White paper for Neutrino Physics (Pillar 2) in Switzerland for the period 2025-2032

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for the Pillar 2 community

1 Introduction

In this white paper we summarize the current status and plans for the funding cycle 2025 to 2028, and propose recommendations for an update of the "CHIPP Roadmap for Research and Infrastructure 2029-2032 and beyond".

The strategic engagement of the Swiss groups in neutrino physics and experiments has been stable over the past decade, certainly related to the long-term nature of the experiments.

The measurement of neutrino properties at long baseline beam experiments is a very high priority for the neutrino pillar in Switzerland. The exploration of the neutrino nature with double beta decay completes fundamentally the picture of neutrino properties. Atmospheric and cosmic neutrinos also enable the study of neutrino properties (oscillations and hierarchy) and of cosmological aspects such as dark matter.

The development of innovative detectors has played a crucial role in all of these activities, besides the theoretical and phenomenological aspects of neutrino physics.

The long baseline neutrino experiments are moving into the construction phase. CERN as the European laboratory for Particle Physics, being located in Switzerland, is closely tied to the Swiss neutrino efforts and is an integral part of the global strategy by hosting the Neutrino Platform. Such program, described in the 2015 white paper (input to the funding cycle 2017-2021), prioritises the physics of neutrino oscillations, with funding planned for the R&D and the operation of experiments based on liquid argon (LAr) detectors (short- and long-baseline in the USA) and the construction of LBNF/DUNE, as well as the near detector upgrades of the T2K experiment and the construction of the Hyper-K water Cherenkov far detector in Japan. **The Swiss participation to both the DUNE and the Hyper-K long-baseline neutrino oscillation programs has since then high and equivalent priority (flagships), key to maximize the scientific reach.**

The University of Bern (UBern) group has focused on the USA-based short-baseline (SBL) and long-baseline (LBL) program with the construction of the DUNE near detector. Also, ETH Zurich (ETHZ) has contributed to the development of the LAr far detector technology. The University of Geneva (UniGe) and ETHZ primarily support the Japanese LBL program with the operation of T2K, the upgrade of the magnetised near detector (ND280) and the construction of the Hyper-K far detector. Such program has been prepared with significant funds, to be allocated to the neutrino oscillation program in the USA and in Japan in 2021-2024, making this a priority for the FLARE funding plan.
To address the nature of the neutrinos the support of neutrino-less double-beta (ν-less $\beta\beta$) decay experiments were also identified as complementary and of strategic importance.

The GERDA experiment, with a strong involvement of the University of Zurich (UZH), is since then supported for its construction, integration and operation. Its follow-up project, LEGEND-200, is acquiring science data at the INFN Gran Sasso National Laboratory (LNGS). Furthermore, neutrino experiments targeting astrophysical sources (IceCube and IceCube-Gen2) are in upgrade phase and strongly encouraged by the P5 progress and may lead to a future request for contributing to construction. The SHiP program has been meanwhile approved by CERN and its core science represents a relevant overlap of this pillar with Pillar 2 together with FASER scientific goals.

The 2020 white paper served as input to the funding cycle 2021-2024 and a major update to the CHIPP RoadMap in view of the SERI "Roadmap for 2025-2028 and beyond". The previously defined strategy was confirmed to focus on neutrino oscillation experiments in the USA and Japan, ν-less $\beta\beta$ decay experiments, along with support for the IceCube program. The neutrino program was further consolidated to start allocating significant funds for the beam-based neutrino oscillation programs, clearing technical development stages and readiness for construction. The GERDA and LEGEND experiments continue to play a fundamental role thanks to the successes and leading role of UZH. UniGe conducts the IceCube activities and consolidated it into a multi-messenger scientific program in synergy with gamma-ray telescopes, such as Fermi-LAT, the first telescope of CTAO in operation, the LST-1, and MAGIC. The recommendation from the white paper 2020 are reflected in the prioritization document from CHIPP for funding period 2021-2024: Link to CHIPP FLARE input.

Since then, tremendous progress has been achieved and the projects have proceeded incrementally to next stages. Continuous developments have also led to major new pieces of information that have precised the scientific landscape and justify this update of the white paper. The status, implementations and planning for 2025-2028 and 2029-2032 and beyond are included in the next sections. The sections below provide details on the Japanese and US accelerator-based LBL oscillation programs, ν-less $\beta\beta$ decay, and the non-accelerator neutrino oscillation program and multi-messenger cosmic searches that Swiss physicists intend to conduct in the coming years. Our conclusions and recommendations are given in Section 8.

The recent reports from P5 and APPEC [1, 2] support the established roadmap of Pillar 2 and the recommendations provided with this document.

2 Neutrinos at the forefront

Neutrinos were first postulated by Wolfgang Pauli in 1930. Since then, much progress has been achieved to understand their properties, but still the particle is so elusive that many questions remain unanswered. Neutrinos play a crucial role in our understanding of the fundamental laws of Nature and it is until now the sole portal to physics beyond the standard model. Due to their very low interaction rate, it is a challenge to obtain high statistics experimental data. Nevertheless, neutrino physics has seen important advances over the last decades, with important results and discoveries about their properties, especially their mass and the related oscillation behaviour. With this, neutrinos, are firmly established as prime research topic and one of three pillars of particle physics in Switzerland. Neutrinos have, furthermore, an important role in cosmology and astroparticle physics as messengers of the far universe.

