Experimental neutrino physics: latest results and a glimpse to future

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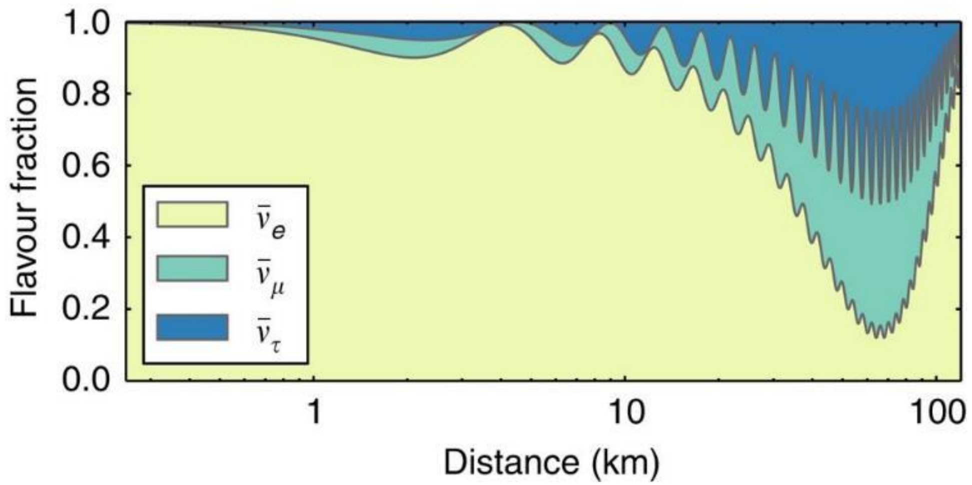
The precision era of neutrino physics

Year 2012 represented a landmark in neutrino physics even if the 2012 discovery it is dubbed (quite technically) as the "discovery of ϑ_{13}".

1998: neutrinos come in three different flavors, which are eigenstates of the weak interaction lagrangian. But each flavor is a linear superposition of three different mass eigengenstates

2012: all neutrino mixing angles are "large" compared with the CKM matrix and we can observe sizable oscillations at distances and energies that can be produced on earth by particle **accelerators** and **reactors**

It is not by chance that 2012 marks the fall of experiments with natural neutrino sources and the rise of large-size large-complexity (large-cost!) experiments based on accelerators and reactors.



$$P_{\nu_\alpha\to\nu_\beta}(t) = |\langle\nu_\beta|\nu_\alpha(t)\rangle|^2$$
$$= \delta_{\alpha\beta} - 4\sum_{i>j}\Re(U^*_{\alpha i}U_{\beta i}U_{\alpha j}U^*_{\beta j})\sin^2(\frac{\Delta m^2_{ij}L}{4E})$$
$$+ 2\sum_{i>j}\Im(U^*_{\alpha i}U_{\beta i}U_{\alpha j}U^*_{\beta j})\sin(\frac{\Delta m^2_{ij}L}{4E}),$$

where $\Delta m^2_{ij} = m^2_i - m^2_j$ and we can rewrite:

$$\frac{\Delta m^2_{ij}L}{4E} \approx 1.267\frac{\Delta m^2_{ij}[eV^2]\times L[km]}{E[GeV]}.$$

Aims of my talk

- **Are we duly exploiting this unique opportunity?** What have we learnt since 2012 and, in particular, in 2020-2022?

  Spoiler: we are doing quite a good job but we also made mistakes we are trying to fix!

- Can we **complete the job** in the decade to come?

  Spoiler: I am very optimistic that – by 2033 – we will know all parameters of the lepton Yukawa sector of the Standard Model… except one

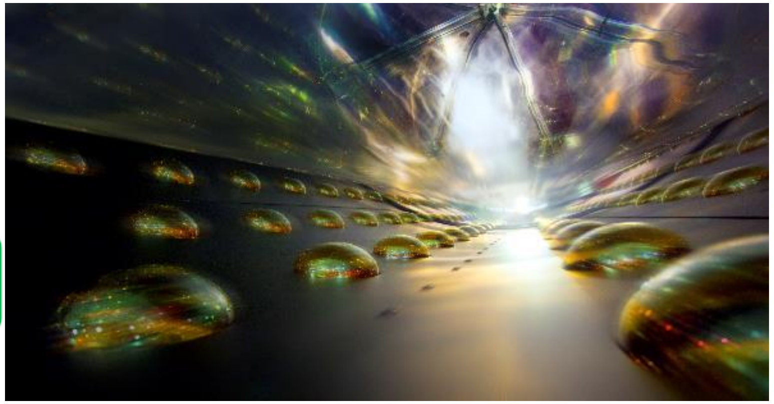
- Are we facing the challenges that cannot be addressed by neutrino oscillations?

  Spoiler: we are brave people, and we are doing our best. Maybe we need a new idea or a breakthrough to pin down the key missing parameter: **the size of the lightest mass eigenstate and, hence, the nature of neutrinos**

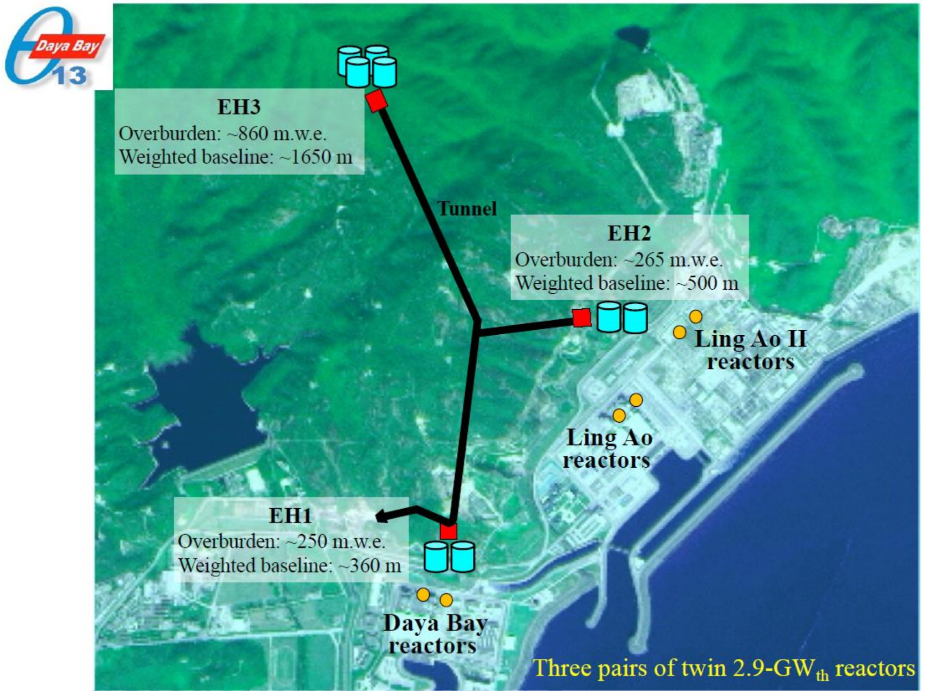
  Here, accelerator and reactor neutrinos play a minor role while cosmology, rare nuclear decays, extragalactic neutrinos, and novel detection techniques are the path to follow

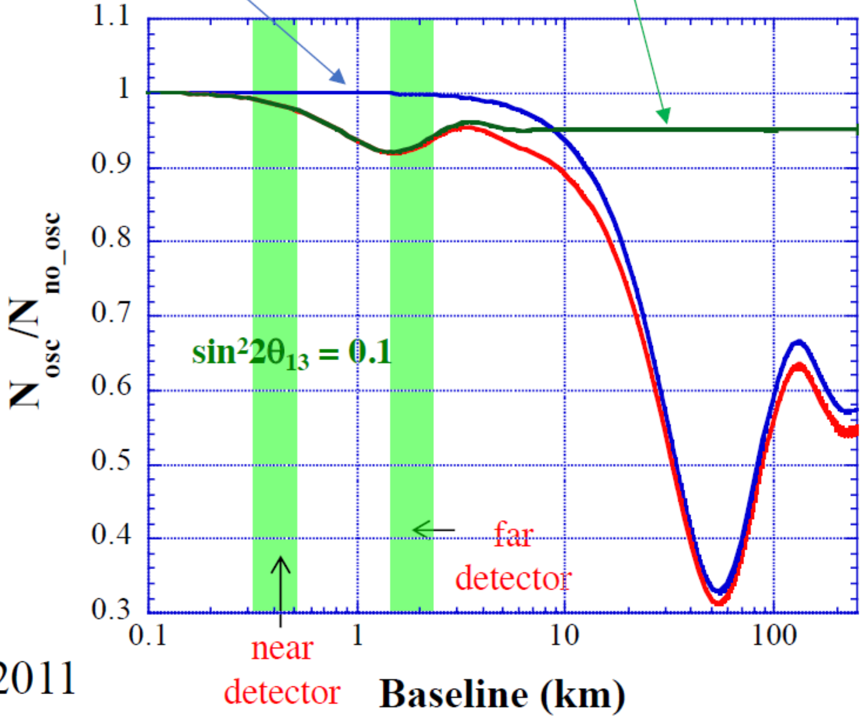
[disclaimer: not covering neutrino telescopes (see talk by D. Berge), solar, and atmospheric neutrinos. No hard feelings ☺ just a matter of time]

Reactor neutrinos… after Daya-Bay



$$P(\bar{\nu}_e \to \bar{\nu}_e) = 1 - \sin^2 2\theta_{13}\left[\cos^2\theta_{12}\sin^2\left(\frac{\Delta m^2_{31}L}{4E}\right) + \sin^2\theta_{12}\sin^2\left(\frac{\Delta m^2_{32}L}{4E}\right)\right] - \cos^4\theta_{13}\sin^2 2\theta_{12}\sin^2\left(\frac{\Delta m^2_{21}L}{4E}\right)$$





Kam Biu Luk, Talk at Neutrino2022

Detector commissioning on 15 August 2011

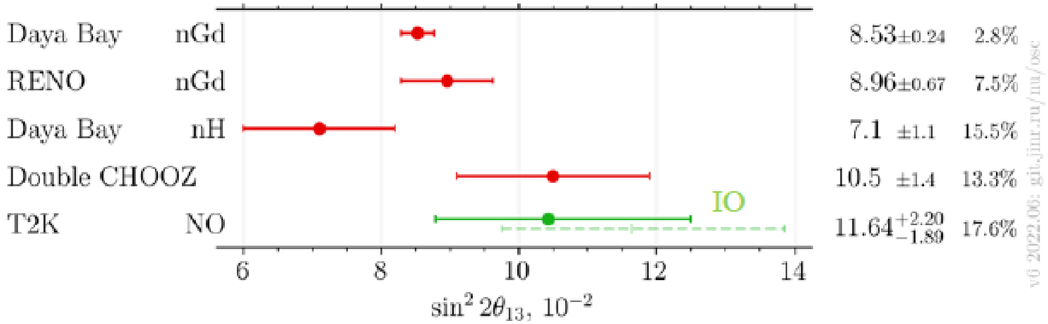
Collection of physics data began on 24 Dec 2011

Collection of physics data ended on 12 Dec 2020

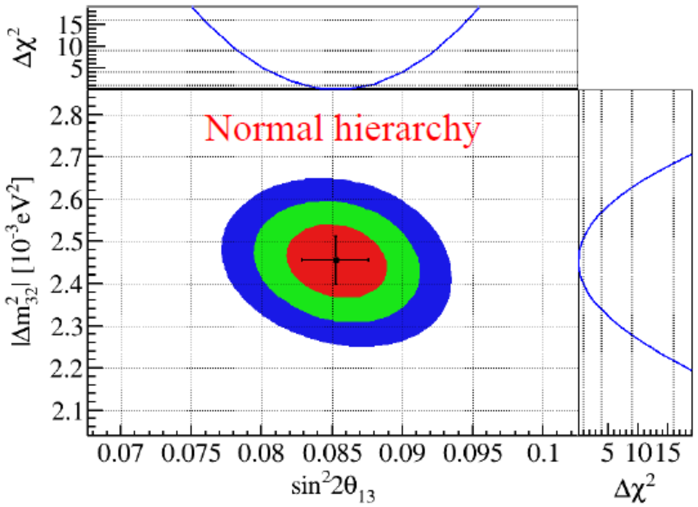
Decommissioning: 12 Dec 2020 – 31 Aug 2021

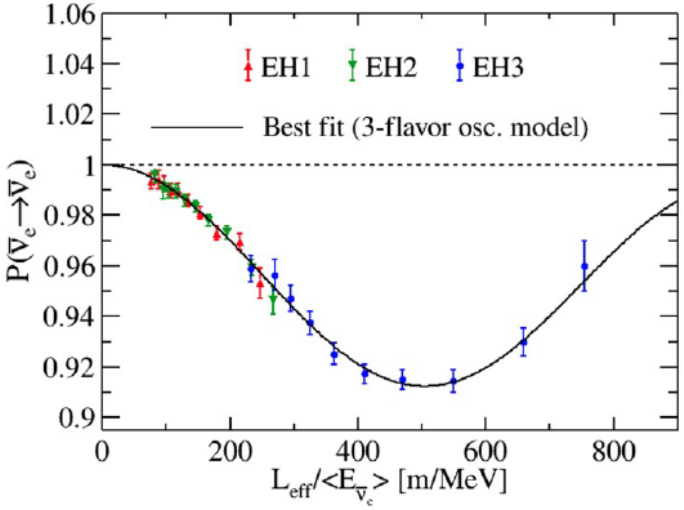
I don't think we will further improve our knowledge of ϑ_{13} in 10 years from now but…

$\sin^2 2\theta_{13}$



Will likely be the best measurement in the foreseeable future





[Daya Bay Jun 2022]

Best-fit results: $\chi^2/\text{ndf} = 559/518$

$$\sin^2 2\theta_{13} = 0.0853^{+0.0024}_{-0.0024}$$ (2.8% precision)

Normal hierarchy: $$\Delta m^2_{32} = +\left(2.454^{+0.057}_{-0.057}\right) \times 10^{-3}\ \text{eV}^2$$

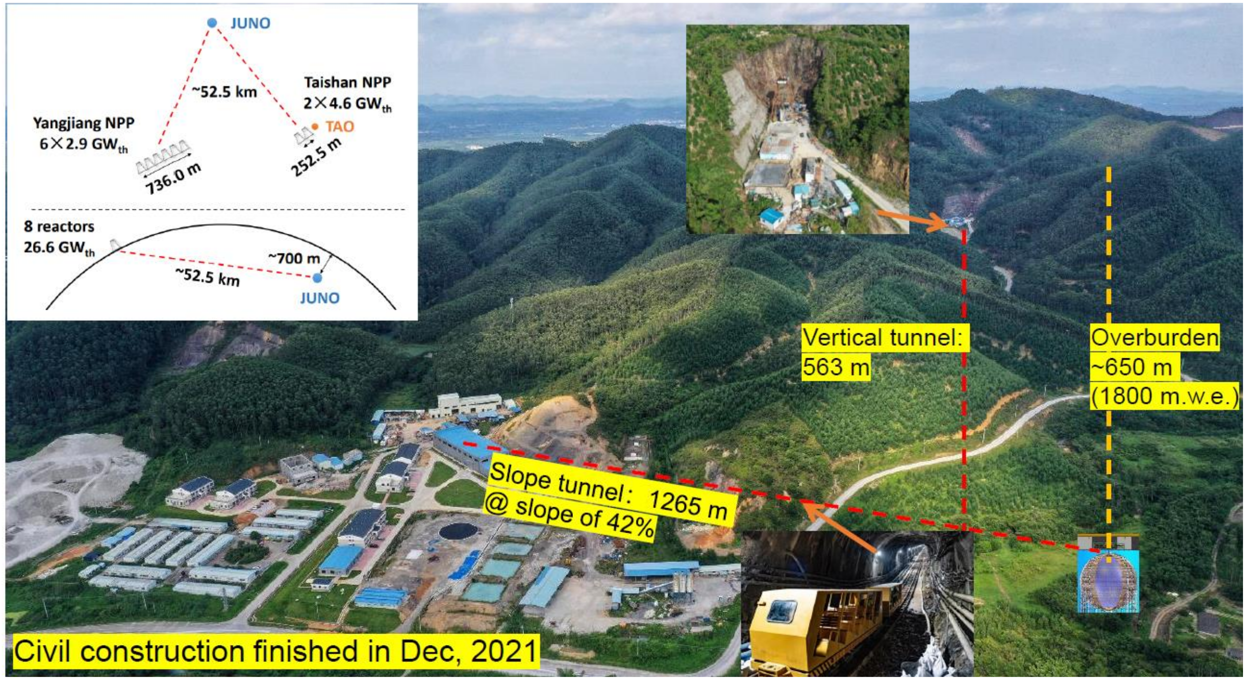
Inverted hierarchy: $$\Delta m^2_{32} = -\left(2.559^{+0.057}_{-0.057}\right) \times 10^{-3}\ \text{eV}^2$$

(2.3% precision)

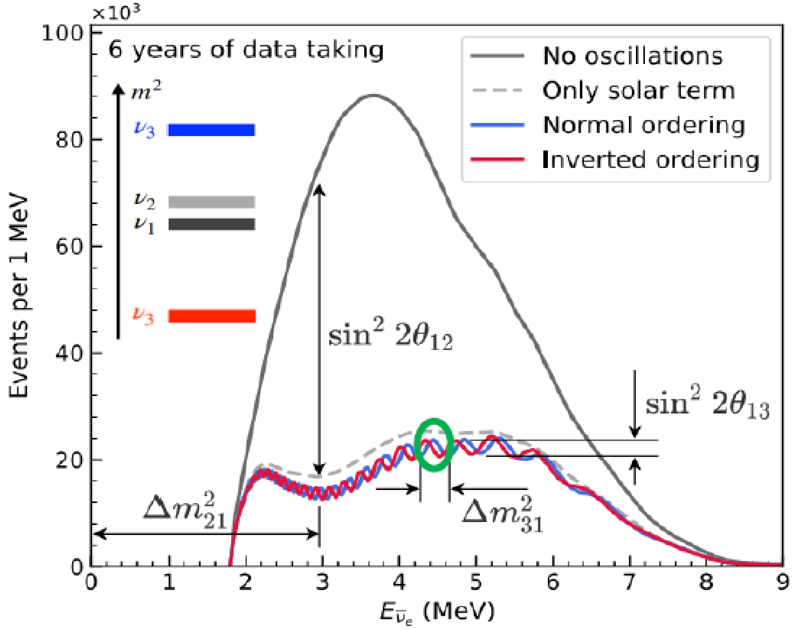
… the brightest show in town has yet to come

JUNO

The largest (20 kton) liquid scintillator experiment ever conceived is ready to go!

