Neutrino Physics: Status and prospects

Davide Sgalaberna (ETH Zurich)

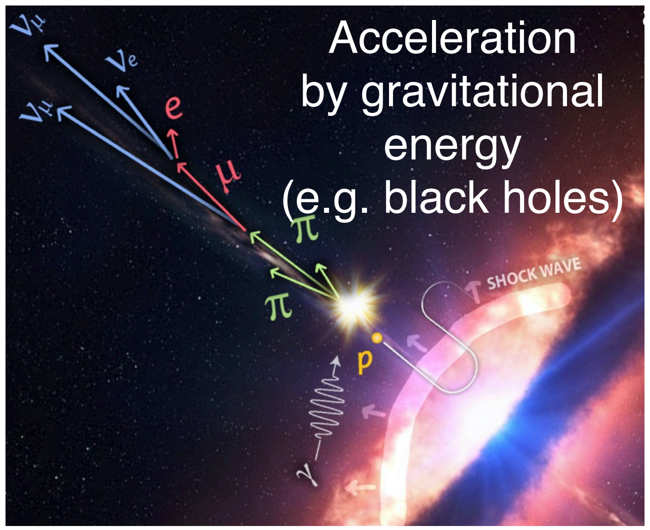
CHIPP/CHART meeting, June 15th 2023

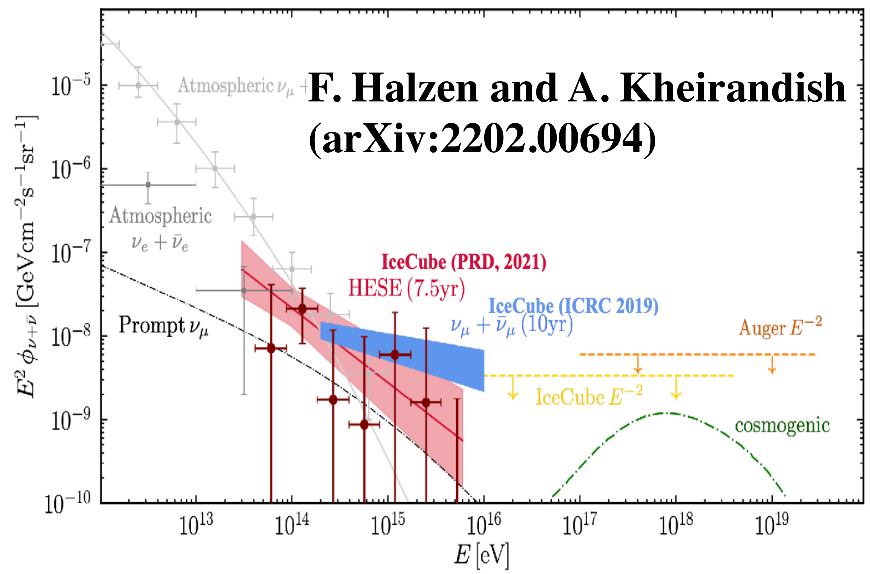
An overview with a focus on CHIPP activities

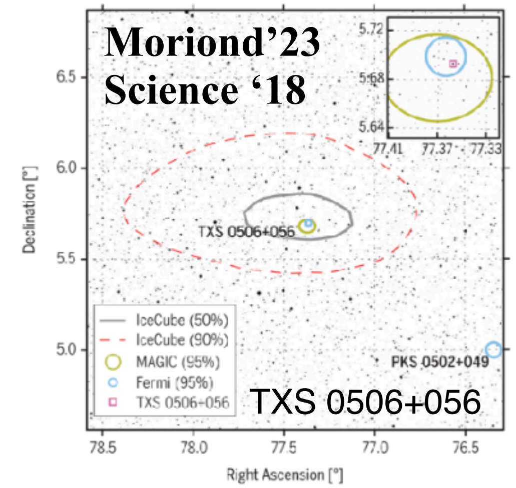
- Astrophysical Neutrinos
- Neutrino oscillation experiments
  - ✓Atmospheric
  - ✓Long-baseline
  - ✓Short-baseline
  - ✓Reactors
- Neutrino Mass
  - ✓ν-less $\beta\beta$ decay experiments
  - ✓Neutrino Mass experiments

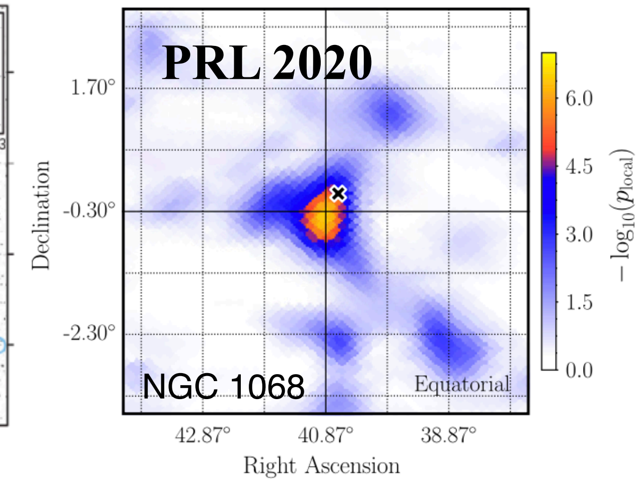
High-Energy astronomical neutrinos

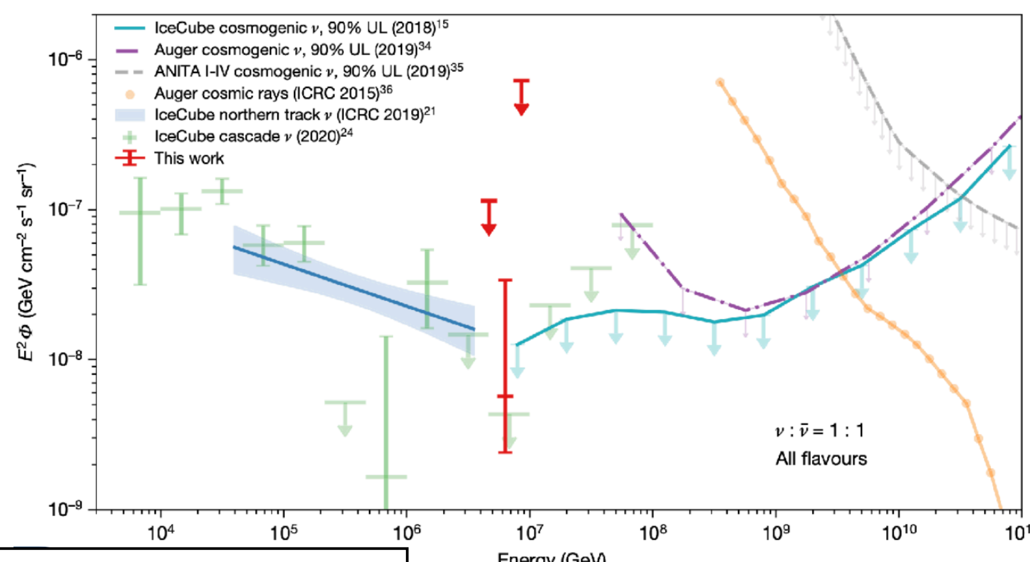
IceCube: 1km³ of ice instrumented with 5’160 PMTs below 1450m in the Antartic



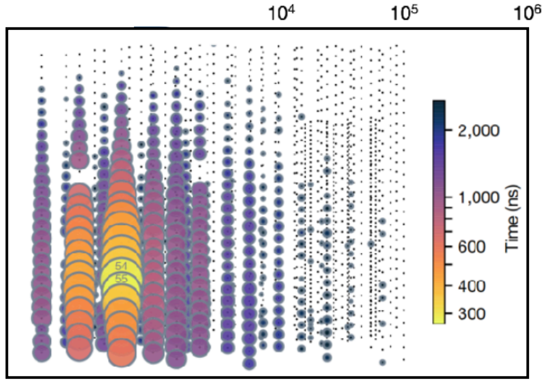








IceCube (Nature, 2021)



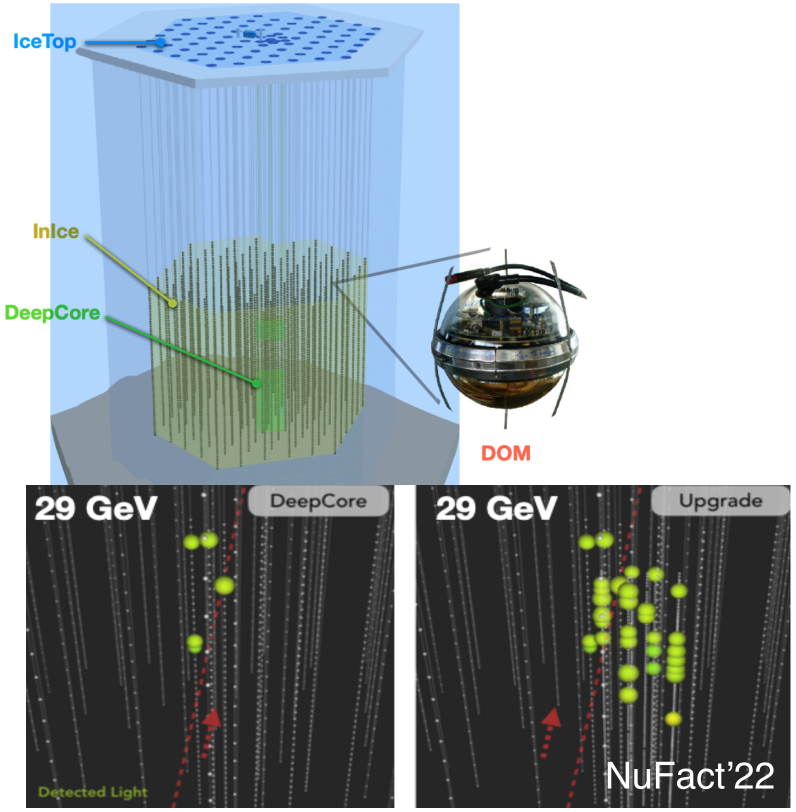
Cascade event (6.05 ± 0.72 PeV) consistent with resonant formation of a W⁻ predicted by Glashow

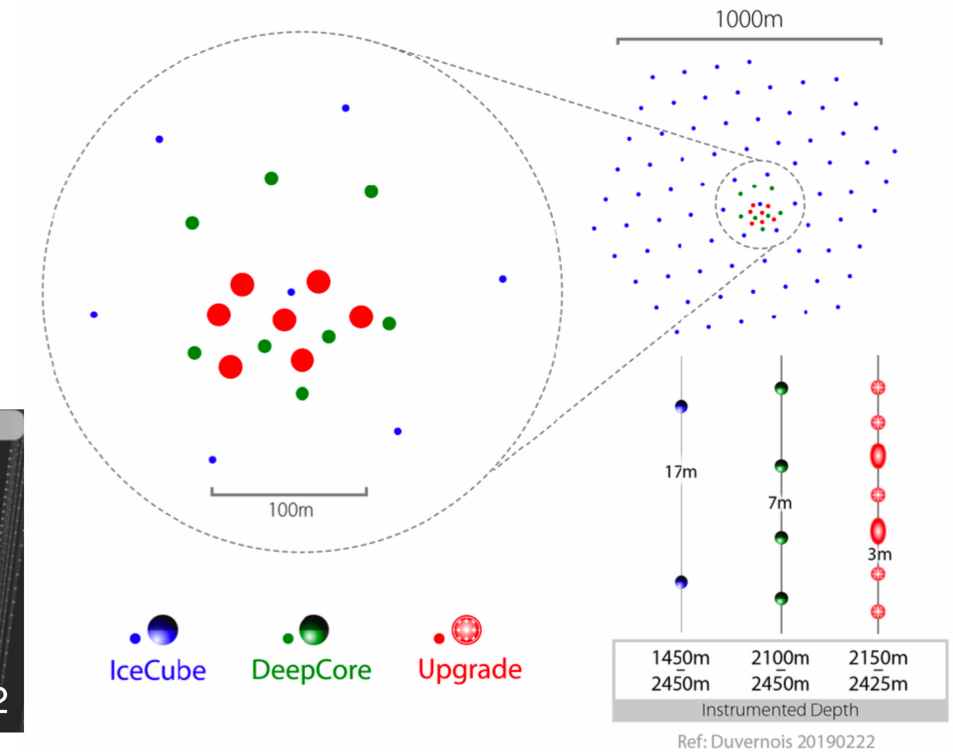
Detection of the origin of the source:

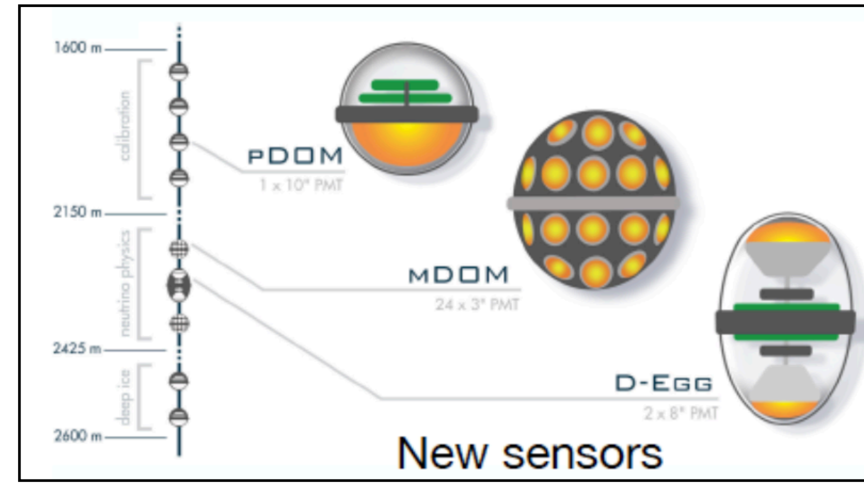
- Galactic (APJL, 2022)
  Supernova, Pulsar, etc.
- Extragalactic
  Active galactic nuclei, gamma ray bursts, clusters, coincidence
- Multi-messenger (ApJ, 2021)
  Blazar TXS 0506+056
- Full-sky scans
  Seyfert II galaxy NGC 1068

Swiss Institute of Particle Physics

IceCube Upgrade and Future Plans

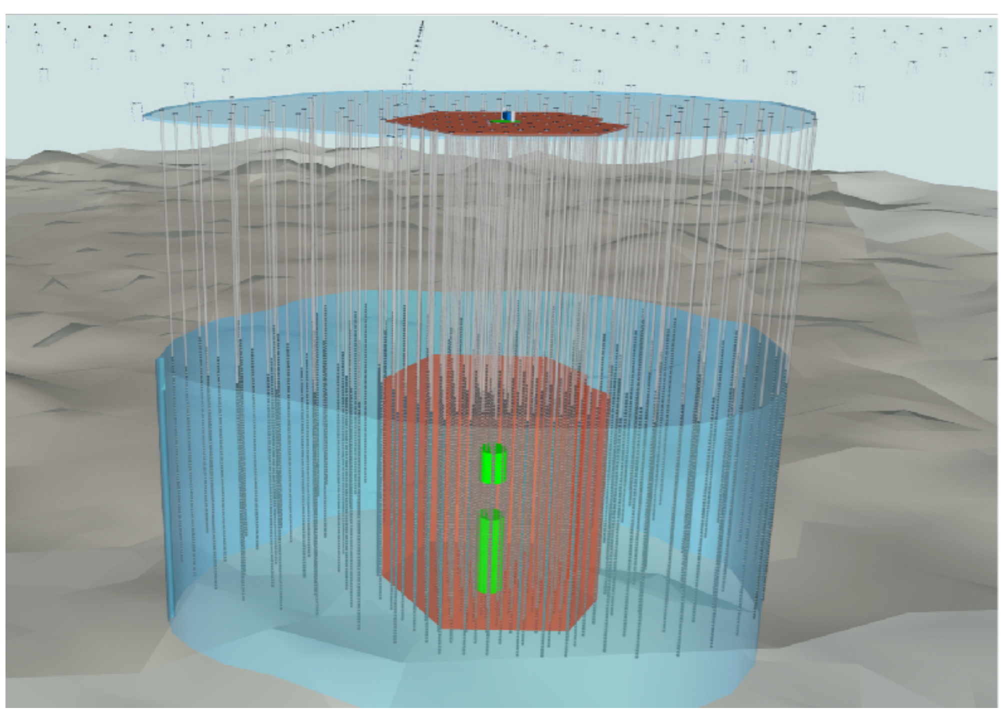






Upgrade: > 800 new devices, reduced spacing between modules. String deployment in 2025-26

New Multi-PMTs per modules
- Larger photocathode area
- Increased angular acceptance



IceCube Gen-2:

✓X5 better sensitivity than IceCube array

✓Eight times larger active volume

✓Surface air shower array for coincidence events and Radio array for EeV neutrinos

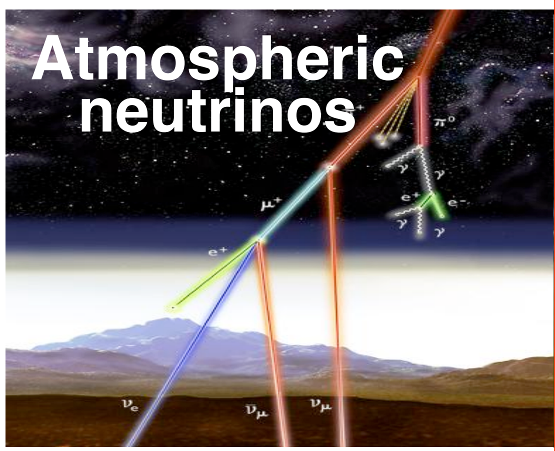
KM3Net: similar concept, located in the Mediterranean see. Installation ongoing

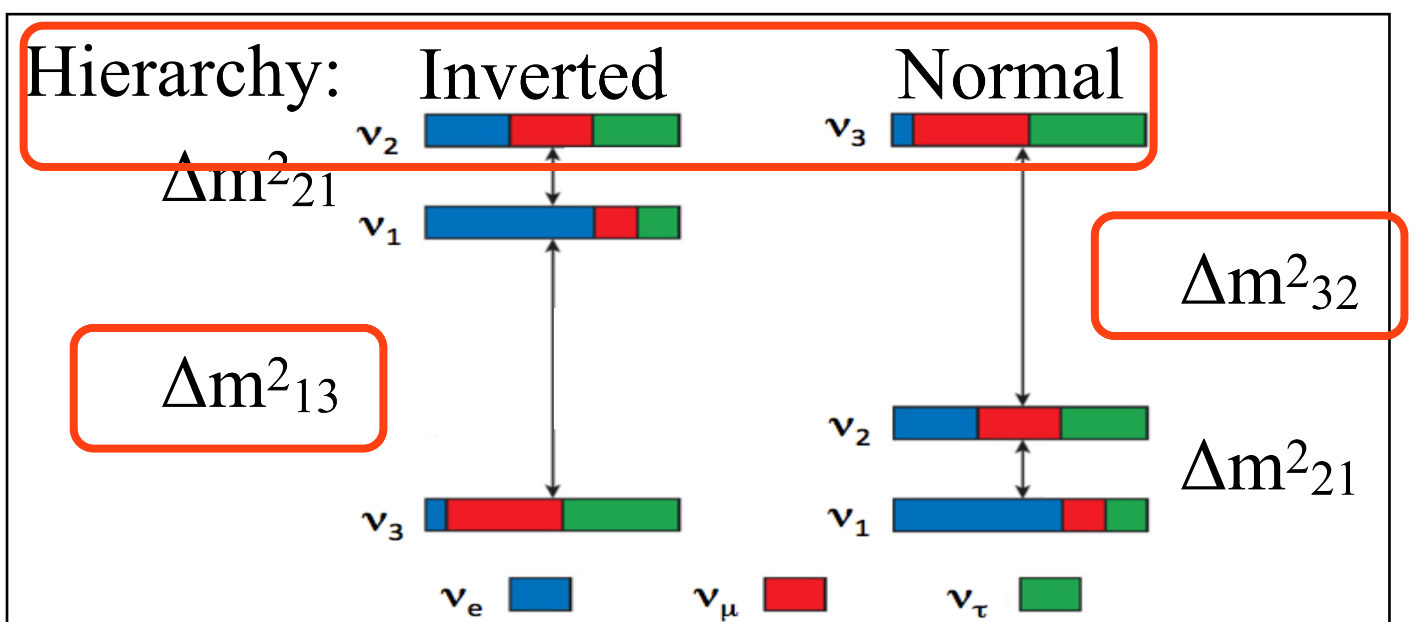
Measuring the neutrino oscillation parameters

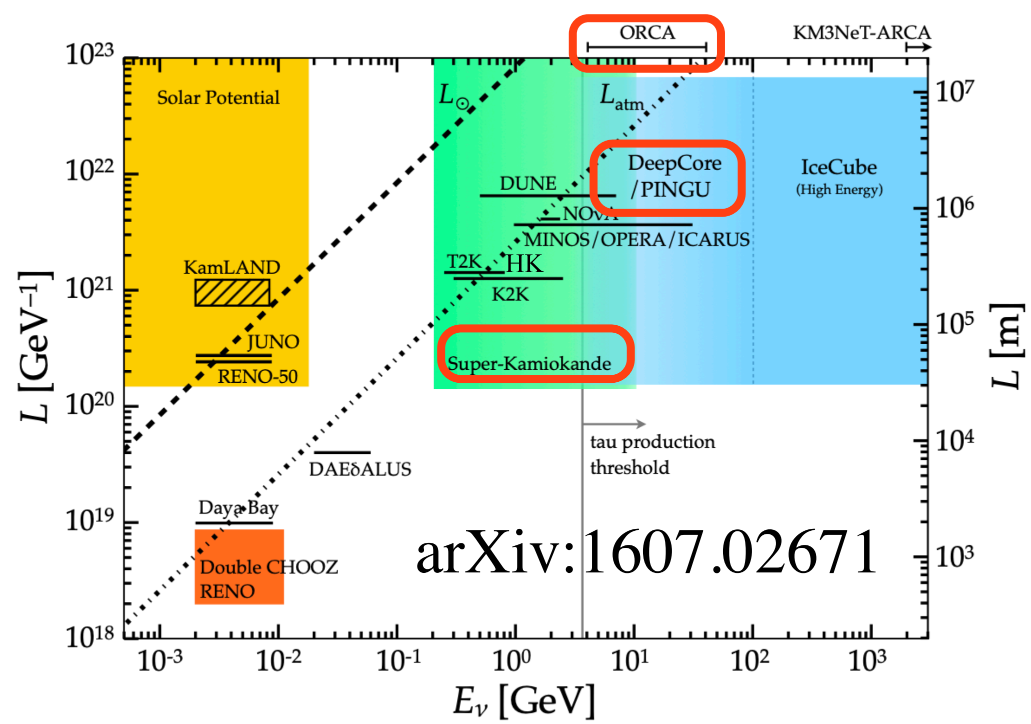
$$U_{PMNS} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta_{CP}} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta_{CP}} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

$c_{ij} = \cos\theta_{ij}$

$s_{ij} = \sin\theta_{ij}$







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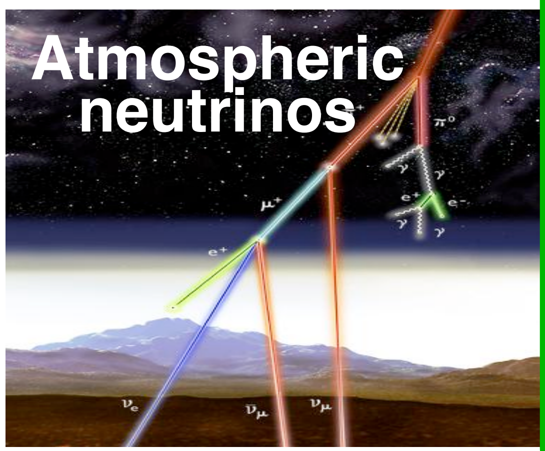

