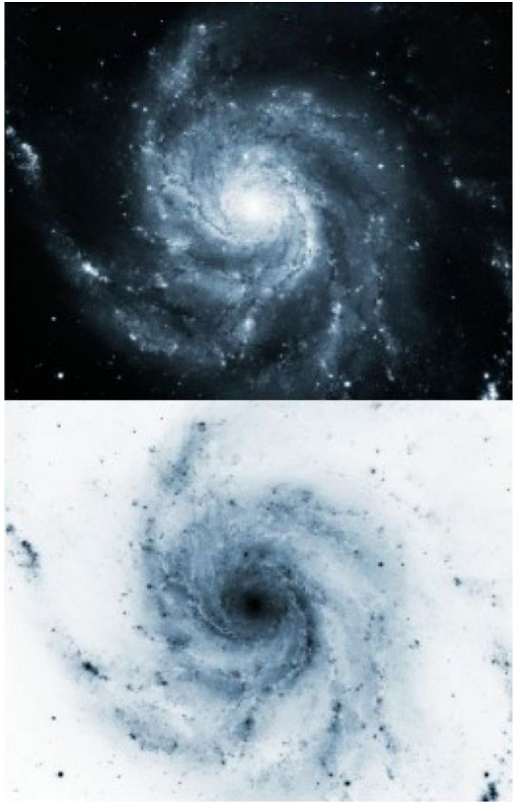
Introduction to Pillar 2

Neutrinos



- SM particle, 2nd most abundant in the universe

- Not fully known
  - Massless in SM, known to have mass through oscillations
  - Absolute mass undetermined
  - Ordering undetermined
  - Nature of mass undetermined (Dirac, Majorana)

- Could reveal CP violation in the lepton sector
- Could reveal BSM
- Astroparticle physics and cosmology (Sun, SN, primordial, HE)
- Hypothetical additional states
- Use of neutrinos as probe (nuclear physics, applications)

- We have the experience and knowledge and technologie to perform measurements to address the above
  - Large set of facilities and experiments ongoing and planned
  - Short-baseline, long-baseline, reactors, sources, low background, ice, ocean, tritium, primordial, BSM, sterile nu, solar hep nu, SN, multimessenger, …

In 2020

- *“The measurement of neutrino properties at long-baseline beam experiments is the highest priority task of the neutrino pillar in Switzerland, and is considered to be a flagship of the overall experimental particle physics programme.”*
- Pursue neutrinoless double-beta decay
- Complementary involvement in IceCube

Table 2: A summary of Swiss involvement in experimental neutrino physics. The experiments are described in Appendix 15.1.2.

Institution	Main involvements
Uni Bern	Long-baseline experiment: DUNE Short-baseline experiments: MicroBooNE, SBN
Uni Genève	Long-baseline experiment: T2K/Hyper-K Ground-based astroparticle experiment: IceCube
Uni Zürich	Neutrinoless double-beta decay experiments: GERDA, LEGEND
ETH Zürich	Long-baseline experiment: T2K/Hyper-K

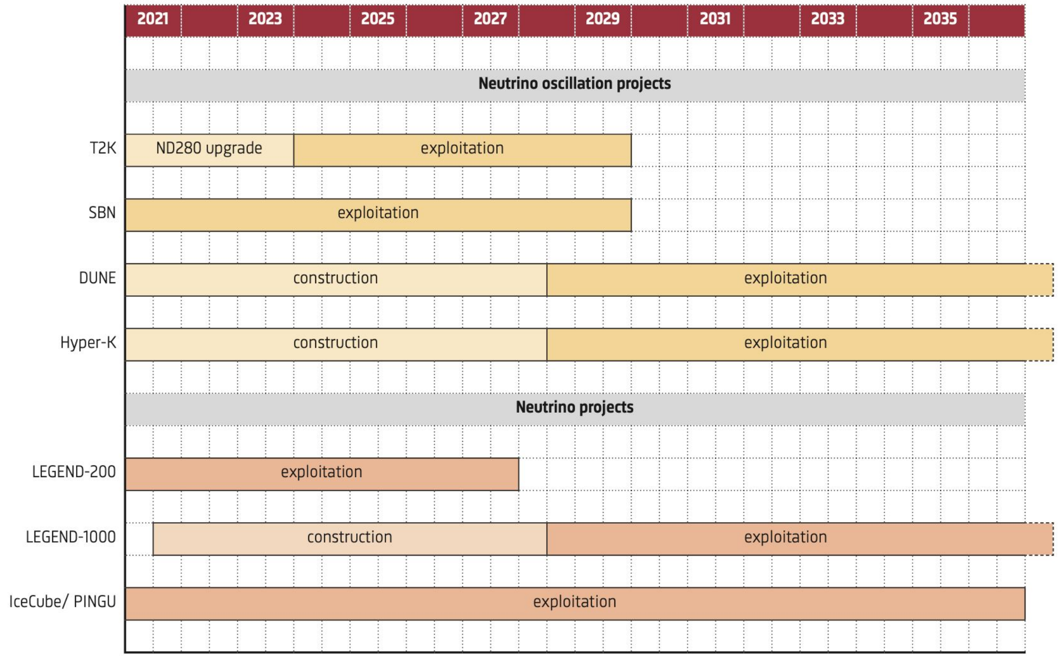
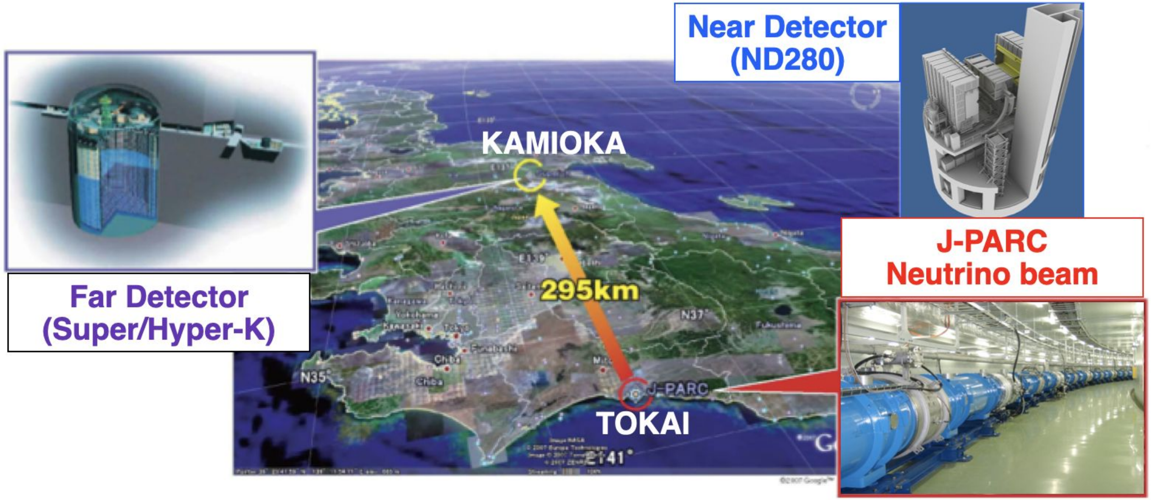


