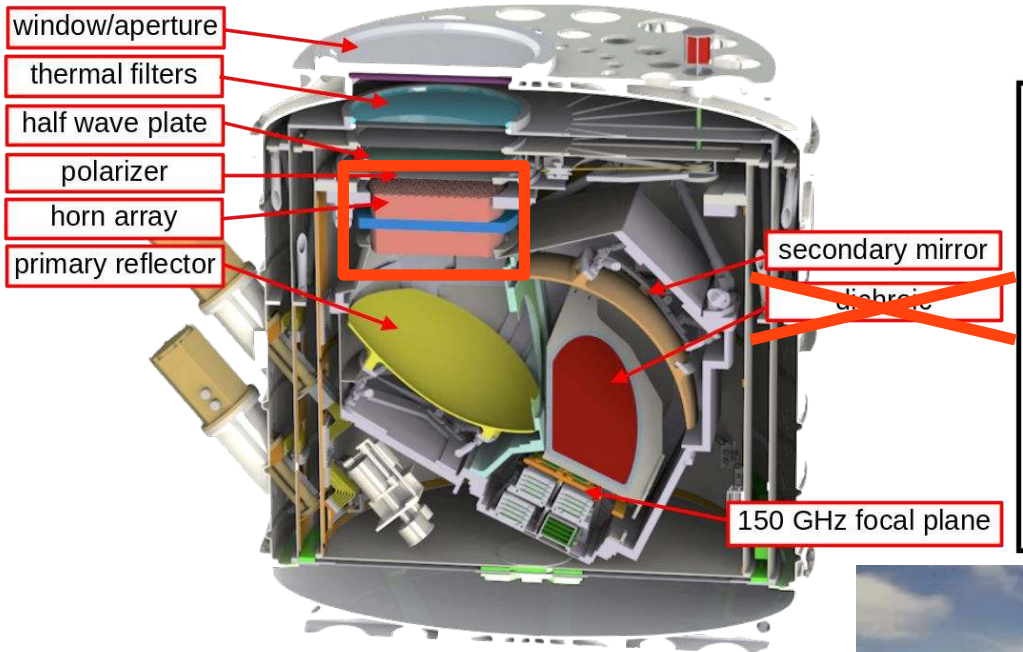
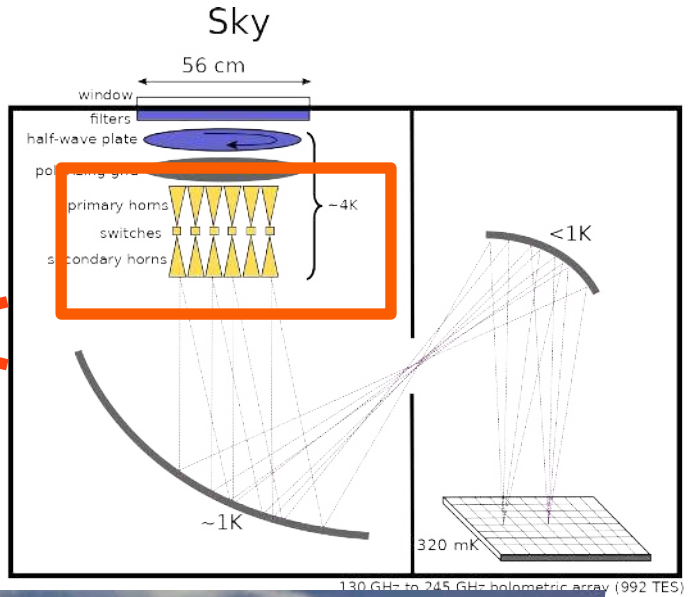
# QUBIC
# Calibration Using Bolometric Interferometry

Steve Torchinsky on behalf of the QUBIC Collaboration
Astroparticle Physics and Cosmology
Observatoire de Paris, Université Paris Cité, CNRS/IN2P3

# Q & U Bolometric Interferometer for Cosmology



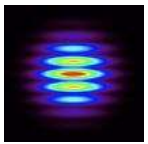




# The QUBIC Concept: adding interferometry

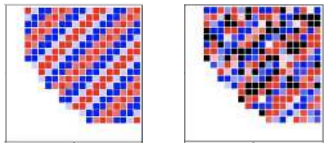
1 Horn open

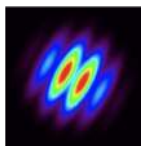
[L. Mousset, PhD, 2021]

