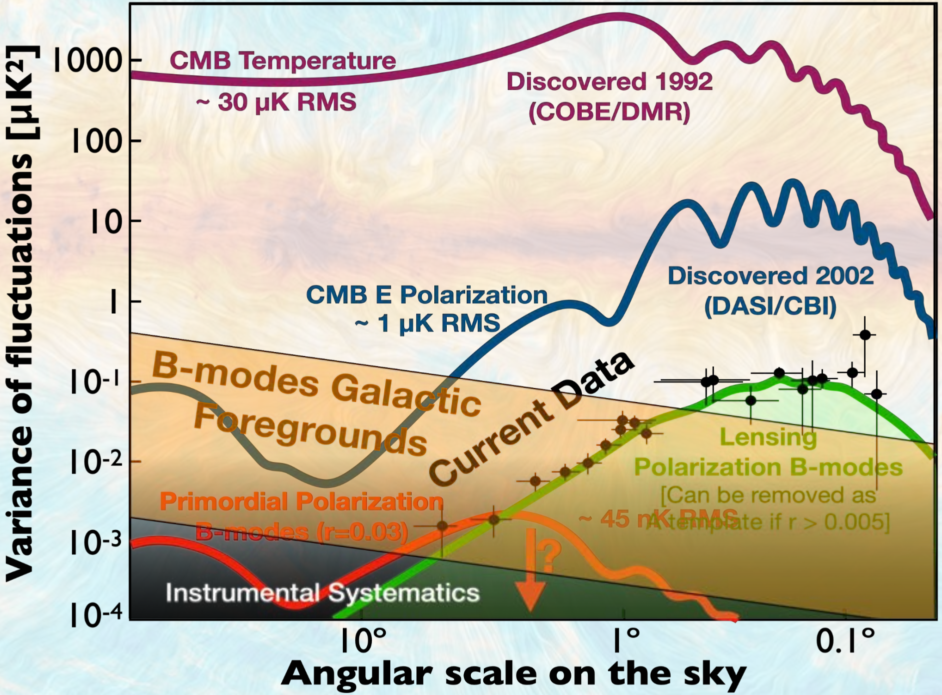
Exploring the primordial Universe with QUBIC

The QU Bolometric Interferometer for Cosmology

J.-Ch. Hamilton (APC-CNRS-IN2P3, Paris, France) on behalf of the QUBIC Collaboration

Challenges for the primordial B-modes quest



Small signal $\lesssim$ 45 nK

Instrumental Systematics $\lesssim$ 1%

Polarized Foregrounds $\gtrsim$ primordial B-modes

J.-Ch. Hamilton
APC - Paris - France
hamilton@apc.in2p3.fr

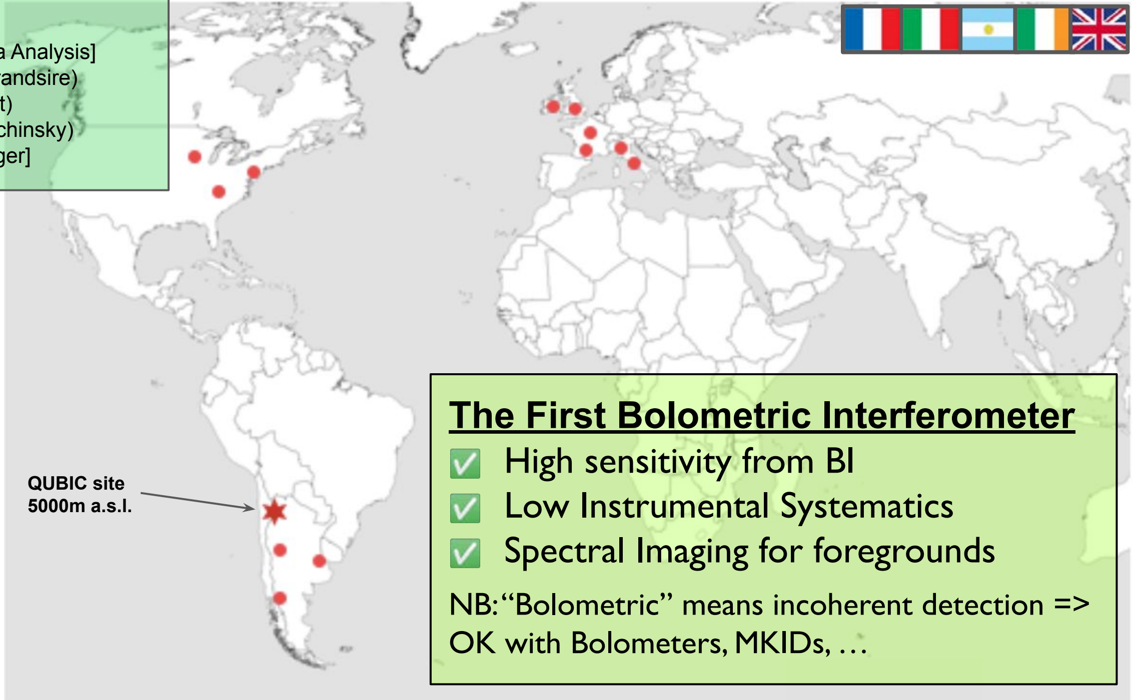
QUBIC

a Q&U Bolometric Interferometer for Cosmology

- APC Paris, France
- IRAP Toulouse, France
- C2N, Saclay, France
- Università di Milano-Bicocca, Italy
- Universitá degli studi di Milano, Italy
- Universitá La Sapienza, Roma, Italy
- Maynooth University, Ireland
- Cardiff University, UK
- University of Manchester, UK
- Brown University, USA
- Richmond University, USA
- University of Wisconsin, USA
- Centro Atómico Constituyentes, Argentina
- GEMA, Argentina
- Comisión Nacional de Energía Atómica, Argentina
- Facultad de Cs Astronómicas y Geofísicas, Argentina
- Centro Atómico Bariloche and Instituto Balseiro, Argentina
- Instituto de Tecnologías en Detección y Astropartículas, Argentina
- Instituto Argentino de Radioastronomía, Argentina

Responsibilities IN2P3:

- Spokesperson (JCH) [+Data Analysis]
- Dep. Project Manager (L.Grandsire)
- Instrument Scientist (M. Piat)
- Calibration Scientist (S. Torchinsky) [+Deputy Operations Manager]



The First Bolometric Interferometer

- ✅ High sensitivity from BI
- ✅ Low Instrumental Systematics
- ✅ Spectral Imaging for foregrounds

NB: "Bolometric" means incoherent detection => OK with Bolometers, MKIDs, …

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)

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Instrumental Systematics →
- Original low cross-polarization design
- Self-Calibration (interferometry)

B.I. → Natural low-systematics design

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

Specific B.I. feature

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[Torchinsky, Hamilton et al. QUBIC III] (JCAP 2022)

Specific B.I. feature

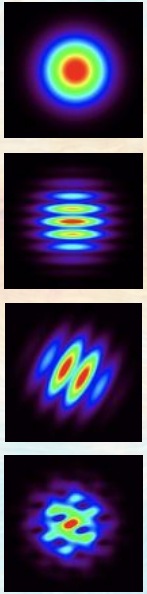
Polarized Foregrounds

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)

