QUBIC
a Q&U Bolometric Interferometer for Cosmology

Paris Centre for Cosmological Physics

Spectral-Imaging with QUBIC : Component Map-Making

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ICNFP

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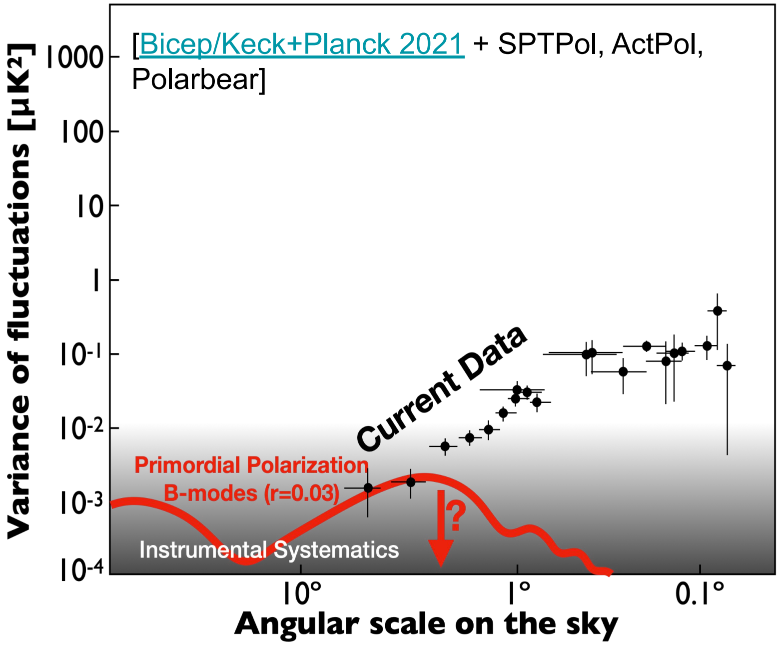
Challenge: B-modes ↦ Small Polarized Signal

CMB Angular power spectrum (C_ℓ)



Small polarized signal:

- high sensitivity detectors
- low systematics (T>>E>>B)

Challenge: Astrophysical Foregrounds

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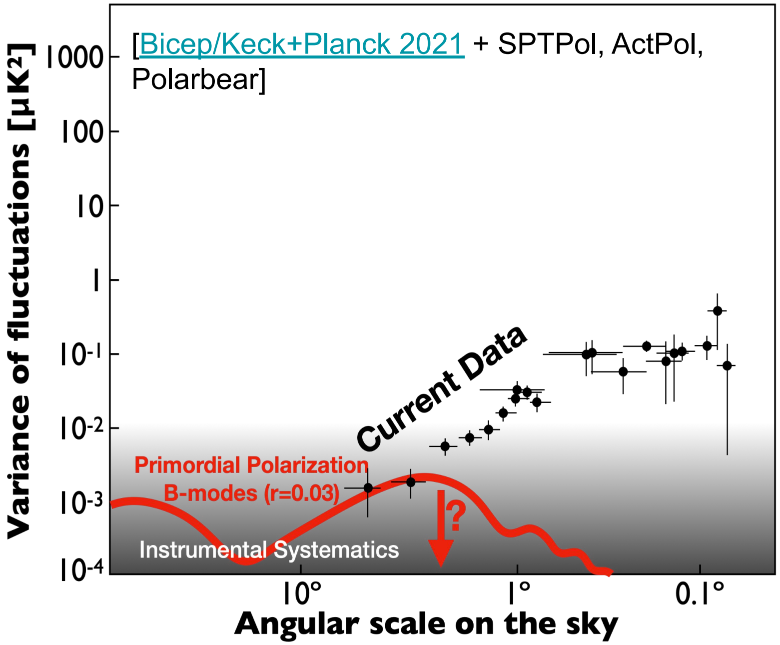

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Astrophysical foregrounds:

- Gravitational lensing
- Galactic foreground emission:
  - Synchrotron & Dust

Challenge: Astrophysical Foregrounds

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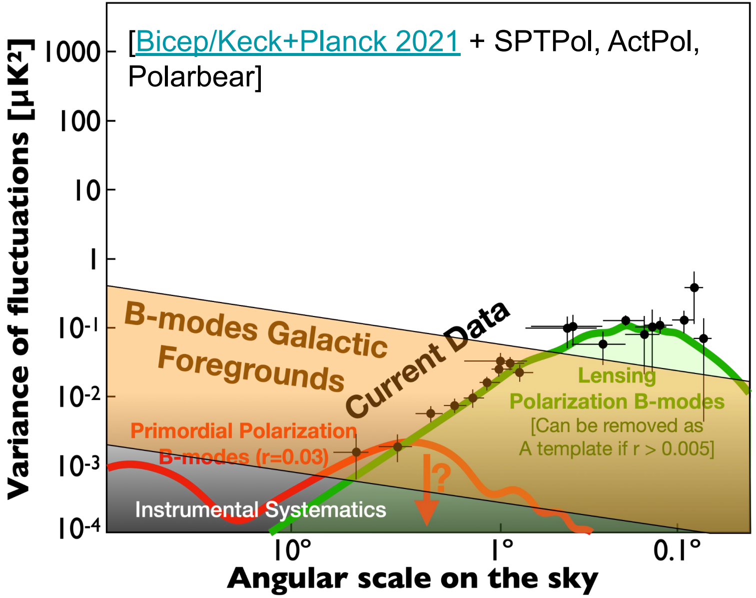

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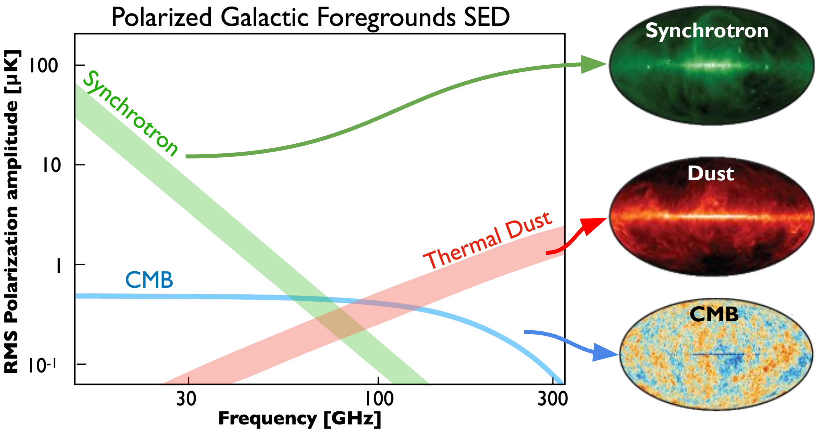
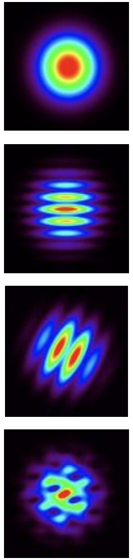


The QUBIC Concept: adding interferometry



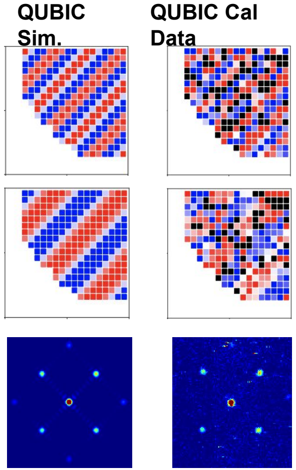
1 Horn open

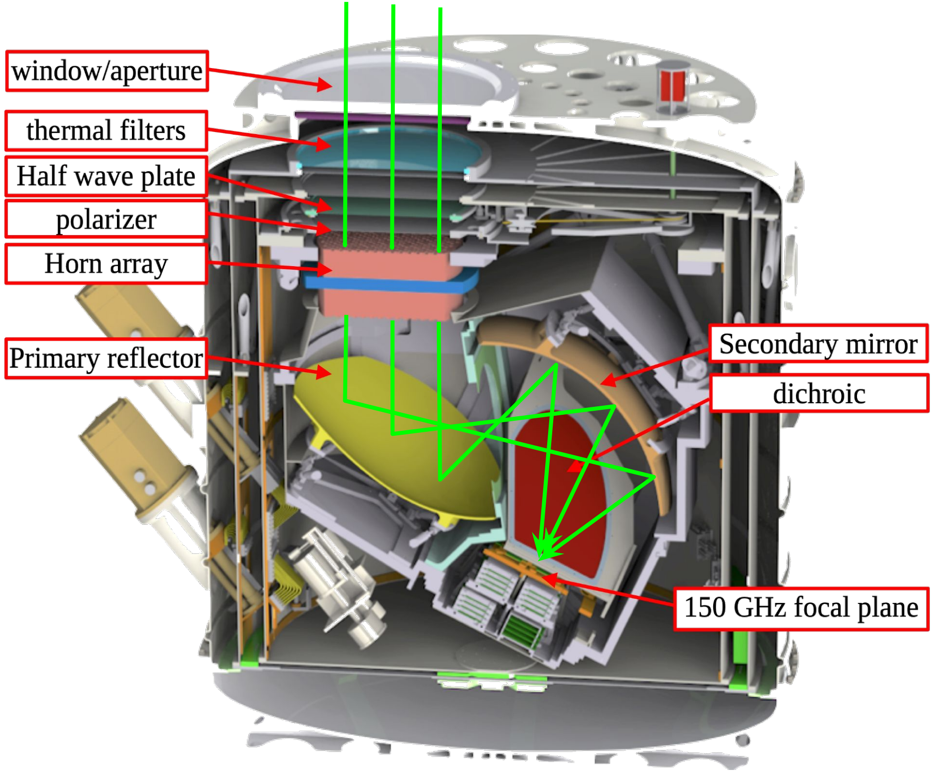
2 Horns open

2 Horns open

All Horns open

[L. Mousset, PhD, 2021]





Fringe and Synthesized Beam data: [Torchinsky et al., QUBIC III, arXiv:2008.10056v3] (Special issue on QUBIC in JCAP, 2022)

Challenges: addressed by QUBIC & B.I.

