Review on Experimental Neutrino Physics

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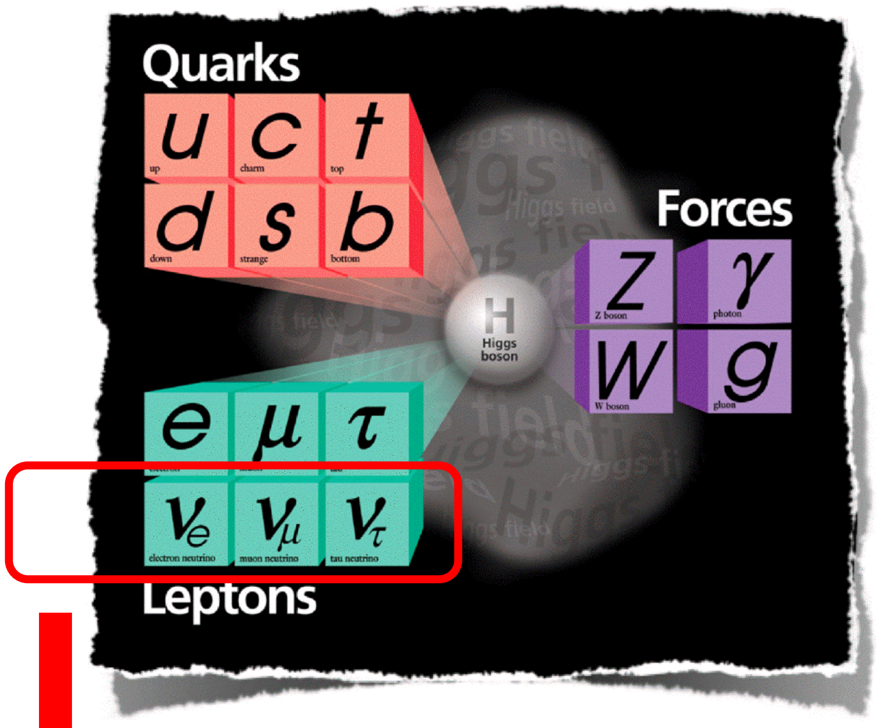
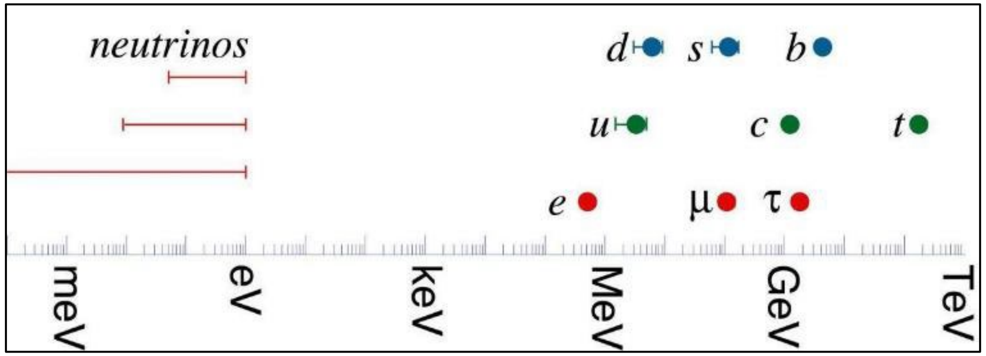
The 23rd International Conference on Few-Body Problems in Physics (FB23)

Neutrinos in a Nutshell

- **Neutrinos**: One of the **fundamental building blocks** of the material world
  - Extremely weakly interact with matter → difficult to detect
  - M_ν=0 in Standard Model of particle physics
  - Large scale structure in Cosmology prefers M_ν!=0
- **Neutrino Oscillations:** neutrinos have **non-zero masses** ➔ huge impact on particle physics & cosmology
- Neutrinos are the possible source of CP violation, which may explain the **matter-antimatter asymmetry** in the Universe
- **A new tool** for studying nuclear physics, astrophysics, and cosmology

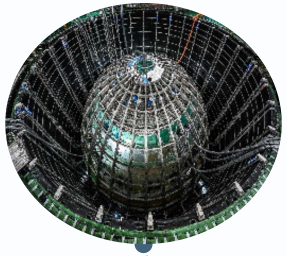




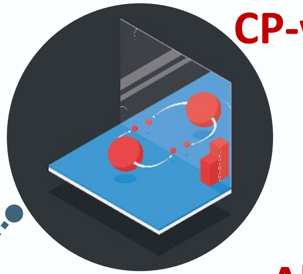
Problems with neutrinos

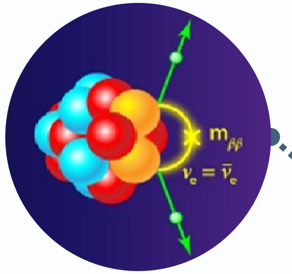
Particle Physics relevant

Mass ordering



Leptonic CP-violation



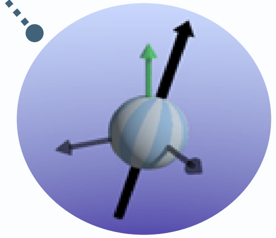


$\nu = \bar{\nu}$?

Fundamental Properties of ν

Absolute mass

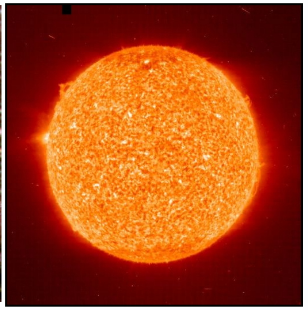
Precise oscillation properties



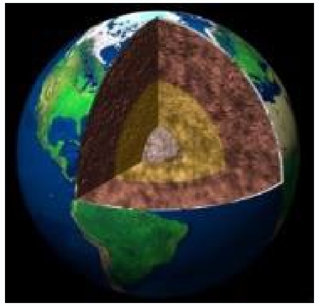
Magnetic moment

Astro-physics, Cosmology relevant

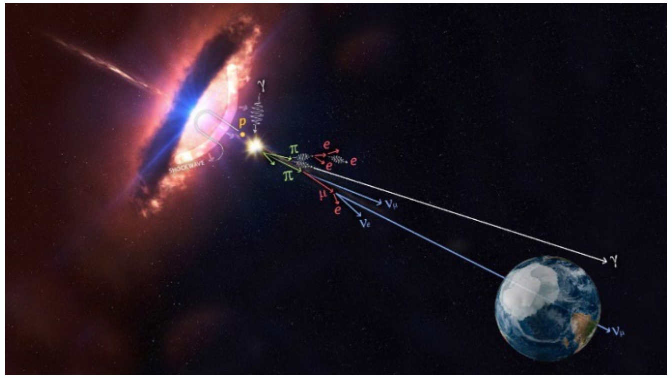
Supernova ν
(mechanism, relic)



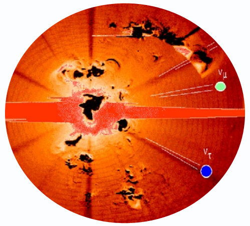
Solar ν
(Metallicity)



Geo ν
(geo phys, geo chem)



Big-Bang ν



ν from extreme astronomical phenomena?
(NS merger, AGN, γ burst, …)

Origin of cosmic rays?

Neutrino Oscillations

$$V = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} e^{i\rho} & 0 & 0 \\ 0 & e^{i\sigma} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

θ_{23} & Δm^2_{32}

Atmospheric, Accelerator

Super-K, *K2K, MINOS, T2K, NOvA, …*

θ_{13} & δ_{CP}

Reactor, Accelerator

Daya Bay, *RENO, Double Chooz, T2K, NOvA, DUNE, Hyper-K, …*

θ_{12} & Δm^2_{21}

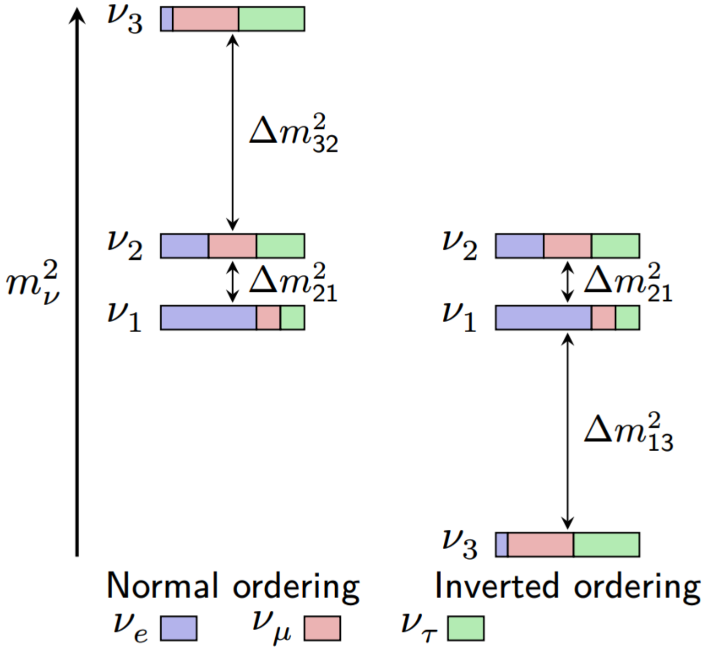
Reactor, Solar

*KamLAND, **SNO**, **JUNO**, …*

Majorana phases

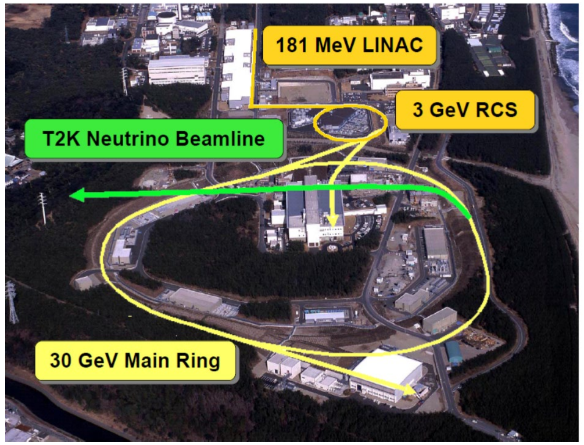
Double beta decays

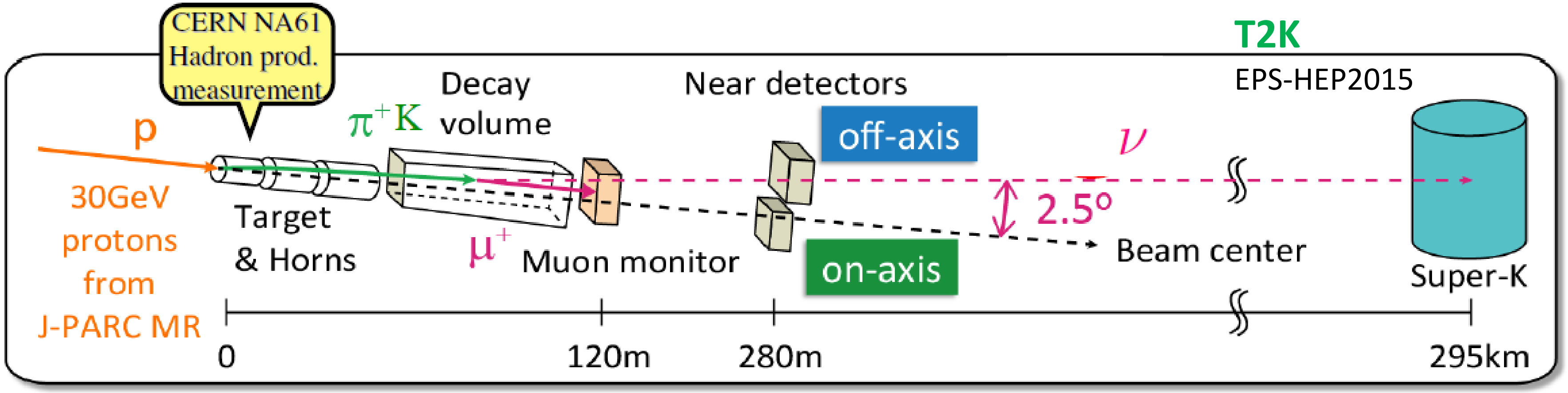
*KamLAND-Zen, Majorana, GERDA, SNO+, CUPID, nEXO, LEGEND, **JUNO**, …*