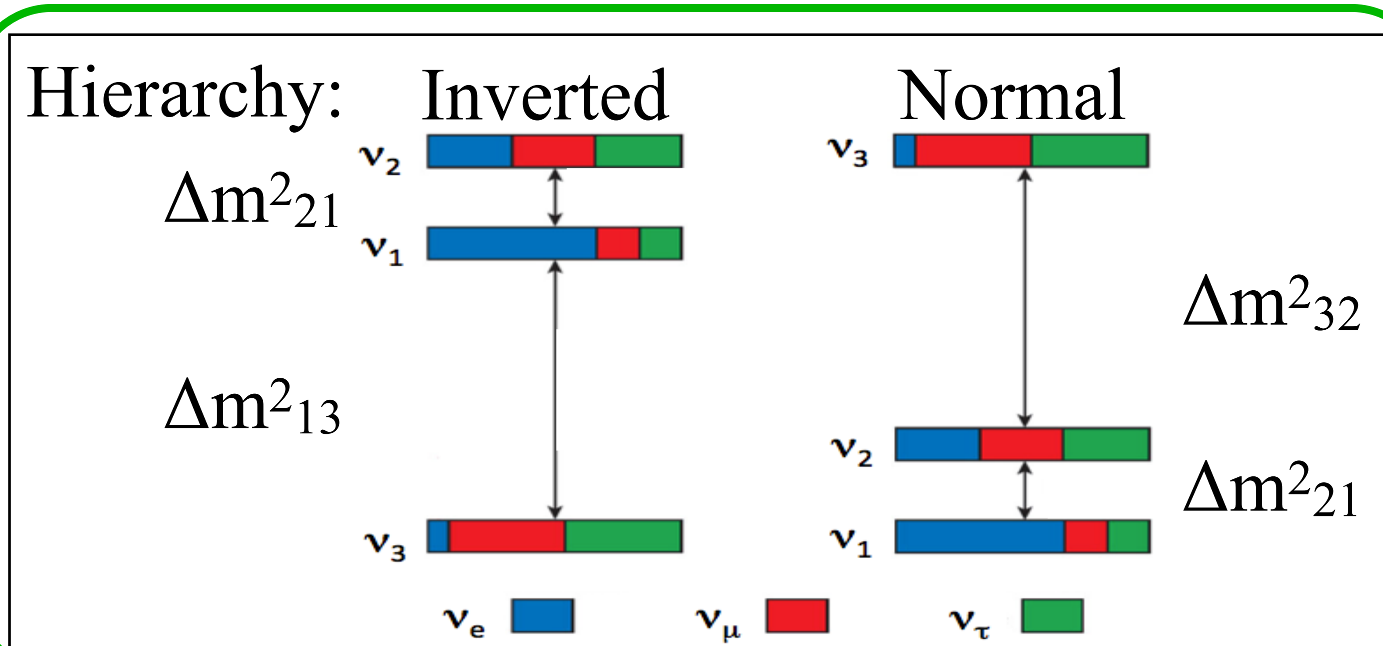

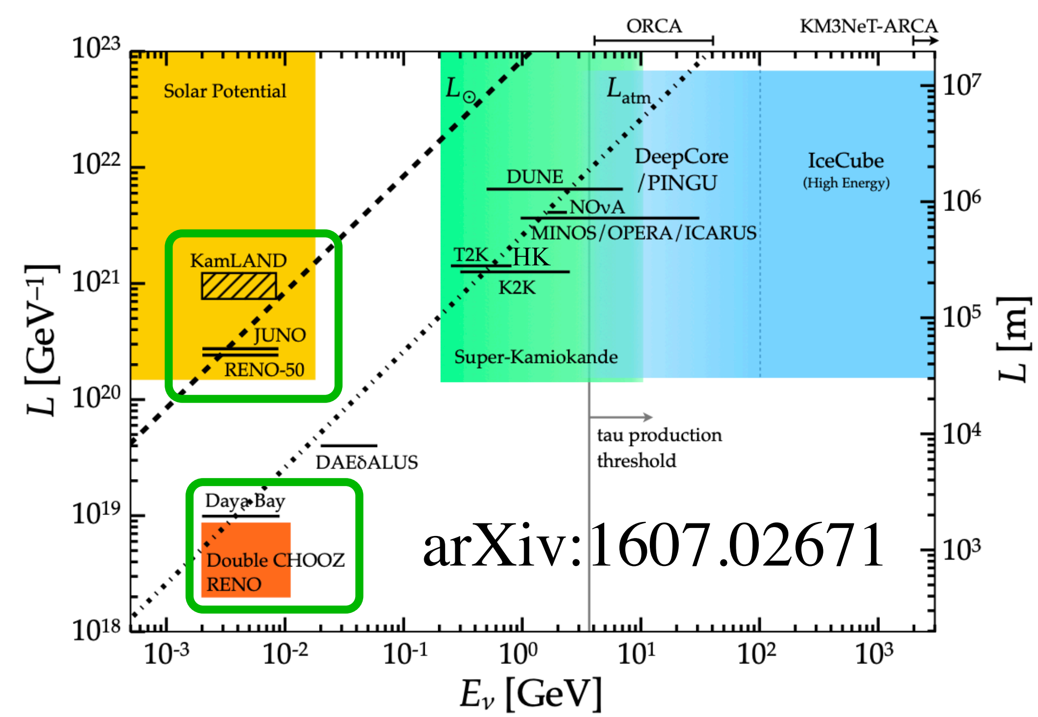

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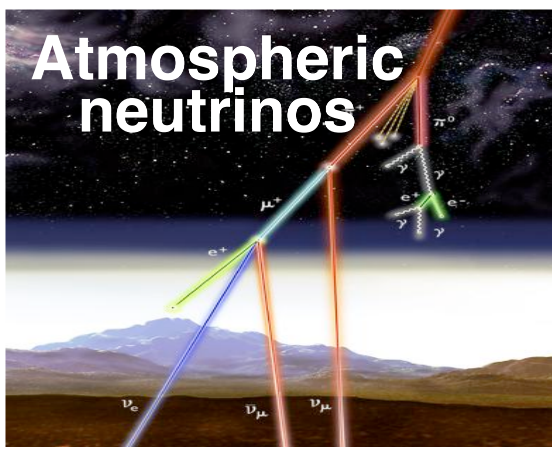

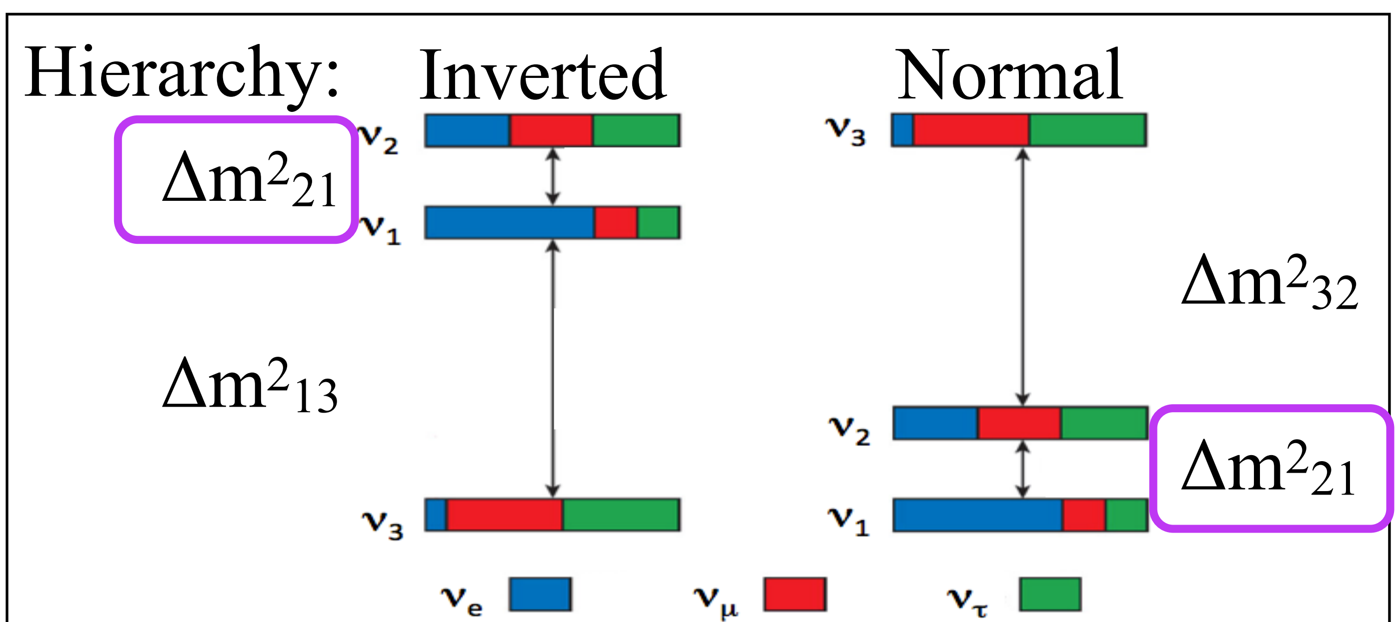

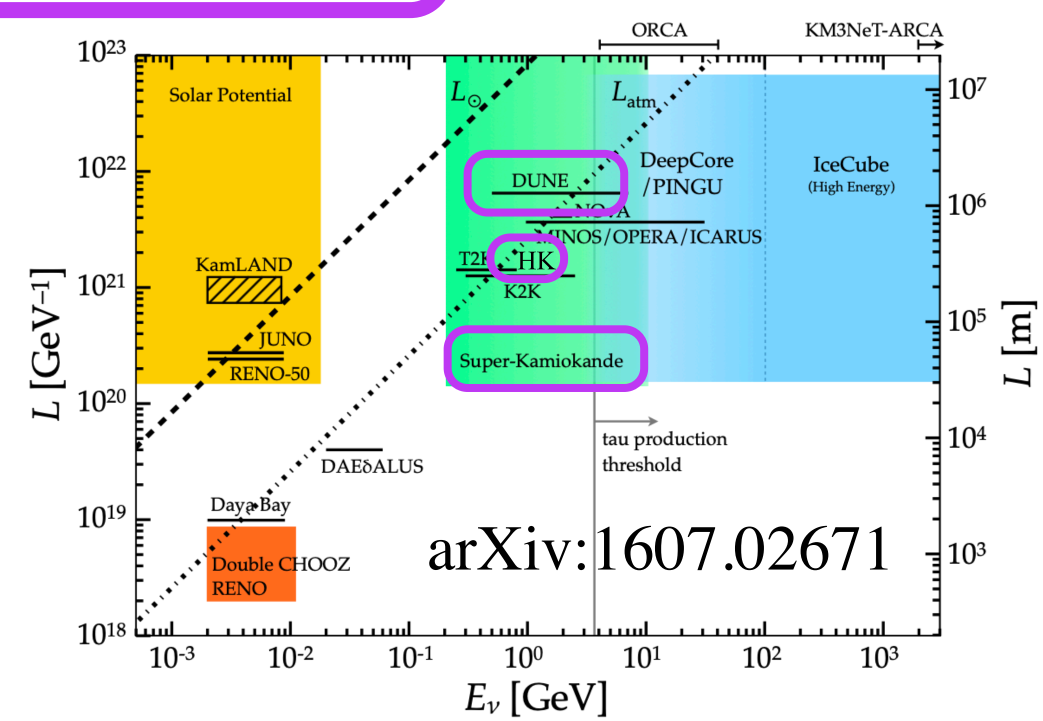

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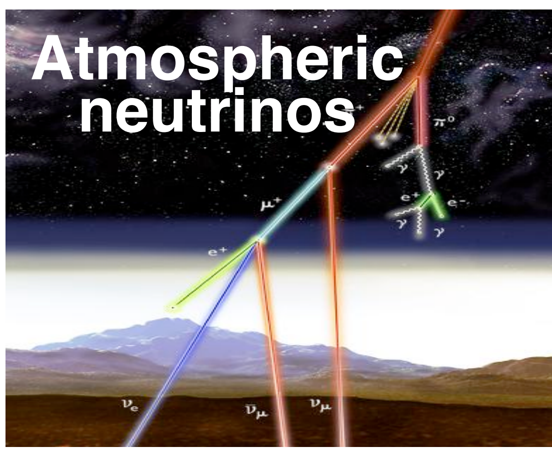
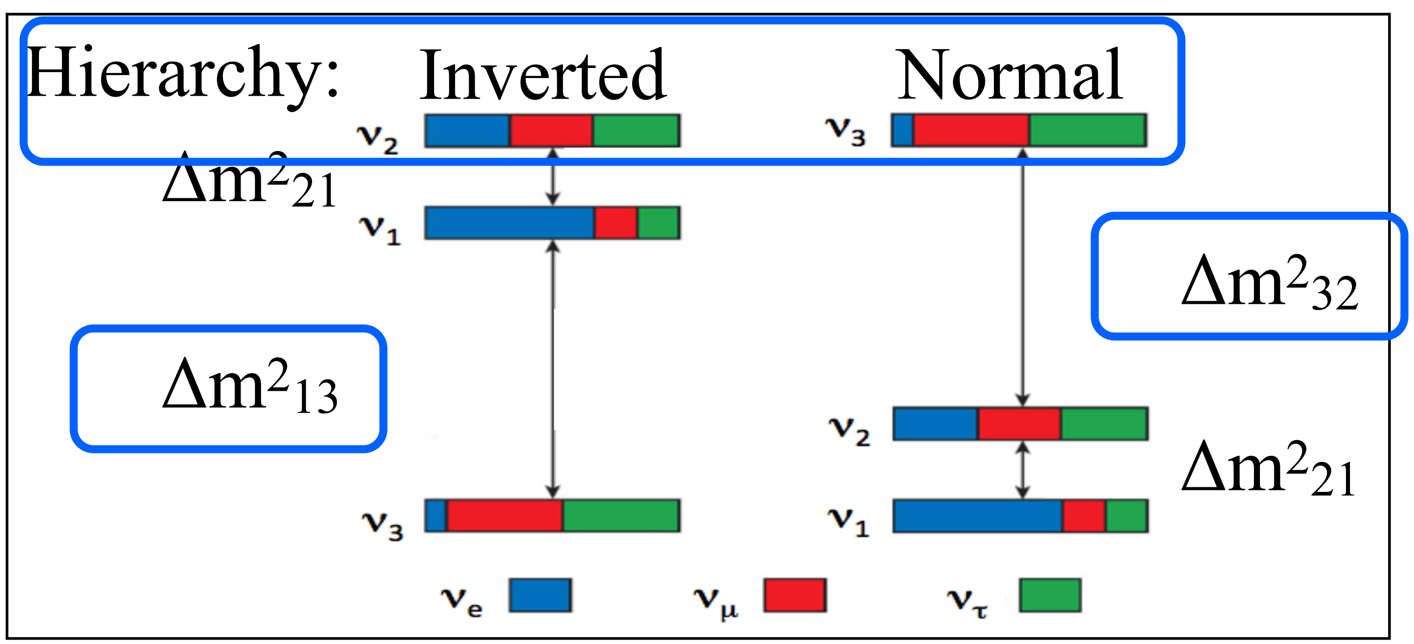
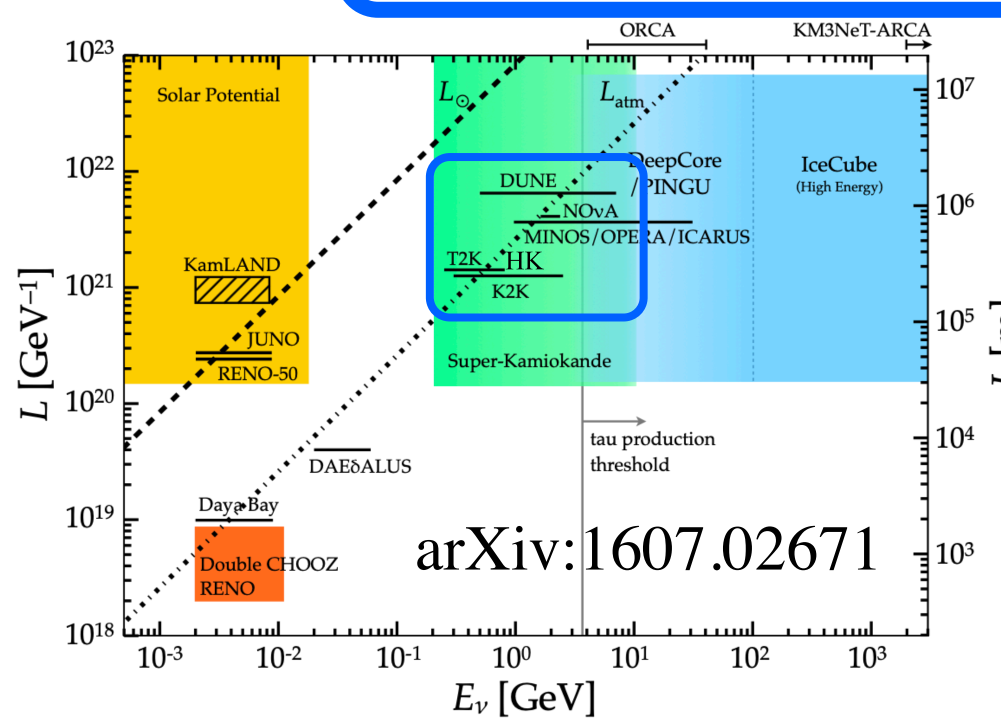
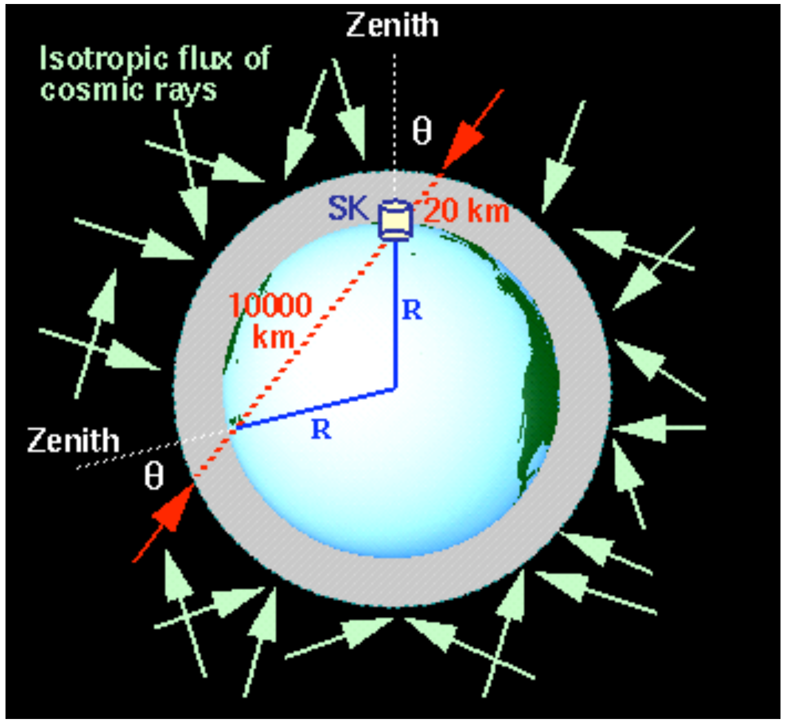
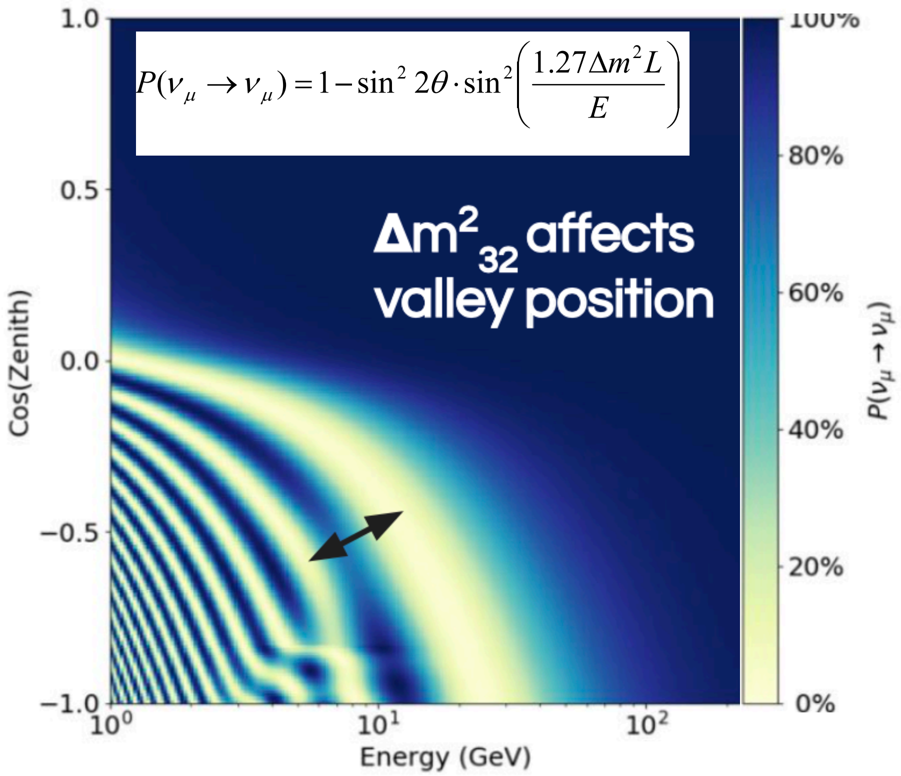


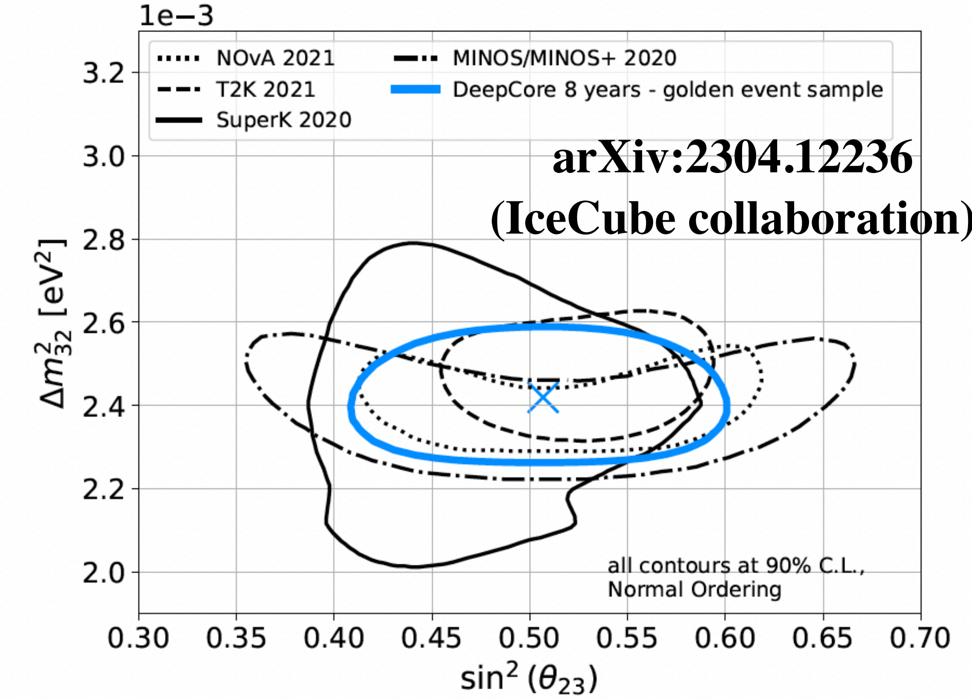




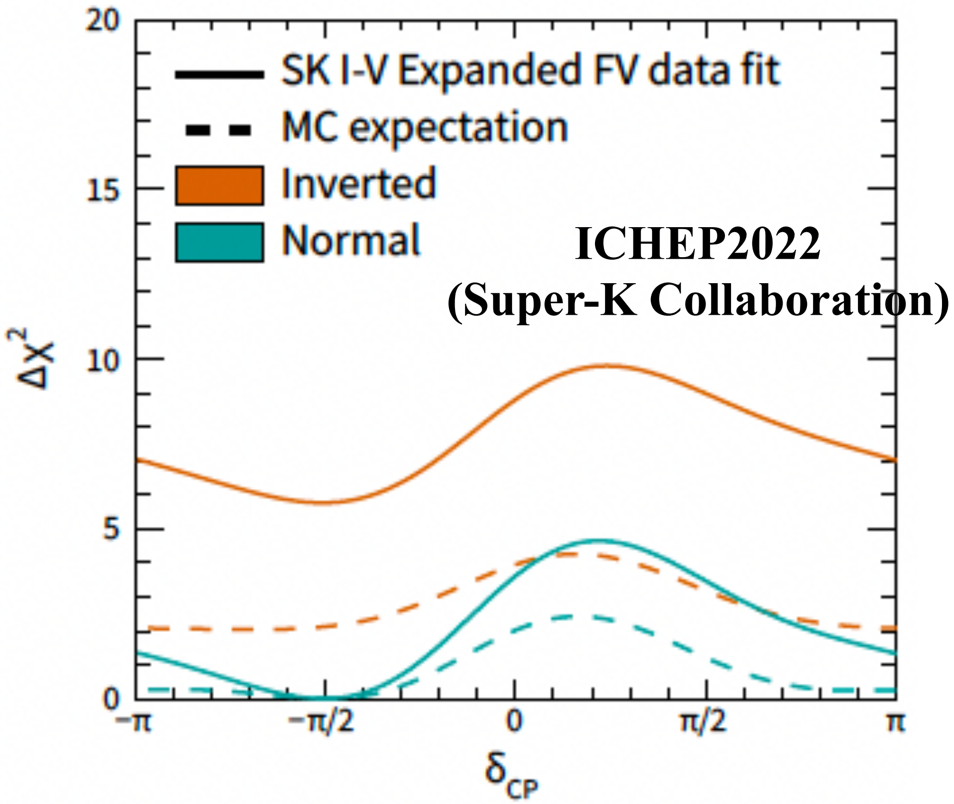
Atmospheric neutrino experiments





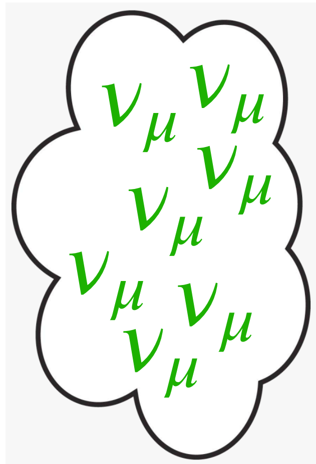


- IceCube DeepCore and Super-K measure $\sin^2\theta_{13}$ and Δm^2_{32}
- Measure the neutrino traveled distance using the arrival direction (zenith)
- Mild preference for normal hierarchy in Super-K $\nu_\mu \to \nu_e$ data

