Measurements of neutrino properties in the SM and beyond

S.Bolognesi (IRFU, CEA)
for the Neutrino & Cosmic messenger Working Group

Neutrino physics cases

- **Neutrino oscillations**
  - granted physics case: **CP violation, ν mass ordering** → tests of fundamental symmetries of Nature
  - **BSM** door *(Pilar's talk)*
- **Neutrino have mass**… but which one?
  - Very important impact on cosmology *(Valerie's talk)*
- Are neutrino new type of particles? **Majorana vs Dirac**
  - **0νββ:** the most compelling and first order BSM case *(Pilar's talk)*
- **Neutrino as cosmic messangers**: from low E (**SuperNovae**) to high E *(Valerie's talk)*
- Neutrino & nuclear physics: **neutrino-nucleus interaction cross-sections**
  - crucial for precision on **oscillation, neutrino astrophysics**
  - new probes to **study neutrino properties and nuclear properties**

Neutrino oscillation experiments

- Accelerator neutrino, long-baseline experiments:
  - controlled production of **ν and $\bar{\nu}$ + near detector** → **CPV and MO, precision PMNS** (θ_{23}, Δm^2_{23})
  - T2K, NOVA → HyperKamiokande, DUNE

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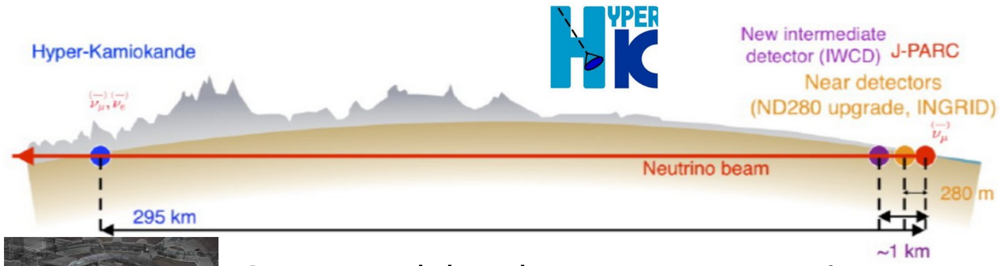
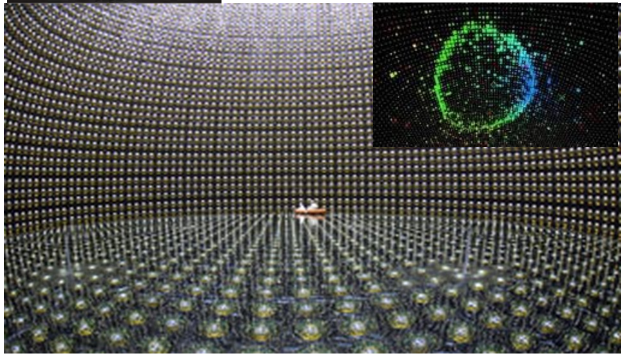


SuperKamiokande
volume x8
(water Cherencov)

T2K beam
X2.6 power



Proven technology boosted by factor ~20

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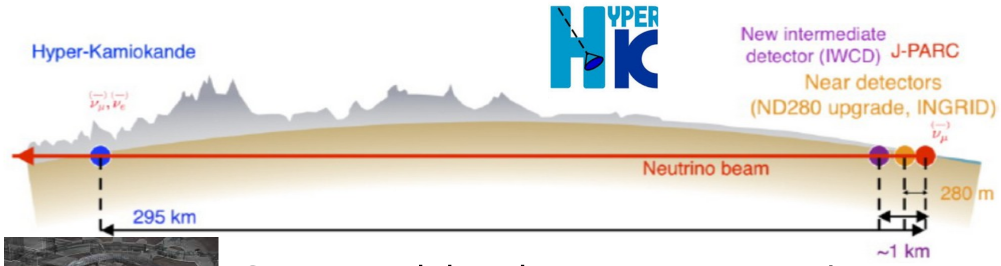

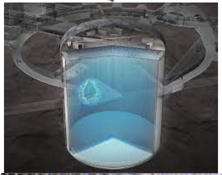

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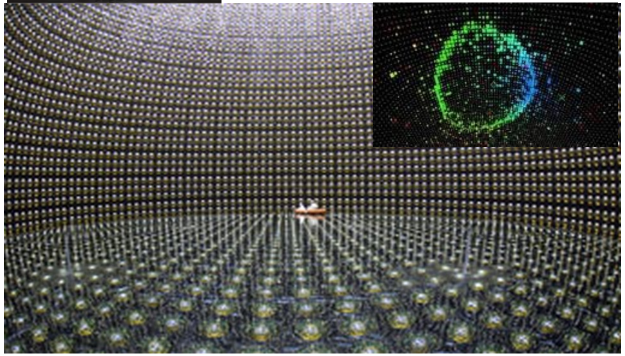

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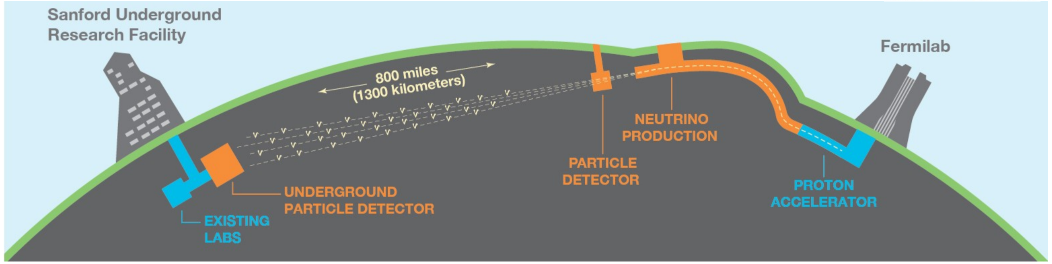
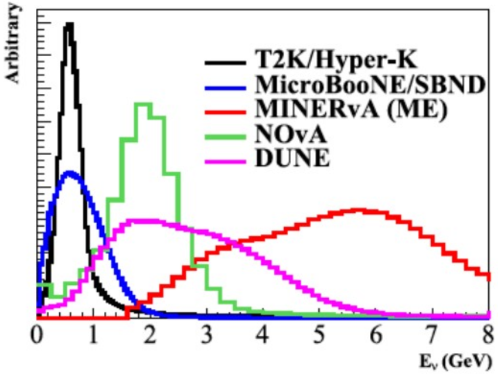


- Start beam in 2031 with staged approach



- **Very long baseline**
- **Wide-band energy beam** (~few GeV)

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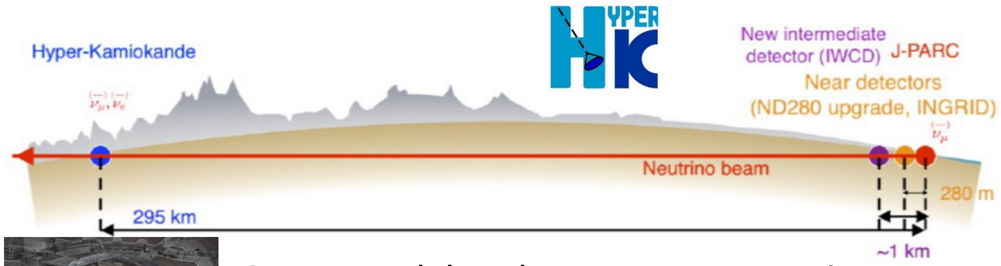
DUNE
DEEP UNDERGROUND NEUTRINO EXPERIMENT



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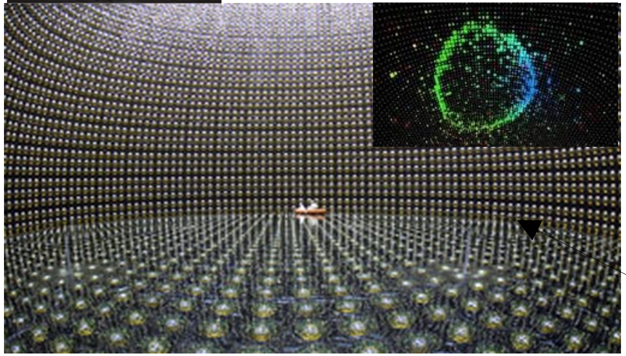

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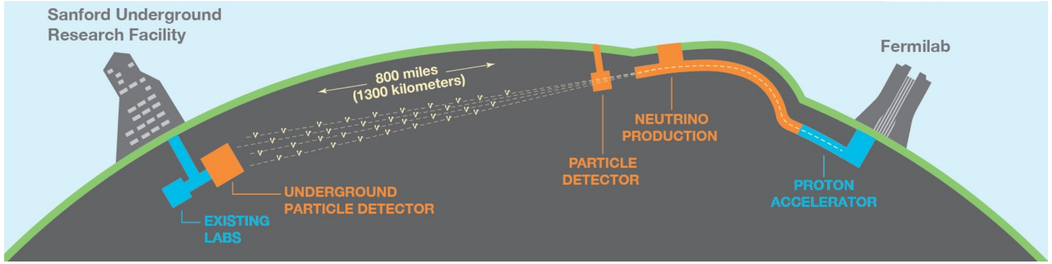

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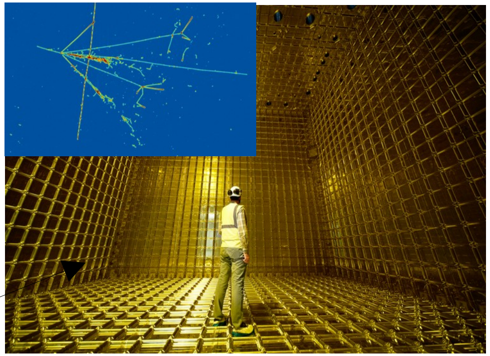

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- **Wide-band energy beam** (~few GeV)
- **LAr technology:** strong CERN contribution with protoDUNE

High complementarity

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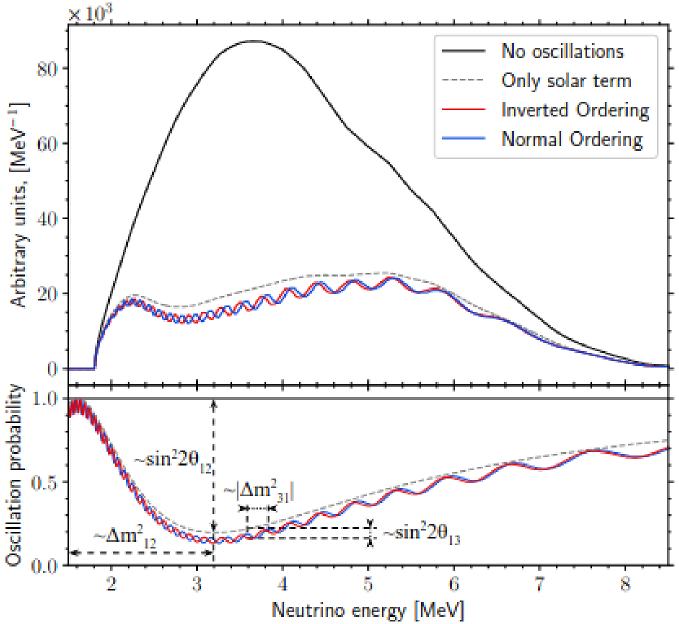
- Reactor neutrinos
  - large statistics of $\bar{\boldsymbol{\nu}}_{\mathbf{e}}$
  - DayaBay, RENO, Double Chooz short baseline: θ_{13}
  - long baseline (KamLand) **JUNO**: $\boldsymbol{\theta_{12}, \Delta m^2}$, **MO** from "phase" of vacuum oscillation



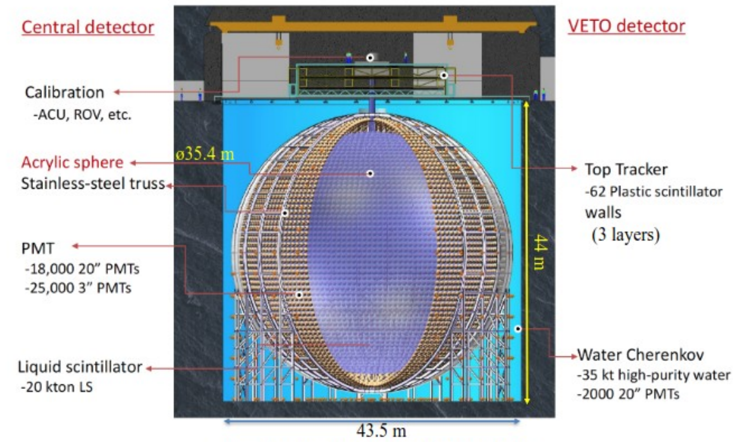
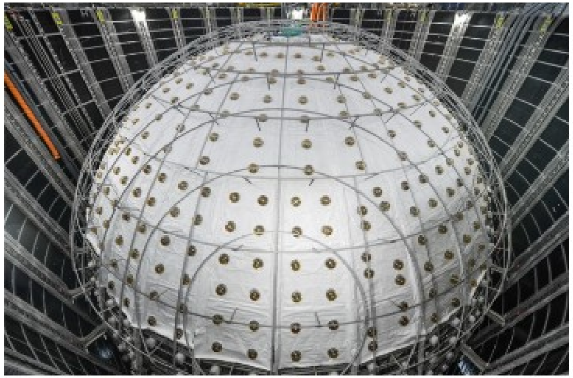


Figure 2: Schematic view of the JUNO detector.



The JUNO detector seen from outside. The Veto PMTs and the earth magnetic field compensation coil are seen.

20kTon liquid scintillator
Starting data taking now!

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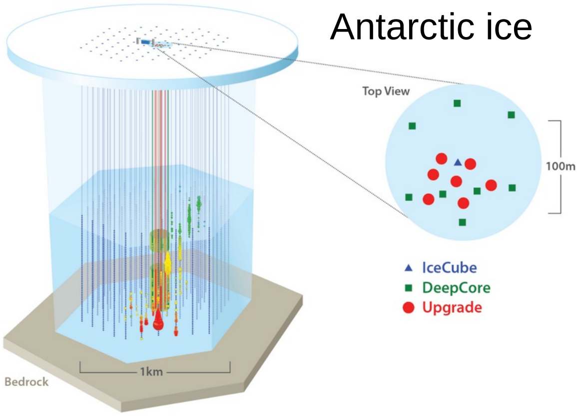
- Atmospheric neutrinos
  - large stat 'for free' but no control on flux: sensitivity to **MO, θ_{23}, Δm^2_{23}**
  - far detectors of LBL (eg SuperKamiokande) + **low-E dense detectors in observatories**: huge statistics (MegaTons) with limited PID and resolution

ICECUBE SOUTH POLE NEUTRINO OBSERVATORY

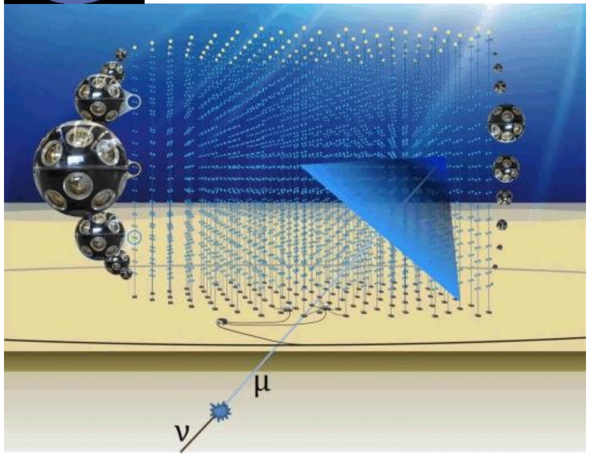
Antarctic ice



IceCube DeepCore 10Mton + Upgrade 2MTon

ORCA KM3NeT

Mediterranean sea

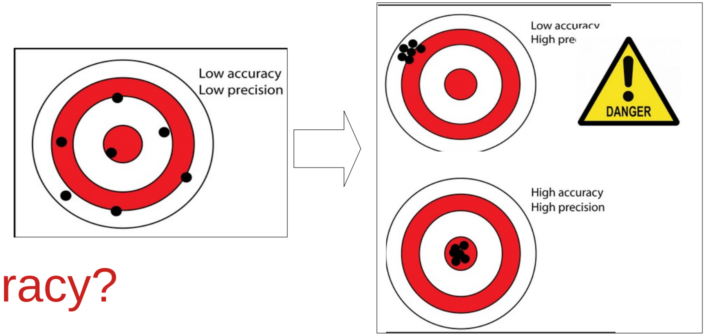


Km3Net: deploying on-going → ORCA 7MTon

Oscillations: where are we going?

- Two clear open physics cases at reach: **CP-Violation and Mass Ordering**

- **Oscillation precision physics** → impact on model building, cosmology, $0\nu\beta\beta$, ...



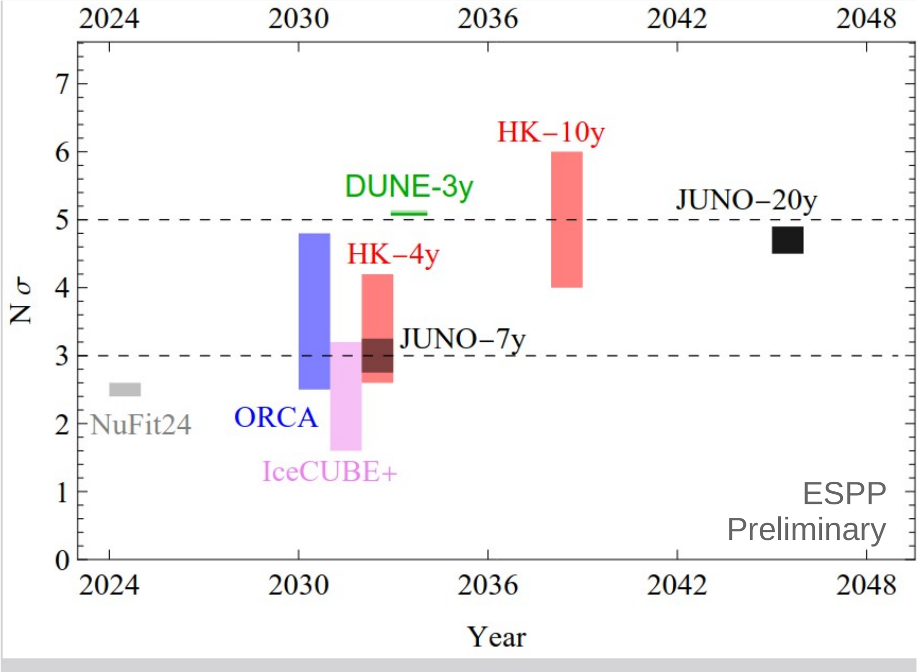
  - number of events in **long-baseline**: x25 to x100 larger than previous generation.
  Importance of **systematics** (flux and xsec): precision → accuracy?

- **JUNO:** solar sector improved by factor 5 to 10 → need accurate **control of gigantic detector**

- Overconstrain the oscillation system by **combination of experiments to boost physics reach:**
  break degeneracies between PMNS parameters – systematics – New Physics

Mass Ordering

Δm^2_{3i} in ν_e and ν_μ disapp (in vacuum)		
JUNO + LBL(T2K/NOVA)	2-3 σ	~2026



Various oscillations effects are sensitive to MO

Various ~3σ hints in the next 5 years:
agreement or tensions?
(Systematic bias or New Physics hints?)

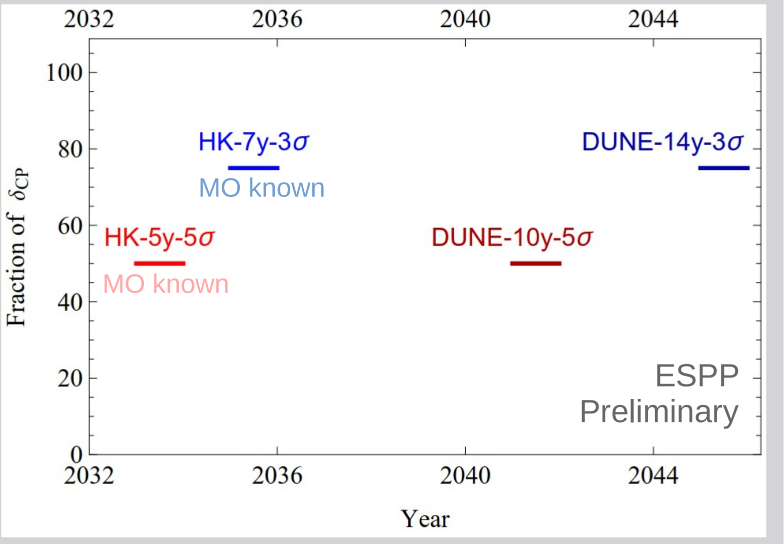
First clear unambiguous MO determination from DUNE beam ν

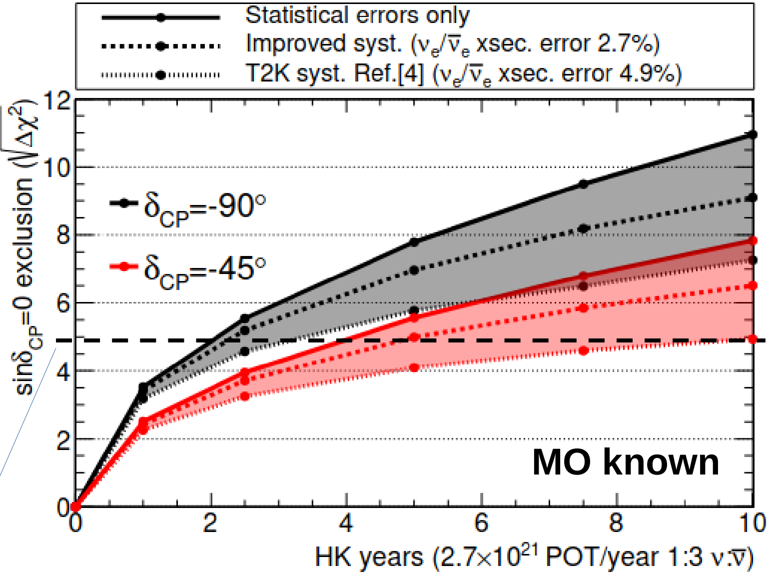
Also 5σ expected ultimately from atmospherics (ORCA, IceCube, HK) and JUNO

→**combination of experiments allowing over-constraints and x-checks**.

