Conférence ELBERETH

February 27th, 2020
Institut d'Astrophysique de Paris

Latest calibration results from QUBIC

The Q&U Bolometric Interferometer for Cosmology

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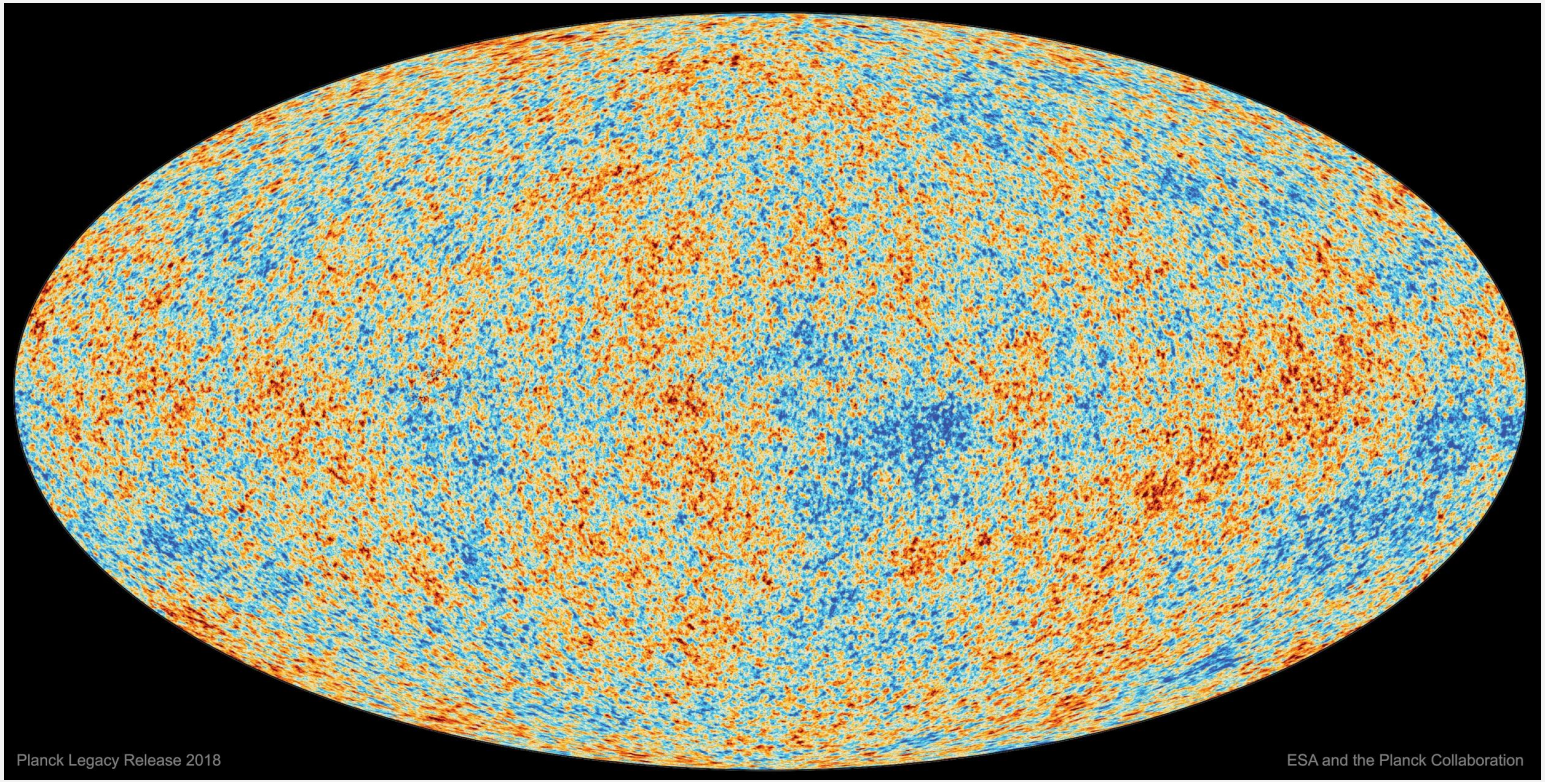
Steve Torchinsky

STEP'UP ÉCOLE DOCTORALE

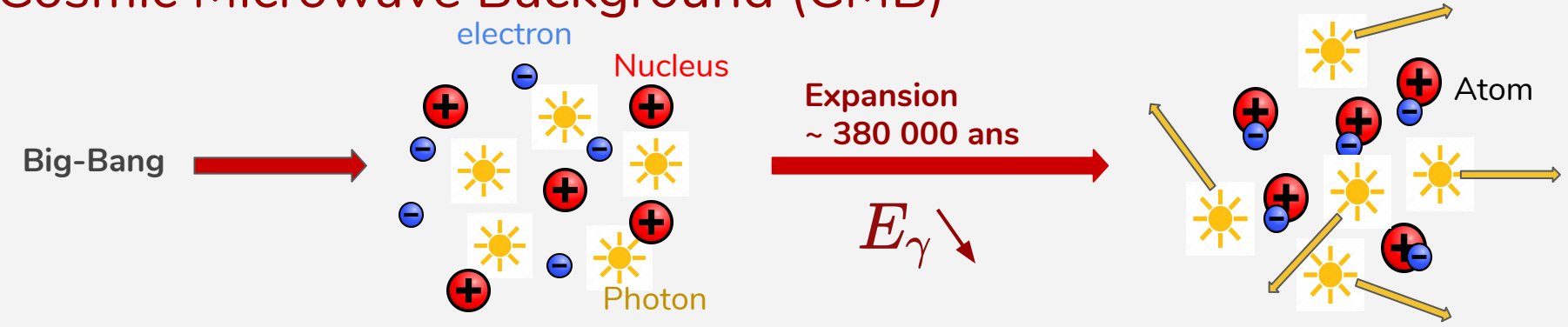
université PARIS DIDEROT PARIS 7

APC

I. Cosmology: CMB and Inflation



Cosmic Microwave Background (CMB)



Cosmic Microwave Background (CMB)

Big-Bang

electron

Nucleus

Photon

Plasma at thermodynamic equilibrium

Expansion
~ 380 000 ans

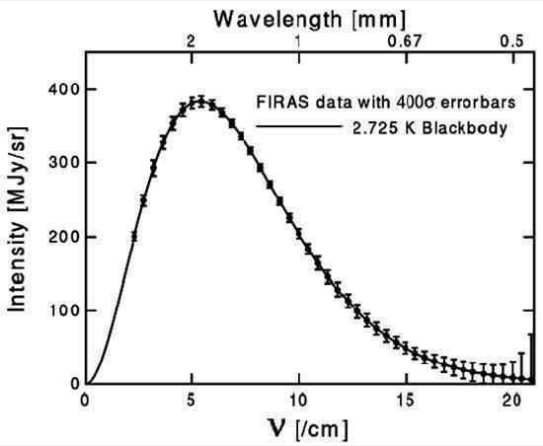
$E_\gamma \searrow$

Atom

CMB emission, Recombination

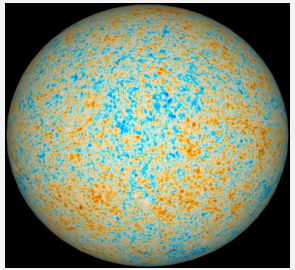
Photons propagate freely in a transparent Universe