Figure 31: The timeline of major neutrino projects with strong Swiss engagement. The intensity of a given colour indicates the project phase, differentiating between construction (light colour) and exploitation of the machine (dark colour). The timeline of DARWIN is shown in Figure 32.

Well-defined goal: measure the CP violating phase in the leptonic sector, searching for a new source of CP violation, and determine the neutrino mass ordering and mass origin in the next decade

The Japanese program: T2K and Hyper-K

- Intense ν_μ anti-ν_μ neutrino beam from J-PARC to the Near Detector (ND280) and the Far Detector (Super-K and Hyper-K)

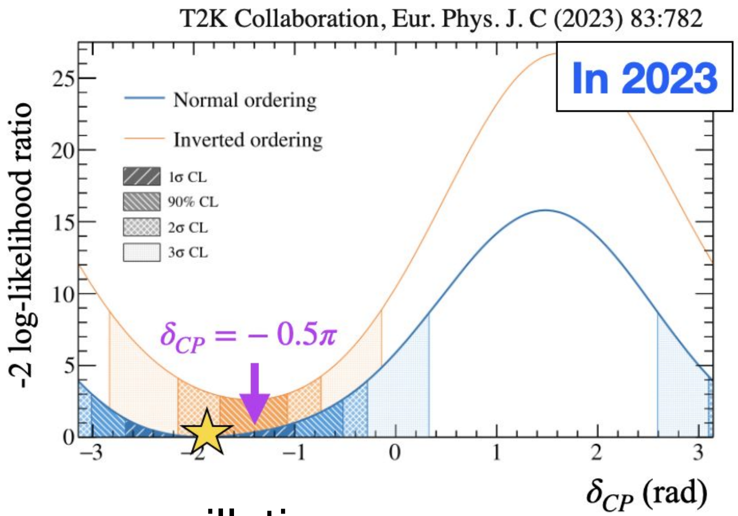


- Search for ν_e appearance
  → Measurement of the last mixing angle θ_{13} and CP violation phase δ_{CP}.

- Precise measurement of ν_μ disappearance → Measurement of θ_{23} and Δm^2_{23}

T2K results: search for CP violation

Leptonic CP violation from asymmetry in $\nu_\mu \rightarrow \nu_e$ and anti-$\nu_\mu \rightarrow$ anti-ν_e oscillations

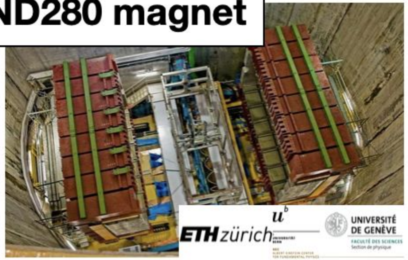


- T2K data observe a maximal difference vs oscillations
  maximal CP violation and normal mass ordering are favoured
- In 2023 also finalised joint analyses with other experiment collaborations:
  - T2K + Super-K atmospheric and T2K + NOvA experiments

The search for CP violation is still dominated by statistical uncertainties

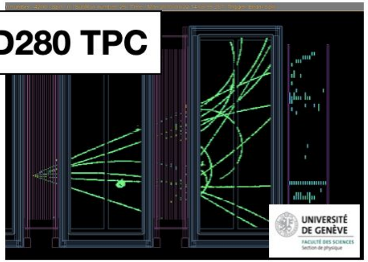
Switzerland’s contributions in T2K: Hardware

ND280 magnet



Refurbishing, Cooling, Maintenance, Slow-control, Mapping, Operation

ND280 TPC



MM R&D and mechanics, Calibration, Operation

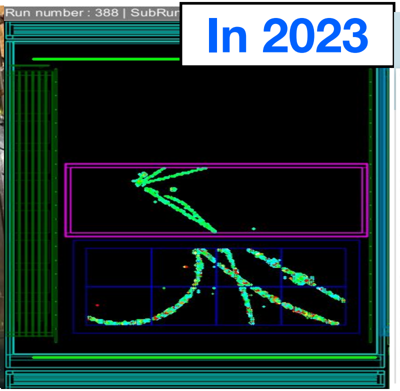
Baby MIND **In 2020**

Concept, Construction, Electronics

Roadmap 2021: “The T2K upgrade, and the near detector infrastructure, to which Swiss groups have made key contributions, are considered to be the precursors of the neutrino observatory Hyper-K, as relates to both the hardware concept and the development of analysis procedures.”