Small signal

B.I. → High sensitivity with fewer detectors

- 1024 Superconducting Bolometers
- Ultra-Wide-Band design (increase Nγ)

End-To-End Simulations: σ(r)=0.01 (3 years)
[Hamilton, Mousset et al. QUBIC I] (JCAP 2022)

Instrumental Systematics

B.I. → Natural low-systematics design

- Original low cross-polarization design
- Self-Calibration (interferometry)

Specific B.I. feature

< 0.6% Cross-Polarization measured in the lab
[Torchinsky, Hamilton et al. QUBIC III] (JCAP 2022)

Polarized Foregrounds

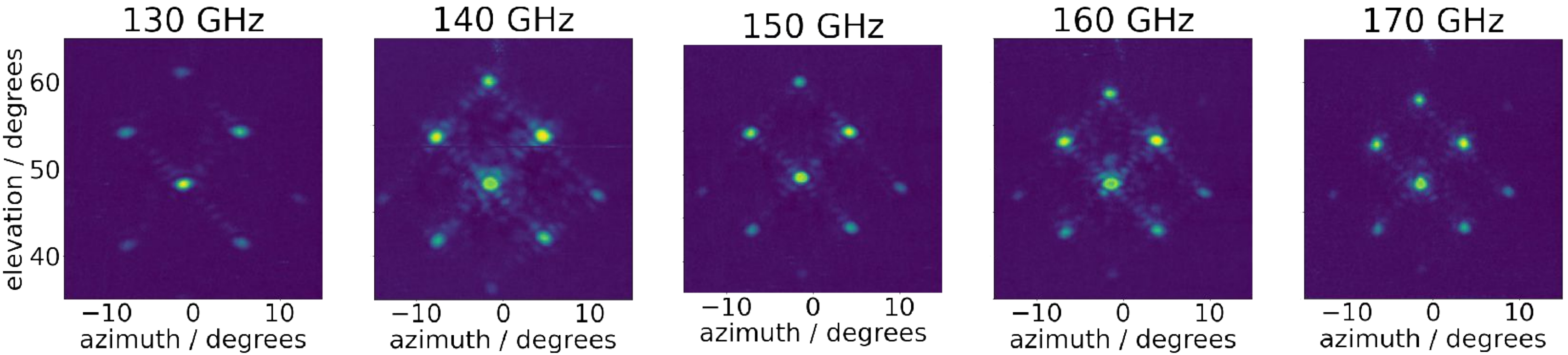
B.I. → Intrinsic Spectral Sensitivity

- Spectral imaging allows ~5 sub-bands for 150 and 220 GHz bands: $\Delta\nu/\nu \sim 0.05$ (TD)

Demonstrated with laboratory data at 150 GHz
[Mousset, Gamboa et al. QUBIC II] (JCAP 2022)

Spectral Imaging: A unique B.I. feature

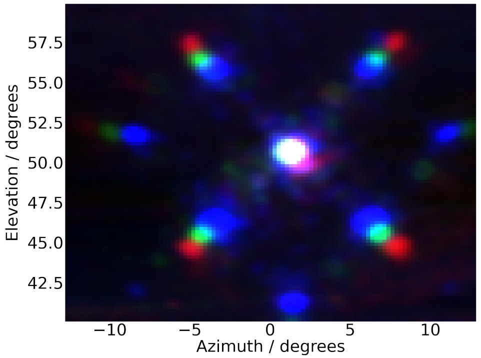
Interpeak distance is related to the shortest baseline D/λ => function of wavelength



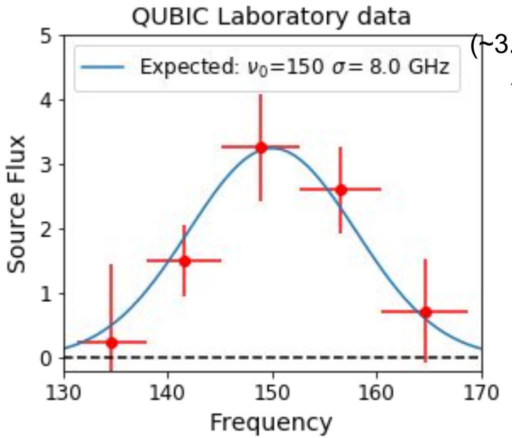
[Torchinsky, Hamilton et al. QUBIC III]
(to appear in JCAP)

[Hamilton, Mousset et al. QUBIC I] (JCAP accepted)

QUBIC Multichroic Synthesized beam measurement (130, 150, 170 GHz)



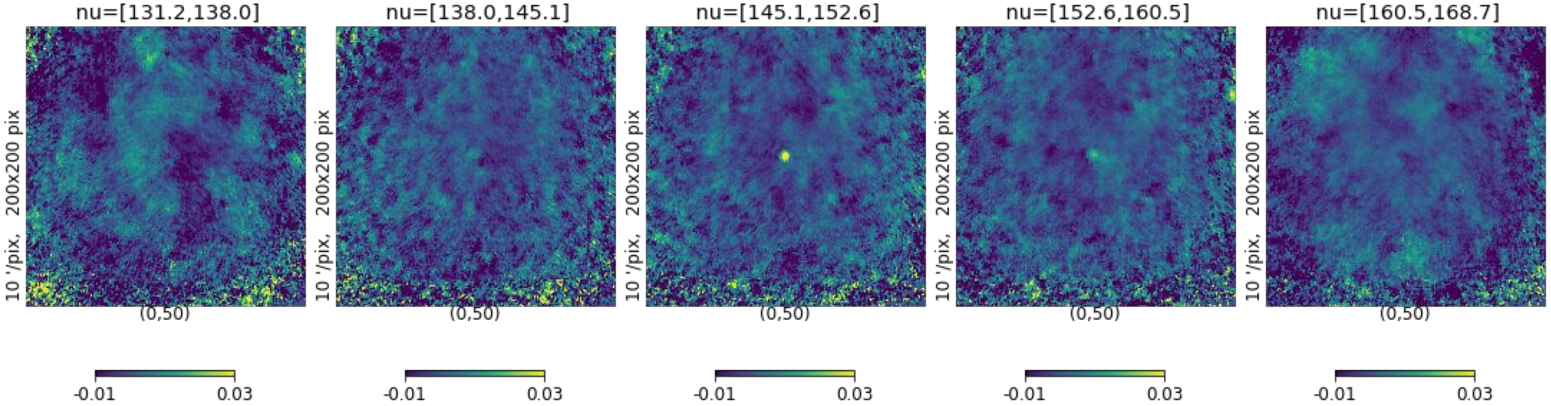
Spectral Imaging with Real Data (26 detectors)



(~3.2 GHz with FI)

Δv/v ~ 0.02

Δv/v ~ 0.05



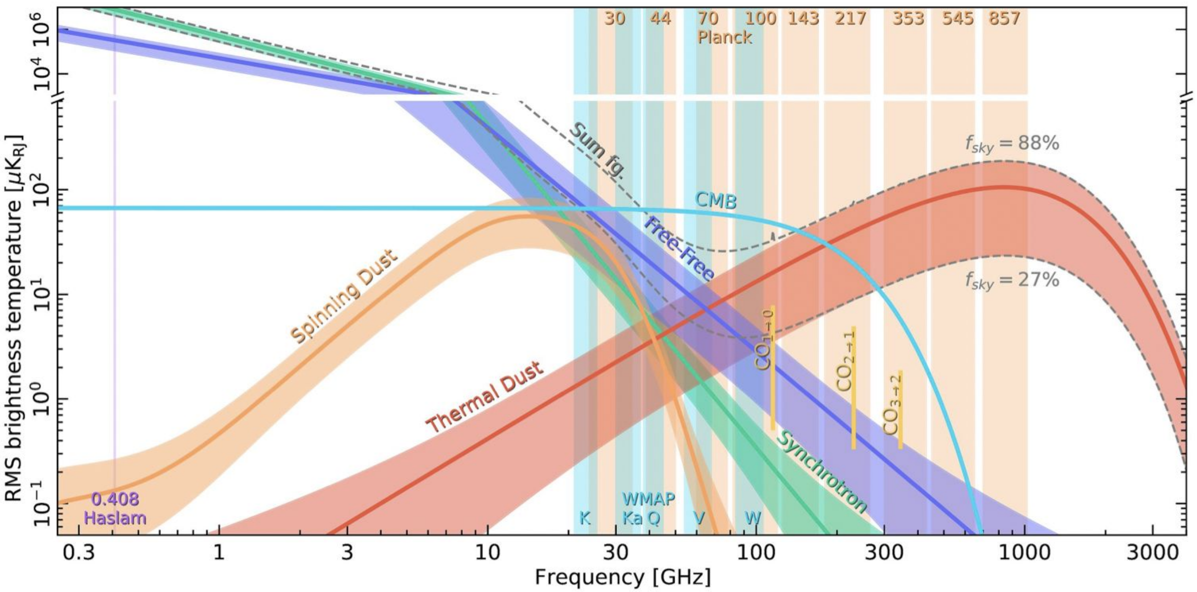
First Spectral Imaging reconstruction with real data (Calibration Source operating at 150 GHz at APC)

[Torchinsky et al., QUBIC III arXiv:2008.10056v3] (Special issue on QUBIC in JCAP, 2022)

This study will allow us to develop an innovative and complete analysis method for QUBIC.

Astrophysical foregrounds emits at every frequency and contaminate the CMB..

We need many frequencies to be able to separe the CMB and the other emission.