Black Body



Temperature isotropy

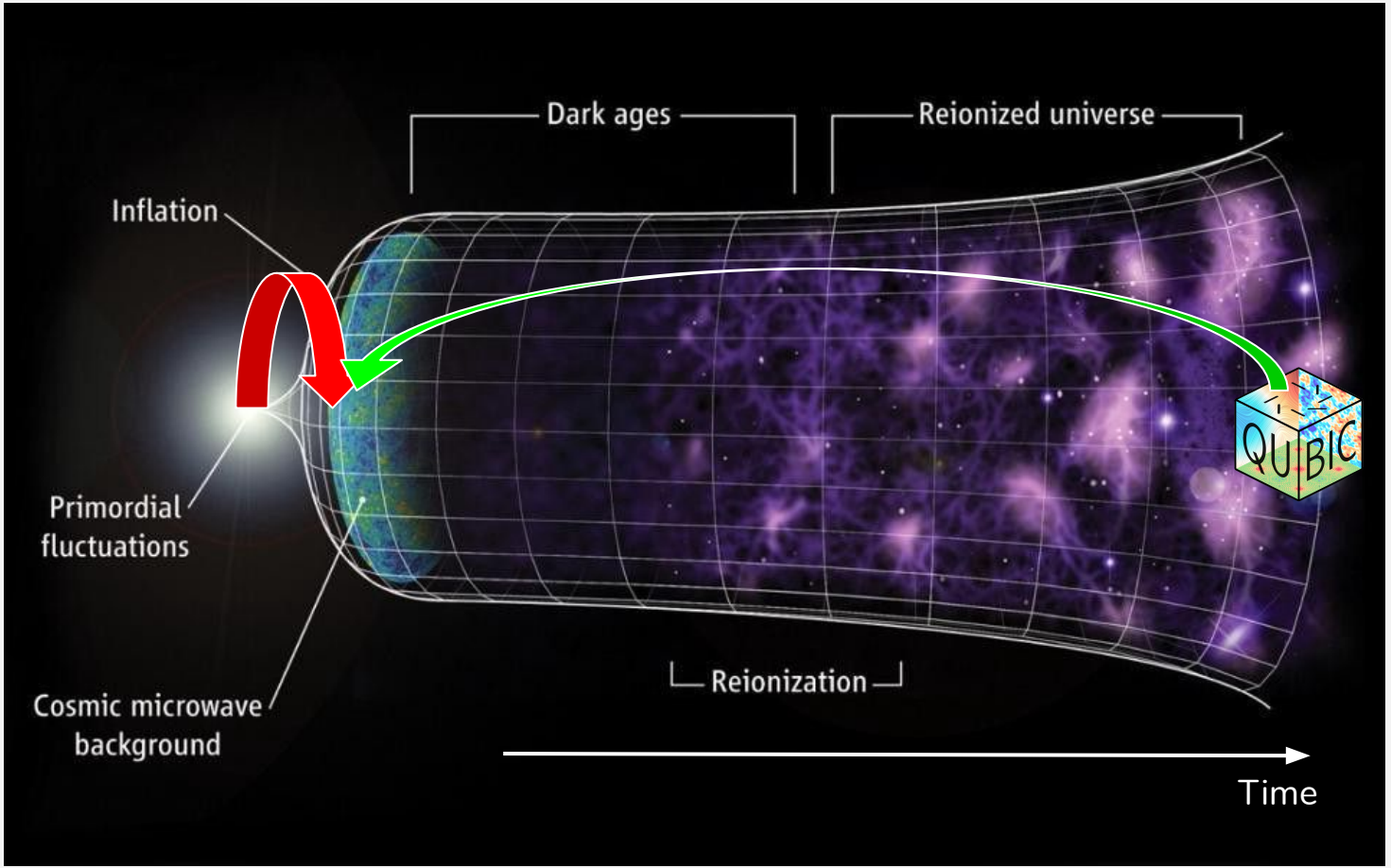
$T - T_0$



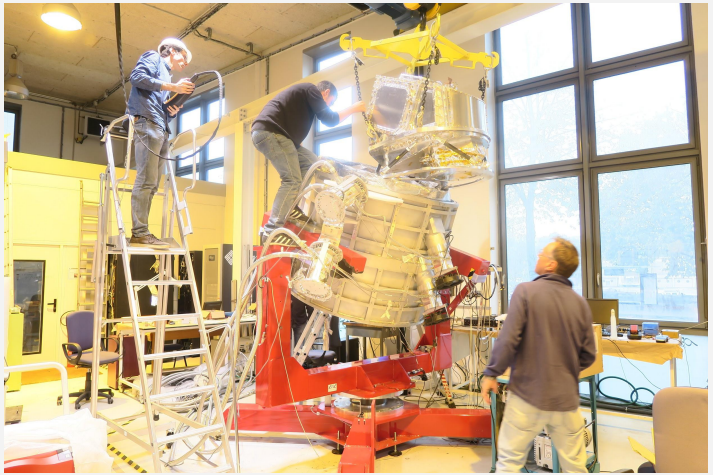
$\frac{\Delta T}{T} \sim 10^{-5}$

A clue for inflation

Primordial fluctuations from inflation are imprinted in the temperature anisotropy and polarization of the CMB.



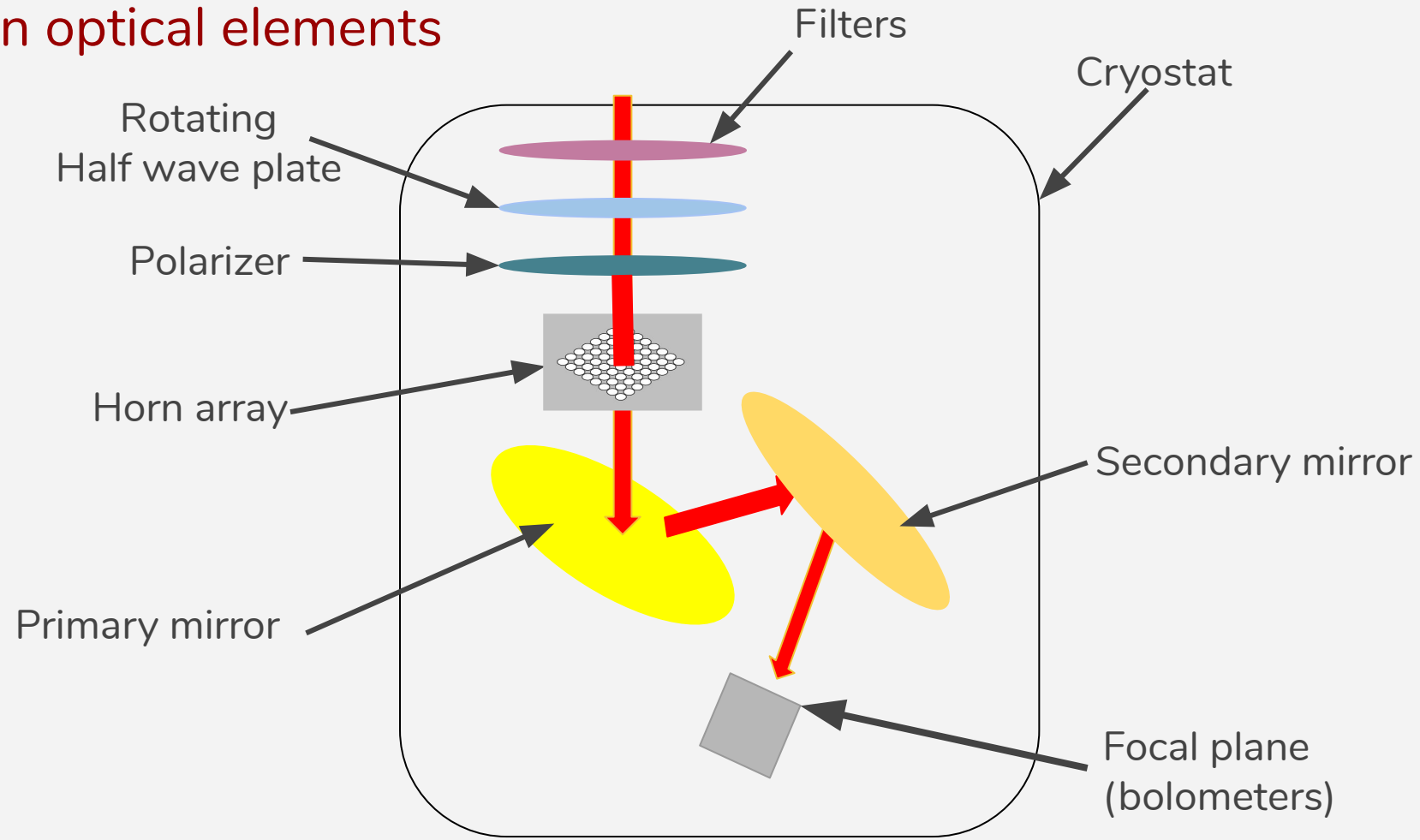
II. The QUBIC instrument



Calibration at APC

Observation site: Argentina, Puna (~5000m)