Together with gravitational waves, they can access the farthest universe at high energies linking to collider physics of particle accelerators and dark matter studies

The study of the neutrino oscillations has involved a suite of experimental measurements worldwide on reactor, solar, atmospheric, and neutrino beams. The parameters of the neutrino mixing described by the PMNS matrix have almost all been determined with high precision. Most recently, the angle θ_{13} has been measured and first indications of a maximally-violated Charge-Parity (CP) symmetry have been published by the T2K experiment in Nature [3] and necessitates of additional confirmations. **Neutrino masses and their flavor oscillations are so far a tantalizing sign for new physics beyond the SM** and thus a goal for further measurements to find answer to remaining open questions such as the **absolute neutrino masses, the mass ordering and the exact size of the CP violating phase.** The nature of the neutrino – the only electrically neutral elementary fermion which could very well be a Majorana particle – is also of utmost scientific relevance. It not only impacts cosmology but also the knowledge itself of the PNMS matrix. Discoveries of additional neutrino states could require more advanced changes in our current understanding of neutrinos, including the expansion of the PMNS matrix, not unitary any longer. Dedicated large-size experiments are under construction in the USA, DUNE/LBNF, and Japan, Hyper-K, and IceCube-Gen2 at the South Pole. They will determine the neutrino mass ordering and measure the CP-violating phase searching for matter-antimatter asymmetry in neutrino oscillations, besides serving as more general purpose observatories for supernova (SN) neutrinos, including searches for relic SN neutrinos, indirect dark matter detection, as well as right-handed sterile neutrinos, proton decay searches, neutrino interactions studies at the GeV-scale (weak proton radius, nuclear processes) and multi-TeV-scale (oscillations through extreme baselines of the cosmos), oscillations in the sun or supernova matter.

The fundamental nature of neutrinos, namely whether they are Majorana or Dirac particles is also still open. The ν-less $\beta\beta$ decay process requires a Majorana neutrino mass, independent of the mass generation mechanism, and its discovery would thus reveal the neutrino nature and would establish lepton number violation. This is a further goal of the neutrino pillar in Switzerland, with the world-leading sensitivity experiment GERDA, completed in 2019, the current LEGEND-200 experiment at LNGS and the future LEGEND-1000[1]. The experimental measurements will also be able to address the question of the absolute scale of neutrino masses, together with constraints from cosmology and dedicated experiments, such as KATRIN.

Neutrinos travel basically undisturbed through the interior of dense environments of astrophysical sources and through the universe radiation background and magnetic fields. Hence, they are excellent messengers, as initially proved by the observation of a neutrino burst few hours before the light signal from the SN1987A. Neutrinos from the Sun first revealed the oscillation phenomenon in matter followed by atmospheric neutrinos, leading to precise measurements of the parameters of the neutrino mass matrix. The cubic-kilometer neutrino telescope, IceCube, proved the existence of > 50 TeV astrophysical flux incompatible at more than 5σ C.L. with atmospheric neutrino origin [4]. These cosmic neutrinos bring information on the super-high energy accelerators of the universe, on neutrino oscillations along extremely long baselines, on PeV scale neutrino cross sections (e.g. Glashow resonance [5]) and other possible exotic phenomena at energy scale which cannot be probed at accelerators. Recently,

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[1] For completeness, we note that XENONnT and DARWIN/XLZD also address neutrinoless double beta decay, as well as the double electron capture process, see Pillar 3.

IceCube observed a few neutrino tau candidate events which could only be produced in oscillations of cosmic neutrino beams. In connection to other messengers, such as gravitational waves, gamma-rays and photon in lower energy bands and charge cosmic rays are providing exciting scientific results shading light to long standing mysteries such as the origin of gamma-ray bursts. The connection between photons with different energies, gravitational waves and neutrinos from SN might unravel the secrets of how black holes form from massive stellar collapses as well the location of dark matter in our universe.

3 The international neutrino long-baseline program in Japan

The LBL neutrino oscillation program in Japan is focused on T2K, currently ongoing, and the upcoming Hyper-K experiments. Both aim to the precise measurement of the neutrino oscillation parameters, including the CP violating phase, and the determination of the neutrino mass ordering. Its high sensitivity is driven by the high-intensity neutrino beam produced at the J-PARC accelerator facility, that will surpass 1.2 MW in 2027, and the two detector complexes, one near the neutrino production target and a massive detector placed 295 km far away. ETHZ and UniGe are founding members of both experiments and largely contributed, in first instance, to the design and construction of the T2K near detector, including its upgrade, and, now, to the construction of the Hyper-K 260 kton water Cherenkov far detector. Such program can lead to the discovery of CP violation in the leptonic sector already within 2-3 years since the start of Hyper-K, if the value of the CP phase is close to 90°.

The 2015 and 2020 white papers highlighted the Japanese LBL neutrino program with the T2K experiment, for full science exploitation, maintenance and upkeep, as well as with its evolution, the Hyper-K experiment, specifically on the R&D and design of the photodetection system of the water Cherenkov far detector (FD). This aims to major investments for the mass production and construction in preparation of the first neutrino beam data in 2027 for physics exploitation.

3.1 Current status and FLARE 2025-2028

The Hyper-K and T2K projects are intrinsically connected and will face a very smooth and natural transition in 2027, when Hyper-K will inherit both the neutrino beamline, the near detector and the related infrastructures. The upgrade of the T2K near detector (ND280) has been completed. The Super Fine-Grained Detector (SuperFGD) and the Time-Of-Flight detector (TOF), both funded by FLARE 2022-2023, have been constructed and installed under the coordination of ETHZ and UniGe in the magnetised near detector complex and have collected their first neutrino data in Fall 2023. They will collect neutrino beam data for the entire duration of the T2K experiment and will continue their activity as magnetised near detector of the approved Hyper-K experiment since 2027 to improve the modelling of neutrino-nucleus interactions, by far the largest systematic uncertainty in the search for CP violation.