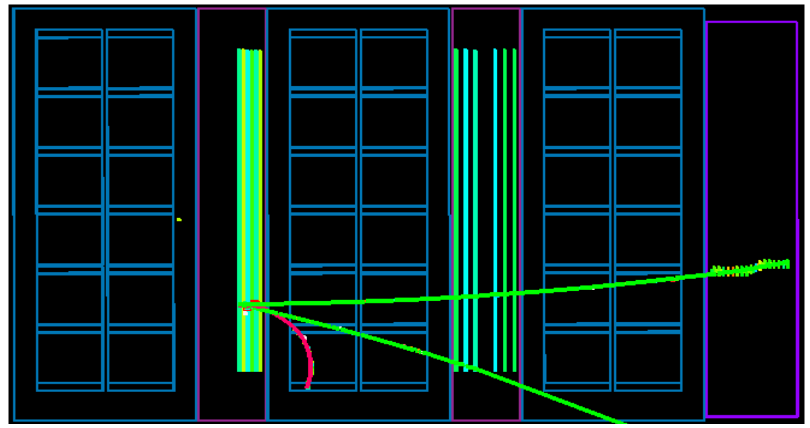


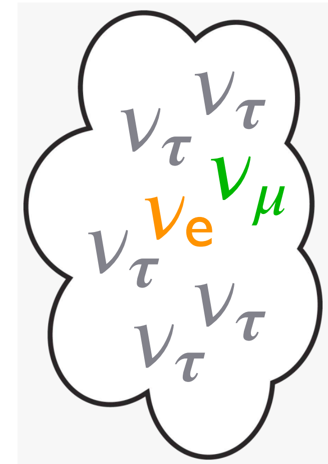
The Long-Baseline (LBL) concept

Proton Accelerator

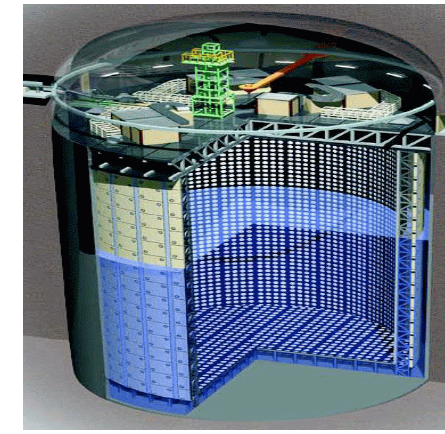


Near Detector

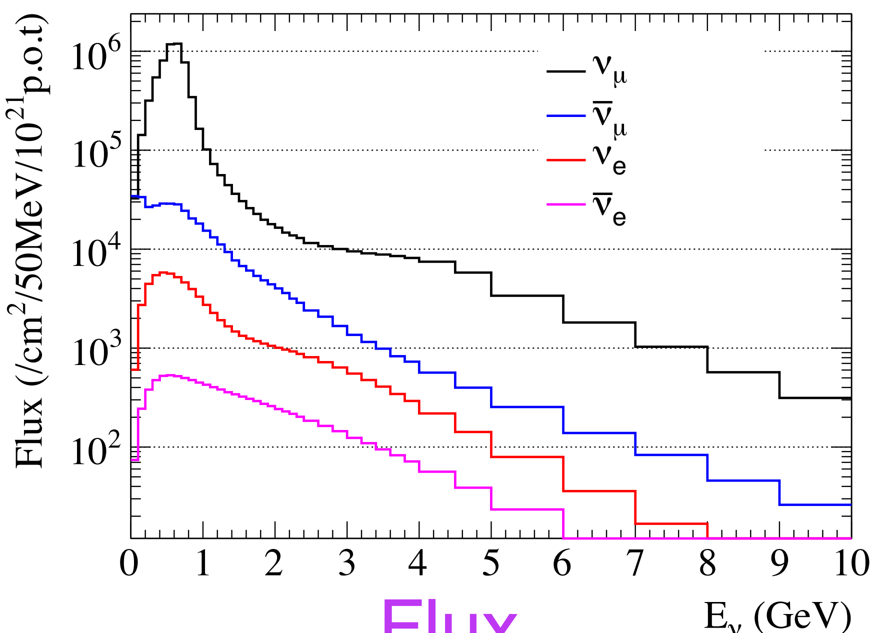




Far Detector

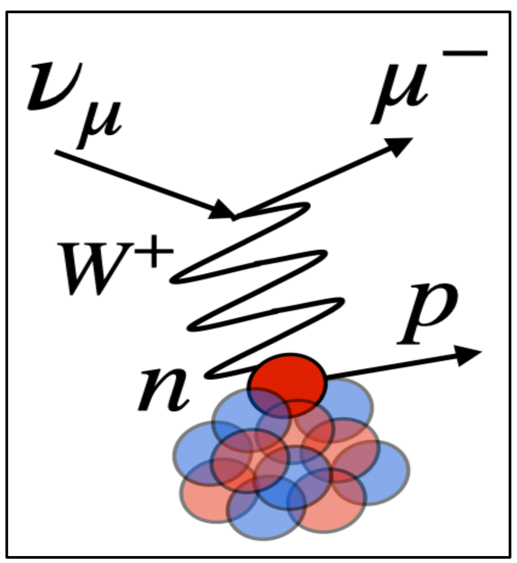


0 km —— 0.1-1 km —— - - - - 100-1000 km →



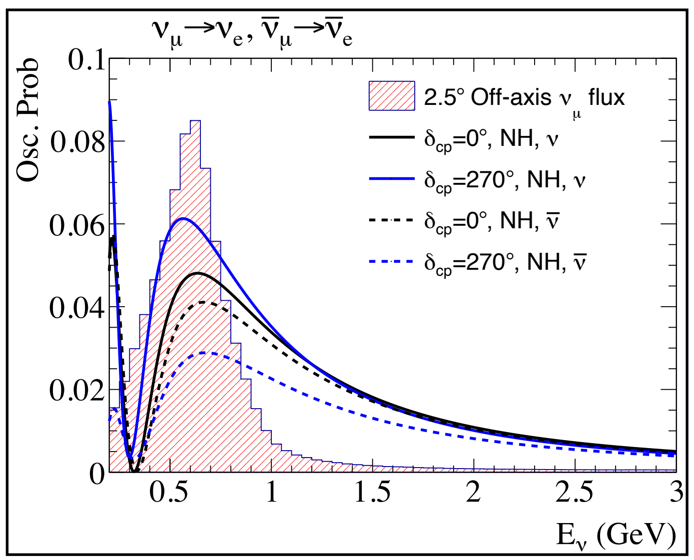
Flux

$\otimes$



Interaction with Matter

$\otimes$

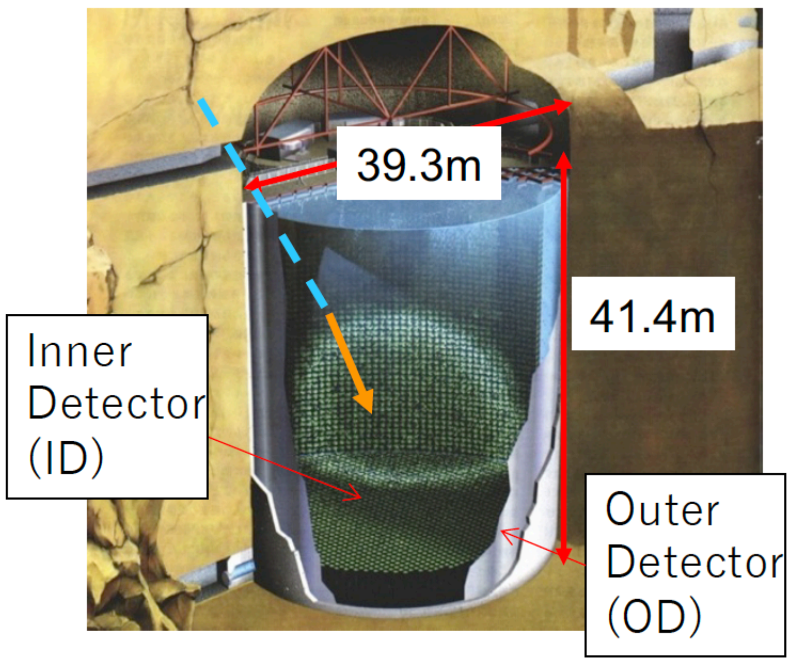


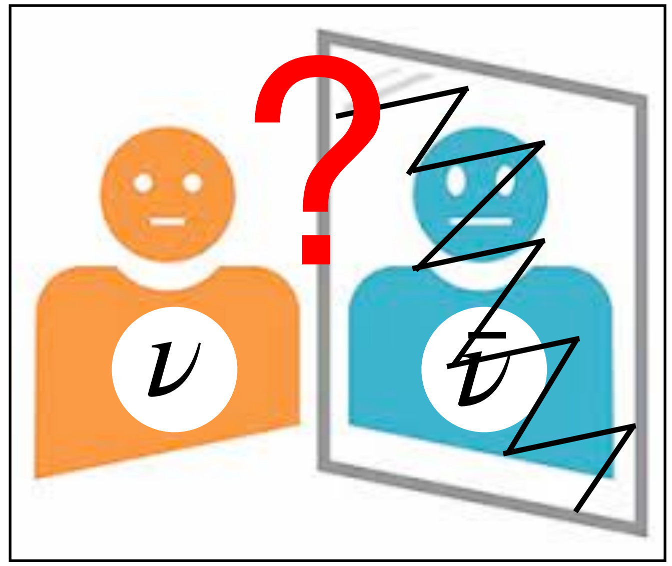
Oscillations

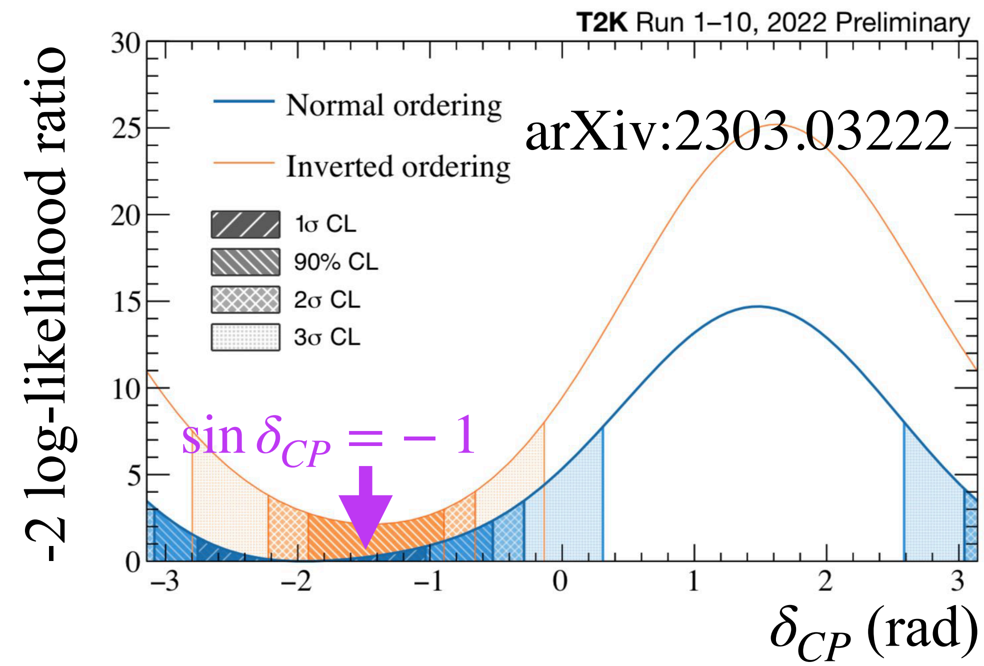
$$N(E_\nu) = \int \Phi(E_\nu) \times \sigma(E_\nu) \times R_{det}(E_\nu, \sigma(E_\nu), \vec{r}) \times P_{osc}(E_\nu)$$

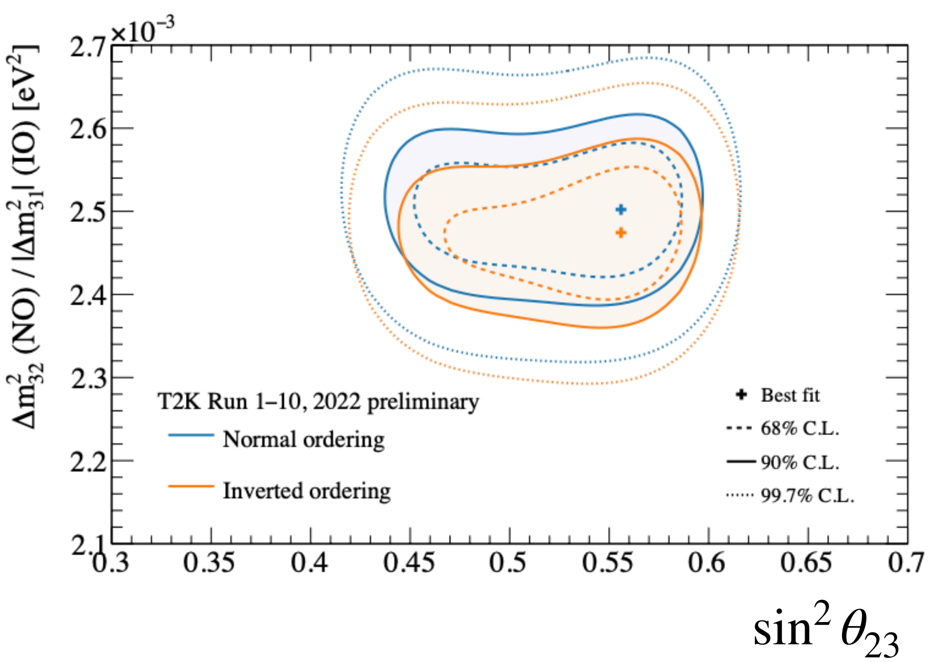
The T2K experiment

Far Detector is Super-K: 22.5 kton water-Cherenkov fiducial mass

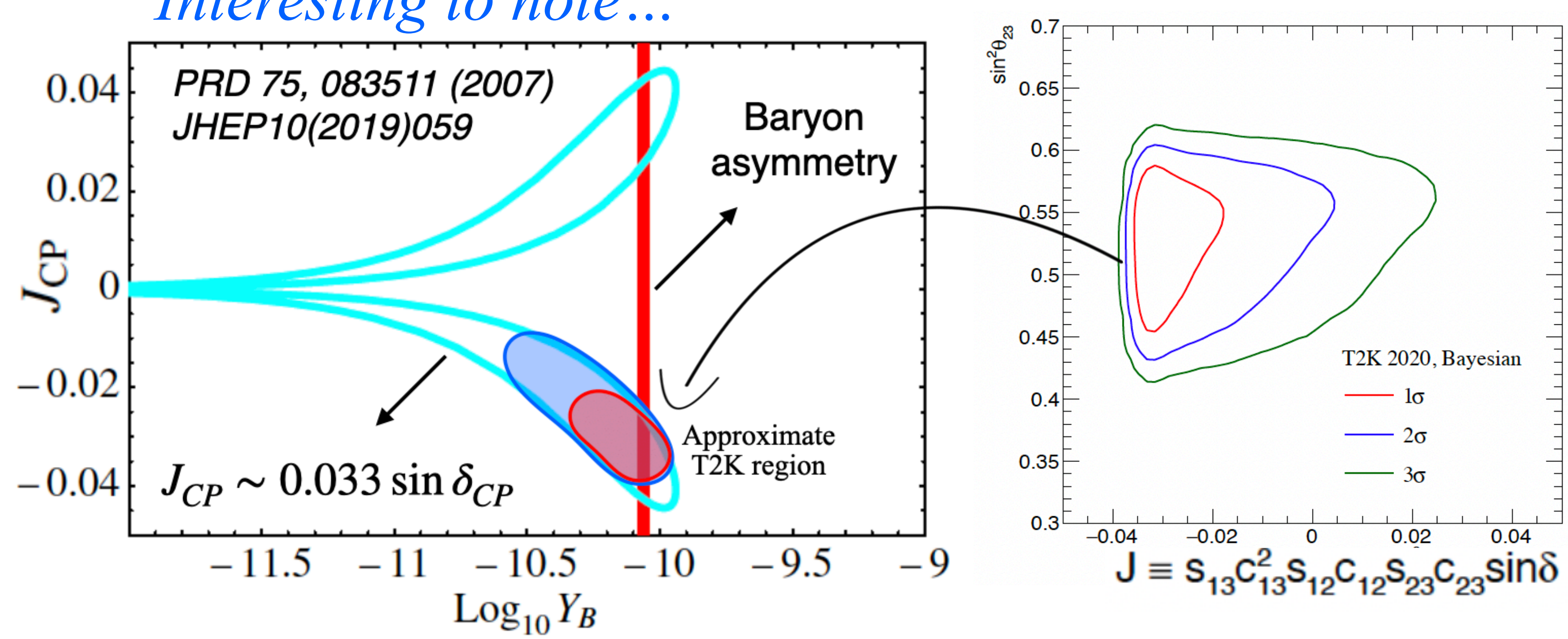








Interesting to note…



Consistent with max. ν_μ disappearance

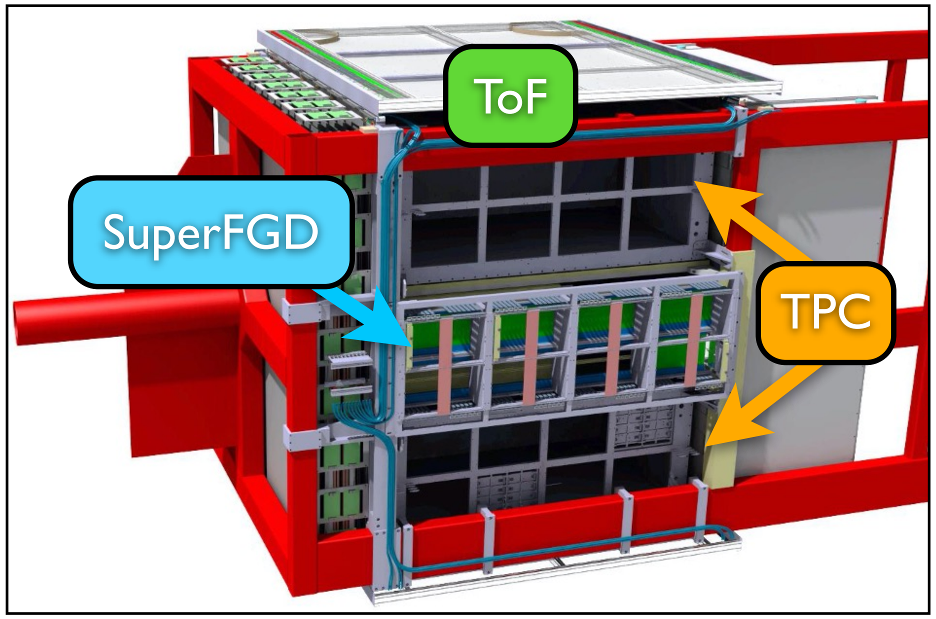
Preference for upper θ_{23} octant

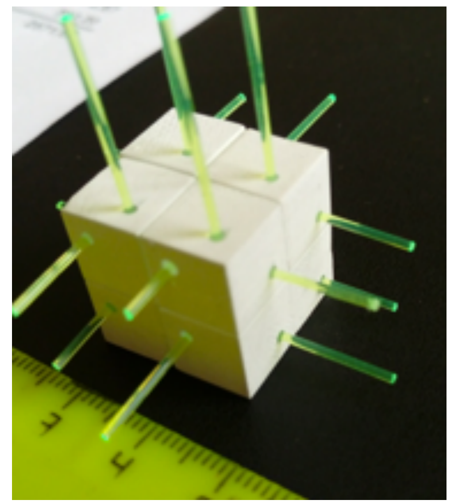
Large CP asymmetry ($\sin\delta_{CP} \sim -1$)

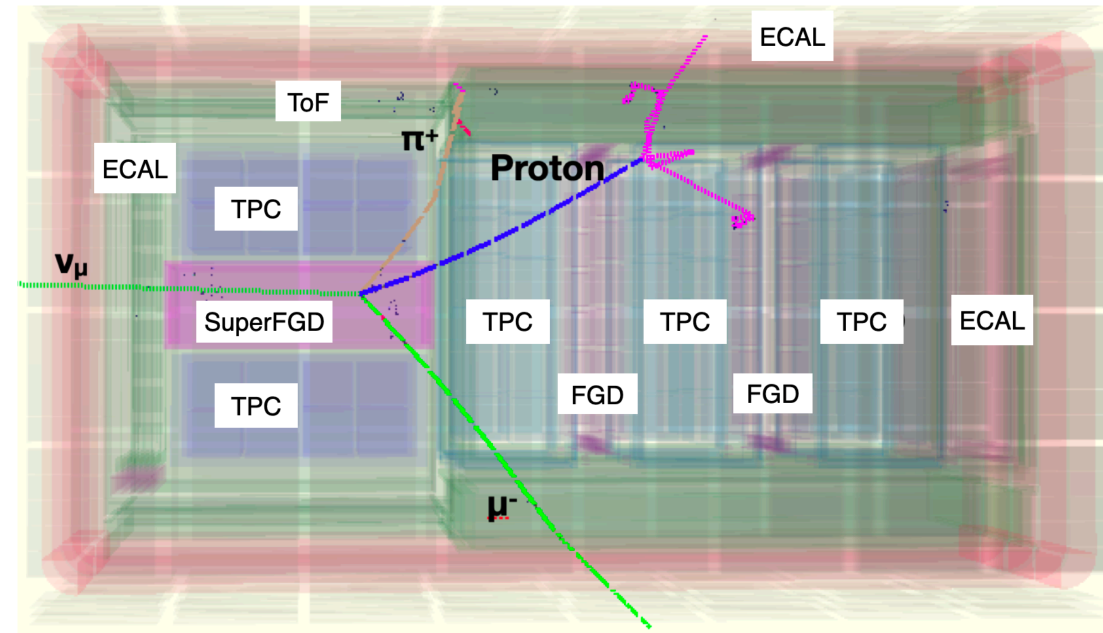
Normal Hierarchy ($m_3 > m_2 > m_1$)

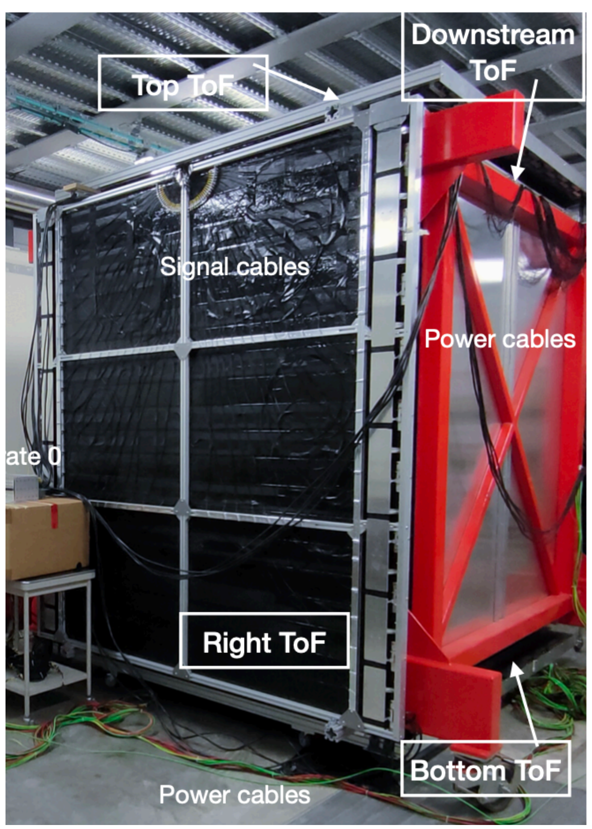
Upgrade of T2K Near Detector

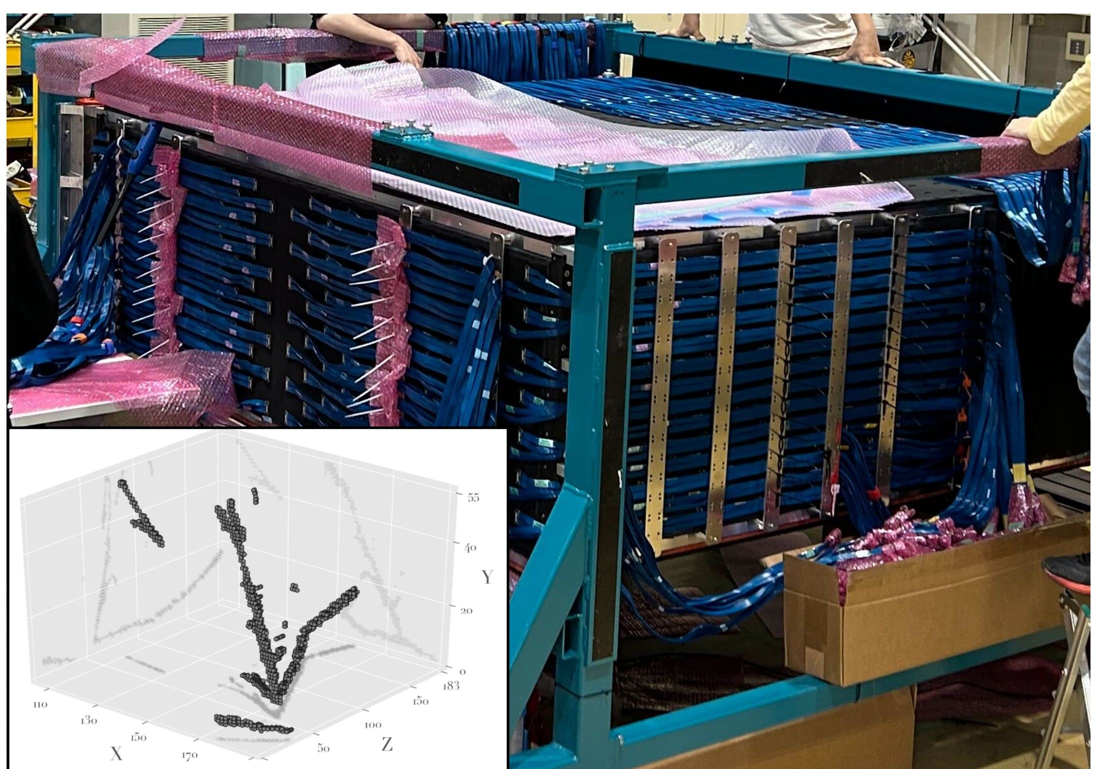
Major proton accelerator upgrade (towards 1 MW). Followed by ND280 upgrade: detect more precisely neutrino interactions and reduce cross section systematics









