Curso intensivo de Cosmología Observacional

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Clase 5 & 6 (jueves 27/03)

- Desafíos en las observaciones del CMB
- Contaminantes: fuentes galácticas y extragalácticas
- ruido y problemas instrumentales
- Experimentos actuales y futuros: QUBIC, Simons Observatory, CMB-S4, LiteBird.

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In search of primordial B-modes: challenges and advances in cosmic microwave background polarization

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3. Observational challenges

The search for primordial B-modes in the CMB polarization is one of the most ambitious goals in modern cosmology. However, this endeavor has significant observational challenges that must be carefully addressed to isolate the faint primordial signal, both from astrophysical foregrounds and instrumental limitations. Below, we discuss the primary difficulties and the strategies being developed to overcome them.

- **Polarized dust emission:** Thermal emission from interstellar dust grains, which align with the Galactic magnetic field, produces polarized radiation (Ade et al., 2025). This emission is particularly strong at high frequencies ($\gtrsim 100\,\mathrm{GHz}$) and varies significantly across the sky. The Planck satellite has provided detailed maps of this dust polarization, revealing its complex spatial structure and frequency dependence (Planck Collaboration et al., 2015, 2016b, 2017). Modeling and subtracting this component require precise multi-frequency observations and robust statistical techniques (Katayama & Komatsu, 2011).
- **Synchrotron radiation:** Electrons spiraling around Galactic magnetic fields emit polarized synchrotron radiation, which dominates at low frequencies ($\lesssim 70\,\mathrm{GHz}$) (Tucci et al., 2000; Fauvet et al., 2011). Like dust emission, synchrotron radiation exhibits spatial variability and frequency dependence, complicating its removal (Miville-Deschênes et al., 2008).

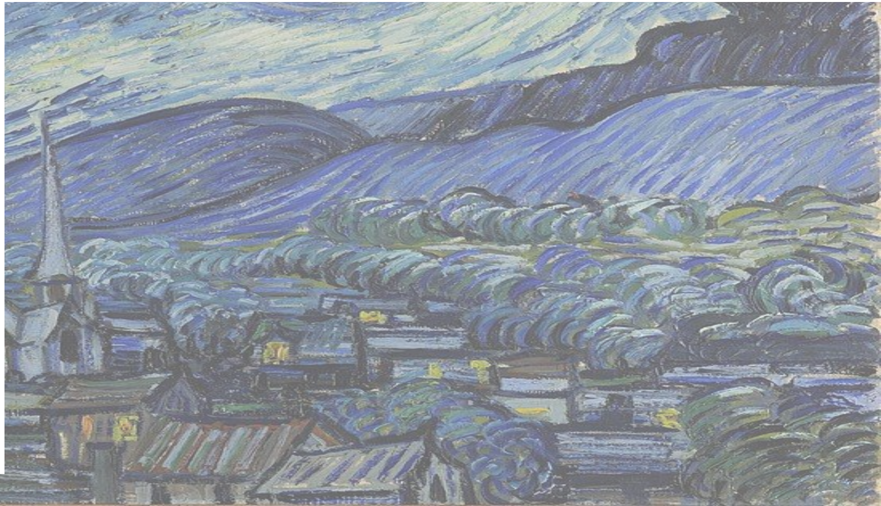
ver más detalles en la clase de Sistemas Estelares, en la carpeta de PDFs

The spatial variability of these foregrounds poses a major challenge. Unlike the CMB, which is statistically isotropic, Galactic foregrounds are highly anisotropic, with intensity and polarization patterns that vary across the sky. This variability necessitates high-resolution, multi-frequency observations to accurately model and subtract the foregrounds. In this context, multi-frequency observations are essential for minimizing foreground residuals in component separation techniques. Bolometric interferometers, with their high spectral resolution and subfrequency information, offer a promising approach for distinguishing and mitigating such residuals (Regnier et al., 2024).

3.2. Instrumental systematics

In addition to astrophysical foregrounds, instrumental systematics present a significant barrier to detecting primordial B-modes (Monelli et al., 2024). Achieving the required sensitivity and precision demands state-of-the-art instrumentation and meticulous control of systematic effects. Key challenges include:

