

QUBIC: specificities and status

Q-U Bolometric Interferometer for Cosmology



CMB-France #7



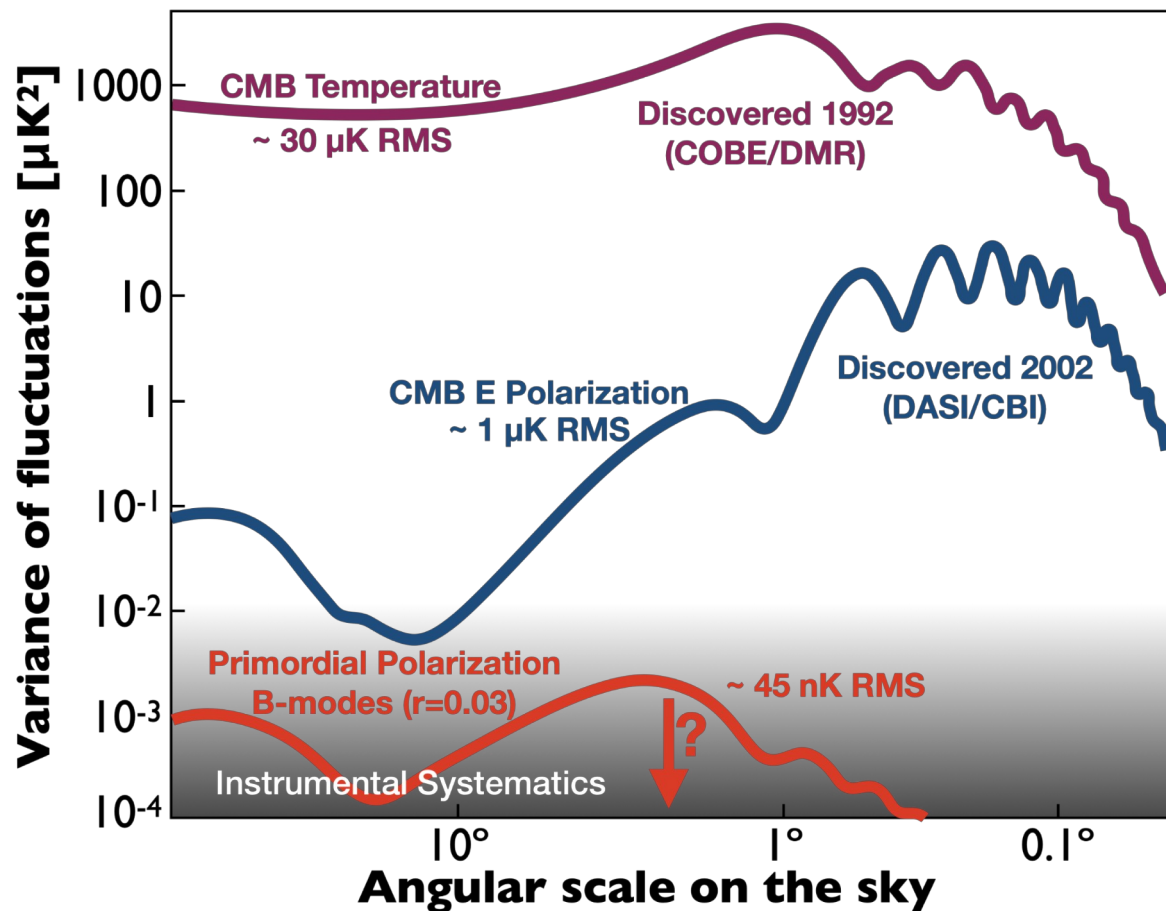


Plan

1. Primordial B modes
2. Bolometric interferometry
3. Map reconstruction
4. Current status

Primordial B modes

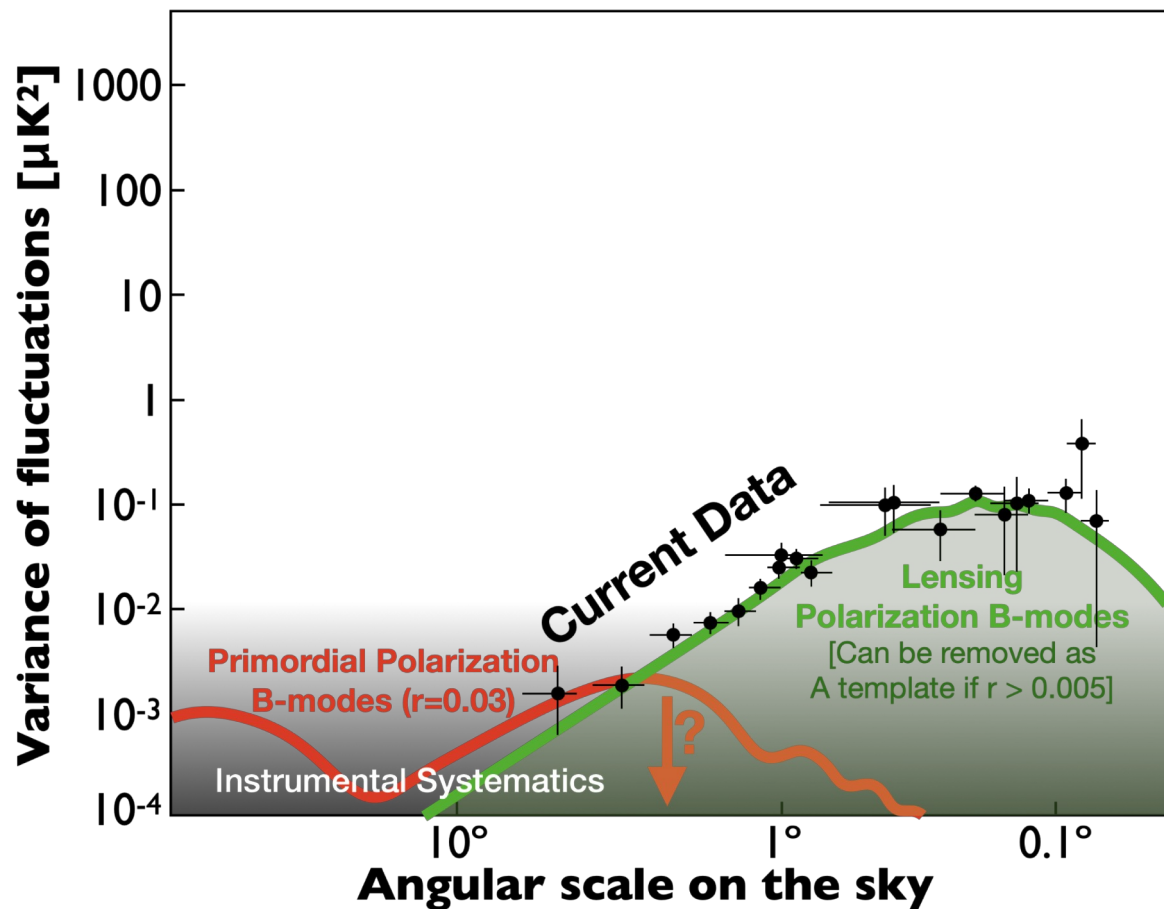
Detect primordial B-modes



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

[Tristram et al., arXiv:2112.07961]

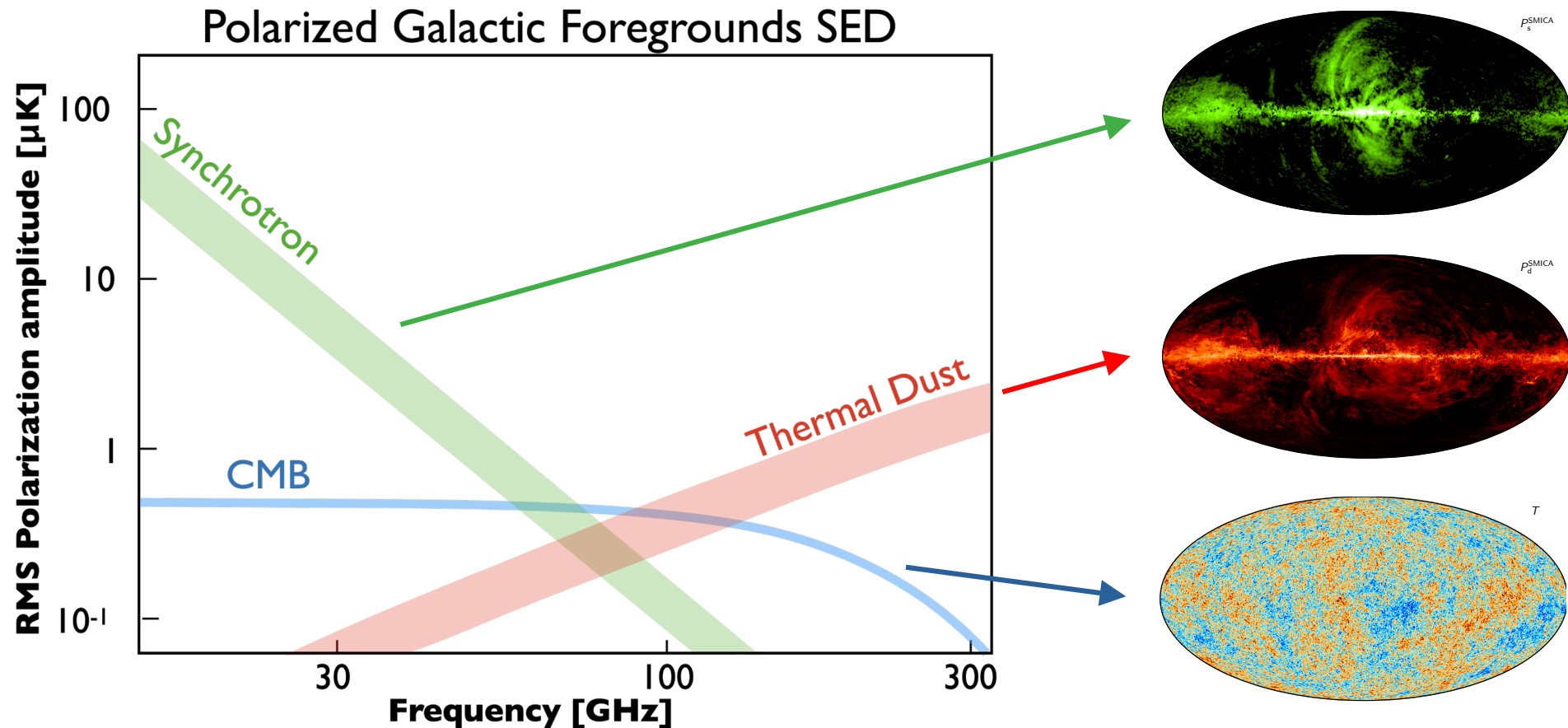
Complex foregrounds: lensing



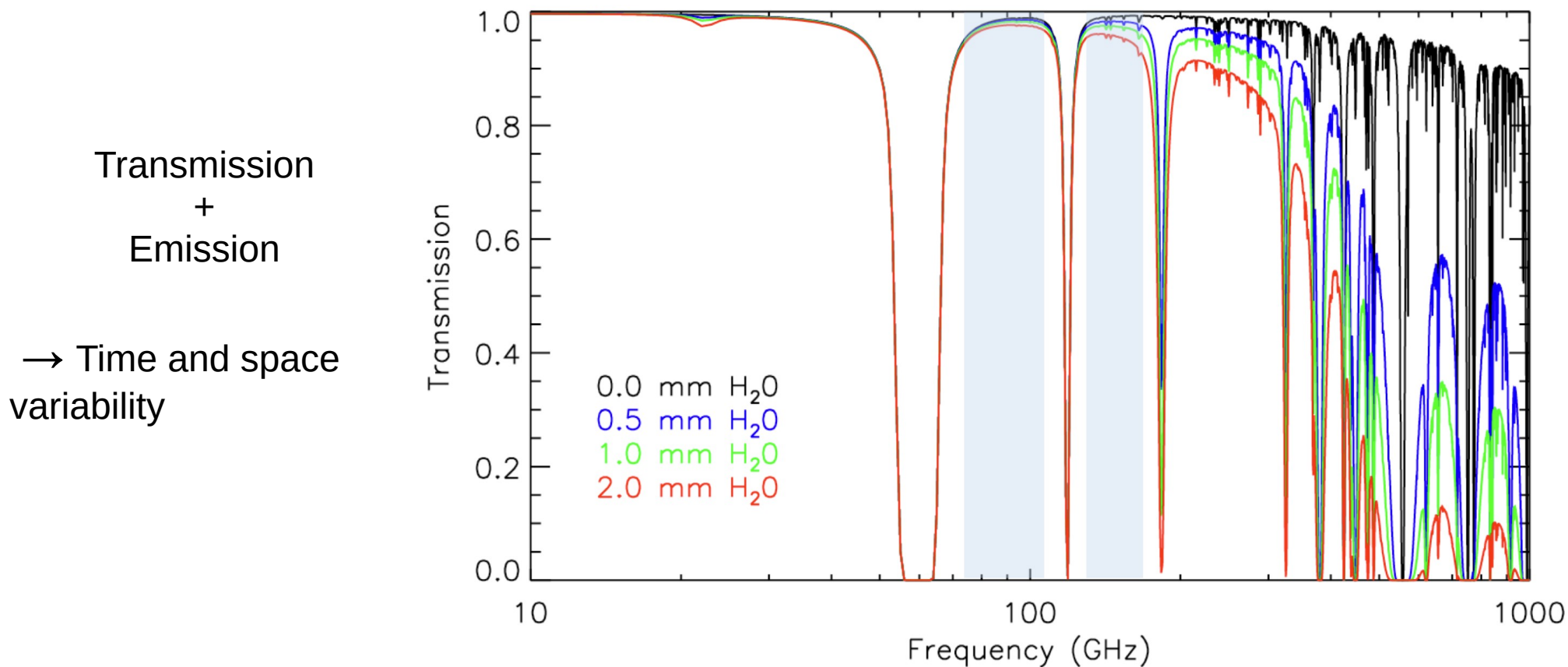
Current upper limit for r from BK18
+ PR4 : $r < 0.032$ at 95% C.L.

