Alessandro Granelli

Curriculum Vitae

Date, place of birth and nationality: 29/09/1994, Arezzo (AR), Italy
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Current position: Ph.D. in Astroparticle Physics at SISSA, Trieste, Italy
Interests: Astroparticle Physics, Neutrino Physics and Phenomenology, Leptogenesis, Dark Matter

Research Experience

01/2023 - 03/2023: **Visitor researcher** at the **Kavli** Institute for the Physics and Mathematics of the Universe (**IPMU**) - University of Tokyo, located in Kashiwa, Chiba, Japan, for a two-month in person scientific collaboration funded by the European Union's Horizon Europe research and innovation programme under the Marie Skłodowska-Curie Staff Exchange grant agreement No 101086085 - **ASYMMETRY**.

11/2022 - present: **Postdoctoral researcher** in theoretical and particle physics at the Department of Physics and Astronomy (**DIFA**) of the **University of Bologna**, Italy.

Education

10/2018-09/2022: **Ph.D. in Astroparticle Physics** awarded **cum laude** at the **International School for Advanced Studies (SISSA)**, Trieste, Italy, worked under the supervision of Prof. Serguey T. Petcov on the leptogenesis mechanism to generate the matter-antimatter asymmetry of the Universe and with Prof. Piero Ullio on dark matter phenomenology. Final thesis entitled "*Aspects of Leptogenesis Scenarios at Grand Unification and Sub-TeV Scales and Their Possible Low-Energy Tests*".

09/2013-11/2019: **Scholarship** for a five years study at the **Galileian School of Higher Education (SGSS)**, Padua, Italy, in the class of **Natural Sciences**.

- 8$^{\text{th}}$ ranked in the national competition for the class of natural sciences. Only 14 students admitted. The selection consisted on two written exams (general knowledge of scientific subjects and chemistry) and two oral examinations (chemistry and physics).
- Very demanding requirements carried out during each year: attendance to seminaries and internal courses, additional to the regular ones provided by the University, with final examinations; average score of at least 27/30 and no less than 24/30 in every single exam (regular and internal).
- *Relevant internal courses:* complements of analysis, complements of algebra, introduction to non-linear partial differential equations, group theory, measure theory, fluid dynamics, open problems in the physics of fundamental interactions, measurements instruments and techniques, complements of quantum mechanics, introduction to string theory, dynamical foundations of statistical mechanics.
- The scholarship ended with a final research project, discussed in front of a commission one year after obtaining the master degree. My final thesis, entitled "*Baryogenesis via Leptogensis*" and supervised by the external Prof. Serguey T. Petcov (SISSA), consisted on a preliminary study on leptogenesis, the main subject of my Ph.D. project.

10/2016-10/2018: **MSc in Physics** awarded with grade **110/110 (cum laude)** from University of Padua, Italy. Final research project with Prof. Francesco D'Eramo entitled "*A novel dark matter mechanism to produce X-ray lines with unique morphology and spectrum*".

09/2013-09/2016: **BSc in Physics** awarded with grade **110/110** from University of Padua, Italy. Final dissertation prepared with Prof. Nicola Bartolo entitled "*Effects of inhomogeneities in the Universe on the propagation of gravitational waves*".

09/2008-07/2013: High-School Diploma, Liceo F. Redi, Arezzo (Italy), in an experimental program named Brocca Scientifico, with great emphasis on physics, mathematics, chemistry and biology. Final Grade 100/100.

Short-term schools

07/01/2020-24/01/2020: Attended the GGI school on Theory of Fundamental Interactions held at the Galileo Galilei Institute (GGI) in Florence, Italy.

17/06/2018-29/06/2018: Attended the Summer School on Cosmology held at the Abdus Salam International Center for Theoretical Physics (ICTP) in Trieste, Italy.

Conferences, Meetings and Seminars

18/07/2022 - 22/07/2022: Participated to the **14th Conference on the Identification of Dark Matter (IDM2022)** in Vienna, Austria, and gave a talk on *Blazar-Boosted Dark Matter*.

06/07/2022 - 13/07/2022: Participated to the **XLI International Conference of High Energy Physics (ICHEP 2022)** in Bologna, Italy, and gave a talk on *Blazar-Boosted Dark Matter*.