- **Sensitivity requirements:** Primordial B-modes are expected to be extremely faint, with amplitudes on the order of tens of nanokelvins (nK). To detect such a weak signal, experiments must achieve noise levels of μK-arcmin or better. This requires large arrays of highly sensitive detectors, such as transition-edge sensors (TES) (Piat et al., 2020) or microwave kinetic inductance detectors (MKIDs) (Johnson et al., 2018), operating at cryogenic temperatures.
- **Beam imperfections:** Imperfections in the beam of the telescope beam can distort the observed polarization patterns, introducing spurious B-modes (Karkare & BICEP/Keck Array Collaboration, 2017). Accurate characterization and calibration of the beam are essential to mitigate this effect.
- **Calibration errors:** Misalignment of polarization angles or errors in gain calibration can also produce false signals (Aumont et al., 2018). Precise calibration techniques, often using celestial sources or dedicated calibration devices, are critical to minimizing these errors (Staggs et al., 2002).
- **Atmospheric noise:** Ground-based telescopes must deal with atmospheric emission, which can introduce noise and systematic effects (Brown et al., 2009). Advanced filtering techniques and careful site selection are employed to reduce this contamination (Errard et al., 2015).



Misiones espaciales para medir el CMB

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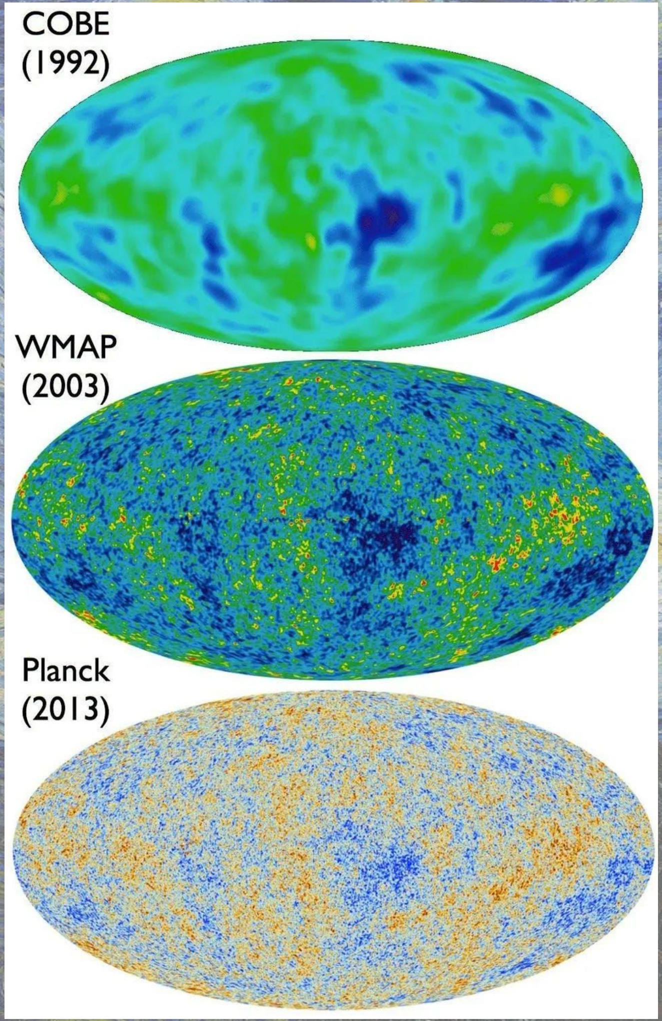