Discovery of CP violation

Unique sensitivity on CPV from LBL experiments:





If CPV large, **discovery in 2-4 years** (2030-2032 depending on systematics) but knowing MO is important in **degenerate regions**

If CPV small, **systematics may be the ultimate limitation** to the discovery

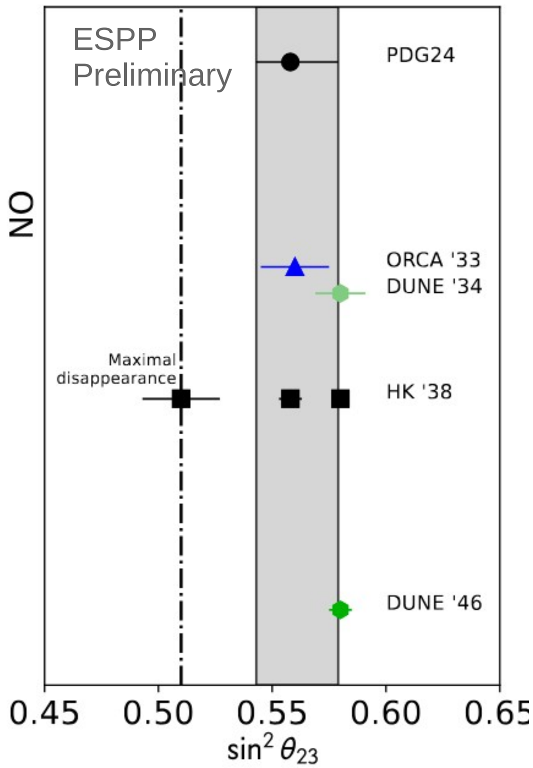
→ **importance of combination of experiments!**

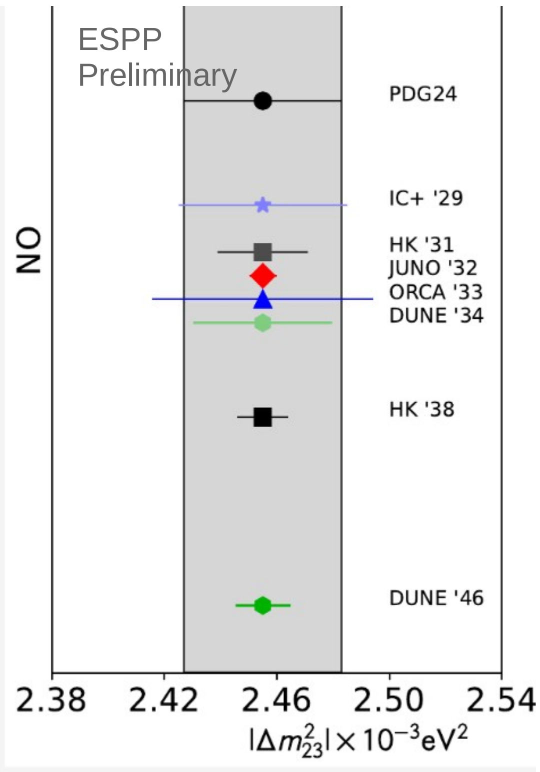
PMNS precision

- Precision physics on solar sector (JUNO):
1% → 0.3% precision on Δm^2_{12}
2% → 0.5% precision on $\sin^2\theta_{12}$

- Precision physics on ν_μ disappearance parameters $|\Delta m_{23}^2|$ and $\sin^2\theta_{23}$ →

- Precision on δ_{CP}
~7 degrees : if small CPV
~18 degrees : if large CPV

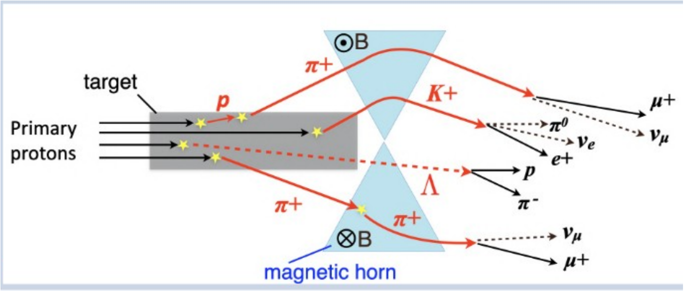




Present precision of LBL oscillation experiments: ν rate~2-4% and E_{scale} ~4%
→ **this precision must improve by a factor 4-5 in HK/DUNE**

→ **Need to improve control of systematics: flux and xsec (neutrino energy reconstruction)**

Flux tuning: NA61/SHINE at CERN



Hadroproduction from proton scattering in the target: complex nuclear&hadronic physics

→ crucial direct tuning by NA61/SHINE
(e.g improved the flux uncertainty by factor ~2 during T2K era)

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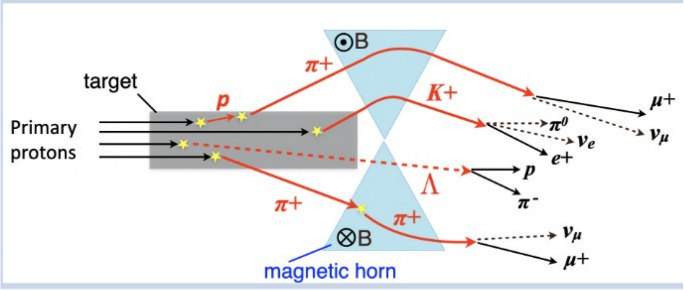

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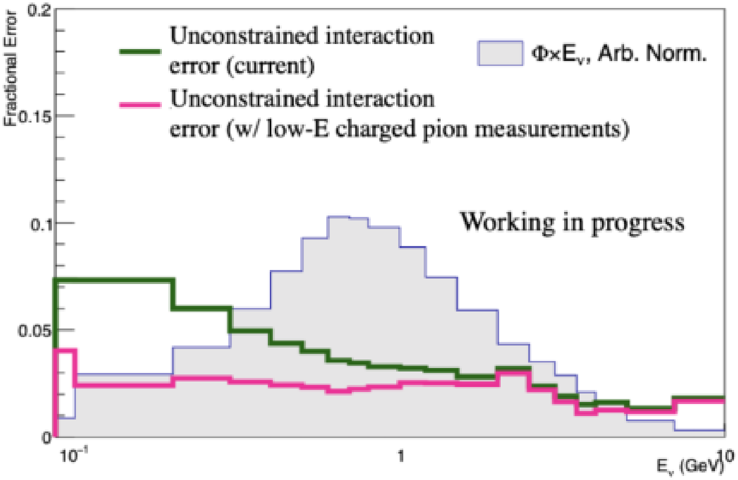
→ **proposal of new low-E beamline at SPS for NA61**



ν background in $\bar{\nu}$ flux

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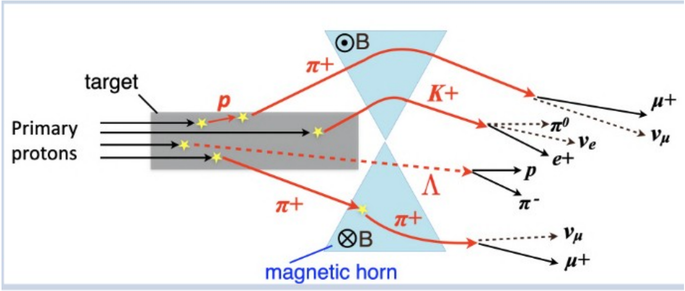

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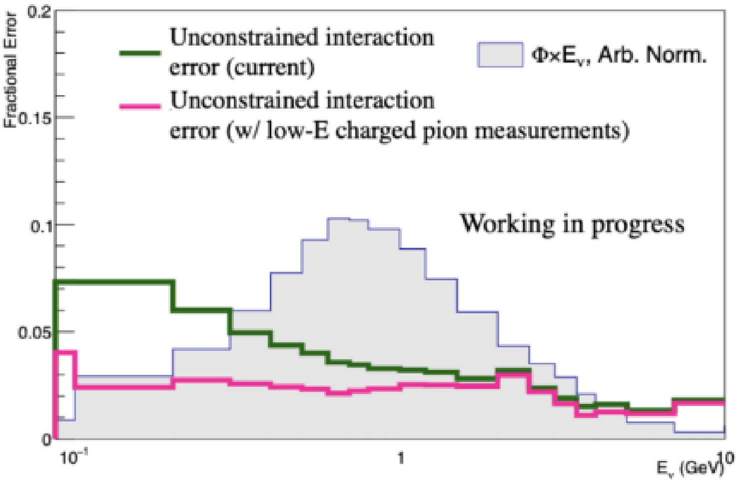
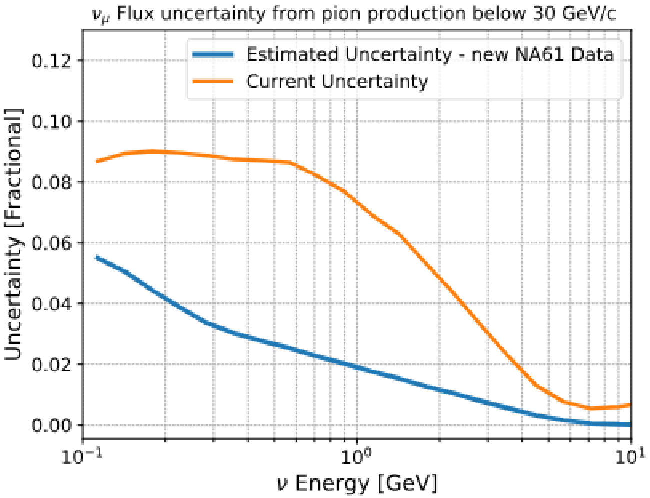


ν background in $\bar{\nu}$ flux

Also big impact on atmospheric neutrino flux uncertainties



Near detectors and xsec measurements

Highly capable (near) detectors: exclusive reconstruction (low momentum protons, neutrons, electron vs γ…) + PRISM technique → **overconstrain the xsec model**

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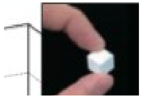
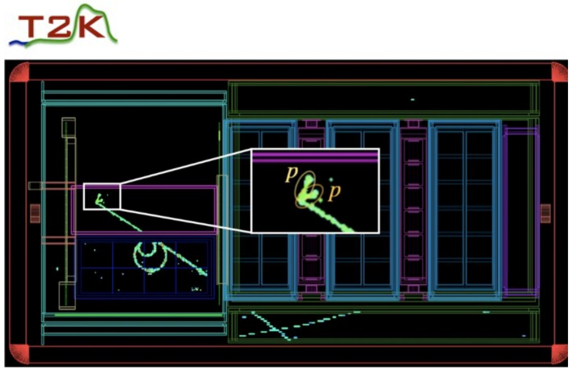
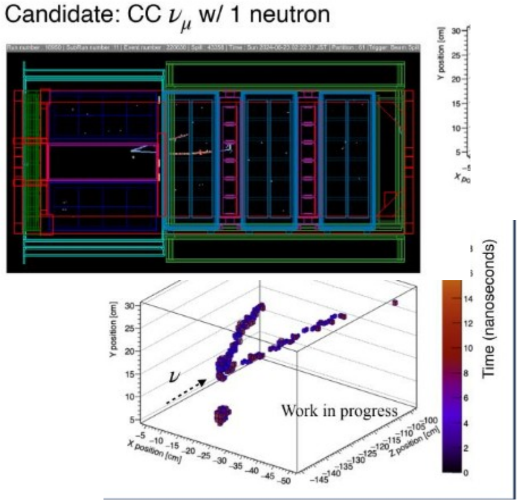
Strong contribution from CERN



- R&D for further upgrade under discussion





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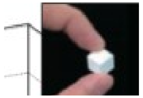

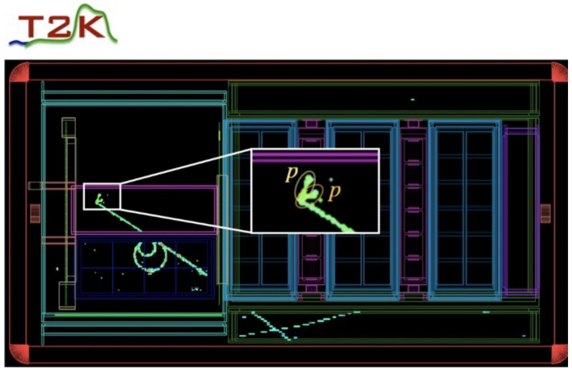

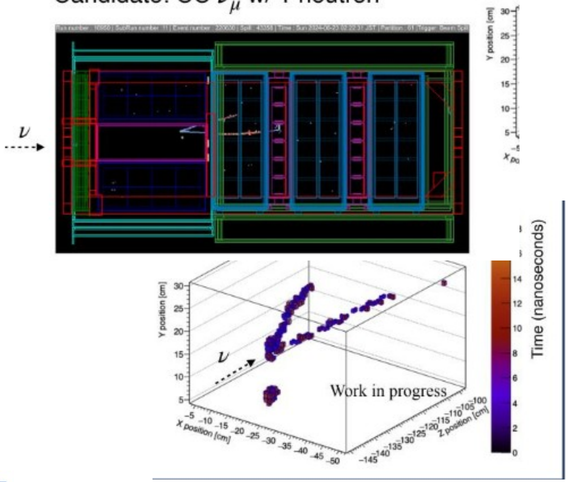

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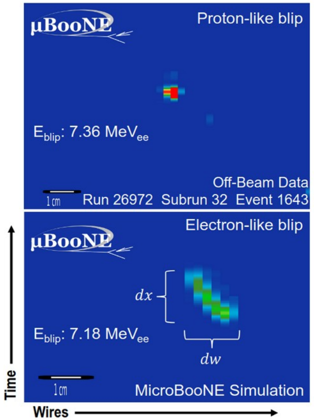
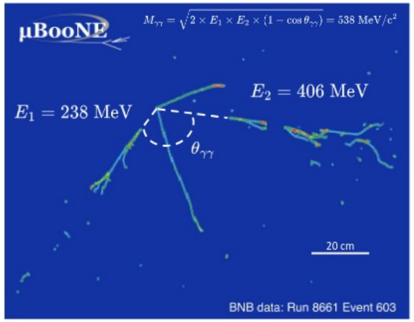
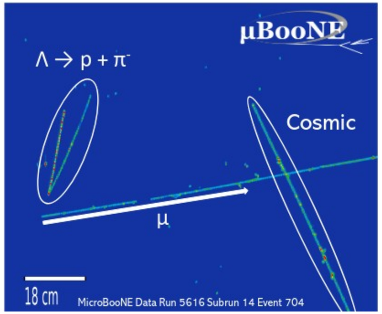
- **SBN@FNAL:** rich xsec program thanks to amazing capabilities of LAr
  - running ICARUS (CERN contribution)
  - LAr TPC + HP Gas Argon TPC for DUNE ND



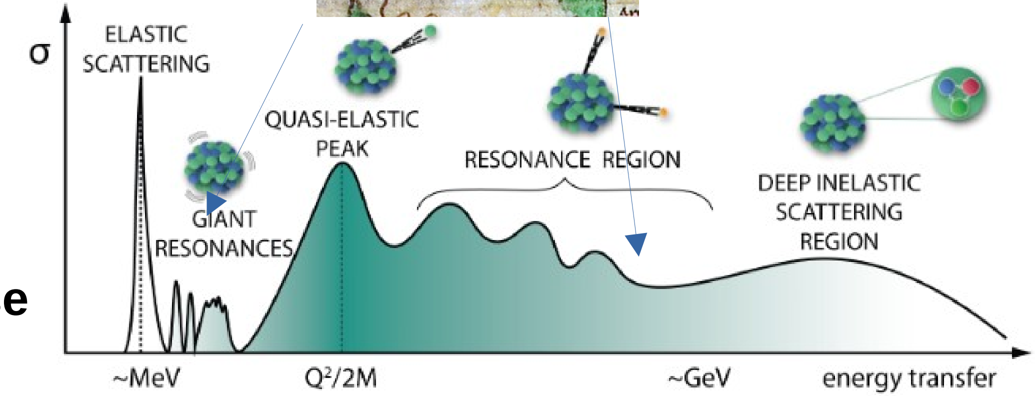




Hic sunt leones!

Lesson from present generation of experiments: known unknowns +
<u>unknown unknowns → biases</u>
Especially away from QE peak

Strong EU (and CERN) physics expertise



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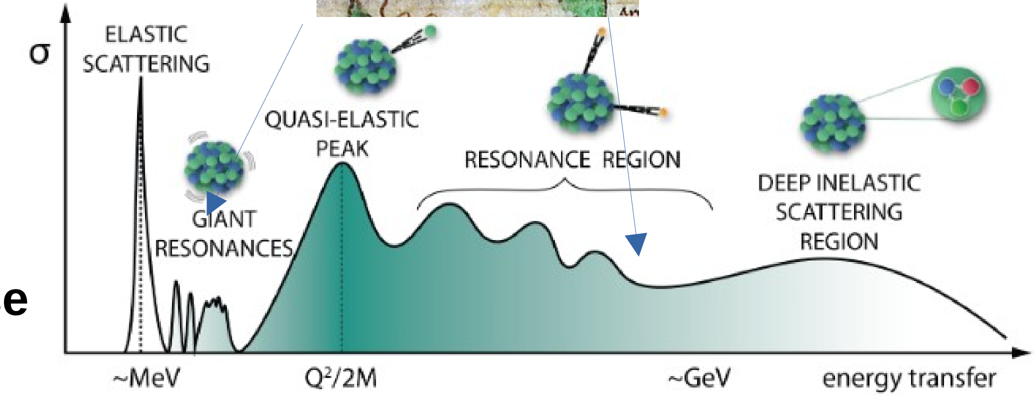

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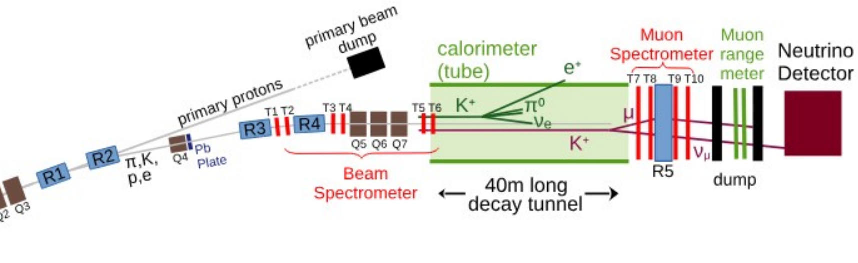
- New project from Neutrino Platform ‘nursery’: **realistic beamline design and detector technology for monitored+tagged beam (nuSCOPE)**



Measuring hadrons/leptons in the beamline →
1% rate ν_e,ν_μ, **1% Eν reso ν_μ**

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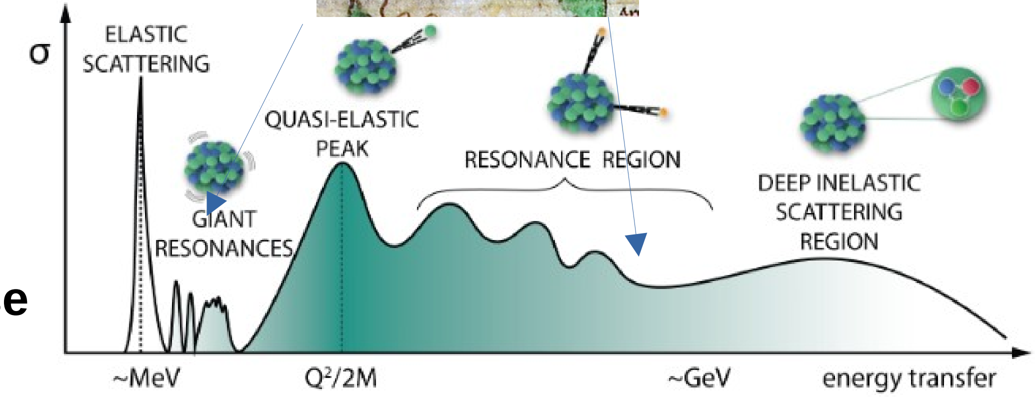