The QUBIC Concept: adding interferometry



1 Horn open

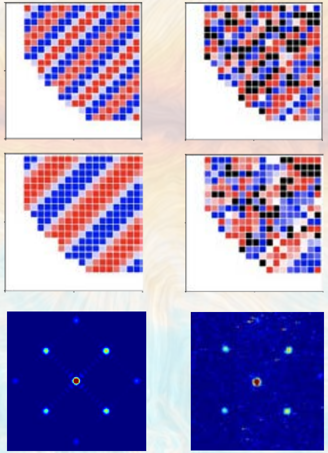
2 Horns open

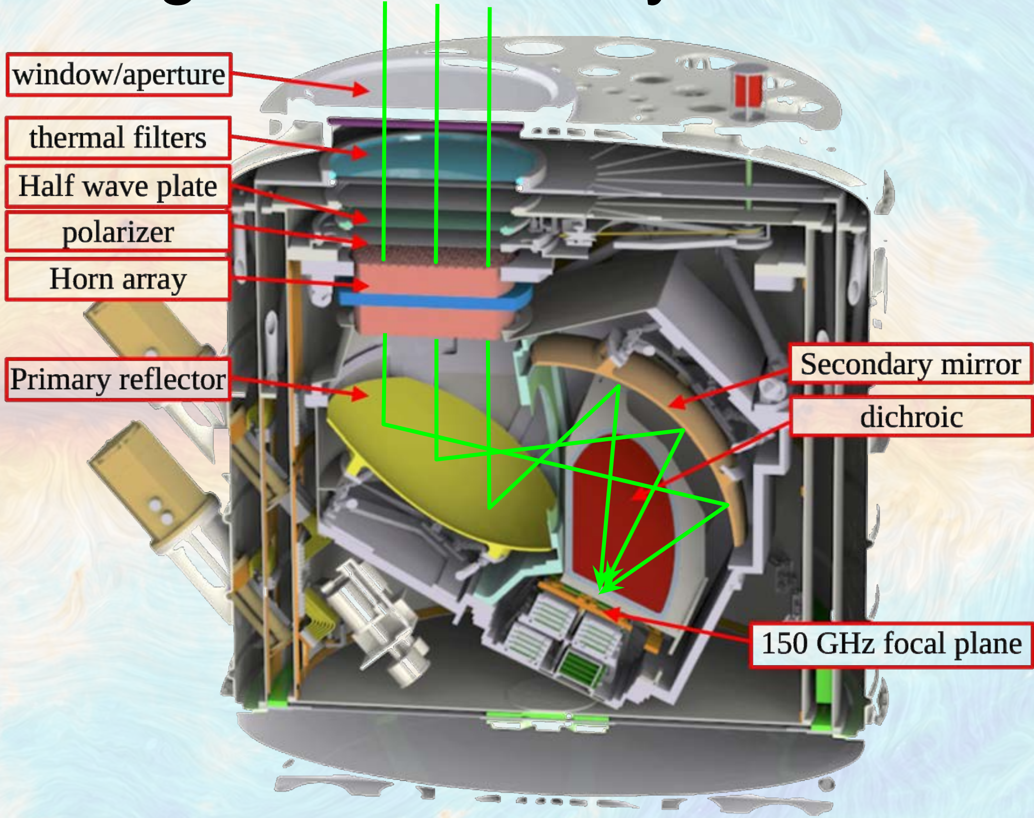
2 Horns open

All Horns open

[L. Mousset, PhD, 2021]

QUBIC Sim. **QUBIC Cal Data**



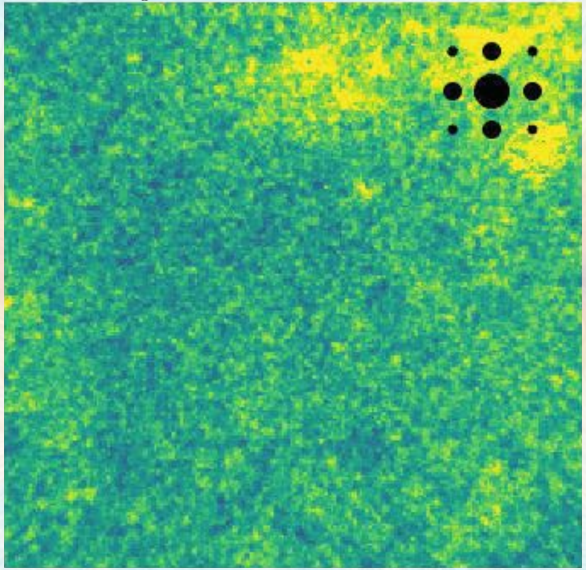


Fringe and Synthesized Beam data: [Torchinsky et al., QUBIC III, arXiv:2008.10056v3] (Special issue on QUBIC in JCAP, 2022)

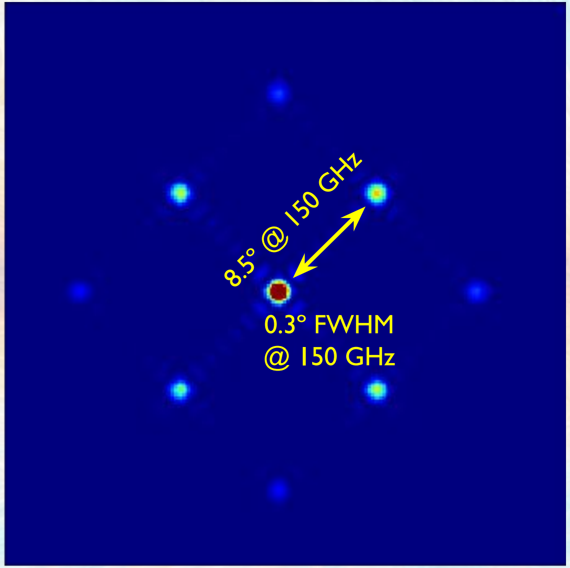
Bolometric Interferometry ⟺ Synthesized Beam Map-Making

We scan the sky with our PSF

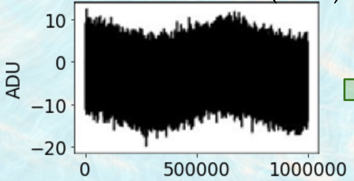
$$d(t) = \int B_s\left(\vec{n} - \vec{n}_{\rm ptg}(t)\right) Sky(\vec{n}) \mathrm{d}\vec{n}$$



QUBIC PSF (BI Synthesized beam)



Time-Ordered Data (TOD)



Map-Making with B.I.

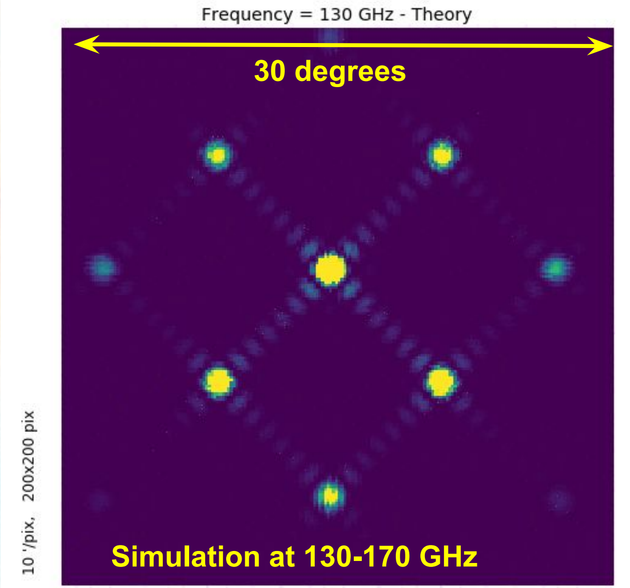
We need to solve for s: $\vec{y} = H \cdot \vec{s} + \vec{n}$

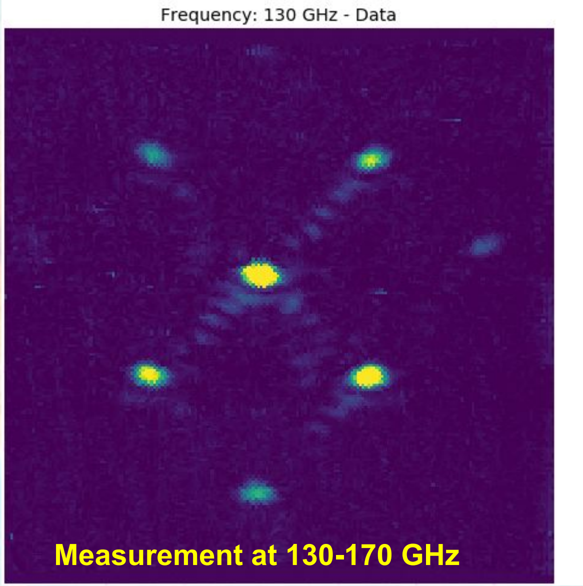
One needs partial deconvolution of the peaks

