Il Colle di Galileo

Program at the Galileo Galilei Institute: "Neutrino Frontiers"

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Maria Cristina Volpe

General information

* Organizers:
  Maria Cristina Volpe (CNRS and APC Paris) – Coordinator, Francesco Vissani (INFN Italy), Olga Mena (Valencia U., IFIC)
* Emails of the organizers:
  volpe@apc.univ-paris7.fr; francesco.vissani@lngs.infn.it; omena@ific.uv.es
* Location of the program: Galileo Galilei Institute (GGI), Arcetri
* Dates of the program: June 25 to July 19, 2024
* Length of the program: 4 weeks

Abstract. The program brought together leading scientists working on key open issues and challenging questions in neutrino physics, a field notoriously rich in interdisciplinary connections, particularly astrophysics and cosmology. This is a domain where crucial progress has been made, many key open questions remain to be answered, important novel developments are ongoing and new connections with other domains are being uncovered. The program had two central goals. The first was to train PhD students and postdocs with lectures on neutrino physics, neutrino astrophysics and cosmology from internationally renowned scientists. The second was to create a collaborative and brainstorming atmosphere around key open issues and to foster our knowledge of neutrino frontiers thanks to a fruitful cross-breeding between different theoretical areas.

Keywords*:* neutrino physics, neutrino astrophysics and cosmology, neutrino experiments, neutrino properties, physics beyond the Standard Model, dense astrophysical environments like core-collapse supernovae and neutron- stars, high-energy astrophysical neutrinos.

1. Scientific context and motivation

Neutrinos can change their flavour while travelling in vacuum, a phenomenon known as neutrino oscillations. This discovery, made by the Super-Kamiokande collaboration in Japan in 1998, was a breakthrough which had an impact in particle physics, astrophysics and cosmology. Neutrino oscillations imply that neu-

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Figure 1. Picture of participants, lecturers and organizers during the training week on neutrino physics, neutrino astrophysics and cosmology, of the Neutrino Frontiers GGI Program.

trinos are massive particles and that their flavour (or interaction) and mass (or propagation) bases do not coincide and are related by a unitary matrix called the Pontecorvo-Maki-Nakagawa-Sakata (PMNS) matrix.

Since the discovery of neutrino vacuum oscillation, atmospheric, solar, reactor and accelerator experiments have precisely measured most of the oscillation parameters. Key questions remain open, namely the neutrino mass ordering and absolute mass value, the mechanism that gives neutrinos a mass, the presence of CP violation in the lepton sector and the existence of sterile neutrinos. Upcoming measurements will measure the (Dirac) CP violation phase and neutrino mass ordering, for which there are hints with a low statistical significance, and will keep searching new physics.

Progress in our knowledge of neutrino properties has gone hand in hand with advances in cosmology and in astrophysics. Interestingly, cosmological probes are sensitive to unknown neutrino properties such as the sum of neutrino masses or the existence of sterile neutrinos. In astrophysics, the solution of the solar neutrino problem identified the Mikheev-Smirnov-Wolfenstein (MSW) effect as responsible for the suppression of the high-energy solar ^{8}B neutrinos. It is to be noted that, in 2002, R. Davis (Homestake) and M. Koshiba (Kamiokande Collaboration) were the recipients of the Physics Nobel Prize with R. Giacconi (X-ray astronomy), "for pioneering contributions in astrophysics, in particular for the detection of cosmic neutrinos". In 2015, T. Kajita (SK Collaboration) and A.B. McDonald (SNO Collaboration) were recipients of the Physics Nobel Prize "for the discovery of neutrino oscillations which shows that neutrinos have a mass".

In astrophysics, the MSW effect is now a reference mechanism for studies of neutrino flavour evolution in matter and in dense environments. This has attracted a lot of interest worldwide. Indeed, understanding how neutrinos change their flavour in core-collapse supernovae or nearby compact objects (neutron star-neutron star or black hole-neutron star) is a challenging, theoretical, open problem due to the presence of sizable neutrino-neutrino interactions, shock waves and turbulence (in supernovae) and new physics, such as non-standard neutrino interactions. Their study has triggered intense investigation and challenged theorists for almost two decades, while uncovering novel connections to other domains, including condensed matter and quantum computing. Neutrino properties and flavour evolution in dense media are important for future observations of supernova neutrinos and to fully unravel how massive stars explode or for the longstanding open question of the sites where elements heavier than iron are made (*r*-process).