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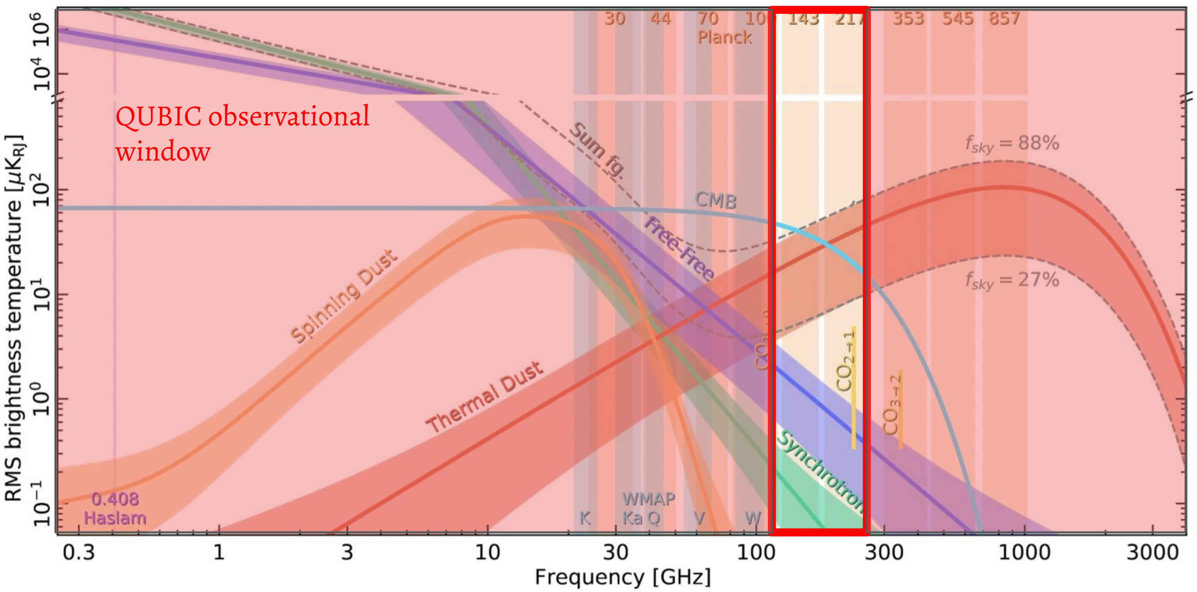
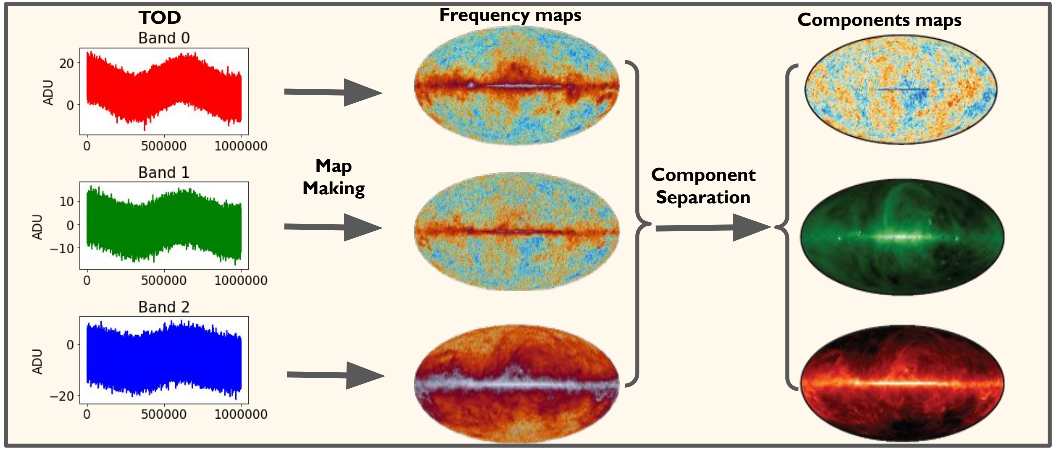


Component Separation Map-Making

- Classical imagers:

  Frequency maps ↦ Component separation

  - Spectral resolution limited by bandwidth Δν/ν~0.25
  - Requires accurate noise covariance in map space



Classical Imager Pipeline

Classical Map-making (in each band)

$$\vec{y} = H \cdot \vec{s} + \vec{n}$$

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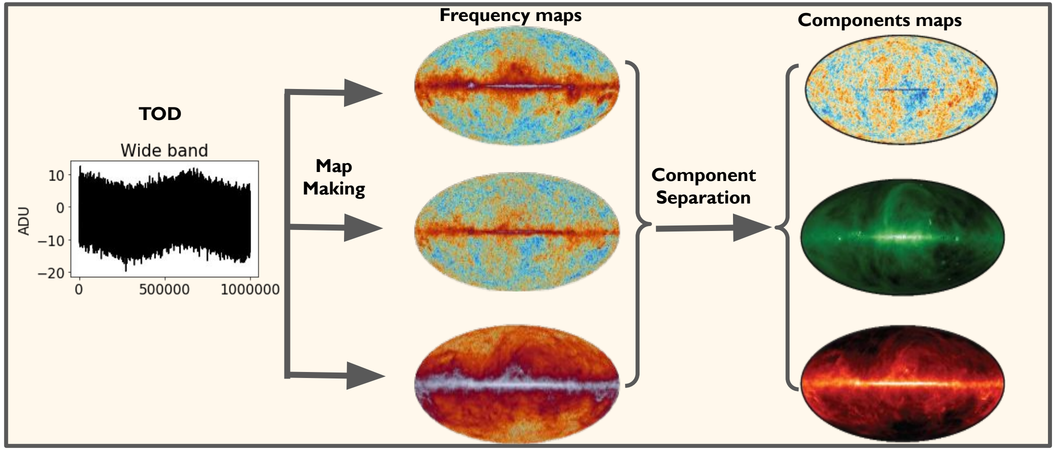


Frequency Mapmaking Bolometric Interferometer Pipeline

Classical Map-making (in each band)

$$\vec{y} = H \cdot \vec{s} + \vec{n}$$

⇓

Frequency Map-making

$$\vec{y} = \sum_{j=0}^{N_{rec}-1} H_j \cdot \vec{s}_j + \vec{n}$$

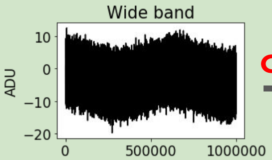
[Régnier et al., in preparation]

Component Separation Map-Making

- Classical imagers: Frequency maps $\mapsto$ Component separation
- <u>B.I.: frequency sensitivity in TOD</u>

  ⇒ directly build components maps from TOD
  - Full Spectral-Imaging resolution
  - Richer spectral modeling
    - Spectral index variations
    - Emission lines (CO, …)
  - Simpler noise covariance

TOD

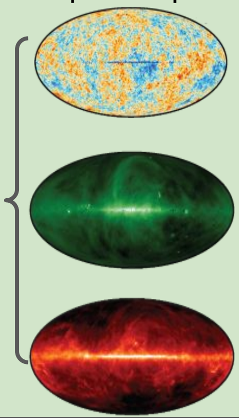


Component Separation Map Making

Spectral-imaging based:
Frequency Information in TOD

<u>Only possible with B.I. !</u>

Components maps



Components Mapmaking Bolometric Interferometer Pipeline

Classical Map-making
(in each band)

$$\vec{y} = H \cdot \vec{s} + \vec{n}$$

⇓

Frequency Map-making

$$\vec{y} = \sum_{j=0}^{N_{rec}-1} H_j \cdot \vec{s}_j + \vec{n}$$

⇓

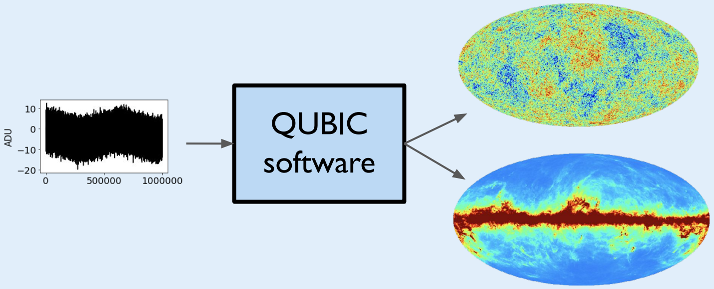
Components Map-making

$$\vec{y} = \left(\sum_{j=0}^{N-1} H_j \cdot A_j \right) \cdot \vec{c} + \vec{n}$$

[Régnier et al., in preparation]

What about external data ?

- Heart of the QUBIC software is to simulate the instrument with the greatest possible precision



- External data can be added easily by defining simple operator that take frequency maps

planck

SIMONS OBSERVATORY

?

CMB-S4

Next Generation CMB Experiment

$$\begin{pmatrix} \mathcal{H}^{\mathrm{QUBIC}} \\ H^{\mathrm{Ext}} \end{pmatrix}$$

$$\begin{aligned}
\chi^2_{\mathrm{Tot}} &= \begin{bmatrix} \boldsymbol{d}_{\mathrm{QUBIC}} - \tilde{\boldsymbol{d}}_{\mathrm{QUBIC}} \\ \boldsymbol{d}_{\mathrm{Ext}} - \tilde{\boldsymbol{d}}_{\mathrm{Ext}} \end{bmatrix}^T \cdot \begin{bmatrix} N^{-1}_{\mathrm{QUBIC}} & 0 \\ 0 & N^{-1}_{\mathrm{Ext}} \end{bmatrix} \cdot \begin{bmatrix} \boldsymbol{d}_{\mathrm{QUBIC}} - \tilde{\boldsymbol{d}}_{\mathrm{QUBIC}} \\ \boldsymbol{d}_{\mathrm{Ext}} - \tilde{\boldsymbol{d}}_{\mathrm{Ext}} \end{bmatrix} \\
&= \left(\boldsymbol{d}_{\mathrm{QUBIC}} - \mathcal{H}^{\mathrm{QUBIC}} \cdot \tilde{\boldsymbol{s}}\right)^T \cdot N^{-1}_{\mathrm{QUBIC}} \cdot \left(\boldsymbol{d}_{\mathrm{QUBIC}} - \mathcal{H}^{\mathrm{QUBIC}} \cdot \tilde{\boldsymbol{s}}\right) \\
&\quad + \left(\boldsymbol{d}_{\mathrm{Ext}} - H^{\mathrm{Ext}} \cdot \tilde{\boldsymbol{s}}\right)^T \cdot N^{-1}_{\mathrm{Ext}} \cdot \left(\boldsymbol{d}_{\mathrm{Ext}} - H^{\mathrm{Ext}} \cdot \tilde{\boldsymbol{s}}\right) \\
&= \chi^2_{\mathrm{QUBIC}} + \chi^2_{\mathrm{Ext}}
\end{aligned}$$