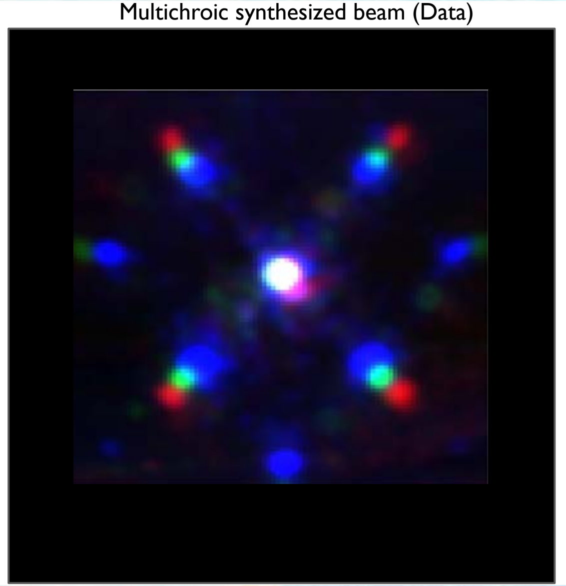
Inverse problem approach
χ^2 in TOD space
Regularization with Planck data

Back to the synthesized beam: **real calibration data**

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



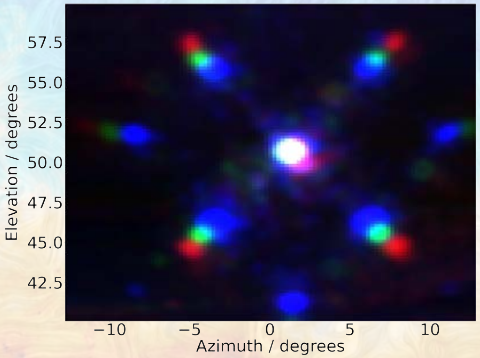




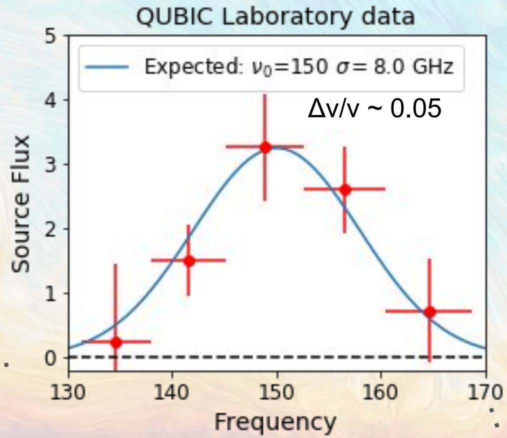
[Torchinsky et al., QUBIC III arXiv:2008.10056v3] (Special issue on QUBIC in JCAP, 2022)

Peaks distance evolution w.r.t. Frequency opens the path to Spectral Imaging ! Unique to BI !

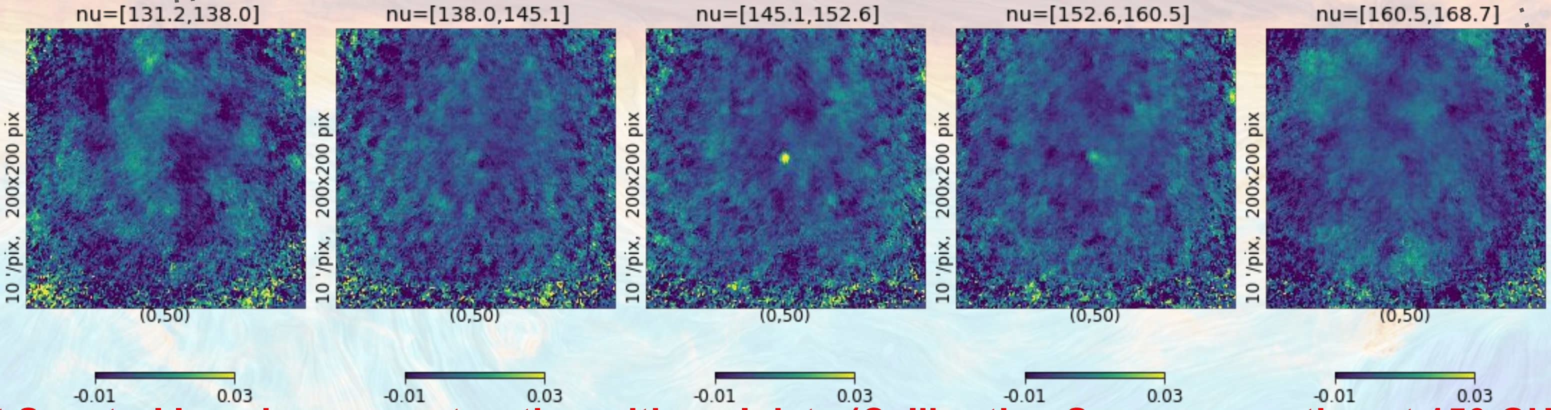
QUBIC Multichroic Synthesized beam measurement (130, 150, 170 GHz)



Spectral Imaging with Real Data (26 detectors)



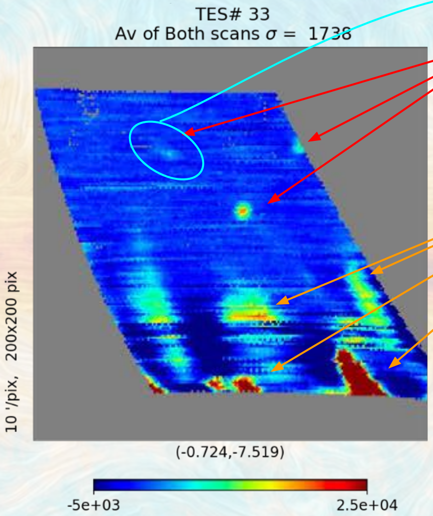
(~3.2 GHz with FI)
Δν/ν ~ 0.02



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)

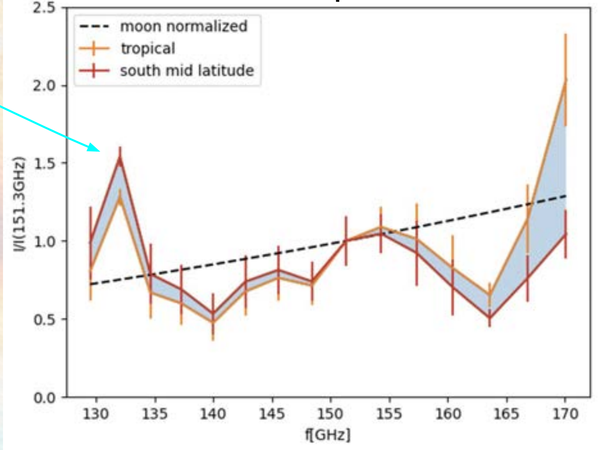
Moon spectrum measurement (Salta, July 2022, few hours)



Moon

Trees

Moon EM Spectrum



[D'Alessandro et al. in prep]

To be improved soon a the site (less sky noise, more integration time)

J.-Ch. Hamilton
APC - Paris - France
hamilton@apc.in2p3.fr

Spectral-Imaging simulations

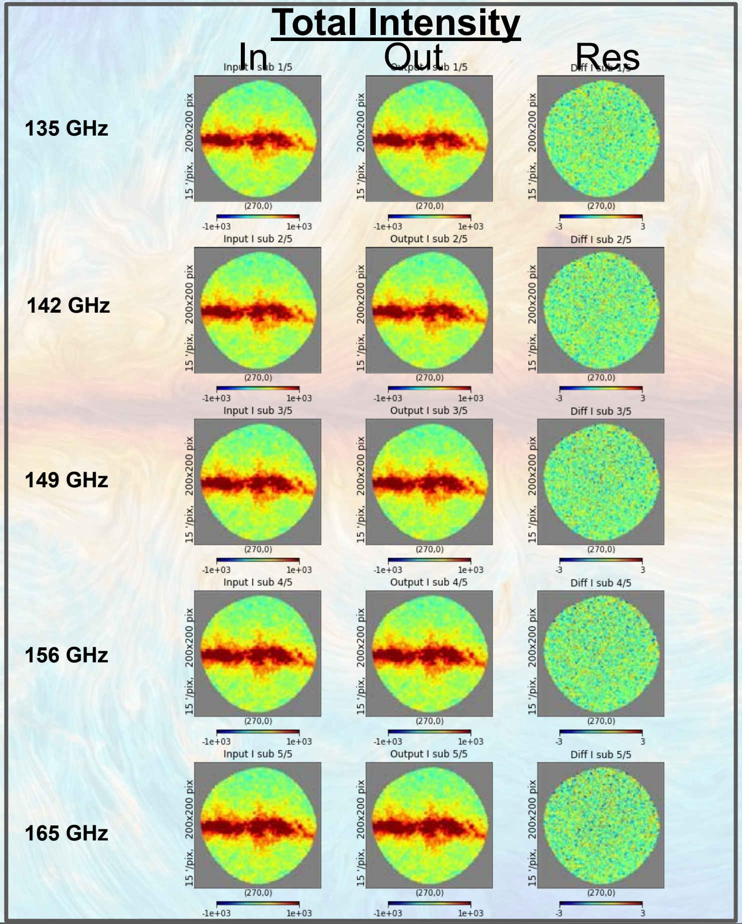
Update of [Mousset, Gamboa et al., QUBIC II, arXiv:2010.15119v1] (Special issue on QUBIC in JCAP, 2022) + [Mathias Regnier, PhD thesis, in progress]