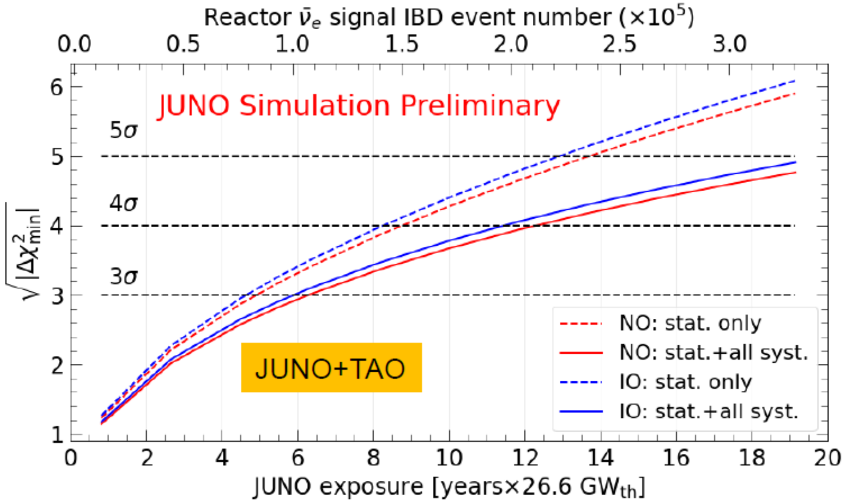


Jie Zhao, Talk at Neutrino2022



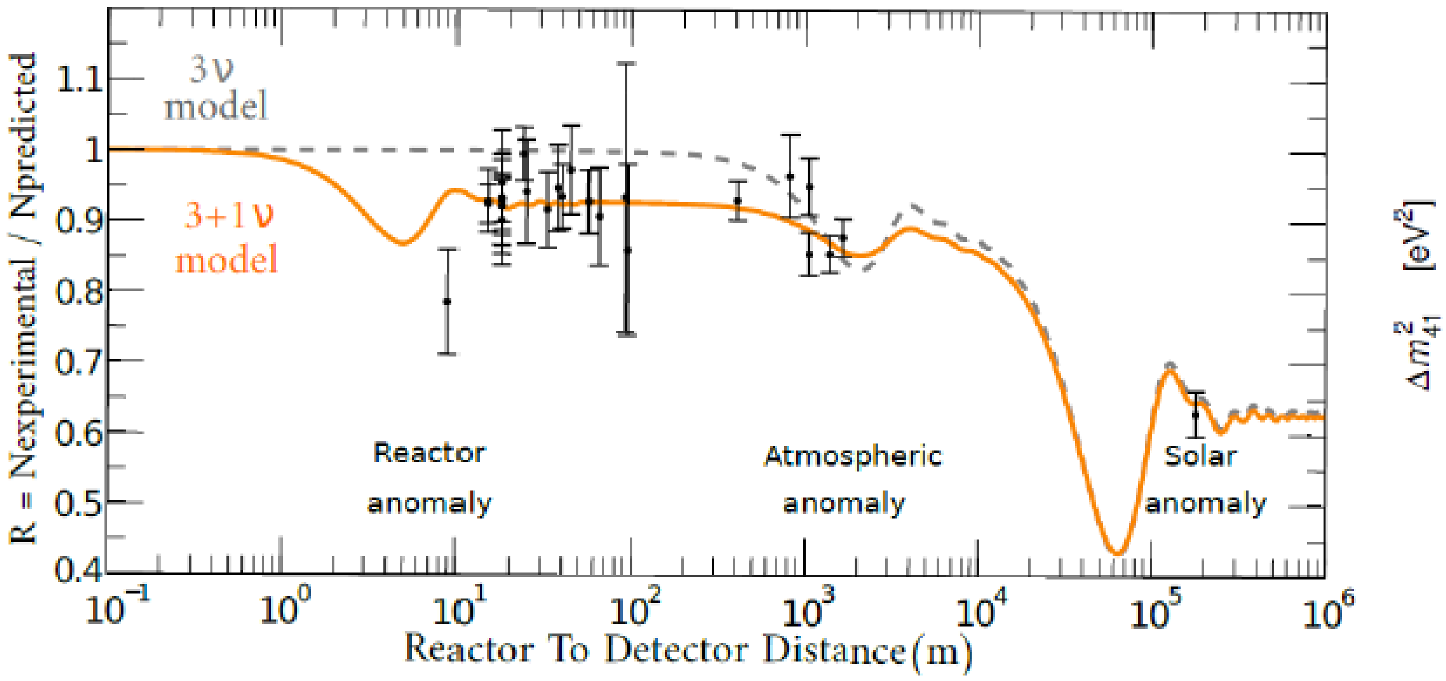
JUNO will observe the disappearance of ne from 8 reactors to an unprecedented precision (energy resolution <3%) to record the beating of the oscillations driven by Δm^2_{12} and Δm^2_{23} !!

Those beatings determine the mass ordering of neutrinos



Dust under the carpet ☺

The current generation of reactor experiments (Double Chooz, RENO, Daya Bay) got their best achievements because they do not rely on the absolute flux of the neutrinos coming from reactor. In particular, Daya Bay has the best precision because it has the biggest redundancy to compare neutrino flux close to the reactor (Near Detector/no oscillation) and far from the reactor (Far Detector). When we cannot rely on it, life is much more difficult!

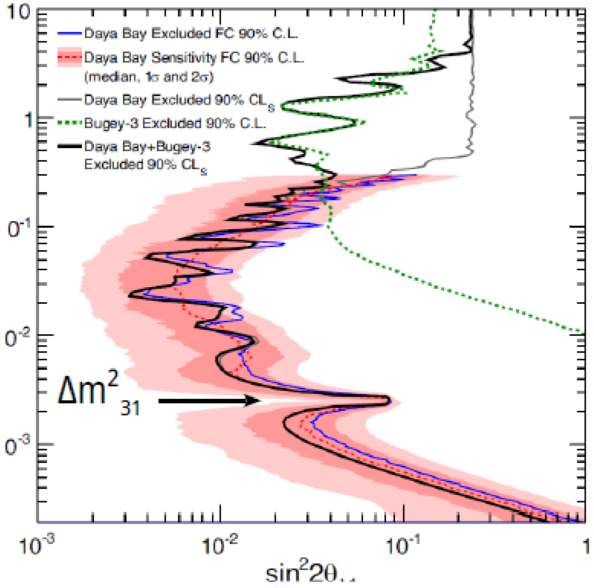


Difficult to disentangle our limited knowledge of neutrino flux at reactor from possible evidence of a new type of neutrino - “sterile neutrino(s)” – with a Δm^2 much larger than Δm^2_{12} and Δm^2_{23}

Are we seeing evidence for a new source of oscillations?

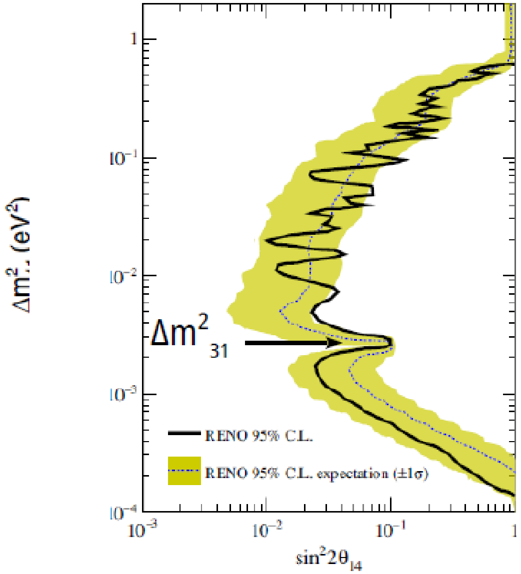
No, as long as we rely on relative measurements:

PRL 125 (2021) 071801



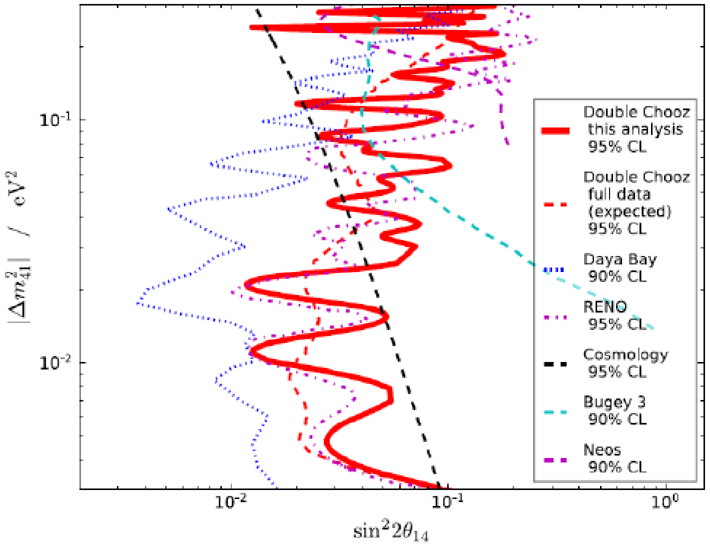
DayaBay

PRL 125 (2020) 191801



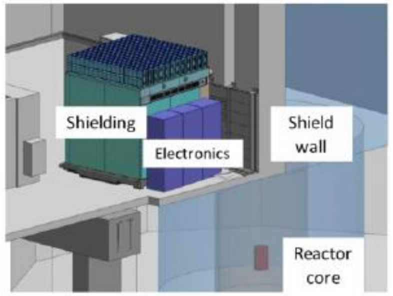
Reno

EPJC 81 (2021) 775



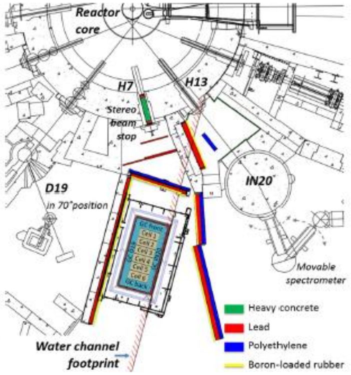
DoubleChooz

But oscillations might run undetected with this method if they occur at L=10 m



Example : PROSPECT ↑

→

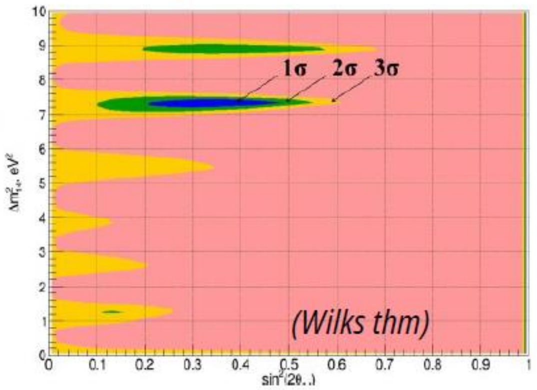


Are we seeing evidence for a new source of oscillations?

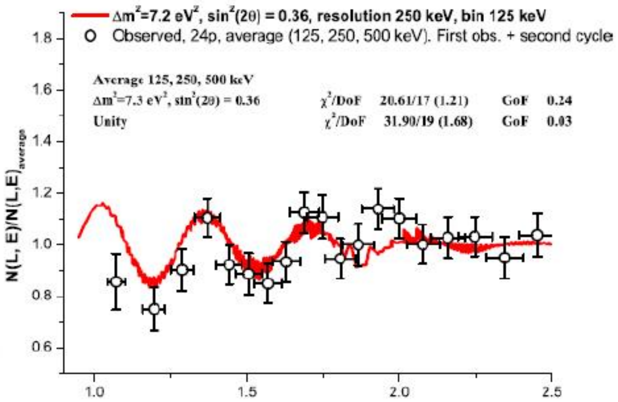
More confusion when we start relying on fluxes

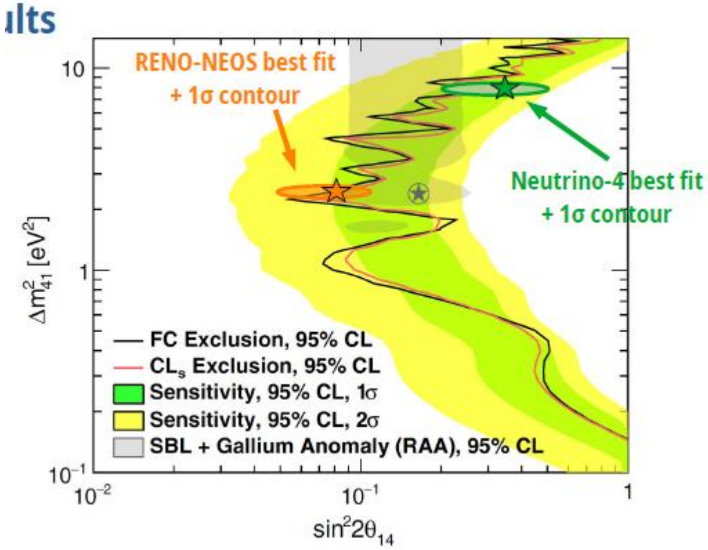
Neutrino-4 [evidence]

Analysis results



PRD 104 (2021) 032003





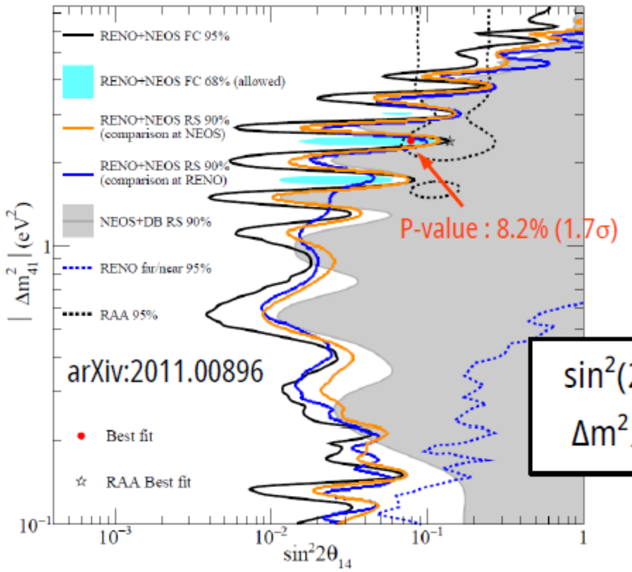
Prospect [no evidence]

[mild evidence]

RENO-NEOS analysis

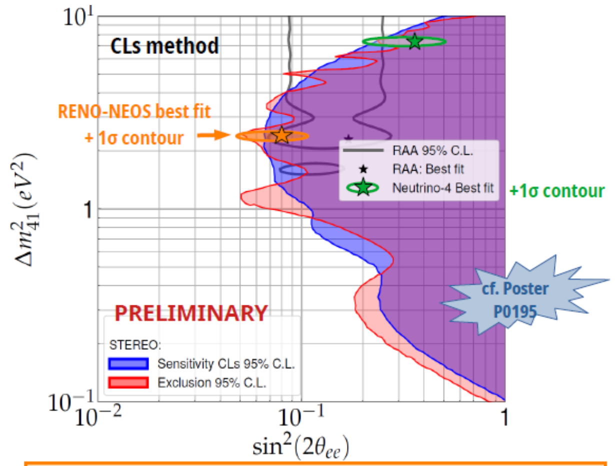
- Use NEOS as prediction for RENO
- Use RENO-ND as prediction for NEOS

→ model independant analyses



$\sin^2(2\theta_{14}) \approx 0.08$
$\Delta m^2_{14} \approx 2.4\ eV^2$

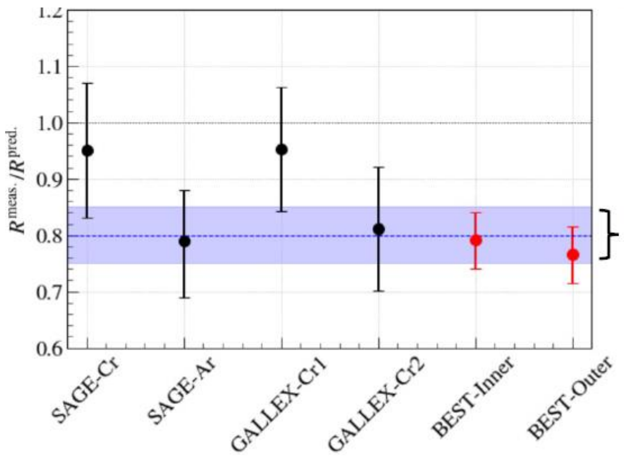
Stereo [no evidence]



- **Strong rejection of the RAA** allowed 95% CL space
  RAA best-fit point : p-value < 10^{-4} (>4σ)
- Neutrino-4 best fit and 1σ contour within sensitivity
  Best-fit **rejected at 3.1σ** (p-value ~ 1.5 10^{-3})
- NEOS-RENO best-fit point excluded at 2.8σ

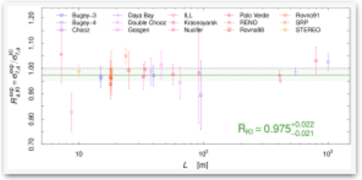
Are we seeing evidence for a new source of oscillations?

