Neutrinos ~ Weird ~ Interesting ~ Unknown

Pablo FM (USC-IGFAE)

IGFAE Retreat, 2026/06/21

Neutrinos

- Neutrinos are the most unknown particles and the first signature of physics beyond the Standard Model.
- Although assumed massless, in 1998 and 2001, it was discovered that neutrinos change flavor during propagation (oscillations) through the measurement of atmospheric (Super-Kamiokande) and solar (SNO) neutrinos (Nobel 2015).
- Since then, experiments not only have delved into their properties but explored their potential to unravel astrophysical (IceCube, Pierre Auger, Km3NeT) and BSM phenomena (indirect dark matter, CPT violation, sterile neutrinos, etc.)

Neutrino Oscillations

- Since then, many experiments have attempted to measure oscillation parameters (solar, reactor, atmospheric, accelerator neutrinos)
- Now, we have a rather clear picture that the mixing of neutrinos (PMNS matrix) is way larger than for quarks (CKM matrix)
- Still, we lack of precision measurements of the most important parameters, namely the CP phase and the mass ordering (which neutrino is the heaviest)
- Phenomenology and experiment work together to improve these crucial measurements in the understanding of our universe

Next generation experiments such as Hyper-Kamiokande and DUNE will improve the statistics and precision of the remaining unknowns, but pose many challenges

** Neutrino oscillations are ignorant of the masses, only see there differences*

Hyper-Kamiokande & WCTE @ IGFAE

Calibration sources for water Cherenkov detectors

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IGFAE Retreat — June 2026

IGFAE – Universidade de Santiago de Compostela

The IGFAE group

Within the Hyper-Kamiokande collaboration (Japan) and the WCTE test experiment (CERN), with Spanish participation (IGFAE, DIPC, IFAE, UAM, UPV, LSC).

IGFAE group

- D. Costas Rodríguez
- J.A. Hernando Morata
- P. Fernández Menéndez

External collaborators

- **DIPC:** H. Almazán, A. Saborido†, E. Ramos
- J. Renner‡

† A. Saborido: previous USC student.

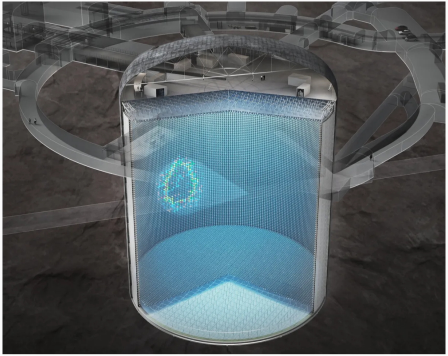
‡ J. Renner: ex-junior fellow IGFAE.

Hyper-Kamiokande (Japan) and its reach

Next-generation 258-kton water Cherenkov detector in Kamioka ($\sim$8$\times$ the SK fiducial volume), $\sim$20,000 50-cm PMTs plus multi-PMTs. Assembly starts autumn 2026; operation likely early 2028.

Physics reach:

- CP violation with $\nu_\mu/\bar{\nu}_\mu$ from the J-PARC beam (upgraded to 1.3 MW).
- Atmospheric neutrinos (mass ordering, oscillation params.).
- Neutrinos from supernovae (burst + diffuse relic).
- Proton decay ($p \to e^+\pi^0$ beyond 10^{35} yr).



HK far detector: 258-kton water Cherenkov tank (cutaway).

WCTE (CERN) and its reach

- Water Cherenkov Test Experiment at CERN's T9 beamline: a $\sim$40-ton, $\sim$4 m cylindrical water tank with $\sim$100 multi-PMTs (Hyper-K style). Operation during 2025.
- Test bench for Hyper-K and the IWCD: verification of the multi-PMTs, the DAQ, and the calibration and reconstruction algorithms.
- Using $e/\mu/\pi$ beams of controlled energies at CERN $\Rightarrow$ particle ID, light yield, detector modelling — and a testbed for the IGFAE NiCf source.

WCTE interior: multi-PMTs lit during operation.