- After >25 years of ν oscillations discovery, still unknow
  - Mass ordering (**Δm^2_{32}>0?**)
  - Leptonic CP phase (**δ_{CP}**)
  - θ_{23} Octant
  - Very **precise** knowledge of **oscillation parameters**

Long-baseline Accelerator Experiments

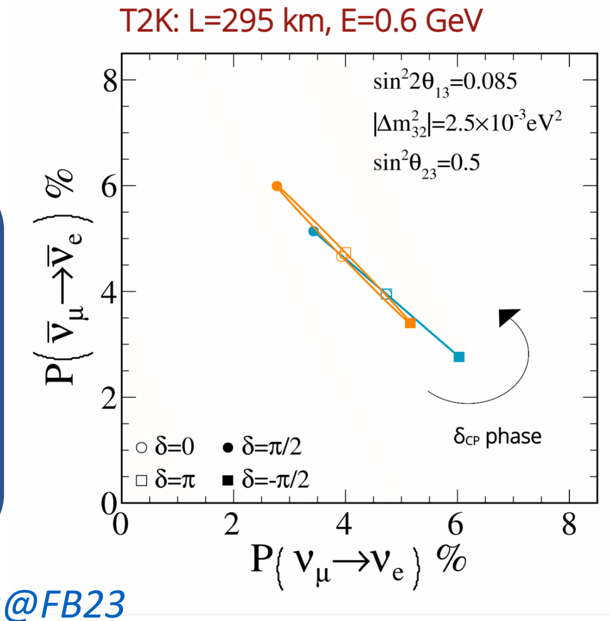




- **NOvA and T2K** in Operation. Both have near-far detectors off-axis, and ν_μ & $\bar{\nu}_\mu$ modes
- Oscillation meas.: ν_μ disppearance & ν_e appearance

$$P(\nu_\mu \to \nu_e) \approx \sin^2\theta_{23}\sin^2 2\theta_{13}\sin^2\left(\frac{\Delta m^2_{32}L}{4E_\nu}\right)\left(1+\frac{2a}{\Delta m^2_{31}}(1-2\sin^2\theta_{13})\right)$$
$$-\sin 2\theta_{12}\sin 2\theta_{23}\sin 2\theta_{13}\cos\theta_{13}\sin\delta\sin^2\left(\frac{\Delta m^2_{32}L}{4E_\nu}\right)\sin\left(\frac{\Delta m^2_{21}L}{4E_\nu}\right)$$

$P(\bar{\nu}_\mu \to \bar{\nu}_e)$: δ turns into – δ and a to -a ("a" matter effect term)

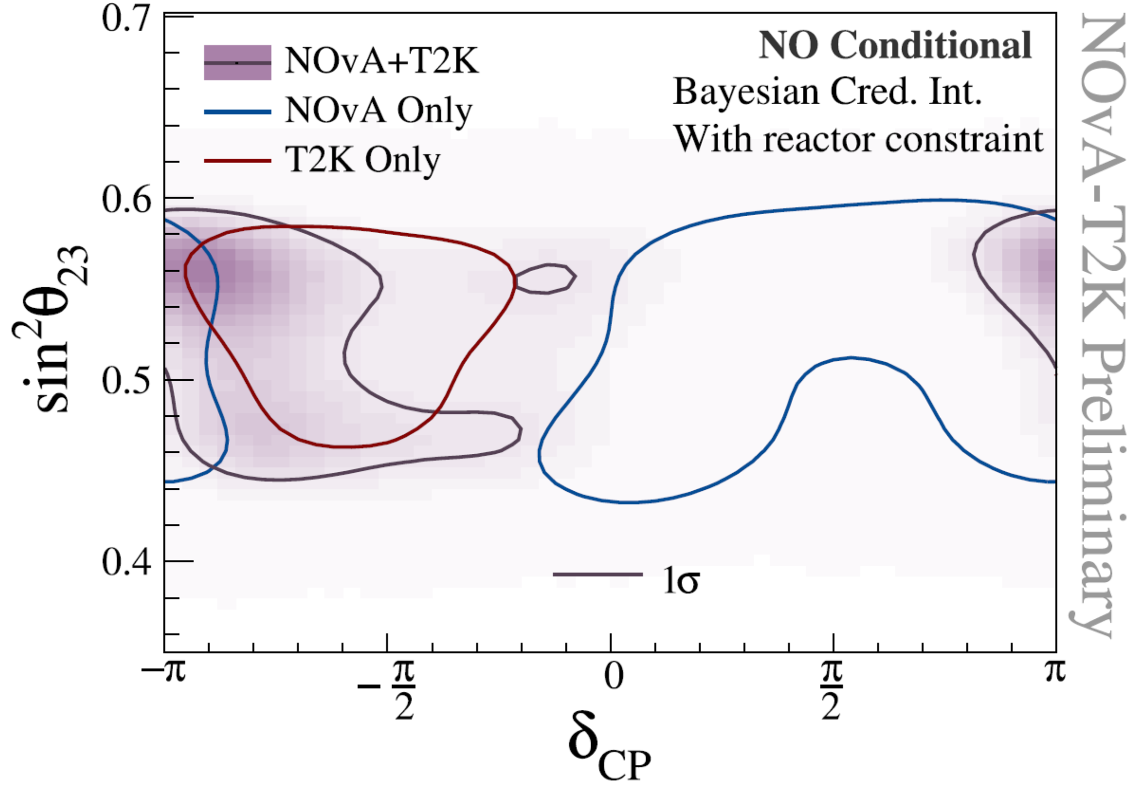


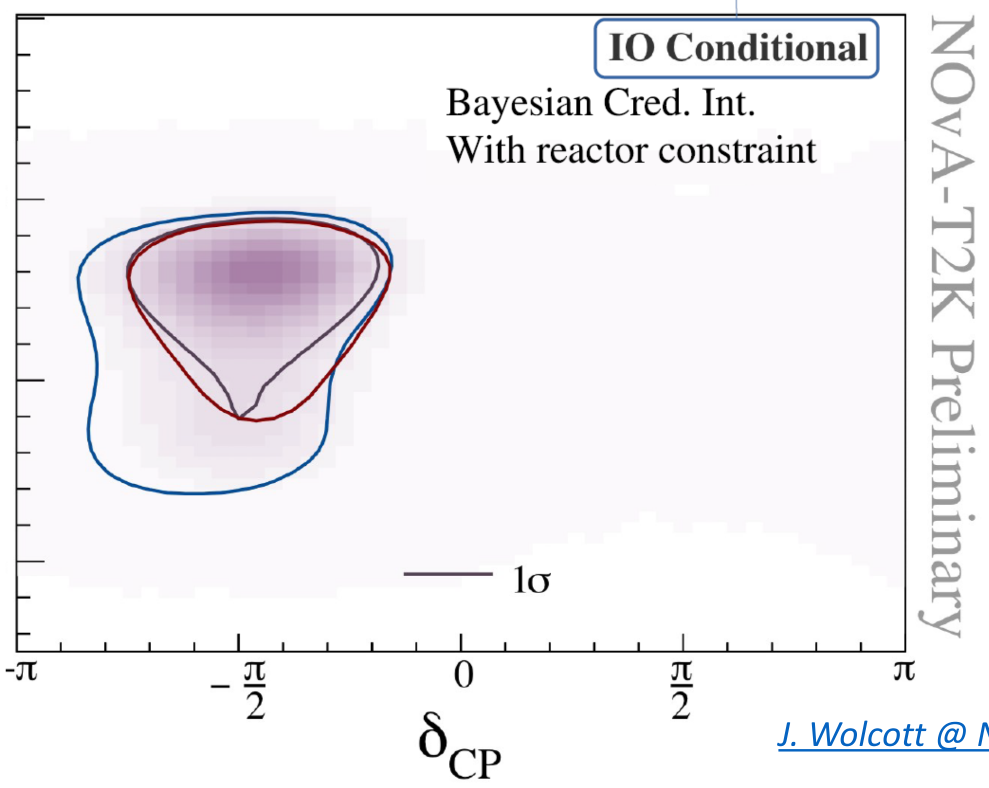
One-loop correction to the MSW potential is ~(6-8)% level, see J.H. Huang@FB23

Current NMO sensitivity from Accelerators

NOvA only: Phys. Rev. D106, 032004 (2022)
T2K only: Eur. Phys. J. C83, 782 (2023)

"assuming IO is true"
(does not include relative probability of IO vs. NO)





J. Wolcott @ Neutrino 2024

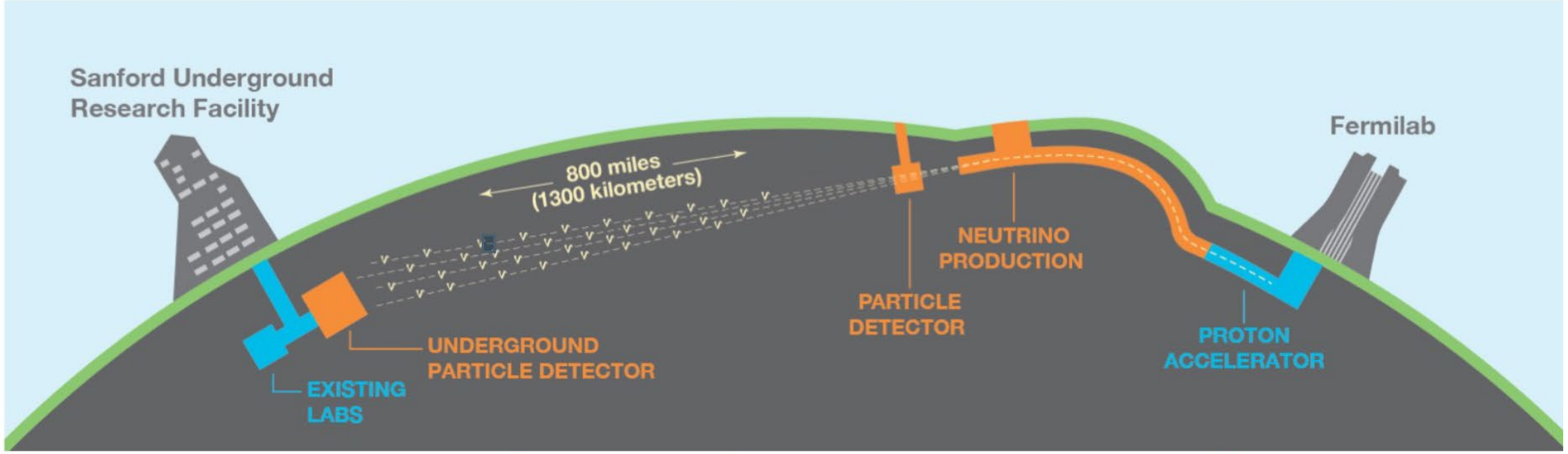
Individually, both T2K and NOvA slightly favor normal mass ordering (NO) and the upper octant of θ_{23}. However, prefer different regions of δ_{CP} if neutrino is NO.