**QUBIC Sim.** **QUBIC Cal Data**

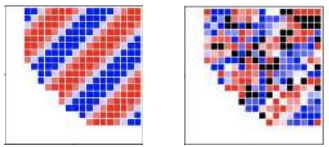


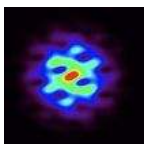
2 Horns open



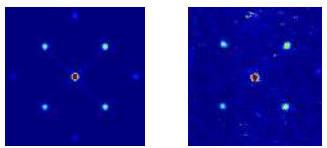


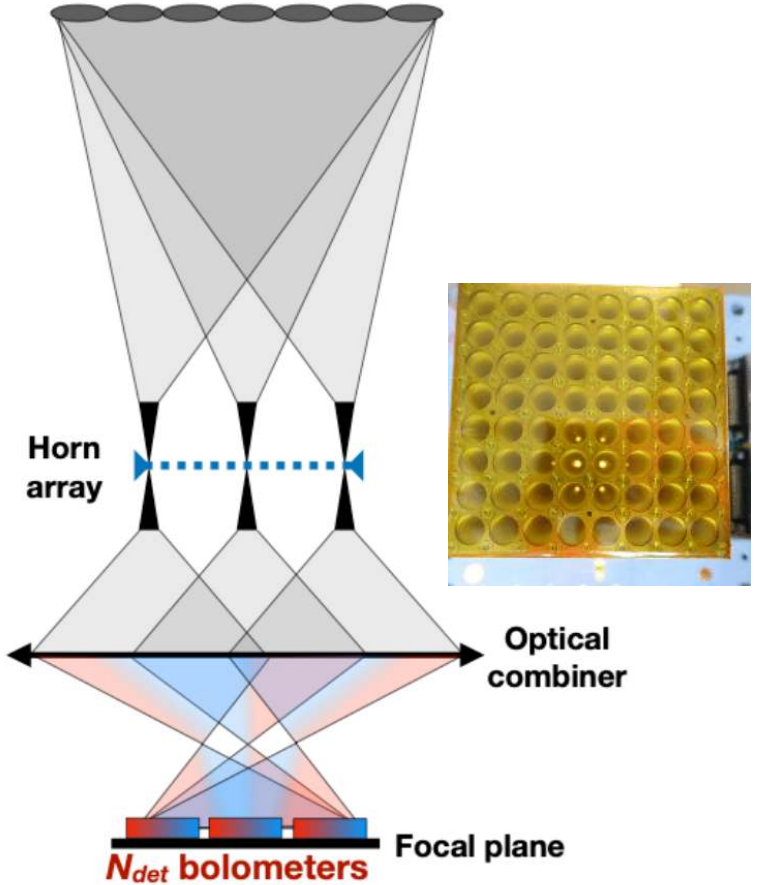
2 Horns open



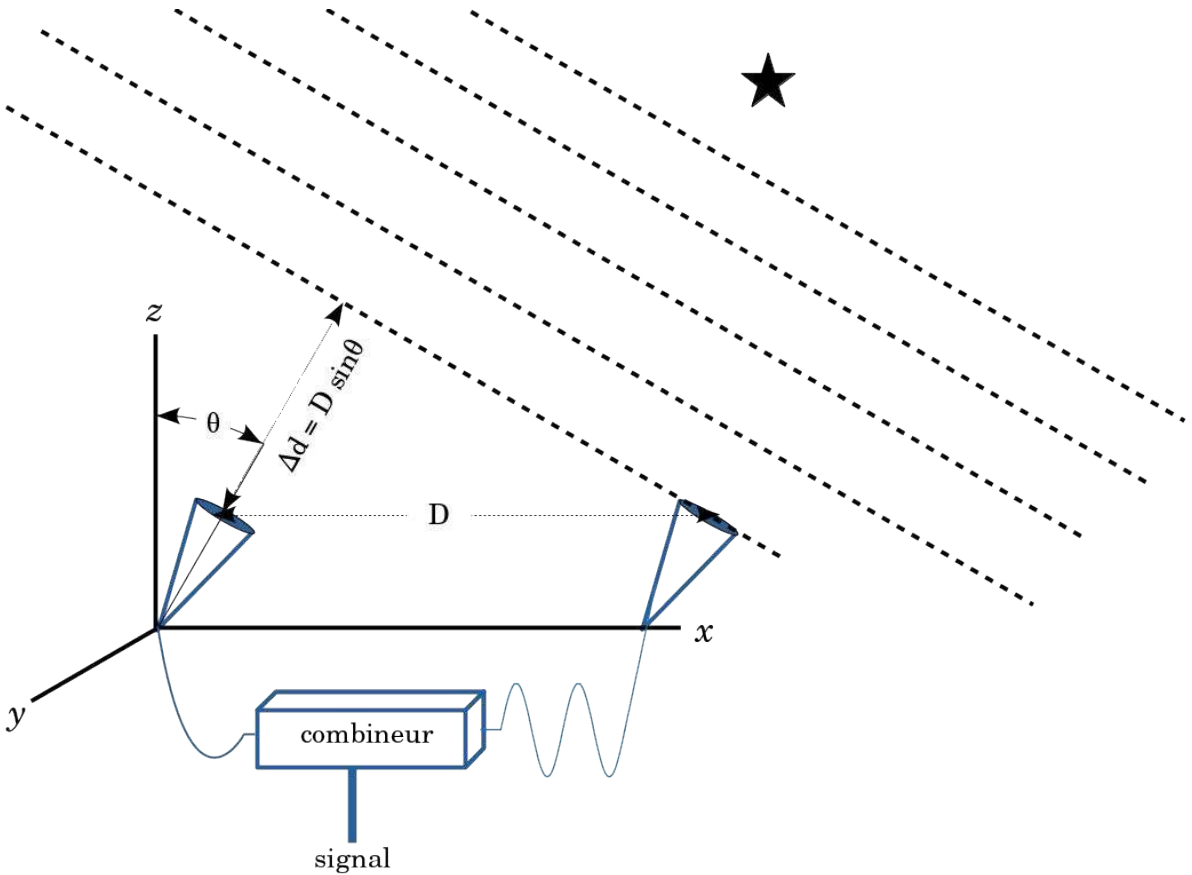


All Horns open

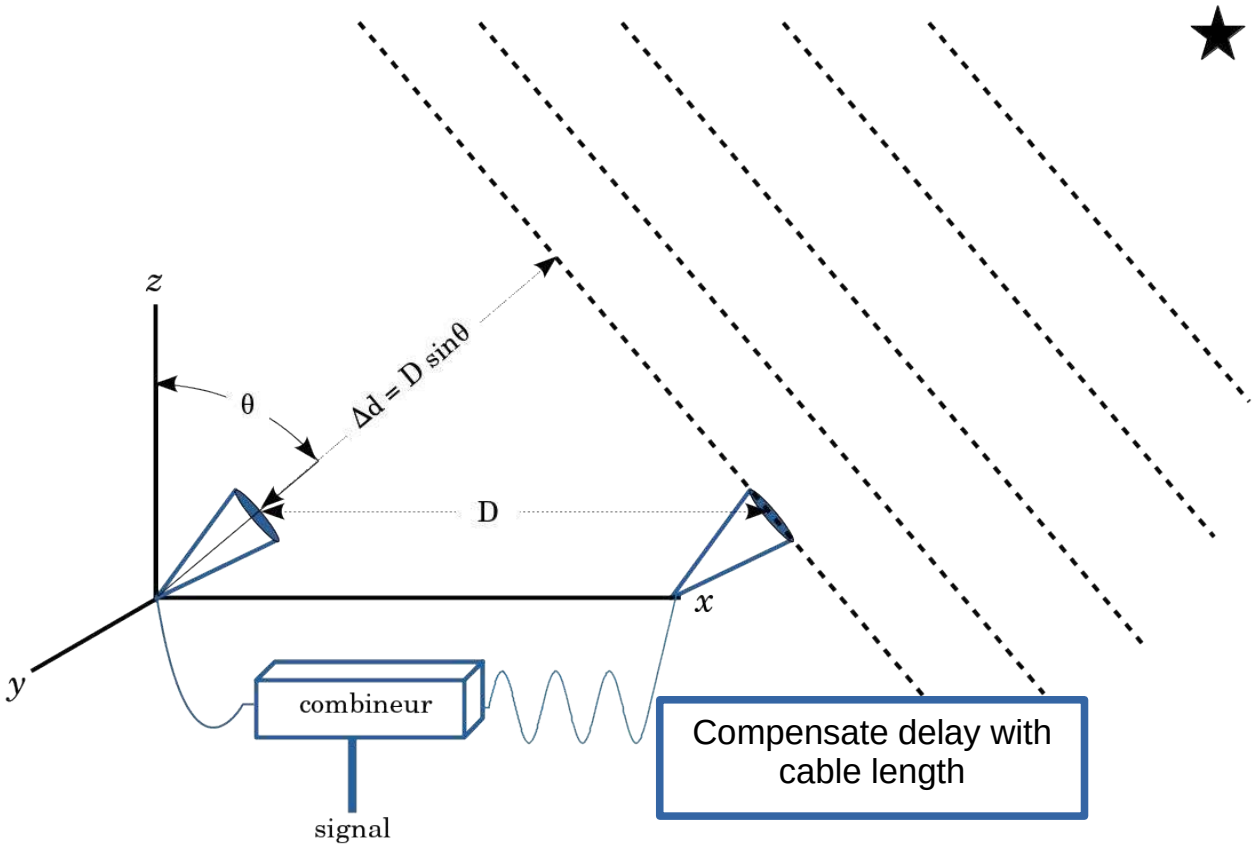




# Interferometer: direction 1

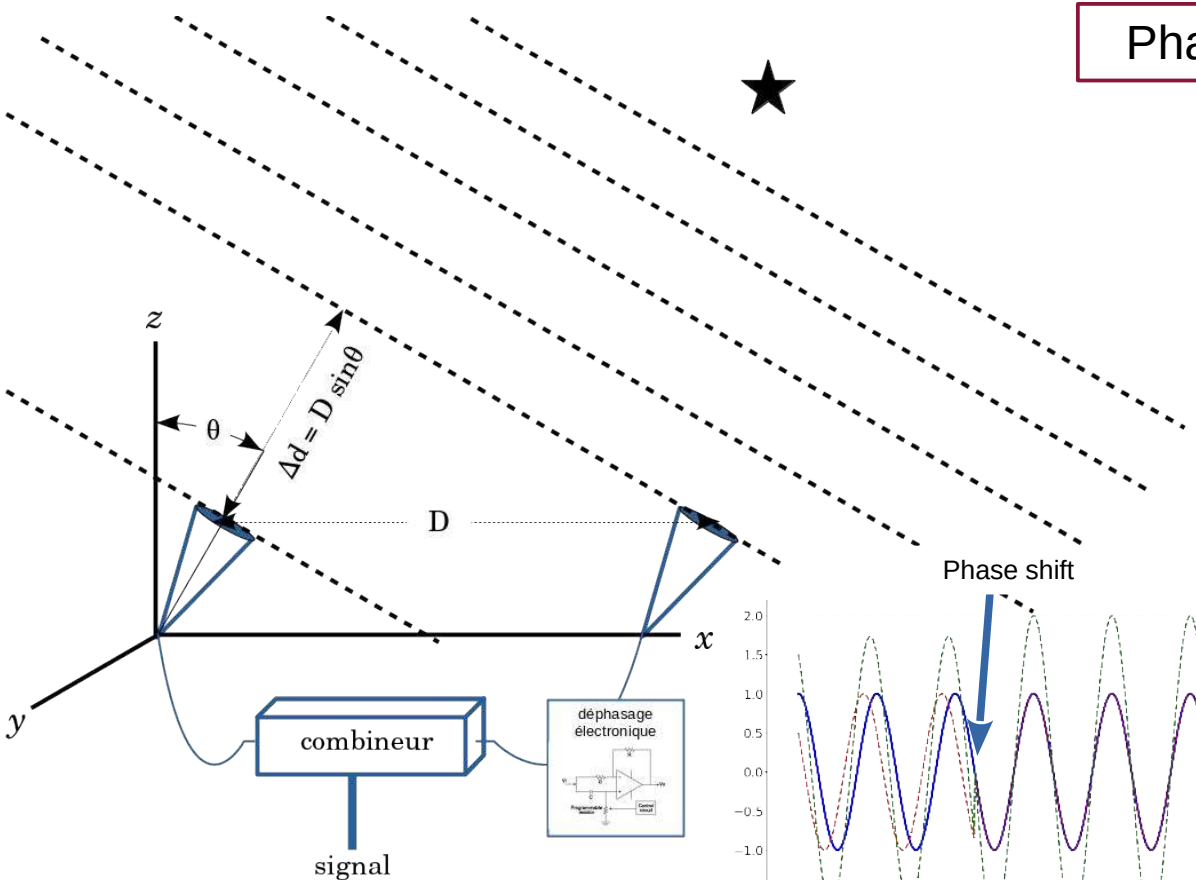


# Interferometer: direction 2

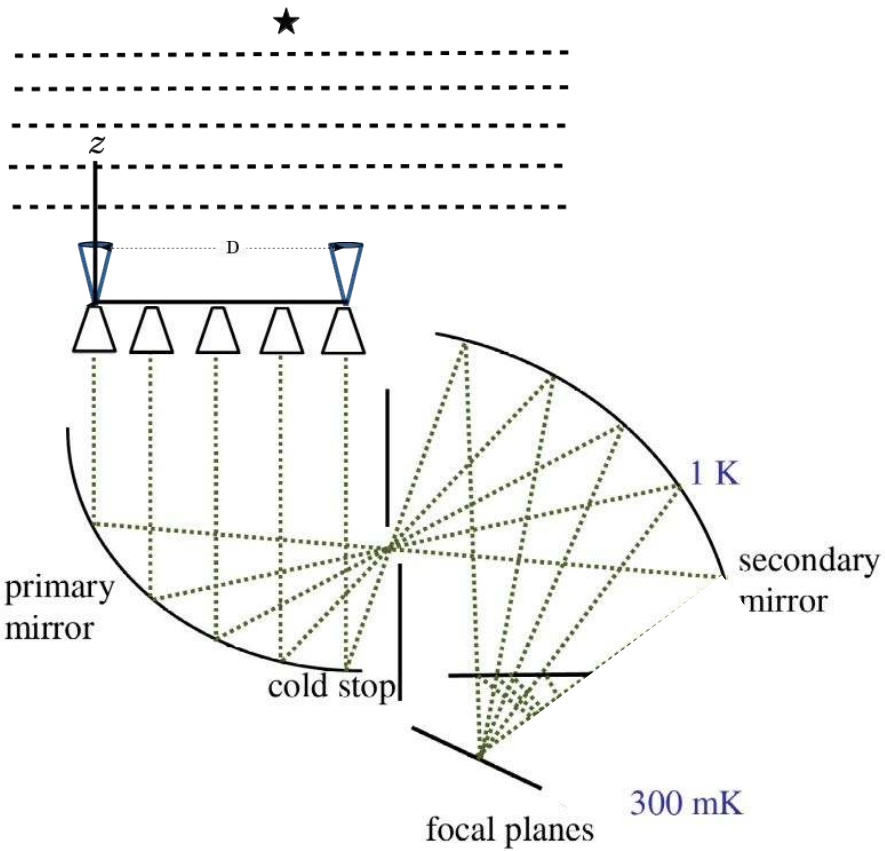


# Interferometer using phase shifting

Phased array

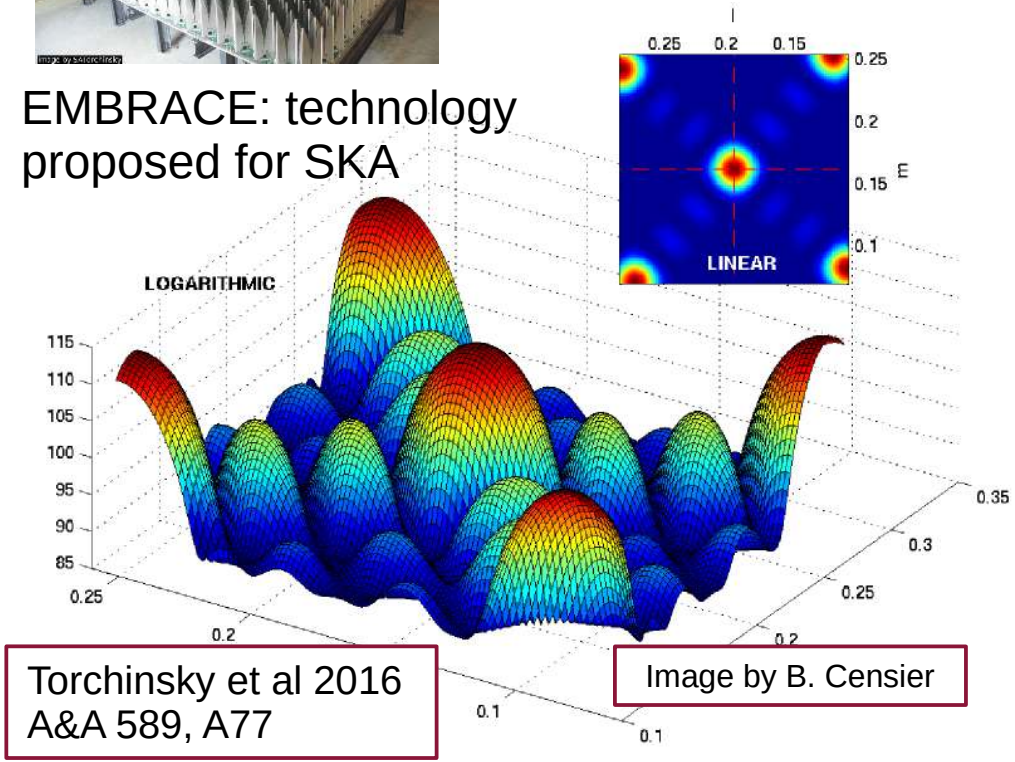


# Interferometer using mirrors




# Interferometer Array on a Regular Grid

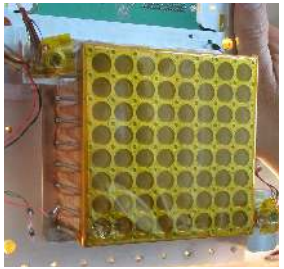
EMBRACE: technology proposed for SKA

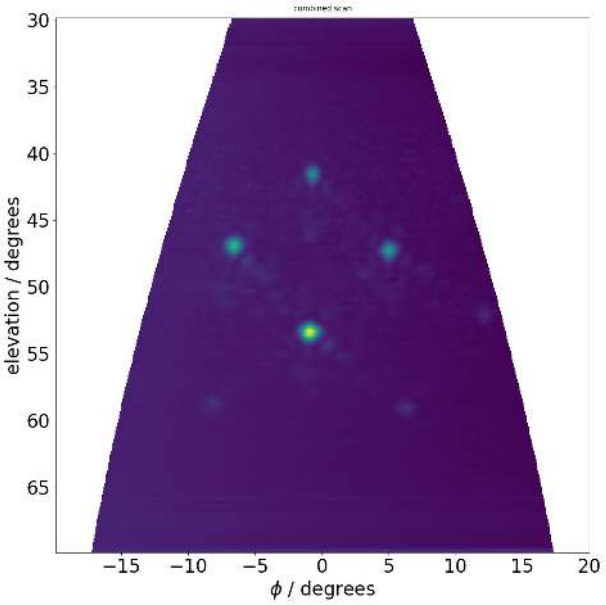



Torchinsky et al 2016
A&A 589, A77

Image by B. Censier