Even more confusion when we look at L=10 m oscillations with radioactive sources ("Gallium anomaly") and L=100 m oscillations with accelerator neutrinos ("LSND/Miniboone anomaly")

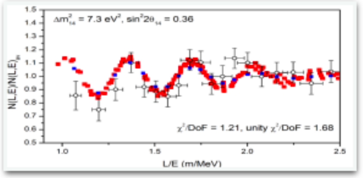


Combined result:
$R_0 = 0.80 \pm 0.05$

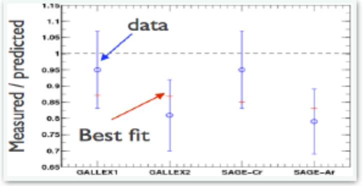
In 2021 the BEST experiment based on a ^{51}Cr source reaffirmed the "old" Gallium anomaly



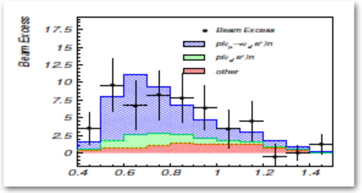
reactor flux anomaly
resolved with new input data to flux calculation



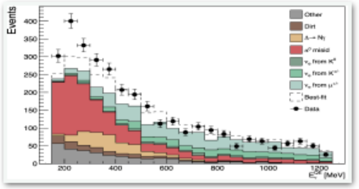
reactor spectra
is there really an anomaly?



gallium anomaly
unresolved, recently reinforced



LSND
unresolved



MiniBooNE
unresolved

J. Kopp, Talk at Neutrino2022

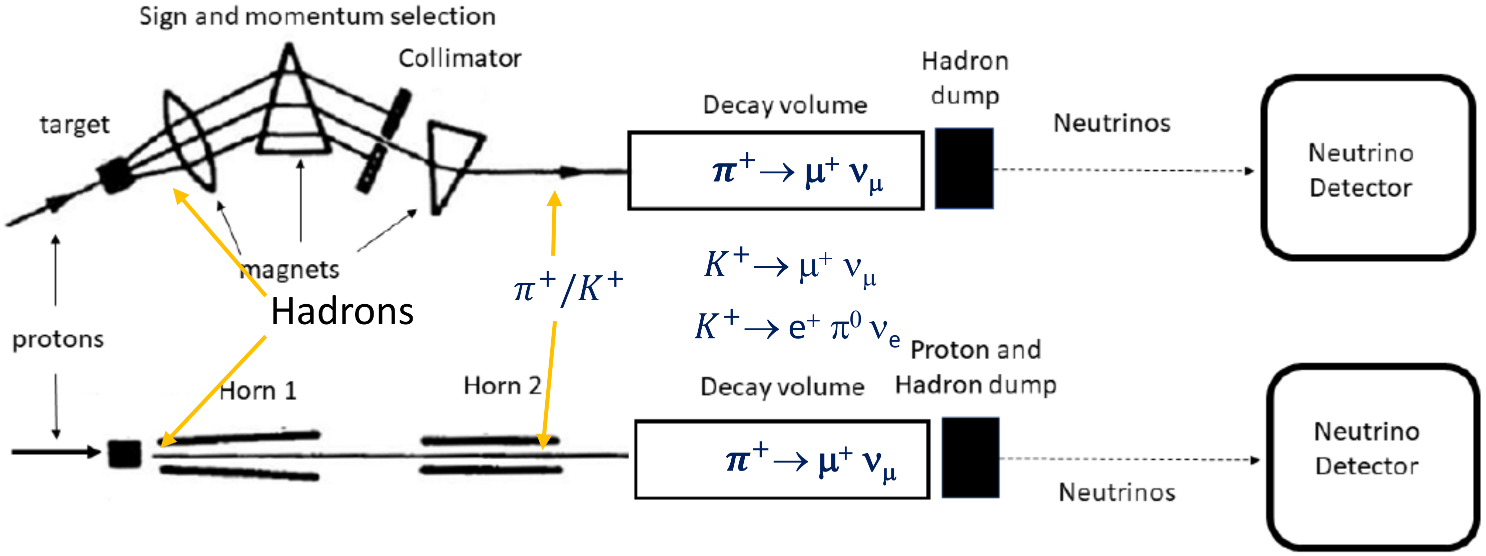
OK, we got the point ☺

Measuring any type of neutrino oscillation requires an exquisite knowledge of the neutrino source. We must first invest time and efforts to establish a gold standard for source characterization, modeling, and cross section computations. If these information are not available or are unreliable, we can only trust relative measurements.

I believe we are moving the right way now:

- Accelerator (LSND/Miniboone anomaly)
  - a high precision experiment based on near/far detector comparison – the SBN programme at Fermilab
  - An experiment based on the same physics channels of LSND without any ansatz about oscillations $\rightarrow$ JSNS-2
- Reactor anomaly:
  - The classical reactor anomaly has been solved in 2020-22 thanks to the impressive amount of data (+model updates) collected to characterize the integral flux of nuclear reactors
  - Still work to be done on reactor spectra – which convinced the JUNO Collaboration to build the JUNO-TAO near detector

Best-in-class: accelerator neutrino beams



«narrow band beam»
(lower flux higher precision)

«wide band beam»
(higher flux lower precision)
Like T2K, NOvA, DUNE, HyperK…

$$
\begin{aligned}
P_{\nu_e \to \nu_\mu} \simeq\ & \sin^2 2\theta_{13} \sin^2\theta_{23} \frac{\sin^2[(1-\hat{A})\Delta]}{(1-\hat{A})^2} \\
+\ & \alpha \sin 2\theta_{13}\, \xi \sin\delta \sin(\Delta) \frac{\sin(\hat{A}\Delta)}{\hat{A}} \frac{\sin[(1-\hat{A})\Delta]}{(1-\hat{A})} \\
+\ & \alpha \sin 2\theta_{13}\, \xi \cos\delta \cos(\Delta) \frac{\sin(\hat{A}\Delta)}{\hat{A}} \frac{\sin[(1-\hat{A})\Delta]}{(1-\hat{A})} \\
+\ & \alpha^2 \cos^2\theta_{23} \sin^2 2\theta_{12} \frac{\sin^2(\hat{A}\Delta)}{\hat{A}^2}.
\end{aligned}
$$

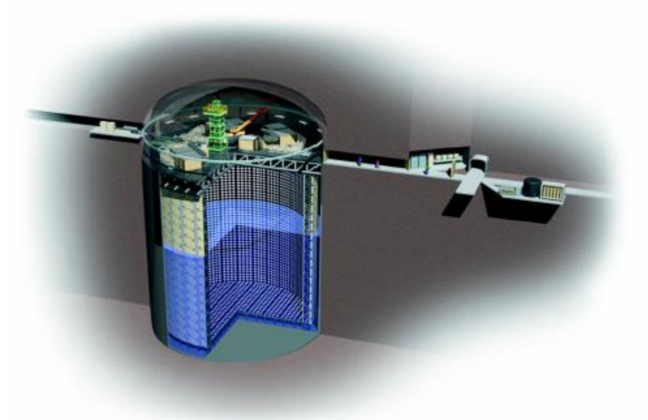
$\Delta \equiv \Delta m^2_{31} L/(4E)$ — Year 2005 → «**oscillation phase**» It is O(1) for E= O(1 GeV) and L= O(100 km)
Cool, we can build experiment on Earth ☺

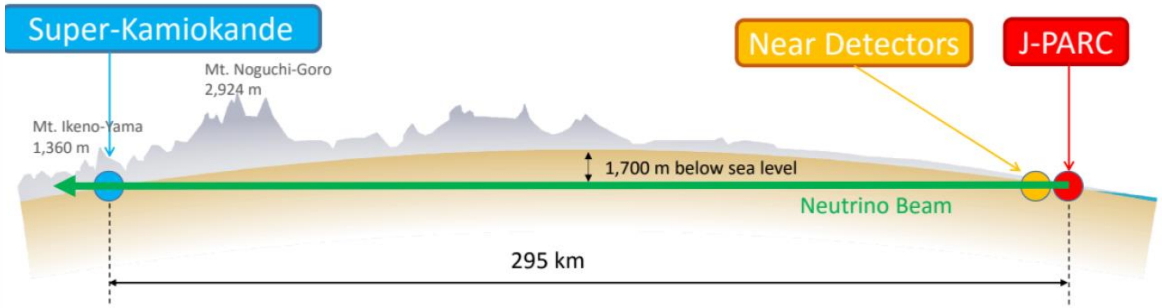
$\alpha \equiv \Delta m^2_{21}/|\Delta m^2_{31}|$ — Year 2003 → Must be <1. The larger the better.
We know now that is 0.28

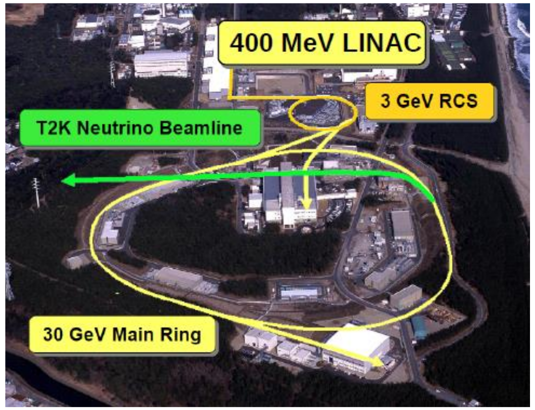
$\xi \equiv \cos\theta_{13} \sin 2\theta_{12} \sin 2\theta_{23}$

$\sin^2 2\theta_{13}$ — **Year 2012** → The larger the better! It is O(1) in neutrinos! (it is tiny in quarks..)

T2K







These physics goals are common to all «long-baseline» (L>100 km) accelerator experiments

Observables:

- $\nu_\mu \rightarrow \nu_e$ oscillations and its CP conjugate $\overline{\nu}_\mu \rightarrow \overline{\nu}_e$
- ν_μ survival probability at the far detector

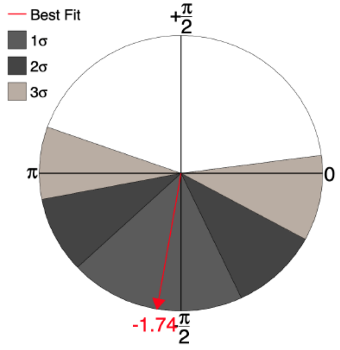
Features:

- T2K is ideally suited for the discovery of CP violation even if the requested exposure for a 5sigma discovery is too large for it (**rationale for HyperKamiokande**)
- Baseline too short to pin down the mass ordering using matter effects

CP symmetry

- difference matter/anti-matter

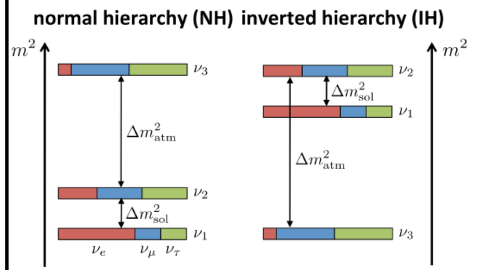
$\not{CP} \Leftrightarrow \sin(\delta) \neq 0$



Nature **580**, 339–344 (2020)

Mass ordering

- Neutrino mass models
- input for other experiments (0νββ, supernova)



Octant of θ_{23}

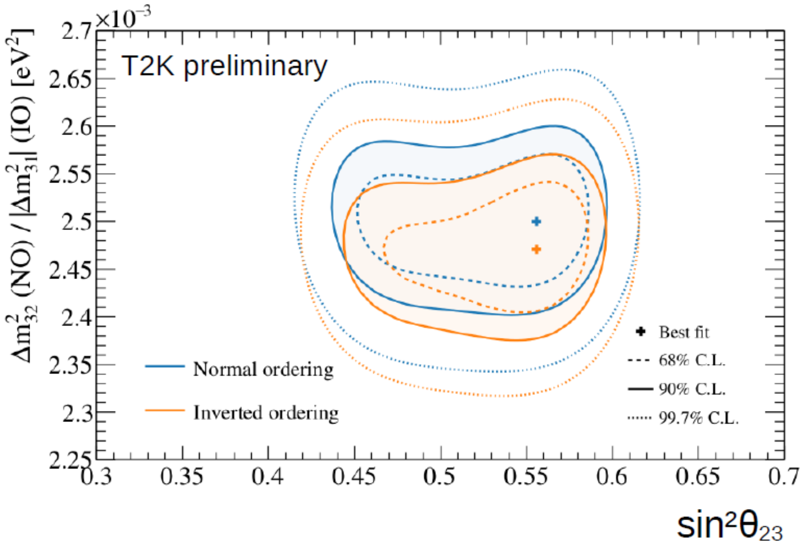
- symmetries in lepton sector

$\theta_{23} > \pi/4$?

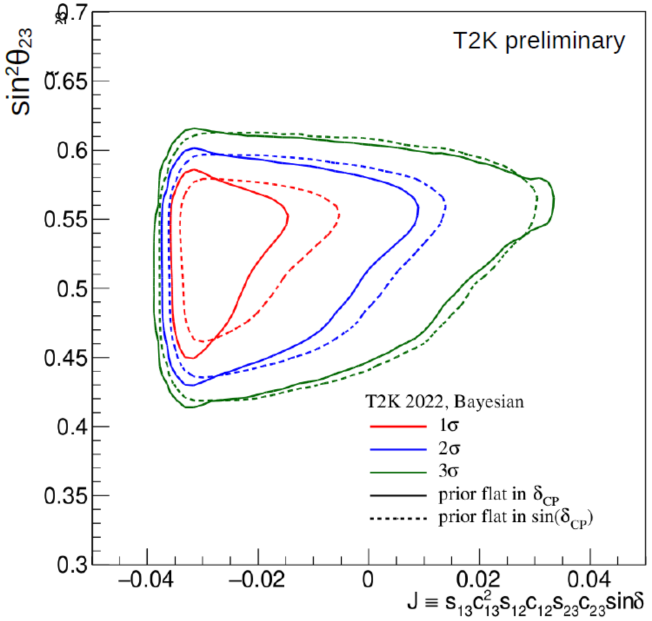
$\theta_{23} = \pi/4$?

$\theta_{23} < \pi/4$?

