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Neutrinos @ INFN: A leap inside the Commissione Scientifica Nazionale 2

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Summary. — INFN coordinates research in the field of astro-particle physics in Italy. Supported experimental activities include the study of cosmic radiation, the search for gravitational waves, the study of the dark universe, general and quantum physics, and the study of neutrino properties. A rich program of experiments installed on earth surface, in space and underground or underwater is supported to provide a possible answer to some of the most important open questions in particle physics, astrophysics and cosmology. In this scheme, neutrino physics plays a crucial role and is one of the research landmarks supported by INFN's National Scientific Commission II.

1. – Introduction

INFN coordinates research in the field of astro-particle physics in Italy [1], a relatively young research discipline that lies at the intersection of particle physics, astronomy and cosmology. It uses infrastructure and methods from nuclear and particle physics to detect a wide range of cosmic particles, including neutrinos, gamma rays, cosmic rays, gravitational waves, and possibly dark matter. In fact, it is often regarded as a bridge between two standard models: the particle Standard Model (SM) and the Lambda Cold Dark Matter (ΛCDM) cosmological model. Both are crowned with success in describing many processes, but in both cases there is a long list of open questions. Just to give one example, the former does not include gravity, while the latter has not yet explanation for dark matter and dark energy. Astro-particle physics assumes that these answers have a common root and strives to study the cosmic background radiation, cosmic rays, neutrinos, gravitational waves, ultra-high-energy gamma rays and other rare particles that could provide important clues to the still open questions. The possibility of observing cosmic phenomena by means of different messengers (*e.g.*, neutrinos and gravitational waves) has opened up incredibly exciting new perspectives. Indeed, the observation of

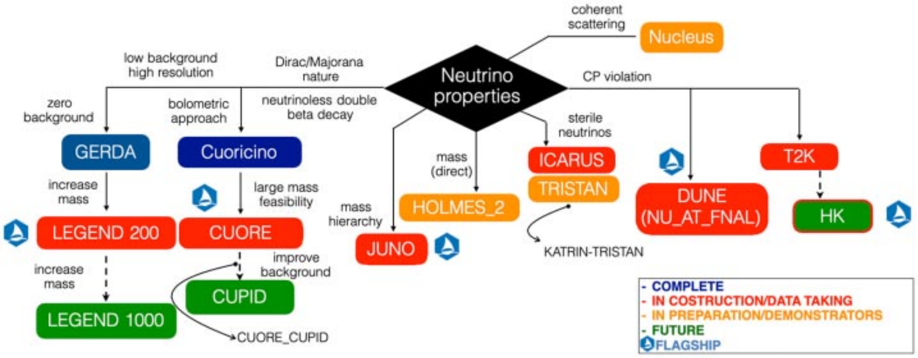


Fig. 1. – Synopsis of neutrino experiments supported by INFN CSN2.

gravitational waves continually unveils new unexpected cosmic phenomena that complement (and often trigger) observations with other cosmic messengers (*e.g.*, the entire electromagnetic spectrum). On the other hand, neutrinos have always been a key to the discovery of new phenomena not predicted or explained by the particle models of the moment, and the study of their properties is central to astro-particle physics.

INFN CSN2 Supports experimental activities on the study of cosmic radiation, the search for gravitational waves, the study of the dark universe, general and quantum physics, and the study of neutrino properties. A rich program of experiments installed on earth, in space and underground or underwater is supported to provide a possible answer to some of the most important open questions in particle physics, astrophysics and cosmology. In this scheme, neutrino physics plays a crucial role and is one of the research landmarks supported by INFN's National Scientific Commission II (CSN2 [2]).

