

Pillar 2 - Neutrino Roadmap update

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Updated whitepaper

Whitepaper for neutrino physics in Switzerland

Additional information to inform the SNSF FLARE instrument 2025-2028 and beyond
Endorsed by the CHIPP Board on XX.YY.2024

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1 Introduction

The last neutrino white paper was written in 2020. In the last few years, many developments have also led to major new pieces of the neutrino physics landscape and justify an update of the document. In this document we summarize the current status and the developments that are planned for the next few years. The document was prepared in parallel to the draft of the "Infrastructure 2025-2028 and beyond" and its prioritisation input to the FLARE Panel for 2021.

In 2020, the white paper referred the reader to the neutrino pillar from FLARE and other instruments. It gave some general points, relevant for the years 2021-2024 and development to be performed at the CERN experiment and T2K/HK long baseline experiment is now close to completion. The Super-Fine-Grained-Of-Flight detector (TOF), under the coordination of the magnetised near detector complex installed in Fall 2023. They will collect neutrino beta decay experiment and will continue their activity as the Hyper-K experiment, that will start in 2027. The with a liquid Argon TPC (ND-LAr) as key element TPC, consisting of 4 modules of about 1/3 final size are being assembled for test the final design. In late 2023 the MoU for DUNE was completed between 2028 and 2030, depending on the funding request. This effort has now been successfully conducted results for future steps. The MicroBooNE experiment at Fermilab, has successfully taken data from 2020 articles with Bern researchers leading the physics construction effort is nearing completion and the first

most continuous data taking as the experiment sea strings will be placed in a thin copper cylinder just the inner and outer liquid argon volumes and prevent inner volume is planned to be filled with underground to minimize the background contribution from ^{39}Ar (and group co-leads the HPGe detector production task characterisation campaigns for new detectors in the UNIGE took over since 2011 the IceCube activity messenger scientific program in synergy with the first telescope of CTAO in operation, the LSST, mostly with PhD students and delivered many of a flaring binary in neutrinos and gamma-rays [4], neutrino source [5], the publication of 10 yr of data science is extremely important for high-energy as they rely on the birth of two new astronomical: gravitational waves. Additionally, IceCube can contribute results on the ordering of neutrino thanks to it. Additionally, it will have excellent sensitivity for the Cloud [6].

More detailed and up-to-date information is included in the following sections of this white paper. Concerning the current period, the 2021 - We conclude the following:

- The engagement in the DUNE program is at a from FLARE to be shared among Swiss groups during a total period of 10 years. FLARE successfully perform the short-baseline DUNE (ProtoDUNE, ArgonCube). In specific infrastructure funds to support via the involvement of CERN in the infrastructure.
- The design and prototyping of the Hyper-K F led to funding request in view of the mass y to be in agreement with the overall Hyper-F start the first neutrino beam physics run in 2020 to support the physics exploitation at the T2.
- The 2015 whitepaper stated that the approval funding request. The need for the facility at ESPP.
- IceCube started construction again for its so difficulties to travel to the South Pole during the neutrino accelerator program. Funding

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 [24], 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." [25].

The UZH group received funding for LEGEND-200 during the last two FLARE periods (2021-2023 and). 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 [26] 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 [27], and will thus be complementary to LEGEND and other dedicated searches.

6 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. In light of the significant past contributions and Switzerland's highly visible commitments to the Japanese and US programs, we have already begun allocating financial resources. T2K upgrades were completed and the mass production of the far-detector underground electronic modules for HyperK has started with support from the CERN Neutrino Platform. The technical designs for the DUNE ND have successfully been demonstrated in prototype tests initiating the construction. Given this investment and the importance of these initiatives, we strongly recommend maintaining the flagship status to fulfill our commitments. We stress that these programs will provide the ultimate answer on CP-violation in the neutrino sector.
- The Swiss participation to DUNE and HyperK 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 while ETHZ and UniGe will primarily