The main goals for T2K are:

- the development of new data analysis tools to exploit the more accurate data by the new detector;

- the development of a more sophisticated modelling of the neutrino-nucleus cross section for the early phase of the Hyper-K experiment;
- the training of young researchers who will be ready to deploy their skills from the first day of the Hyper-K operation.

Hence, the 2025-2026 FLARE request will also include:

- T2K Common-Fund until 2027.

After the approval of the Hyper-K project and the constitution of its international collaboration in 2020, ETHZ and UniGe, the Swiss institutions founding members of the collaboration, have taken a major role. The upgrade of the J-PARC proton accelerator and neutrino beamline has been completed in 2023 and is now fully operating. The accelerator will increase its intensity year-by-year, surpassing 1 MW in 2026 and reaching the unprecedented maximum of 1.3 MW after the first year of Hyper-K. The neutrino beam upgrade will be complemented by the construction of the massive 260 kton water-Cherenkov far detector (FD), allowing for the precision measurement of the leptonic CP-violating phase in neutrino oscillations, with the real possibility of discoverying the matter-antimatter asymmetry after only 2 years of data taking if CP symmetry is maximally violated. The Swiss institutes (ETHZ and UniGE) are working tightly together complementing each other. They lead the design of the far-detector front-end (FE) electronics that collects and digitizes the analogue signal produced by photomultiplier tubes (PMTs) when Cherenkov light is detected. The underwater FE unit consists of the FE components (Digitizer, Data Processing board, High-Voltage, Low-Voltage) installed inside a mechanical vessel, all sitting underwater and exposed to pressures up to 8 bars. ETHZ is responsible for the High-Voltage (HV), the Low-Voltage (LV) and the water-tight mechanical vessel. U.Kose (ETHZ, Group Rubbia) is deputy supervisor of the “Electronics components” sub-WG and leader of the HV and LV power supply system; A.Gendotti (ETHZ, Group Rubbia) is supervisor of the “Underwater vessel and related components” WG. UniGe is leading the mechanical design for the photosensor and FE electronics vessels integration in the far detector water tank. F.Cadoux (UniGe, Group Sanchez) is leader for the vessel fixation and logistics and installation. Hyper-K has now entered into the mass production phase and will start to assemble all the 900 underwater FE units in 2025. The FD electronics group sees most of its contributions coming from European countries (France, Italy, Poland, Spain, Switzerland and UK). Hence, the full system calibration, assembly and final functional tests of the 900 underwater FE units will be performed at CERN, and shipped to the far detector site in Japan. A project collaboration consisting of 23 institutes and more than 100 collaborators has been formed under the leadership of Prof. Sgalaberna (ETHZ), and the technical coordination of Dr. Kose (ETHZ). A Letter of Intent has been submitted to the CERN SPSC [6] to host the underwater FE unit assembly project at CERN under the framework of the Neutrino Platform. In the short term, the main goals for Hyper-K are:

- the mass production of the far-detector components;
- the assembly and construction of the far detector.

Consequently, the core of the 2025-2026 FLARE request will aim to cover:

- the costs (equipment, technical personnel) related to the assembly at CERN of the 900 FE underwater units, to be completed by the end of 2026;
- shipment of the assembled units to Japan and installation at the Hyper-K far site.

3.2 Plans for the period 2029 - 2032

During this period, the Hyper-K experiment will be collecting accelerator and atmospheric neutrino data, hence, efforts will be devoted to its operation and to the data analysis, to search for leptonic CP violation.

After a few years since its start, Hyper-K will enter the high-statistics phase. The discovery of a potentially non-maximal CP violation, the precision measurement of the CP phase, as well as the determination of the neutrino mass ordering will necessitate a further reduction of the systematic uncertainty through:

- high-purity cross section measurements of neutrinos in water, i.e., same target medium as that of the water-Cherenkov far-detector;
- a high-purity and high-statistics sample of electron neutrinos and anti-neutrinos, that contaminate the muon-neutrino dominated beam with an only 1% component;
- the detection of low-momentum protons (below 300 MeV/c), invisible to the current ND280 detectors to resolve the so-called "nuclear effects" i.e., those nuclear processes that can induce a large bias in the measurement of the oscillation probability if not properly modelled;
- high-efficiency detection and energy reconstruction of neutrons, also critical in resolving the nuclear effects.

Hence, the need for an additional upgrade of the magnetised Near Detector is finding a wide consensus in the collaboration. ETHZ is leading the detector R&D to address the physics requirements listed above. The R&D aims to develop novel neutrino active targets, such as: scintillating-fiber neutrino target read out with single-photon avalanche diode (SPAD) array sensors, as proposed in [7]; 3D printing of highly-segmented plastic scintillator (a-la-SuperFGD) to allow scalability up to 10 tonnes, as demonstrated in [8–10], whose development is conducted by international collaboration hosted by CERN [11]; 3D segmented (a-la-SuperFGD) water-based liquid scintillator for a high-performance water detector capable of both particle tracking and calorimetry.

The Hyper-K collaboration is planning to complete the conceptual design report of the final upgrade of ND280 (ND280++) in the next couple of years to potentially move towards its construction in the period 2029-2032, once the far detector will be fully operative.

4 The international long-baseline neutrino program in the USA

The international neutrino program is the USA is based on the technology of liquid Argon TPCs, which provide precision imaging of neutrino interactions. A short-baseline program started at Fermilab a decade ago with the operation of the MicroBooNE experiment in 2015, which already produced over 60 scientific results. This program continues over the next decade with a near detector (SBND, start 2024) and a second far detector (ICARUS) which started operation recently. This will lead to a long-baseline program (DUNE/LBNF), building on liquid argon TPCs and the USA-based MINOS and NOvA experiments. DUNE/LBNF will be a world-class multipurpose observatory for neutrinos from beam and astrophysical origin and for matter instability searches. Two complexes will be built, with a "near" site facility at Fermilab and a "far" site at the Sanford Underground Research Facility (SURF). The world's most intense beam of neutrinos will be produced at Fermilab with a new neutrino beamline, aimed at the SURF site at a distance of 1300 km from Fermilab.