30/05/2022 - 04/06/2022: Participated (remotely) to the **XXX International Conference on Neutrino Physics and Astrophysics (NEUTRINO 2022)** in (virtual) Seoul, South Korea, and presented a poster entitled *Aspects of High Scale Leptogenesis with Low-Energy Leptonic CP Violation* (available at this link).

16/05/2022 - 21/05/2022: Participated (remotely) to the **7th Symposium on Neutrinos and Dark Matter in Nuclear Physics (NDM22)** in Asheville (NC), USA, and gave a talk on *Blazar-Boosted Dark Matter*.

19/03/2022 - 26/03/2022: Participated to the **56th Rencontres de Moriond (2022)** in La Thuile (Italy) at the Very High Energy Phenomena of the Universe (VHEPU) session, invited to give a talk on *Blazar-Boosted Dark Matter*.

08/09/2021 - 10/09/2021: Participated to the **Barolo Astroparticle Meeting (BAM)** hosting the *PRIN meeting* in Barolo (CN), Italy, and presented a talk on *Aspects of High Scale Leptogenesis with Low-Energy Leptonic CP Violation*.

26/08/2021 - 03/09/2021: Participated to the **17th International Conference on Topics in Astroparticle and Underground Physics (TAUP 2021)**, hosted by IFIC Valencia and held online, and presented the talk entitled: *Aspects of High Scale Leptogenesis with Low-Energy Leptonic CP Violation*.

Working Experiences and Other Activities

Student Representative

24/03/2020-24/03/2022: Representative of the Ph.D. students in Astroparticle Physics (APP) at SISSA. The activity consists on taking part to meetings with professors of the APP area, as well as with the other students' representatives of the school (Students' Council). Some important roles of a student representative at SISSA are:

- Ensuring high-quality learning experiences at SISSA (hands on teaching/courses improvement).
- Assisting students of the relevant area and reporting eventual problems to Professors (effective communication at different levels).
- Understanding school departments policies, related to academic and student support.
- Communicating new ideas and concepts within the Student Council and other higher-level committees and bodies (requires public speaking, negotiating, effective communication skills).
- Being an active part of the SISSA community (networking, collegiality, teamwork).

Academic Tutoring

Selected as a tutor, on the base of merit, teaching skills and attitudes, evaluated with oral examinations and written exams, in different subjects for the first-year students of Information Engineering at the University of Padua.

- *09/2017-01/2018:* (Math4U project) 72h of complementary lessons in Analysis I, preparing the students to the written exam with exercises in class and assisting them via mail.
- *02/2018-06/2018:* 50h of tutoring for the course of Linear Algebra and 30h for Physics: exercises in class.

Proofreader

06/2019-09/2019: Worked for Zanichelli to correct the exercises of a book of Physics intended for high-school students.

Programming Skills

Programming Languages and Computational Softwares: Python, Mathematica, R (and RStudio), C++.

Language Skills

English: Fluent (C1 TAL level reading and listening, B2 TAL level speaking and writing, CLA, University of Padua).

Italian: Mother tongue.

Spanish: Basic knowledge.

Other Interests

Music: Lead singer, guitarist and lyricist in the italian progressive rock band named Tacita Intesa. Recorded two albums: the first one self-titled released on 1st June 2014; the second one, named FARO, published on November 2018. Few hundreds of CDs sold in Italy and abroad, especially in Japan, where we toured for two concerts in Osaka and Tokyo, in October 2019. This activity requires lot of creativity and organization abilities, as much as public speaking and communication skills.

Sports: Tennis player since the age of 6. Amatorial fencer (weapon: épée). Regular runner.

List of Publications

[1] A. Granelli, K. Moffat, Y. F. Perez-Gonzalez, H. Schulz and J. Turner, *ULYSSES: Universal LeptogeneSiS Equation Solver*, *Computer Physics Communications* **262** (2021) 107813, [arXiv:2007.09150].

[2] A. Granelli, K. Moffat and S. T. Petcov, *Flavoured Resonant Leptogenesis at Sub-TeV Scales*, *Nuclear Physics B* **973** (2021) 115597, [arXiv:2009.03166].