Component Separation Map-Making

- Classical imagers: Frequency maps ↦ Component separation
- <u>B.I.: frequency sensitivity in TOD</u>
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    - Spectral index variations
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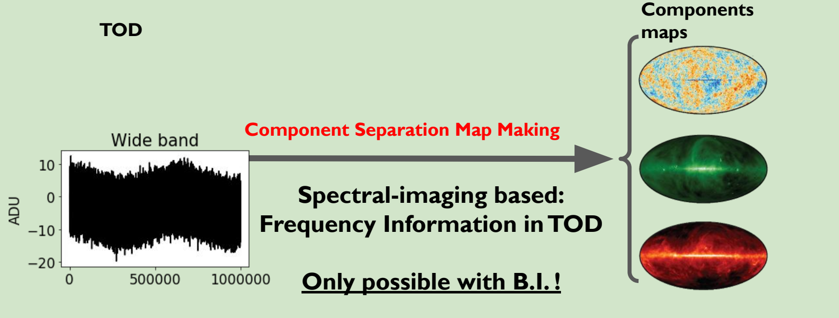
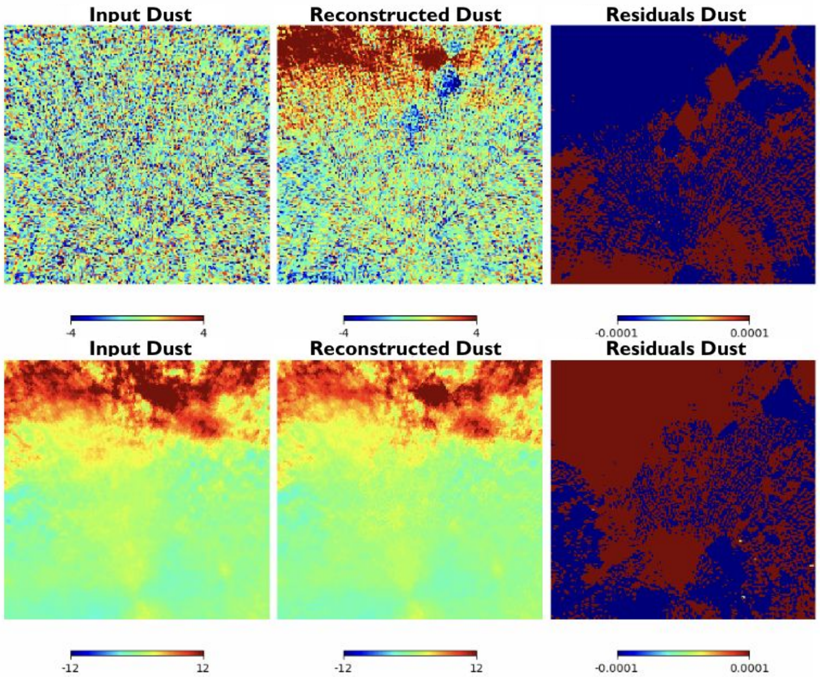


Frequency Mapmaking Bolometric Interferometer Pipeline

First TOD → Components MapMaking (parametric) !

(noiseless)

<u>single broadband TOD → Unbiased maps of 2 components</u>



[Régnier et al., in preparation]

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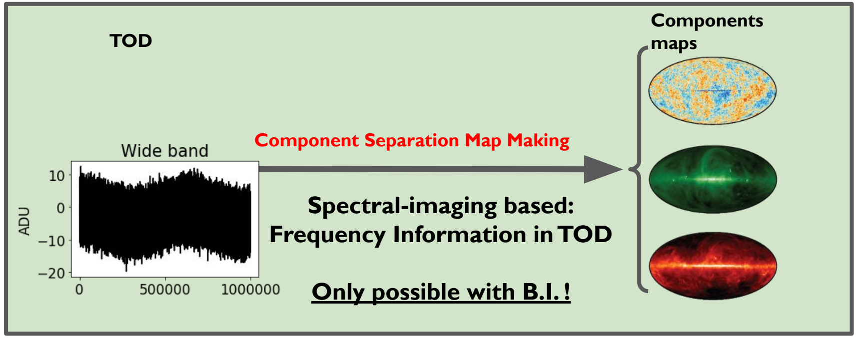

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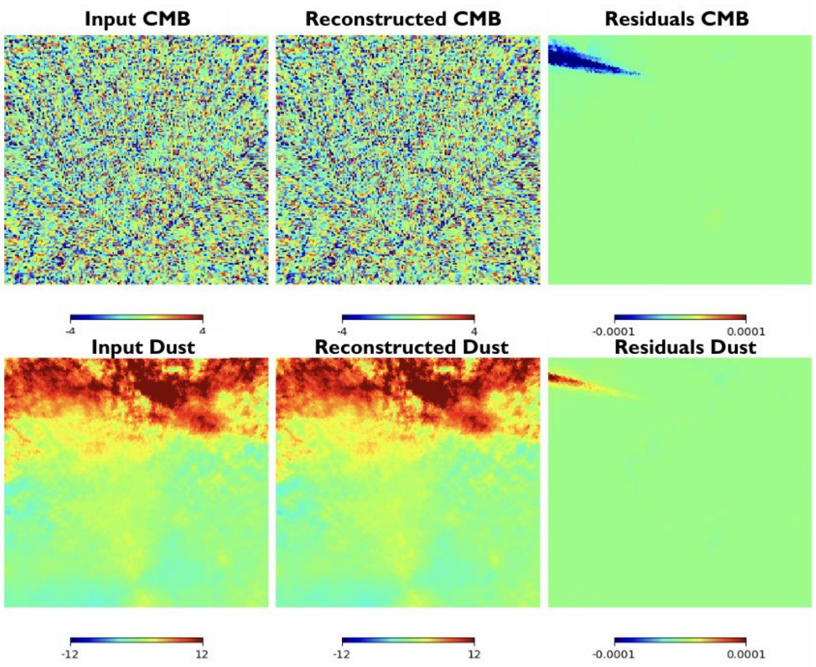

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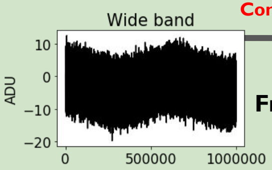

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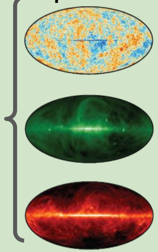
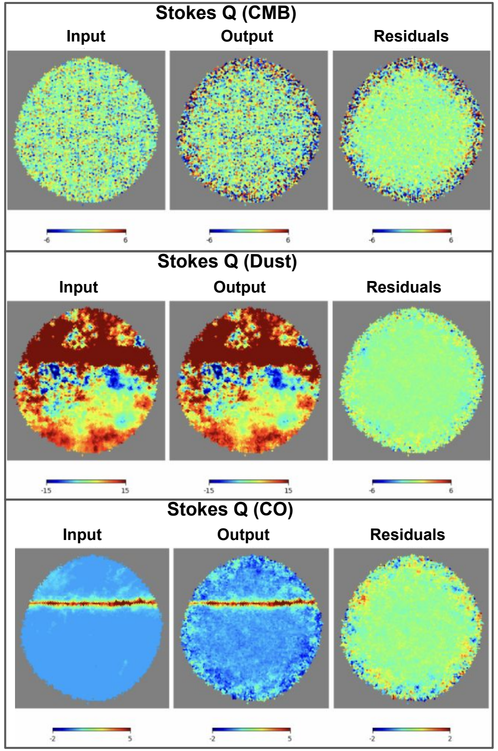


Frequency Mapmaking Bolometric Interferometer Pipeline

First TOD → Components MapMaking (parametric) !

<u>Nominal noise - 3 components: CMB, Dust, CO line</u>



CO emission line

[Régnier et al., in preparation]

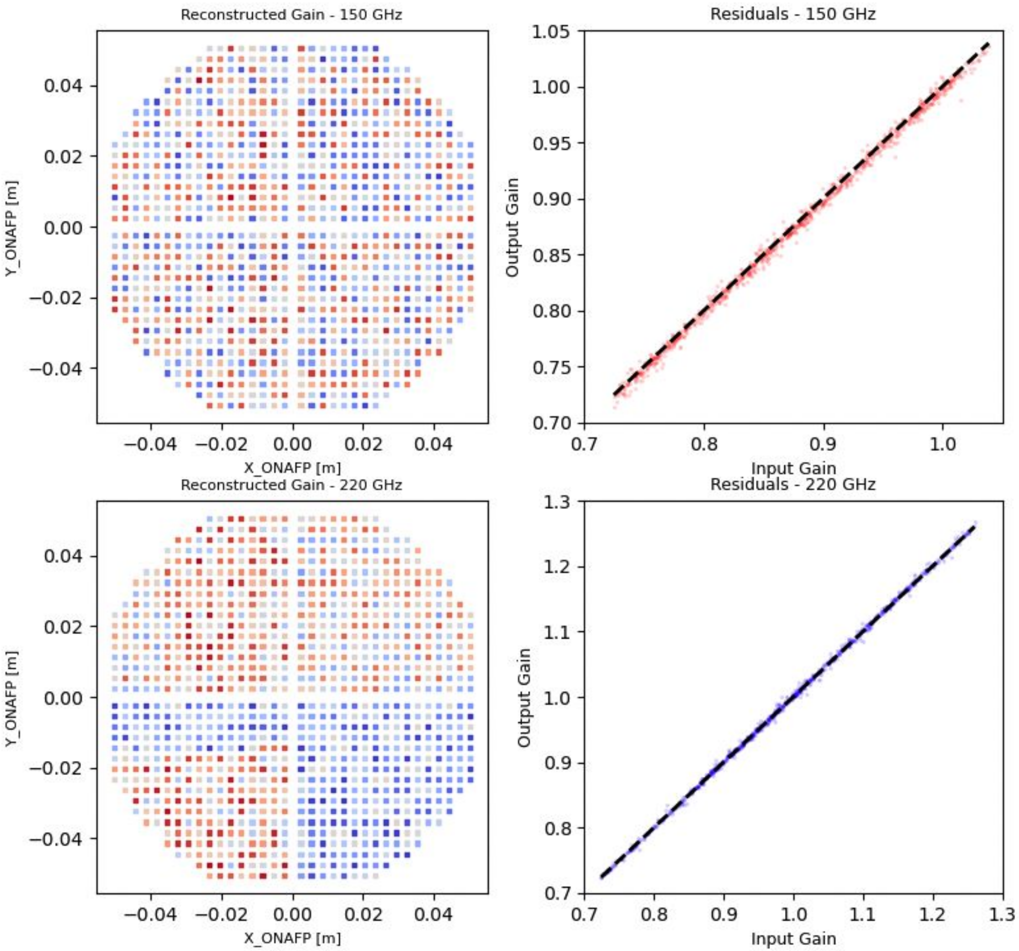
Component Separation Map-Making

We fit the intercalibration factor of the instrument using a semi-analytical method.

$$g = \frac{d}{H \cdot c} \qquad d^{obs} = g \cdot d_{\text{intercalibrated}}$$

Component Map-Making is a way to take into account instrumental systematics during the convergence.

