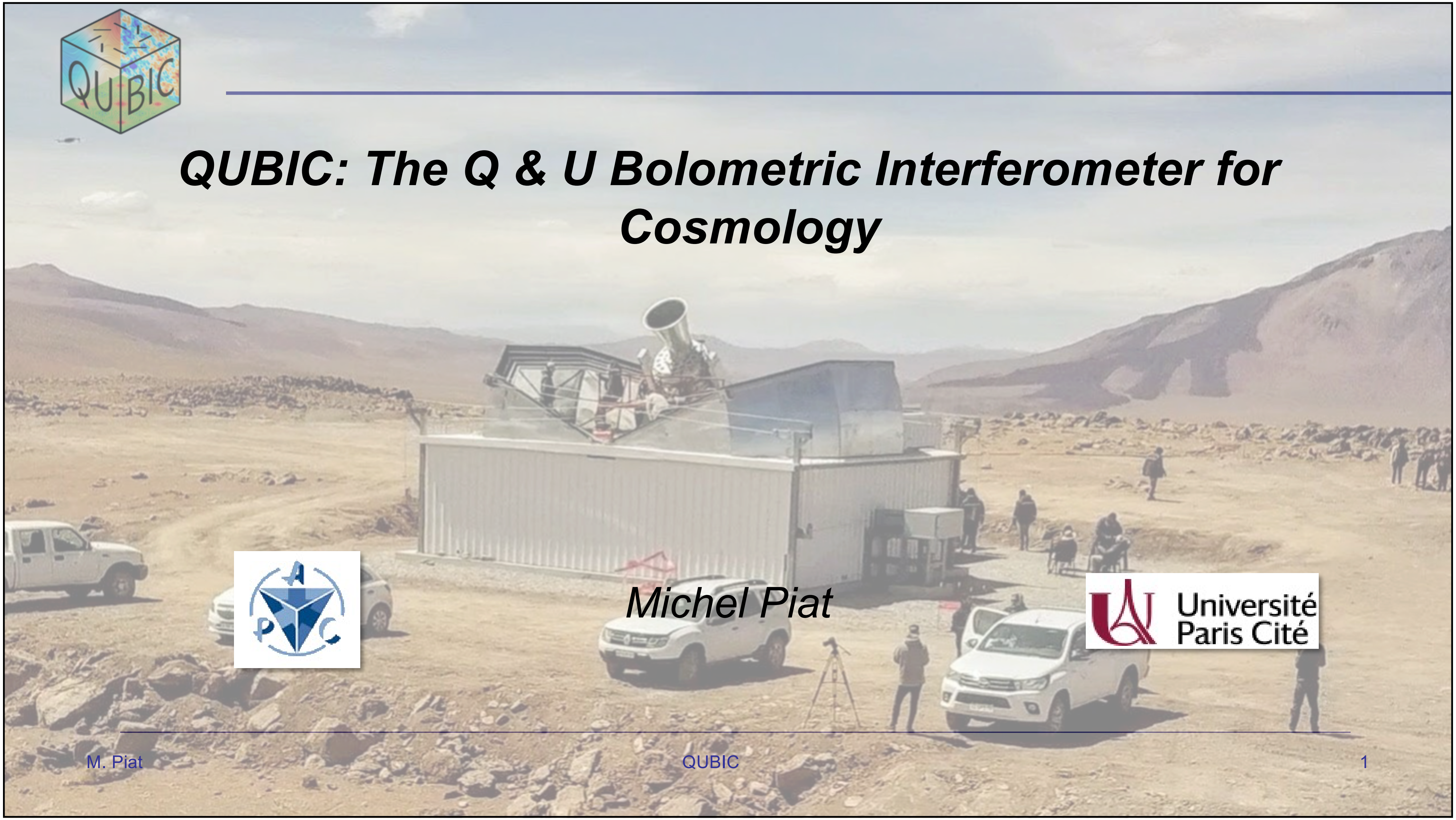
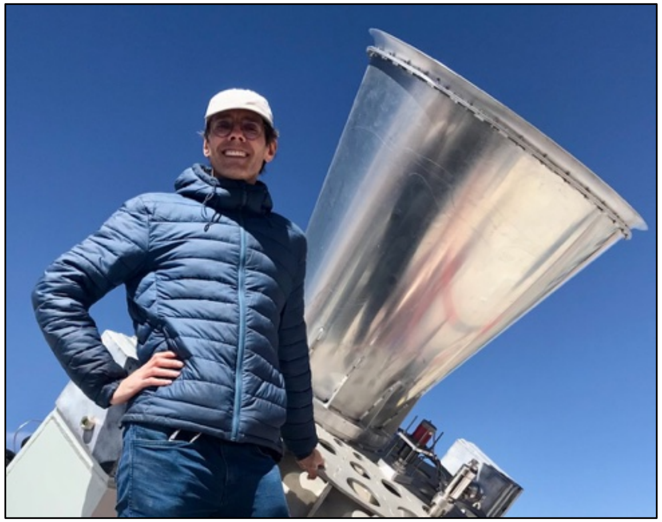


QUBIC: The Q & U Bolometric Interferometer for Cosmology

Michel Piat

Université Paris Cité

Who am I



Michel Piat (Professor at APC, Paris Cité University)

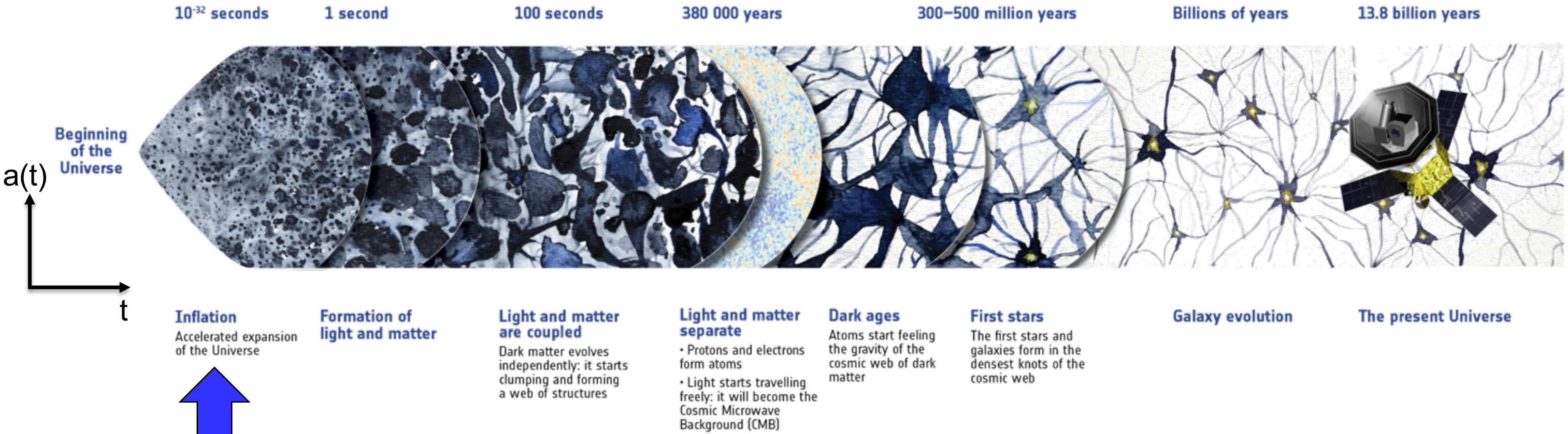
- Planck-HFI
  - Deputy Instrument Scientist
  - Very low frequency stability (thermal stability, readout)
  - Calibration on Earth orbital motion dipole
- R&D
  - PI, BSD project (B-mode Superconducting Detectors): TES arrays + readout developments
  - PI, NGKID project (Next Generation Kinetic Inductance Detectors): antenna coupled KIDs for CMB polarization observations.
  - PI, NGCryo project (Next Generation Cryogenic systems): sub-K minifridges
- PI, CRYOMAT platform: characterizations of material at sub-K temperatures
  - Electrical, thermal and mechanical properties
- CMB projects:
  - ESA-CNES space mission proposals (SAMPAN, BPol, COrE, PRISM, COrE+, CORE)
  - PI ESA contract: feasibility study of a polarization millimeter space mission
  - LiteBIRD MHFT: in charge of thermal modeling
  - Instrument Scientist of QUBIC (Q & U Bolometric Interferometer for Cosmology)

Outline

1. CMB polarisation
2. QUBIC instrument
3. Spectral Imaging with QUBIC

1. Origin of the CMB

Now

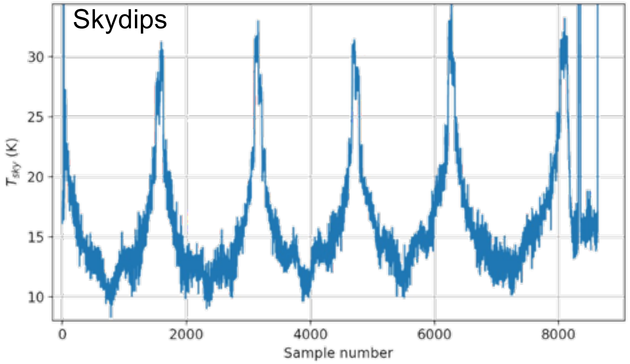


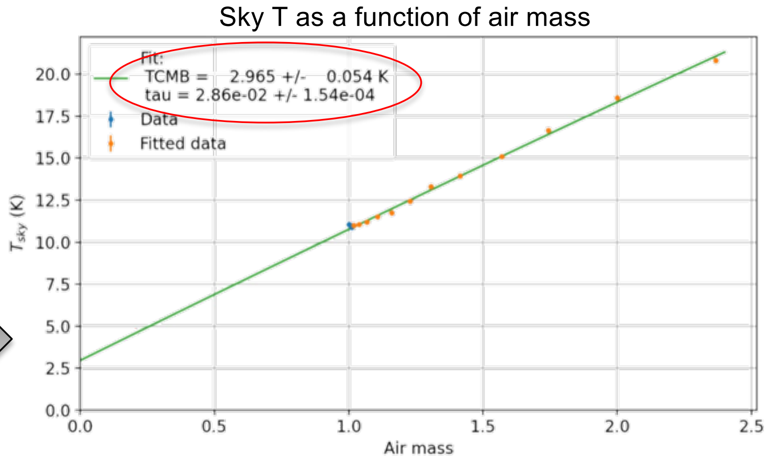
Inflation?

Cosmic Microwave Background (CMB)

You can detect the CMB from your garden

- With a satellite TV antenna...
  - Heterodyne instrument operating at 10GHz
  - 1GHz frequency band
  - about 5 deg angular resolution
- …. and some tricks
  - Dicke switching
  - Sidelobes shields
  - Calibration with LN2

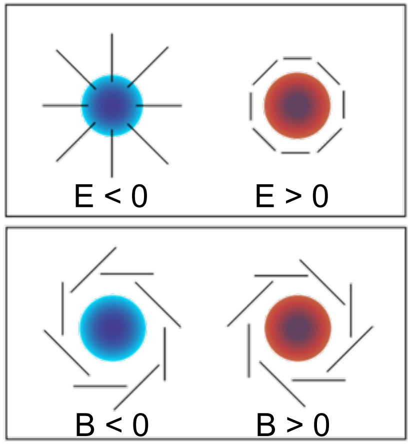




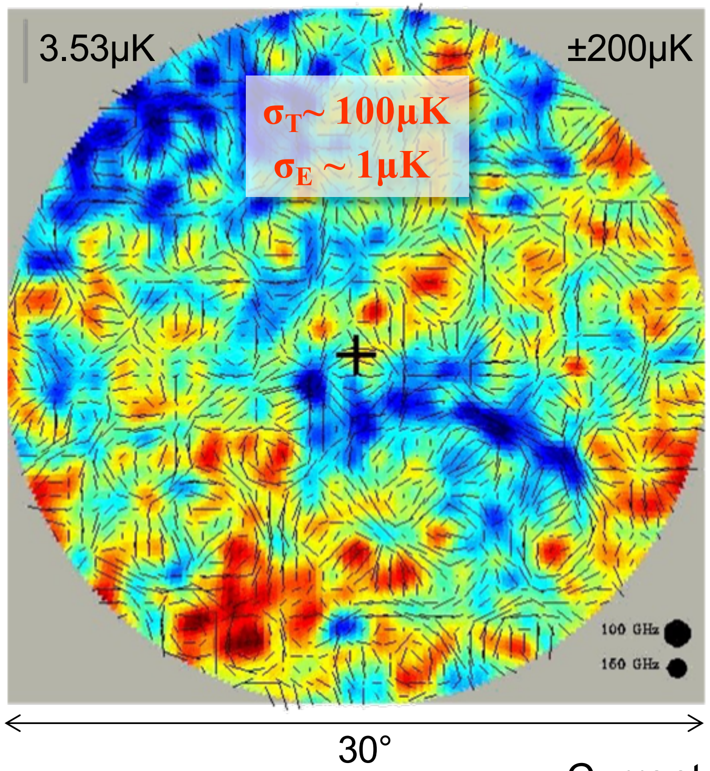
More:
https://youtu.be/Ou5fgeNnMcM?si=miRbdesqauOc2mSB