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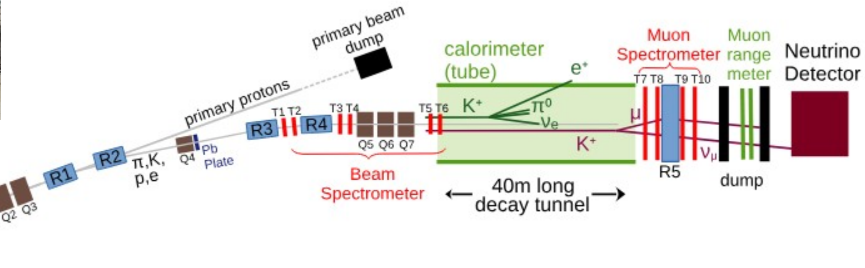
- Another opportunity will rise from muon collider roadmap: **NuSTORM**



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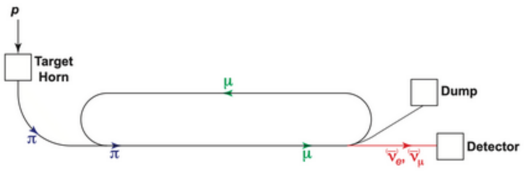
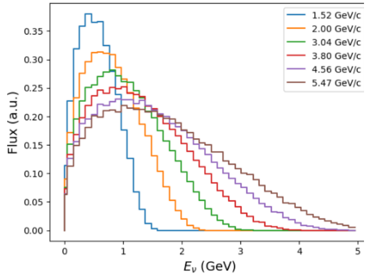




$\mu^- \rightarrow e^- \; \nu_\mu \; \bar{\nu}_e$:
- 1% precision on rate
- scanning Eν by beam tuning

Future projects

- European funded **exploratory studies:**

ESSνSB: new neutrino beam line exploiting the proton beam at the ESS

SuperChooz: new gigantic short baseline at Chooz reactor experiment

- Opportunity for interesting **detector R&D**

Water based liquid scintillator (**ND280++**)

High Pressure Gas Argon TPC (**DUNE ND**)

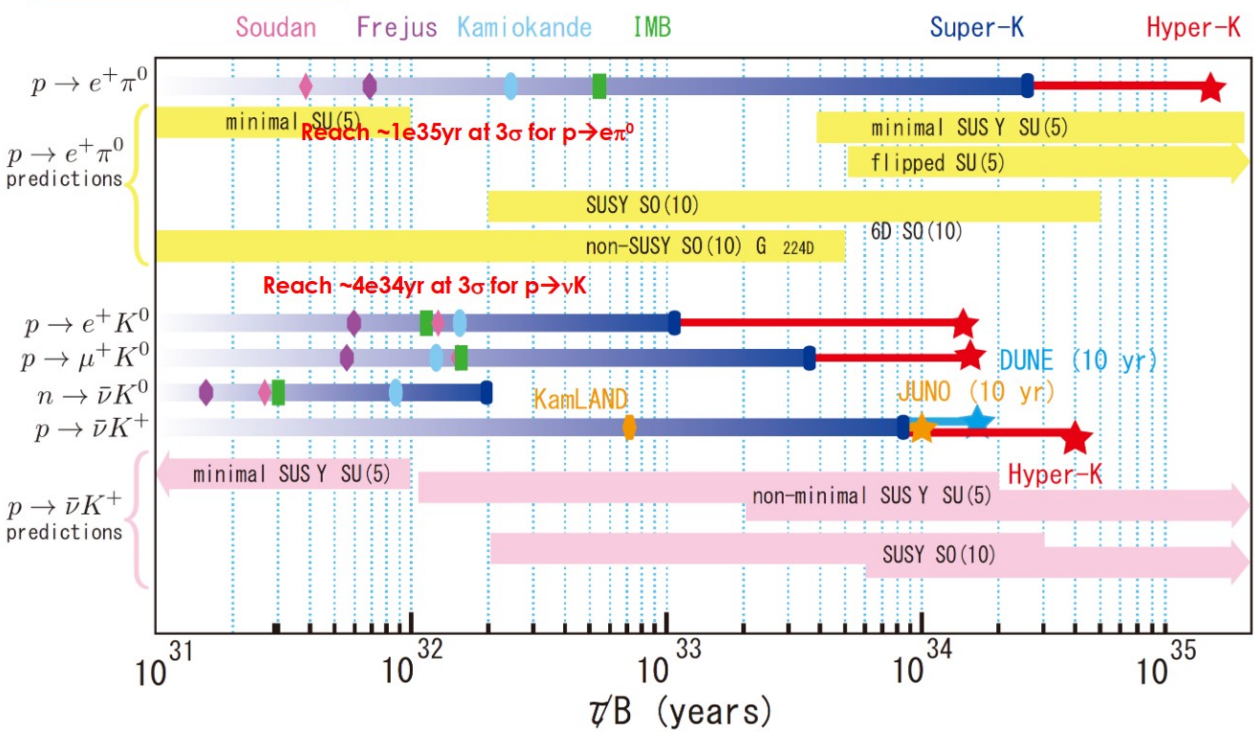
Enhanced optical readout for LAr TPC (**DUNE FD3/4**)

Combination of water Cherencov and liquid scintillator (**Theia** proposal for DUNE Module of opportunity)

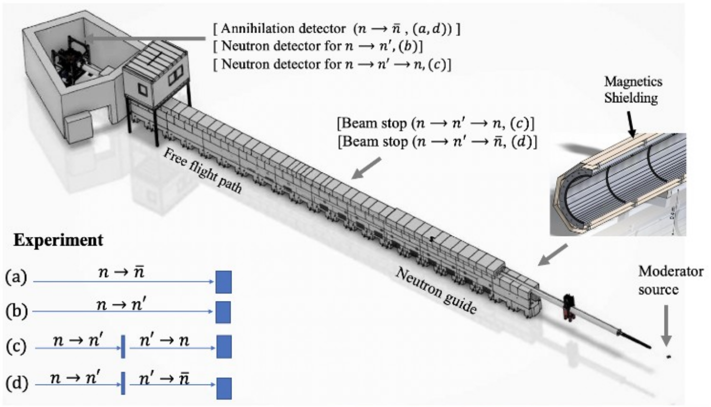
Opaque scintillator (**LiquidO**)

Beyond oscillations: Baryon Number Violation

Proton decay:
$>10^{34}$ years → $>10^{35}$ years



Neutron-antineutron oscillations:
unique sensitivity at ESS with a new proposed experiment (HIBEAM)

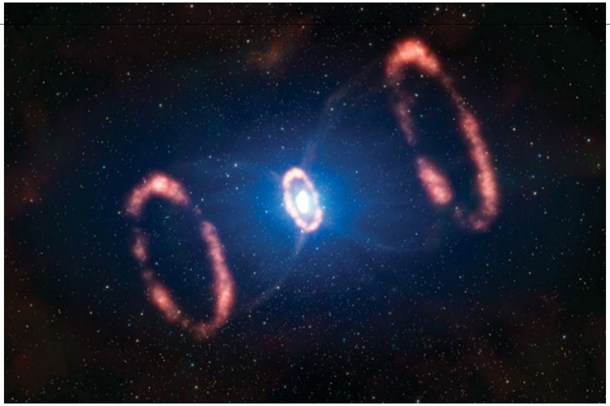


Neutrinos & astrophysics

- Neutrino, **a new messenger from the cosmos** *(see Valerie's talk)*
  Here focus on low energy neutrinos from **SuperNovae** (but also Sun, geoneutrinos)

- **New technologies being developed for low energy neutrino detection**
- **New approaches for xsec measurements at very high energy**

Neutrinos from SuperNovae burst



Rich information: direct look ‘inside’ a complex astrophysical process

- HK has largest statistics (tenths of thousands of events at 10kPc) & very good pointing (1 degree)

- DUNE: unique clean sample of ν_e

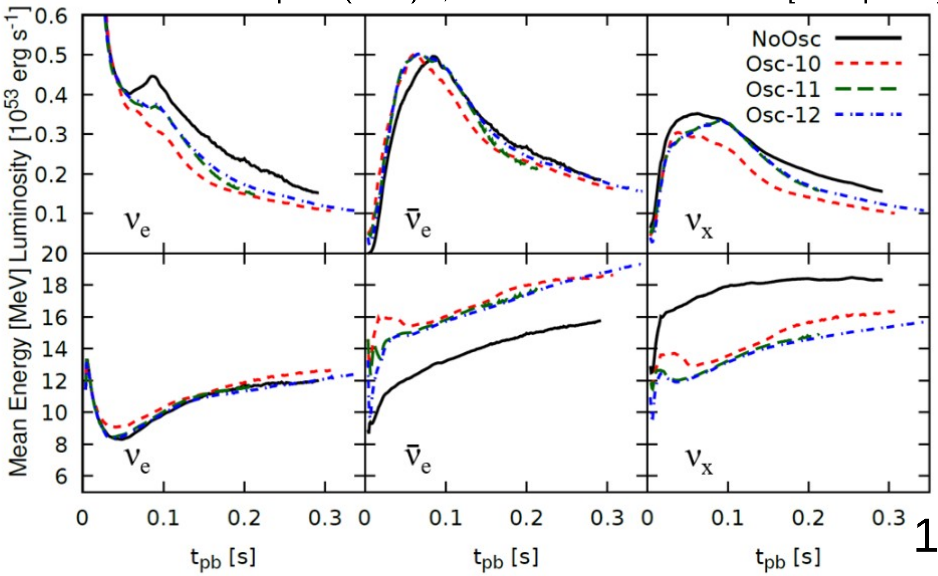
- JUNO: best neutrino energy resolution and lowest threshold (pre-collapse neutrinos)

- IceCube (& ORCA)

→ timing triangulation with ~degrees pointing resolution

→ SNEWS: combined trigger network crucial to enable multimessanger

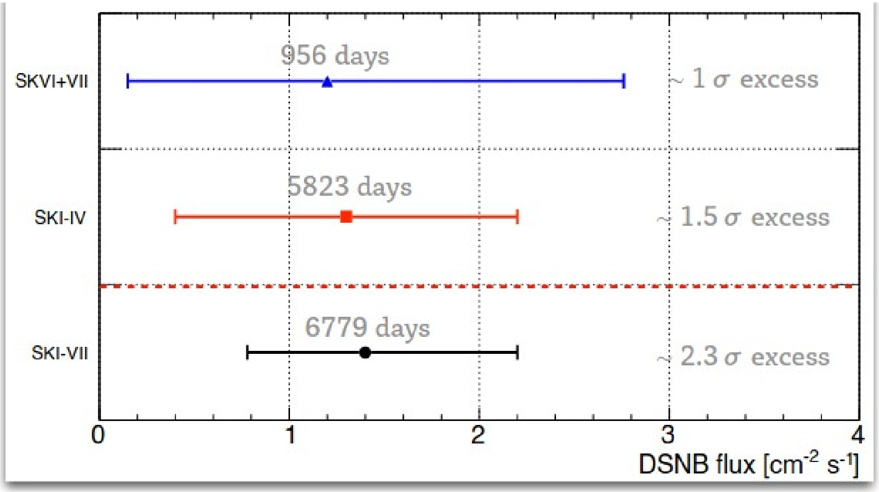
Publ.Astron.Soc.Jap. 77 (2025) 2, L9-L15 e-Print: 2501.15256 [astro-ph.HE]

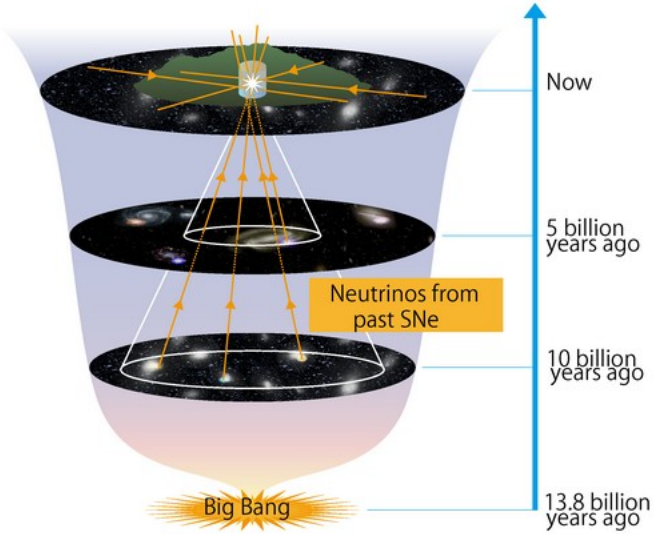


From observation of one SN (Kamiokande, Nobel prize 2002) with ~24 events to thousands of events in multiple experiments: **a brand new field would open !**

Diffuse SuperNovae background

Crucial **insights in star formation history** → present models of DSNB flux differs by order of magnitudes!





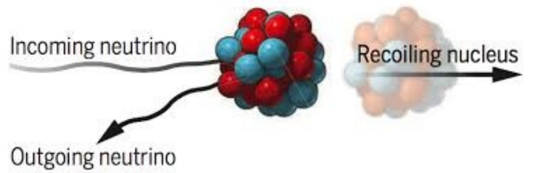
Consistent excess from SK (both pure water and Gd loading): 2.3σ ! (1-5 events expected)

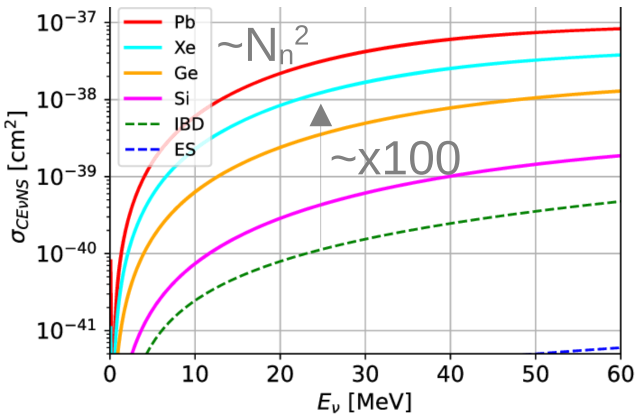
SK-Gd has realistic possibility for discovery!
→ next generation dominated by **HK and JUNO** (50-100 events each in 10 years)

~keV detectors for ~MeV neutrinos

Coherent-elastic neutrino-nucleus scattering: large xsec
Requires to measure of ~0.2-10 keV from nucleus recoil

Allow to probe SM and BSM with low-E neutrinos (w/o gigantic detector)





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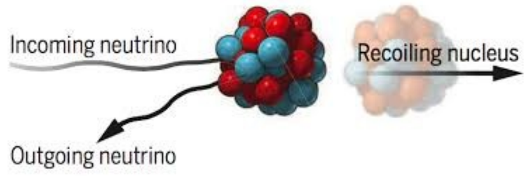
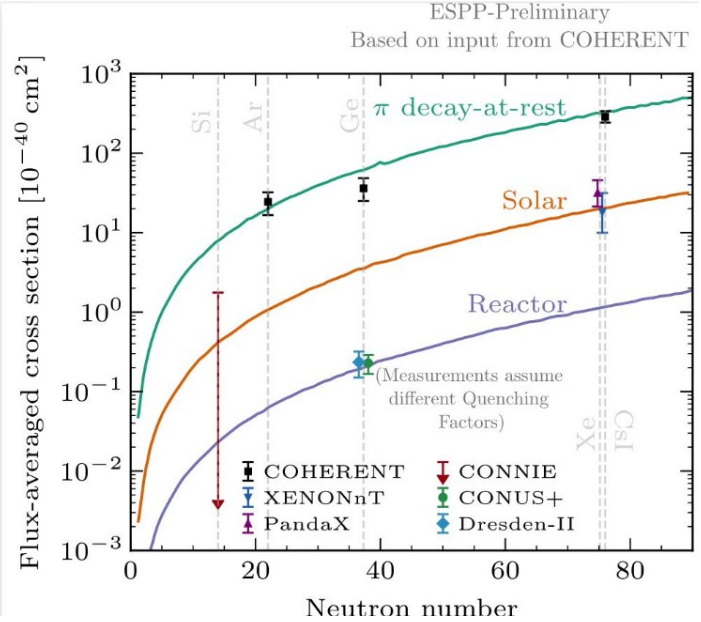


Available measurements

Experiment	Neutrino source	Detector material	Detection?	Reference
COHERENT	Pion-decay-at-rest	CsI, 14.6 kg	Yes	arXiv:2110.07730
COHERENT	Pion-decay-at-rest	Ar, 24 kg	Yes	arXiv:2003.10630
COHERENT	Pion-decay-at-rest	Ge, 17.6 kg	Yes	arXiv:2406.13806
Dresden II	Reactor	Ge, 3 kg	Yes	arXiv:2202.09672
CONUS+	Reactor	Ge, 2.83 kg	Yes	arXiv:2501.05206
Connie	Reactor	Si, 36.2 g (very low threshold)	No	arXiv:2110.13033
Texono	Reactor	Ge, 1.4 kg	No	arXiv:2411.18812
nuGen	Reactor	Ge, 1.4 kg	No	arXiv:2502.18502
Red 100	Reactor	Xe, 126 kg	No	arXiv:2411.18641
XENONnT	Solar	Xe, 6 ton	Yes	arXiv:2407.02877
PandaX-4T	Solar	Xe, 5.5 ton	Yes	arXiv:2407.10892



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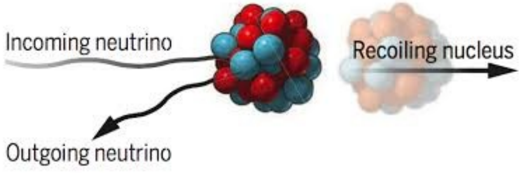
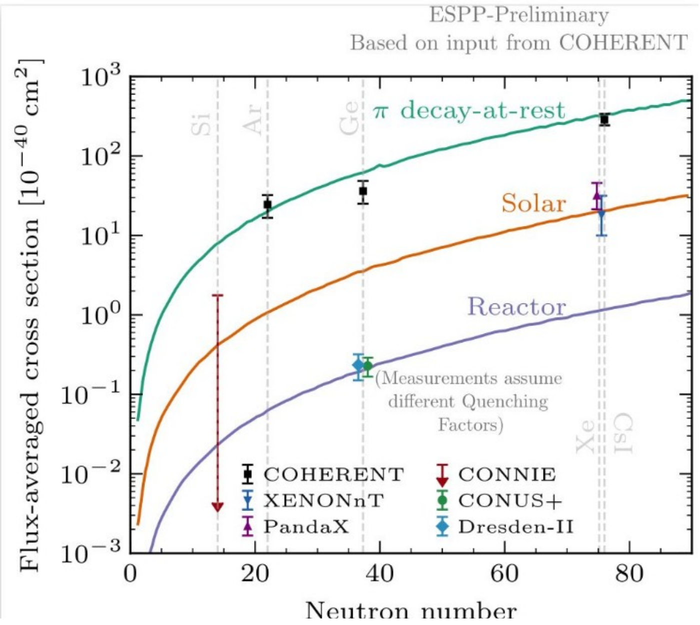


'Explosion' of proposals

Experiment	Neutrino source	Detector material	Deployed?	Reference
COHERENT	Pion-decay-at-rest	NaI (3500 kg)	3/7 modules deployed	COHERENT input
COHERENT	Pion-decay-at-rest	Liquid Ar (750 kg)	Cryostat under commissioning	COHERENT input
COHERENT	Pion-decay-at-rest	Cryogenic CsI (low threshold)	No	COHERENT input
COHERENT	Pion-decay-at-rest	Ne	No	COHERENT input
Captain Mills	Pion-decay-at-rest	Ar	Commissioning last year	arXiv:2105.14020
ESS	Pion-decay-at-rest	CsI, Si, Xe, Ge, Ar, C_3F_8 (large ν flux)	No	arXiv:1911.00762
SuperCDMS	Solar	Si, Ge	Commissioning	Proceedings
RES_NOVA	Solar	Pb	No	arXiv:2004.06936
CYGNUS	Solar	He	No	arXiv:2404.03690
BULLKID	Solar	Si	Demonstrator commissioned	arXiv:2209.14806
CONUS100	Reactor	Ge	No	CONUS input
CONNIE upgrade	Reactor	Si (low threshold)	No	CONNIE input
MINER	Reactor	Ge, Si	Engineering runs done	arXiv:1609.02066
NEON	Reactor	NaI	Yes	arXiv:2204.06318
NUCLEUS	Reactor	Al_2O_3, $CaWO_4$ (low threshold)	Yes	arXiv:2211.04189
Ricochet	Reactor	Ge (low threshold)	Yes	arXiv:2111.06745
SBC	Reactor	Ar	Prototype under construction	arXiv:2101.08785
NUXE	Reactor	Xe	No	Paper
PALEOCCENE	Reactor	Different materials (exploits defect formation, low threshold)	No	arXiv:2203.05525