In this context, the interplay among experiments on Earth and, astrophysical and cosmological observations appears crucial to foster progress in the field. Moreover, thanks to the numerous experimental developments, two new windows in neutrino astrophysics could be potentially open novel observational and theoretical developments. At low neutrino energies, the Super-Kamiokande experiment with the addition of Gadolinium (running since 2020) might be close to the discovery of the diffuse supernova neutrino background formed from past core-collapse supernova explosions. Indeed, the combined analysis of the twenty-year running (without Gadolinium) has already shown a positive fluctuation over background at 1.5 sigma. On the high energy side, the launch of experiments such as KM3NET was expected.

4. Scientific activity

The scientific activity was structured around a "Training week", a "Focus week" and a "Topical Workshop". The program lasted four weeks overall. The "Training week" covered "Introductory lectures on neutrino physics", lectures on "Neutrinos in Astrophysics", "Neutrinos in cosmology", "Neutrino interactions", "Neutrinos and physics beyond the Standard Model" and lectures on "A path to discovery: neutrinos and gravitational waves" by the Nobel Laureate – Prof. Takaaki Kajita.

The key topics of the "Focus week" on *Neutrinos in cosmology, non-standard neutrino physics and neutrino anomalies* were neutrino mass from cosmology, sterile neutrinos, neutrinos and BBN, non-standard neutrino properties and cosmology, the current status on anomalies and the significant progress made in clarifying them. The "Topical workshop" on *Astrophysical neutrinos at the frontiers* lasted two weeks and focussed on CNO measurement(s) and the metallicity problem, low energy (inelastic) neutrino-nucleus cross sections and the measurements of SNS, neutrinos and gravitational waves, neutrinos and dark matter from stars,

neutrinos from stars and non-standard neutrino properties, the diffuse supernova neutrino background and its discovery, neutrino flavour evolution in dense environments and ultra-high energy neutrinos. Besides the participants' contributions of excellent quality, intense and lively discussions among the participants were triggered throughout the program by the experimental results and theoretical developments on the crucial open issues, also giving birth to new collaborations.

5. Participation and impact within the community

This interdisciplinary program brought together leading scientists and promising young researchers in neutrino physics, astrophysics and cosmology. It was enthusiastically supported by the international community. About 100 participants contributed to the program, with numerous participants staying for extended periods. It is to be noted that special attention was paid to encouraging participation by experts and promising young students from developing countries and belonging to minorities, also considering gender balance. All participants, including students, were given the opportunity to present their work.

One of the key aspects of the proposal was timing, as the suggested period between the end of June and the end of July was just after the most important international conference in the field, NEUTRINO2024. The conference location that year was in Milano. Scientifically speaking, this timing was one of the elements of the program's success. It should be noted that some participants were able to present new, eagerly-awaited and also unexpected results, which had just been announced at NEUTRINO2024.

The first analysis (with Gadolinium) on the diffuse supernova neutrino background by the Super-Kamiokande collaboration was presented, showing an increase in statistical significance at 2.3σ, which might indicate that discovery is imminent. Moreover, the KM3NET Collaboration announced the measurement of a neutrino event of the highest energy ever observed. Talks on these and many other experiments, their implications and ongoing theoretical developments generated lively discussions during the four weeks of the program, creating a fertile and brainstorming atmosphere among participants.

6. Simons Senior Fellows

Three Simons Fellow scientists contributed to the success of the program, with lectures or seminars of outstanding quality. These Simons Fellows are

- Prof. Takaaki Kajita, 2015 Physics Nobel Laureate, who shared his experience with the young generations
- Prof. James Lattimer (SUNY, Stony Brook)
- Yvonne Wong (New South Wales University).

7. Final considerations and acknowledgements

Neutrino physics continues to be a very lively domain, in which important measurements keep gathering data, new observational windows are being opened and theoretical developments foster progress at neutrino frontiers. The program was very successful at scientific level. The participants enjoyed the stimulating and fruitful scientific atmosphere, as well as the positive environment for discussion and working. The visit to Villa il Gioiello was very much appreciated.

The success of the program is also due to the financial support allocated by the GGI and the Simons Foundation. This particularly helped the presence of participants from distant and/or developing countries, of key and renowned speakers and famous scientists. The organizers are grateful to the administrative staff of the GGI for their invaluable help and assistance both before the event and during the program. It is a sincere pleasure to thank the Director of the GGI, Stefania De Curtis, and staff members Mauro Morandini, Annalisa Anichini, Mirella Ridi and Alessio Attardi.