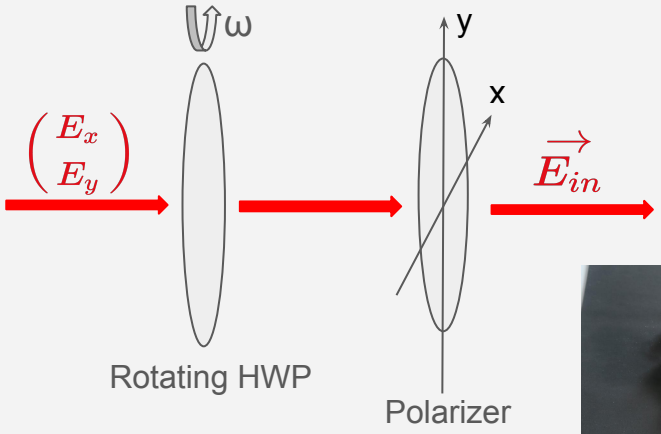
Main optical elements

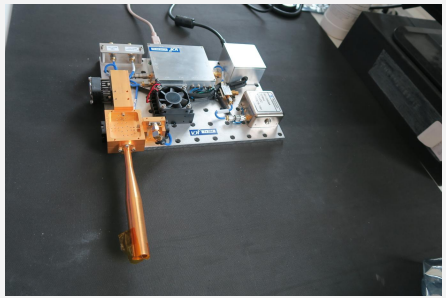


HWP performance

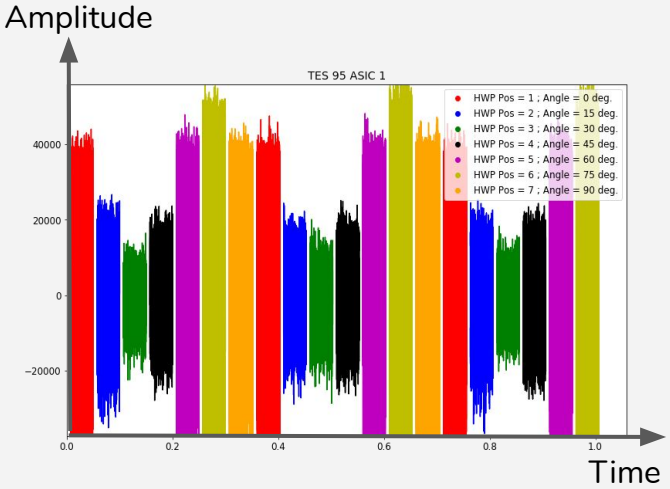
The rotating Half Wave Plate allows QUBIC to modulate the polarization angle on the sky.

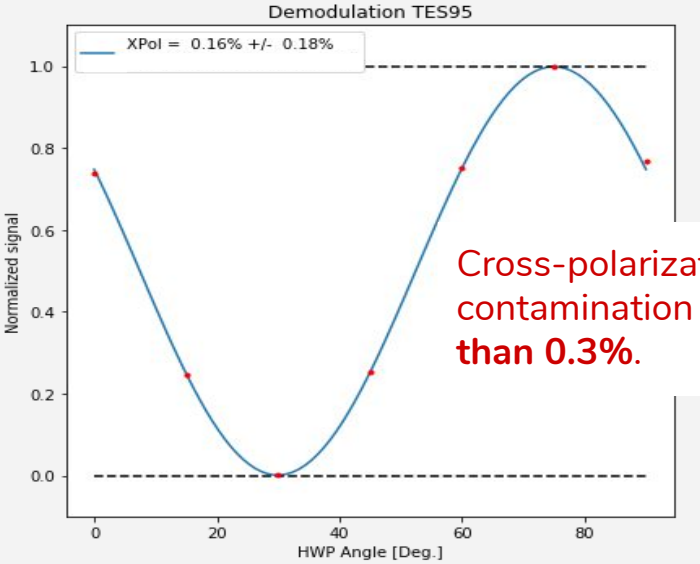
$$I_{in} = \left| E_x \cos(2\omega t) + E_y \sin(2\omega t) \right|^2$$





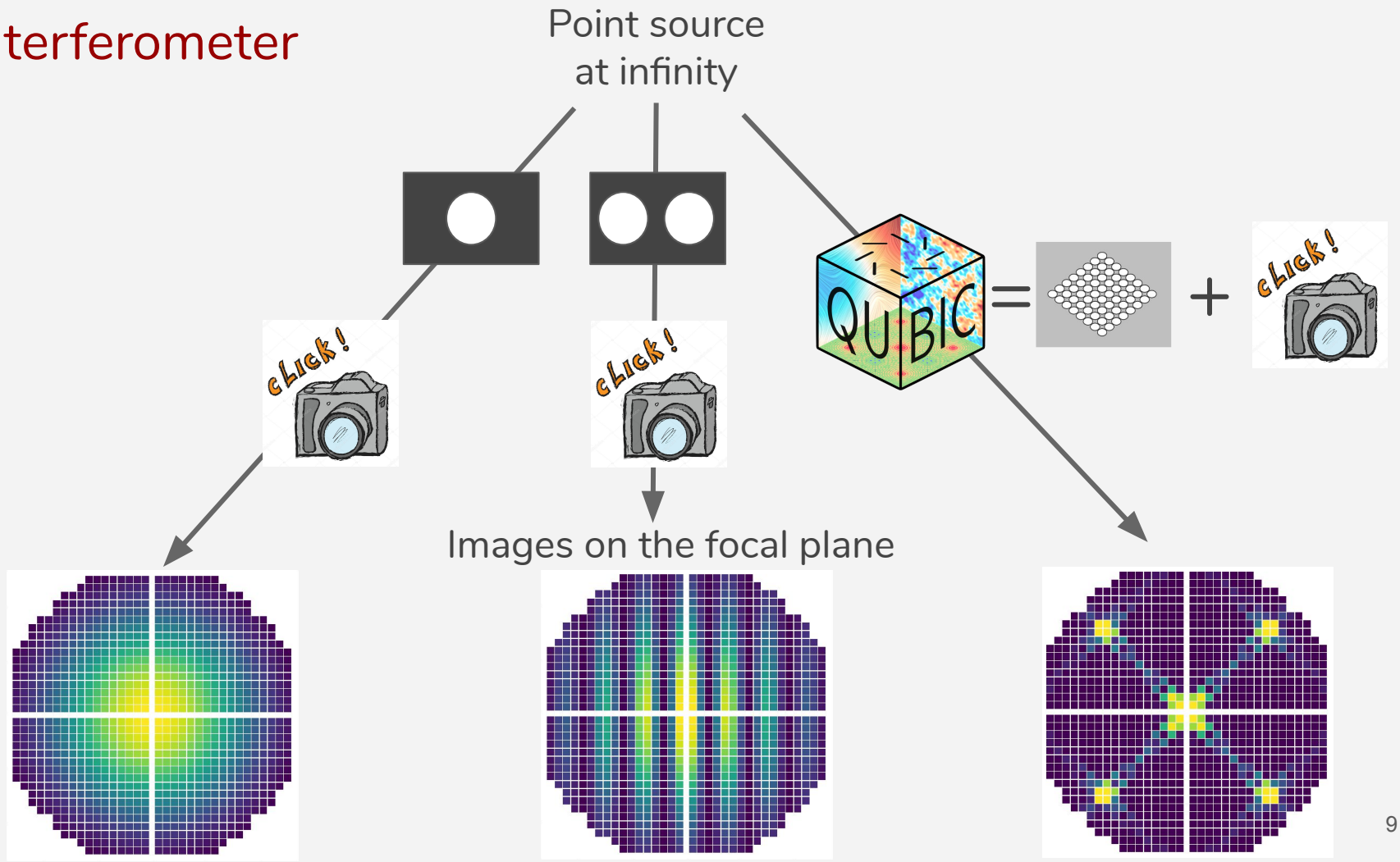
Calibration source



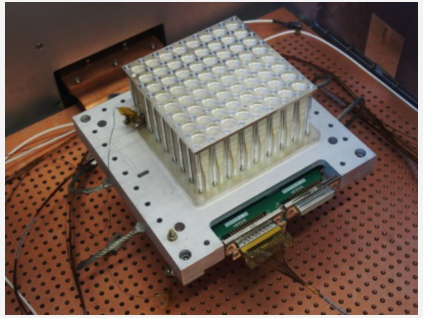


Cross-polarization contamination is **less than 0.3%**.

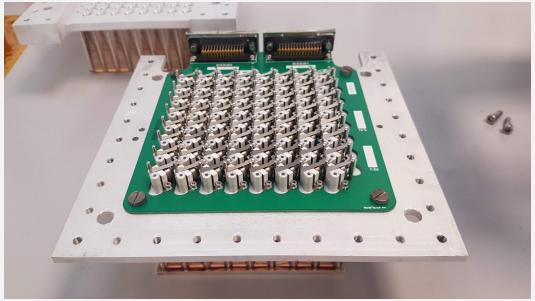
An interferometer



Self-calibration



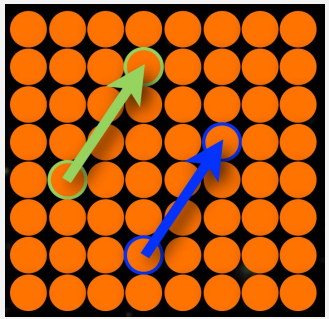
Horn array (8x8)



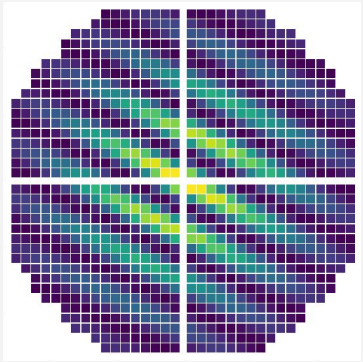
Switches

Method :

For 2 equivalent baselines, in case of a perfect instrument, you should obtain the same interference pattern on the focal plane.
The measured differences are used to characterize systematic effects.