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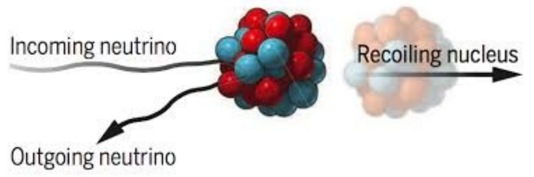
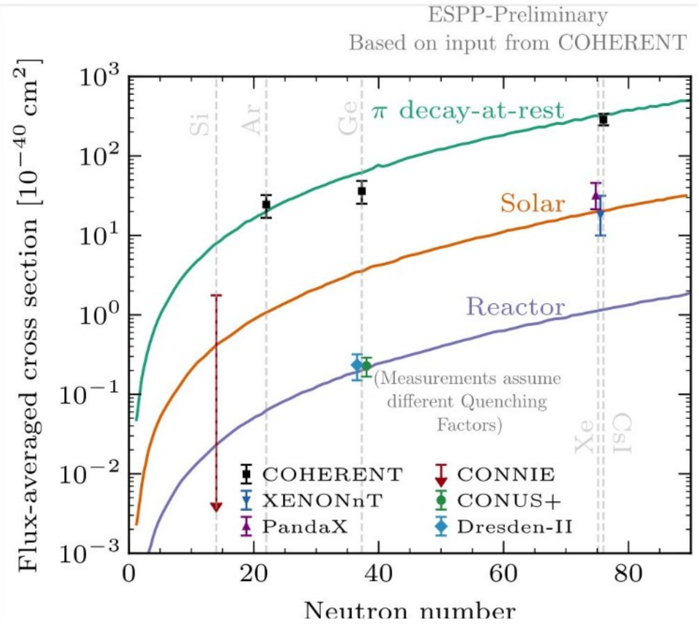


Experimental challenges to improve the measurements:

- π-DAR at neutron spallation source (ν_e, ν_μ) ~30 MeV
  - need to improve flux uncertainty (can use ν_e/ν_μ ratio)
- at reactors ($\bar{\nu}_e$) ~5 MeV
  - need better calibration of quenching factor (CRAB approach + measure heat+ionization)
- from Sun (in large DM detectors) all flavours ~10 MeV

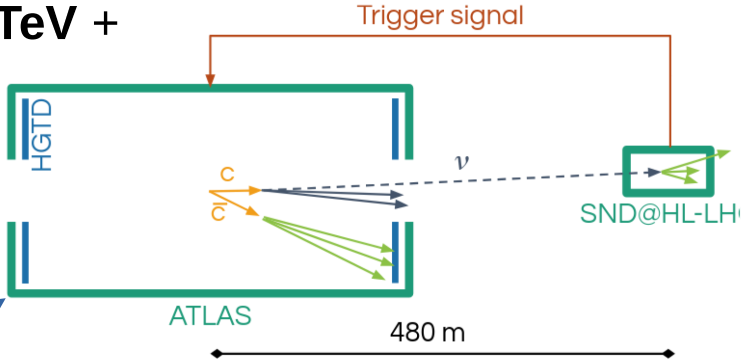


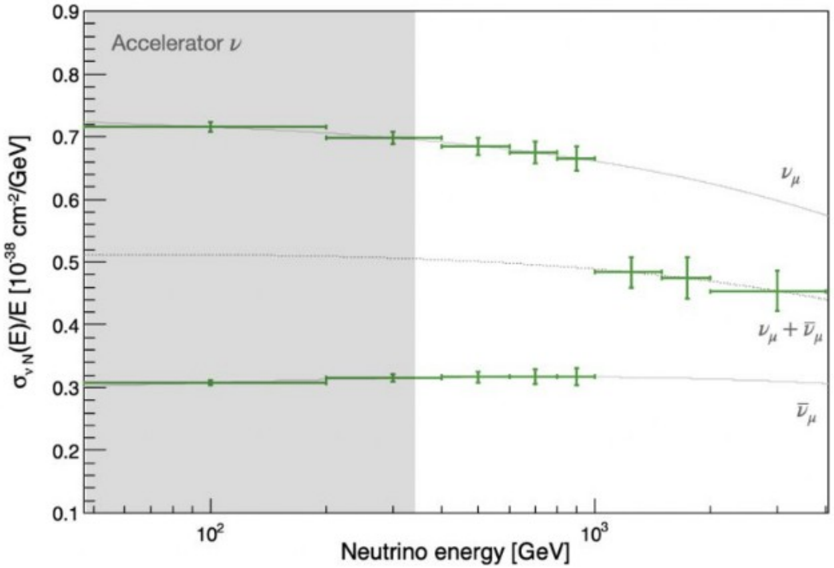
Forward-LHC for ~TeV neutrinos

New way **to probe production (PDF) and xsec at TeV** + to search for BSM signatures (eg, FIP):

SND@HL-LHC

Measurement	Uncertainty Stat.	Uncertainty Sys.
Gluon PDF	2%	5%
ν_e/ν_τ ratio for LFU test	6%	10%
ν_e/ν_μ ratio for LFU test	2%	5%
Charm-tagged ν_e/ν_μ ratio for LFU test	10%	< 5%
ν_μ and $\overline{\nu}_\mu$ cross-section	1%	5%





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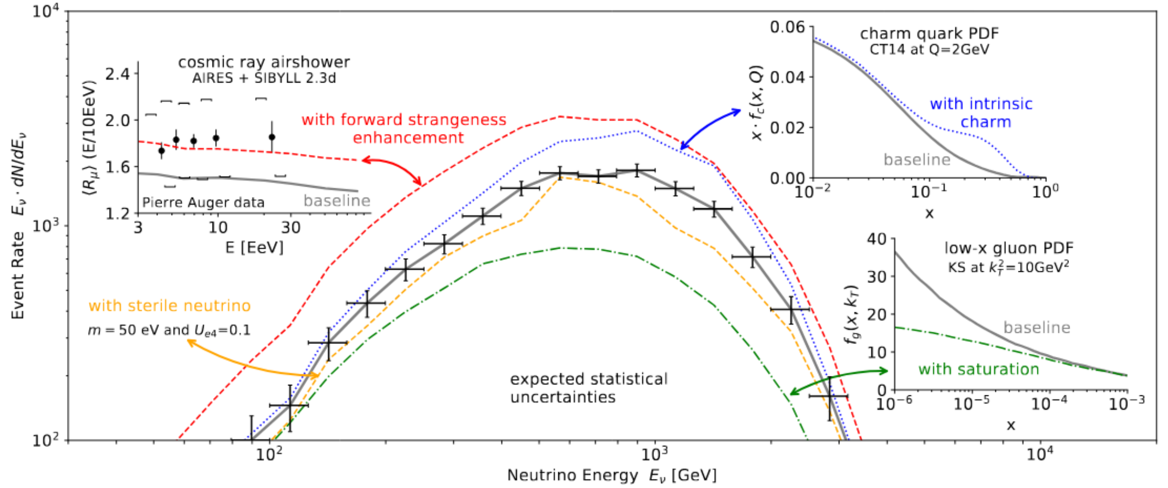
FASER Upgrade



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- An obvious serendipitous opportunity

- Proposal for a much bigger dedicated facility in future (Forward Physics Facility)

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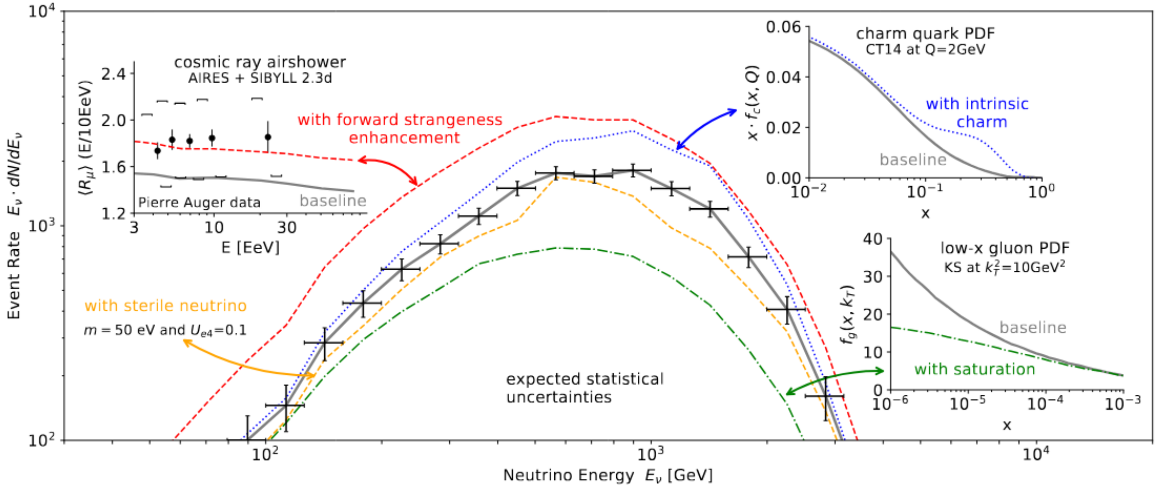

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- Proposal for a much bigger dedicated facility in future (Forward Physics Facility)

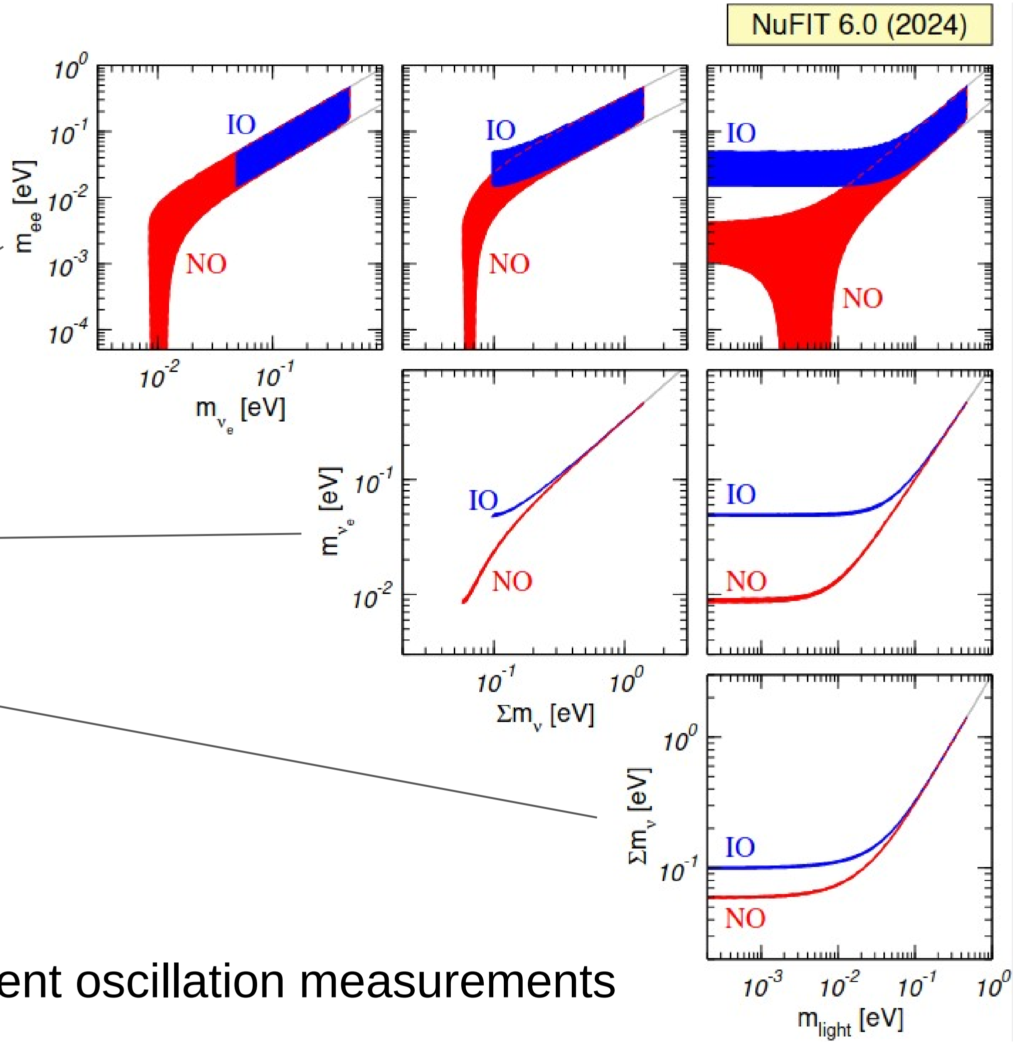
- SHIP **granted physics case: 10-100 GeV neutrinos**, enriched in ν_τ

	CC DIS	Charm CC DIS
N_{ν_e}	2.0×10^6	1.2×10^5
N_{ν_μ}	5.8×10^6	2.8×10^5
N_{ν_τ}	5.9×10^4	3.2×10^3
$N_{\overline{\nu}_e}$	4.0×10^5	2.1×10^4
$N_{\overline{\nu}_\mu}$	1.3×10^6	5.0×10^4
$N_{\overline{\nu}_\tau}$	4.3×10^4	2.5×10^3

Neutrino mass

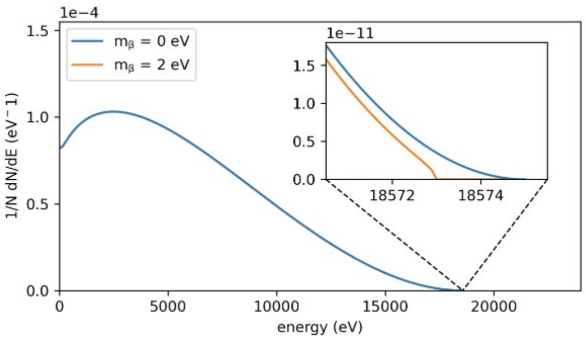
Various correlated observables:

- **0νββ**
- **direct m_ν in lab**
- **cosmology**
  (Valerie's talk)



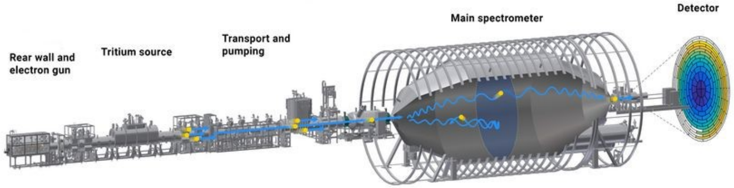
(Bands corresponds to value allowed by present oscillation measurements and unknown Majorana phases)

$m_{\nu e}$<0.45 eV (90%)



β decay: KATRIN++, Project8, QTNM, PTolemy

$^3H \rightarrow {}^3He + e^- + \bar{\nu}_e$



Atomic tritium production mandatory to avoid de 1eV broadening of molecular tritium → global consortium

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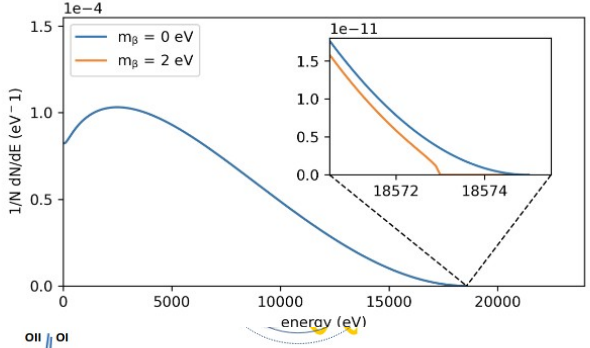

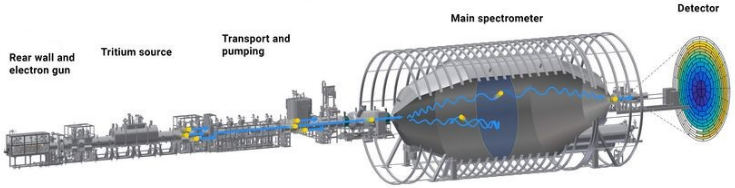

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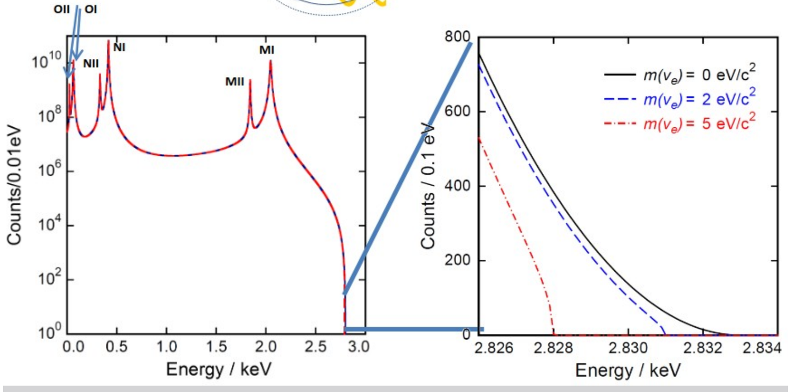
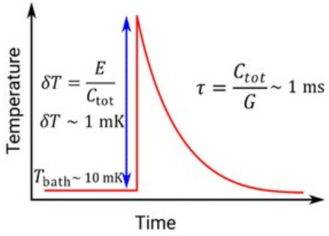
⇨ **Atomic tritium production** mandatory to avoid de 1eV broadening of molecular tritium → global consortium



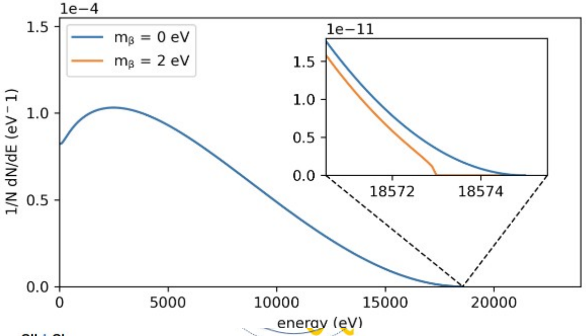
e- capture: ECHo, HOLMES

$^{163}Ho + e^- \rightarrow \nu_e + {}^{163}Dy^*$



⇨ Challenge of **scalability** for bolometers

$m_{\nu e}$<0.45 eV (90%)



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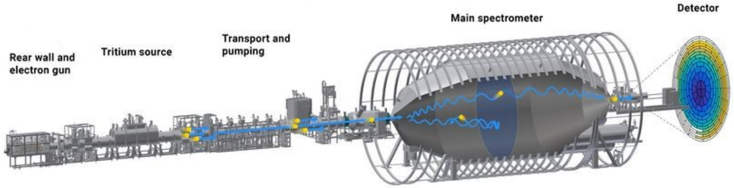

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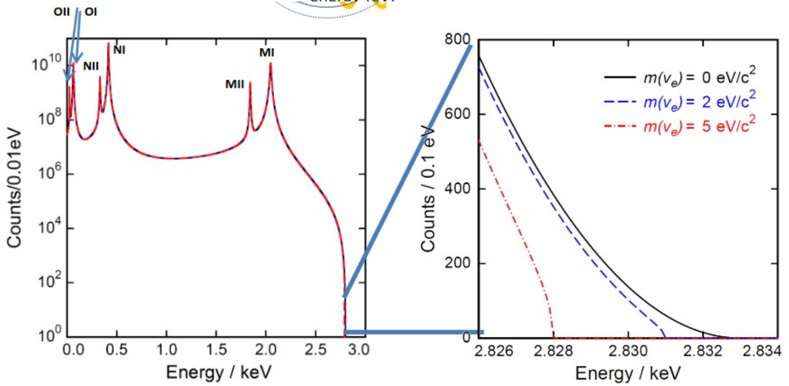

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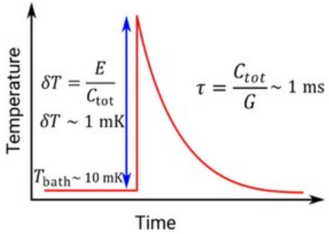

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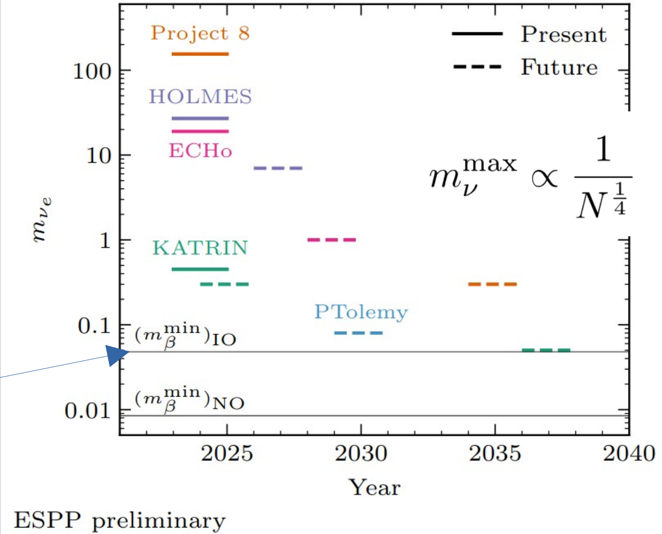
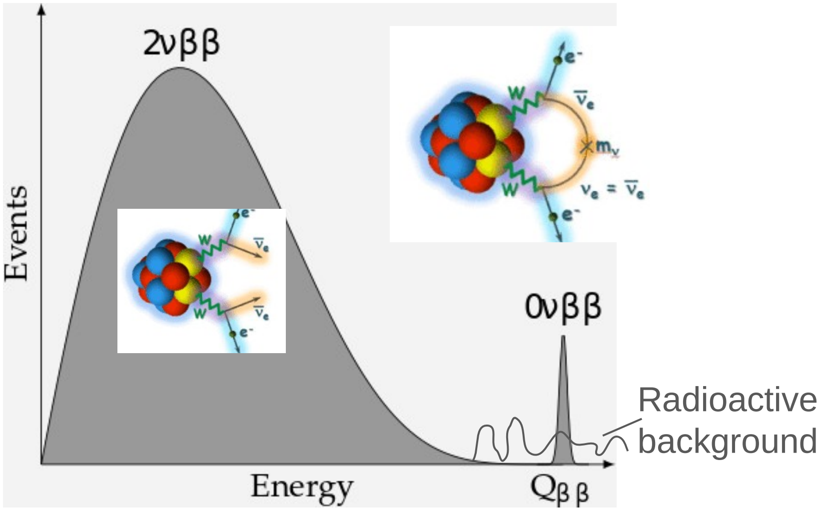
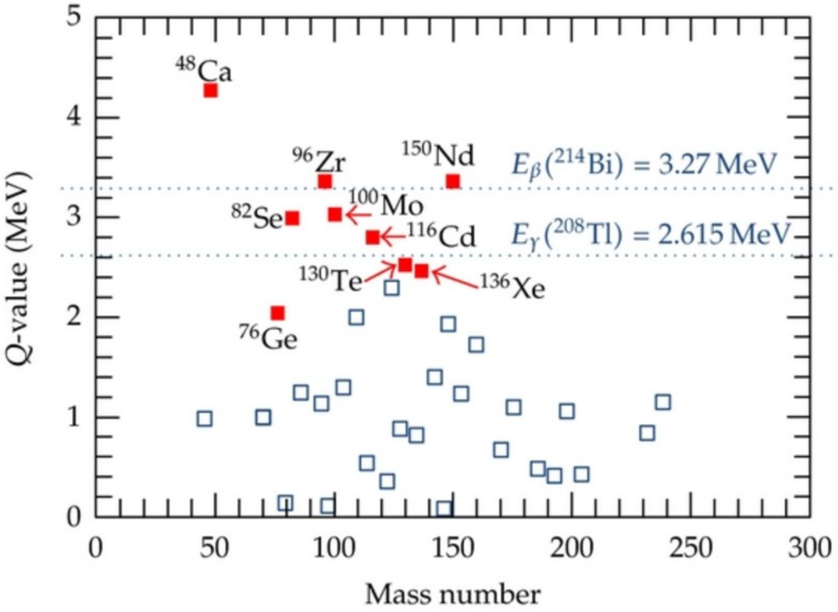