The **joint fit** splits the differences in the NO case, and slightly favors IO

Long-baseline Experiment Prospects

DUNE:

- > 2 MW beam
- Liquid-Argon TimeProjection Chamber (LArTPC) technology
- ≥ 40 kton far detector fiducial mass
- First physics in ~2029

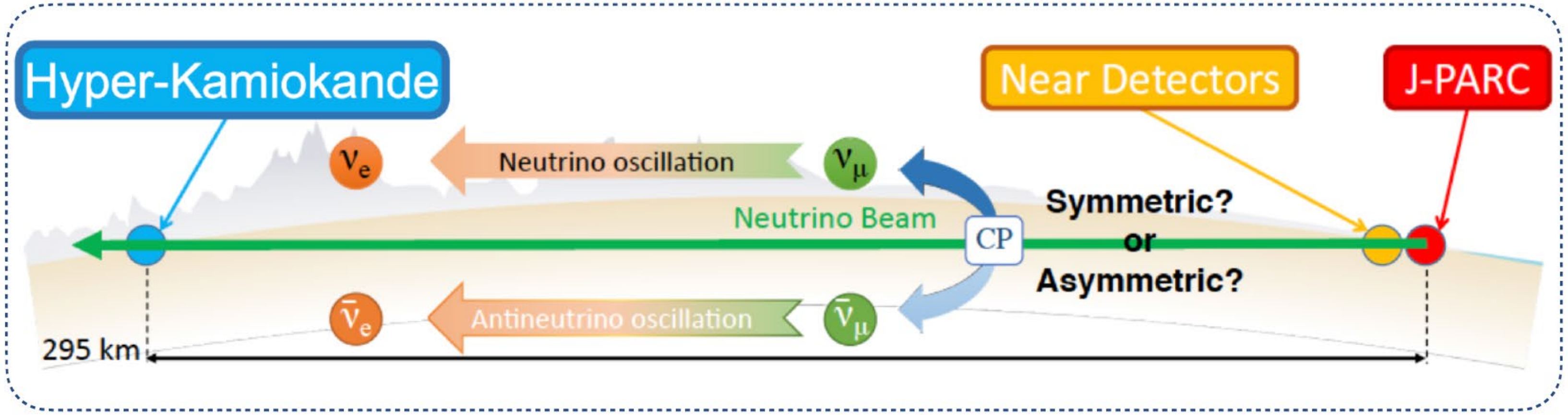


Large degree of complementarity:

	matter effects	energy spectrum	detection systematics
DUNE	large	wide band, higher energy	LArTPC
Hyper-Kamiokande	small	narrow band, lower energy	Water Cherenkov

Hyper-Kamiokande:

- 1.3 MW beam
- Water Cherenkov far detector
- 190 kton far detector fiducial mass
- First physics in ~2027

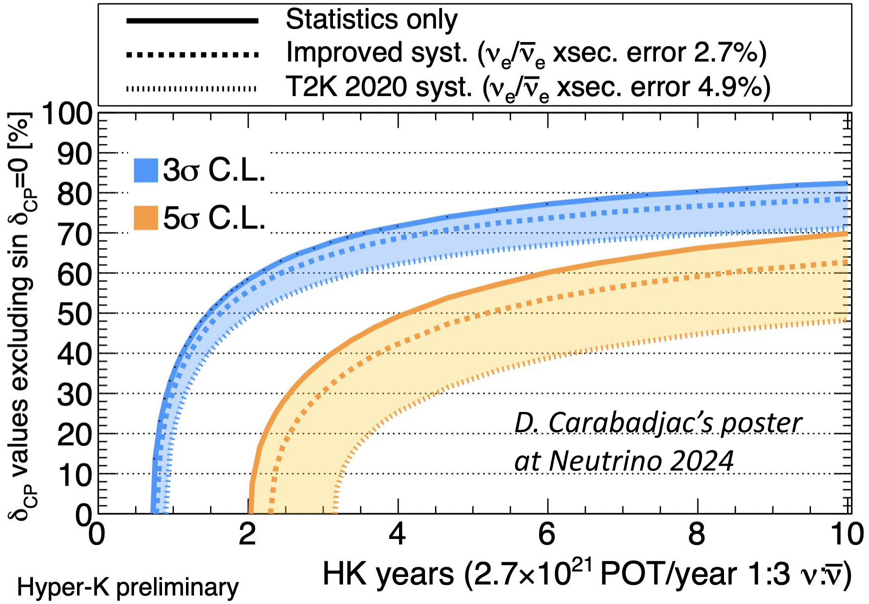


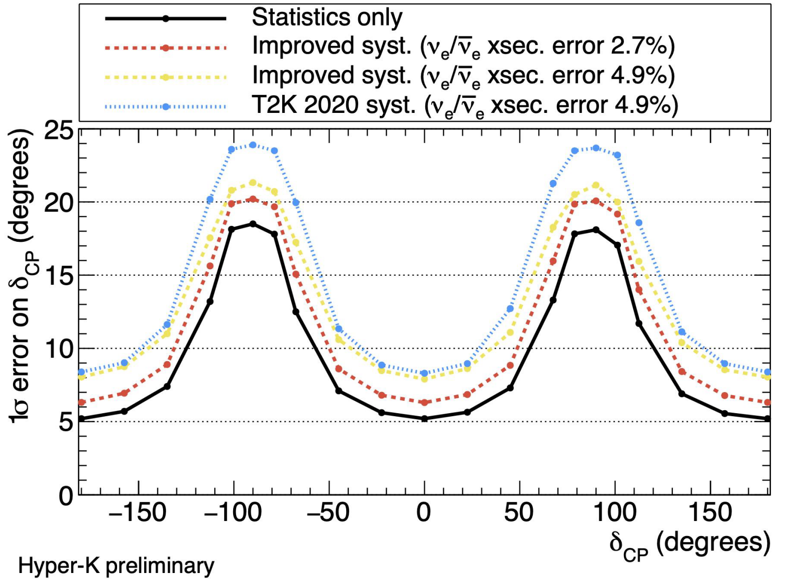
P. Ochoa @ ICHEP2024

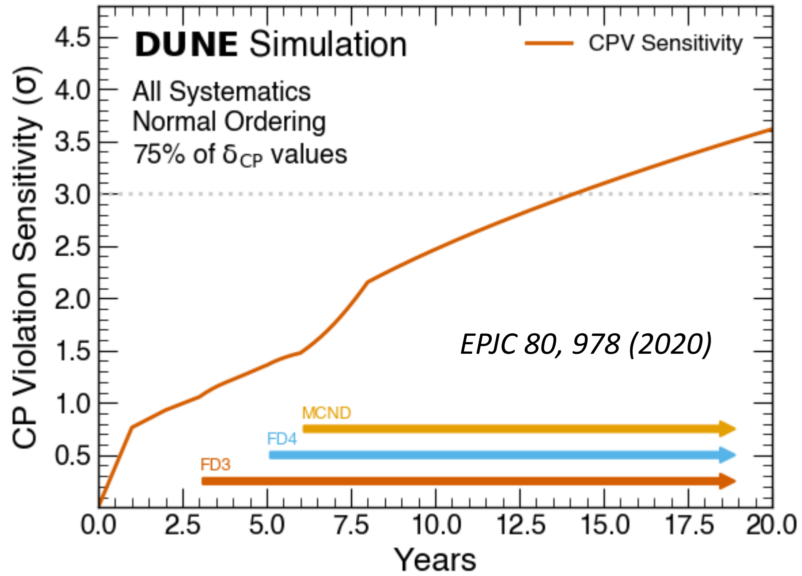
Long-baseline Experiment Prospects

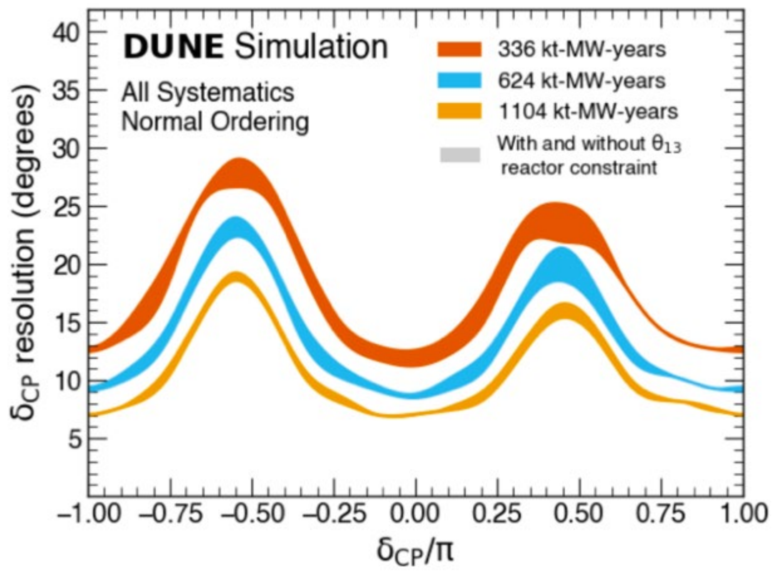
- **Mass ordering**
  - DUNE: 5σ between 1 and 3 years (depending on how kind nature is)

- **CP violation**
  - 3σ over 75% of δ_{CP} values: ~(10-15) yrs
  - Similar 10-year precision of δ_{CP} in both experiments

