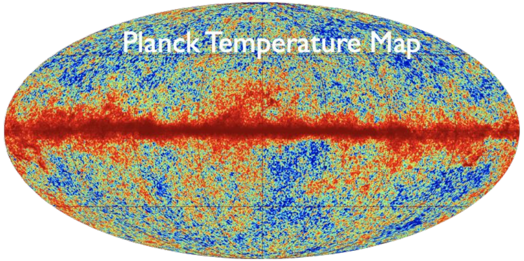
Spectral Imaging with QUBIC :

Component separation using Bolometric Interferometry

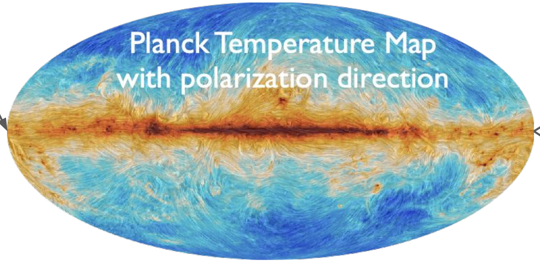
Tom Laclavère on behalf of the QUBIC Collaboration

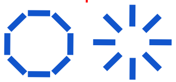
Scientific context

Fluctuations in the CMB

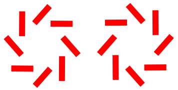


Density fluctuations in the primordial plasma





E-modes:
Well measured



B-modes:
Not observed

Expected from Primordial Gravitational Waves
⟺ Inflation

Tom Laclavère for the QUBIC Collaboration
APC - Paris - France
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Scientific purpose

QUBIC goal : Constraints on cosmic inflation by the detection of primordial polarization B modes in the cosmic microwave background

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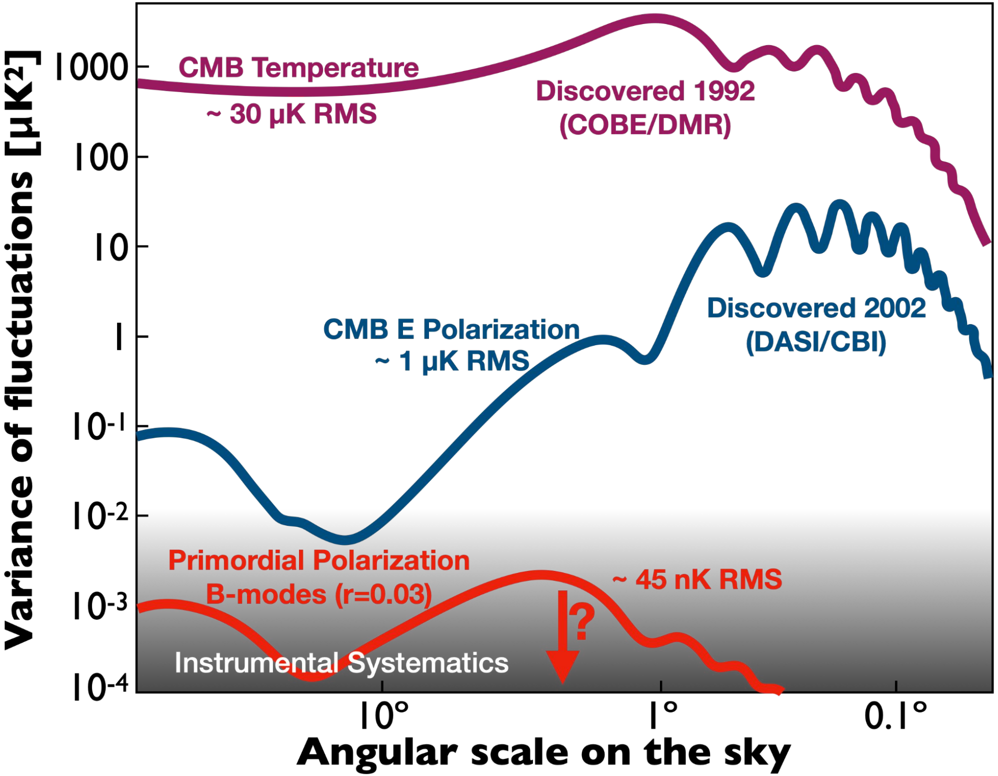
→ Difficulties :

- Sensitivity
  - Very small signal



[Bicep/Keck+Planck 2021 + SPTPol, ActPol, Polarbear]

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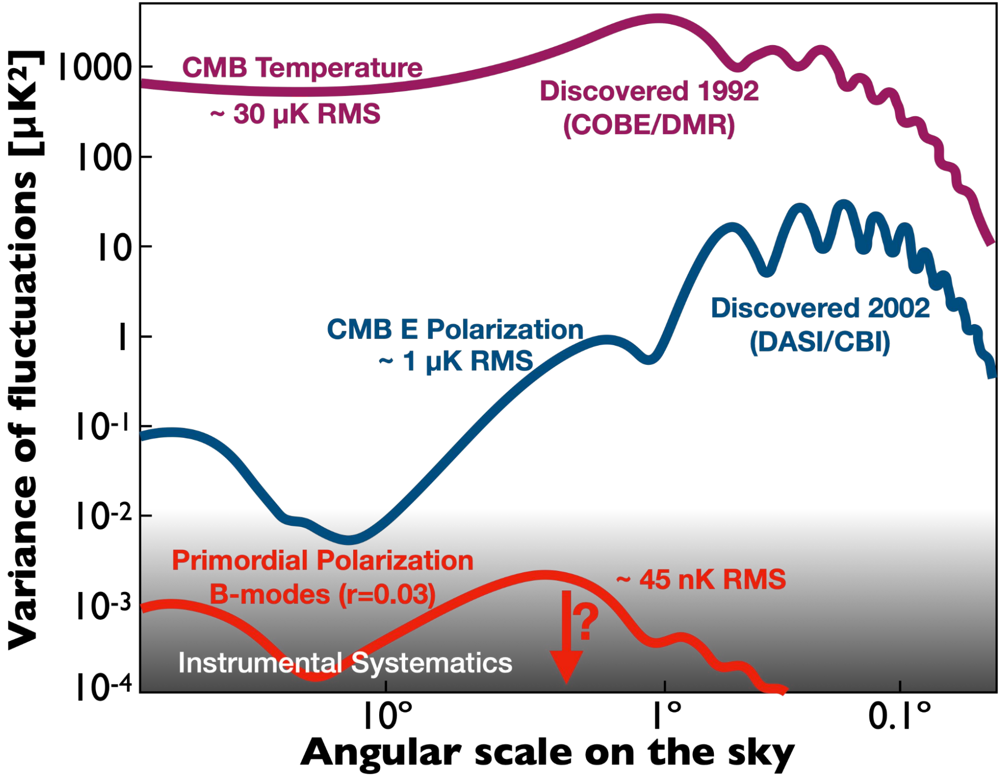
    - Instrumental systematics



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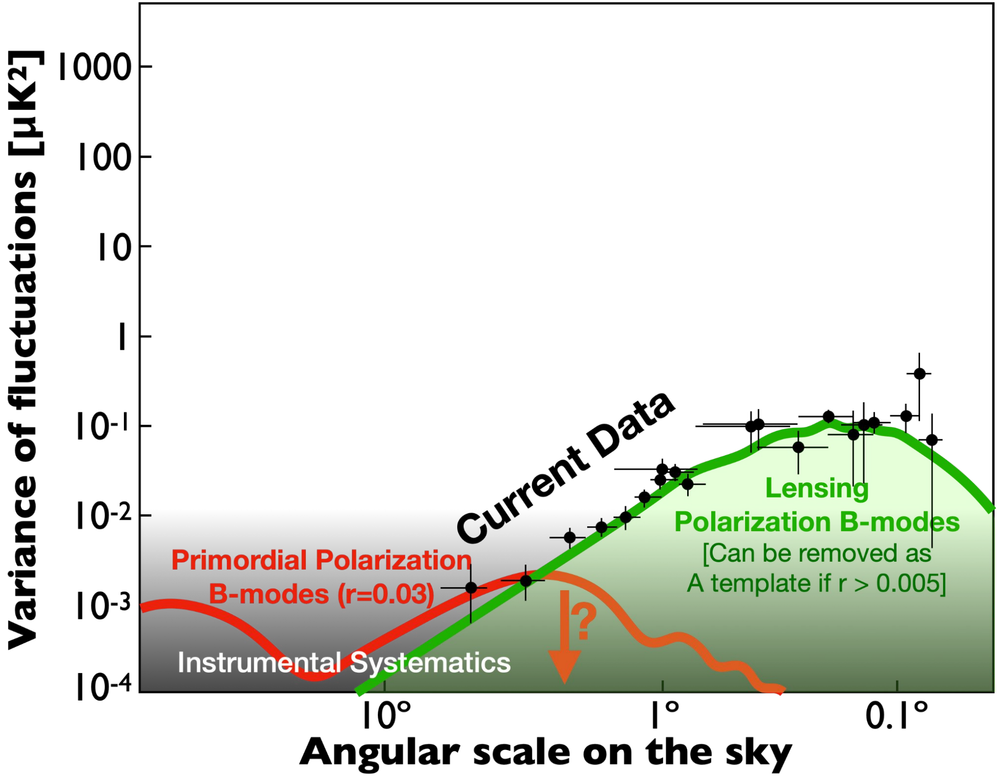
- Polarized astrophysical foregrounds :
  - Gravitational lensing



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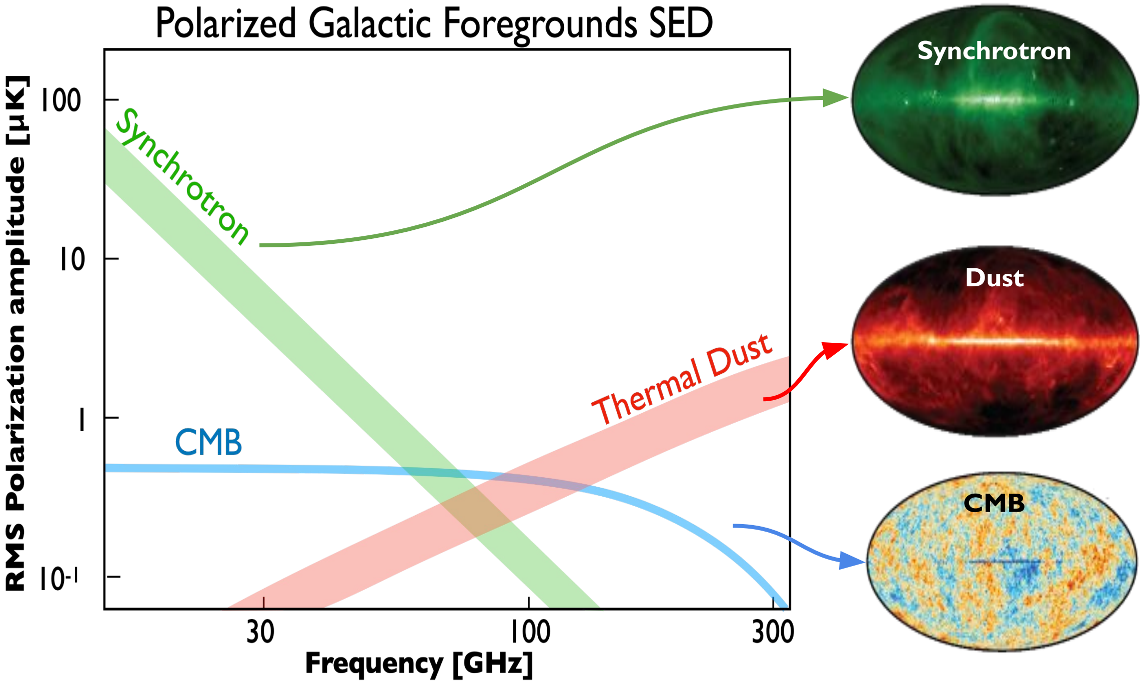

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→ Difficulties :

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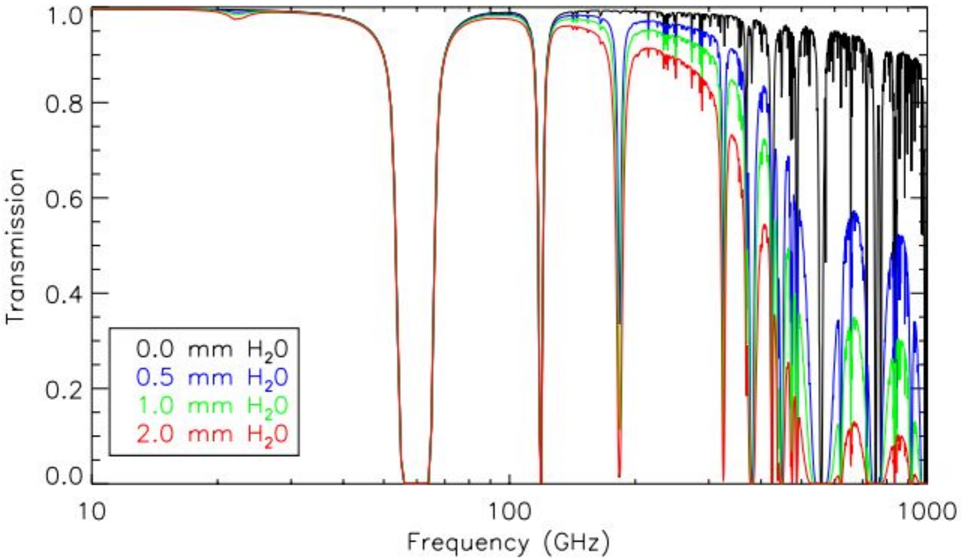
  - Very small signal
  - Instrumental systematics

- Polarized astrophysical foregrounds :
  - Gravitational lensing
  - Dust & Synchrotron

- Atmospheric contamination



Contribution to the temperature of the detectors

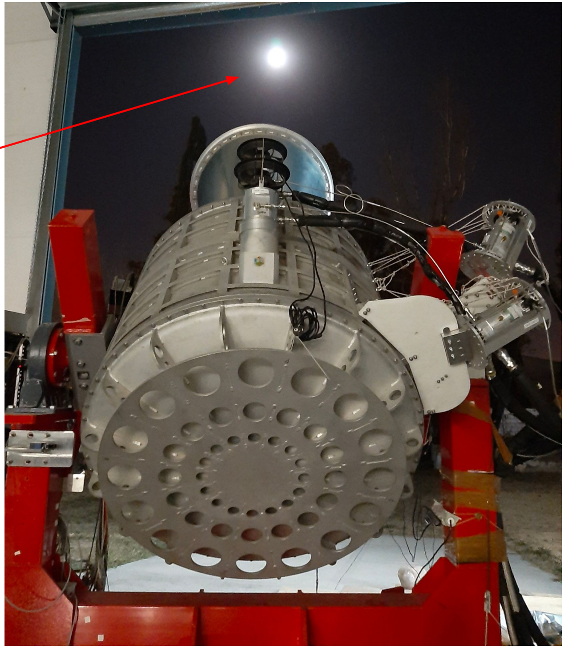
Water vapor distribution is inhomogeneous and moving:
⇒ Temporal and spatial correlations

[J. Errard et al., arXiv:1501.07911]

QUBIC:
Q & U Bolometric Interferometer for Cosmology

The collaboration

- 130 collaborators
- Observing site: Argentina (5000m a.s.l.)
- **First light: July 2022 (Moon from Salta)**
- **QUBIC is cold !!**



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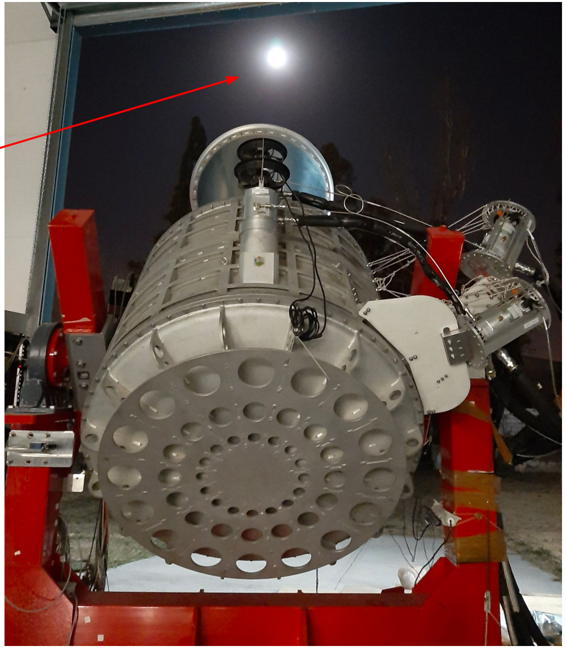
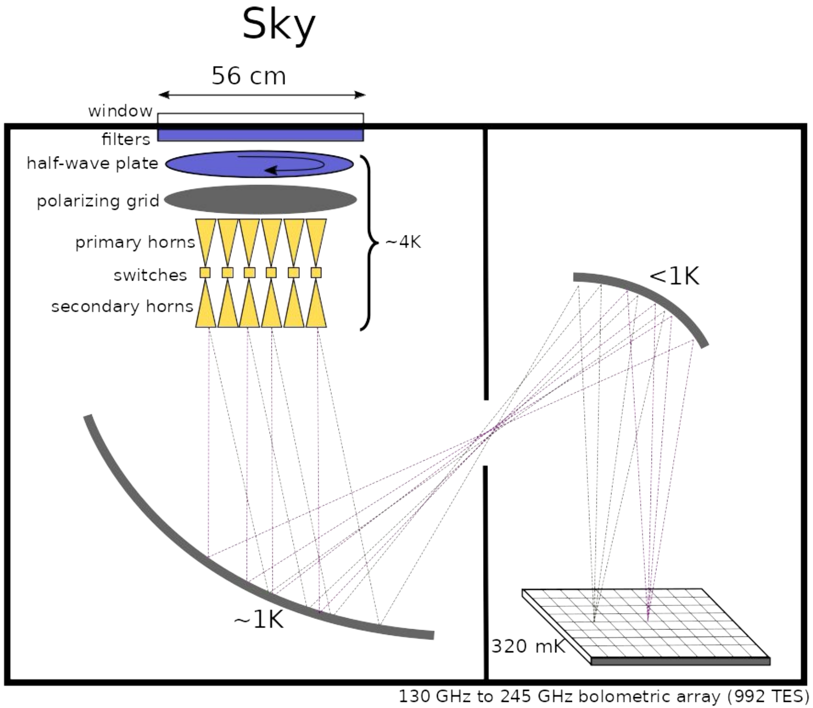


The first Bolometric Interferometer

Bolometers → - High Sensitivity (Transition-Edge-Sensor)

Interferometry → - Instrumental Systematics control (Self-Calibration)
- Polarized Galactic foregrounds separation (High spectral resolution)

Bolometric Interferometry:
Spectral Imaging



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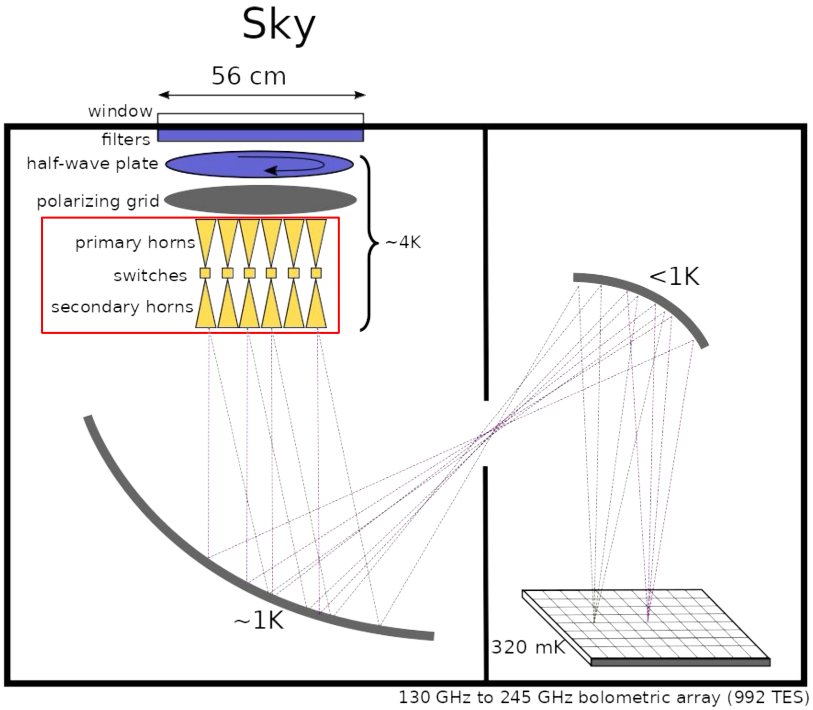
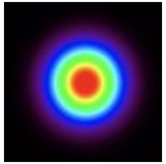
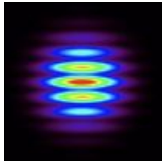
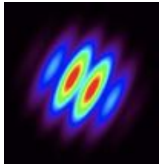




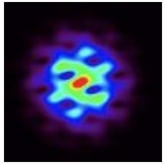
1 Horn open



2 Horns open



2 Horns open

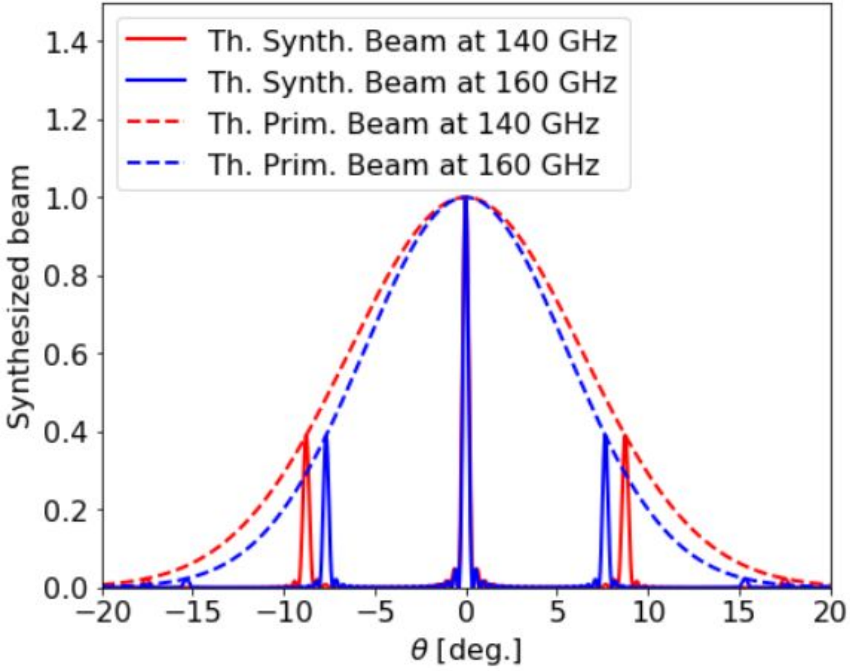


All Horns open

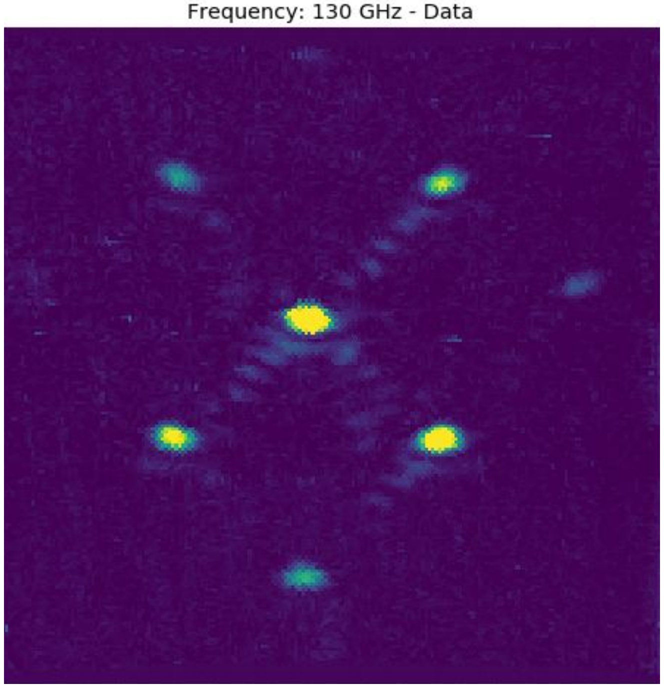
Fringe and Synthesized Beam data: [Torchinsky et al., QUBIC III, arXiv:2008.10056v3] (JCAP 2022)