- **Significant R&D effort is required in the next years to demonstrate the technology to reach IO scale**
  This will be essential also to achieve the long-term goal of detecting the cosmic neutrino background (CvB) -> next major step beyond CMB

Neutrinoless double beta decay





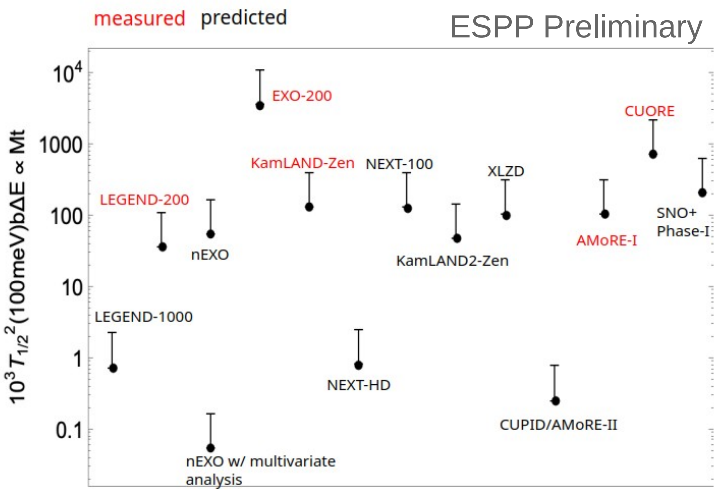
$$\frac{1}{m_{\beta\beta}^2} \sim G_{0\nu} |M_{0\nu}|^2 \sqrt{\frac{Mt}{b \Delta E}}$$

(Nuclear matrix element) x (phase space): S ~ $Q_{\beta\beta}^6$

Background ~10^{-4} - 10^{-5} cts/keV/kg/y
Energy resolution ~ 50-5 keV
Mass x time ~ (100 kg → ton) x 10 years

Technologies

- **Te** (CUORE* bolometers → SNO+ in LS): **large natural abundance** (30%), low $Q_{\beta\beta}$
- **Xe**: low $Q_{\beta\beta}$
  - Kamland-Zen LS: **easy scalability** but limited resolution (240 → 120 keV)
  - **liquid TPC**: EXO → nEXO, XLZD: improved resolution (~50 keV) and **multivariate analysis**
  - **gas TPC** (NEXT*): **good resolution** (12 keV), **backgr. rejection with topological cuts**
- **Ge** (GERDA, Legend*): very low $Q_{\beta\beta}$ but **amazing resolution** (2 keV), difficult scalability
- **Mo bolometers** (CUPID*, Amore): **high** $Q_{\beta\beta}$, **good resolution** (8 keV), difficult scalability



Technological comparison:
half-life for fixed $m_{\beta\beta}$ x background x ΔE

→ exposure needed for a fixed sensitivity

* Underground laboratories in Europe

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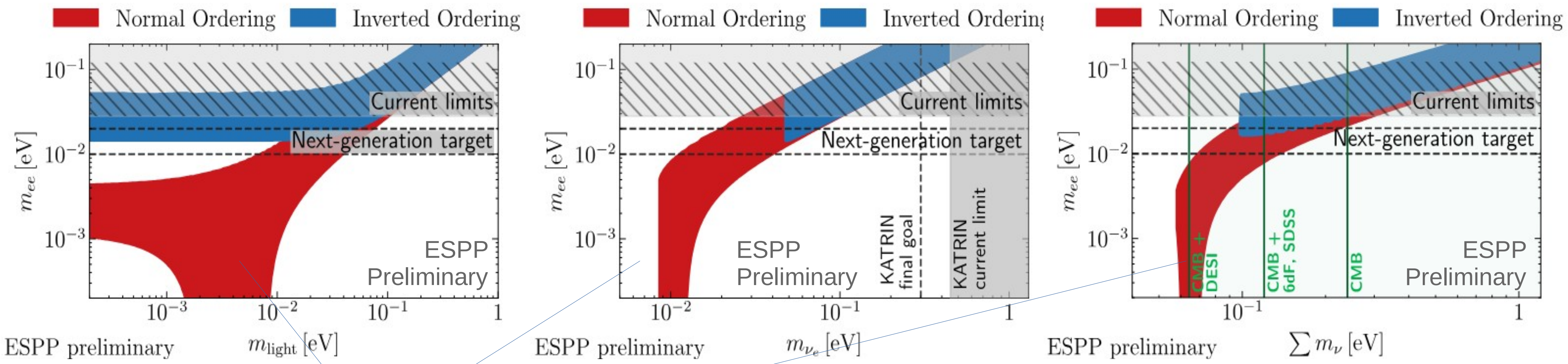
Not one winning option: we need to keep the technological development on various fronts.
Complex control of background → **confirmation from at least two different technologies**.
Discovery on different isotopes will bring complementary info (NME vs BSM)

→ **next-to-next generation:**
- Ba++ tagging in Xe detectors (scale with mass instead of √mass)
- bolometers with very high $Q_{\beta\beta}$ isotopes: Zr,Nd

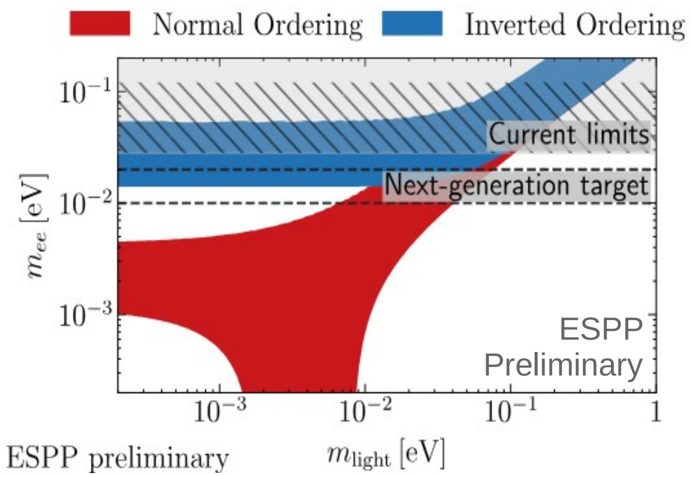
Status and prospects

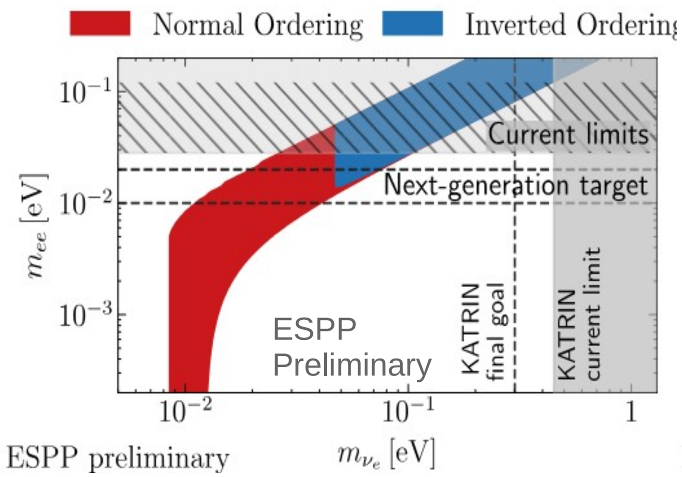


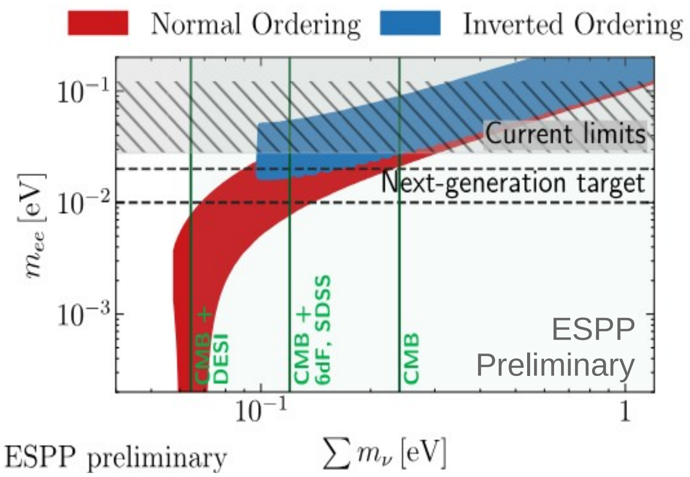
$m_{\beta\beta}$ < meV needs cancellations/fine tuning

$$m_{\beta\beta}=|m_1 c_{13}^2 c_{12}^2 e^{2i(\alpha_1-\delta_{CP})}+m_2 c_{13}^2 s_{12}^2 e^{2i(\alpha_2-\delta_{CP})}+m_3 s_{13}^2|$$

Status and prospects



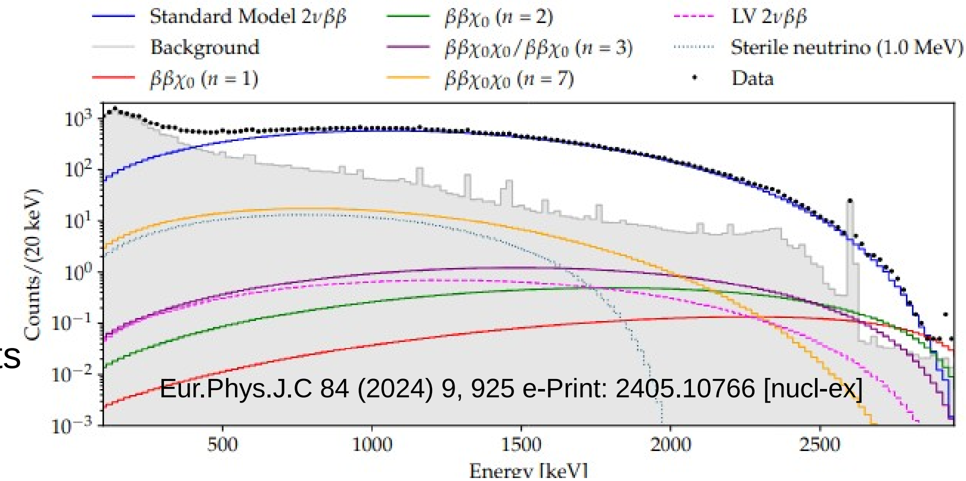




- **Already putting limits on BSM** *(see Pilar's talk)*

- These detectors are exquisite measurement devices: **new nuclear measurements and BSM searches in the 2νββ spectrum**

- **modeling of matrix elements** to interpret a signal (and evaluate future sensitivities):
    - input from single and double charge exchange measurements
    - convergence when short- & long-range correlations included
    - correlations (in some models) between 2νββ and 0νββ



Eur.Phys.J.C 84 (2024) 9, 925 e-Print: 2405.10766 [nucl-ex]

Summary

- **Oscillations** experiments**:** MO, CPV, PMNS precision + BSM reach.
Improved control of systematics and combination of experiments are game changers

- Particularly crucial **expertise in Europe (and at CERN) on flux and xsec for LBL**: new opportunities and new projects (**NA61/SHINE low-E beamline, nuSCOPE, nuSTORM**)

- Success of **Neutrino Platform** for DUNE and T2K → future: DUNE FD3/4 modules, HK ND280++
→ **complete 'hub' for neutrino analysis pivotal for combination of experiments**

- Neutrino rich physics case beyond oscillations **from very low-E: CEvNS, SuperNovae, … to very high-E: forward neutrinos at HL-LHC, astrophysics sources**

  - Need to settle SM effects and nuclear physics → new door to BSM

- Neutrino masses in lab: major technological challenge to go beyond present generation.
Important impact on cosmology

- 0νββ: the most compelling BSM physics case. A big technological challenge: R&D should continue

References (beyond ESPP input)

~100 relevant inputs submitted

DUNE Phase II white paper: https://arxiv.org/pdf/2408.12725

DUNE Contribution toSnowmass 2021e-Print:2203.06100 [hep-ex]

HyperKamiokande LBL sensitivity: https://arxiv.org/abs/2505.15019

HyperKamiokande TDR: e-Print: 1805.04163 [physics.ins-det]

JUNO Chin.Phys.C 46 (2022) 12, 123001 e-Print: 2204.13249 [hep-ex]

JUNO – T2K/NOVA pheno combination: Phys.Rev.D 111 (2025) 1, 1 e-Print: 2404.08733 [hep-ph]

JUNO - Chin.Phys.C 49 (2025) 3, 033104 e-Print: 2405.18008 [hep-ex]

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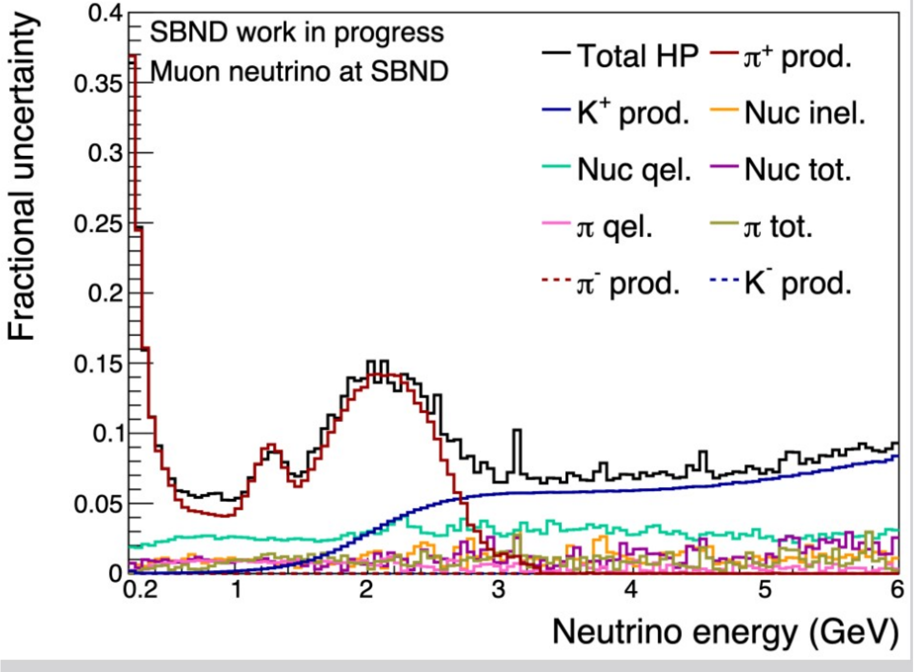
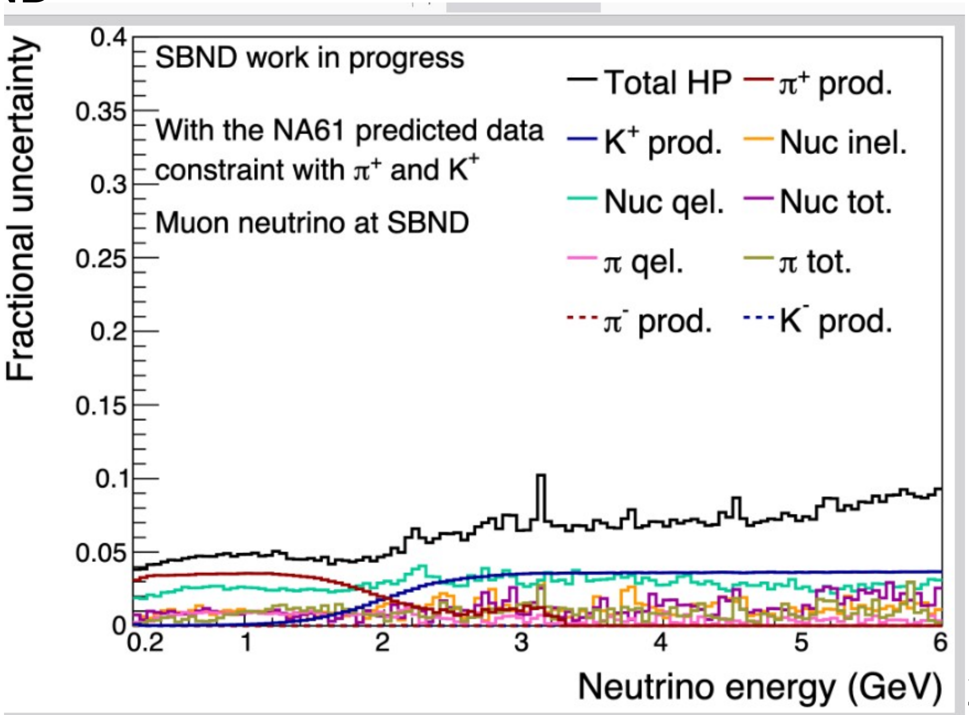
nEXO:
https://arxiv.org/pdf/2106.16243
D. Leonard, 1° Yemilab Workshop 2024
KamLAND2-Zen:
Itaru Shimizu,
International Conference on the Physics of the two Ininities, 2023
AMoRE: document submitted to ESPPU
SNO+: document submitted to ESPPU
CUPID: slides submitted to ESPPU
LEGEND: slides submitted to ESPPU
XLZD: M. Schumann, 3rd Summit on DBD 2025

NA61/SHINE additional impact

Knowing the flux precisely is also crucial in order to enable precise neutrino xsec measurements at SBN@FNAL.