- HWP angles
- Detector gain
- Cross-polarization



Conclusion

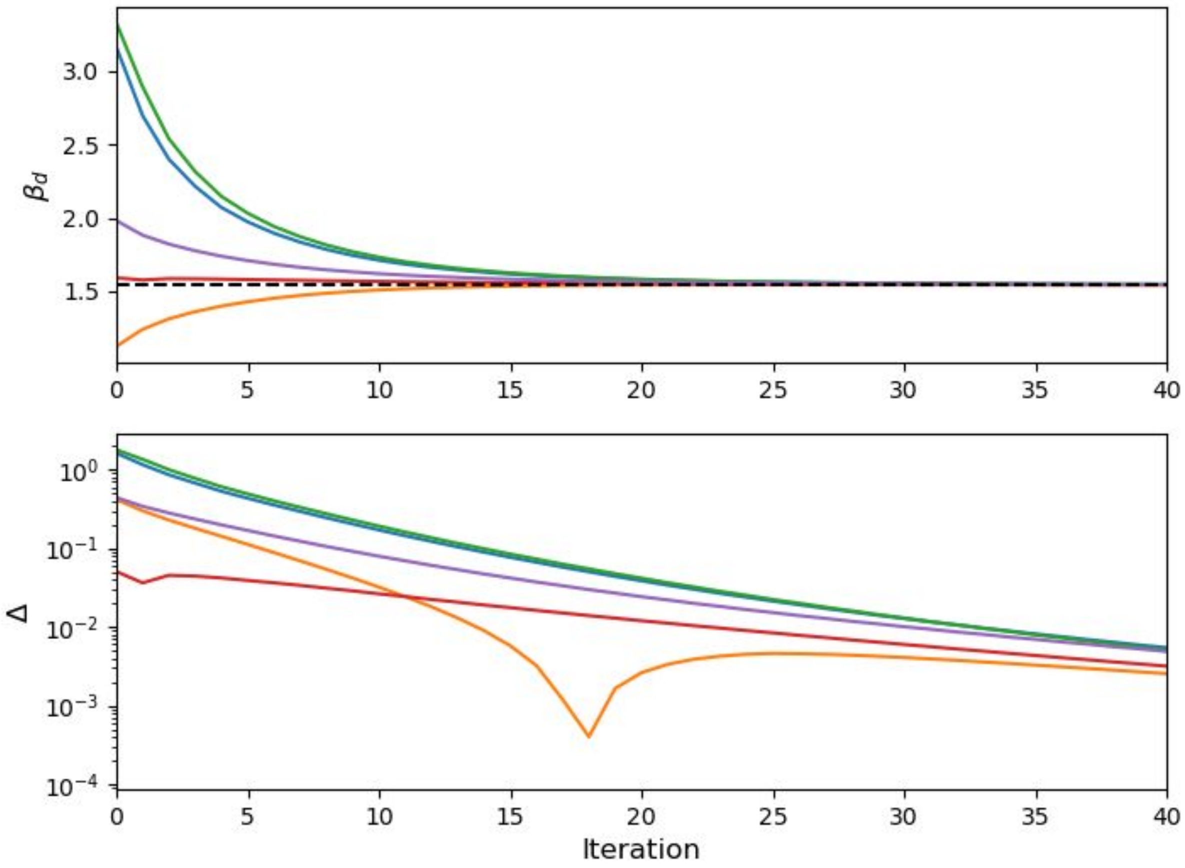
- *New component separation process specially design for bolometric interferometer and so QUBIC*
- *Can work also for classical imager but need to have a numerical description of the instrument*
- *Allows to perform joint analysis such as Commander3*
- *New steps should be to implement removal process for atmospheric contribution*
- *First component separation method based on time domain and not frequency data*

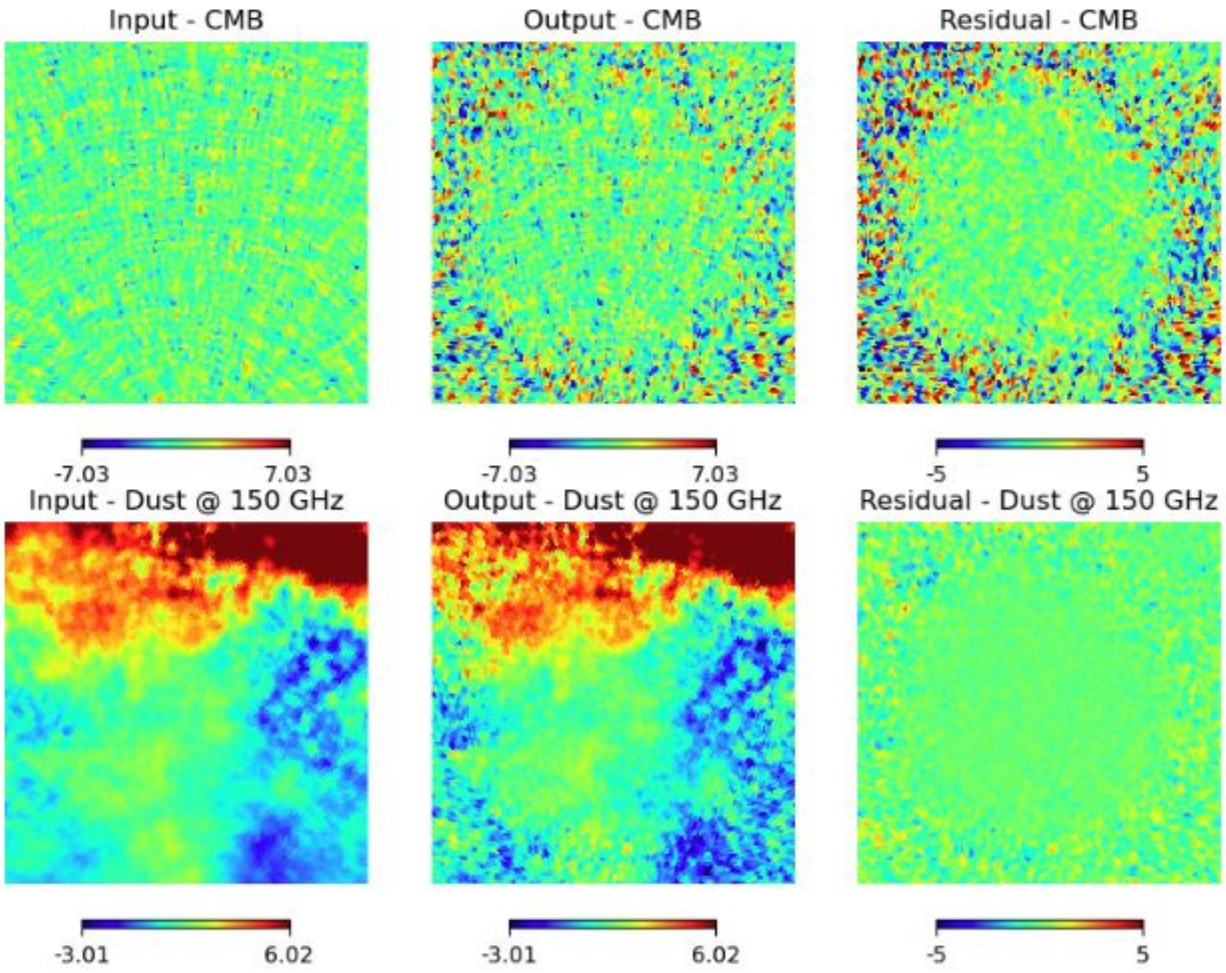
Back-up

We use iterative process to converged towards the solution.

We need to be sure that the starting point will not change the solution.

We produce here several simulations using differents initial guess for spectral indices.




Input - CMB
Output - CMB
Residual - CMB
-7.03
7.03
-7.03
7.03
-5
5
Input - Dust @ 150 GHz
Output - Dust @ 150 GHz
Residual - Dust @ 150 GHz
-3.01
6.02
-3.01
6.02
-5
5

Spectral indices fitting

We have build a new kind of QUBIC operator which depend on the spectral indices. To fit them, we just construct a minimization like :

$$\chi^2(\vec{\beta}|\vec{c},\vec{g}) = \left(\vec{d} - H(\vec{\beta}|\vec{g}) \cdot \vec{c}\right)^t \cdot N^{-1} \cdot \left(\vec{d} - H(\vec{\beta}|\vec{g}) \cdot \vec{c}\right)$$

With $$H = \sum_{i=0}^{N_{\text{sub}}} H_{\nu_i} \cdot A_{\nu_i}$$

This works well and is quiet fast but assumes that the estimation is performed over only one number.

For constant spectral indices across the sky it is good enough but for varying spectral indices, we need to make a loop on hundreds of parameters… So, in the code we have a method which using multiprocessing to fit several parameter at the same time.

You need to parallelize a lot the code to run it in reasonable time. This is done by the last operator just below.

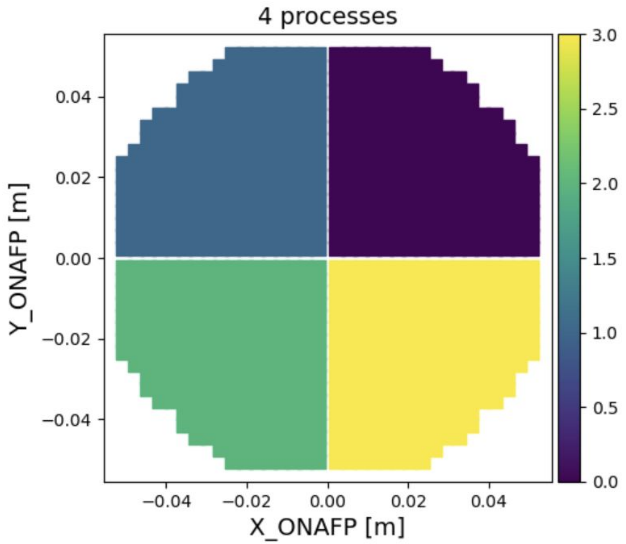
$$H = \mathcal{R}_{\rm det}\mathcal{T}_{\rm inst}\mathcal{I}_{\rm det}\mathcal{P}_{\rm ol}[\mathcal{H}_{\rm WP} * \mathcal{P}_{\rm roj}]\mathcal{F}_{\rm ilt}\mathcal{A}_{\rm p}\mathcal{T}_{\rm atm}\mathcal{U}_{\rm nit}\mathcal{D}_{\rm ist}$$

$$\mathcal{D}_{\rm dist} = \begin{bmatrix} I & 0 \\ 0 & I \end{bmatrix} \longleftarrow \textit{Rank 0}$$

$$\begin{bmatrix} I & 0 \\ 0 & I \end{bmatrix} \longleftarrow \textit{Rank 1}$$

$$\begin{bmatrix} I & 0 \\ 0 & I \end{bmatrix} \longleftarrow \textit{Rank 2}$$

This operator is actually giving a copy of input at all processes to be able to treat each set of detectors independently.