Bolometric Interferometry:
Spectral Imaging

Monochromatic source (Diagram)



Monochromatic source (Laboratory)



[Louise Mousset et al., **arXiv:2010.15119**]

Bolometric Interferometry:
Spectral Imaging

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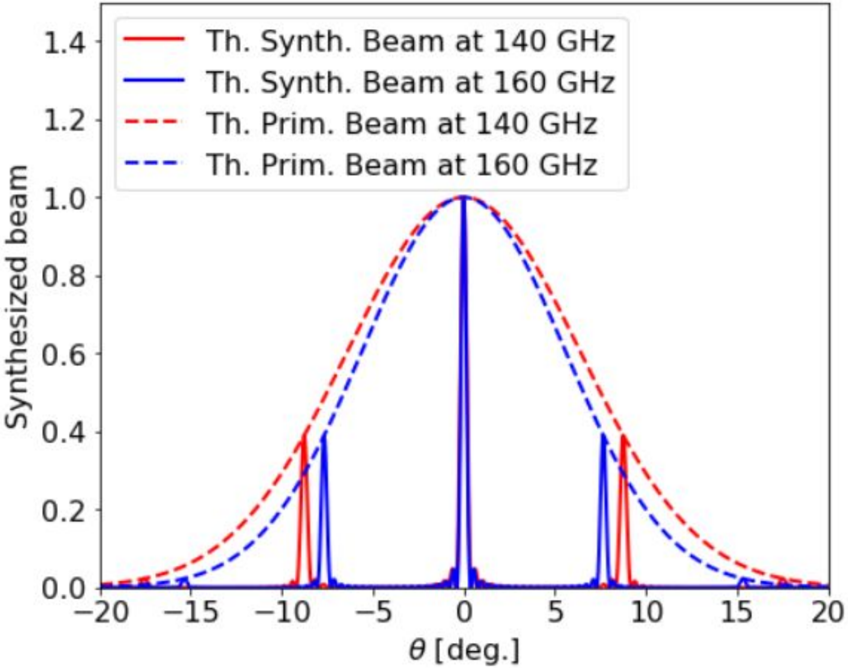
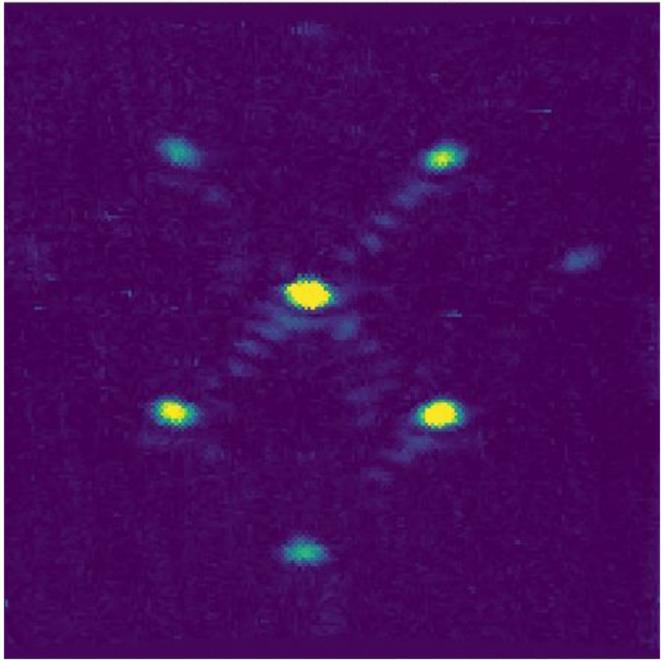


We can increase our spectral sensitivity by using the secondary peaks data

Monochromatic source (Laboratory)

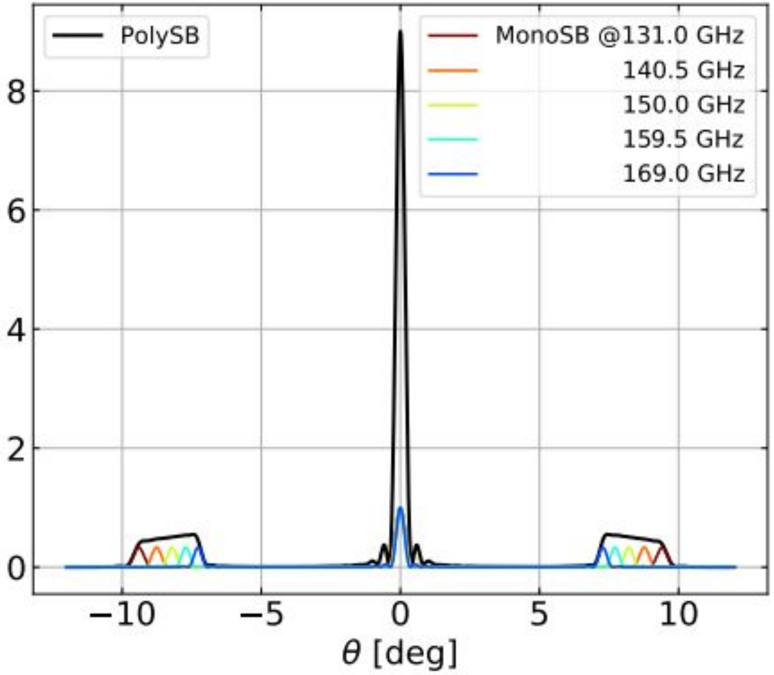
Frequency: 130 GHz - Data



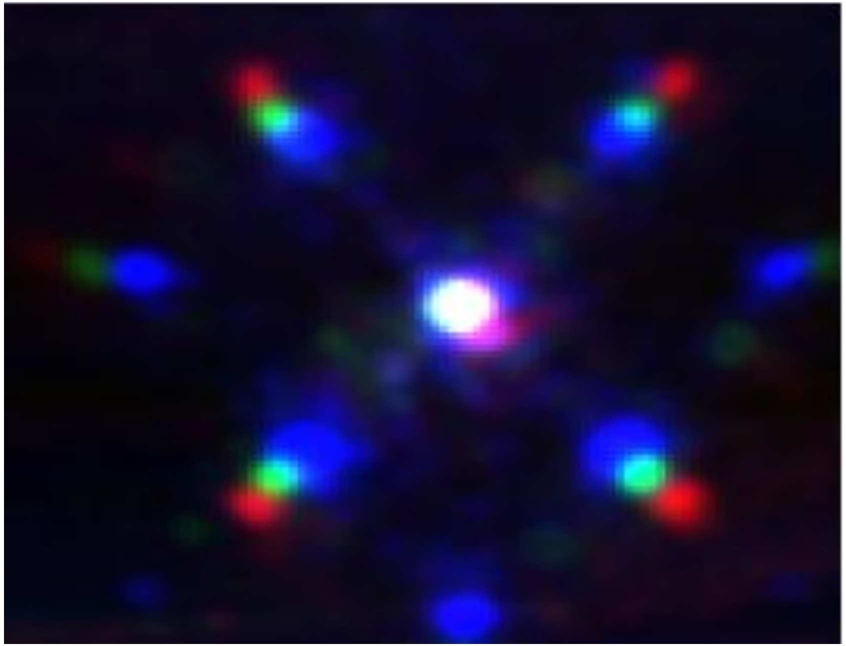
[Louise Mousset et al., **arXiv:2010.15119**]

Bolometric Interferometry:
Spectral Imaging

Polychromatic source (Diagram)



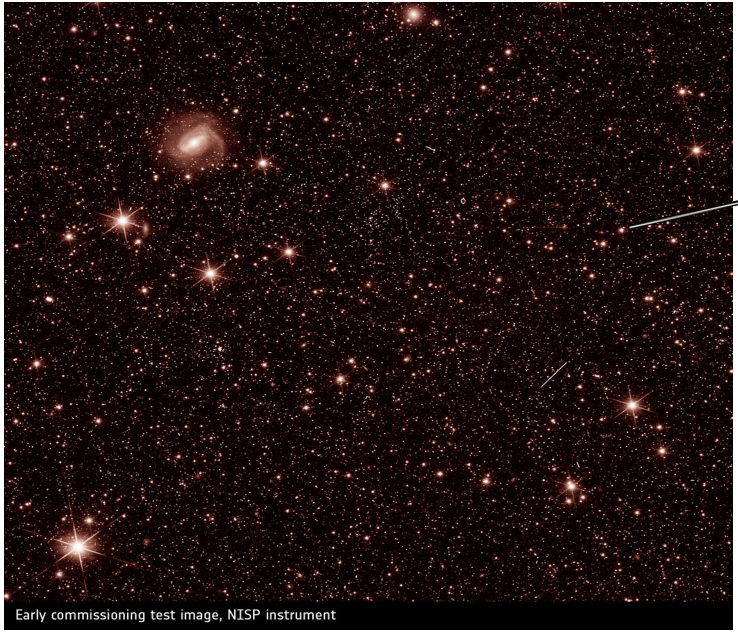
Polychromatic source (Laboratory)

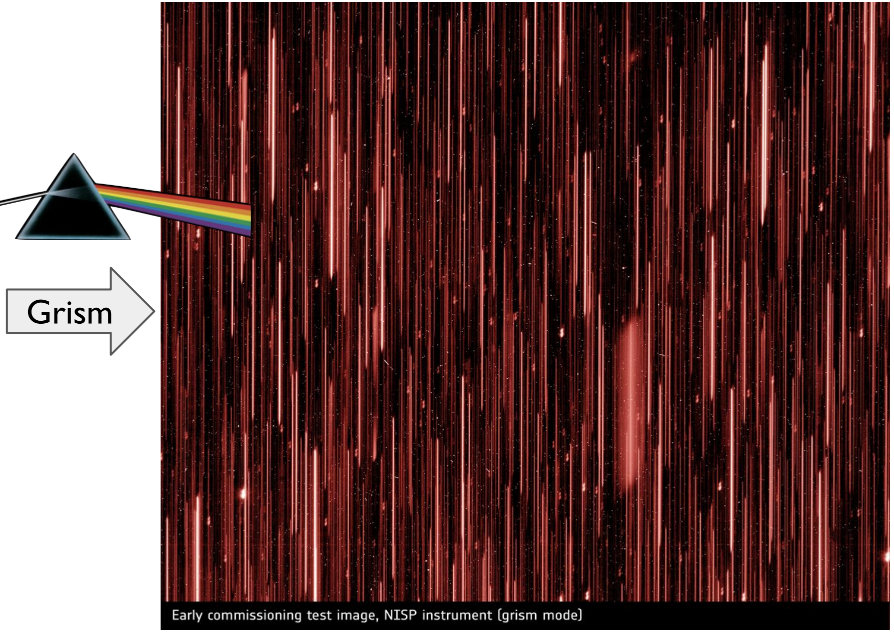


[Louise Mousset et al., **arXiv:2010.15119**]

Bolometric Interferometry:
Spectral Imaging

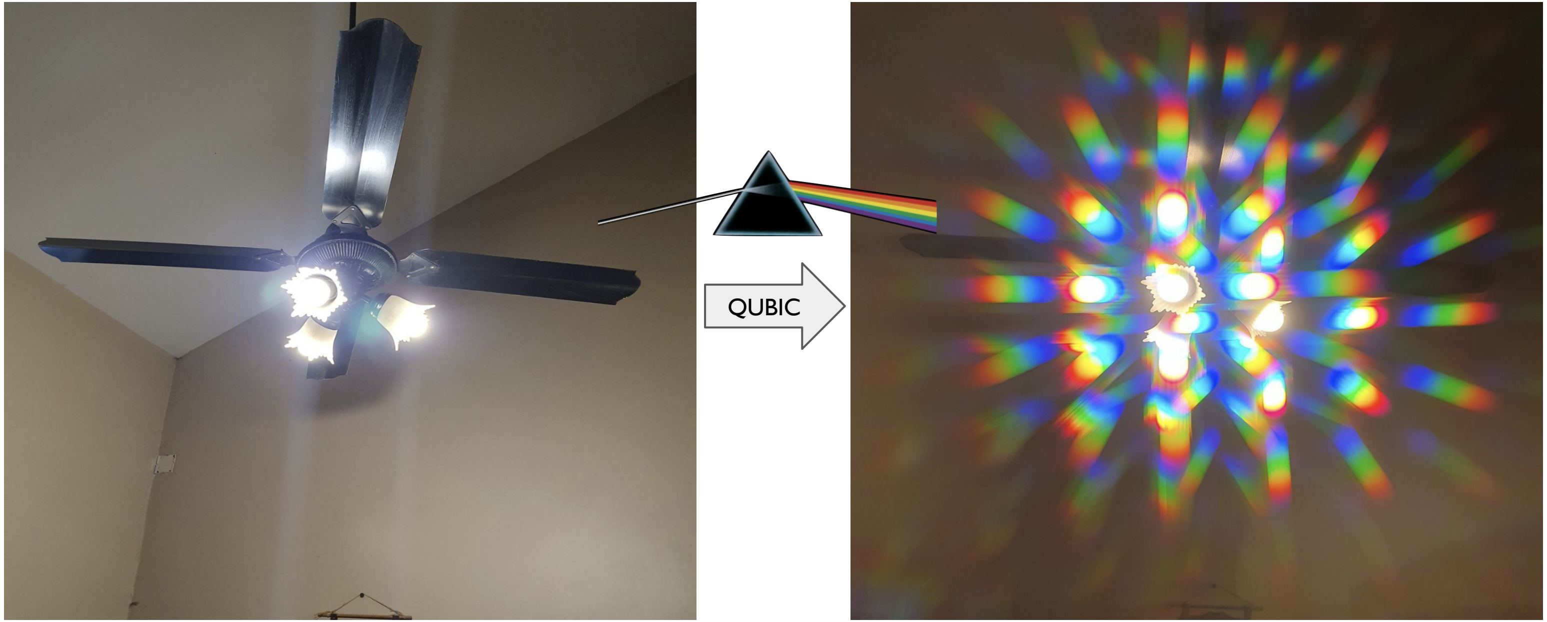
Perfect analogy with "grism spectroscopy" (Euclid test images)





Bolometric Interferometry:
Spectral Imaging

Seeing the world like QUBIC



Bolometric Interferometry:
Spectral Imaging

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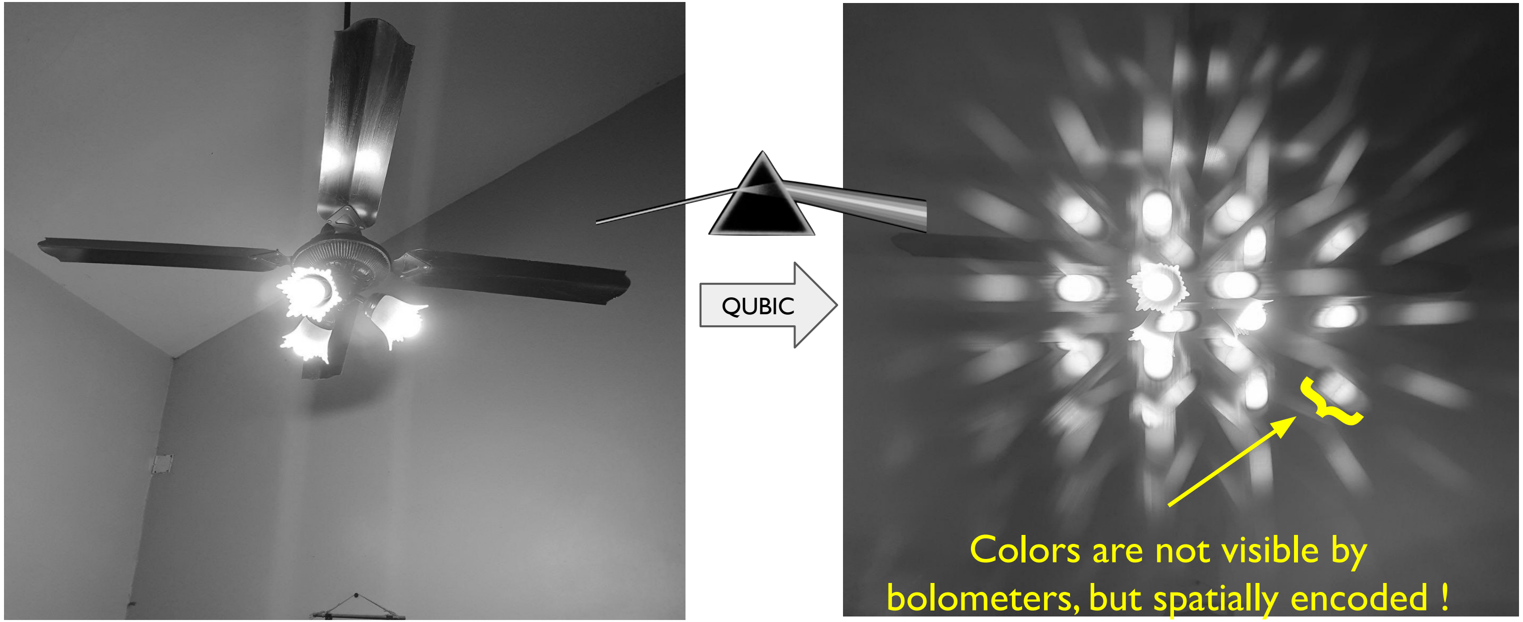

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Frequency Map-Making

Bolometer data (TOD)

Inst. model

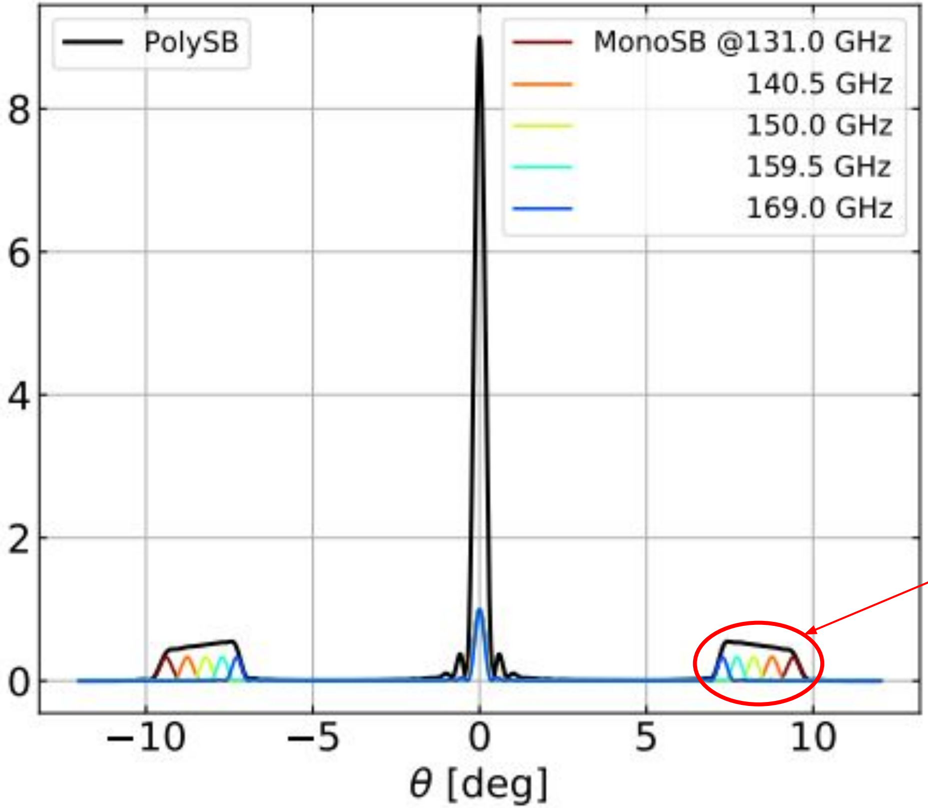
Sky

noise

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

[Chanial, Régnier, et al., A&A submitted, arXiv:2409.18698]

Frequency Map-Making



Bolometer data (TOD)

Inst. model

Sky in sub-bands

noise

$$\vec{y} = \sum_{\text{bands}} H_b \cdot \vec{s}_b + \vec{n}$$

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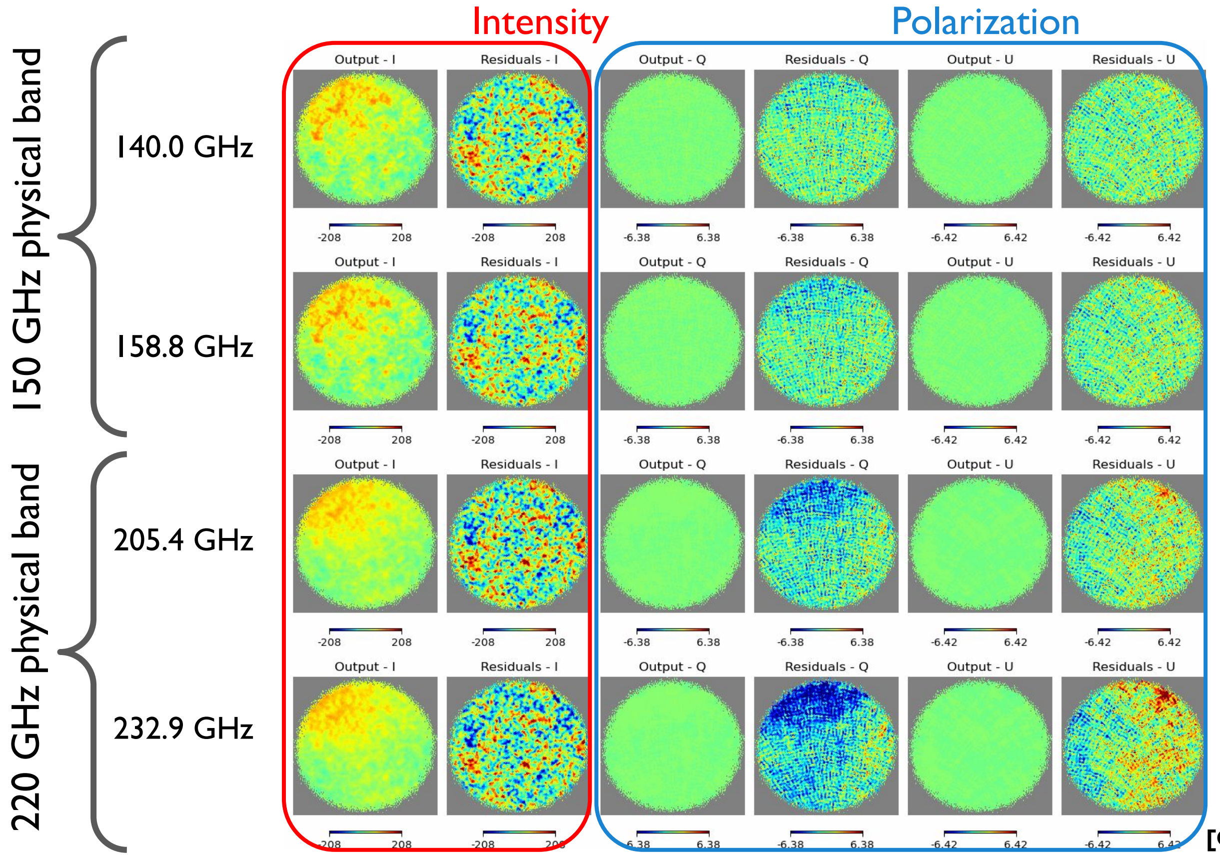
Frequency Map-Making