[Tristram et al., arXiv:2112.07961]

Complex foregrounds: galactic

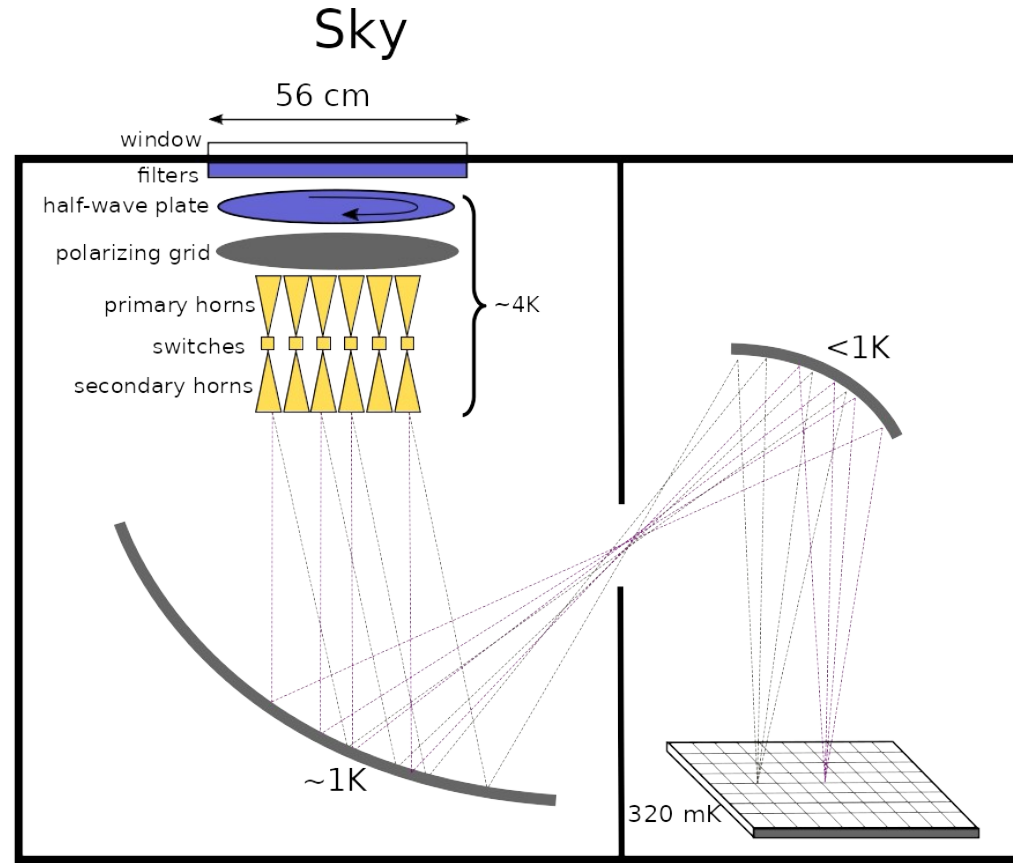


Complex foregrounds: atmosphere



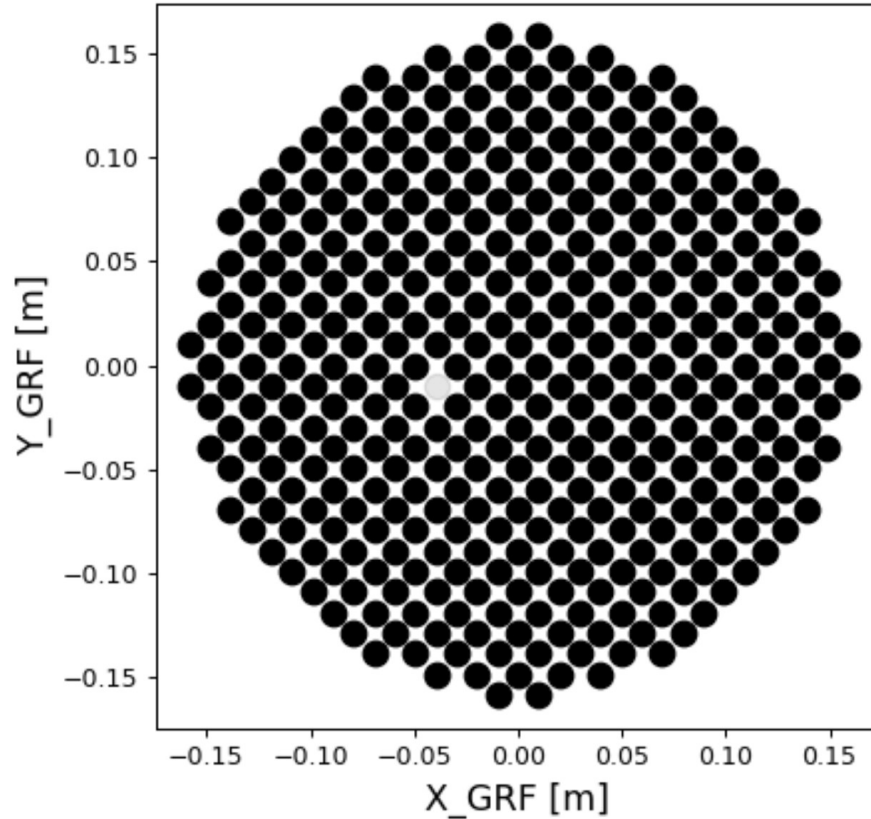
Bolometric interferometry

QUBIC architecture

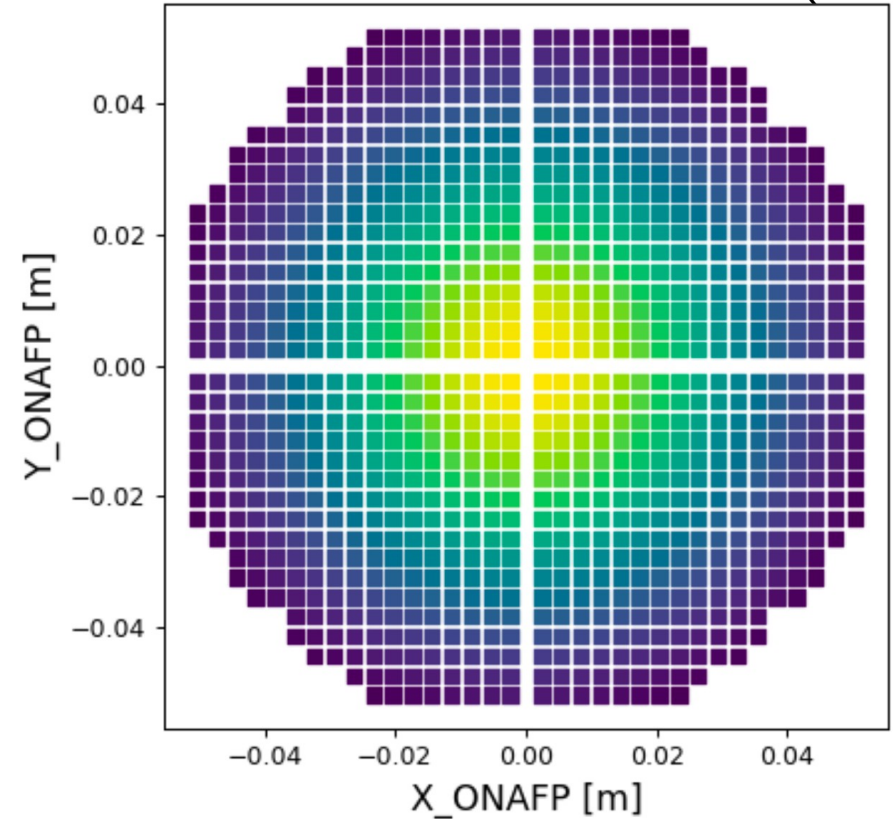


QUBIC synthesized beam

Credit: Louise Mousset's PhD (2021)



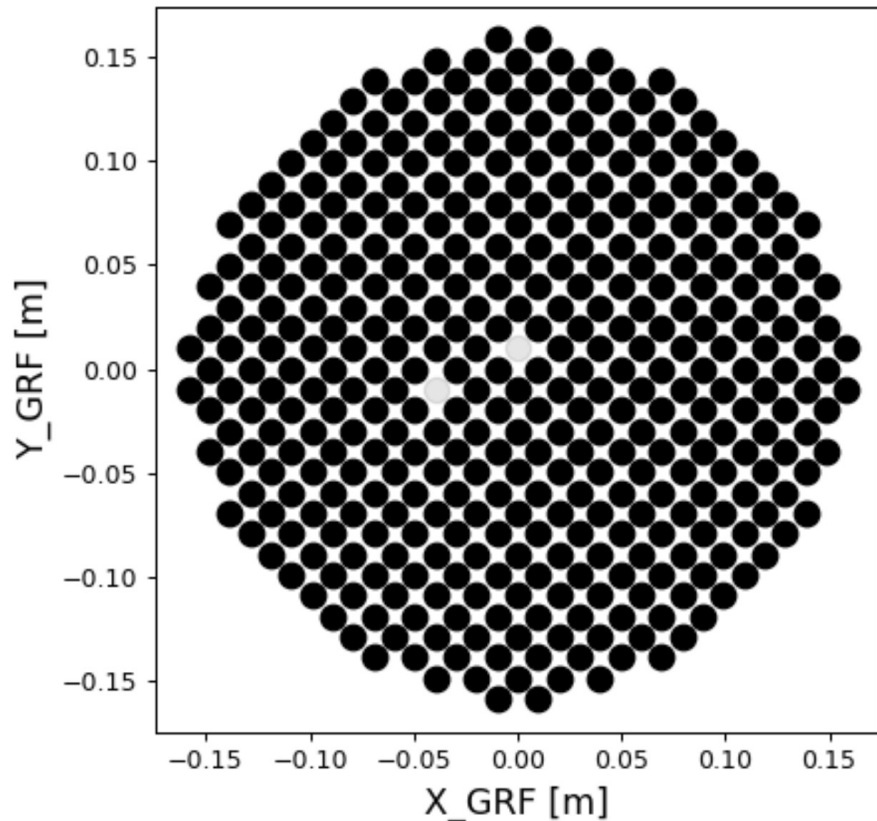
Horn array



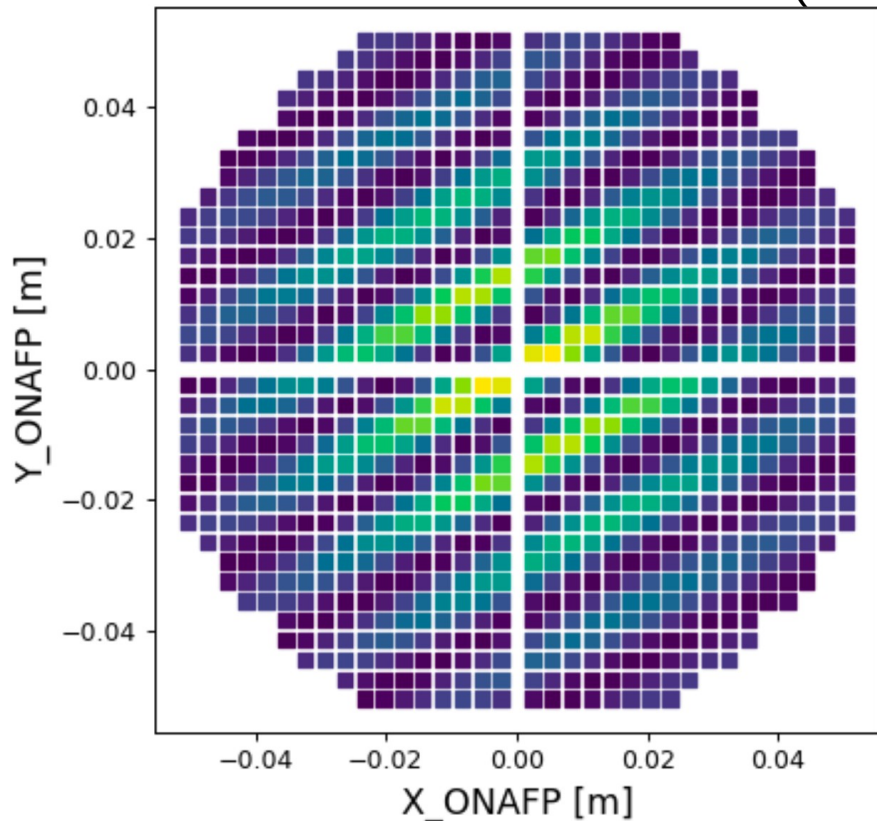
Focal plane (TES)

QUBIC synthesized beam

Credit: Louise Mousset's PhD (2021)