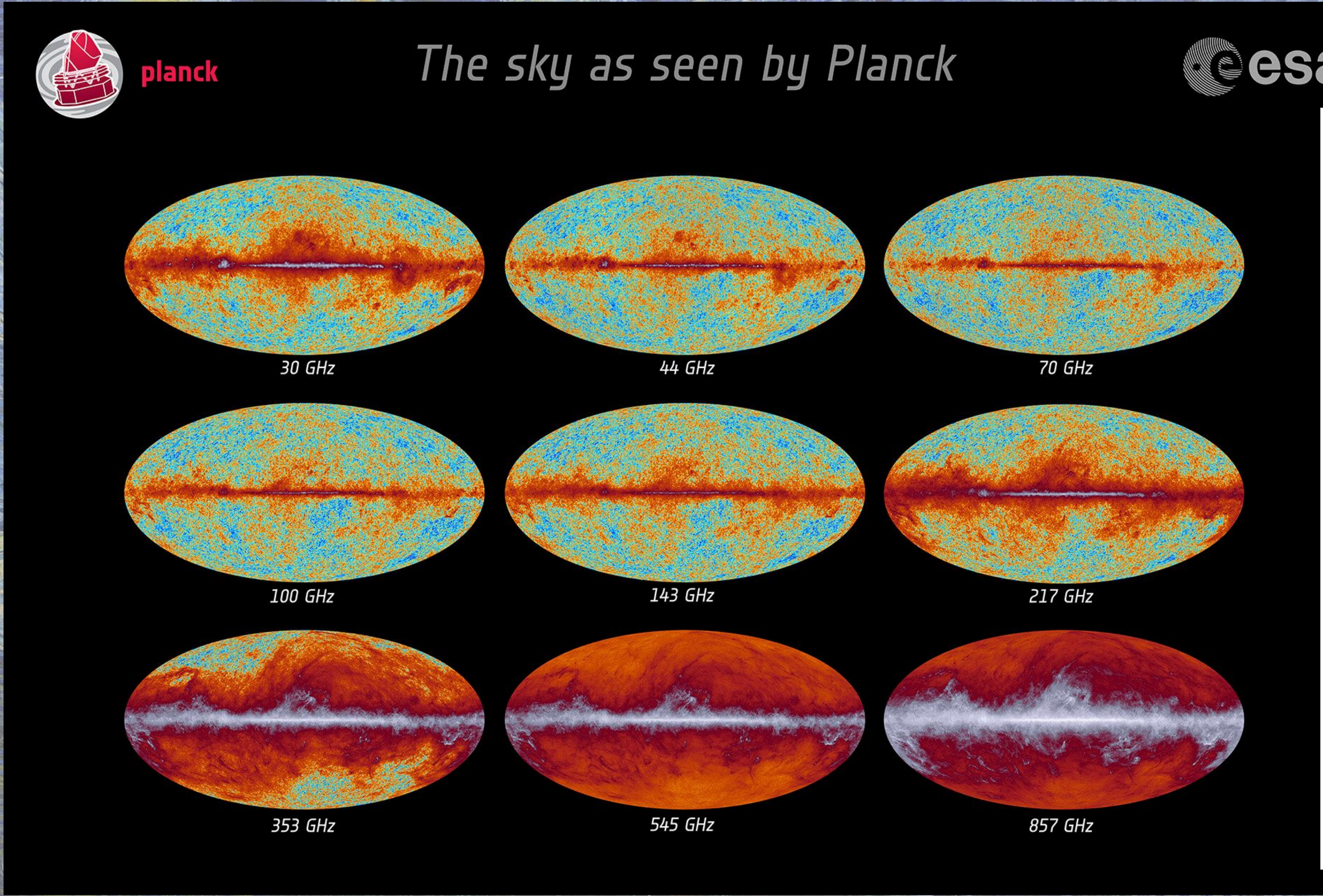
Mejor resolución angular

Ejercicio propuesto en la práctica 1 (new version):

Calcule un espectro con CAMB, eligiendo parámetros cosmológicos adecuados

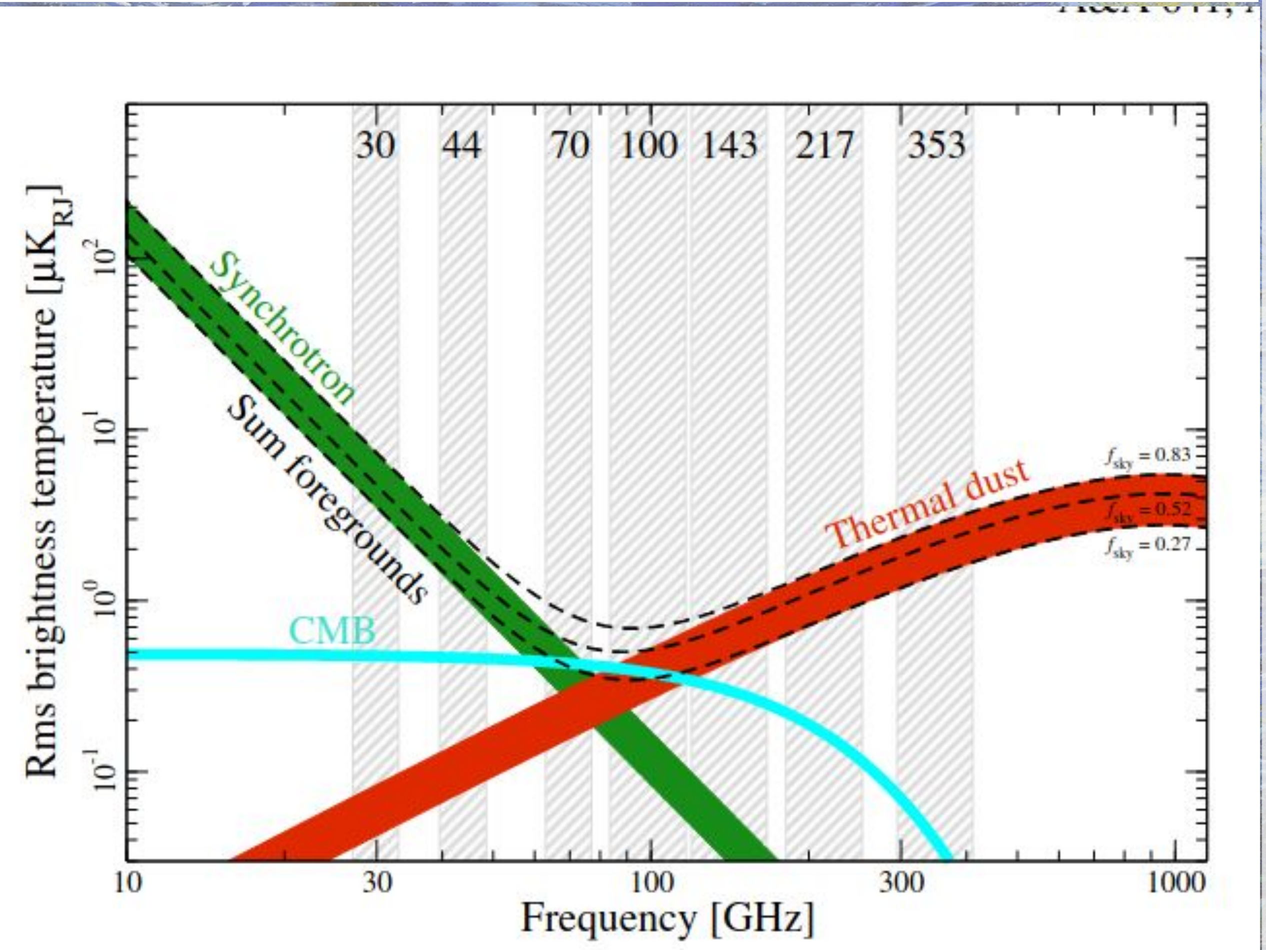
A partir del espectro, con Healpy, calcule los a_lm y a partir de ellos, mapas con las resoluciones de cada uno de los telescopios espaciales que estudiaron el CMB.
El objetivo es recuperar algo similar a la figura.

