Current status of the QUBIC experiment

C.G. Scóccola[1,2], P. Ade[3], J.G. Alberro[4], A. Almela[5], G. Amico[6], L.H. Arnaldi[7], D. Auguste[8], J. Aumont[9], S. Azzoni[10], S. Banfi[11,12], B. Bélier[13], E.S. Battistelli[6,14], A. Baù[11,12], D. Bennett[15], L. Bergé[8], J.-Ph. Bernard[9], M. Bersanelli[16,12], M.-A. Bigot-Sazy[17], J. Bonaparte[18], J. Bonis[8], E. Bunn[19], D. Burke[15], D. Buzi[6], F. Cavaliere[16,12], P. Chanial[17], C. Chapron[17], R. Charlassier[17], A.C. Cobos Cerutti[5], F. Columbro[6,14], A. Coppolecchia[6,14], G. D'Alessandro[6,14], P. de Bernardis[6,14], G. De Gasperis[20,14], M. De Leo[6,21], M. De Petris[6,14], S. Dheilly[17], C. Duca[5], L. Dumoulin[8], A. Etchegoyen[5], A. Fasciszewski[18], L.P. Ferreyro[5], D. Fracchia[5], C. Franceschet[16,12], M.M. Gamboa Lerena[1], K.M. Ganga[17], B. García[5], M.E. García Redondo[5], M. Gaspard[8], D. Gayer[15], M. Gervasi[11,12], M. Giard[9], V. Gilles[6], Y. Giraud-Heraud[17], M. Gómez Berisso[7], M. González[7], M. Gradziel[15], L. Grandsire[17], J.-Ch. Hamilton[17], M.R. Hampel[5], D. Harari[7], S. Henrot-Versillé[8], F. Incardona[16,12], E. Jules[8], J. Kaplan[17], C. Kristukat[22], L. Lamagna[6,14], S. Loucatos[17,23], T. Louis[8], B. Maffei[24], S. Marnieros[8], W. Marty[9], S. Masi[6,14], A. Mattei[14], A. May[25], M. McCulloch[25], L. Mele[6,14], D. Melo[5], A. Mennella[16,12], L. Montier[9], L. Mousset[17], L.M. Mundo[4], J.A. Murphy[15], J.D. Murphy[15], F. Nati[11,12], E. Olivieri[8], C. Oriol[8], C. O'Sullivan[15], A. Paiella[6,14], F. Pajot[9], A. Passerini[11,12], H. Pastoriza[7], A. Pelosi[14], C. Perbost[17], M. Perciballi[14], F. Pezzotta[16,12], F. Piacentini[6,14], M. Piat[17], L. Piccirillo[25], G. Pisano[3], M. Platino[5], G. Polenta[26], D. Prêle[17], R. Puddu[27], D. Rambaud[9], E. Rasztocky[28], P. Ringegni[4], G.E. Romero[28], J.M. Salum[5], A. Schillaci[29], S. Scully[15,30], S. Spinelli[11], G. Stankowiak[17], M. Stolpovskiy[17], A.D. Supanitsky[5], A. Tartari[31], J.-P. Thermeau[17], P. Timbie[32], M. Tomasi[16,12], S.A. Torchinsky[17,33], G. Tucker[34], C. Tucker[3], D. Viganò[16,12], N. Vittorio[20,14], F. Voisin[17], F. Wicek[8], M. Wright[25], M. Zannoni[11,12], A. Zullo[14]

[1] *List of affiliations at the end*

Contact / cscoccola@fcaglp.unlp.edu.ar

Resumen / El experimento Q & U Bolometric Interferomer for Cosmology (QUBIC) está diseñado para medir los modos B de polarización primordiales en el fondo cósmico de radiación, y será instalado en Alto Chorrillos, provincia de Salta, Argentina. La detección de los modos B primordiales no se ha logrado aún, no sólo por tratarse de una señal muy débil, sino también por la contaminación de señales galácticas, especialmente la emisión térmica del polvo, emitidas en las mismas frecuencias. En este trabajo resumimos el estado actual del experimento QUBIC.

Abstract / The Q & U Bolometric Interferometer for Cosmology (QUBIC) is an experiment to measure the primordial B modes polarization of the cosmic microwave background (CMB), that will be installed in Alto Chorrillos, province of Salta, Argentina. The detection of the primordial B modes has not been achieved yet, not only because it is an extremely faint signal, but also because of contamination by foregrounds that emit at the same frequencies, most noticeably the galactic thermal dust emission. In this work, we summarize the current status of the QUBIC experiment.

