Searching for Primordial Gravitational Waves with **QUBIC**
(Q & U Bolometric Interferometer for Cosmology)
Pipeline development and cosmological constraints

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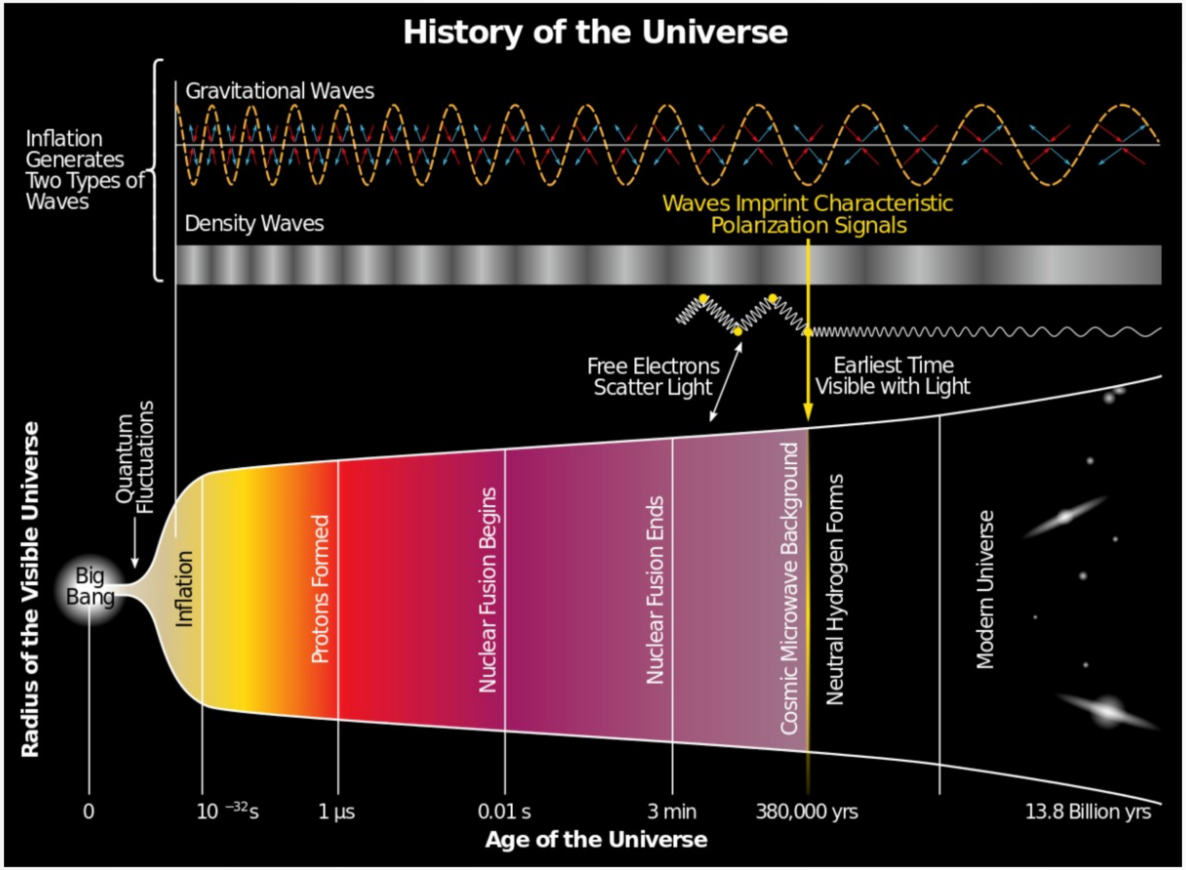
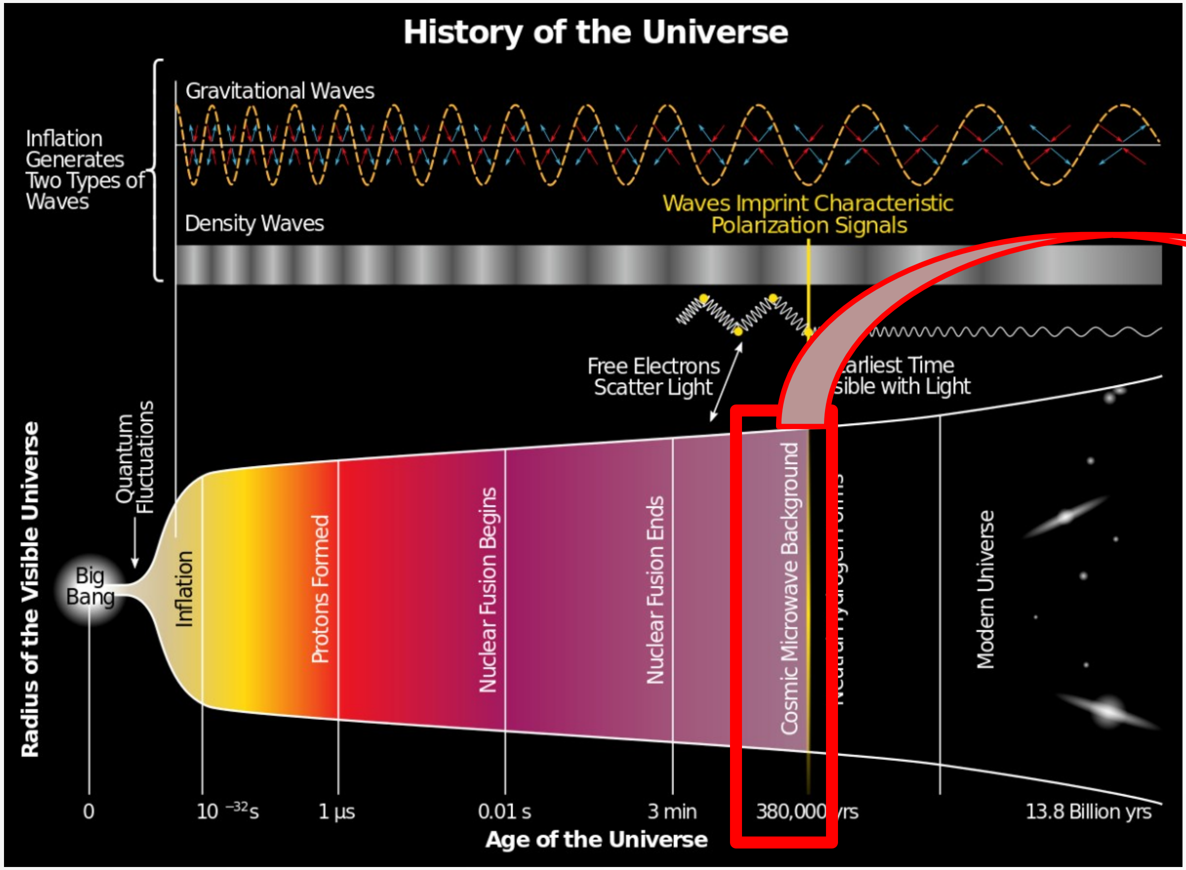
CMB polarization

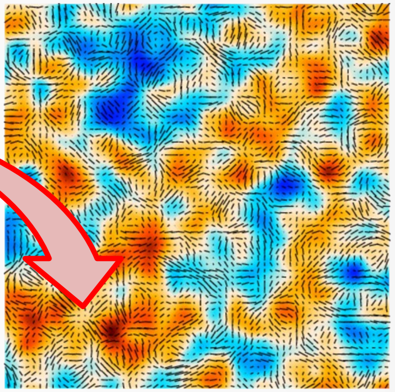


CMB polarization



CMB Sky

Color = Temperature - Vectors = Polarization



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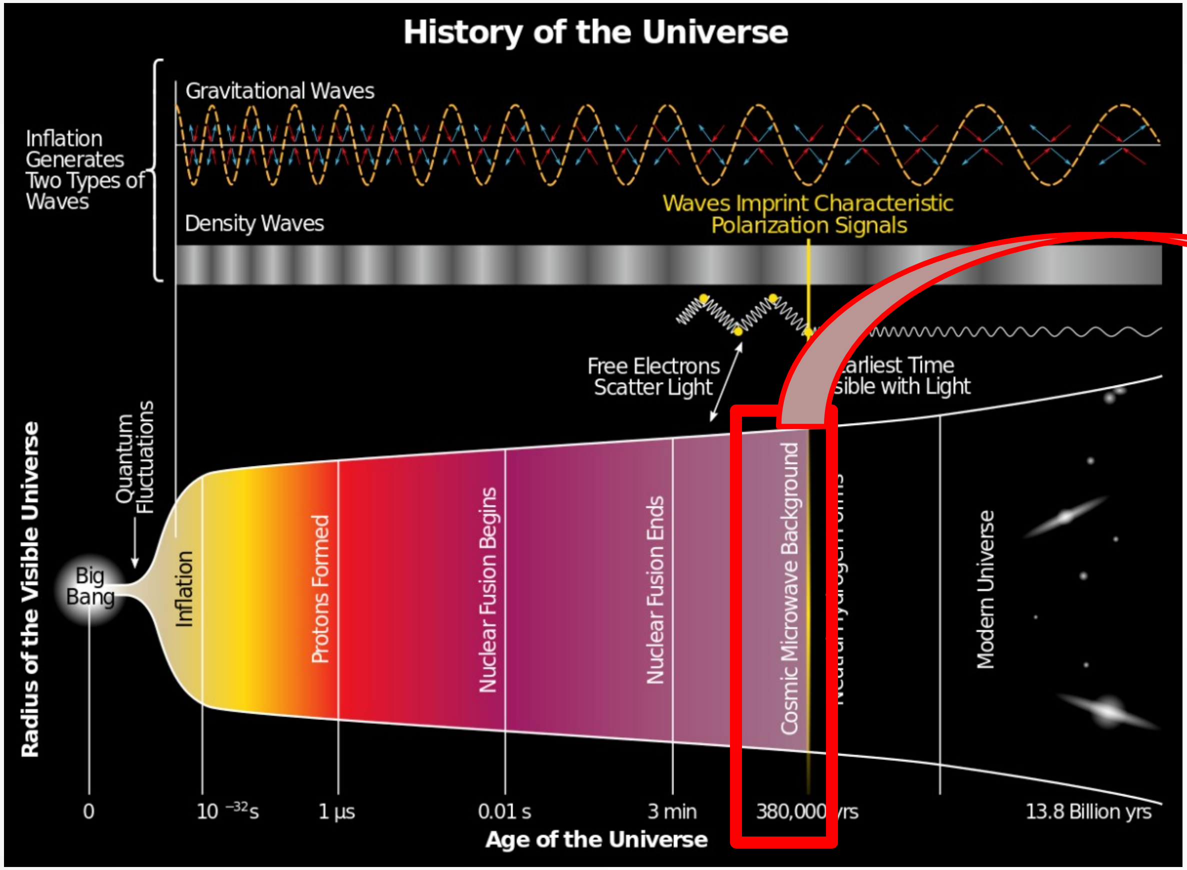