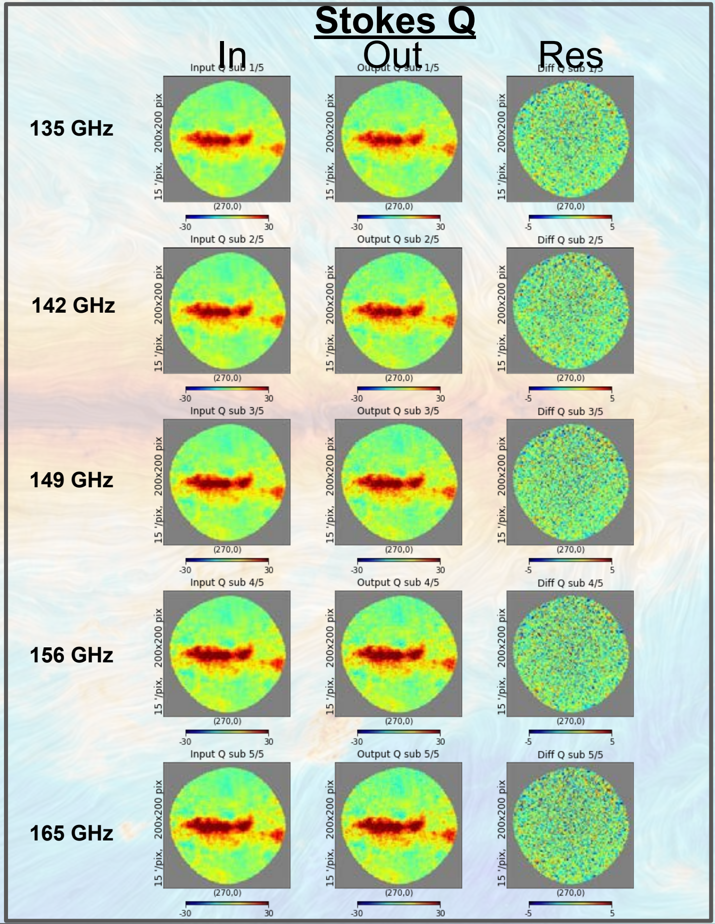
150 GHz physical band (filter)

A single TOD projected onto 5 sub-bands

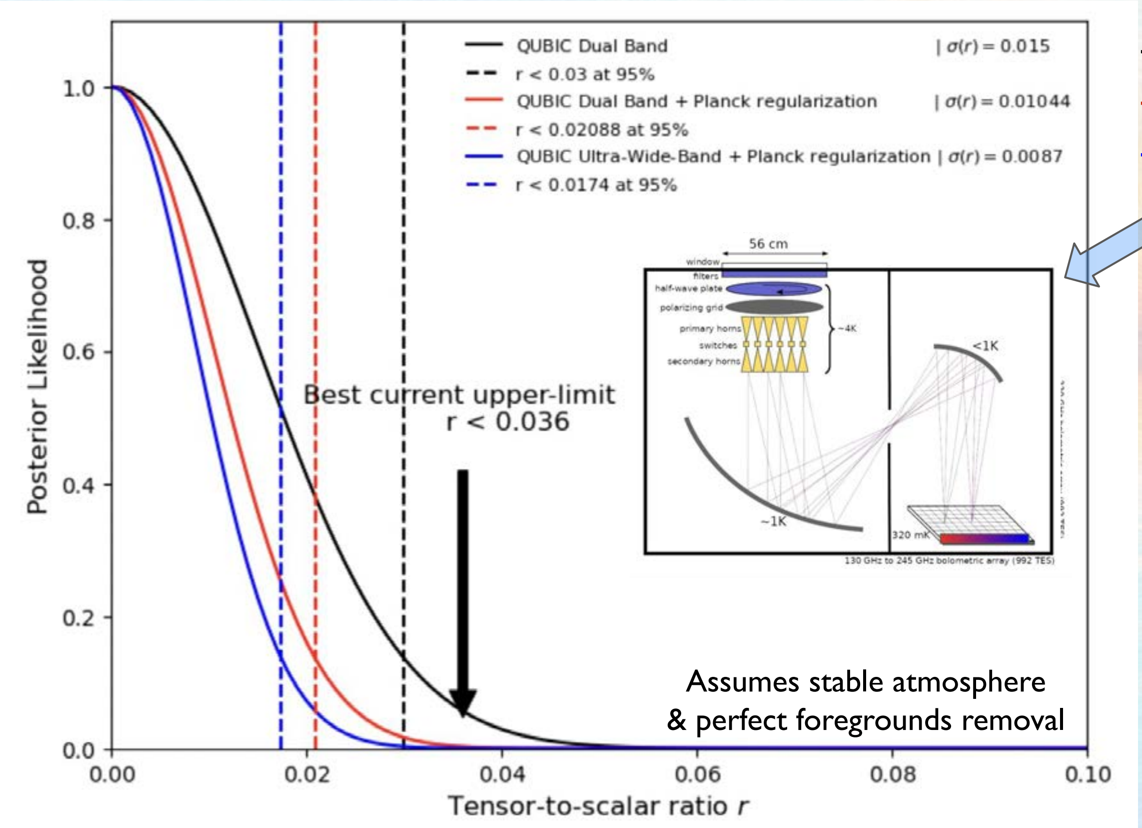
Unique to B.I.

NB: similar at 220 GHz





Sensitivity forecasts (3 years QUBIC FI): $\sigma(r) = 0.01$

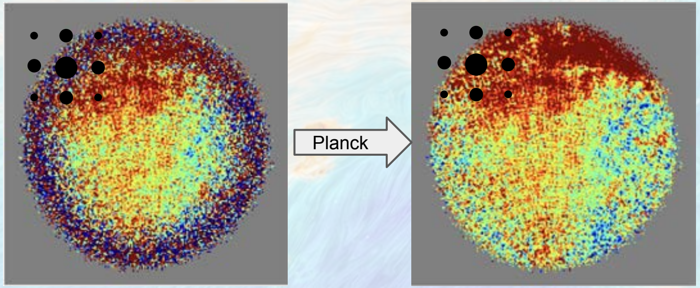


→ QUBIC Papers 2022 — $\sigma(r)=0.015$

→ With Planck regularization — $\sigma(r)=0.01$

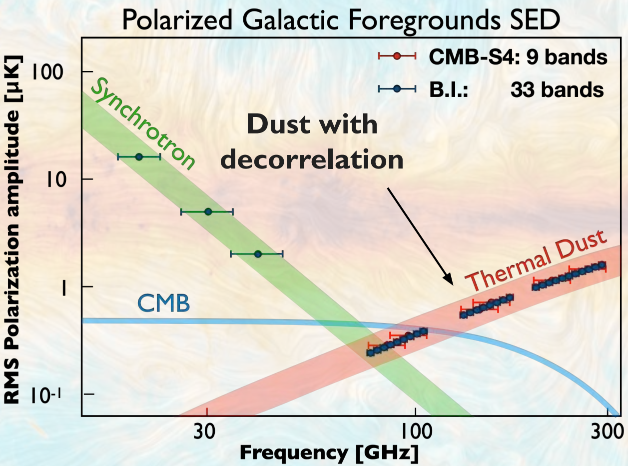
→ Ultra-Wide-Band + Planck — $\sigma(r)=0.009$

NB: Planck is used to regularize QUBIC map reconstruction near the edges.