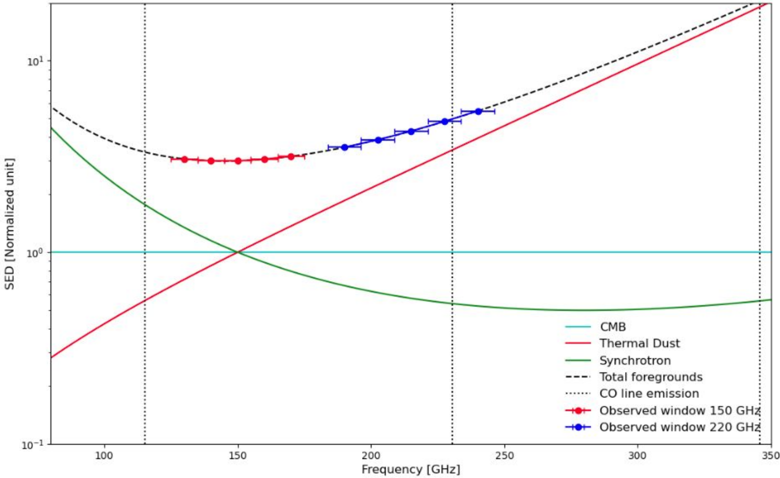
CO line emission

We assume from now that every foregrounds emit at each frequency. In reality, there are monochromatic emissions (CO line). One of those is at nu = 230.538 GHz within the 220 GHz band.
We have to rewrite the QUBIC operator such as :

$$H = H_\nu + H_{\mathrm{CO}}$$

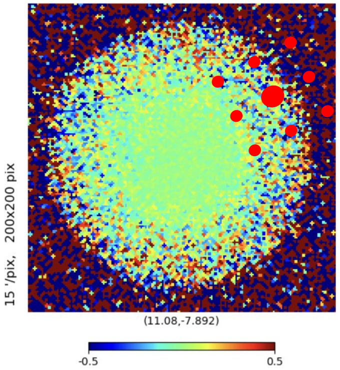
We distribute the components inside as :

$$\vec{d} = H_\nu \cdot C_\nu + H_{\mathrm{CO}} \cdot C_{\mathrm{CO}}$$

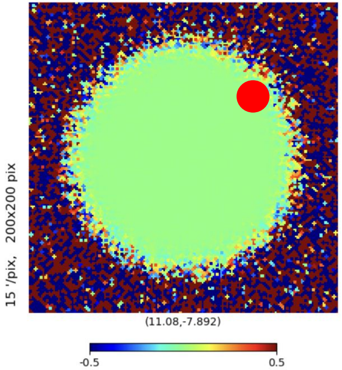


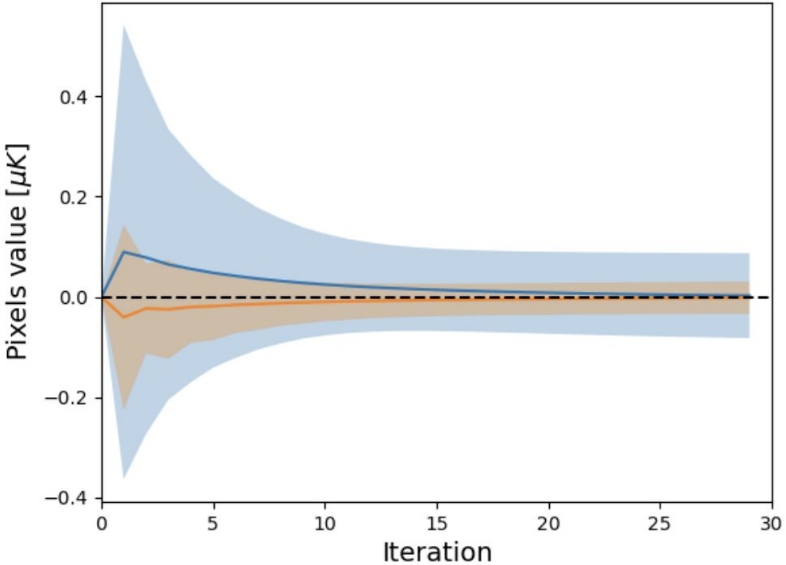
with $\vec{c} = [C_\nu, C_{CO}]$ *is the components vector.*

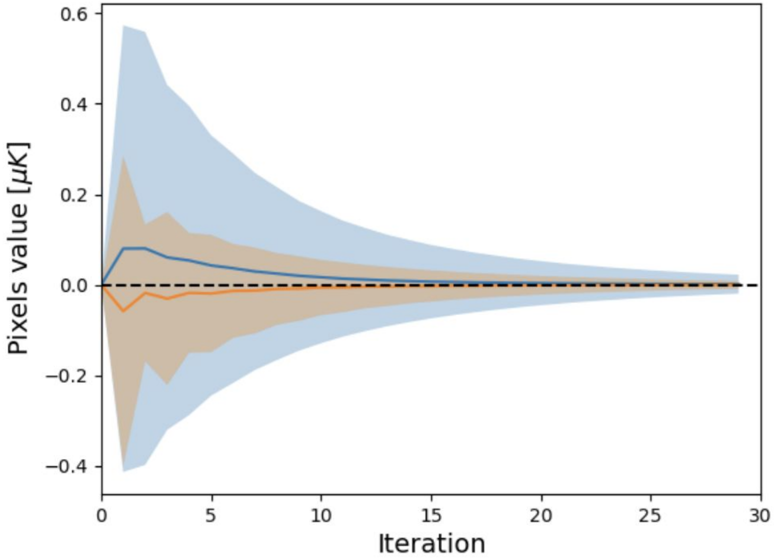
Synthetized beam noise effect



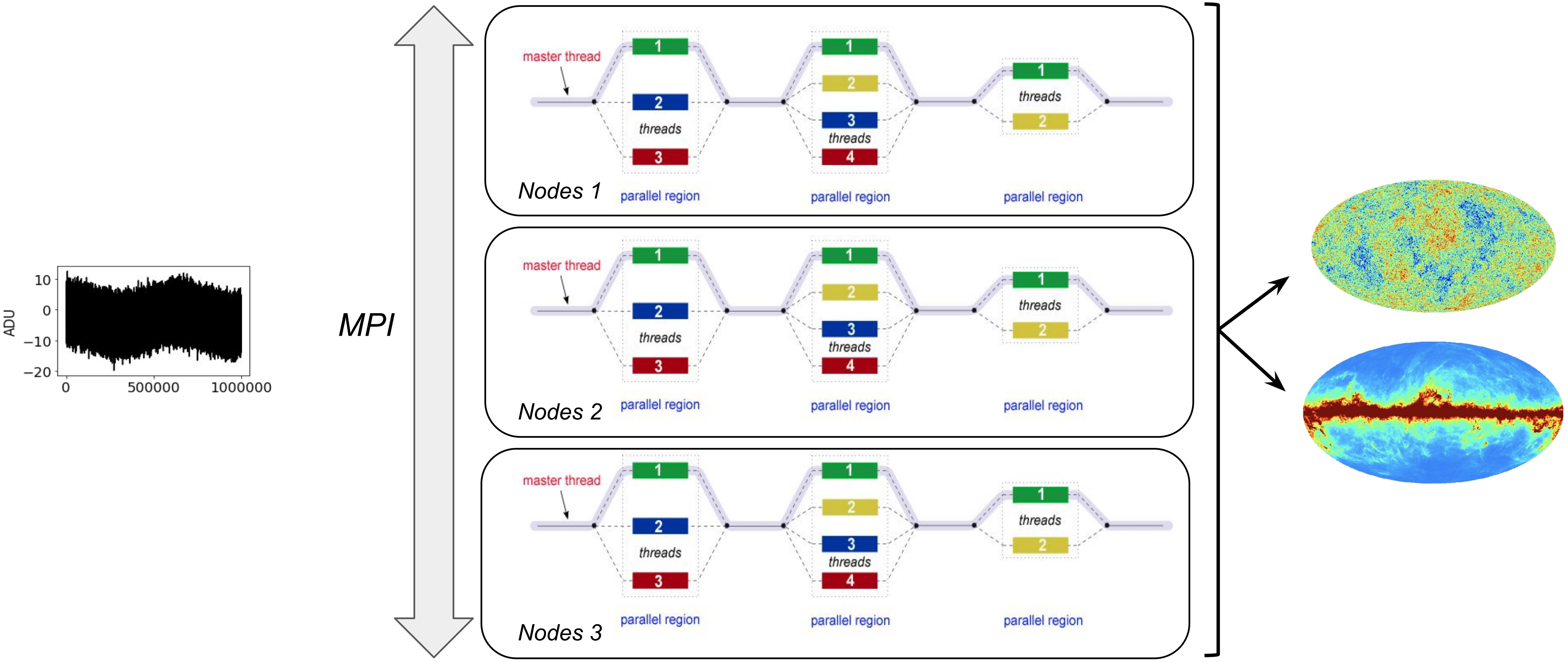
*Simulations perform with the exact same initial configuration, but **on left** we keep 9 peaks, **on right** we keep only the central peak*







Hybrid Open MP / MPI



QUBIC heart

In the QUBIC map-making, we are using a specific topology of MPI communicator, a 2 dimensional grid.

$$\underbrace{\begin{bmatrix} n_{1,1} & n_{2,1} & \cdots & n_{N,1} \\ n_{1,2} & n_{2,2} & \cdots & n_{N,2} \\ \vdots & \vdots & \ddots & \vdots \\ n_{1,N} & n_{2,N} & \cdots & n_{N,N} \end{bmatrix}}_{\text{\# of detectors}} \left.\vphantom{\begin{bmatrix} n \\ n \\ \vdots \\ n \end{bmatrix}}\right\} \text{\# of samplings}$$

