PhD name: Matteo Billi
PhD Cycle: XXXIV a.a. 2020/2021
Tutor: Dr. Alessandro Gruppuso

RESEARCH PROJECT:
NON STANDARD SIGNATURES FROM CMB POLARISATION

The aim of my PhD thesis is to test fundamental physics through the Cosmic Microwave Background (CMB) polarisation observations, both from a theoretical and observational point of view.
With the Planck ESA mission, CMB temperature anisotropies have been observed at the cosmic variance limit, but polarisation remains to be further investigated. The measure of CMB polarisation represents a technological challenge, since the polarised signal is much fainter than the signal in temperature, and to make accurate estimates of this signal, one has to keep an exquisite control of the systematic effects. One of the latter that I have investigated during a stay at Stockholm University is the interplay between half-wave plates non-idealities and the beams providing some forecast for forthcoming CMB experiments. CMB polarisation data are important not only because they contribute to provide tighter constraints of cosmological parameters but also because they allow the investigation of physical processes that would be precluded if just the CMB temperature map were considered. In particular, my research has been focused on non-standard signatures from CMB polarisation, which might hint at the existence of new phenomena beyond the ΛCDM cosmological model and the standard model of particle physics. I took polarisation data into account to assess the statistical significance of the anomalies currently observed only in the CMB temperature map and to constrain the Cosmic Birefringence (CB) effect, which is expected in parity-violating extensions of the standard electromagnetism.

1.1 CMB anomalies

The so-called CMB anomalies are unexpected features observed at large angular scale in the CMB map (above a few degrees), observed by the WMAP and Planck satellites, that deviate from the cosmological model ΛCDM with a statistical significance typically around 2-3 sigma C.L.. My research in this field has been focused on the lack of power anomaly: the CMB temperature anisotropy pattern exhibits less power with respect to that foreseen by ΛCDM model. An early fast-roll phase of the inflaton could naturally explain such a lack of power: this anomaly might then witness a new cosmological phase before the standard inflationary era. However, with only the observations based on the CMB temperature map its statistical significance is currently not strong enough to support that. In our work (Billi et al, PDU 2020) we revisit the former statement by also considering polarisation data. To this aim, we propose a new one-dimensional estimator capable of taking both temperature and polarisation into account jointly. By employing this estimator on Planck 2015 low-ℓ data, we find that the probability that a random ΛCDM realisation is statistically accepted decreases by a factor of two when the polarisation is taken into account, even though with this dataset the polarisation contributes a mere 4% to the total information budget. Moreover, we have forecasted that future CMB polarised measurements, like those expected by the LiteBIRD satellite, can increase the polarisation contribution up to 6 times further. We argue that the large-scale E-mode polarisation may play an important role in analysing CMB temperature anomalies with future mission.

1.2 Cosmic Birefringence

In the last two years, I have been working on the Cosmic Birefringence, i.e. the in vacuum rotation of the linear polarisation direction of a photon during propagation. This effect is a tracer for new parity-violating physics beyond the standard model of particle physics. Different models for dark matter and dark energy introduce scalar fields φ, which can couple to the photons through a Chern-Simons term, adding new parity violating terms to the

standard electromagnetism Lagrangian. CMB is linearly polarised due to Thomson scattering and therefore it represents a good candidate to perform these investigations. This rotation mixes the Q and U Stokes parameters and consequently the E- and B-mode polarisation. CB is dubbed isotropic if the rotation angle does not depend on the direction of observation. CB is instead called anisotropic if the rotation is a function of the direction of observations. Current estimates for both isotropic and anisotropic birefringence are compatible with null effect. However, very interestingly, a recent analysis on Planck 2018 data (Minami and Komatsu, PRL 2020) provides a hint of detection for the isotropic birefringence at the level of 2.4σ. As a first contribution to this subject, I developed in detail the formalism of new fully harmonic-based estimators which are able to evaluate the power spectrum of Cosmic Birefringence rotation angle starting from the EE and BB observed angular power spectra of the CMB anisotropies. We have employed these estimators on Planck 2018 data, exploring a much wider harmonic range of CB power spectrum with Planck data (Billi et al, in preparation) with respect to what can be found in the literature at present. In addition, in collaboration with the Cosmology group of the University of Ferrara led by Prof. Paolo Natoli, we are working on a pipeline aimed at the building of CB maps at large angular scales [Bortolami et al, in preparation]. This analysis extends the paper by Gruppuso et al. JCAP 2020, along various directions, in particular providing the cross-correlation between polarised CMB and CB.