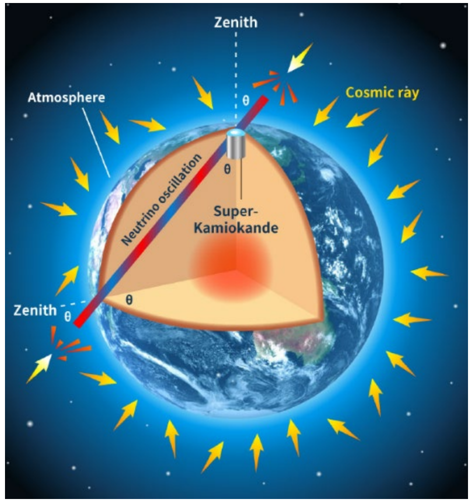




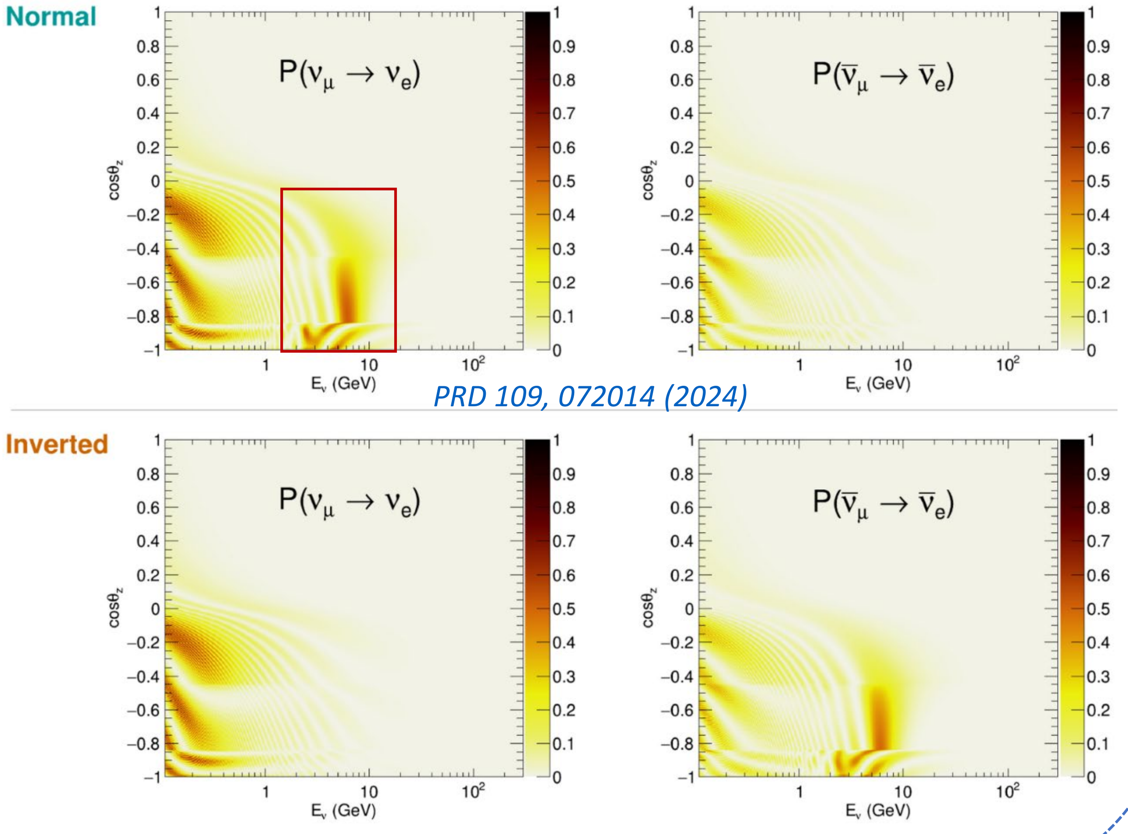


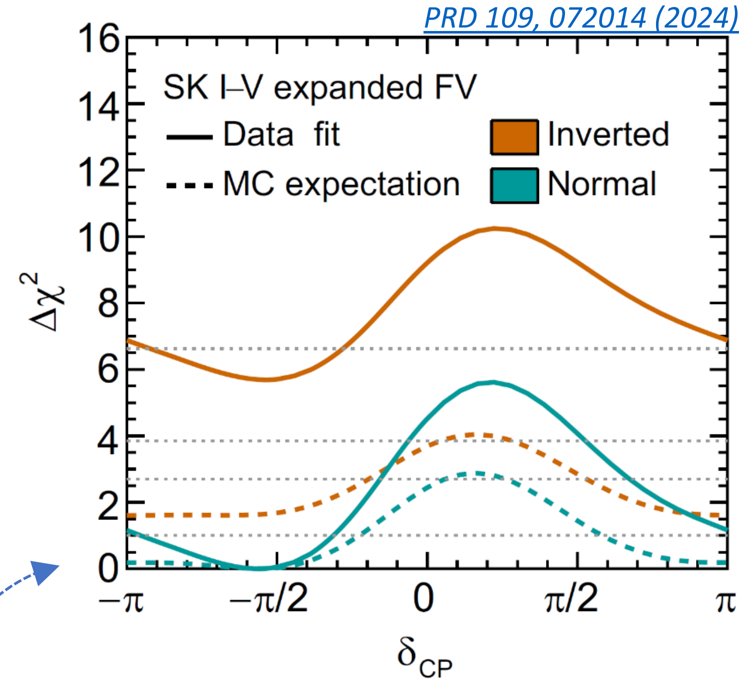


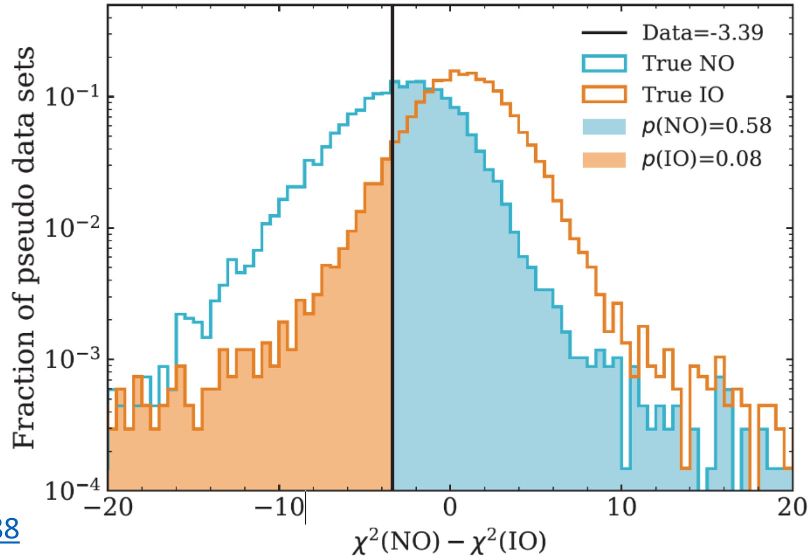
Atmospheric ν – Super-K



Resonance from matter effects: enhancement of $\nu_e(\bar{\nu}_e)$ appearance in the NO (IO) case



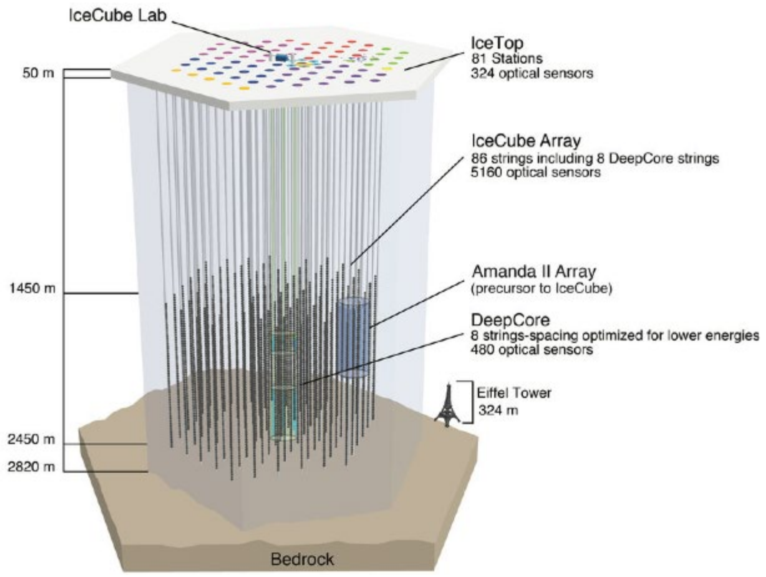




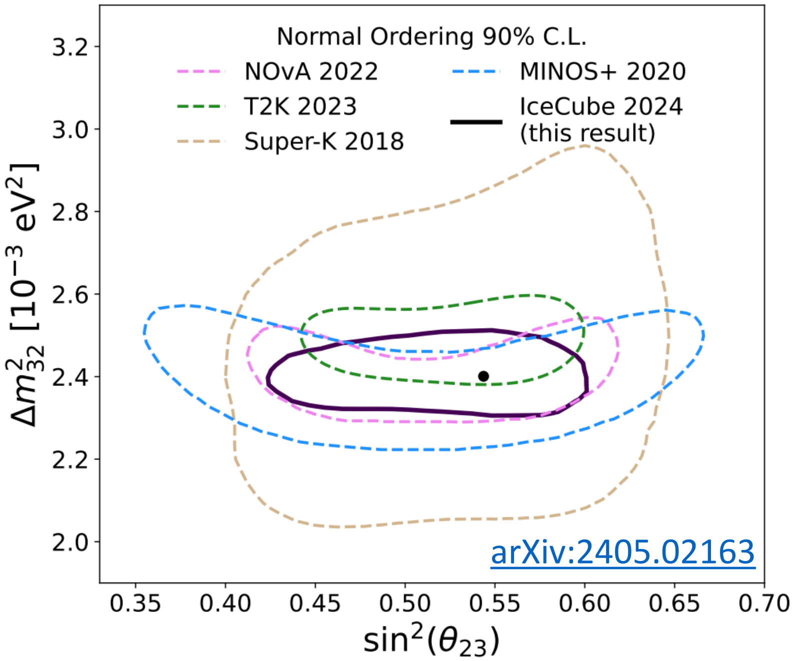
- Latest atmospheric neutrino results from **Super-K.**
  NO favored at 92.3% level
- Joint result between **Super-K and T2K**.
  Exclude CP conservation to 1.9σ