CMB polarisation: E and B modes

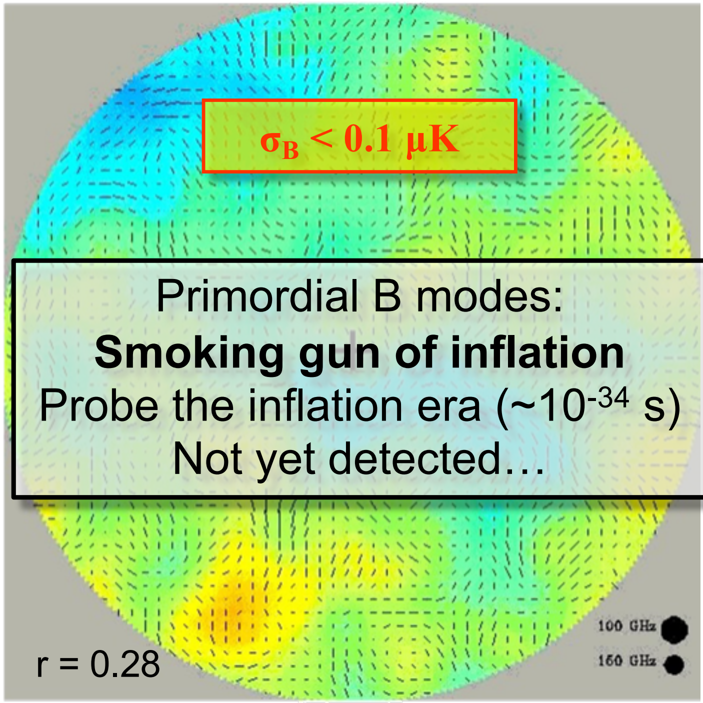
Q, U ⇒ E, B



Density fluctuations (scalar modes): T anisotropies and E modes



Primordial gravitational waves (tensor modes): T, E modes **and B modes**

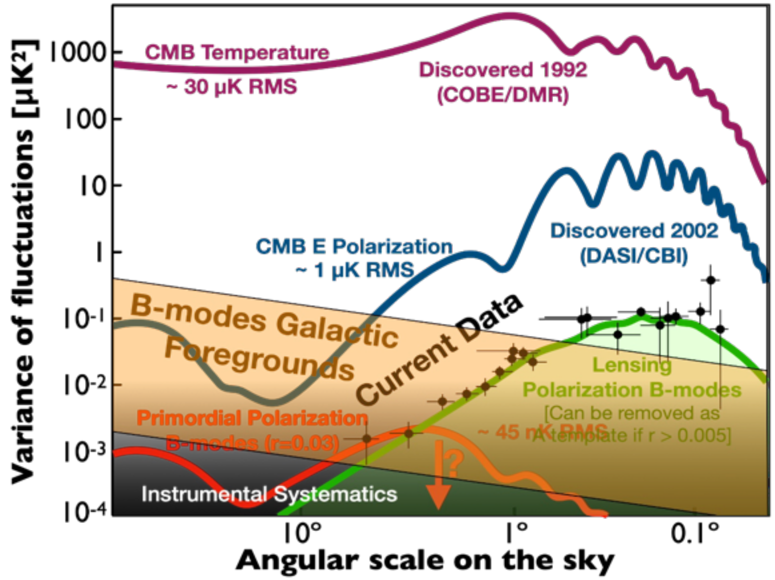


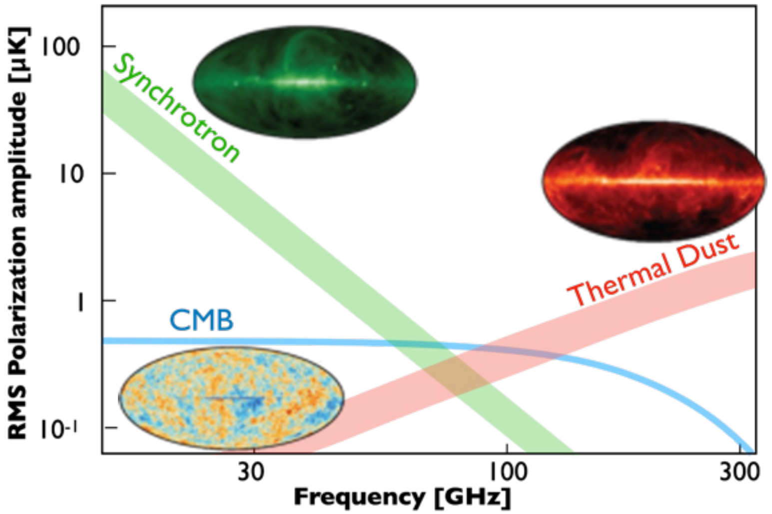
Credit: BICEP team

Current constraints: r < 0.032 [Tristram et al. 2022]

Challenges to measure B modes

- Challenges:
  - Small signal ≲ 45 nK
  - Instrumental systematics ≲ 1%
  - B-modes ≲ polarized foregrounds





- Foregrounds have distinct colors:
  - Need many frequencies

2. The Q & U Bolometric Interferometer for Cosmology

130 Collaborators
22 laboratories
6 countries

+SISSA Joined

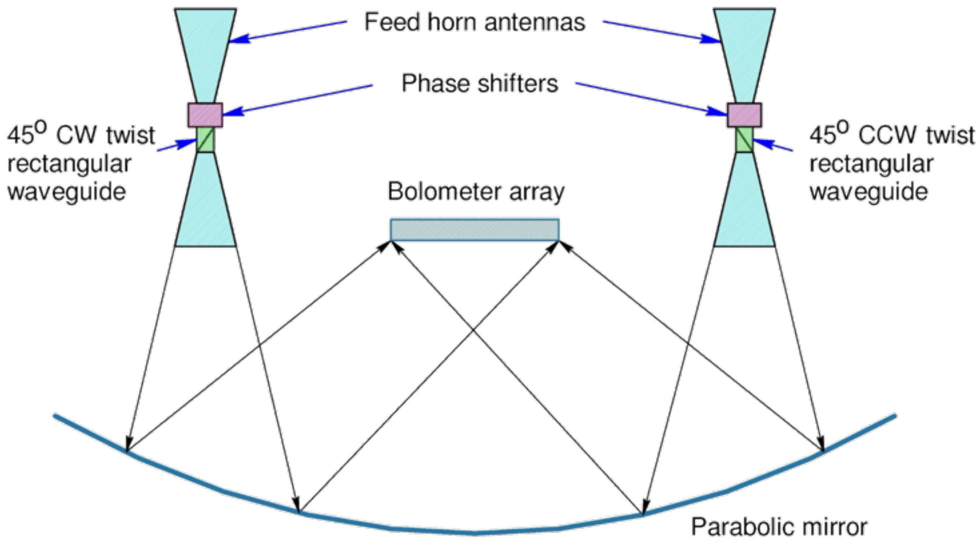
APC Paris, France
C2N Orsay, France
CSNSM Orsay, France
IAS Orsay, France
IRAP Toulouse, France
LAL Orsay, France
Universita di Milano-Bicocca, Italy
Universita degli studi di Milano, Italy
Universita La Sapienza, Roma, Italy
Maynooth University, Ireland
Cardiff University, UK
University of Manchester, 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

Observation site:
San Antonio de los Cobres
(Salta, Argentina)
5000m a.s.l.

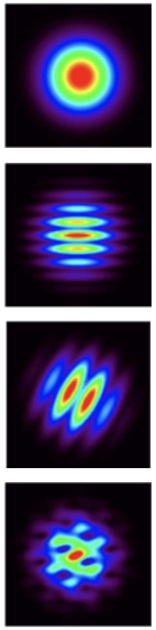
Adding interferometry?

- First idea from Peter Timbie and Lucio Piccirillo (1998)
  - Superimpose all horns EM waves on all bolometers
  - Telescope = beam combiner
  - One detector on the focal plane sees all horns
- Motivations:
  - *High sensitivity* with incoherent low temperature detectors
  - *Systematics control* with interferometry
  - *Self-calibration* and *Spectro-Imaging* thanks to interferometry

Adding interferometry



The QUBIC Concept



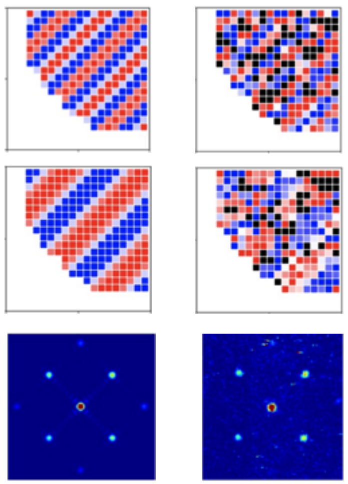
1 Horn open

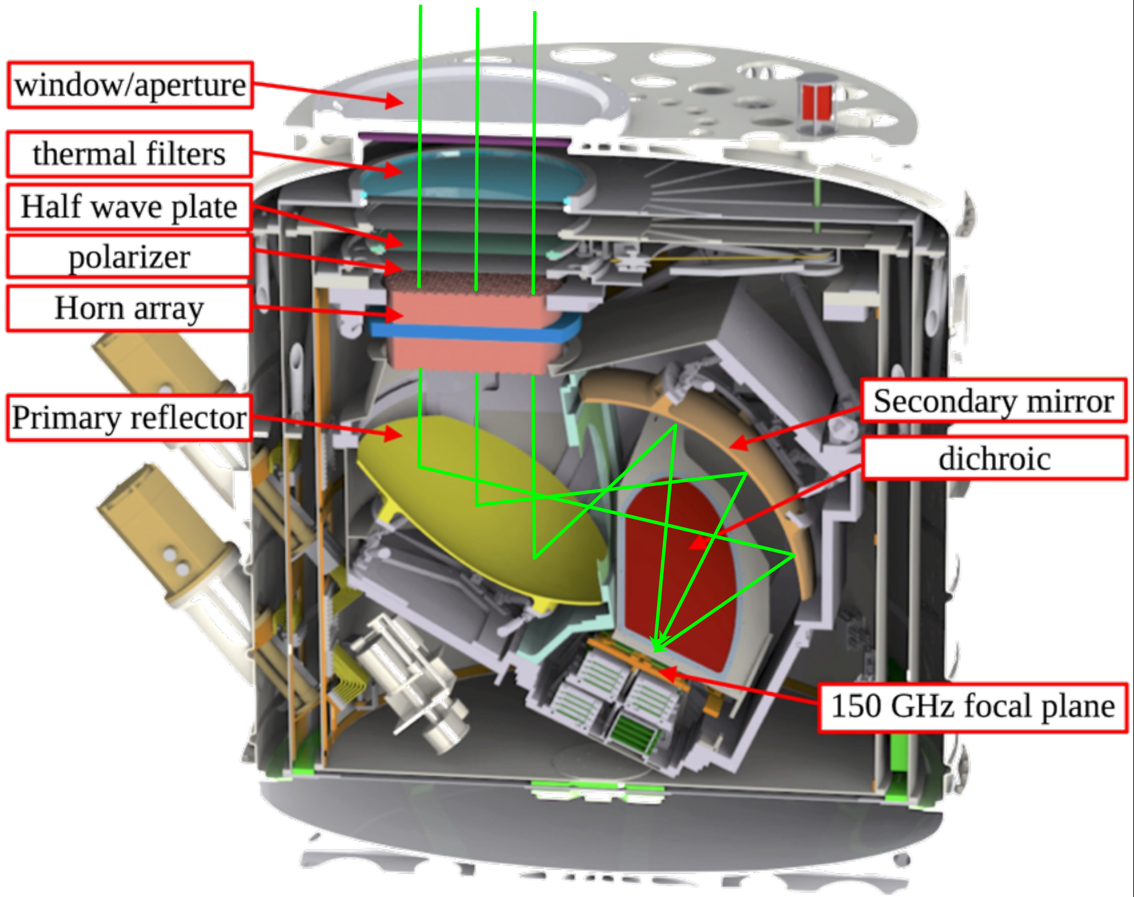
2 Horns open

2 Horns open

All Horns open
synthesized beam

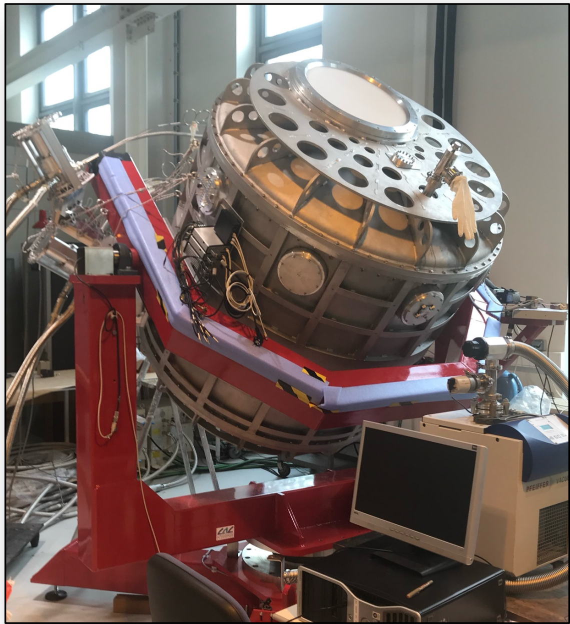
[L. Mousset, PhD, 2021]





Fringe and Synthesized Beam data:
[Torchinsky et al., QUBIC III, 2022]

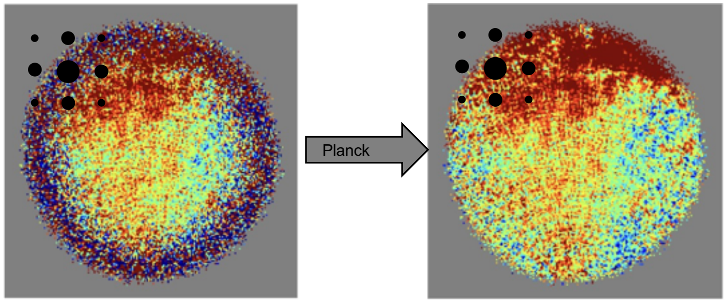
The QUBIC instrument

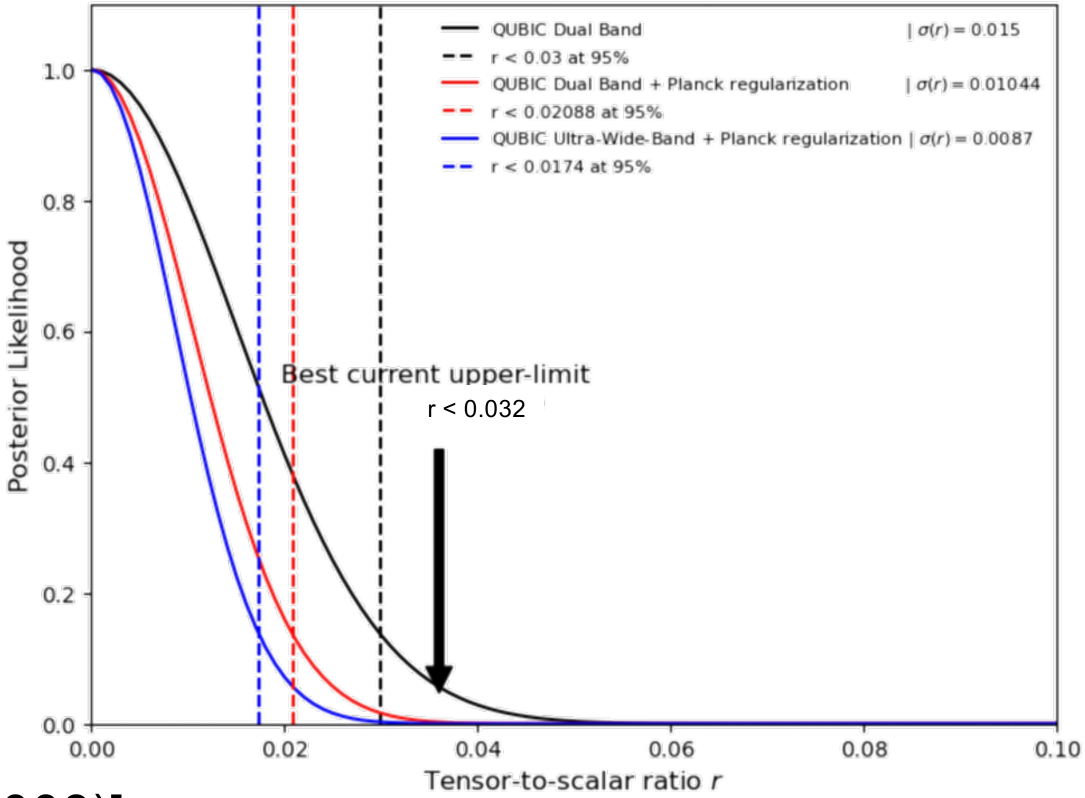


- Cryostat: 1.547m high, 1.42m diameter, ~800kg
- **Final Instrument (FI)**
  - 20x20 horn array
  - 2 x 1024 TESs @ 320mK (150GHz and 220GHz)
- **Technological Demonstrator (TD)**
  - Same cryostat and cryogenics as FI
  - 8 x 8 horn array
  - ¼ focal plane (256 TESs at 150GHz)
- Mid-2018-2021: TD integrated and tested at APC
- 2021-2022: integration and tests in Salta
- **Since Nov 2022: instrument on site, commissioning going on**
- Upgrade toward FI: 2025