Grating lobes

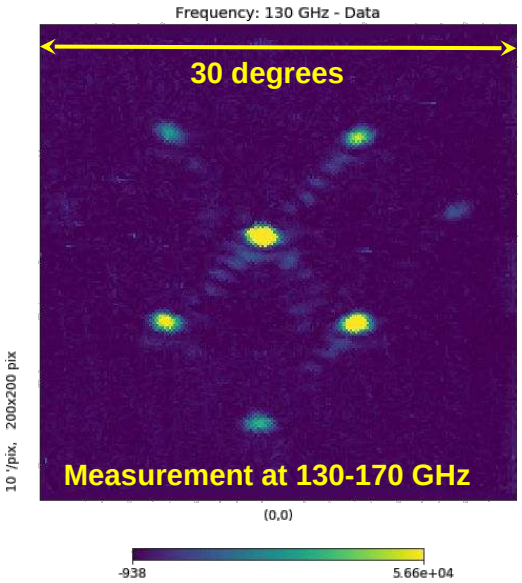


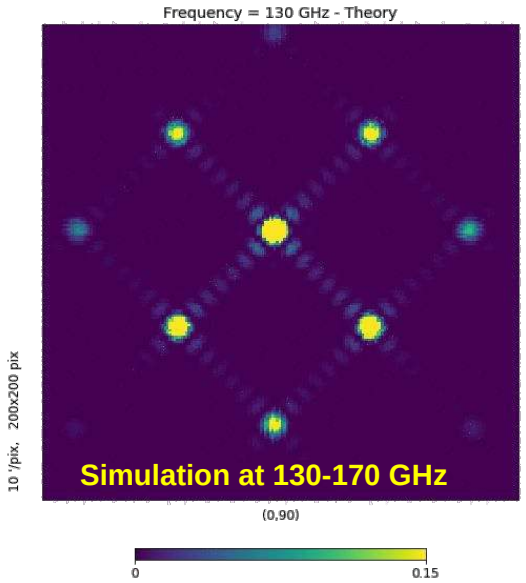


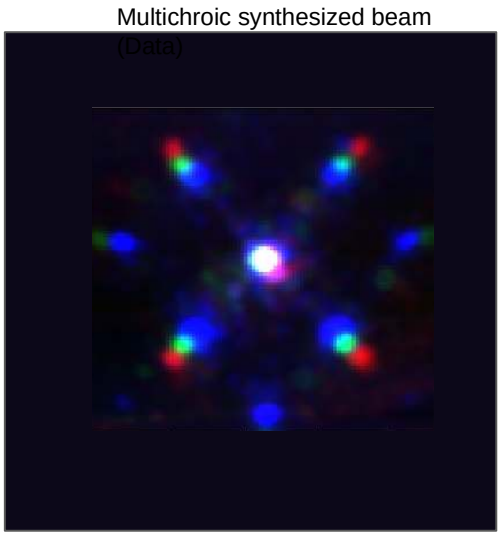

Torchinsky et al 2022
JCAP 04, 036T

# Measured Synthesized Beam

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



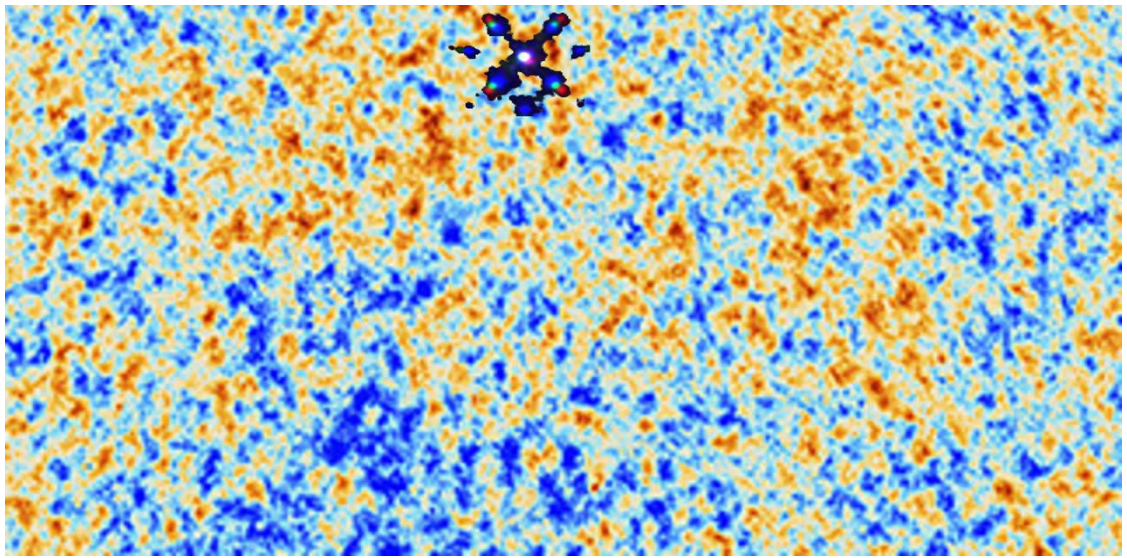




[Torchinsky et al., QUBIC III arXiv:2008.10056v3 ] (JCAP 2022)

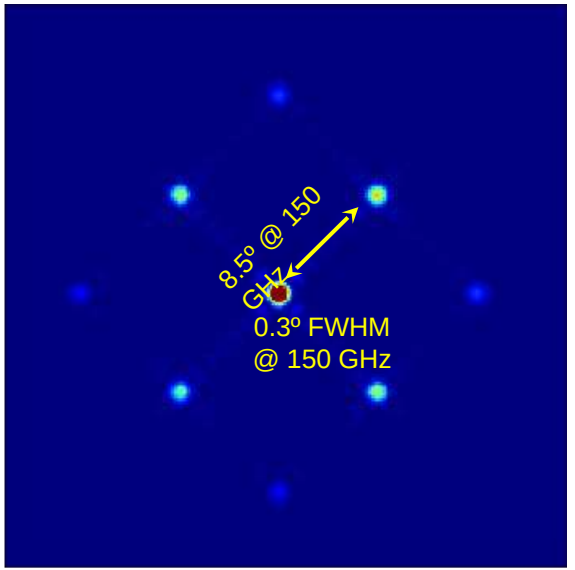
**Peaks distance evolution w.r.t. Frequency opens the path to Spectral Imaging !**

# Bolometric Interferometry ⟺ Synthesized Beam Map-Making

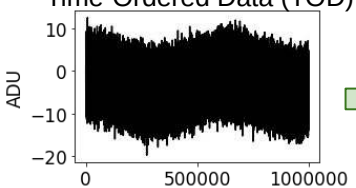
We scan the sky with our PSF



QUBIC PSF (BI Synthesized beam)




Time-Ordered Data (TOD)




Map-Making with B.I.

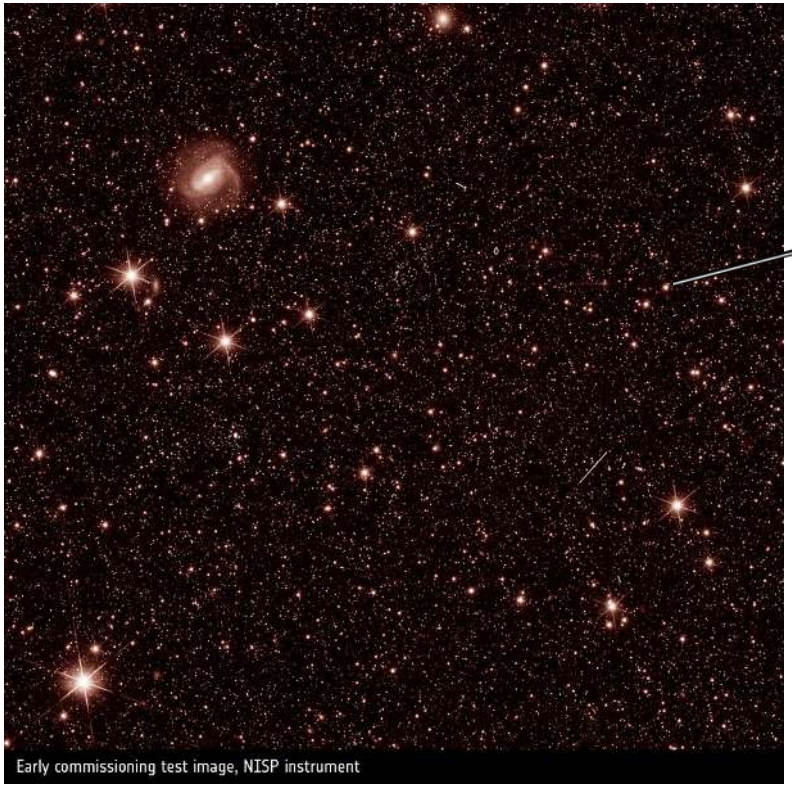
We need to solve for s: $\vec{y} = H \cdot \vec{s} + \vec{n}$