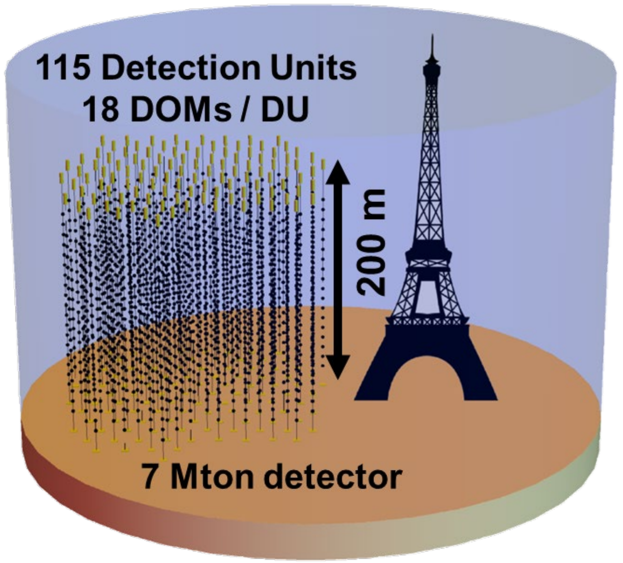
arXiv:2405.12488

Atmospheric ν – IceCube and KM3Net/ORCA

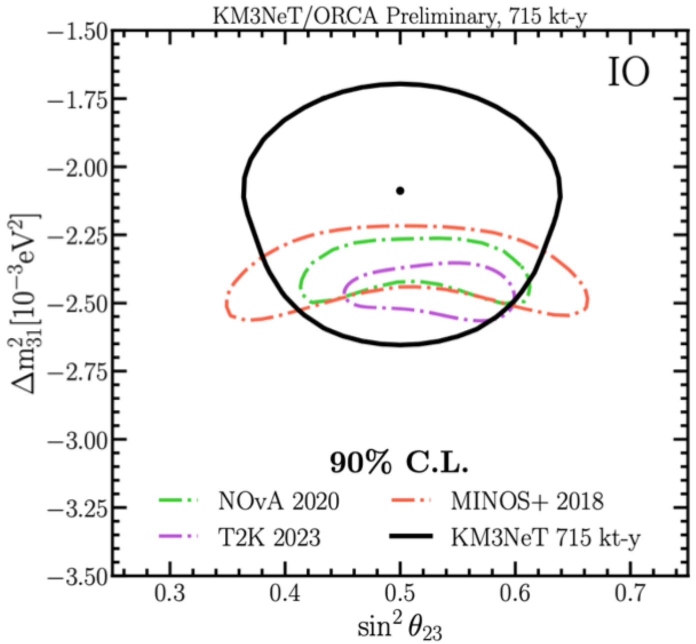


~km^3 lattice detector in ice, instrumented with optical sensors





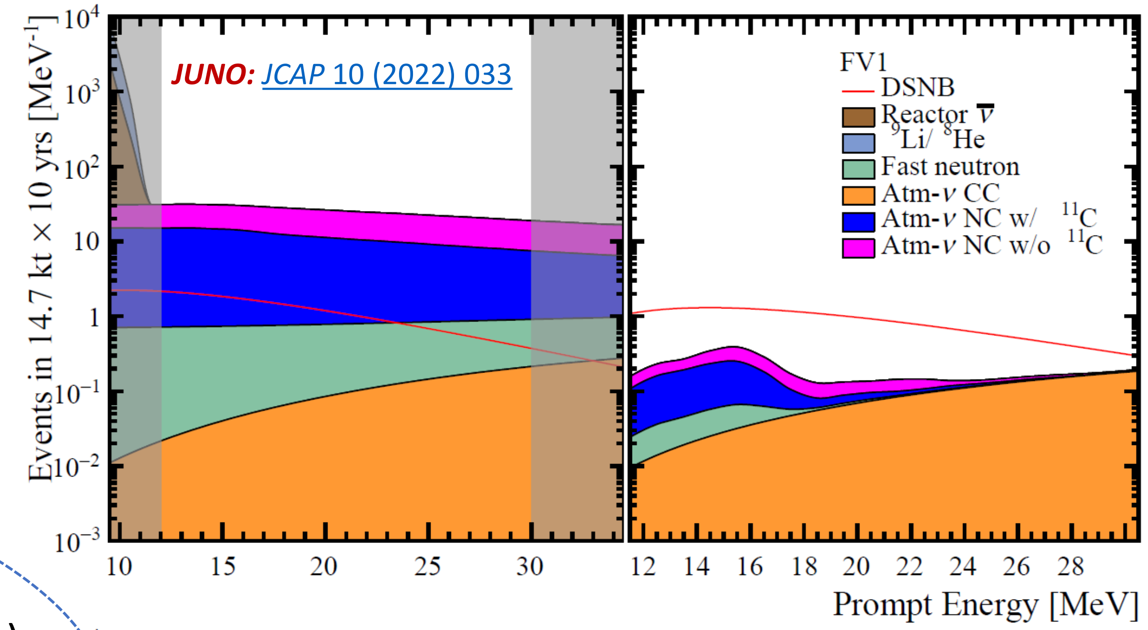
J. Coelho @ Neutrino2024



- Oscillation results with 9.3 yrs of **IceCube-DeepCore** data
  Slight preference for NO
- Oscillation results with data set equivalent to 37 days of full **ORCA**
  Slight preference for IO
- Good agreement and comparable precision with accelerator results

Atmospheric ν backgrounds for rare searches

- ***Neutral current (NC)* interactions** are the key backgrounds for rare searches, take JUNO as an example
  - Diffused Supernova Neutrino background (DSNB)
  - Proton Decay
  - Neutron Invisible Decay



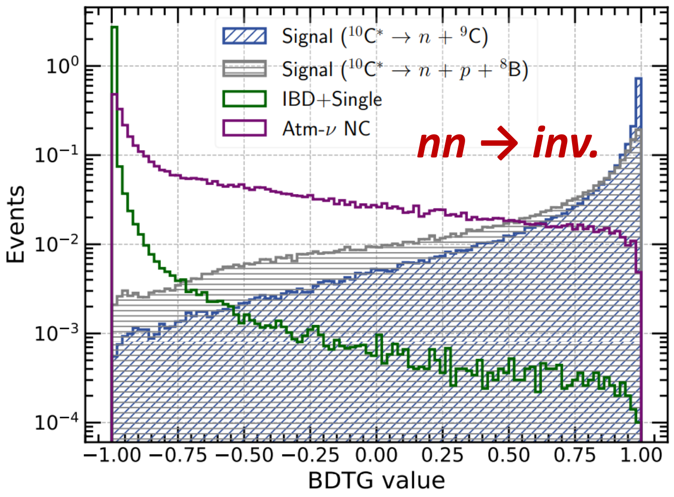
- Background reduction techniques
  - pulse shape discrimination (multi-variate, deep learning)
  - Triple coincidence

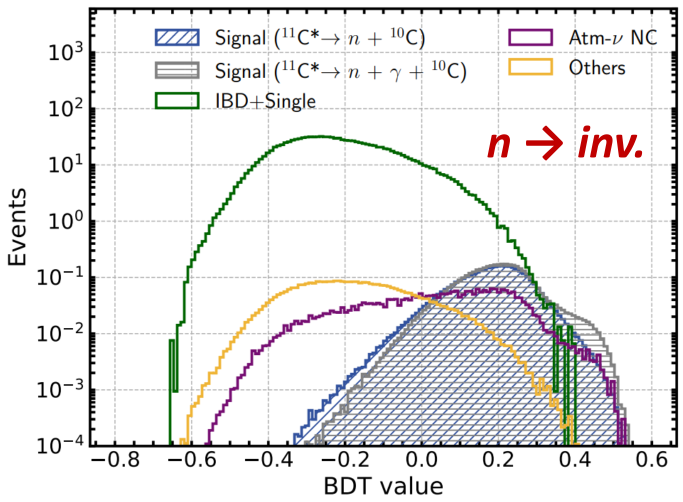
Criteria		Survival rate of $p \to \bar{\nu} K^+$ (%)			Survival count (fraction) of atmospheric ν		
		Sample 1	Sample 2	Sample 3	Sample 1	Sample 2	Sample 3
Basic selection	E_{vis}		94.6			51299 (32.1%)	
	R_V		93.7			47849 (29.9%)	
Delayed signal selection	N_M	74.4		4.4	20739 (13.0%)		1143 (0.7%)
	ΔL_M	67.0		4.4	13796 (8.6%)		994 (0.6%)
	N_n	48.4	17.9	–	5403 (3.4%)	6857 (4.3%)	–
	ΔL_n	–	16.6	–	–	4472 (2.8%)	–
Time character selection	R_χ	45.9	9.0	3.8	4326 (2.7%)	581 (0.4%)	716 (0.4%)
	ΔT	28.3	7.7	2.4	121 (0.07%)	18 (0.01%)	30 (0.02%)
	E_1, E_2	27.4	7.3	2.2	1 (0.0006%)	0	0
Total			36.9			1	

Atmospheric background suppression factor: 6×10^{-6} ➔ 0.2 counts/(200 kton*yrs)