Contaminantes del CMB

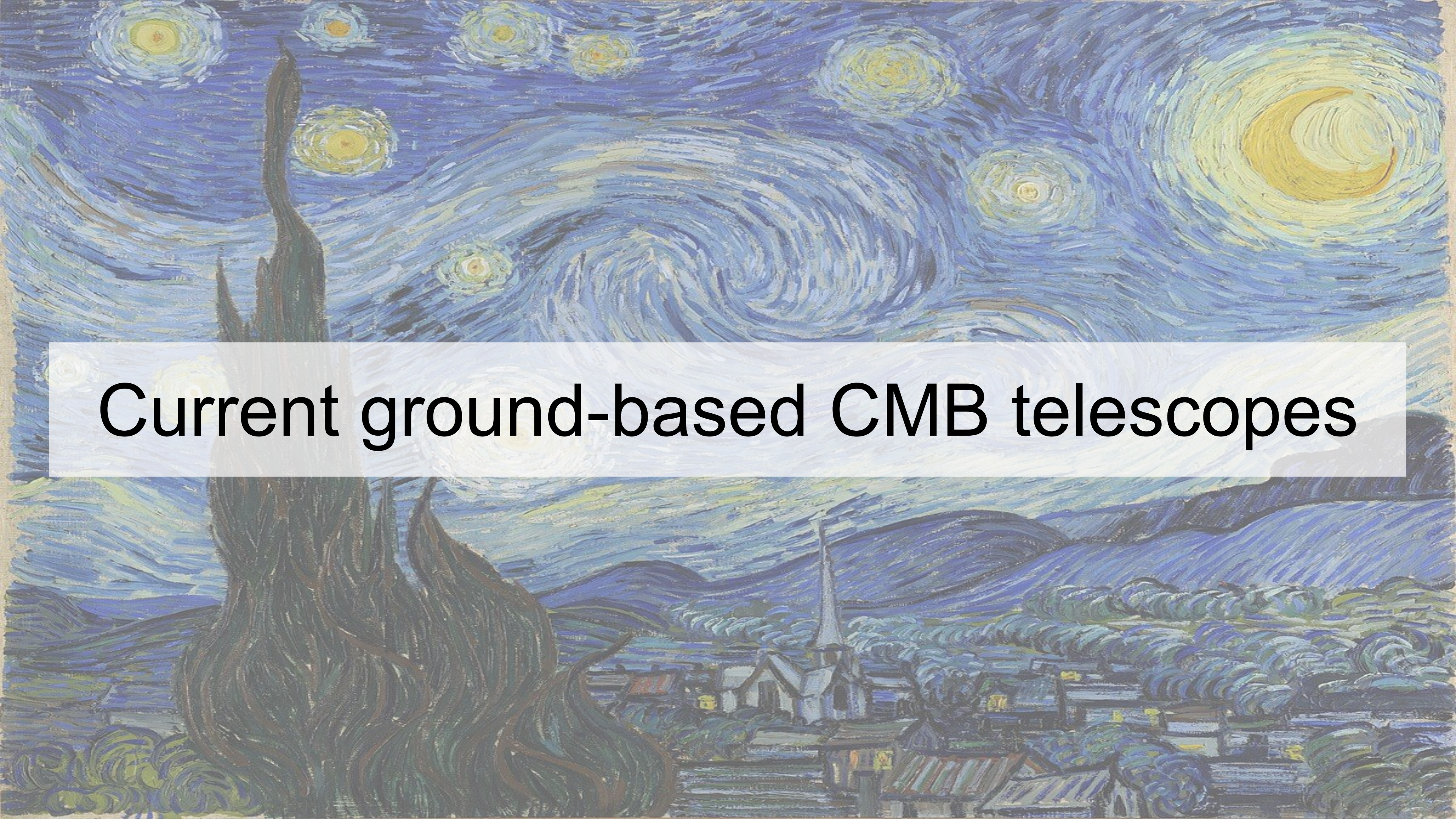


Ejercicio propuesto en la Práctica 3:
Con **pysm** realice simulaciones del mapa CMB y emisión galáctica a distintas frecuencias (polvo y sincrotrón), y recupere el comportamiento esperado, similar a los mapas de Planck.

https://www.aanda.org/articles/aa/pdf/2020/09/aa33881-18.pdf



Amplitud RMS de la polarización en función de la frecuencia y los componentes astrofísicos, evaluada a una escala de suavizado de 40′ FWHM. La banda verde representa la emisión polarizada de sincrotrón, mientras que la banda roja representa la emisión polarizada de polvo térmico. La curva cian muestra la RMS del CMB para un modelo ΛCDM con τ=0.05, que está dominada principalmente por la polarización en modos E. Las líneas negras discontinuas indican la suma de los foregrounds evaluados en tres máscaras diferentes