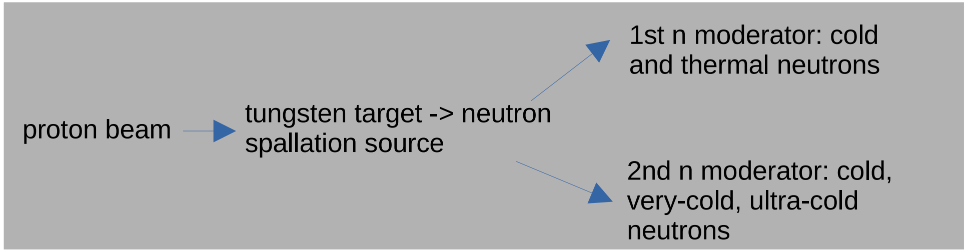
Impact of new proposed low-E beamline on SBND





ESS (+ ESSνSB)

Fundamental (nuclear and) particle physics center for neutron physics (**complementary to colliders**)



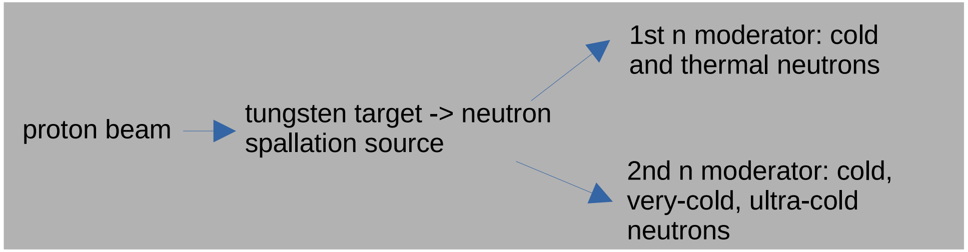
Rich particle physics program with neutron:

- CEνNS
- n,nbar oscillations
- n EDM, charge
- high precision n decay
- n interferometry
- n spin and spin procession

Construction on-going

ESS (+ ESSνSB)

Fundamental (nuclear and) particle physics center for neutron physics (**complementary to colliders**)



Rich particle physics program with neutron:

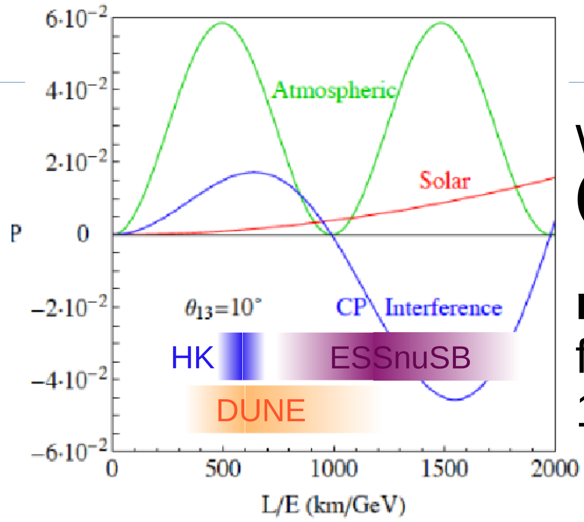
- CEνNS
- n-nbar oscillations
- n EDM, charge
- high precision n decay
- n interferometry
- n spin and spin procession

Construction on-going

Further opportunities being explored:

New target and beamline for oscillations

Alternatives:
- different monitored/tagged beamline
- use pions to feed a low energy muon storage ring



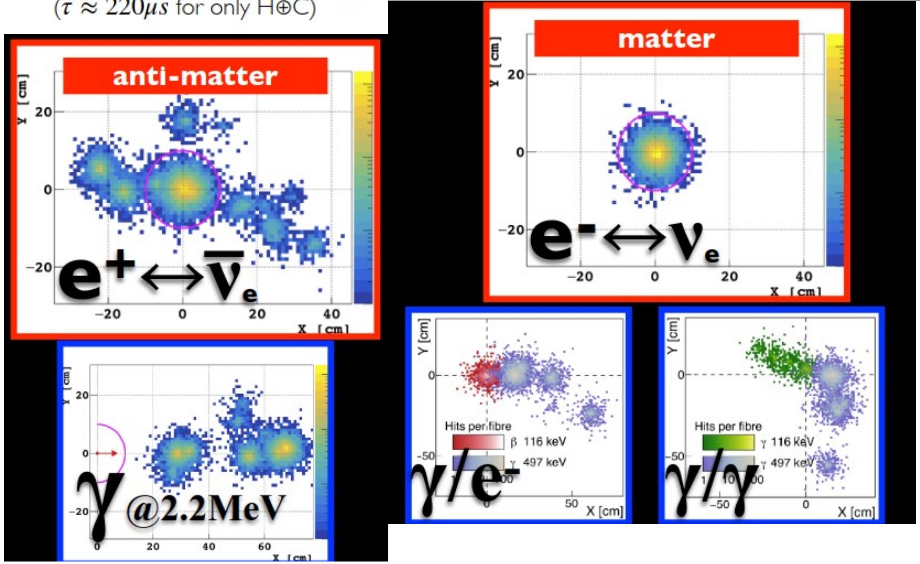
With new ND and FD **(HK mass x2)** → **improved δ_{CP} resolution:** for large CPV 18 → 7 degrees

SuperChooz

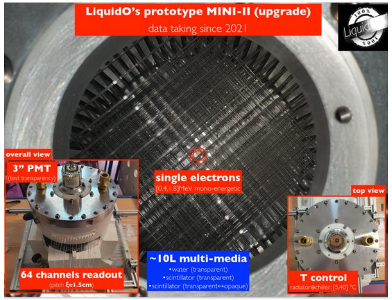
New large detector (10 kTon) for **reactor $\bar{\nu}_e$** (Chooz site, θ_{13}) but also **ν_e and NC → solar and geo-neutrinos and new measurements at reactor**

CC: $\bar{\nu}_e + p \rightarrow e^+ + n$ ($\tau \approx 220\mu s$ for only H⊕C)

CC: $\nu_e + {}^{115}In \rightarrow e^- + \gamma + \gamma/e^-$ ($\tau \approx 4.7\mu s$ decay of **Sn***)



Technology based on LiquidO: R&D on-going



Exploratory study funded by AntiMatterOTech and CLOUD

Step into the future

Systematics control crucial for PMNS precision physics but also for **BSM searches**

- Measure oscillations in model-independent way → characterizes L/E

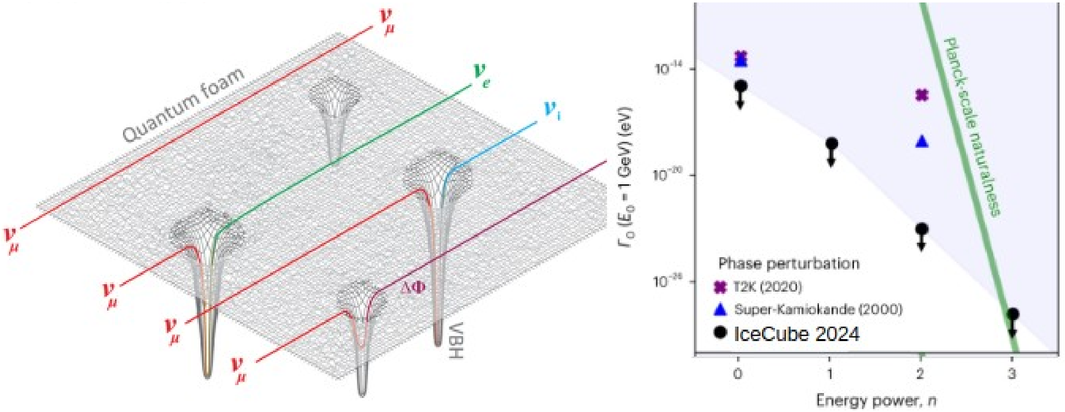
Eg: drop all SM assumptions (allows for steriles, NSI…)
CP <-> T violation = L-even dependency at fixed E
Phys.Rev.Lett. 128 (2022) 9, 091801 e-Print: 2106.16099 [hep-ph]

- Explore neutrino reach with open mind: new observables

Eg: Quantum Correlations, Bell's like inequality in the time domain (LGI), coherence on thousands of km
Phys.Rev.Lett. 117 (2016) 5, 050402 e-Print: 1602.00041 [quant-ph]

- Search for Quantum Gravity effects along the baseline

- CPT: AD/Elena CPT baryonic -> nm vs nmbar disappearance: CPT leptonic



Nature Phys. 20 (2024) 6, 913-920 e-Print: 2308.00105 [hep-ex]

We should look at the topic from a **wider prospective** (beyond the present "simplistic" paradigm of the measurement of PMNS parameters)

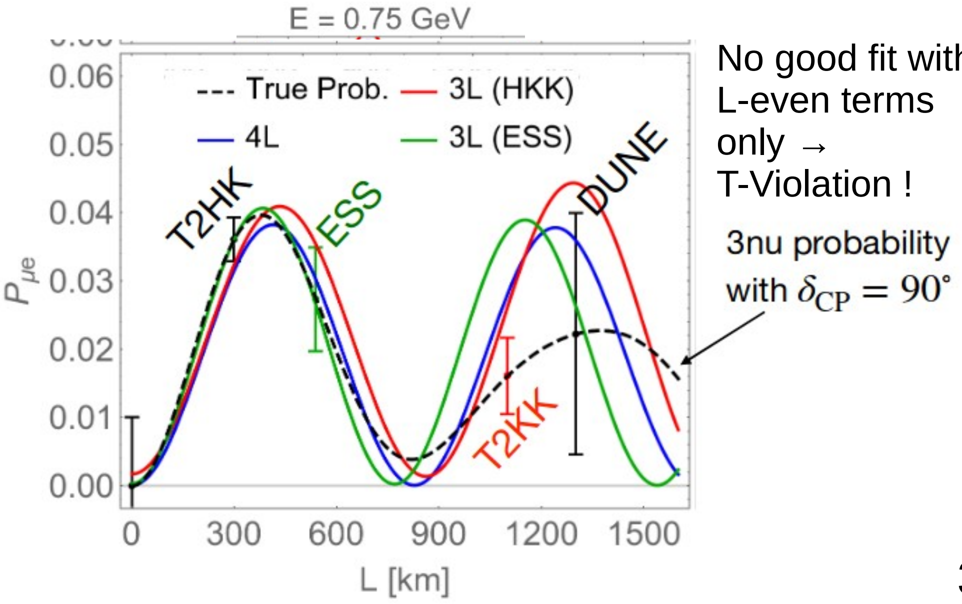
- **The 'standard' oscillation paradigm (PMNS-based) is very strict and 'accidental'**

In particular it assumes
- minimal 3-flavour scenario
- standard neutrino interactions for production and detection
- standard matter effects along propagation

What we want to do is to characterize **precisely** the oscillation as a function of the fundamental variable **L/E: combine different L and different E**

Example:
CP violation in a more model-independent way → search for T-violation → look for L dependency of oscillations at fixed energy

Phys.Rev.Lett. 128 (2022) 9, 091801

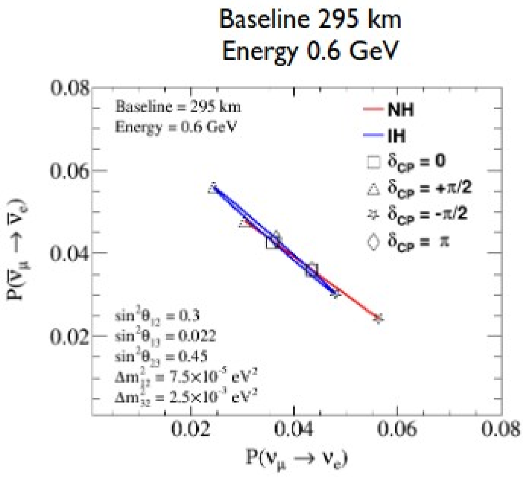


No good fit with L-even terms only → T-Violation !

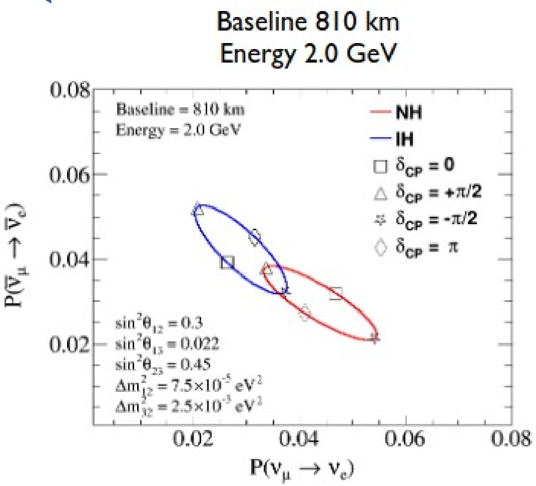
Events at LBL

Experiment	T2K	NOvA	Hyper-K	DUNE
Baseline (km)	295	800	295	1300
$N^{FD}_{\nu_\mu}$ (ν-mode)	318	211	≈10100	≈13500
$N^{FD}_{\bar{\nu}_\mu}$ ($\bar{\nu}$-mode)	137	125	≈14000	≈5000
$N^{FD}_{\bar{\nu}_e}$ (ν-mode)	94	82	≈2100	≈2000
$N^{FD}_{\bar{\nu}_e}$ ($\bar{\nu}$-mode)	16	33	≈1900	≈600

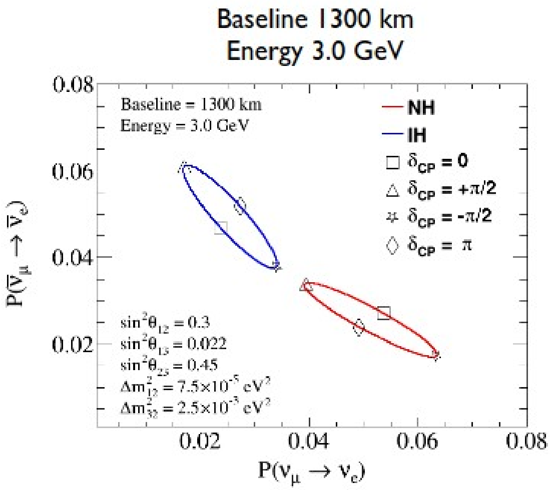
Ultimate statistics
(HK 10 years – 2038
DUNE 15 years - 2046)



~T2K, HK

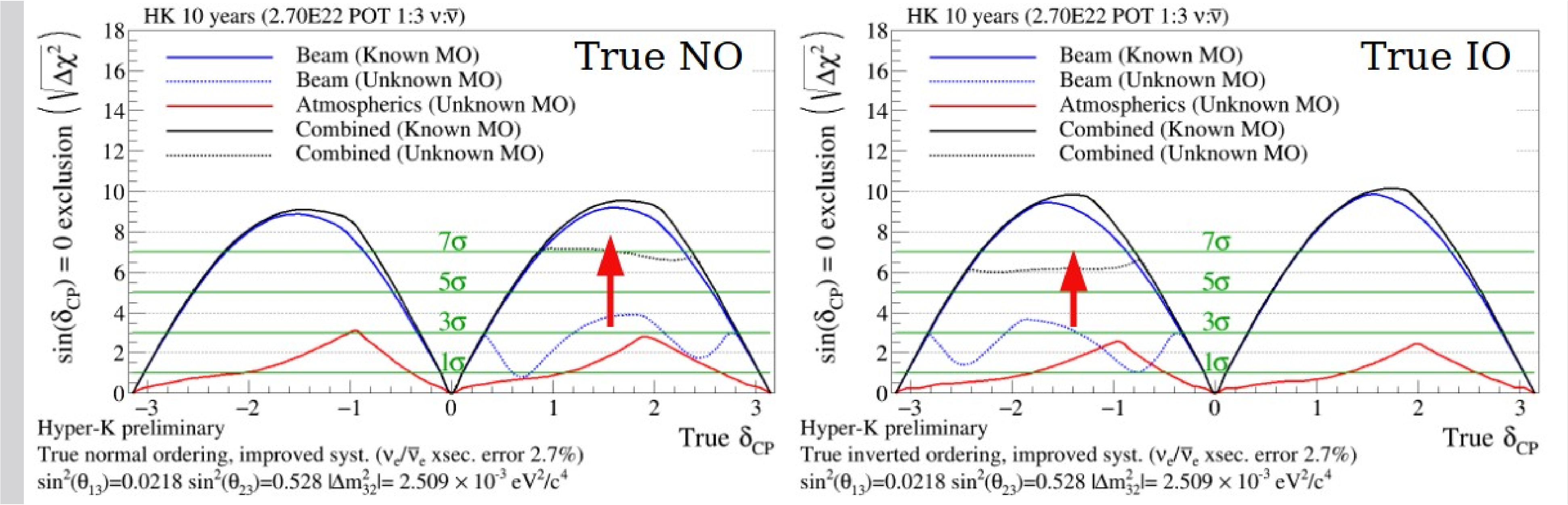


~NOVA



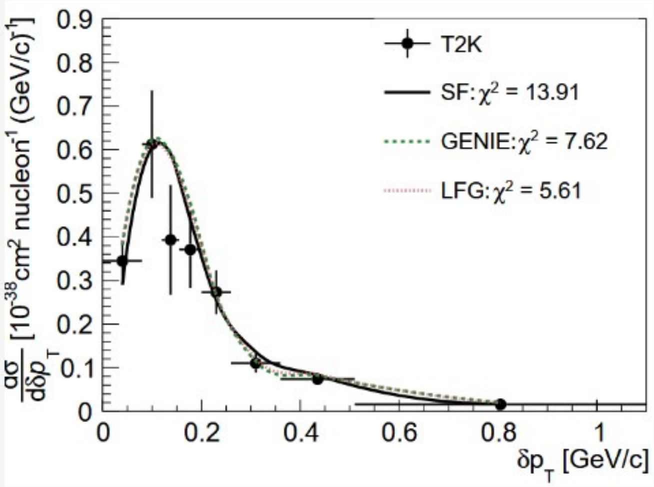
~DUNE

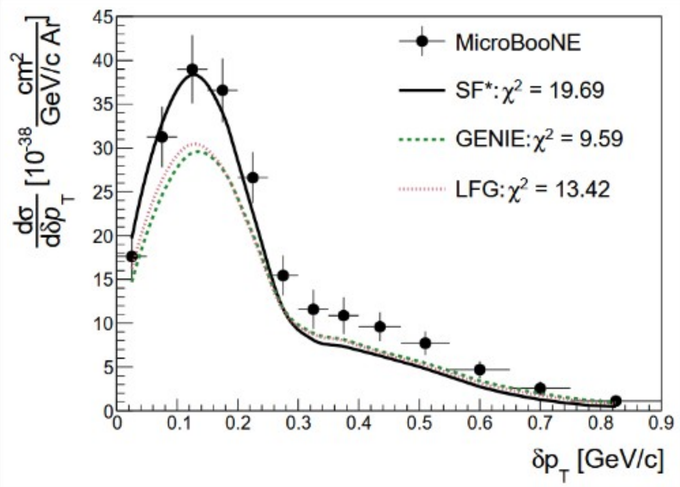
δ_{CP} vs MO degeneracies

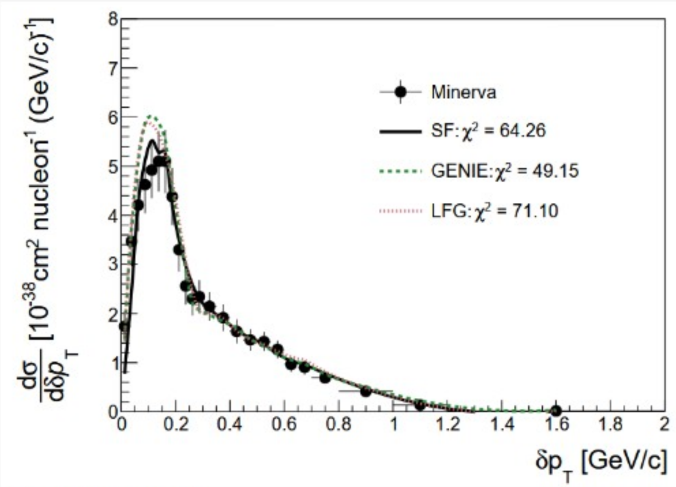


Neutrino cross sections in Long-baseline Experiments
Neutrino scattering ~1 GeV

- At GeV-scale neutrino event generators must model both interaction of neutrino with a nucleon and the impact of the surrounding nucleus on this process
  - Final state interactions, collective nuclear excitations, hadron-quark transition, low-W hadronization…
- Models do reasonably well for quasi-elastic interactions





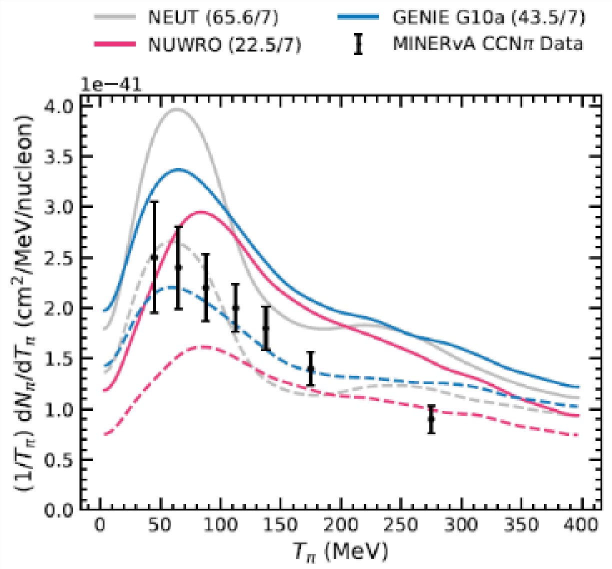


W. Filali et al, https://arxiv.org/pdf/2407.10962

Neutrino cross sections in Long-baseline Experiments

Neutrino scattering ~1 GeV

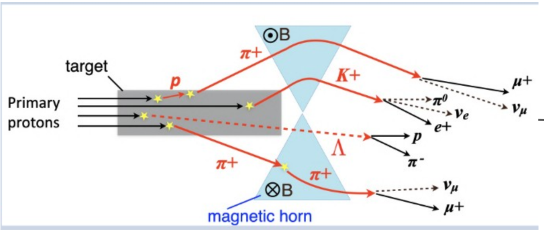
- At GeV-scale neutrino event generators must model both interaction of neutrino with a nucleon and the impact of the surrounding nucleus on this process
  - Final state interactions, collective nuclear excitations, hadron-quark transition, low-W hadronization…
- Models struggle to describe other data samples well (one example below)



- T2K experiment developing interaction model and uncertainties for neutrinos with energies from 0.3 - 2 GeV for Carbon and Oxygen targets
  - Hyper-K benefits from this
- DUNE uses argon target, beam neutrino energy mainly above 1 GeV
  - No existing data on argon in this energy range
  - Some data from SBN program at lower energy

Systematics in long-baseline experiments

Present precision of oscillation experiments: nu rate~2-4% and E_{scale} ~4% → **this precision must improve by a factor 4-5 in HK/DUNE**



Protons → hadrons (focusing) → leptons and neutrinos.

highly capable
Near Detectors

oscillations along baseline

huge underground
Far Detector(s)

$$N(E_\nu^{reco}) = \int \phi(E_\nu) \times \sigma(E_\nu) R(E_\nu, E_\nu^{reco}) dE_\nu$$

$$N(E_\nu^{reco}) = \int P_{\nu_\mu \to \nu_e}(E_\nu) \phi(E_\nu) \times \sigma(E_\nu) R(E_\nu, E_\nu^{reco}) dE_\nu$$