The design of the LBNF/DUNE facilities and detectors are driven by the scientific goals of carrying out a comprehensive program of neutrino oscillation measurements, besides also significantly improving the search sensitivity for proton decays, detecting and measuring neutrinos from core-collapse supernovae and be ready for unexpected discoveries. One main goal is to reach sensitivity to measure charge-parity symmetry violation (CPV) in neutrino oscillations, which would give insight into the origin of the mentioned matter-antimatter asymmetry.

The DUNE Near Detector design is established with a liquid Argon TPC (ND-LAr) as key element, with a technology initiated Bern researchers (ArgonCube concept). The near detector establishes the null hypothesis (i.e., no oscillations) under the assumption of the three neutrino paradigm by measuring the neutrino flux at the beam origin, it constrains the systematic uncertainties in a global fit, and provides essential input for the neutrino interaction model. It is therefore key to have a target with the same element as the far detector, which is ND-LAr. It involved independent modules that are combined to a detector in a common bath of liquid argon. The modular design is necessary due to the pile-up of neutrino interactions at the near site in the very high intensity neutrino beam.

Since 2015, much progress has been accomplished in finalizing the design and conducting the corresponding R&D and detector demonstration programs. Agreements with Fermilab (iCRADA) and an MoU for DUNE were established in 2019 and 2023, respectively. The Technical Design Report (TDR) for DUNE was published in early 2020 for the overall physics program, the beam and the far site detectors (arXiv:2002.03005), the near detector Conceptual Design Report was completed in 2019 and the Preliminary Design review of ND-LAr in 2022. Concurrent with the Conceptual Design in 2020 a consortium of institutions was created for building ND-LAr within the DUNE collaboration, with the University of Bern in the lead. The construction of ND-LAr is funded by the USA and Switzerland in about equal shares, with other funding agencies being explored.

4.1 Current status and FLARE 2025-2028

A demonstrator TPC for ND-LAr, consisting of 4 modules (called "2x2") of about 1/3 final size (0.7 m × 0.7 m × 1.4 m), was successfully built and tested in Bern and assembled in the NuMI neutrino beam at Fermilab. Data taking started in July 2024. Furthermore a single module in the final 1:! size ("fulls-scale") is being assembled in Bern for testing and demonstrating the technology and performance in view of the final design review.

FLARE funds have so far been made available to successfully perform the short-baseline program and R&D program towards DUNE (ProtoDUNE, ArgonCube). In addition, SERI also made available specific infrastructure funds to support the construction of LBNF/DUNE via the involvement of CERN in the far detector cryostat and cryogenic infrastructure. After supporting the 2x2 demonstrator physics experiments at the Fermilab NuMI neutrino beam and the full-scale module in Bern, the initial 20% of the near detector (already funded), the production readiness will be established over the next years and lead to the completion of the production of the near detector.

For the construction phase, contributions to the following core detector components are foreseen:

- Common funds
- Module structure for 40 modules
- Light detection panels ("ArcLight") covering 50% of the area and associated electronics
- High Voltage, filters and distribution
- Calibration systems
- Share of integration and testing

In the period 2025-2028 priority is given to the components need to assemble the ND-LAr modules, so that they can be inserted in the cryostat, expected to be completed in 2029. The construction of the modules is expected in 2026 to 2028. Integration and installation of the detector is expected in 2029. Some components (like High Voltage power supplies) can be procured for that date.

The remaining fraction of the light readout system was covered by JINR. Negotiations for additional and alternate contributions from Europe are at an advanced stage, following the geopolitical developments. The electric field shell, the charge readout, management as well as the cryostat are covered by the USA.

4.2 Plans for the period 2029 to 2032

In the previous four-year period 2025-2028 the core detector components for the construction of the LArTPC modules were prioritized. The schedule is to complete the ND-LAR DUNE near detector in 2029/2030. In the period 2029-2032 the remaining components will be procured, including in particular:

- High Voltage system
- Dedicated off-detector electronics for readout and controls
- Share of integration and testing

Overall the DUNE program is set up in two phases, namely Phase-I and Phase-II, based on the availability of resources and the ability to reach science milestones. Phase-I includes the construction of the LBNF neutrino beam, the excavation and facilities at the near and far sites, the installation of two liquid argon modules in the far detector and a near detector consisting of a liquid argon TPC (with associated magentized tracker) and a beam monitor. Phase-I is the part of the program starting the science program in 2029 with the operation of the far detectors and beam operation in 2031. The primary objective of DUNE Phase-II is to increase the statistical power of the detectors by adding two additional far detector modules and by exceeding 2MW beam power, along with controlling the neutrino interaction systematic uncertainties on argon with an upgraded and more capable near detector to reduce the systematic uncertainties to be able exploit the power of this dataset. The Phase-II R&D program is a global effort with contributions from all major DUNE partners. Part of the R&D is carried out within the framework of the European Committee for Future Accelerators (ECFA) Detector R&D (DRD) collaborations hosted by CERN. The expertize of the Bern group in the pixelated liquid argon TPC is key to the developments for the improved 3rd and 4th far detector modules. This effort is a main technology option that will be explored and a significant contribution from Switzerland is planned. The pixelated native 3D readout, and its combination with the light readout also provides capabilities to study solar neutrinos, e.g. from the hep process, that have never been observed before. A prototype experiment (SoLAr) is being planned to be installed at the Boulby underground laboratory and could lead to a FLARE funding request if successful (period 2029-2032). Furthermore, ND-LAr will continue to be the key components of the DUNE near detector. It will require maintenance and operation engagement throughout the DUNE program data taking, with associated funding. It is expected that some off-detector electronics components will be upgraded to improve the efficiency of the light readout system and addition of systems to make online matching of charge and light data. Such upgrades could lead to a funding request 2029-2032 or future periods.