Sensitivity forecast

- 3 years QUBIC FI: σ(r) = 0.015
- Planck is used to regularize QUBIC map reconstruction near the edges



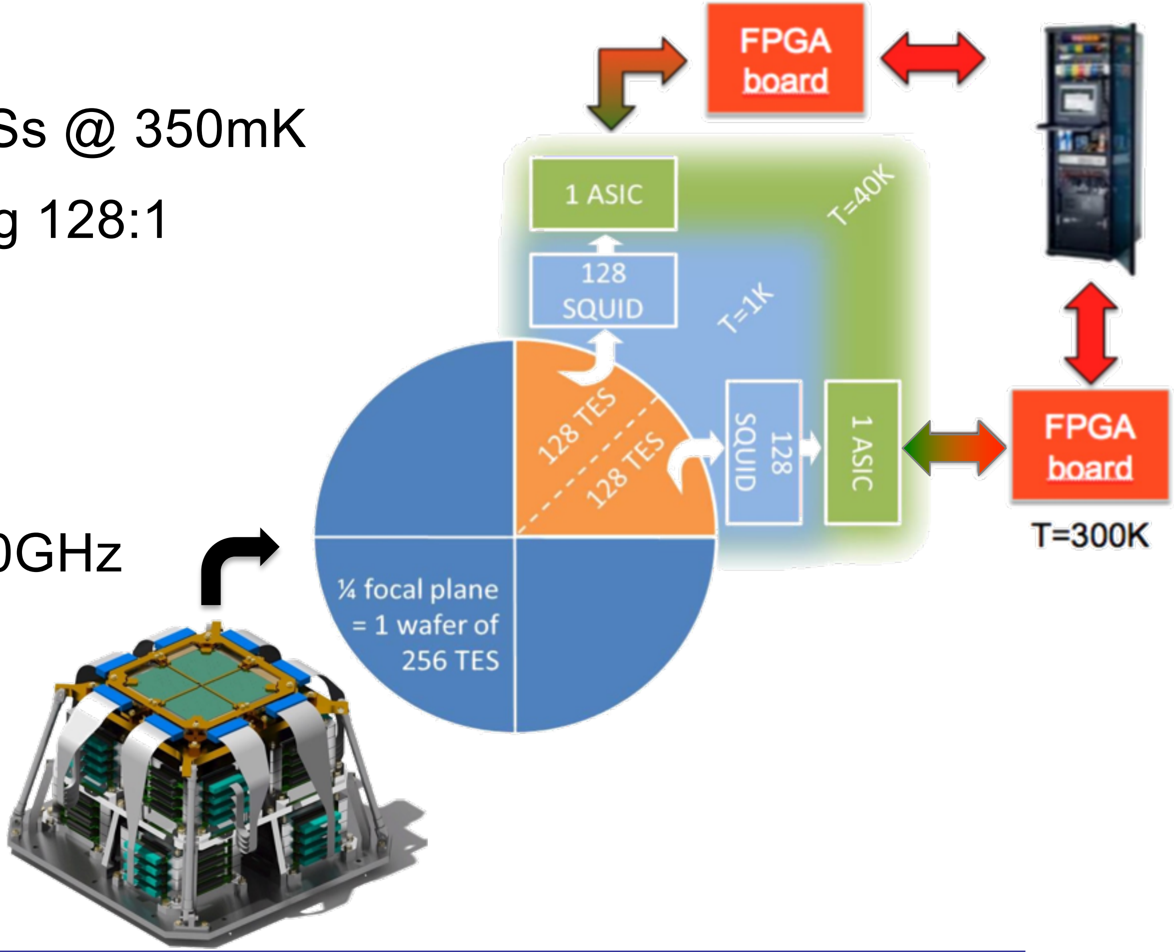


- BI sensitivity:
  [Hamilton et al. A&A 491, 923-927 (2008)]

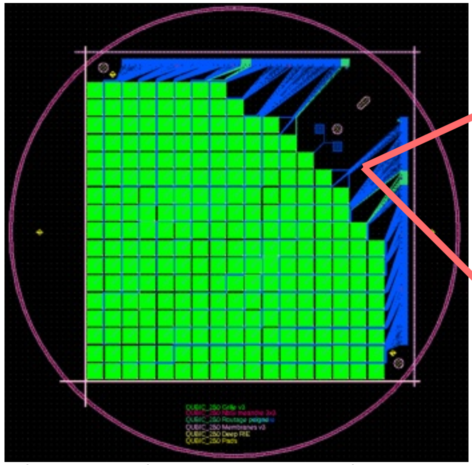
QUBIC detection chain

- 1 focal plane = 4 wafers of 256 TESs @ 350mK
- Readout: Time Domain Multiplexing 128:1
  - 128 SQUIDs @ 1K
  - 1 ASIC @ 40 K
- Warm readout: FPGA board
- FI: 2 focal planes: 150GHz and 220GHz
- TD: 1 focal planes with 256 TESs (150GHz)

[Piat et al., QUBIC IV, 2022]



QUBIC TES array

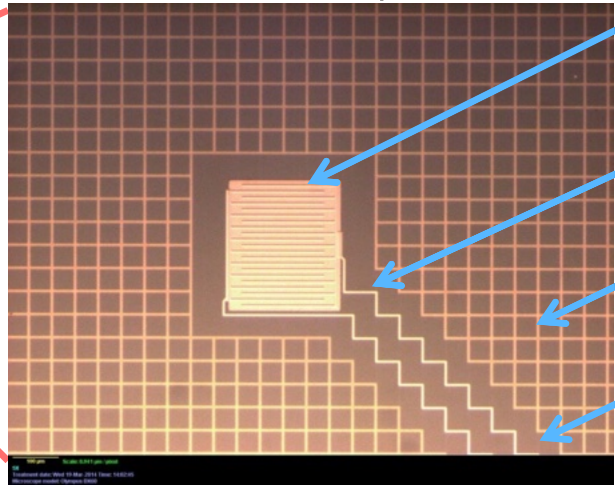


Substrat: SiN low-stress on 3 inches SOI

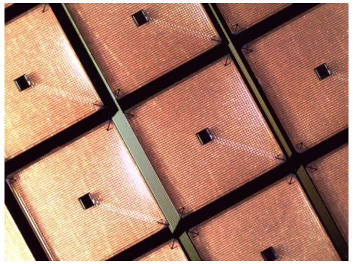
1. Al Routing Al
2. TES NbSi
3. Pd absorber
4. Al pads
5. Deep etching
6. Membrane etching
7. XeF_2 etching

Dual band: same design

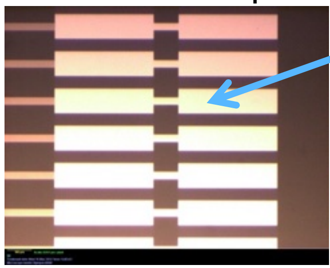
Zoom on a pixel

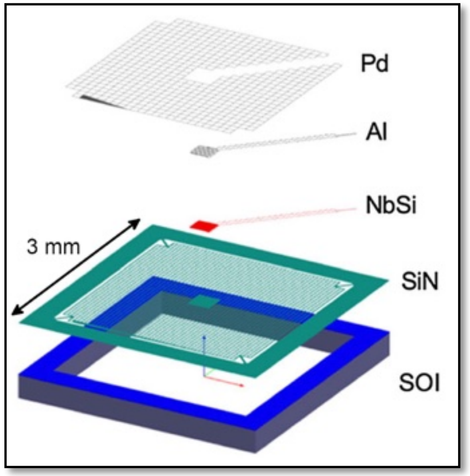


Membranes



Interconnexion pads



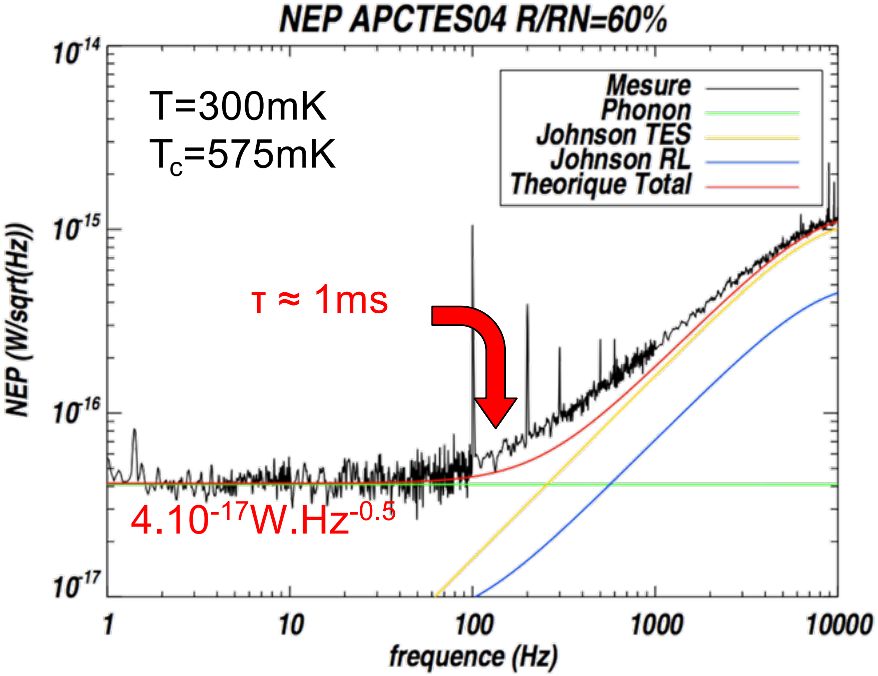


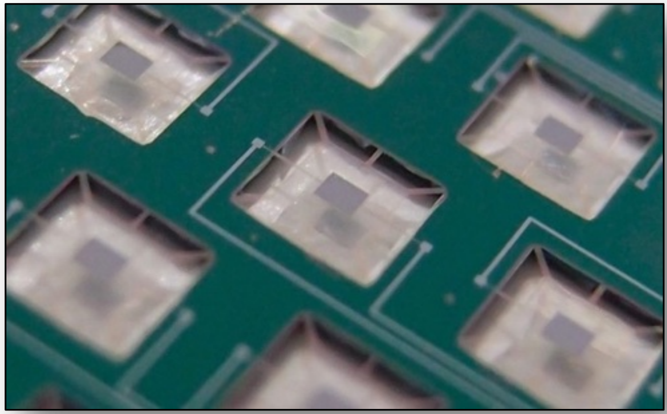
G = 250 pW/K
NEP = 5.10^{-17} $W.Hz^{-0.5}$
τ = 100ms without ETF

[S. Marnieros 2018]
[Salatino et al. SPIE 2018]

QUBIC TES prototype

- Open membranes, NbSi sensor (IJCLab, IEF)



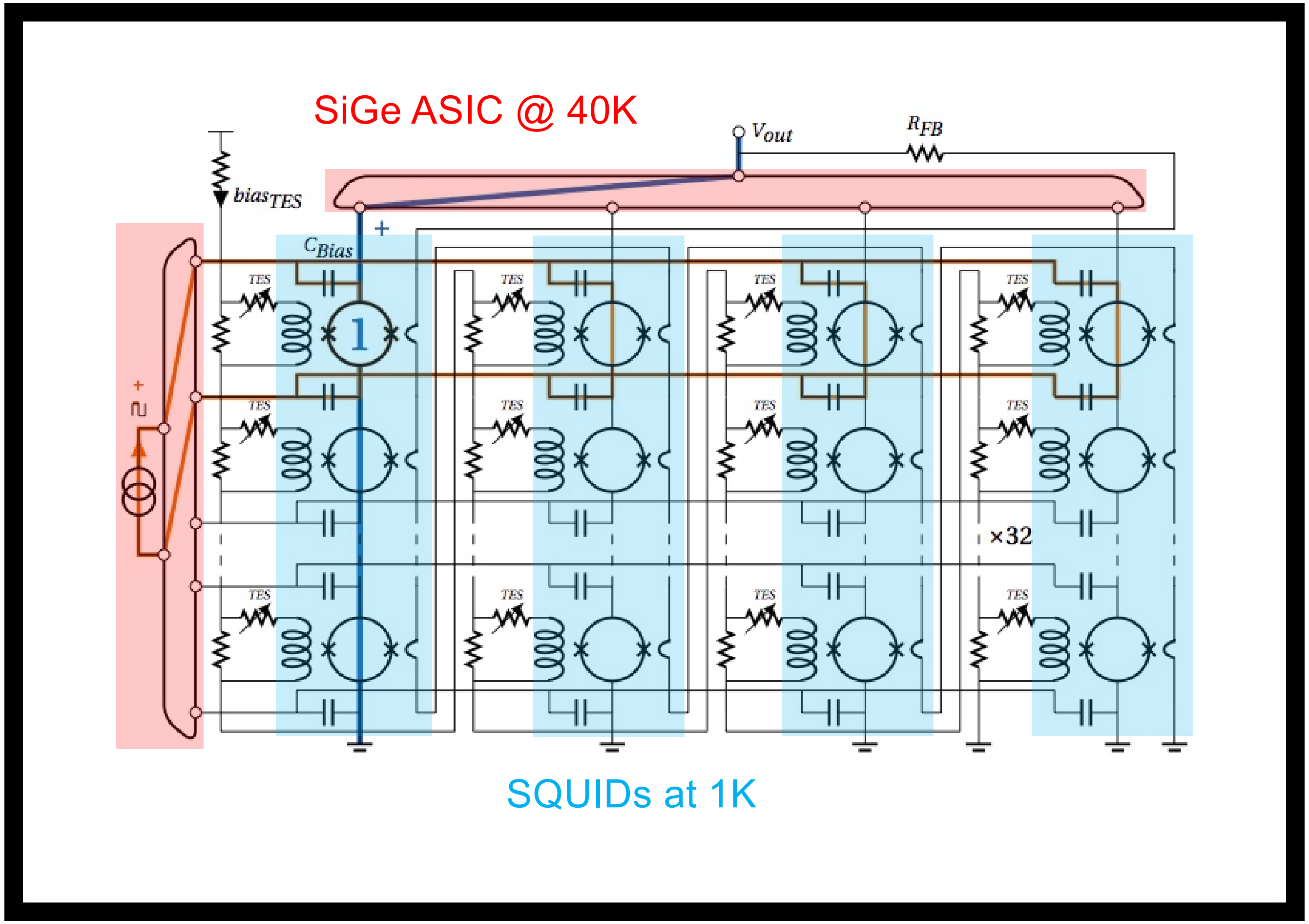


- No excess noise
- Fully compliant with QUBIC requirements

[Martino PhD, 2012]