One needs partial deconvolution of the peaks

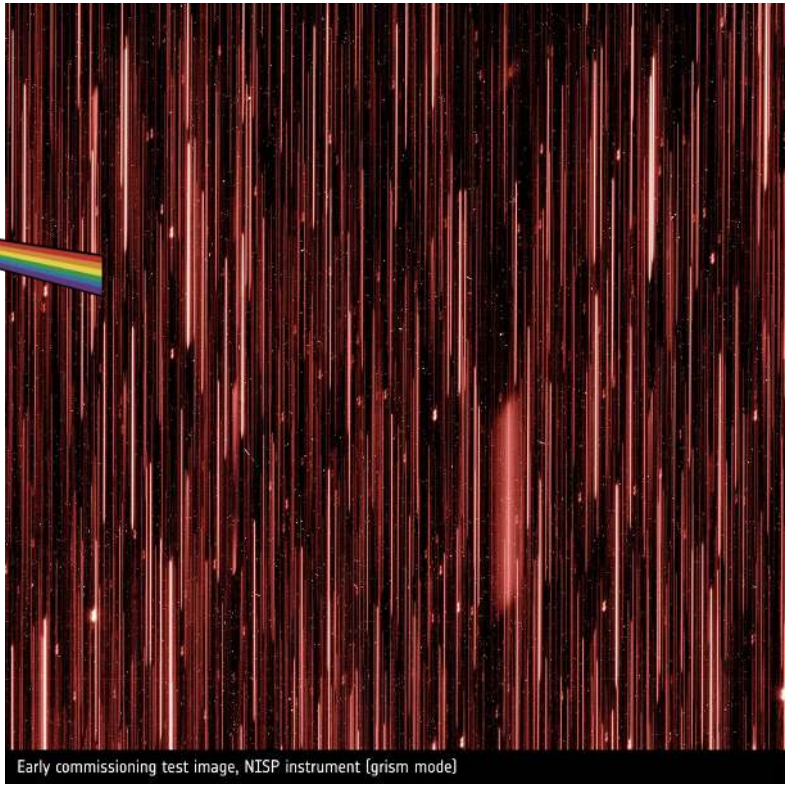
Forward modeling approach:
$\chi^2$ in TOD space
Regularization with Planck data

Regnier et al 2023 arXiv:2309.02957
Manzan et al 2023 arXiv:2311.01814
Chanial et al 2024 arXiv:2409.18698
Regnier et al 2024 arXiv:2409.18714

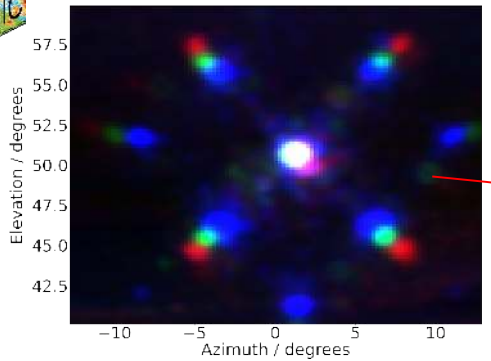
# Analogy with “grism spectroscopy” (Euclid test images)





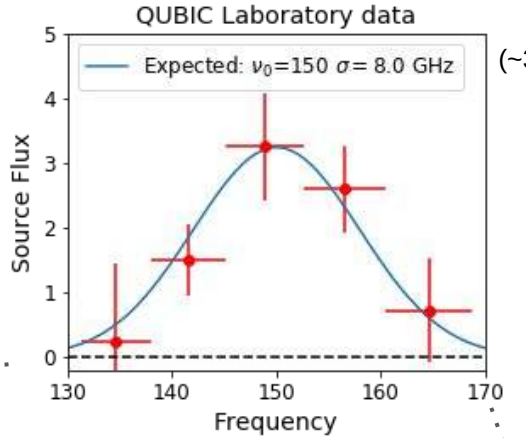


QUBIC Multichroic Synthesized beam measurement (130, 150, 170 GHz)

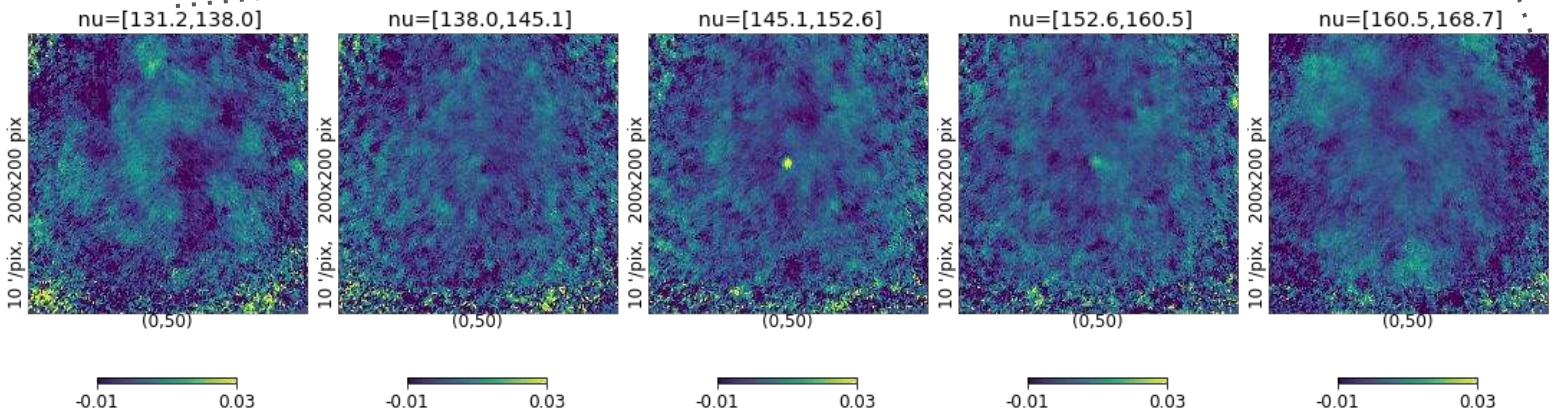



# With Real Data (26 detectors) [indoor calibration source]

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



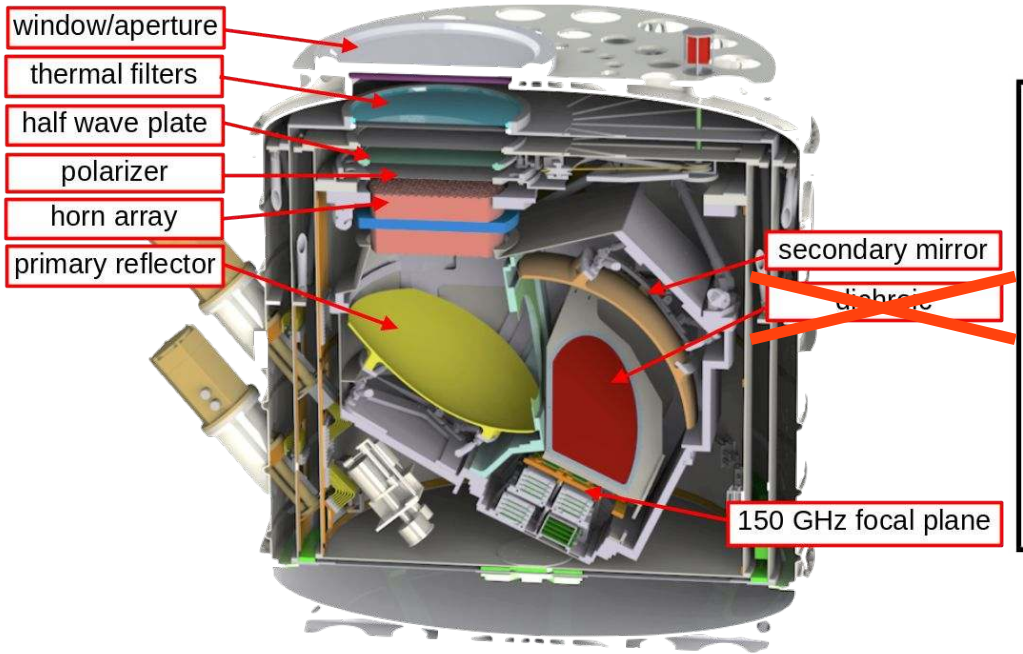

(~3.2 GHz with FI)

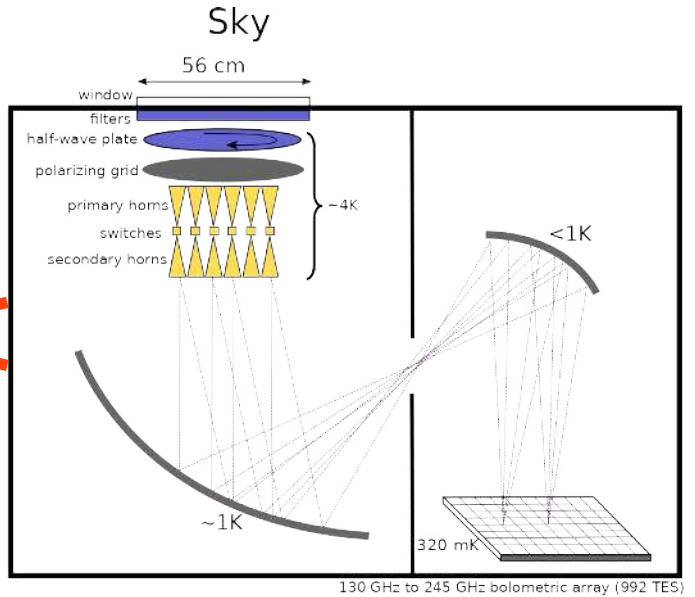


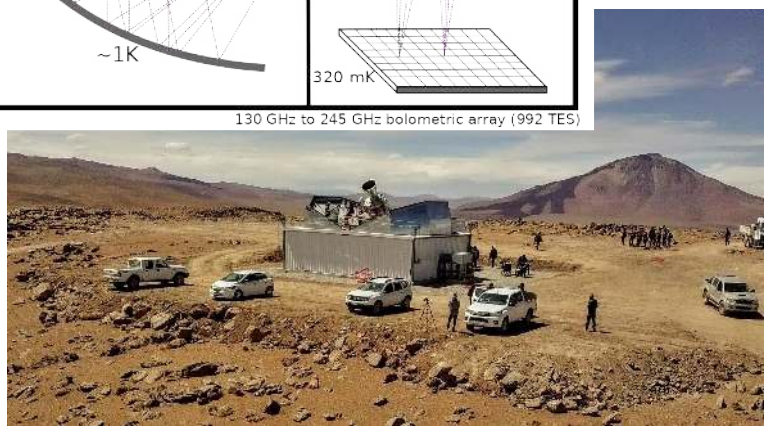

**First Spectral Imaging reconstruction with real data (Calibration Source operating at 150 GHz at APC)**

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

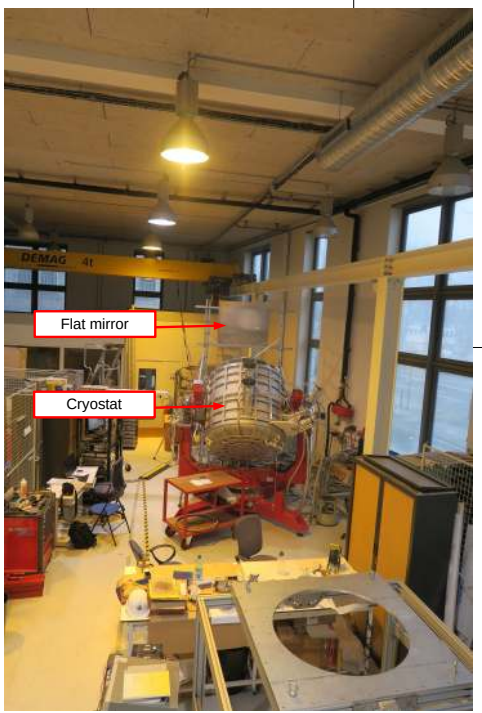
# Spectral Imaging allows us to eliminate the dichroic and half the bolometers!