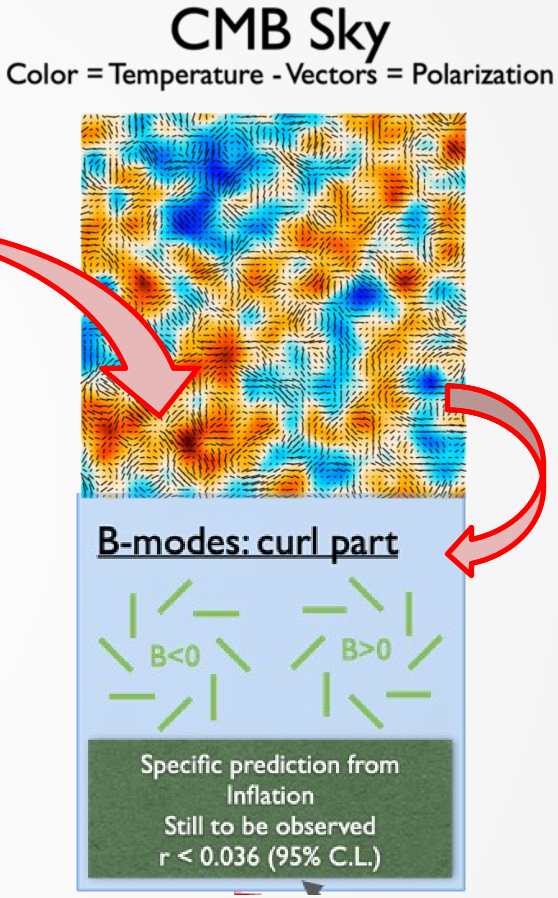

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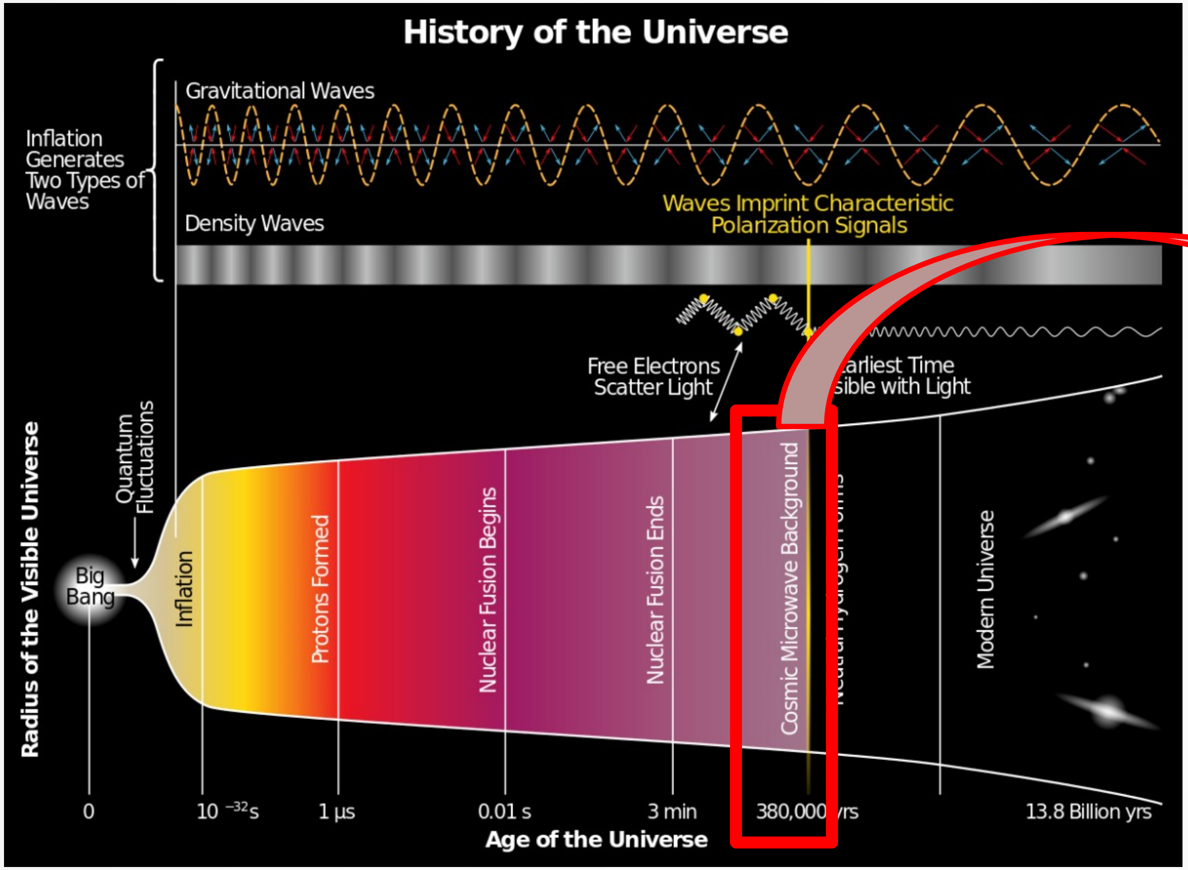
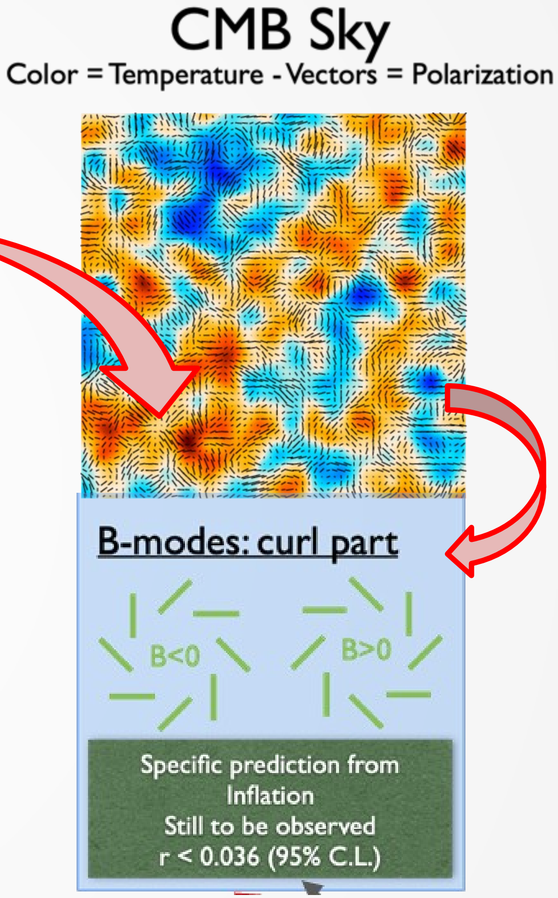




Primordial B-modes → Primordial Gravitational Waves → Inflation

Challenges

Challenges

Small signal

CMB B-mode polarization =
faint signal

Observation of the CMB polarization

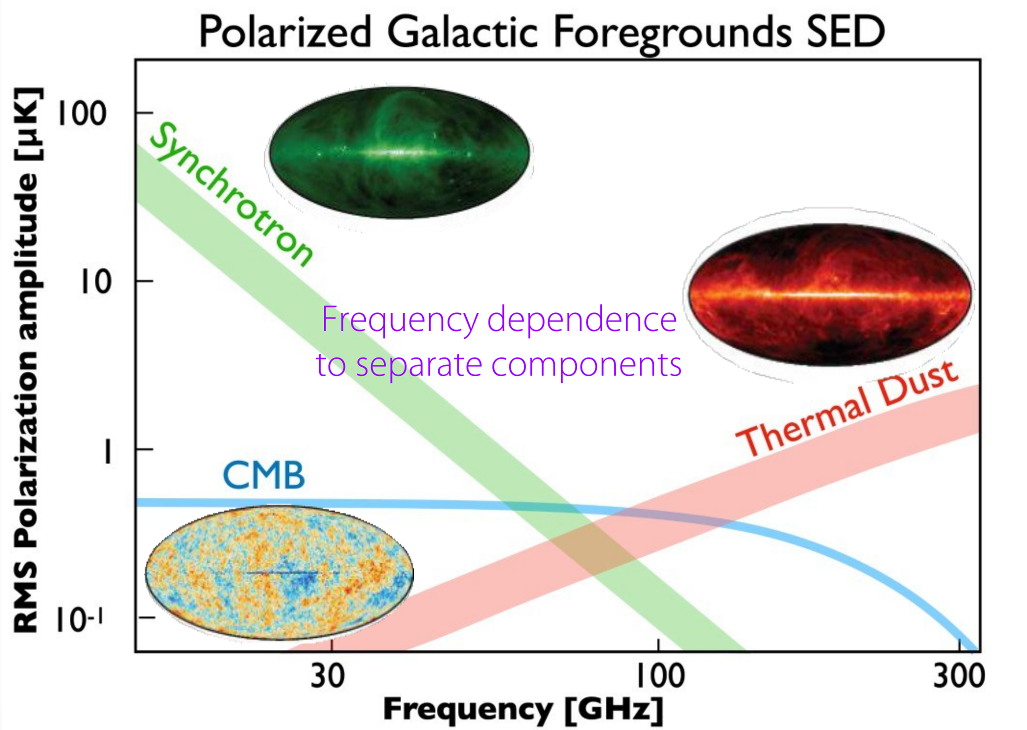
Challenges

Small signal

CMB B-mode polarization =
faint signal

Polarized foregrounds

Mixed with foreground contaminations
→ Need to separate CMB from foregrounds
→ Precise knowledge of frequency spectra