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Sky in sub-bands

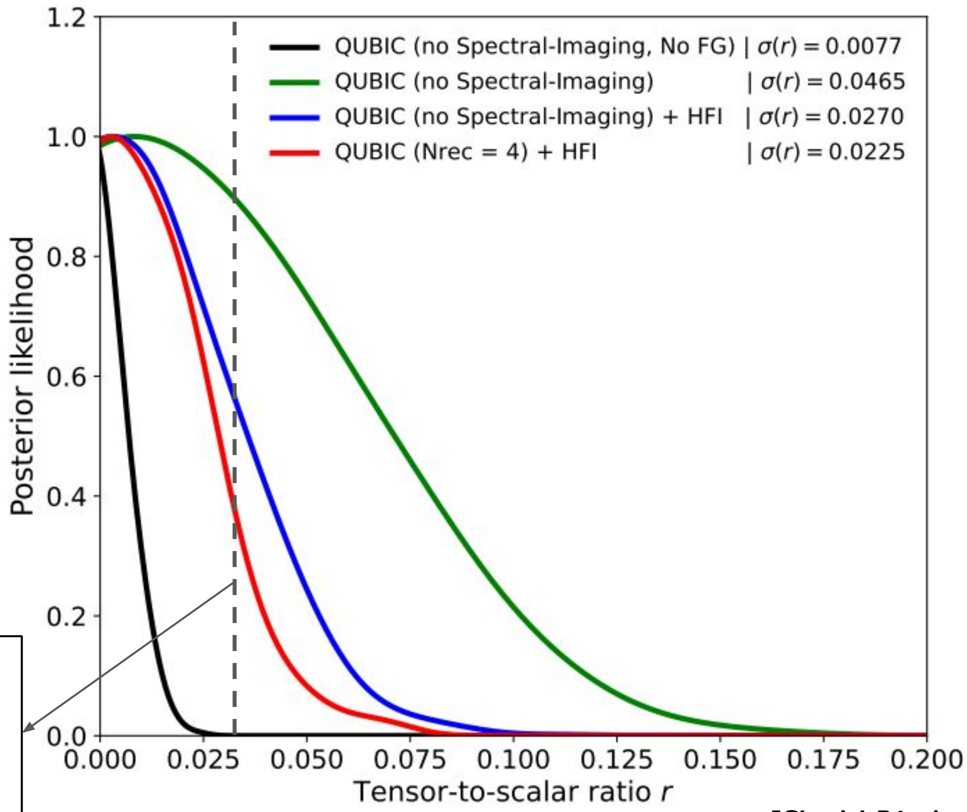
noise

$$\vec{y} = \sum_{\text{bands}} H_b \cdot \vec{s}_b + \vec{n}$$

Solution for $\vec{s}_b$:
Preconditioned Gradient Descent (PCG)

[Chanial, Régnier, et al., A&A submitted, arXiv:2409.18698]

Frequency Map-Making: Forecasts



Current upper limit for r from BK18 + PR4 : r < 0.032 at 95% C.L.

[Tristram et al., arXiv:2112.07961]

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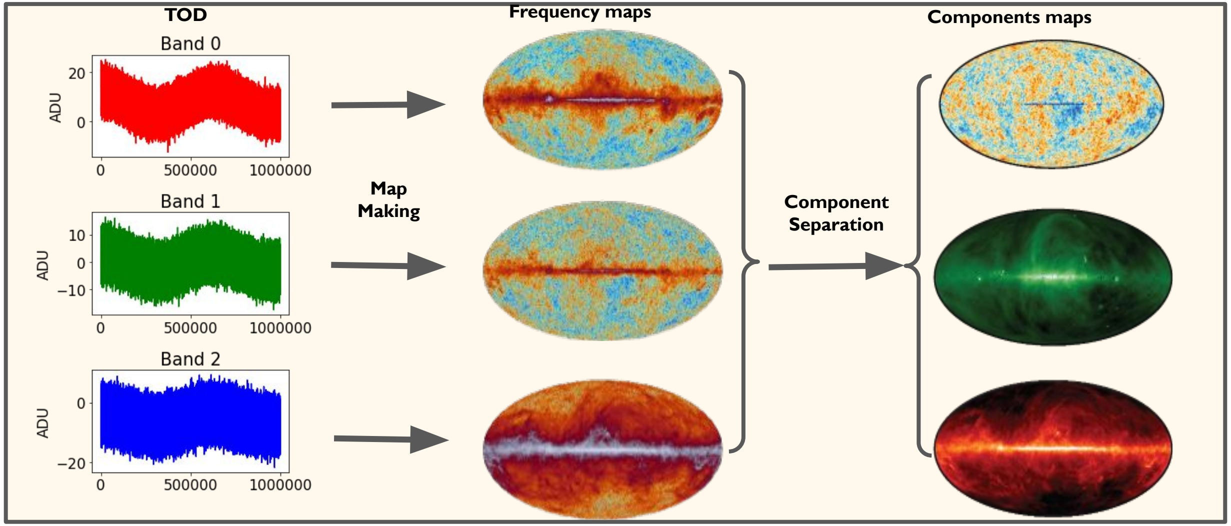
From Frequency to Component Map-Making

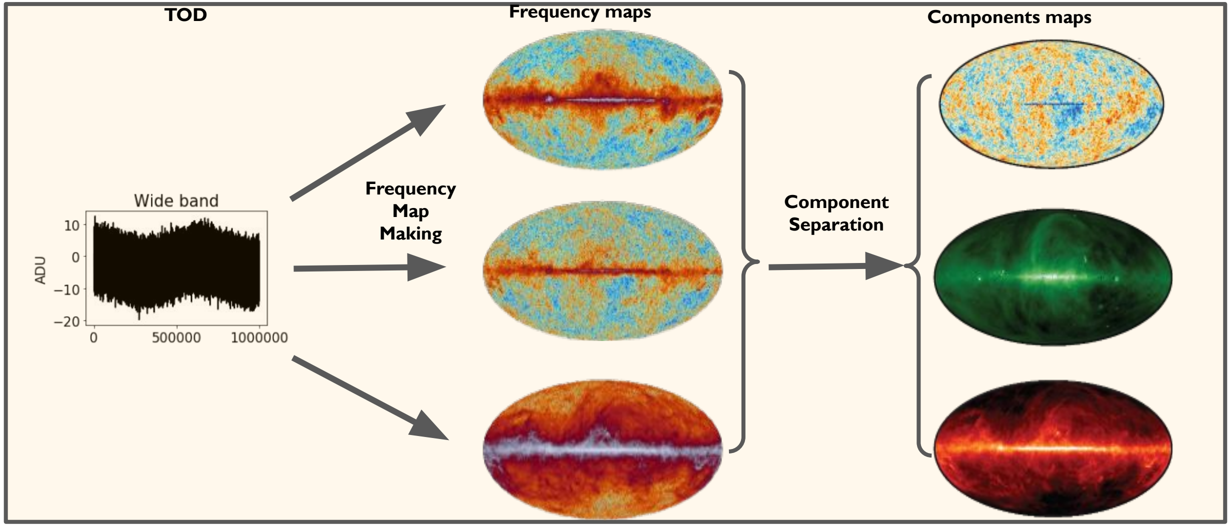
$$\vec{d_i} = H_i \cdot \vec{s_i} + \vec{n_i}$$



Classical Imager Pipeline

From Frequency to Component Map-Making

$$\vec{d} = \sum_{i=1}^{Nsub} \Delta\nu_i H_{\nu_i} \cdot \vec{s_{\nu_i}} + \vec{n}$$



Bolometric Interferometer Pipeline
Frequency Map-Making

Component Map-Making

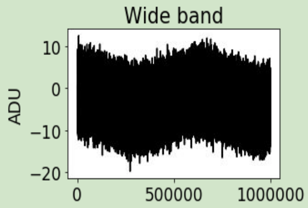
$$\vec{d} = \sum_{i=1}^{Nsub} \Delta\nu_i H_{\nu_i} \cdot \vec{s_{\nu_i}} + \vec{n} \longrightarrow \vec{d} = \sum_{i=1}^{Nsub} \Delta\nu_i H_{\nu_i} \cdot A_{\nu_i}\vec{c} + \vec{n}$$

Sky

Mixing Matrix

Component Maps

TOD

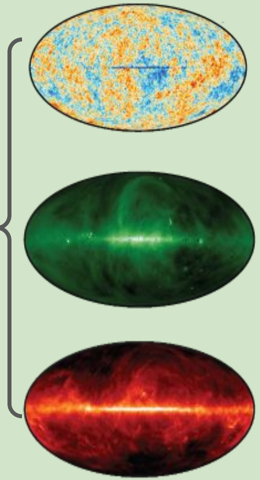


Component Separation Map Making

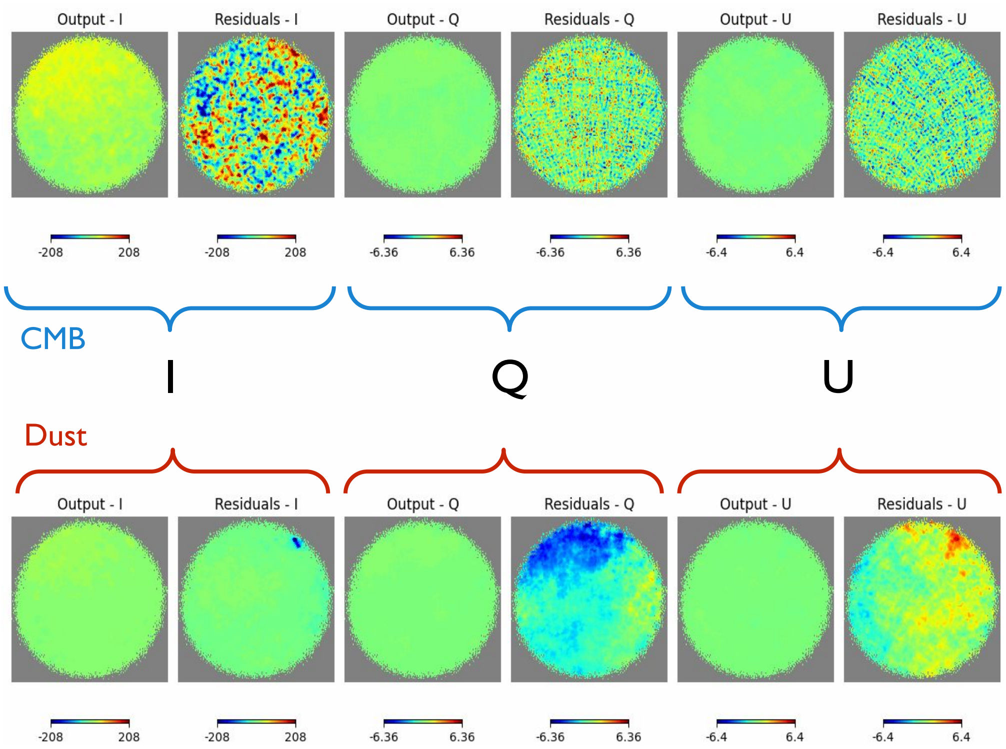
Spectral-imaging based:
Frequency Information in TOD

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

Components maps



Component Map-Making



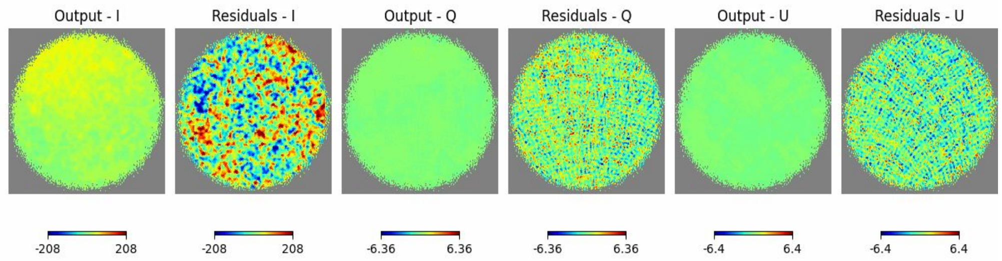
$$\vec{d} = \sum_{i=1}^{Nsub} \Delta\nu_i H_{\nu_i} \cdot A_{\nu_i}\vec{c} + \vec{n}$$

Component Maps

Mixing Matrix

[Régnier, Laclavère, et al., A&A submitted, arXiv:2409.18714]

Component Map-Making



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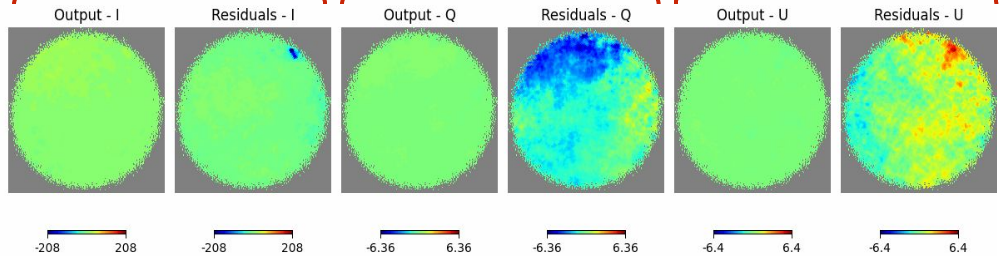
Component Maps

Mixing Matrix

CMB

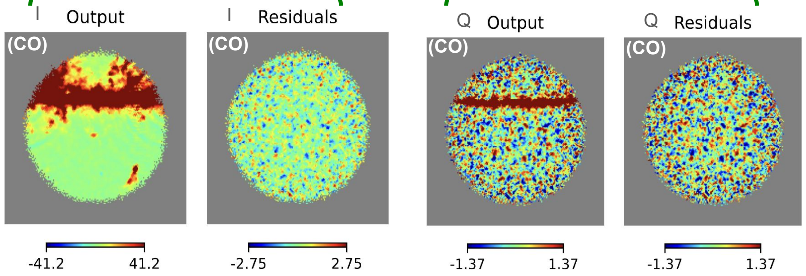
I Q U

Dust



I Q

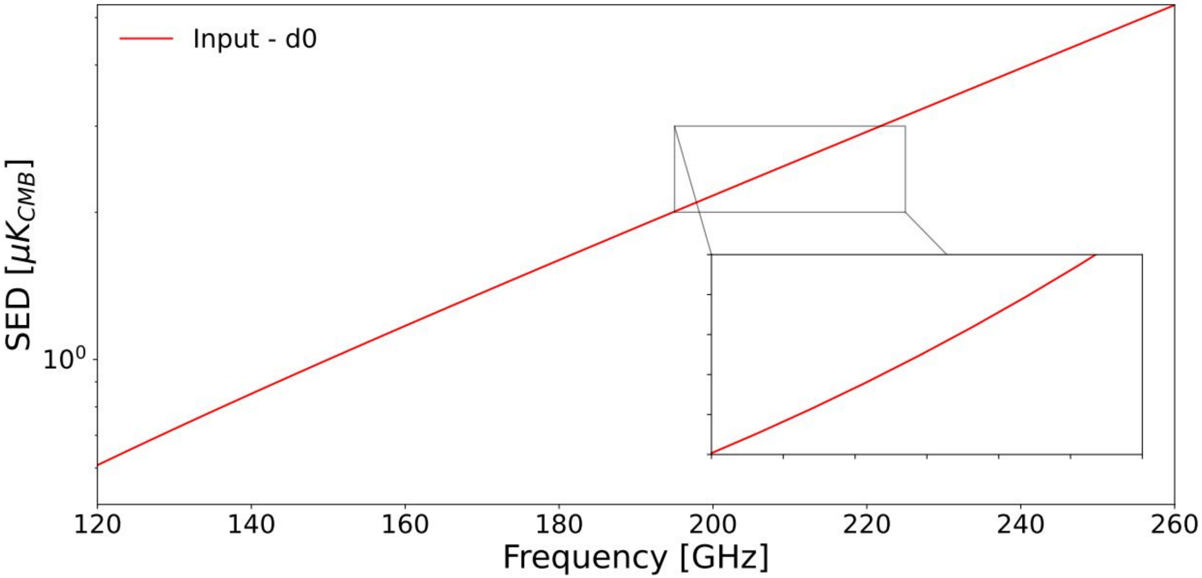
CO Line

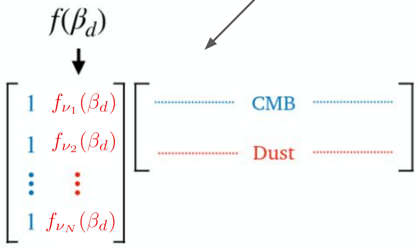


[Régnier, Laclavère, et al., A&A submitted, arXiv:2409.18714]

Component Map-Making: Parametric or Blind

$$\vec{d} = \sum_{i=1}^{Nsub} \Delta\nu_i H_{\nu_i} \cdot \boxed{A_{\nu_i}\vec{c}} + \vec{n}$$





Parametric dust model

[Régnier, Laclavère, et al., A&A submitted, arXiv:2409.18714]

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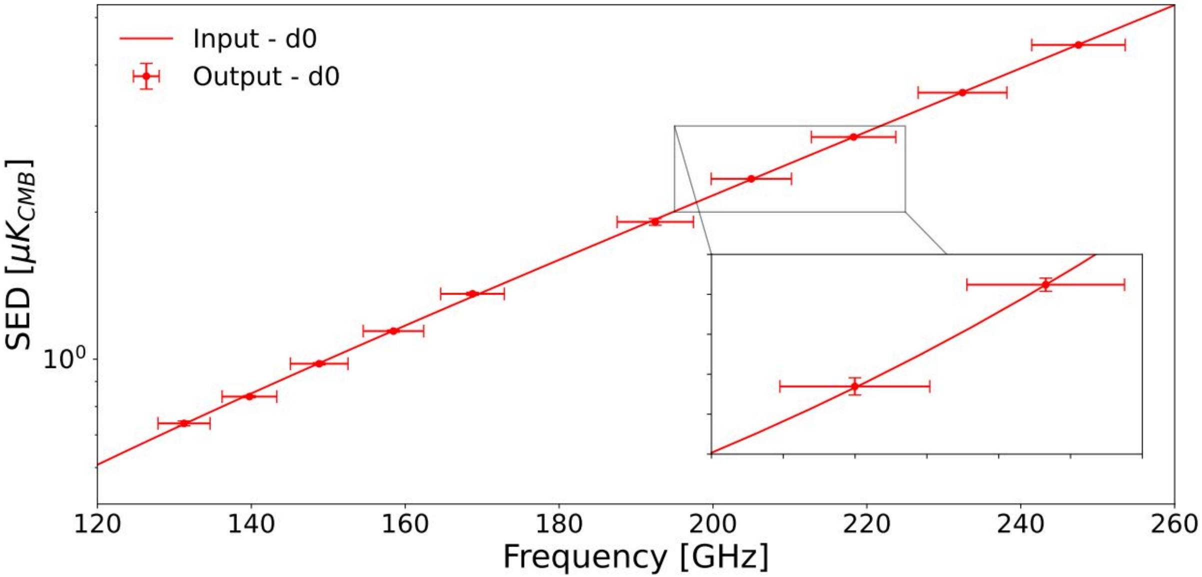

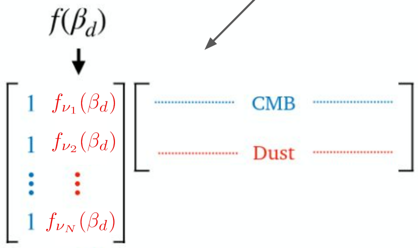

Parametric dust model

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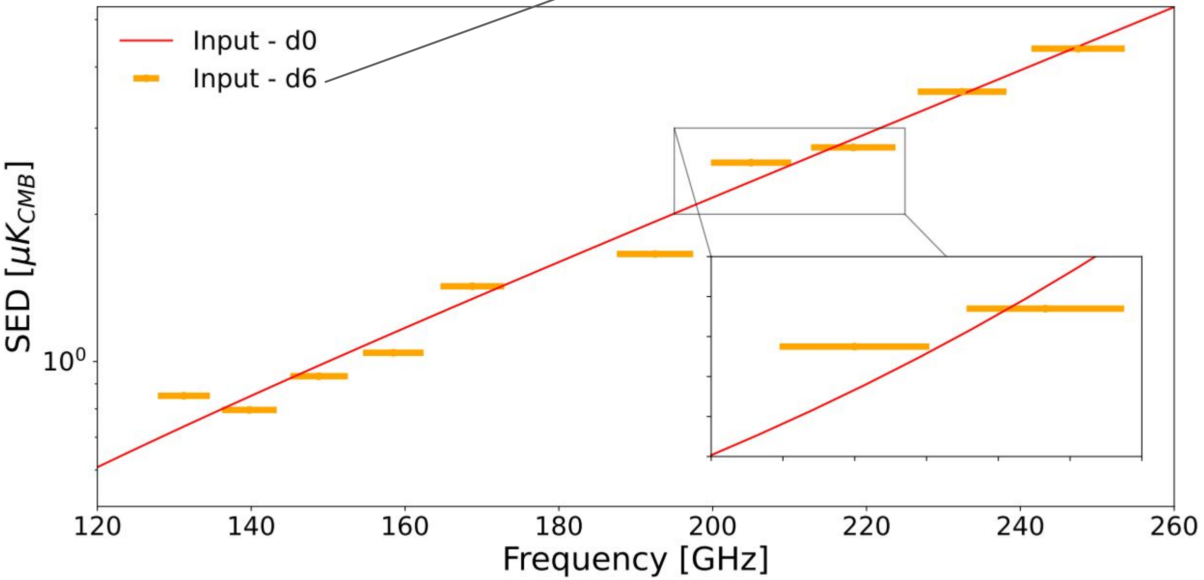
Component Map-Making: Parametric or Blind