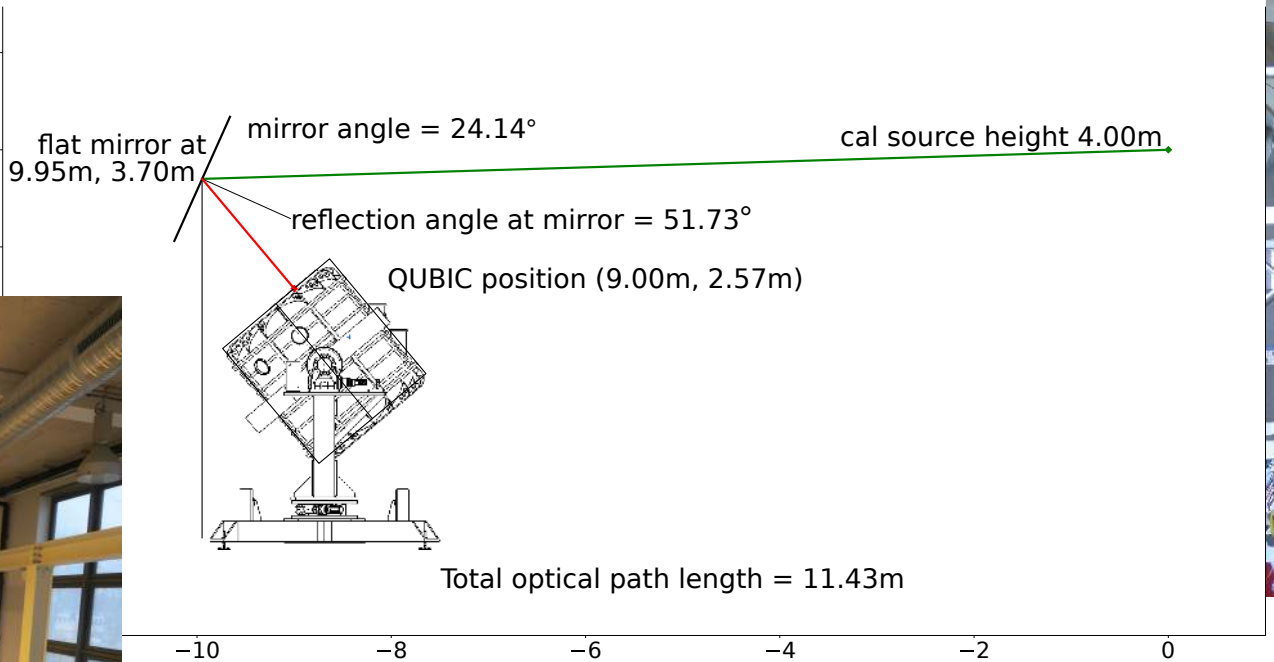


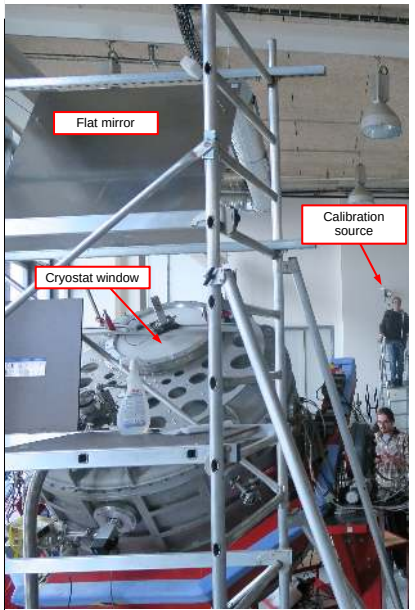



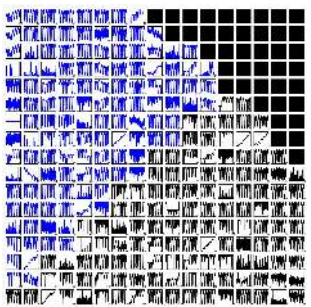



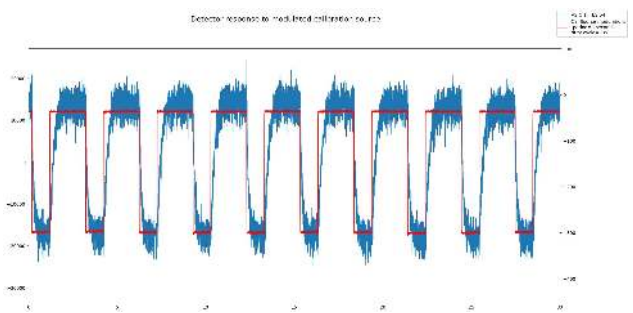
# QUBIC characterization at APC

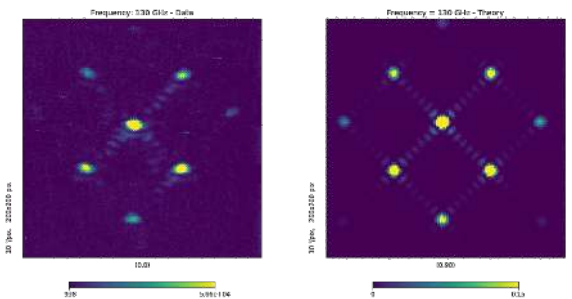


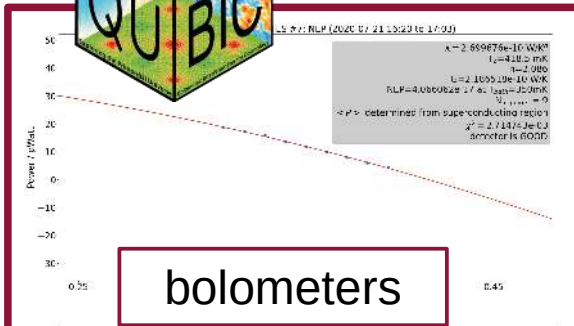


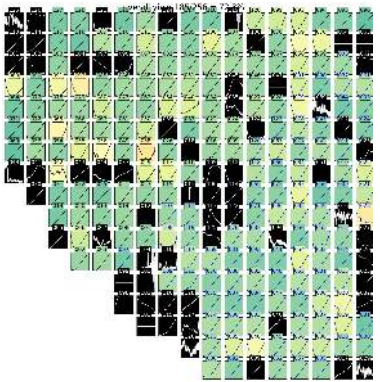


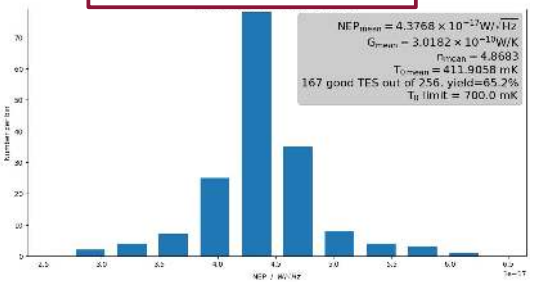
# Some results

Torchinsky et al JCAP 2022

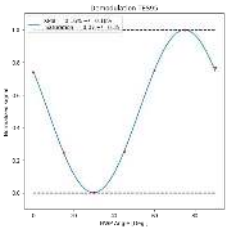
## bolometers

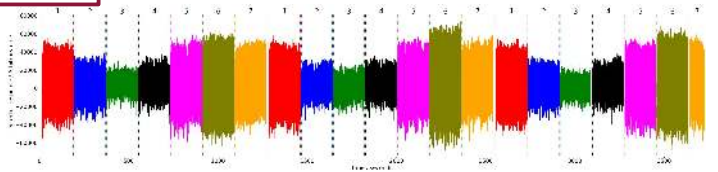




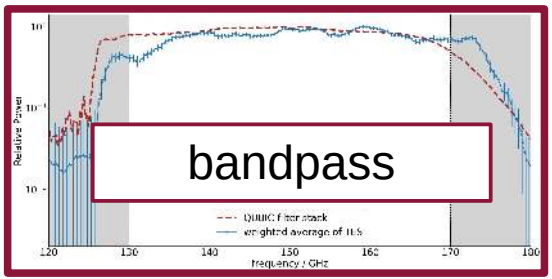



## Polarization modulation with the HWP

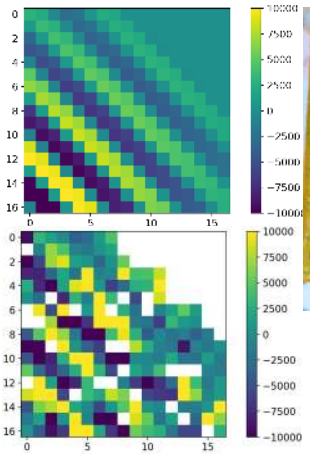


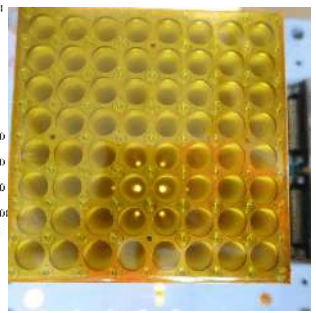


## bandpass



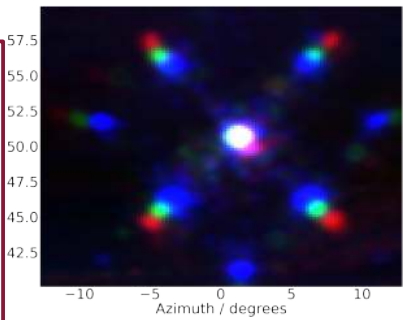

## fringes

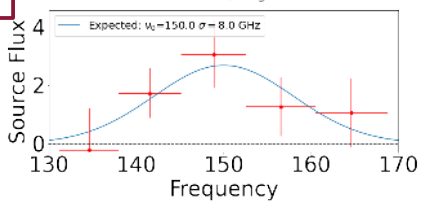




