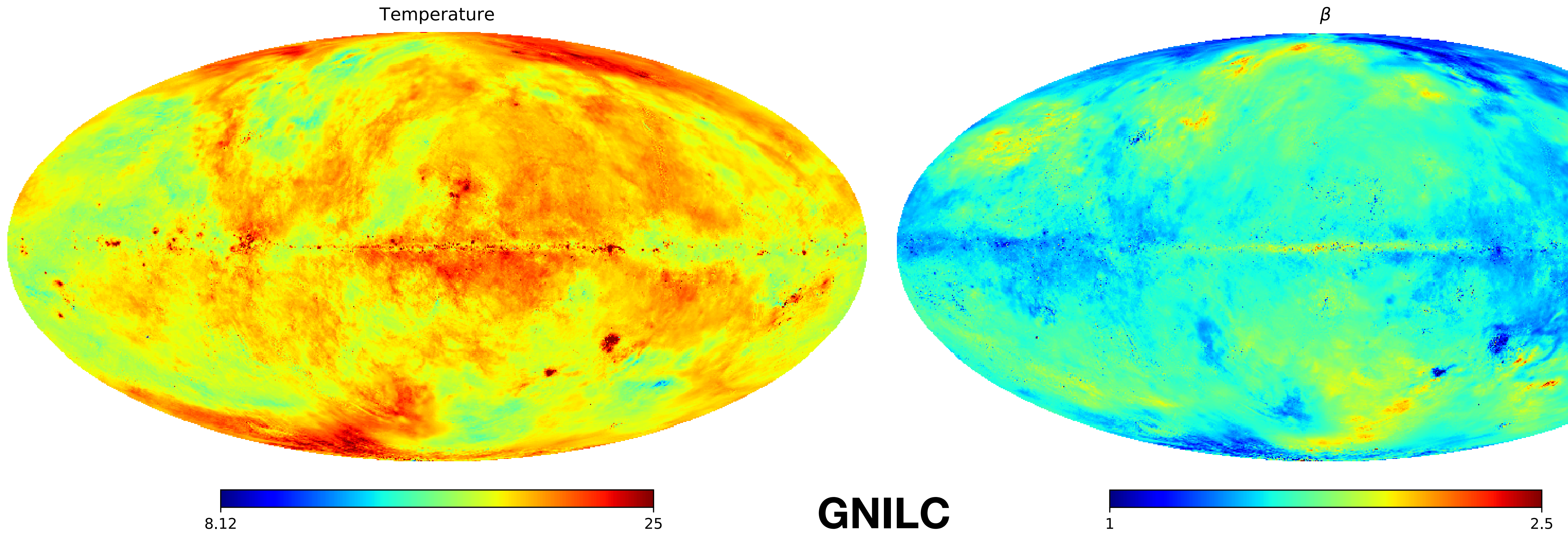
Gram-Schmidt orthogonal basis



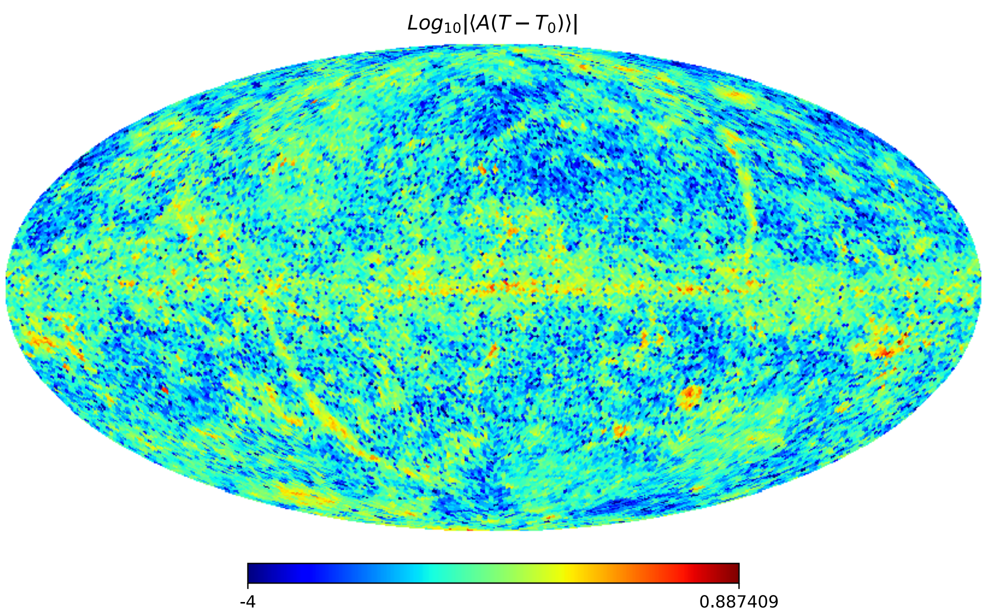
Two component MBB: [9.75 K, 1.63] + [15.7,2.82]

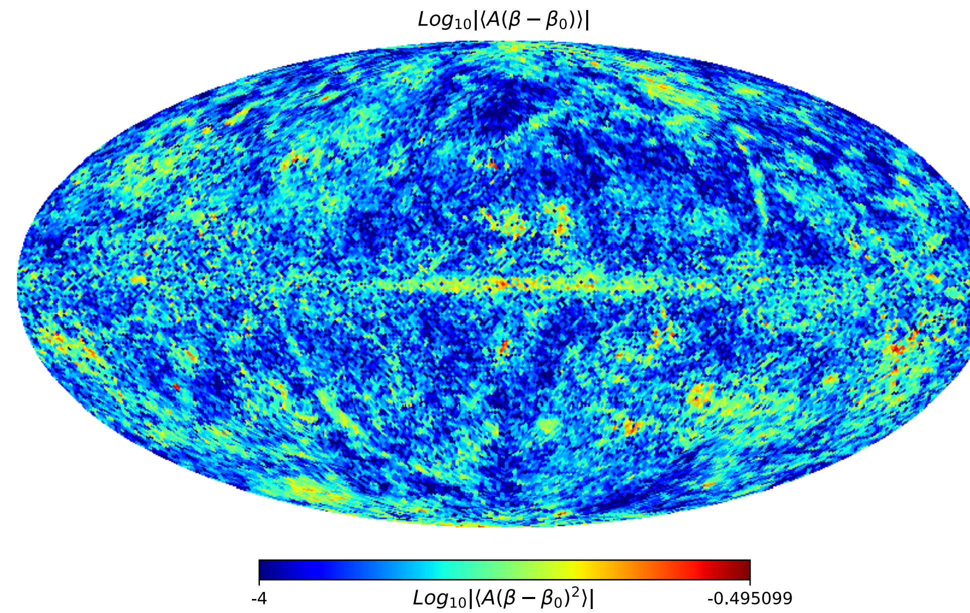
In preparation

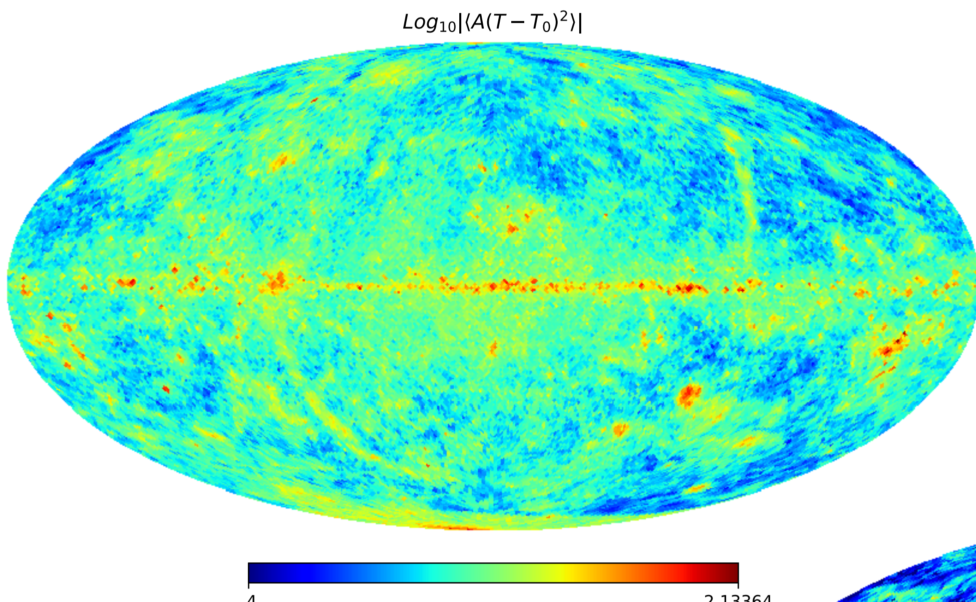
What moments do we expect from galactic dust emission?