Frequency decorrelation



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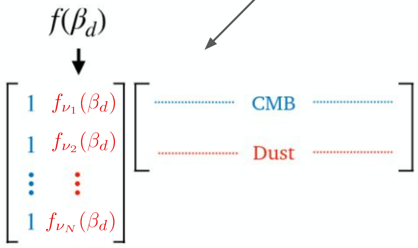

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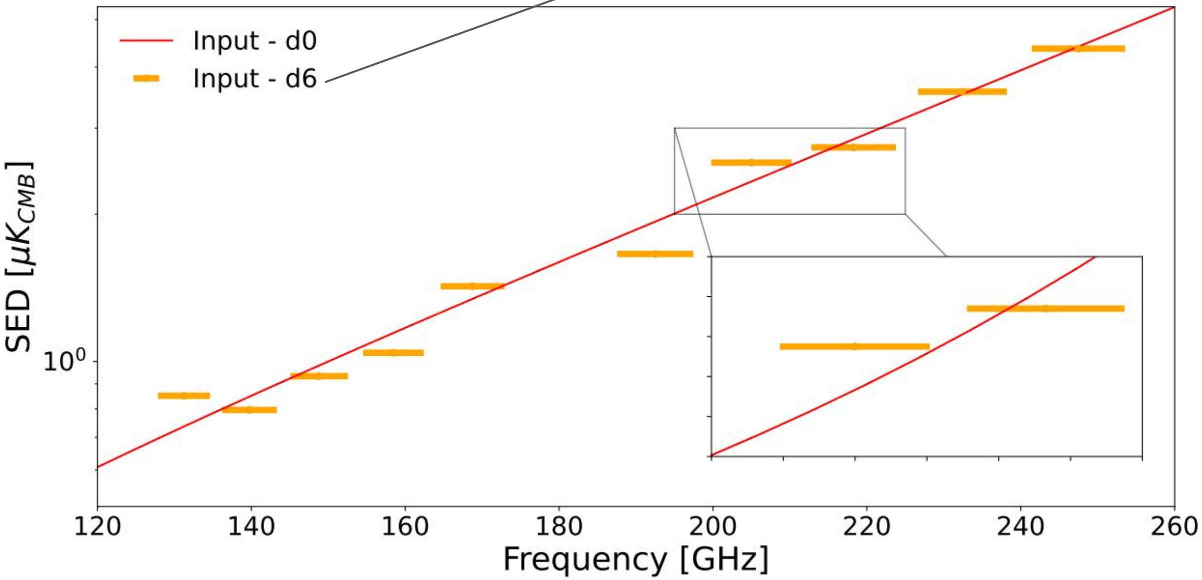
Component Map-Making: Parametric or Blind

Frequency decorrelation



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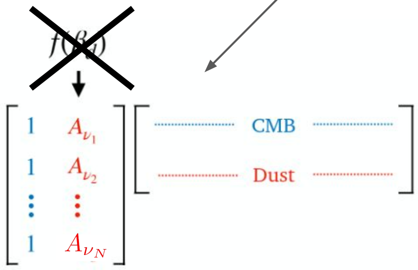

Reconstruct mixing matrix elements

~~Parametric dust model~~

[Régnier, Laclavère, et al., A&A submitted, arXiv:2409.18714]

Component Map-Making: Parametric or Blind

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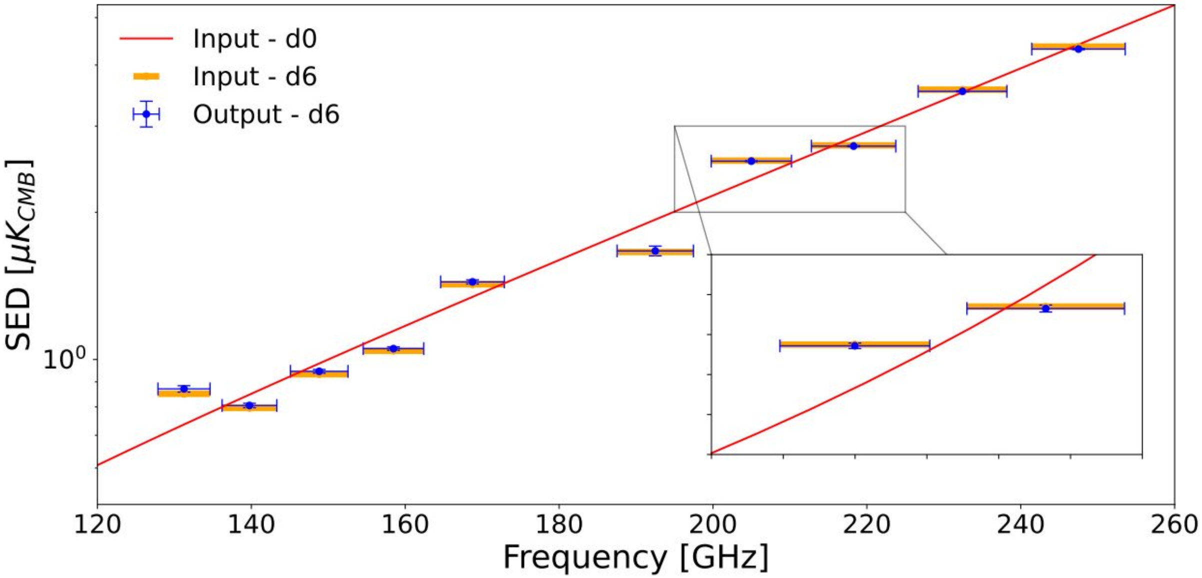
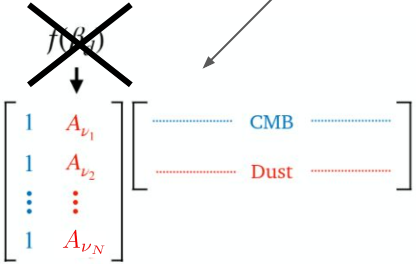




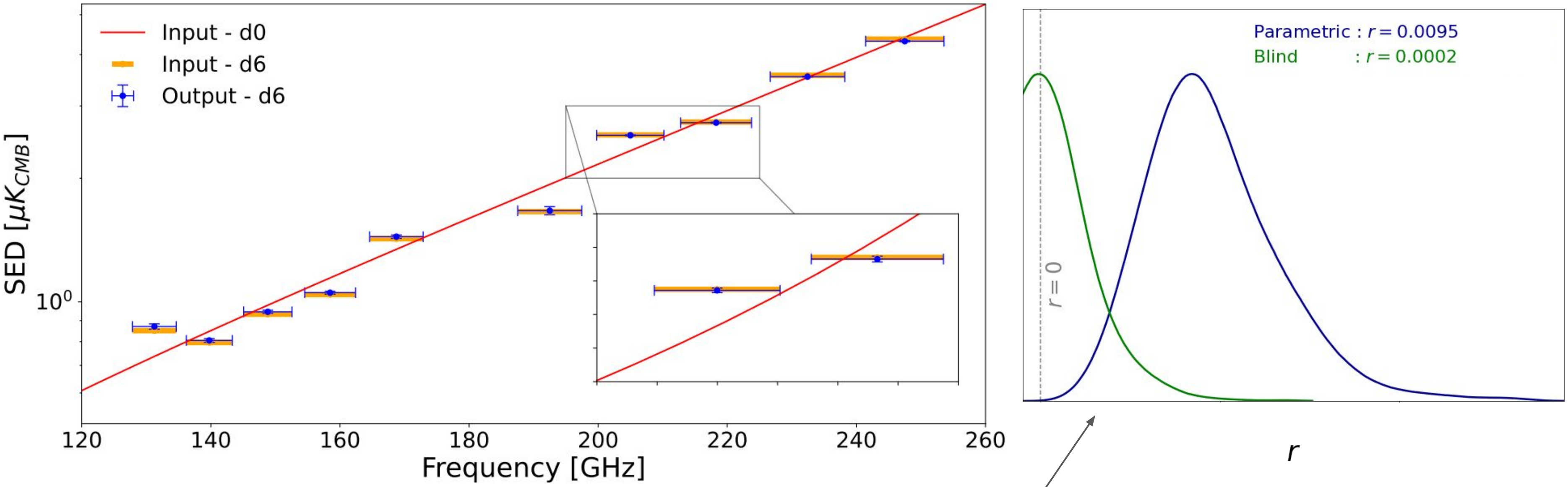
Reconstruct mixing matrix elements

~~Parametric dust model~~

[Régnier, Laclavère, et al., A&A submitted, arXiv:2409.18714]

Component Map-Making: Parametric or Blind

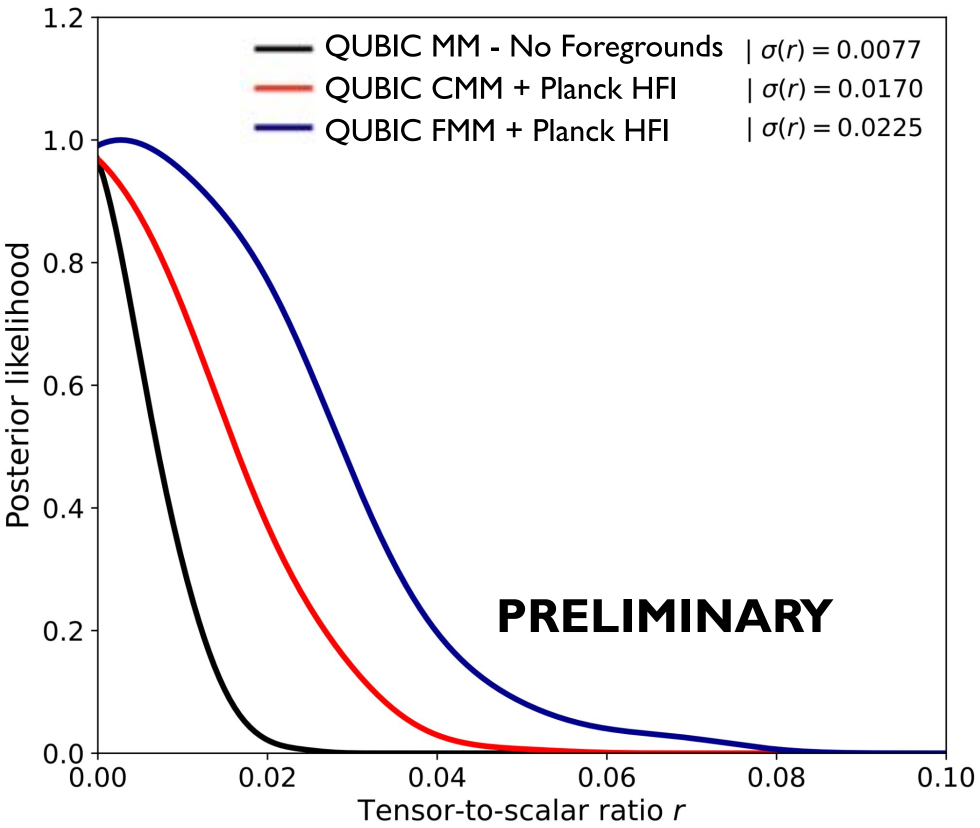
[BI with enhanced sensitivity assumed]



Unbiased result !

[Régnier, Laclavère, et al., A&A submitted, arXiv:2409.18714]

QUBIC Forecasts (end-to-end simulations)



Current upper limit for r from BK18 + PR4 : r < 0.032 at 95% C.L.

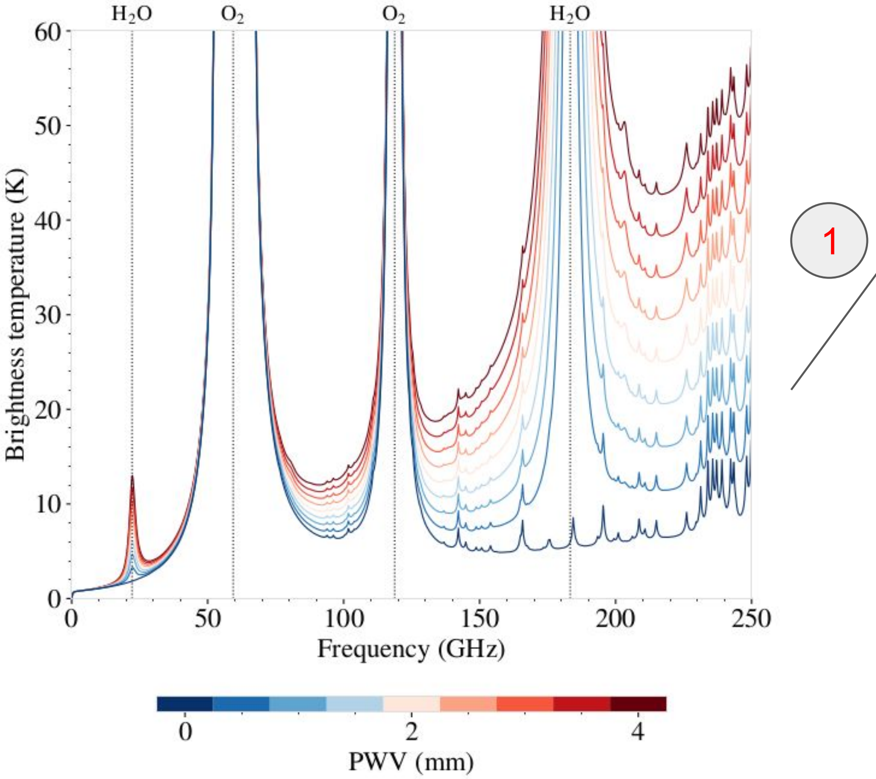
[Tristram et al., arXiv:2112.07961]

[M. Régnier, PhD Thesis]

Atmosphere Map-Making

[T. W. Morris et al., The Atacama Cosmology Telescope: Modeling Bulk Atmospheric Motion, 2021]

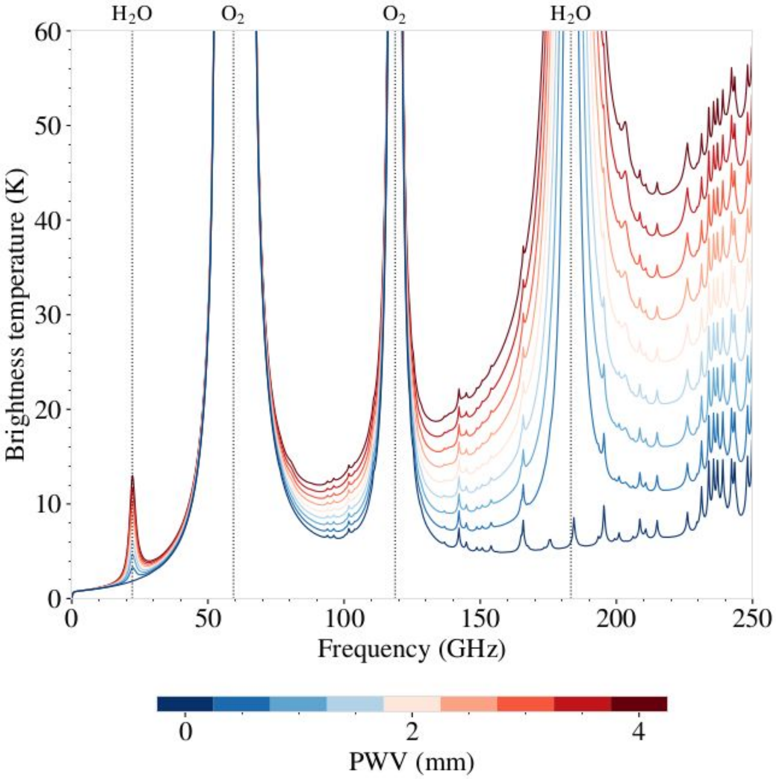
Atmosphere Map-Making



Contribution to the photonic noise
⇒ Limited by observing through 150 GHz and 220 GHz windows
⇒ Instrument placed in a dry location and at high altitude

[T. W. Morris et al., The Atacama Cosmology Telescope: Modeling Bulk Atmospheric Motion, 2021]

Atmosphere Map-Making



1

2

Contribution to the photonic noise

⇒ Limited by observing through 150 GHz and 220 GHz windows

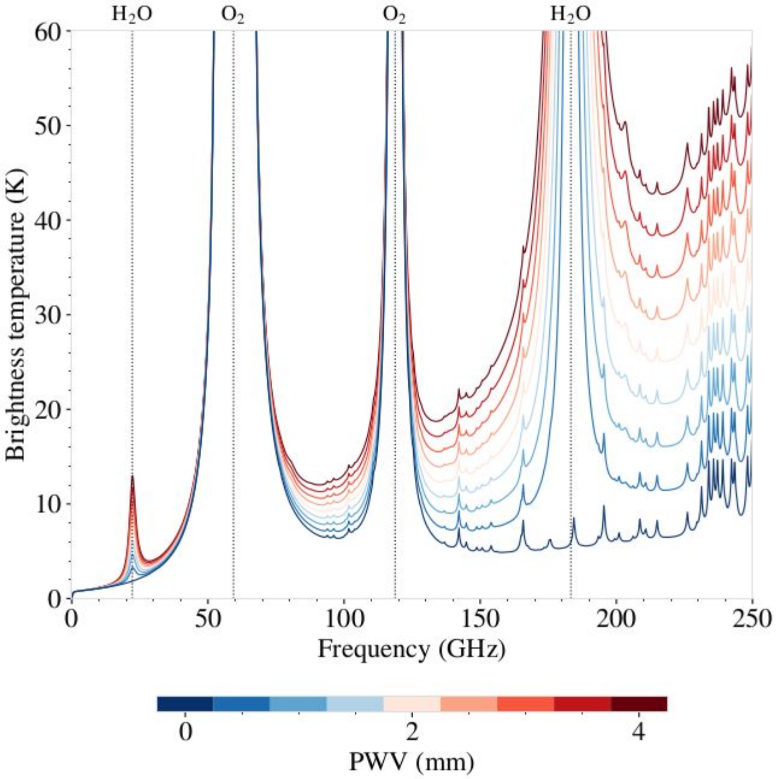
⇒ Instrument placed in a dry location and at high altitude

Inhomogeneous + time-dependent

⇒ Temporal and spatial correlation between detectors

[T. W. Morris et al., The Atacama Cosmology Telescope: Modeling Bulk Atmospheric Motion, 2021]

Atmosphere Map-Making



1

Contribution to the photonic noise
⇒ Limited by observing through 150 GHz and 220 GHz windows
⇒ Instrument placed in a dry location and at high altitude

2

Inhomogeneous + time-dependent
⇒ Temporal and spatial correlation between detectors

3

Specific spectrum depending on water vapor density
⇒ Can be used for component separation

[T. W. Morris et al., The Atacama Cosmology Telescope: Modeling Bulk Atmospheric Motion, 2021]

Atmosphere Map-Making

Water vapor density fluctuations :
↪ modeled by Kolmogorov power spectrum :

-8/6 (2D) -11/6 (3D)

$$P_{adj}(\mathbf{k}) \propto (r_0^{-2} + |\mathbf{k}|^2)^{\alpha}$$

r0 : max size of turbulences

[T. W. Morris et al., The Atacama Cosmology Telescope: Modeling Bulk Atmospheric Motion, 2021]

Atmosphere Map-Making

Water vapor density fluctuations :
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-8/6 (2D)   -11/6 (3D)

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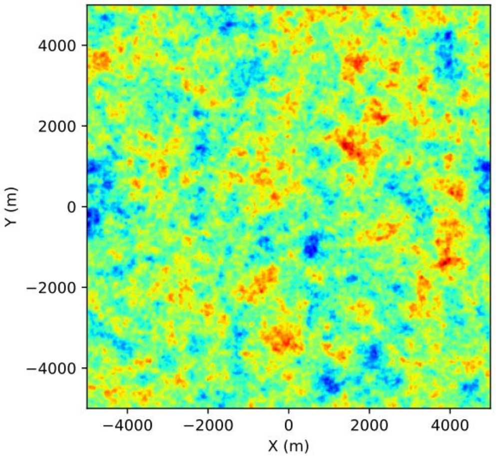
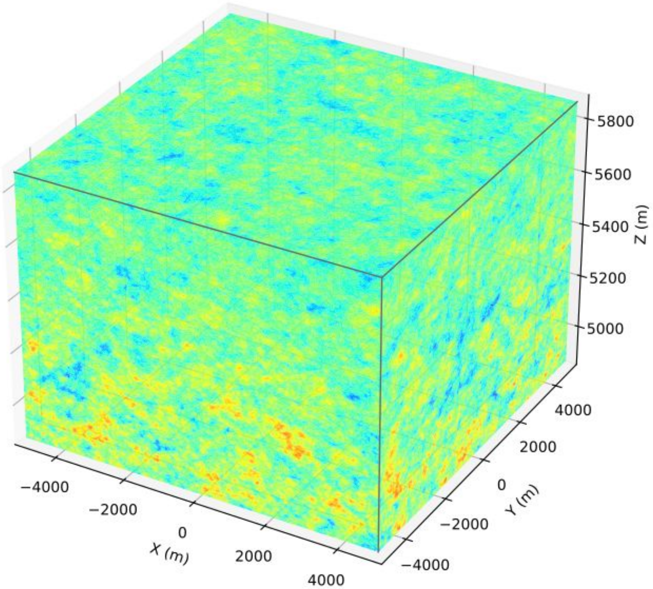
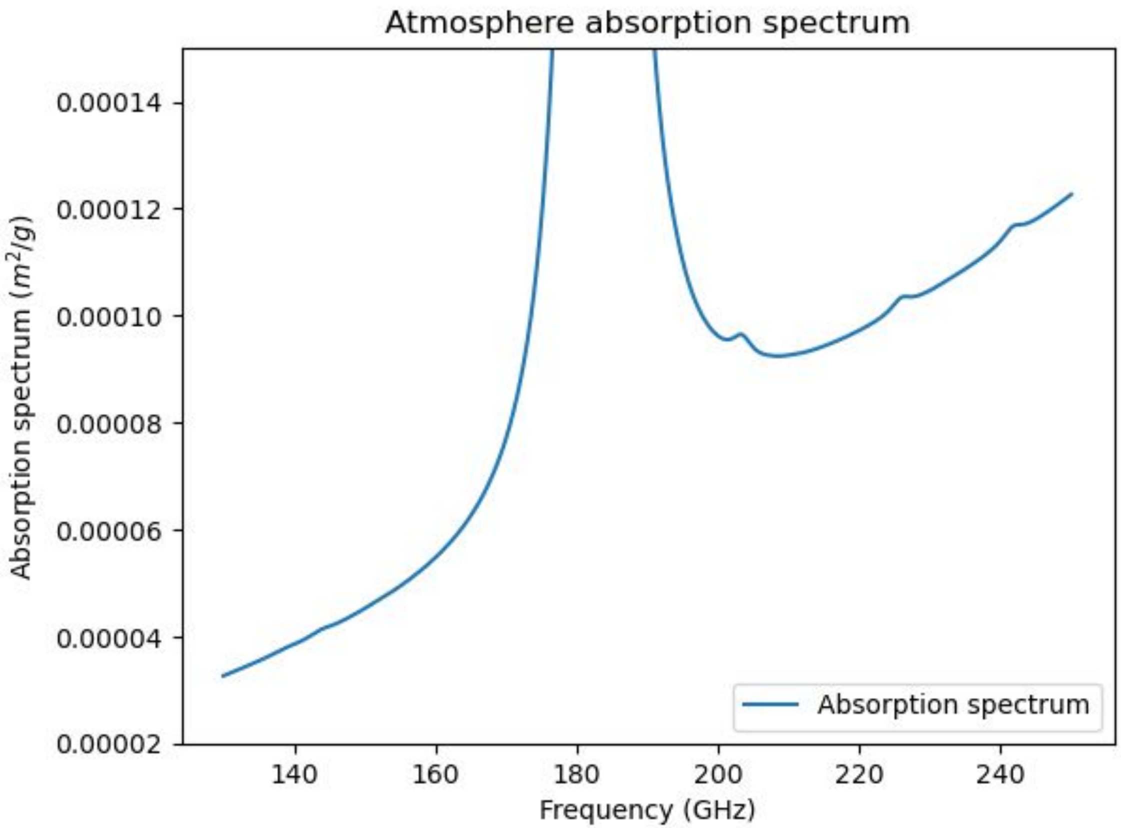