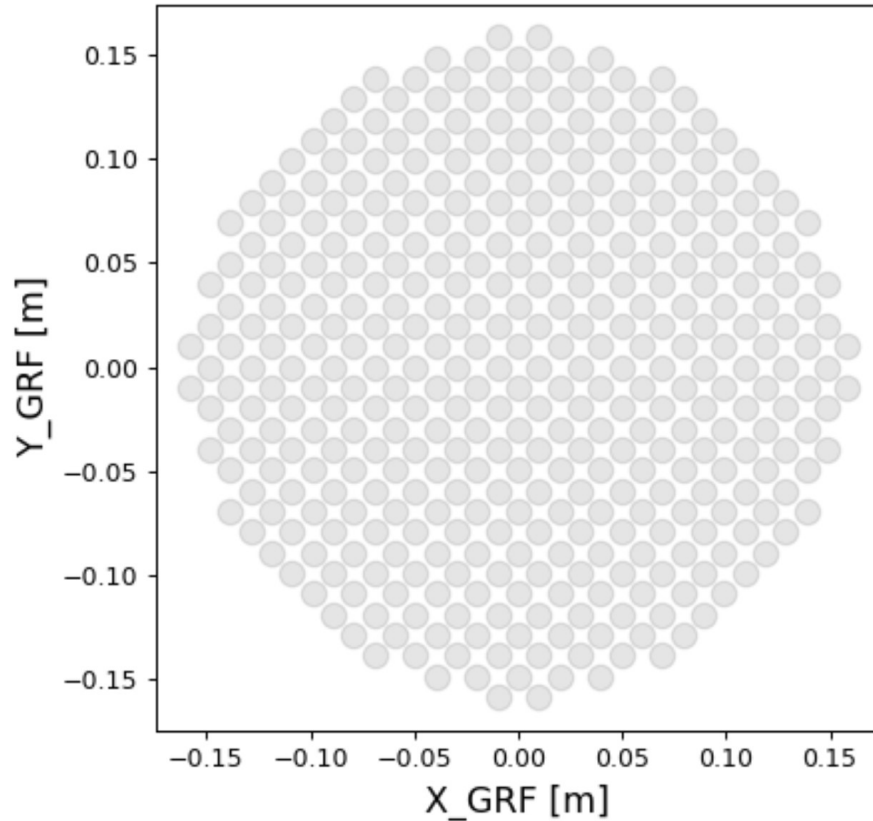
Horn array



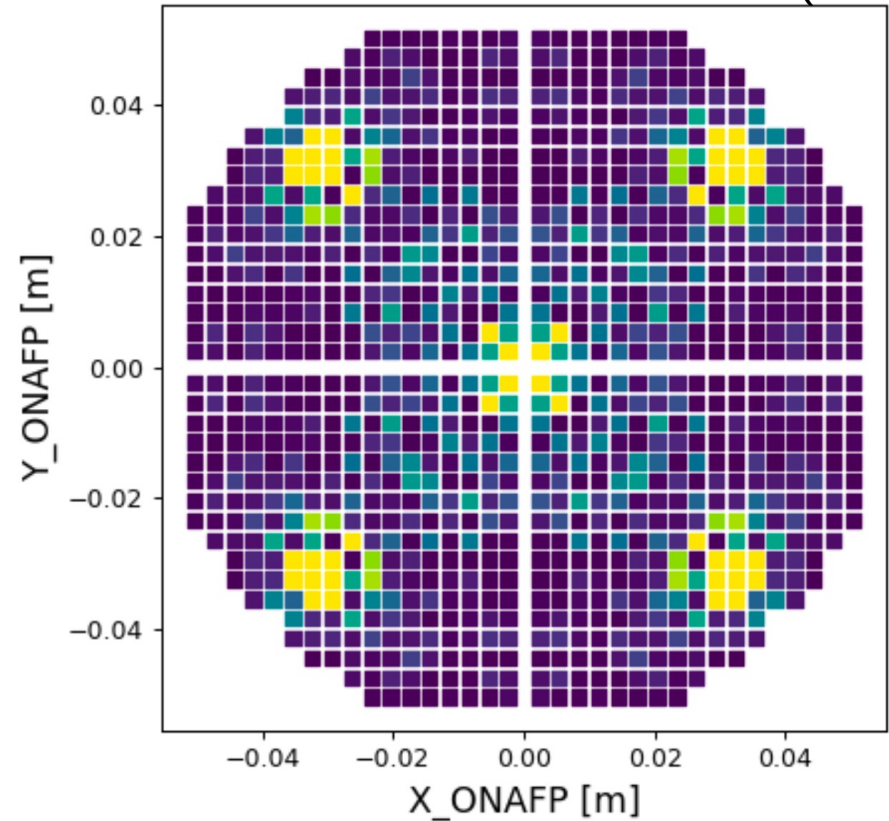
Focal plane (TES)

QUBIC synthesized beam

Credit: Louise Mousset's PhD (2021)

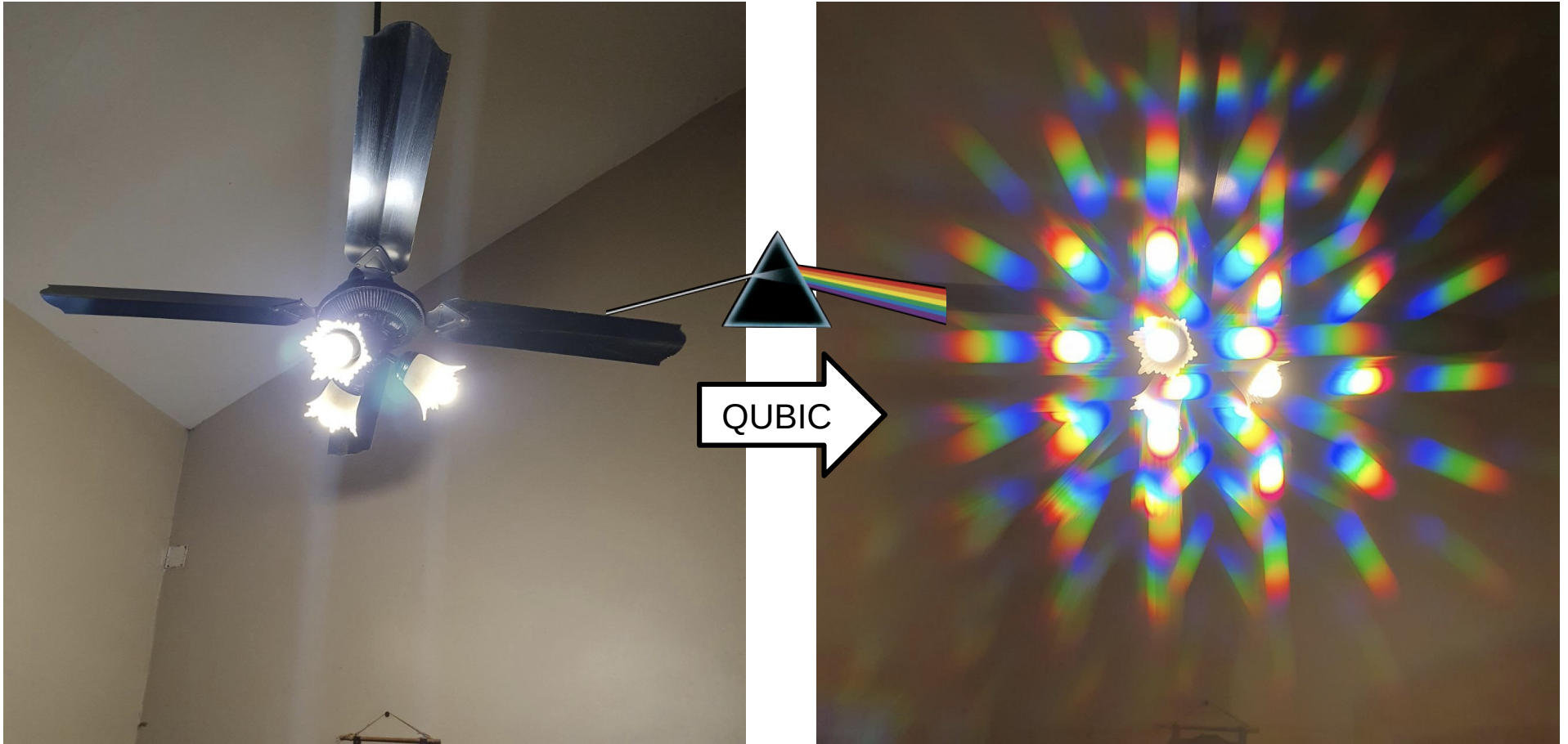


Horn array

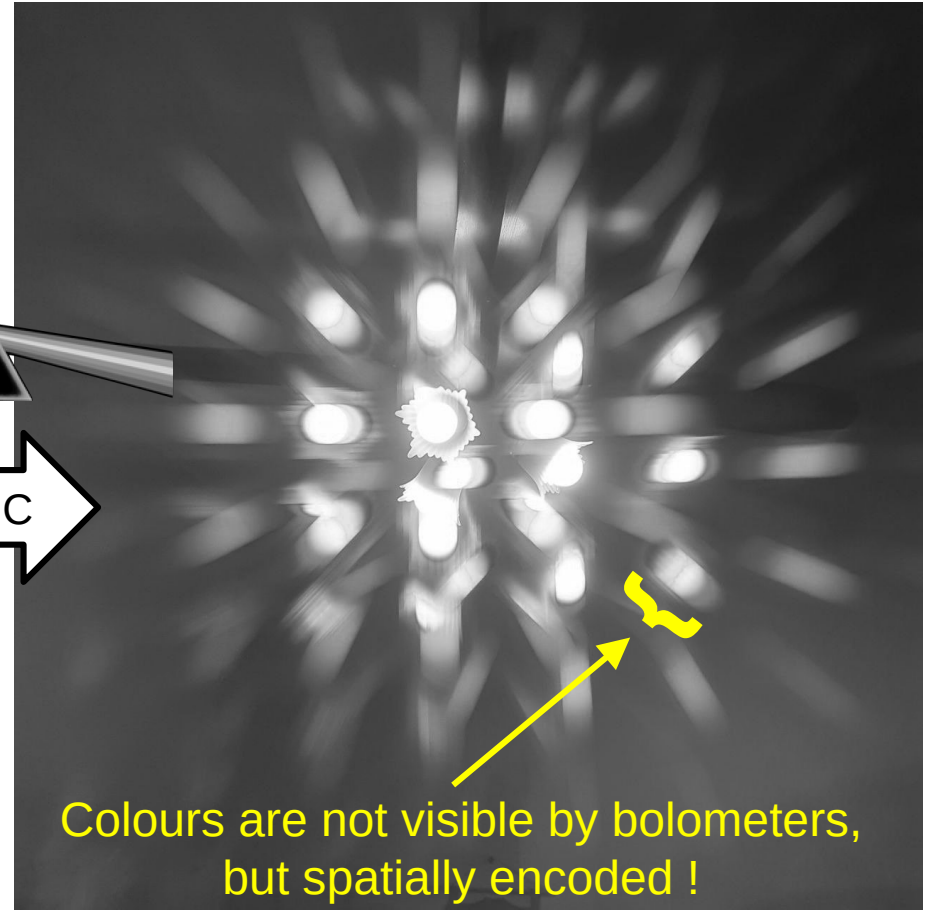
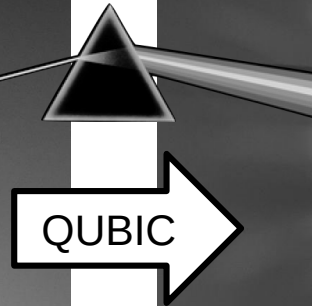


Focal plane (TES)

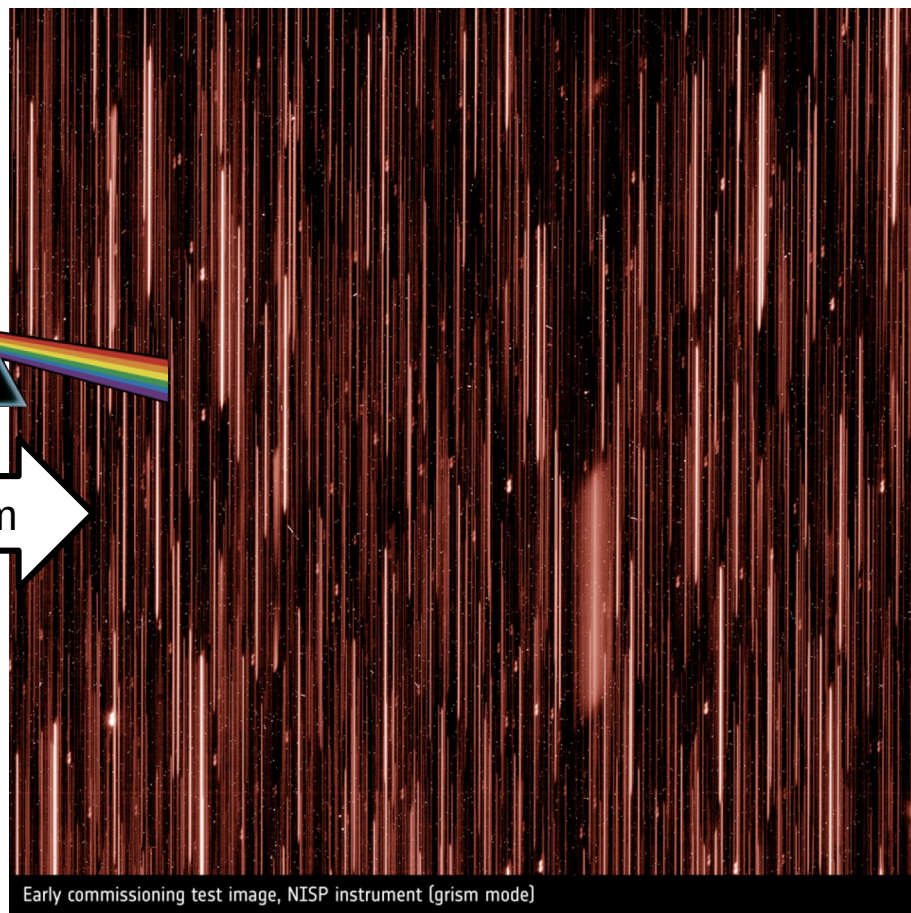
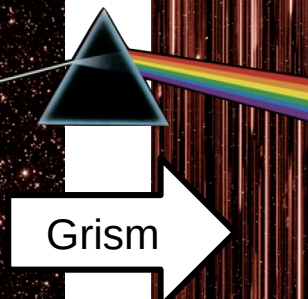
Bolometric interferometry