Keywords / cosmic background radiation — cosmological parameters — cosmology: observations

1. Introduction

Within the standard cosmological model, the inflationary paradigm came to solve many of the problems of the Big Bang model, namely, the large scale homogeneity, the flatness problem, and most importantly, the origin of cosmic structure. However, this inflationary period occurs at the very beginning in the history of our universe, and remains unreachable to observations. Inflationary models predict the existence of tensor fluctuations (primordial gravitational waves) that leave a particular pattern in the polarization of the cosmic microwave background (CMB) called the B-mode polarization. This weak signal, expected to be of the order of a few tens of nK, has not been detected yet. Its measurement will constitute the first indirect observation of the inflationary epoch.

The quest to measure the B-mode polarization in the CMB has been undertaken by many ongoing experiments, among which we mention SPTPol (Sayre et al., 2019), POLARBEAR (Ade et al., 2014), ACTPol (Louis et al., 2017), and BICEP2 (Ade et al., 2018). Planned experiments include CLASS (Dahal et al., 2020), POLARBEAR 2 + Simons Array (Suzuki et al., 2016), Simons Observatory (Ade et al., 2019), advanced ACT (Henderson et al., 2016), PIPER (Gandilo et al., 2016), upgrade of the BICEP3/Keck array (Grayson et al., 2016), LSPE (Addamo et al., 2020), CMB-

S4 (Abazajian et al., 2019) and LiteBird (Suzuki et al., 2018; Hazumi et al., 2019).

QUBIC is an experiment that aims at measuring the B-mode polarization in the CMB. Its novel infrastructure of a bolometric interferometer allows for a high sensitivity and an exquisite control of systematic effects (Mennella et al., 2019). The main features of QUBIC, that distinguish it from a traditional imager are:

- Scanning of the sky with a synthesized beam which is the result of the interefometric pattern produced by an array of horns. The synthesized beam has a series of nearly gaussian peaks, and an angular resolution of $\approx 23.5'$ at 150 GHz.
- The angular separation between the main and secondary peaks is of $\approx 8.8°$ at 150 GHz. This separation varies as a function of frequency within the broad bandwidth, allowing the reconstruction of maps at different subfrequencies within the physical band, using spectro-imaging.
- The polarization grid is located before any optical component (except the half-wave plate (HWP) and the filters), and the sensors measure the full power. Hence, QUBIC is insensitive to cross-polarization within the instrument.

The QUBIC full instrument (FI) will work in two frequency bands: 150 GHz and 220 GHz. A smaller version of the instrument, called the technological demonstrator (TD) operates at 150 GHz with a smaller horns array and a smaller focal plane. The TD has been characterized in the lab, and it will be shipped to Argentina in the following months, to operate at the observation site, while the FI is constructed.

In the following, we briefly present the main results that have been obtained recently by the QUBIC collaboration, and that have been described in detail in the following publications. In Hamilton et al. (2020), a general overview of the experiment and the scientific case is presented. A description of the spectro-imaging capabilities of QUBIC is presented in Mousset et al. (2020). In Torchinsky et al. (2020), we describe the TD QUBIC prototype, and its characterization in the lab. In Piat et al. (2021), we study the performance of the TES bolometers and the readout electronics. The criogenic system is described in Masi et al. (2020). The design and performance of the half wave plate rotator is reported in D'Alessandro et al. (2020), while Cavaliere et al. (2020) describe the feedhorn-switches system, and O'Sullivan et al. (2020) focuses on the optical design and performance.

2. Main results

The signal of the B-modes polarization of the CMB is expected to be very weak, highly contaminated by astrophysical foregrounds, and subject to instrumental systematic effects. To carefully account for these effects, it is important to have observations at many frequencies. QUBIC properly addresses these observational issues thanks to its unique capability to control systematic effects due to its interferometric nature, and the high sensitivity enabled by the bolometric detectors. Moreover, the QUBIC synthesized beam has a frequency-dependent shape that enables to produce CMB polarization maps in different sub-bands within the two broadbands of the instrument (150 and 220 GHz). This feature facilitates the removal of galactic foregrounds.