ND280 upgrade

In 2023



T2K experiment enters a new phase with significantly improved sensitivity for its world leading neutrino oscillation research

16 January 2024 - High Energy Accelerator Research Organization (KEK)

The T2K Collaboration has started data taking using the enhanced neutrino beam and new neutrino near-detectors from December 2023. The KEK/J-PARC center has upgraded the main ring accelerator and the neutrino beamline to increase the beam power. T2K has also upgraded its neutrino production instruments. The stable operation of neutrino beam has been successfully achieved at a record high beam intensity (about 710 kW), an increase of about 40% compared to before the upgrade. Furthermore, on December 25th, the continuous operation of neutrino beam has been successfully achieved at 760kW, which is greater than the initial design beam power. The pulsed electromagnet (electromagnetic horn) system, the heart of the neutrino generator, was also upgraded. The current applied to the electromagnetic horn has been increased from 250 kA to 320 kA. This allowed us to increase the neutrino intensity by about 10%. In addition, T2K installed new neutrino detectors that can measure neutrino interactions with even higher precision than before. The newly installed detectors consist of SuperFGD, which detects tracks around a neutrino interaction point inside the detector, High-Angle TPC, which measures momentum of particles emitted over a wide range of angles, and Time-of-Flight, which can detect incoming or outgoing particles and identify particles. Neutrino event candidates were successfully observed during a technical run of the new detectors after the start of beam operation. In 2020, the T2K gave the first hints that the symmetry between matter and antimatter could be violated in neutrino oscillations. With these enhancements, T2K will continue to lead the world in advancing the understanding of neutrino properties and unraveling the mystery of the absence of antimatter in the universe.

More detailed information on this announcement can be found from the KEK webpage:
https://www.kek.jp/en/press-en/202401171405/

DATE ISSUED:
January 16th, 2024

SOURCE:
High Energy Accelerator Research Organization (KEK)

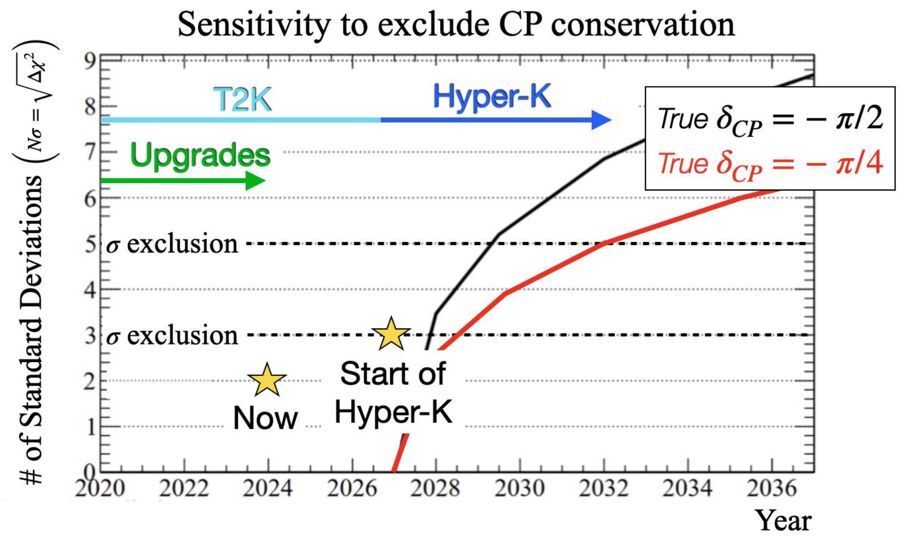
CONTENT:
Press Release

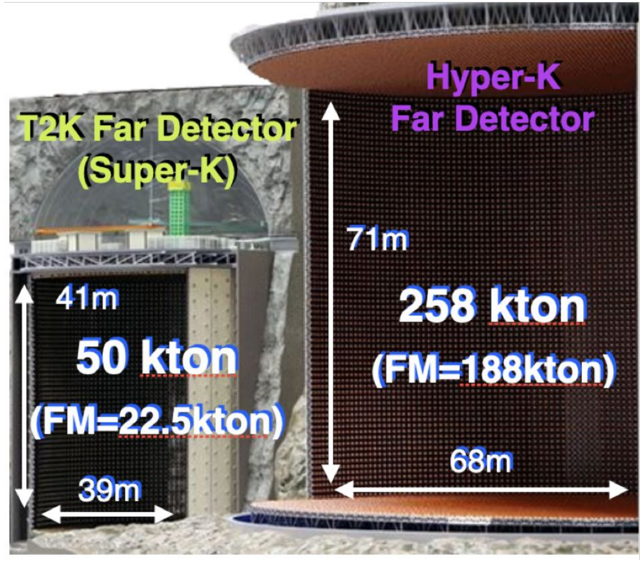
CONTACT:
High Energy Accelerator Research Organization (KEK)
E-mail: press@kek.jp

Press release !

Major contributions and leadership on design, construction of finely-segmented scintillator neutrino target (mechanics, electronics) and ToF detector with the CERN Neutrino PLATFORM → first ν_μ data in 2023 with upgrade beam @764 kW