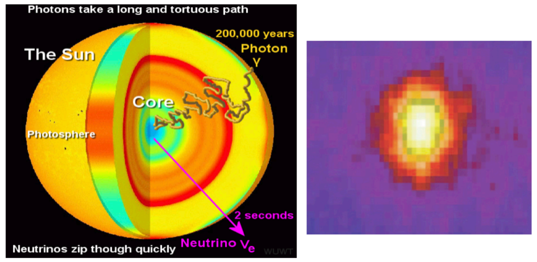


- ✓3D plastic scintillator
- ✓Time-of-Flight detector
- ✓Horizontal TPCs

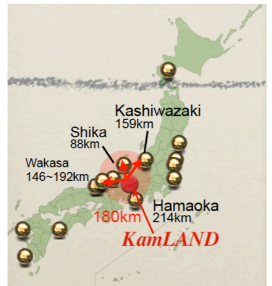
Isotropic tracking and lower momentum threshold, neutron speed reconstruction

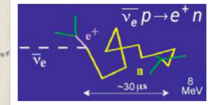
Current Status of the Oscillation parameters

Solar experiments

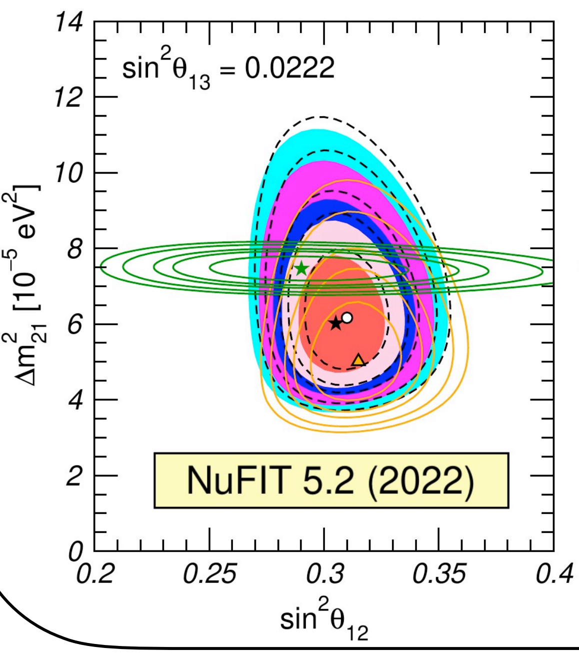


KAMLAND experiment

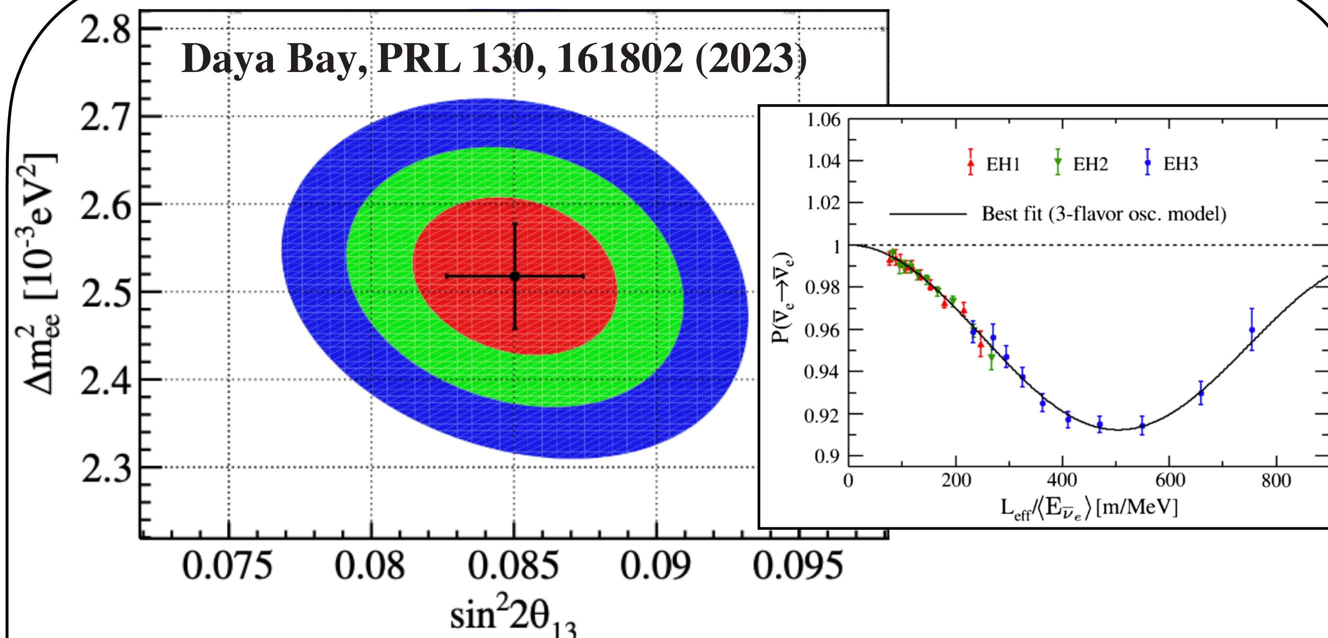




NuE flux from reactors in Japan on a baseline of 180 km



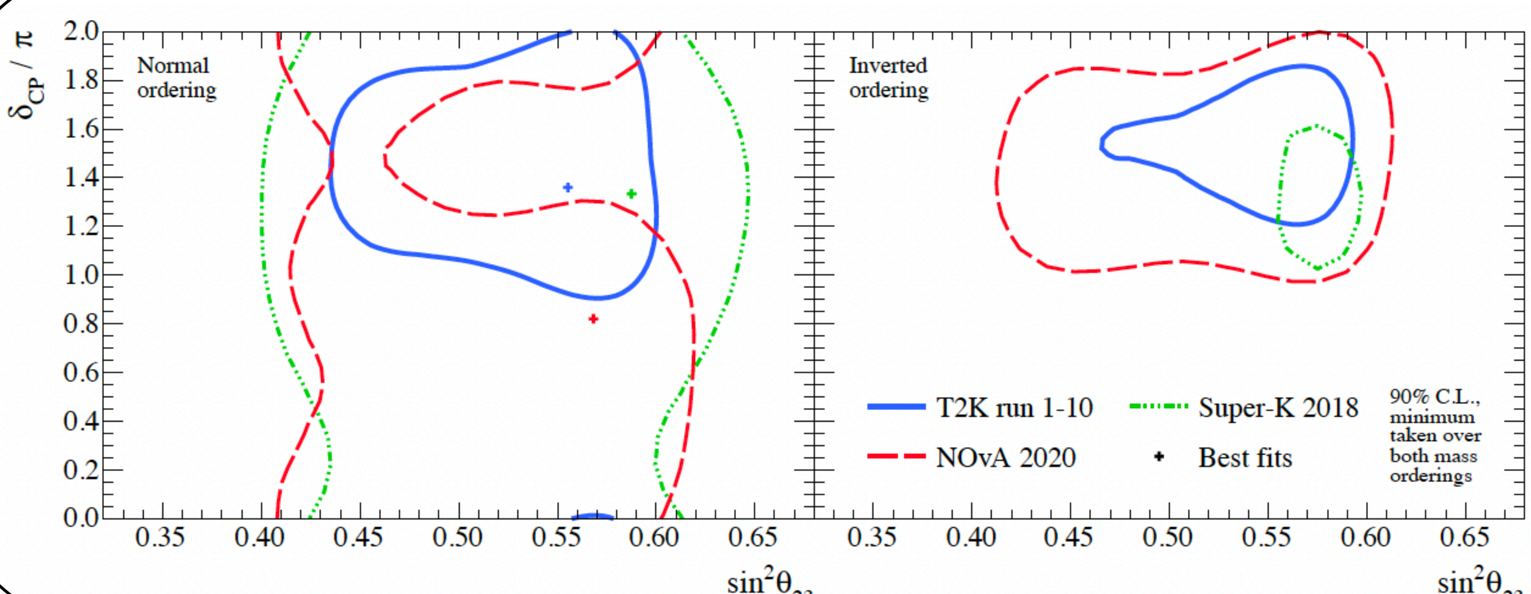
Tension between solar global and KamLAND in Δm^2_{21}



$$\sin^2 2\theta_{13} = 0.0851 \pm 0.0024 \quad \text{(2.8\% precision)}$$

$$\Delta m^2_{32} = (2.466 \pm 0.060) \times 10^{-3}\ \text{eV}^2 \quad \text{Normal Hierarchy}$$

$$\Delta m^2_{32} = (-2.571 \pm 0.060) \times 10^{-3}\ \text{eV}^2 \quad \text{Inverted Hierarchy}$$



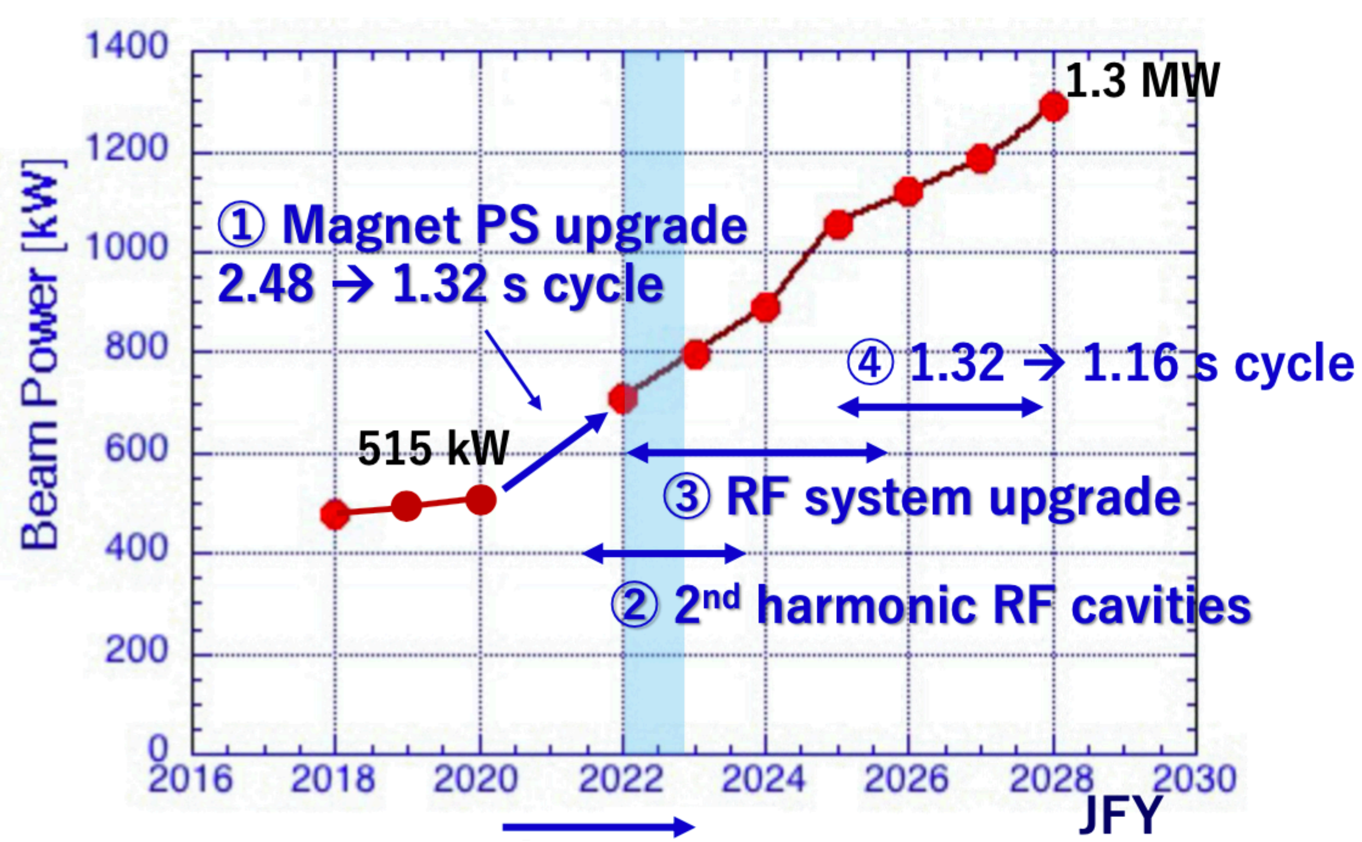
Work in progress on combined analyses of T2K + SK (access.+atm.) and T2K+NOvA (accel.)

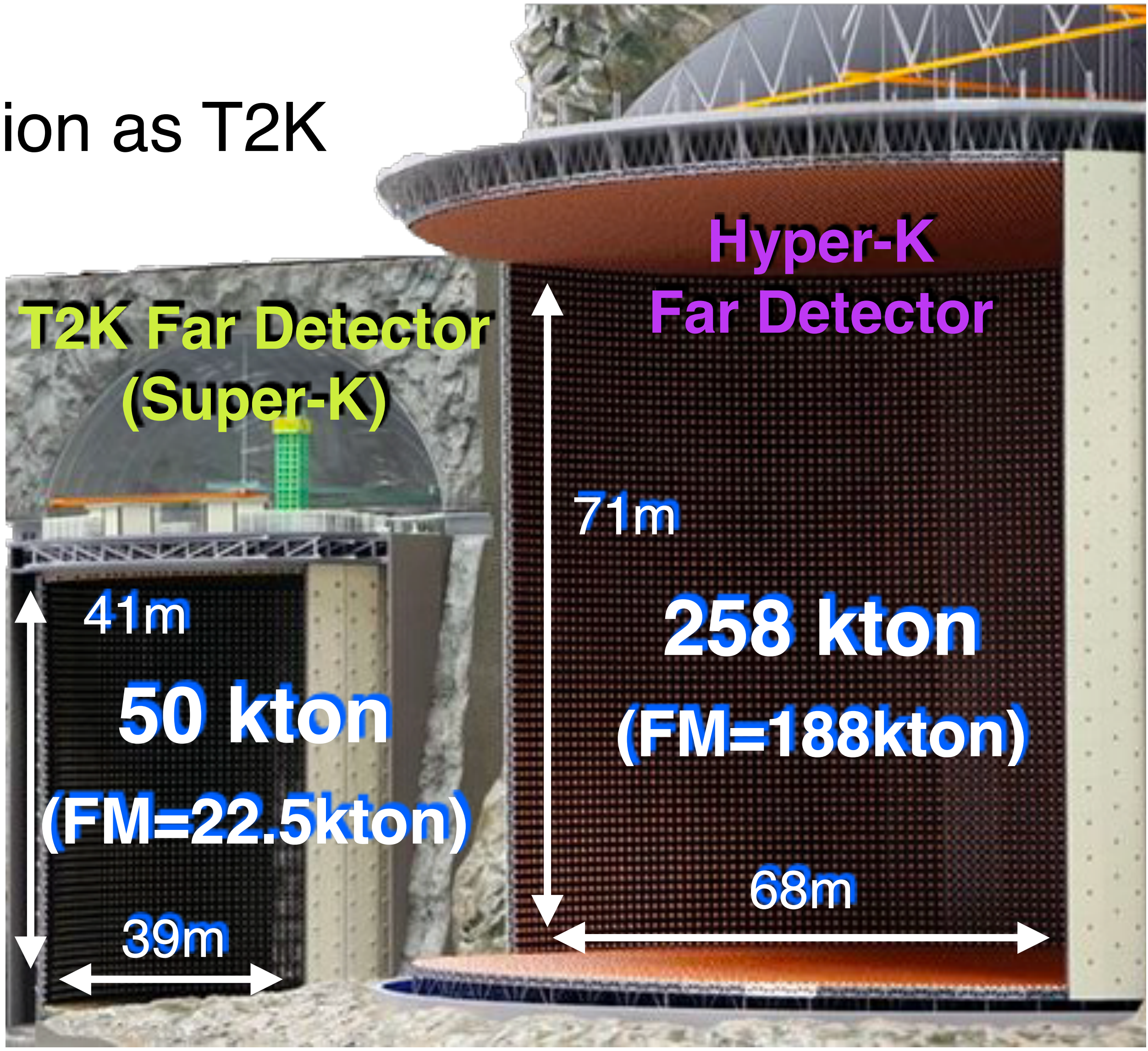
Hyper-Kamiokande

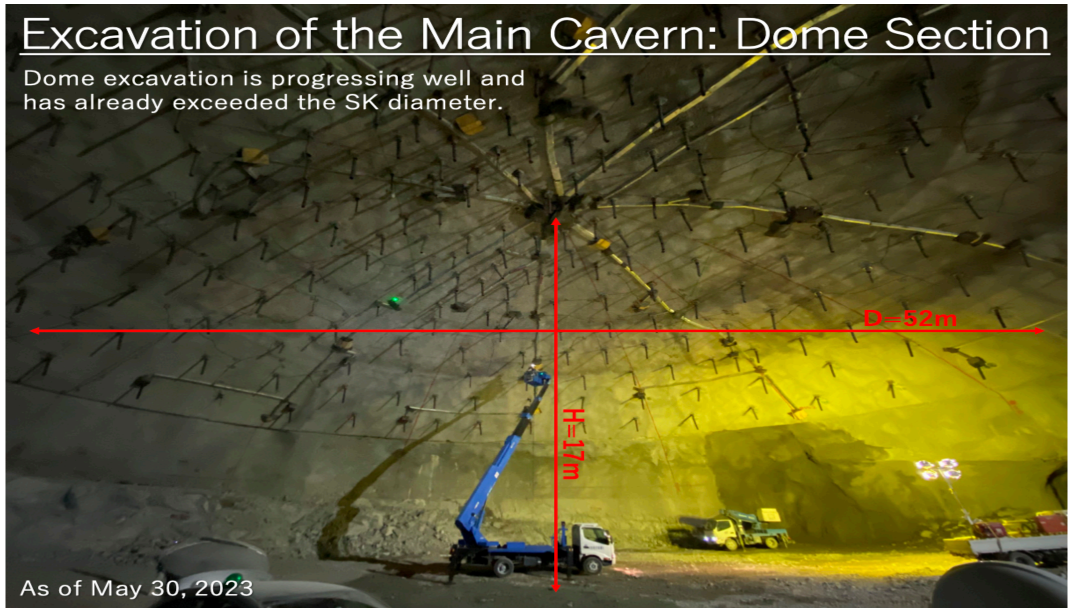
Exactly the same experimental configuration as T2K

✓Inherit the neutrino beam and ND280

✓Additional water Cherenkov detector at the near site (~800m)