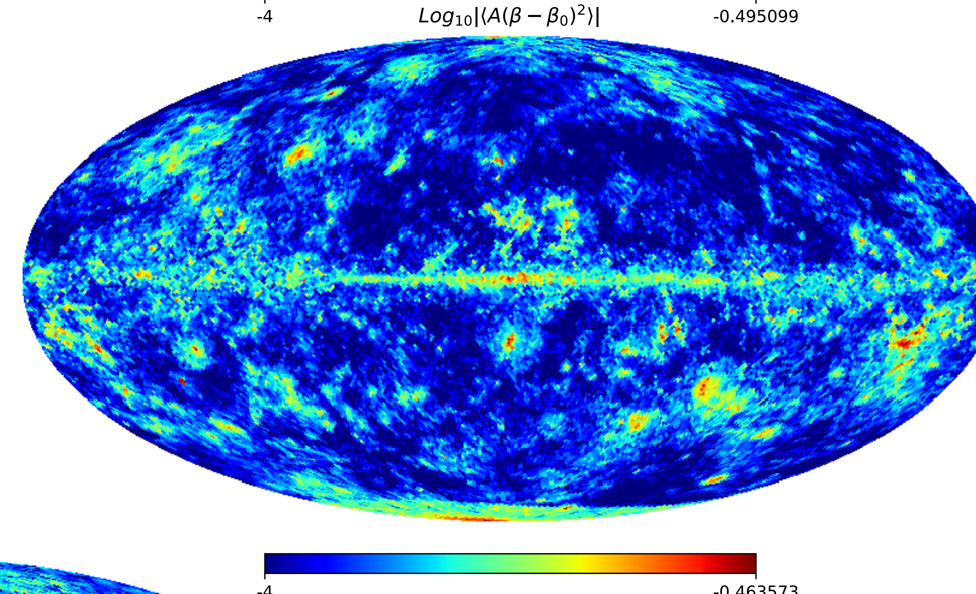


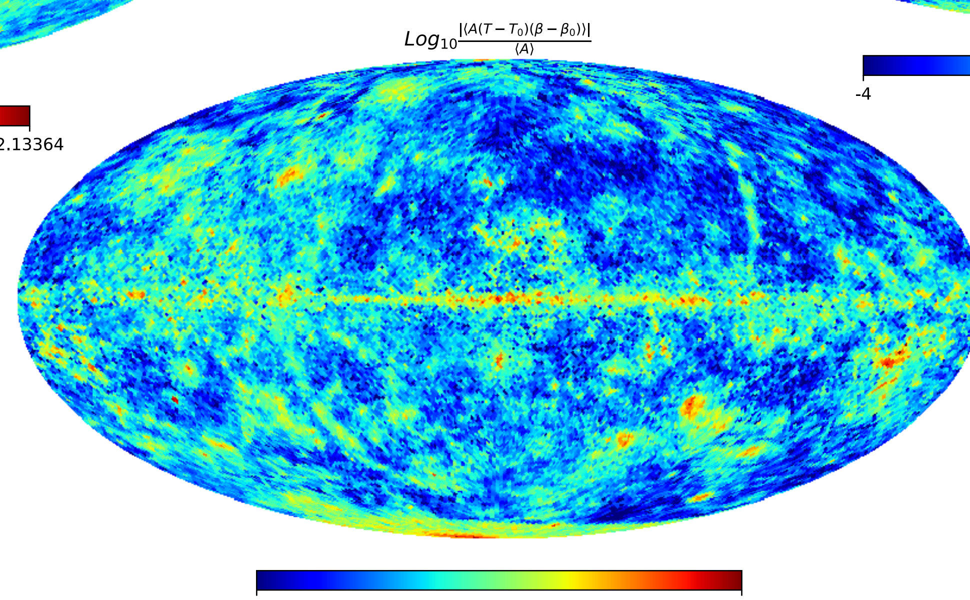
Expected dust moments





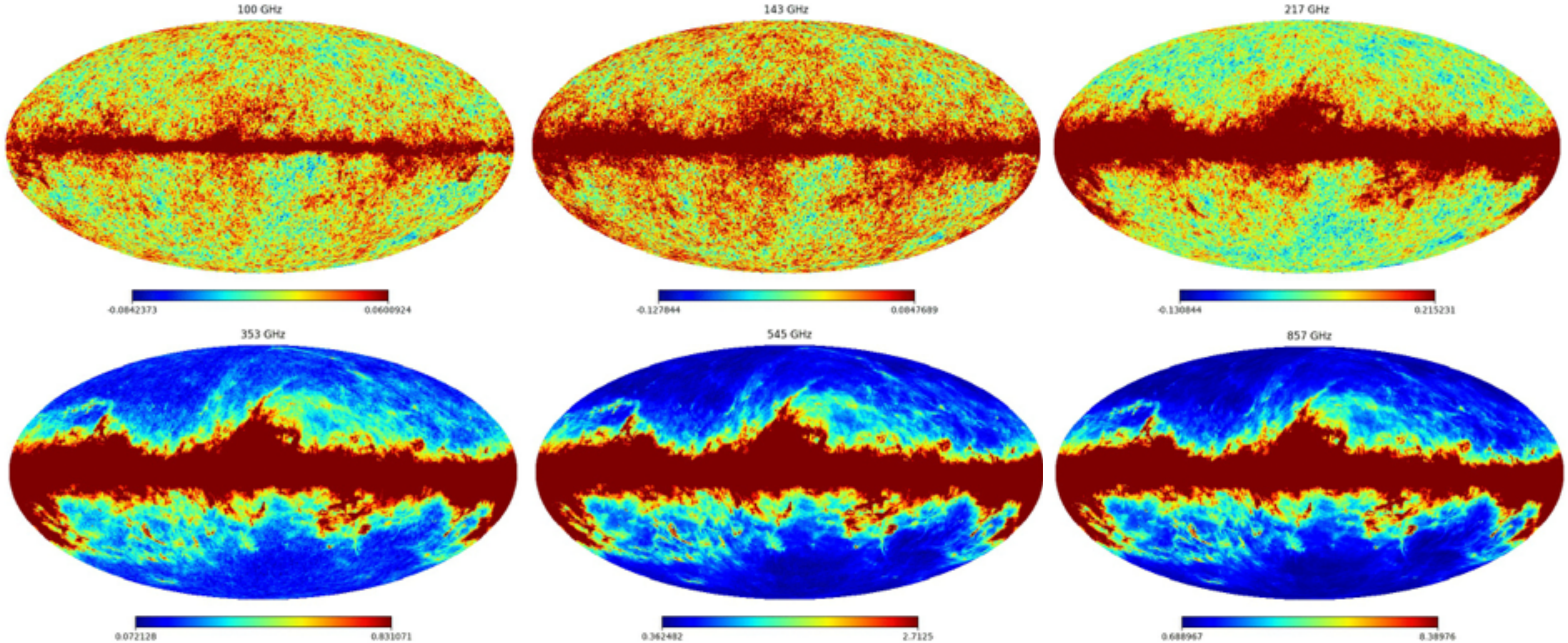






In preparation

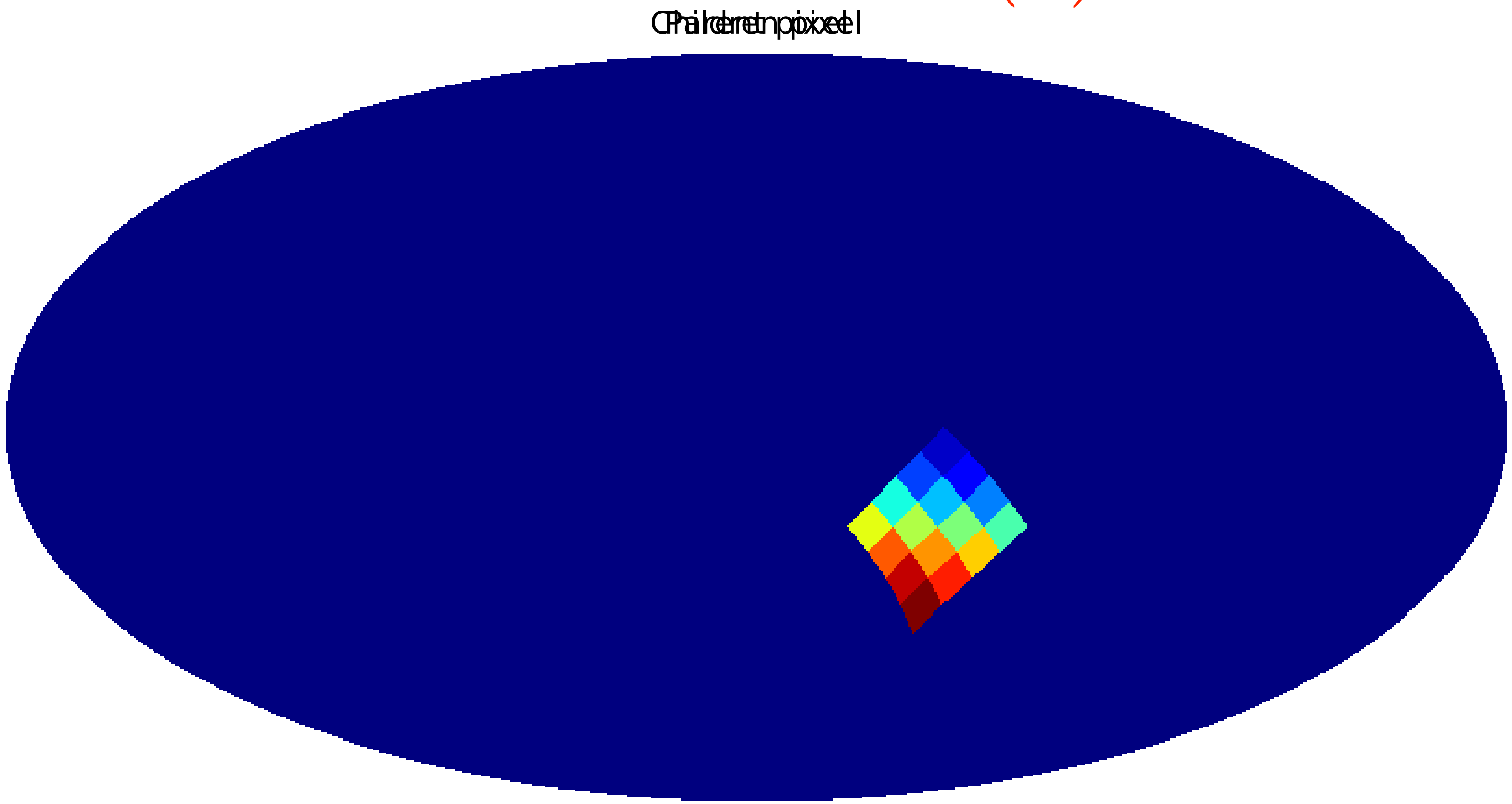
Planck HFI - CMB



Analysis strategy

Solve for the frequency dependent part in coarser **parent pixels**

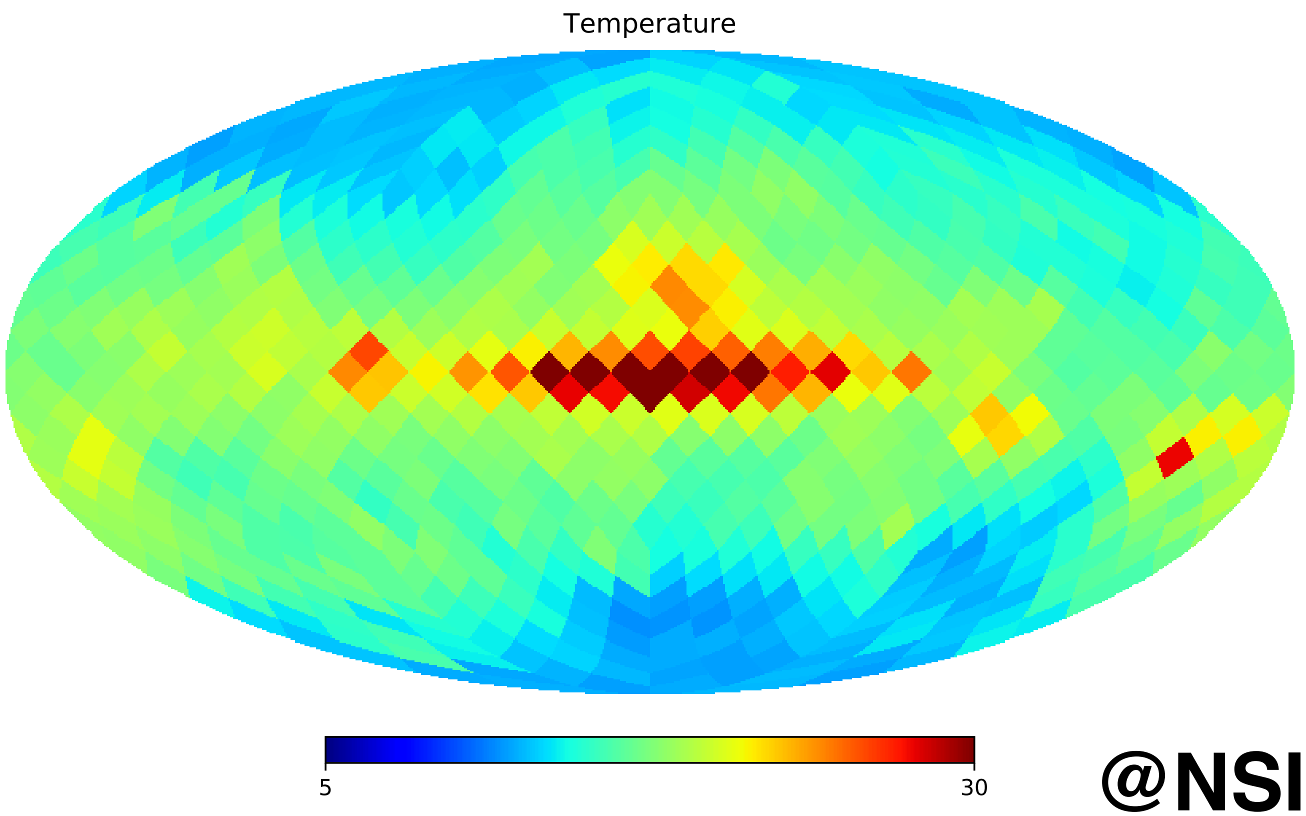