T2K results in 2022

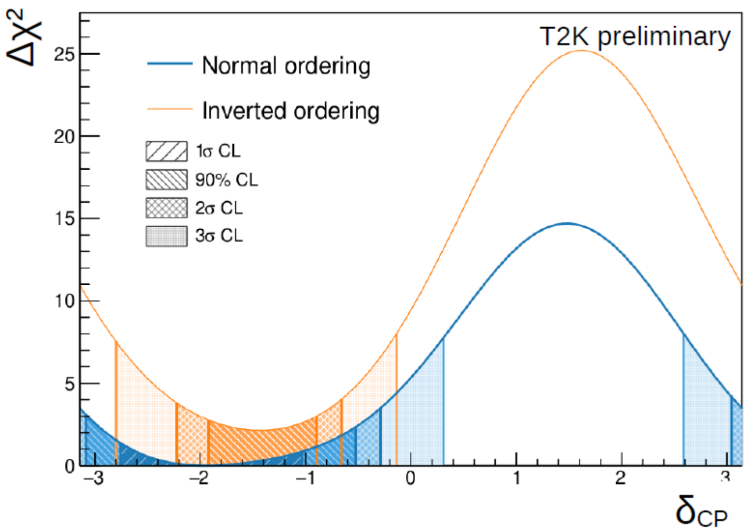


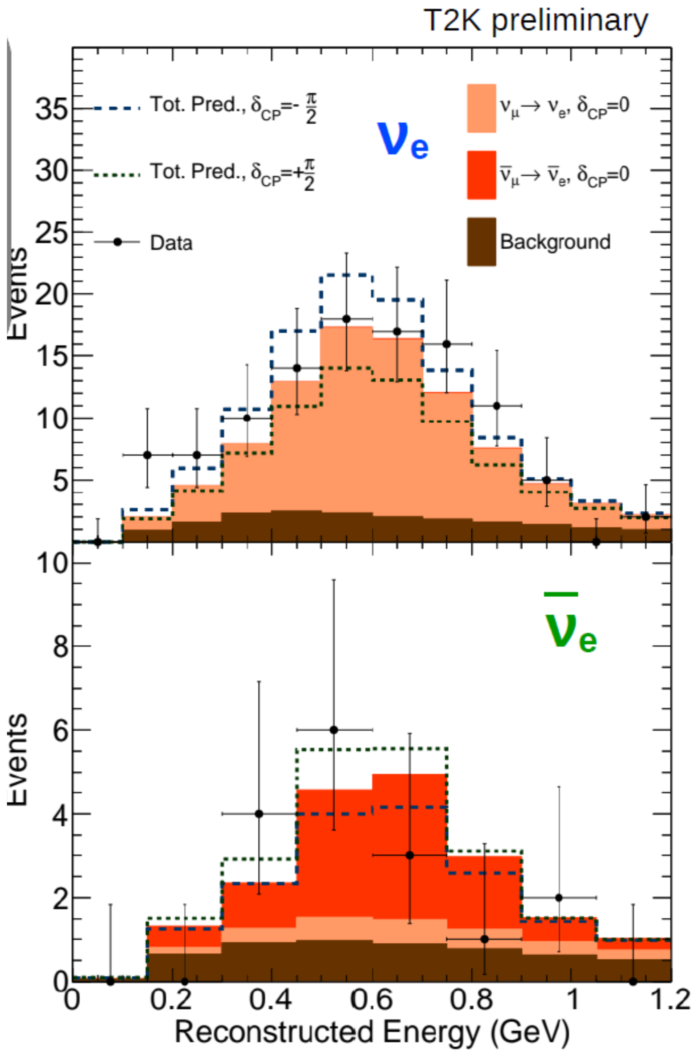
NEW! Jarlskog Invariant



Marginalized over mass ordering hypotheses
Using θ_{13} constraint from reactor experiments: $\sin^2(2\theta_{13}) = 0.0861 \pm 0.0027$

Is CP violated bt neutrinos?





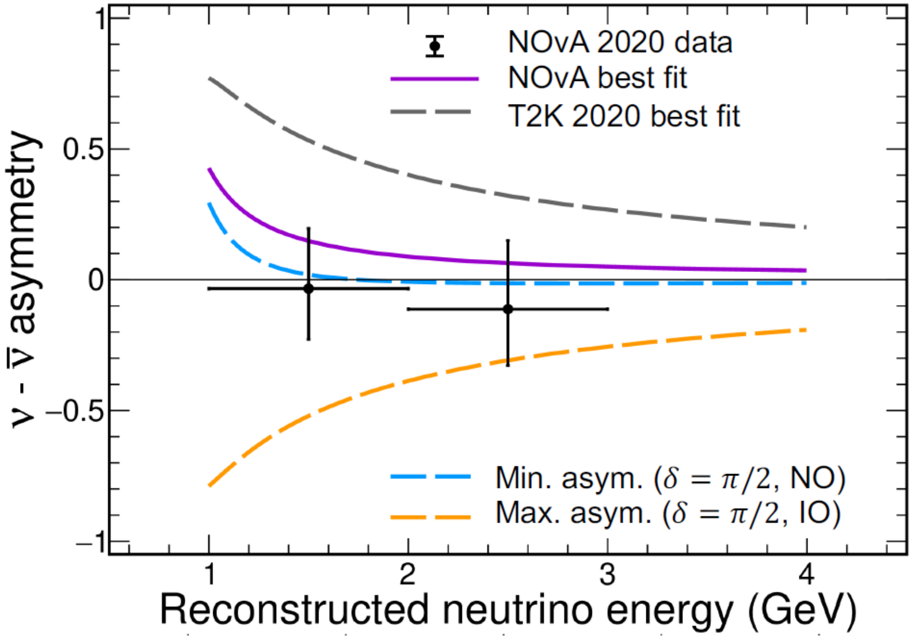
C. Bronner, Talk at Neutrino2022

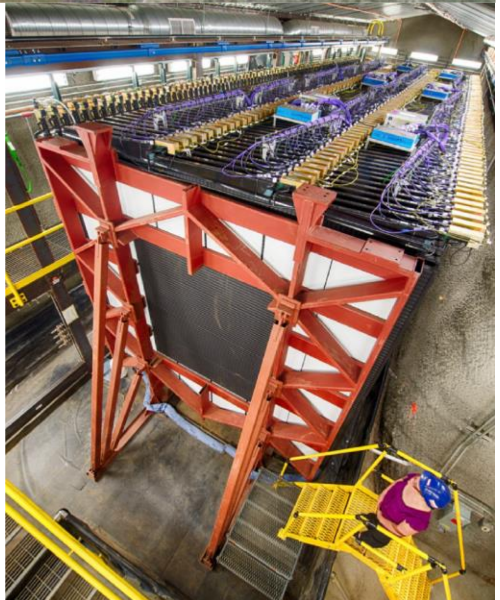
NOvA

Features:

- NOvA is ideally suited for the measurement of the mass ordering because the baseline is long (L=810 km)
- Gives its best when combined with T2K because we can unfold mass ordering and CP violation effects
- Again, the detector mass and beam intensity is too small to gain a 5sigma evidence for CP violation and for normal (inverted) ordering (**rationale for DUNE**)

At present, we are not benefiting for the T2K+NOvA combination because theis is a moderate **tension between them**





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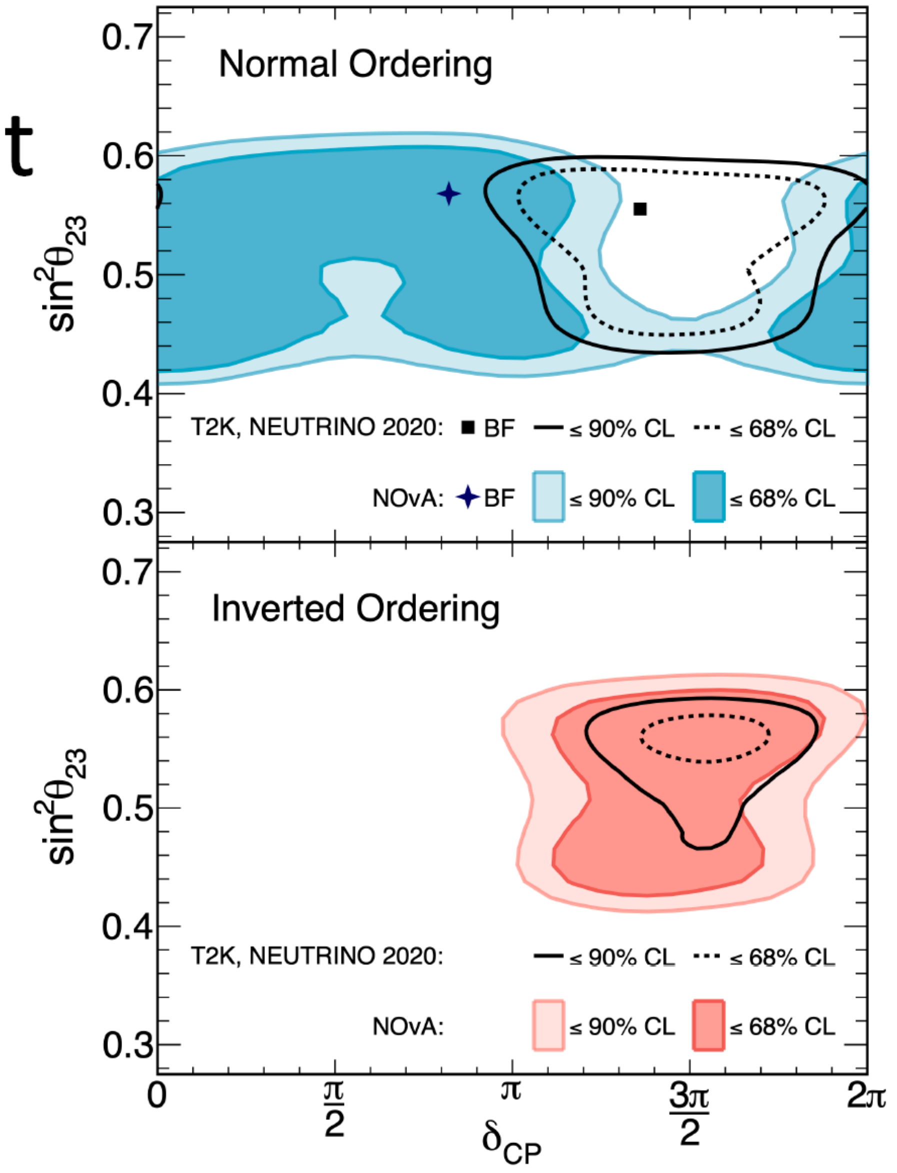
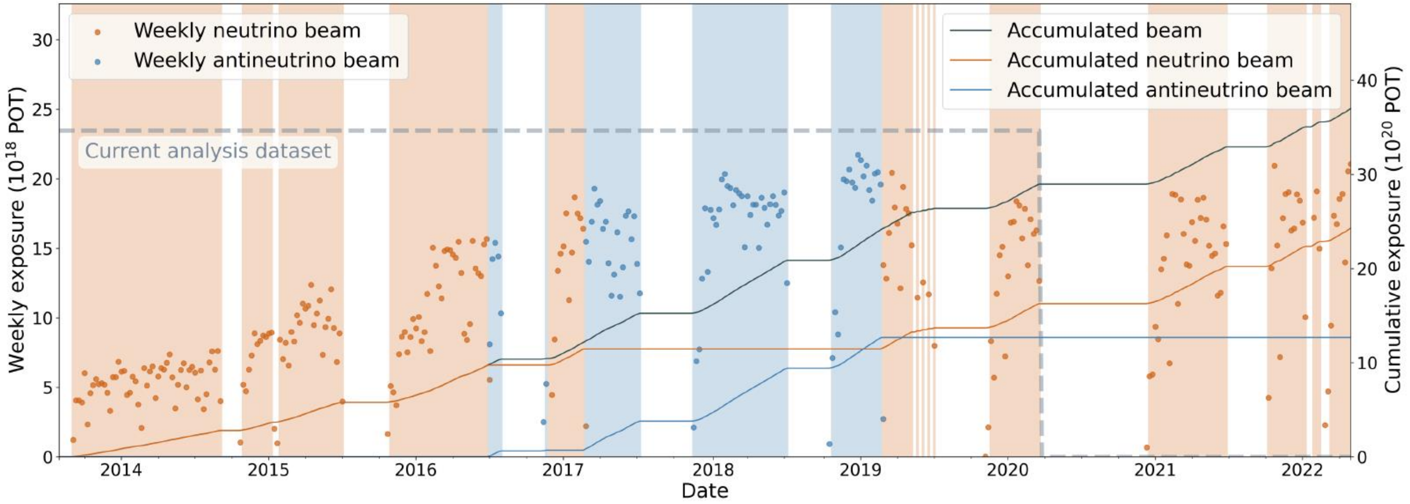
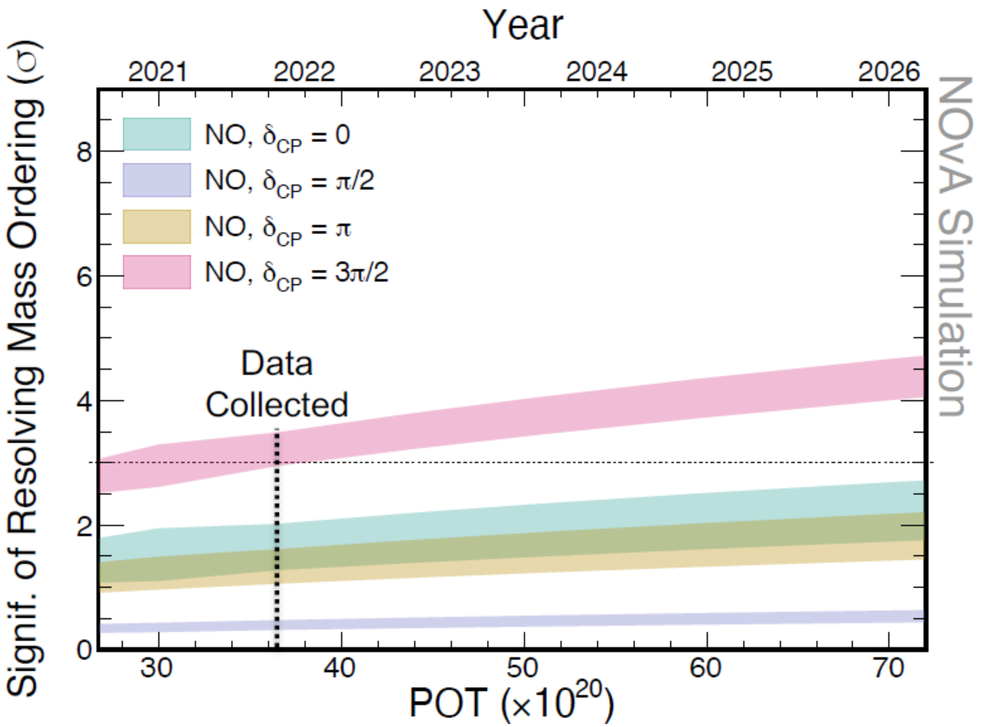
2020 data set: https://arxiv.org/abs/2108.08219





Projected sensitivity to mass ordering



Joined T2K-NOvA analysis expected soon

J. Hartnell, Talk at Neutrino2022

DUNE and HyperKamiokande

T2K and NOvA were designed well before the discovery of ϑ_{13}. Now, we have the opportunity to build experiments that fully reap this opportunity by establishing CP violation and the mass ordering in a conclusive manner, and perform high precision measurements of all mixing parameters.

Features:

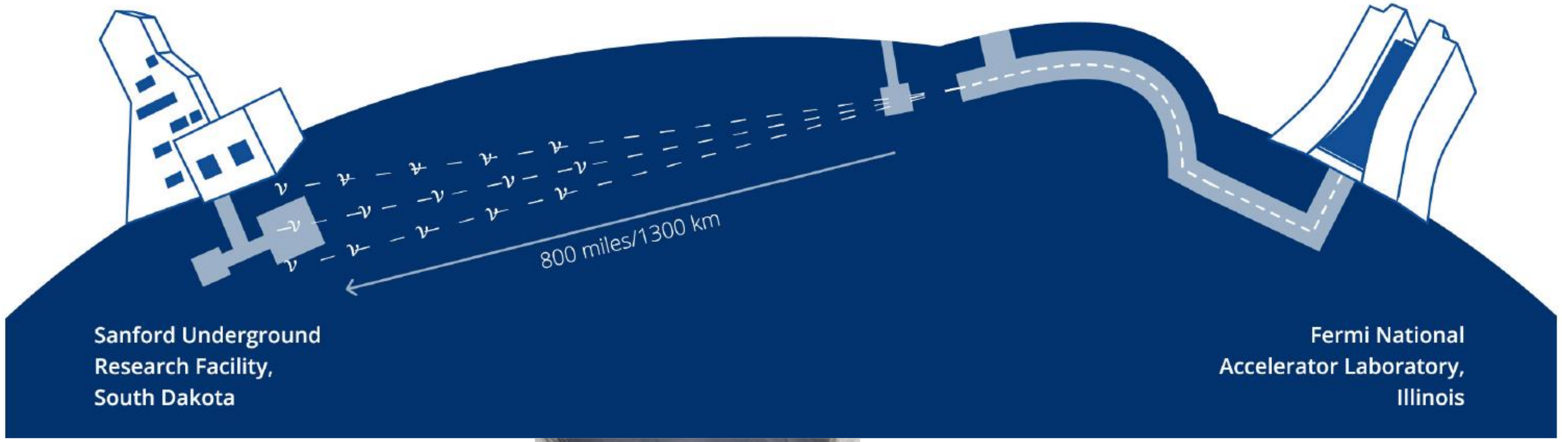
- Unprecedented exposure to reach systematic limited measurements
  - HyperKamiokande 500 kton water cherenkov detector, 1.2 MW beam
  - DUNE 40 kton liquid argon detector 1.2-> 2.4 MW beam
- Unprecedented control of beam systematics:
  - Hybrid Near Detectors (water Cherenkov + MD280 for HyperK, liquid argon + SAND + gas argon for DUNE)
  - Movable near detectors: PRISM technique
- Unprecedented resolution for the reconstruction of final state interactions