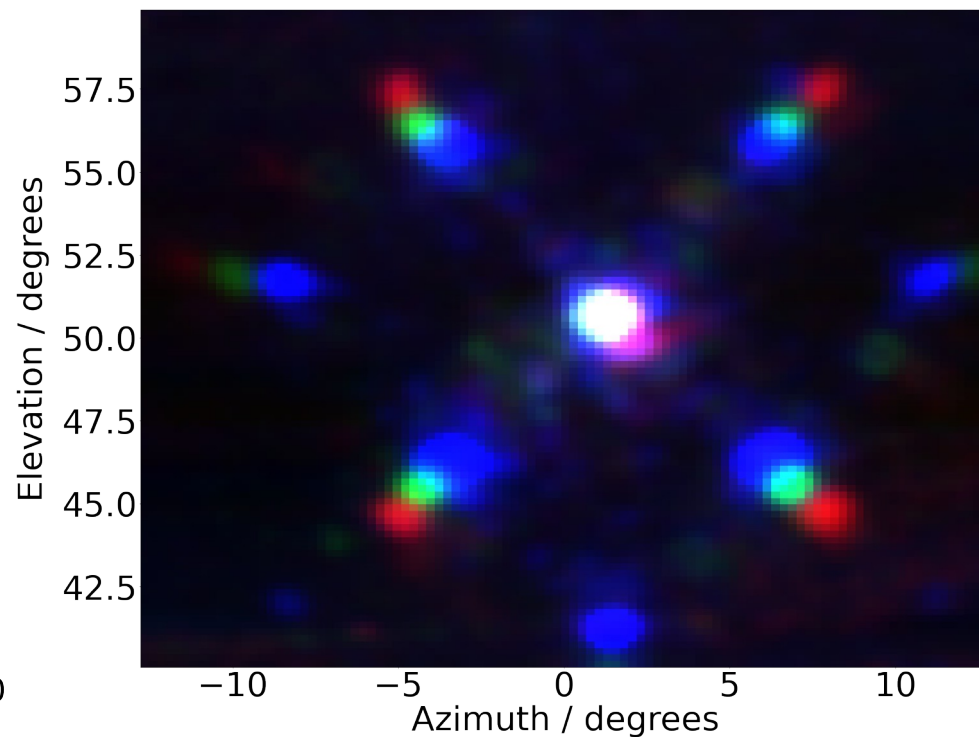
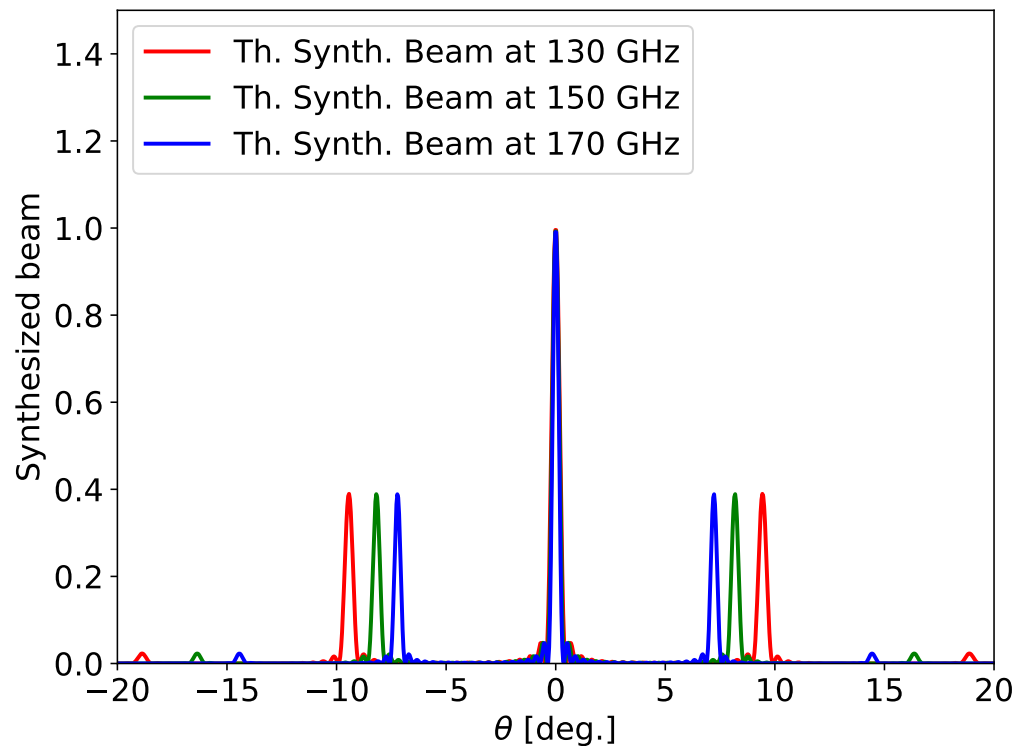
Bolometric interferometry