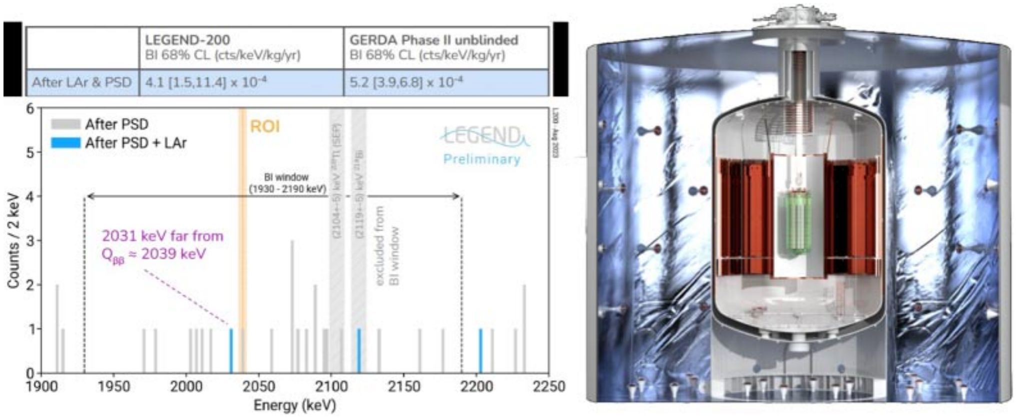
2. – Neutrino physics

Neutrinos are the most elusive particles in the Universe. Billions of them pass by the Earth every second because they interact with matter only via weak and gravitational forces. This is why it has taken decades of experimental effort to detect them and understand their characteristics. They are neutral fermions that exist in 3 different flavours, can oscillate with each other, and have non-zero mass (although very small).

However, there are fundamental properties that we still ignore: i) the exact value of their masses and their ordering among different eigenstates, ii) whether they coincide with their antiparticle (Majorana fermion), and iii) the role they played in the creation of a matter-dominated universe, There are also hints that other types of neutrinos might exist, which do not interact weakly and are therefore known as sterile. Finally, a large amount of very low-energy (10^{-6}-10^{-4} eV) relic neutrinos produced immediately after the big bang ($\sim$1 sec) should represent the analogue of cosmic microwave background radiation, but it has never been observed -so far- due to the extremely low cross section of such low energy energy neutrinos.

A worldwide effort is underway to shed light on these questions, which are considered at the forefront of particle physics.

The INFN neutrino community represents about 20% of researchers and technologists interested in astroparticle research and it absorbs an average of 35-40% of CSN2's annual regular budget. Neutrino experiments supported by CSN2 (fig.1) seek to cover as many experimental topics as possible, consistent with community size and budget constraints



	LEGEND-200 BI 68% CL (cts/keV/kg/yr)	GERDA Phase II unblinded BI 68% CL (cts/keV/kg/yr)
After LAr & PSD	4.1 [1.5,11.4] x 10^{-4}	5.2 [3.9,6.8] x 10^{-4}

Fig. 2. – Preliminary spectrum [3] (left) and scheme (right) of LEGEND-200 at LNGS.

A wide variety of experimental techniques are in use, which share a common feature: a massive detector and an extremely low background induced by cosmic rays and radioactive nuclei. The former is necessary to have a measurable signal, the latter to distinguish any possible false event that could mimic the signal and ruin the experimental sensitivity. To reduce the cosmic-ray-induced background, most experiments are placed underground, immersed in so-called cosmic silence.

2·1. *Neutrino-less double beta decay.* – More than 80 years after Majorana's description was introduced, the observation of neutrino-less double beta decay (NDBD) or sometimes known as *matter creation*) is still the only practical way to test whether it describes the true nature of neutrinos. INFN has been engaged in this experimental research since the 1960s. A long series of experiments has been devoted to this research by exploiting different detection techniques. Indeed, the use of germanium diodes and bolometers was pioneered by INFN, and the Laboratori Nazionali del Gran Sasso (LNGS) has hosted some of the most sensitive experiments (Heidelberg-Moscow, GERDA, Cuoricino) and is currently supporting the operation of CUORE and LEGEND-200 and is preparing to host their successors in the near future, supported by a broad international community. The goal of these experiments is to finally observe the hypothetical $(A, Z) \rightarrow (A, Z+2) + 2e^-$ decay that, unfortunately, has never been observed so far, with lifetime limits of this extremely rare decay exceeding 10^{26} years: about 10^{15} times the age of the Universe.