[3] A. Granelli, K. Moffat and S. T. Petcov, *Aspects of High Scale Leptogenesis with Low-Energy Leptonic CP Violation*, *Journal of High Energy Physics* **11** (2021) 149, [arXiv:2107.02079].

[4] J.-W. Wang, A. Granelli and P. Ullio, *Direct Detection Constraints on Blazar-Boosted Dark Matter*, *Physical Review Letters* **128** (2022) 221104, [arXiv:2111.13644].

[5] A. Granelli, P. Ullio, and J.-W. Wang, *Blazar-Boosted Dark Matter at Super-Kamiokande*, *Journal of Cosmology and Astroparticle Physics* **07** (2021) 013, [arXiv:2202.07598].

[6] A. Granelli, J. Klarić and S. T. Petcov, *Tests of Low-Scale Leptogenesis in Charged Lepton Flavour Violation Experiments*, *Physics Letters B* **837** (2023) 137643, [arXiv:2206.04342].

Research Statement

Astroparticle Physics is by definition a wide field of research, being interdisciplinary between Cosmology, Astrophysics and Particle Physics. Because of the natural broadness of the subject, astroparticle physicists are often required to be versatile and to have theoretical expertise to asses fundamental problems, as well as phenomenological model-builder minds to connect with up-to-date experiments. Moreover, programming skills to tackle numerical systems of equations and data analysis abilities to deal with experimental data sets typically characterize the tools-kit of a researcher in astroparticle physics. These are in general the capabilities that I have been learning during my Ph.D. activity at SISSA.

The first part of my Ph.D. project has been supervised by Prof. Serguey T. Petcov and focused on the leptogenesis mechanism to generate the present Baryon Asymmetry of the Universe (BAU). A fascinating version of leptogenesis is the one based on the type-I seesaw model, which basically consists of adding to the Standard Model of particle physics at least two right-handed neutrinos with a Majorana mass term, or, equivalently, heavy Majorana neutrinos, that couple to the left-handed lepton doublet and Higgs field via Yukawa interaction. Notably, the type-I seesaw model can account both for the generation of the active neutrino small masses and the present BAU (eventually, the lightest RH neutrino could also be a viable dark matter candidate). The scenario of leptogenesis within the type-I seesaw model is the one I have been working on with Prof. Petcov.

Although much effort has been put already by the scientific community to study the subject over the past 35 years, leptogenesis still remains an active and rich field of research. The reason for this is that it deals with a broad energy range from the sub-GeV to the Grand Unification Theories scales ($\sim 10^{16}$ GeV) and many different effects (e.g. thermal effects, flavour effects, spectator processes, neutrino oscillations) have to be taken into account depending on the considered scale. One common aspect of the different leptogenesis scenarios is the need to solve complicated sets of differential equations (e.g. Boltzmann equations, density matrix equations) which may be numerically demanding when many effects are included in the analysis. In relation to this point, during the second year of my Ph.D. I have entered an already-going project with K. Moffat, Y. F. Perez-Gonzalez, H. Schulz and J. Turner and helped finalising a Python package named `ULYSSES` (*Universal LeptogeneSiS Equation Solver*) that computes the baryon asymmetry produced from leptogenesis within the type-I seesaw model solving semi-classical Boltzmann equations. The emphasis of the code, which, by the way, is the first publicly available package for the task, is on its user flexibility and rapid evaluation. A paper on the code [1] was published online in Computer Physics Communication by the end of

2020 and `ULYSSES` has already been cited and used in many leptogenesis-related works, including my other projects. Major updates and further implementations of the `ULYSSES` code are currently under development.