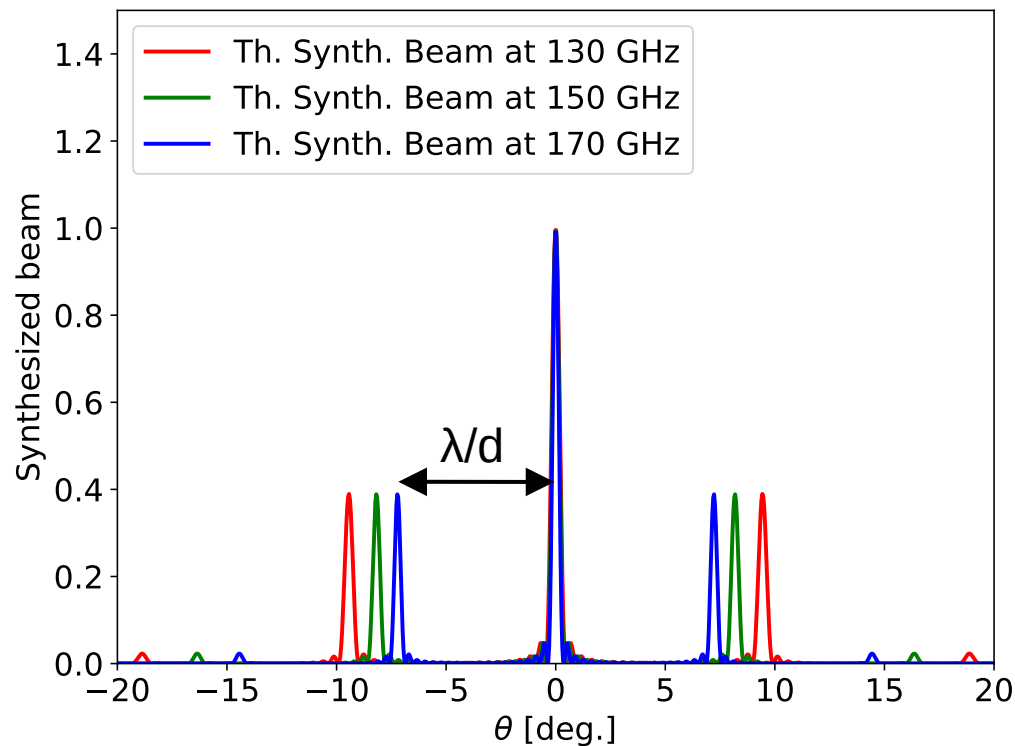
Bolometric interferometry ↔ Grism



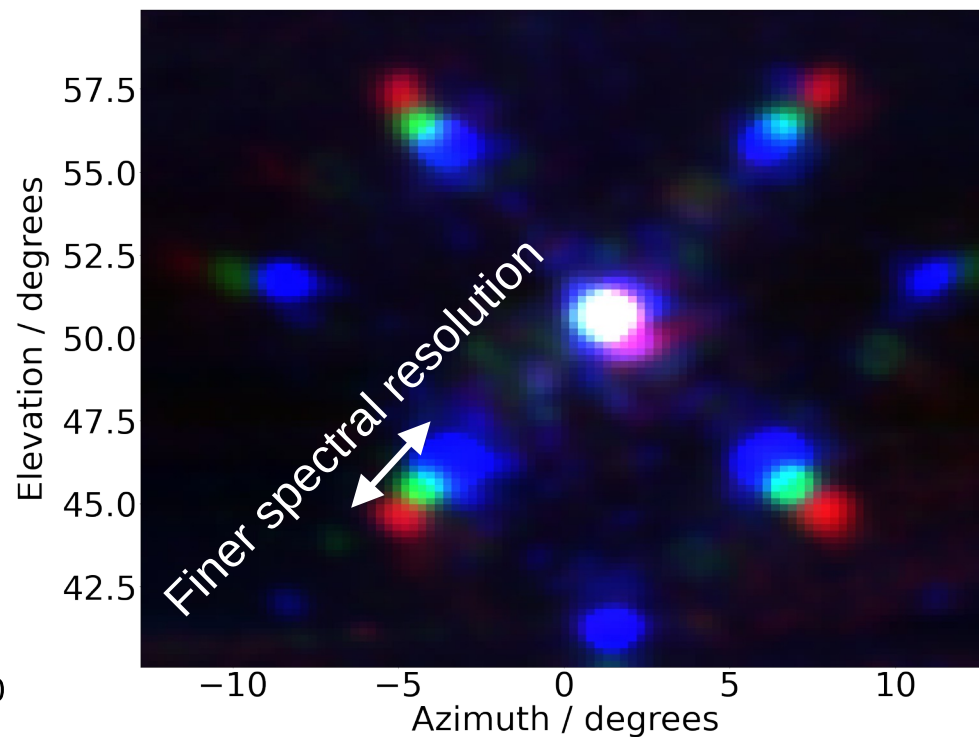
QUBIC beam



QUBIC beam

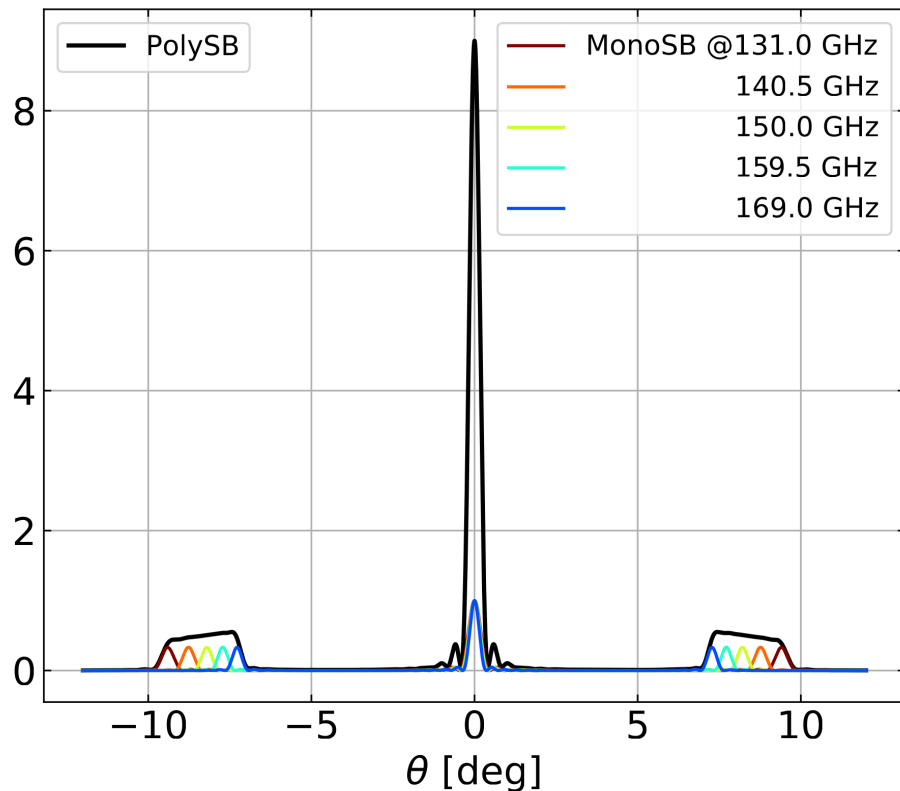


1 dimension, theory

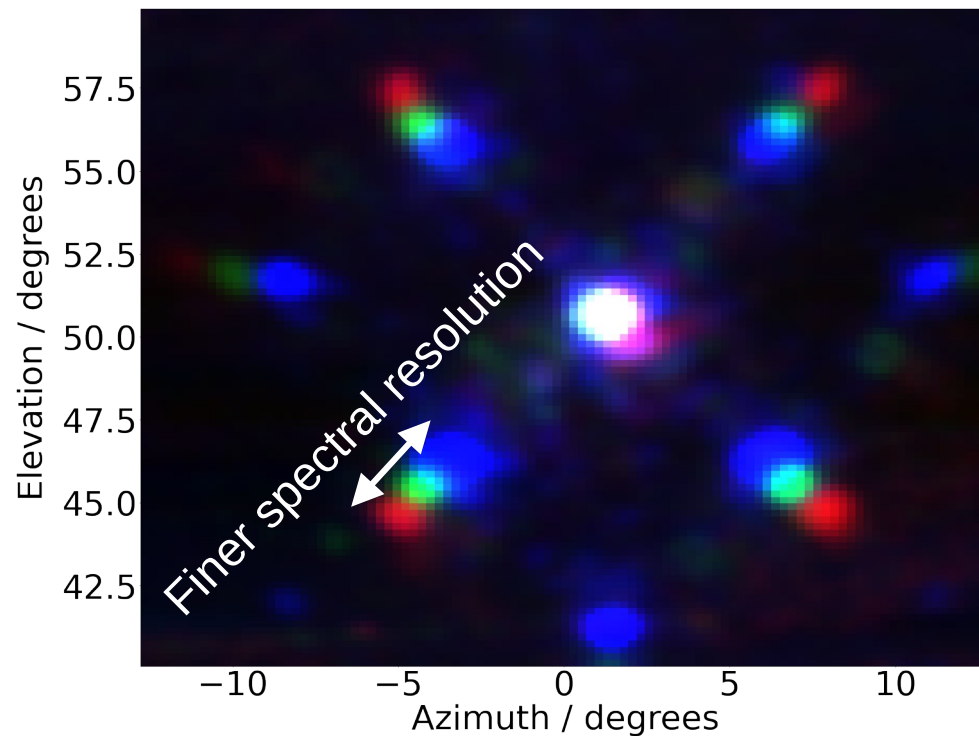


2 dimensions, lab

QUBIC beam

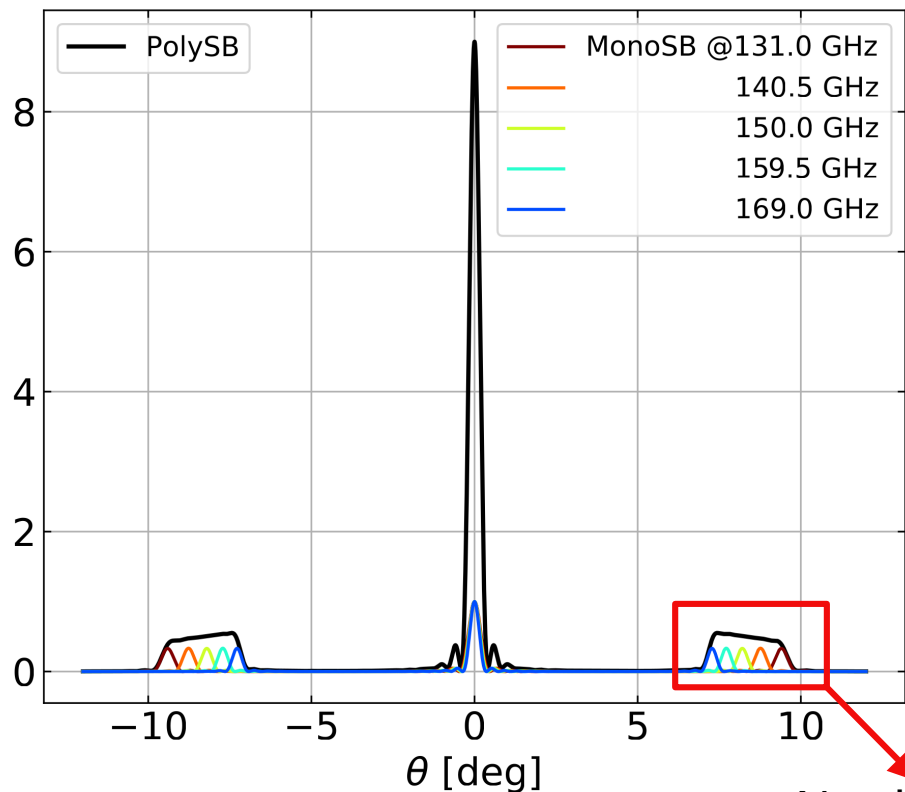


1 dimension, theory



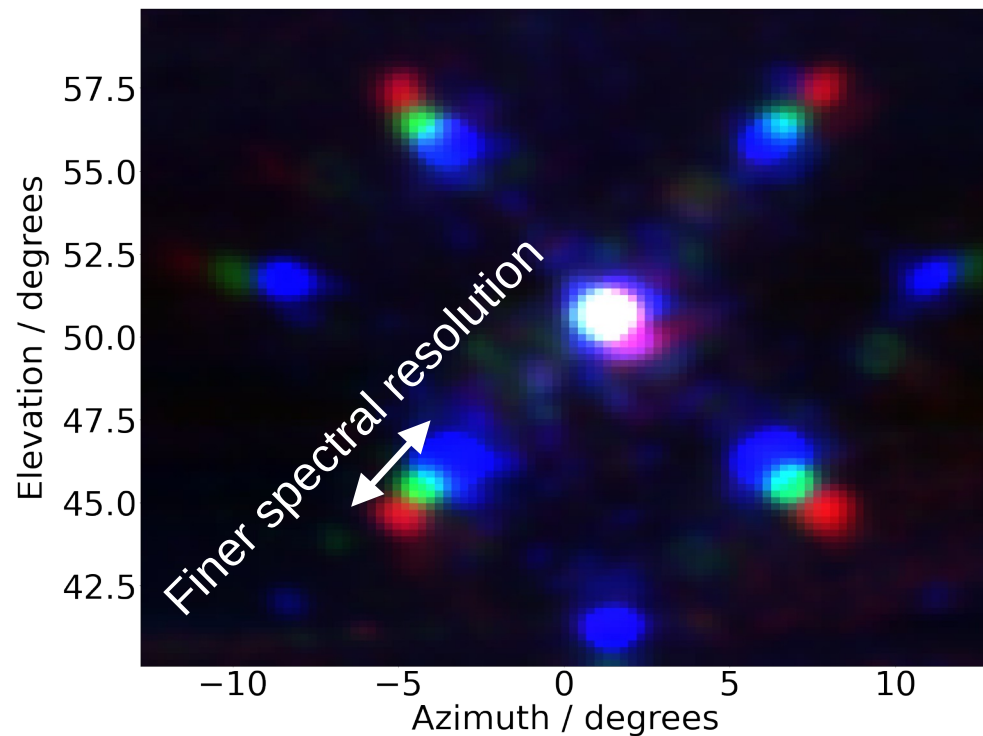
2 dimensions, lab

QUBIC beam



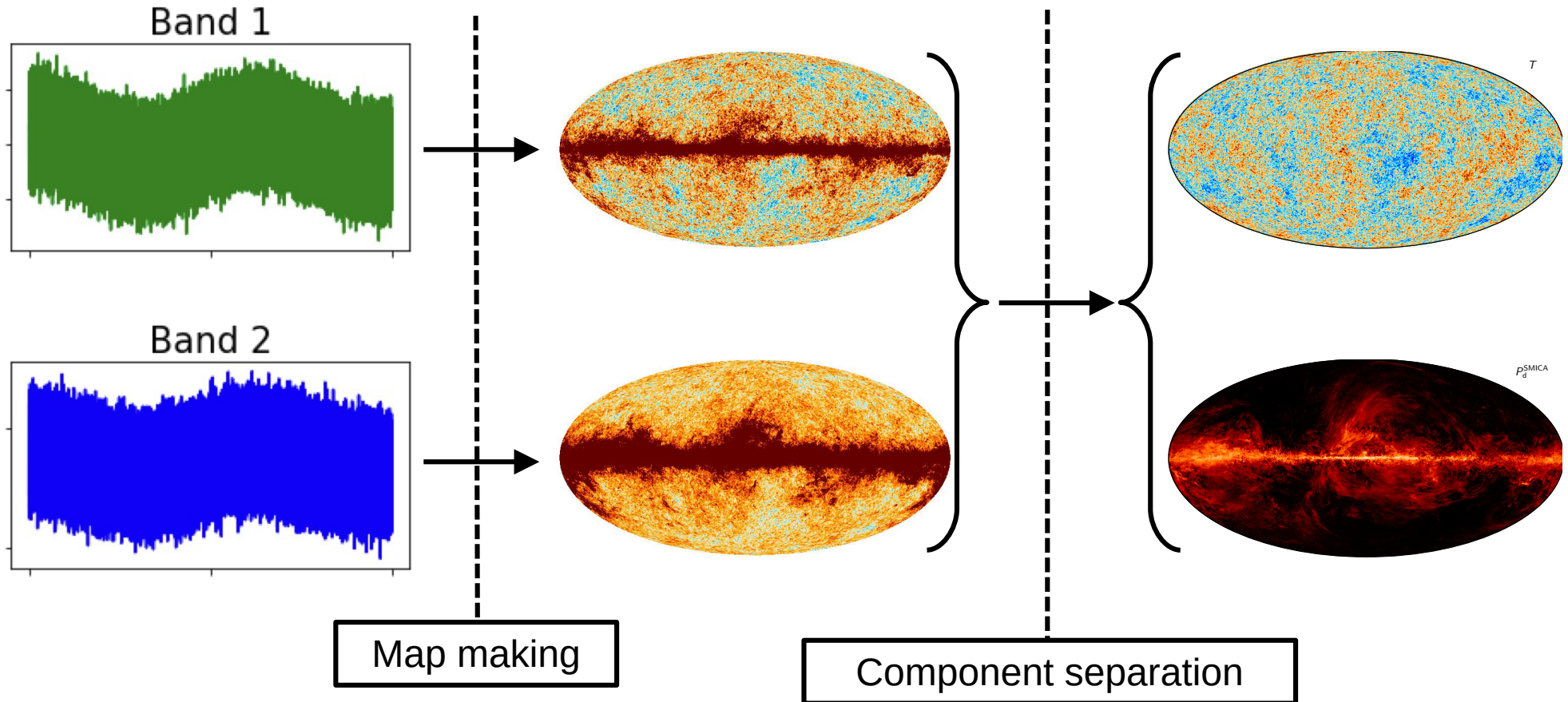
N sub-bands

→ spectral imaging



Map reconstruction

Classical map making



Classical map making

$$\vec{d}_i = H_i \cdot \vec{s}_i + \vec{n}_i$$

Data (TOD) Instrument model Sky map Noise

Classical map making

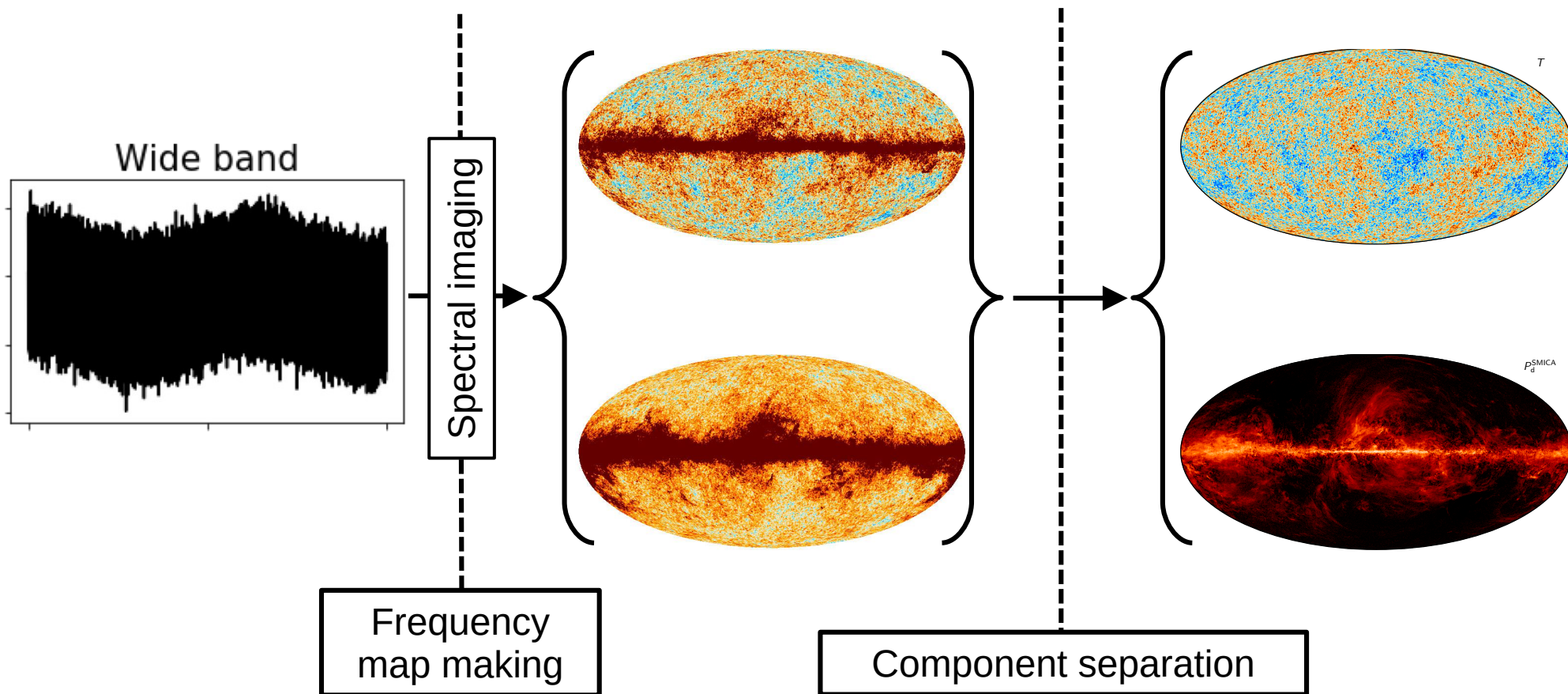
The diagram illustrates the equation for classical map making: $\vec{d}_i = H_i \cdot \vec{s}_i + \vec{n}_i$. The input vector $\vec{d}_i$ is enclosed in a green box and labeled "Input" above it, with a blue arrow pointing to the label "Data (TOD)". The instrument model H_i has a blue arrow pointing to the label "Instrument model". The output vector $\vec{s}_i$ is enclosed in a red box and labeled "Output" above it, with a blue arrow pointing to the label "Sky map". The noise vector $\vec{n}_i$ has a blue arrow pointing to the label "Noise".

$$\vec{d}_i = H_i \cdot \vec{s}_i + \vec{n}_i$$

Data (TOD) Instrument model Sky map Noise

Impossible to invert H → can use a Preconditioned Conjugate Gradient method (PCG)

Frequency map making



Frequency map making

$$\vec{d} = \sum_{i=1}^{N_{sub}} \Delta\nu_i H_{\nu_i} \cdot \vec{s}_{\nu_i} + \vec{n}$$

Diagram illustrating the frequency map making equation:

- $\vec{d}$ is labeled **Data**.
- $\Delta\nu_i H_{\nu_i}$ is labeled **Sub-instrument model**.
- $\vec{s}_{\nu_i}$ is labeled **Sky map**.
- $\vec{n}$ is labeled **Noise**.