- ND always sensitive to xsec x flux: $\sigma_{true} \cdot \phi_{true} \sim \sigma_{wrong} \cdot \phi_{wrong}$
- ND and FD are different (acceptance, En)
- Flux is not monochromatic → En must be reconstructed from final state particles (neutrons, thresholds, …)

We need:

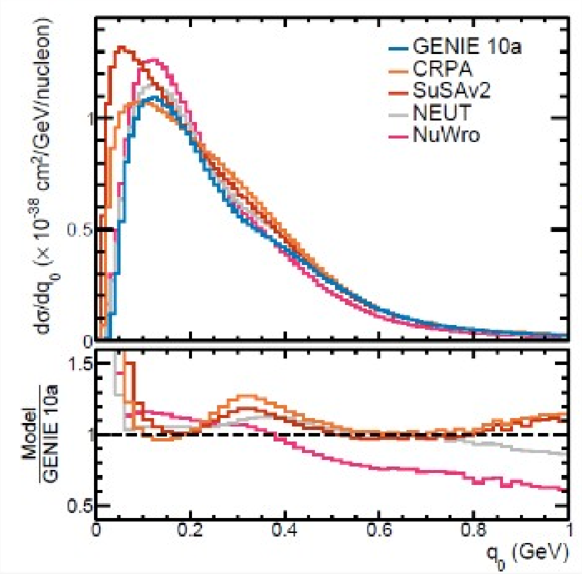
→ **predictive and tuned flux and xsec models**

→ **highly capable near detectors**

Neutrino cross sections in Long-baseline Experiments

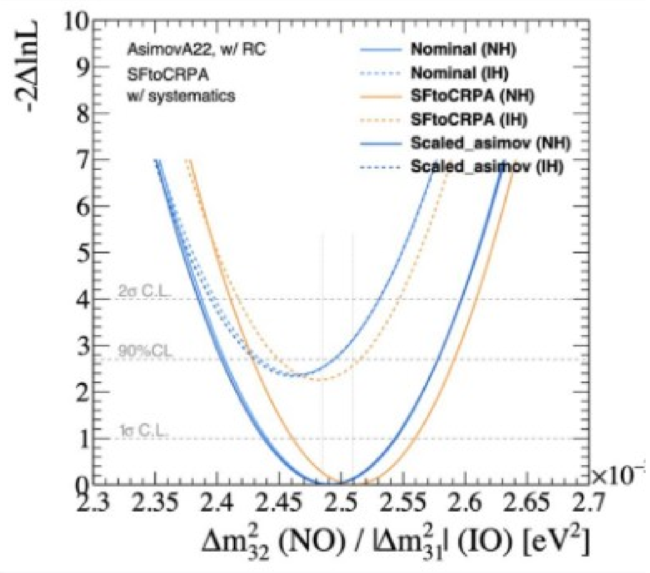
Impact on oscillation physics – T2K

- Neutrino event generator cross section predictions differ by 50% at low energy transfer (right)
- T2K study:
  - Fit simulated data from CRPA model at near and far detector,
  - Extract oscillation parameters
  - Compare to expected value from nominal sensitivity fit



L. Munteanu, NuFACT 2024

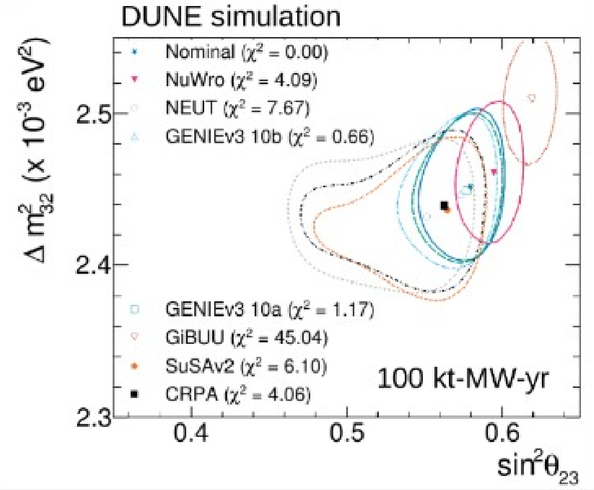
- Observed shift in best-fit value of Δm^2_{32}
  - Shift as large as total systematic error on Δm^2_{32}
  - Added as additional error

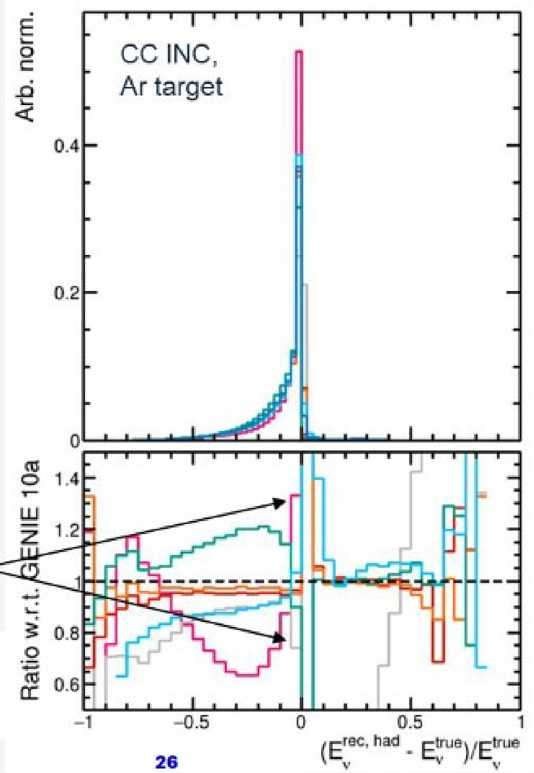


Neutrino cross sections in Long-baseline Experiments

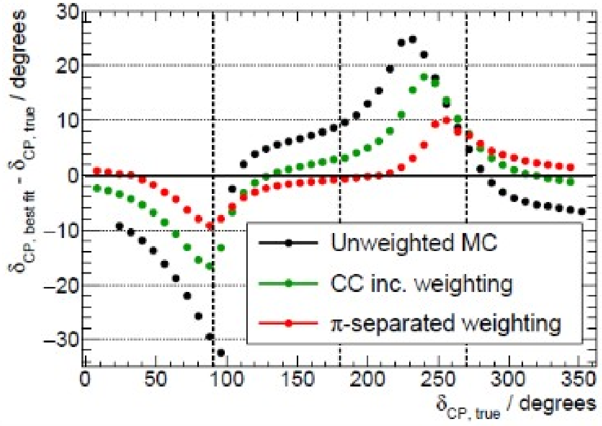
Impact on oscillation physics - DUNE

- DUNE has wide-band beam at higher energy
  - Modelling of neutrino energy v. important
  - Need to measure hadronic part of neutrino interaction as well as leptonic
  - Mis-modelling the amount of energy that is not detected can have significant impact

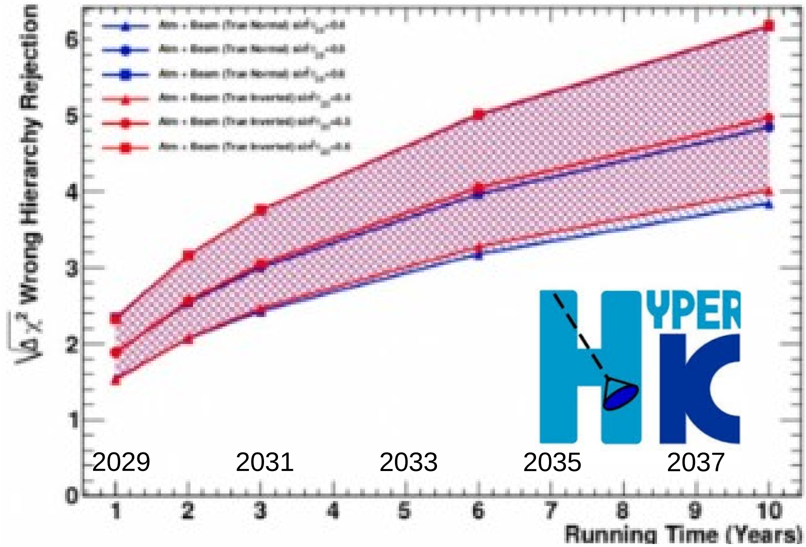


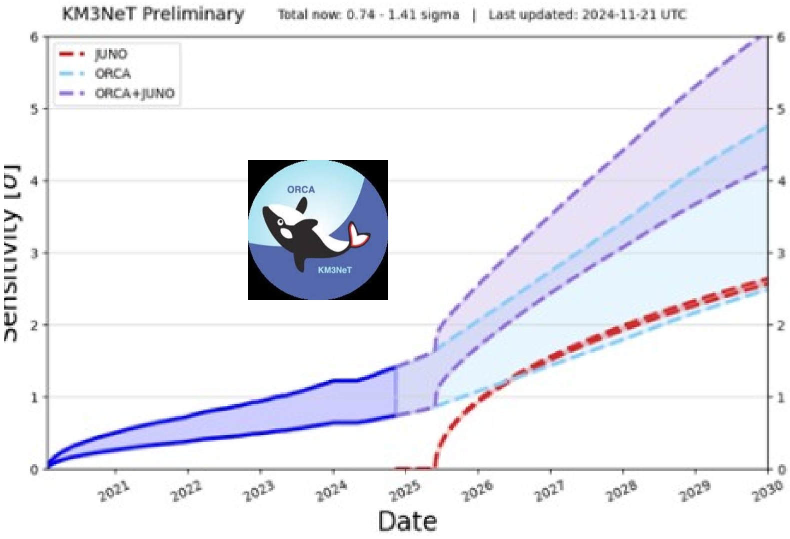


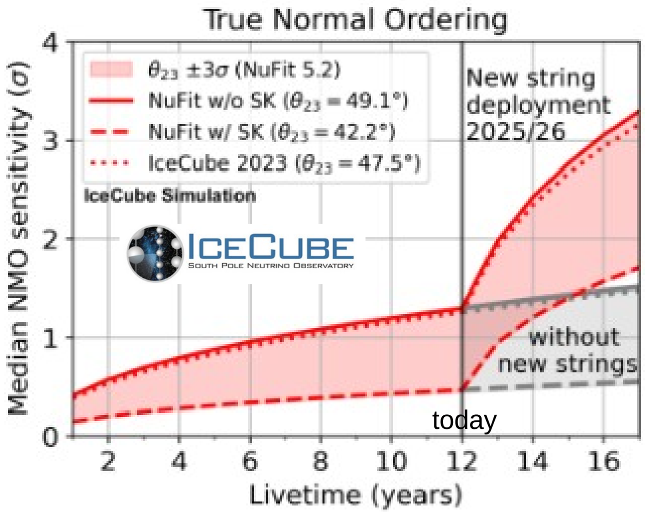
Proportion of E_ν reconstructed within 10% of the true E_ν differs by more than 20%

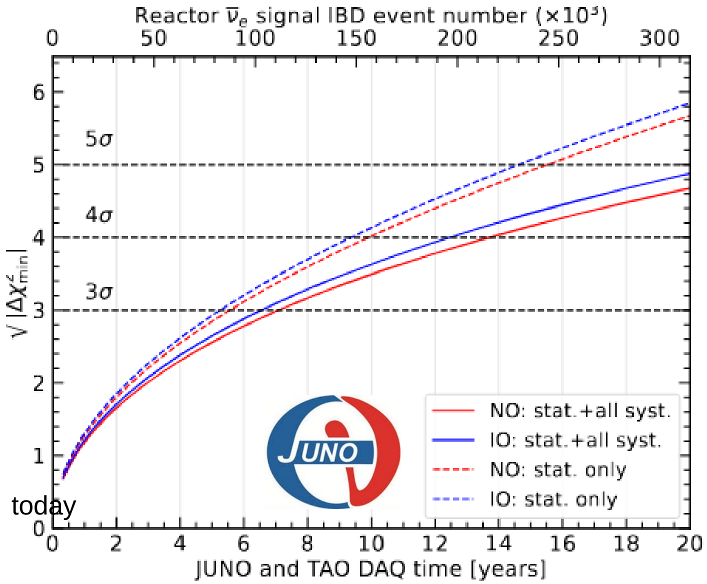


Mass Ordering

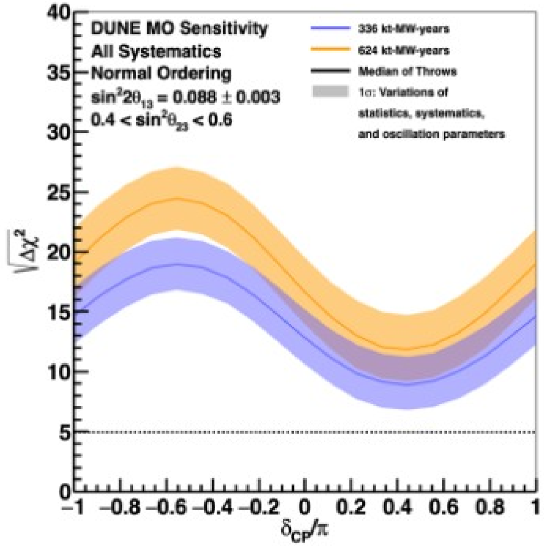


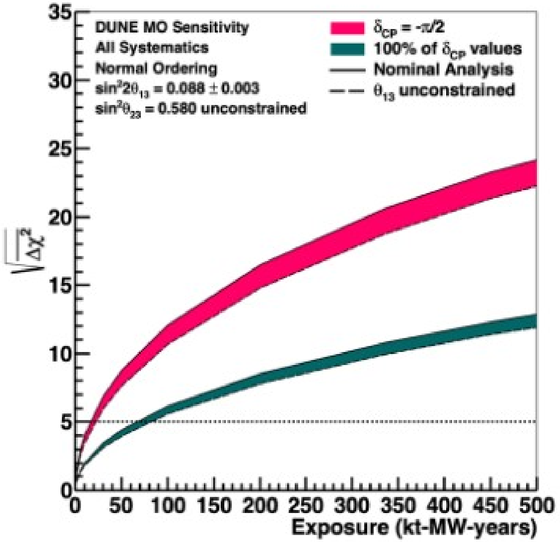


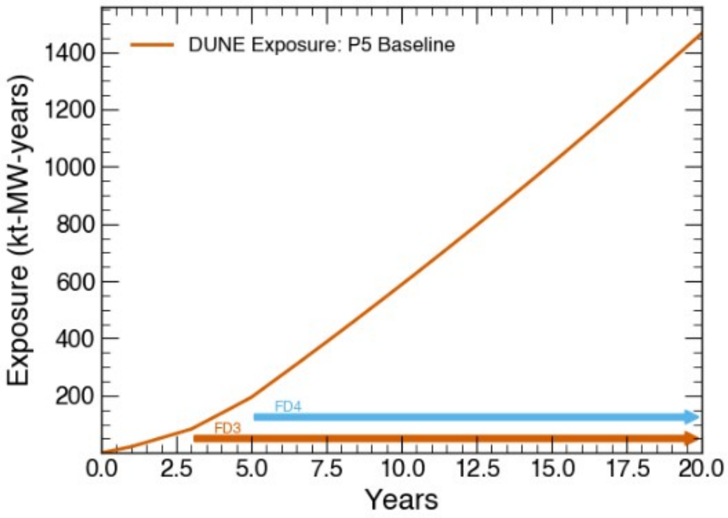




Mass Ordering: DUNE







DUNE
DEEP UNDERGROUND NEUTRINO EXPERIMENT

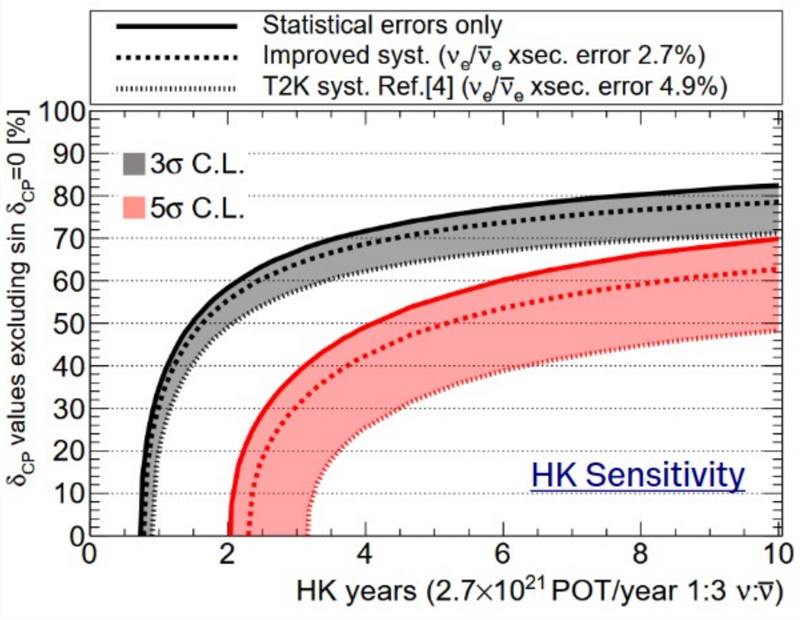
Benchmark	DUNE's Projected Reach	Assumptions
Sensitivity to CP violation	5σ (50% of δ_{CP} values)	600 kt-MW-yr
	3σ (75% of δ_{CP} values)	1000 kt-MW-yr
Precision on δ_{CP} as a function of true δ_{CP}	$11°$ ($\delta_{CP} = 0$) – $27°$ ($\delta_{CP} = -\pi/2$)	300 kt-MW-yr
	$8°$ ($\delta_{CP} = 0$) – $22°$ ($\delta_{CP} = -\pi/2$)	600 kt-MW-yr
	$7°$ ($\delta_{CP} = 0$) – $18°$ ($\delta_{CP} = -\pi/2$)	1000 kt-MW-yr
Sensitivity to mass ordering	5σ (100% of δ_{CP} values)	70 kt-MW-yr
Precision on mixing angles and mass differences in PMNS	$\sin^2 2\theta_{13}$ resolution of 5%	1000 kt-MW-yr
	Δm^2_{32} resolution of 1%	100 kt-MW-yr
	Δm^2_{32} resolution of 0.4%	1000 kt-MW-yr

→ ~2.5 years (2033)

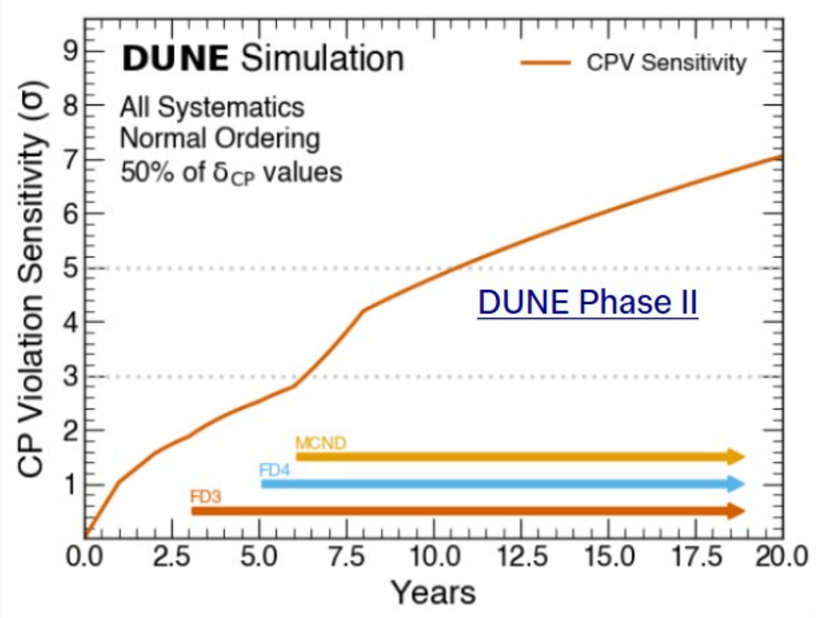
CP Violation sensitivity

Hyper-K and DUNE

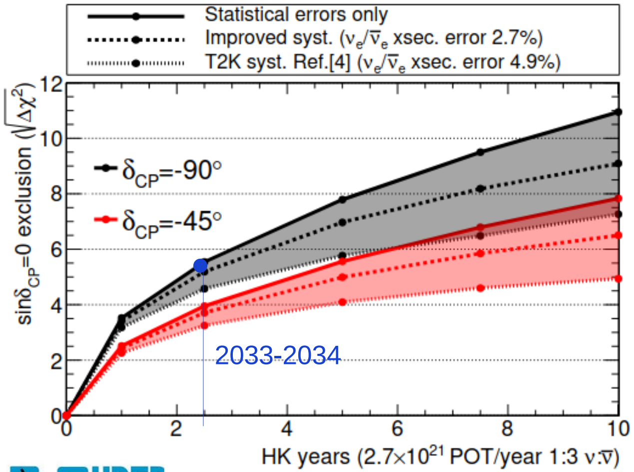
- Hyper-K expects 5σ CPV sensitivity for 50% of values of δ_{CP} after ~5 years beam exposure
- 75% of values at 3σ after ~7 years