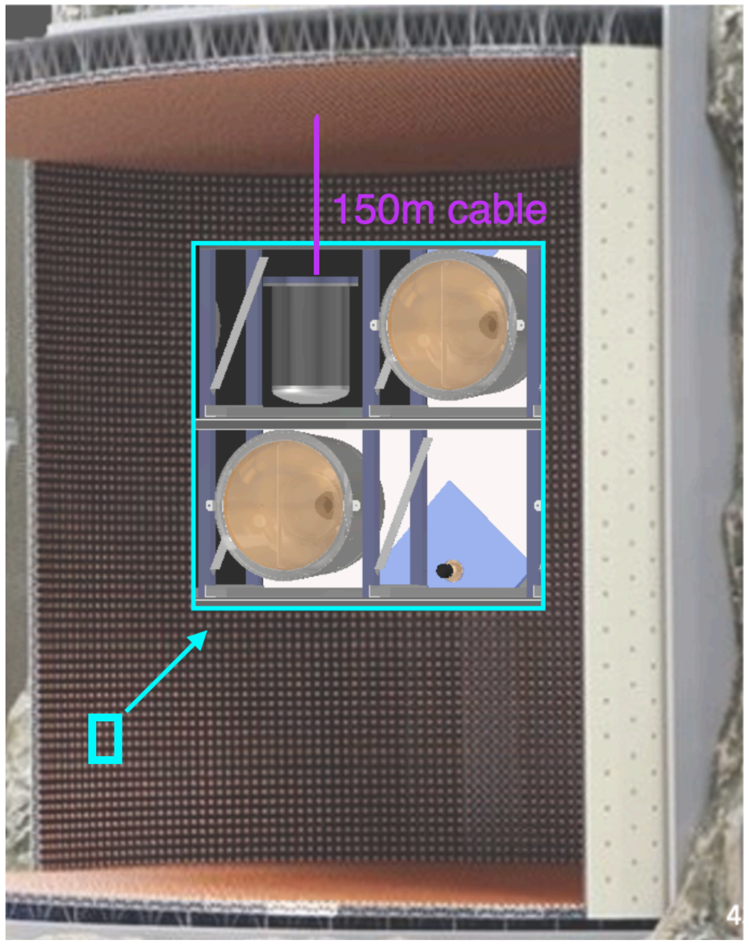


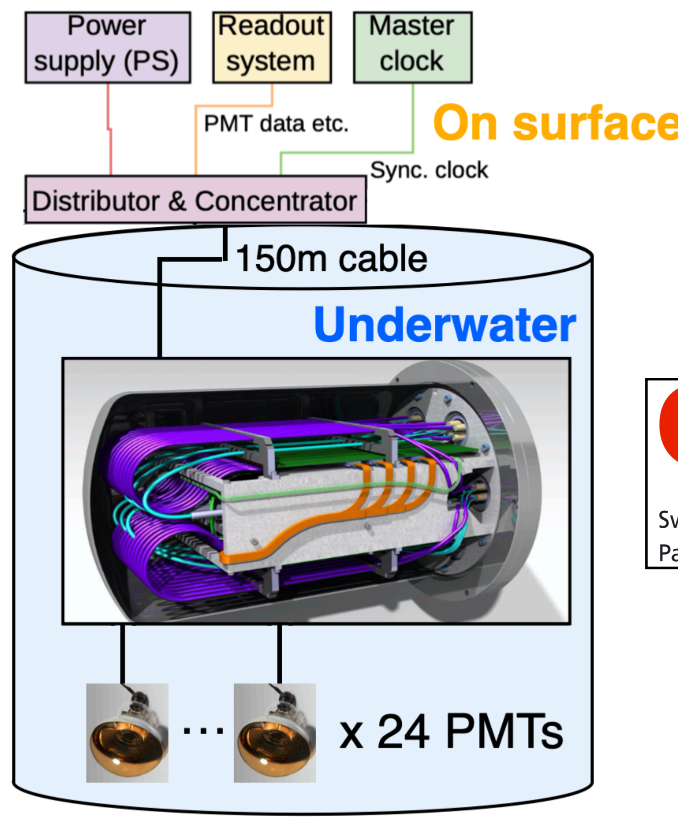


Comparison with T2K before shut down in 2020: beam power x2 & Target mass x8

⇒ x16 more data

Hyper-Kamiokande



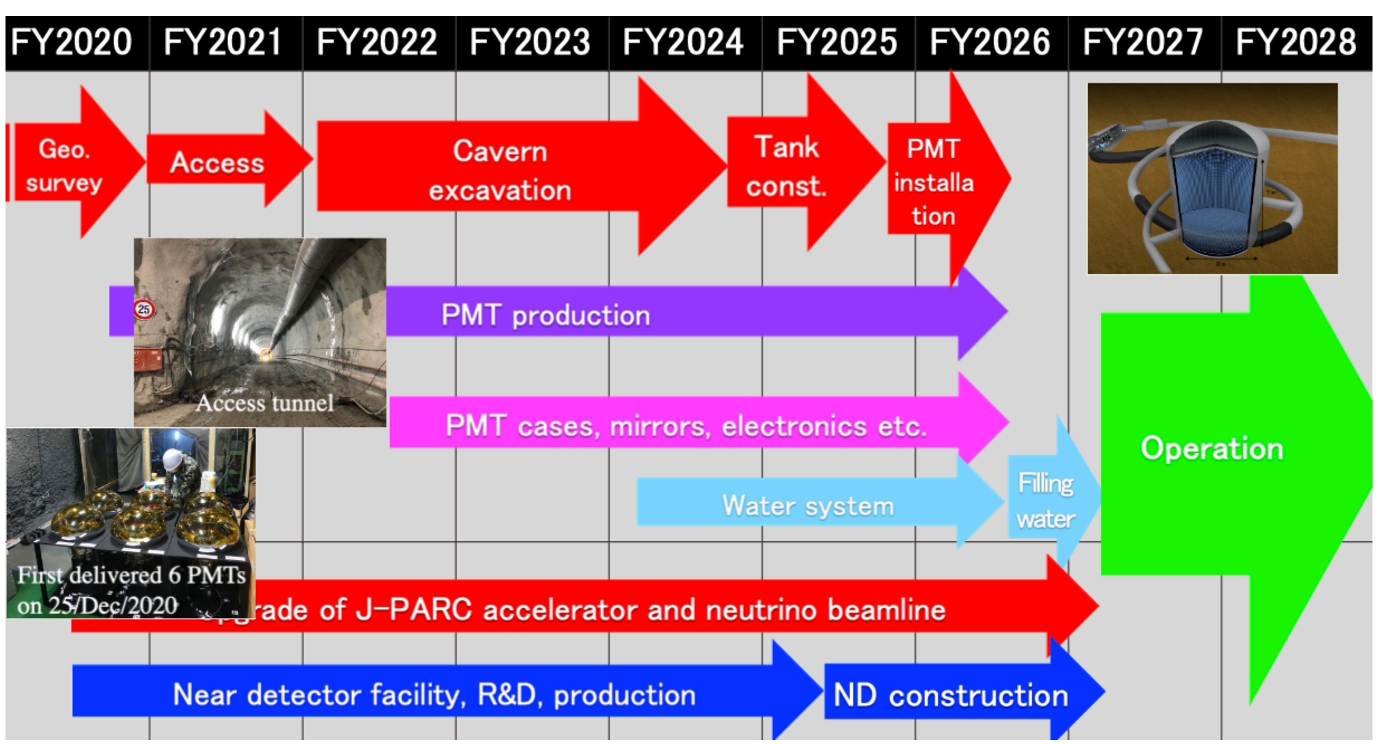


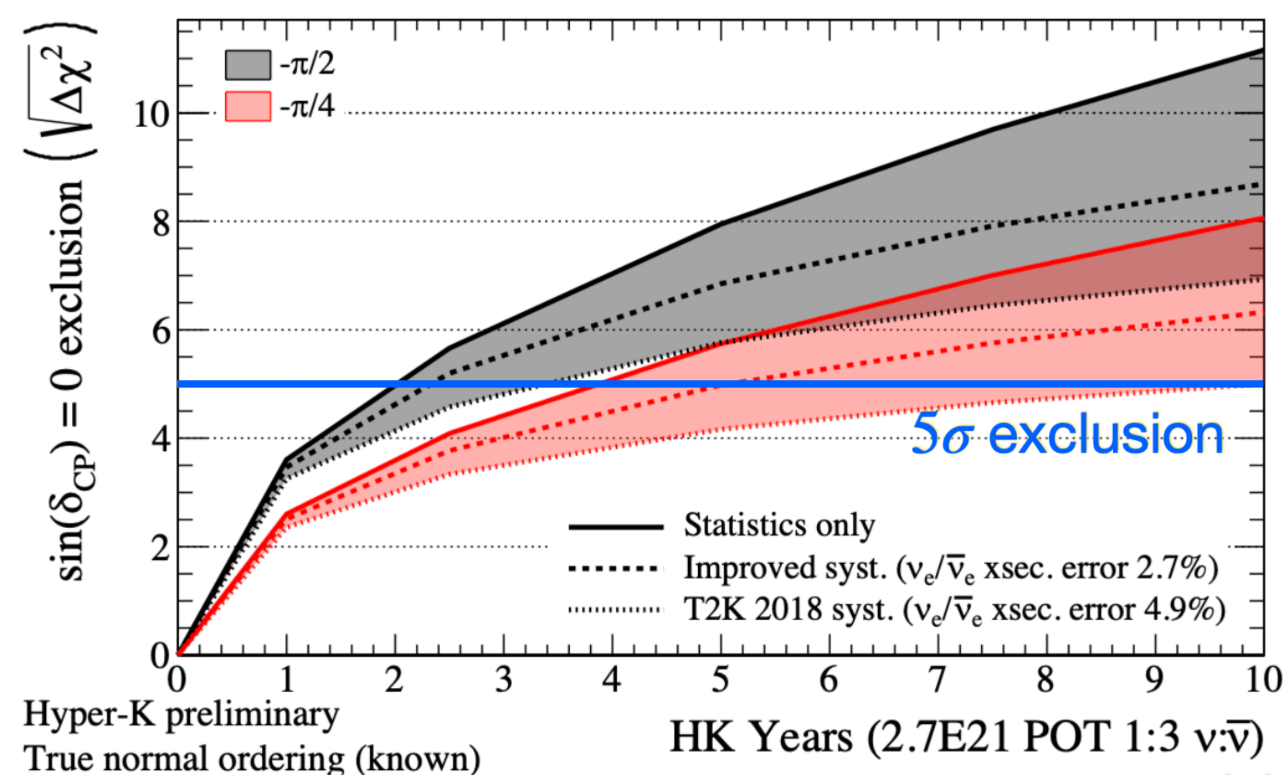
Hyper-K will start in 2027:

- PMT production started
- Start soon production of water-tight vessel, High/Low Voltage, etc.

Resolution on $\delta_{CP} < 20°$

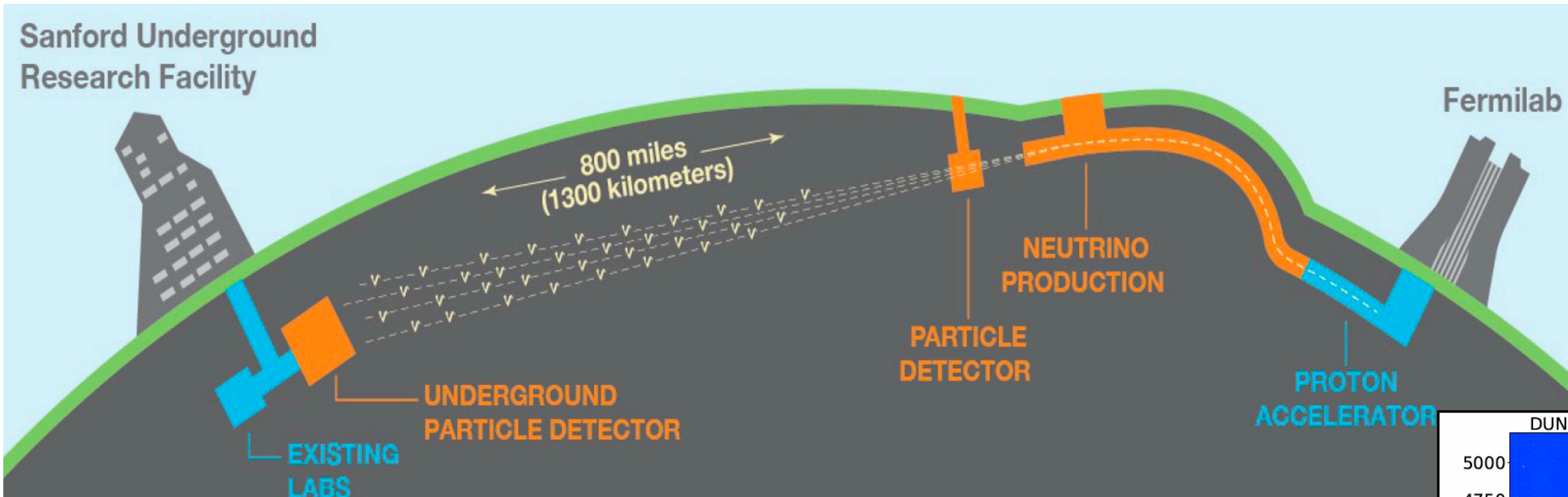
Mass Hierarchy $\sim 4\sigma$

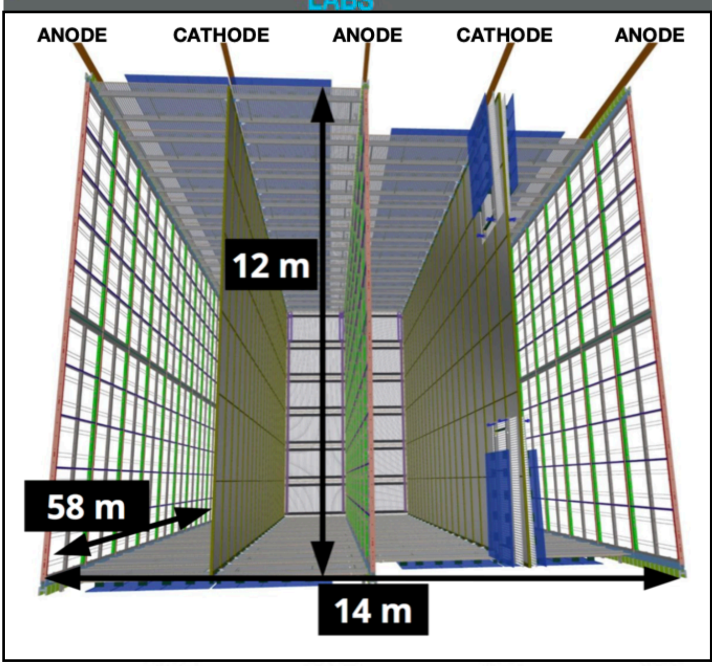


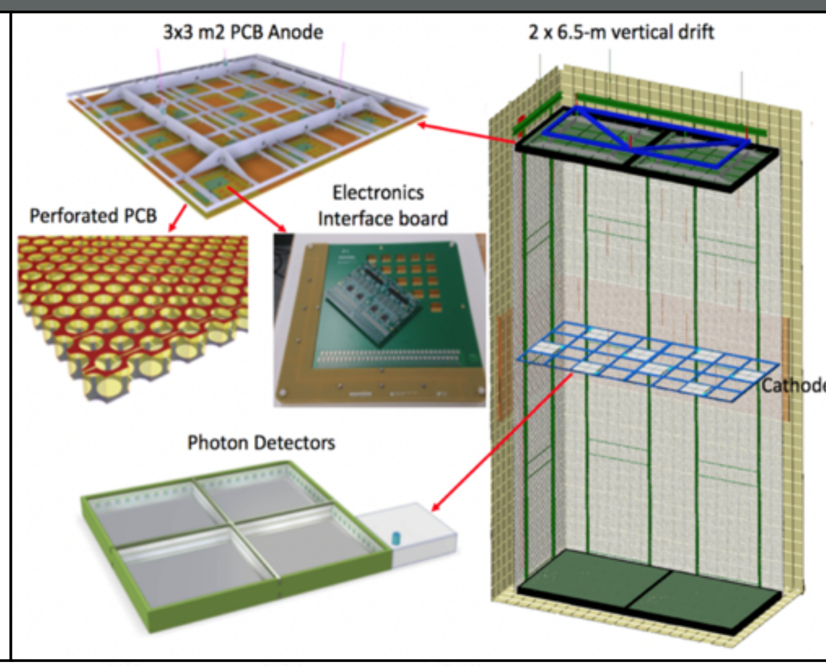


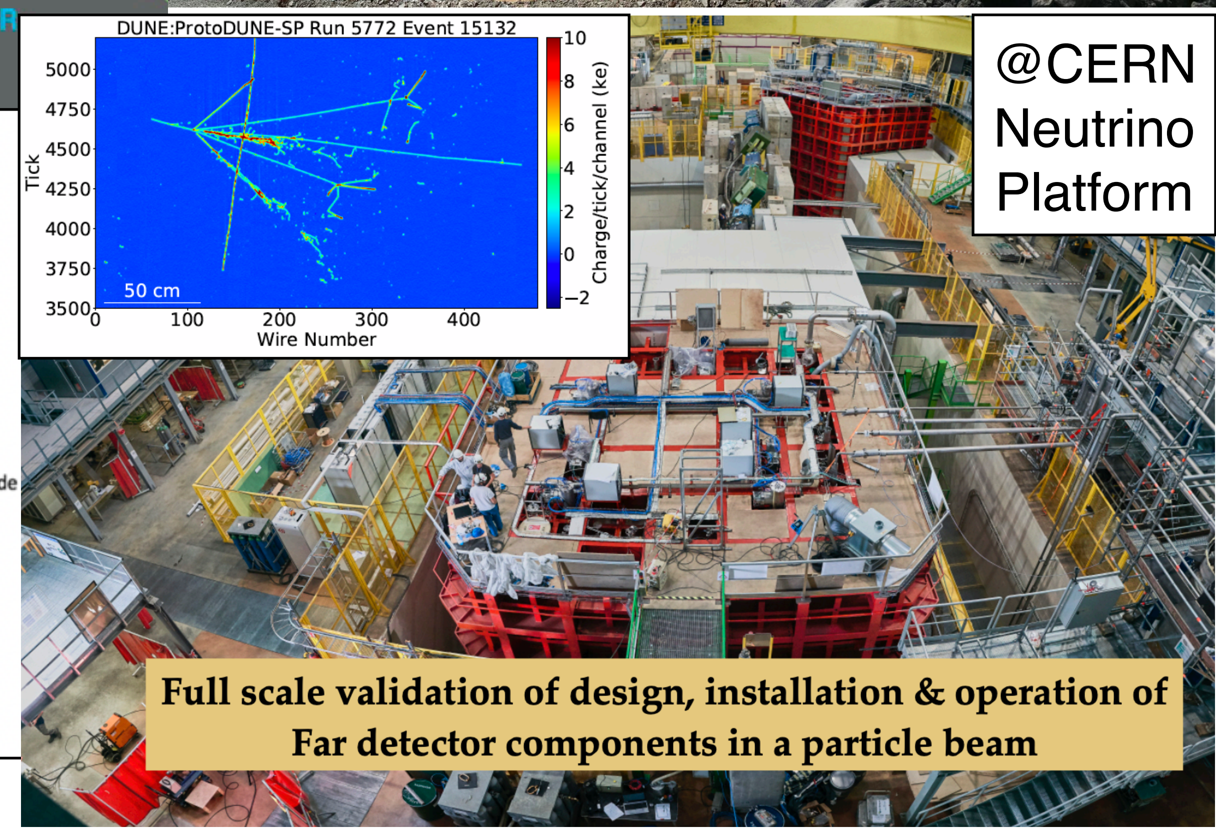
DUNE

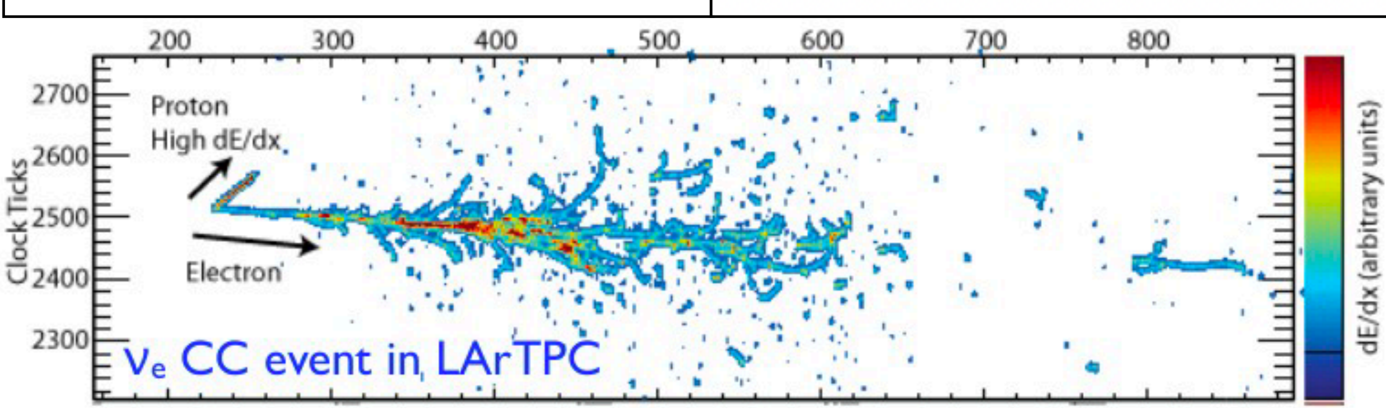
Different technology and baseline ⇒ complementarity with Hyper-K







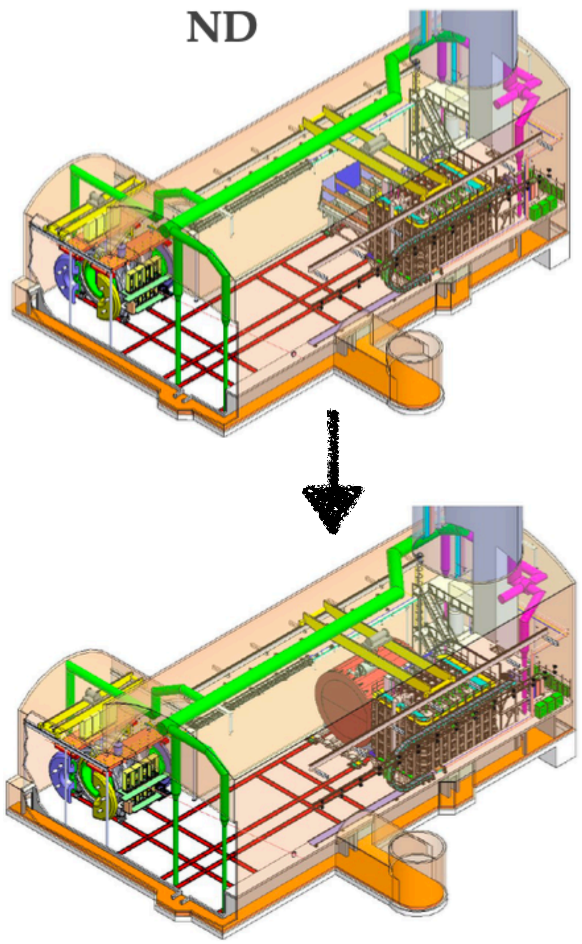




Four FD modules (~10 kt fiducial each)
Two major LAr technologies:
Horizontal drift and Vertical drift

DUNE

NuFact'22



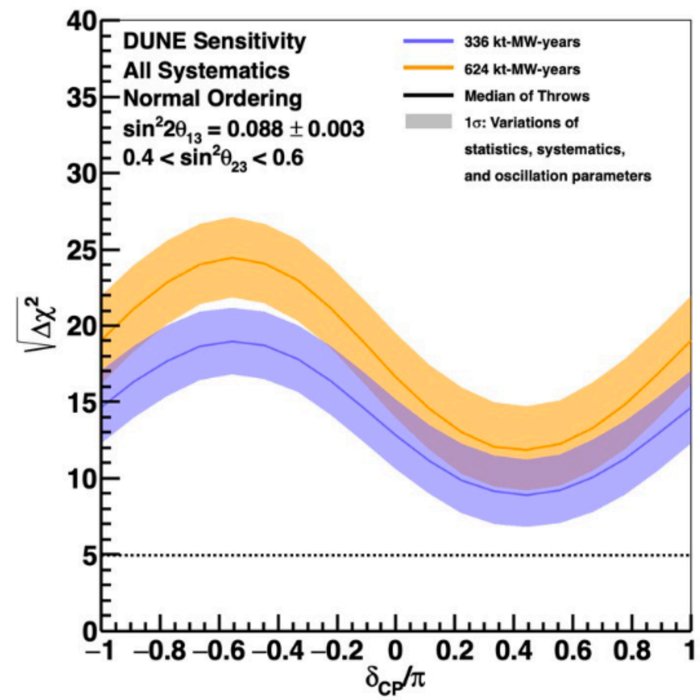
Phase I

- **FD:** 2 x 17 kt LArTPC modules
- **ND:** ND-LAr+TMS (with PRISM) + SAND
- FD turns on late 2020s
- 1.2 MW capable beamline and ND by 2031

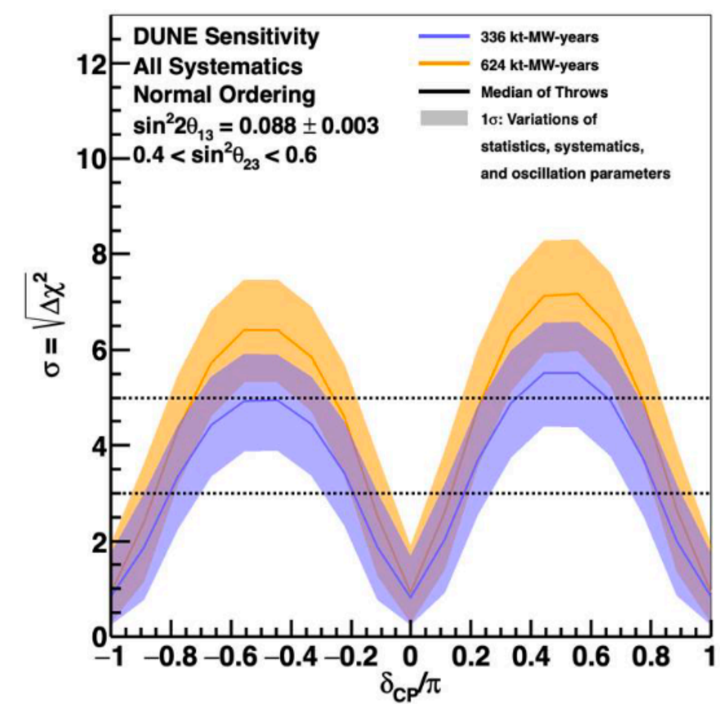
Phase II

- **FD:** 4 x 17 kt modules
- **ND:** ND-LAr+ND-GAr (with PRISM) + SAND
- Proton beam 1.2 MW to 2.4 MW

Mass Ordering Sensitivity



CP Violation Sensitivity

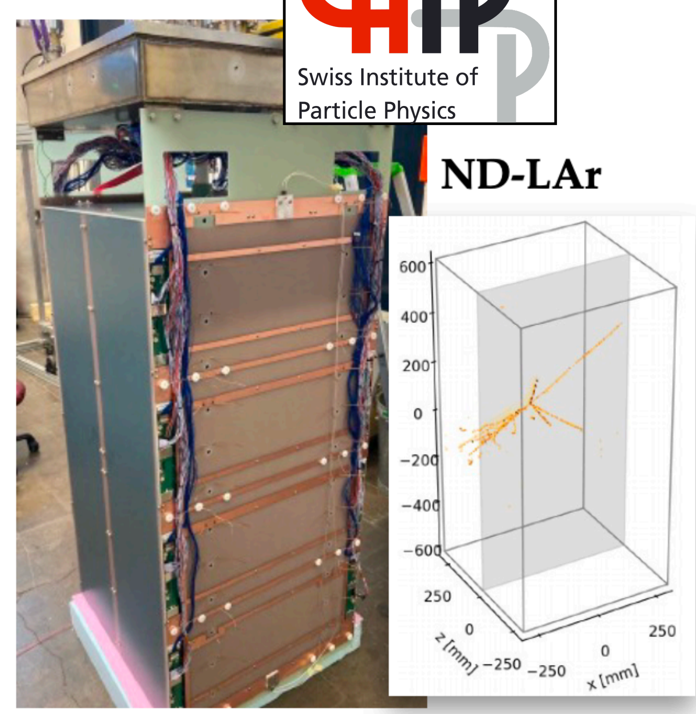


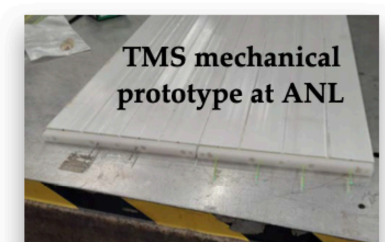
Different technologies at the Near Detector