2.1. The QUBIC site

QUBIC will be installed in Alto Chorillos (24°11′11.7″ S; 66°28′40.8″ W, altitude of 4869 m a.s.l.), near the city of San Antonio de los Cobres in the Salta Province (de Bernardis, 2018). The site will also host the LLAMA 12 m antenna*. It exhibits excellent quality sky for CMB studies: zenith optical depth at 210 GHz $\tau_{210} < 0.1$ for 50% of the time and < 0.2 for 85% of the time as well as relatively quiet atmosphere (winds < 6 m/s for 50% of the time). The average atmospheric temperature is 270 K with an average emissivity 0.081 and 0.138 at 150 and 220 GHz respectively.

Due to Pulse-Tubes-Coolers, the posible elevations will be between 30 and 70 degrees. The mount is an alt-azimuthal mount on the top of a well-adapted container. A fore-baffle at the window entrance will reject side lobes for angles larger than 20 degrees from bore-sight direction. A ground-shield will minimize the brightness contrast between the sky and the ground. The calibration source used for self-calibration (see Torchinsky et al., 2020, for details) will be installed on a 50 m-high tower placed at a distance of 50 m, being naturally in the far field of the instrument.

2.2. Scientific forecasts

In Hamilton et al. (2020), we give forecasts for typical observations and measurements. With three years of integration, and assuming perfect foreground removal and stable atmospheric conditions from the argentinian site, we can achieve a statistical sensitivity to the effective tensor-to-scalar ratio r (including primordial and foreground B-modes) of $\sigma(r) = 0.015$. Assuming the 220 GHz is used to subtract foreground contamination together with data from other surveys such as Planck 353 GHz channel, our sensitivity to primordial tensors is given by that of the 150 GHz channel alone and is $\sigma(r) = 0.021$.

2.3. Spectroimaging

Thanks to the multi-peaked nature of its synthesized beam, QUBIC is able to reconstruct sky maps in several sub-bands within the broad frequency band. This provides a powerful spectral method to discriminate between the CMB and astrophysical foregrounds. In Mousset et al. (2020), we study the reconstruction of a point source, as well as of galactic dust maps. We also characterize the frequency response of the instrument. The non-trivial shape of the synthesized beam implies a non-trivial map-making procedure, in which the final maps are computed with an iterative method.

*`https://www.llamaobservatory.org/en/`

The residual maps are correlated both spatially and in frequency. We study the noise properties of spectro-imaging, especially the correlations between sub-bands, using end-to-end simulations together with a fast noise simulator. We repeat the study for different numbers of subbands, and conclude that the spectro-imaging performance is nearly optimal up to five sub-bands.

3. Summary

The QUBIC experiment, with its novel infrastructure as a bolometric interferometer, has the high sensitivity and good control of systematics necessary to measure the B-mode polarization of the CMB. Thanks to its ability to perform spectro-imaging, it will allow the construction of CMB polarization maps at many frequencies, which will improve the separation of the CMB signal from that of the foregrounds.

The TD is soon to be shipped to Argentina, to be installed in its deployment site. This smaller version of the QUBIC instrument will be able to demonstrate the spectro-imaging capabilities of the instrument, and will allow the characterization of the contaminants. Meanwhile, we will advance with the construction of the full instrument. The infrastructure at San Antonio de los Cobres is already well advanced.

Acknowledgements: QUBIC is funded by the following agencies. France: ANR (Agence Nationale de la Recherche) 2012 and 2014, DIM-ACAV (Domaine d'Interet Majeur-Astronomie et Conditions d'Apparition de la Vie), Labex UnivEarthS (Université de Paris), CNRS/IN2P3 (Centre National de la Recherche Scientifique/Institut National de Physique Nucléaire et de Physique des Particules), CNRS/INSU (Centre National de la Recherche Scientifique/Institut National des Sciences de l'Univers). Italy: CNR/PNRA (Consiglio Nazionale delle Ricerche/Programma Nazionale Ricerche in Antartide) until 2016, INFN (Istituto Nazionale di Fisica Nucleare) since 2017. Argentina: MINCyT (Ministerio de Ciencia, Tecnología e Innovación), CNEA (Comisión Nacional de Energía Atómica), CONICET (Consejo Nacional de Investigaciones Científicas y Técnicas).