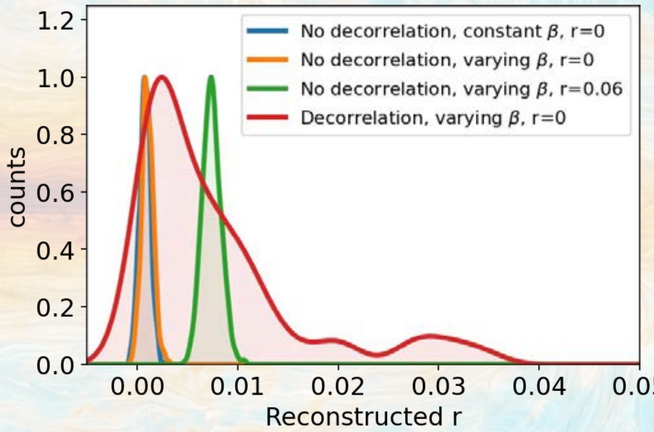


BI as a complement to CMB-S4: foreground mitigation

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



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

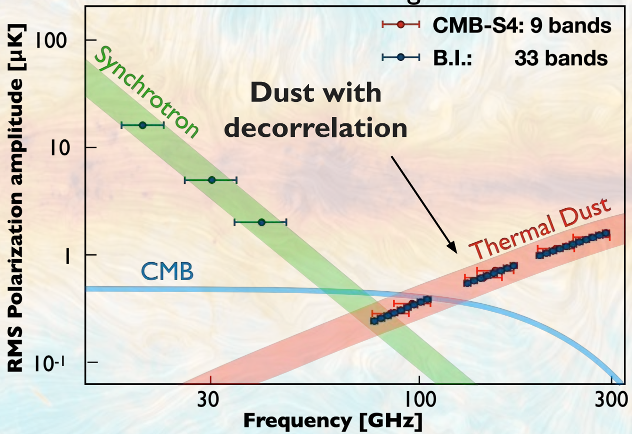


[Régnier, Manzan et al., submitted]

BI as a complement to CMB-S4: foreground mitigation

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

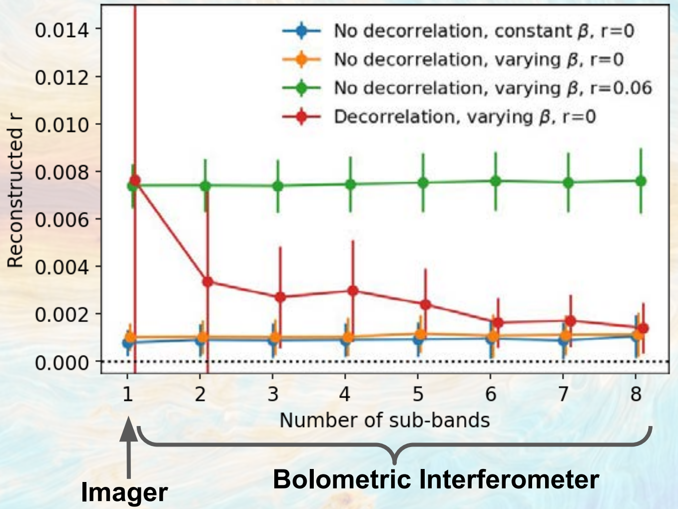
Polarized Galactic Foregrounds SED



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

Multi-band analysis with B.I. reveals the effect !

Range of reconstructed r Vs #sub-bands



[Régnier, Manzan et al., submitted]

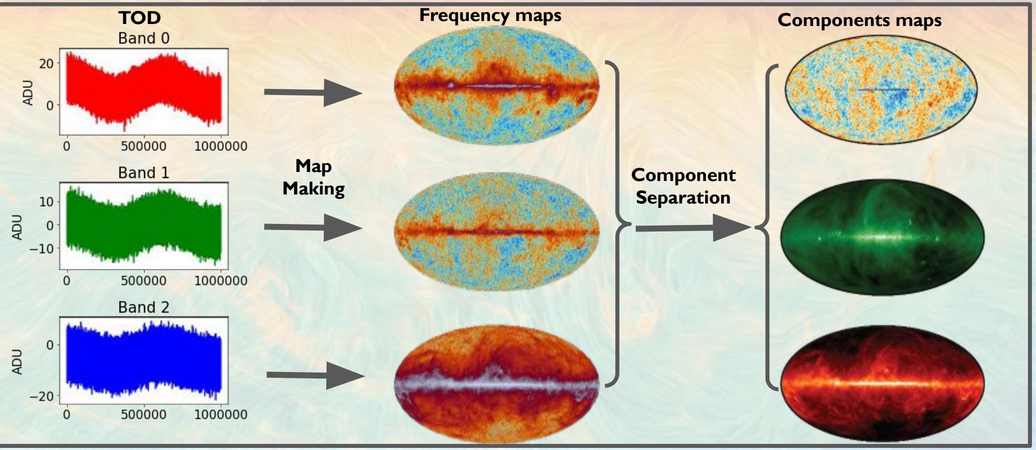
B.I. is needed to complement direct imaging: Dust decorrelation is to be expected from realistic dust

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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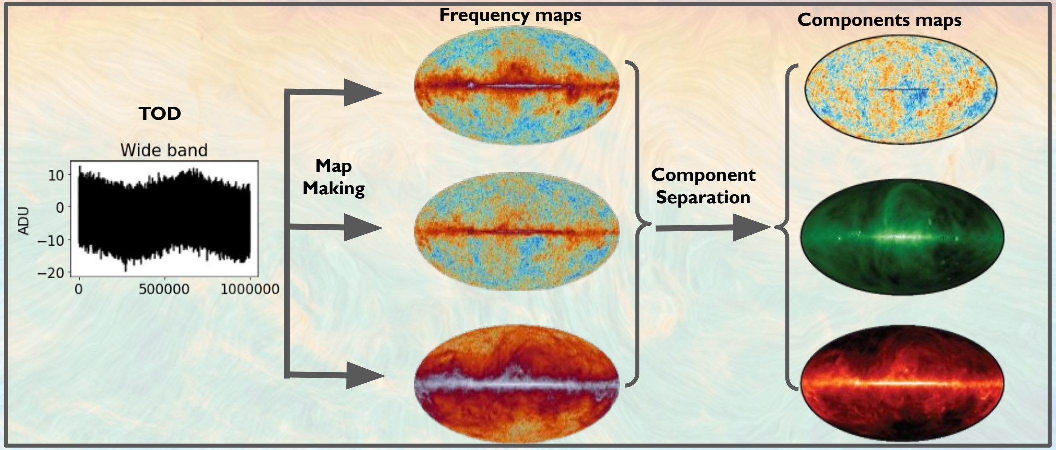
Classical Map-making (in each band)

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

⇩

Frequency Map-making

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



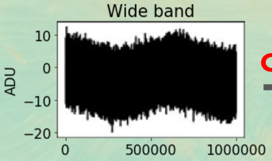
Frequency Mapmaking Bolometric Interferometer Pipeline

Component Separation Map-Making

- Classical imagers: Frequency maps ↦ 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]

Component Separation Map-Making

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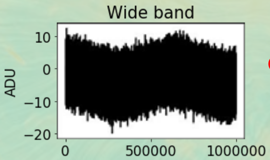
TOD