con f_sky=0.83, 0.52 y 0.27. Los anchos de las bandas de sincrotrón y polvo térmico están determinados por las coberturas del cielo más grande y más pequeña.



Current ground-based CMB telescopes

Many experiments to measure the **CMB polarization**, in search of the **B modes**

QUBIC telescope

- ❖ Alto Chorrillos, Salta, Argentina (obs. middle 2020s).
- ❖ Wide frequency: 150 - 220 GHz, spectro-imaging.

Simons Observatory

- ❖ Cerro Toco in Chile (obs. early 2020s).
- ❖ 6 Freqs: 27, 39, 93, 145, 225 y 280 GHz.

CMB-S4 Atacama desert

- ❖ 2 x 6m telescopes
- ❖ 274,760 detectors

More than 130 researchers (**France, Italy, Argentina, Ireland, and UK**).

QUBIC

The Q & U Bolometric Interferometer for Cosmology

Alto Chorrillos, Salta Prov, at 4.900 m a.s.l.

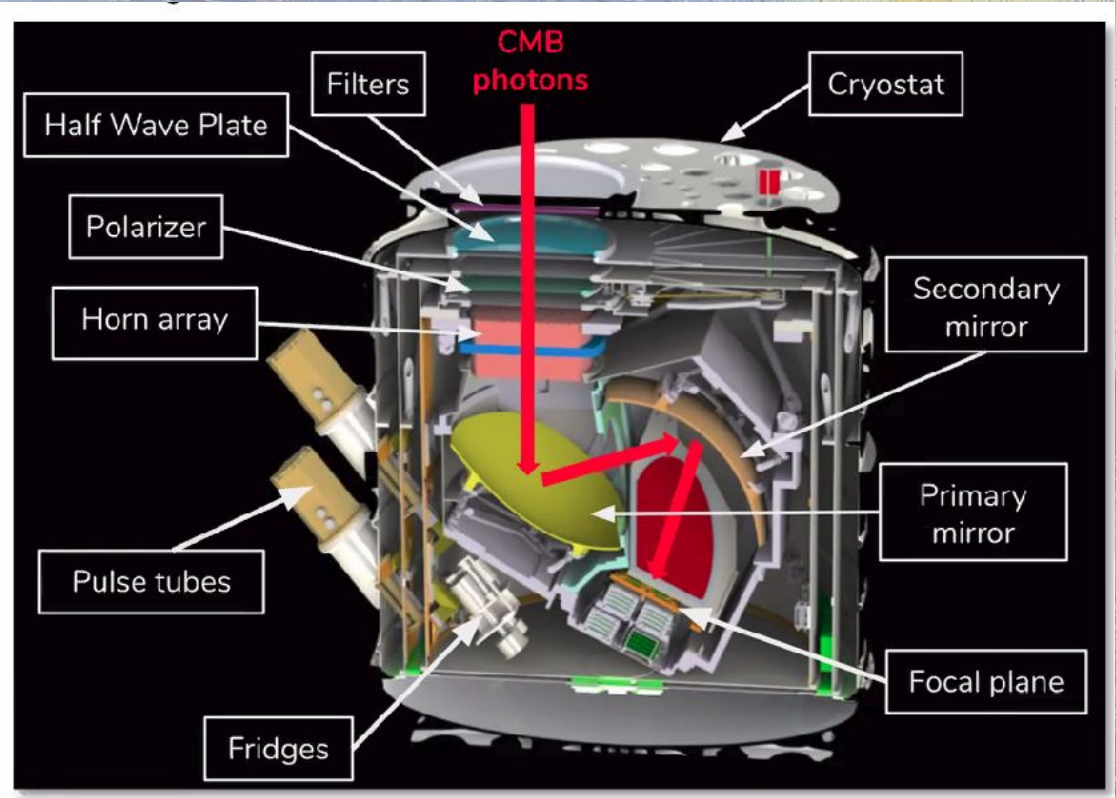
QUBIC novel concept - Bolometric interferometer