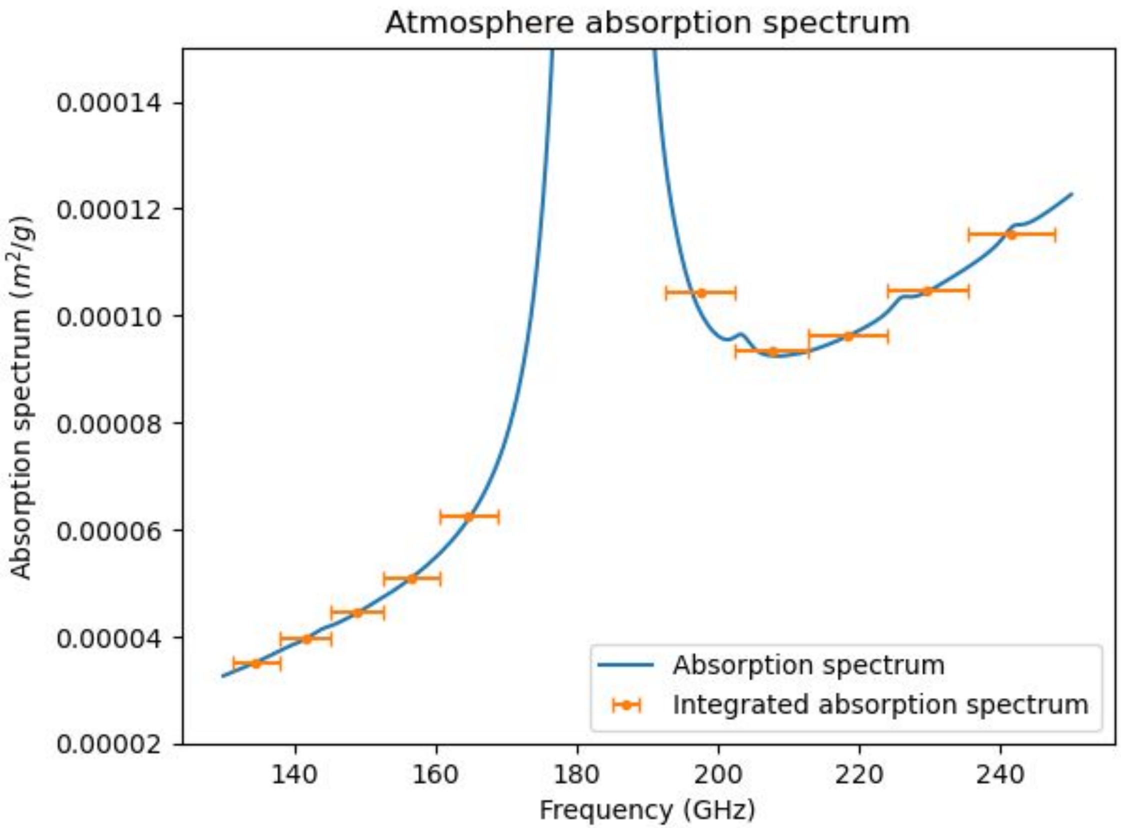
[T. W. Morris et al., The Atacama Cosmology Telescope: Modeling Bulk Atmospheric Motion, 2021]

Atmosphere Map-Making



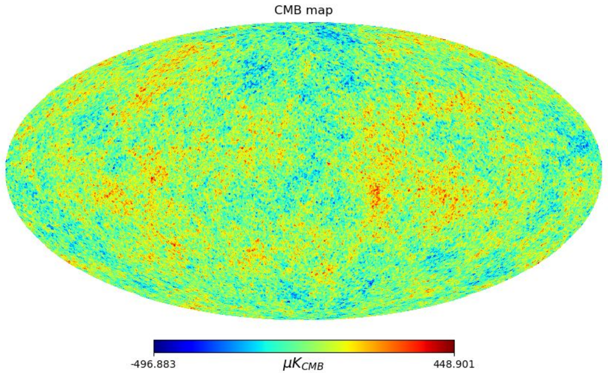
[The am Atmospheric Model, S. Paine, https://lweb.cfa.harvard.edu/~spaine/am/]

Atmosphere Map-Making

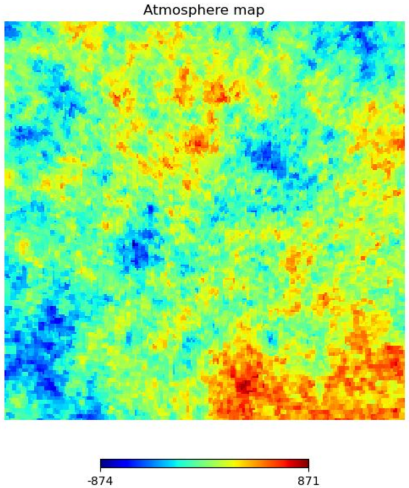


[The am Atmospheric Model, S. Paine, https://lweb.cfa.harvard.edu/~spaine/am/]

Atmosphere Map-Making



Galactic coordinates

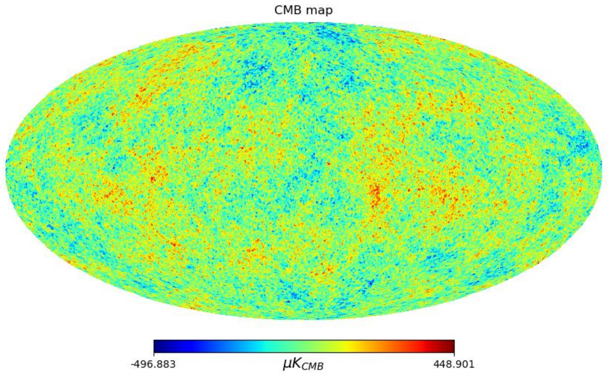


Local coordinates

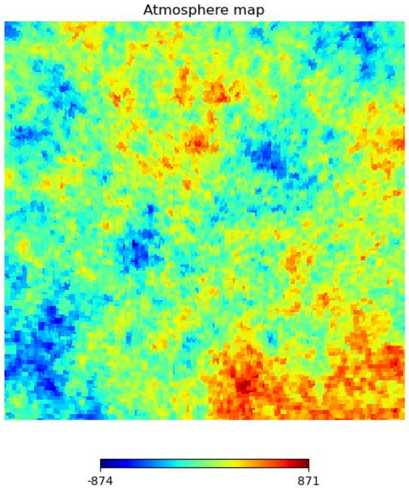
Atmosphere Map-Making

Simplifying hypothesis:

- Atmosphere = 2d plane
- Stable Atmosphere Spectrum
- No wind

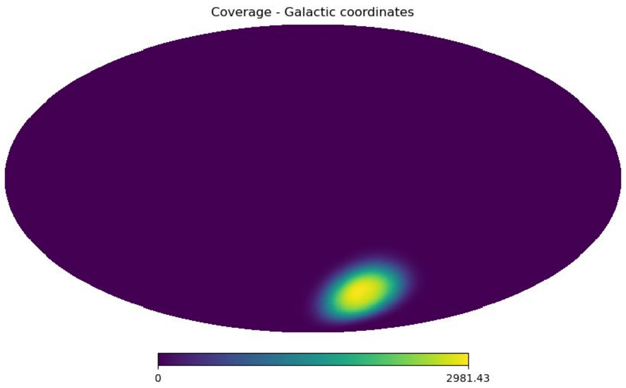


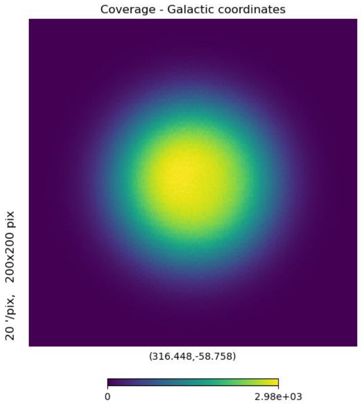
Galactic coordinates



Local coordinates

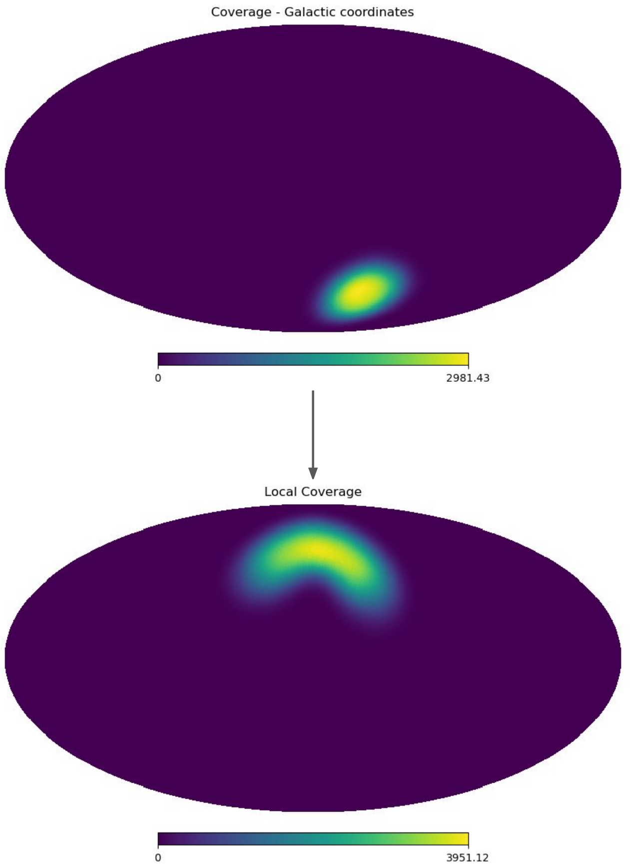
Atmosphere Map-Making

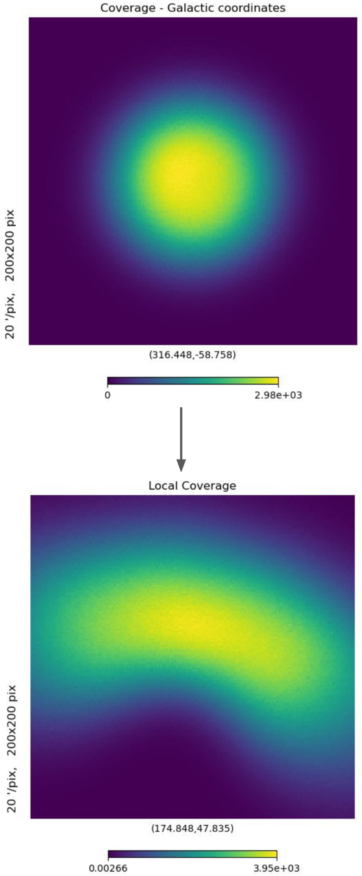




Uniform pointing in 15° radius circle centered on the QUBIC patch position

Atmosphere Map-Making

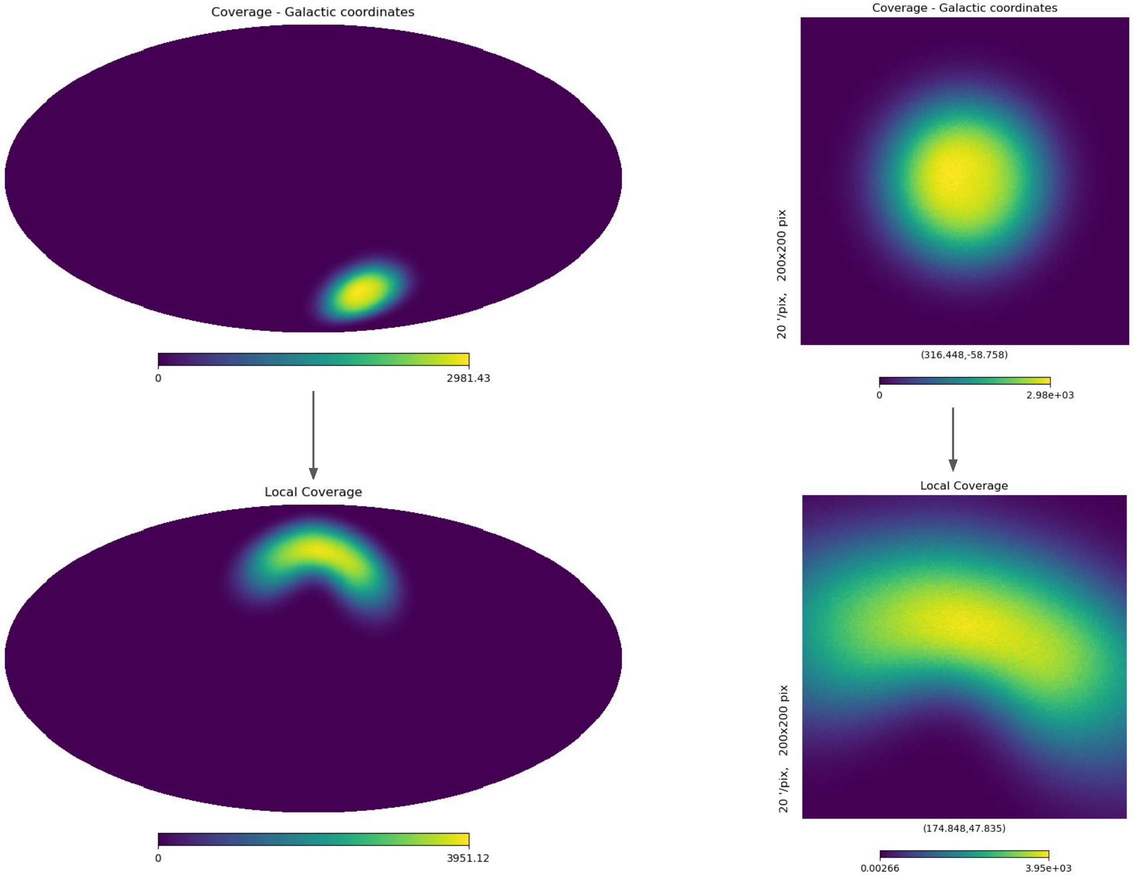




Uniform pointing in 15° radius circle centered on the QUBIC patch position

No longer a circle in local coordinates, as the patch moves in the sky

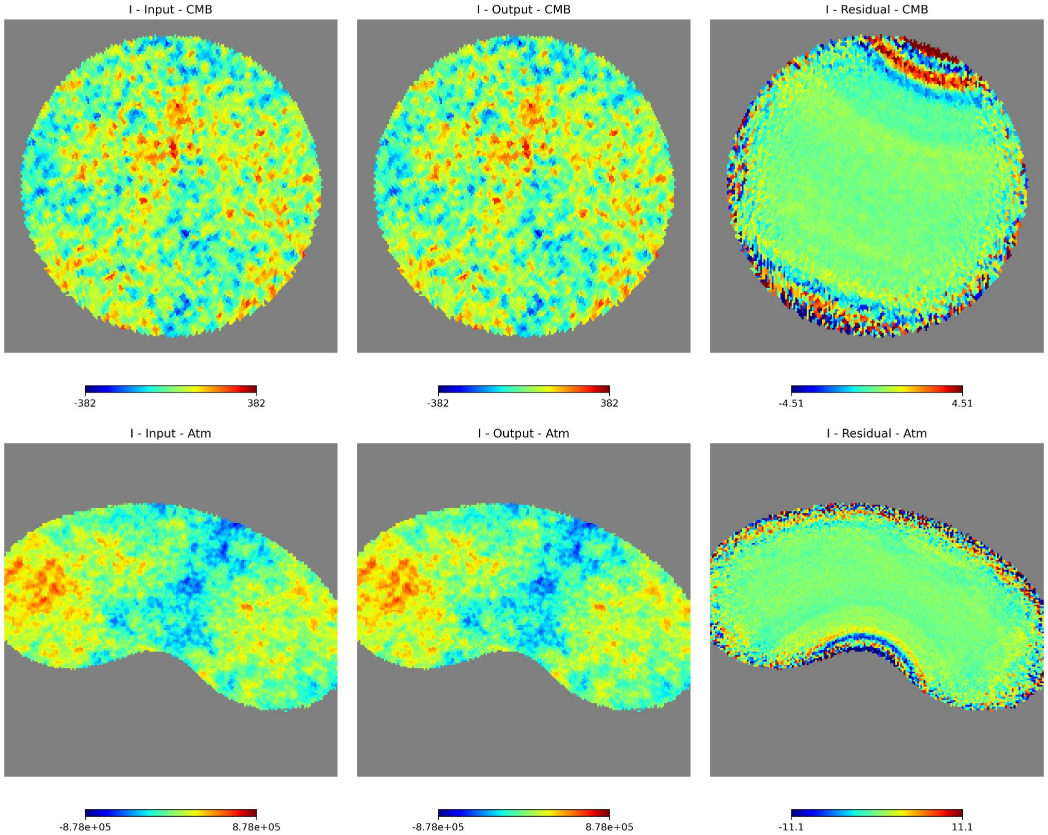
Atmosphere Map-Making



$$
\begin{aligned}
\vec{TOD} &= H_{gal}\vec{s}_{cmb} + H_{local}\vec{s}_{atm} \\
&= \vec{TOD}_{cmb} + \vec{TOD}_{atm}
\end{aligned}
$$

Atmosphere Map-Making

Intensity

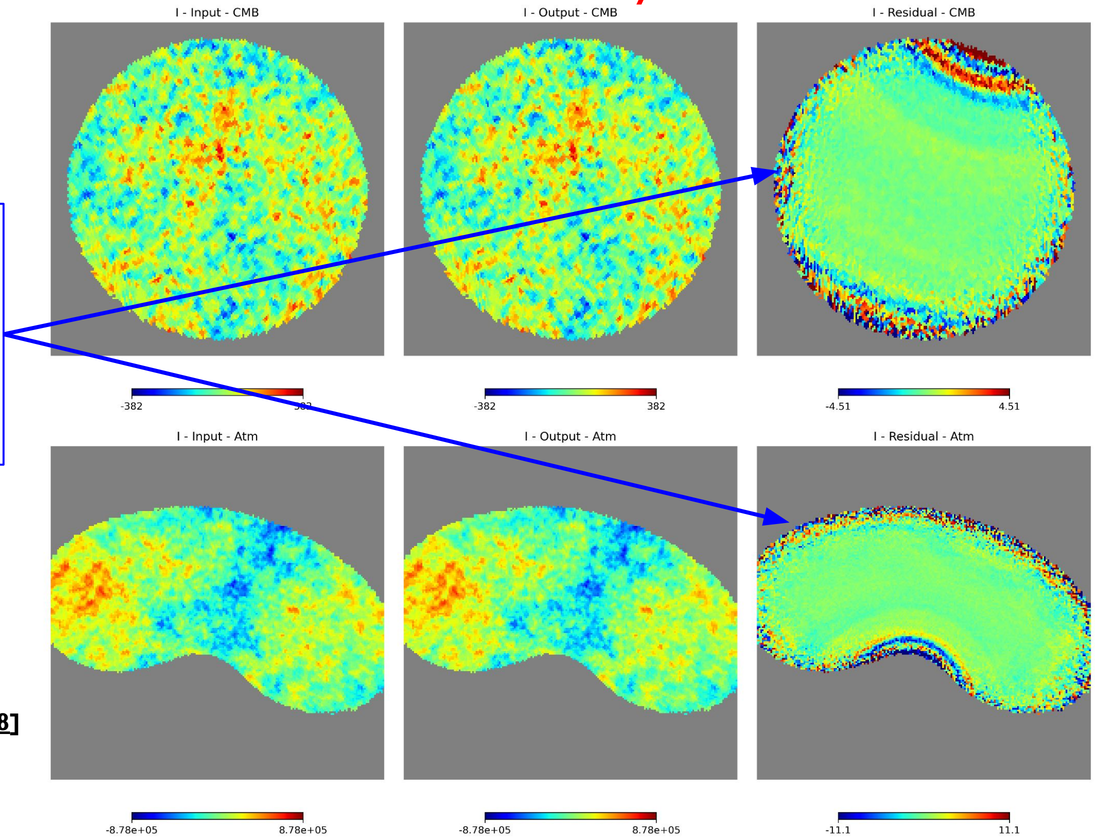


Atmosphere Map-Making

Intensity

Edge effect :
secondary peaks falling outside the patch

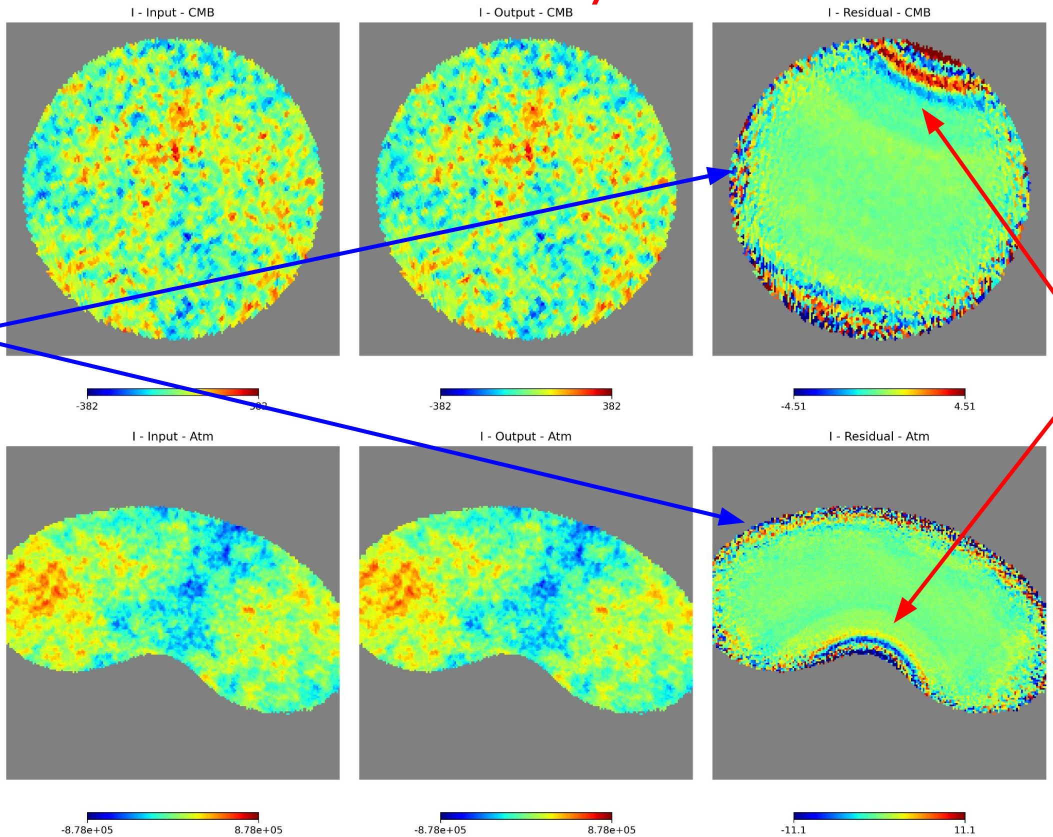
⇒ Adding external data (Planck)