Towards leptonic δ_{CP} with Hyper-K



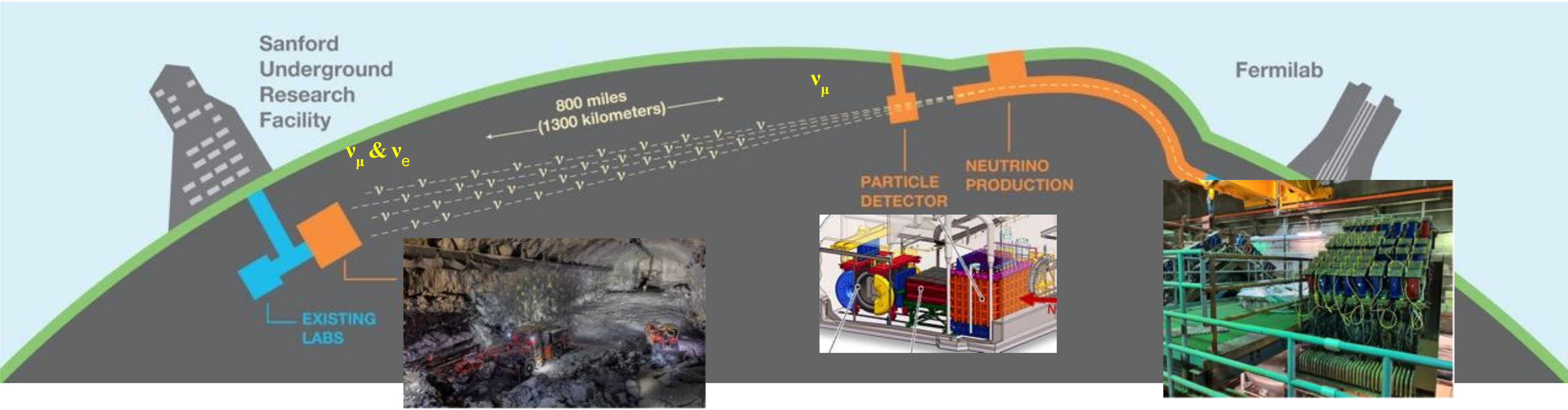


Smooth transition from T2K to Hyper-K, that will inherit the ND280 detector and the neutrino beam that will gradually increase the intensity

2020: we were exploring possible contributions to the electronics of the Hyper-K water-Cherenkov far detector

2023: designed the far detector electronics and, now, moving to the mass production of the underwater mechanics and HV and HV modules

The LBL Neutrino Program in U.S.



Far Detector

- Excavation is >95% complete
- ProtoDUNE tests at CERN
- First detector “wire planes” at SURF (capability to move them underground)
- CH delivers cryogenic equipment

Direct Confederation funding

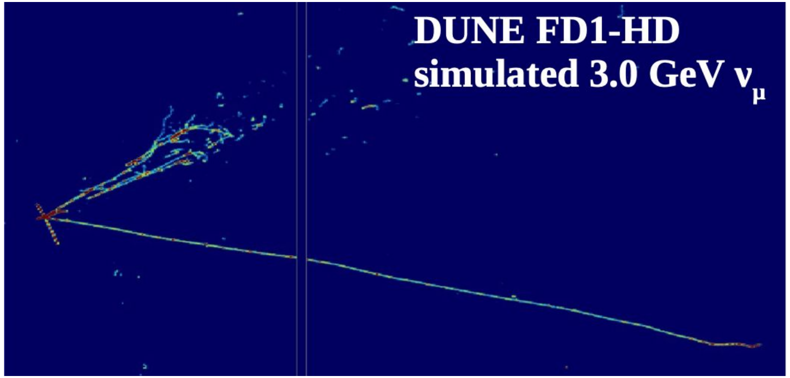
Near Detector

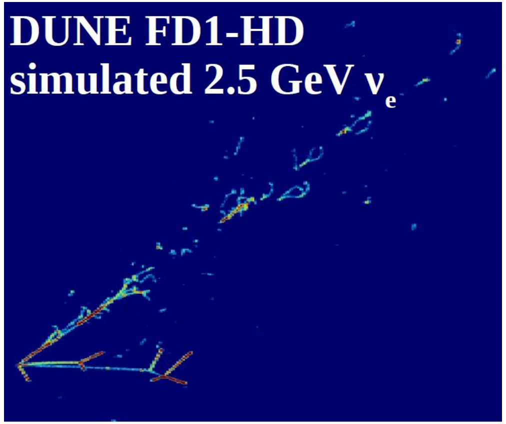
- Near Detector design completed
- CH leading the core component of the ND (ND-LAr)
- 50% scope is CH
- Near site facilities 100% designed

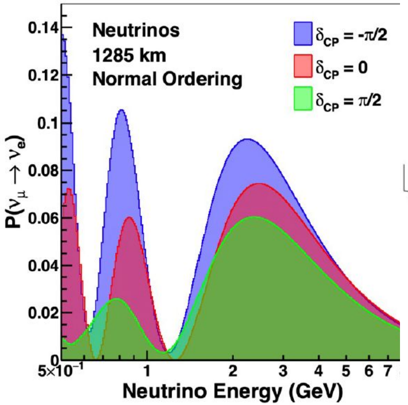
Critical Swiss role in global strategy

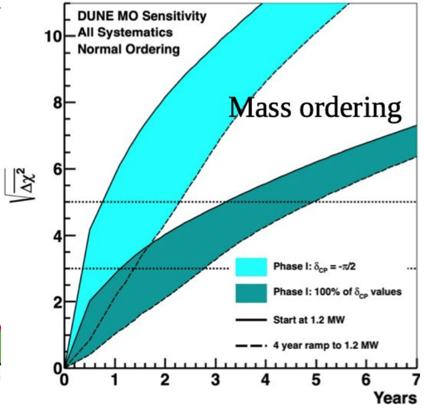
DUNE program

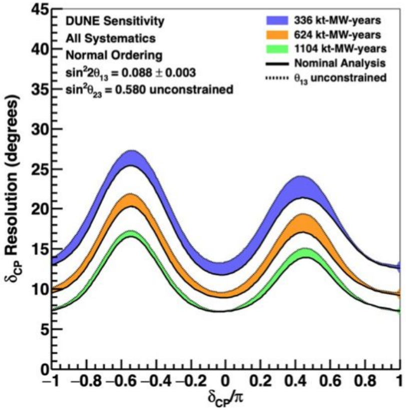
- Based on liquid argon TPCs
  - 3D imaging of neutrino interactions
- Wideband beam and 1300 km
  - resolve degeneracies by measuring flavor transitions as a function of energy over more than a full oscillation period
- Broad physics program for astroparticle and BSM
  - Capable near detector in a very intense neutrino beam
  - Large detectors underground at the far detector