QUBIC TES array

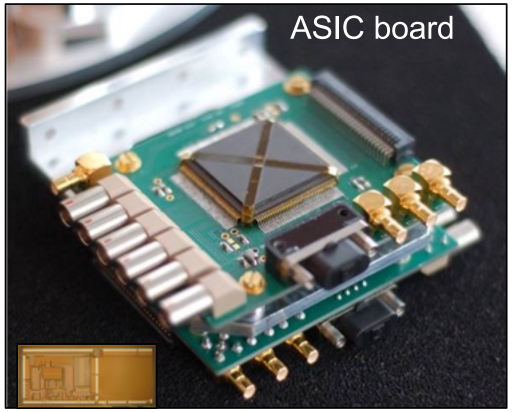
QUBIC cold readout

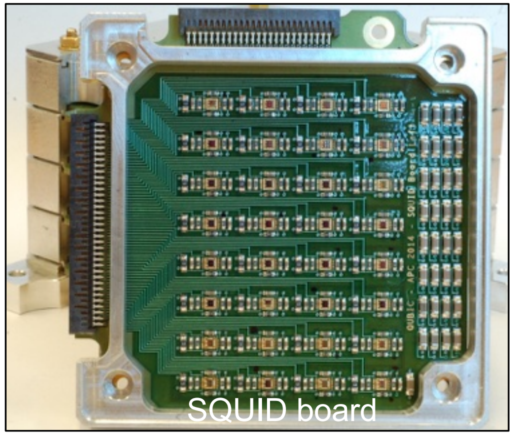


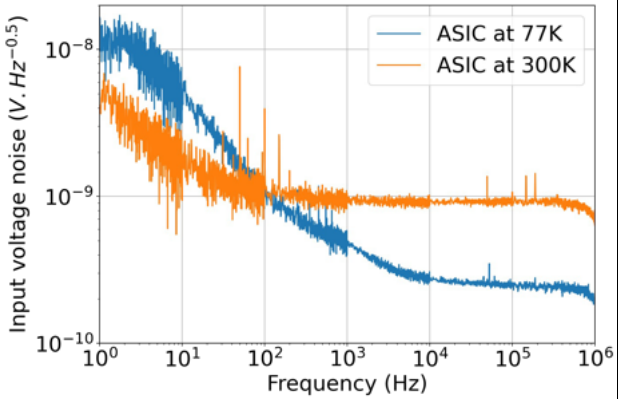
[Prêle]

QUBIC cold readout: SQUIDs and ASIC

- SQUIDs: SQ600S from StarCryoelectronics
- ASIC SiGe at 70K:
  - SQUID rows addressing:
    - Through capacitors with AC multiplexed current sources (1:32)
  - Low noise amplifier with multiplexed inputs:
    - en = 0.3nV.Hz$^{-0.5}$
    - Column multiplexing (1:4)
  - Digital addressing circuit controlled by an external clock

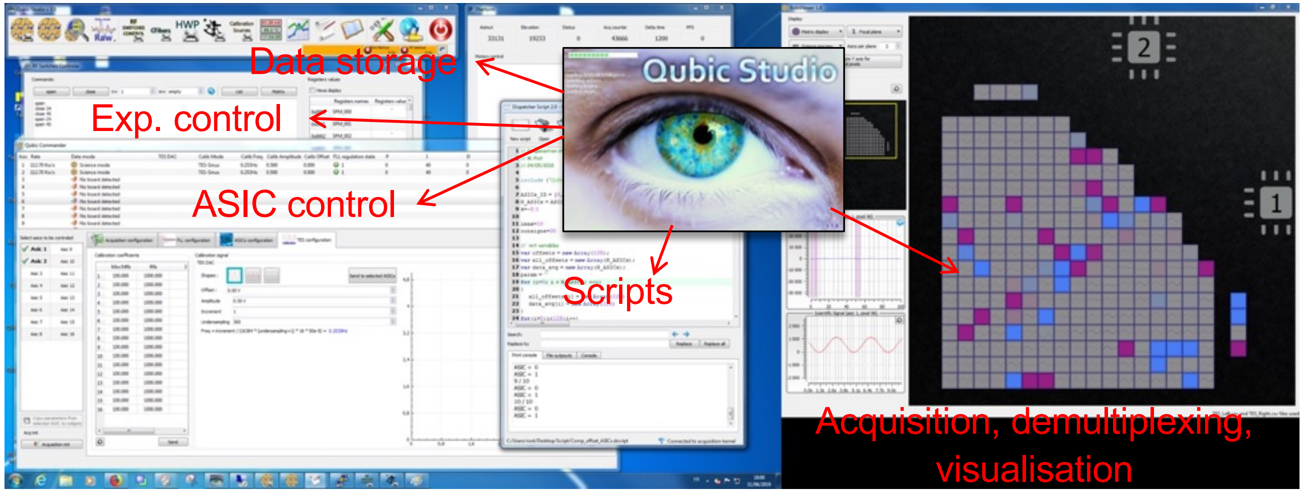






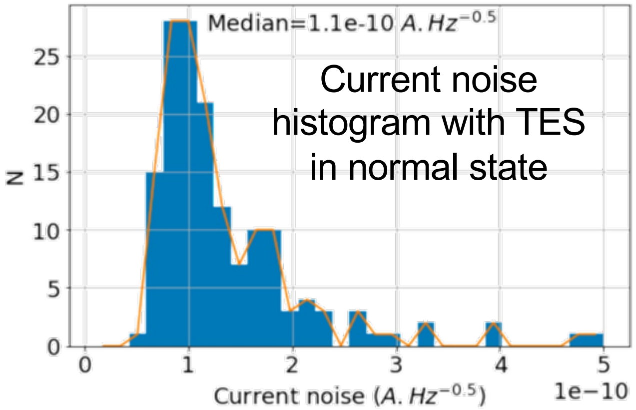
QUBIC warm readout and acq. sys.

- FPGA board and acquisition system at 300K:
  - 2MHz ADC and DACs
  - Digital Flux Locked Loop (FLL) in FPGA
  - $\Phi_0/2$ flux modulation implemented
- Software QUBIC Studio:

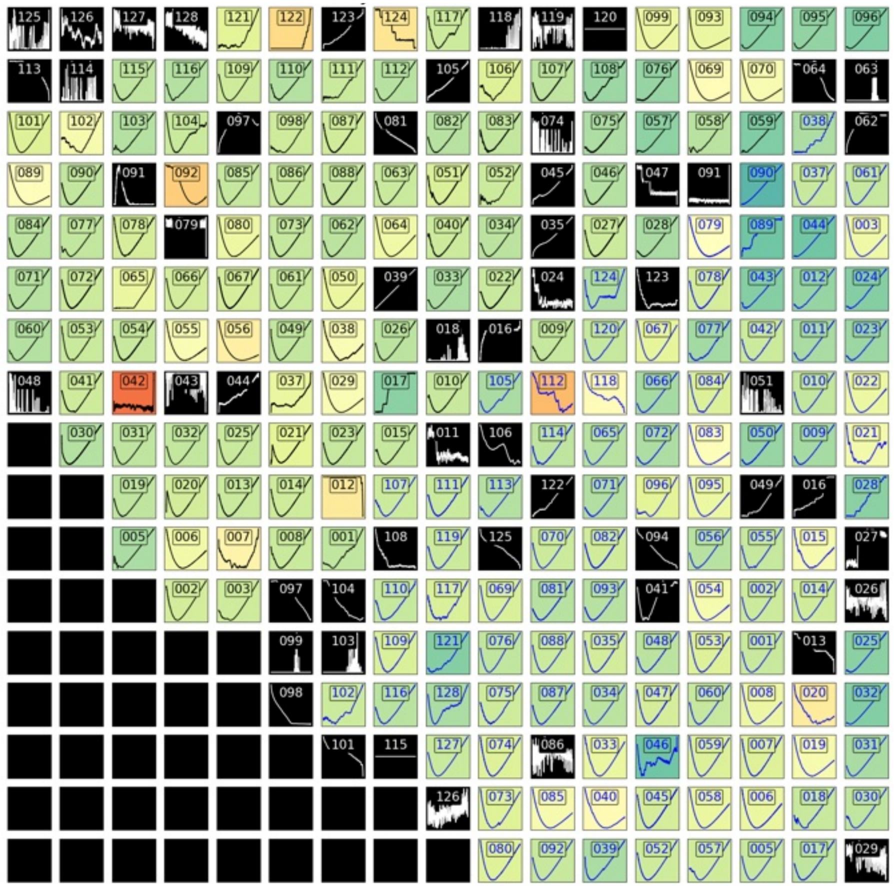


Detection chain characterizations

- Detection chain overall yield of 77% at 320mK in Salta
- Readout noise currently limited to $100pA.Hz^{-0.5}$ by aliasing noise from multiplexing
  - Nyquist inductor being implemented

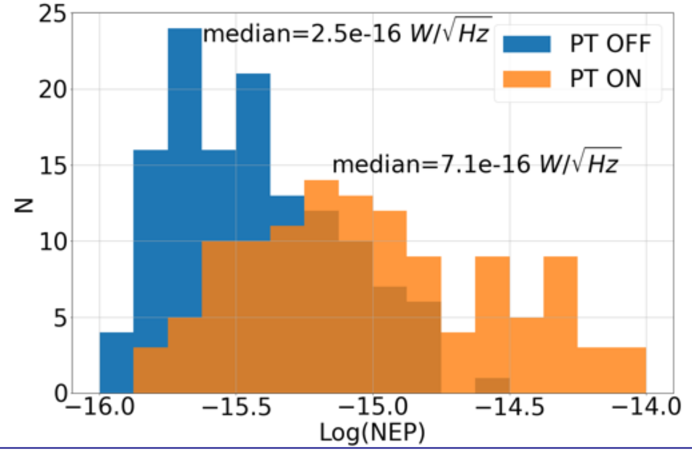


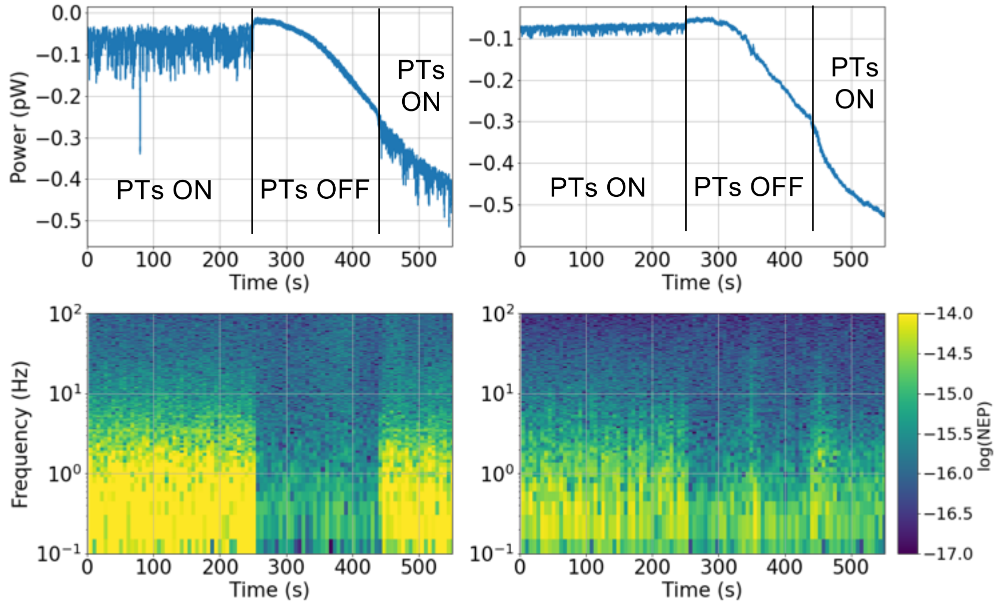
I-V measurements at 320mK



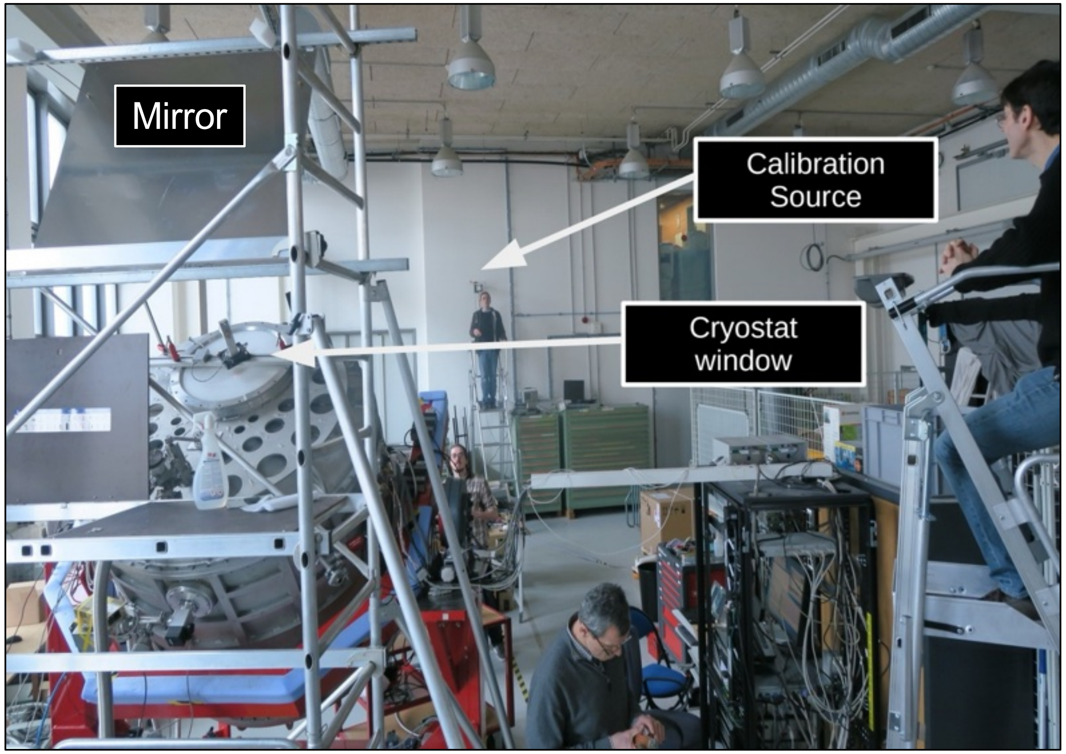
Detection chain characterizations

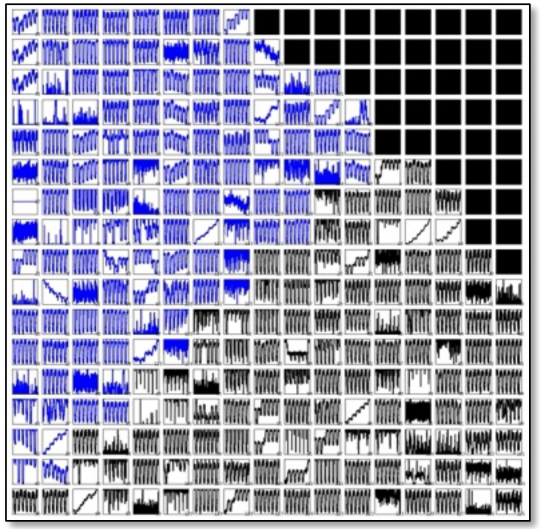
- Sensitivity limited by microphonics from Pulse Tubes (PT)
  - Excitation of mechanical resonances
  - Heat dissipation
  - Better mechanical decoupling to be implemented for FI
- Sensitivity limited to few 10^{-16}W.Hz$^{-0.5}$