2 redondant baselines on the horn array

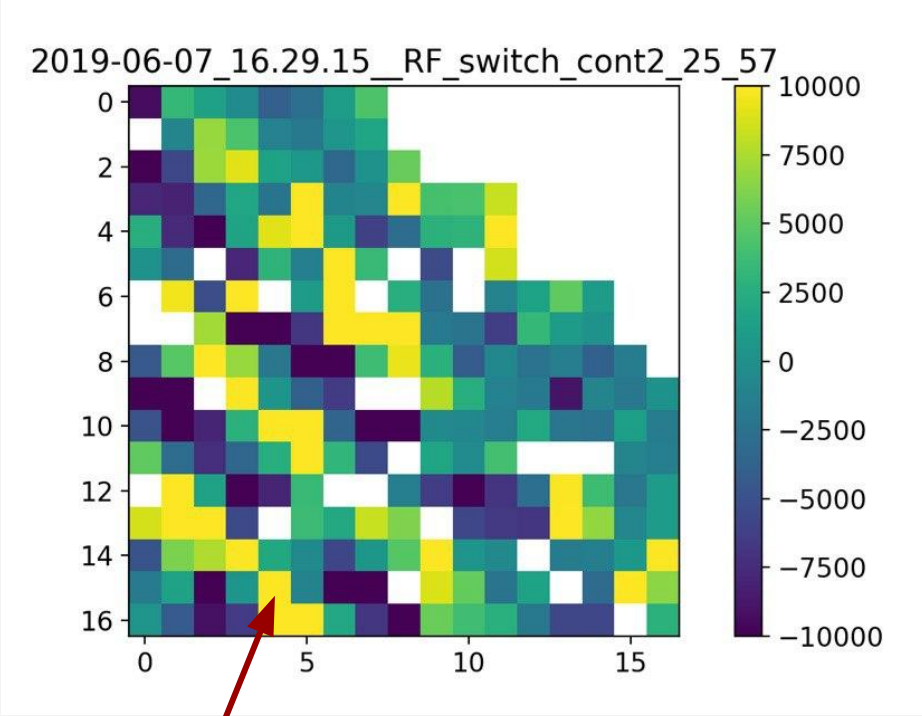


Fringes on the focal plane created by one baseline

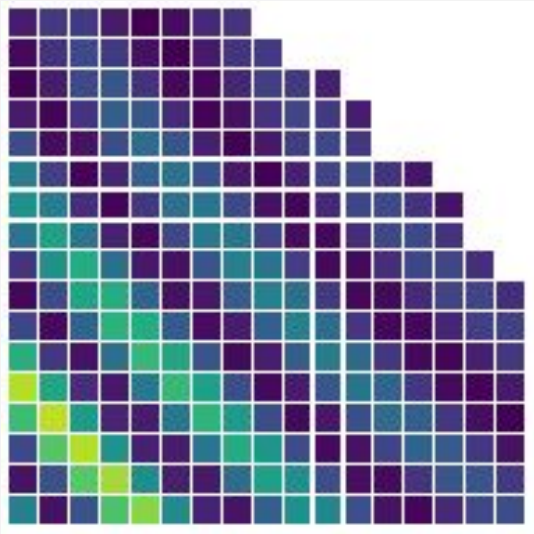
[Bigot-Sazy et al., A&A 2012, arXiv:1209.4905]

Fringes measurement

A quarter of the focal plane (17x17)