[Chanial, Régnier, et al., arXiv:2409.18698]

Frequency map making

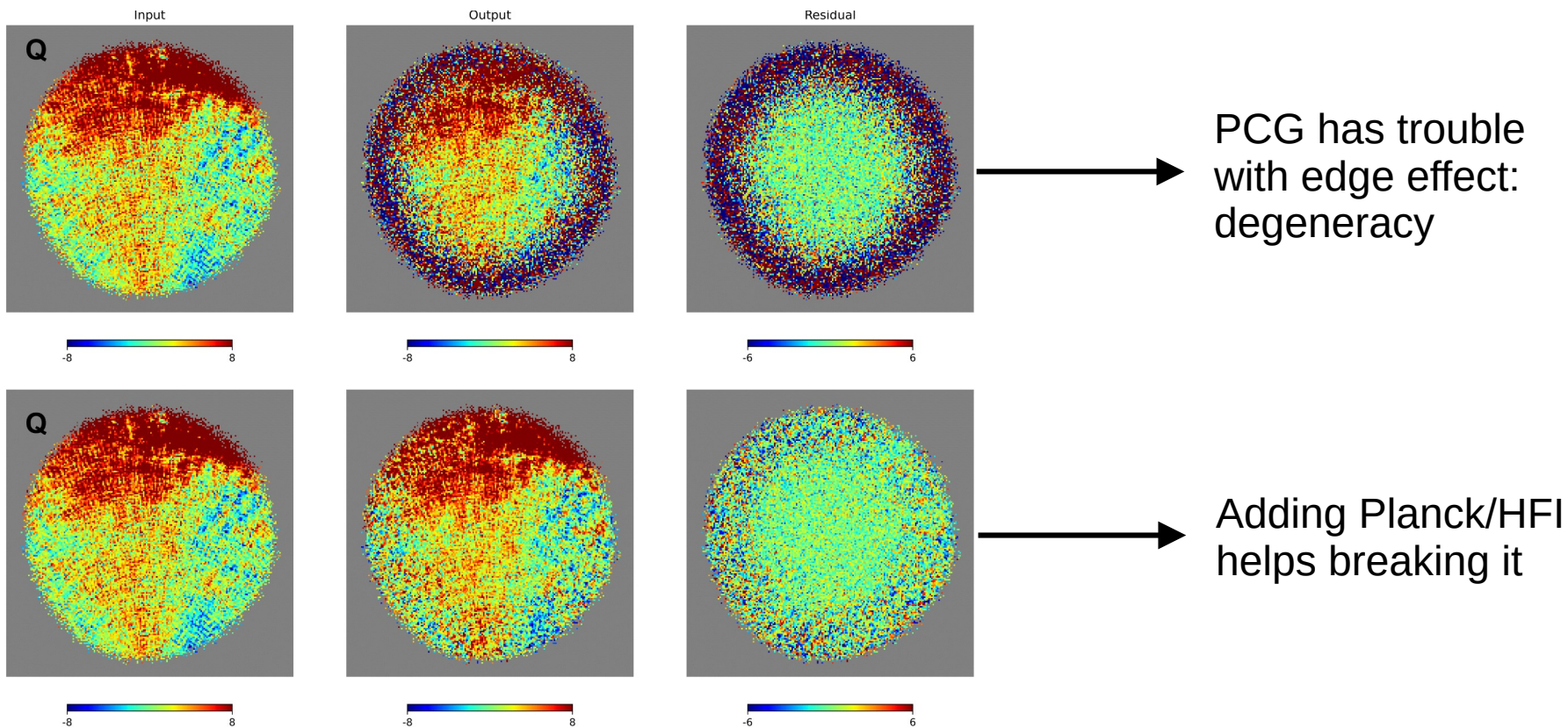
The diagram illustrates the equation for frequency map making. The equation is:
$$\vec{d} = \sum_{i=1}^{Nsub} \Delta\nu_i H_{\nu_i} \cdot \vec{s}_{\nu_i} + \vec{n}$$
 The terms are labeled as follows:

- $\vec{d}$ is labeled "Input" in green and "Data" with a blue arrow pointing to it.
- $\sum_{i=1}^{Nsub}$ is labeled "Sub-instrument model" with a blue arrow pointing to it.
- $\Delta\nu_i H_{\nu_i}$ is labeled "Sub-instrument model" with a blue arrow pointing to it.
- $\vec{s}_{\nu_i}$ is labeled "Output" in red and "Sky map" with a blue arrow pointing to it.
- $\vec{n}$ is labeled "Noise" with a blue arrow pointing to it.

Impossible to invert $H \rightarrow$ can use a Preconditioned Conjugate Gradient method (PCG)

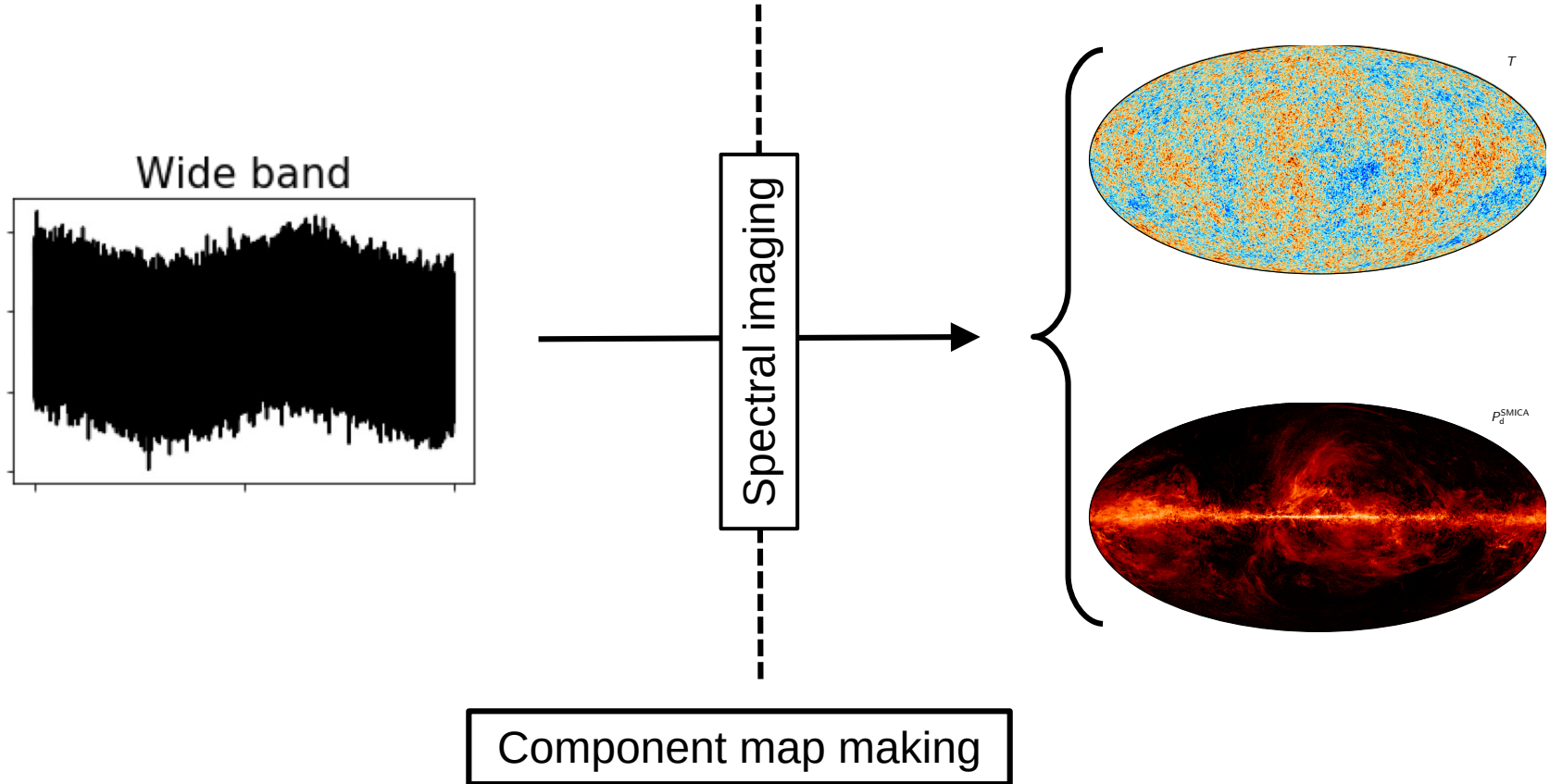
[Chaniel, Régnier, et al., arXiv:2409.18698]

Frequency map making



[Chaniel, Régnier, et al., arXiv:2409.18698]

Component map making



Component map making

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

Diagram illustrating the equation for component map making, with arrows indicating the mapping of terms to their physical meanings:

- $\vec{d}$ maps to Data
- $\sum_{i=1}^{N_{sub}}$ maps to Sub-instrument model
- A_{ν_i} maps to Mixing matrix
- $\vec{c}$ maps to Component maps
- $\vec{n}$ maps to Noise

[Régnier, Laclavère, et al., arXiv:2409.18714]

Component map making

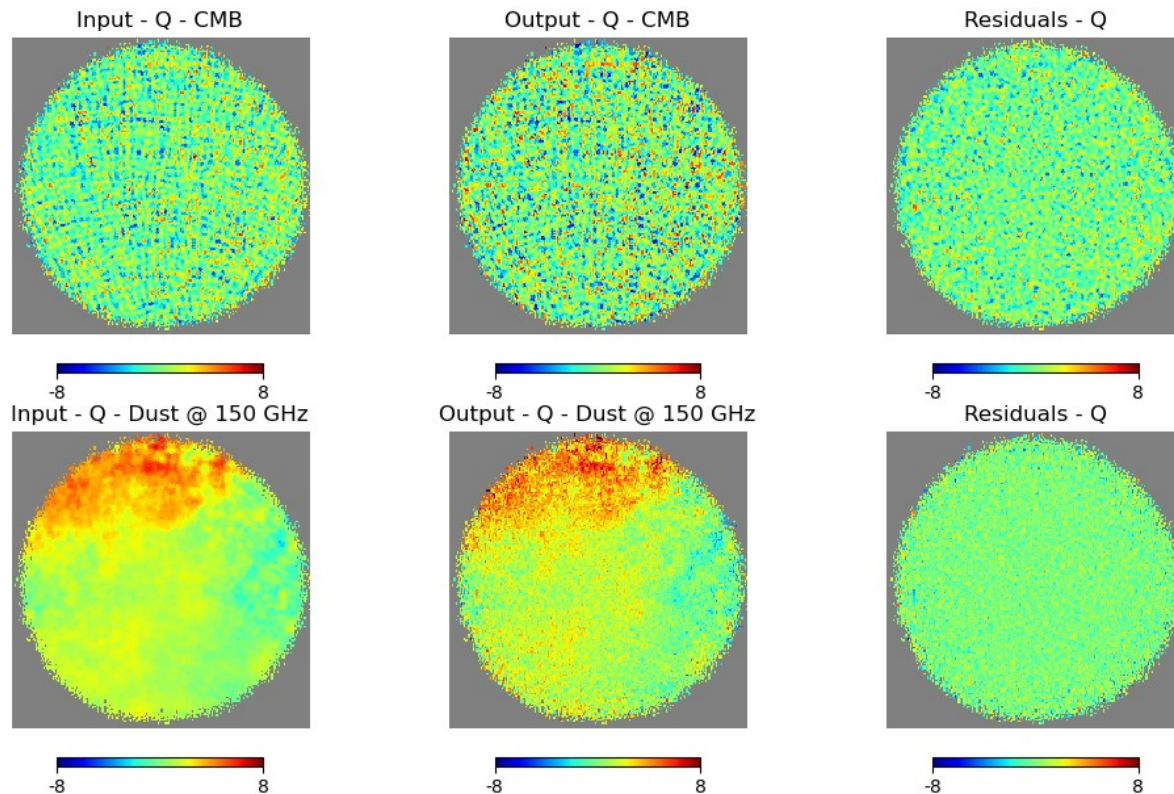
The diagram illustrates the equation for component map making. The equation is:
$$\vec{d} = \sum_{i=1}^{N_{sub}} \Delta\nu_i H_{\nu_i} \cdot A_{\nu_i} \vec{c} + \vec{n}$$
 Each term in the equation is enclosed in a colored box and has a label with an arrow pointing to it:

- $\vec{d}$ is in a green box labeled "Input" above it and "Data" below it.
- $\sum_{i=1}^{N_{sub}}$ is labeled "Sub-instrument model" below it.
- $\Delta\nu_i H_{\nu_i}$ is labeled "Sub-instrument model" below it.
- A_{ν_i} is in a purple box labeled "Byproduct" above it and "Mixing matrix" below it.
- $\vec{c}$ is in a red box labeled "Output" above it and "Component maps" below it.
- $\vec{n}$ is labeled "Noise" below it.