QUBIC

Combines the sensitivity of bolometers

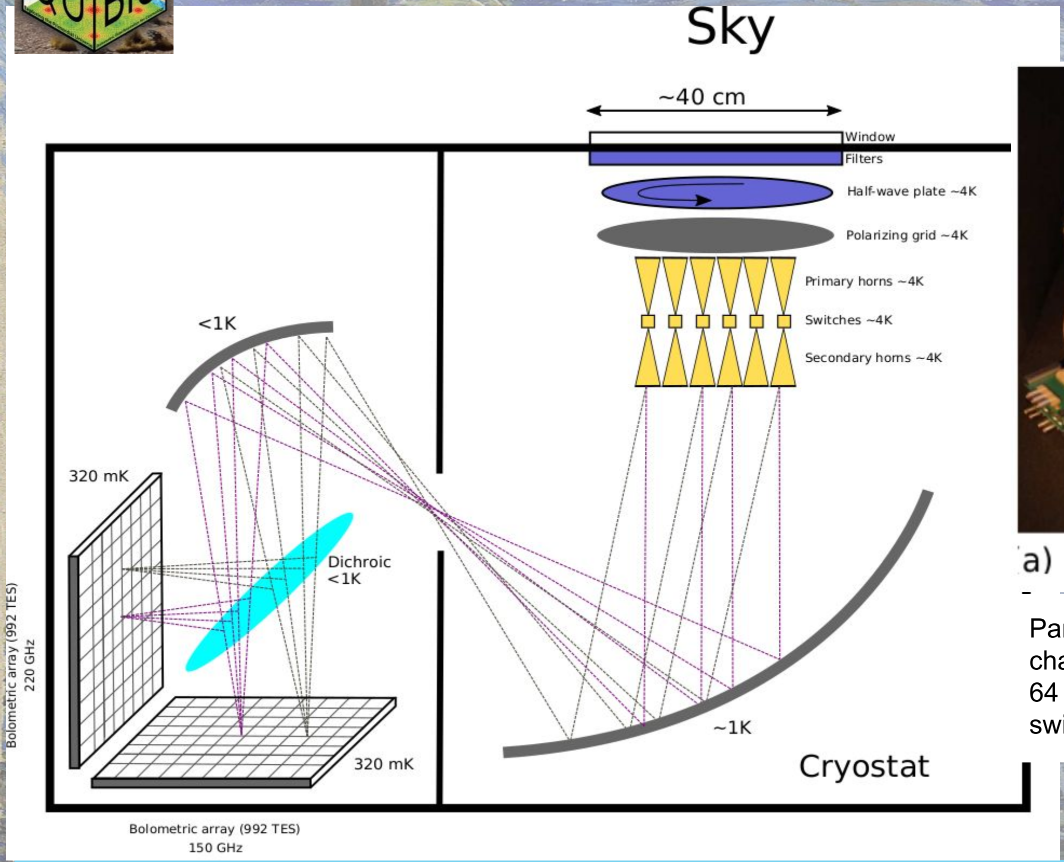
with

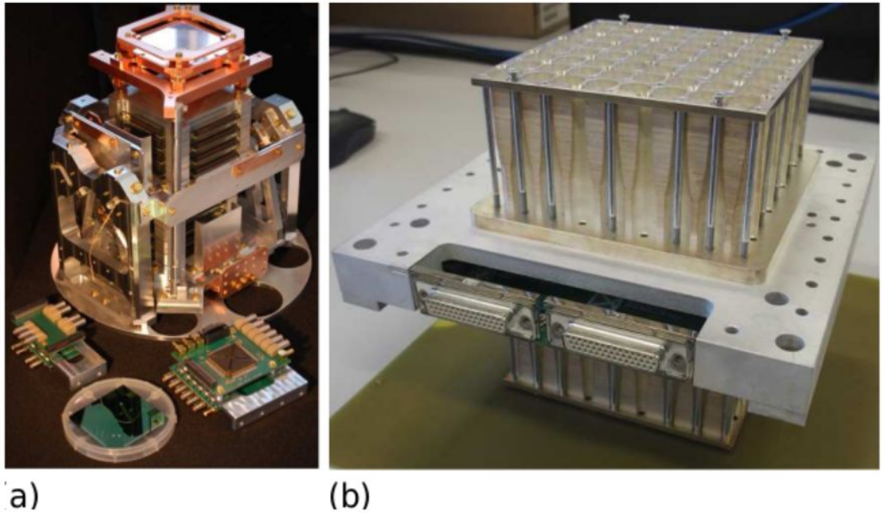
the exquisite systematics control of interferometers



shelter

QUBIC - the instrument





Panel (a) shows one of the two cryogenic detection chains. On top of the chain, one can see the TES focal plane. Panel (b) shows