References

Abazajian K., et al., 2019, arXiv e-prints, arXiv:1907.04473
Addamo G., et al., 2020, arXiv preprint arXiv:2008.11049
Ade P., et al., 2014, ApJ, 794, 171
Ade P., et al., 2018, PhRvL, 121, 221301
Ade P., et al., 2019, JCAP, 2019, 056
Cavaliere F., et al., 2020, arXiv e-prints, arXiv:2008.12721
Dahal S., et al., 2020, JLTP, 1–9
D'Alessandro G., et al., 2020, arXiv e-prints, arXiv:2008.10667
de Bernardis P., 2018, BAAA, 60, 107
Gandilo N.N., et al., 2016, *Proc. SPIE, Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series*, vol. 9914, 99141J
Grayson J., et al., 2016, *Millimeter, Submillimeter, and Far-Infrared Detectors and Instrumentation for Astronomy VIII*, vol. 9914, 99140S, International Society for Optics and Photonics
Hamilton J.C., et al., 2020, arXiv e-prints, arXiv:2011.02213
Hazumi M., et al., 2019, JLTP, 194, 443
Henderson S.W., et al., 2016, JCAP, 184, 772
Louis T., et al., 2017, JCAP, 2017, 031
Masi S., et al., 2020, arXiv e-prints, arXiv:2008.10659
Mennella A., et al., 2019, Universe, 5, 42
Mousset L., et al., 2020, arXiv e-prints, arXiv:2010.15119
O'Sullivan C., et al., 2020, arXiv e-prints, arXiv:2008.10119
Piat M., et al., 2021, arXiv e-prints, arXiv:2101.06787
Sayre J., et al., 2019, arXiv preprint arXiv:1910.05748
Suzuki A., et al., 2016, JLTP, 184, 805
Suzuki A., et al., 2018, JLTP, 193, 1048
Torchinsky S., et al., 2020, arXiv e-prints, arXiv:2008.10056

List of affiliations:

[1] Facultad de Ciencias Astronómicas y Geofísicas, UNLP, Argentina
[2] Consejo Nacional de Investigaciones Científicas y Técnicas, Argentina
[3] Cardiff University, Reino Unido
[4] Grupo de Ensayos Mecánicos Aplicados, UNLP, Argentina
[5] Instituto de Tecnologías en Detección y Astropartículas, CNEA–CONICET–UNSAM, Argentina
[6] Sapienza Università di Roma, Italia
[7] Centro Atómico Bariloche e Instituto Balseiro, CNEA, Argentina
[8] Universitè Paris-Saclay, CNRS–IN2P3, Francia
[9] Institut de Recherche en Astrophysique et Planétologie, CNRS-INSU, Francia
[10] Department of Physics, University of Oxford, Reino Unido
[11] Università degli Studi di Milano-Bicocca, Italia
[12] Istituto Nazionale di Fisica Nucleare, Sezione di Milano Bicocca, Italia
[13] Centre de Nanosciences et de Nanotechnologies, Francia
[14] Istituto Nazionale di Fisica Nucleare, Sezione di Roma, Italia
[15] National University of Ireland, Irlanda
[16] Università degli studi di Milano, Italia
[17] Université de Paris, CNRS–APC, Francia
[18] Centro Atómico Constituyentes, CNEA, Argentina
[19] Richmond University, EE.UU.
[20] Università di Roma Tor Vergata, Italia
[21] Department of Physics, University of Surrey, Reino Unido
[22] Escuela de Ciencia y Tecnología, UNSAM y Centro Atómico Constituyentes, CNEA, Argentina
[23] Astroparticule et Cosmologie, CNRS–IN2P3, Francia
[24] Institut d'Astrophysique Spatiale, Université Paris-Saclay, CNRS–INSU, Francia
[25] University of Manchester, Reino Unido
[26] Italian Space Agency, Italia
[27] Pontificia Universidad Catolica de Chile, Chile
[28] Instituto Argentino de Radioastronomía, CONICET–CICPBA–UNLP, Argentina
[29] California Institute of Technology, EE.UU.
[30] Institute of Technology, Irlanda
[31] Istituto Nazionale di Fisica Nucleare, Sezione di Pisa, Italia
[32] University of Wisconsin, EE.UU.
[33] Observatoire de Paris, Université Paris Science et Lettres, Francia
[34] Brown University, EE.UU.