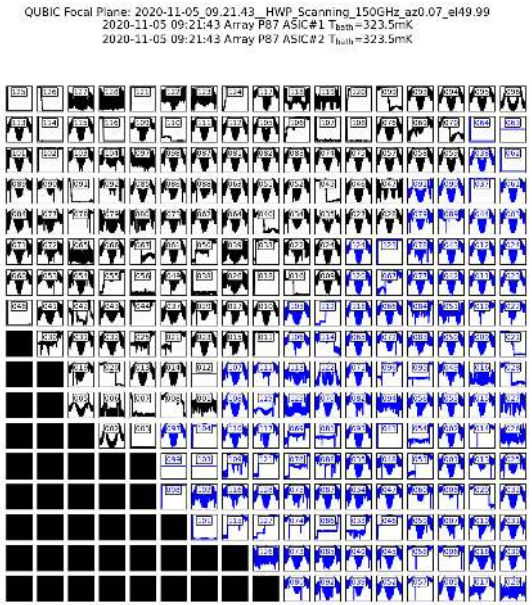
Louise Mousset
Phd 2021

## Spectral response with secondary lobes

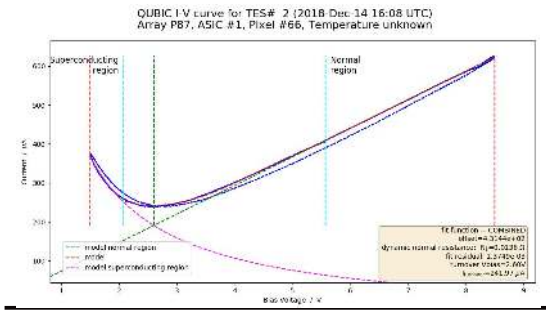


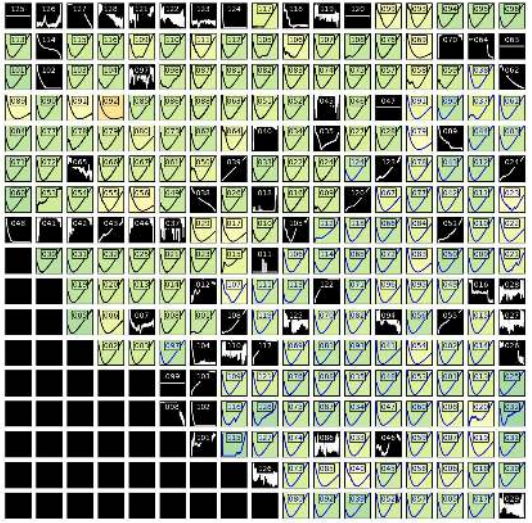



# qubicpack example plots

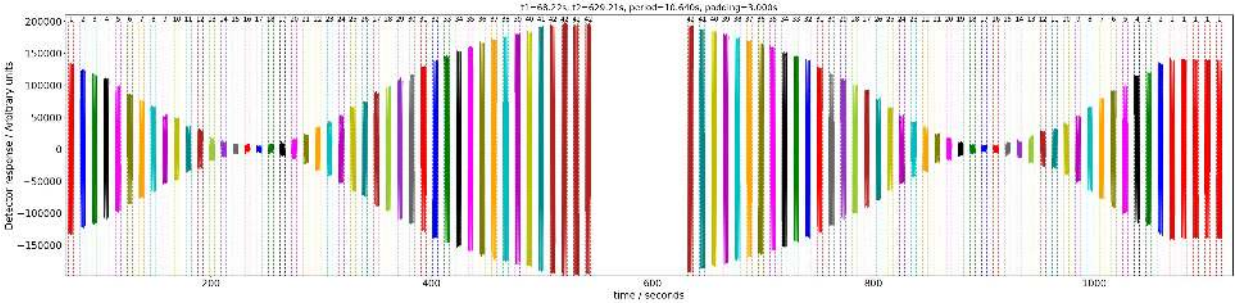



Scientific data: timeline for each pixel

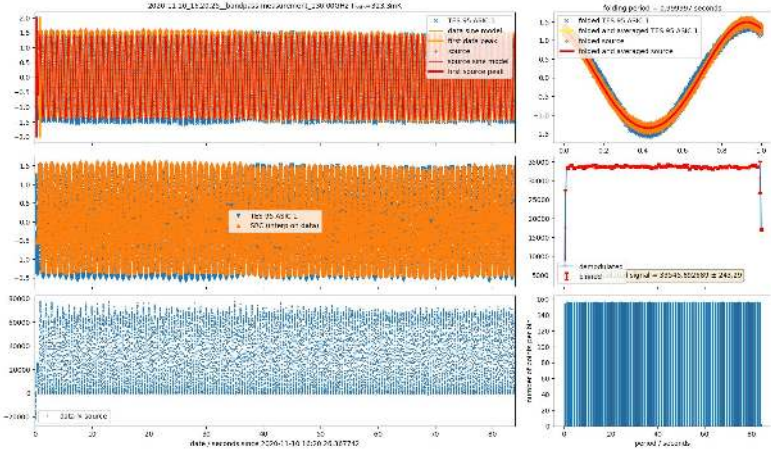



I-V curve for each pixel



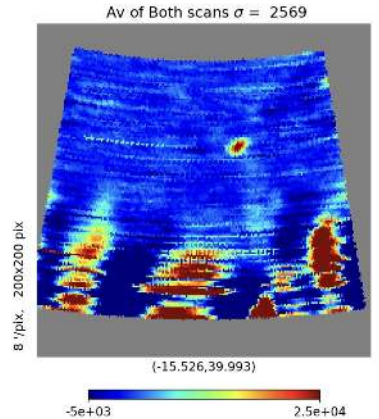

HWP timeline per position



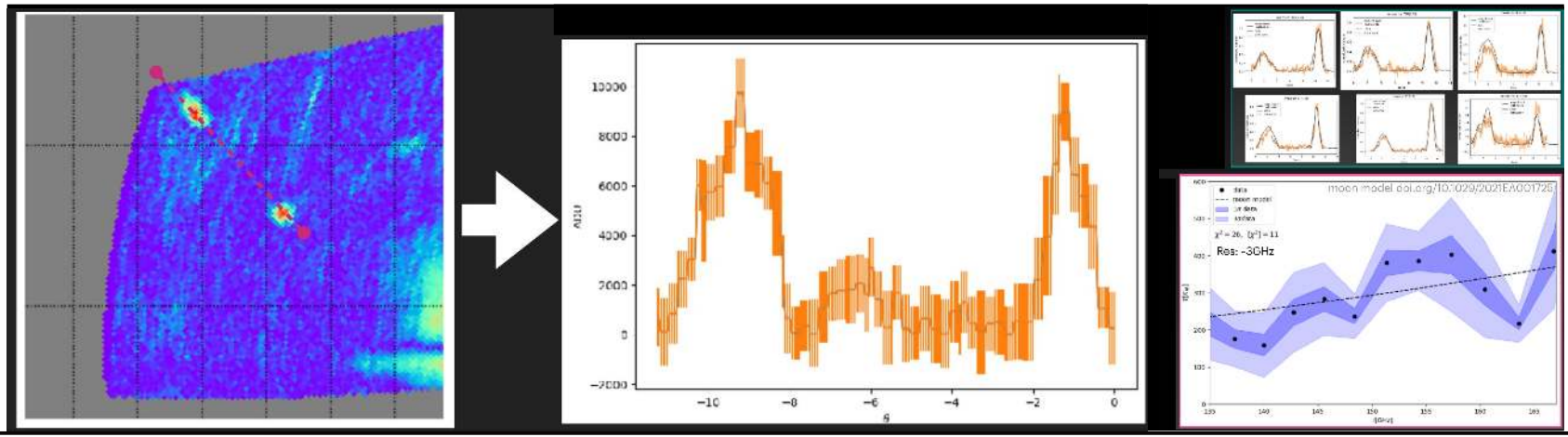
Demodulation diagnostic

# Reintegration and characterization in Salta

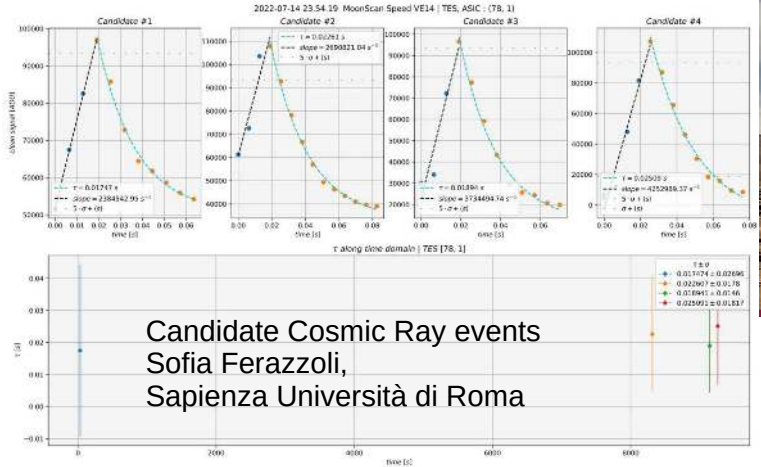

Moon Observation 14 july 2022



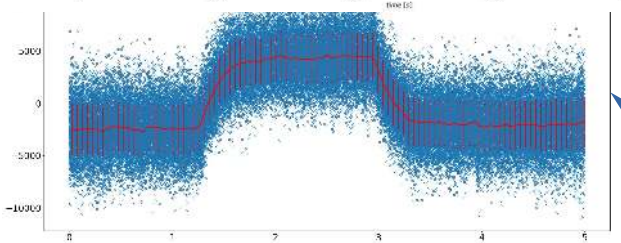

application of spectral imaging by Giuseppe D'Alessandro (D'Alessandro et al, 2023)