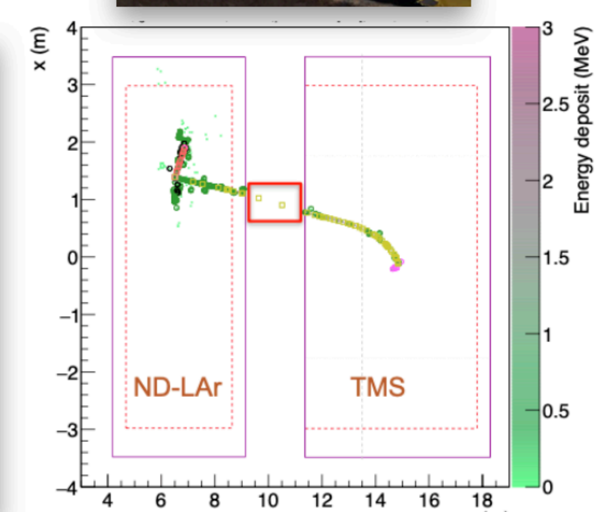
Central is ND-LAr: massive argon active target with pixel-based charge readout

✦ Neutrino beam tests @Fermilab

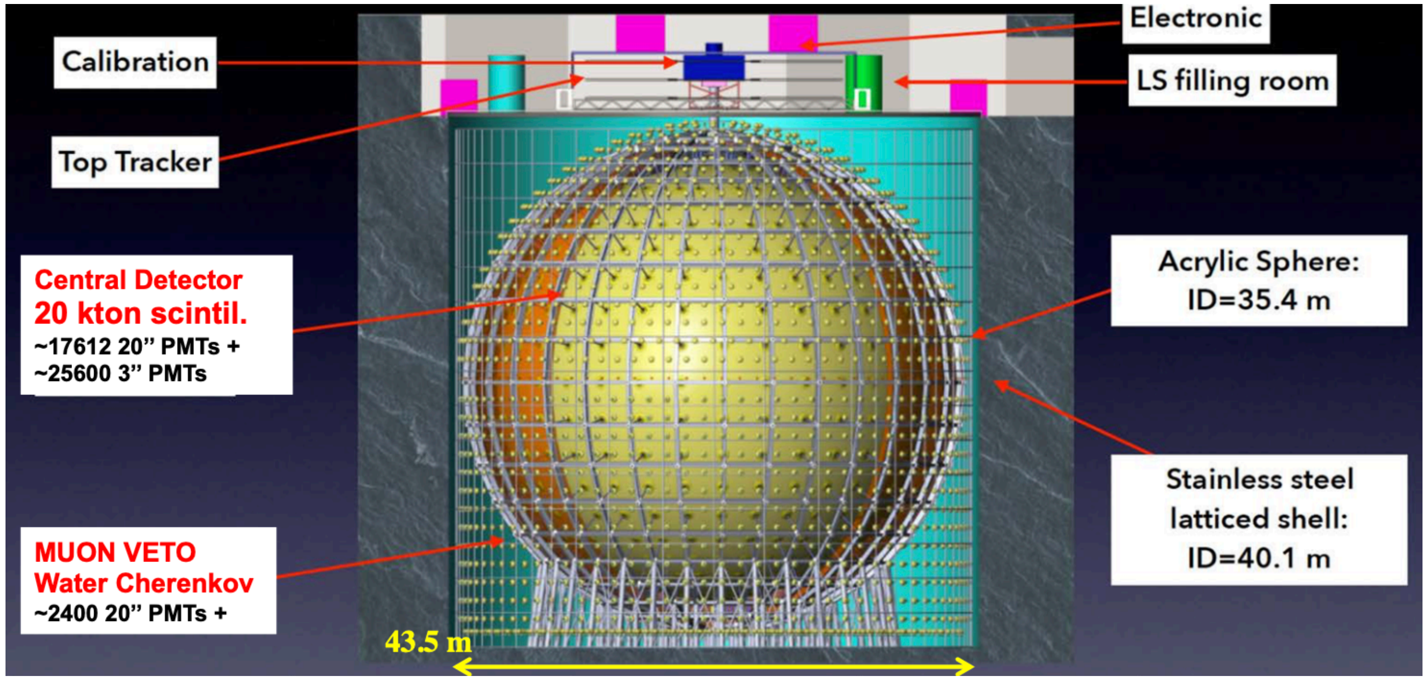
Swiss Institute of Particle Physics

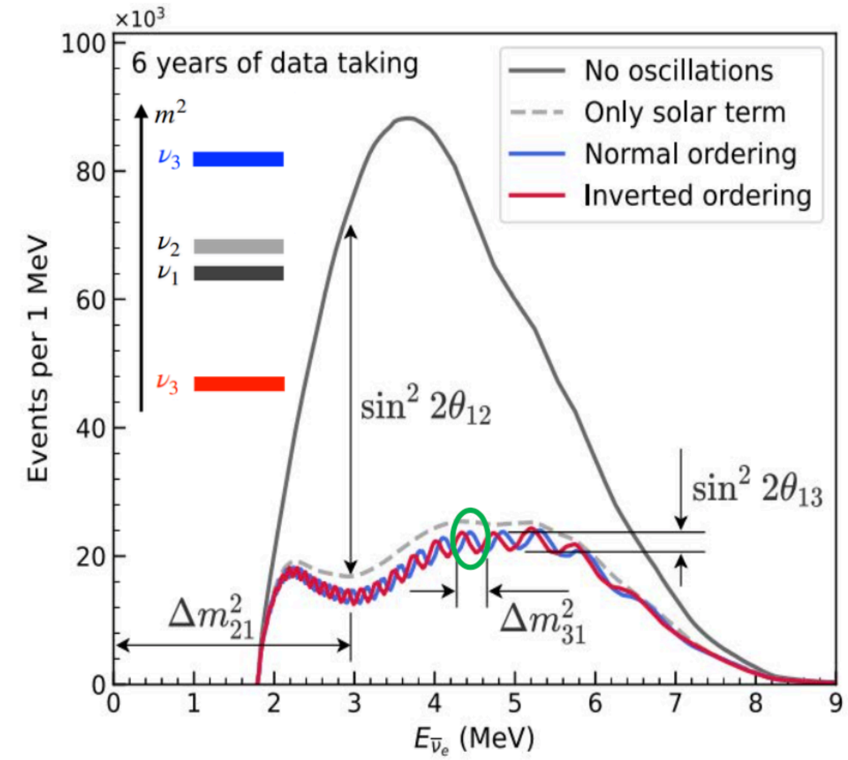


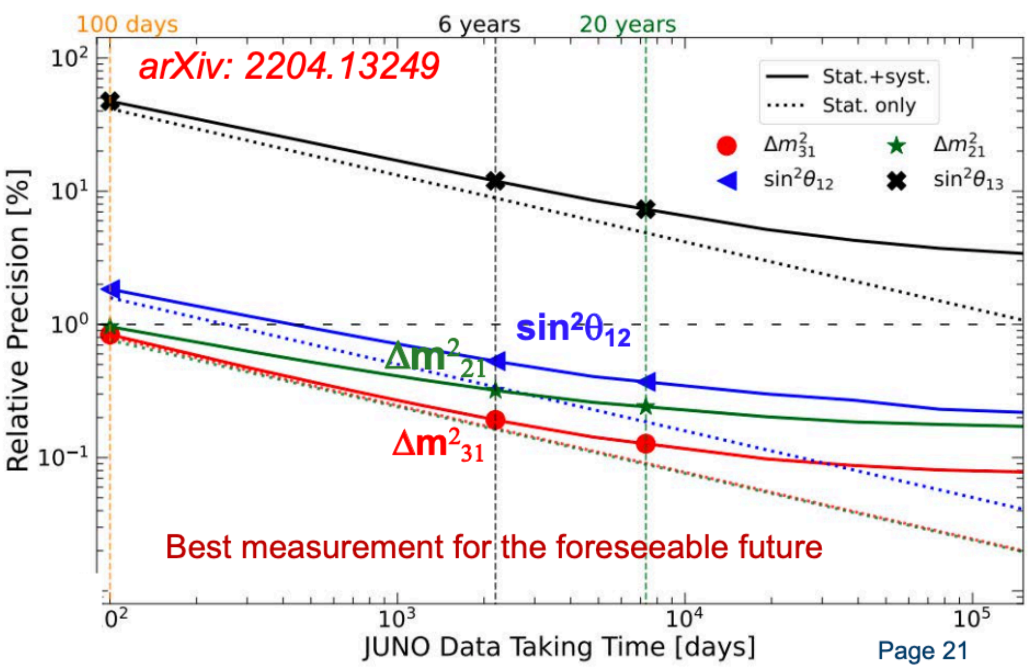


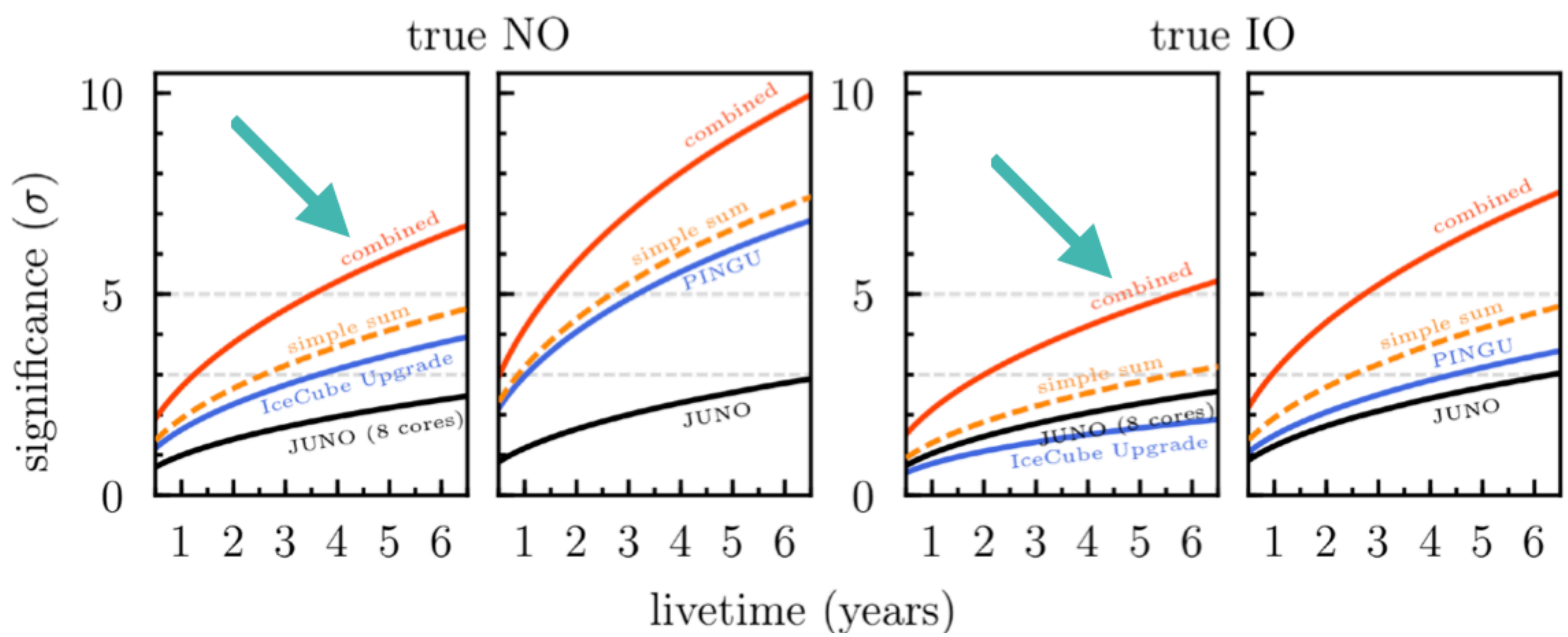


Mass Hierarchy with JUNO reactor experiment







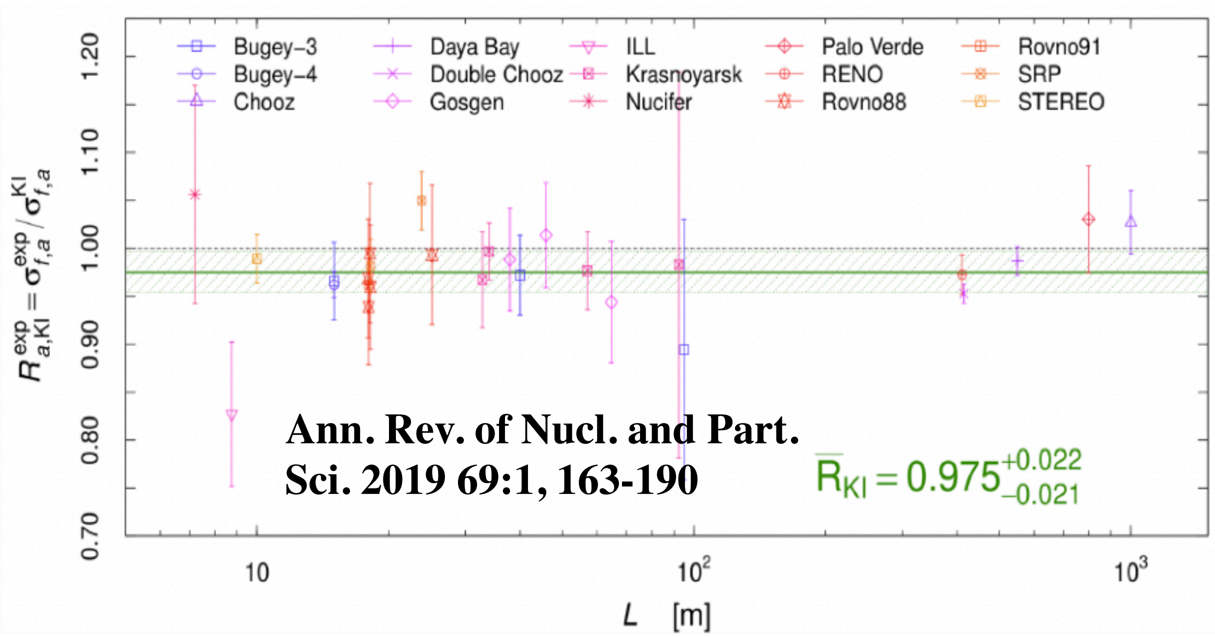


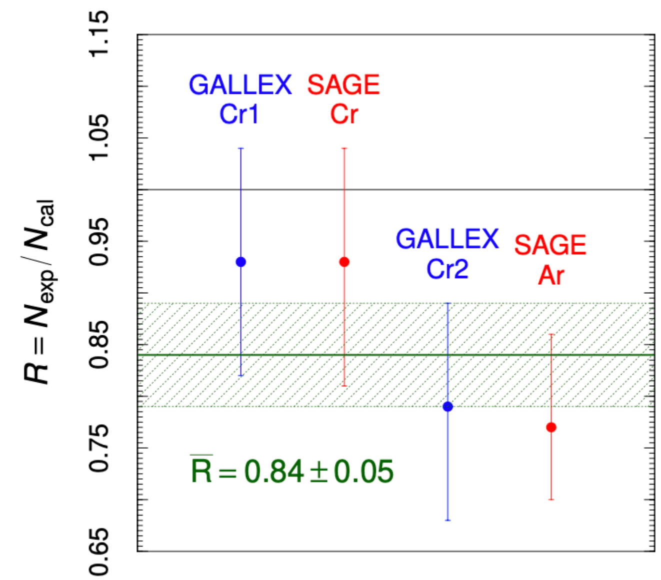
- 3σ sensitivity to mass hierarchy @6yrs
- Precision of $\sin^2\theta_{12}$, Δm^2_{21} and $\sin^2\theta_{13}$ <0.5%

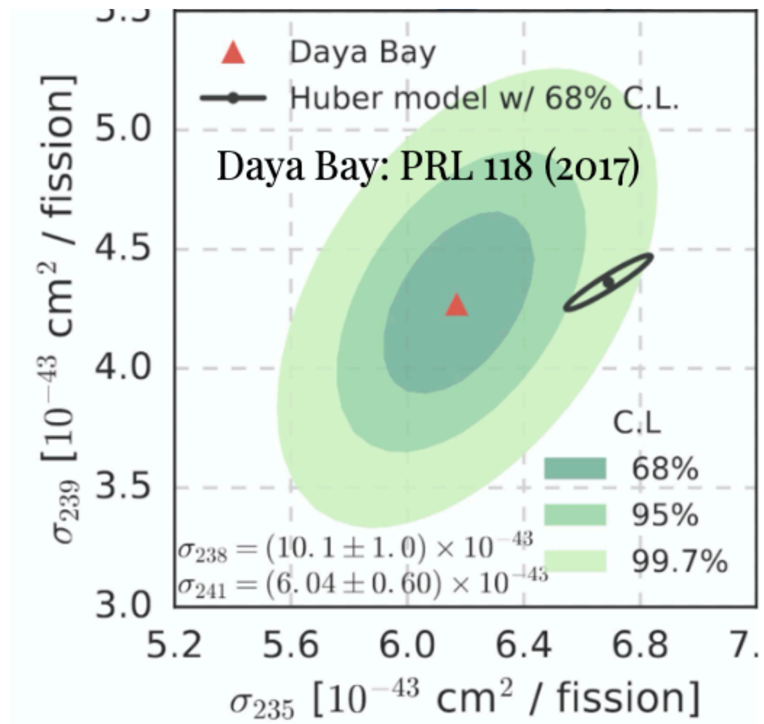
Sensitivity to MH enhanced by combining with Atmospheric (IceCube) data

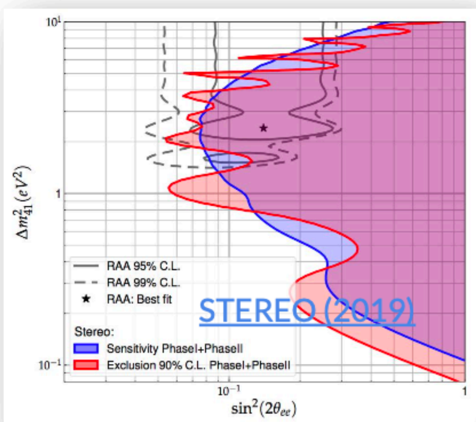
Sterile Neutrinos: reactors and radioactive sources

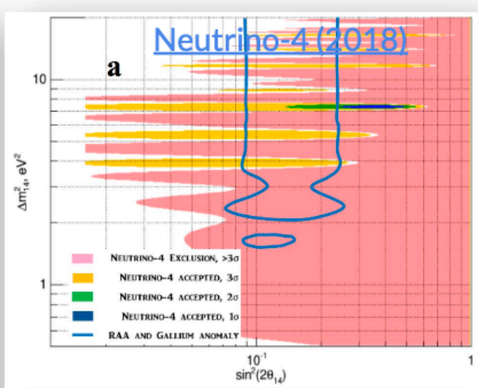
Observed anomalies, i.e. deficit in reactor $\bar{\nu}_e$ and gallium rad. source ν_e events

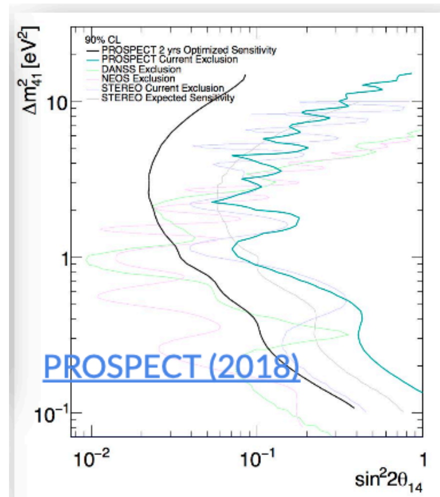


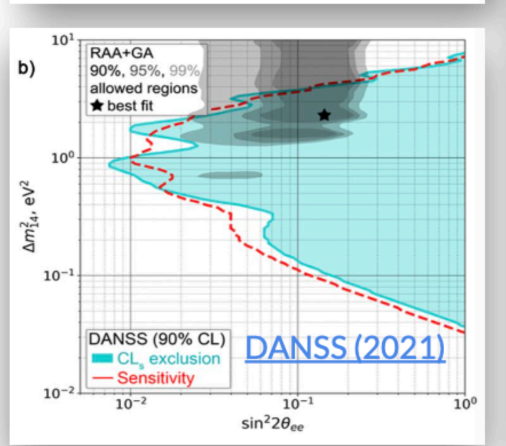


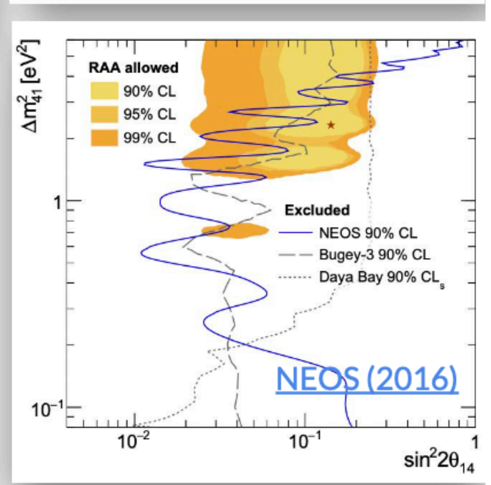










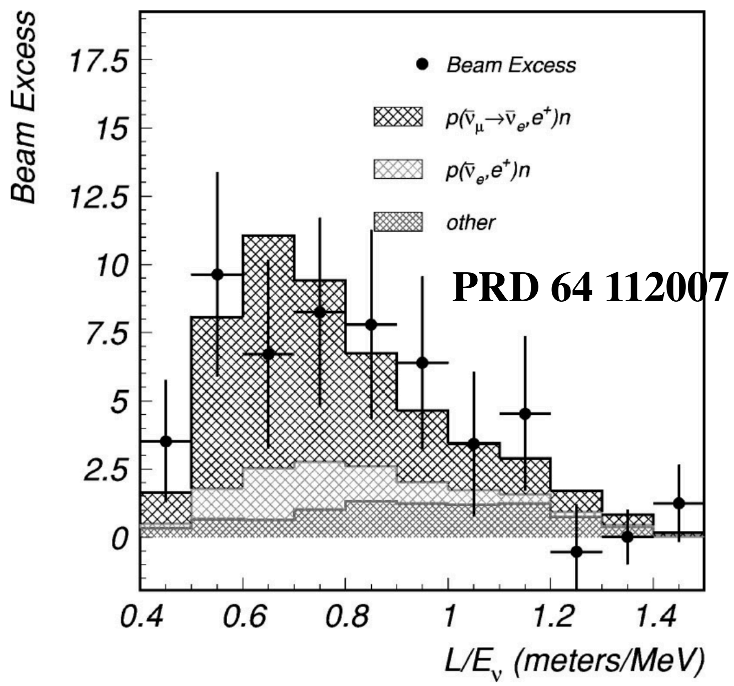


Revealed clear deficiencies in reactor flux modeling. Similarly for Gallium anomaly

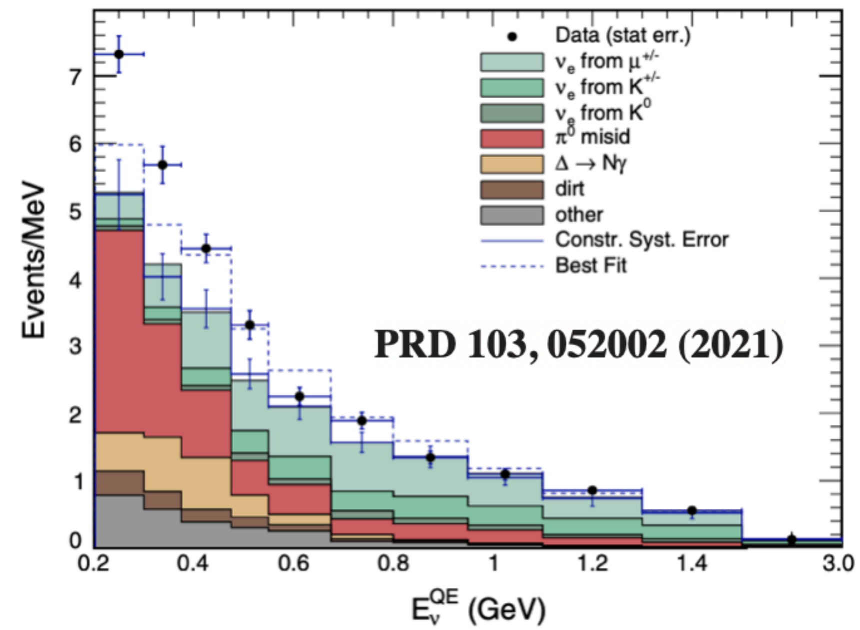
Most of recent reactor-based searches excluded the majority of low-Δm^2 region

Tension between ν_e reactor/gallium disappearance and ν_e accelerator appearance data