Fit a modified black body: $B_\nu(\alpha, T) = \frac{2h\nu^3}{c^2}\left(\frac{\nu}{\nu_0}\right)^{\alpha}\frac{1}{e^{\frac{h\nu}{kT}}-1}$

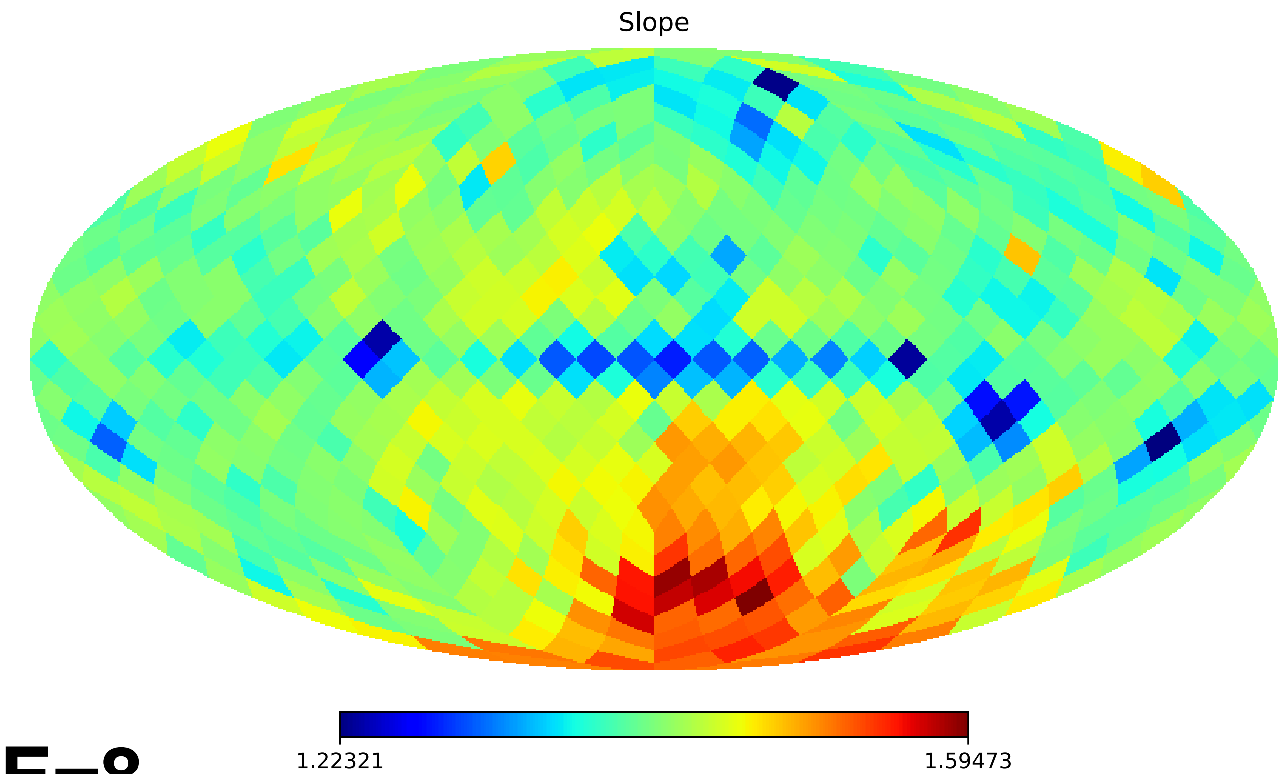


Solve for spatially varying moments in the **children pixels**

$\mathscr{M} = [B^T N^{-1} B] B^T N^{-1} S_{nu}$ $\quad\quad$ $C_{\mathscr{M}\mathscr{M}'} = [B^T N^{-1} B]^{-1}$