1.3 Half-wave plates (HWP) non-idealities

I have also been working on the analysis of the impact of some non-idealities coming from the half-wave plates (HWP). The latter is a polarisation modulator which may be used in forthcoming CMB missions. Non-ideal HWPs impede perfectly controlled modulation and indirectly cause spurious polarised signal of their own. I started working on the assessment and the simulations of some instrumental systematics related to the HWP when I visited Dr. Jon Gudmundsson and his group at Stockholm University (Sept-Dec 2019). The outcome of this collaboration is a study of how different HWP configurations optimised for detectors sensitive to both 95 and 150 GHz impact our ability to reconstruct primordial B-mode polarisation in the CMB. We extended the capabilities of the publicly available *beamconv* code (https://github.com/AdriJD/beamconv). To our knowledge, we produced the first time-domain simulations that include both HWP non-idealities and realistic full-sky beam convolution. With the upgraded version of *beamconv*, we were able to estimate contamination of the BB power spectrum due to the interplay between dust modelling, beam and HWP non-idealities. Our analysis suggests that certain HWP configurations, depending on the complexity of Galactic foregrounds and the beam models, significantly impacts the B-mode reconstruction fidelity and could limit the capabilities of next-generation CMB experiments. As conclusion of the PhD project, I computed a first study of the impact of non-ideal HWPs on Cosmic Birefringence, both isotropic and anisotropic, which is not fully covered in literature.

WORKSHOPS, CONFERENCES & MEETINGS

III YEAR: a.a. 2020-2021

- Attending regular Journal Club with the Cosmology group of the University of Ferrara led by Prof. Paolo Natoli. **Presented papers**: *George Efstathiou 2021, Heather Prince and Jo Dunkley 2021, Namikawa 2021, Tsiapi 2021, Klimenko 2021, Cahn 2021.*
- Regular weekly meeting with the Cosmology group of the University of Ferrara.
- Regular monthly meeting with the Dr. Gudmundsson's group and the Prof. Komatsu's group.
- 6-9 September 2021 – 11th Young Researcher Meeting 2021. **Presented talk:** "New estimators for anisotropic birefringence from CMB observations".
- 13 May 2021 – Weekly PhD Seminars. **Presented talk:** "New estimators for anisotropic birefringence from CMB observations".
- 13 April 2021 – Astrophysics Talk organized by INAF OAS Bologna. **Presented talk:** "New estimators for anisotropic birefringence from CMB observations".
- 8 March-12 March 2021 – Attended the virtual meeting: "CMB-S4 spring 2021 collaboration meeting".
- 18-20 November 2020 – Attended the virtual conference: "BeyondPlanck release conference"

II YEAR: a.a. 2019-2020

- May-July 2020, Online seminars – Virtual seminars series on multimessenger astronomy; organized by the CRC "Neutrinos and Dark Matter in Astro and Particle Physics" .
- 22-26 June 2020, Online conference – ESO Conference: H0 "Assessing Uncertainties in Hubble's Constant Across the Universe".
- 30 March – 2 April 2020 Online meeting – Virtual meeting: "CMB-S4 spring 2020 collaboration meeting".
- 28 January 2020, Ferrara – Seminar at University of Ferrara: "Precision cosmology with CMB lensing, delensing and cross-correlation with galaxy surveys".
- 13 December 2019, Stockholm – Lecture at Stockholm University, OKC Auditorium Albanova: "P. James Peebles", held by Nobel Prize in Physics 2019 James Peebles.
- 21 November 2019, Stockholm – Conference at Stockholm University, OKC Auditorium Albanova: "New ideas for Dark Matter", held by Lisa Randal.

I YEAR: a.a. 2018-2019

- 04 March 2019 Milano – Workshop at University of Milano: "4th ASI/COSMOS Workshop: Ground-based CMB experiments".
- 11 June 2019 Ferrara – Workshop at University of Ferrara: "The Hubble constant day".

PhD SCHOOLS

III YEAR: a.a. 2020-2021

- April 2021, online – Attended the online CMB Data School: **"ACT Data School".**
- February 2021, online – Attended the SIGRAV International School 2021: "**Gravity of Compact Astrophysical Objects and Gravitational Waves**".

II YEAR: a.a. 2019-2020

- 3-7 February 2020, Vietri sul Mare, Salerno(Italy) – "**SIGRAV International School 2020 Gravity: General Relativity and beyond. Astrophysics, Cosmology and Gravitational Waves**".

I YEAR: a.a. 2018-2019

- 10-14 December 2018, Passo del Tonale, Italy – 12th Tonale Winter School in Cosmology 2018: "**Theory for Observers & Observations for Theorists**".
- 11-19 March 2019, Galilelo Galileo Institute (GGI) , Arcetri(FI), Italy - 2019 GGI Postgraduate School: '**Theoretical Aspects of Astroparticle Physics, Cosmology and Gravitation**'

INTERNAL COURSES

III YEAR: a.a. 2020-2021

- 5-14 May 2021 – Attending the online Ph.D. course on: " **Writing, talking and presenting Science**", organized by Department of Physics and Astronomy of the University of Bologna for the Ph.D. students in Astrophysics.