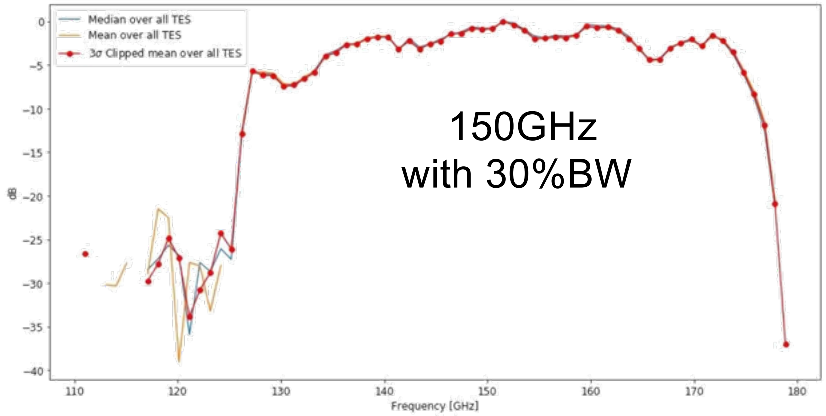


Characterizations with agile external source at APC



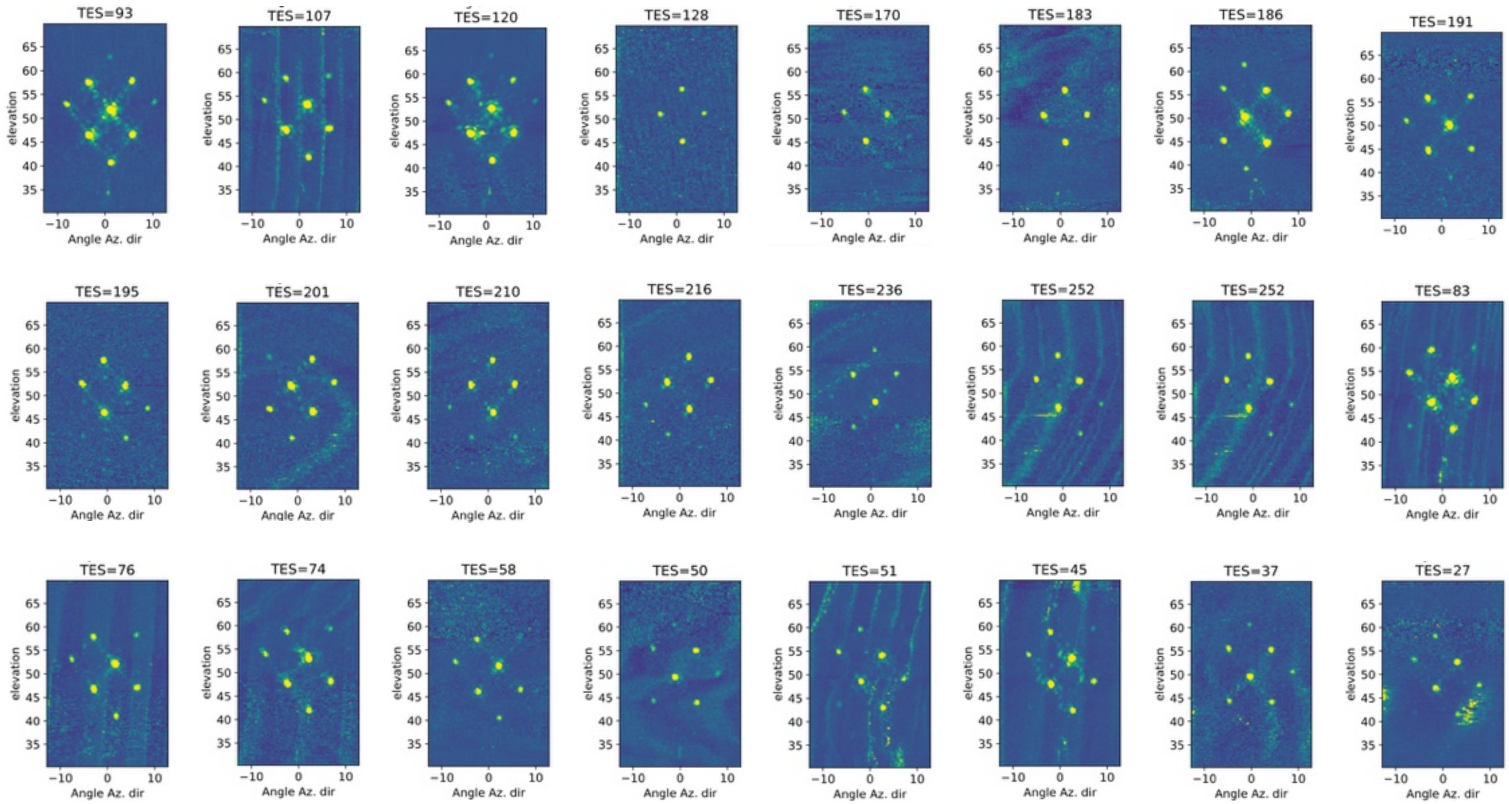


Calibration source signal



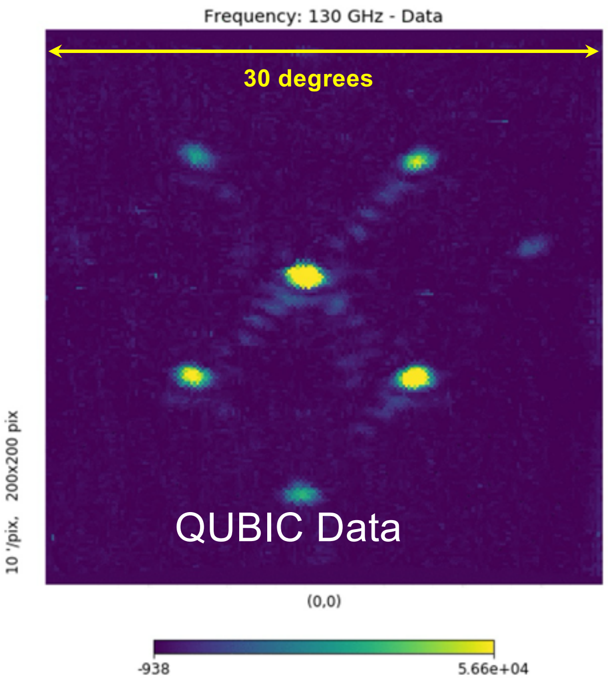
Measured median Xpol: < 0.6%

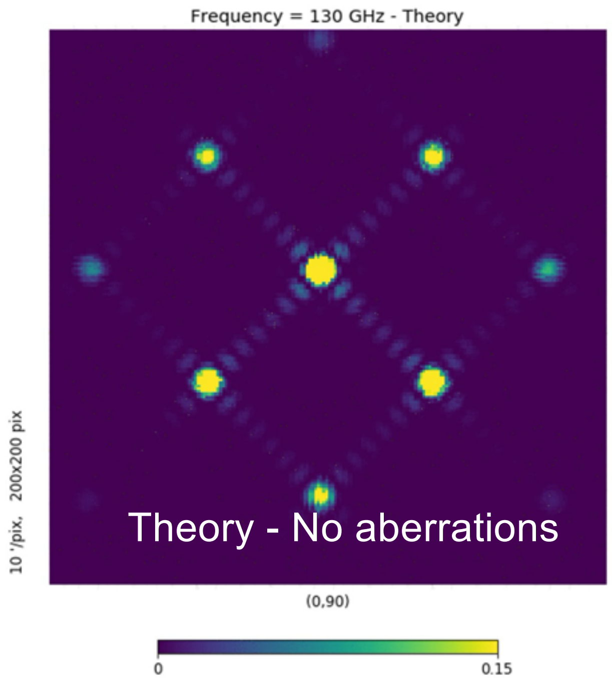
Synthesized beam



Synthesized beam as a function of frequency

130GHz to 170GHz



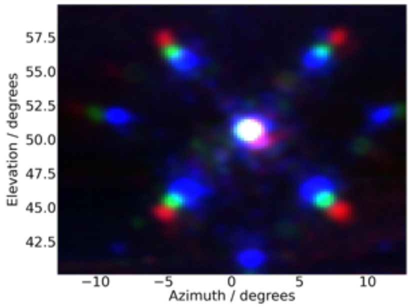


Frequency scaling is the basis of Spectro-Imaging
A possibility unique to Bolometric Interferometry to constrain foregrounds

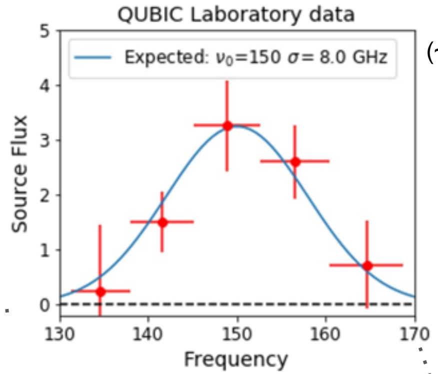
[Torchinsky et al., QUBIC III 2022]

Map making with real data

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

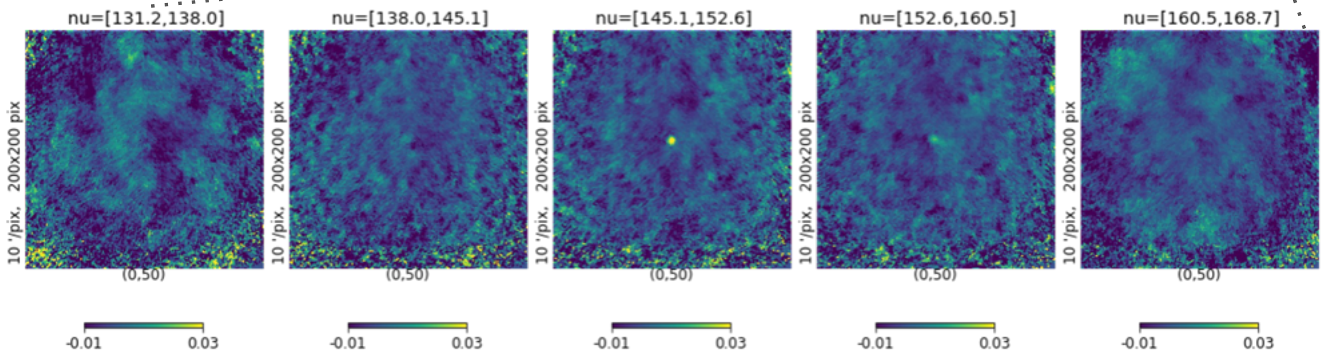


With Real Data (26 detectors) [indoor calibration source]



(~3.2 GHz with FI)

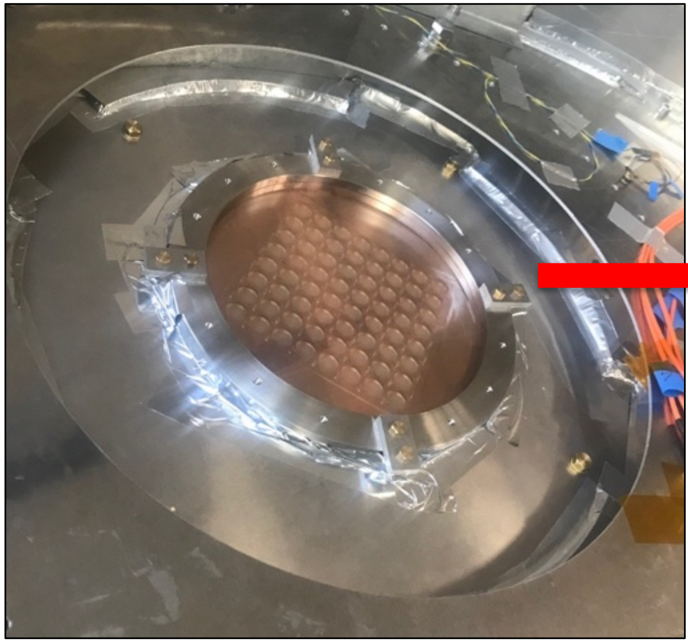
Calibration Source operating at 150 GHz at APC



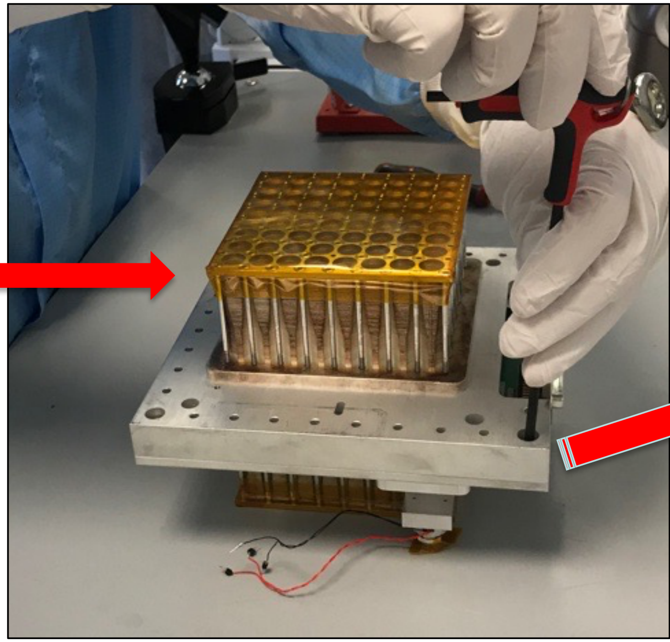
First Spectral Imaging reconstruction with real data

[Torchinsky et al., QUBIC III, 2022]

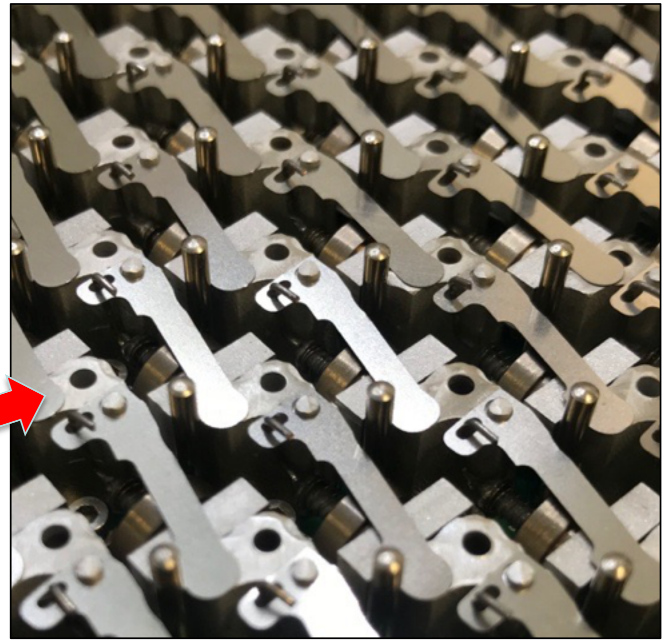
TD: 8x8 horn array and RF switches (4K)