Leptogenesis typically necessitates relatively large heavy Majorana neutrino masses and remains difficult to test at laboratories. However, there are certain very intriguing versions in which it can connect to low-energy observables. A possibility is when the required CP-violation is provided only by the Dirac and/or Majorana phases of the Pontecorvo-Maki-Nakagawa-Sakata (PMNS) neutrino mixing matrix. This possibility has been explored in the literature already. However, in the extensive study presented in [3], I have analyzed (together with K. Moffat and S. T. Petcov) in greater detail such scenario in the case of a strong hierarchy in the heavy neutrino mass spectrum, covering a wide range of mass scales (from 10^8 to 10^{14} GeV). We have considered the quantum Density Matrix Equations (DMEs) and classical Boltzmann Equations (BEs) and compared their different predictions in the various flavour regimes of the early Universe. The classical BEs do not include the quantum flavour decoherence contributions and can be regarded as limiting cases of the DMEs, which instead do account for these quantum effects. Consequently, the BEs can be valid only in ranges of temperatures for which either none, one or all the lepton flavours are fully decoherent, while the DMEs can correctly describe the 1-to-2 and 2-to-3 flavour transitional regimes. We have found that the quantum flavour decoherence effects accounted for in the formalism of DMEs can play a dominant role in the generation of the BAU in the whole considered mass range, while the BEs may fail to describe the BAU generation in many cases. More precisely, when the CP-violation is provided solely by the PMNS phases, the BEs do not predict any baryon asymmetry in the single-flavour regime for masses above 10^{12} GeV. On the contrary, the DMEs successfully predict the present BAU even in this scenario. We have found that the DMEs predictions can strongly differ from the BEs ones even in the 2-flavour regime. Moreover, the sign of the solution to the DMEs depends on the mass scale of leptogenesis in the sense that, for a given set of parameters, the predicted BAU can have different signs in the different flavour regimes. This led us to discover important consequences in terms of ranges of mass scales and values of the PMNS phases for having successful leptogenesis in the cases of normal and inverted hierarchical neutrino mass spectrum. The most remarkable one is that, when the CP-violation is only due to the Dirac phase δ, there is a one-to-one correspondence between the sign of $\sin\delta$ and the sign of the BAU in the regions of viable leptogenesis. This result could not have been found in the classical BEs formalism. Excitingly, future low-energy neutrino experimental data on PMNS phases can support or severely constrain the corresponding leptogenesis parameter spaces of the cases studied in our work.

If the leptogenesis scale is lowered, say, below tens of TeV, it becomes compatible with the energy reach of direct searches at colliders and one could possibly have hints of leptogenesis by detecting signatures of the presence of heavy Majorana neutrinos at terrestrial experiments. In the scenario of resonant leptogenesis, two heavy Majorana neutrinos are separated in mass by a tiny mass splitting and the generation of the observed BAU is compatible with masses even smaller than the electroweak scale. Their decays into Higgs bosons and leptons, as well as the corresponding Higgs bosons decays into heavy Majorana neutrinos and leptons that can be allowed kinematically due to thermal masses, may still provide the right amount of CP-violation to produce the present BAU through leptogenesis. I have investigated in [2] (together with K. Moffat and S. T. Petcov) the framework of "Freeze-In" and "Freeze-Out" resonant leptogenesis within the type-I seesaw model below the electroweak scale. We have performed the study using the formalism of the Boltzmann equations, including flavour and thermal effects. Including thermal effects in the analysis, in particular, was technically rather challenging. We have shown that it is possible to reproduce the present BAU for masses of the heavy Majorana neutrinos in the range $0.3 - 100$ GeV by relying only on the heavy neutrino and Higgs decay mechanism, which by the way dominates over the mechanism of heavy Majorana neutrino oscillations for masses above ~ 50 GeV. More importantly, we have demonstrated that such scenario is compatible with values of the charged and neutral current couplings of the heavy Majorana neutrinos in the weak interaction Lagrangian that can be tested, e.g., at the future FCC-ee facility. This opens up the exciting possibility of validating or falsifying the considered leptogenesis scenarios in future low-energy experiments.

When resonant leptogenesis is considered with three quasi-degenerate in mass heavy Majorana neutrinos, within the formalism of density matrix equations and, in particular, with both the heavy Majorana neutrino oscillation and decay mechanisms taken into account. In this context, the parameter space of viable leptogenesis for masses in the range $(0.05 - 5 \times 10^5)$ GeV enlarges considerably, becoming compatible with heavy Majorana neutrino couplings to the SM that are large enough to be accessible to direct searches at the LHC, as well as in fixed target experiments and future colliders. In [6], I have demonstrated (together with J. Klarić and S. T. Petcov) that currently running and planned experiments on charged lepton flavour violating processes with muons $\mu^{\pm}$, specifically MEG II on $\mu \to e\gamma$ decay, Mu3e on $\mu \to eee$ decay, Mu2e and COMET on $\mu - e$ conversion in aluminium and PRISM/PRIME on $\mu - e$ conversion in titanium, can test significant region of the viable leptogenesis parameter space with three quasi-degenerate in mass heavy Majorana neutrinos and may potentially establish, within the next coming years, the first hint of such low-scale leptogenesis scenario.