Component Separation Map Making

Spectral-imaging based:
Frequency Information in TOD

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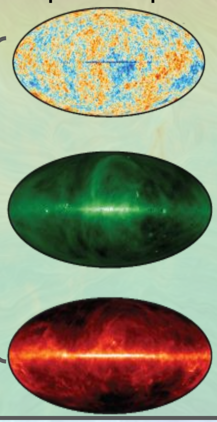
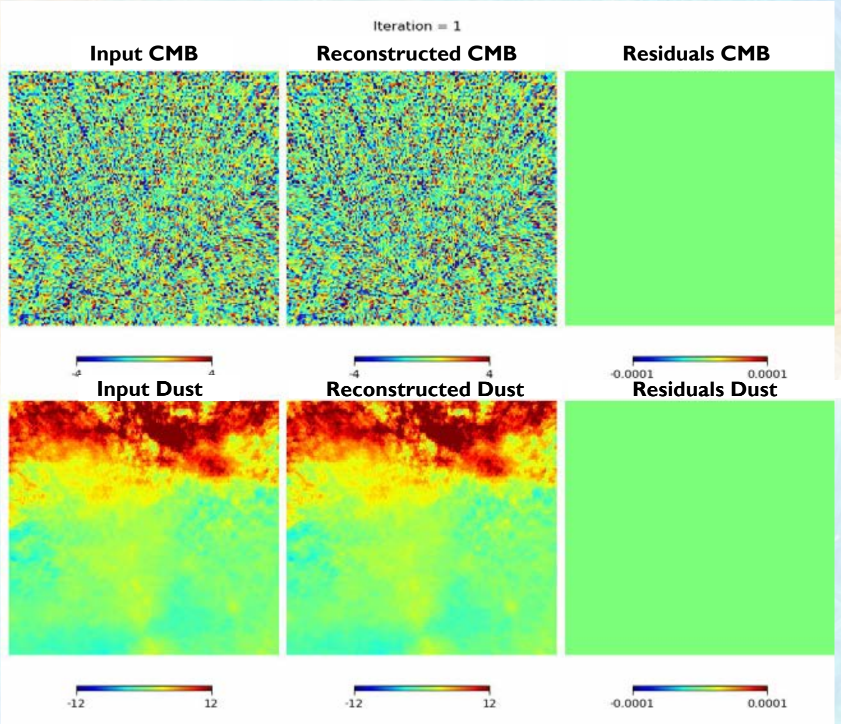
Components maps



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]

J.-Ch. Hamilton
APC - Paris - France
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Component Separation Map-Making

- Classical imagers: Frequency maps ↦ Component separation
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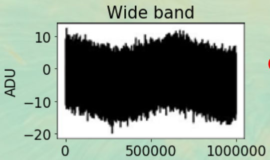
TOD



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Spectral-imaging based:
Frequency Information in TOD

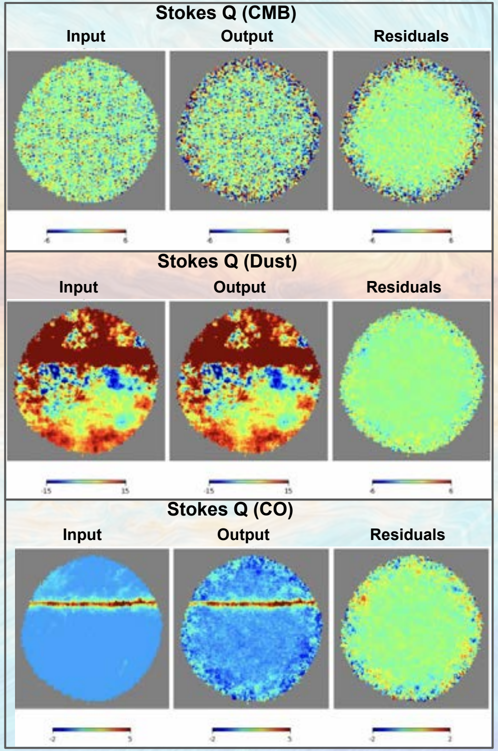
<u>Only possible with B.I. !</u>

Components maps

Frequency Mapmaking Bolometric Interferometer Pipeline

First TOD → Components MapMaking (parametric) !

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

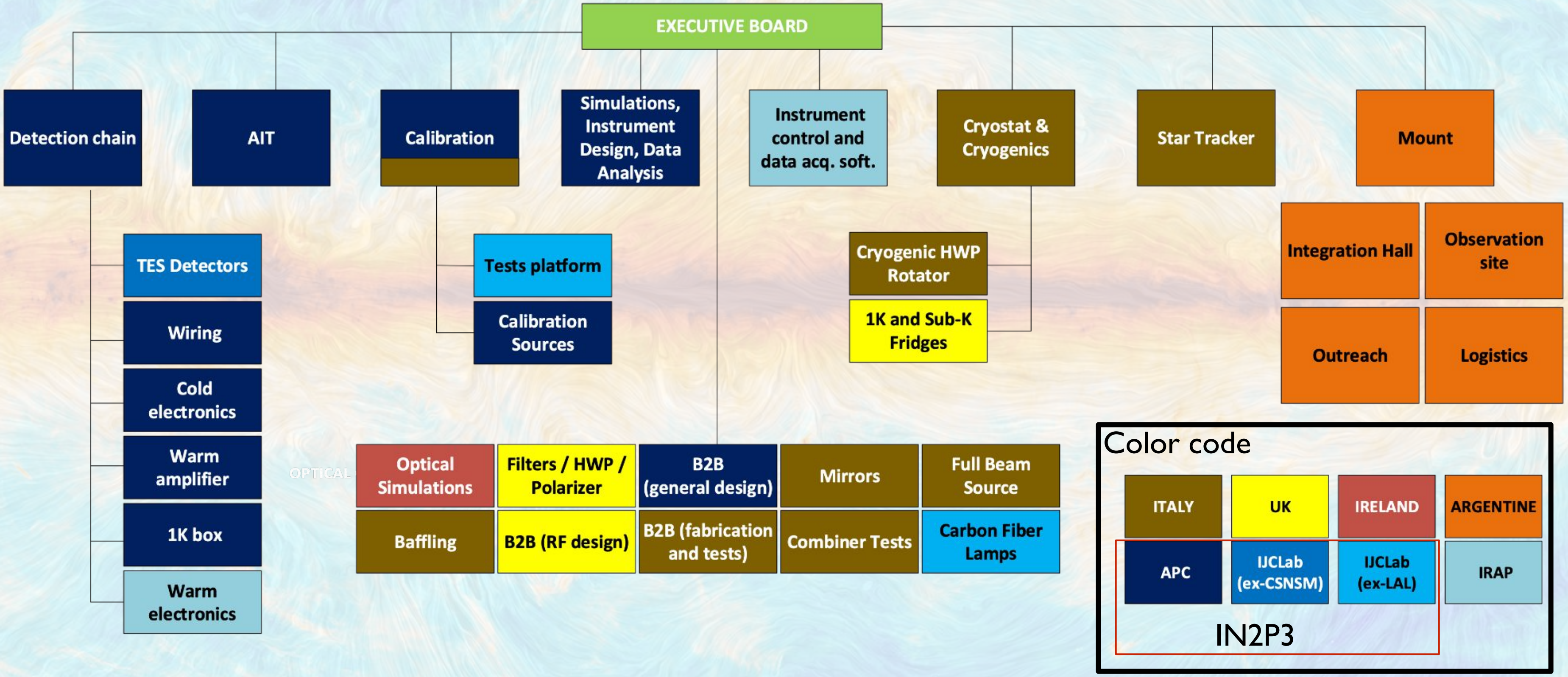


CO emission line

[Régnier et al., in preparation]