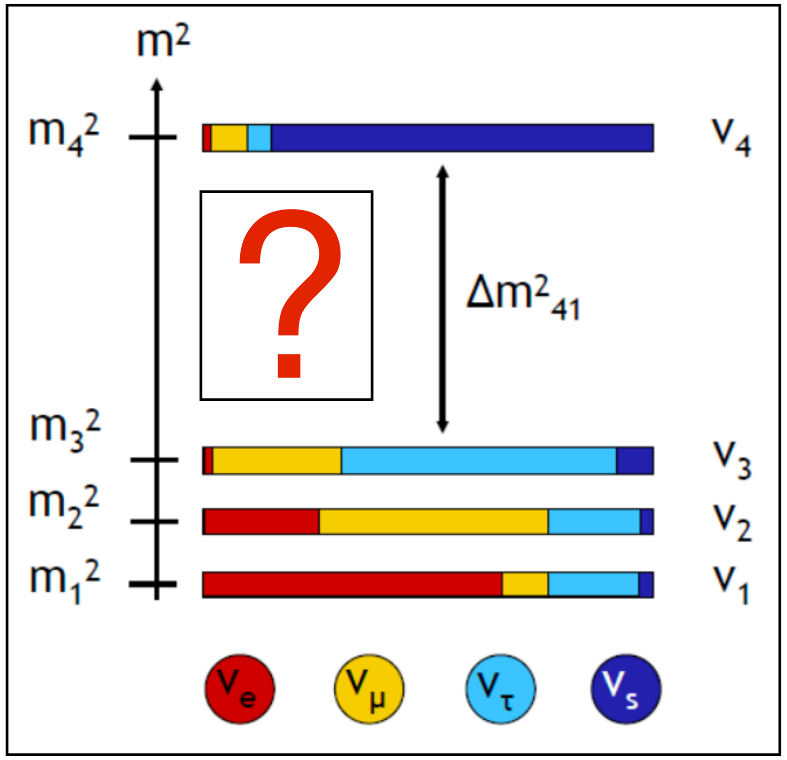
Short-Baseline Neutrino at Fermilab

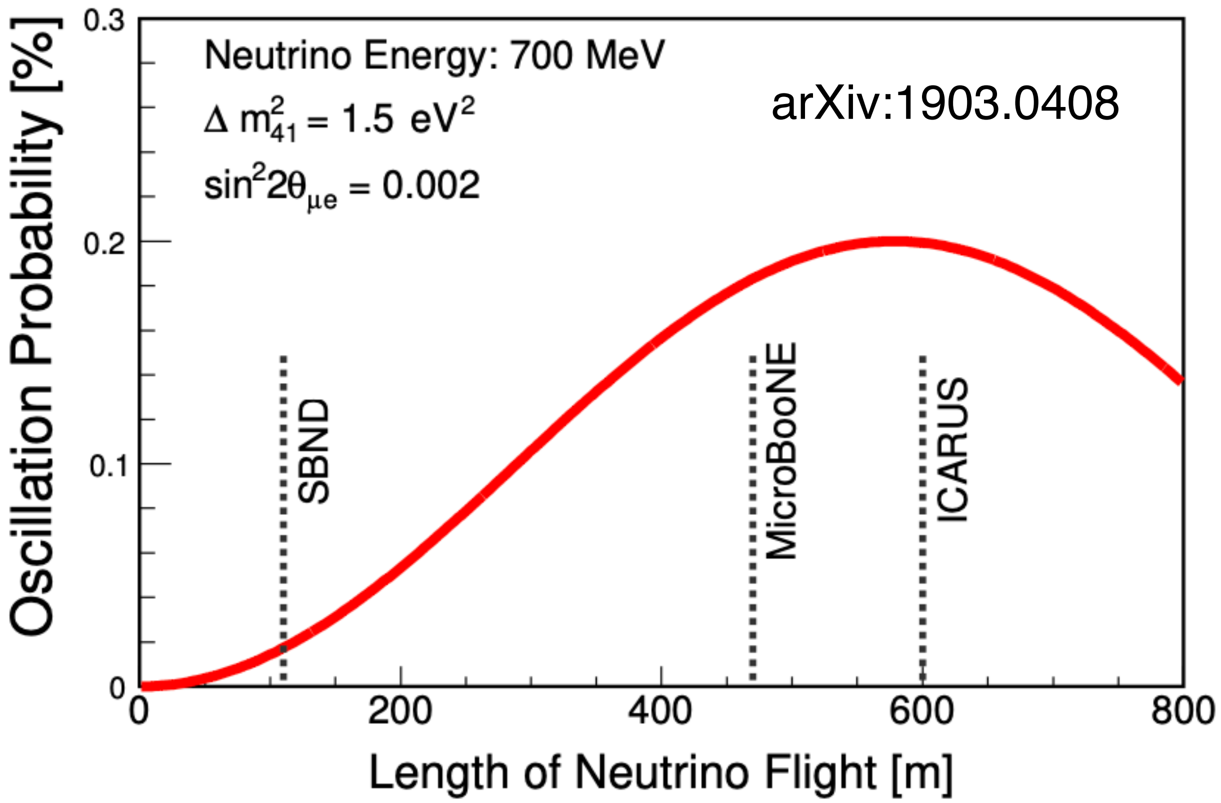


Excess $\bar{\nu}_e$ in a $\bar{\nu}_\mu$ dominated beam, 3.8σ



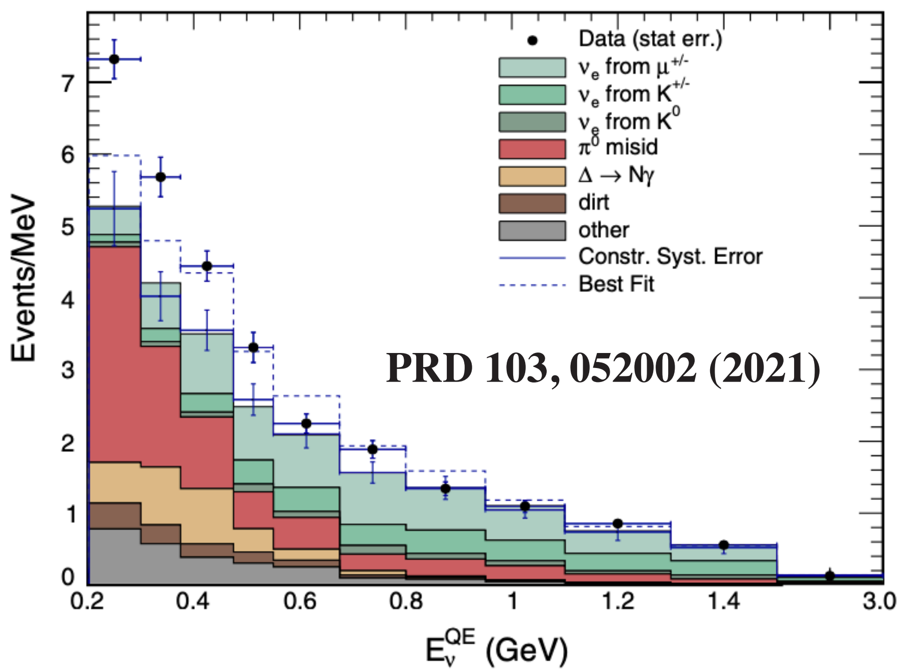
Excess of $\nu_e/\bar{\nu}_e$ in a $\nu_\mu/\bar{\nu}_\mu$ dominated beam, 4.8σ

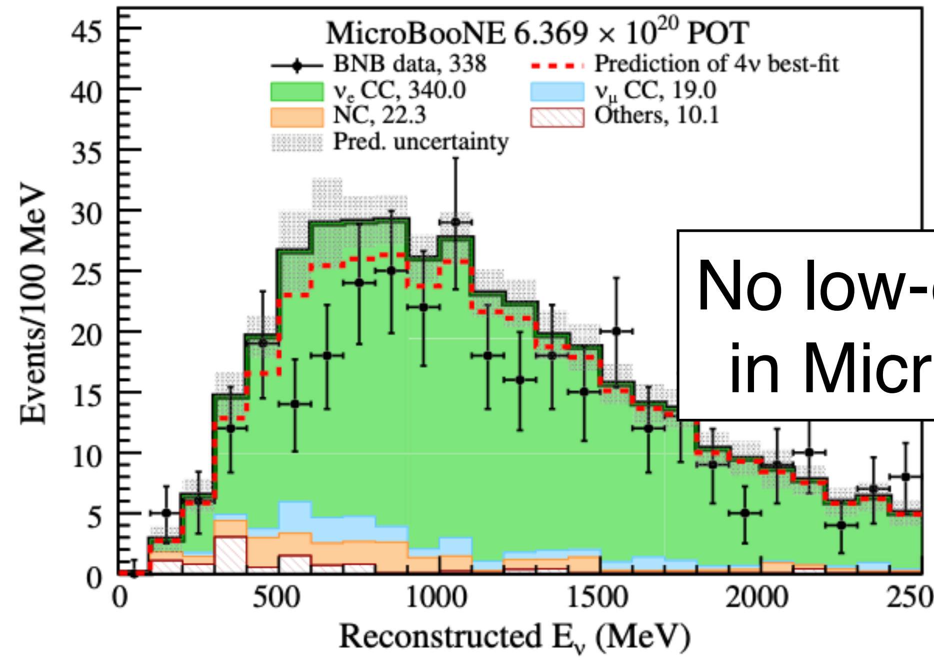




- Three different LAr detectors at different baselines
- Cancel out systematic effects to reliably fit the $\nu_{e,\mu} \leftrightarrow \nu_s$ oscillation probability
- MicroBooNE has completed the data taking. ICARUS has started. SBND soon to come

MicroBooNE and other GeV searches

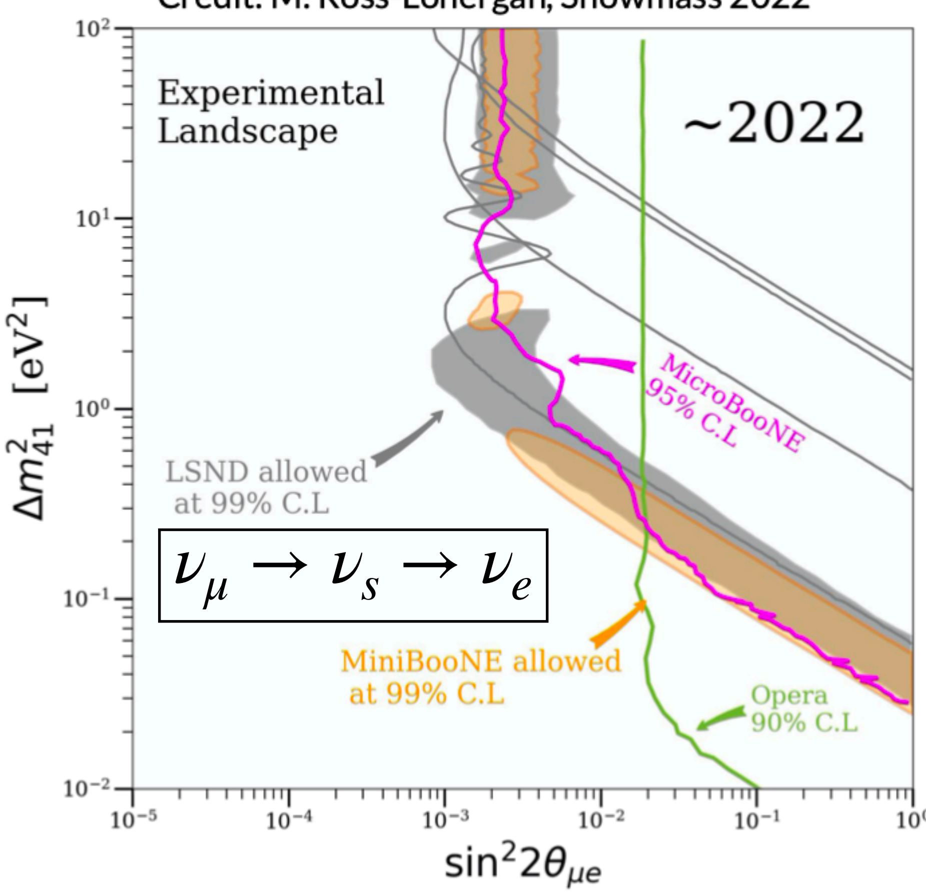


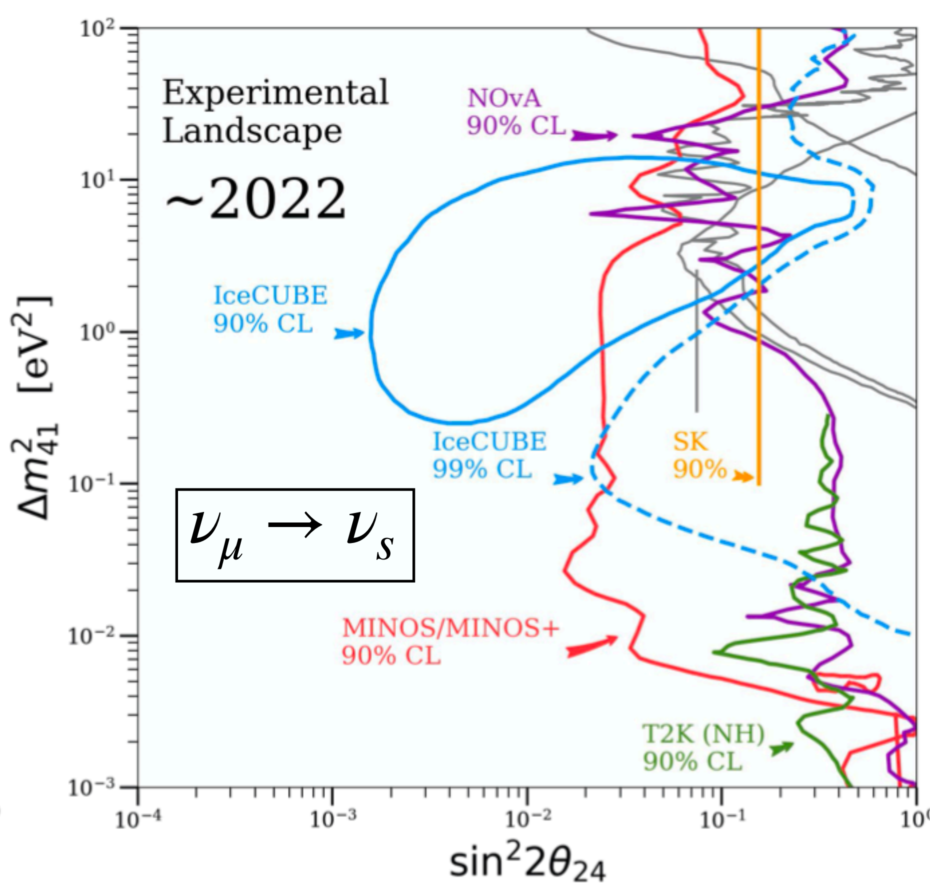


No low-energy excess in MicroBooNE data

PRL 130, 011801 (2023)

Credit: M. Ross-Lonergan, Snowmass 2022



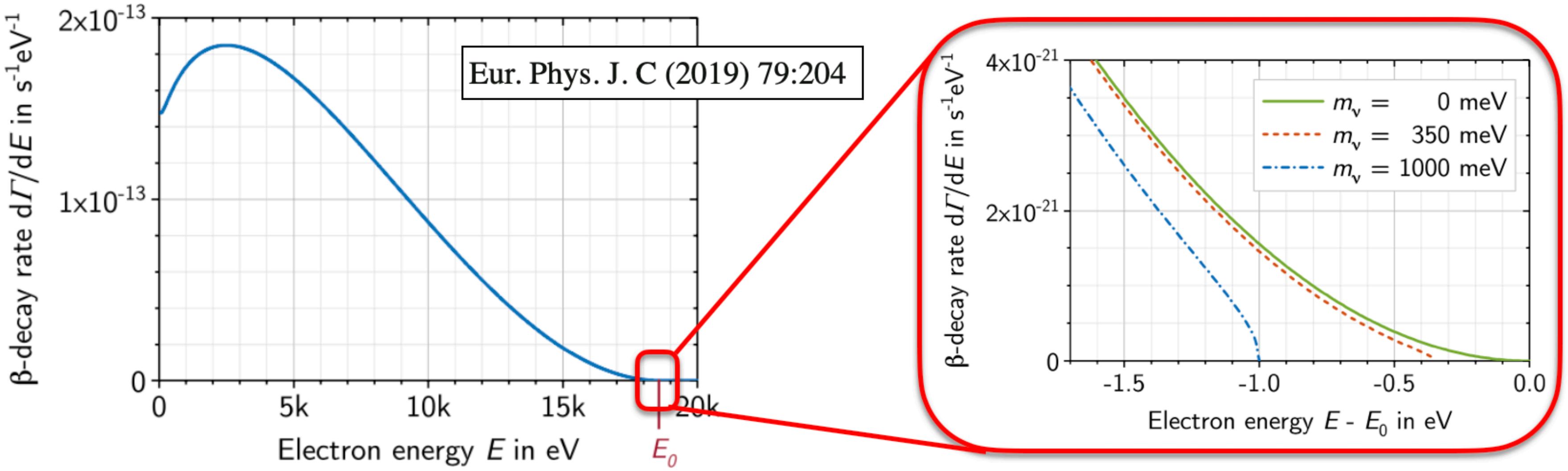


ICARUS has started collecting data

SBND to come soon

IceCube shows preference for non-zero $\sin^2 2\theta_{24}$ but not significant

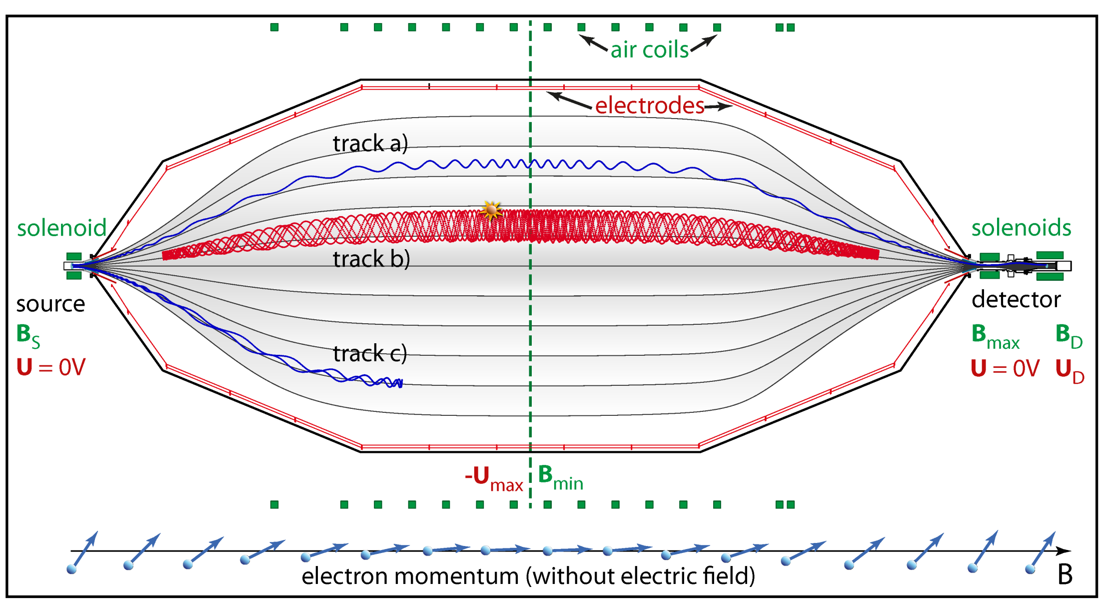
β decay experiment: KATRIN



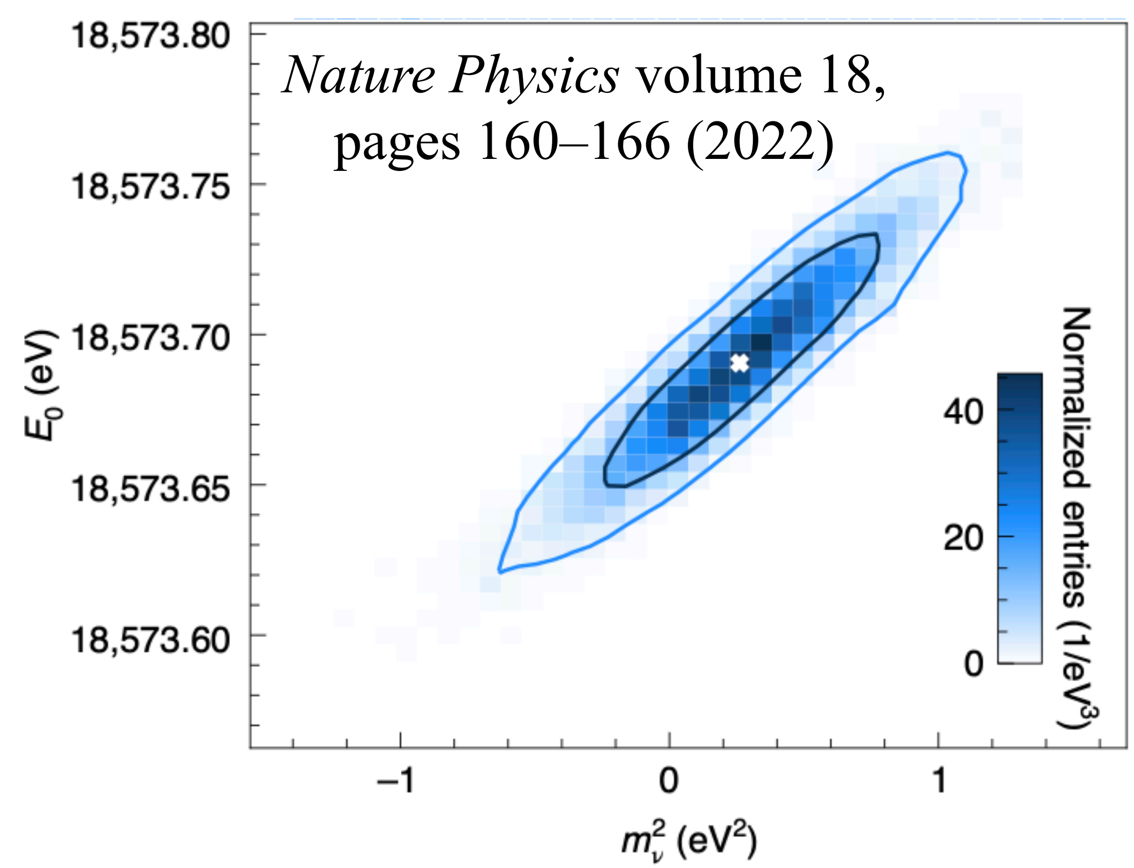
$$^3H \rightarrow {}^3He + e^- + \bar{\nu}_e$$
$$(Q_\beta = 18.574 \text{ keV}, T_{1/2} = 12.3 \text{ yr})$$

10^{-8} of all decays in last 40 eV

Strong tritium source (10^{11} decays/s),
Background <0.1 cps, Energy resolution ~ 1 eV,
0.1% systematic on spectrum shape



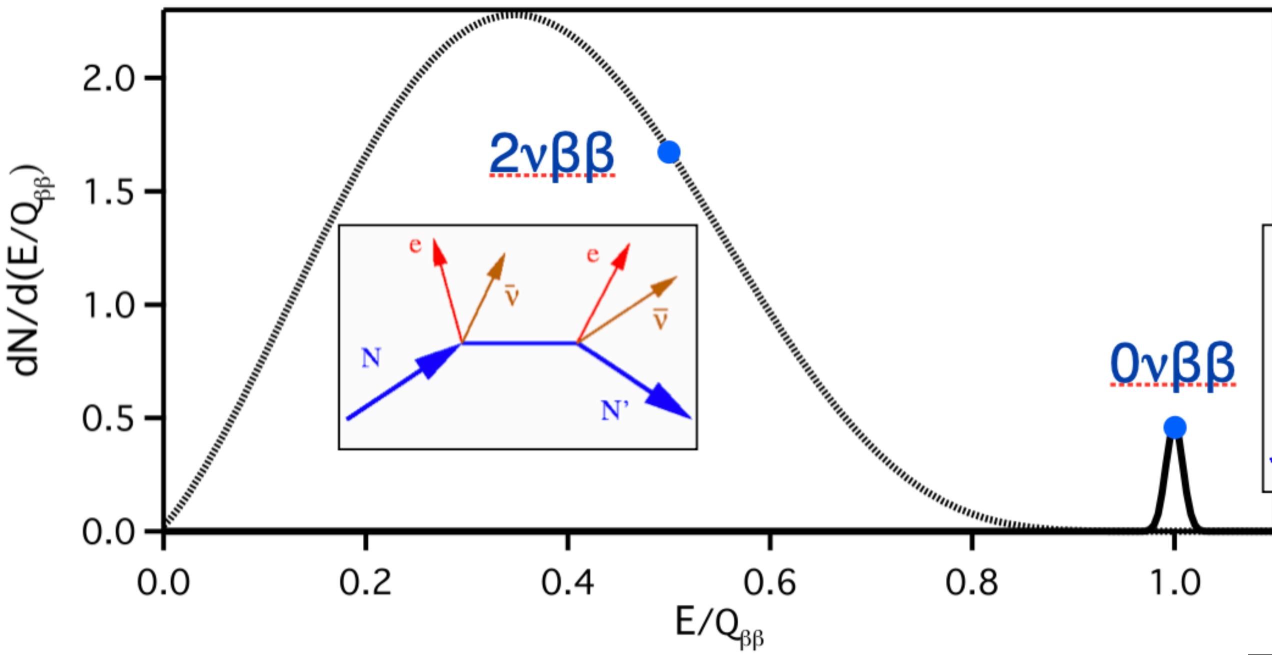
Magnetic spectrometers used to measure
the β spectrum at the endpoint