During the last year of my Ph.D activity at SISSA, I have also started to work (together with Post-doc. Jin-Wei Wang and Prof. Piero Ullio) on dark matter (DM) phenomenology. We have investigated in [4, 5] the possibility that protons and electrons in the highly-relativistic jets of blazars (e.g. from TXS 0506+056, which has also been claimed to be the first point source of high-energy astrophysical neutrinos detected by IceCube) can hit DM particles in the vicinity of the source and boost them to Earth. We have found the the flux of DM boosted via this mechanism can be stronger than the one induced by galactic cosmic rays colliding with DM in the Milky Way halo and be sizeable enough to leave signals at neutrino and direct DM detectors such as XENON1T, Borexino, MiniBooNE and Super-Kamiokande. Since no signal has been detected yet at those detectors, relying on up-to-date experimental data, we have extrapolated competitive limits on DM-nucleus and DM-electron scattering cross sections for DM masses below 1 GeV, which, depending on the modelization of the source and DM profile, can improve on current limitations by orders of magnitude.

For the future, I would like to expand and enrich my knowledge and expertise in Astroparticle Physics, Neutrino Theory and Phenomenology. In particular, on the leptogenesis side, I am interested in connecting more deeply with current and future experiments. For instance, detectors such as DUNE and T2HK as well as neutrinoless double beta decay experiments can provide insights on the low-energy CP-violation in the neutrino sector. In particular, they can constraint the PMNS phases and possibly support or falsify certain leptogenesis scenarios, as the one considered by me in [3]. Can we establish a more robust connection between leptogenesis and PMNS phases, possibly also in the computationally more demanding case of three heavy Majorana neutrinos, with either strong or mild hierarchy, or in the resonant scenario? How the inclusion of different contributions from, e.g., decoherence effects, spectator processes and, at low-scales, neutrino oscillations can affect such considerations? Further improvements on the numerical code `ULYSSES` for solving the leptogenesis equations would definitely allow me to extend and refine the leptogenesis analysis, perhaps elucidating other interesting features. Besides, the type-I seesaw model is the minimal extension one can think of to explain the observed light neutrino masses and mixing scheme, but many theoretical questions, such as the emergence of three flavours and/or the light neutrino mass and mixing patterns and/or the right-handed neutrino masses (e.g. the latter can arise from a dynamical breaking of a high-scale U(1) lepton number symmetry) remain unanswered. Extending further the model to a larger theory could, at the same time, solve some of these open problems, imply gravitational wave signals (e.g., from the breaking of a U(1) symmetry) and, eventually, also connect to a dark matter sector. To me, it would be of great phenomenological interest to understand how leptogenesis can work in such extended scenarios and to establish further connections between leptogensis and low-energy observables, possibly in relation also to gravitational waves and dark matter detection. My future research plans also include studies of other classes of mechanism for the origin of the matter-antimatter asymmetry in the early Universe and models of active neutrino mass generation.

On the dark matter side, I would like to refine the analysis related to the acceleration mechanism induced by blazars that my collaborators and I have proposed in [4, 5], and in extending the discussion to the full statistical ensemble of blazars. This would allow, for instance, to get rid of the model uncertainties of our pilot study. Also, I am interested in understanding whether there exists, or it is possible to construct, a theoretical dark matter model for which the blazar-boosted signal is optimal, as well as analysing how the blazar-boosted dark matter flux could leave signatures at other class of detectors, such as, e.g., the future and planned neutrino facilities DUNE and Hyper-Kamiokande, or the fancy paleo-detectors. I am also particularly intrigued by the possibility to link the neutrino sector with dark matter, both from the theoretical and phenomenological points of view.

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