Observation of the CMB polarization

Challenges

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CMB B-mode polarization =
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Polarized foregrounds

Mixed with **foreground contaminations**
→ Need to separate CMB from foregrounds
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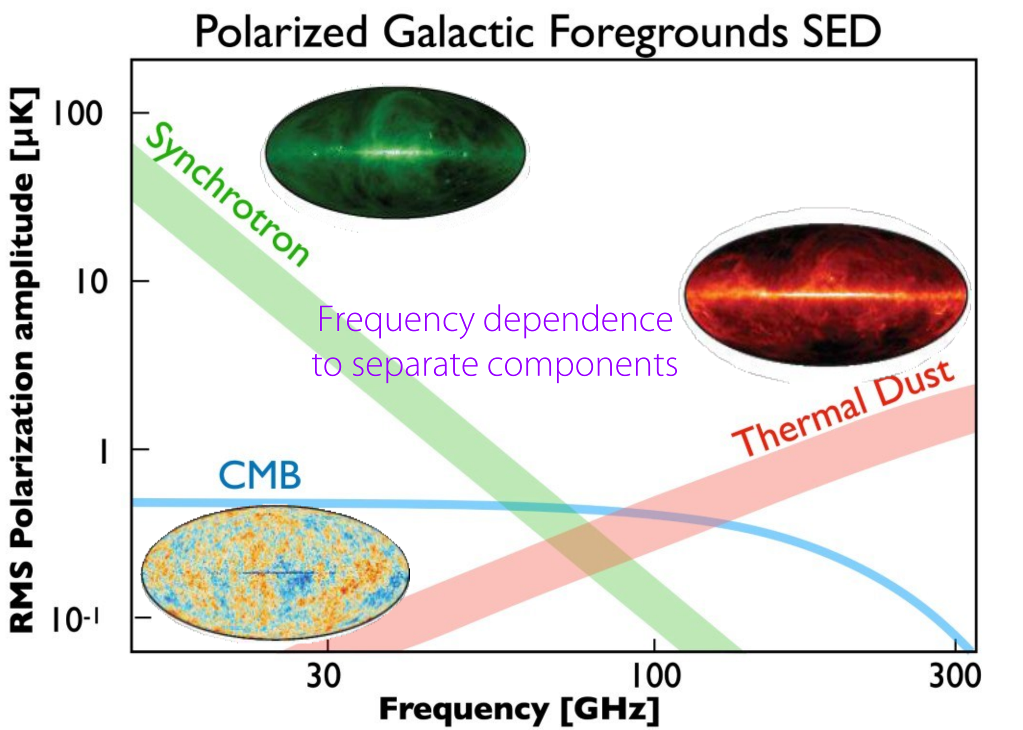
Instrumental systematics

Need of **high sensitivity** + **negligible instrumental systematic** effects



Instrumental design

QUBIC = Bolometric Interferometry

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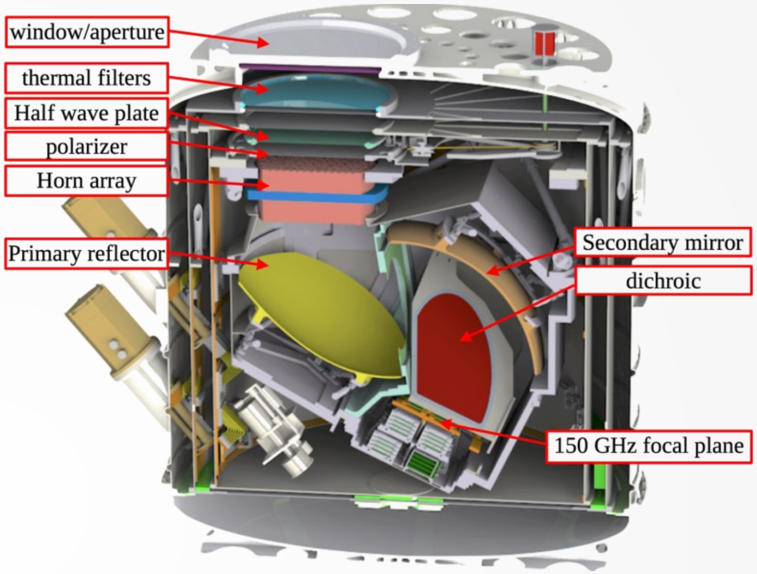
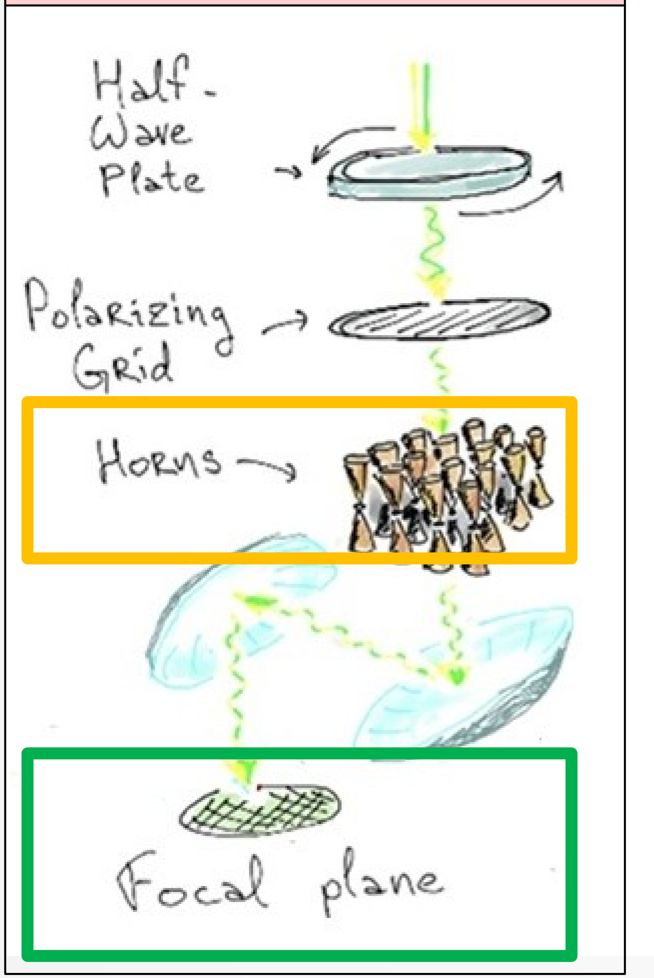
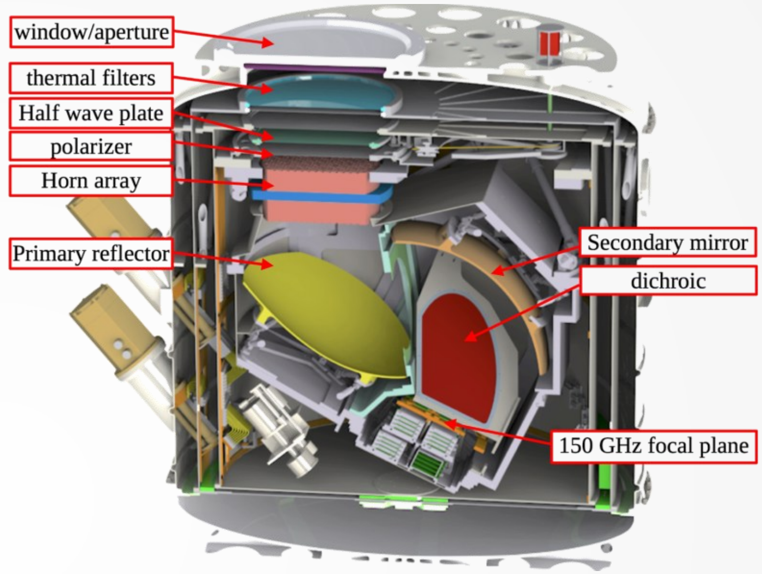