8x8 horn array below the polarizer



Platelet back-to-back horns
with RF switch module in the middle

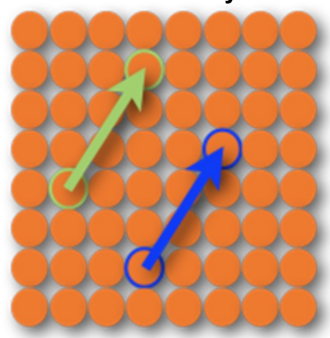


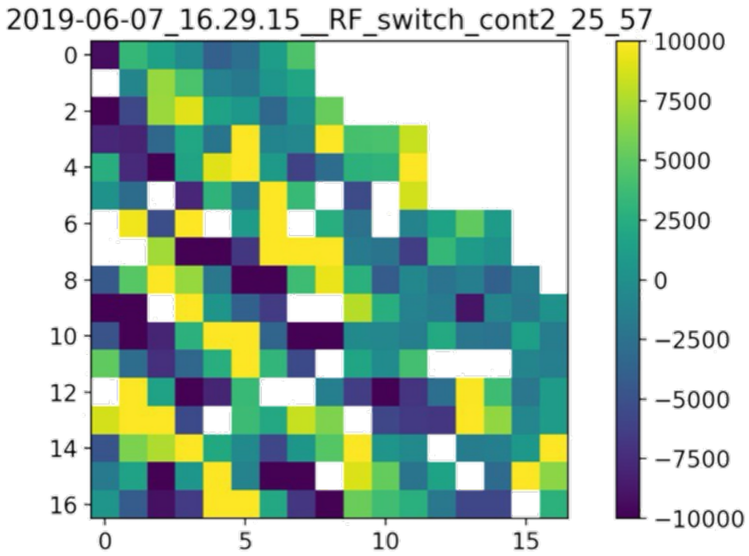
Electromagnet to open or close
each RF switch
(max 2 at the same time)

Self calibration - Fringes

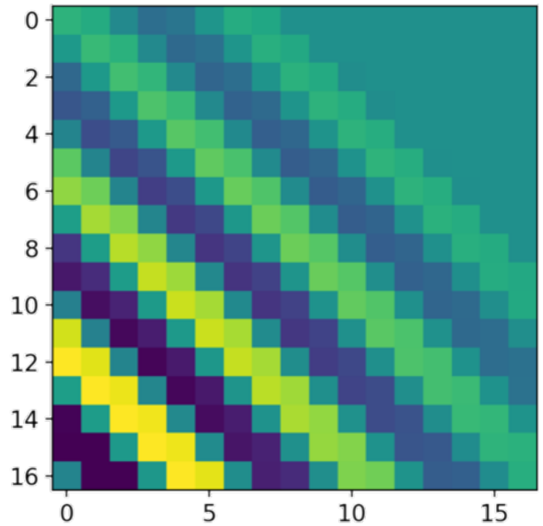
- Self calibration: [Bigot-Sazy et al., A&A 2012, arXiv:1209.4905]
  - Use horn array redundancy to calibrate systematics
  - Imaging fringes with different baselines is fundamental to performing “Self Calibration”

Horn Array



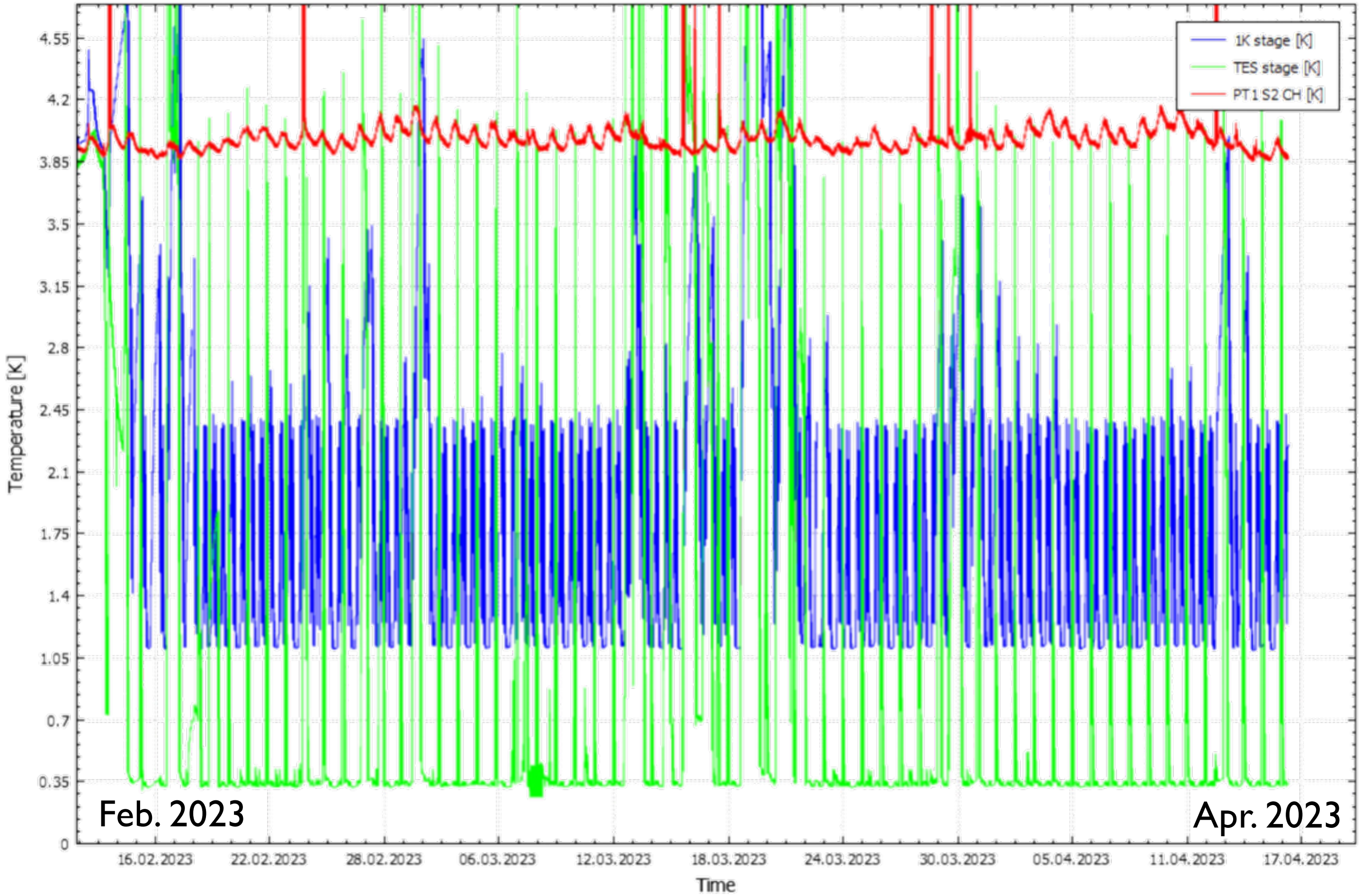


Simulations:



QUBIC on site near San Antonio de los Cobres, Argentina, at 5000m a.s.l. (inaugurated Nov. 22nd 2022)

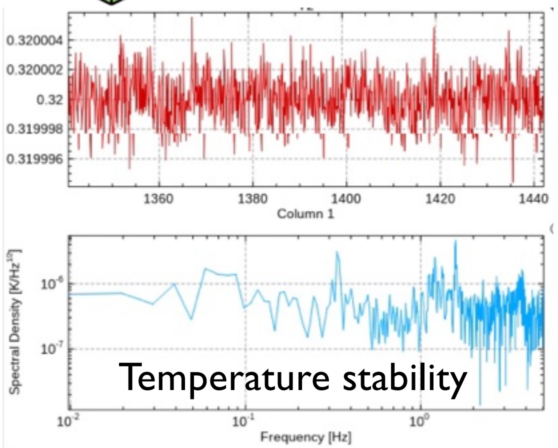
QUBIC Commissioning: Cryogenic yield 50%



Could be further improved

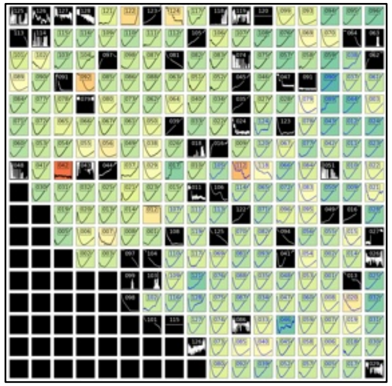
Cooldown continued until early June

QUBIC Commissioning: tuning the instrument

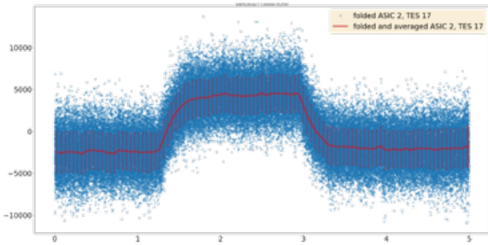


Temperature stability

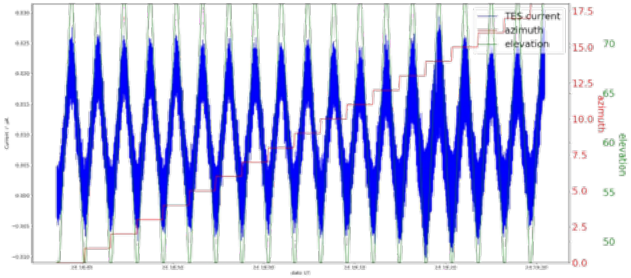
Detector characterizations

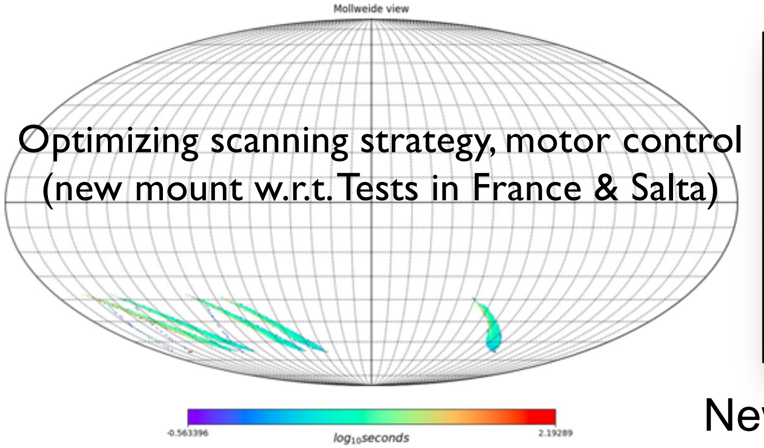


Internal C fiber source



First skydips

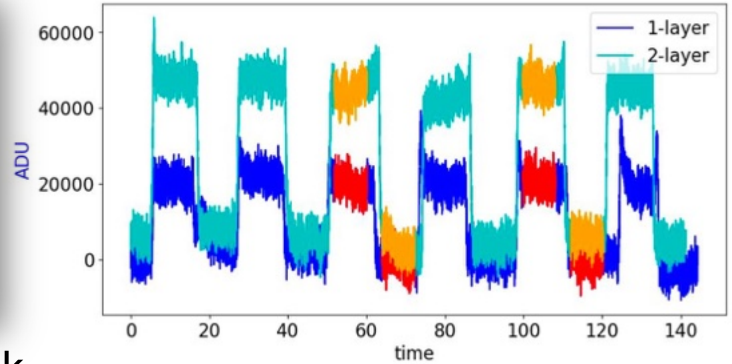




Optimizing scanning strategy, motor control (new mount w.r.t. Tests in France & Salta)

New cooldown started last week

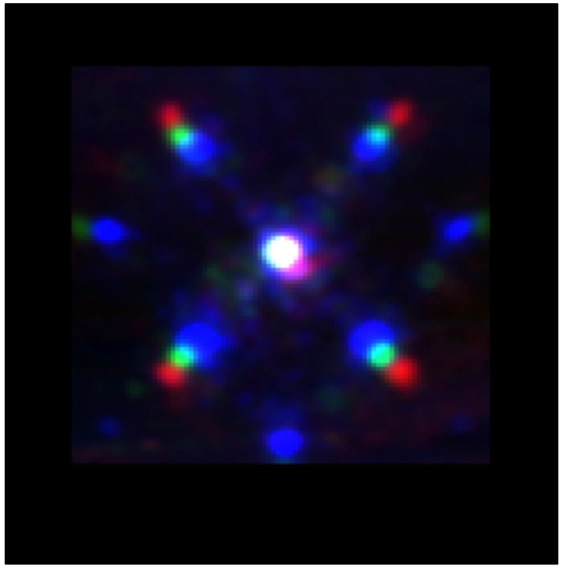
Calibration with foam

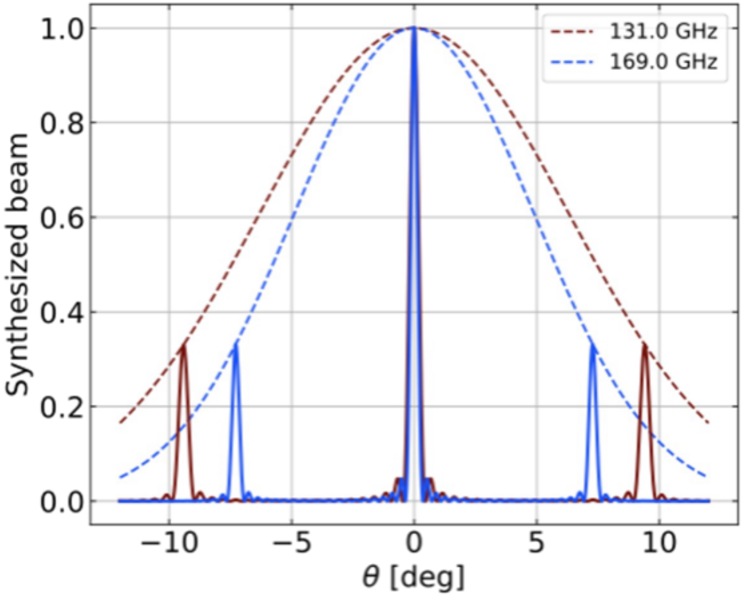


3. Spectral imaging

- Secondary beam positions dependance with frequency
- Could be used for spectral imaging! [Mousset et al., QUBIC II, 2022]

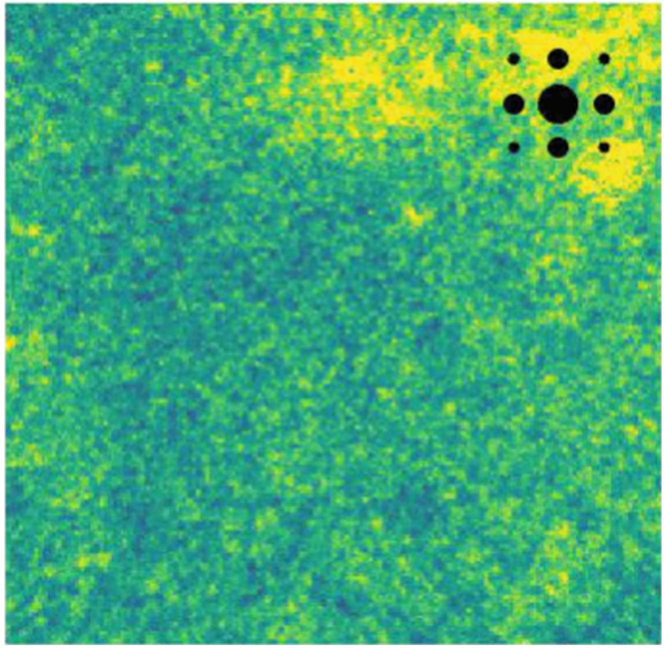
Multichroic synthesized beam (Data)