the array of the 64 + 64 back-to-back dual-band corrugated horns interfaced with the switch array.

QUBIC novel concept **Bolometric interferometer**

QUBIC is an interferometer

can do **self-calibration**

Transition Edge Sensors (bolometers)

exquisite **sensitivity**

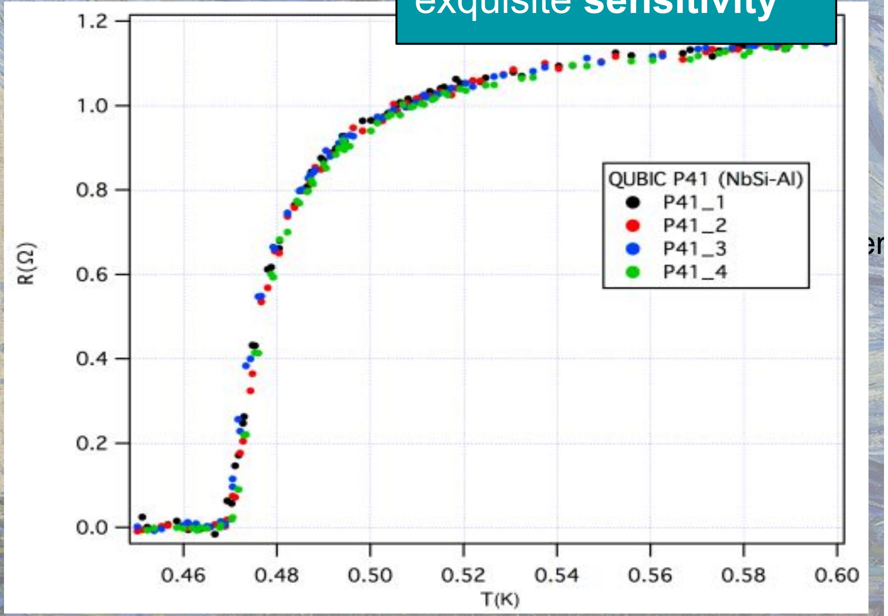
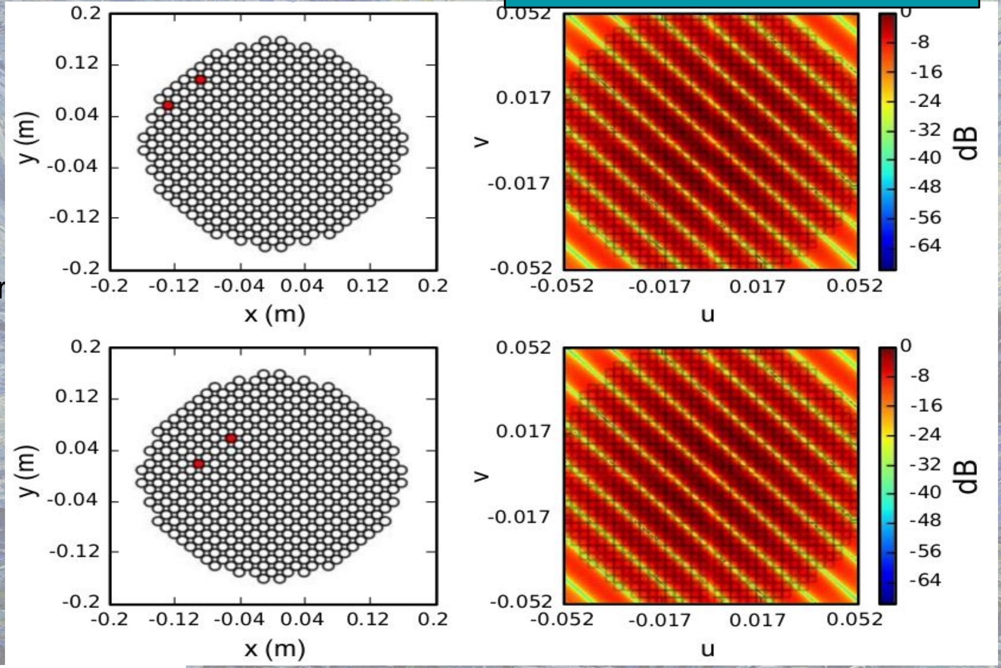