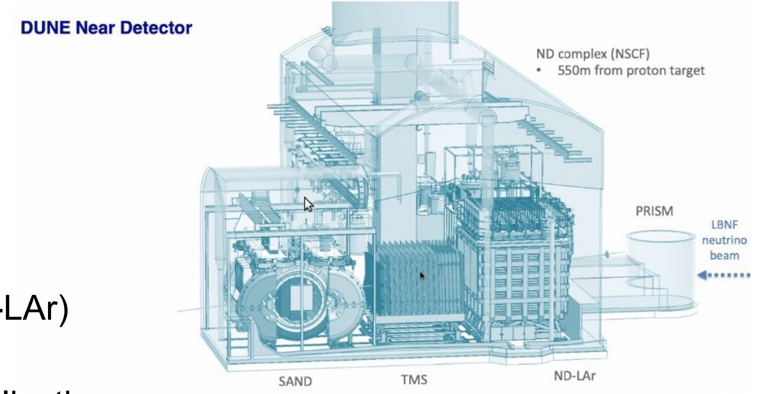


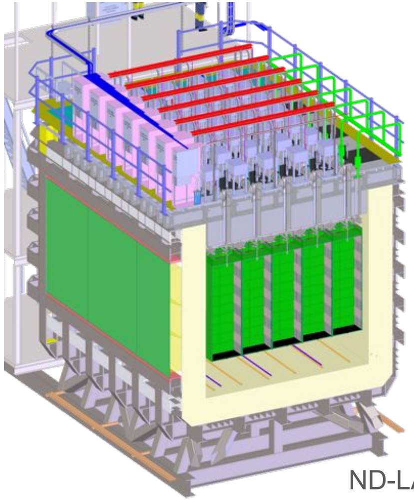




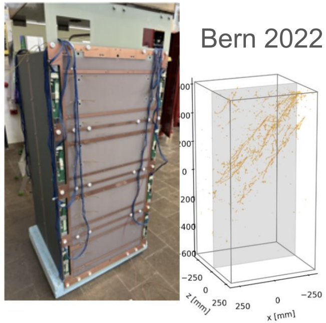
Swiss contributions and plans

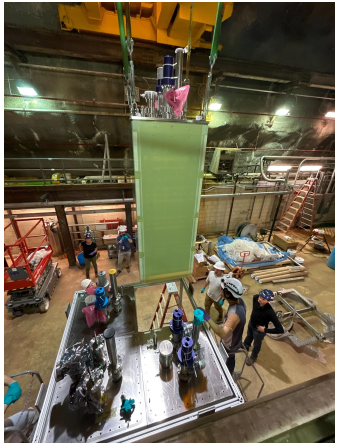
- long-time experience in the LArTPC technology, with major breakthroughs in Switzerland
  - Dual-phase, modular design, native 3D imaging, …
- ArgonCube design developed in Bern chosen as ND option (ND-LAr)
- Involvement in the short-baseline program also using LAr, cosmic ray mitigation, calibration, physics coordination, 50+ publications
- Completed R&D in 2019, successful prototyping in Bern 2020–2023.
- Beam test with neutrinos to start taking data at Fermilab imminently
- Reconstruction and analysis frameworks developed
- Full 1:1 size pre-production module test in Bern 2024
- Production 2025–2027




ND-LAr

Module 2


Bern 2022

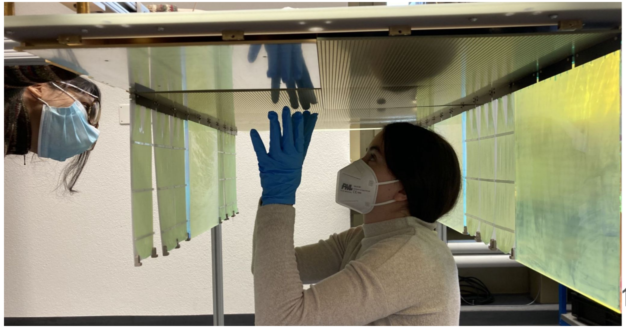

FNAL, 2x2, Dec 2023

DUNE – CH progress, path

- **CDR** July 2020 *(Instruments 2021, 5(4), 31);* **PDR/TDR** June 2022
  - Technical design confirmed, meets requirements; recommendations for demonstrator program (for FDR)
  - Switzerland covers 50% of the CORE scope, overall detector concept expertize
- Negotiations CH-USA starting in 2013,
  DUNE in Swiss infrastructure Roadmap 2017—2020,
  funds in FLARE 2021—2024
- Reciprocal visits USA—CH—CERN (2018, 2019, 2021, 2022)
- MoU signed 2023
- 2029 start of physics with FD
- 2028 Near Detector Hall completed, 2030 ND and beam

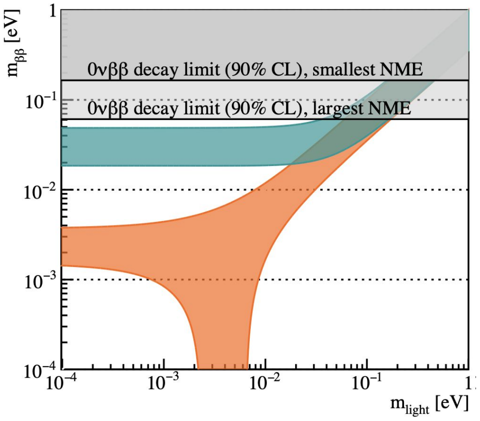
New building at Fermilab for ND-LAr construction