J.-Ch. Hamilton
APC - Paris - France
hamilton@apc.in2p3.fr

QUBIC WBS



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Instrument control and data acq. soft.
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Star Tracker
Mount
TES Detectors
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Mirrors
Full Beam Source
Baffling
B2B (RF design)
B2B (fabrication and tests)
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Color code
ITALY
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IJCLab (ex-LAL)
IRAP
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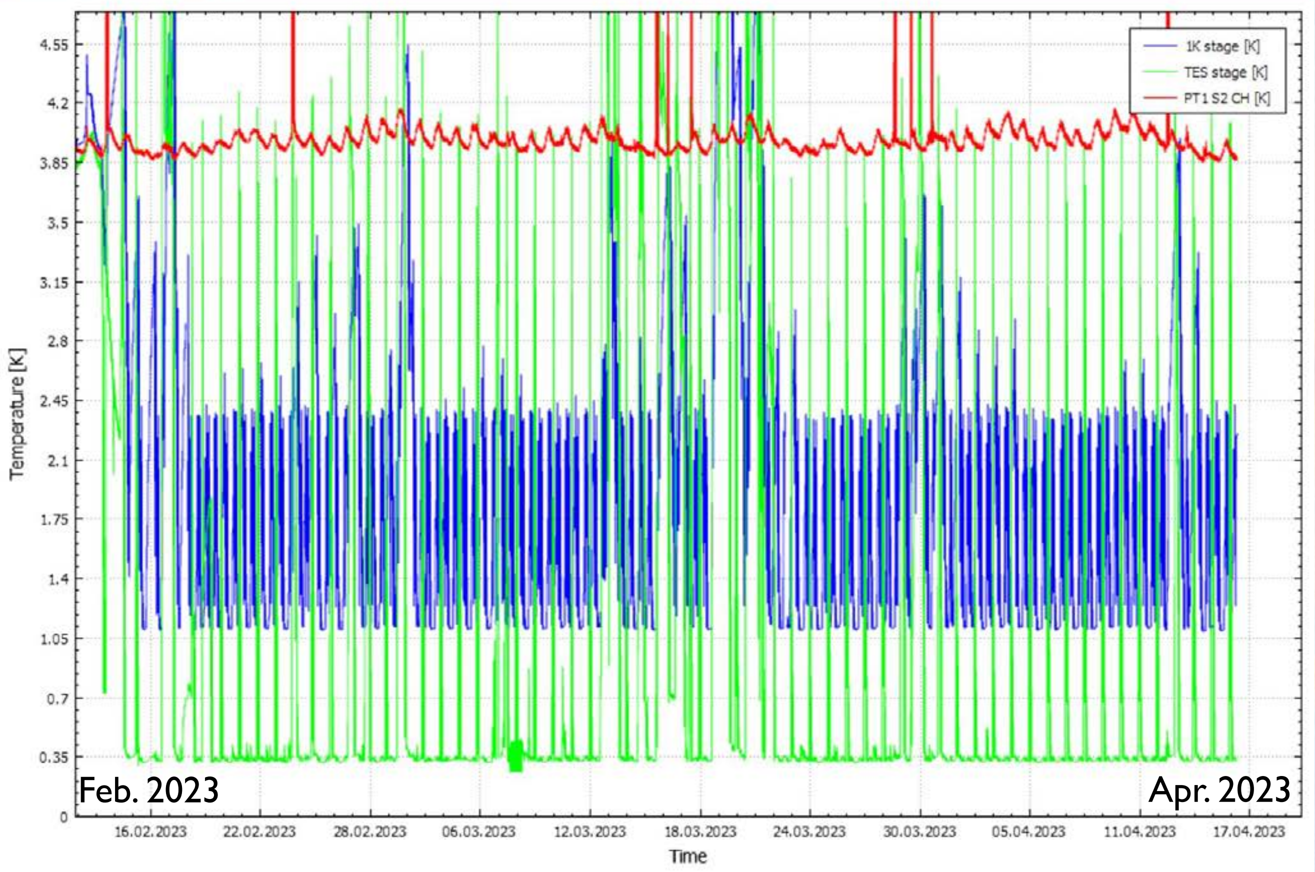
	2023	2024		2025	2026	2027
QUBIC Instrument phases	Data Taking with TD	Upgrade to FI (~ANR funded)	Data Taking with FI			QUBIC2 (SO, S4 ?)
Proposal Scientific phases and objectives	**Phase 1: QUBIC TD Science On-Sky demonstration of BI** ➔ First spectro-imaging results on bright Galactic regions		**Phase 2: QUBIC FI Science σ(r) = 0.01 (with Planck)** ➔ Self-Calibration operational ➔ Constraints on diffuse dust SED in the "clean" QUBIC field ➔ SED of bright Galactic regions			

- **QUBIC - 1st Bolometric Interferometer - inaugurated in Nov. 2022 - Commissioning is on its way !**
  - Sensitivity to **primordial B-modes**: **σ(r)=0.01 (3 years)**
  - Self Calibration & Low cross-polarization (**measured XPol < 0.6%** : a few times better than competitors)

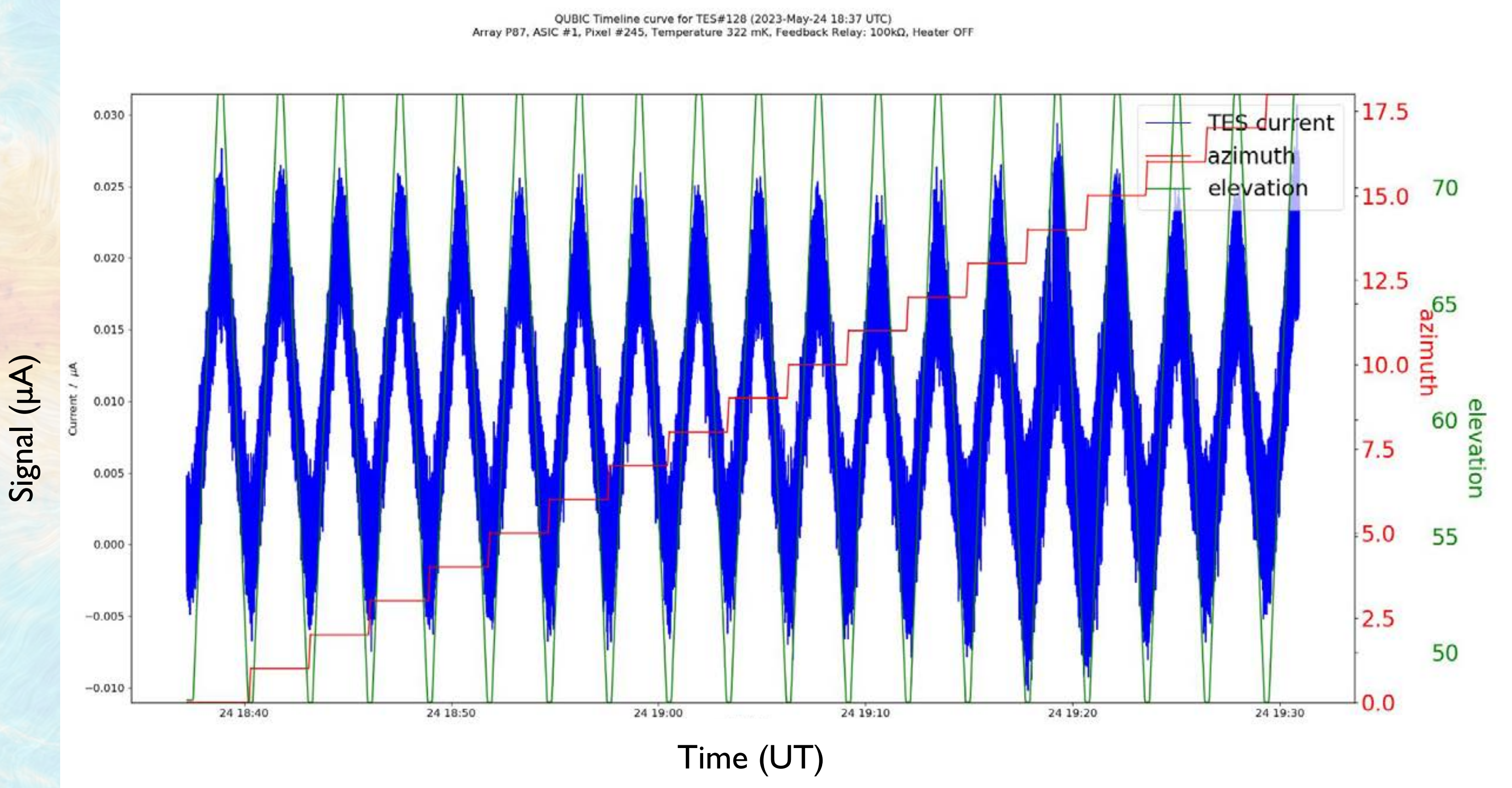
Welcome to join us !