To achieve the necessary sensitivities, extremely pure environments and sophisticated techniques are indispensable. In addition to the well-known use of germanium detectors, very promising is the use of bolometric detectors, which are characterized by excellent energy resolutions and an almost free choice of the material under examination.

Based on the excellent results of GERDA, which achieved sensitivities on the order of 10^{26} years on the half-life of ^{76}Ge demonstrating that it can operate under conditions of zero background counts, CSN2 approved LEGEND-200, an experiment featuring 200 kg of Ge enriched in ^{76}Ge that by operating under improved background conditions compared to GERDA should demonstrate the feasibility of its successor, LEGEND-1000, currently under discussion to be operated at LNGS by a large international collaboration. LEGEND-200 is in data taking starting in early March 2023. The first results were first presented at the summer conferences and confirm the excellent performance of the

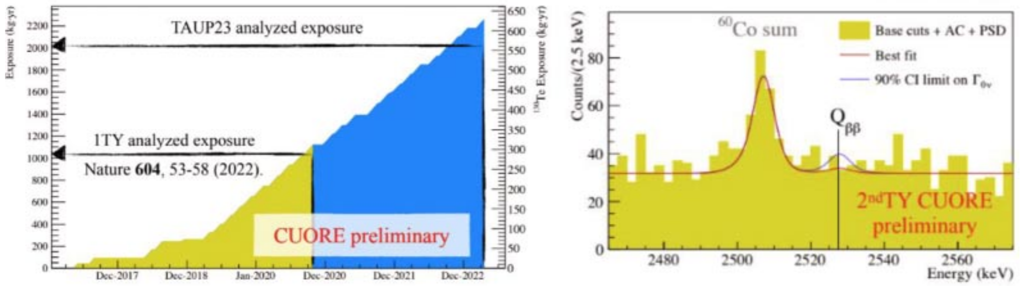


Fig. 3. – CUORE exposure (left) and spectrum (right) [3].

detectors oltra to a background compatible, given the limited statistics, with that of GERDA (fig.2). The commissioning of the experiment has taken over a year and has resulted in optimization of the germanium detector supply voltages, improved calibration sequence, study of acquisition frequency as thresholds and trigger configurations vary, etc. The plan for the near future is to collect sufficient exposure to be able to determine the background level in the region of interest with sufficient care and build an initial model of it. At the same time, the experiment is expected to achieve sensitivity on the order of 10^{27} years on the neutrino-less doble beta dacay (NDBD) half-life of the ^{76}Ge, while the collaboration will fix the details for the realization of LEGEND-1000.

The successful operation of CUORE, which has now reached an exposure of more than 2 ton·year (fig.3) and is nearing completion of its science program, has shown that stable operation of ton-sized calorimeters is possible on scales on the order of years. In fact, CUORE consists of about 750 kg of tellurite crystals in operation at LNGS since 2017 to search for NDBD of ^{130}Te. When combined with information on major background sources and the successful development of scintillation bolometers, this has paved the way for CUPID, a new proposal that aims to take advantage of CUORE's infrastructure by reducing the background contribution.

CUPID will fill CUORE's experimental volume with isotopically enriched Li^{100}MoO$_4$ scintillation bolometers after the completion of CUORE's science program. The expected sesnsitivity is on the order of 10^{27-28} years over the half-life of ^{100}Mo. The experiment was approved by CSN2 almost concurrently with the outbreak of conflict between Russia and Ukraine, which cast doubt on the hoarding of the needed isotope. After more than a year of efforts to find an alternative solution it is finally beginning to see the light, with an alternative supplier being identified.