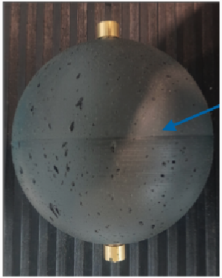
IGFAE calibration sources: NiCf (γ) and AmBe (n)

NiCf γ-source — PMT calibration (WCTE & HK)

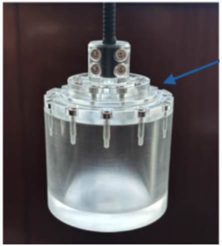
- $\sim$isotropic light source for the single-photoelectron (SPE) response of the multi-PMTs.
- ^{252}Cf spontaneous fission $\rightarrow$ neutrons; capture $^{58}\mathrm{Ni}(n,\gamma)^{59}\mathrm{Ni}$ $\rightarrow$ $\sim$9 MeV γ cascade.
- ^{252}Cf (10 μCi) in a Ni ball (NiO+epoxy+HDPE), $\sim$9 cm diameter. Built at IGFAE, taking data in WCTE.

AmBe neutron source — neutron detection efficiency

- Goal: optimise and determine the neutron-detection efficiency of WCTE / HK.
- AmBe+BGO tagged source: (α, n) on ^{9}Be $\rightarrow$ neutron + 4.4 MeV γ (tagged in BGO), then delayed n-capture.



NiCf ball (γ)

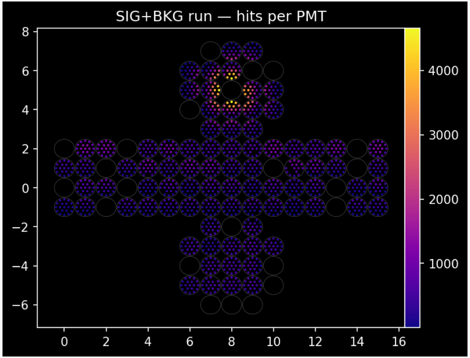


AmBe + BGO (n)

IGFAE-built sources.

First results: simulation + WCTE data

- **Simulation (WCSim + standalone).** ^{252}Cf spontaneous fission needs GEANT4.11 (standalone), fed into WCSim. With the HK far-detector geometry: ∼32 hits/event, consistent with SK; ∼0.002 hits/PMT/event (SK ref. 0.004). Source size adequate; HK may need a slightly larger one.
- **WCTE data.** NiCf used to calibrate the relative quantum efficiency (RQE, data/MC) and the angular acceptance across 4 source positions. A group of mPMTs shows lower RQE, consistent with the cosmic-muon study.
- Demonstrated: the NiCf source works for RQE + angular-acceptance calibration. Now starting NiCf manufacturing for HK.
- Article in preparation (description, deployment and results) with our DIPC colleagues.



WCTE data: detector illuminated by the NiCf γ-source — hits per PMT.

Conclusions — IGFAE in WCTE / HK

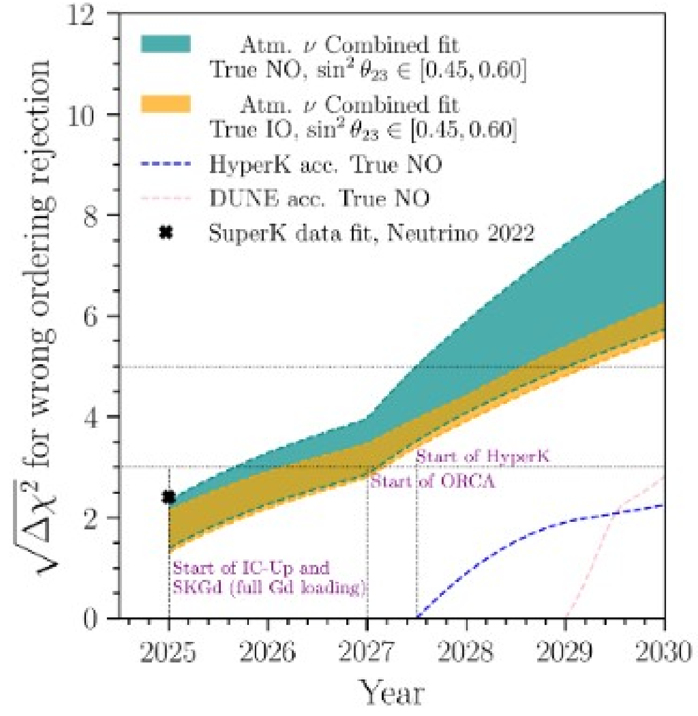
- IGFAE contribution to the WCTE/HK calibration (γ and neutron sources).
- Contribution on NN reconstruction in WCTE.
- Analysis of the diffuse supernova neutrino background.
- Contributions on neutrino-oscillation fitting procedures.
- Preparation of the Spain HK meeting (IGFAE, 6–7 July 2026 — soon!).
- Preparing for installation: shifts in HK — we need you!