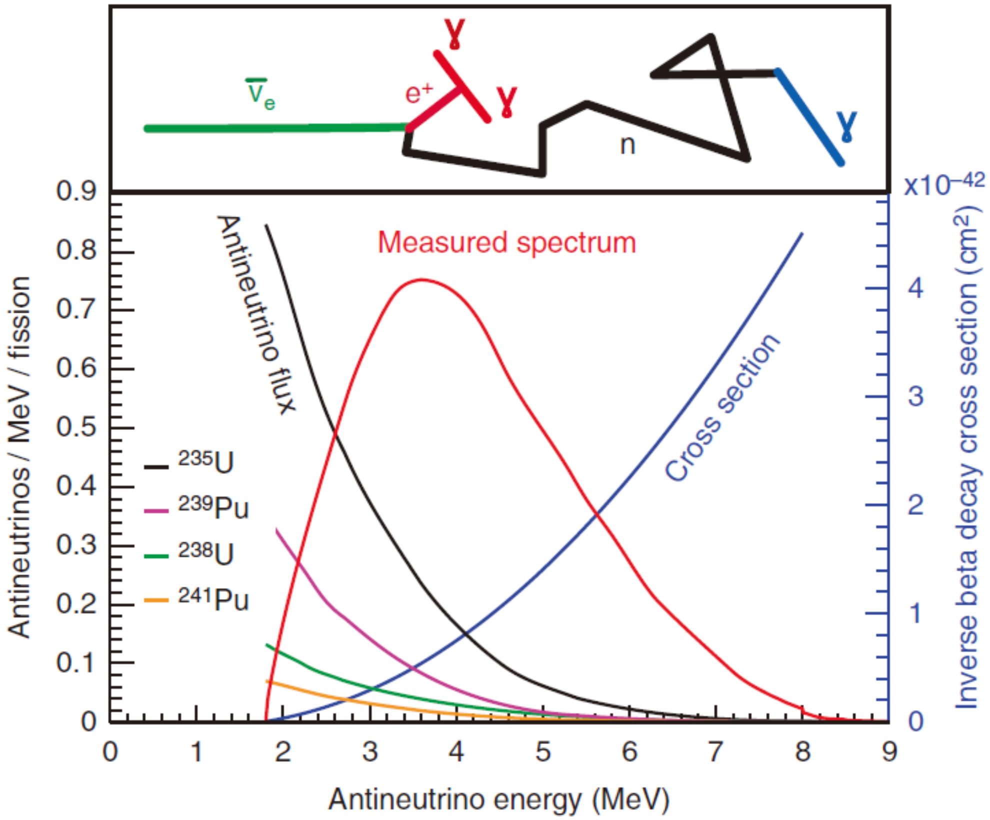
JUNO: CPC 47, 11 (2023) 113002

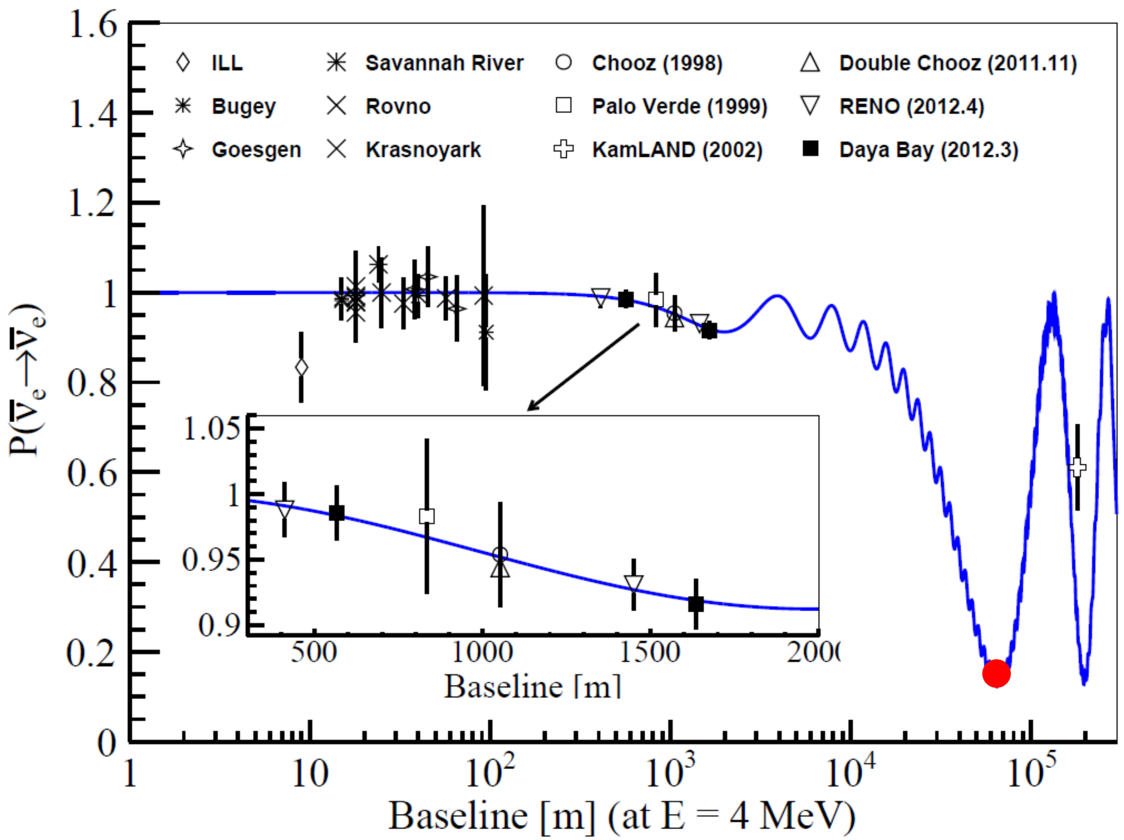
JUNO: ariXiv:2405.17792



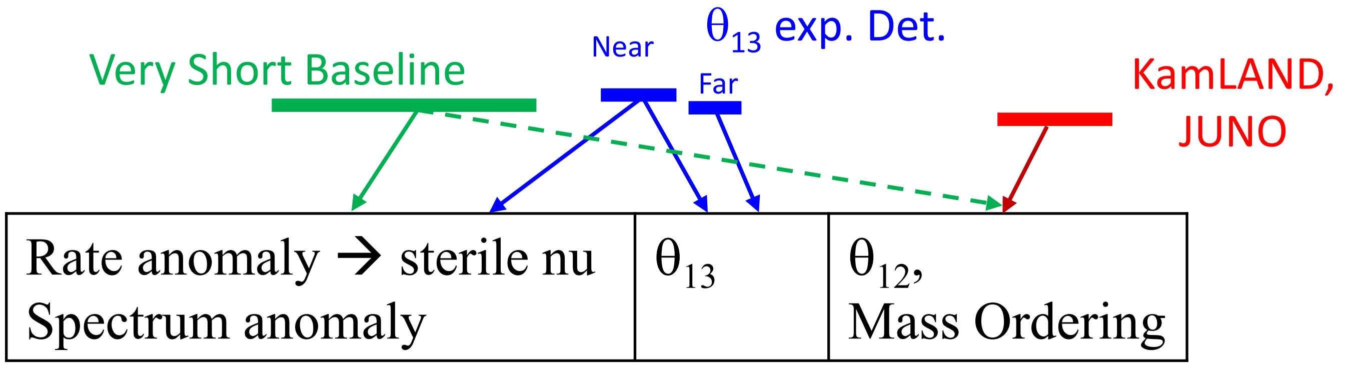


Reactor Neutrinos





- Reactor antineutrino: $\bar{\nu}_e$ emitted as fission products decay
- Commercial reactor (LEU) ^{235}U, ^{238}U, ^{239}Pu, ^{241}Pu; Research HEU (^{235}U)
- Usually detected via Inverse Beta Decay (IBD)



Daya Bay, RENO & Double Chooz

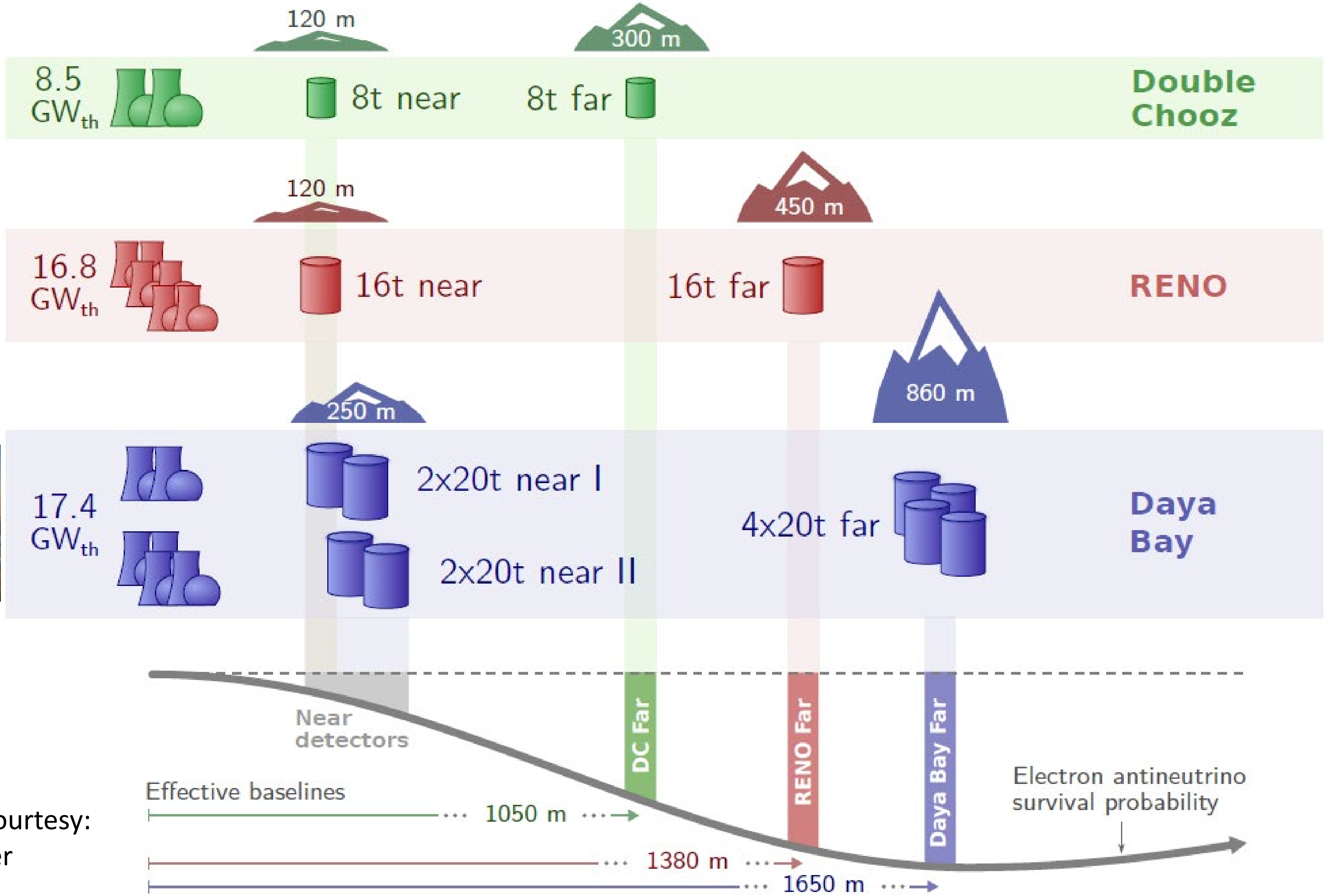
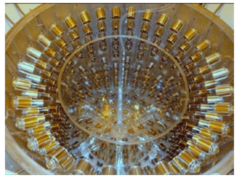
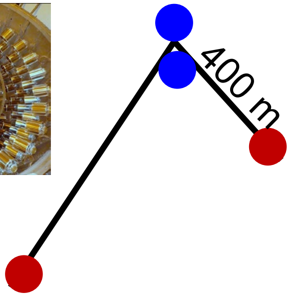
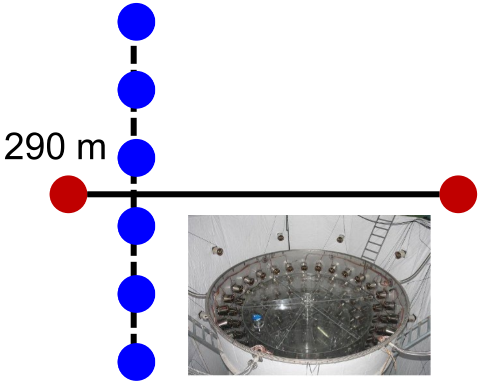
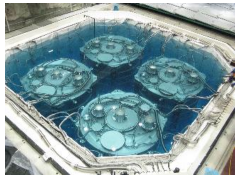


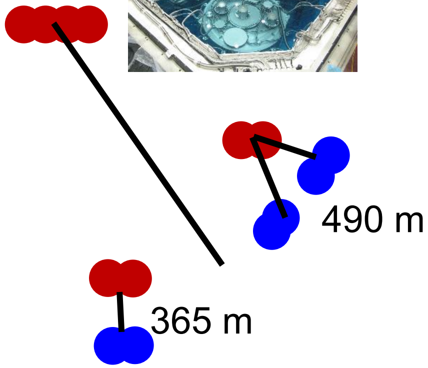
Diagram Courtesy:
Soren Jetter











θ_{13} measurement at Daya Bay

- Completed in Dec. 2020, **3158** days in total.
- Two datasets: delayed neutron capture on H or Gd
- **Side-by-side** measurements confirm detector related systematic uncertainty
  - n-Gd: 0.13%, n-H: 0.34%

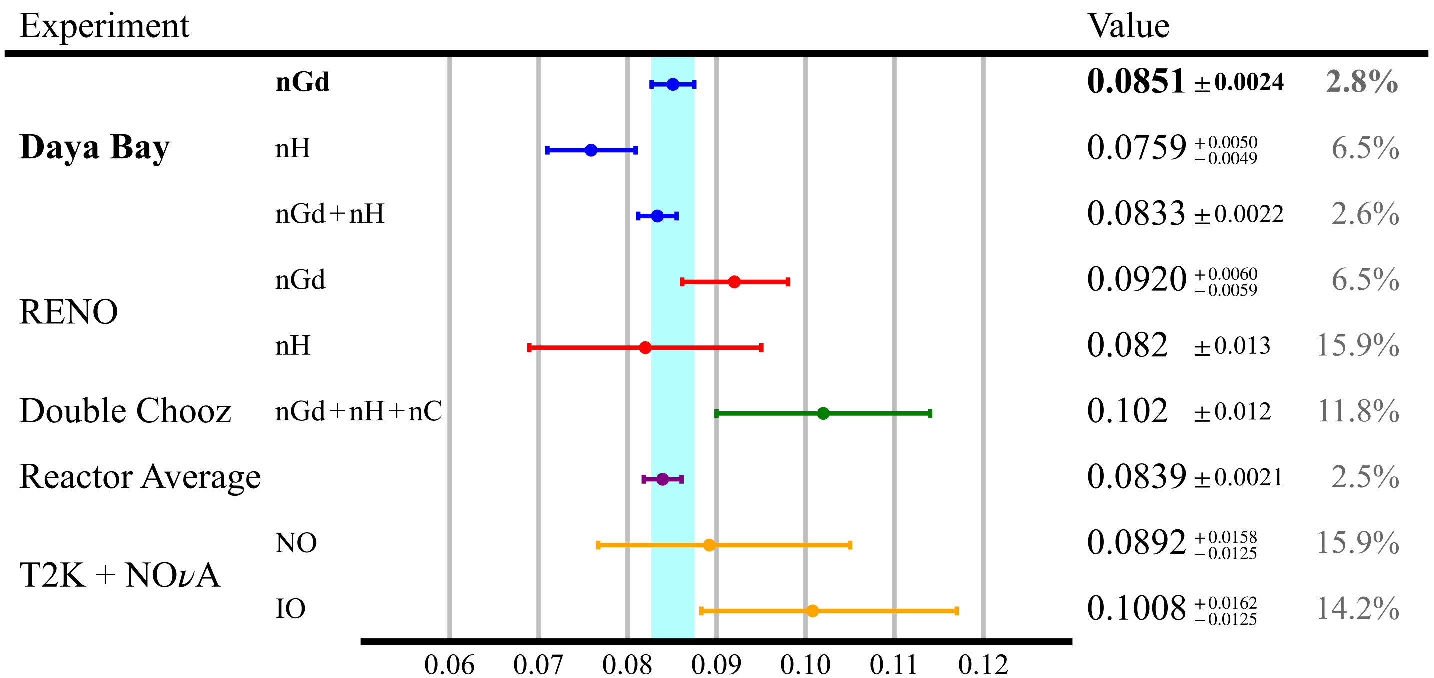
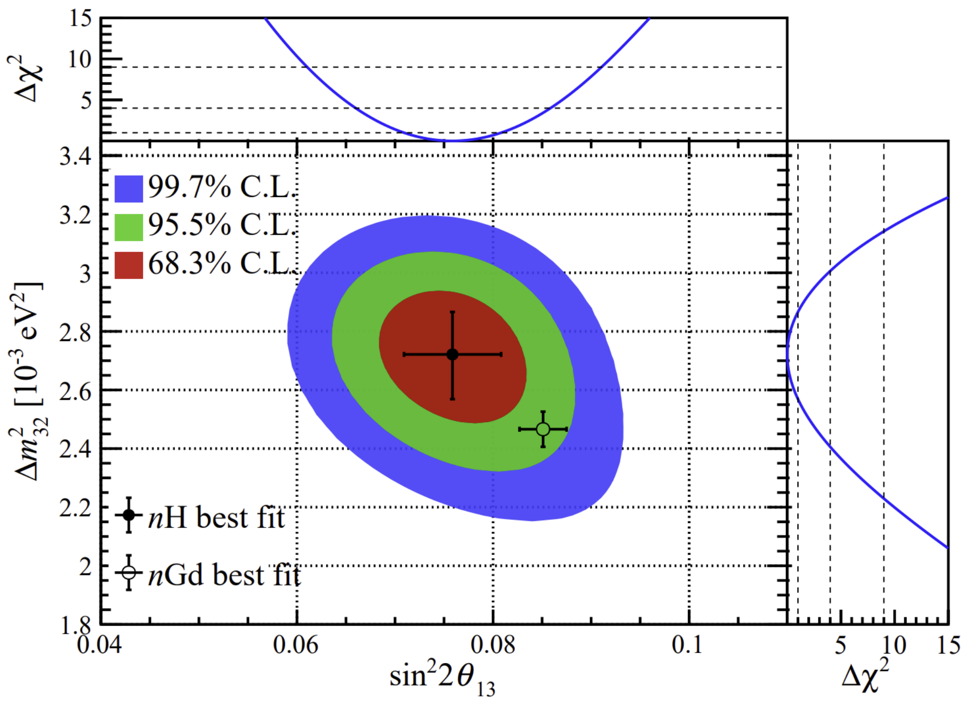