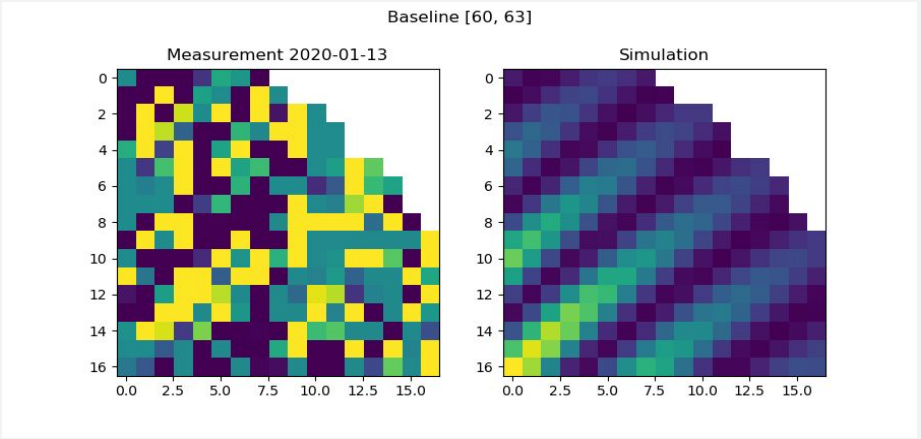


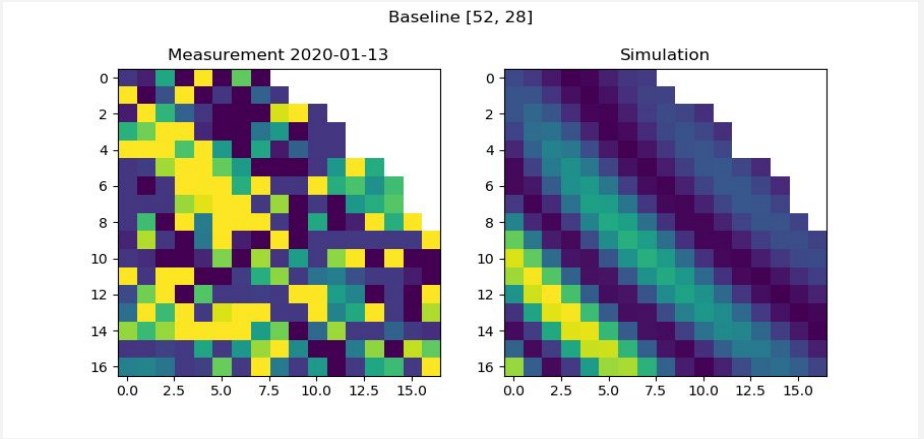
One bolometer

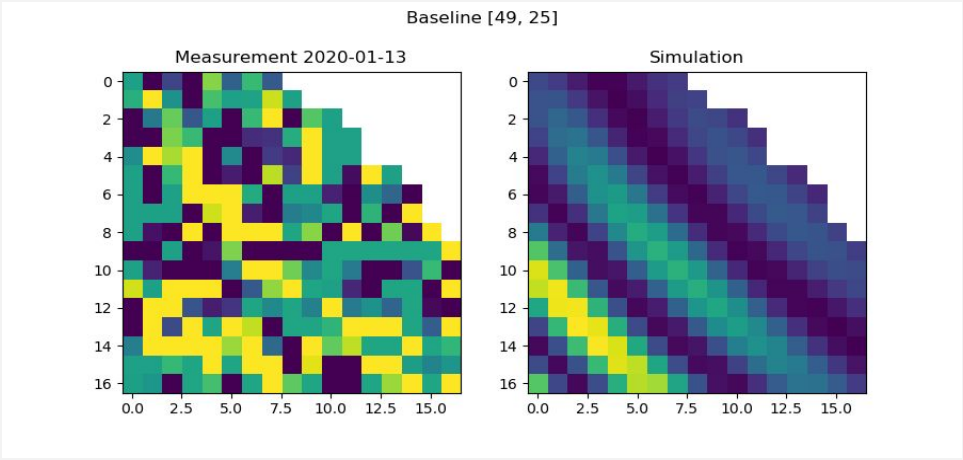


Simulation taking into account optical aberrations

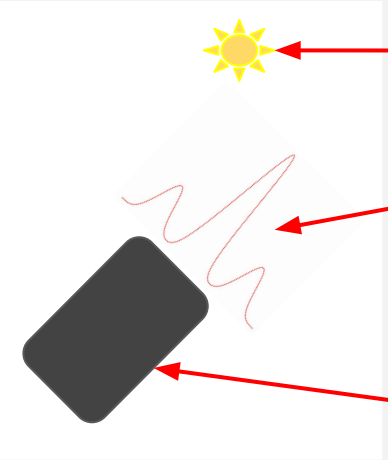
Other baselines

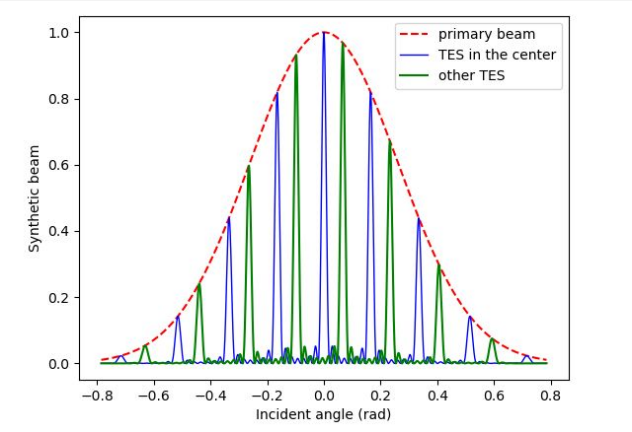






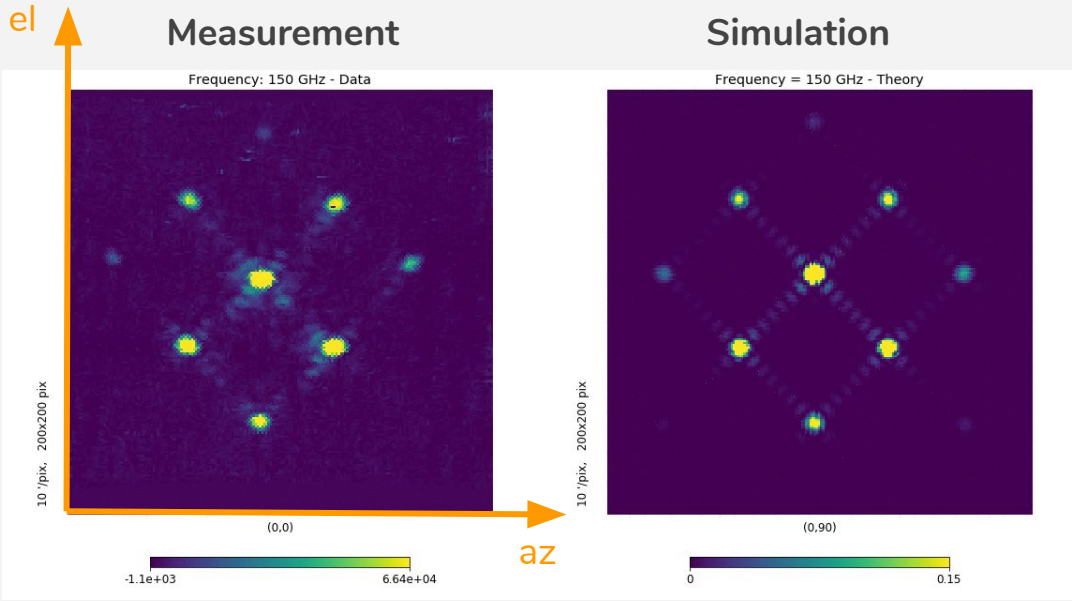
Synthetized beam on the sky





Scan in azimuth and elevation

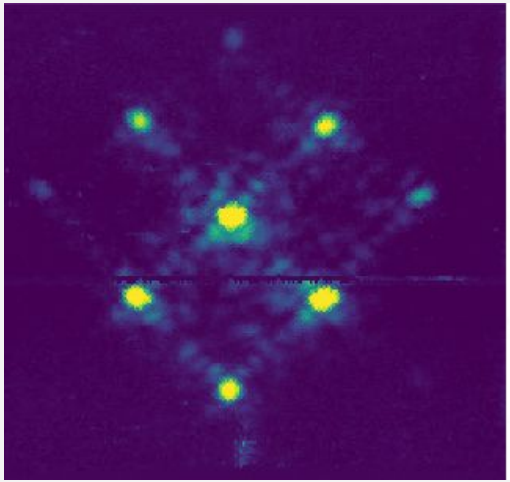
Example for detector 93:



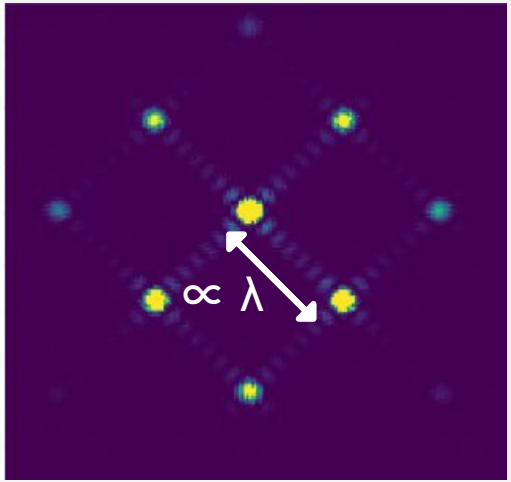
Frequency dependency

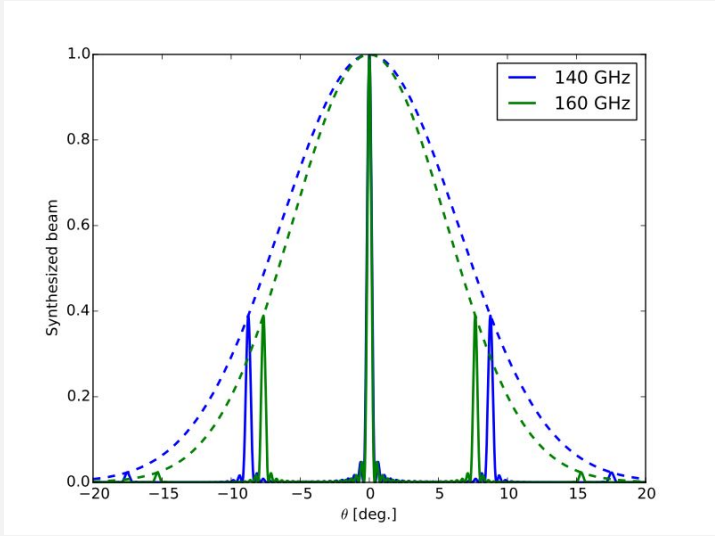
Source at 130 GHz:

Measurement



Simulation





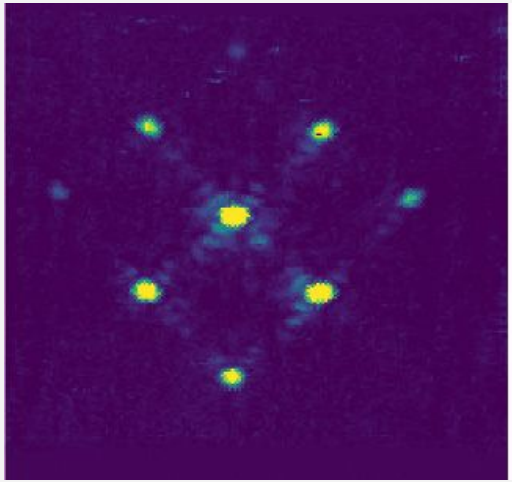
The key for **spectro-imaging** = making sky maps in several frequency bands

⇒ Essential to remove **foregrounds** (ex: galaxy dust emission)

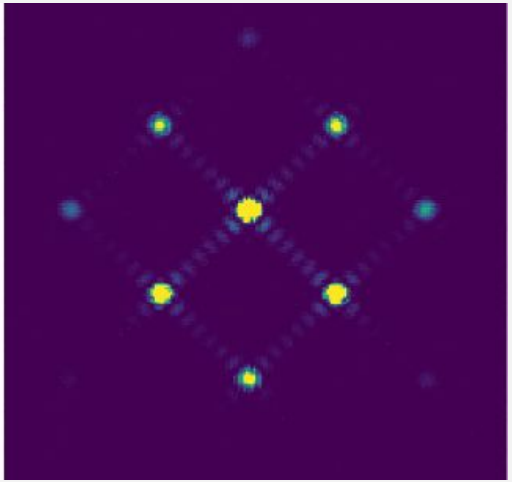
Frequency dependency

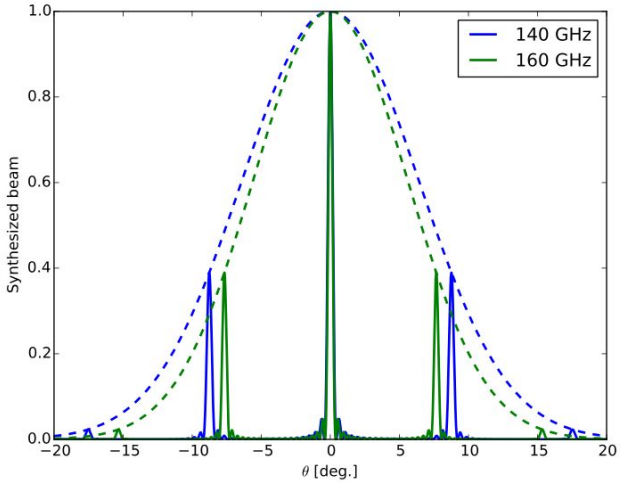
Source at 150 GHz:

Measurement



Simulation





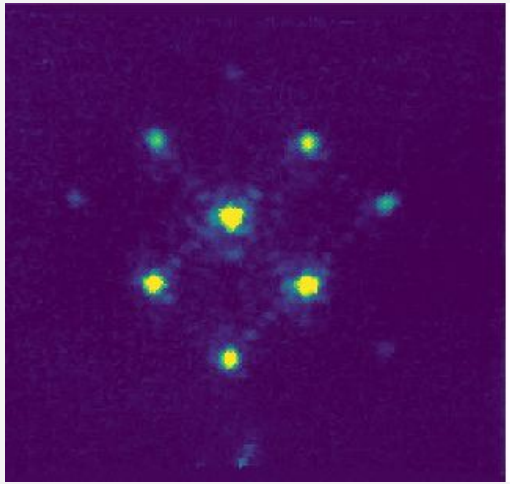
The key for **spectro-imaging** = making sky maps in several frequency bands

⇒ Essential to remove **foregrounds** (ex: galaxy dust emission)

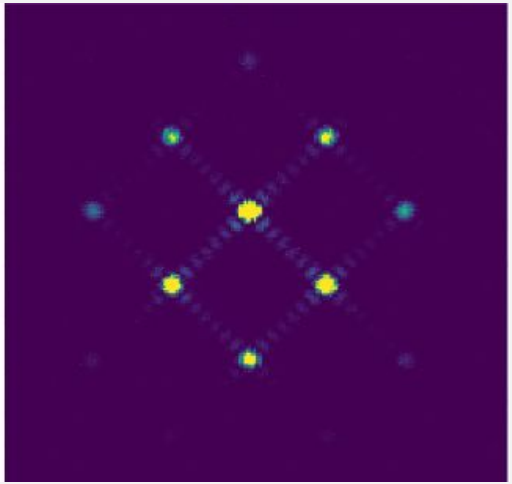
Frequency dependency

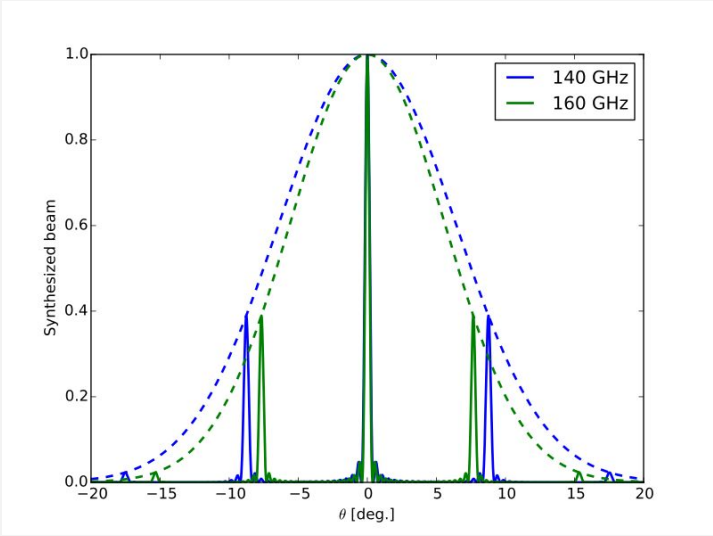
Source at 170 GHz:

Measurement



Simulation



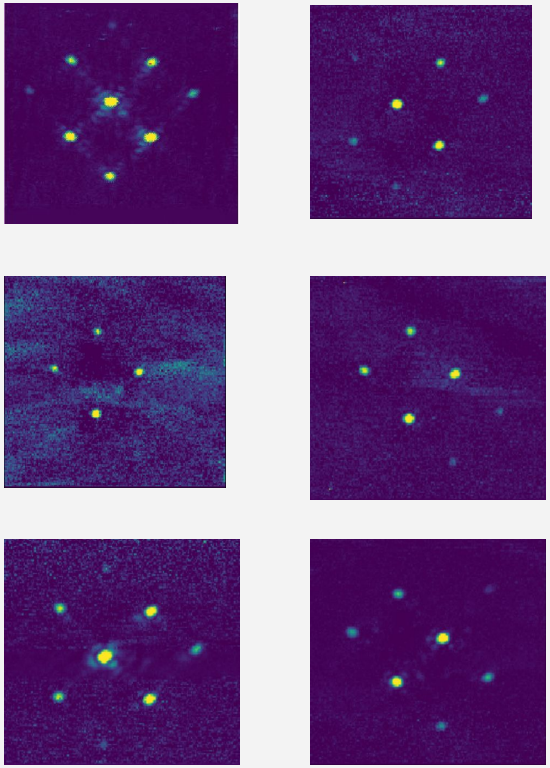


The key for **spectro-imaging** = making sky maps in several frequency bands

⇒ Essential to remove **foregrounds** (ex: galaxy dust emission)

Map making with real data

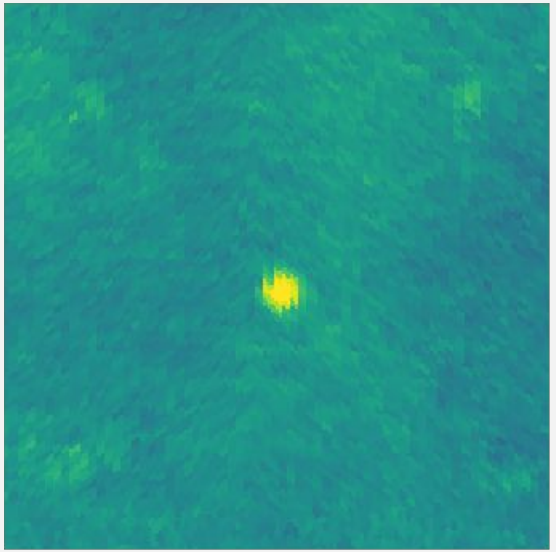
Beams from 6 detectors



Map-making

Software data analysis

Reconstructed point source



Measured FWHM: 1.0209 +/- 0.0015 deg.
Expected: 1.02 deg.

Conclusion

- QUBIC will observe the CMB polarization in order to learn about the primordial universe (Inflation era).

- The instrument is now calibrated at APC and will be installed in Argentina.

- It successfully pass the in2p3 review in January. The demonstration has been made that bolometric interferometry is achieved.

- Its unique design brings new possibilities:
  →Self-calibration
  →Spectro-imaging

Thank you !