Greetings from
Kamioka
INSTITUTO GALEGO DE FISICA DE ALTAS ENERXIAS
IGFAE

Don’t miss the HyperK seminar on July 6 at 12:00!!

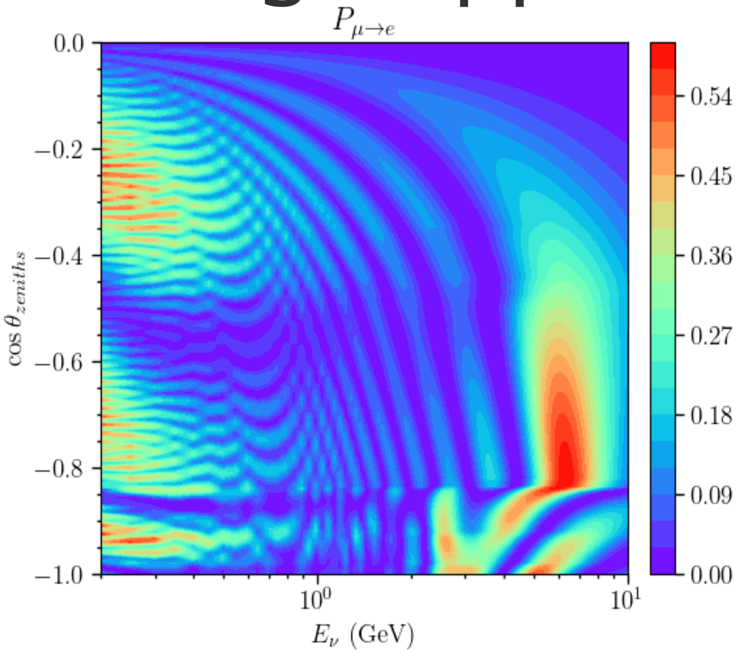
Strategic approach

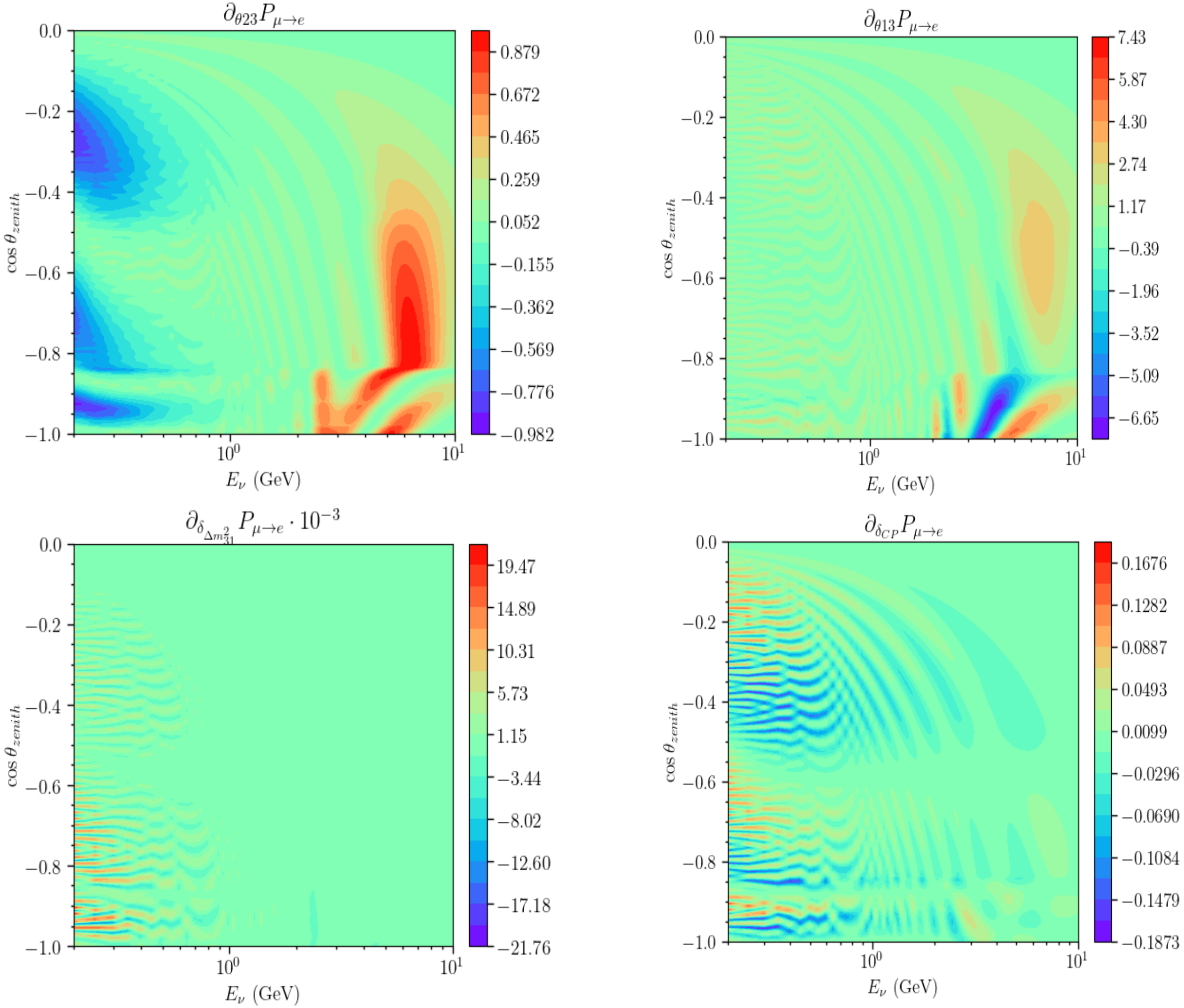
- Atmospheric neutrinos are still the most sensitive to the neutrino mass ordering through the resonance in oscillations through Earth’s core and mantle.
- Pioneering a combined fit of all atmospheric data to enhance the precision of this measurement before the next-generation experiments begin.
  → A combined analysis of SuperK, IceCube and OR
  - First step: Pheno studies, virtually finished
  - Next: Coordinate with the three collaborations to conduct this fit with official tools and data (~next year)



- This kind of analyses require more advance tools which are included in the framework “Pynu”. Built for flexibility, accommodating many experiments and correlations efficiently, and newer methods mostly based on differentiation