[Chanial, Régnier, et al., A&A submitted, arXiv:2409.18698]

Atmosphere Map-Making

Intensity



Edge effect : secondary peaks falling outside the patch

⇒ Adding external data (Planck)

[Chanial, Régnier, et al., A&A submitted, arXiv:2409.18698]

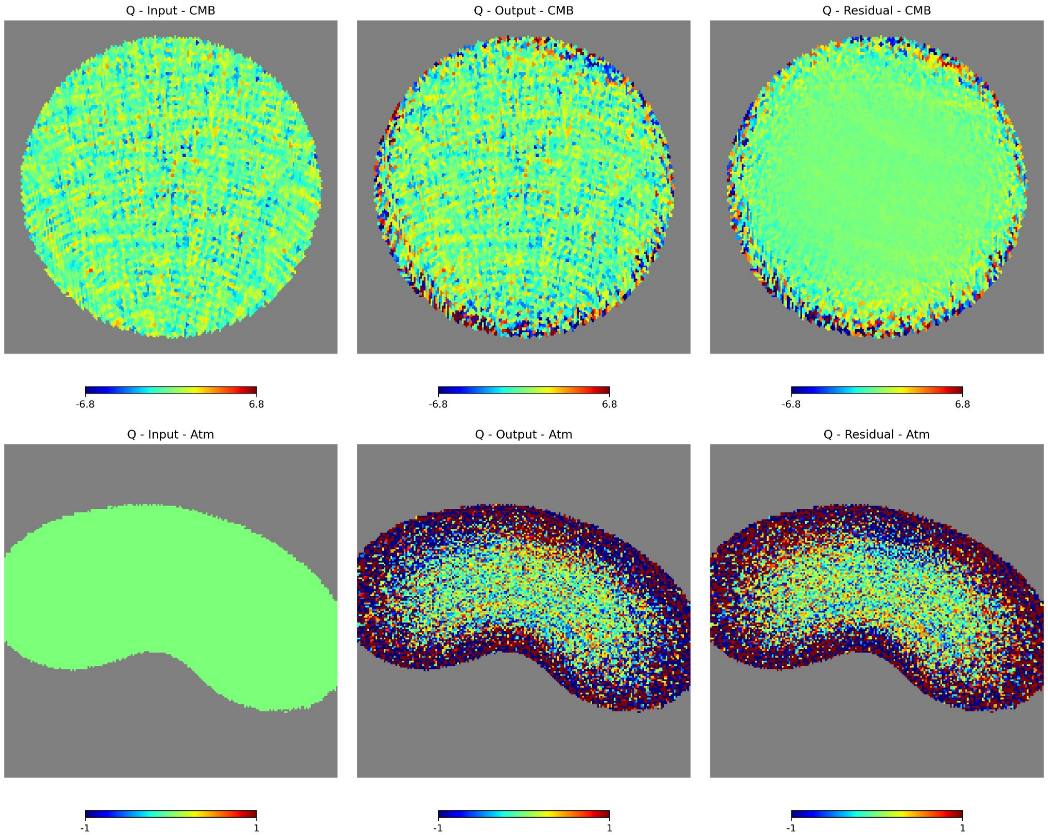
Stripes : Movement of the atmosphere

⇒ Improve convergence

Tom Laclavère for the QUBIC Collaboration
APC - Paris - France
laclavere@apc.in2p3.fr

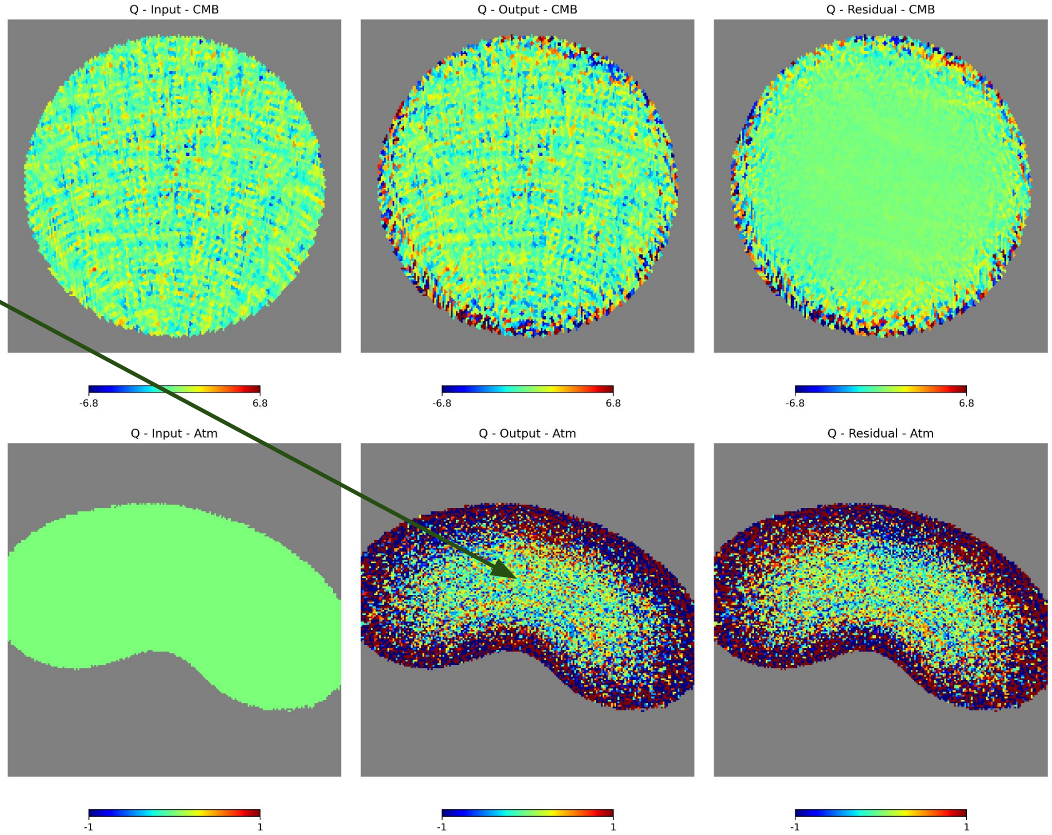
Atmosphere Map-Making

Polarisation



Atmosphere Map-Making

Polarisation



Lack of convergence ?

Atmosphere Map-Making

Next steps :

1. Fix edge effect : add external data outside patch
2. Improve convergence : compute proper preconditioner
3. Add constraints : CMB Intensity, Atm Polarisation
4. External Atm information : weather station, camera
5. Add wind
6. 3d atmosphere

Spectral Imaging with QUBIC :

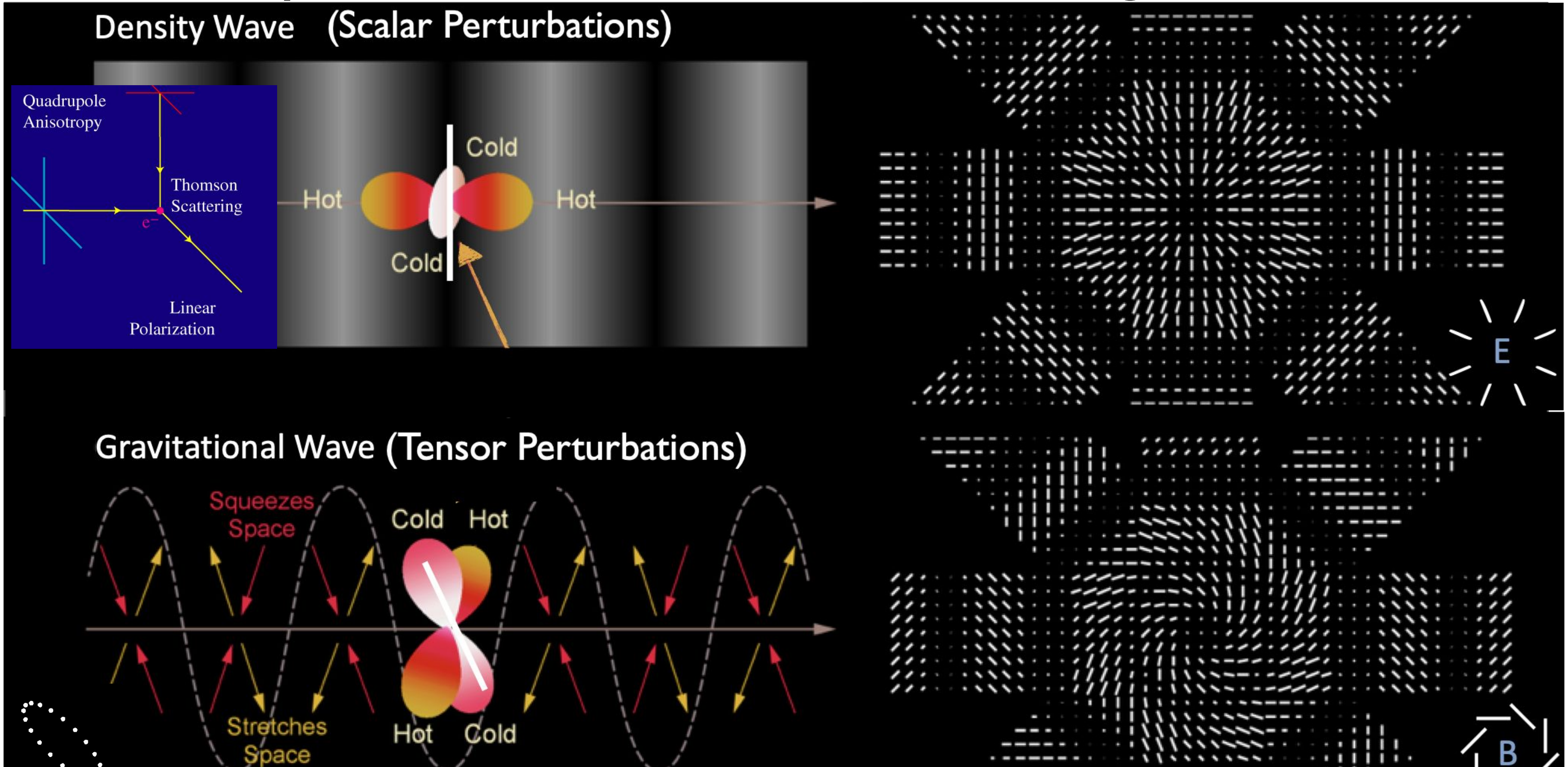
Component separation using Bolometric Interferometry

Tom Laclavère on behalf of the QUBIC Collaboration

Back-up Slides

Cosmology

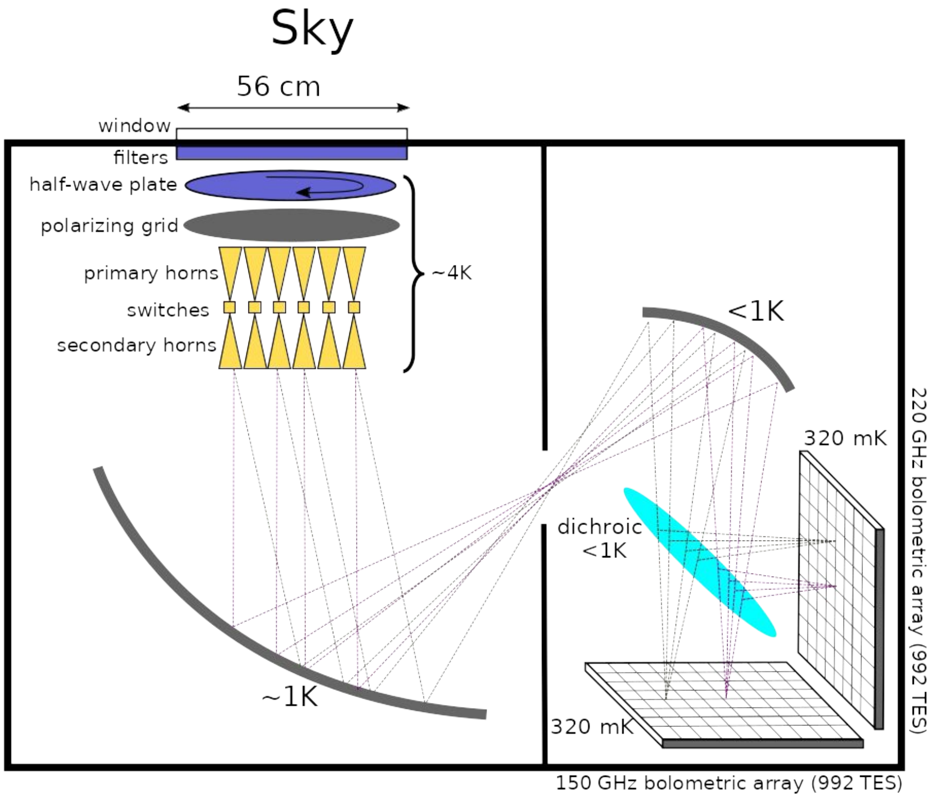
Anisotropic fluxes on the Last Scattering Surface



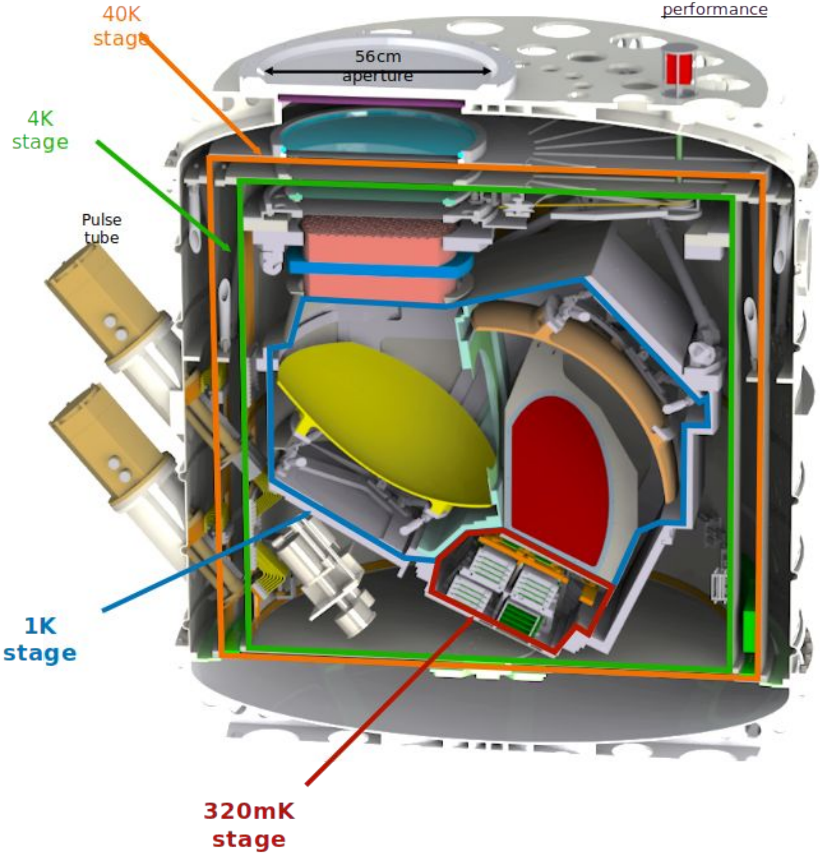
Credit: BICEP Collaboration

QUBIC

QUBIC design



QUBIC V : Cryogenic system design and performance



Instrumental model

$$H(\beta) = \underbrace{\mathcal{R}_{\mathrm{det}}\mathcal{T}_{\mathrm{inst}}\mathcal{I}_{\mathrm{det}}\mathcal{P}_{\mathrm{ol}}[\mathcal{H}_{\mathrm{WP}} * \mathcal{P}_{\mathrm{roj}}]}_{\text{Time domain}}\underbrace{\mathcal{F}_{\mathrm{ilt}}\mathcal{A}_{\mathrm{p}}\mathcal{T}_{\mathrm{atm}}\mathcal{U}_{\mathrm{nit}}\mathcal{D}_{\mathrm{ist}}\mathcal{A}_{\mathrm{comp}}}_{\text{Pixels domain}}$$

Time domain

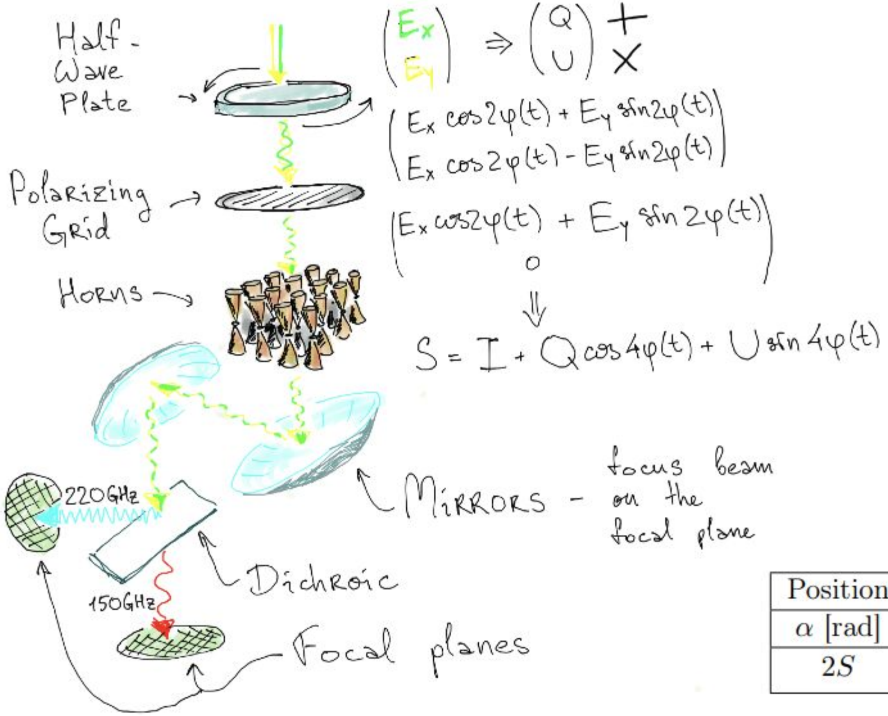
- *Instrumental systematics determination*

Pixels domain

Various foregrounds model :

- *Parametric methods*
  - *constant spectral index*
  - *Varying spectral indices*
- *Blind methods*

Polarisation



[Drawing: M. Stolpovskiy]
[Louise Mousset, https: //hal-cea.archives-ouvertes.fr/tel-03783687/]

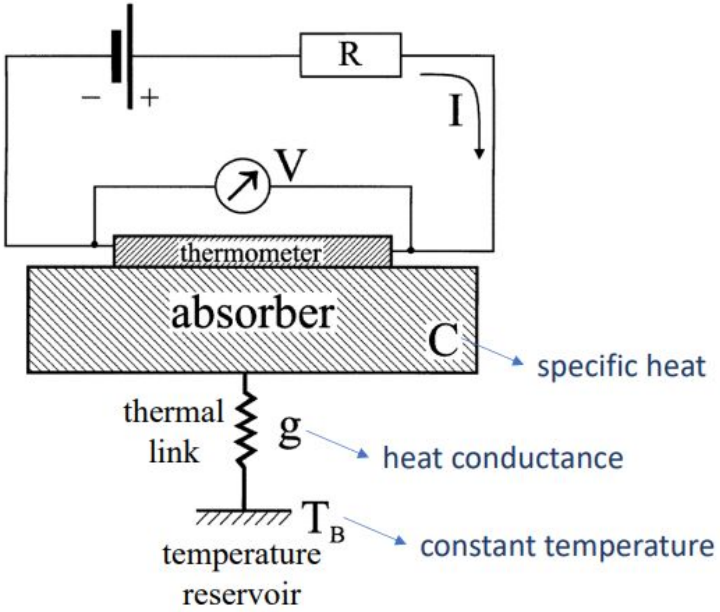
Stokes parameter

$$
\begin{cases}
I = |E_x|^2 + |E_y|^2. \\
Q = |E_x|^2 - |E_y|^2. \\
U = 2\,\mathrm{Re}(E_x E_y^*).
\end{cases}
$$

Position	0	1	2	3	4	5	6	7
α [rad]	0	$\frac{\pi}{16}$	$\frac{\pi}{8}$	$\frac{3\pi}{16}$	$\frac{\pi}{4}$	$\frac{5\pi}{16}$	$\frac{3\pi}{8}$	$\frac{7\pi}{16}$
$2S$	$I+Q$	$I+\frac{Q+U}{\sqrt{2}}$	$I+U$	$I-\frac{Q-U}{\sqrt{2}}$	$I-Q$	$I-\frac{Q+U}{\sqrt{2}}$	$I-U$	$I+\frac{Q-U}{\sqrt{2}}$

Table 1.1: Intensity measured as function of I, Q, U for the eight HWP steps of QUBIC.

TES



Absorbed photon ⇒
Absorber temperature increases ⇒
Thermometer resistance increases ⇒
Voltage decreases

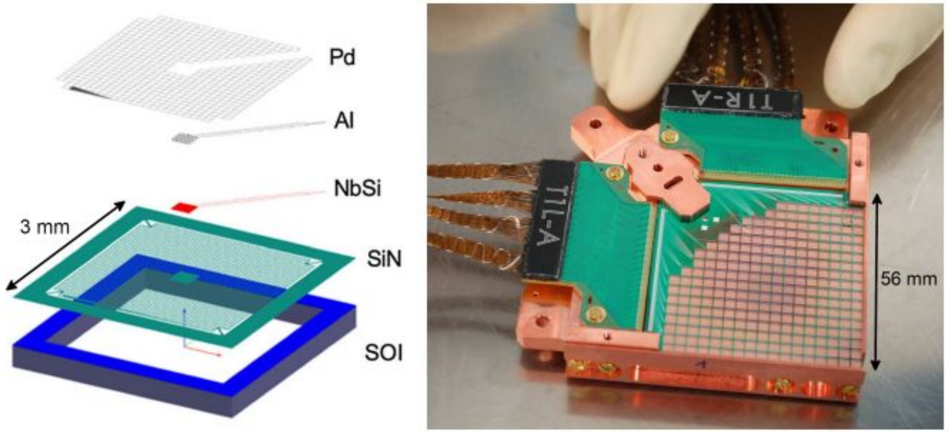
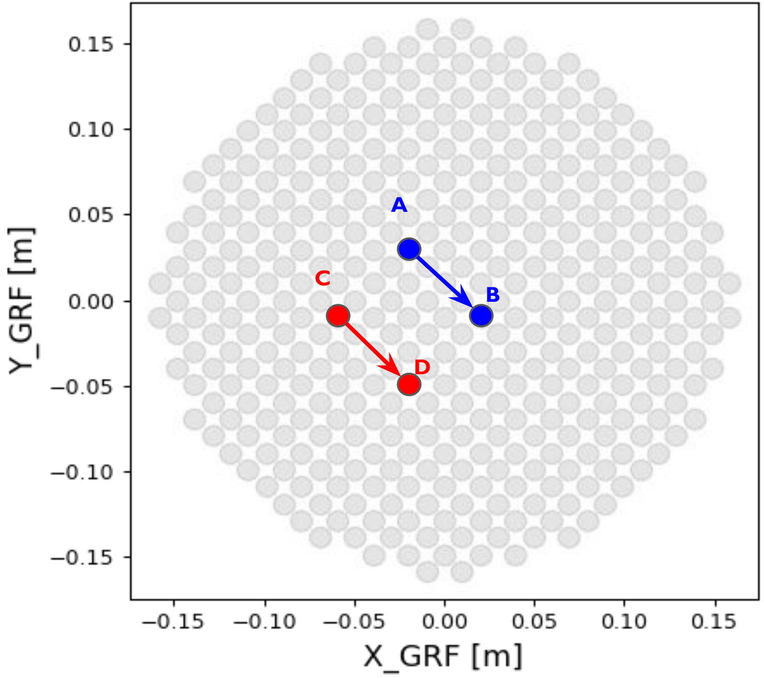


Figure 3. *Left*: Layout of the 3-mm pitch pixel structure. Pd grid for light absorption, NbSi for temperature sensing, SiN structure for decoupling the sensor from the cold bath and Al for routing the signal to the SQUID amplifiers *Right*: A 256 TES array being integrated.