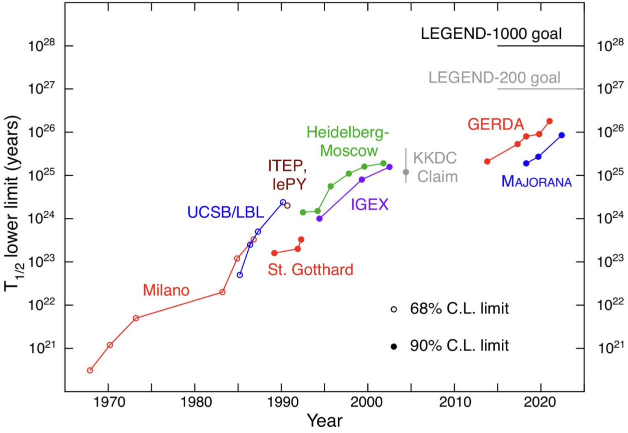
Visit M. Hirayama FNAL, Nov 2022



GERDA and LEGEND

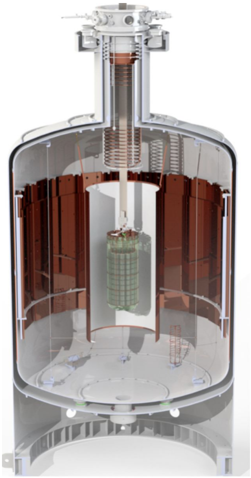
- Search for 0νββ-decay of ^{76}Ge with enriched, HPGe detectors operated in LAr
- Excellent energy resolution, quasi zero-background, high efficiency for the 2 e^-
- GERDA final results (PRL 125), 127.2 kg y exposure: $T_{1/2} > 1.8 \times 10^{26}$ y (90% CL)

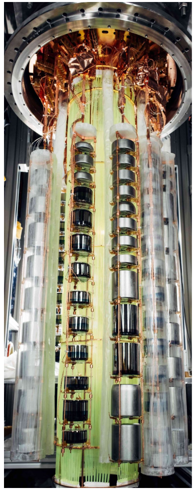




LEGEND: a two-phase approach

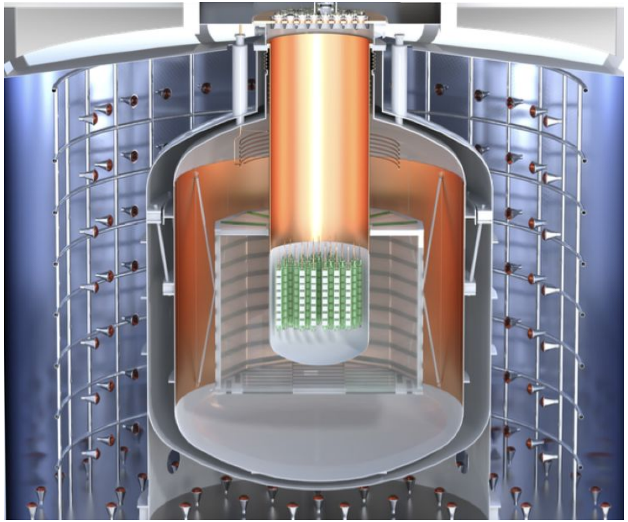
- LEGEND-200: taking data with 142 kg enriched HPGe detectors in upgraded GERDA infrastructure at LNGS
- LEGEND-1000: CD1 review phase; to be constructed in Hall C of LNGS





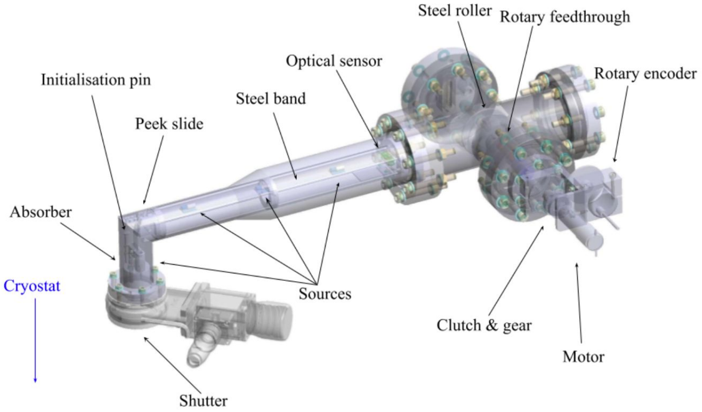
LEGEND-200
Science data since
early 2023

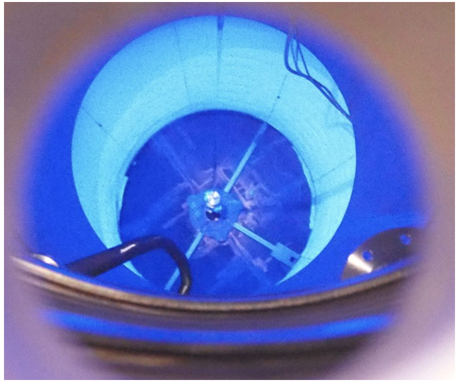
LEGEND-1000
CD1 review phase
First data: ~ 2030

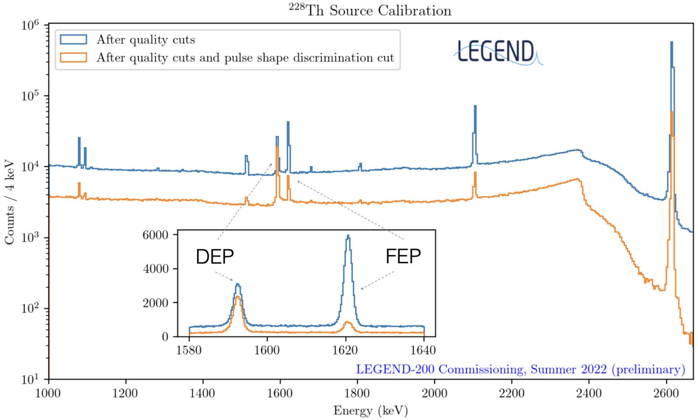


UZH contributions to LEGEND

- Calibration systems hardware and software (co-leading calibration task group, with LANL)
- Liquid argon instrumentation (with TUM)
- Detectors and characterizations (co-leading HPGe detector production task group, with UNC)
- Materials radio-assay with dedicated HPGe facility (Gator) at LNGS