Strategic approach

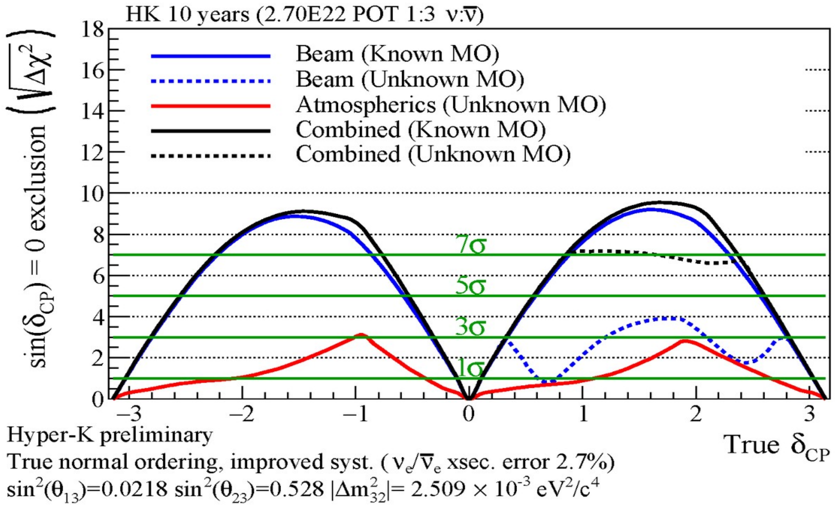


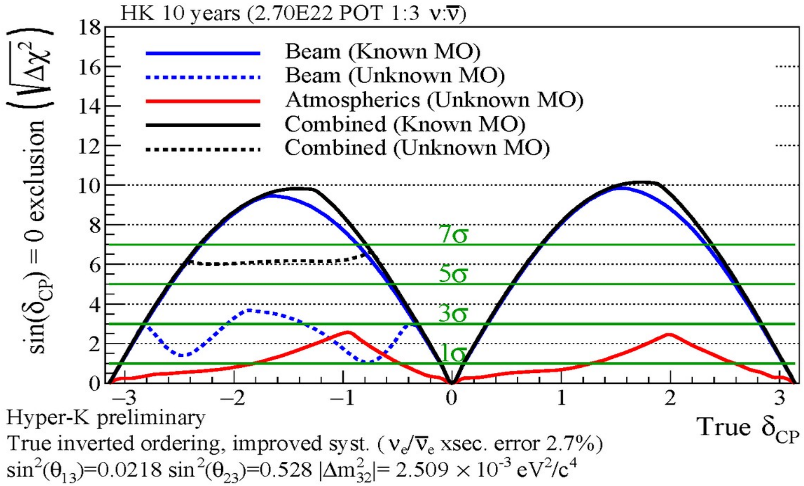


- One of the recent advancements is the CHIC program to compute oscillations and their derivatives
- Bringing new physics insights and analysis capabilities

Strategic approach

- Next, we will use these new tools and results to analyze the new atmospheric and accelerator neutrino data of Hyper-Kamiokande with the aim of measuring with precision the leptonic CP phase





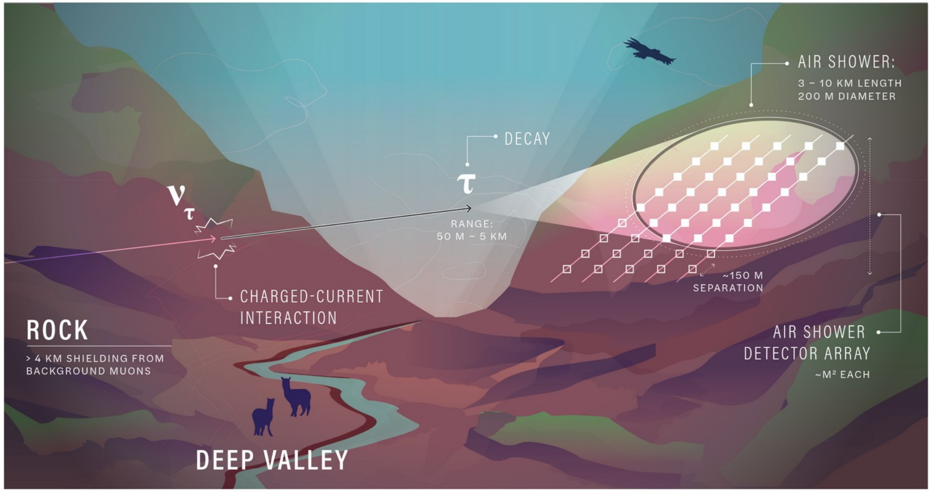
- Along the way, these new approaches
  - Enable new phenomenological studies that enrich the physics programs
  - Improved treatment of experimental calibration and uncertainties

Experiments: TAMBO

- Besides, we are (re)starting our involvement in TAMBO (Tau Air-shower Mountain-Based Observatory)

- Study astrophysical tau neutrinos
  - Little background
  - Unexplored energy region

- To be built at the Colca Valley (Perú), it will consist on arrays of detectors at the hill
  → Exploring contributions in the R&D of water-Cherenkov detectors and physics



TAU AIR-SHOWER MOUNTAIN-BASED OBSERVATORY (TAMBO)