Figure by Hongzhao Yu



n-Gd dataset (3158 days): Phys. Rev. Lett. 130, 161802 (2023)
n-H dataset (1958 days): arXiv:2406.01007, to appear in PRL

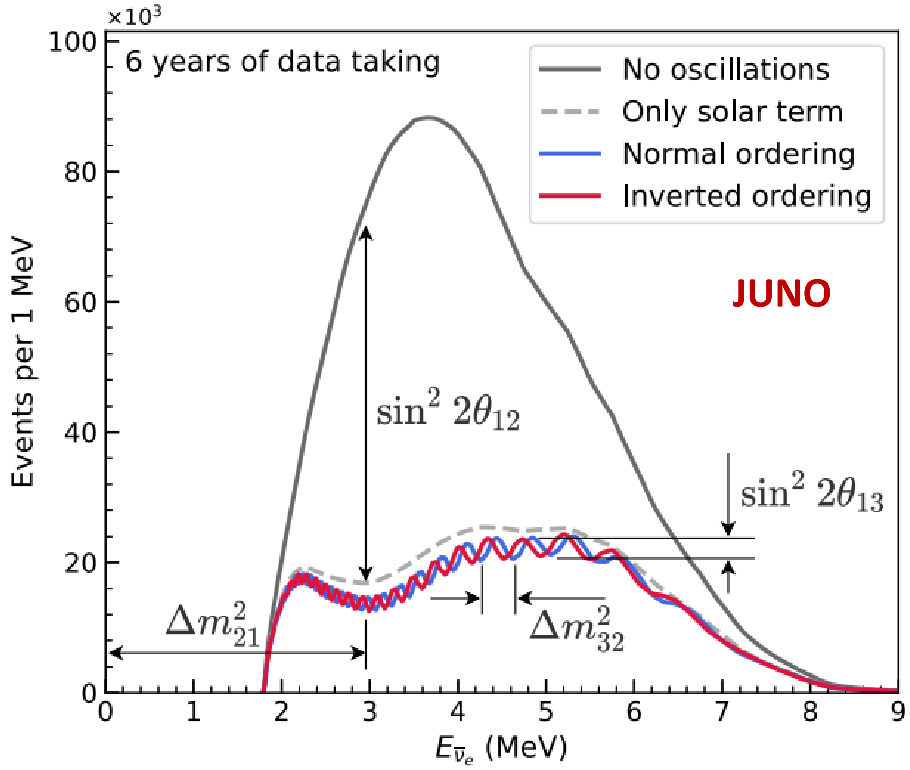
Current reactor measurement of θ_{13} likely to remain the world's most precise for a long time

Mass Ordering w/ reactors

- 'Vacuum oscillation' with reactor neutrinos → unique and complementary with accelerator/atmospheric experiments to determine neutrino mass ordering

$$
\begin{aligned}
P_{ee}(L/E) &= 1 - P_{21} - P_{31} - P_{32} \\
P_{21} &= \cos^4(\theta_{13})\sin^2(2\theta_{12})\sin^2(\Delta_{21}) \\
P_{31} &= \cos^2(\theta_{12})\sin^2(2\theta_{13})\sin^2(\Delta_{31}) \\
P_{32} &= \sin^2(\theta_{12})\sin^2(2\theta_{13})\sin^2(\Delta_{32})
\end{aligned}
$$

- Precision measurements of θ_{12} , Δm^2_{21} , Δm^2_{32}
- Require huge mass and high energy resolution



(matter effect contributes maximal ~4% correction at around 3 MeV, *arXiv:1605.00900, arXiv:1910.12900*)

Δm^2_{31} and Δm^2_{32} interplay	Δm^2_{ee} and $\Delta m^2_{\mu\mu}$ difference	Matter Effect

Reactor

Atmospheric

Accelerator

$\Delta m^2_{ee} = \cos^2\theta_{12}\Delta m^2_{31} + \sin^2\theta_{12}\Delta m^2_{32}$

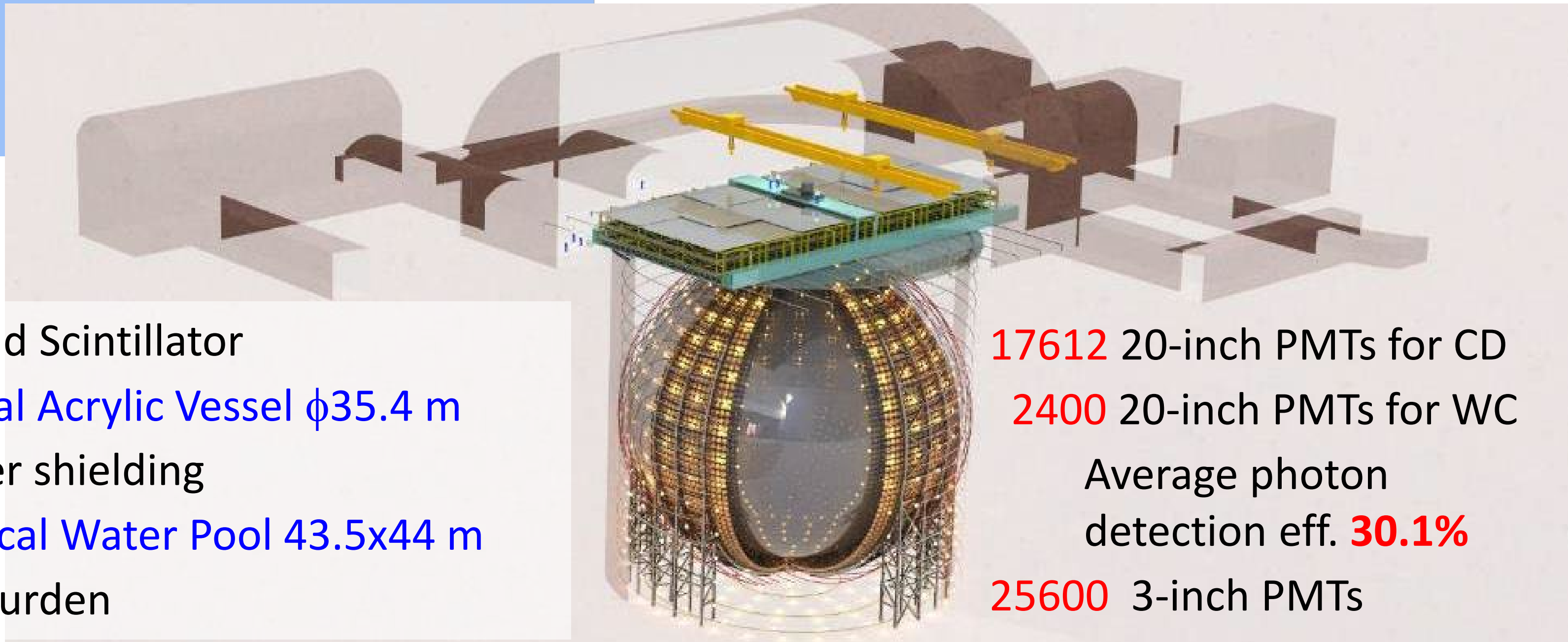
$\Delta m^2_{\mu\mu} = \sin^2\theta_{12}\Delta m^2_{31} + \cos^2\theta_{12}\Delta m^2_{32} + \cos\delta\,\sin\theta_{13}\,\sin 2\theta_{12}\tan\theta_{23}\Delta m^2_{21}$

$|\Delta m^2_{ee}| - |\Delta m^2_{\mu\mu}| = \pm\Delta m^2_{21}(\cos 2\theta_{12} - \cos\delta\,\sin\theta_{13}\,\sin 2\theta_{12}\tan\theta_{23})$

JUNO (Jiangmen Underground Neutrino Observatory)

- Proposed in 2008
- Approved in Feb. 2013
- Detector completion in 2024
- Physics goals: ν mass ordering (>4σ, 6yrs), precision measurement (<1%), supernova ν, geo-ν, solar-ν, nucleon decay, etc. Upgradable for 0νββ searches

Yangjiang NPP: 2.9 GW x 6
Taishan NPP: 4.6 GW x 2
Equal baseline: 52.5 km



20 kton Liquid Scintillator
Spherical Acrylic Vessel ϕ35.4 m
35 kton water shielding
Cylindrical Water Pool 43.5x44 m
700 m overburden

17612 20-inch PMTs for CD
2400 20-inch PMTs for WC
Average photon detection eff. 30.1%
25600 3-inch PMTs