Impossible to invert $H \rightarrow$ can use a Preconditioned Conjugate Gradient method (PCG)

[Régnier, Laclavère, et al., arXiv:2409.18714]

Component map making



Planck HFI was added to mitigate the edge effect

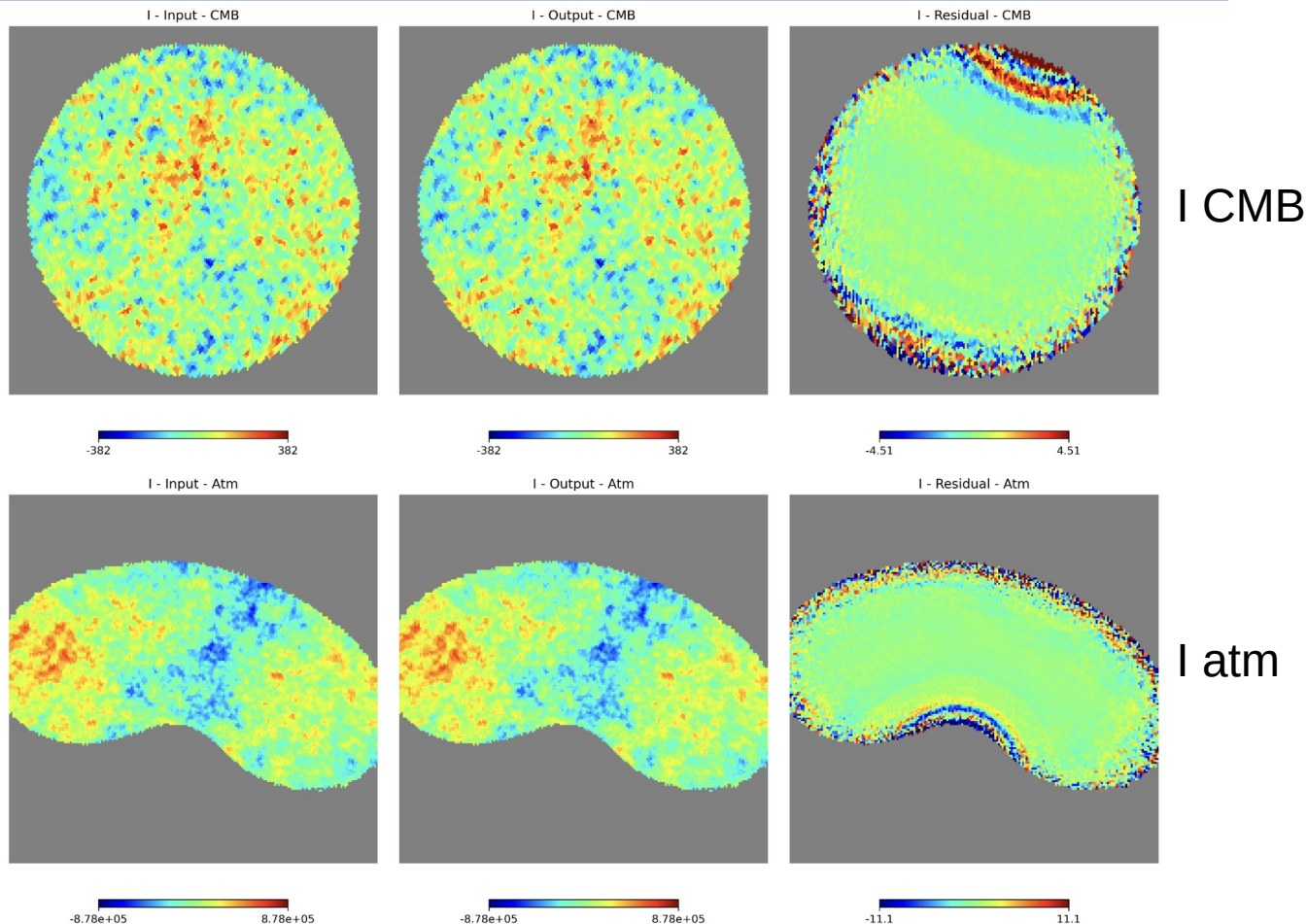
[Régner, Laclavère, et al., arXiv:2409.18714]

Map-making at APC

Atmosphere as component

Simple modelling:

- no noise
- no wind
- 2D atmosphere

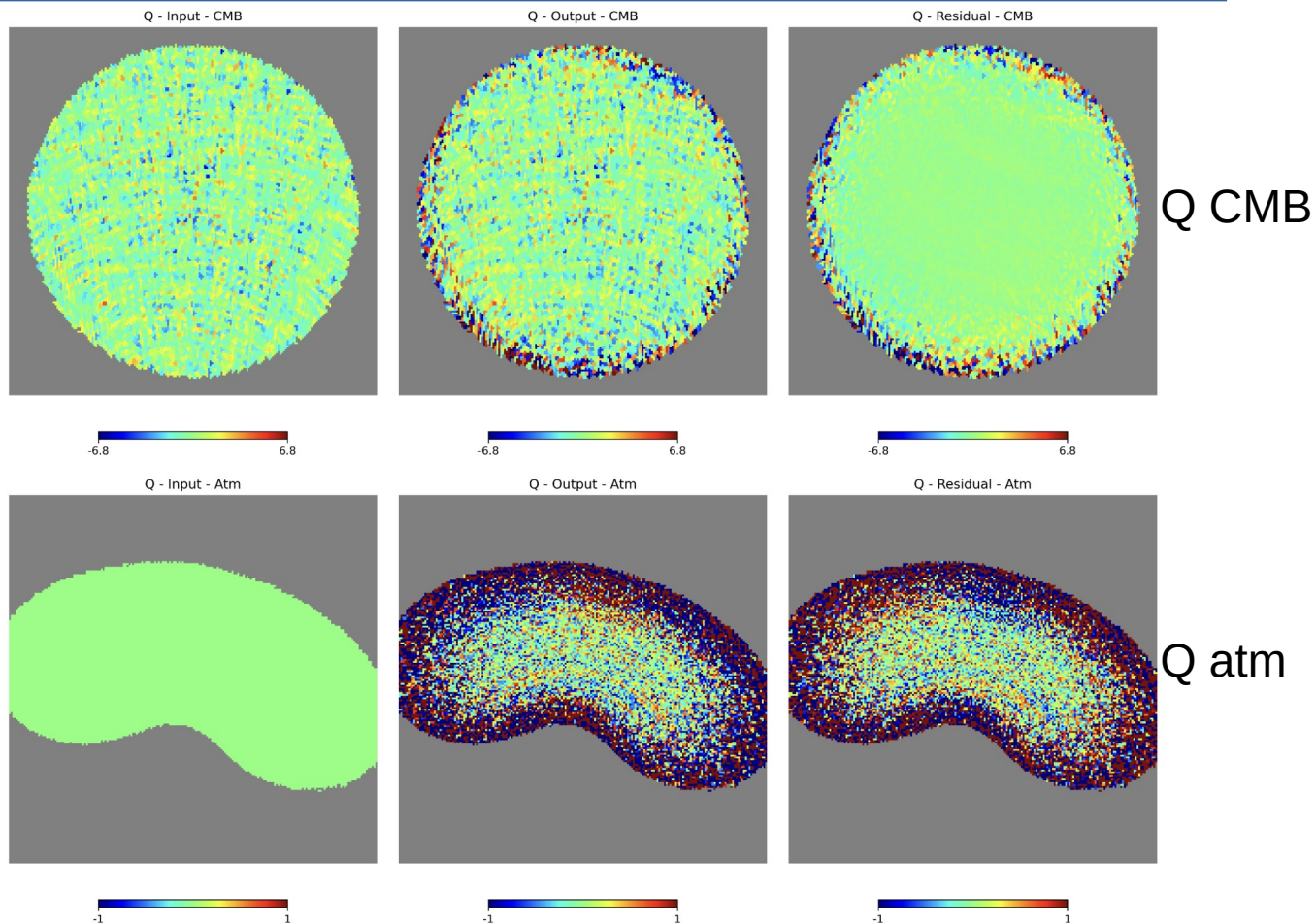


Tom Laclavère, PhD (APC)

Atmosphere as component

Simple modelling:

- no noise
- no wind
- 2D atmosphere



Tom Laclavère, PhD (APC)

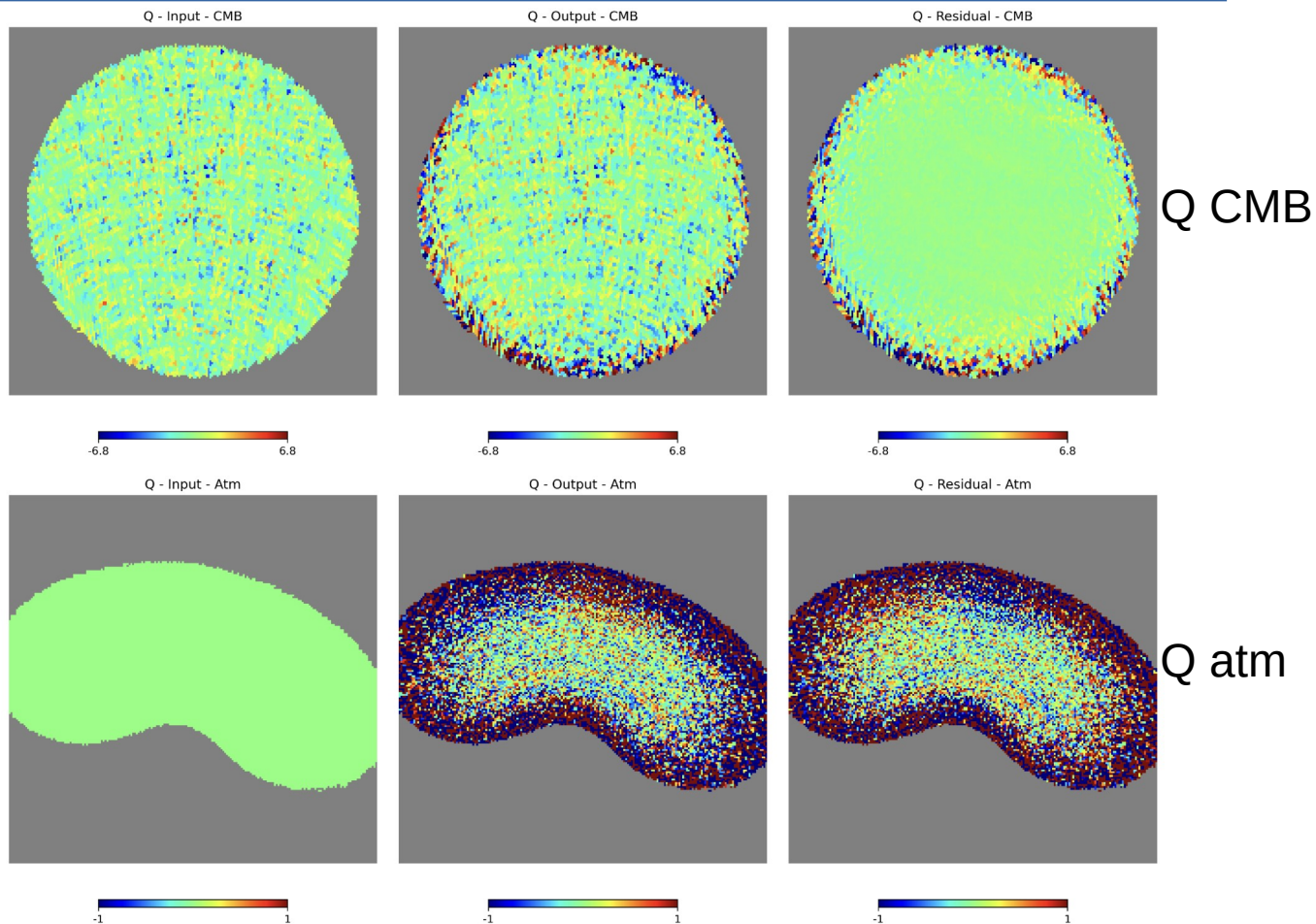
Atmosphere as component

Simple modelling:

- no noise
- no wind
- 2D atmosphere

Information to add:

- Planck
- Atmosphere is not polarised



Tom Laclavère, PhD (APC)

Physics-guided Machine Learning

The diagram illustrates the equation $\vec{d}_i = H_i \cdot \vec{s}_i + \vec{n}_i$. The term $\vec{d}_i$ is enclosed in a green box with the word "Input" above it in green. A blue arrow points from this box to the text "Data (TOD)". The term H_i has a blue arrow pointing to the text "Instrument model". The term $\vec{s}_i$ is enclosed in a red box with the word "Output" above it in red. A blue arrow points from this box to the text "Sky map". The term $\vec{n}_i$ has a blue arrow pointing to the text "Noise".

$$\vec{d}_i = H_i \cdot \vec{s}_i + \vec{n}_i$$

Input

Output

Data (TOD)

Instrument model

Sky map

Noise

Approximate an invert of H with Machine Learning

Leonora Kardum, postdoc (APC)

Physics-guided Machine Learning

All steps between sky and TOD

$$H = \overbrace{B \cdot I \cdot D \cdot L \cdot Hw \cdot P \cdot F \cdot A \cdot T \cdot U}$$

Leonora Kardum, postdoc (APC)

Physics-guided Machine Learning

All steps between sky and TOD

$$H = \overbrace{B \cdot I \cdot D \cdot L \cdot H_w \cdot P \cdot F \cdot A \cdot T \cdot U}$$

$$\tilde{H}^{-1} = U^{-1} \cdot T^{-1} \cdot A^{-1} \cdot F^{-1} \cdot P^{-1} \cdot H_w^{-1} \cdot L^{-1} \cdot D^{-1} \cdot I^{-1} \cdot B^{-1}$$

Leonora Kardum, postdoc (APC)

Physics-guided Machine Learning

All steps between sky and TOD

$$H = \overbrace{B \cdot I \cdot D \cdot L \cdot H_w \cdot P \cdot F \cdot A \cdot T \cdot U}$$