Sensitivity of bolometers

Instrumental design

QUBIC = Bolometric Interferometry

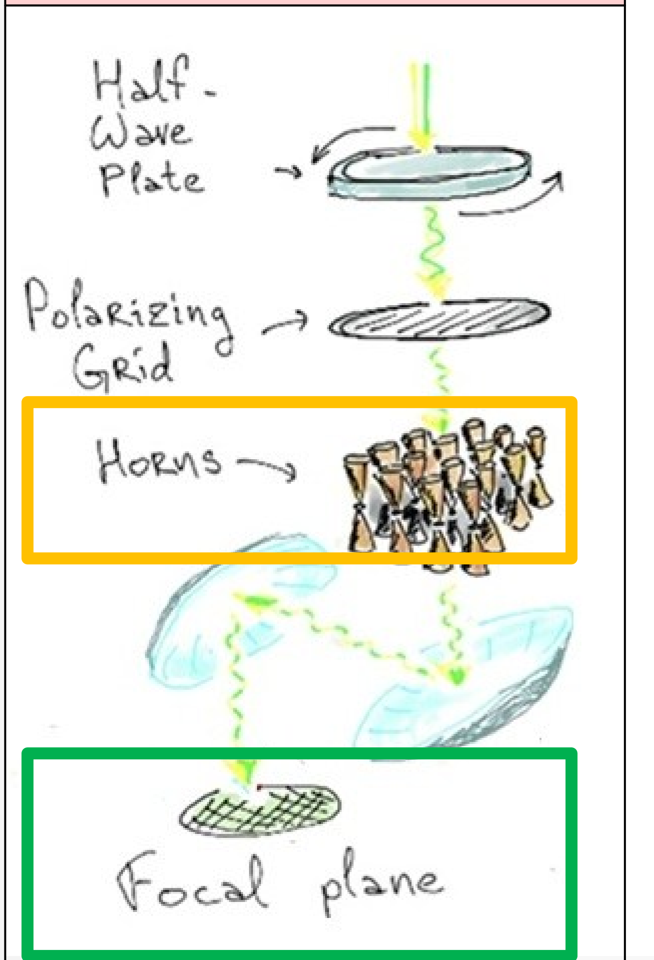


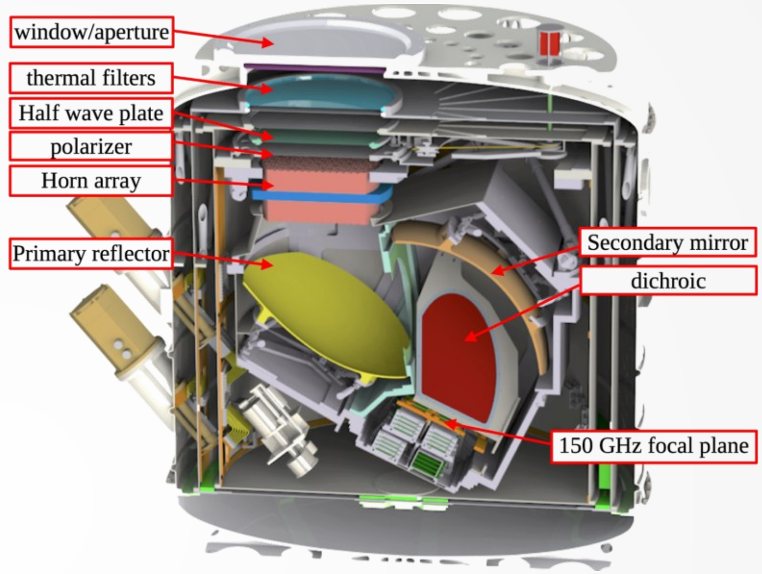


Sensitivity of bolometers + Interferometry

Instrumental design

QUBIC = Bolometric Interferometry



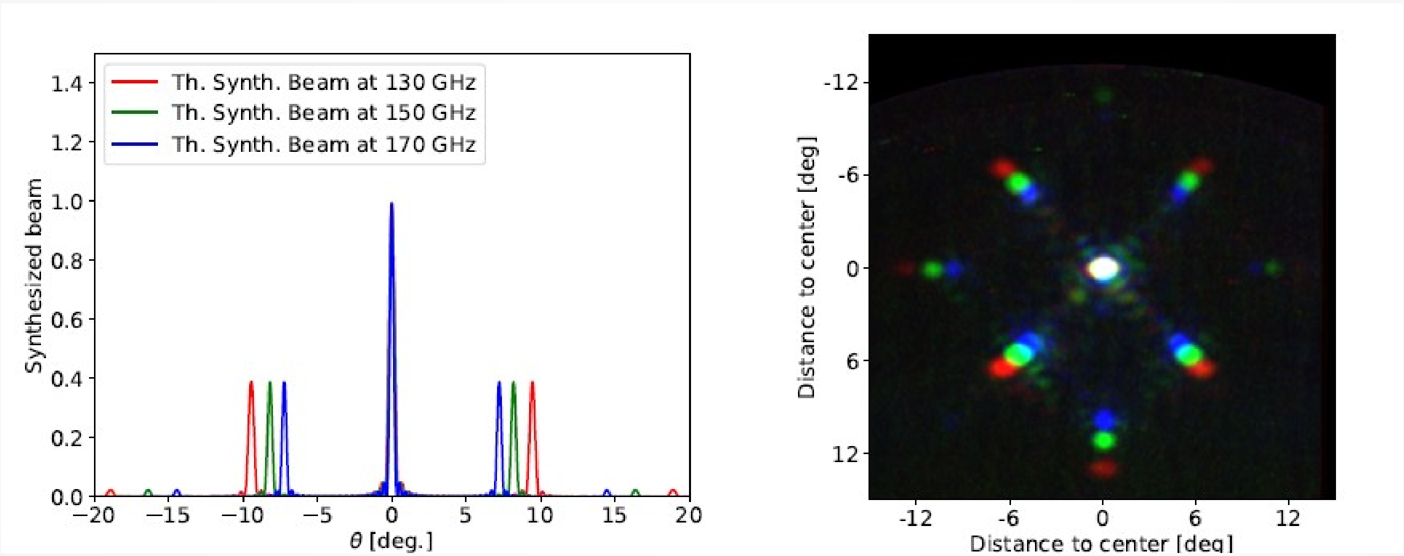


Sensitivity of bolometers + Interferometry

CMB vs foregrounds mitigation → Spectral Imaging

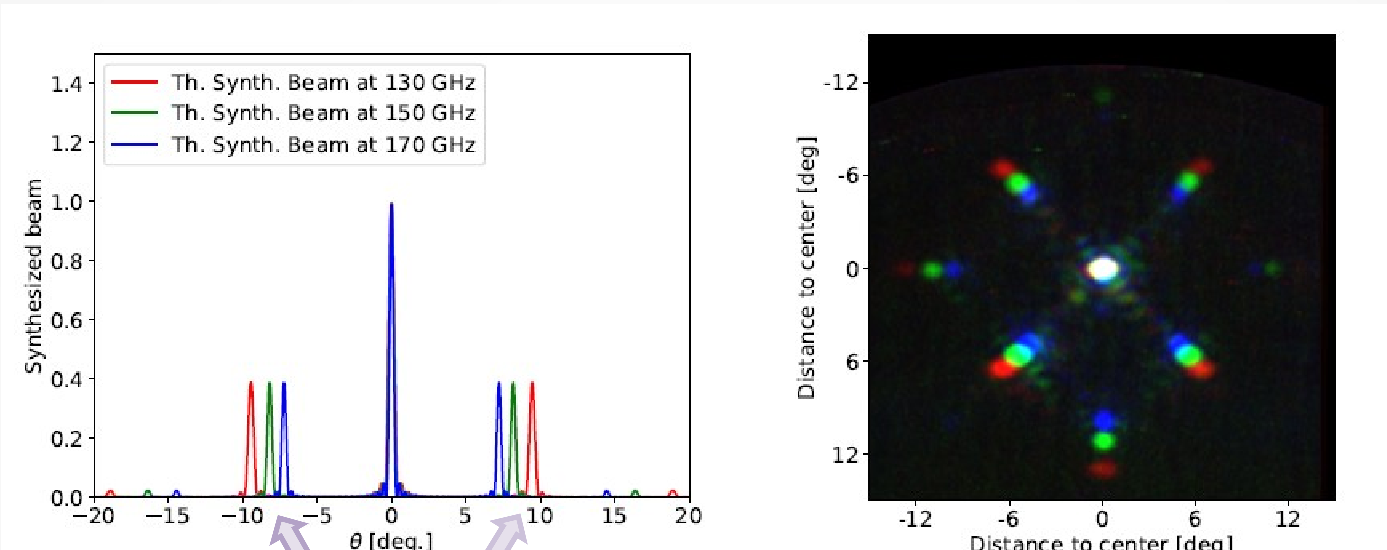
Control over instrumental systematics → Self-calibration

Spectral imaging



- Interferometry fringe patterns

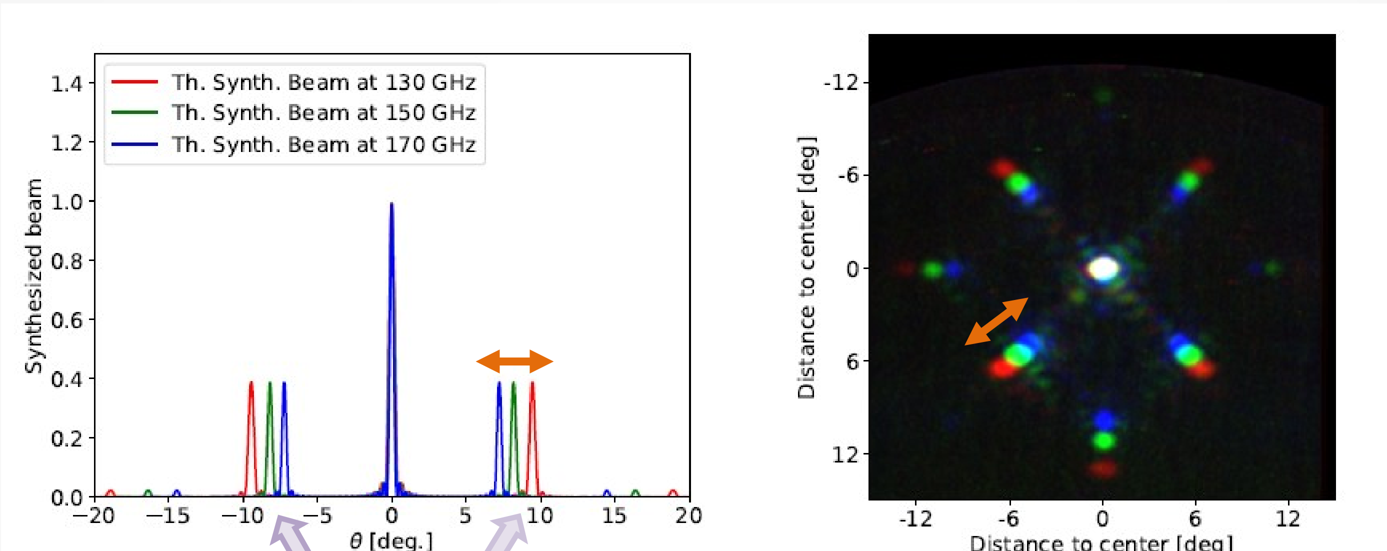
Spectral imaging



Multiple peaks

- Interferometry fringe patterns
- Frequency-dependent peaks position

Spectral imaging

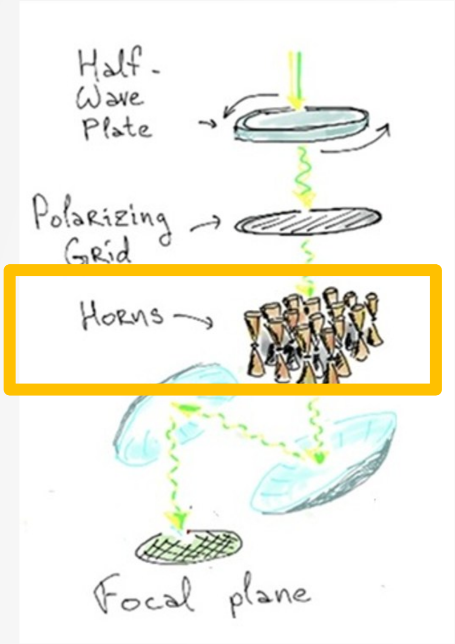


Multiple peaks

- **Interferometry fringe patterns**
- Frequency-dependent peaks position
- Spectral-imaging = **spatial variations → spectral information**