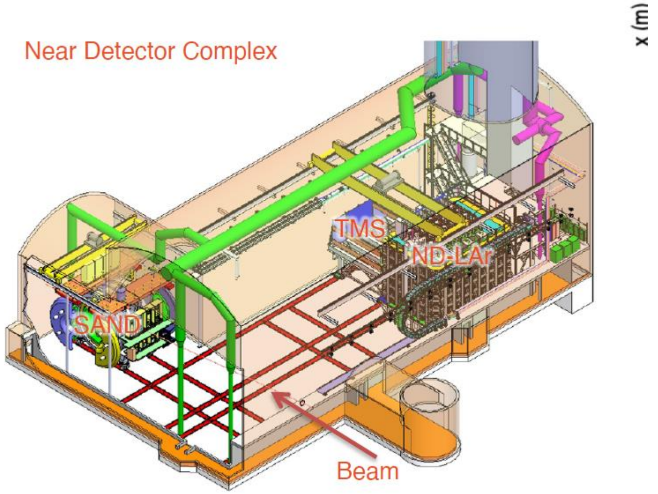
Complementarity between DUNE and HyperKamiokande:

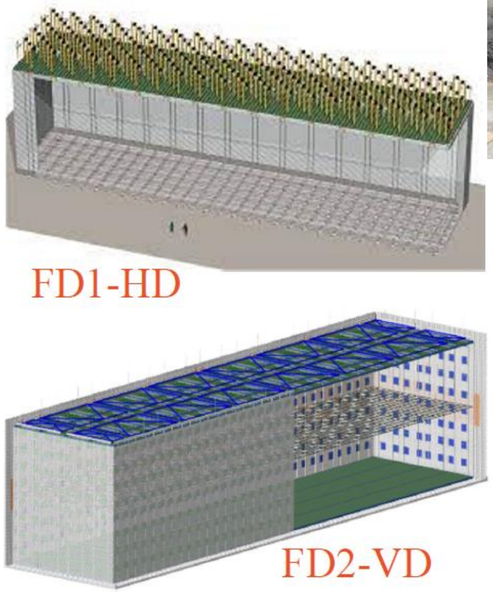
- L=200 km (HyperK) versus L=1300 km (DUNE)
- Mass versus particle identification capability (water cherenkov versus liquid argon TPC)
- Narrow band (maximum sensitivity to CP violation - HyperK) versus wide band (systematic mitigation and maximum sensitivity to mass hierarchy- DUNE) beam

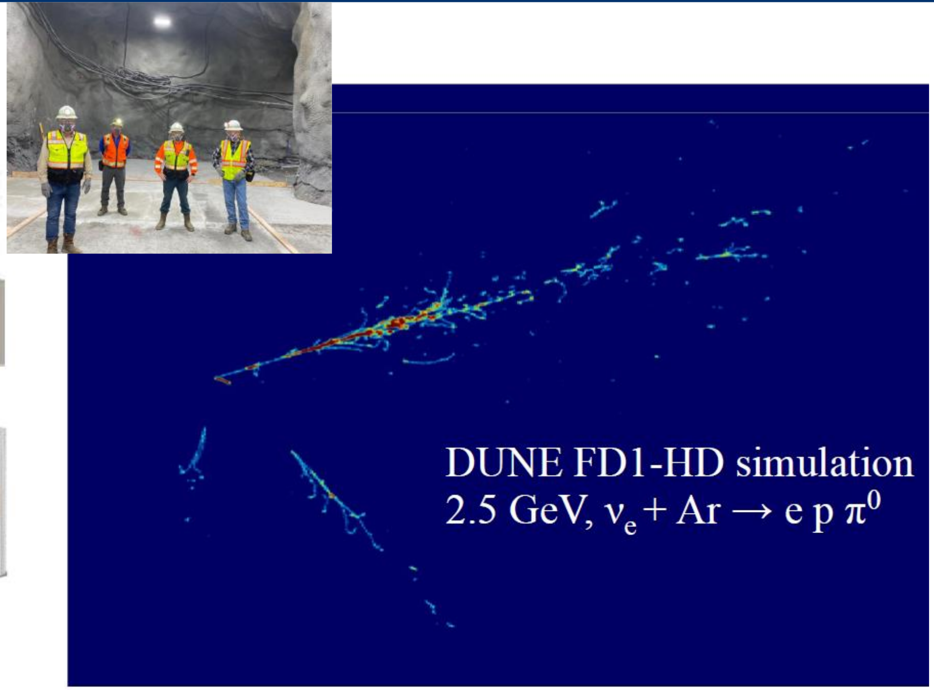
Both projects have the size, complexity, and cost of a LHC experiment and – for the first time in the history of neutrino physics – we are setting up LHC-like Collaborations committed to run these experiments for at least twenty years with a physics programme that encompasses neutrino oscillation (this talk), astroparticle physics, proton decay, Supernova detection, solar and atmospheric neutrino physics, Dark matter search, etc. (not covered in this talk)

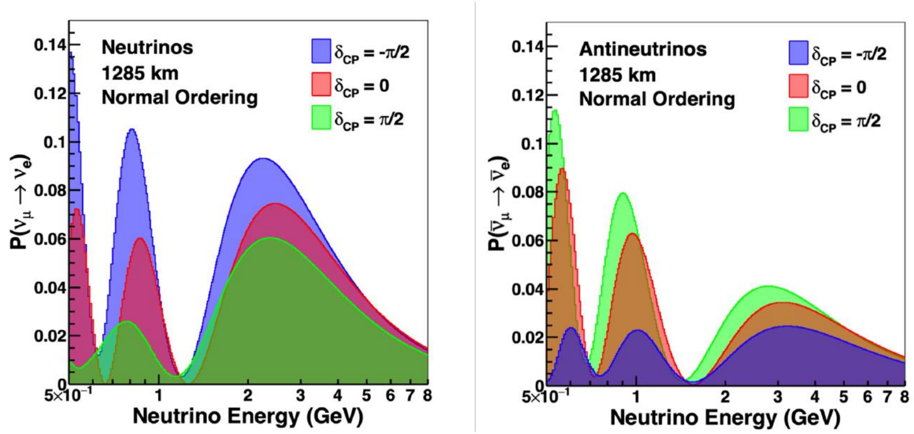
DUNE


800 miles/1300 km
Sanford Underground
Research Facility,
South Dakota
Fermi National
Accelerator Laboratory,
Illinois


Near Detector Complex
x (m)
TMS
ND-LAr
SAND
Beam

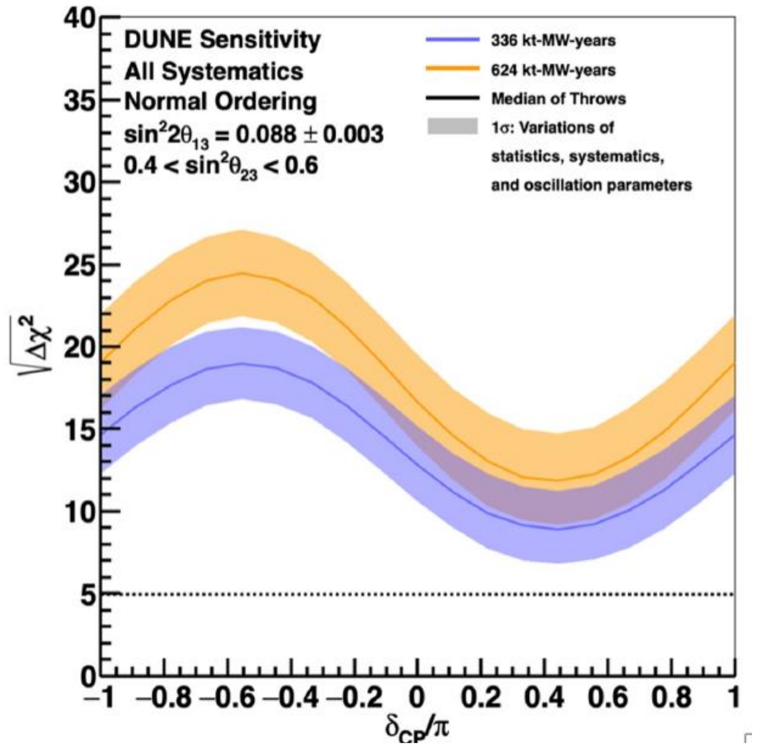

FD1-HD
FD2-VD

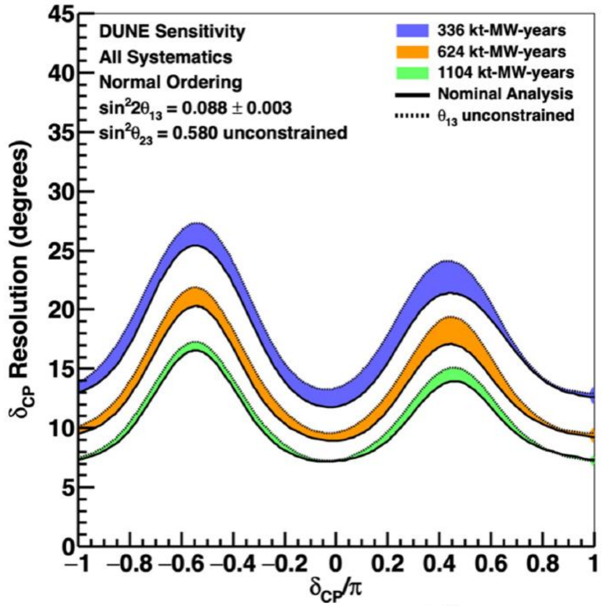

DUNE FD1-HD simulation
2.5 GeV, $\nu_e + Ar \rightarrow e\ p\ \pi^0$

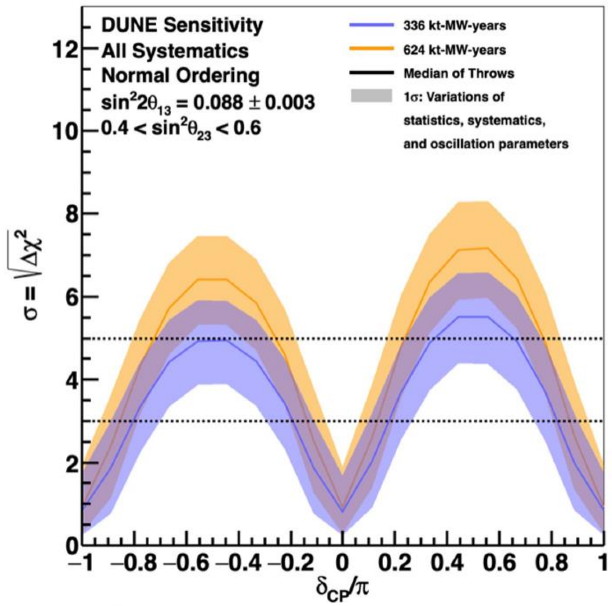

Neutrinos
1285 km
Normal Ordering
$\delta_{CP} = -\pi/2$
$\delta_{CP} = 0$
$\delta_{CP} = \pi/2$
$P(\nu_\mu \rightarrow \nu_e)$
Neutrino Energy (GeV)
Antineutrinos
1285 km
Normal Ordering
$P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e)$
Neutrino Energy (GeV)

- 5σ discovery potential for CP violation over >50% of δ_{CP} values
- 7-16° resolution to δ_{CP}, *with external input for only solar parameters.*

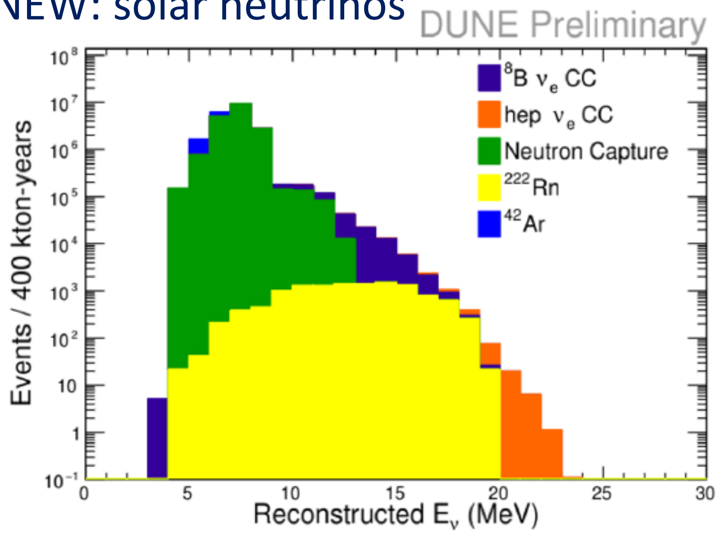
M. Bishai, Talk at Neutrino2022



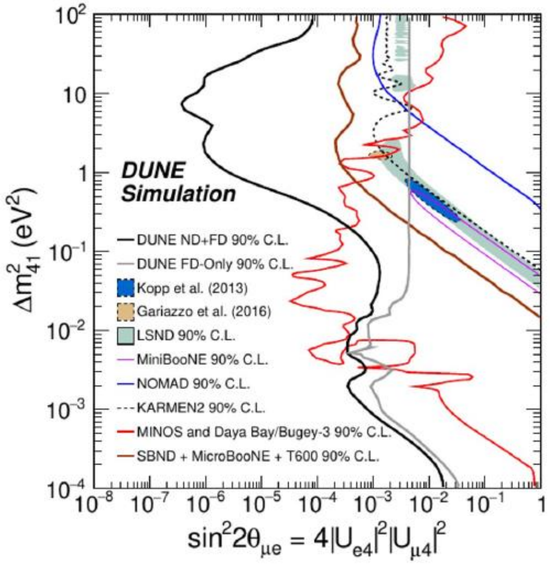




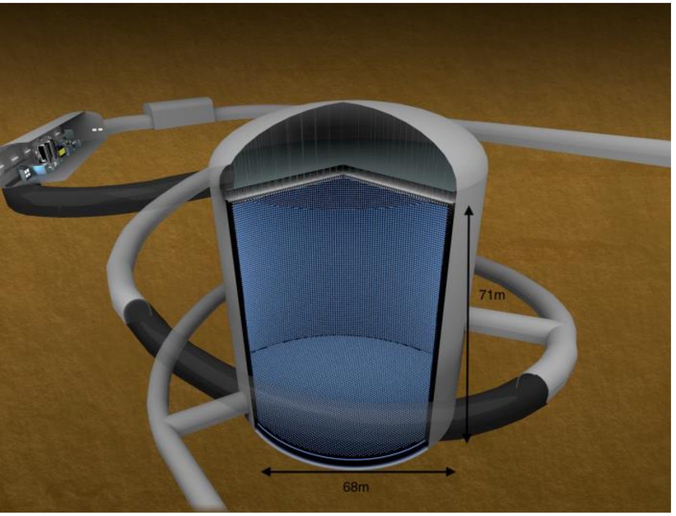
NEW: solar neutrinos

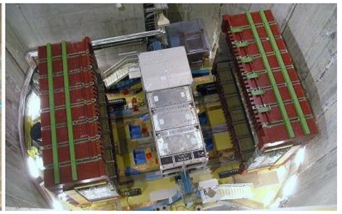


sterile neutrinos

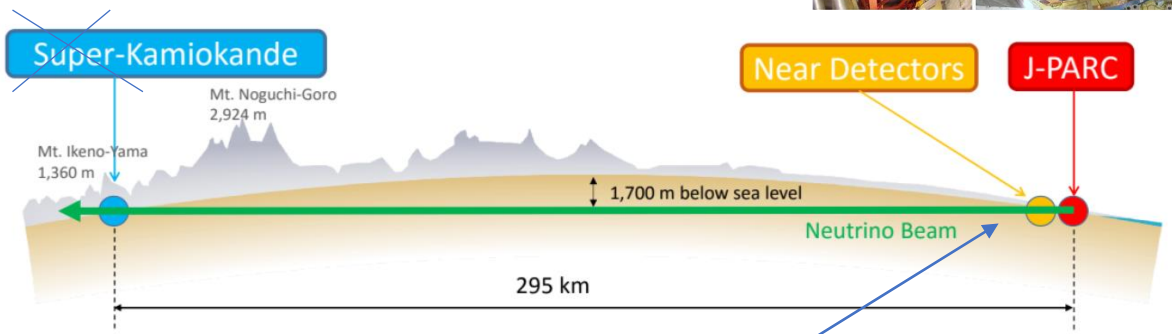


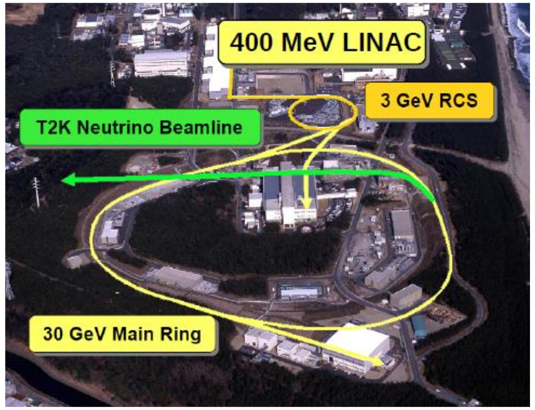
HyperKamiokande



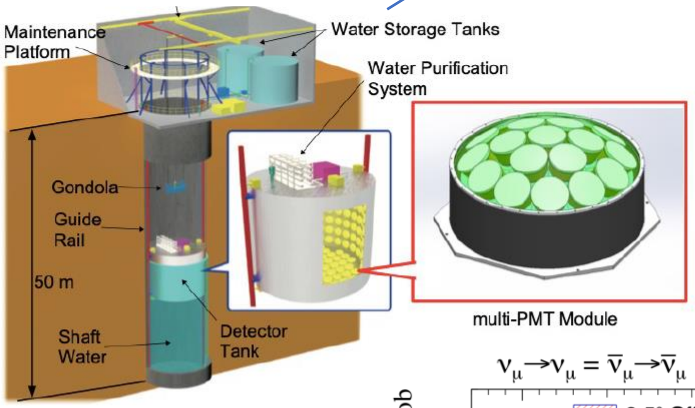


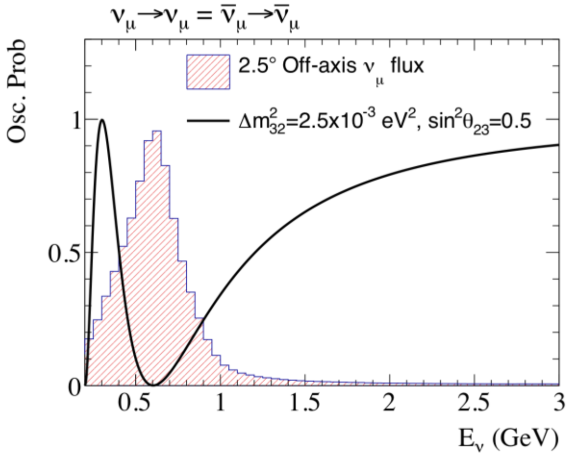
Hyper!!