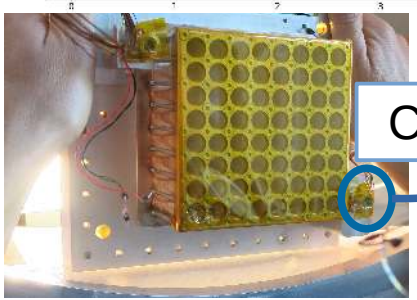


# QUBIC at Alto Chorrillos



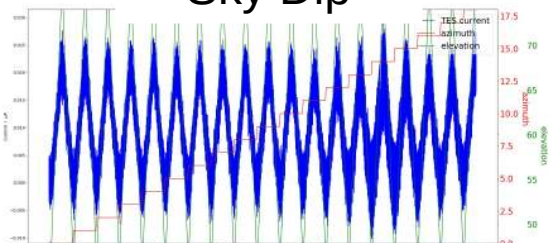

Candidate Cosmic Ray events
Sofia Ferazzoli,
Sapienza Università di Roma



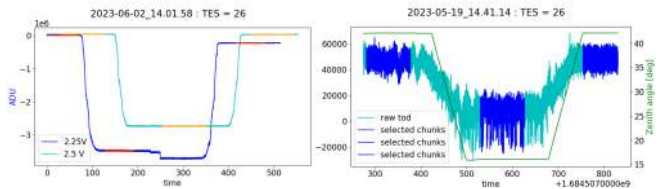


Carbon fibre

## “Sky Dip”

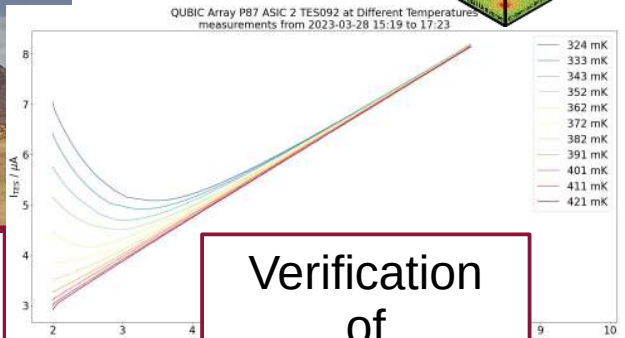



TES = 26 - case 2.5 V

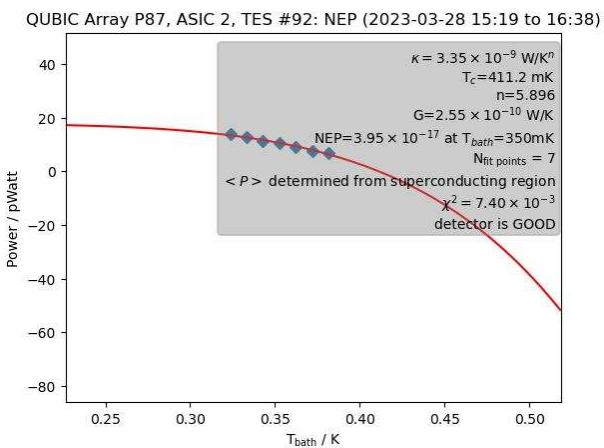



$$\hat{T_{atm,0}} = 7.5\,K_{RJ}$$

Elenia Manzan, Università degli Studi di Milano Statale




Verification of bolometers



# Next step: Self Calibration

Self calibration was developed in the 1980's evolving from the "phase closure" technique used in the 1970's

Multiple apertures → large number of visibilities
Much more than the number of physical parameters

*Mon. Not. R. astr. Soc.* (1981) **196**, 1067–1086

**A new method for making maps with unstable radio interferometers**

T. J. Cornwell* and P. N. Wilkinson *University of Manchester, Nuffield Radio Astronomy Laboratories, Jodrell Bank, Macclesfield, Cheshire SK11 9DL*

*Ann. Rev. Astron. Astrophys. 1984. 22: 97–130*


IMAGE FORMATION BY SELF-CALIBRATION IN RADIO ASTRONOMY

*T. J. Pearson and A. C. S. Readhead*

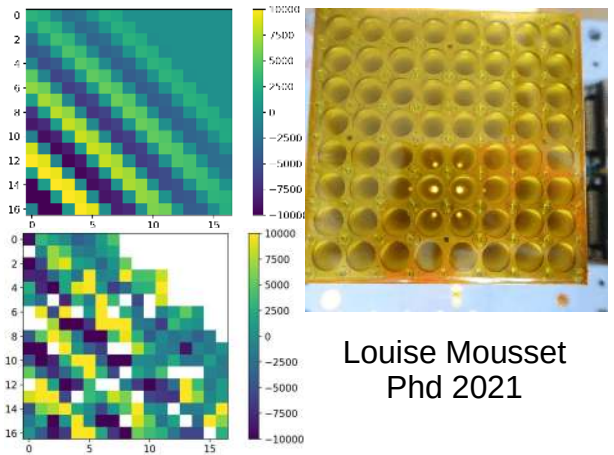
A&A 550, A59 (2013)
DOI: 10.1051/0004-6361/201220429


Astronomy & Astrophysics

**Self-calibration: an efficient method to control systematic effects in bolometric interferometry**

M.-A. Bigot-Sazy[1], R. Charlassier[2], J.-Ch. Hamilton[1], J. Kaplan[1], and G. Zahariade[1]

fringes



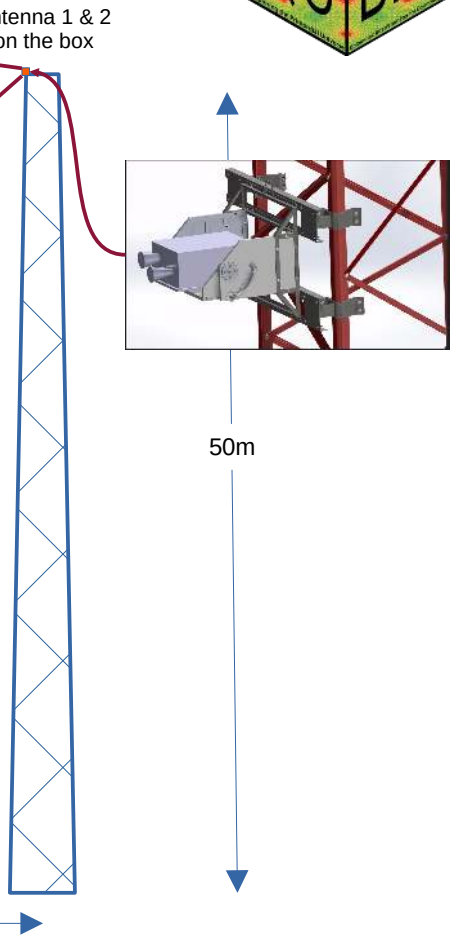
Louise Mousset
Phd 2021

**For self-calibration, we need a stable point source...**

# QUBIC Calibration Tower

On the roof at APC in Paris


Tower under construction on site

# Recent QUBIC Publications

**JCAP special issue on QUBIC (2022)**

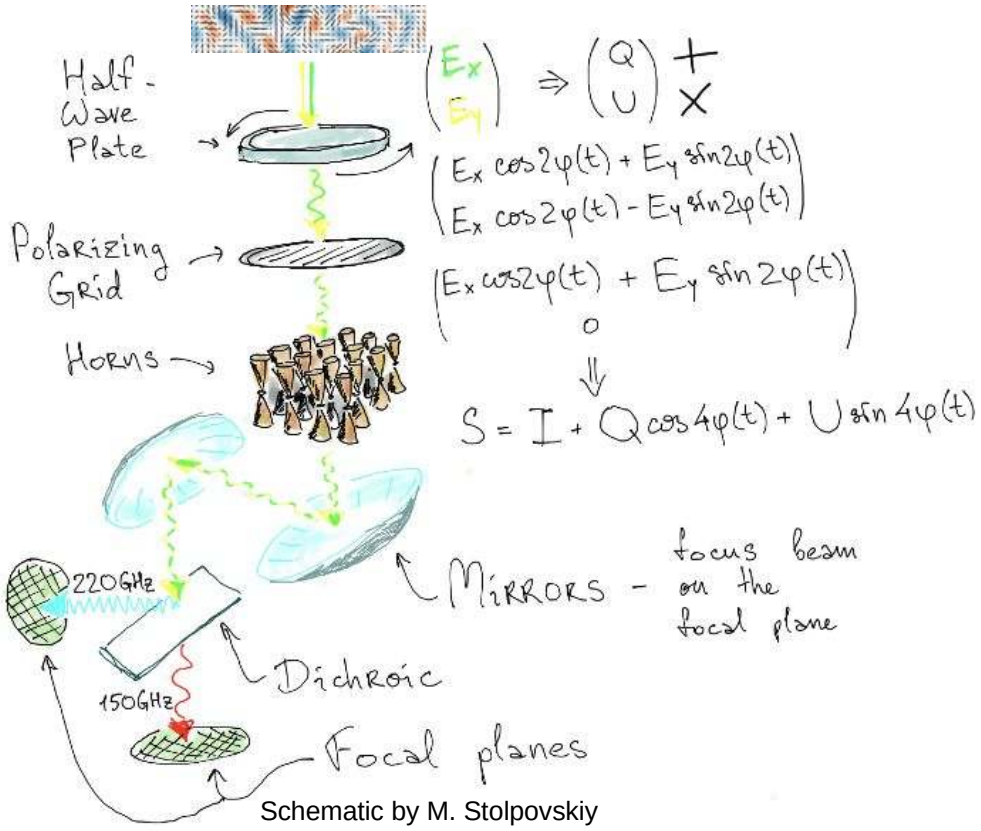
- QUBIC I: Overview and Science Program
  arXiv:2011.02213
- QUBIC II: Spectro-Polarimetry with Bolometric Interferometry
  arXiv:2010.15119
- QUBIC III: Laboratory Characterization
  arXiv:2008.10056
- QUBIC IV: Performance of TES Bolometers and Readout Electronics
  (to be released soon)
- QUBIC V: Cryogenic system design and performance
  arXiv:2008.10659
- QUBIC VI: Cryogenic half wave plate rotator, design and performance
  arXiv:2008.10667
- QUBIC VII: The feedhorn-switch system of the technological demonstrator
  arXiv:2008.12721
- QUBIC VIII: Optical design and performance
  arXiv:2008.10119

**QUBIC Map Making using Spectral Imaging**

- Regnier et al “Frequency Decorrelated Dust...”
  arXiv:2309.02957
- Manzan et al “Galactic Foreground Contamination…”
  arXiv:2311.01814
- Chanial et al “Frequency Map Making”
  arXiv:2409.18698
- Regnier et al “Component Map Making”
  arXiv:2409.18714

# Extra

# QUBIC Optical Architecture




Schematic by M. Stolpovskiy

# Aperture Synthesis

Delay: $\nu\tau_g = \vec{D_\lambda} \cdot \vec{R} = \vec{D_\lambda} \cdot (\vec{R_0} + \vec{\sigma})$

Correlator response: $F = \cos 2\pi\nu\tau_g$

Power: $dP = A_e(\vec{\sigma}) I(\vec{\sigma}) \Delta\nu d\Omega$

Visibility $\mathcal{V} = |\mathcal{V}|\, e^{i\phi} = \int_{4\pi} A(\vec{\sigma}) I(\vec{\sigma}) e^{-i(2\pi(\vec{D_\lambda}\cdot\vec{\sigma})} d\Omega$