5 Neutrinoless double beta decay

Another fundamental open question in neutrino physics is whether neutrinos are identical to their own anti-particles, i.e., Majorana fermions, a property connected to the origin of their mass. The only known feasible probe of the Majorana nature of the neutrino is the neutrinoless double beta decay ($0\nu\beta\beta$), a yet unobserved second order weak transition. Experiments using high-purity Ge (HPGe) detectors enriched in ^{76}Ge are at the forefront of the search.

The experimental observable in $0\nu\beta\beta$-decay is the half-life, and the principal challenge is the ability to measure the extremely long half-lives predicted by current estimates and experimental constraints (between $\mathrm{T}^{0\nu}_{1/2} \sim 10^{26} - 10^{28}$ y for the inverted neutrino mass ordering, and $\mathrm{T}^{0\nu}_{1/2} > 10^{28}$ y for the normal mass ordering scenario [12]). Experimental searches use different isotopes and techniques, requiring an ultra-low background level, an excellent energy resolution, a high isotopic abundance, and a high efficiency for detecting the two electrons emitted in the decay. At present, the most stringent constraints are set by experiments using the isotope ^{76}Ge (GERDA and LEGEND-200) and ^{136}Xe (KamLAND-Zen), with lower bounds on the half-life surpassing 10^{26} years. These limits constrain the effective Majorana neutrino mass at the scale of 100 meV. An experiment able to discover the decay by covering the inverted ordering region (with effective Majorana neutrino masses in the range 18-50 meV) requires about a tonne of isotope with extremely low background levels and excellent energy resolution. The GERDA experiment achieved an intrinsic energy resolution (at FWHM) of 0.12% and operated in a quasi-free background regime (an order of magnitude lower in the

$0\nu\beta\beta$-signal region compared to other experiments).

The GERDA experiment, using enriched, HPGe detectors immersed in an active liquid argon shield, also achieved an unprecedented low background rate of 5×10^{-4} events/(keV·kg·y) in the signal region and met its design goal to acquire an exposure of 100 kg·y in a background-free regime. No signal was observed in 127.2 kg·y of data and a half-life limit for ^{76}Ge of $T_{1/2} > 1.8 \times 10^{26}$ y at 90% C.L., setting the best lower limit achieved by a $0\nu\beta\beta$-decay search experiment [13]. The LEGEND-200 experiment uses much of the infrastructure from GERDA, with several new components added: a new lock system that allows for the deployment of longer detector strings into the LAr cryostat, four new calibration systems to deploy multiple sources per system, a wavelength shifting reflector (WLSR) surrounding the detector strings, as well as a new fibre shroud for the detection of the scintillation light. The new HPGe detectors were produced by ORTEC (Oak Ridge) and Mirion Technologies (Canberra), and are of inverted-coaxial point-contact (ICPC) type, with a mass of about 2 kg per crystal. The UZH group is responsible for the calibration systems hardware, as well as for the offline calibration data analysis pipeline. Weekly calibrations are performed to determine and monitor the energy scale of the HPGe diodes, to measure their energy resolution, and to train and validate pulse shape analysis algorithms for background reduction based on the waveforms of events. The UZH group is also co-responsible for the LEGEND-200 LAr instrumentation, through the characterization of WLSR materials [14], the construction of a system to evaporate TPB on ∼13 of the reflective Tetratex shroud surrounding the LAr instrumentation and the *in situ* coating of the large surface inside the cryostat. The tonne-scale project LEGEND-1000 [15] is in advanced planning stage, with a US DOE CD-1/3A review scheduled for 2024. A modular approach is planned, with different payloads being instrumented over the course of several years. This approach allows for almost continuous data taking as the experiment scales up to its full size. The HPGe detector strings will be placed in a thin copper cylinder inside the main cryostat in order to separate the inner and outer liquid argon volumes and prevent radon drifting through the liquid. The inner volume is planned to be filled with underground-sourced liquid argon (UGLAr) to minimize the background contribution from ^{42}Ar (and ^{39}Ar, relevant at low energies).

5.1 Swiss contributions and FLARE 2025-2028

The GERDA experiment to search for the neutrinoless double beta decay of ^{76}Ge, with significant Swiss contributions (UZH) reached a world-leading lower limit on the half life of $T^{0\nu}_{1/2} > 1.8 \times 10^{26}$ y (90% C.L.), for an exposure of 103.7 kg y. GERDA [16–18] was completed at the Laboratori Nazionali del Gran Sasso (LNGS) of INFN, Italy, in December 2019, and since then the infrastructure is available for LEGEND, the next-generation ^{76}Ge experiment.

The collaboration, based on the experiments GERDA and MAJORANA together with new members[2], aims to build a ton-scale experiment with a large discovery potential in two phases. The first phase, LEGEND-200, has been constructed and is currently operating at LNGS with 142 kg of enriched Ge detectors installed (out of 200 kg). First results from an exposure of 48.3 kg y were presented at Neutrino 2024. The second phase, LEGEND-1000, is in advanced design phase with LNGS selected as the host laboratory. The experiment will be in Hall C, in the space that previously housed the Borexino detector. The goals

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[2] Currently the LEGEND collaboration has 270 members from 55 institutions in 11 countries.

are to achieve a sensitivity of $T_{1/2}^{0\nu\beta\beta} > 10^{27}$ y and $T_{1/2}^{0\nu\beta\beta} > 10^{28}$ y respectively and thus to be sensitive to the full inverted neutrino mass region for $0\nu\beta\beta$-decay via light Majorana neutrino exchange [19]. By combining the lowest background levels and the best energy resolution in the field, LEGEND-1000 will perform a quasi-background-free search, and can make an unambiguous discovery of $0\nu\beta\beta$-decay with only a handful of counts in the signal region, at $Q_{\beta\beta}$=2039 keV.