# of samplings

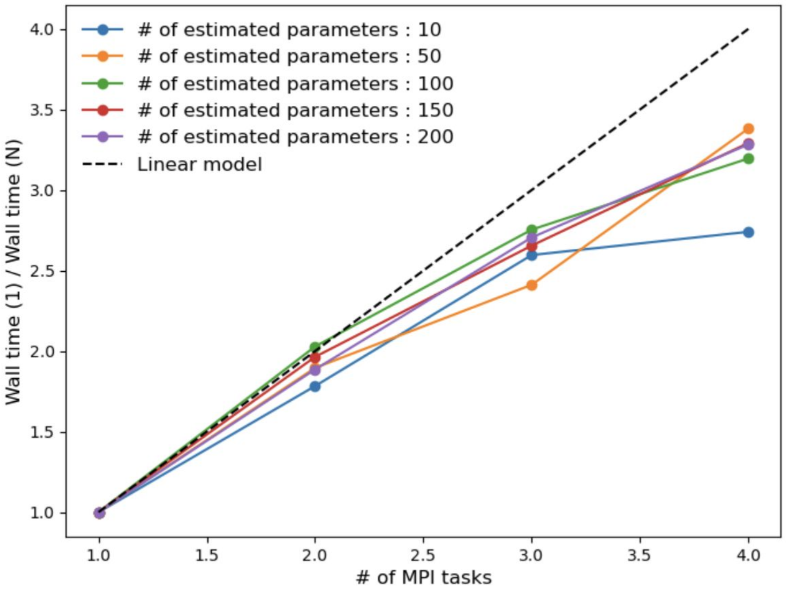
# of detectors

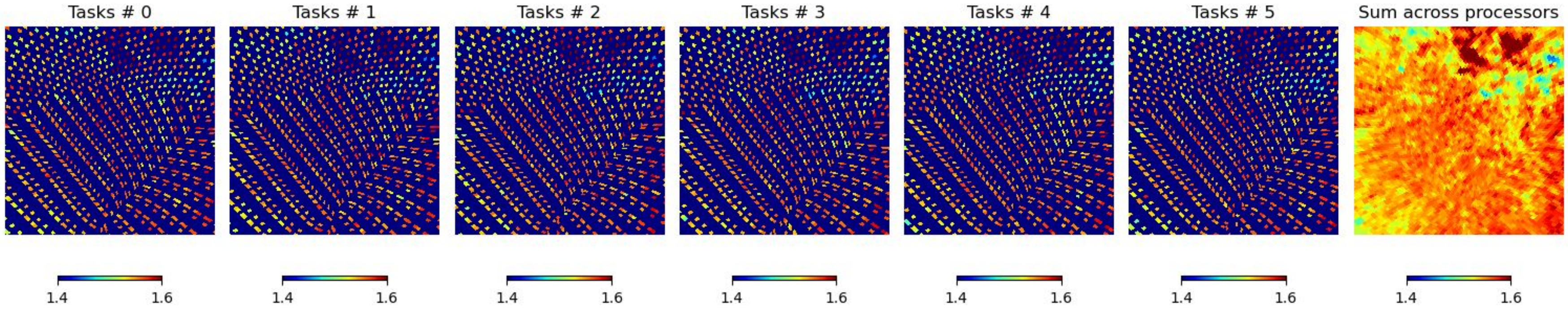
This allows to perform reduction on 2 differents axis.

Direct application : fit the spectral indices

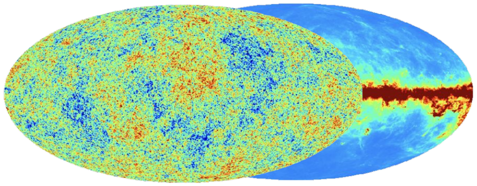
```python
def __call__(self, index):

    res = np.zeros(index.shape)
    x_per_process = self._split_params(index)
    if self.verbose:
        print(self.rank, x_per_process)

    for ii, i in enumerate(x_per_process):

        start = time.time()
        res[i] = self._apply_minimize(args=(index[i]))
        end = time.time()

        if self.verbose:
            print(f'Minimized parameter {index[i]} with rank {self.rank} in {end - start:.6f} s')

    return self.comm.allreduce(res, op=MPI.SUM)
```

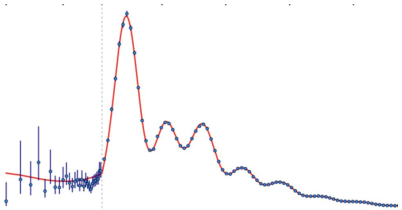
You can test it with the script test.py inside the folder

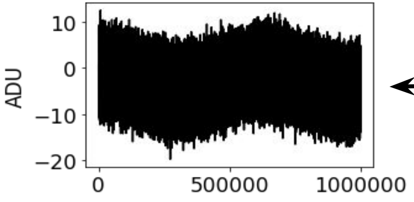




The convolution operation is long because we need to go to alm space, perform multiplication by a given kernel and then return back to map space. Why we don't directly fit the alm coefficient to be in a space where the convolution is simple ?







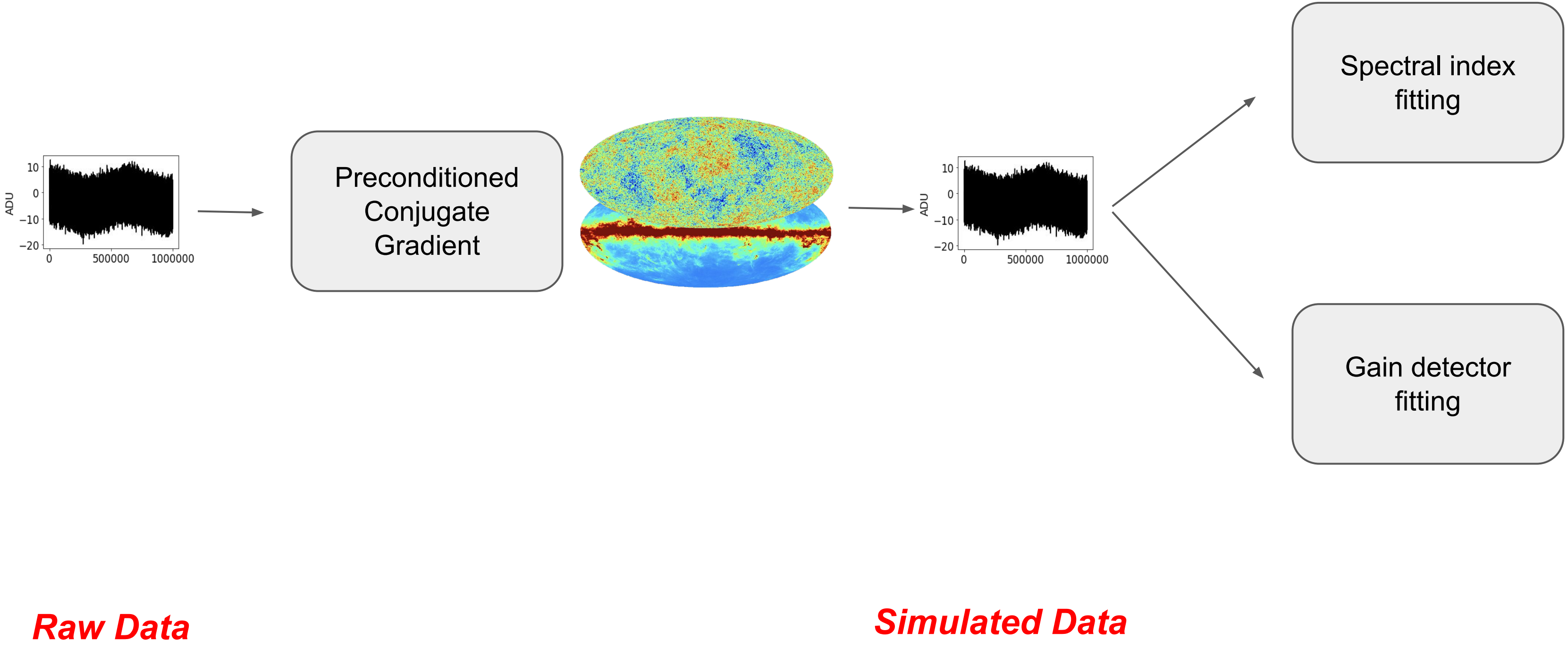
$$\leftarrow H_{\mathrm{QUBIC}} \leftarrow \mathcal{C}_\sigma \leftarrow \mathcal{A}^{\mathrm{CMB}}_{\mathrm{comp}}, \; \mathcal{A}^{\mathrm{Dust}}_{\mathrm{comp}}$$

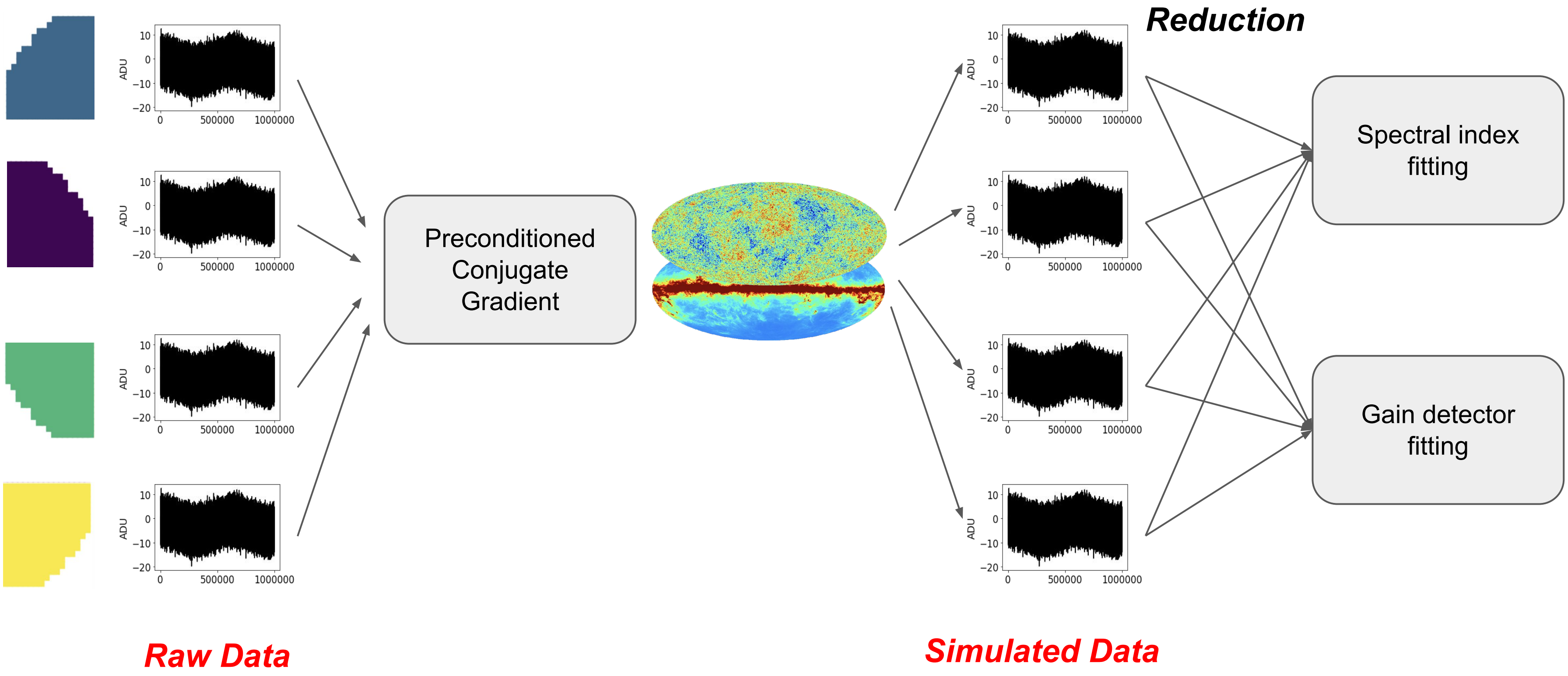
Output are the component maps

Output are the Alm coefficients

- *Build component maps from Alm*
- *Direct reconstruction of the spectra*
- *Maybe a B-modes mapping like Bicep ?*

$$H_{\mathrm{QUBIC}} = \mathcal{R}_{\mathrm{det}} \mathcal{T}_{\mathrm{inst}} \mathcal{I}_{\mathrm{det}} \mathcal{P}_{\mathrm{ol}} [\mathcal{H}_{\mathrm{WP}} * \mathcal{P}_{\mathrm{roj}}] \mathcal{F}_{\mathrm{ilt}} \mathcal{A}_{\mathrm{p}} \mathcal{T}_{\mathrm{atm}} \mathcal{U}_{\mathrm{nit}} \mathcal{D}_{\mathrm{ist}}$$


