Exploring the primordial Universe with QUBIC
the QU Bolometric Interferometer for Cosmology

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On behalf of the QUBIC Collaboration
QUBIC
QU Bolometric Interferometer for Cosmology

130 Collaborators
22 laboratories
6 countries

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 Tecnologias en Detección y Astroparticulas, Argentina
Instituto Argentino de Radioastronomía, Argentina

+SISSA Joining!
Primordial B-modes with QUBIC

Very weak signal

Focal Plane:
- 2048 TES with NEP ~ $4 \times 10^{-17}$ W.Hz$^{-1/2}$
- 128:1 SQUIDs+ASIC Mux Readout
- End-To-End Sims. show $\sigma(r) = 0.01$ with 2 years

Instrumental systematics

Cryogenic Optics after HWP and Polarizer + Full power detectors
- Instrumental Polarization has no effect

Polarized foregrounds

400 elements Interferometer
- Synthesized Imaging (well controlled beam) – angular resolution 23.5 arcmin
- Self-Calibration using switches + active source

Two wide bands: 150 and 220 GHz
- 1 focal plane for each channel
- Spectro-Imaging allows to form $\geq 2+3$ bands
- Increased Frequency Resolution
- More Complex dust models can be constrained
**QUBIC concept: Quasi optical correlator**

\[
\begin{align*}
\begin{pmatrix}
E_x \\
E_y
\end{pmatrix}
&\Rightarrow
\begin{pmatrix}
Q \\
U
\end{pmatrix}
\times \\
\begin{pmatrix}
E_x \cos 2\phi(t) + E_y \sin 2\phi(t) \\
E_x \cos 2\phi(t) - E_y \sin 2\phi(t)
\end{pmatrix} \\
\begin{pmatrix}
E_x \cos 2\phi(t) + E_y \sin 2\phi(t) \\
0
\end{pmatrix}
\downarrow \\
S &= I + Q \cos 4\phi(t) + U \sin 4\phi(t)
\end{align*}
\]

- Half-Wave Plate
- Polarizing Grid
- Horns
- Mirrors - focus beam on the focal plane
- Dichroic
- Focal planes

**QUBIC**

QU Bolometric Interferometer for Cosmology

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Integration being finalized in Paris

- Outer cryostat: Roma
- 1K Box / detectors: APC, CSNSM / IRAP
- Fridges: Manchester
- Optics: Roma / Maynooth / Cardiff

1st integrated (detectors, optics,…) cooldown this week
QUBIC Site:
near San Antonio de los Cobres (Salta, Argentina)

- 5000m a.s.l.
- Logistics + mount: Argentina
- Access road built, works started on site and in Salta city (integration hall)
Primary horns array

Window: 403.0mm - Nhorns=400

150-220 GHz, 20x20 horns, 13 deg. FWHM, D=1.2 cm

Synthesized beam used to scan the sky as with an imager

Synthesized beam (on the sky)

B.I. = Synthesized imager

Single detector beam - 400 horns
25% BW - 3 mm detectors
(including detector finite size and 30% BW)

8.5 deg.

FWHM 23.5 arcmin

[Interestingly close to an analogic and polarization sensitive version of the « Omniscope » discussed in 2009 by Tegmark & Zaldarriaga]
Profile of a point source on a reconstructed map

- 23.5 arcmin FWHM
- 1st replication: nothing remains in map!
Systematics: Self-Calibration

- Unique possibility to handle systematic errors
  - Use horn array redundancy to calibrate systematics
    - In a perfect instrument redundant baselines should see the same signal
    - Differences due to systematics
    - Allow to fit systematics with an external source on the field
  - Unique specificity of Bolometric Interferometry!


Redundant baselines: same Fourier Mode

Calibration Source (APC/Paris)
- Installation on-going at APC
- Simulations done by Maynooth & Roma

Calib. Source sweeping at 150 & 220 GHz

Expected signal (r=0.05)

Initial E→B leakage

Residual E→B leakage

Self-Calibration
QUBIC is a Synthesized Spectro-Imager

- **Synthesized beam:**
  ★ Depends on horns configuration
  ★ AND on frequency!
    - ex: a point source emitting at 140 and 160 GHz

- There is spatial + frequency information!