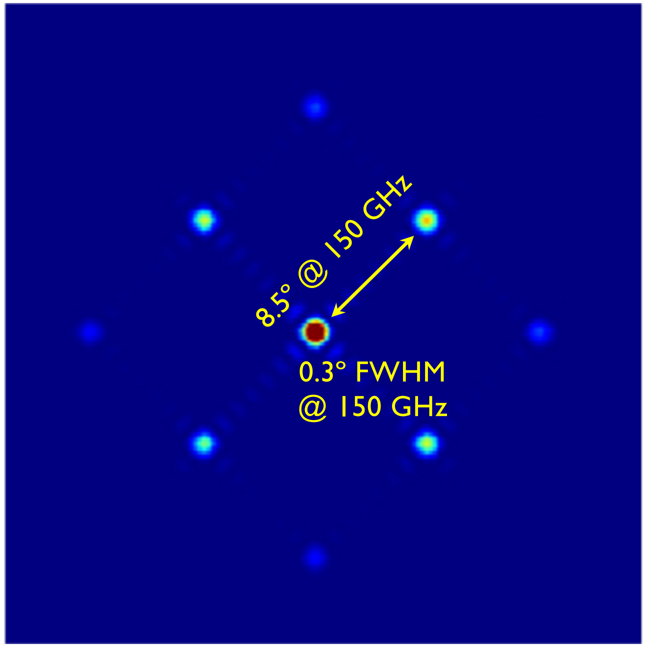


Synthesized Beam Map-Making

- Scanning the sky with QUBIC PSF:
- Classical map making with multiple beams
- Generalized to multi-frequency map making

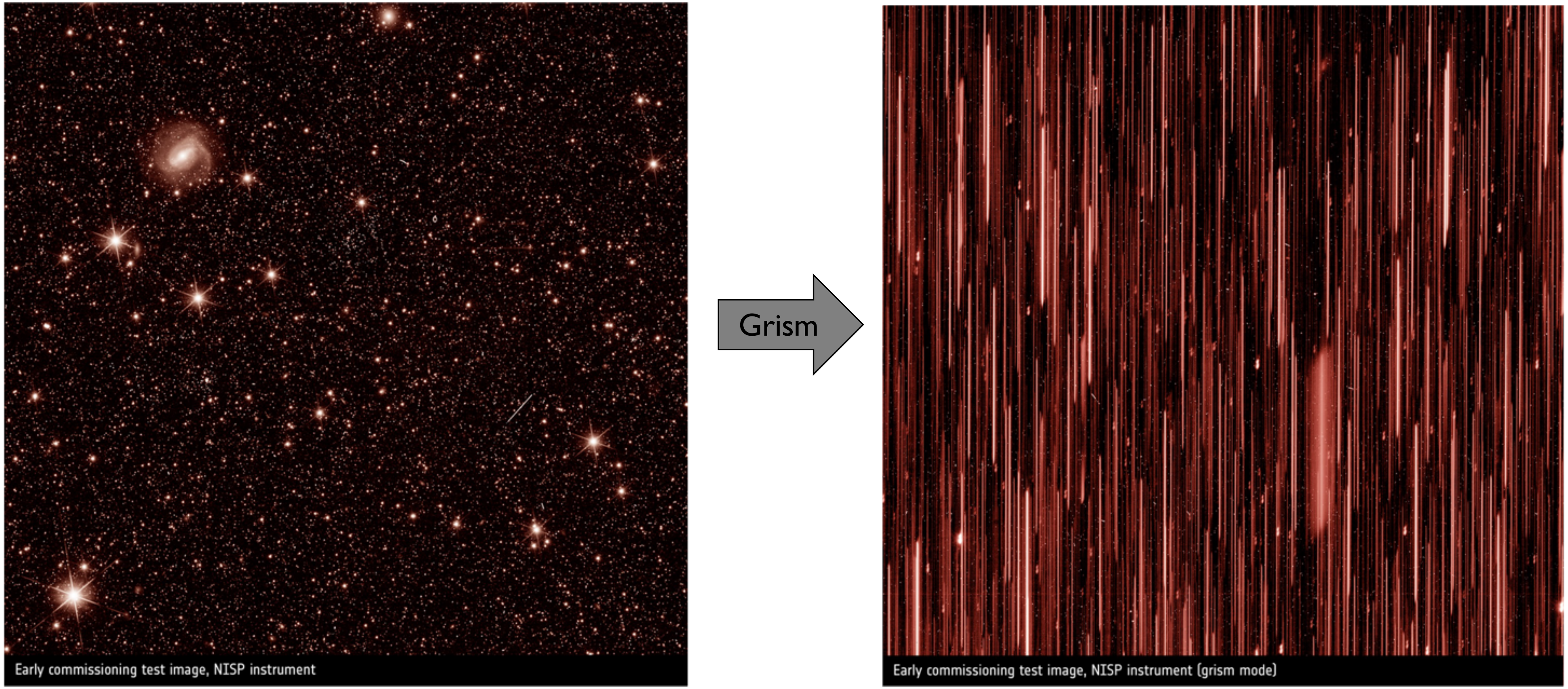


QUBIC PSF (BI Synthesized beam)



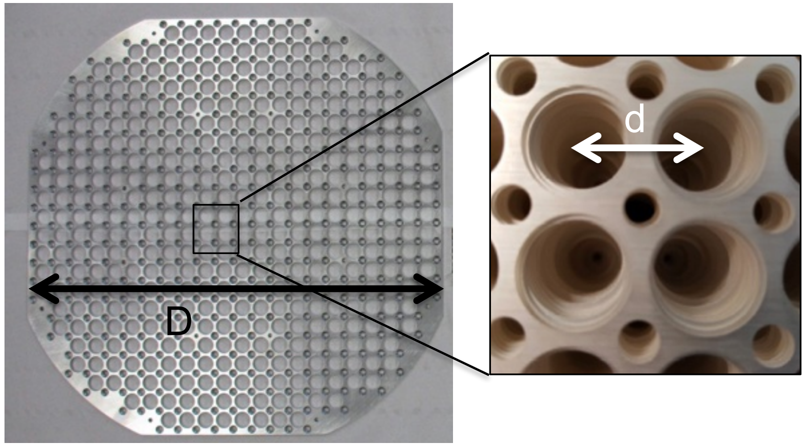
[Mousset et al., QUBIC II, 2022]
[Chanial, Régnier, et al., in prep]

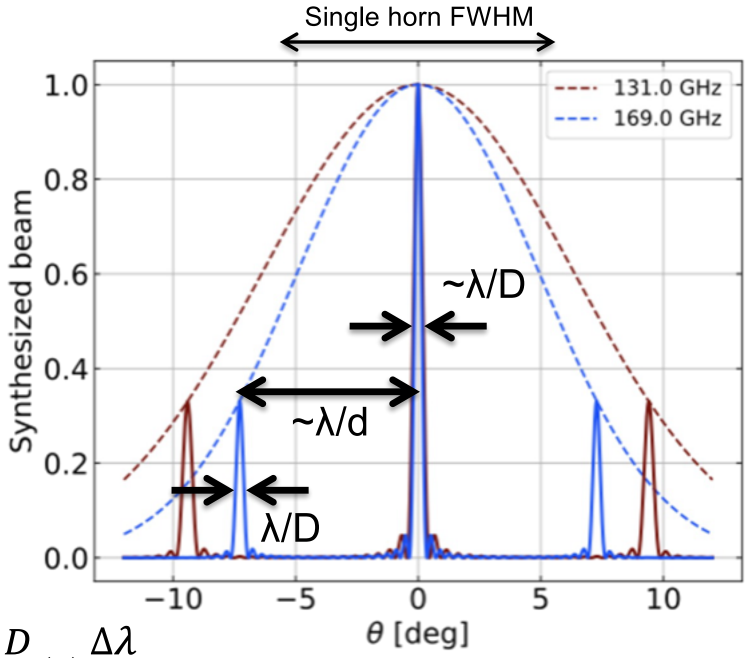
Perfect analogy with "grism spectroscopy" (Euclid test images)



Spectral imaging: how many bands?

- Horn array and synthesized beam:



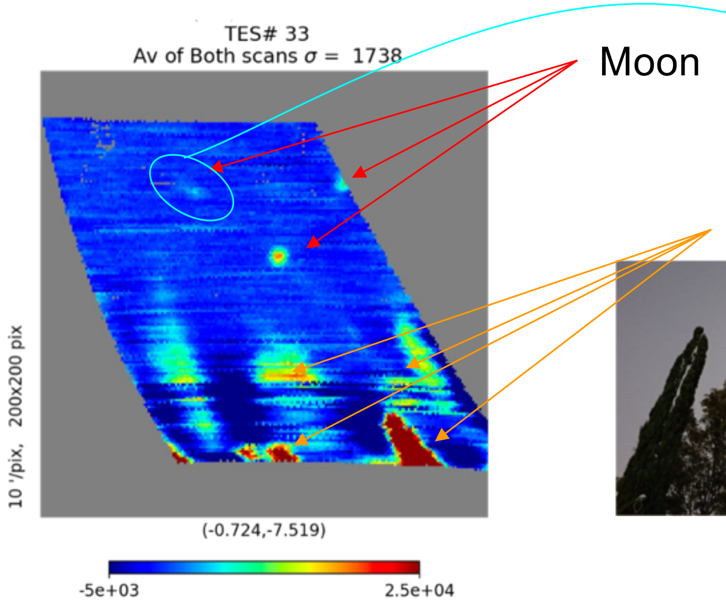


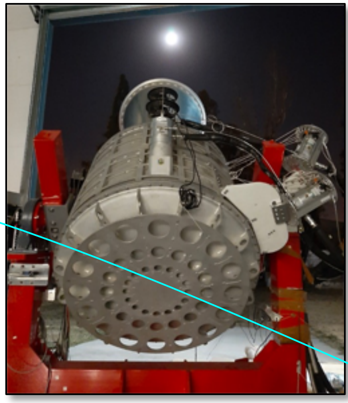
- Number of independent bands: $N_{bands} \approx \frac{D}{d} \times \frac{\Delta\lambda}{\lambda}$
  - TD: $N_{bands} \approx 3$
  - FI: $N_{bands} \approx 6$
- Implemented in the map making

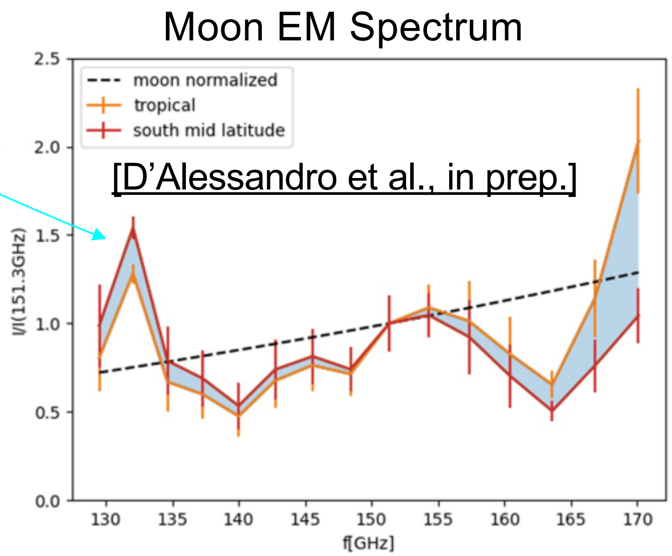
[Mousset et al., QUBIC II, 2022]

Moon spectrum measurement

- Done in Salta, July 2022, few hours:







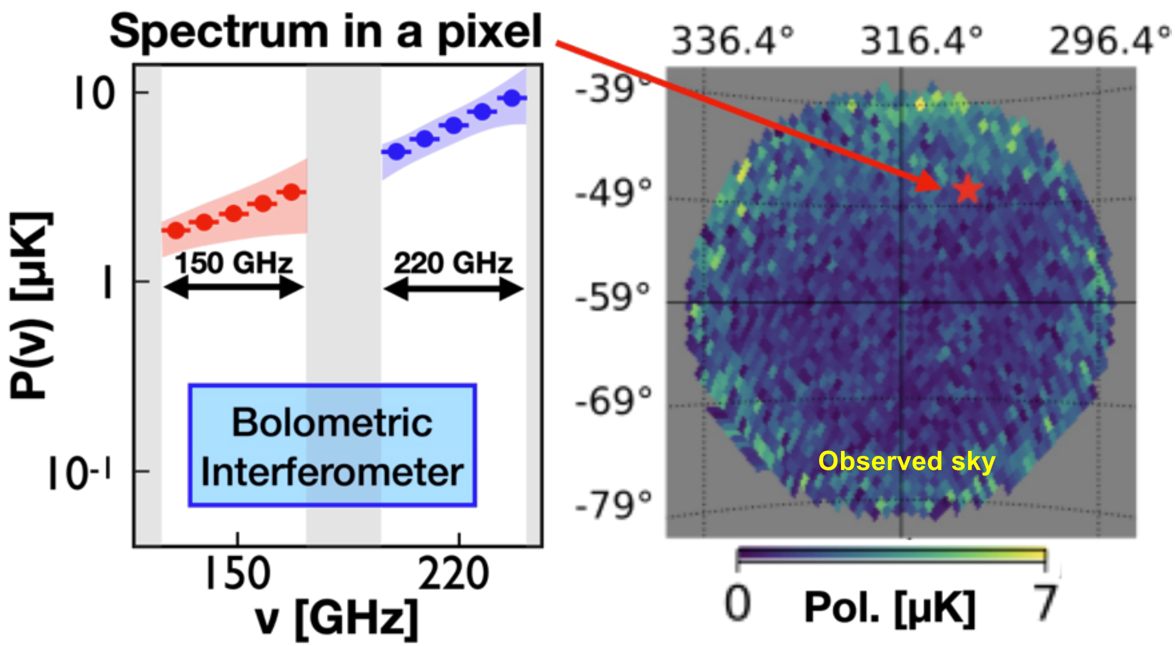
- To be improved soon at the site (less sky noise, more integration time)

Spectral imaging: a unique BI feature

Higher spectral resolution:

⇒ Better mitigation of foreground contamination

NB: performed at data analysis level:
- no hardware modification required
- One can perform the analysis with Nsub = 1, 2, 3, ...