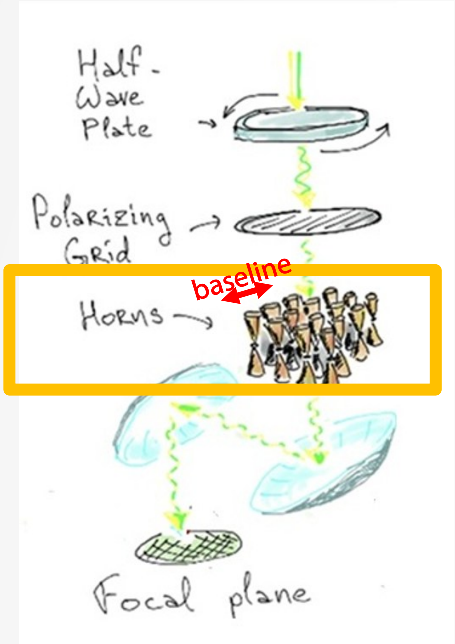
Self-calibration

Self-calibration



- **Self-calibration** = +++ baselines, combinations > number of instrumental parameters

Self-calibration



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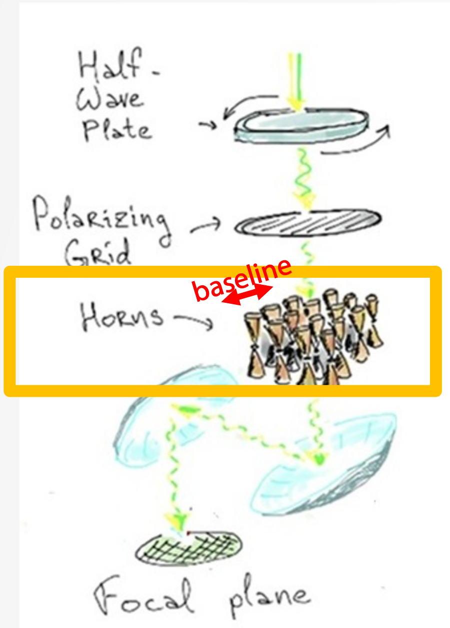
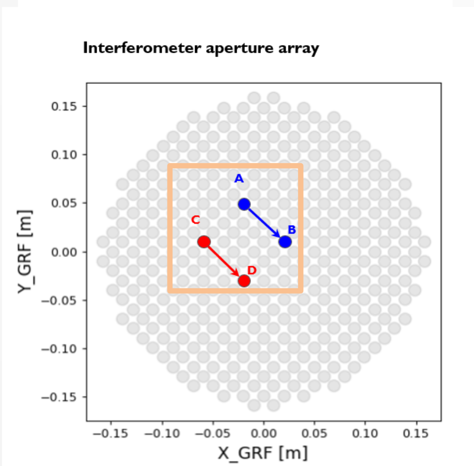
Self-calibration

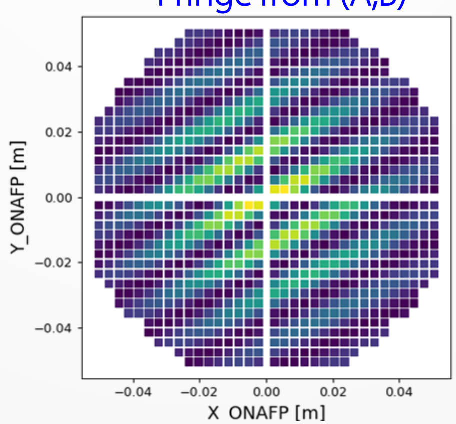


- **Self-calibration** = +++ baselines, combinations > number of instrumental parameters
- Fringe differences ⟶ **instrumental systematics**

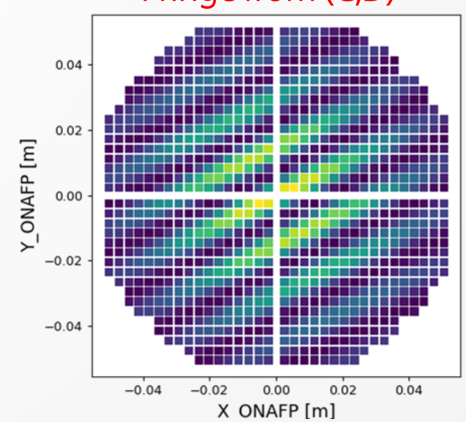


[Louise Mousset, https: //hal-cea.archives-ouvertes.fr/tel-03783687/]

Fringe from (A,B)



Fringe from (C,D)

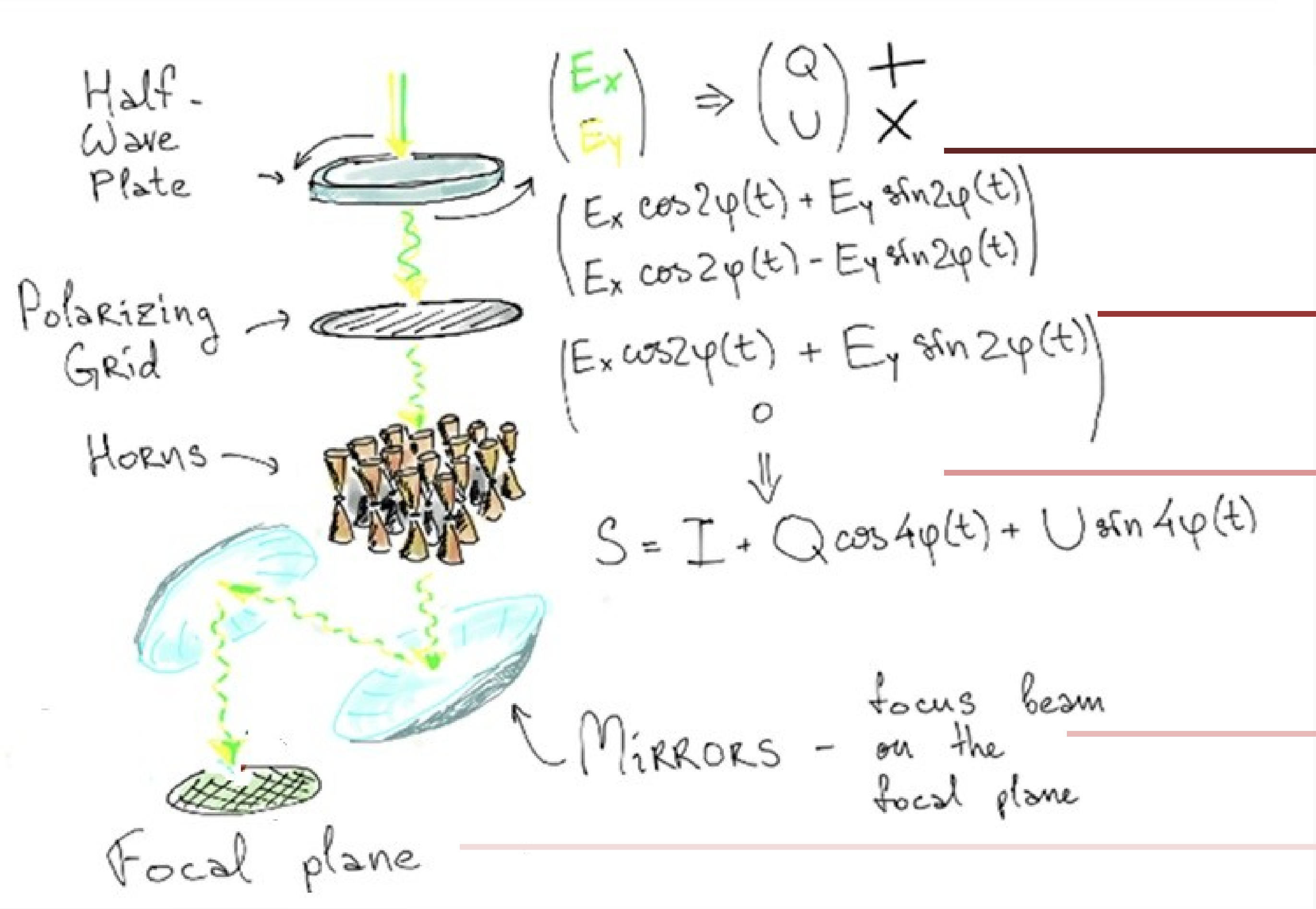


Focal Plane signal (Simulation)