LNGS has also hosted the operation of Borexino for about 20 years, the sensitive part of which consists of a large volume of organic scintillator to detect neutrinos arriving from the Sun or Earth to investigate their properties or other, otherwise inaccessible processes, such as those occurring in the cores of stars. Borexino has successfully unveiled details of the mechanism of energy production in the Sun, changes in the properties of neutrinos in their propagation to Earth, and the role of radioactivity in the Earth's mantle in the thermal dynamics of our planet.

After successfully operating in the Cern-to-Gran Sasso Neutrino Beam program, the ICARUS experiment, a 20-meter-long time projection chamber (760 tons in weight), was finally transferred to Fermilab (FNAL) where it is currently in operationr along the Neutrino Beam Booster to search for a possible new physics signal that could indicate the sterile neutrino.

Table I. – *Neutrino oscillation experiments supported by CSN2.*

Main goal	source	technique	experiment	By-products
θ_{23},Δm^2_{32}	Atmospheric	W. Cherenkov	KM3NeT (ORCA)	MH θ_{13}, δ_{CP}
δ_{CP}	Accelerator	W. Cherenkov	T2K-HK	θ_{23},Δm^2_{32}, θ_{13}, ν^S
δ_{CP}, ν^S, MH	Accelerator	LAr	ICARUS, DUNE	θ_{23},Δm^2_{32}, θ_{13}
ECνNS	Reactor	TES	NUCLEUS	μ_ν, q
MH, Δm^2_{21}, θ_{12}	Reactor	LS	JUNO	θ_{13}, θ_{23},Δm^2_{32}
Δm^2_{21}, θ_{12}	Solar	LS	JUNO	μ_ν, q

2˙2. *Neutrino oscillation experiments*. – The precision determination of the parameters of the Pontecorvo-Maki-Nakagawa-Sakata neutrino mixing matrix as well as of a possible parity violation related to a nonzero value of the phase factor implied in its parameterization characterizes another important CSN2 effort (tableI).

In this area, INFN is collaborating on the DUNE program, a long-running experiment starting at Fermi National Laboratory, in USA, and ending at the SURF underground laboratory (South Dakota) that aims to determine the mass order of neutrinos and measure the value of the above-mentioned phase of the neutrino mixing matrix. Based on the same technology pioneered by ICARUS, DUNE will see a strong involvement of INFN groups in the design and construction of the near detector (SAND), which will be critical in eliminating most systematic effects.

In addition to its long-standing collaboration with the T2K experiment, INFN has started participation in the HyperKamiokande (HK) program which, in addition to its goal of determining missing neutrino parameters, will feature a rich program of physics beyond the Standard Model (particularly proton decay). Approved in February 2021, HK is expected to start data taking in 2027. The excavation of the underground laboratory at Kamioka (Japan) is steadily progressing (fig.4) while a large international collaboration has started the preparation of the huge 200 kton water Cherenkov detector.

Starting in 2024, by decision of the INFN executive board, experiments such as ICARUS, DUNE and T2K that make use of accelerator-produced neutrinos will be gradually moved to CSN1, which is dedicated precisely to accelerator physics programs.

Fig. 4. – HK dome excavation at July 2023 (left) and one of the nPMT's (right).

Consisting of a 35-meter acrylic sphere filled with 20000 tons of liquid scintillator, the JUNO experiment is under advanced construction in Kaiping, China. Its main goal is to measure the mass hierarchy of neutrinos and precisely evaluate the oscillation parameters by studying neutrinos mainly from nuclear power plants at 50 km, but also neutrinos from the Sun, the Earth, the atmosphere, and neutrinos from Supernovae.

The spherical acrylic container that will contain the 20000 ton liquid scintillator is now assembled for more than half of its constituent sectors, along with the 20" photomultiplier-tubes (PMTs) and readout electronics. Problems encountered with observed fractures on the top of the canister caused a net delay of about six months but are now being resolved. The entire readout electronics and PMTs, as well as the missing sectors of the canister, are stored at the site, and all facilities for scintillator preparation and purification are ready for the test phase and the next filling phase, expected in the second half of 2024.