[Diagram bolometer : NPAC detector physics courses, A. Tonazzo]
[M. Piat et al., arXiv:2101.06787]

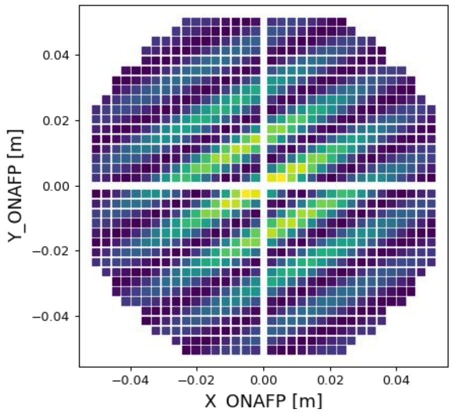
Self-Calibration

Interferometer aperture array

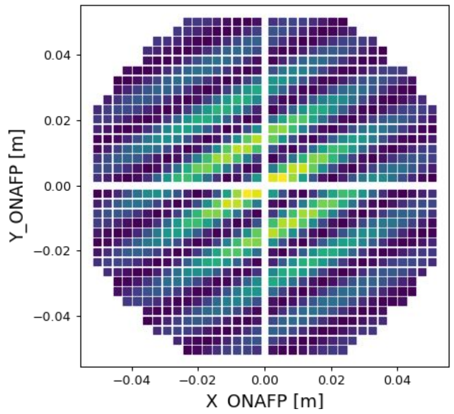


Fringe differences for **baselines** on focal plane can only come from **instrumental systematics** (cross-polarization, differential beams, intercalibration, …)

Fringe from (A,B)



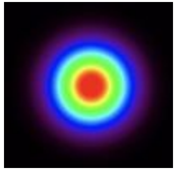
Fringe from (C,D)



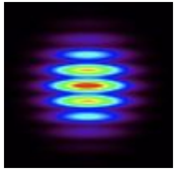
[Louise Mousset, https: //hal-cea.archives-ouvertes.fr/tel-03783687/]

Focal Plane signal (Simulation)

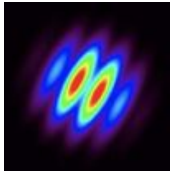
The QUBIC Synthesized beam from baselines



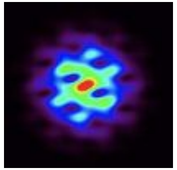
1 Horn open



2 Horns open



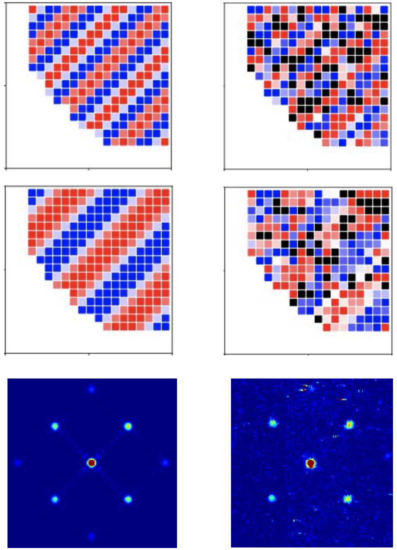
2 Horns open

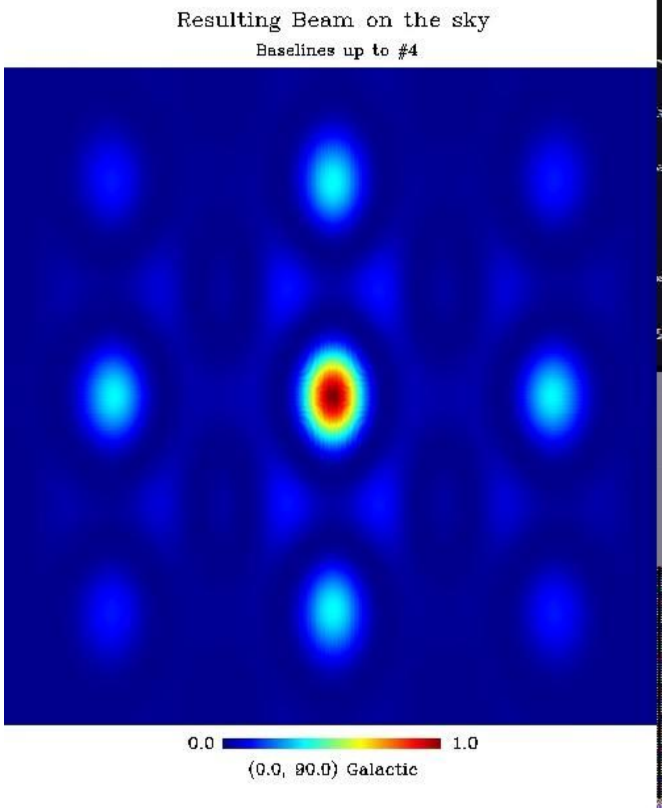


All Horns open

[L. Mousset, PhD, 2021]

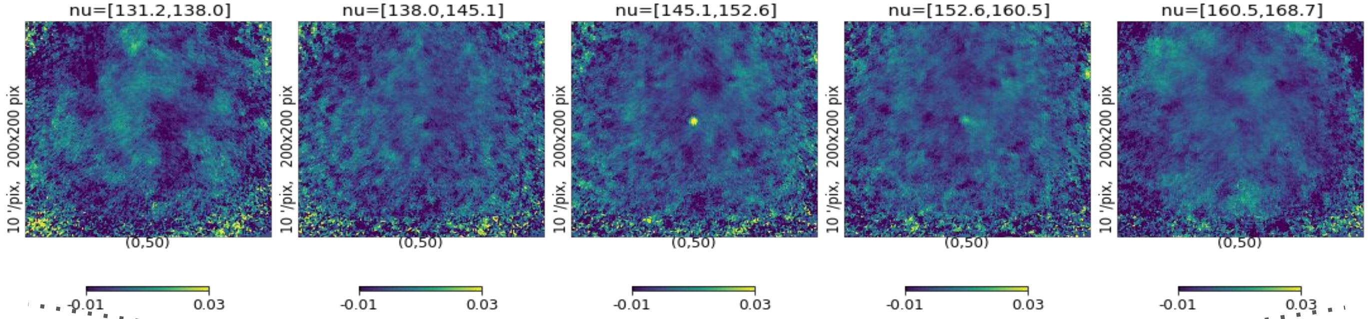
QUBIC Sim. **QUBIC Cal Data**

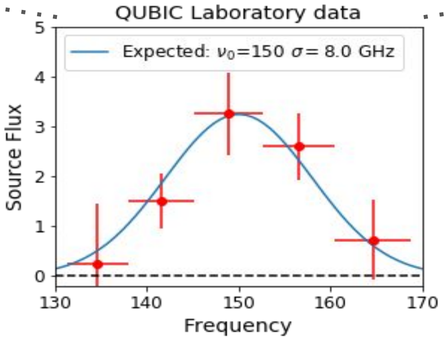




Bolometric Interferometry: Spectral Imaging

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

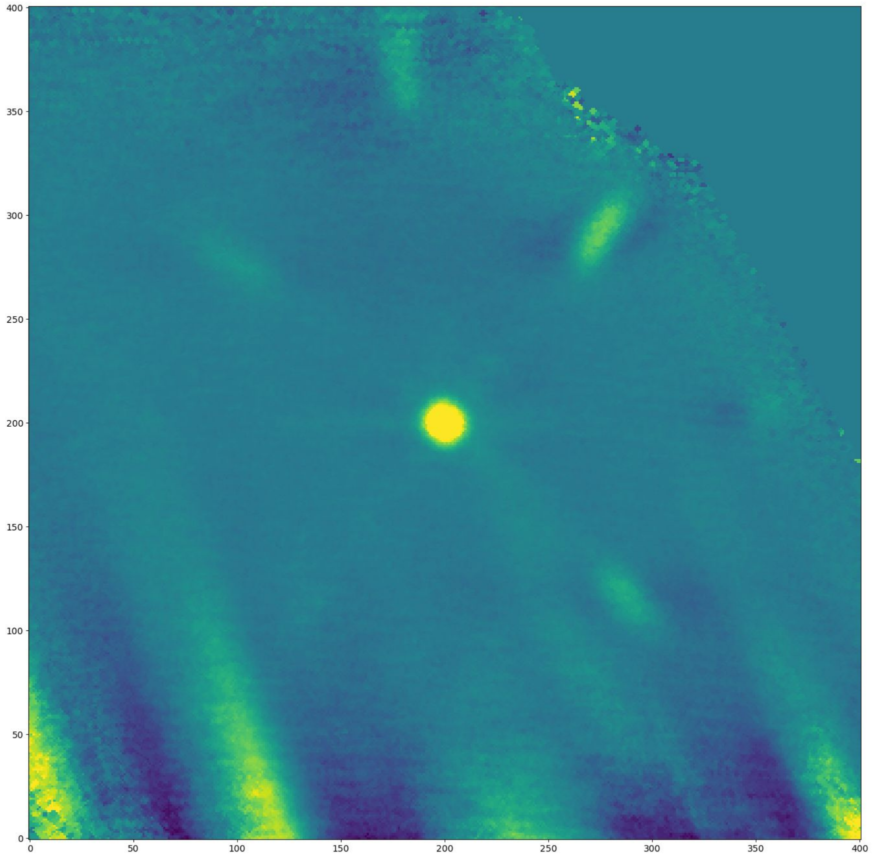




With Real Data (26 detectors) [indoor calibration source]

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

Moon observation



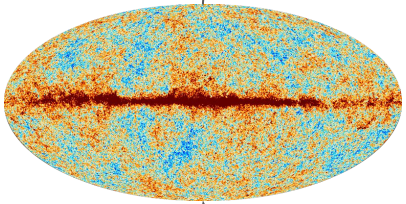
Frequency Map-Making

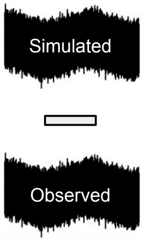
$$\vec{d} = H \cdot \vec{s} + \vec{n} \approx \sum_{i=1}^{Nsub} H_{\nu_i} \cdot \vec{s_{\nu_i}} \Delta\nu_i + \vec{n}$$

Sum over the bandwidth

Instrumental Model

$$\vec{d} = \sum_{i=1}^{Nsub} H_{\nu_i} \cdot \vec{s_{\nu_i}} \Delta\nu_i + \vec{n}$$

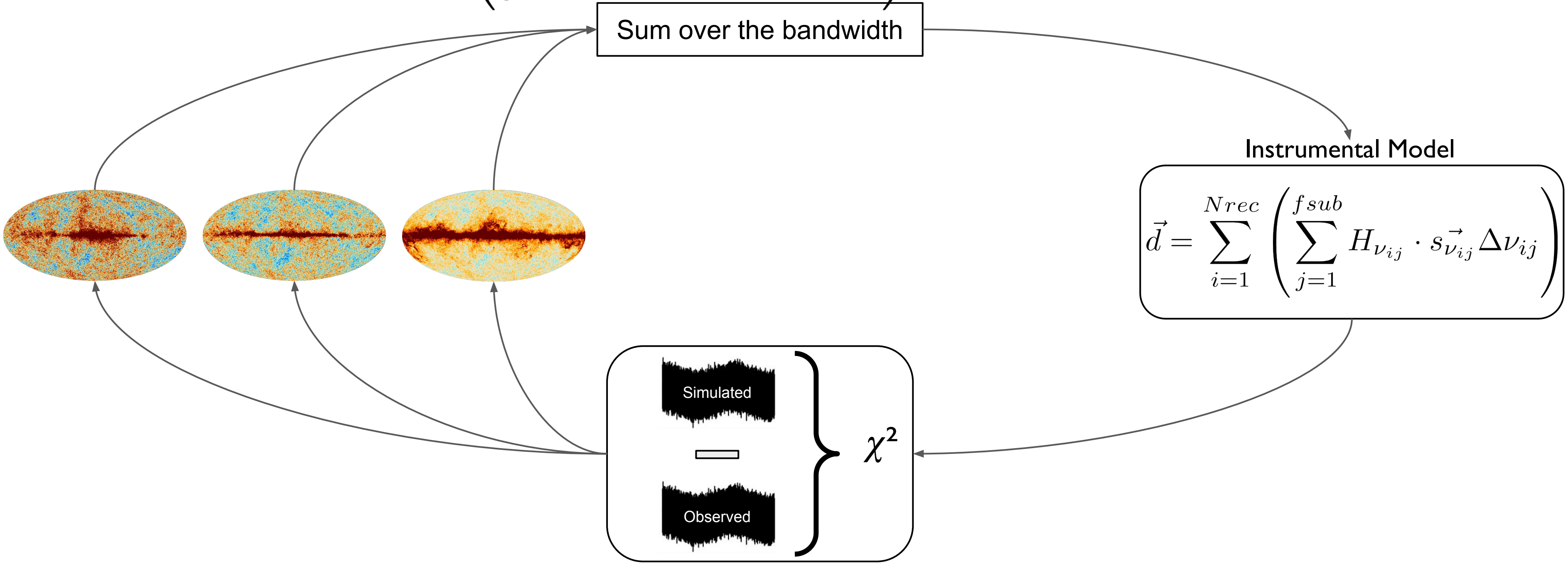




χ^2

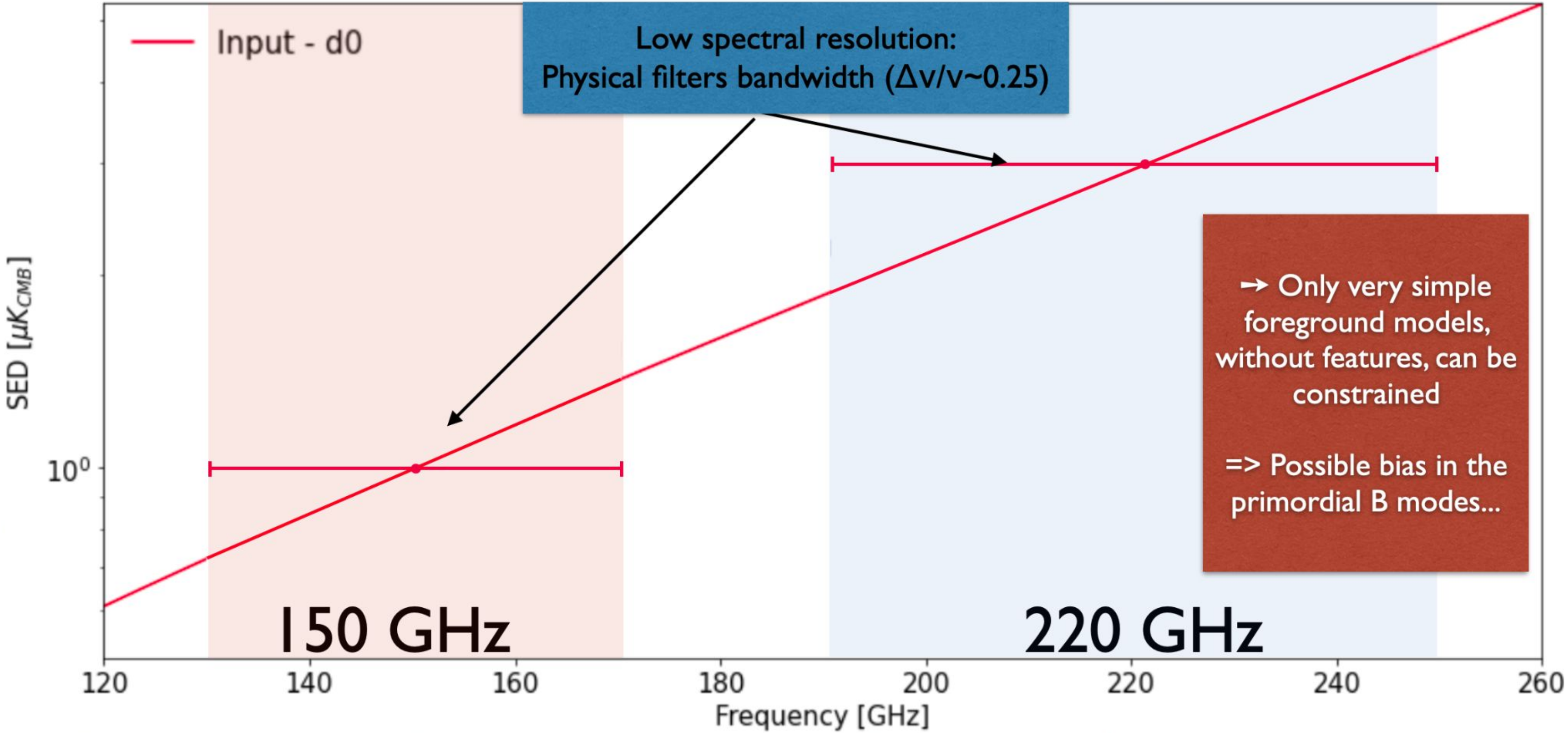
Frequency Map-Making

$$\vec{d} = H \cdot \vec{s} + \vec{n} \approx \sum_{i=1}^{Nrec} \left(\sum_{j=1}^{fsub} H_{\nu_{ij}} \cdot \vec{s_{\nu_{ij}}} \Delta\nu_{ij} \right)$$

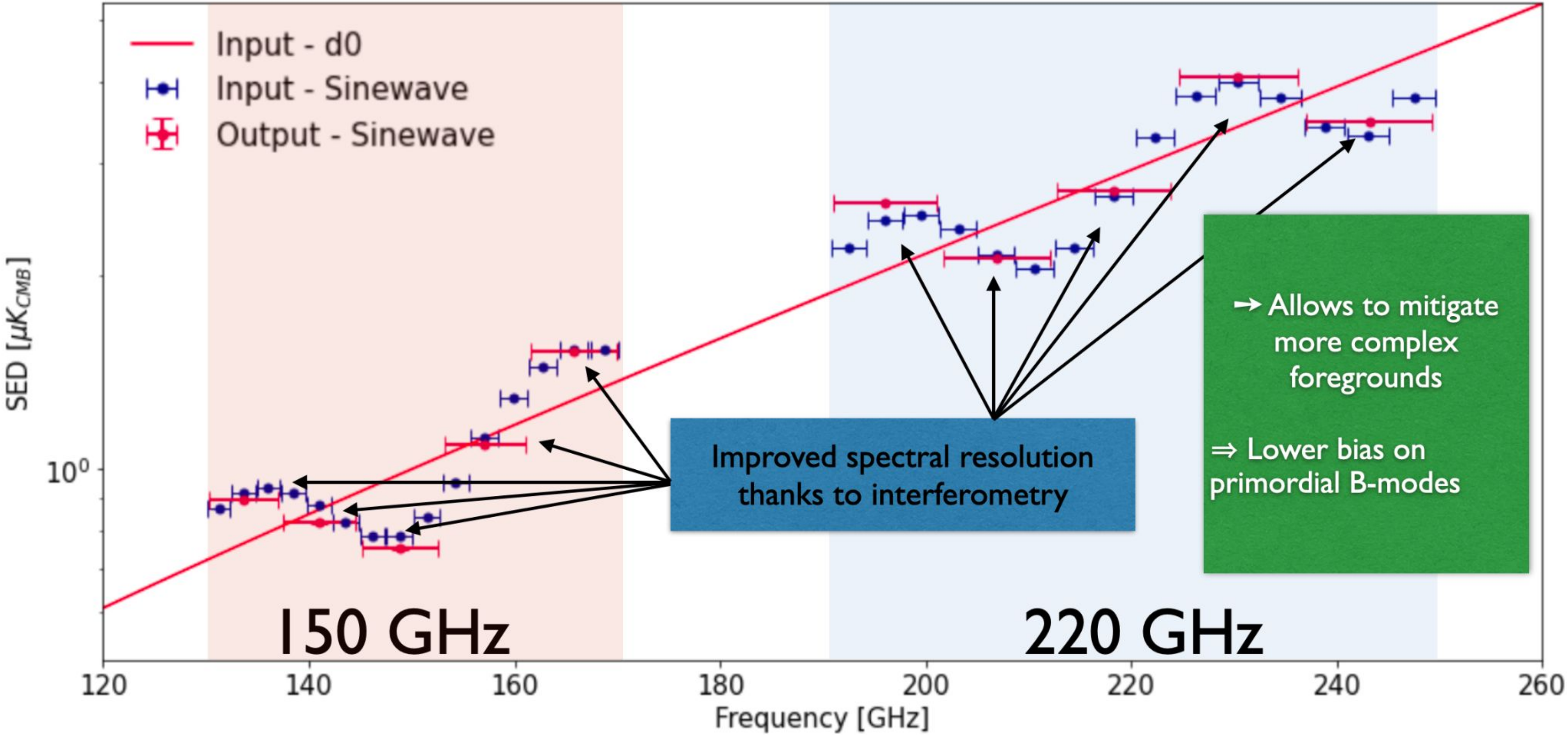


Tom Laclavère for the QUBIC Collaboration
APC - Paris - France
laclavere@apc.in2p3.fr