Fitting a MBB





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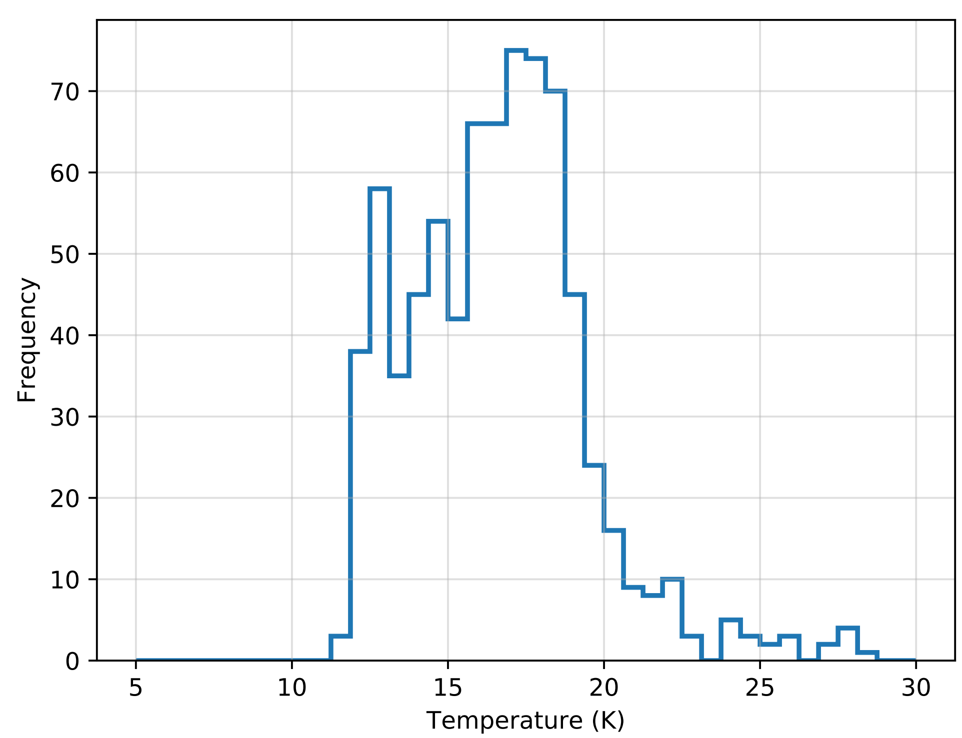
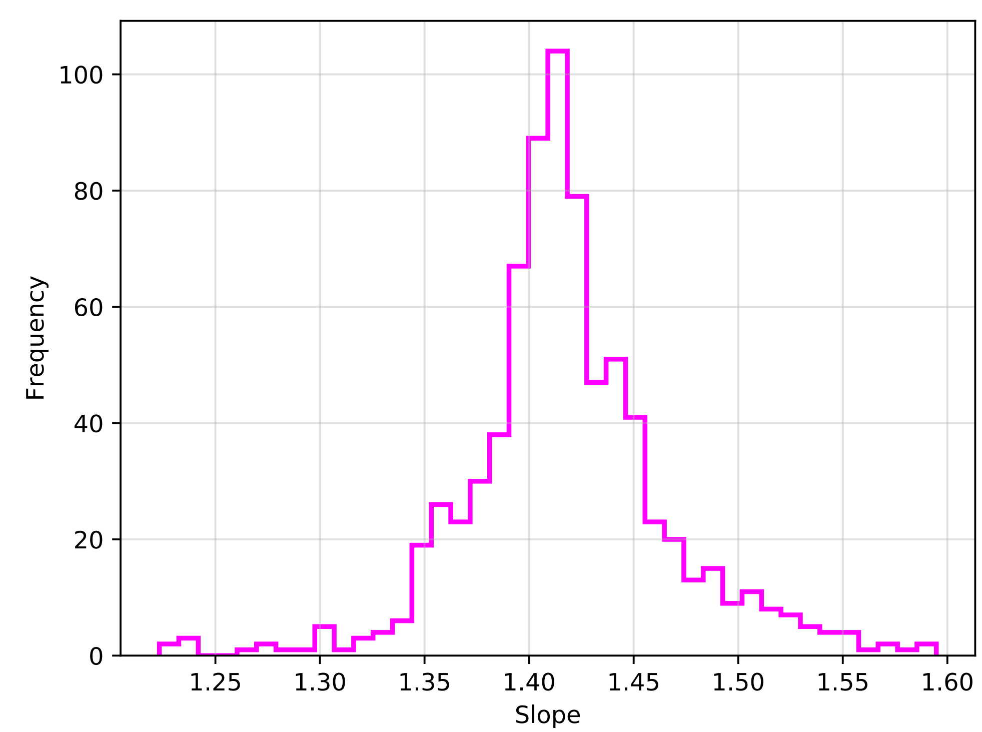
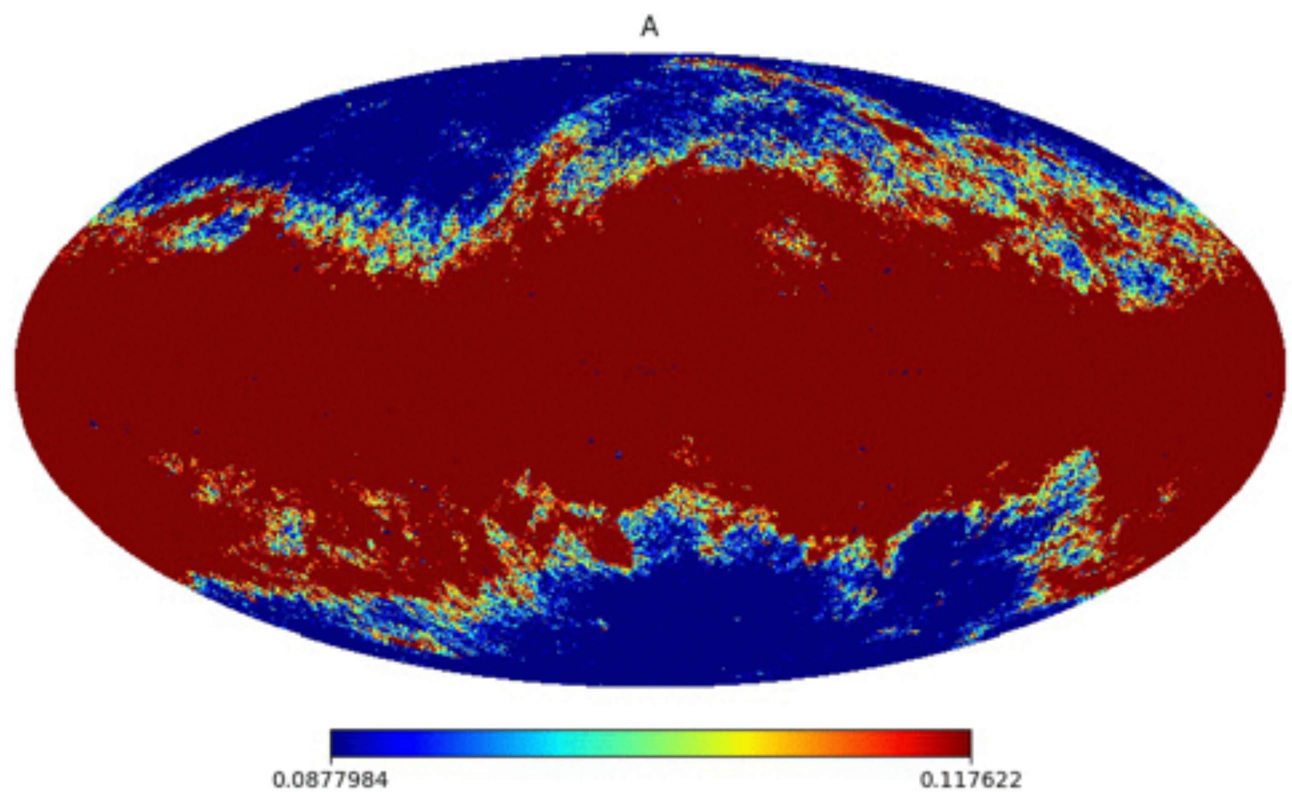
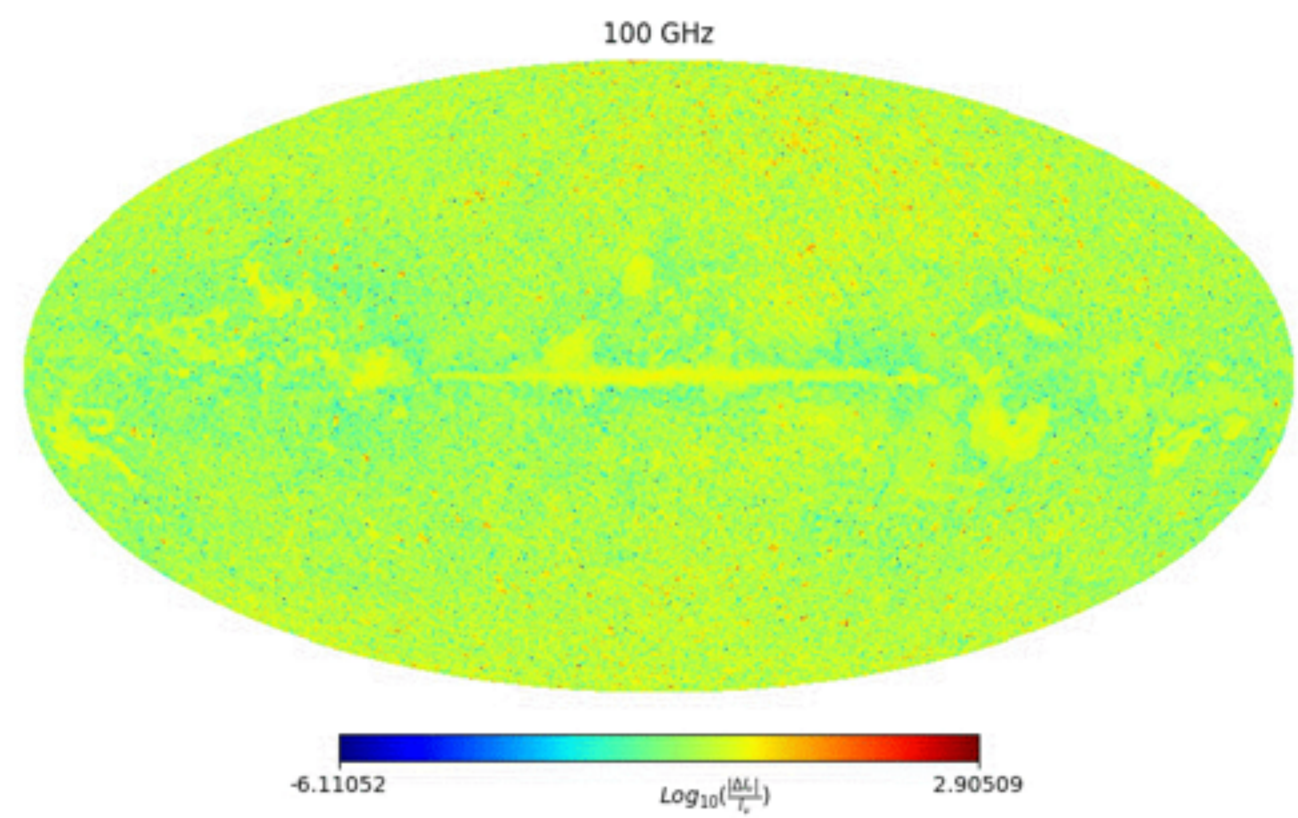




Moments maps measured from Planck HFI (3 moments)