Thank you for your attention

Back-up

Instrumental design



Modulates the signal

Selects 1 polarization

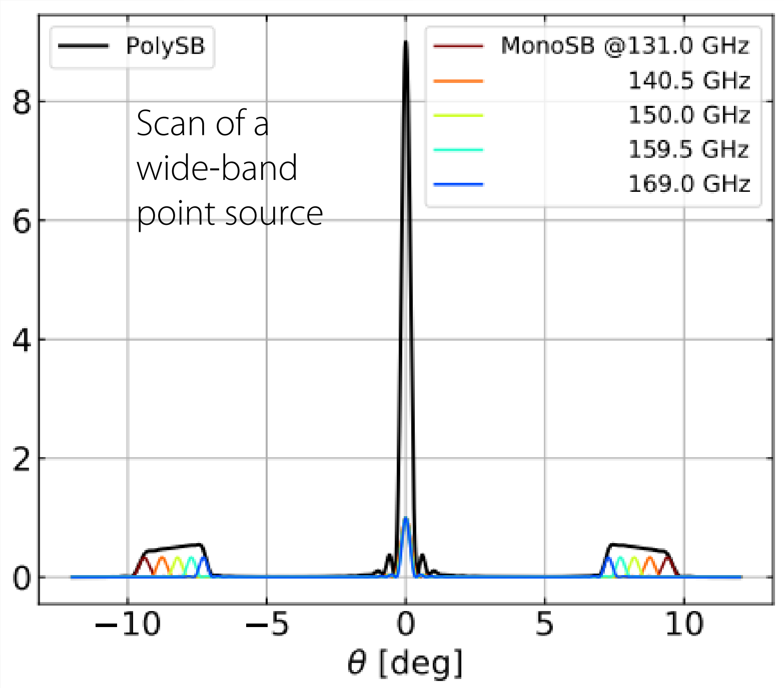
⇔ Antennas in interferometers

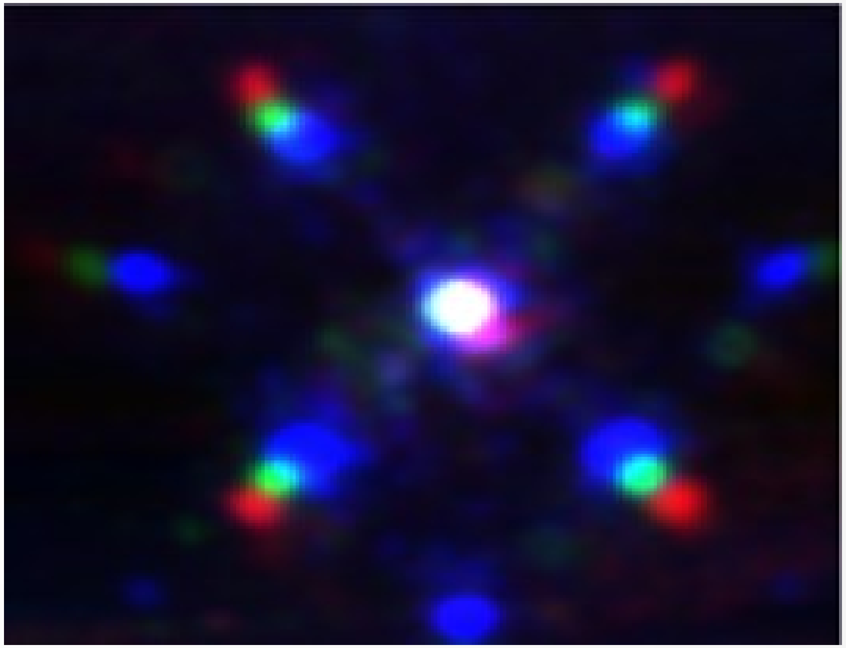
Combines the beams on the focal plane

Detects the fringe pattern

NB: Optical combiner + bolometers are equivalent to multi-elements correlator

Spectral imaging





The Q&U BI for Cosmology (QUBIC)

QUBIC : First **Bolometric Interferometer**

<u>The collaboration</u>:

- International teams (France, Italy, UK, Ireland, USA, Argentina)
- 130 collaborators
- Observing site: Argentina (5000m a.s.l)

<u>Advantages:</u>

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

Frequency Map Making (Map reconstruction)

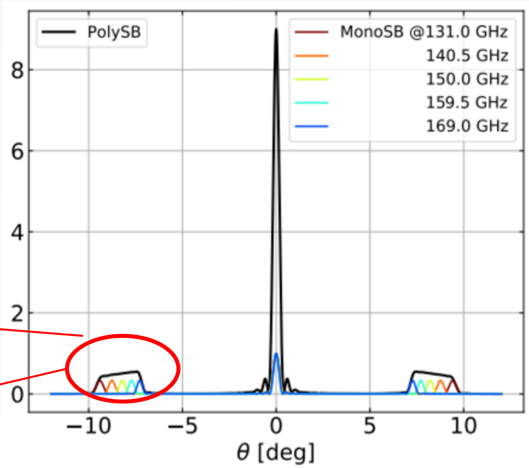
$$\vec{y} = \sum_{\text{bands}} H_b \cdot \vec{s}_b + \vec{n}$$

Bolometer data (TOD) ← $\vec{y}$

Instrumental model ↑ H_b

Sky in sub-bands ↑ $\vec{s}_b$ — Unknown

$\vec{n}$ → noise

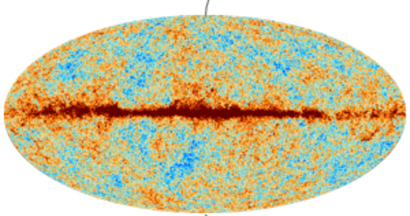


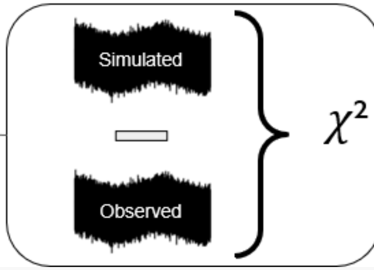
Sum over the bandwidth

Instrumental Model

$$\vec{d} = \sum_{i=1}^{Nsub} H_{\nu_i} \cdot \vec{s_{\nu_i}} \Delta\nu_i + \vec{n}$$

Sub-Frequency separation done offline at MapMaking stage.





Forward modeling approach:
χ^2 in TOD space
Regularization with Planck data

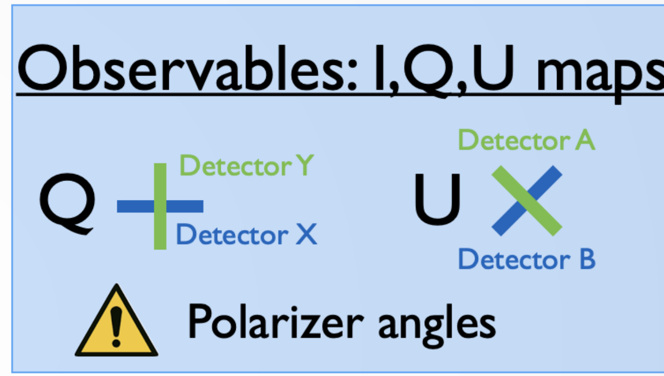
Cross-polarization

<u>Most serious effect: Cross-Polarization</u>

- polarizer angle uncertainties
- PSF uncertainty
- parasitic light (ground pickup)
- …

⇒ Induce mixing between Q and U
- E to B leakage (and E>>B !)
- Even worse T to B leakage…

Typical XPol requirements:
- <1.5% if r=0.01
- < 0.5% if r=0.001



- <u>Solutions:</u>
  - Instrumental design (eg. QUBIC)
  - Care with mechanical fabrication
  - Polarization modulation (HWP)
  - Self-Calibration at Data Analysis stage (specific to QUBIC)

From Q and U to E and B

From Q and U to E and B

- Spin-2 Spherical Harmonics expansion (Q&U are spin 2)

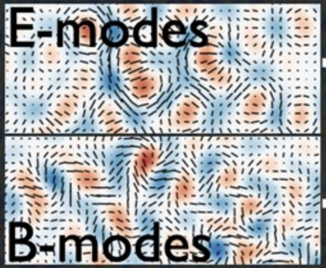
$$Q(\vec{n}) + iU(\vec{n}) = \sum_{\ell m} a_{2,\ell m}\ {}_2Y_{\ell m}(\vec{n})$$

$$Q(\vec{n}) - iU(\vec{n}) = \sum_{\ell m} a_{-2,\ell m}\ {}_{-2}Y_{\ell m}(\vec{n})$$

- Any polarization field can be decomposed into 2 scalar fields E and B

$$a_{E,\ell m} = -\frac{a_{2,\ell m} + a_{-2,\ell m}}{2} \quad \text{(even)}$$

$$a_{B,\ell m} = i\frac{a_{2,\ell m} - a_{-2,\ell m}}{2} \quad \text{(odd)}$$



$$C_\ell^{TT} \quad C_\ell^{TE} \quad C_\ell^{EE} \quad C_\ell^{BB}$$

Inflationary models

Measuring r = discriminating between different inflationary scenarios :

r related to inflaton potential slope → shape of this potential determines r value.

- **Large-field models** (chaotic inflation, e.g., ϕ^2, ϕ^4)

→ $r \approx 0.1$–0.3
→ Disfavored by current data

- **Starobinsky model** (exponential plateau) : inspired by modified gravity

→ $r \approx 0.003$
→ In good agreement with observations

- **Natural inflation** : inspired by axion physics

→ $r \approx 10^{-3}$
→ Roughly consistent with data

- **Small-field models** (hilltop, plateau models with flat potentials)

→ $r < 0.01$
→ favored by current data

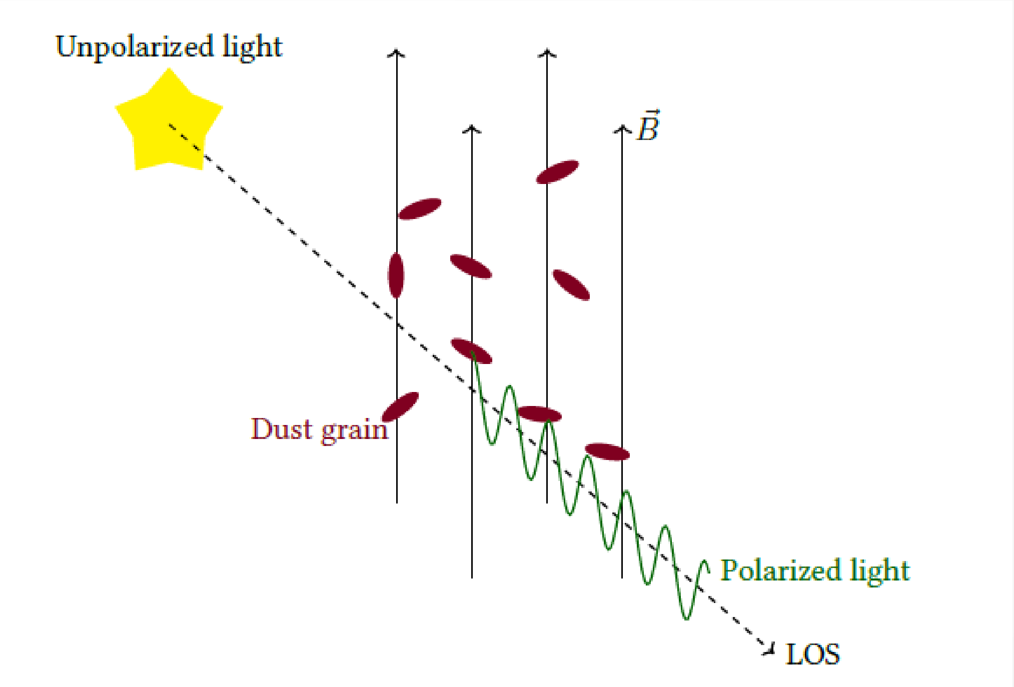
Thermal dust

- Interstellar medium ⟶ clusters of **tiny grains** aligned with a magnetic field.