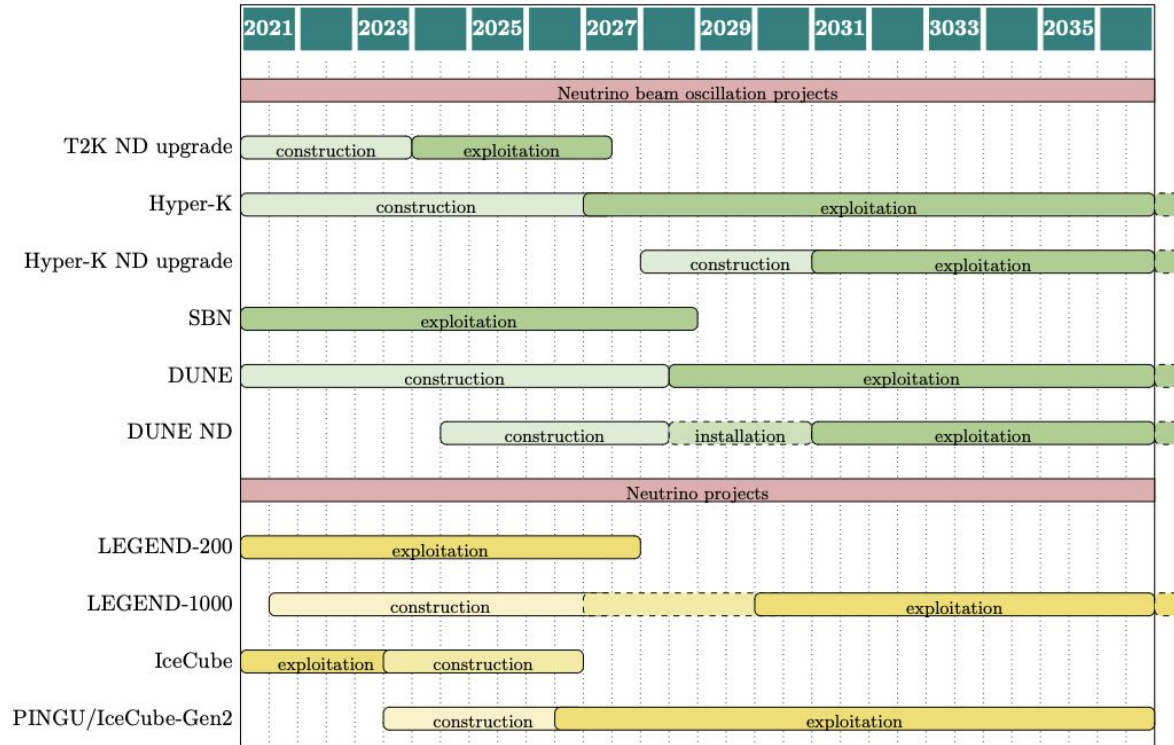
FLARE Calls	2021-2022 approved kCHF	2023-2024 approved kCHF	to be requested kCHF	to be requested kCHF	2029-2032 Roadmap kCHF
HK	1,244	4,401	3,000	$\approx 2,000$	$\approx 2,500$
DUNE	1,000	1,961	3,000	2,500	$\approx 1,500$
$0\nu\beta\beta$	502	471	600	600	
IceCube	0	0	0	?	
Total		7,578		$\approx 11,700$	$\approx 4,000$

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

support the construction of the HyperK 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. The participation to the ongoing experiments T2K in Japan and SBL at FNAL should be pursued in order to maximally benefit from previous investments, prepare for future long-baseline neutrino programs and supporting new generations of students.
- The quest for the nature of neutrino and lepton number violation is another 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 $T_{1/2}^{0\nu} > 1.8 \times 10^{26}$ 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. The LEGEND-200 experiment was constructed and has started its first science run in early 2023.
- The next phase, LEGEND-1000, will also be constructed in Gran Sasso. The goals are 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.
- 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.

Updated timeline of neutrino projects (minimal changes)



Achievements and recommendations 1/4 (LBL)

- Achievement: Long baseline neutrino programs at accelerators have benefited from the flagship status. Approval of 6.6 MCHF subsidies during the period 2021-2024.
 - T2K upgrades completed, mass production of the far-detector HyperK electronic modules started with support from the CERN Neutrino Platform.
 - The technical designs for the DUNE ND demonstrated with prototypes, initiating construction.
- Recommendation: Given this investment and the importance of these initiatives, **we strongly recommend maintaining the flagship status** to fulfill our commitments.
- Comment: Swiss participation to DUNE and HyperK should be supported with an equivalent priority. Bern will focus on the DUNE near detector, ETHZ and UniGE will primarily support the HyperK far detector and, in the longer term, plan to lead final upgrade of the near detector for the high-statistics phase

Achievements and recommendations 2/4 (SBN, T2K)

- Achievement: The SBN (FNAL) and T2K (Japan) have provided critical insights into neutrino flavor oscillations. Provided a framework to develop state-of- art detector technologies in view of the LBL programs
- Recommendation: The participation to the ongoing experiments T2K in Japan and SBL at FNAL should be pursued (and operation funded)
- Comment: Maximally benefit from previous investments, prepare for future long-baseline neutrino programs and supporting new generations of students.

Achievements and recommendations 3/4 (0nubb)

- Achievement: 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 $T > 1.8\text{E}26 \text{ y}$ (90% C.L.). The LEGEND-200 experiment was constructed and has started its first science run in early 2023.
- Recommendation: 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. **The Swiss investment in the construction of the LEGEND-1000 experiment is strongly recommended**, in view of its unique physics potential.
- Comment: 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

Achievements and recommendations 4/4 (IceCube)

- Achievement: The IceCube program started its expansion and has tremendous impact on astrophysical neutrino and atmospheric neutrino oscillations
- Recommendation: The science is compelling for multi-messenger astrophysicists and should be pursued in Switzerland
- Comment: There is currently no plan to contribute to the construction of PINGU or IceCube-Gen2 through infrastructure investments via the FLARE instrument

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Total	7'578		$\simeq 13,200$		$\simeq 2'500$



Effort to shift 10% of budget request to 2029-2032 with limited impact to the physics program

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