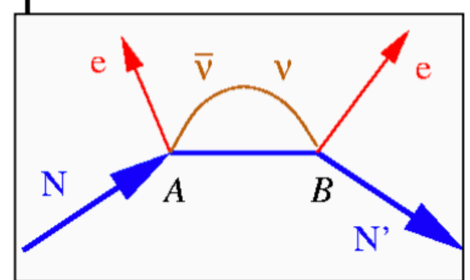


$m_\nu < 0.8$ eV (90% C.L.)
Final sensitivity goal: $m_\nu < 0.2$ eV

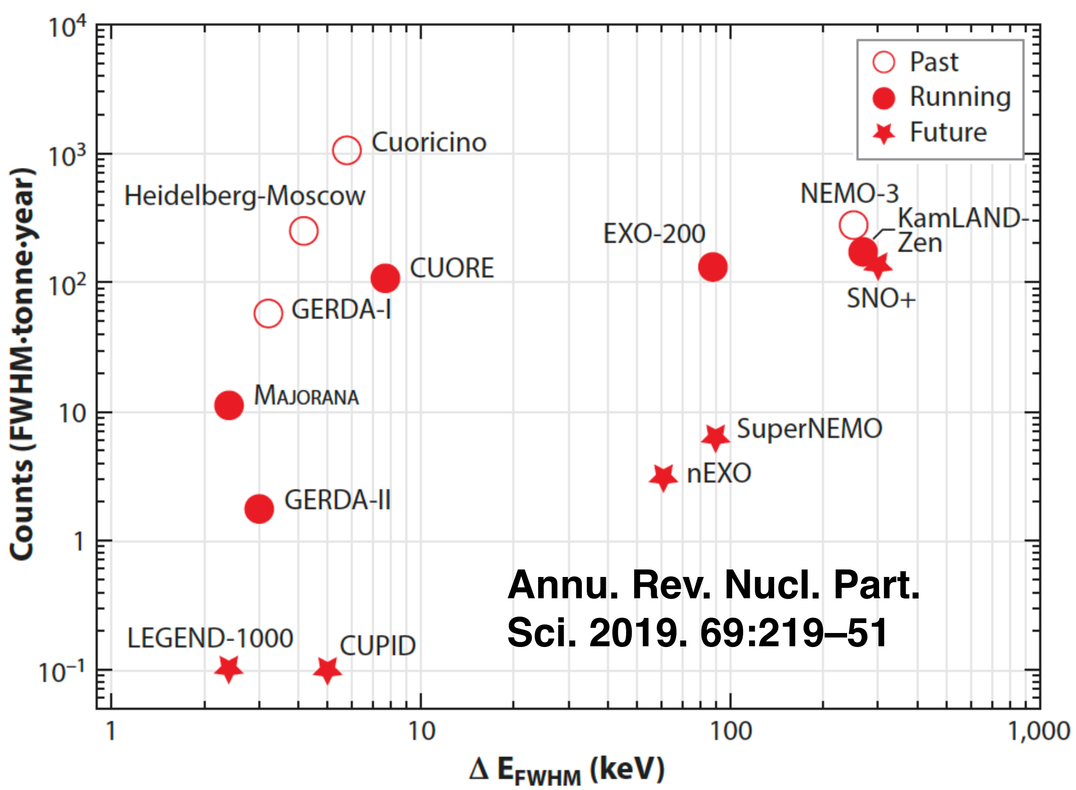
ν-less $\beta\beta$ decay experiments

Neutrinos are neutral: we don't know whether they are Dirac or Majorana ($\nu = \bar{\nu}$)





If Majorana nature also implies lepton number violation, ingredient necessary with CP violation to generate baryon asymmetry via Leptogenesis

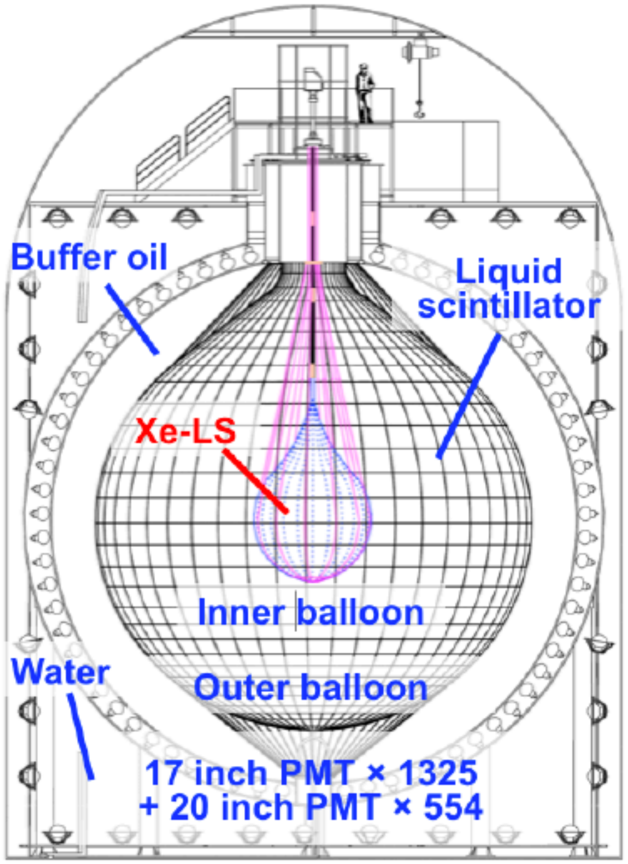


$$T^{0\nu}_{1/2}(n_\sigma) = \frac{4.16 \times 10^{26} y}{n_\sigma} \left(\frac{\varepsilon a}{W}\right) \sqrt{\frac{Mt}{b\Delta(E)}}$$

If background free $\Rightarrow T^{0\nu}_{1/2}(n_\sigma) \propto Mt$

Combine a large mass with very low background contamination

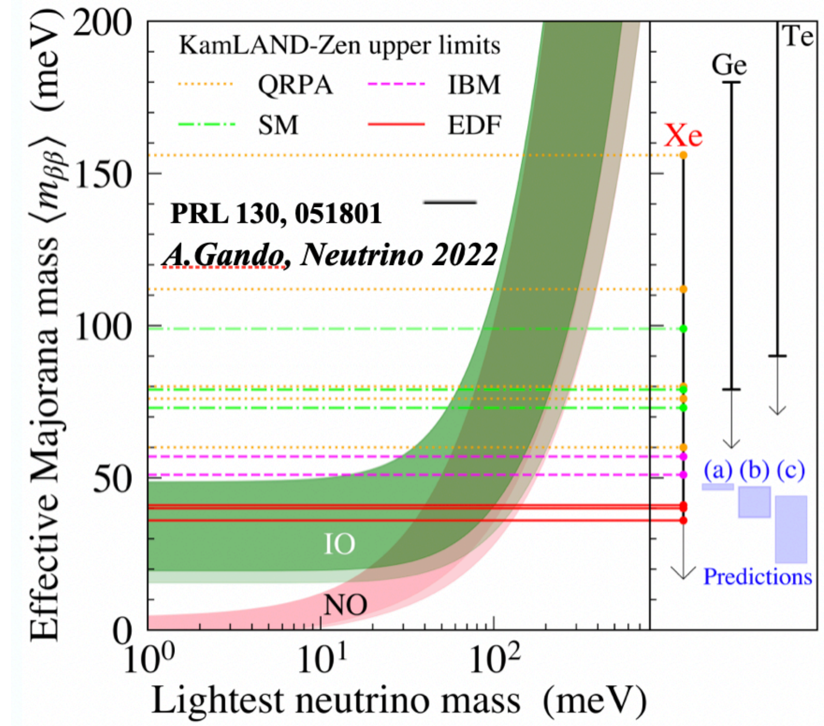
ν-less $\beta\beta$ decay experiments



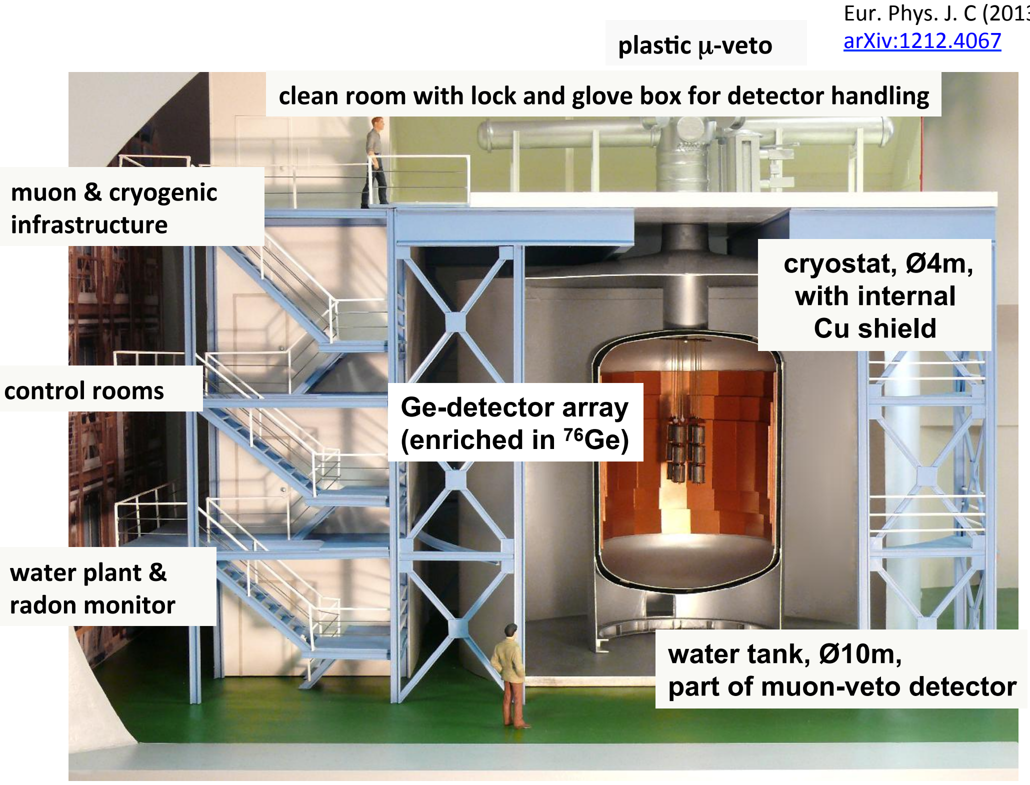
KamLAND-Zen

750 kg of liquid scintillator loaded with Xenon (larger mass but poorer energy resolution)

$m_{\beta\beta} < 35 - 156$ meV (90%CL)

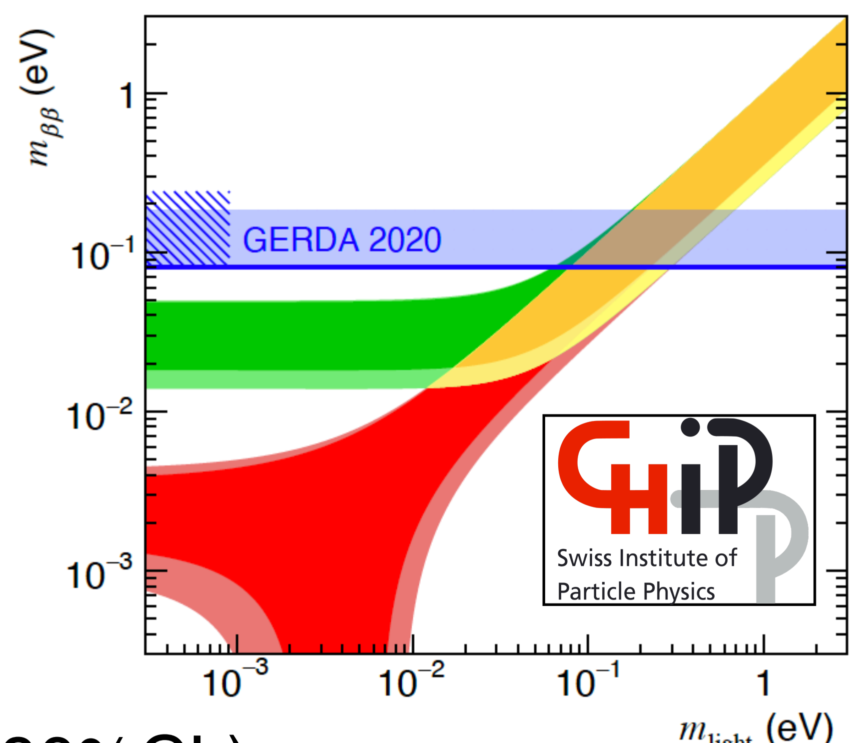


Eur. Phys. J. C (2013) 73:2330
arXiv:1212.4067



GERDA
(completed in 2019)

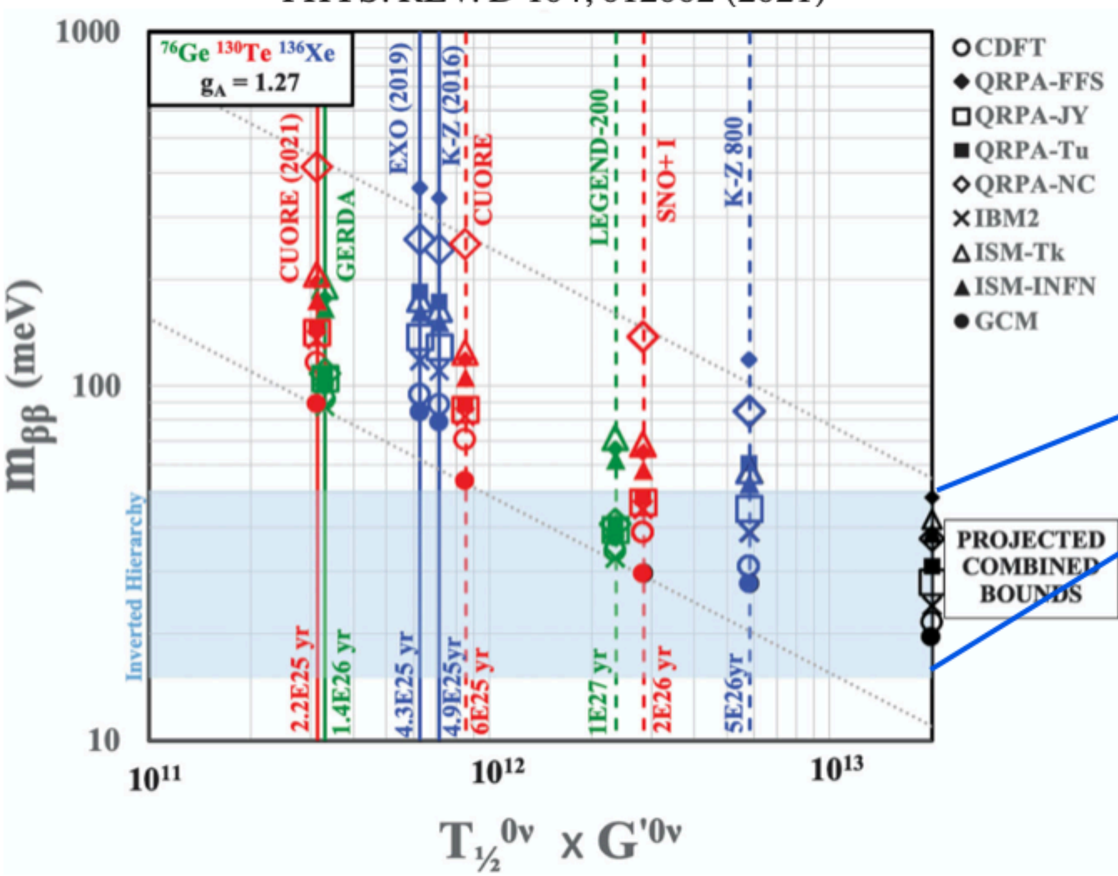
“Bare” enriched Germanium array in liquid argon (~40 kg enriched detector)

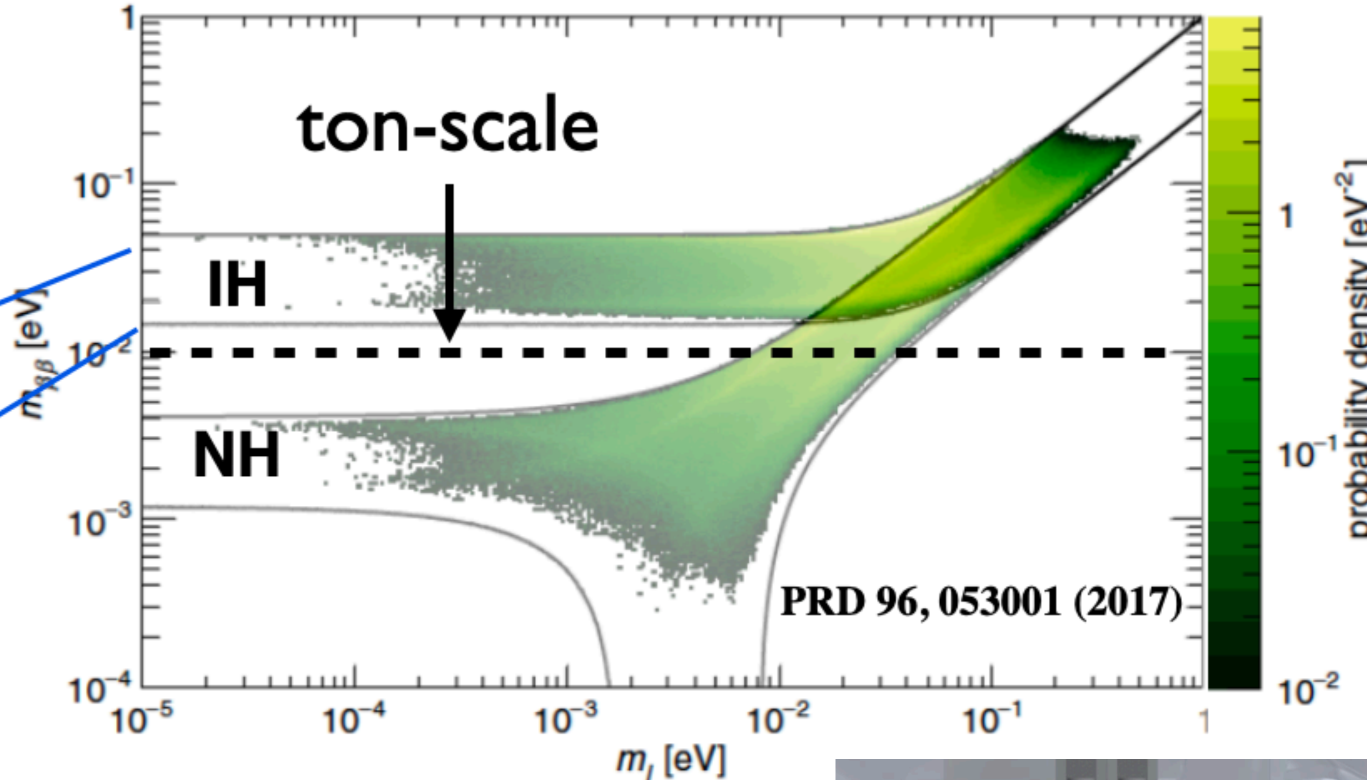


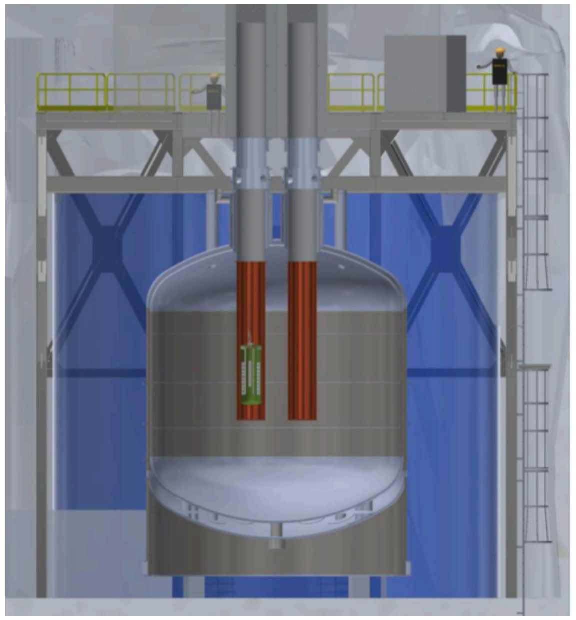
$m_{\beta\beta} < 79 - 180$ meV (90%CL)

ν-less $\beta\beta$ decay: future prospects

PHYS. REV. D 104, 012002 (2021)





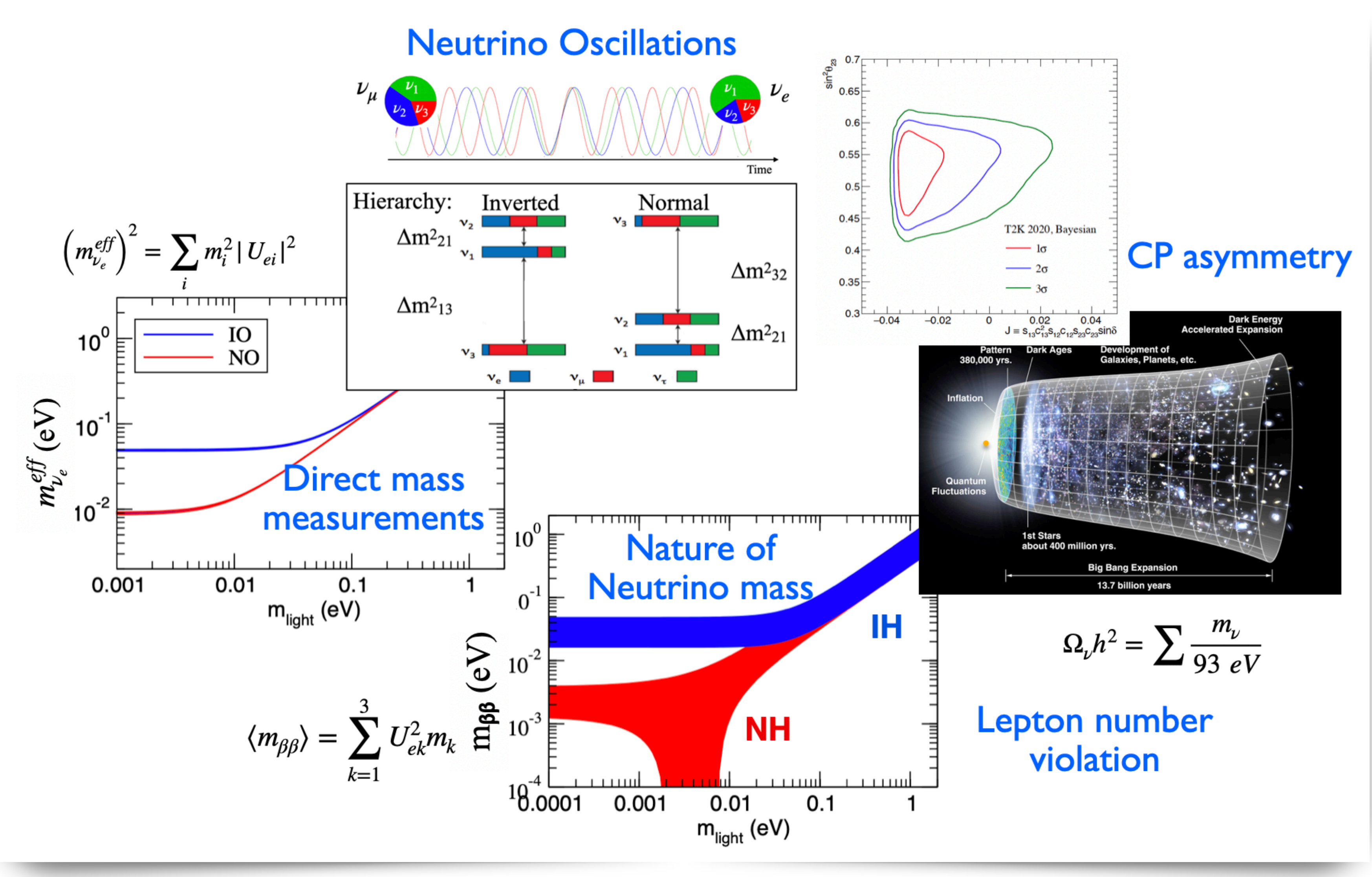


- KamLAND 2-Zen at ~20 meV sensitivity with x5 light yield
- Future ^{76}Ge experiments aim to reach 10-20 meV
  ⇒ LEGEND-200 (kg) running at LNGS (GERDA + Majorana + new detectors) and, later, LEGEND-1000 (kg) to fully cover the IH band
- DARWIN: next-generation dark matter Xenon-based experiment will also provide complementary sensitivity to ν-less $\beta\beta$ decay with 3.5tons ^{136}Xe

Conclusions

Neutrino experiments are in an era of greatly increased baseline, intensity, and diversity, lower background, bigger masses

Well-defined roadmap towards a more comprehensive understanding of Nature



Swiss institutes are playing key roles and leading many of these efforts