The UZH group lead by Laura Baudis has been involved in GERDA since 2007, and has major responsibilities in both GERDA and LEGEND in hardware, software and data analysis. Relevant for the FLARE request, the group is responsible for the design, construction and operation of the calibration systems [20, 21], for the analysis of the weekly calibration runs and stability monitoring of the energy calibration and resolution of the Ge diodes, and for the production and characterisation of the low neutron emission calibration sources in collaboration with LBNL [22]. The group is also involved in the production and characterisation of enriched germanium diodes [23] and in the development and production of the wavelength shifting system for the liquid argon veto system [14, 24]. Further, the group is involved in material radio-assay with the Gator HPGe detector facility operated by UZH at LNGS [25, 26]. In terms of management, Laura Baudis is a member of the LEGEND Steering Committee, and she co-leads two DOE WBS level three tasks, calibration (together with LANL) and detector production (together with UNC).

The LEGEND experiment is one of the three large $0\nu\beta\beta$-decay projects with leading European contributions (together with CUPID and NEXT) recommended in the Double Beta Decay APPEC Committee Report [27], and one of the three leading projects in the DOE 2023 Long Range Plan for Nuclear Science (November 2023, together with nEXO and CUPID): “These three experiments have undergone a rigorous DOE portfolio review, are ready to start construction, and are actively preparing for the Critical Decision (CD) process.” [28].

The UZH group received funding for LEGEND-200 during the last two FLARE periods (2021-2023 and 2023-2025). For the next FLARE calls, the following costs are foreseen for LEGEND-200 and LEGEND-1000:

- Common funds and operation of LEGEND-200
- New calibration sources for LEGEND-200
- Calibration systems for LEGEND-1000
- Enriched HPGe detectors for LEGEND-1000
- Liquid argon veto for LEGEND-1000

We note that the DARWIN [29] project, a next-generation xenon-based experiment for direct dark matter detection will also be able to probe the $0\nu\beta\beta$-decay of ^{136}Xe with half-life sensitivity of 2.4×10^{27} yr [30], and will thus be complementary to LEGEND and other dedicated searches.

5.2 Plans for the period 2029 - 2032

The LEGEND-1000 experiment is a ton-scale Large Enriched Germanium Experiment for Neutrinoless Double Beta Decay. It will consist of 1000 kg of Ge detectors, enriched to 90%

in ^{76}Ge, operated in a LAr active shield at LNGS in Italy. The experiment is designed to probe $0\nu\beta\beta$ with discovery sensitivity to ^{76}Ge half-lives beyond 10^{28} years. LEGEND-1000 will perform a quasi-background-free search and can make an unambiguous discovery of $0\nu\beta\beta$ decay for an effective neutrino mass above 9–21 meV.

Currently LEGEND-1000 is in the design and planning stage, with the construction and installation of the liquid argon cryostat to start in 2025 and 2026, respectively. The enriched Ge production will happen in 2027 until mid 2028. Detector production will start as soon as 30 kg of enriched material is available, and will extend until mid 2029. Assembly and installation underground will start with the assembly of detectors into strings, with each string holding a nominal mass of 24 kg of detectors (8 detectors on average). Strings will be installed in subsets of six strings, where each subset will be centered around one of the seven calibration ports. First data and operation of LEGEND-1000 will start in 2030, and the plan is that the experiment will operate for 12-15 years, to reach its ultimate sensitivity with a 10 t·y exposure. LEGEND-200, which operates in Hall A of LNGS, will continue operation until the start of LEGEND-1000.

Thus, for the 2029-2032 FLARE calls, the costs foreseen for LEGEND-200 and LEGEND-1000 are mainly operation costs, as well as funds to produce new calibration sources. Funds for detector production might be requested should the production be delayed and thus not end in 2029.

6 Extraterrestrial Neutrinos

Atmospheric neutrinos, mostly muonic and in lower number electronic neutrinos, are produced in hadronic showers induced by the cosmic ray interactions (mostly protons) on atmospheric nuclei. The cosmic ray spectrum extends from GeV energies to 10^{21} eV. Up to PeV energies they are produced by galactic sources and beyond 10^{19} eV they are surely originating in intergalactic space from cosmic ray interactions with the background radiation of the Universe or in the biggest accelerators of the universe, such as black hole winds and jets or gamma ray bursts (from kilonova events of galaxy mergers or hypernova - collapsed massive stars). Astrophysical or cosmic neutrinos can originate from the protons/nuclei accelerated in cosmic sources or by their interactions on the cosmic radiation (cosmogenic neutrinos). We can consider cosmic ray protons and nuclei as the parents of neutrinos and gamma-rays, so that these cosmic particles are intimately related. Atmospheric and cosmic neutrinos allow for studies of neutrino oscillations and ordering.

Recent highlights of IceCube are:

1. the discovery of a diffuse flux of astrophysical neutrinos reaching up to PeV energies and dominated by extragalactic sources (mostly black holes embedded in active galaxies) [4];
2. the discovery of neutrino and gamma-ray emissions from an active galaxy, TXS 0506+056, during a flare [31, 32];
3. the discovery of 7 tau neutrinos of > 100 TeV energy most probably from cosmic neutrino oscillations [33];

4. the discovery of the first standalone neutrino source [34], a Seyfert galaxy, with gamma-ray absorption;
5. the discovery of the diffuse flux of neutrinos from the Galactic Plane [35];
6. the finding of a ~ 6 PeV electronic neutrinos in region of the Glashow resonance [5].