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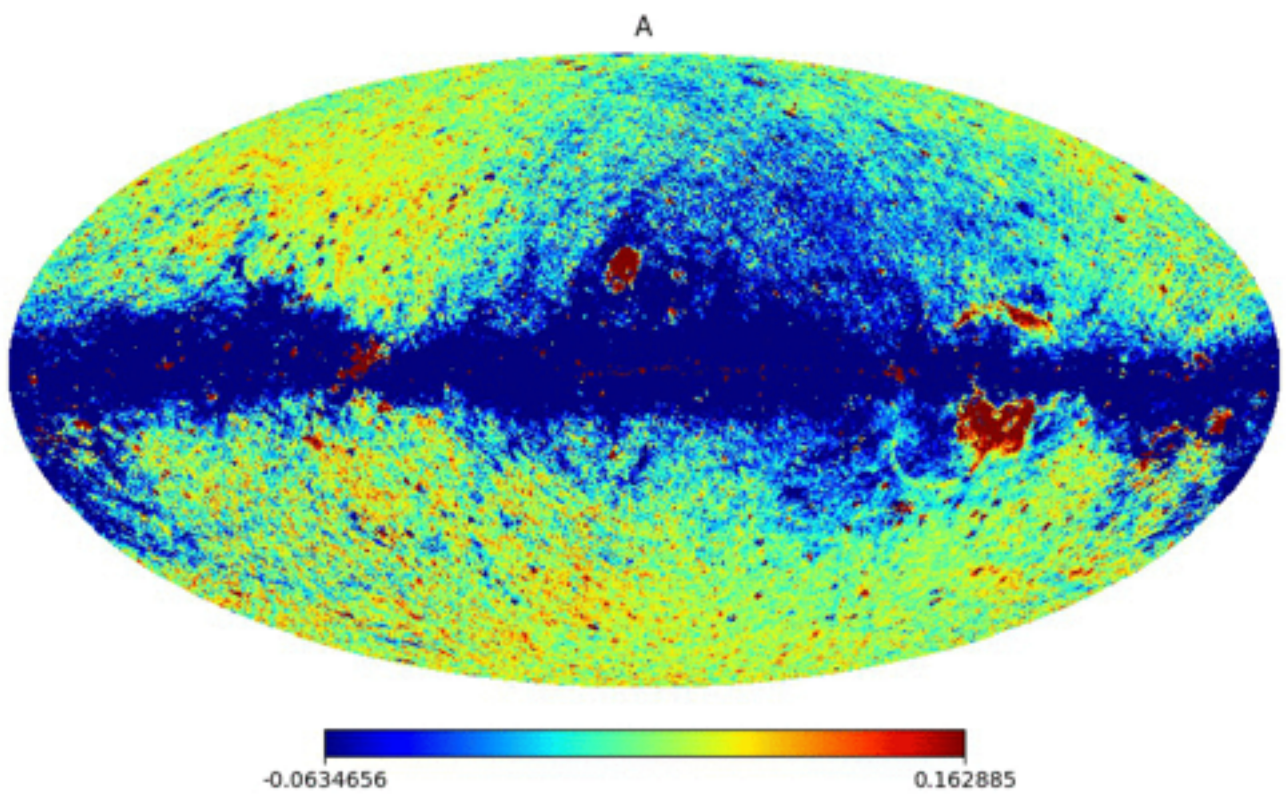
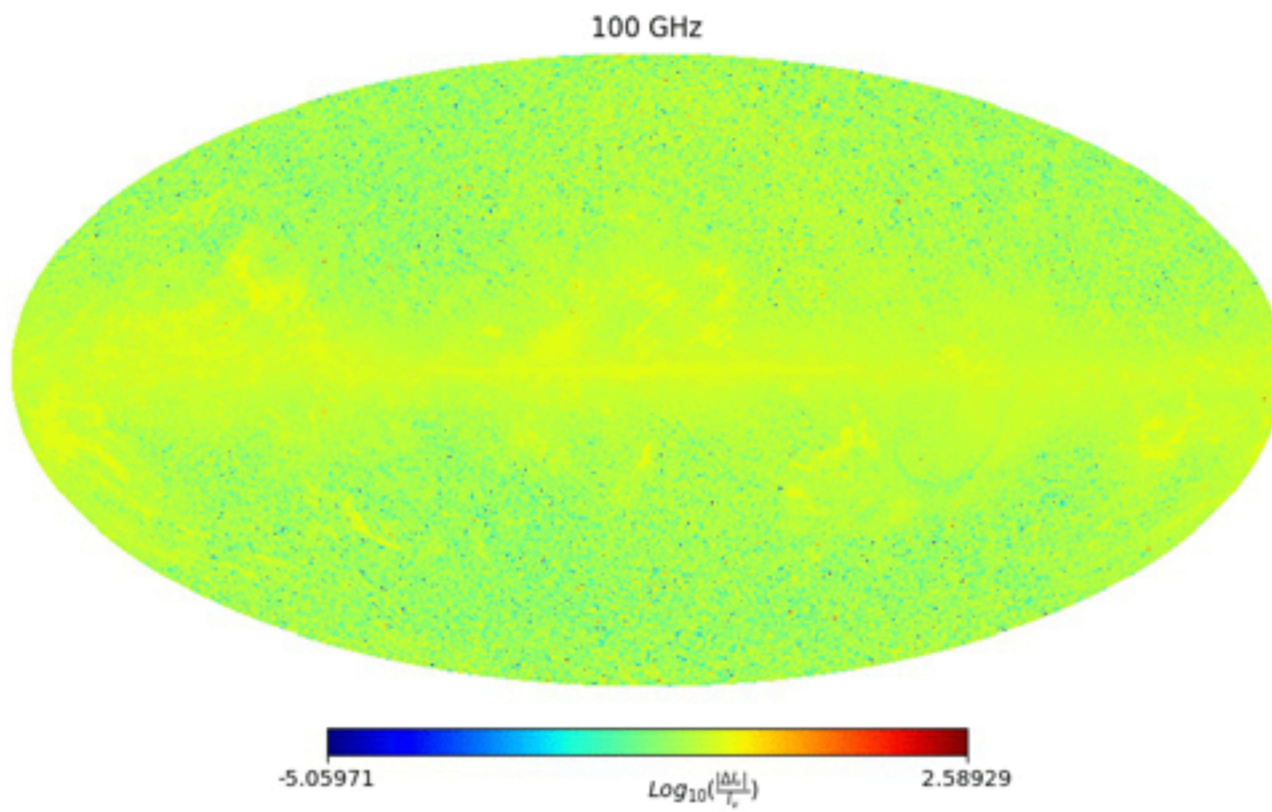
Moments maps measured from Planck HFI (4 moments)





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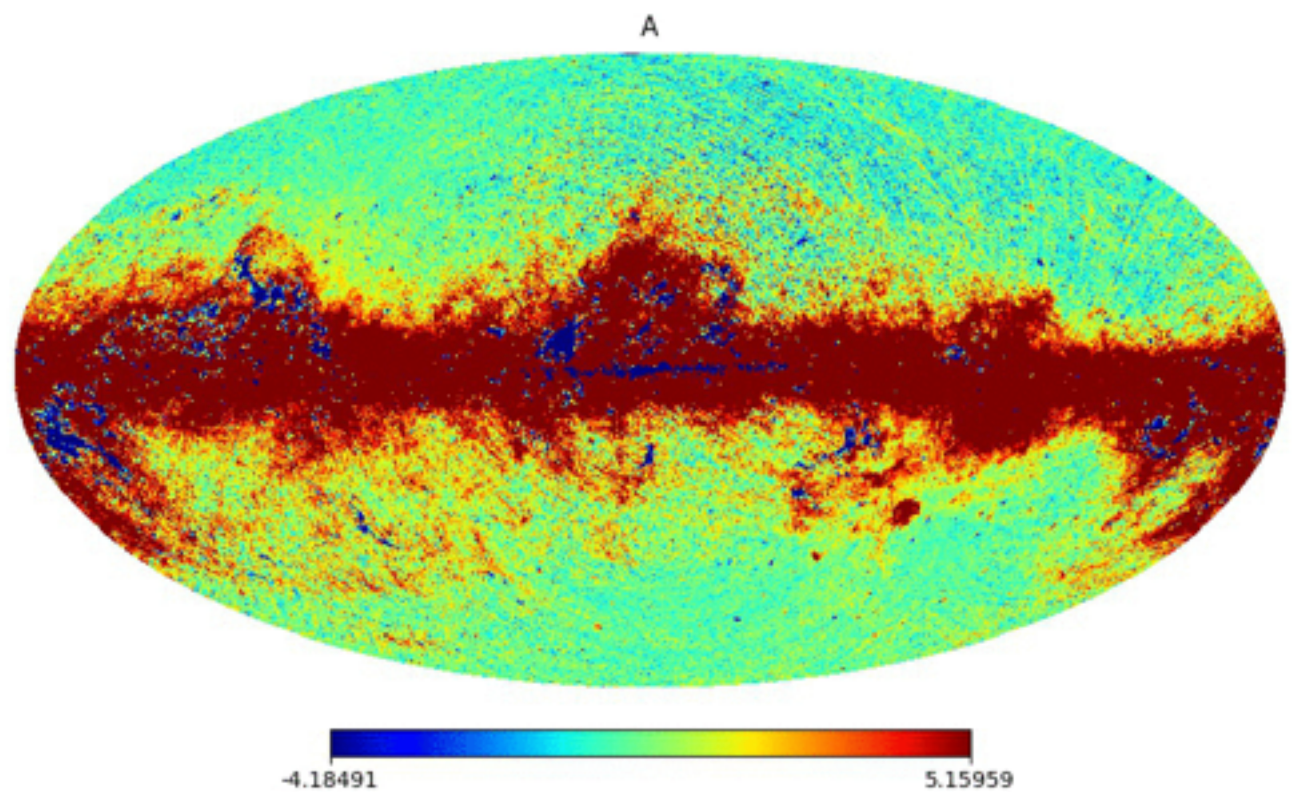
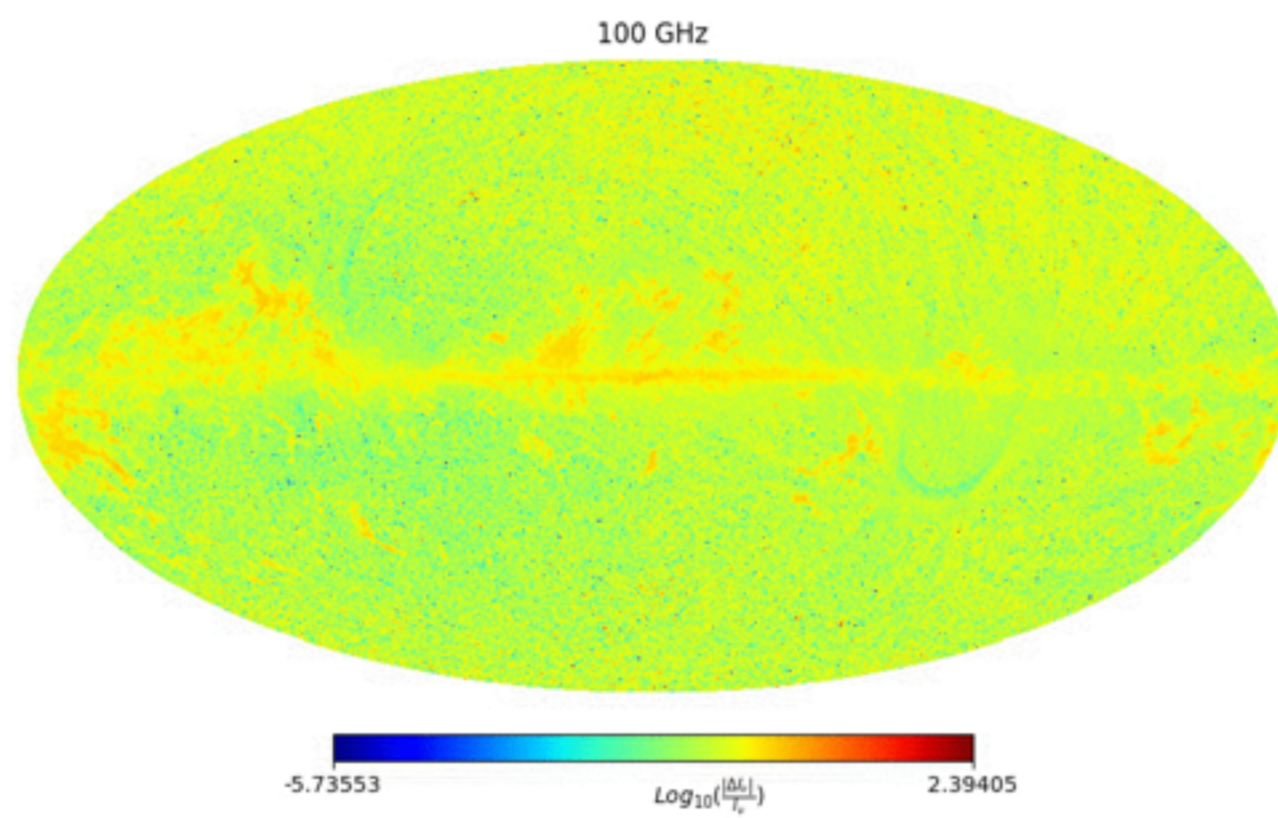
Moments maps measured from Planck HFI (5 moments)





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Summary:

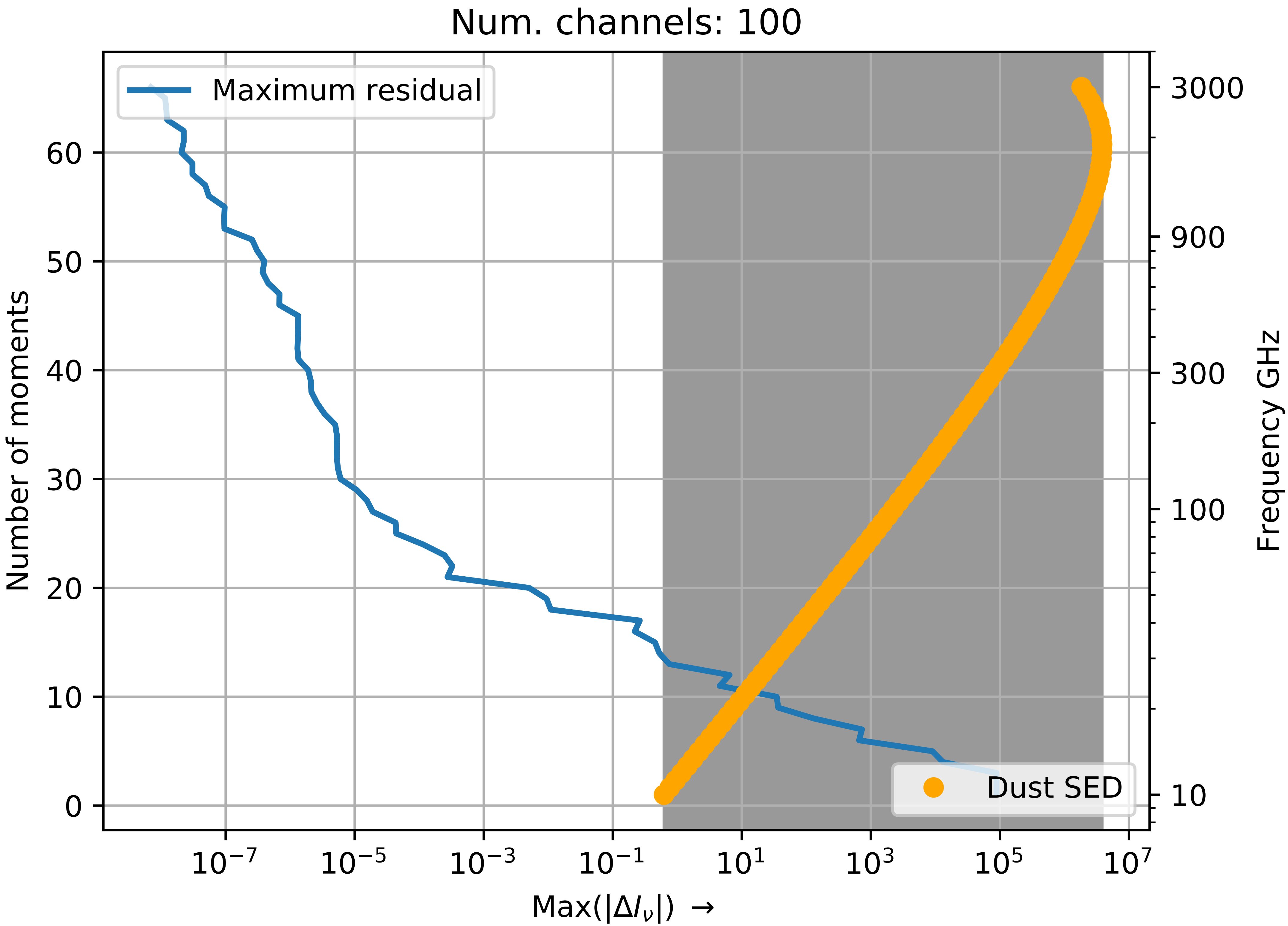
- **Due to averaging processes, simple foreground models are expected to fail at some sensitivity!**
- **The moment expansion can in principle be used to model the foregrounds to any desired accuracy** - of course at the **cost** of having a some **minimum number of frequency** channels - **determined by the desired accuracy** - and the **foreground complexity.**
- **Performed the first moment analysis on Planck HFI maps to derive constraints on higher moment maps. [PRELIMINARY]**

Ongoing:

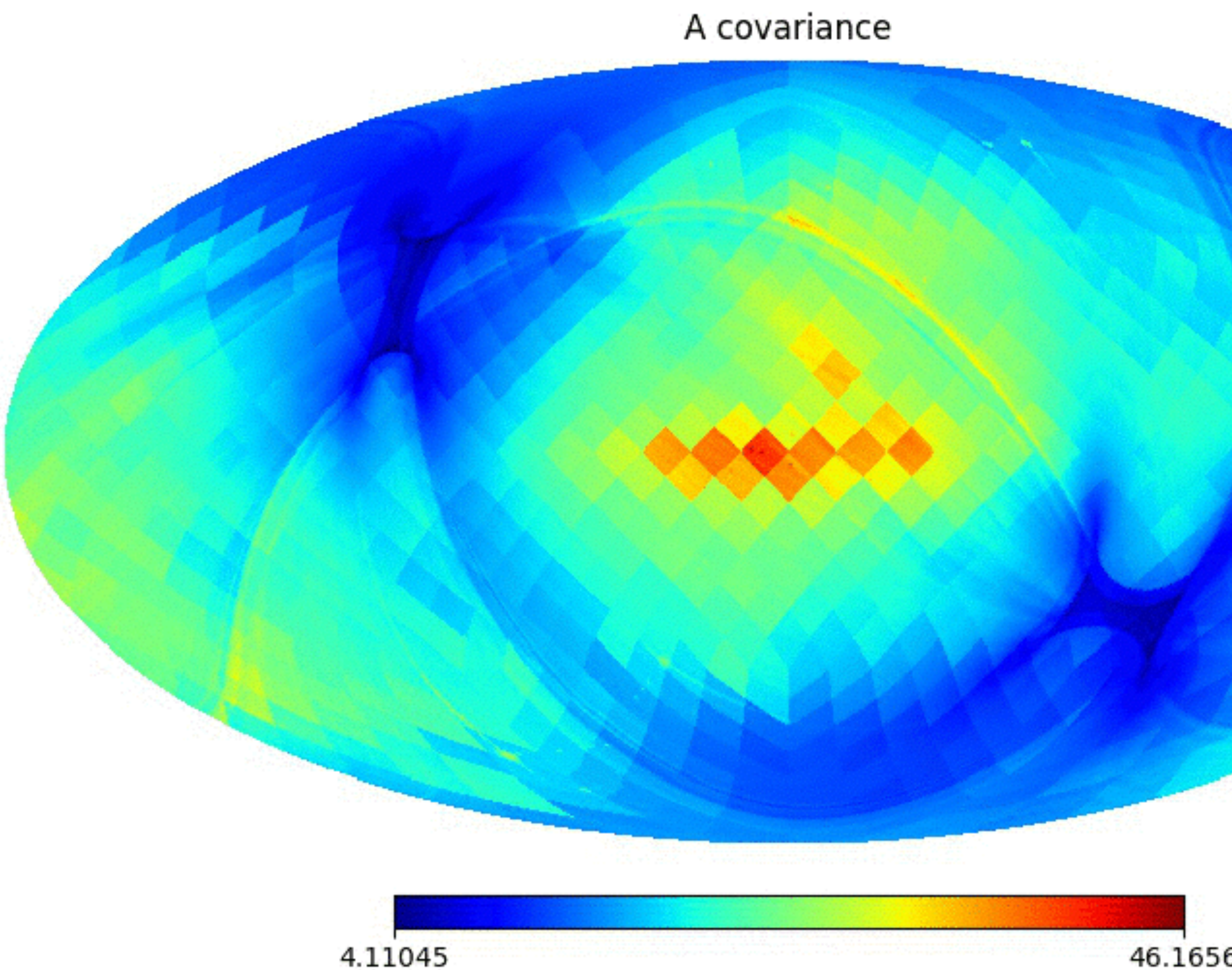
- **Moment analysis on other components (dust, synchrotron, free-free, AME etc.) for intensity data.**
- **Extending the moment formalism for polarization.**