2˙3. *Direct mass measurements and sterile neutrinos.* – Direct (or kinematic) neutrino mass measurements are also aprart of the CSN2 science program. These measurements are particularly important because they represent the only model-independent approach to the determination of neutrino masses. So far, mass spectrometry has provided the best sensitivities, but the last experiment in the saga, KATRIN, characterized by a sensitivity of 0.2 eV, is believed to have no successor. INFN quickly recognized the importance of developing new experimental approaches, and since the 1990s has supported a series of R&D projects (MANU, MIBETA, MARE) based on the use of micro-bolometer arrays. The latest development is the HOLMES experiment, which aims to demonstrate the feasibility of a large Transition Edge Sensor (TES) based bolometer array to study the electron capture (EC) of ^{163}Ho.

The interest aroused by the experimental observation of coherent neutrino scattering has aroused particular interest in the INFN community, both for the process itself and for possible applications to the investigation of dark matter. CSN2 is contributing to this research by participating in a European program (NUCLEUS) that will start taking data in 2024 at the CHOOZ reactor.

CSN2 also supports searches for the possible existence of sterile neutrinos. In addition to the aforementioned participation in ICARUS at FNAL, a small community is making an important contribution to the development of KATRIN-TRISTAN. Currently focused on a precision measurement of the end part of the tritium spectrum with a giant spectrometer, for the determination of the mass of the electron antineutrino, the experiment aims at a second phase of measurement in which thanks to a new design of the final detector it will be possible to measure the entire spectrum of emitted electrons and thus search for a possible signal of sterile neutrinos with masses on the order of a few keV.

2˙4. *Neutrinos from the Universe.* – Although for CSN2 the observation of very high energy neutrinos from the most extreme regions and processes of the Universe belongs to the line studying cosmic radiation, it is hard not to mention it here. The experiment is called KM3NeT and consists of two sites: ORCA off the coast of Toulon of smaller size and dedicated to the study of cosmic neutrino oscillations with the aim of determining their mass hierarchy and ARCA off the coast of Capo Passero (extreme southern tip of Sicily), which aims to realize at about 3500 m depth an active volume of the size of about one km^3 for the determination of point sources of neutrino. Both sites experienced a very strong development during 2021 when, the technological problems that for years slowed down the realization of the project finally found a solution.