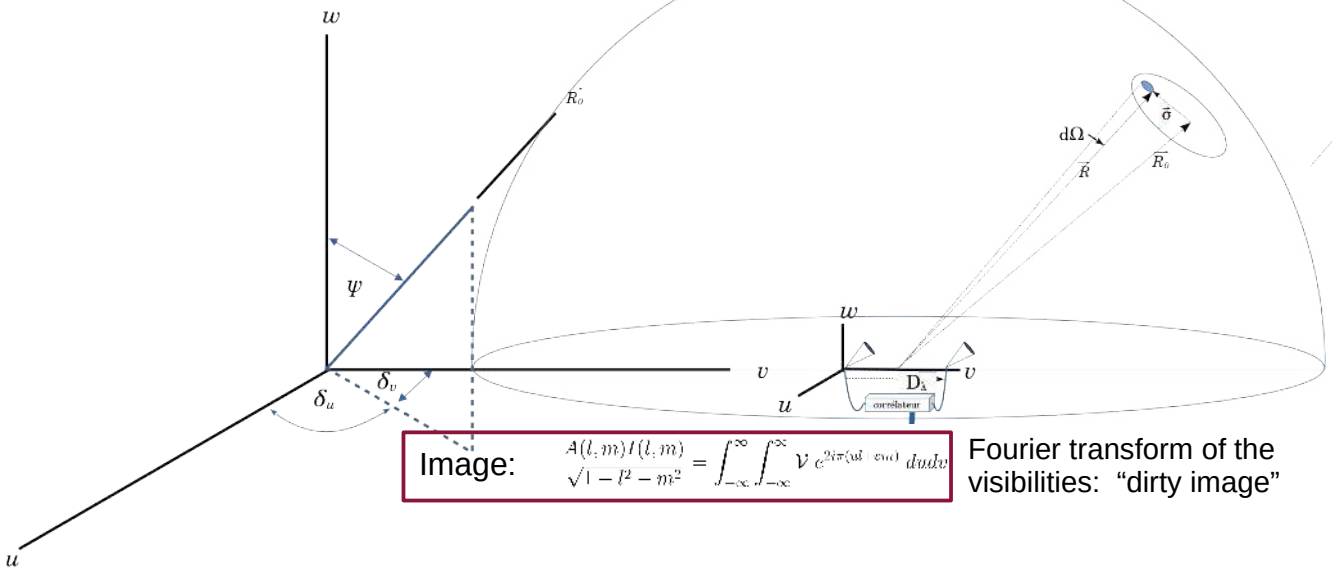
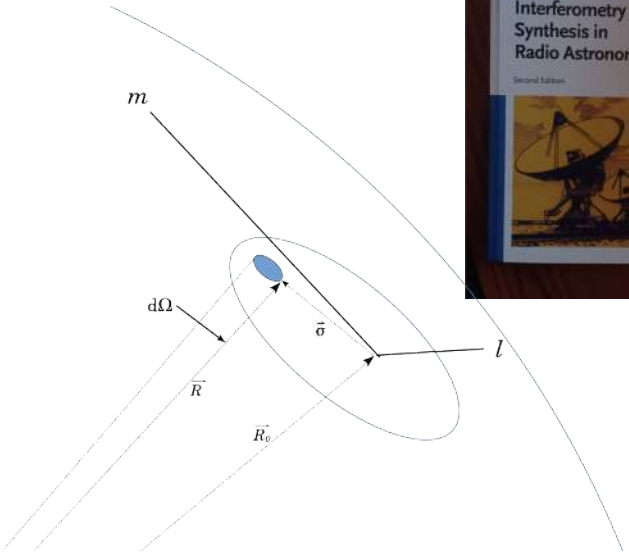
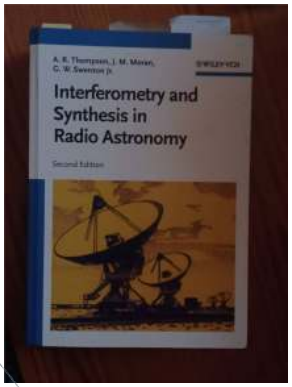



Image: $\frac{A(l,m)I(l,m)}{\sqrt{1-l^2-m^2}} = \int_{-\infty}^{\infty}\int_{-\infty}^{\infty} \mathcal{V}\, e^{2i\pi(ul+vm)}\, du dv$

Fourier transform of the visibilities: “dirty image”

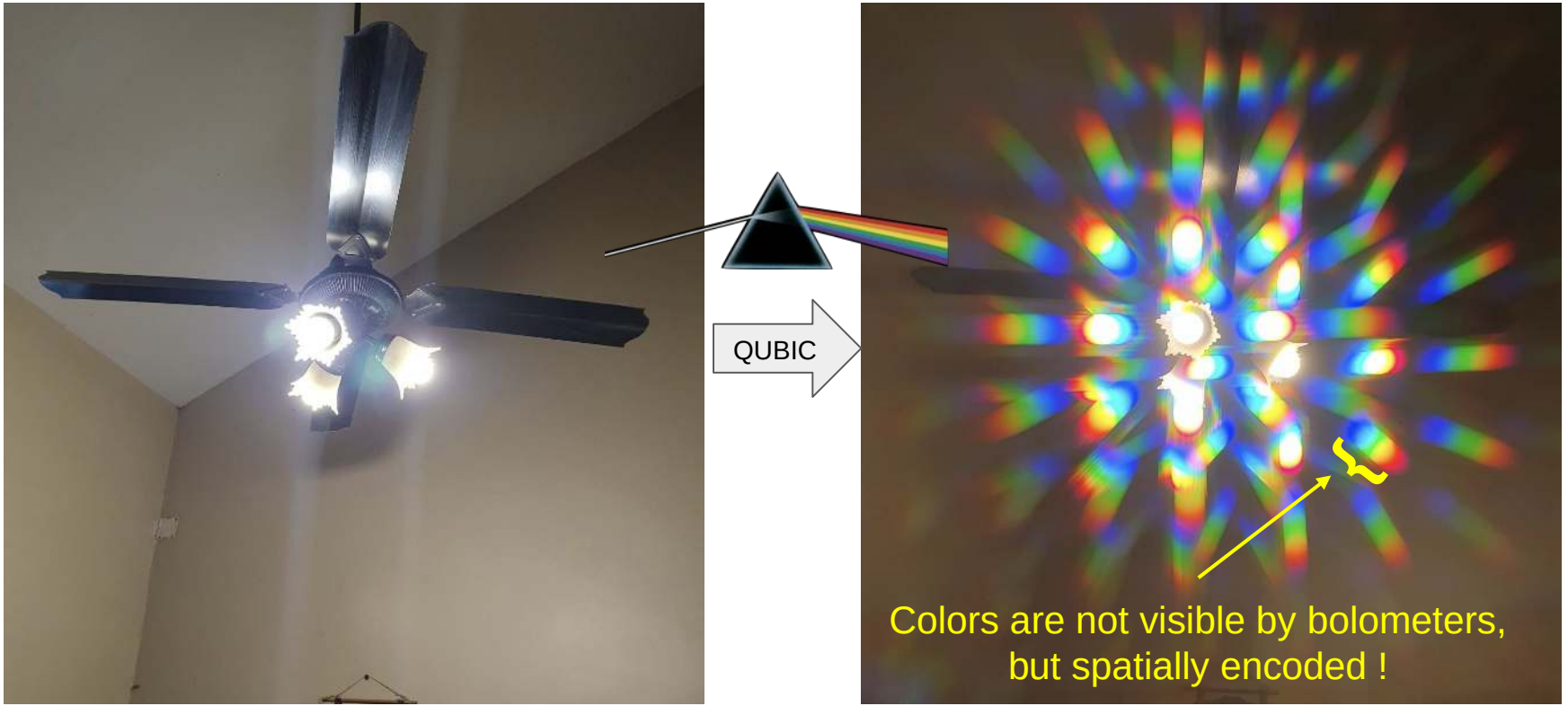


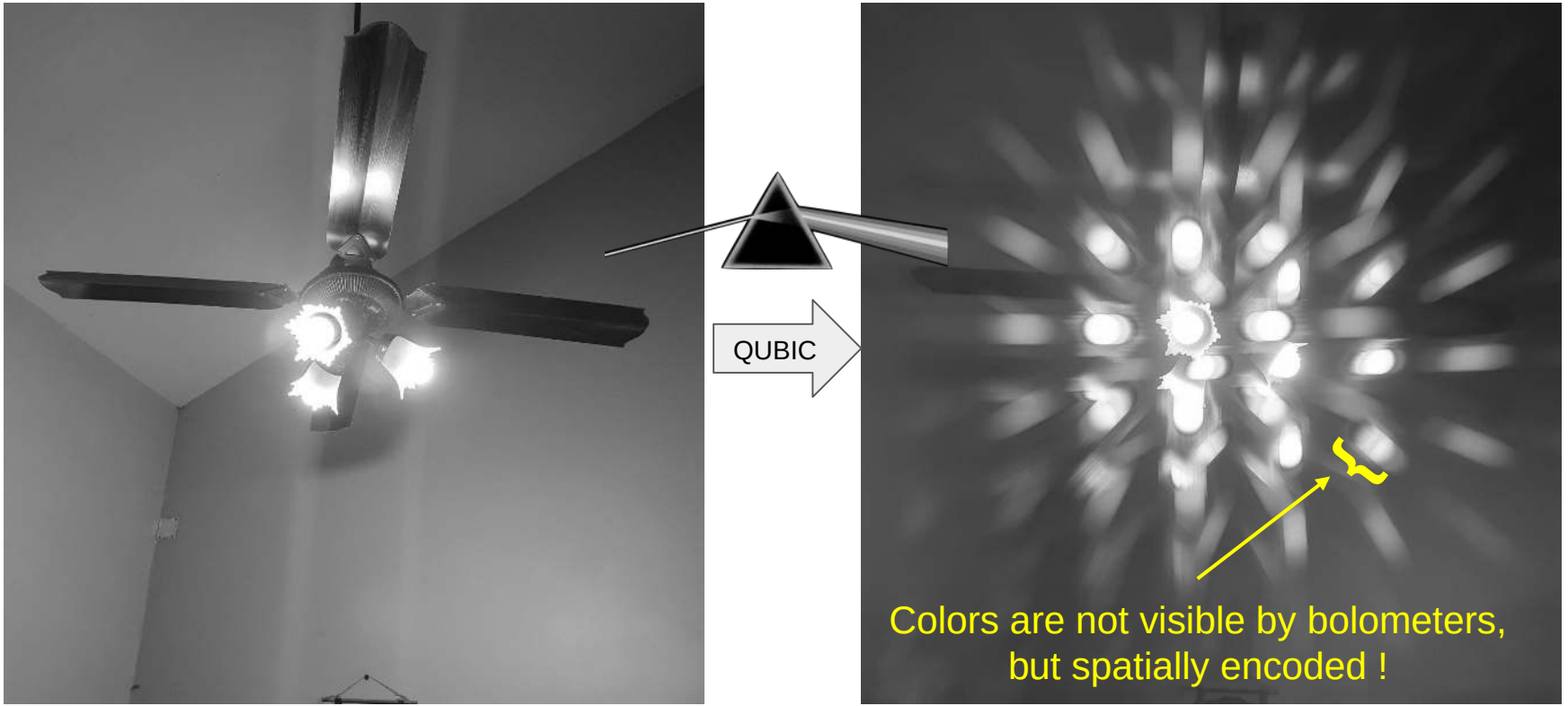

Galactic Centre: First image by MeerKAT

**For self-calibration, we need a stable point source...**

# Seeing the world like QUBIC



# Seeing the world like QUBIC



# Techno Geek Details