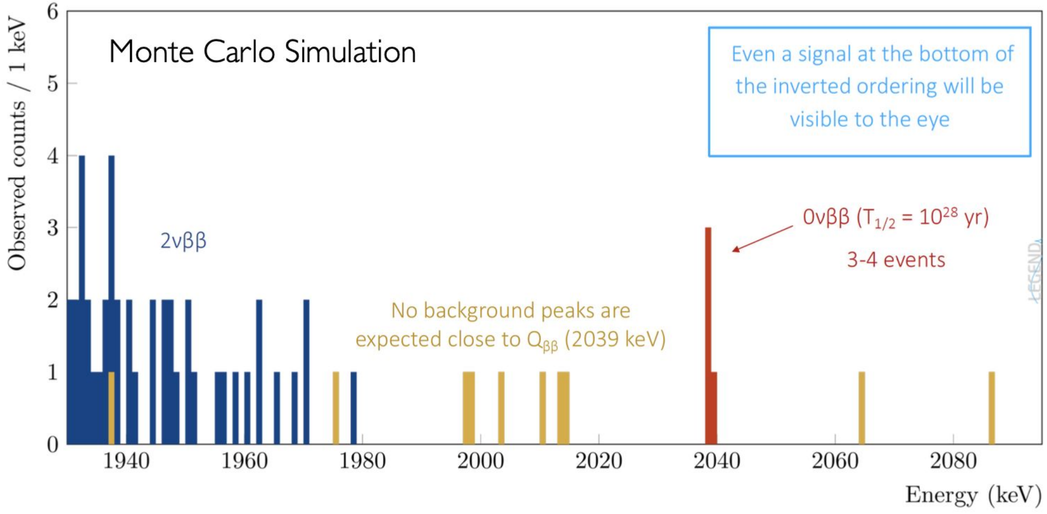


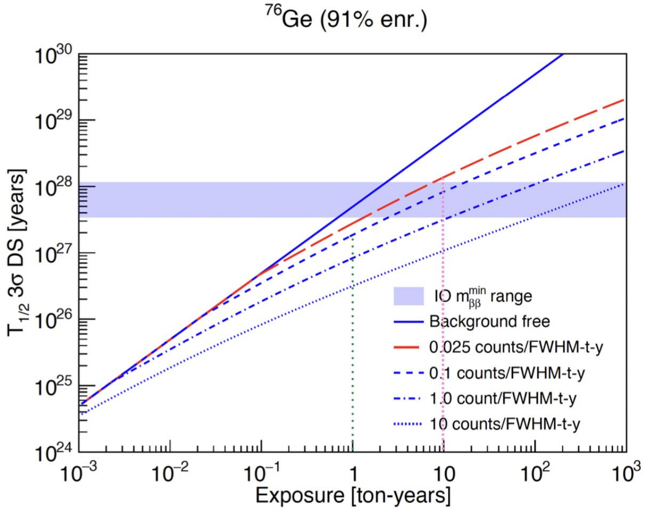




What would a discovery in LEGEND look like?

- Due to superb energy resolution (σ/E ~ 0.05%): no peaks near the ROI
- Background measured in situ, no reliance on modeling





IceCube and its future

IceCube 2005-2012

DeepCore $1\nu_\mu$/15 min; Upgrade $1\nu_\mu$/4 min for atmospheric neutrino oscillations

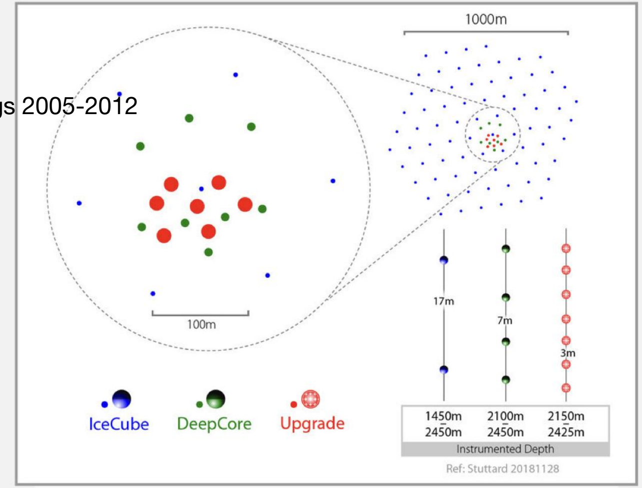
- IceCube
  - DeepCore
  - IceTop

  } Done & Delivering

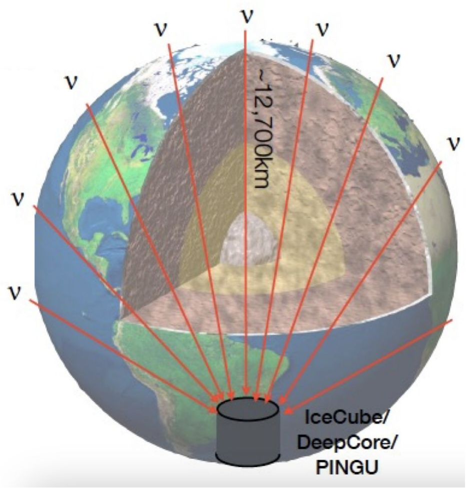
  86 + Deepcore 8 strings 2005-2012
- Upgrade } Underway

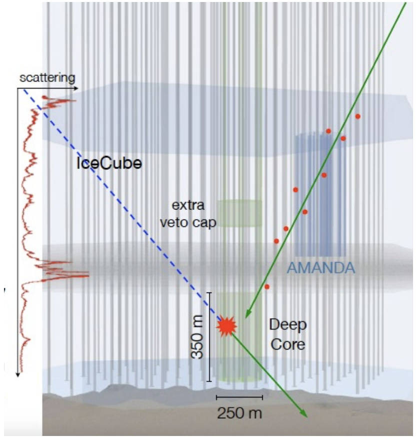
  7 strings 2023-2026
- IceCube-Gen2
  - Full } X 10 IceCube

    Astro2020 Review Preliminary Design in Preparation



- 10 megaton volume
- string spacing : 125m → 35m → 22m
- module spacing: 17m → 7m → 3 m