In Nov. 2023, IceCube started an upgrade construction, which will last to 2026. It will add 7 new strings to the inner core denser strings DeepCore. DeepCore detects an atmospheric neutrino every 15 min, while the upgrade of IceCube will detect a neutrino every 4 min and improve by more than a factor of 3 precision on oscillation parameters. For the upgrade, the drilling tools at the South Pole have been renewed to achieve the capacity to evolve into PINGU with 26 strings, which will deliver important results on neutrino ordering. Indeed, P5 prioritized the readiness of the logistics tools at South Pole with respect to other programs as CMB detection from South Pole and follows up of the South Pole telescope. IceCube and its evolution is a high priority in P5.

The coming publication on neutrino oscillation uses 9.3 yr of DeepCore data including 210k ν-events with 97.3% purity between 5-55 GeV. Impressively, 6.9k ν_τ neutrinos come from ν_μ oscillations. The Upgrade will reach a precision of 6% in 3 yr on the ν_τ normalization and will measure directly tau neutrinos from muon neutrino oscillations with a better sensitivity by a factor of 3. The next step, PINGU, will exclude the IO for true NO after 4 years of data taking at 3.2σ c.l [36]. Combined with JUNO reactor experiment, it has the potential to determine the mass ordering at 5σ c.l. in 5 yr [36].

The ultimate extension of IceCube is IceCube Gen-2, focusing also on cosmic neutrinos. It is planned to be a factor of 10 bigger than IceCube, namely 10 km^3 of instrumented ice with a surface detector as veto which will be very extended and made of radio antennas. It should become fully operational in 2033 [36].

This is an excellent program, complementary to accelerator neutrino physics, that should be continued in Switzerland. Future requests on FLARE might be foreseen once IceCube-Gen2 construction is approved in the next few years. Additionally, data taking by the KM3NeT neutrino telescope in the Mediterranean sea has started. It can provide further synergy in this extra-terrestrial neutrino program.

7 Synergies with other Pillars

7.1 Overlap with Pillar 1 - Energy frontier

Synergies with Pillar 1 sit in the study of the interaction cross section of neutrino produced at the Large Hadron Collider (LHC) at CERN, where the FASER and SND@LHC experiments are currently collecting data. Their primary goal is to search for Feebly Interacting Particles (FIP), that could provide an explanation for the very tiny mass of the three active neutrinos. On the other hand, they will also detect a few thousand neutrinos (including ν_τ) and measure the interaction cross section up to the TeV range, where it is still unconstrained. The comparison of cross sections for the three active flavors will also provide a test of lepton universality in neutrino scatterings. Both the FASER and the SND@LHC experiments are planning an upgrade to be completed by 2028. In the future, this programme might evolve into the Forward Physics Facility (FPF), a proposed new underground cavern at the LHC to host a suite of new experiments during the High-Luminosity LHC (HL-LHC) era. If approved, it would start the operation around 2031.

The Search for Hidden Particles (SHiP) experiment and the associated SPS Beam Dump Facility is a new general-purpose experiment. Approved in 2024, it is now in preparation at the SPS, aiming to start the operation in 2032. The experiment is designed to search for any type of FIP, including heavy neutral leptons (HNL). SHiP is optimised to perform measurements on tau neutrino interactions with energies around 60 GeV.

Although such programme show important synergies with Neutrino Pillar 2, these experiment utilise infrastructures common to those of LHC collider experiments. Hence, it is part of the Pillar 1 framework (high-energy frontier).

7.2 Overlap with Pillar 3 -

8 Conclusions and recommendations

We list below the conclusions and the agreed upon recommendations of the neutrino community on the neutrino pillar. They consist of a number of bullet points:

- The long baseline neutrino programs at accelerators have benefited from the flagship status for several years following the update of the CERN strategy, which has resulted in the approval of 7.6 MCHF subsidies during the period 2021-2024. T2K upgrades were completed and the mass production of the far-detector underwater electronic modules for Hyper-K has started with support from the CERN Neutrino Platform. The SBN program finished construction and physics exploitation is underway, the technical designs for the DUNE ND have successfully been demonstrated in prototype tests initiating the construction. In light of the significant past contributions and Switzerland's highly visible commitments as well as the importance of these initiatives to the global community, **we strongly recommend maintaining the flagship status throughout the periods 2025-2028 and 2029-2032 to fulfill our commitments.** The completion of the construction and integration as well as necessary upgrades will continue into the next decade, thus included in the period 2029-2032. We stress that these programs will provide the ultimate answer on CP-violation in the neutrino sector.
- The Swiss participation to DUNE and Hyper-K should be supported with an equivalent priority to maximize the scientific reach. **The Bern group will focus on the construction of the DUNE near detector for Phase-I and Phase-II, while ETHZ and UniGE will primarily support the construction of the Hyper-K far detector and, in the longer term, there is a plan to lead the final upgrade of the Hyper-K near detector for the high-statistics phase.**
- The SBN at FNAL and T2K experiment in Japan have provided critical insights into neutrino flavor oscillations. They have also provided a framework to develop state-of-art detector technologies in view of the LBL programs. They have provided a clear path towards the conclusive discovery of CP-violation in the next generation of experiments.