Supplementary slides

An alternate view



Moment statistics



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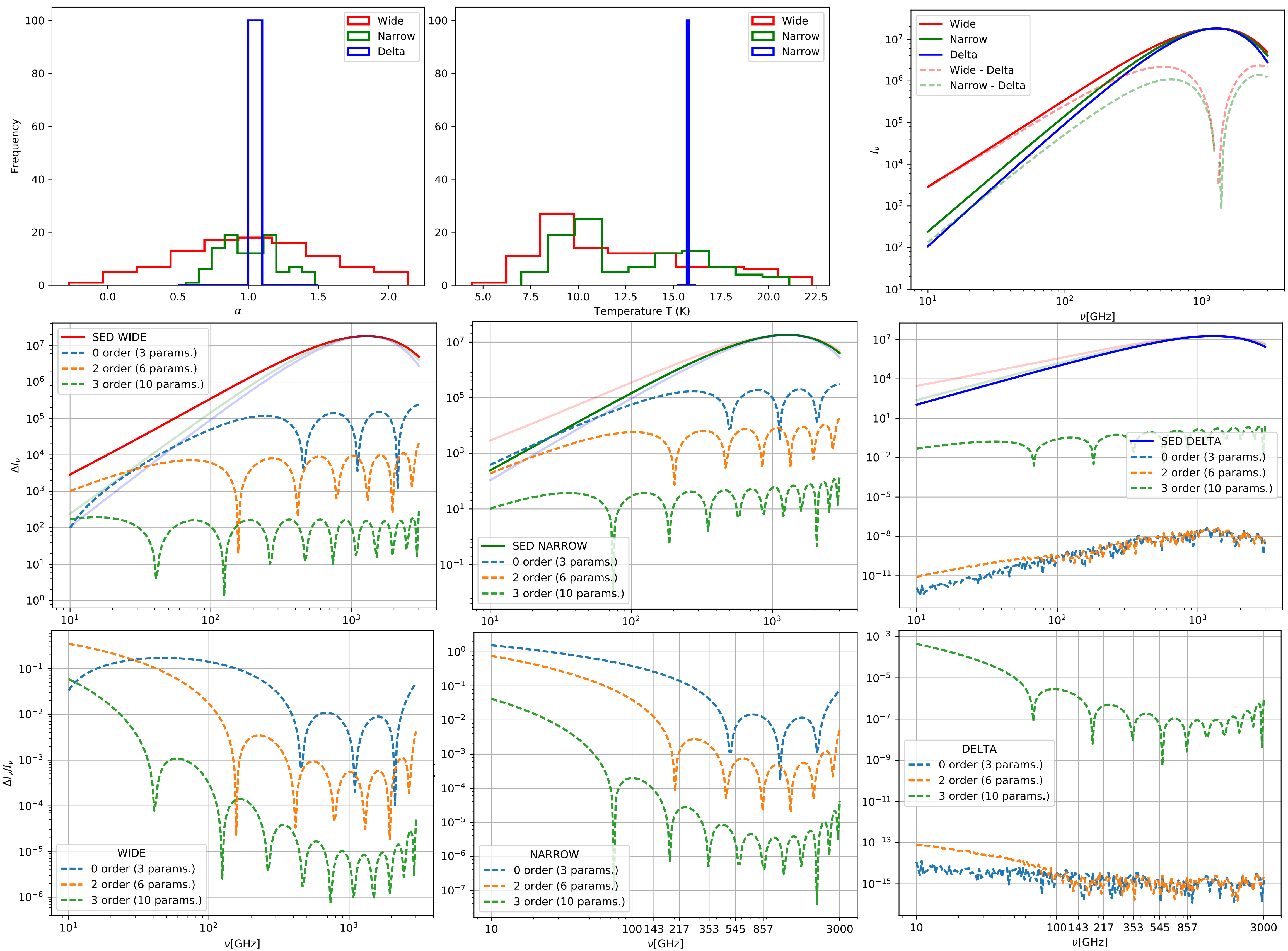
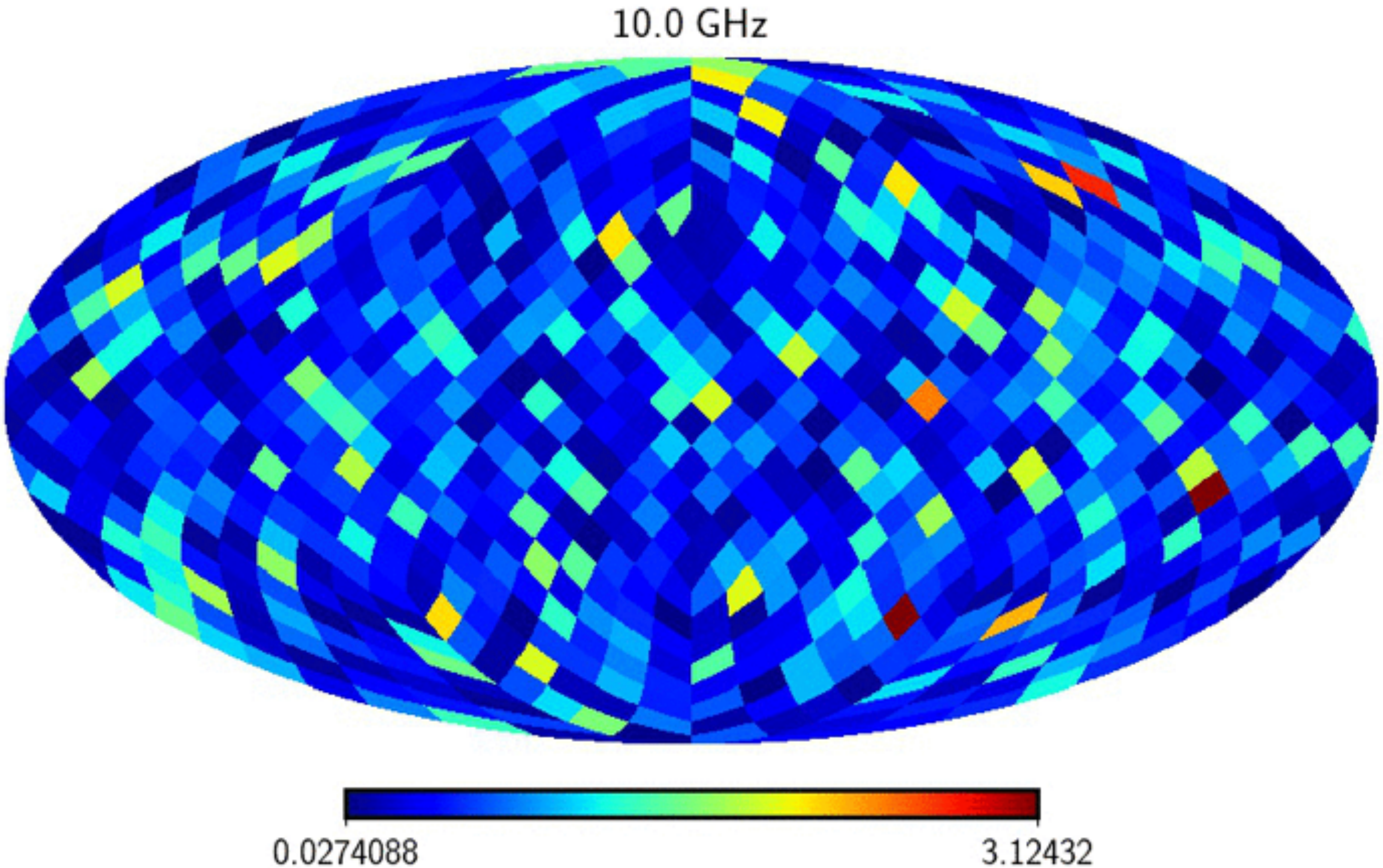
Toy model SED's

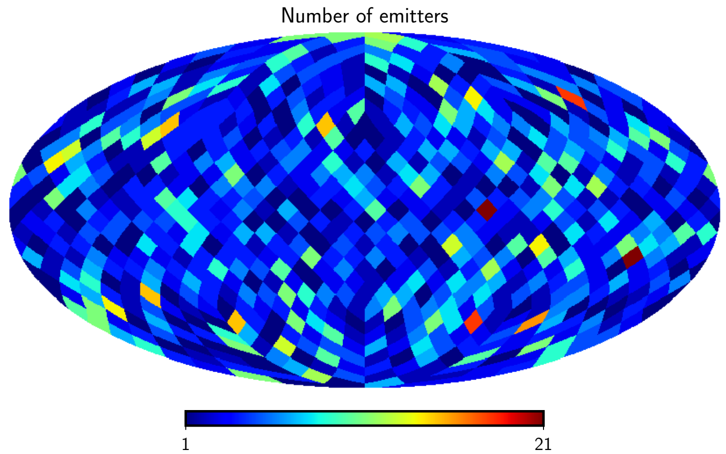


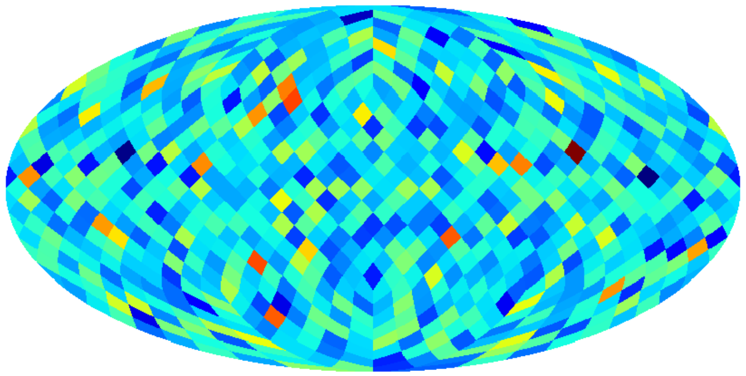
The path to connecting parametric and non-parametric methods

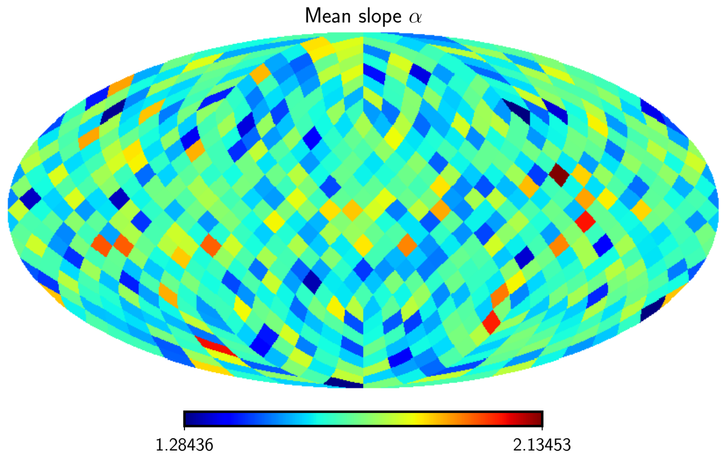
$$C_\ell^{\bar{\nu}} = F_{\bar{\mu}}^{\bar{\nu}}(\overrightarrow{p}_\ell)C_\ell^{\bar{\mu}} + n_\ell^{\bar{\nu}}$$