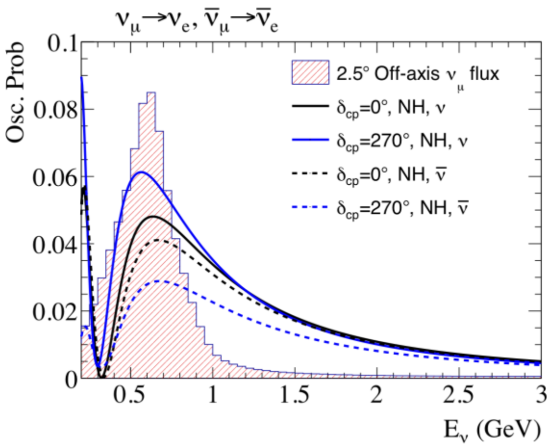


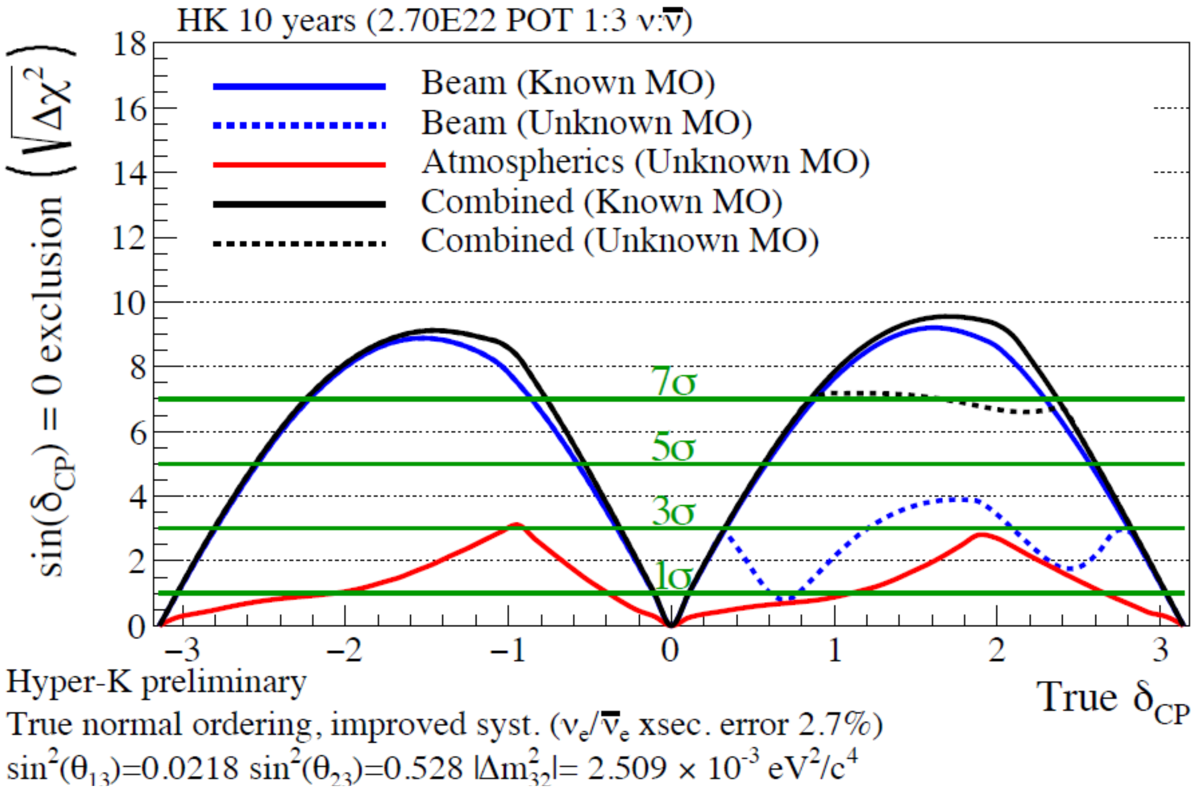


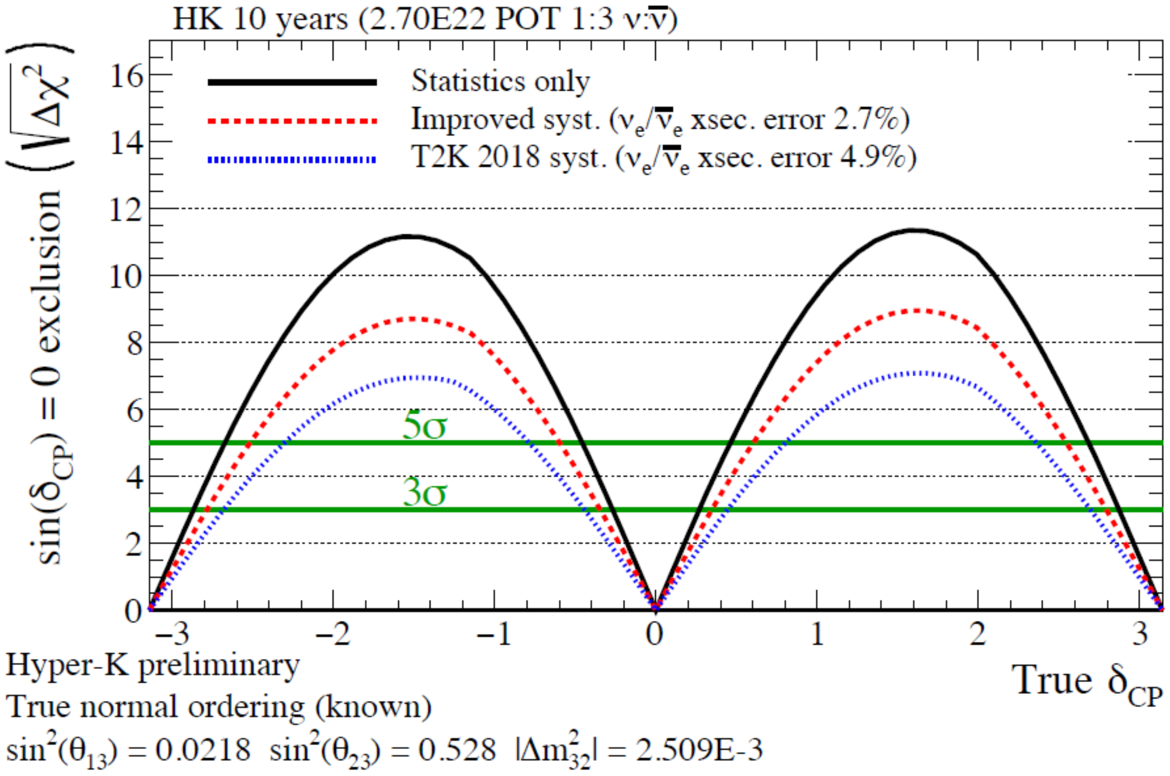
Intermediate detector





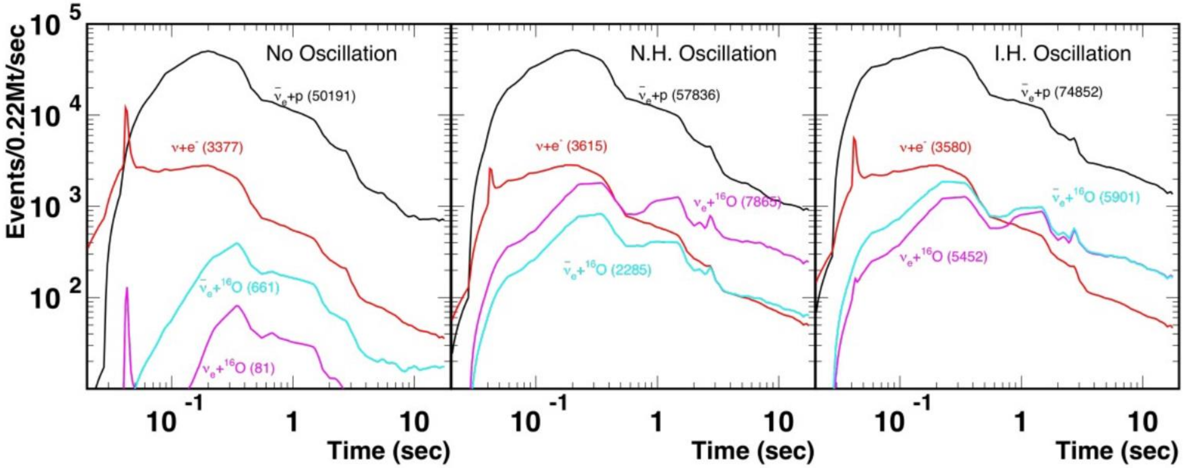


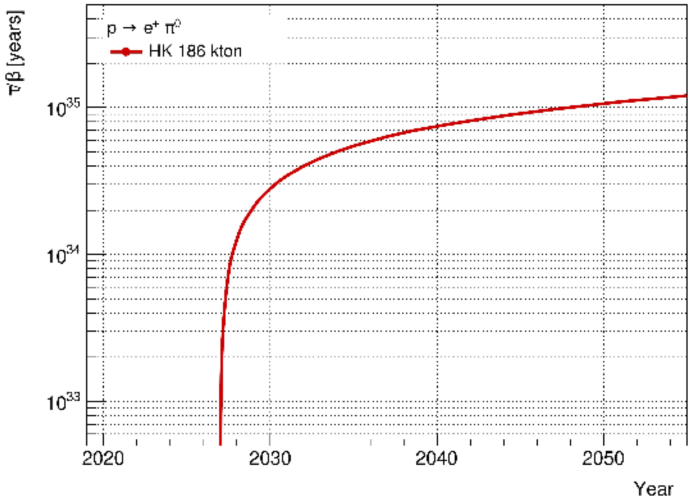




supernova burst

J. Wilson, Talk at Neutrino2022





Proton decay

Dust under the carpet or… opportunities!

DUNE and HyperKamiokande are so powerful that their physics reach is now completely systematic limited! We must be prepared to address those systematics by 2030

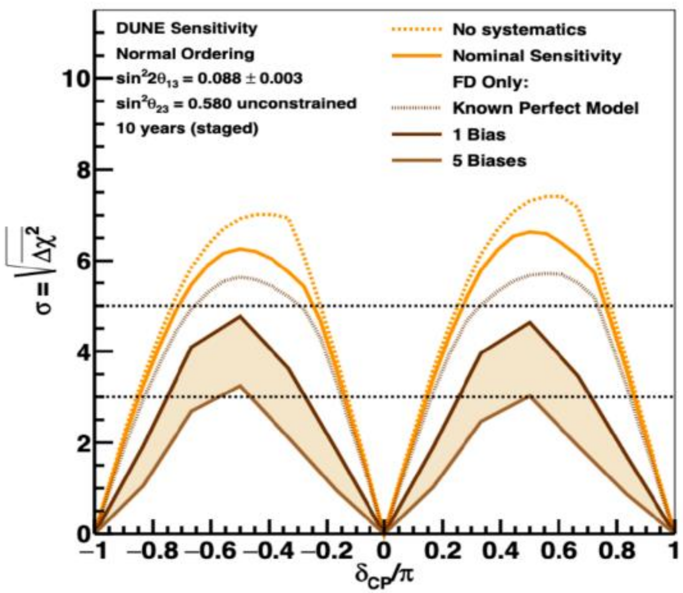
- Major impact on the sensitivity of DUNE and HyperKamiokande (already dominant in T2K…)

T2K

	Systematic uncertainties		
Beam mode	Neutrino		
SK sample	1 Ring μ-like	1 Ring e-like	1 Ring e-like 1de
Flux	5.1%	4.8%	4.9%
Cross-section	10.1%	10.3%	12.0%
SK	2.9%	4.4%	13.4%

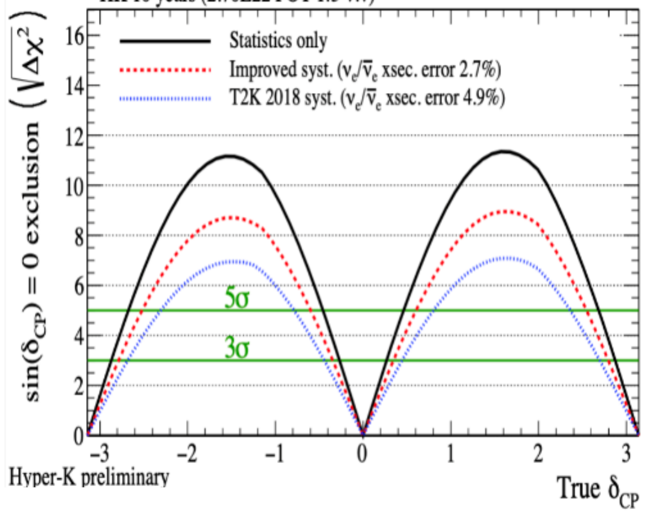
- Modeling of nuclear effects in neutrino interactions

DUNE



We should learn from past mistakes and plan a new generation of cross-section experiments ("short baseline experiment") to measure at 1% level the cross section of relevance for DUNE and HyperKamiokande

HyperK

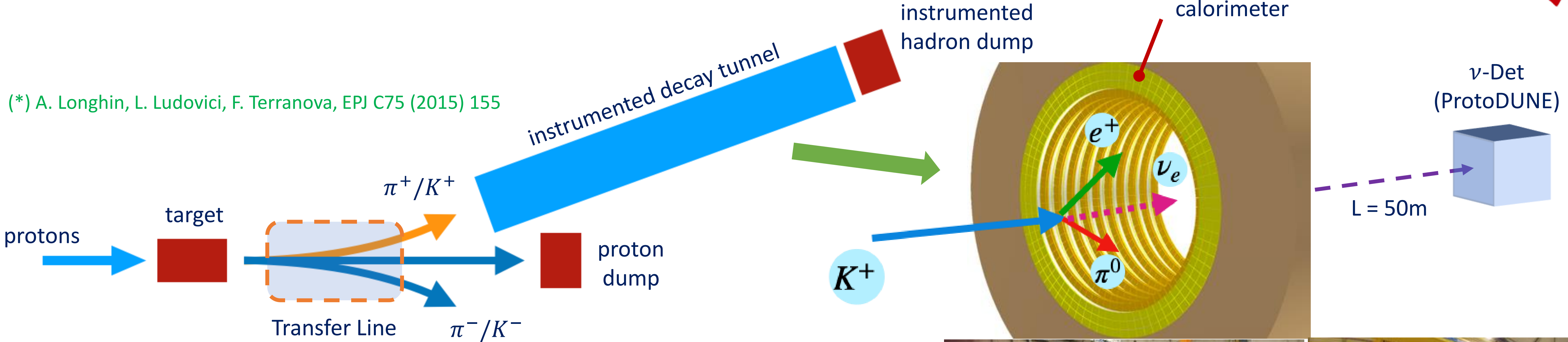


From the **European Strategy for Particle Physics Deliberation document**:

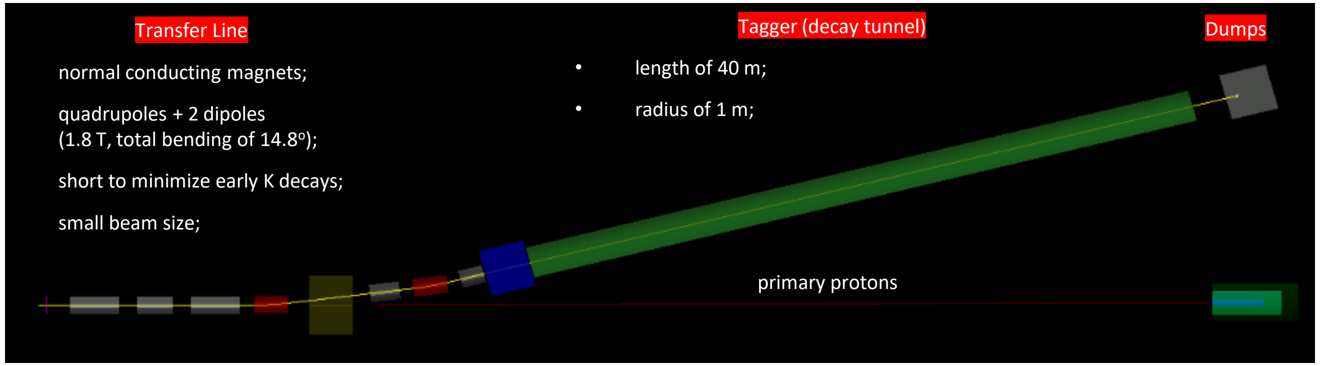
To extract the most physics fromDUNE and Hyper-Kamiokande, a complementary programme of experimentation to determine neutrino cross-sections and fluxes is required. Several experiments aimed at determining neutrino fluxes exist worldwide. The possible implementation and impact of a facility to measure neutrino cross-sections at the percent level should continue to be studied.