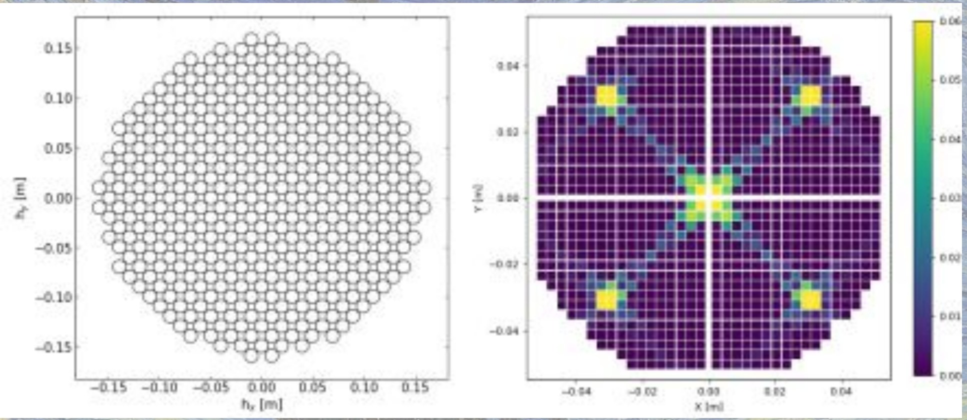
Figure 2. Superconducting transition characteristics (resistance R versus temperature T) of four $Nb_{0.15}Si_{0.85}$ TESs distributed far away from each other on the 256 pixel array reference P41.



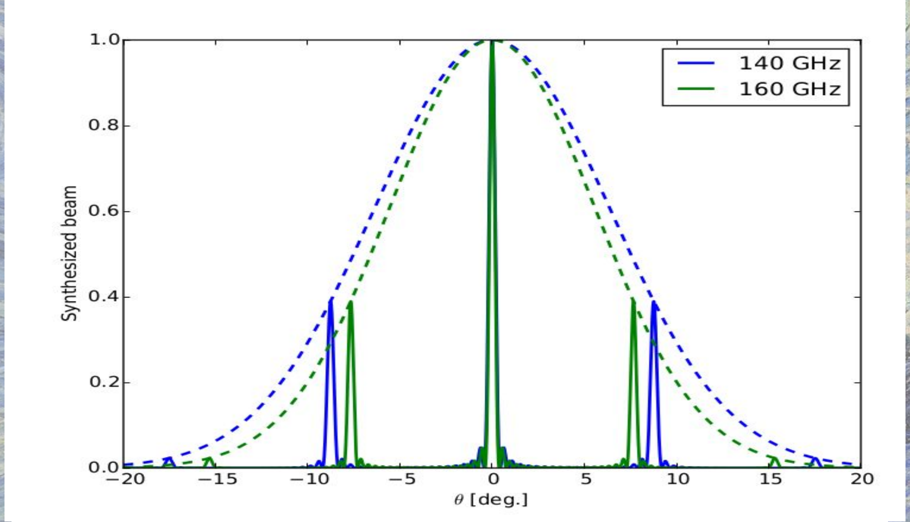
arXiv:2101.06787 **QUBIC IV paper**

Spectro-imaging

Synthesized beam: multiple nearly gaussian peaks. Resolution of 23.5 arcmin, at 150 GHz.



When all horns are open, the interferometric pattern results in an effective “beam” with multiple peaks.



Angular separation between two peaks is frequency dependent: **we can reconstruct maps at different sub-frequencies** using *spectro-imaging*.