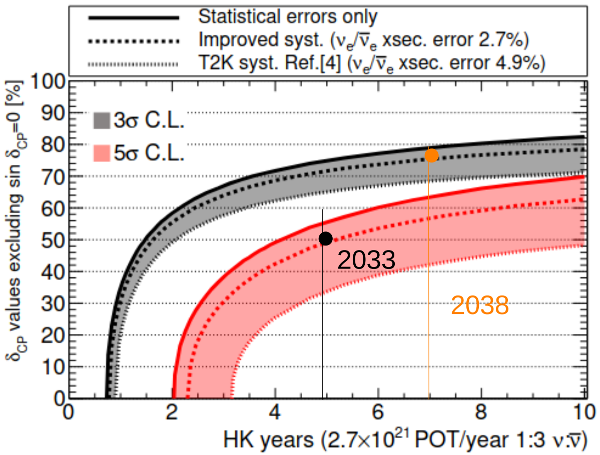


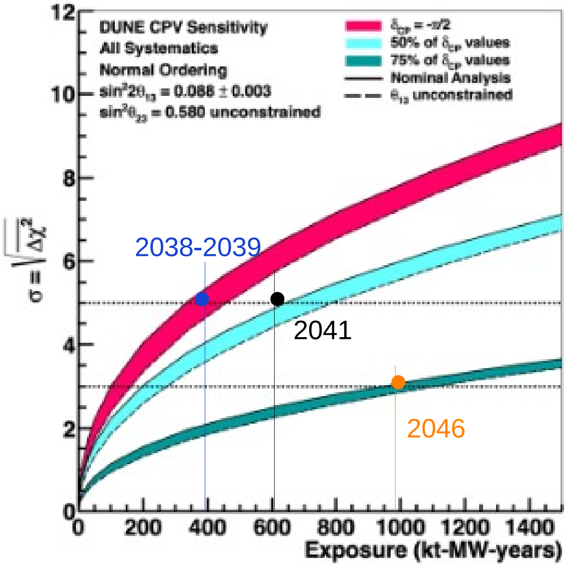
- DUNE expects 5σ CPV sensitivity for 50% of values of δ_{CP} with 600 kt-MW-years exposure (~10 years)
- 75% of values at 3σ with 1000 kt-MW-years (~14 years)

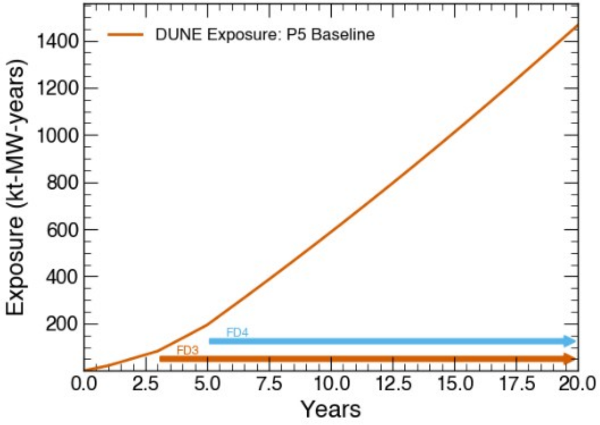


CP violation





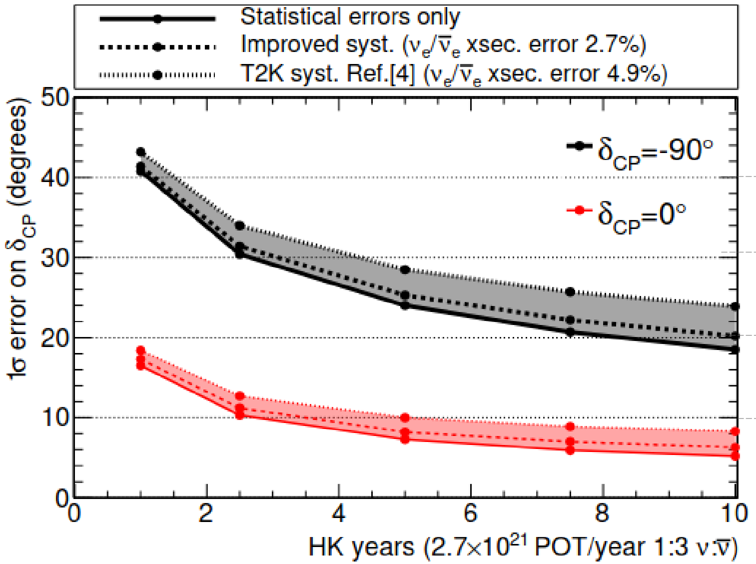


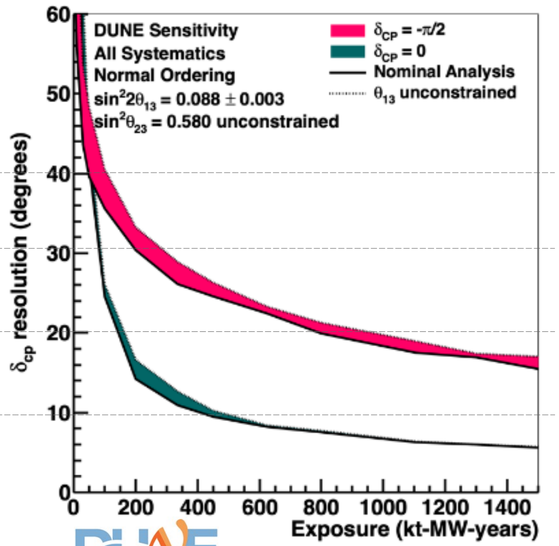


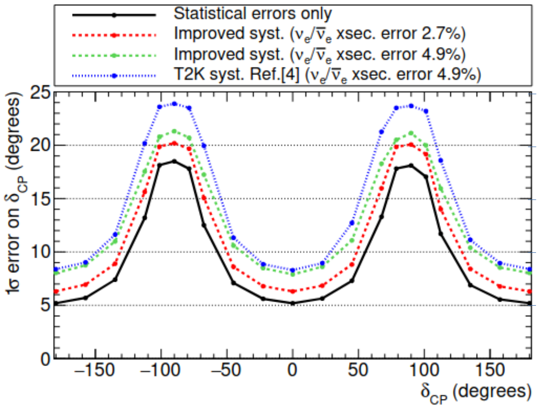
Benchmark	DUNE's Projected Reach	Assumptions
Sensitivity to CP violation	5σ (50% of δ_{CP} values) 3σ (75% of δ_{CP} values)	600 kt-MW-yr 1000 kt-MW-yr
Precision on δ_{CP} as a function of true δ_{CP}	11° ($\delta_{CP} = 0$) – 27° ($\delta_{CP} = -\pi/2$) 8° ($\delta_{CP} = 0$) – 22° ($\delta_{CP} = -\pi/2$) 7° ($\delta_{CP} = 0$) – 18° ($\delta_{CP} = -\pi/2$)	300 kt-MW-yr 600 kt-MW-yr 1000 kt-MW-yr
Sensitivity to mass ordering	5σ (100% of δ_{CP} values)	70 kt-MW-yr
Precision on mixing angles and mass differences in PMNS	$\sin^2 2\theta_{13}$ resolution of 5% Δm^2_{32} resolution of 1% Δm^2_{32} resolution of 0.4%	1000 kt-MW-yr 100 kt-MW-yr 1000 kt-MW-yr

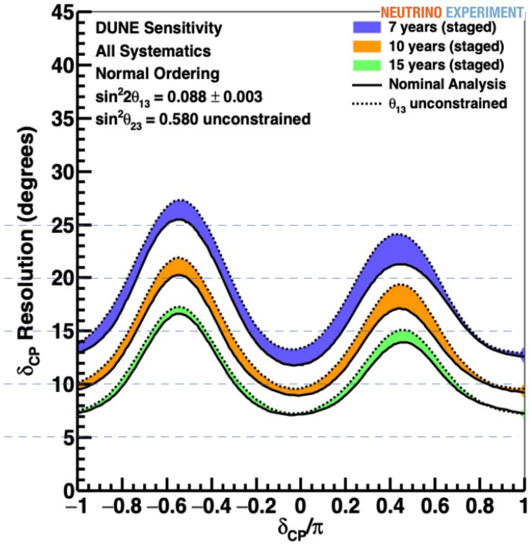
~10 years (2041)
~15 years (2046)
~10 years (2041)
~15 years (2046)

δ_{CP} resolution









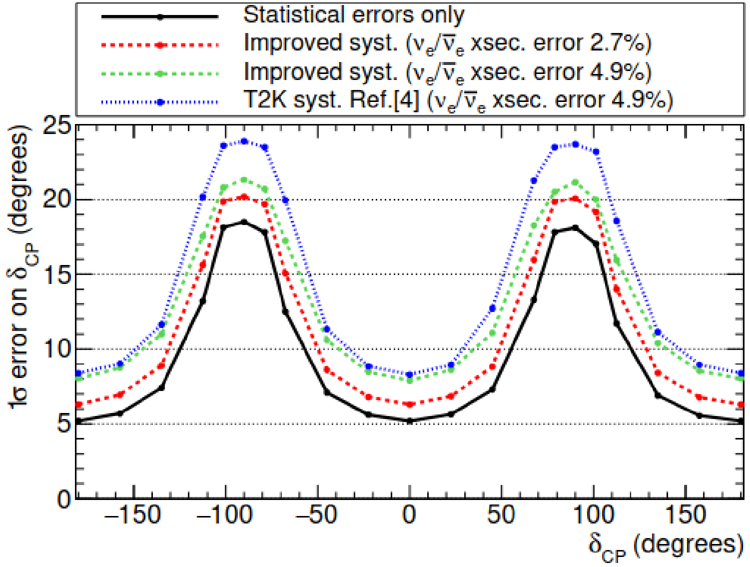
Ultimate results
(HK 10 years – 2038
DUNE 15 years - 2046)

HK best resolution for small CPV (large stat)

DUNE bring shape info useful for δ_{CP} resolution in case of large CPV

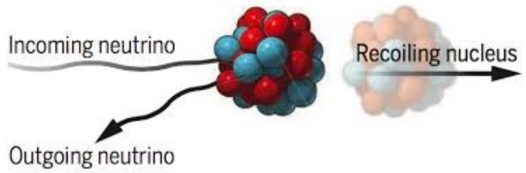
δ_{CP} resolution

	HK 3 years (2031)	HK 10 years (2038)	DUNE 300kt-MW-yr (2037)	DUNE 1000kt-MW-yr (2046)	ESSnuSB
δ_{CP}=0	10 degrees	6 degrees	11 degrees	7 degrees	5 degrees
δ_{CP}=-π/2	30 degrees	20 degrees	27 degrees	18 degrees	6 degrees



Dominant factors:
- small CPV → statistics (nue/nuebar dominat syst)
- large CPV → spectral shape (many systematics: E scale, NC background, ...)

CEνNS



- **SM, already done**
  - Weak mixing angle
  - Neutrino charge radius
  - Nuclear form factors
- **SM, doable in the future**
  - Supernova detection via Neutral Currents
    $\mathcal{O}(10)$ events/tonne for a 10 $M_\odot$ supernova at 10 kpc [arXiv:1606.09243]
  - Inelastic cross sections for $E_\nu \sim 10\,\mathrm{MeV}$, for supernova detection elsewhere
    ν_e–O [Super/Hyper-K] and ν_e–Ar [DUNE], never measured. D_2O detector taking data, 750 kg Ar detector proposed.
  - Potentially, reactor monitoring (CEνNS detectors are small)

- **BSM**
  - NSI
  - Light mediators
  - Neutrino millicharge
  - Neutrino magnetic moment
  - Dark matter produced in the beam
  - Sterile neutrinos

Rate measurements → **major technological challenge: control of E_{recoil} and extract reliable differential information vs Q^2**

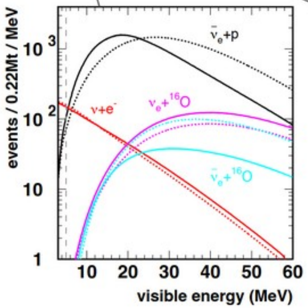
+ measurement at different energies and lowest possible threshold (reactors)

Flavour ratio at π-DAR unique feature for sterile searches and very useful for NSI

SuperNovae burst

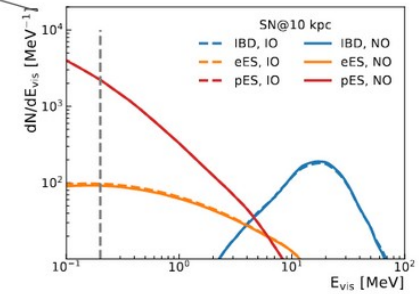
Look at 10kpc rate for easy comparison, then distance to see 100 events, required for model measurements

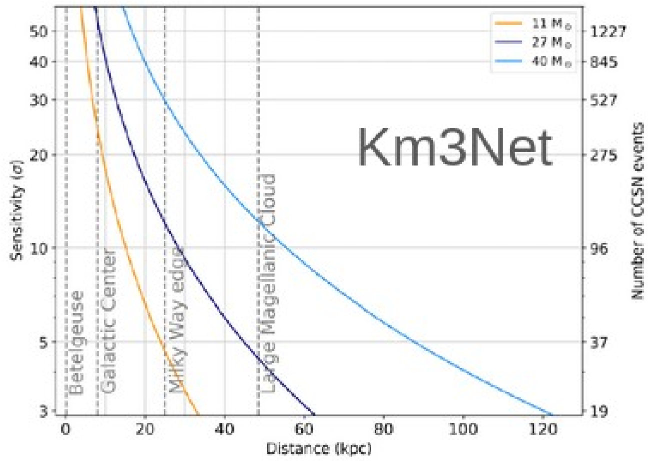
Experiment	10-kpc event rate	10-kpc pointing	Range for 100 events
Hyper-K	54,000 - 90,000	1.3 degrees	~300 kpc
JUNO	7300	25 degrees	~40 kpc
DUNE (40kt)	3656	4.3 degrees	~40 kpc

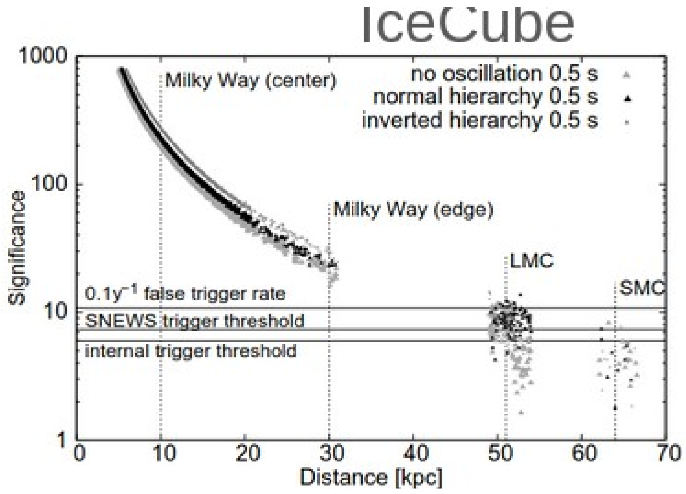


Channel	Liver-more
$\nu_e + {}^{40}Ar \rightarrow e^- + {}^{40}K^*$	2648
$\bar{\nu}_e + {}^{40}Ar \rightarrow e^+ + {}^{40}Cl^*$	224
$\nu_X + e^- \rightarrow \nu_X + e^-$	341
Total	3213

DUNE misses IBD since no free protons (H)
-> clean nue sample



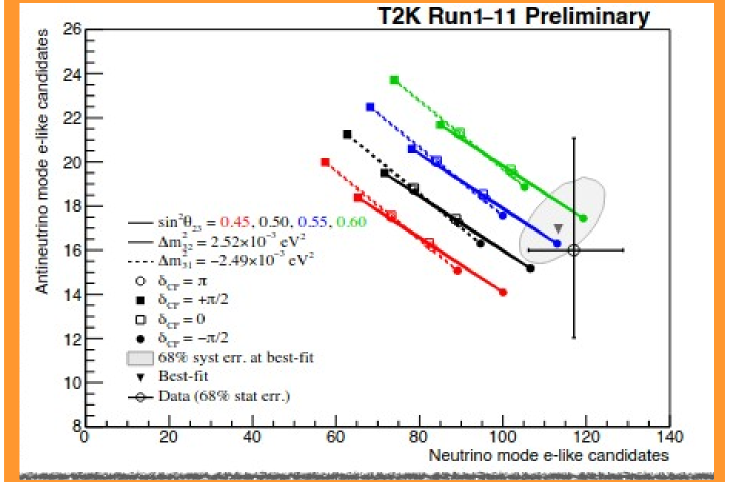


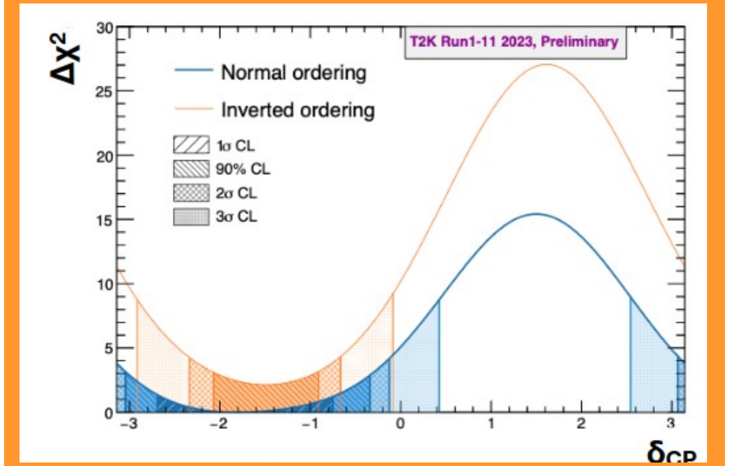


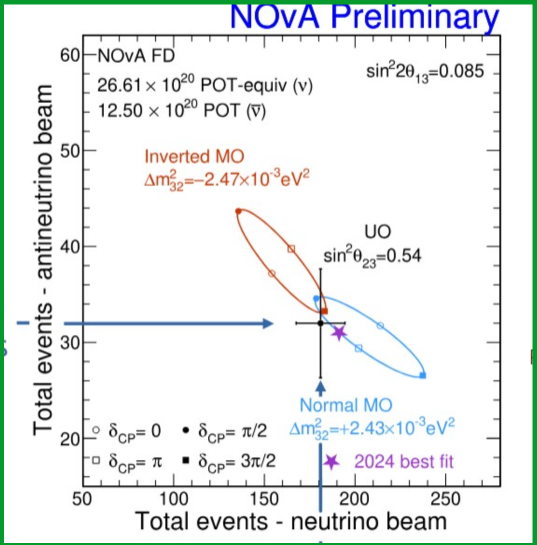
Theia proposal

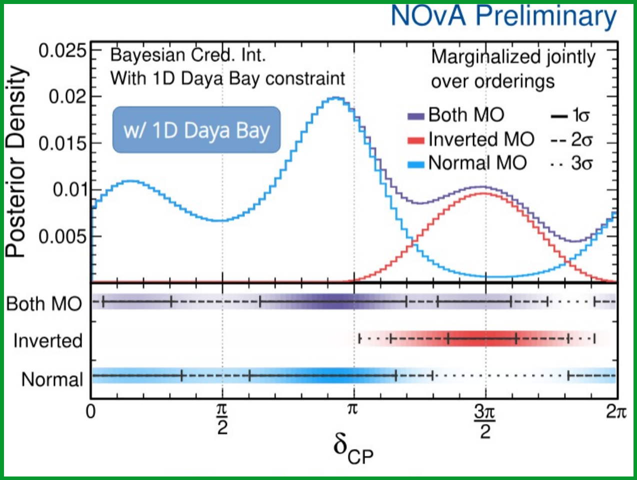
Reach	Exposure / assumptions
< 1(2)° pointing accuracy 20,000 (5,000) events	100(25)-kt detector, 10 kpc

T2K and NOVA



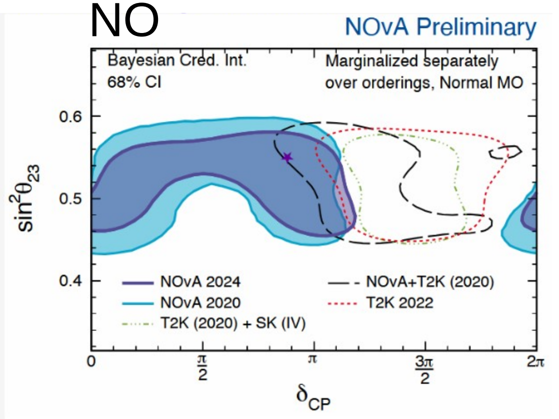




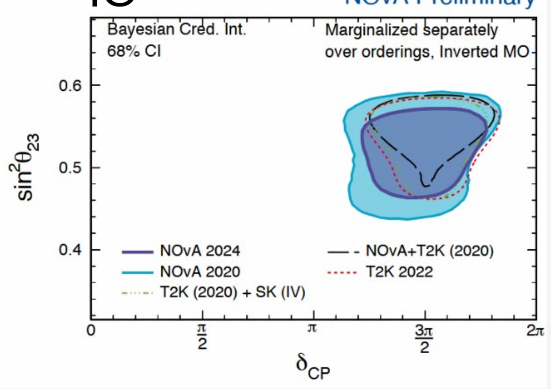


Direct comparison

NO



IO



T2K beam + SK atmospherics

- The CP-conserving value of the Jarlskog invariant is excluded with a significance between 1.9 and 2 σ
- In the frequentist analysis, p-value for CPC is 0.037 but increase to 0.05 when potential biases due to cross-section mis-modeling are included
- Normal ordering is preferred, p-value for IO 0.08