II YEAR: a.a. 2019-2020

- 17–22 September 2020 Bologna, Italy – Online PhD course on: " **Gaia: Great advances in Astrophysics**".

I YEAR: a.a. 2018-2019

- 17–25 June 2019 Bologna, Italy – " **Statistics for Astrophysics"** held by Prof. Ben Metcalf.

RESEARCH PERIOD ABROAD: **15 September–15 December 2019**

Visiting student at Stockholm University, Stockholm. Research collaboration with Dr. Jon Gudmundsson to develop and test algorithms that describe systematics associated with a particular class of polarisation modulators, called half-wave plates (HWP), generelly used in Cosmic Microwave Background (CMB) radiation experiments as LiteBIRD satellite.

ISA LECTURES

- 4 November 2021 - “Towards systemic modeling of goal-directedness”
- 23 March 2021 - “Mathematics that counts”
- 16 March 2021 - “How Tragedy Can Heal Society: The Oresteia as Political Therapy”
- 19 January 2021 - “Extreme events: how to describe and predict them using mathematical theories”
- 7 May 2019 - “You have to be cool to go to Mars”.
- 13 November 2018 - “ A heart attack: can we re-wire the heart?”.

OTHER RELEVANT ACTIVITIES

III YEAR: a.a. 2020-2021

- **Public competition win:**
  Postdoctoral fellowship for the year 2022 (from April to December) at the Instituto de Física de Cantabria (IFCA), Santender (Spain), founded by the italian “Angelo Della Riccia” foundation (http://theory.fi.infn.it/casalbuoni/dellariccia/), to develop a project in collaboration with Observational Cosmology and Instrumentation group at the IFCA.

- **Referee activity:**
  Reviewer for Physics of the Dark Universe.

- **Teaching activities:**
  - Teaching tutor for the course 'Physics Education Laboratory, Module 3', a.a.2021-22 (second semester) in the Master's Degree in Physics at the University of Bologna .
  - Teaching tutor for the course 'Mathematical Analysis 1, Module 1’, a.a.2021-22 (first semester) in the Bachelor's Degree in Astronomy at the University of Bologna.
  - Teaching tutor for the course 'Physics Education Laboratory, Module 1', a.a. 2020-21 in the Master's Degree in Physics at the University of Bologna.
  - Tutor for the 2021 summer stage at University of Ferrara: ‘Stage estivi a UNIFE: laboratori e seminari per studenti di scuola secondaria superiore’.

- **Other courses:**
  - September – November 2021 – ‘CLA Academics: Academic English Skills (AcES)’. Provided by ‘CENTRO LINGUISTICO DI ATENEO – CLA’.
  - Sept-Dec 2020 Università di Ferrara – Online PhD course (16 hours) on: “Introduction to theoretical cosmology with examples of data analysis” held by Dr. Alessandro Gruppuso.

II YEAR: a.a. 2020-2021

- Febraury – May 2020, Università di Bologna – Course 90569, LM in Astrofisica e Cosmologia (48 hours, 6CFU) - “High performance computing for astrophysics and cosmology”, held by prof. Marco Baldi.

PUBBLICATIONS

[1] **M. Billi**, A. Gruppuso, N. Mandolesi, L. Moscardini, P. Natoli.
"Polarisation as a tracer of CMB anomalies: Planck results and future forecasts".
Physics of the Dark Universe, Volume 26, December 2019, 100327,
doi:10.1016/j.dark.2019.100327, [arXiv:1901.04762 [astro-ph.CO]]

[2] A. Duivenvoorden, A. Adler, **M. Billi**, N. Dachlythra, J. Gudmundsson.
"Probing frequency-dependent half-wave plate systematics for CMB experiments with full-sky beam convolution simulations"
Monthly Notices of the Royal Astronomical Society, Volume 502, Issue 3, April 2021, Pages 4526–4539, doi:10.1093/mnras/stab317,
[arXiv:2012.10437 [astro-ph.CO]]

[3] **M. Billi,** M. Bortolami, A. Gruppuso, P. Natoli, L. Pagano.
"New estimators for anisotropic birefringence from CMB observations: the formalism and the application to Planck 2018 data."
In preparation.

[4] M. Bortolami, **M. Billi**, A. Gruppuso, P. Natoli, L. Pagano.
"Constraints on anisotropic birefringence and its cross-correlation with CMB".
In preparation.