Frequency Map-Making: improve spectral resolution

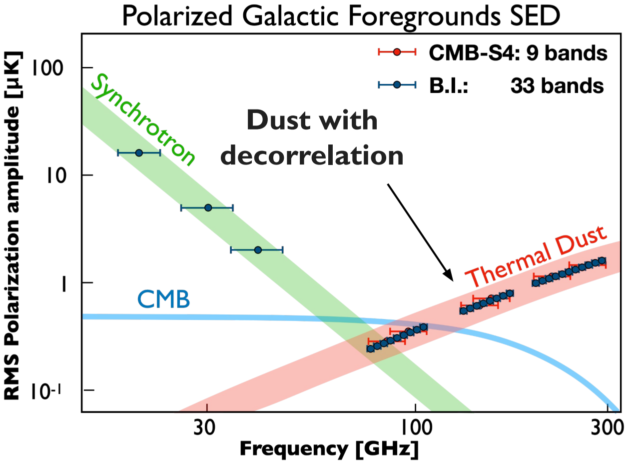


Frequency Map-Making: improve spectral resolution



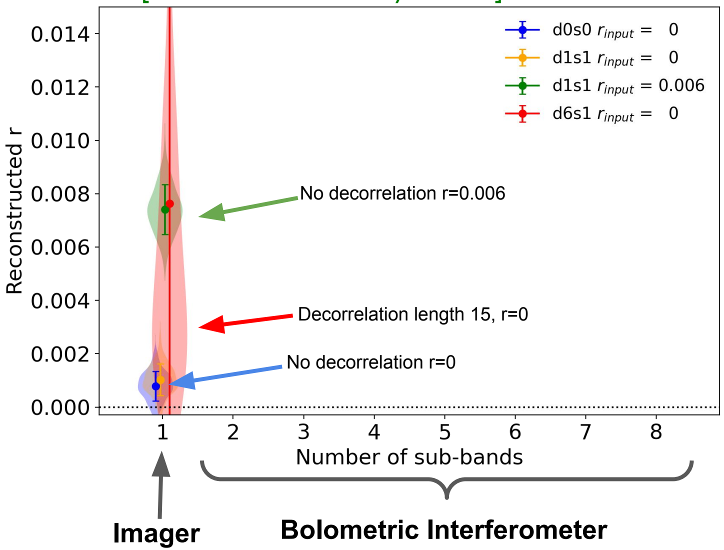
Frequency Map-Making: improve spectral resolution

Non-minimal dust model: Dust SED decorrelation (Corr_length = 15: 3x smaller than current constraints)



⇒ Decorrelation undetected by direct imager
⇒ Dust residuals in CMB
⇒ **Wrong r detection!**

[BI with CMB-S4 sensitivity assumed]

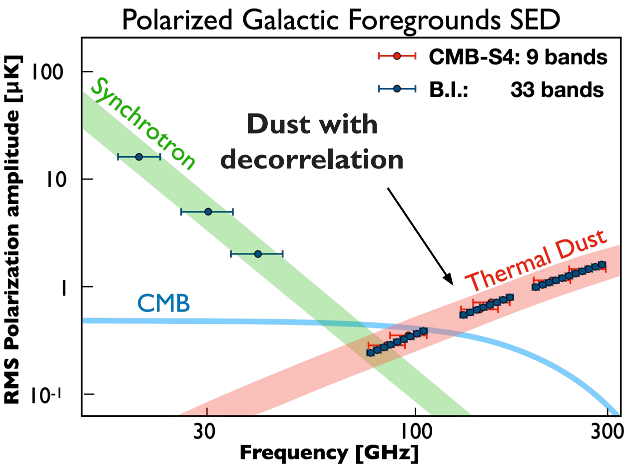


[Régnier et al. A&A 2024]

B.I. is needed to complement direct imaging: Dust decorrelation is to be expected from realistic dust

<u>Frequency Map-Making:</u> improve spectral resolution

Non-minimal dust model: <u>Dust SED decorrelation</u> (Corr_length = 15: 3x smaller than current constraints)



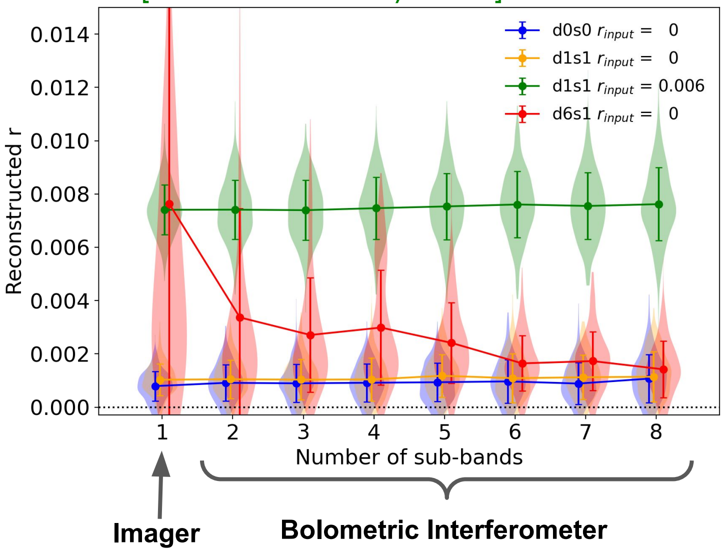
⇒ Decorrelation undetected by direct imager

⇒ Dust residuals in CMB

⇒ **Wrong r detection!**

<u>Multi-band analysis with B.I. reveals the effect</u>

[BI with CMB-S4 sensitivity assumed]

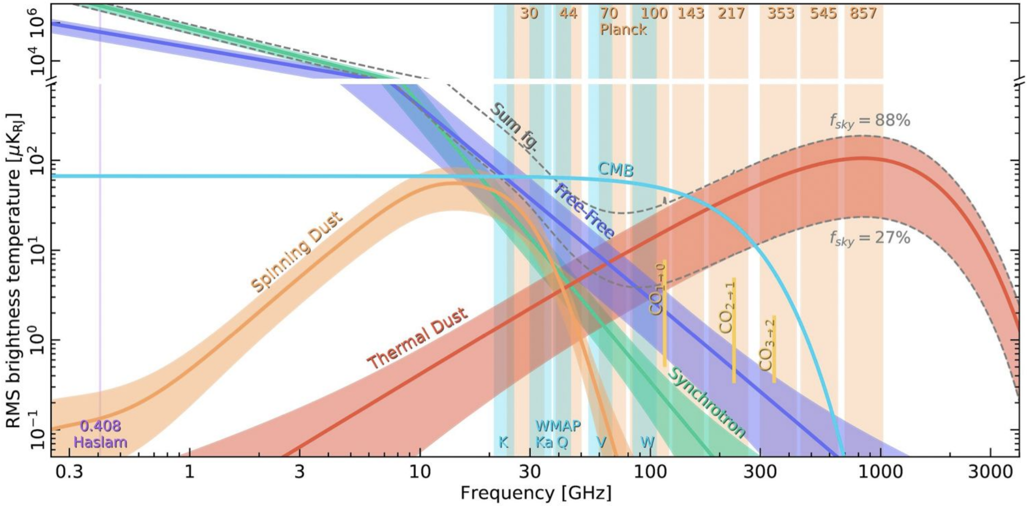


[Régnier et al. A&A 2024]

B.I. is needed to complement direct imaging: Dust decorrelation is to be expected from realistic dust

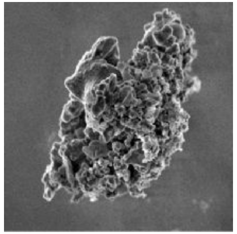
Astrophysical Foregrounds

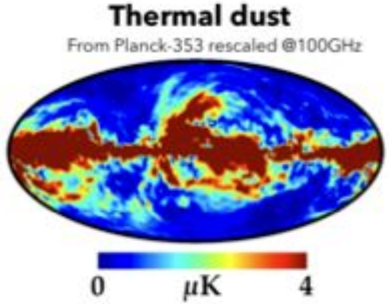
Astrophysical components



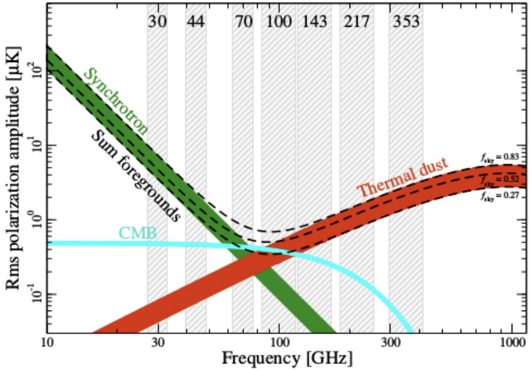
[K. J. Andersen et al., arXiv:2201.08188]

Dust grains

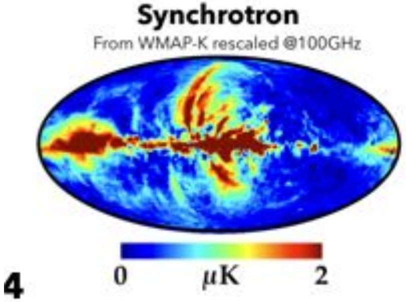




$$c_{dust} = A_d \frac{\nu}{\exp(h\nu/kT_d) - 1} \frac{\exp(h\nu_0/kT_d) - 1}{\nu_0} \left(\frac{\nu}{\nu_0}\right)^{\beta_d}$$



Synchrotron



Atmosphere

Atmospheric contribution to one detector (aligned with the line of sight)

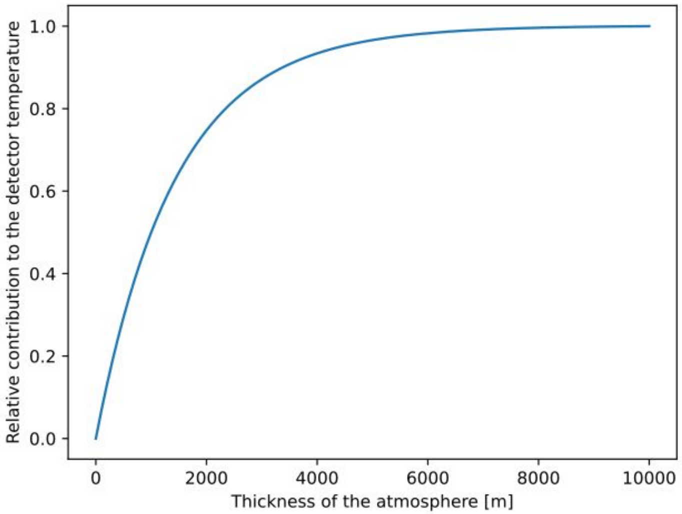
$$\langle T(\widehat{\mathbf{r}})\rangle = \alpha_b(\nu) \iiint \langle \rho(h(\mathbf{r}))\rangle T_{atm}(h(\mathbf{r})) B_{n,\nu}(\mathbf{r}) d\mathbf{r}$$

$$\langle \rho(h)\rangle = \rho_0 e^{-\frac{h}{h_0}}$$

$\rho_0 \approx g.m^{-3}$ $\quad h_0 \approx 1km$

$$T_{atm}(h) = T_{ground} e^{-\frac{h}{h_{atm}}}$$

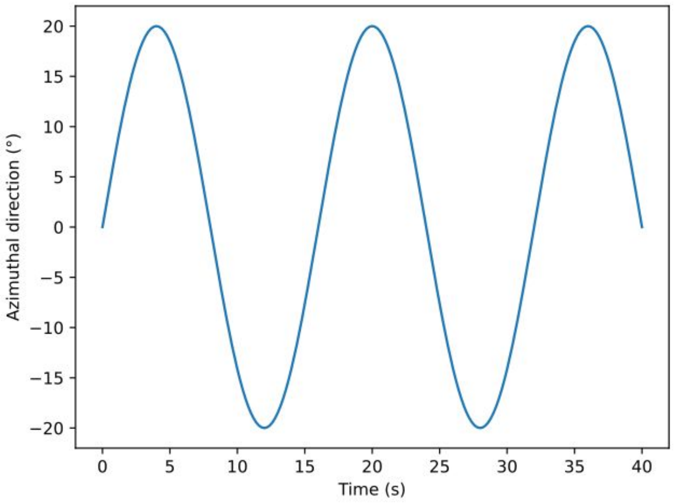
$T_{ground} \approx 280K$ $\quad h_{atm} \approx 40km$

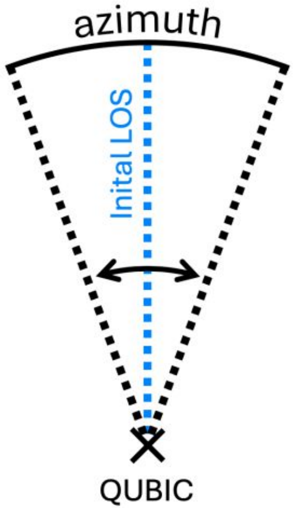


$$C_{ij}^{tt'} = \alpha_b(\nu)^2 \iiint \iiint D(r_{ij})\langle\rho(h(\mathbf{r}_i))\rangle T_{atm}(h(\mathbf{r}_i)) B_{n,\nu}^i(\mathbf{r}_i)\langle\rho(h(\mathbf{r}_j))\rangle T_{atm}(h(\mathbf{r}_j)) B_{n,\nu}^j(\mathbf{r}_j) d\mathbf{r}_i d\mathbf{r}_j$$

Let's simulate a simple scanning strategy : $az(t) = \frac{\Delta az}{2} sin\left(2\pi \frac{ss}{2\Delta az} t\right)$

5°/s



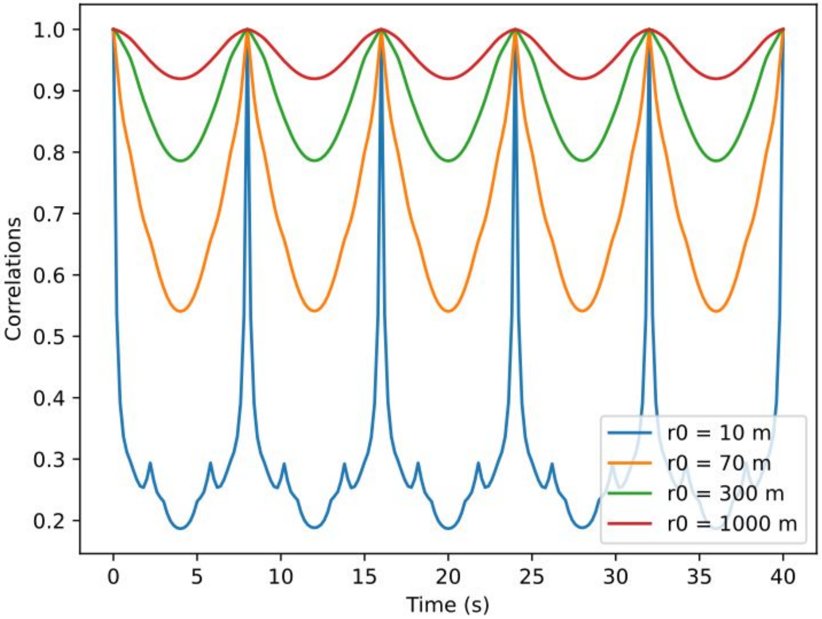


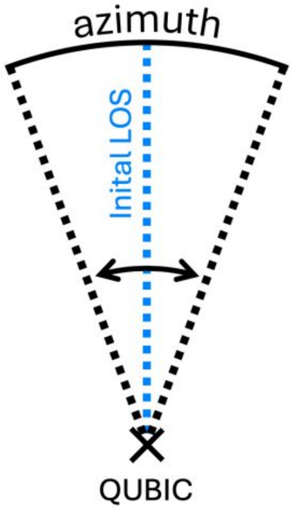
[Errard, 2015]

$$C_{ij}^{tt'} = \alpha_b(\nu)^2 \iiint \iiint D(r_{ij}) \langle \rho(h(\mathbf{r}_i)) \rangle T_{atm}(h(\mathbf{r}_i)) B^i_{n,\nu}(\mathbf{r}_i) \langle \rho(h(\mathbf{r}_j)) \rangle T_{atm}(h(\mathbf{r}_j)) B^j_{n,\nu}(\mathbf{r}_j) d\mathbf{r}_i d\mathbf{r}_j$$

$$D(r) = \frac{2^{\frac{2}{3}}}{\Gamma(1/3)} \left(\frac{r}{r_0}\right)^{\frac{1}{3}} K_{\frac{1}{3}} \left(\frac{r}{r_0}\right)$$

wrt to the
initial LOS

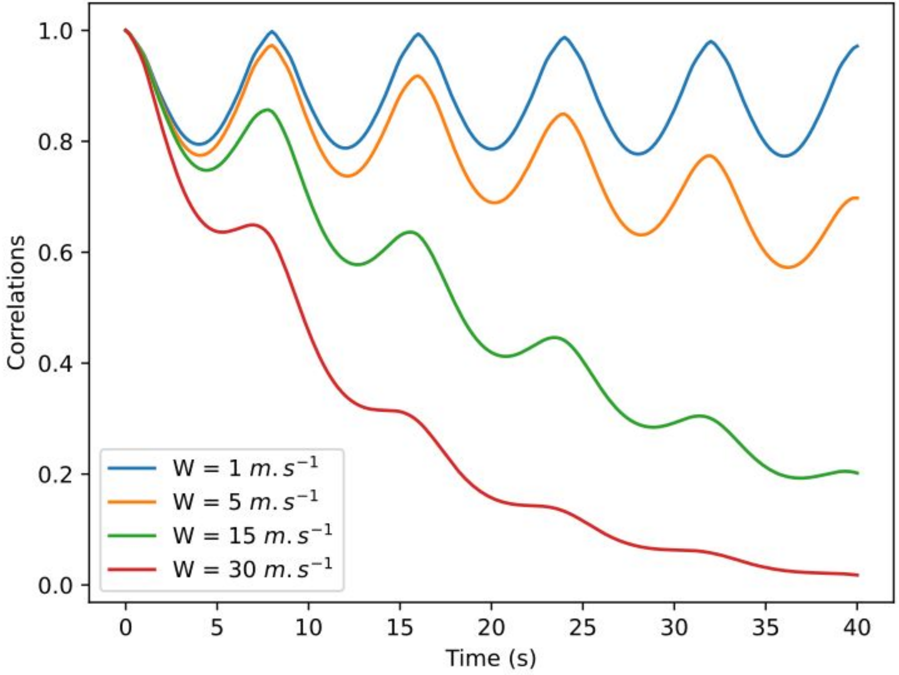


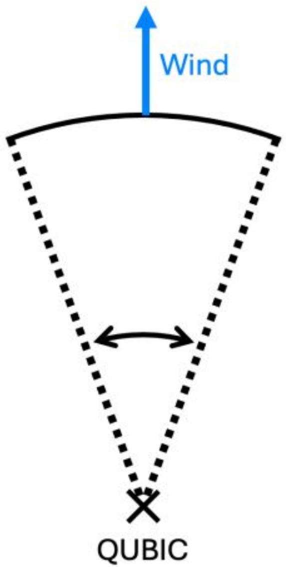


[Errard, 2015]

$$C_{ij}^{tt'} = \alpha_b(\nu)^2 \iiint \iiint D(r_{ij})\langle\rho(h(\mathbf{r}_i))\rangle T_{atm}(h(\mathbf{r}_i))B_{n,\nu}^i(\mathbf{r}_i)\langle\rho(h(\mathbf{r}_j))\rangle T_{atm}(h(\mathbf{r}_j))B_{n,\nu}^j(\mathbf{r}_j)d\mathbf{r}_i d\mathbf{r}_j$$

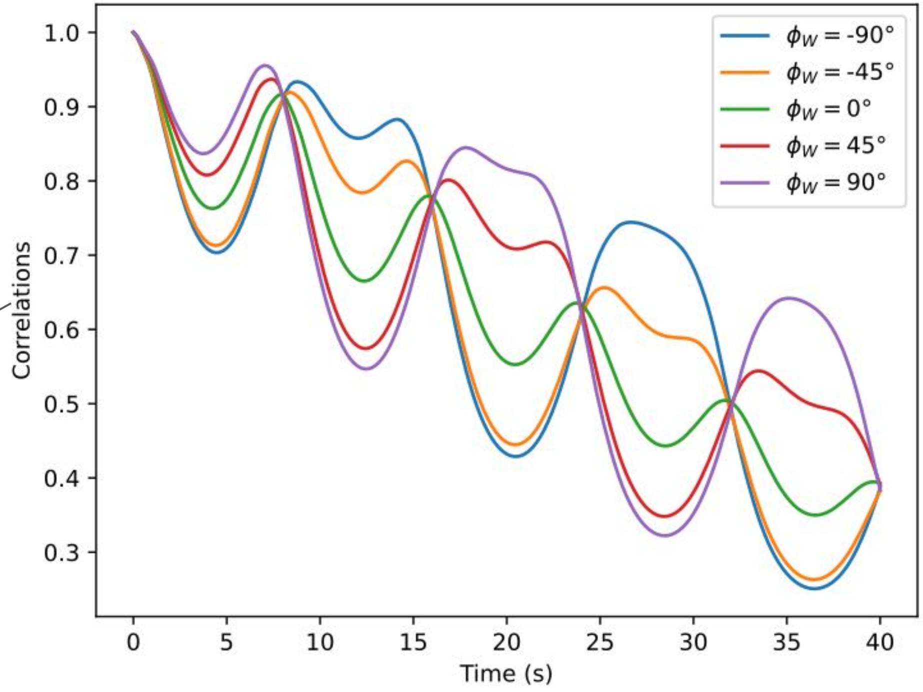
wrt to the initial LOS



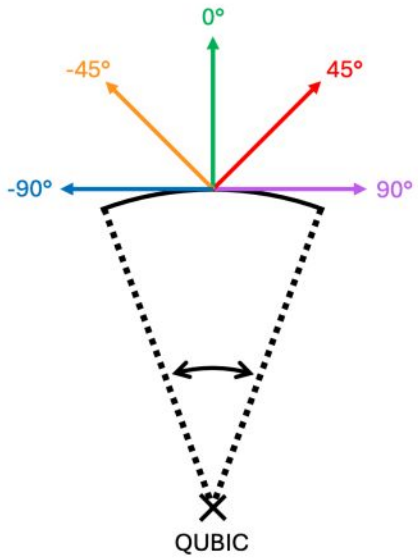


[Errard, 2015]

$$C_{ij}^{tt'} = \alpha_b(\nu)^2 \iiint \iiint D(r_{ij}) \langle \rho(h(\mathbf{r}_i)) \rangle T_{atm}(h(\mathbf{r}_i)) B_{n,\nu}^i(\mathbf{r}_i) \langle \rho(h(\mathbf{r}_j)) \rangle T_{atm}(h(\mathbf{r}_j)) B_{n,\nu}^j(\mathbf{r}_j) d\mathbf{r}_i d\mathbf{r}_j$$

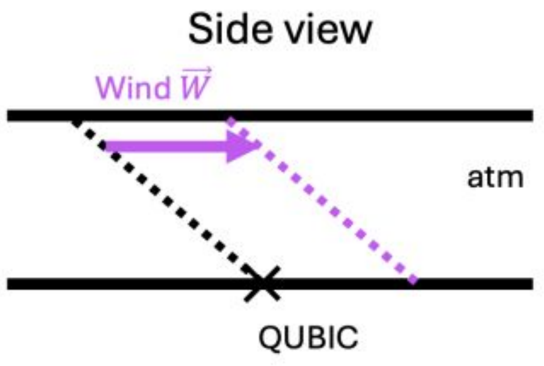


wrt to the initial LOS



[Errard, 2015]

Parallax effect of the atmosphere



Atmosphere is a 3d system:

→We will lost the correlation information with time due to the wind
→It will be even worse if we consider that wind is altitude-dependent