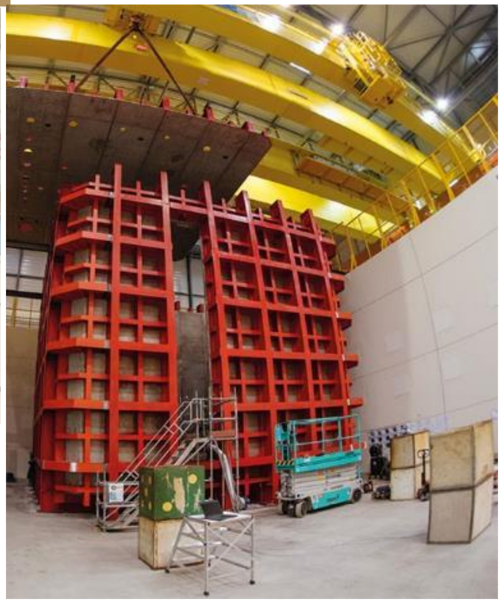
NP06/ENUBET: the first monitored neutrino beam (*)

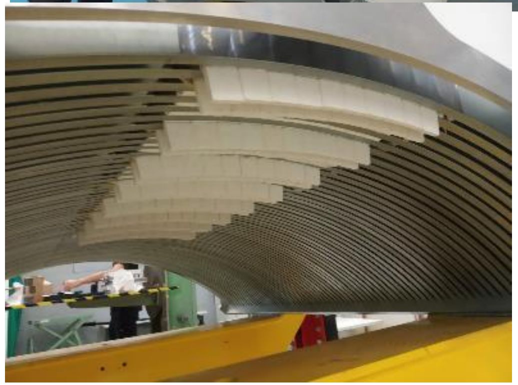
(*) A. Longhin, L. Ludovici, F. Terranova, EPJ C75 (2015) 155



CERN SPS







https://www.pd.infn.it/eng/enubet/

A different path: ESSnuSB

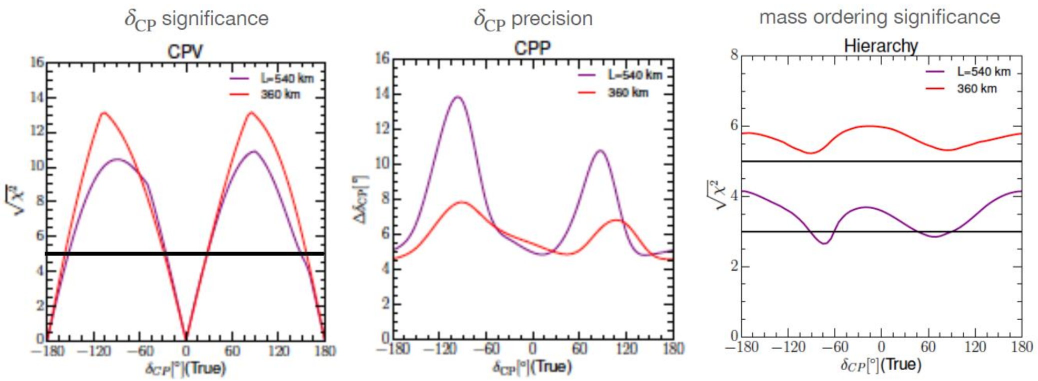
Features:

- Exploit an existing proton source with unprecedented power
- Set the baseline (L=300-1000 km) and the energy (0.3 GeV) to work at the second oscillation maximum and minimize systematics uncertainties

ESSnuSB is an interesting concept but it will happen in a post-HyperK era (>3035) to address issues that will not be covered by DUNE-HyperK because it needs a significant upgrade of ESS (compressor) and the construction of a HyperK-like detector

Still, we can take advantage of the ESS well before ESSnuSB employing the ENUBET technique to measure cross sections at 1% level for HyperK. This idea (**an ENUBET-like monitored neutrino beam at ESS**) is being investigated in the framework of ESSnuSB+ (HORIZON-INFRA-2022-DEV-01, start date: Jan 1, 2023 – WP6)

10 year beam exposure



~70% region of δ_{CP} can be measured at 5σ

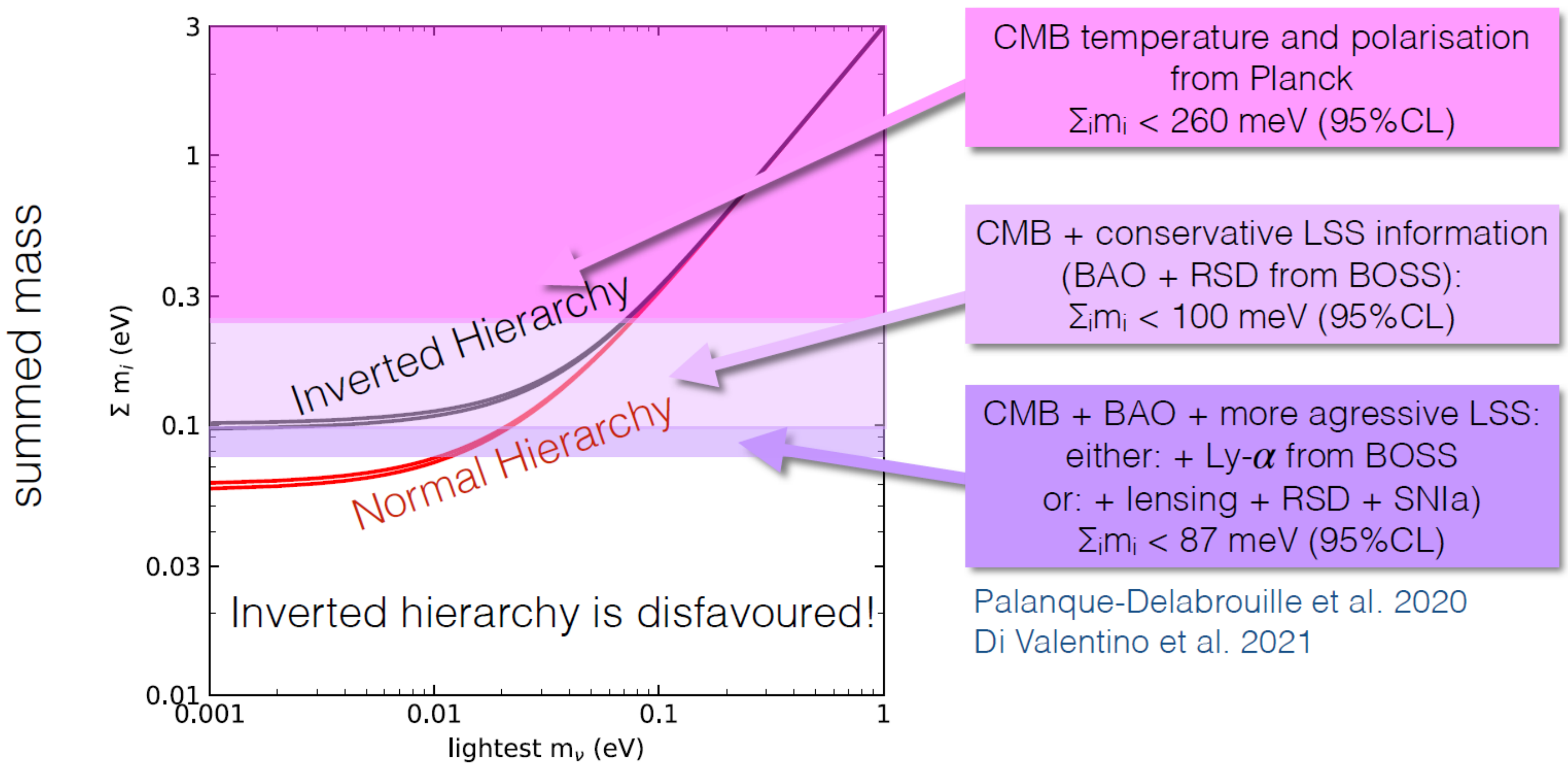
<8° (14°)

Eur.Phys.J.C81 (2021) 12, 1130

The lightest mass eigenstate

The size of the lightest mass eigenstate is the portal toward neutrino physics >2030 because it cannot be accessed by neutrino oscillation. At present, cosmology plays a key role because it constraints $\mathbf{m_1+m_2+m_3}$

95%CL upper bounds on $\Sigma_i m_i$ for 7 parameters

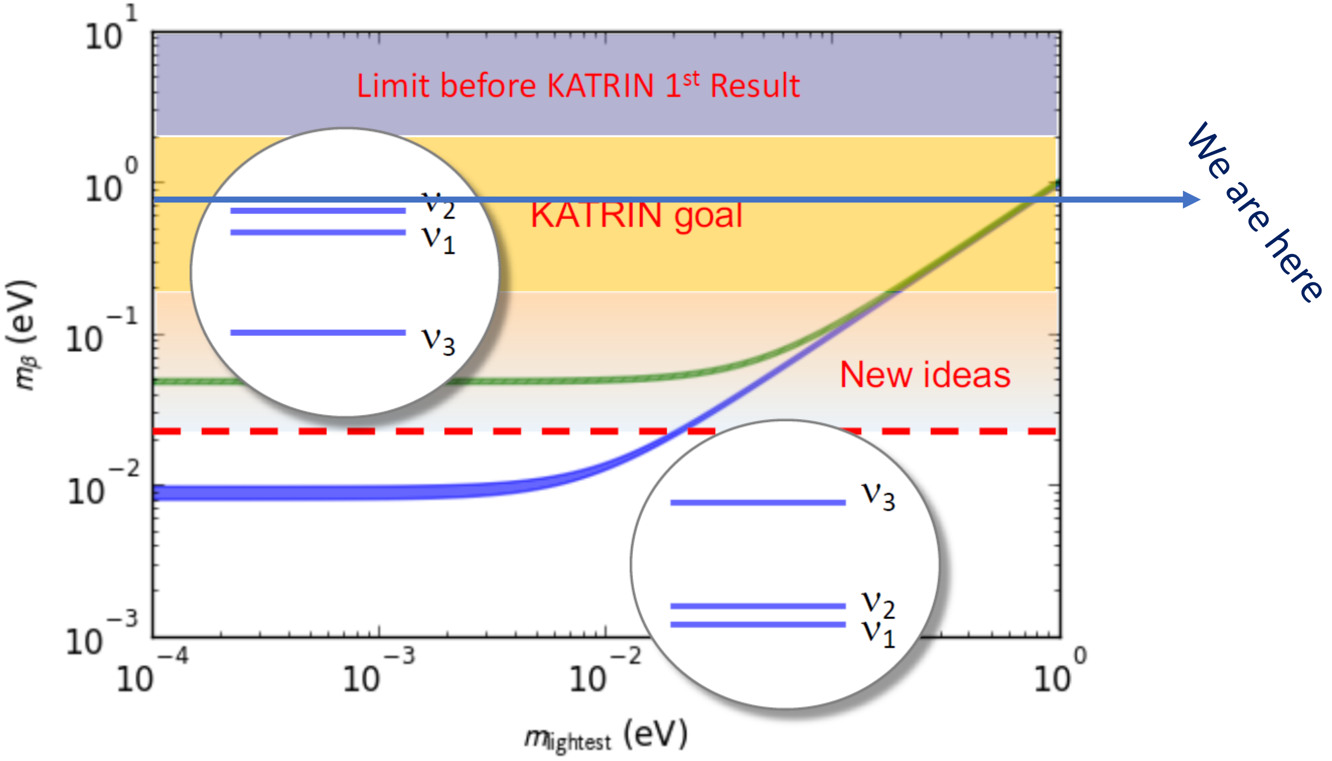


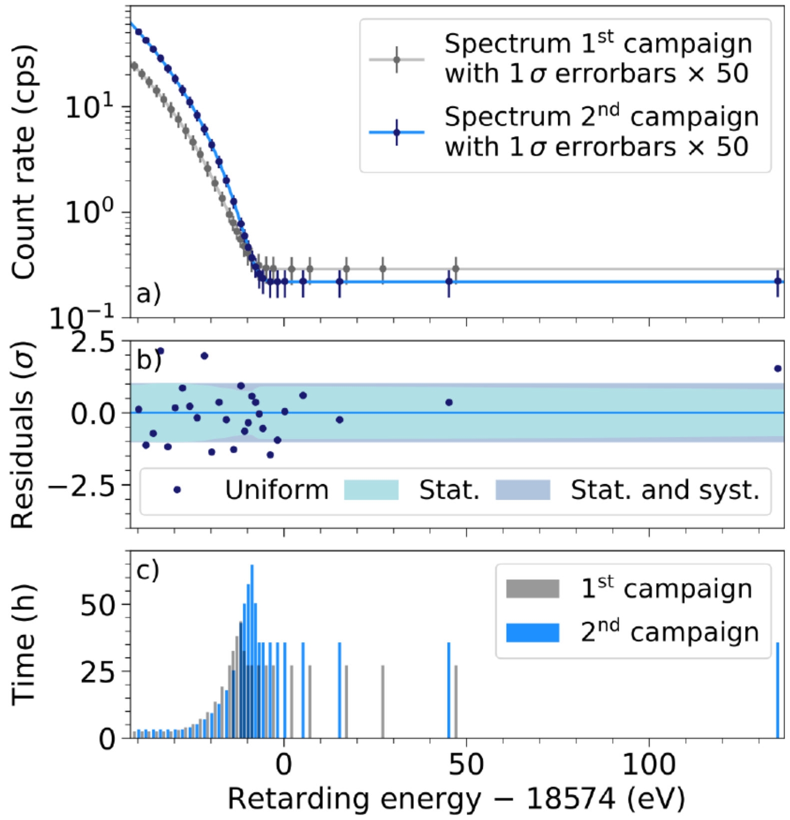
Palanque-Delabrouille et al. 2020
Di Valentino et al. 2021

Those powerful bounds (evidence for normal mass ordering!) hold as long as Λ_{CDM} is a reliable paradigm for cosmology. There are some tensions in Λ_{CDM} , which needs to be resolved: value of the Hubble constant, matter spectrum amplitude, Lyman-α vs CMB – but all in all the paradigm is in good shape. Can we improve/confirm/disprove this claim with laboratory measurements?