Model: $\sigma_T = 5\,, \sigma_\alpha = 0.2\,, N = Chi^2(5)$

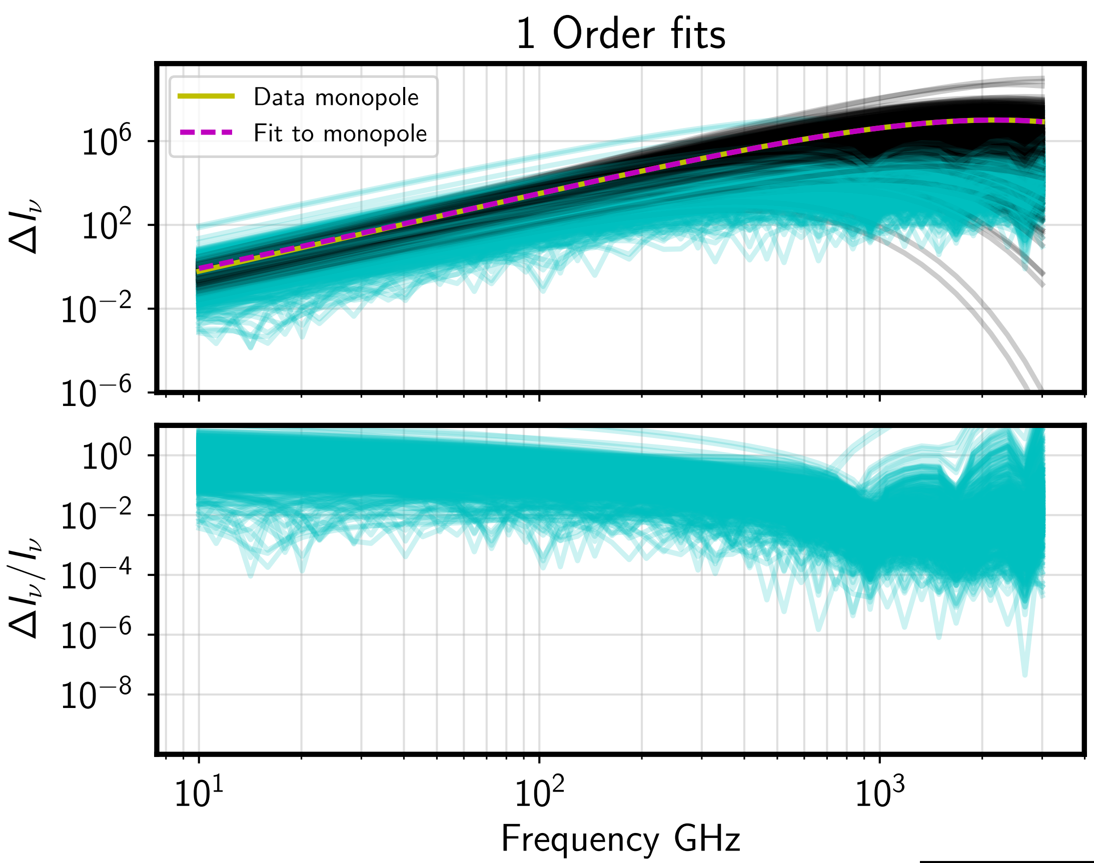


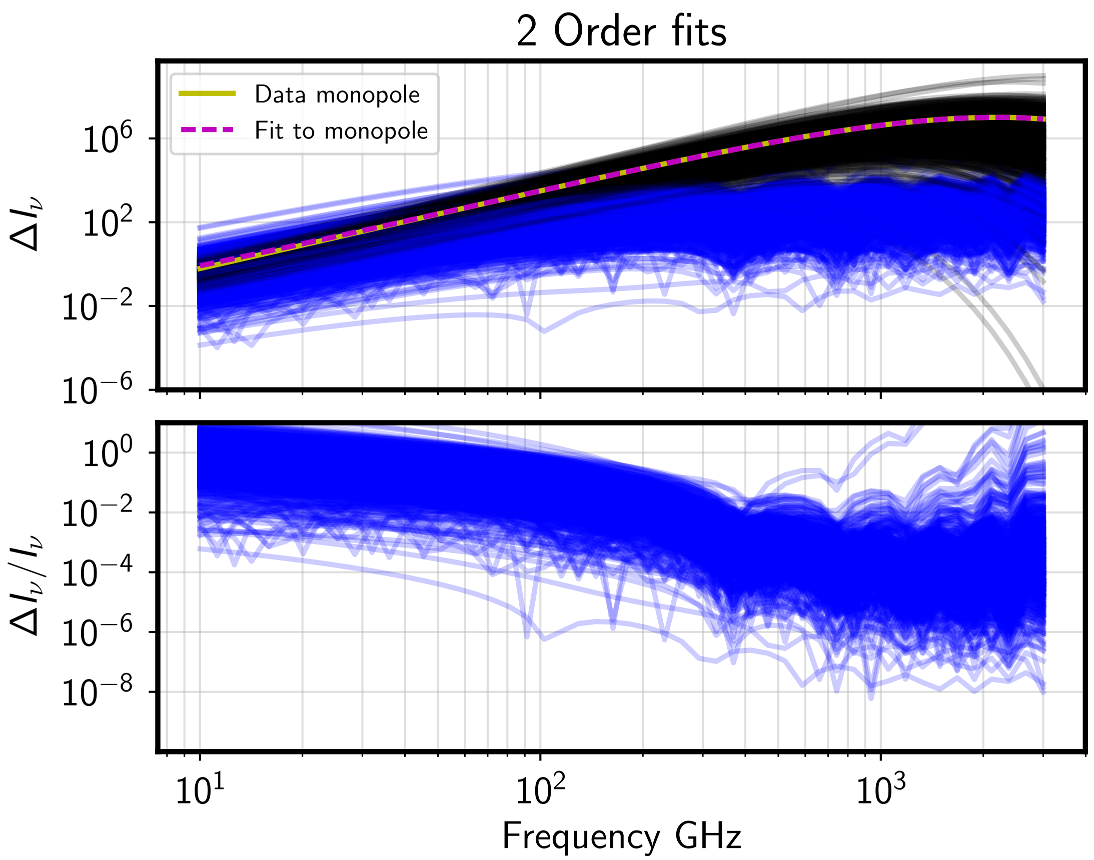


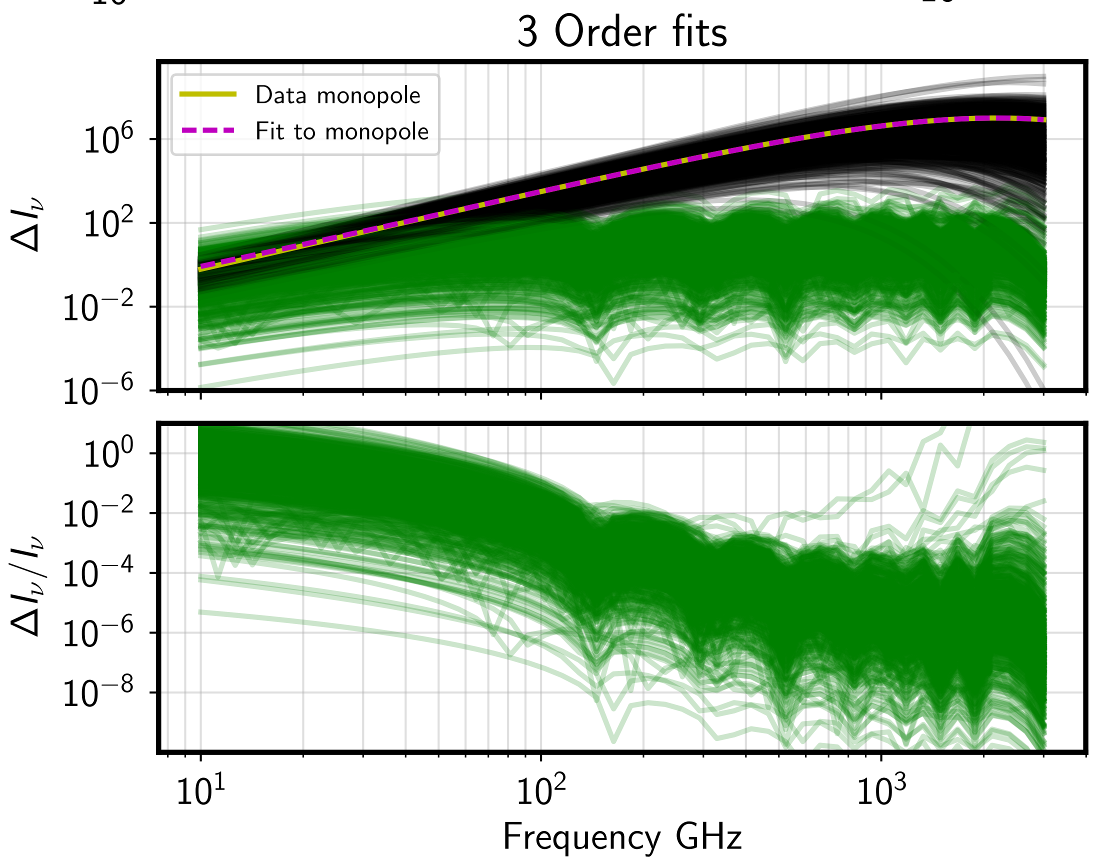




Moment fits

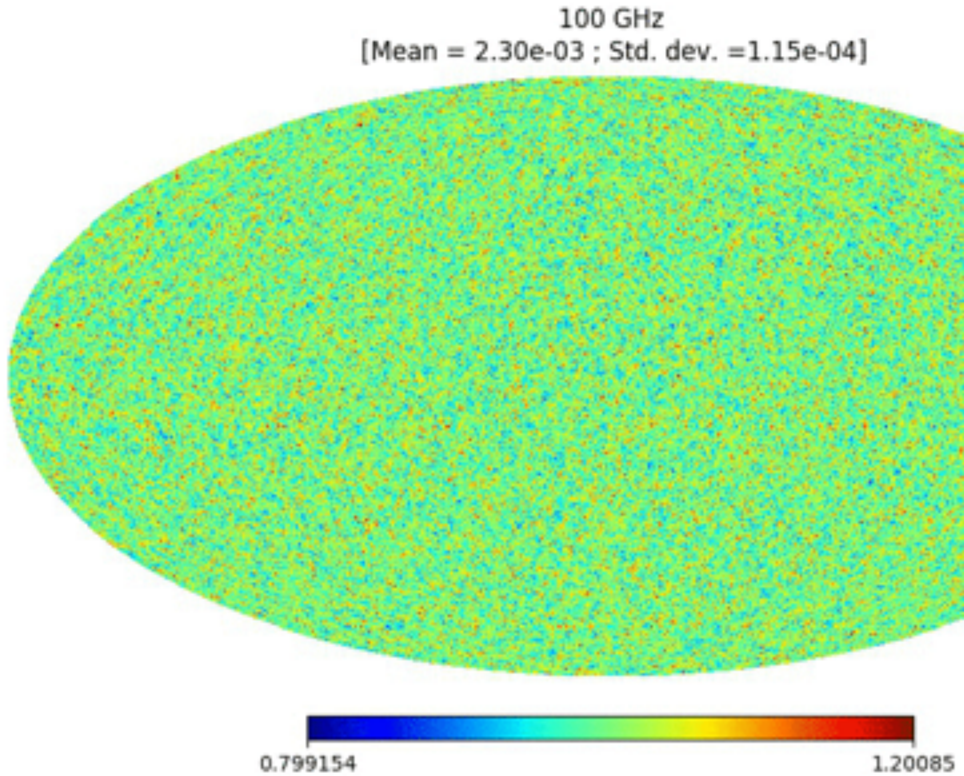

1 Order fits
Data monopole
Fit to monopole
ΔI_ν
$\Delta I_\nu / I_\nu$
Frequency GHz


2 Order fits
Data monopole
Fit to monopole
ΔI_ν
$\Delta I_\nu / I_\nu$
Frequency GHz


3 Order fits
Data monopole
Fit to monopole
ΔI_ν
$\Delta I_\nu / I_\nu$
Frequency GHz

Visualizing moments

Data



Moments