[Hamilton, Mousset et al. QUBIC I] (JCAP 2022)

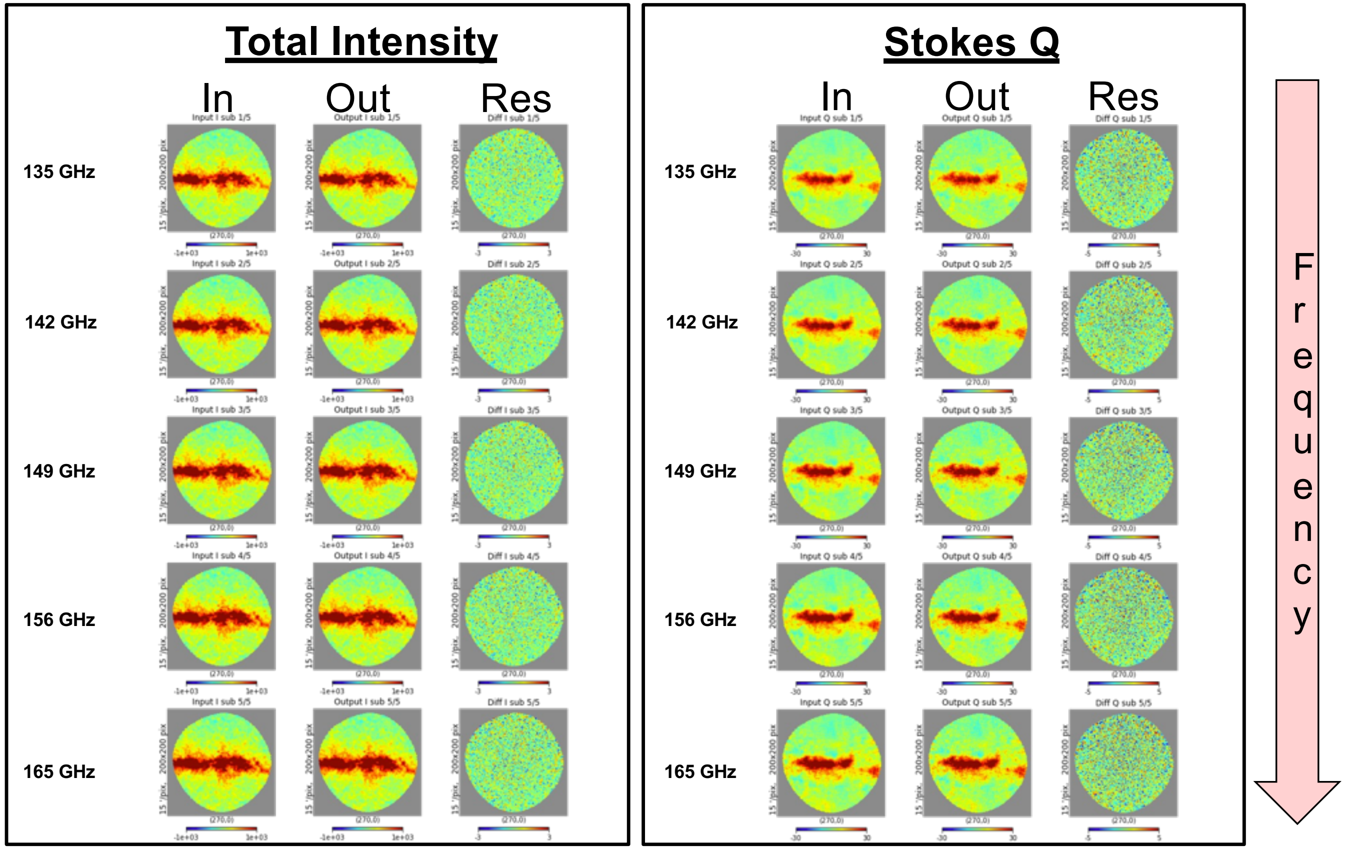
Spectral imaging simulations

Update of [Mousset, Gamboa et al., QUBIC II, 2022]

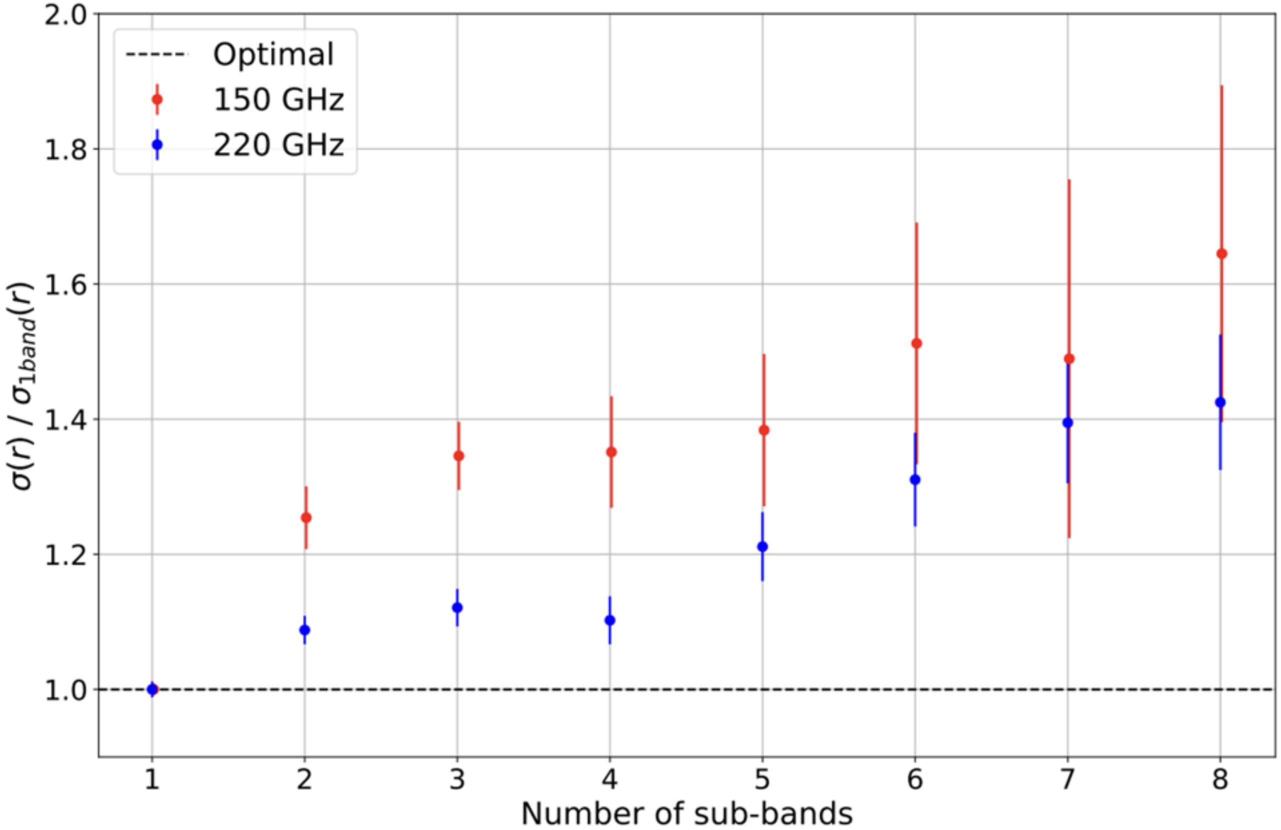
150 GHz physical band (filter)
⇔
A single TOD projected onto 5 sub-bands

[Chanial, Régnier, in prep.]

NB: similar at 220 GHz

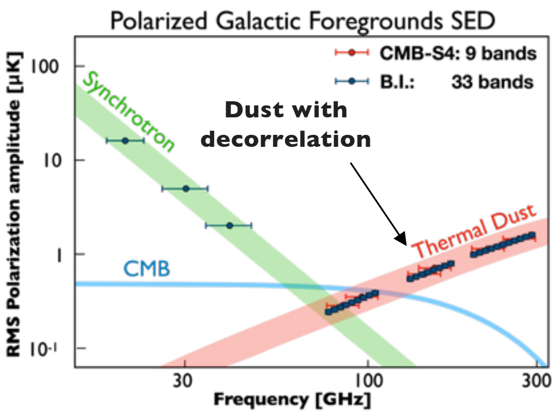


Suboptimality of Spectral Imaging



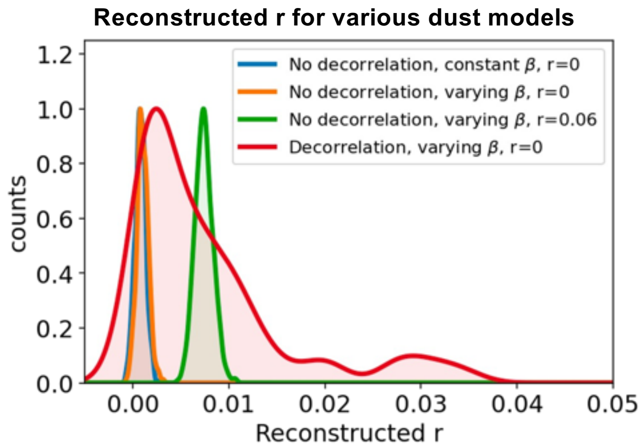
Spectral imaging: a unique BI feature

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



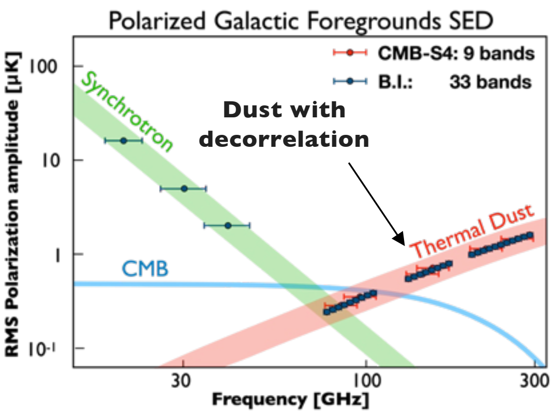
[Régnier, Manzan et al., in prep.]

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



Spectral imaging: a unique BI feature

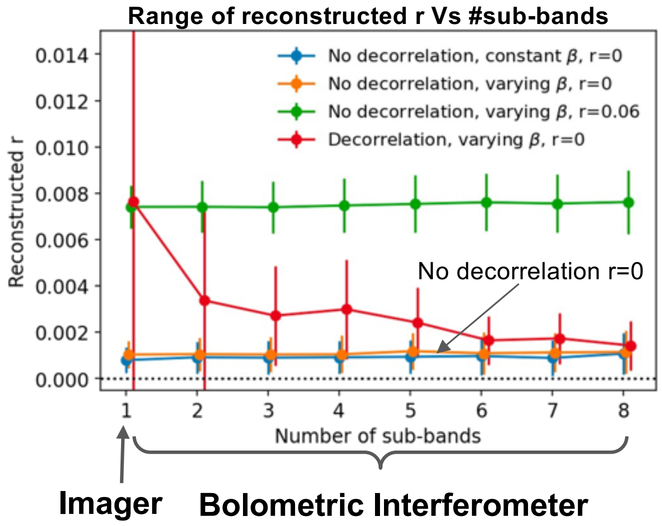
Non-minimal dust model: Dust SED decorrelation (d6 Corr_length = 15: 3x smaller than current constraints)



[Régnier, Manzan et al., in prep.]

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

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



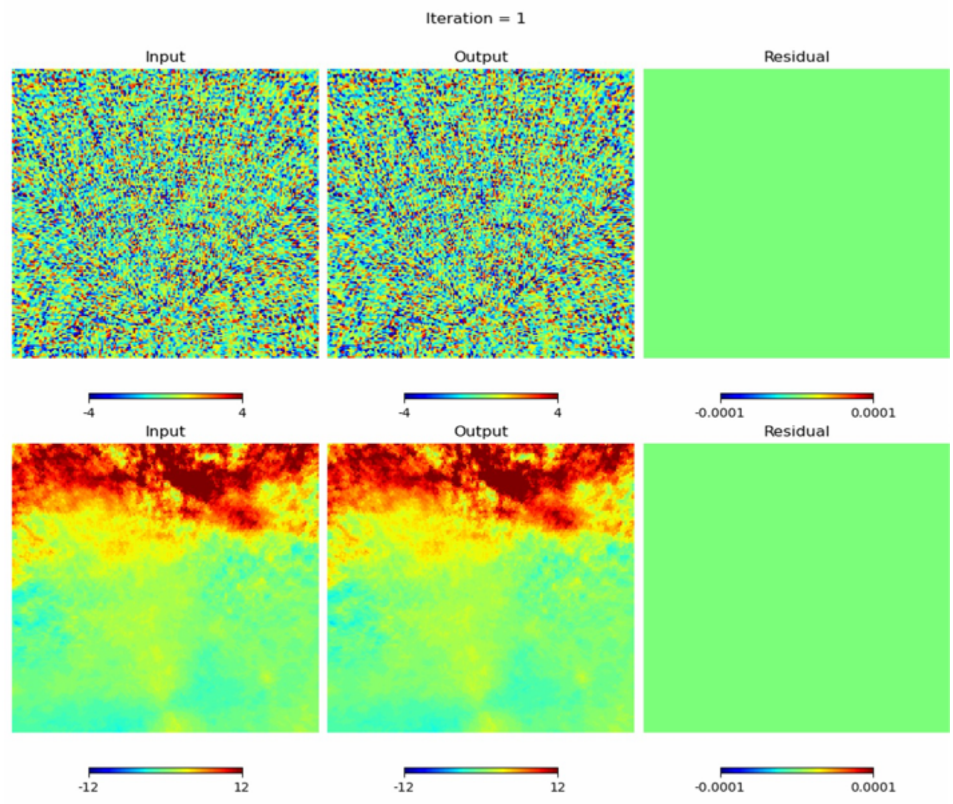
B.I. is complementary to direct imaging:
Dust decorrelation is to be expected from realistic dust

Components Map-Making

- Classical imagers: Frequency maps → Component separation
- B.I.: frequency sensitivity in TOD
  ⇒ **directly build components maps from TOD**
  – Full Spectral-Imaging resolution
  – Richer spectral modeling
    - Spectral index variations
    - Emission lines (CO, …)
  – Atmosphere

[Régnier, et al., in prep]

First TOD → Components MapMaking (parametric) !
(d1, noiseless)



Components Map-Making

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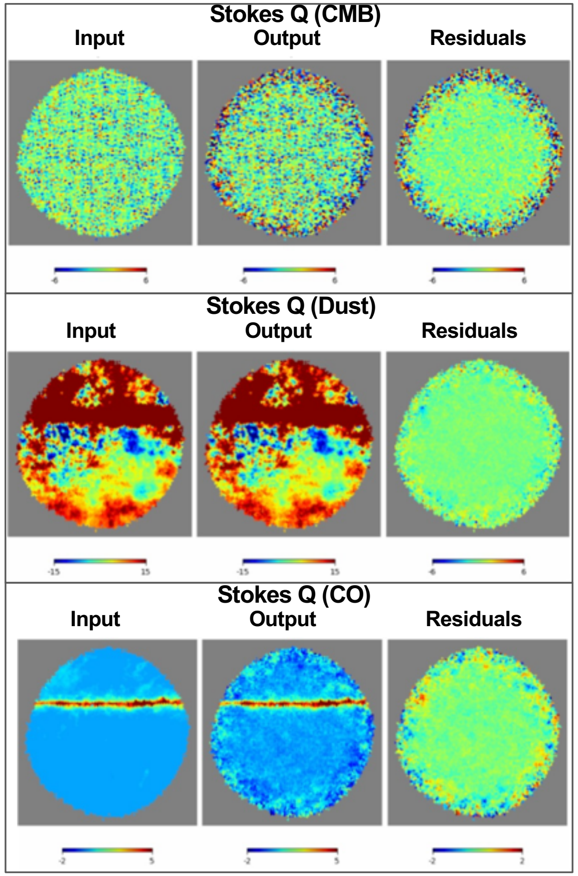
[Régnier, et al., in prep]

First TOD → Components MapMaking (parametric) !

Nominal noise - 3 components: CMB, Dust, CO line



CO emission line

To conclude

- QUBIC: the 1st Bolometric Interferometer inaugurated in Nov. 2022. Commissioning is on its way
  - Sensitivity to primordial CMB B-modes: $\sigma(r)=0.015$ (3 years, conservative)
  - As an Interferometer, QUBIC has several specificities w.r.t. classical imagers:
    - Self Calibration and low cross-polarization
    - Spectral Imaging: a possible new path to foreground mitigation
      - Make images in up to 6 sub-bands within the physical detectors bandwidth
      - Measure “locally” the contamination from astrophysical foregrounds (including decorrelated dust)
      - New direct TOD → Components approach (improves component separation)
- Check the JCAP special Issue on QUBIC (2022): 8 papers covering forecasts, lab calibration and hardware design