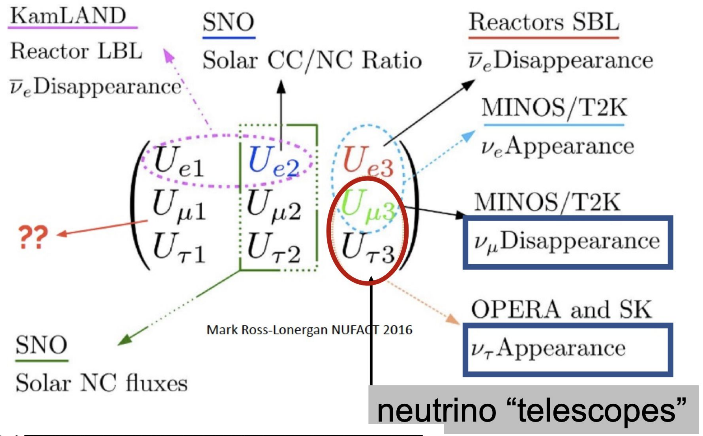




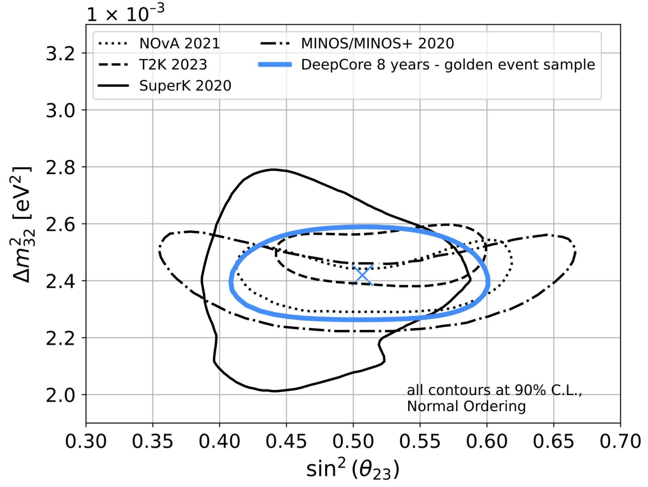
Recent results

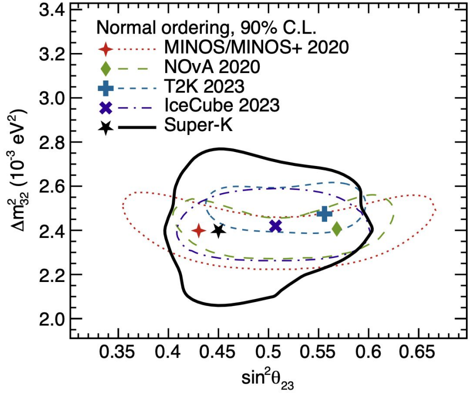
IceCube 2023 8 yr

The PMNS mixing matrix

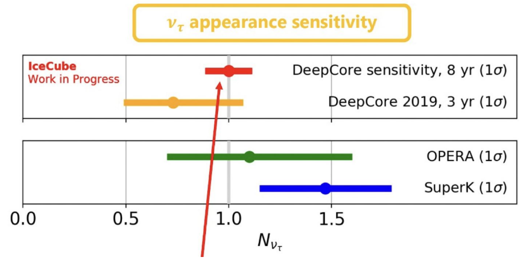


$\sin^2\theta_{23} = 0.51 \pm 0.05$ $\Delta m^2_{32} = 2.41 \pm 0.07 \times 10^{-3}$ eV^2





Upgrade is x 3 improvement with respect to DeepCore



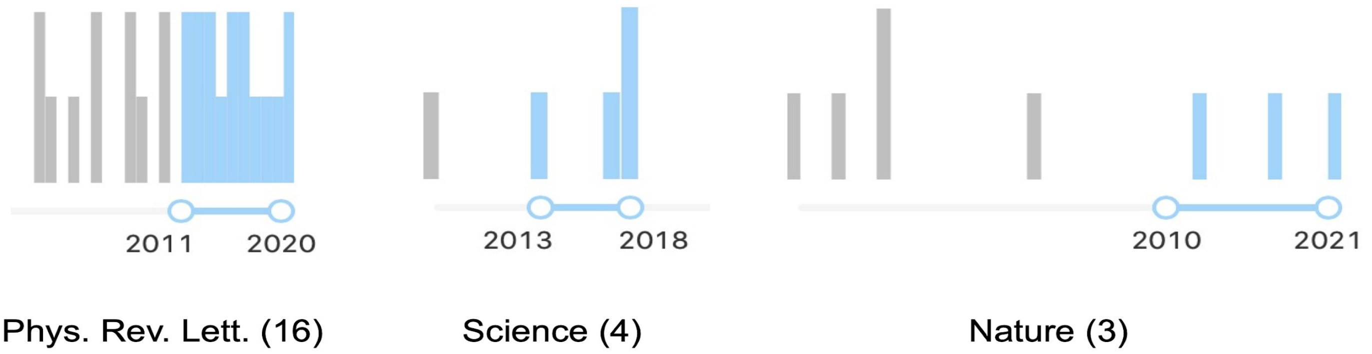
New 8 yr analysis sensitivity → 11,000 ν_τ expected
12% precision expected → 2.5x current world best

SK
https://arxiv.org/pdf/2311.05105.pdf

The future

Excellent science complementary to accelerator neutrinos + sensitivity to supernova neutrinos + discovered cosmic extragalactic and galactic neutrinos

- Upgrade 2023-2026
- PINGU + 40 strings
- IceCube-Gen 2 x 10 to 2033



no evidence of decline of new results in 10 years

Conclusions

Well-defined goal: measure the CP violating phase in the leptonic sector, searching for a new source of CP violation, and determine the neutrino mass ordering and mass origin in the next decade

Coherent program that focuses on very few experiments and involvements:

- HK and DUNE
- LEGEND
- IceCube

Well balanced plan that takes advantage of the extraordinary experience and capability of Swiss groups -> great impact and visibility for Swiss particle physics

Swiss researchers held/holding major responsibility roles (Spokespeople, coordinators, international review bodies, representations)