QUBIC Commissioning: Cryogenic yield 50%

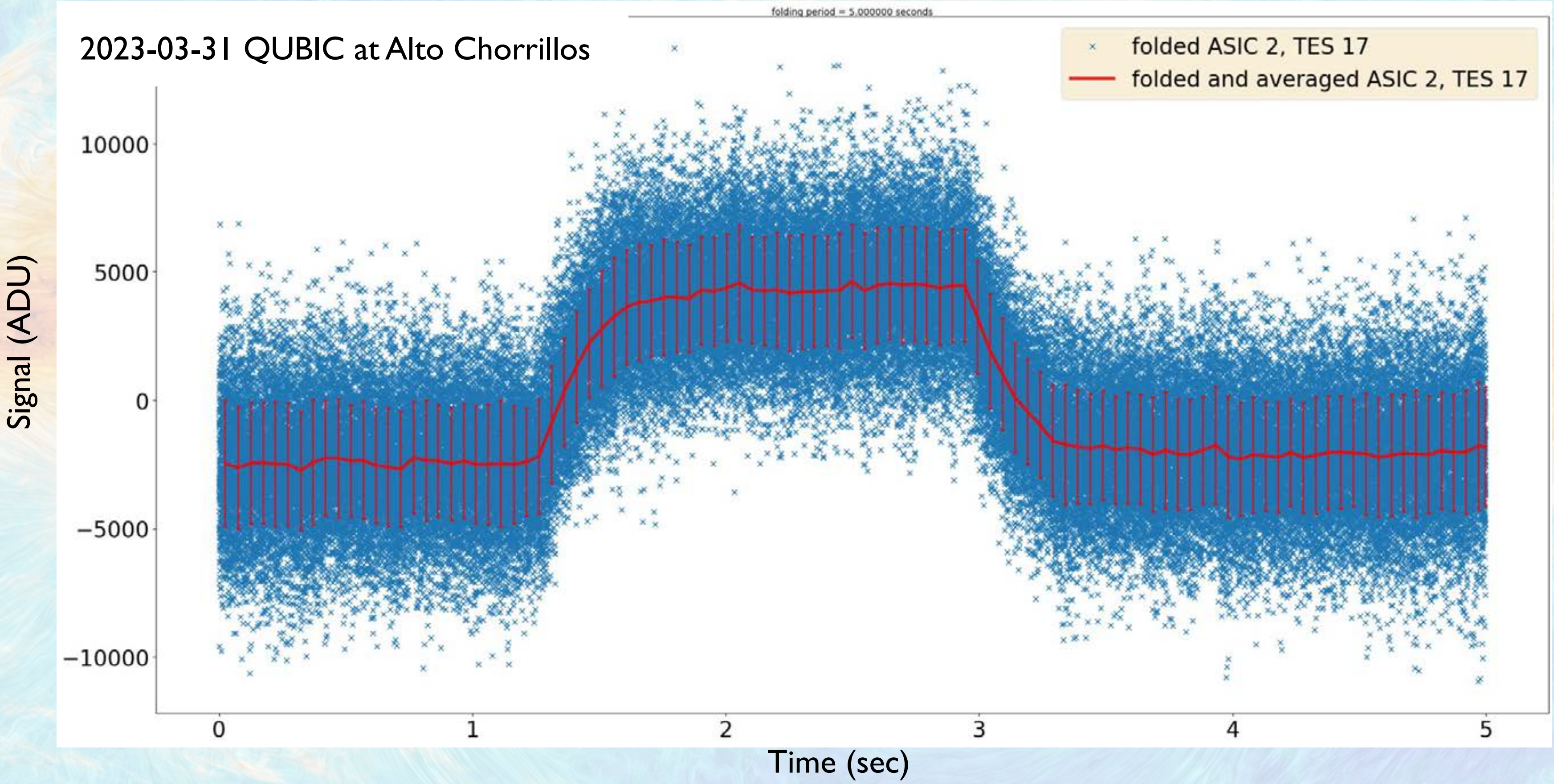


Cooldown continued until early June

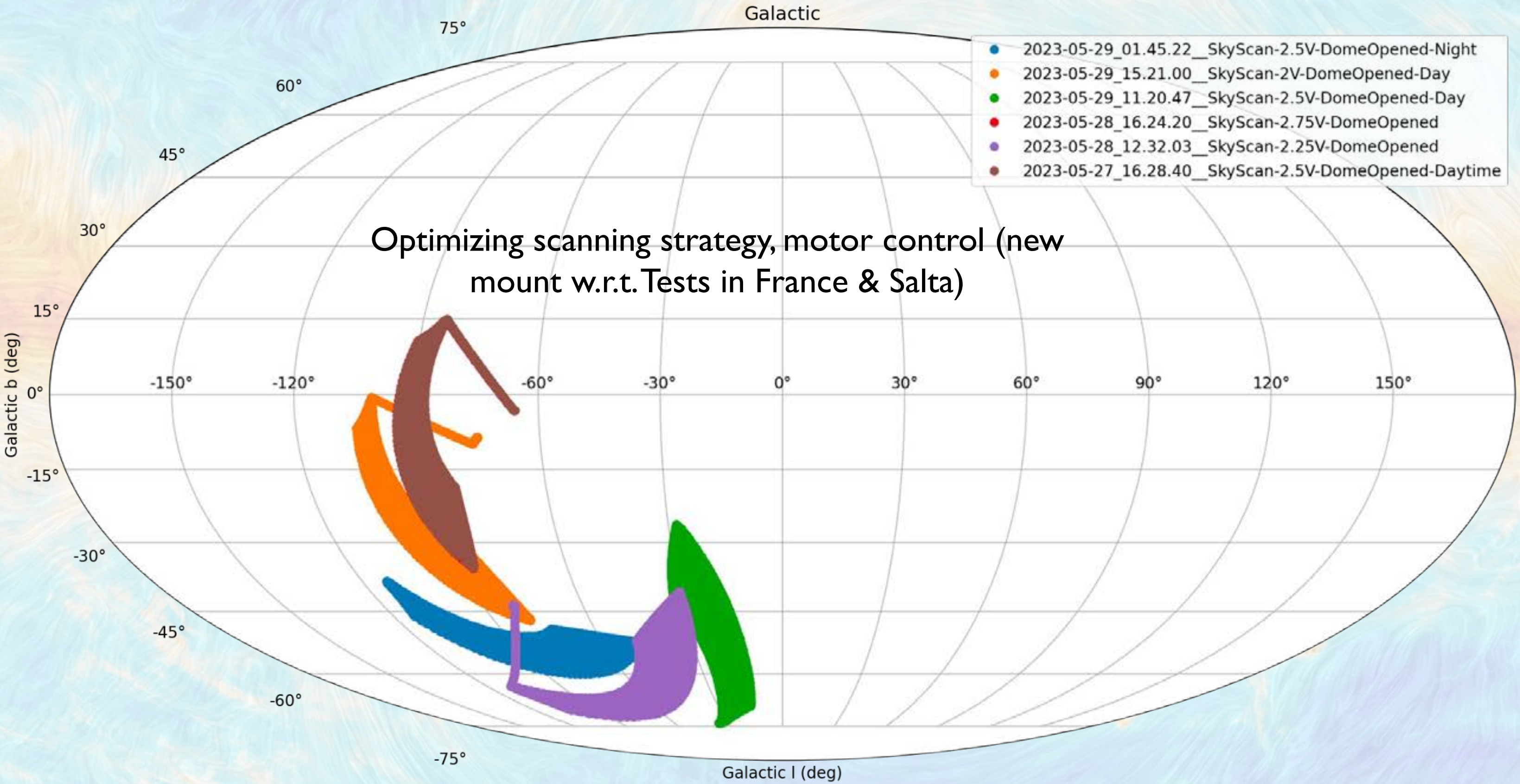
QUBIC Commissioning: Sky Dips



QUBIC Commissioning: Carbon Fibers



QUBIC Commissioning: Sky Scans (ongoing analysis)



Optimizing scanning strategy, motor control (new mount w.r.t. Tests in France & Salta)

	2023	2024	2025	2026	2027
QUBIC Instrument phases	**Data Taking with TD** / **Upgrade to FI** (~ANR funded)	**Data Taking with FI**			**QUBIC2 (SO, S4 ?)**
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Welcome to join us !

- BI: **Spectral-Imaging**:
  - Improve Foreground Mitigation ($\Delta\nu/\nu$ 5-8 times better than imager) : **crucial for realistic dust**
  - Direct **TOD→Components approach** including external (Planck data)
  - Ultra-Wide-Band design: **a unique focal plane covering [130-250 GHz]** (with notch filter) => **$\sigma(r)=0.009$ (3 years)**
    [alternative way of improving CMB detectors sensitivity: increase number of photons with increased bandwidth]

JCAP special Issue on QUBIC (2022)

- Bolometric Interferometry beyond QUBIC
  - Ultra-Wide-Band ⇒ increase frequency coverage of simple detectors (TES, MKIDs) ⇒ Gain in mapping speed (sensitivity) !
  - **Possible to incorporate a BI in a SO or S4 SAT tube with MKIDs for a unifying IN2P3 contribution (+ INFN, …)**