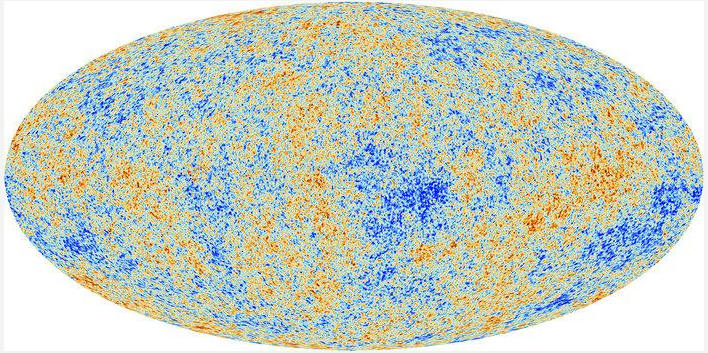
Backup slides

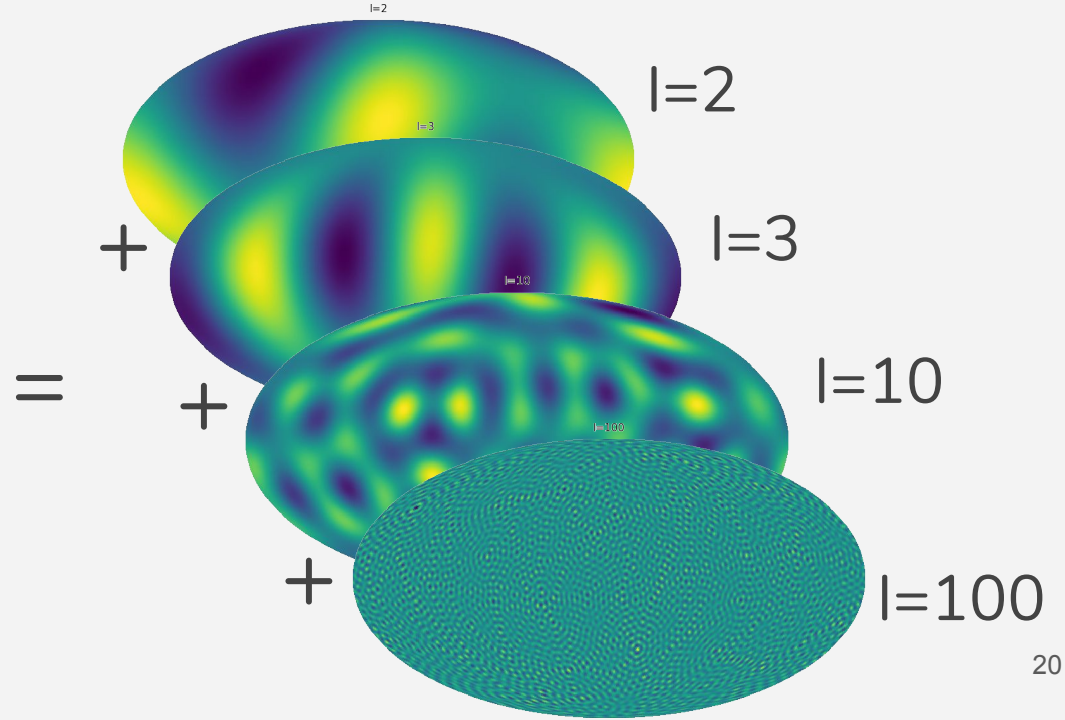
Spherical harmonic transform

$$T(\mathbf{n}) = T_0 + T_0 \sum_{l=1}^{\infty} \sum_{m=-l}^{l} a_{lm} Y_{lm}(\mathbf{n})$$

with $a_{lm} = \int_{4\pi} T(\mathbf{n}) Y^*_{lm}(\mathbf{n})$

$$l \sim \frac{\pi}{\theta}$$

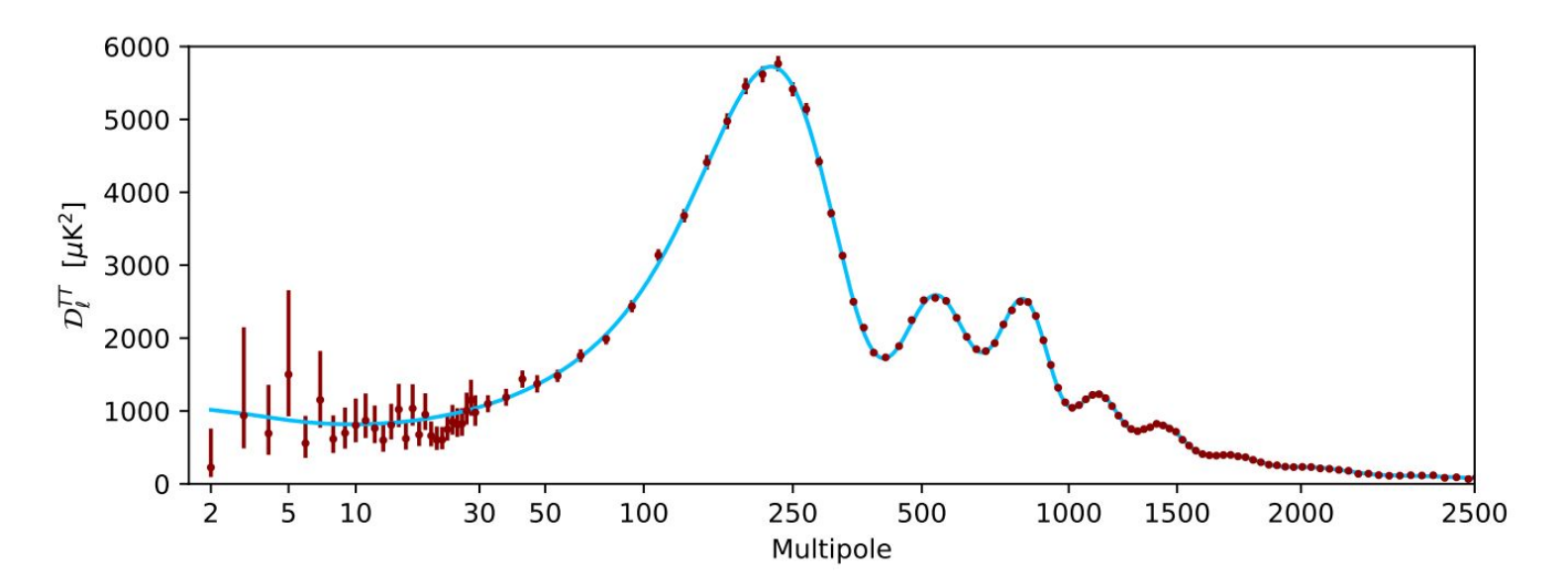




Power spectrum

Variance of the a_{lm}: $C_l = \langle a_{lm}^* a_{lm} \rangle_m = \frac{1}{2l+1} \sum_{m=-l}^{l} |a_{lm}|^2$

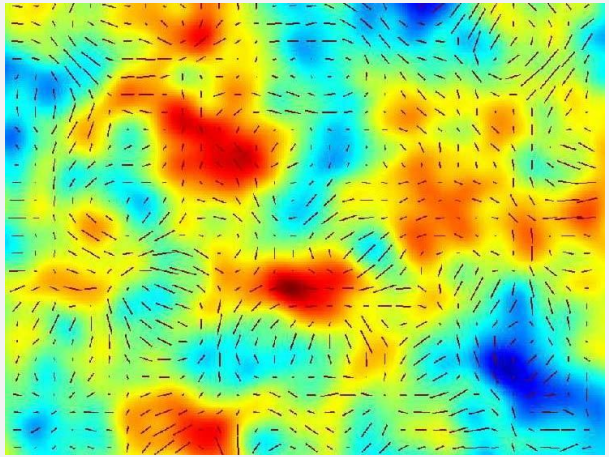
$$D_l = \frac{l(l+1)}{2\pi} C_l$$



Credit: *Planck, 2018*

The CMB polarization

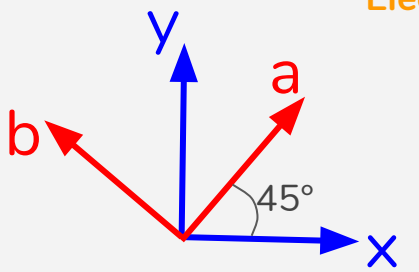
For each position on the sky, one can define the Stokes parameters:



$$I = E_x^2 + E_y^2 \quad \rightarrow \text{Intensity (temperature)}$$

$$\left.\begin{aligned} Q &= E_x^2 - E_y^2 \\ U &= E_a^2 - E_b^2 \end{aligned}\right\} \text{ Linear polarization}$$

Electric field



E and B modes

$$(Q \pm iU)(\mathbf{n}) = \sum_{l=2}^{\infty} \sum_{m=-l}^{l} a_{\pm 2lm} \; {}_{\pm 2}Y_{lm}(\mathbf{n})$$

You can form 2 scalar quantities :

- E modes

$$E(\mathbf{n}) = \sum_{l=2}^{\infty} \sum_{m=-l}^{l} a^E_{lm} \; Y_{lm}(\mathbf{n}) \quad \text{with} \quad a^E_{lm} = -\frac{a_{2lm} + a_{-2lm}}{2}$$

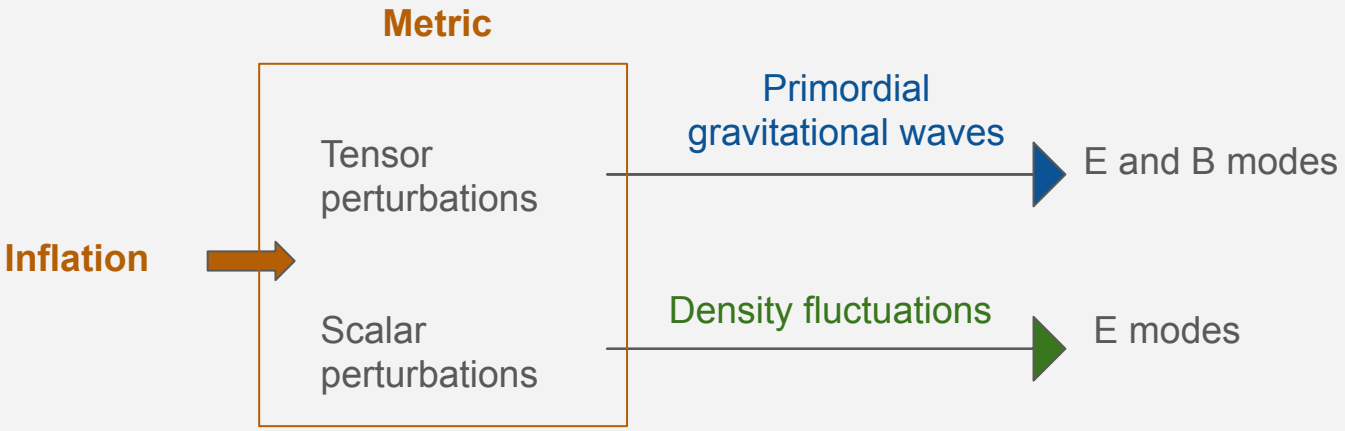
- B modes

$$B(\mathbf{n}) = \sum_{l=2}^{\infty} \sum_{m=-l}^{l} a^B_{lm} \; Y_{lm}(\mathbf{n}) \quad \text{with} \quad a^B_{lm} = i\frac{a_{2lm} - a_{-2lm}}{2}$$