FLARE Calls	2021-2022 approved kCHF	2023-2024 approved kCHF	2025-2026 to be requested kCHF	2027-2028 to be requested kCHF	2029-2032 Roadmap kCHF
Hyper-K	1,244	4,401	3,000	$\simeq$ 2,000	$\simeq$ 2,500
DUNE	1,000	1,961	3,000	2,500	$\simeq$ 2,500
$0\nu\beta\beta$	502	471	600	600	$\simeq$ 500
Total	7,578		$\simeq 11,700$		$\simeq$ 5,000

Table 1: Summary of the FLARE funding plan in kCHF for the various years.

The operation of the ongoing experiments T2K in Japan and SBL at FNAL should be supported in order to maximally benefit from previous investments, in preparation for future long-baseline neutrino programs and supporting new generations of students.

- The quest for the nature of neutrino and lepton number violation is a fundamental scientific goal in particle physics, requiring long-term involvements and a steady support of experiments. The GERDA experiment to search for the neutrinoless double beta decay of ^{76}Ge, with significant Swiss contributions from UZH, reached a world-leading result of $T^{0\nu}_{1/2} > 1.8 \times 10^{26}$ y (90% C.L.). GERDA was successfully completed at the Gran Sasso Laboratory, and the infrastructure was taken over by LEGEND-200, the next-generation ^{76}Ge experiment and its operation should be supported.
- The next phase, LEGEND-1000, will also be constructed in Gran Sasso. The goal is to be sensitive to the full inverted neutrino mass ordering region. By combining the lowest background levels and the best energy resolution in the field, LEGEND-1000 will perform a quasi-background-free search, and can make an unambiguous discovery of $0\nu\beta\beta$-decay with only a handful of counts in the signal region. **The Swiss investment in the construction of the LEGEND-1000 experiment is strongly recommended, in view of its unique physics potential.** We note that the DARWIN experiment is also extremely valuable to the neutrino pillar.
- The IceCube program started its expansion and has tremendous impact on astrophysical neutrino and atmospheric neutrino oscillations. There is currently no plan to contribute to the construction of PINGU or IceCube-Gen2 through infrastructure investments via the FLARE instrument. Nonetheless, the science is compelling for multi-messenger astrophysicists in Switzerland and a future proposal can be envisaged when IceCube-Gen2 will be fully approved after 2028.

The expected financial requests for each funding period are summarised in the table 1.

The timeline of the major neutrino projects is shown in Figure 1.

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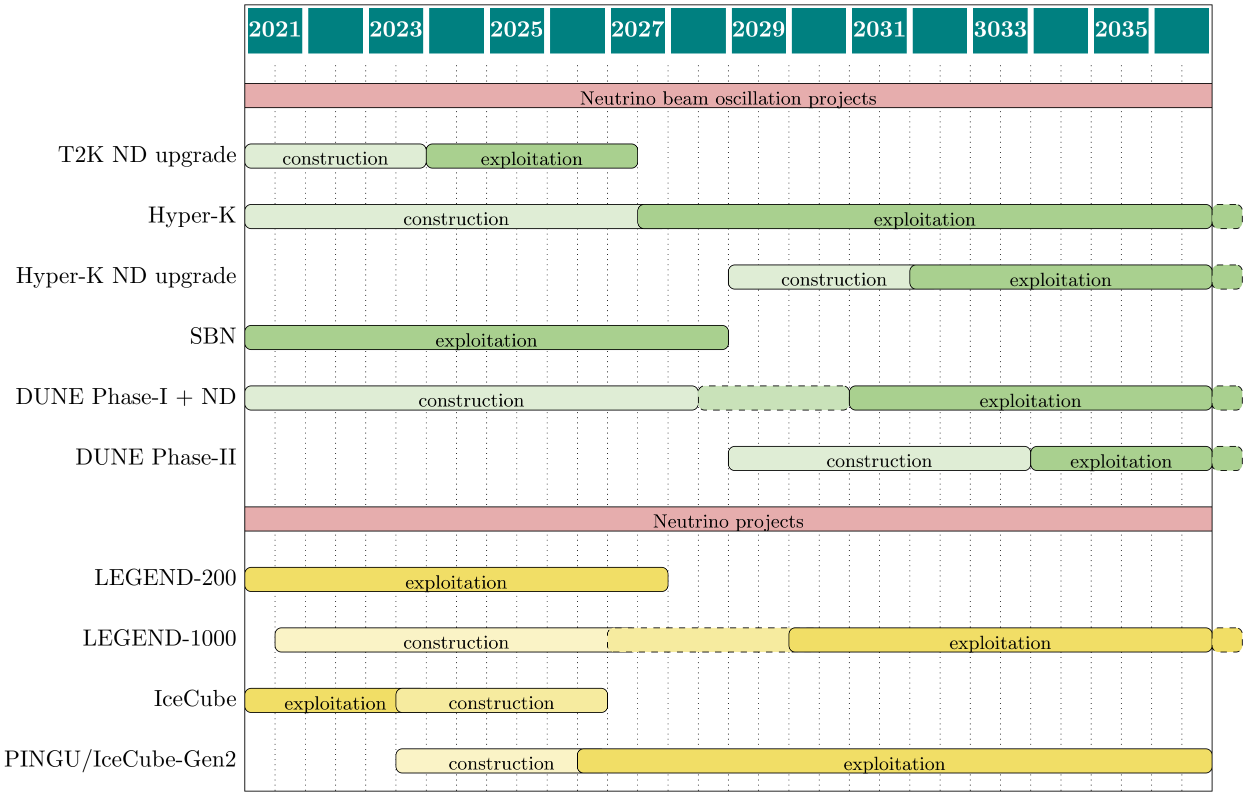

Figure 1: The timeline of major neutrino projects with strong Swiss engagement. The intensity of a given colour indicates the project phase, differentiating between construction (light colour) and exploitation of the machine (dark colour).

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