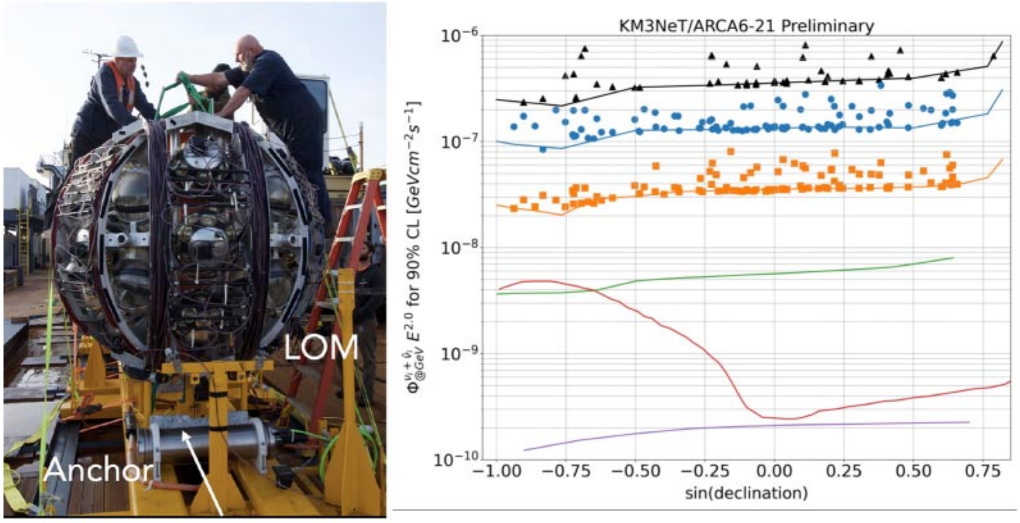


Fig. 5. – Preparation for the deployment of a string of optical modules (left). Right: detector sensitivity (lines) and observed limits (markers) to point sources with E^{-2} spectrum, as a function of declination. Black: ARCA 6 lines 92 days; blue: ARCA 6/8 lines 302 days; orange: ARCA 6/8/21 lines 424 days; green ANTARES 15 years: red IceCube 10 years; violet ARCA 320 lines 10 years (extrapolation) [4].

Since then, the preparation and deployment of strings has been proceeding steadily. Funding for the detector has also recently found significant support in the National Resilence and Recovery Plan (PNRR), funded under the Next Generation EU initiative which, in addition to ensuring the construction of 65 new strings (bringing the total number of strings funded for ARCA to 130), has also made it possible to hire the personnel needed for their construction. With these new funds, it is expected that all of ARCA's new strings can be in operation by 2027.

With the September 2023 marine campaign, the number of ARCA strings has risen to 28, but more importantly, the learning curve is showing increasing effects with fully functioning detectors and increasingly reliable procedures.

Taking advantage of the favorable location in the northern hemisphere, ARCA is expected to soon reach the expected sensitivity for studying neutrino sources in the center of the galaxy. The results presented with the first available strings already demonstrate the great potential of this instrument, which has already exceeded the sensitivity of its predecessor ANTARES and aims to match that of IceCube (fig.5).

3. – Conclusions

Interest in astro-particle physics has grown steadily in recent decades. The discovery of neutrino oscillations and the observation of gravitational waves, as well as precise measurements of CMBR radiation and increasing capabilities in detection of cosmic high-energy radiation, have initiated a huge international experimental effort that aims to provide answers to some of the most long-standing questions in particle physics and cosmology.

INFN's efforts in this field are coordinated by the Second National Scientific Committee (CSN2). The committee consists of one member from each of the INFN facilities where astro-particle physics activities are present. It implements a bottom-up approach in the selection of experiments and ensures that even younger people have access to decision-making processes. The CSN2 spans a wide range of topics from the study of cosmic radiation, to the dark universe, to gravity and neutrino physics, maintaining a balance between large, established projects and new research and development initiatives and projects. In all cases (*i.e.*, regardless of the type of project or collaboration) CNS2 provides, together with economic and administrative support, participation in the international effort by contributing with the INFN's recognised expertise in the design, development and construction of particle detectors at the cutting edge of technology. CSN2 selects and supports experiments on astro-particle physics, by a constant monitoring of the project progresses (at national level) with financial and scientific audits. The committee operates in synergy with the facilities directly managed or supported by INFN, namely LNGS and CERN, and supports the national community in international enterprises.

Following a century-old tradition - from Fermi, Majorana and Pontecorvo to Fiorini - neutrino physics is a central scientific topic at INFN's CSN2. Approximately 200 FTEs (full-time equivalents), or 20% of the researchers affiliated with CSN2, are involved in experiments aimed at studying and understanding neutrino masses, ordering and mixing, which remain the focus of CNS2-funded experimental activities. Following the scientific success of Borexino and OPERA at the LNGS, the Italian community has recently joined large-scale projects under construction (or starting up) in China (JUNO), Japan (T2K-HK) and the United States (DUNE). LNGS remains a reference laboratory for NDBD and neutrino mass measurement experiments. Meanwhile, INFN has supported the construction of the Mediterranean High Energy Neutrino Submarine Telescope, KM3NeT-ARCA; to date, the largest submarine neutrino detector and still expanding with funding from the PNRR.

The steady growth of CNS2's budget and affiliates testifies to the national scientific community's interest in astro-particle physics.

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