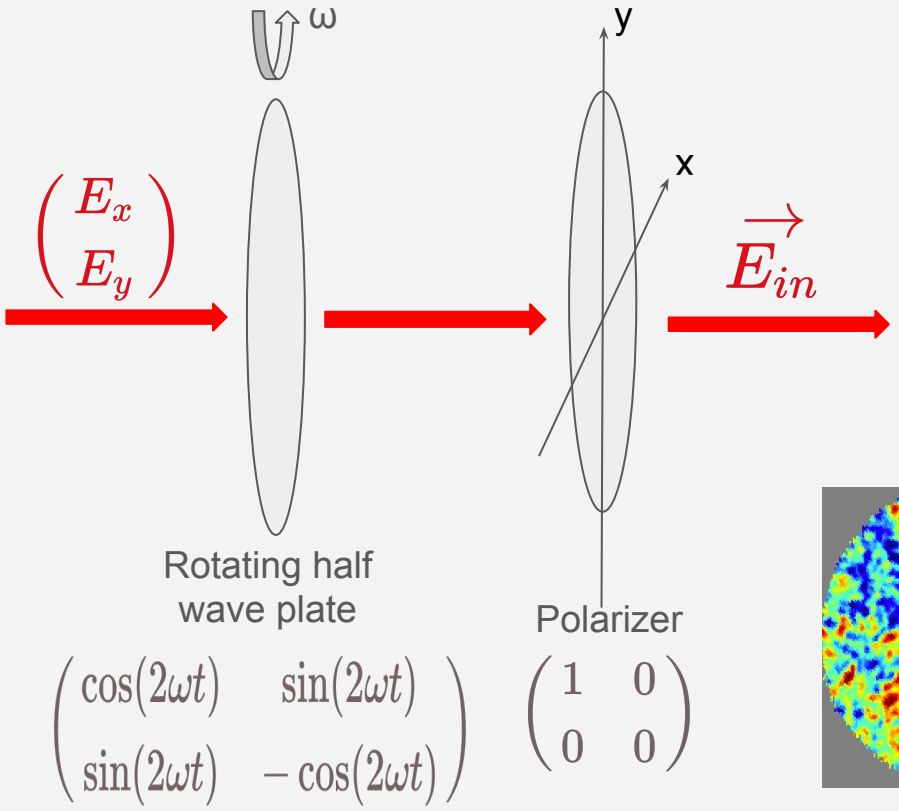
⇒ A global definition over the sky

Primordial B modes, a clue for inflation

Inflation :
Accelerated expansion phase right after the Big-Bang (~10^{-34} s)



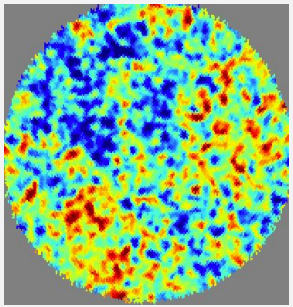
Polarization modulation



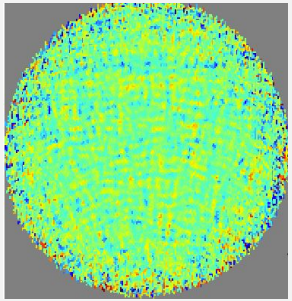
$$I_{in} = \left|E_x \cos(2\omega t) + E_y \sin(2\omega t)\right|^2$$
$$= I + Q\cos(4\omega t) + U\sin(4\omega t)$$

Using a correct rotating speed, we can reconstruct I, Q, U for each position on the sky.

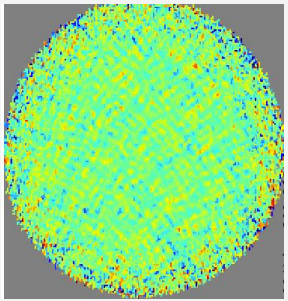
→ 3 sky maps



I



Q

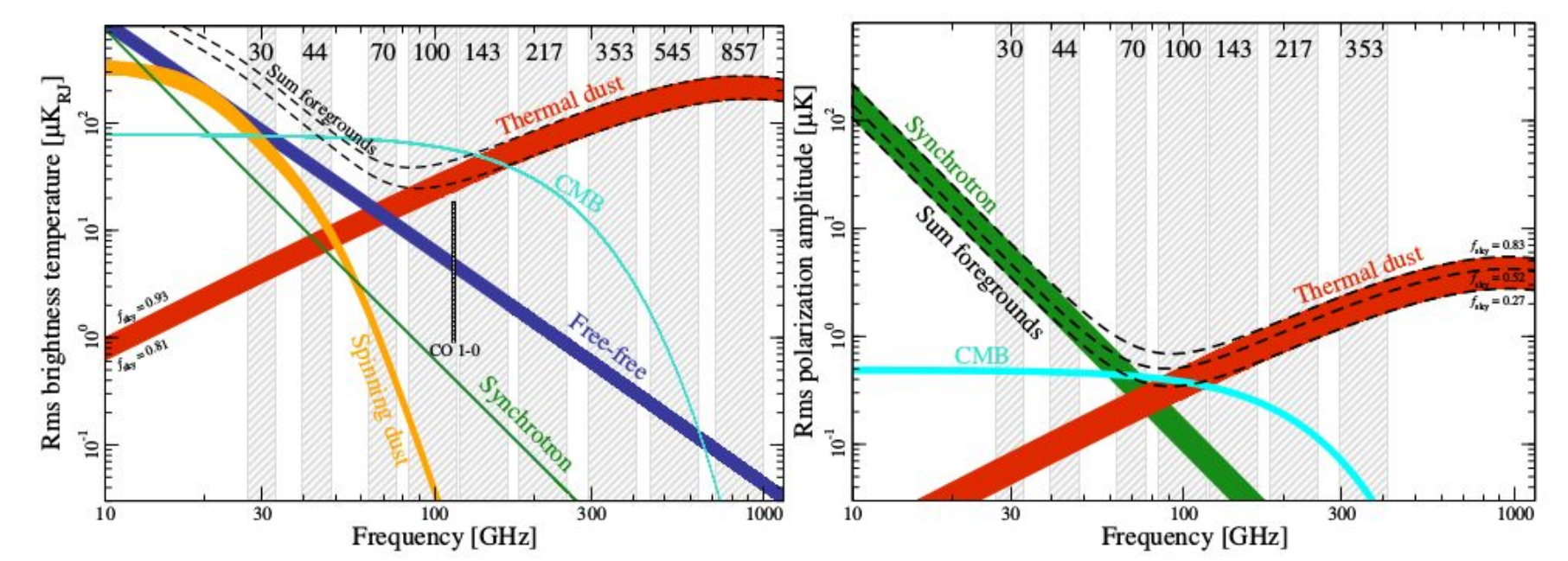


U

Removing foregrounds

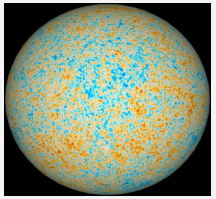
Temperature

Polarization



Credit: Planck, 2018

Data simulation and map-making

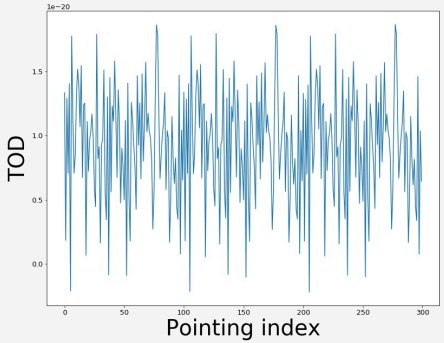


- Time Order Data (TOD)

Matrix containing the pointing strategy over the sky

Map

TOD for one bolometer



Noise

$$\mathbf{d}_{bolo} = A\mathbf{T} + \mathbf{n}_{bolo}$$

- Map-making in temperature and polarization

Covariance noise matrix

$\vec{d}$ → $T = \left(A^t \cdot N^{-1} \cdot A\right)^{-1} \cdot A^t \cdot N^{-1} \cdot \vec{d}$

TOD from the 992 bolometers

Map: Maximum-Likelihood solution

=> Not so easy !
For one day of observation, N is already a (3e6 x 3e6 x 992) operator.