- **Multi-frequency map-making with the same TOD**
  ★ Spectral resolution $\Delta \nu/\nu \sim 0.05$
  ★ Shown to be quasi-optimal with simulations
  ★ article being finalized

\[
\text{TOD} = \sum \text{tod}(\nu_i)
\]

Output: N broadband frequency maps
Data Analysis more complex but richer than with a classical imager

- Complex shape of synthesized beam
- Frequency dependence of synthesized beam
- Map-making more complex
- Spectro-Imaging
- CPU...
- Foregrounds!
Ex: Split one QUBIC band into two sub-bands ($\Delta v/v \sim 0.125$)
Noise penalty for Spectro-Imaging?

\[ \frac{RMS(maps)}{\sqrt{N_{freq}}} \]

- **Correlation Matrix for 4 sub-frequencies**

  Significant gain expected for foreground removal:
  - More frequency resolution
  - Frequency-localized foreground constraints (less sensitive to extrapolations with simplistic models)

**Optimal Spectro-Imager**

- **non-optimality \( \leq 10\% \)**

**Graph:**
- **Noise increase on maps**
- **Number of sub-frequencies**
- **Optimal \( \sqrt{N} \)**
- **Q**
- **U**
QUBIC Spectro-Imaging

Sky:
« Infinite # bands »

Instrument:
2 wide bands

Data Analysis:
5 narrow bands

TOD(150 GHz)

TOD(220 GHz)

238 GHz

218 GHz

201 GHz

159 GHz

148 GHz

End-to-End Simulation
(no systematics)
2 years
σ(r)=0.01

=> Increased Spectral Resolution
=> Dust subtraction
=> More complex models can be constrained
[specific index varying simulations being done]
QUBIC Integration and sub-systems

Calibration support
LAL, Orsay

Switches and electronics
Milano Bicocca + APC

Mount
GEMA-CNEA, Argentina

Works in progress

Site and Integration Hall

1:128 SQUIDs+ASIC Mux
2048 TES Bolometers
(256 for TD)

Both cycled successfully inside the QUBIC cryostat

Filters, HWP, Polarizer
Cardiff

HWP 1K Box - Mirrors + alignment
Milano, Roma, APC

1K and 300mK He4 fridges
Manchester

Detection chain
APC-CSNSM-IRAP

1:128 SQUIDs+ASIC Mux
2048 TES Bolometers
(256 for TD)

APC internal

Switches and electronics
Milano Bicocca + APC

Mount
GEMA-CNEA, Argentina

Works in progress

Detection chain
APC-CSNSM-IRAP

1:128 SQUIDs+ASIC Mux
2048 TES Bolometers
(256 for TD)
QUBIC Deployment Plan

2018: at APC
- Integration and testing on the way
- Technological Demonstrator (reduced QUBIC)
  - 1/4 focal plane, 64 horns, small mirrors
- Followed by: Upgrade to full size mirrors and 400 horns

In-Lab demonstration of Bolometric Interferometry

2019: Argentina
- First Half 2019: Installation on site
- First Light Mid-2018 with ¼ focal plane

On-Sky demonstration of Bolometric Interferometry

Stage III
$\sigma(r) = 0.01$

2019: Argentina
- Upgrade to QUBIC 1st module (2 focal planes 150 and 220 GHz)
- Data taking: 2-3 years $\sigma(r)=0.01$

2020-...: QUBIC evolves towards Stage-IV
- European extension of the collaboration
- Improved designs being investigated: eg/ BI tube in CMB-S4
- Excellent quality site open to development

Evolution to Stage IV
$\sigma(r) = 0.001$
Summary

★ QUBIC is a novel instrumental concept
- First Bolometric Interferometer
- Dedicated to CMB polarimetry and inflationary physics
- High sensitivity with ~2000 TES bolometers
- Optimized to handle systematics:
  - Self Calibration allowed by observing individual fringe patterns (Unique to QUBIC)
- Spectro-Imaging with two physical bands (150 / 220 GHz) and 5-10 sub-bands:
  - Foregrounds contamination control and removal with up to 10 bands (unique to QUBIC)
- Target:
  - First module (150-220 GHz): \( \sigma(r)=0.01 \) (incl. dust)
  - Stage IV evolution of QUBIC \( \sigma(r)=0.01 \) hopefully through a wider European collaboration + CMB-S4 tube(s)

★ QUBIC deployment is on the way:
- TD Integration ongoing at APC
- Calibration measurements up to 1st term 2019
- First light in Argentina mid-2019
- Upgrade to First Instrument in 2019

★ Welcome to jump-in anytime !!!
Thank you

Exciting times ahead !!!