- Unpolarized light from stars + dust grains ⟶ grains emit **polarized light** in sub-mm wavelength range

- SED = **Modified Black Body model**, with 2 free parameters:
    - $T_d = 20\text{K}$
    - Slope characterizing the spectral distribution or spectral index β_d

- Measured by Planck.

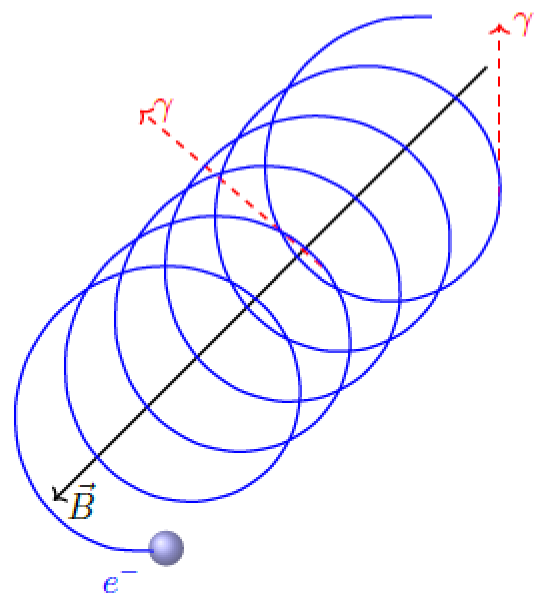


Synchrotron

- **Synchrotron effect** = photon emission from electrons captured by magnetic field lines.

- Follows **power law** in the frequency space.

- 2 parameters:
  - A_s the amplitude
  - β_s the spectral index



- Measured by WMAP + Planck.

- Low frequency range

- Neglected in QUBIC (thermal dust + CMB emissions dominate.)

Dedicated missions to B-modes

Ground-based experiments :

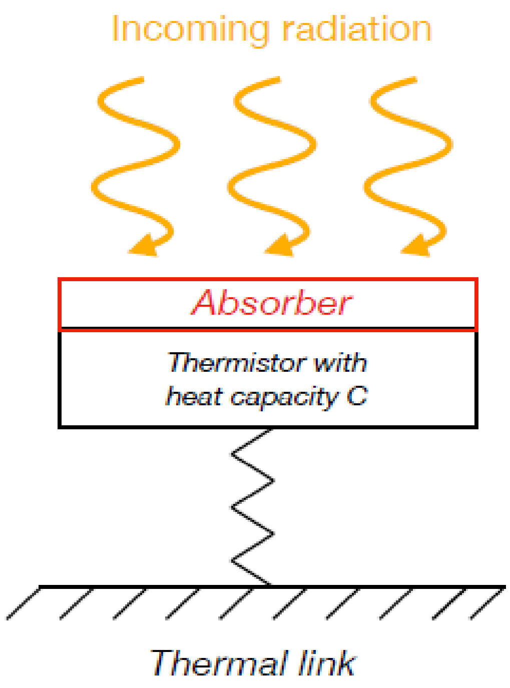
- Bicep/Keck:
  - Most advanced to date
  - 3 frequencies: 150, 220, 95 GHz.
  - r < 0.032 at 95% CL
- Simons Observatory:
  - Under construction
  - Located in Chile
  - 3 SATS + 3 LATS
  - 6 frequencies (30-280 GHz)
- CMB-S4:
  - 4th generation CMB instrument
  - Best chance of success (high sensitivity)
  - 21 instruments, 500 000 detectors.
  - Many telescopes in Chilean Andes.

Space missions :

- LiteBird:
  - High precision, large sky coverage
  - 4500 TES
  - 15 frequency bands (34 to 448 GHz)
  - Planned to launch in 2030

→ *Extensive sky coverage + access to large angular scales + complete sampling of SED + no atmospheric fluctuations*

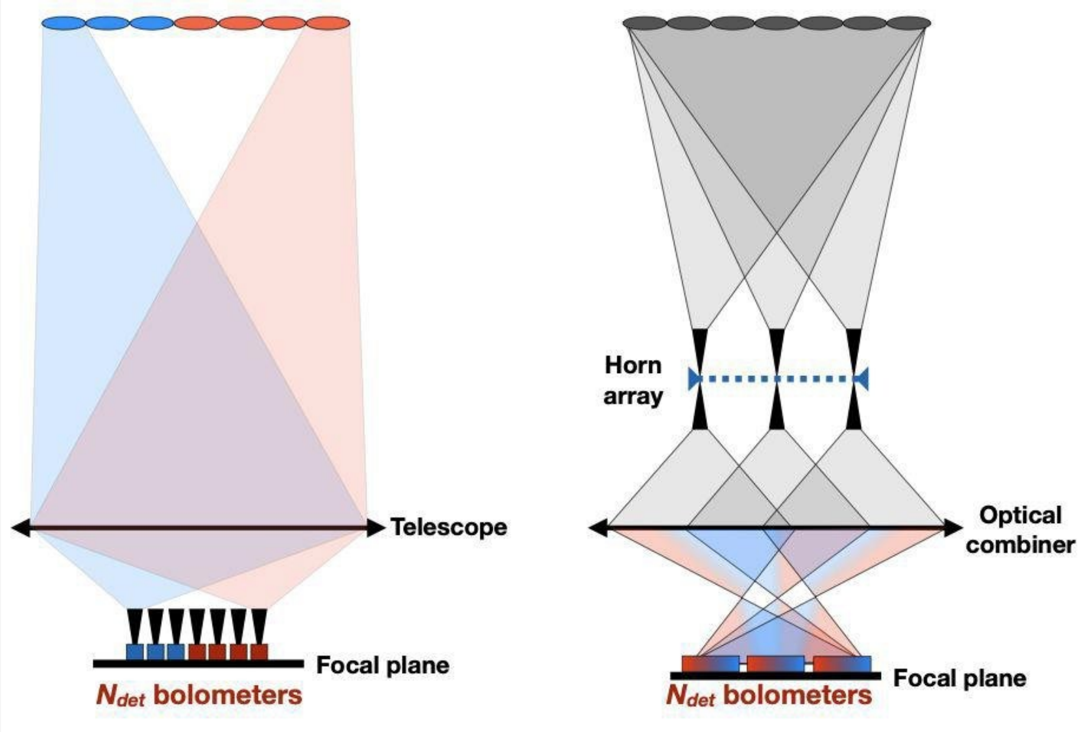
Bolometers



- **Bolometer** = tool for measuring the deposited incident power using the material resistive state.
- Temperature variations measured directly from resistance variation (thermistance)
- **Superconducting bolometer** = thermalization of a material at the transition between superconductive and non-superconductive state

→ Small temperature variation = steep rise in resistance

Imager VS BI



- **Sensitivity**:
  - Imager = number of detectors
  - BI = number of antennas
- **Angular resolution**:
  - Imager = aperture diameter of the telescope
  - BI = largest baseline

- BI: **fewer bolometers** + captures **more modes** on the sky with same physical band.
- QUBIC will be able to reach a good sensitivity with fewer detectors
- Few bolometers = less cost (bolometer array very expensive).

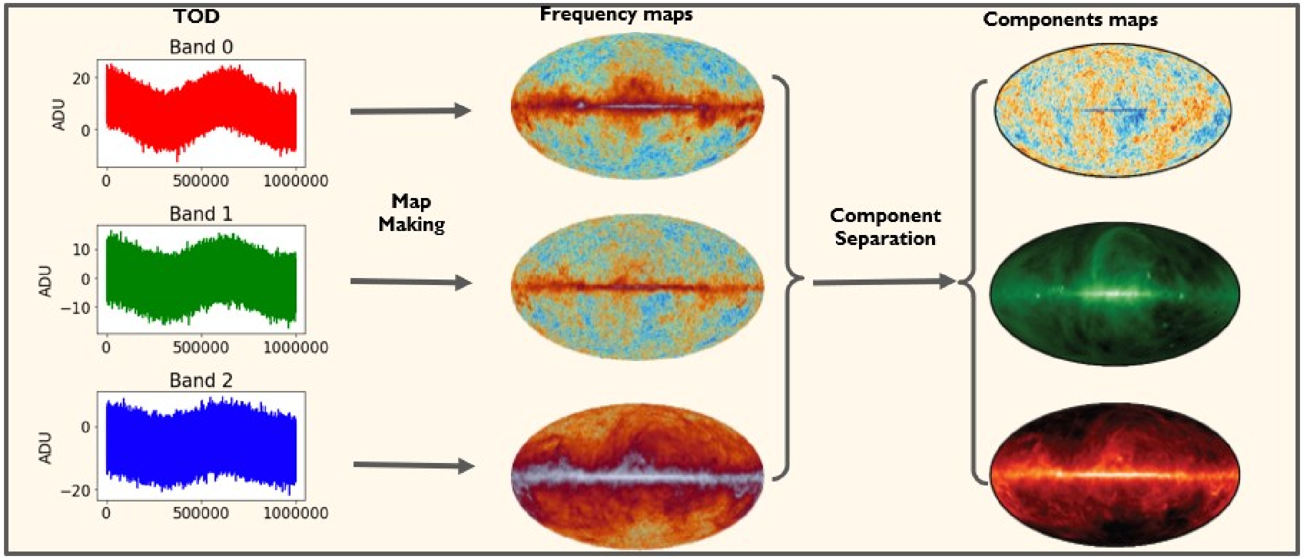
QUBIC polychromatic beam

- **Secondary peaks** = intrinsic property of the interferometer.
- QUBIC measures a set of **visibilities** corresponding to the **phase differences between antennas**.
- Finite number of baselines → **periodic structure in angular response**.