Measurements of absolute mass

$$m^2_{\nu/\beta} = \sum_i |U_{ei}|^2 \cdot m_i^2$$





Nat. Phys. **18**, 160–166 (2022)

We desperately need a good idea…

$m(\nu_e) < 225\ eV$ **

1980 — 1990 — 2000 — 2010 ECHo, HOLMES — 2020

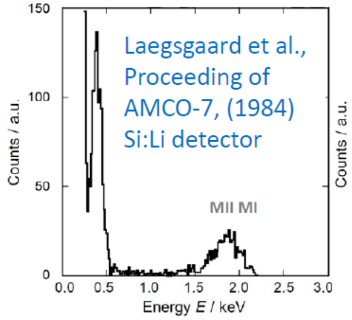
Modern ^{163}Ho experiments

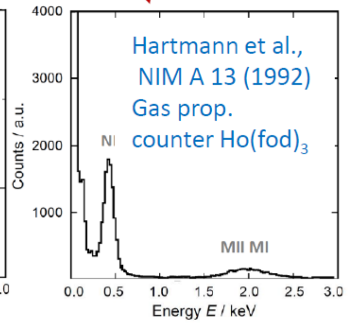
The holmium path (ECHO, HOLMES)

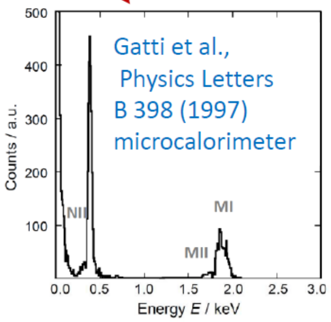
* Proposal for calorimetric measurements

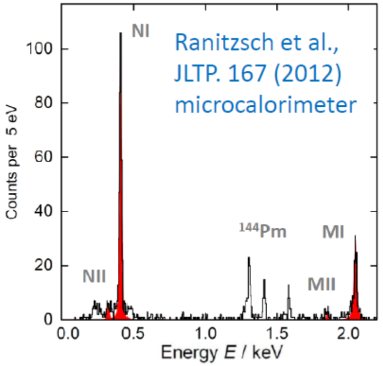
$m(\nu_e) < 150\ eV$ ***

C. Velte et al (Echo Collaboration), Eur. Phys. J. C 79 (2019) 1026









The CRES (Cyclotron Radiation Emission Spectroscopy) path: Project8

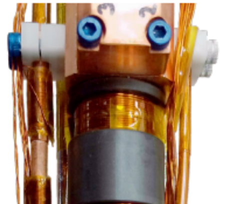
2015 2016 2017 2018 2019 2020 2021 2022 2023 2024 2025 2026 2027

Phase I → Single-electron detection; spectroscopy → ^{83m}Kr conversion-electron spectrum

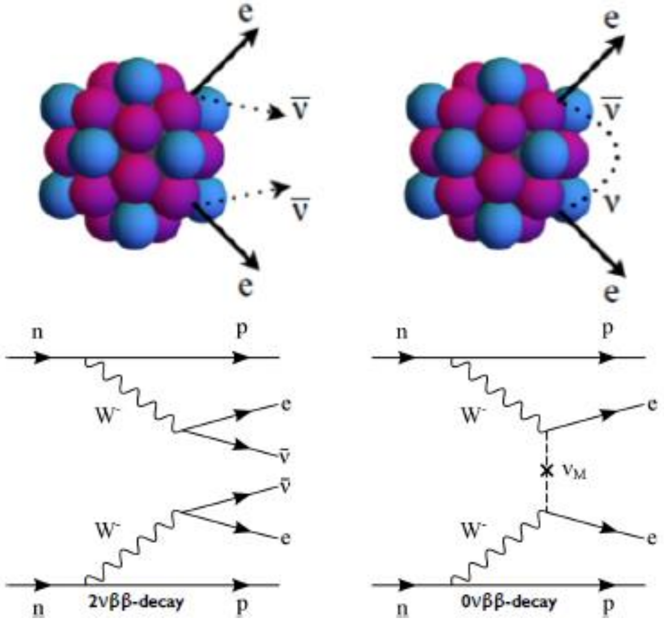
Neutrino 2022

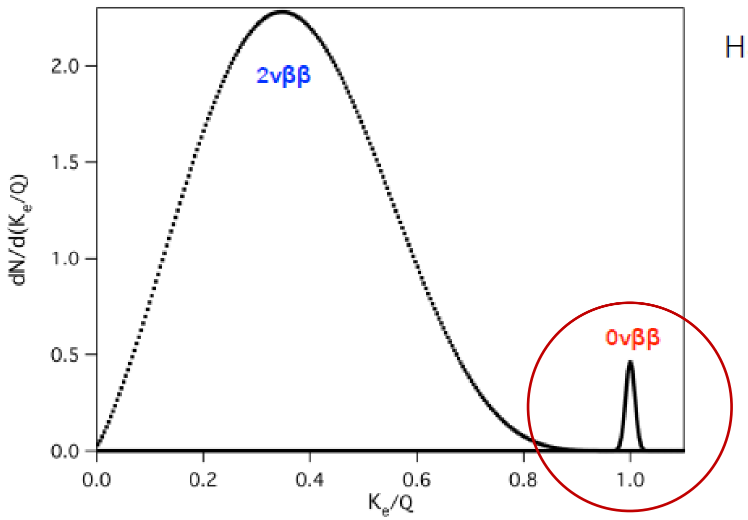
1 mm^3 effective volume

Phase II: Construction | Data-taking | Analysis → Systematic & background studies → T_2 spectrum and endpoint measurement



Neutrino-less double beta decay (NLDBD)





Half-life — Phase space factor

$$\frac{1}{T^{0\nu}_{1/2}} = G^{0\nu}|M^{0\nu}|^2|\langle m_{\beta\beta}\rangle|^2$$

Nuclear matrix element

Effective Majorana neutrino mass: $m_{\beta\beta} \equiv \left|\sum_{i=1}^{3} U_{ei}^2 m_i\right|$

(exact form depends on the lepton flavor violating mechanism!)

To date, NLDBD is the only viable option to show that neutrinos are Majorana particles $(\nu = \bar{\nu})$

Experimental observation of neutrino-less double beta decay

It will establish **violation of lepton number** in particle physics

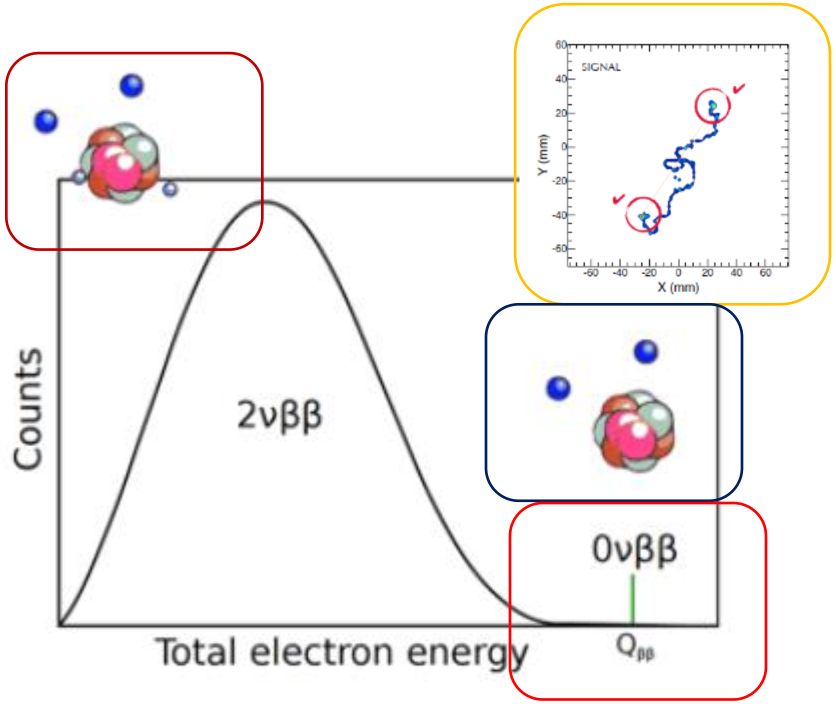
Shed light on **mass generation mechanisms** and the smallness of neutrino masses

Open a window to understand **matter dominance** in the universe

Provide information on the **size and pattern** of neutrino masses

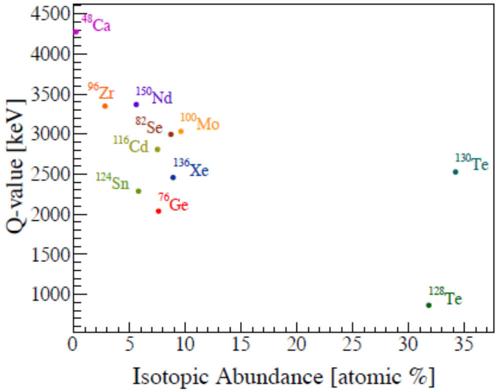
The perfect experiment

The experimental signature of NLDBD is extremely simple: two electrons whose energy sum (Q-value) is known in advance with very high precision (Penning traps). “Intrinsic” background: (A,Z) $\rightarrow$ (A,Z+2) $2e^{-}$ 2ν



Track the out-coming electrons to separate α, β, γ from $\beta\beta$

Choose the detector with the best energy resolution (<1% FWHM) to reduce the “intrinsic” 2ν background



Select isotopes with high Q-value against natural radioactivity and high isotopic abundance

$\beta\beta$ Decay Reaction	Isotopic Abundance [atomic %]	Q-value [keV]
^{48}Ca$\rightarrow^{48}$Ti	0.2	4274
^{76}Ge$\rightarrow^{76}$Se	7.6	2039
^{82}Se$\rightarrow^{82}$Kr	8.7	2996
^{96}Zr$\rightarrow^{96}$Mo	2.8	3348
^{100}Mo$\rightarrow^{100}$Ru	9.6	3034
^{116}Cd$\rightarrow^{116}$Sn	7.5	2814
^{124}Sn$\rightarrow^{124}$Te	5.8	2288
^{128}Te$\rightarrow^{128}$Xe	31.8	866
^{130}Te$\rightarrow^{130}$Xe	34.2	2528
^{136}Xe$\rightarrow^{136}$Ba	8.9	2458
^{150}Nd$\rightarrow^{150}$Sm	5.6	3368

Back to earth….

The number of candidate isotopes is rather small and we often end up choosing among alternative options:

Superior energy resolution (0.1%)

Germanium detectors	**Gerda**, Majorana, Legend
Bolometers	**CUORE**, CUPID-0, AMORE, Cupid

Compromise:

Superior tracking capability

	Compromise:
Source not in detector	**SuperNemo**
TPC with source in detector	EXO-200, **Next**, PandaX-III, nEXO

Huge isotope masses (1 ton)

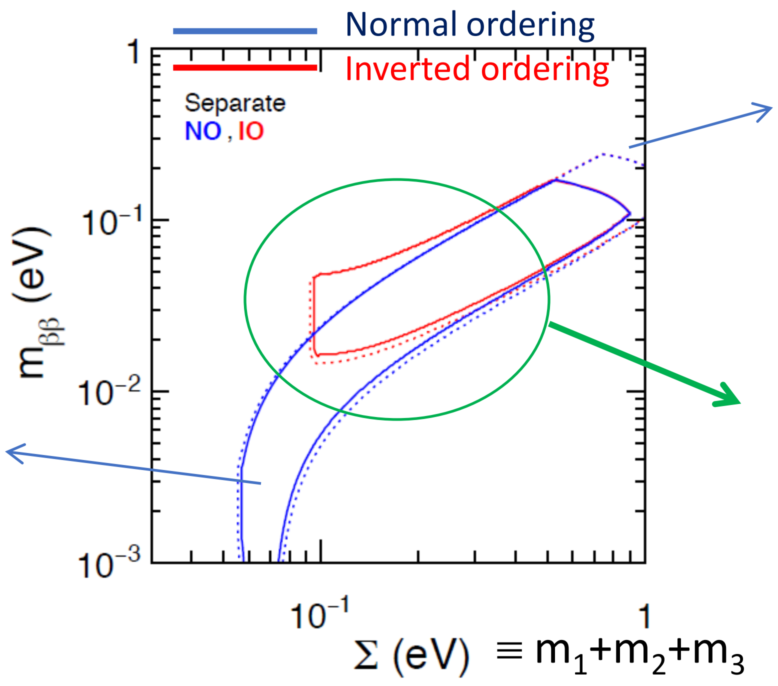
Loaded scintillators	**Kamland-Zen**, SNO+
Cherenkov	Theia

Compromise:

- energy resolution
- restricted isotope list
- tracking capability
- mass scalability

From the “perfect” to the “best” experiment

After 2012, $m_{\beta\beta}$ is well constrained from neutrino (and cosmology) data. Now we know where to look for.



Accidental cancellation among CP phases. Worst case scenario: possible but unlikely

Nearly degenerate mass eigenstate. Best case scenario: possible but unlikely (cosmology)

We want to be here: possible and likely

We are developing technologies that are able to explore NLDBD half-lifes at the level of 10^{26} y and that are potentially scalable up to 10^{28} y.

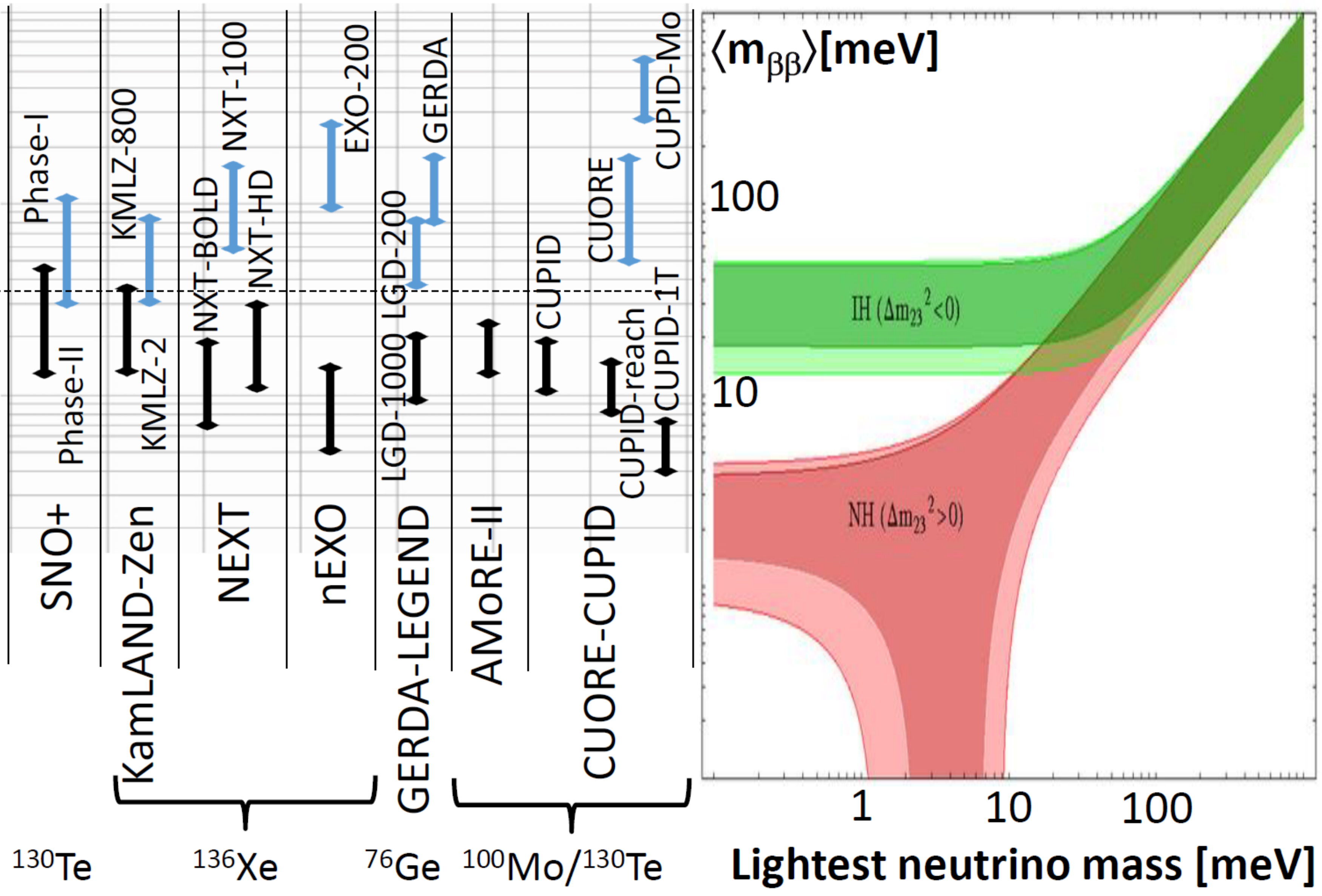
For “zero background experiments”, sensitivity ~ exposure

For finite background: sensitivity ~ $(\text{exposure})^{1/2}$

Neutrinoless double beta decay in 2022

Current generation
(final sensitivity for recently concluded - running - on- commissioning projects)

Next generation
(projects to be started during the next decade)



A. Giuliani, Talk at NOW 2022

Conclusions

The discovery of θ_{13} opened up a wealth of opportunity that we are exploiting to

- Perform the most precise measurements of the mixing angles (Daya Bay, 2022; T2K, 2022) at reactors and accelerators
- Pin down the neutrino mass ordering (JUNO, DUNE, SuperKamiokande)
- Establish the existence of light sterile neutrinos (SBN, 2022; Prospect, 2021; BEST, 2022; JSNS)
- Discover CP violation in the leptonic sector with accelerator neutrino beams (Nova, 2022: T2K, 2022, DUNE, HyperKamiokande, ESSnuSB)

Still, the size of the neutrino mass and its Dirac/Majorana nature is beyond our experimental capabilities:

- Neutrinoless double beta decay will cover inverted mass ordering by 2030
- We cannot beat accidental cancellations in the occurrence of normal mass ordering (but why should we be so unlucky?)
- Cosmology is still ahead of absolute neutrino mass experiments. My take: it will stay like this for long

We can do most of the job with earth-based experiments (and a 2 B$ budget ☺)
but to get the job done…

we might need more
than the earth