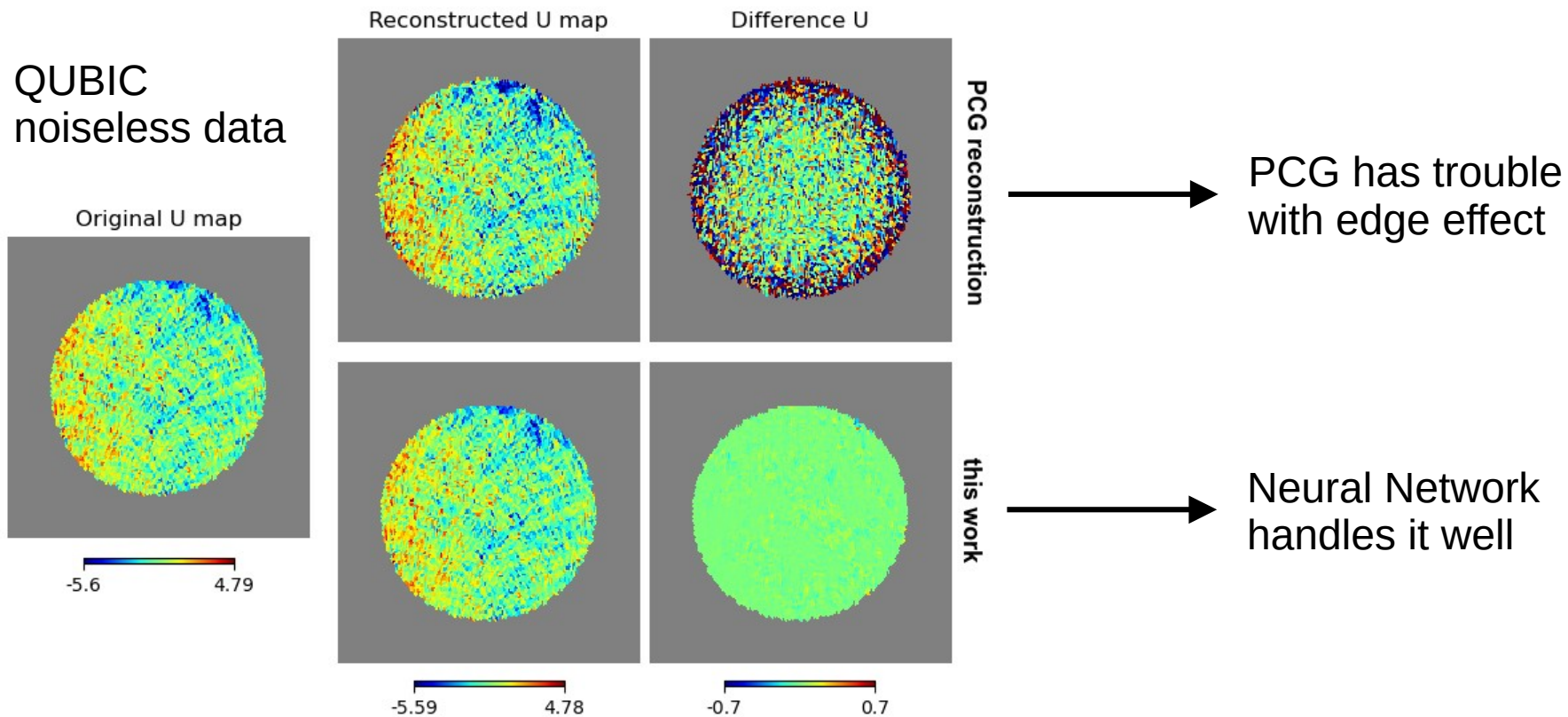
$$\tilde{H}^{-1} = U^{-1} \cdot T^{-1} \cdot A^{-1} \cdot F^{-1} \cdot P^{-1} \cdot H_w^{-1} \cdot L^{-1} \cdot D^{-1} \cdot I^{-1} \cdot B^{-1}$$

Limit free parameters based on the physics of each sub-system

→ Result is modular and interpretable

Leonora Kardum, postdoc (APC)

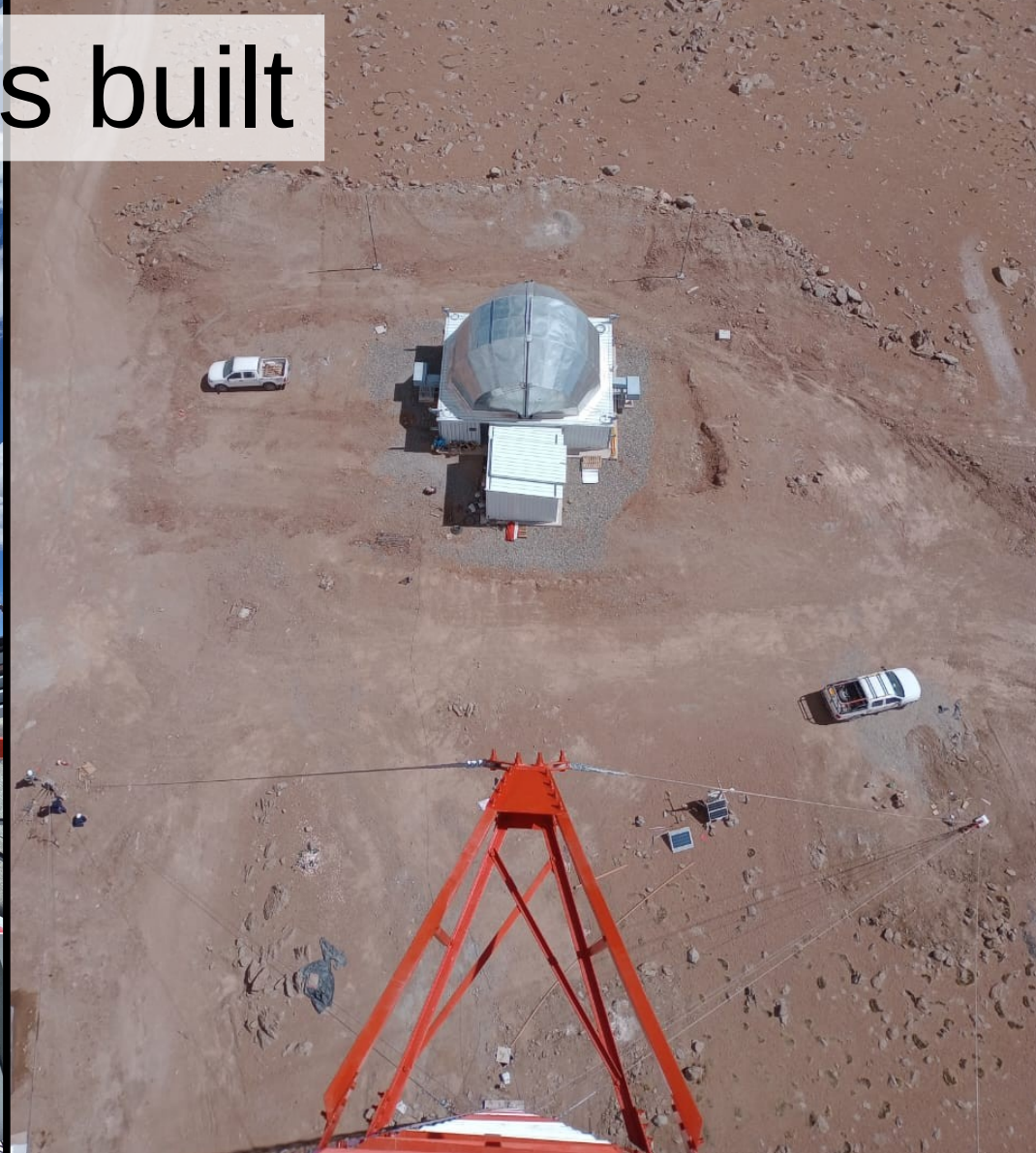
Physics-guided Machine Learning



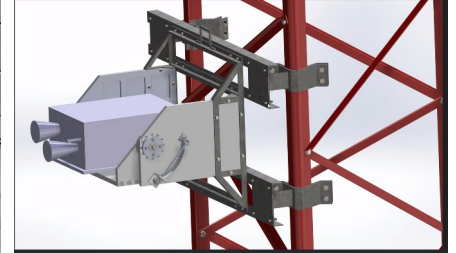
Leonora Kardum, postdoc (APC)

Current status of the instrument

Calibration tower is built



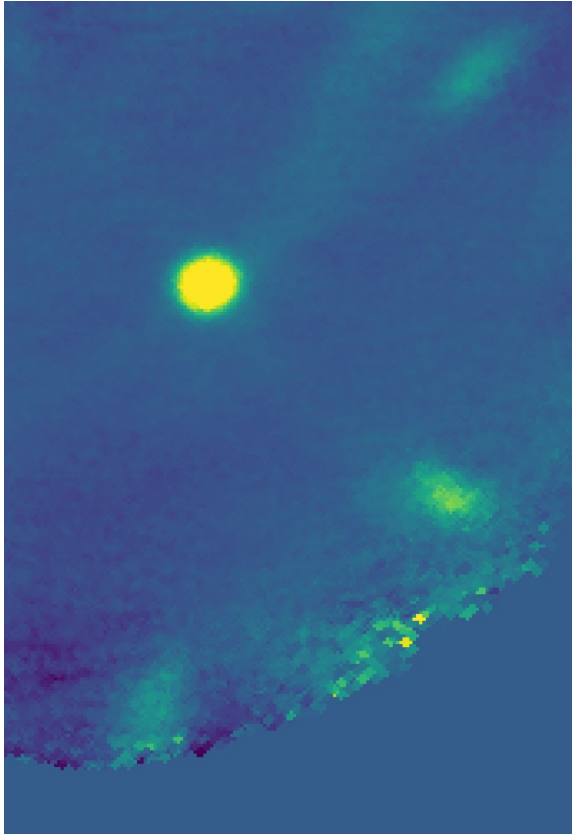
Calibration box: in 2025



Cable carrier: this week

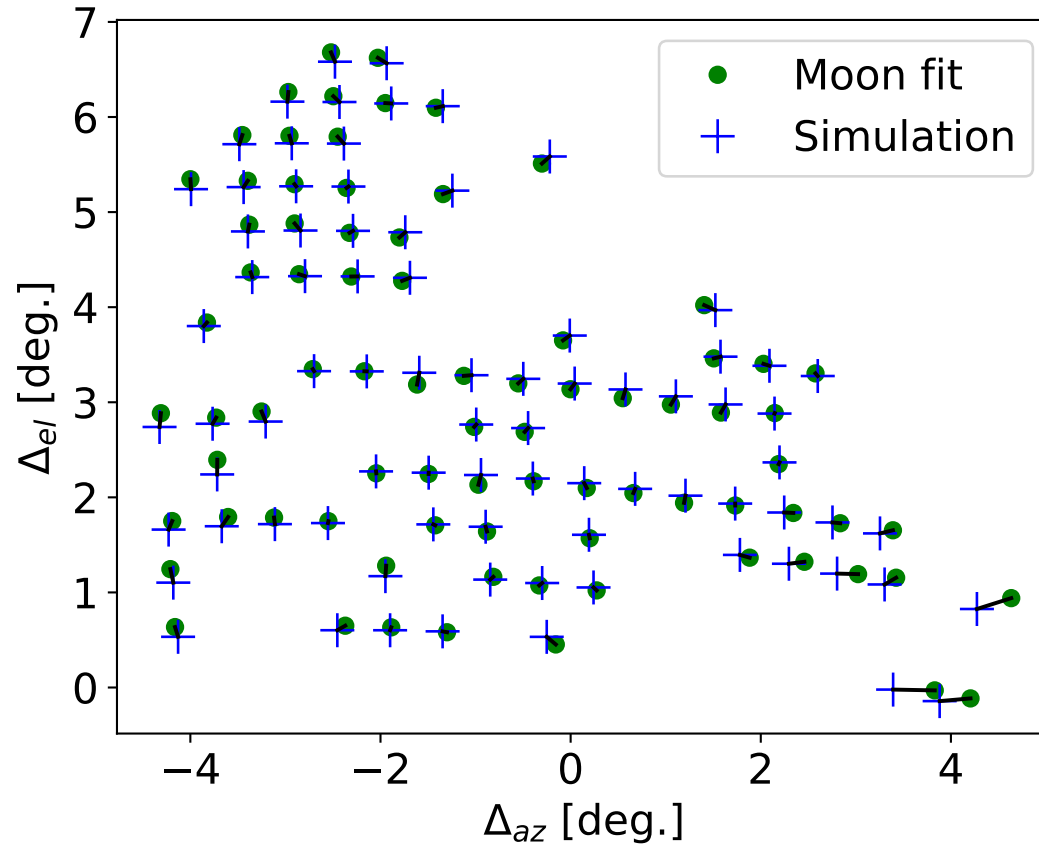


Moon maps



- 81 TES maps stacked
- 3.5 hours of observation in suboptimal conditions

Test calibration



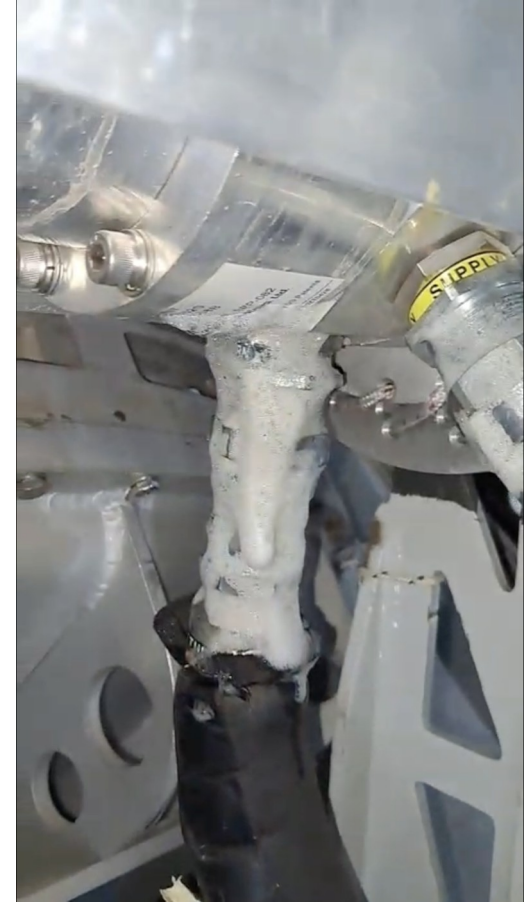
Delta with the l.o.s. of the instrument for 81 TES

Thank you for your attention



Backup slides

Three snow storms, leak



Generators down



Ground shield: after cable carrier