ADU
10
0
−10
−20
0
500000
1000000
Preconditioned Conjugate Gradient
ADU
10
0
−10
−20
0
500000
1000000
Spectral index fitting
Gain detector fitting
Raw Data
Simulated Data


Reduction
ADU
10
0
−10
−20
0
500000
1000000
Preconditioned Conjugate Gradient
Spectral index fitting
Gain detector fitting
Raw Data
Simulated Data

Why parallelization is needed ?

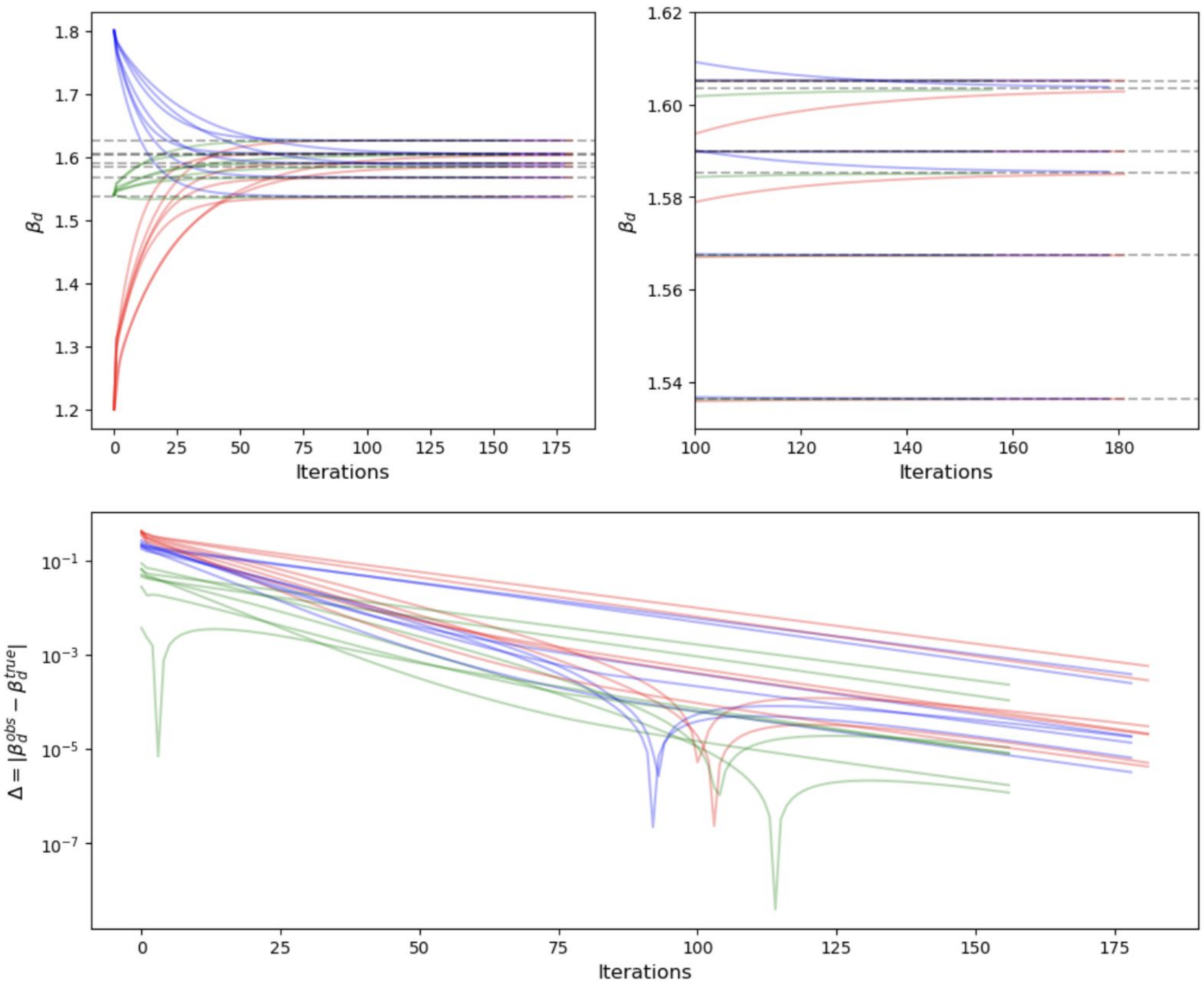
The data we will receive from the instrument are very huge. There are many detectors and each of them can be treated independently.

$$N_{\rm sub} \times 10000 \times 992 \times 9 \times 16 \approx N_{\rm sub} \times 1.5\text{GB}$$

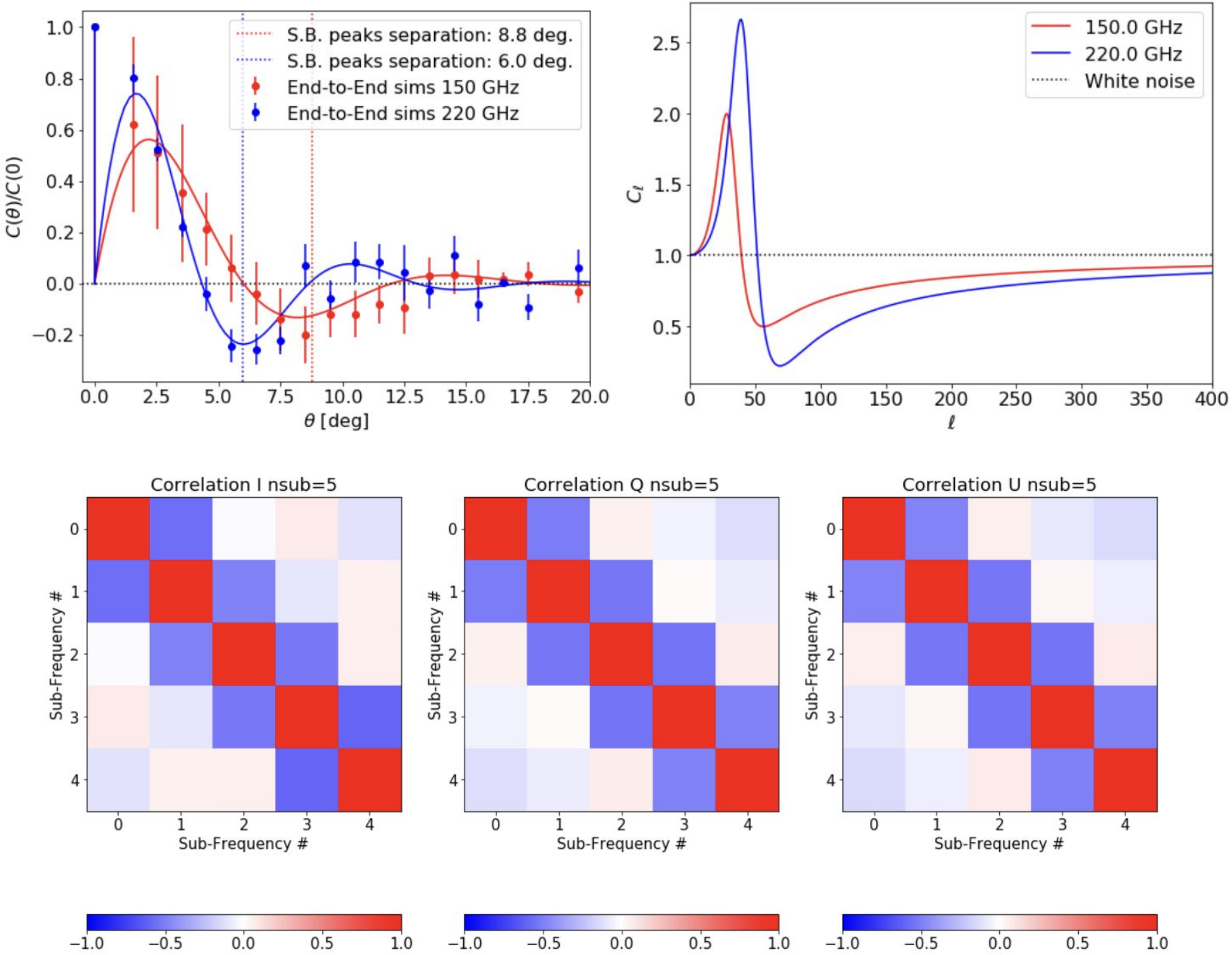
The number of sub-acquisitions should be higher than 10 and the number of pointing higher for real data. The required memory will be high.

In the Qubicsoft, there are two kind of parallelization :

- *Multiprocessing to use several cores using MPI*
- *Multithreading to use several computation lines using OpenMP*



1.8
1.7
1.6
1.5
1.4
1.3
1.2
β_d
0
25
50
75
100
125
150
175
Iterations
1.62
1.60
1.58
1.56
1.54
β_d
100
120
140
160
180
Iterations
10^{-1}
10^{-3}
10^{-5}
10^{-7}
$\Delta = |\beta_d^{obs} - \beta_d^{true}|$
0
25
50
75
100
125
150
175
Iterations


S.B. peaks separation: 8.8 deg.
S.B. peaks separation: 6.0 deg.
End-to-End sims 150 GHz
End-to-End sims 220 GHz
C(θ)/C(0)
θ [deg]
150.0 GHz
220.0 GHz
White noise
C_ℓ
ℓ
Correlation I nsub=5
Correlation Q nsub=5
Correlation U nsub=5
Sub-Frequency #