→ Angular periodicities manifest as **multiple peaks in the spatial frequency domain** = **periodic sky copies/artifacts** caused by the **discrete horn array geometry** + the **harmonic structure of the interference fringes**.

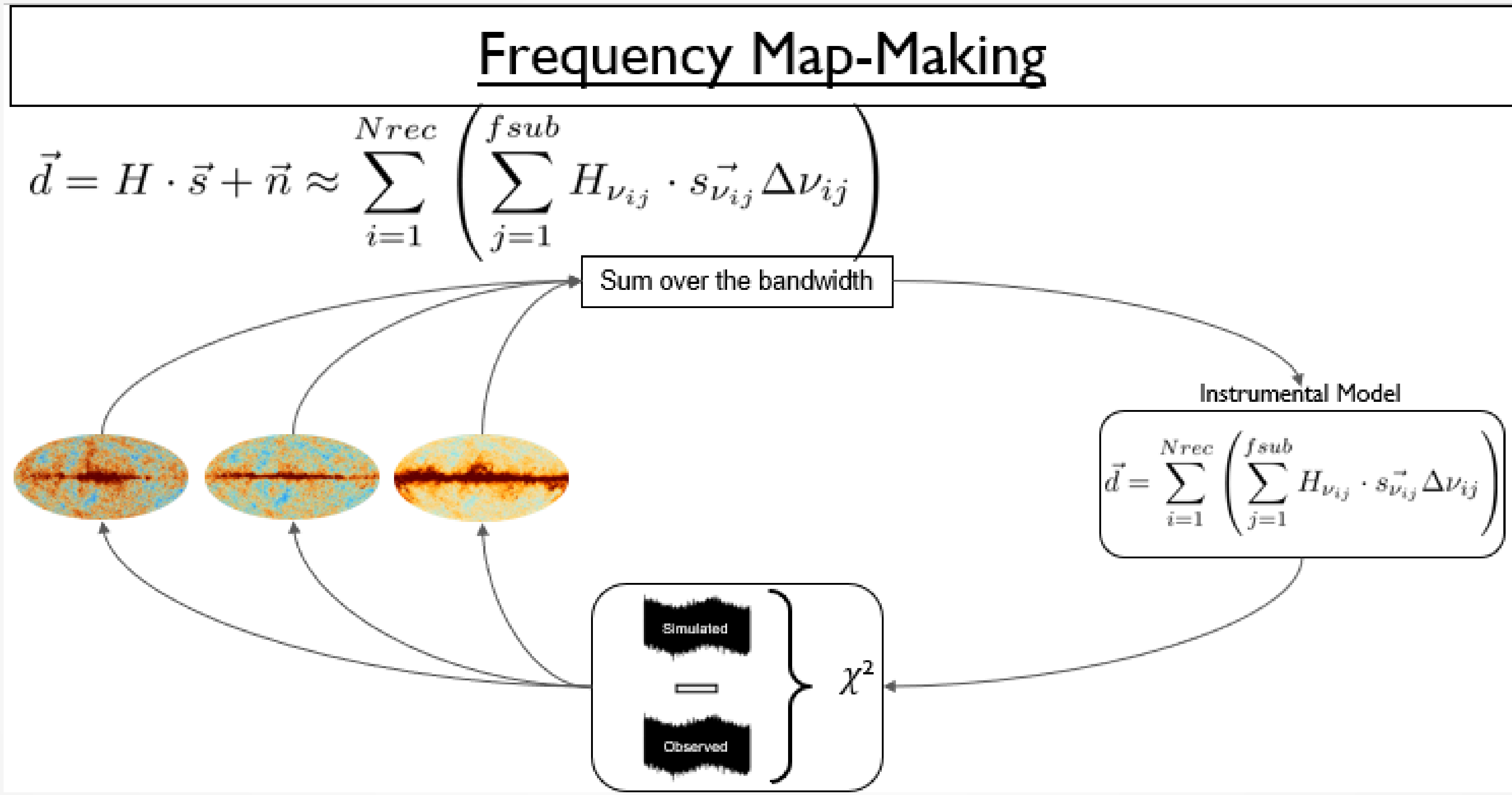
Classical Imager pipeline

$$\vec{d_i} = H_i \cdot \vec{s_i} + \vec{n_i}$$



Classical Imager Pipeline

Frequency Map-Making



Complete reconstruction pipeline

→ **Raw TES data** (bolometric measurements of I, Q, U)

→ **Processing of the TOD** (demodulation, calibration, cleaning)

→ **Multi-frequency reconstruction** (spectral imaging) = reconstruction of mixed maps Q, U at each frequency

→ **Spectral modeling** of components

→ **Parametric component separation** (CMB vs. foregrounds)

→ Clean CMB Q and U maps

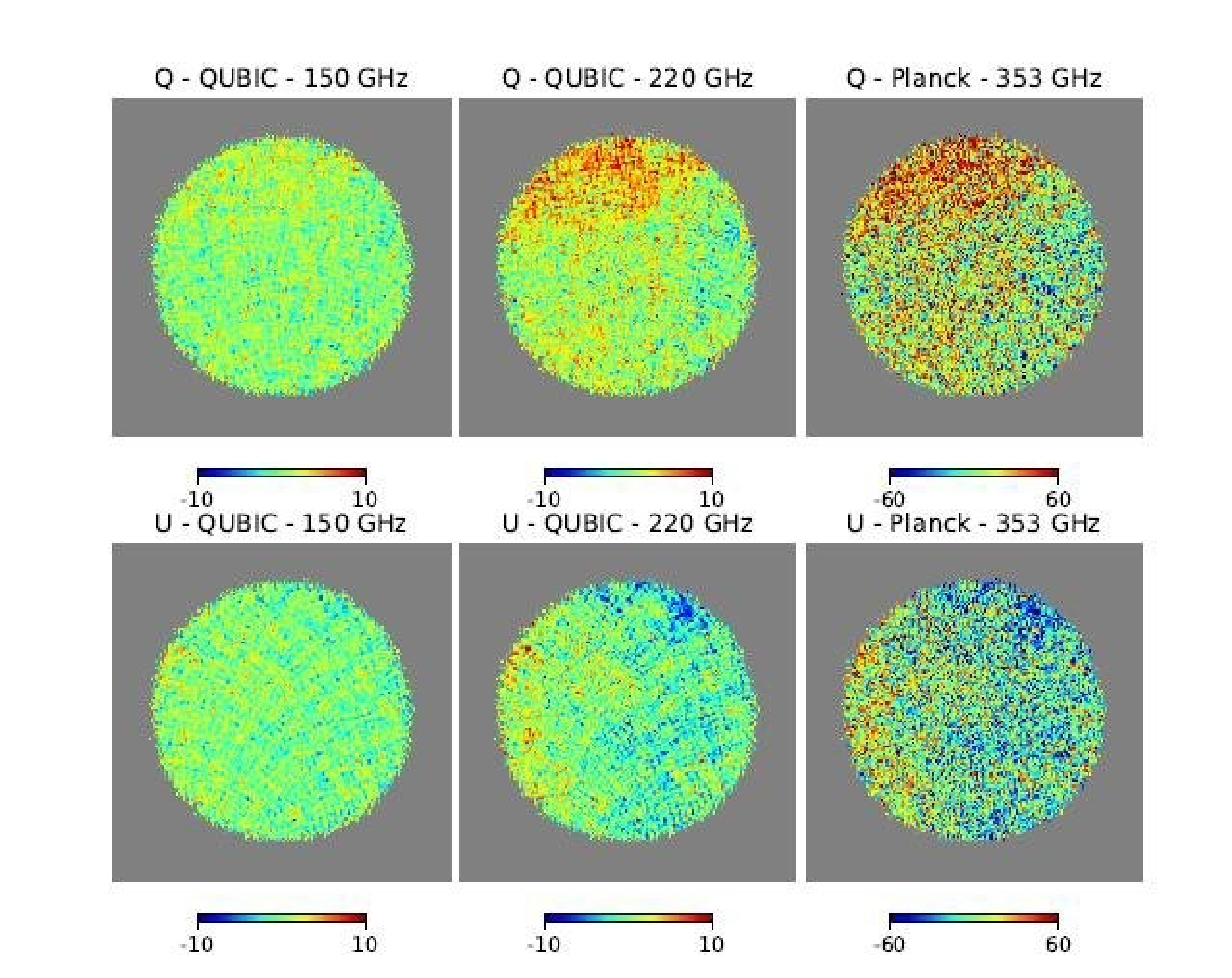
→ **Transformation** to E/B modes

→ **Estimation of power spectra** C^{BB}_{l}

→ **Theoretical fitting** (via likelihood or MCMC)

→ Estimation of cosmological parameters or **constraint on** r

Q, U reconstructed maps



Noise in the data

- **Detector noise + readout noise**, constant with frequency
  - Johnson noise of the resistive charge (thermal fluctuations of electrons in electronics)
  - Shot noise (non-continuousity of electric current which is composed of discrete charges)

- **Photon noise** due the to discrete nature of light :
  - Poisson fluctuations of CMB photons
  - Thermal radiation of instrument's optical elements
  - Atmospheric fluctuations

QUBIC advantages and disadvantages

- **Advantages of spectral imaging:**

  - With more frequency points → **better constrain the spectral indices** of the components → better fits to spectral laws (imagers average frequency data to reconstruct frequency maps).
  - Improved **handling of frequency-dependent systematics** (e.g., slowly varying instrumental effects across frequency)
  - **Competitiveness**: spectral imaging → finer spectral separation despite only a few physical channels.

- **Challenges:**

  - **Complex inversion**: reconstructing sub-bands = delicate deconvolution with strong correlations between sub-bands.
  - Requires a highly **accurate instrument model**: spectral separation relies on precise modeling of the instrument, beam, and frequency response.