Challenges…

50 m x 70 m
Exp. Hall

35.4 m
acrylic sphere,
vs. 13 m@ SNO

20 kton
Liquid scintillator,
Borexino X40,
KamLAND X20
λ>20 m,
U/Th<10^{-17} g/g

20,000
20-in PMT, **ε~30%**

Best Light yield
Borexino X2,
KamLAND X5

Challenges…

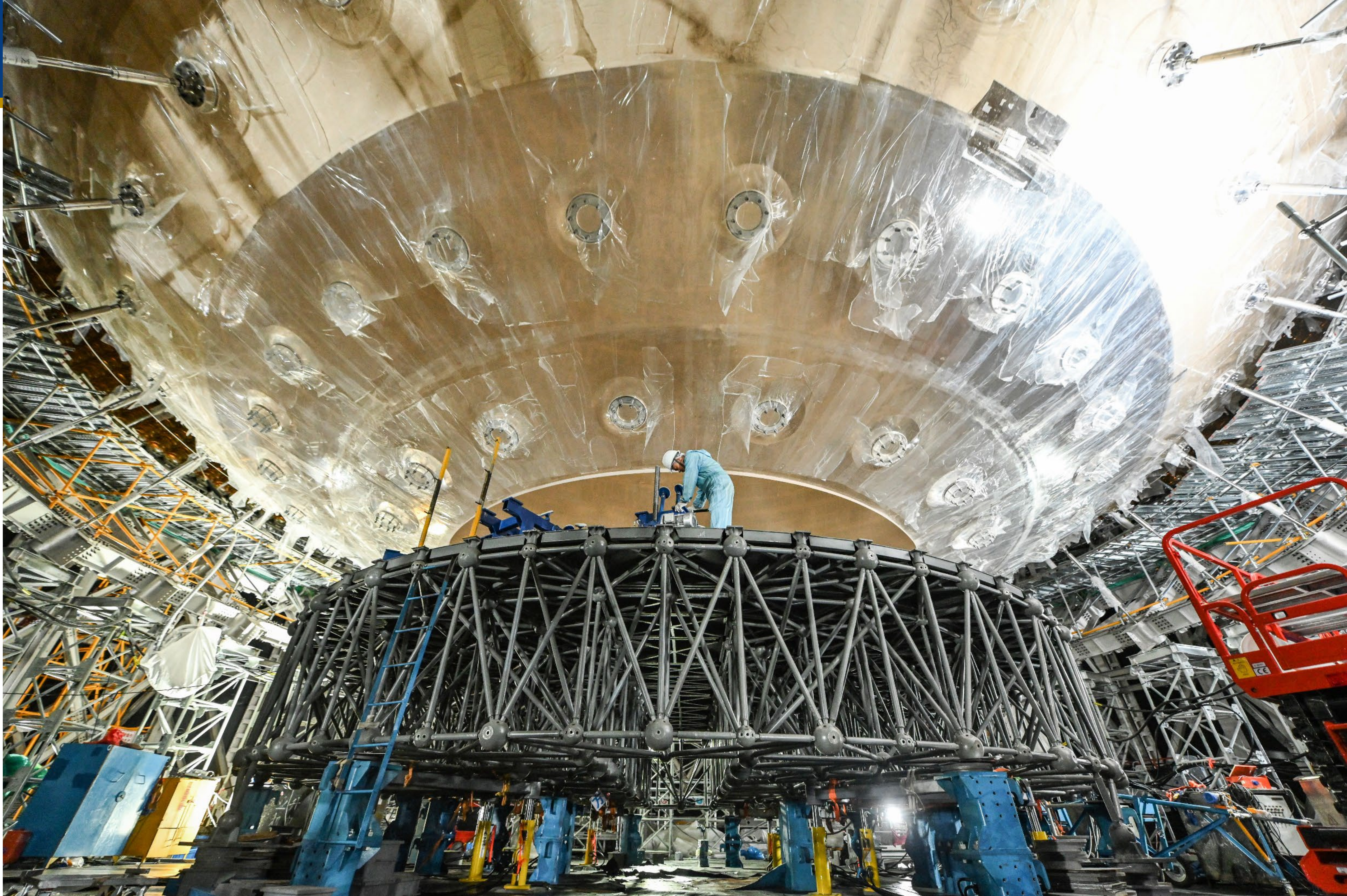
50 m x 70 m
Exp. Hall

35.4 m
acrylic sphere,
vs. 13 m@ SNO

20 kton
Liquid scintillator,
Borexino X40,
KamLAND X20
λ>20 m,
U/Th<10^{-17} g/g

20,000
20-in PMT, **ε~30%**

Best Light yield
Borexino X2,
KamLAND X5



Challenges…

50 m x 70 m
Exp. Hall

35.4 m
acrylic sphere,
vs. 13 m@ SNO

20 kton
Liquid scintillator,
Borexino X40,
KamLAND X20
λ>20 m,
U/Th<10^{-17} g/g

20,000
20-in PMT, ε~30%

Best Light yield
Borexino X2,
KamLAND X5

Physics Potentials with JUNO

JUNO has great potentials on the physics topics below, although except for CP phases, θ_{23} Octant

Exp.	Time	Mass ordering	CP phases	Precision Meas.	CCSN burst @ 10 kpc	DSNB	Geo-ν	Solar	Proton Decay (sensitivity@10 y)
JUNO (20 kt)	2024	**3-4 σ** *6 y*	—	**$\sin^2\theta_{12}$ (0.5%), Δm^2_{21} (0.3%), Δm^2_{31} (0.2%),** *6 y*	**all-flavor ν (IBD, eES, pES)**	**3σ**, *3 y*	**~400/y**	**^{7}Be, pep, CNO, ^{8}B**	> 9.6x10^{33} y ($\bar{\nu}K^+$)
DUNE (17 kt*4)	2030	**>5 σ** *1-3 y*	5σ (50%) *10 y*	Δm^2_{32} ~0.4%, $\sin^2\theta_{23}$~*1.1% *, 15 y*	**^{40}Ar CC & NC, eES**	^{40}Ar CC	—	^{8}B, hep	>8.7x10^{33} y ($e^+\pi^0$) >1.3x10^{34} y ($\bar{\nu}K^+$)
HyperK (260 kt)	2027	**3-5 σ** *10 y*	**5σ (60%)** *10 y*	Δm^2_{32} ~0.6%, $\sin^2\theta_{23}$~*1.6% *, 10 y*	**eES, IBD**	*3σ, 6 y*	—	^{8}B, hep	**>7.8x10^{34} y ($e^+\pi^0$) >3.2x10^{34} y ($\bar{\nu}K^+$)**
ORCA (7 Mt)	Un-known	**2-4 σ** *3 y*	—	Δm^2_{32} ~2% , *3 y*	rate excess	—			
IceCube Upgrade	2026	**2-4 σ** *7 y*	—	Δm^2_{32} ~1.3% , *3 y*	rate excess	—			

** Upper octant assumption*

eES: ν-electron scattering, pES: ν-proton scattering, IBD: inverse beta decay

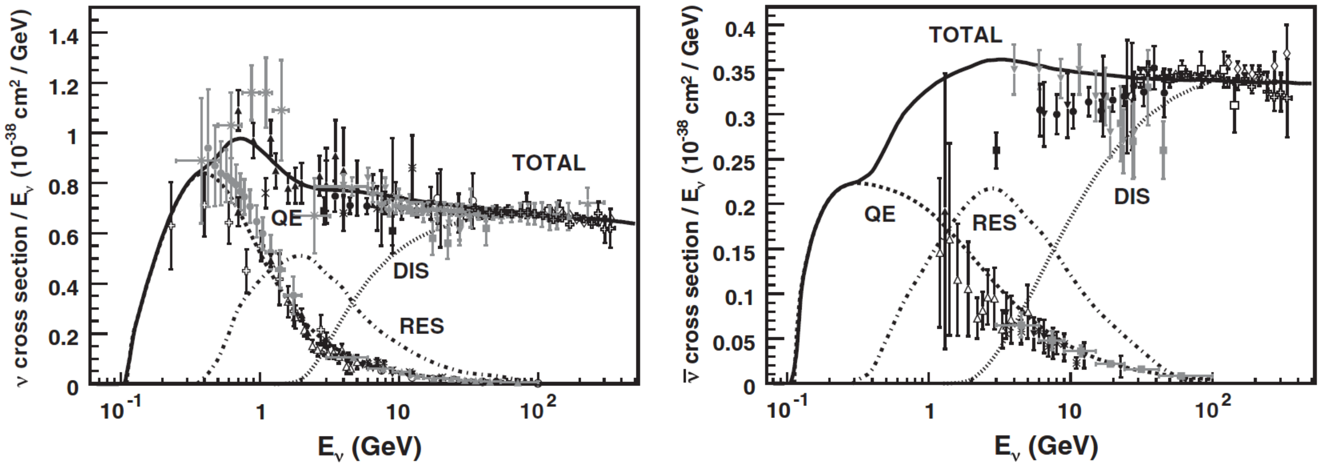
Systematics: Flux

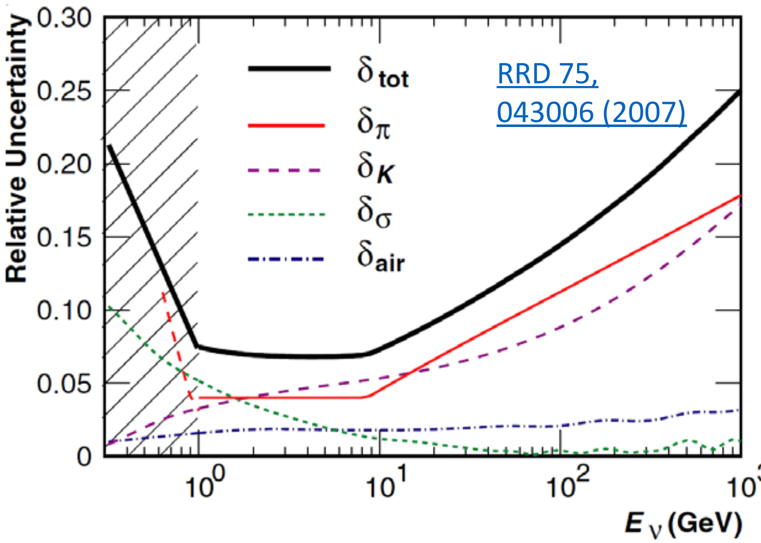
- Increased precision of experiment requires better understanding of sources (Flux), final states, and interaction cross sections
- Different experiments have specific issues

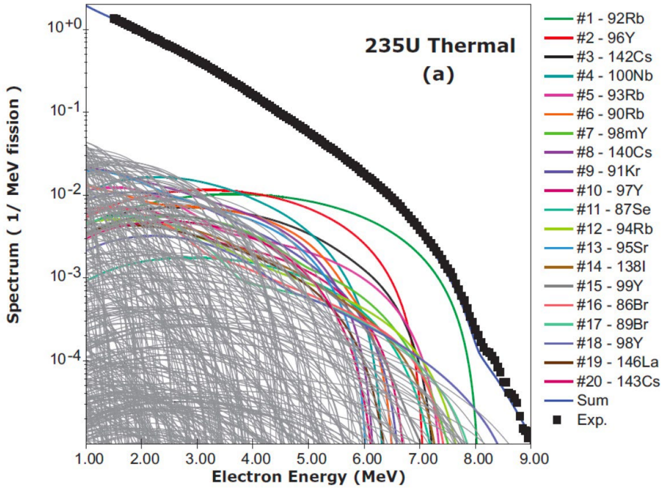
	Flux
Reactor	~ 2%
Atmospheric	**~ (5-10)%** [1]
Accelerator	**~ (5-15)%** [2] **~ 5%** [3]
Solar	~ (1-5)%

[1] long time development of atmospheric ν flux
[2] main source is hadron production Xsec
[2] w/ near detectors

Rev. Mod. Phys. 84, 1307 (2012)



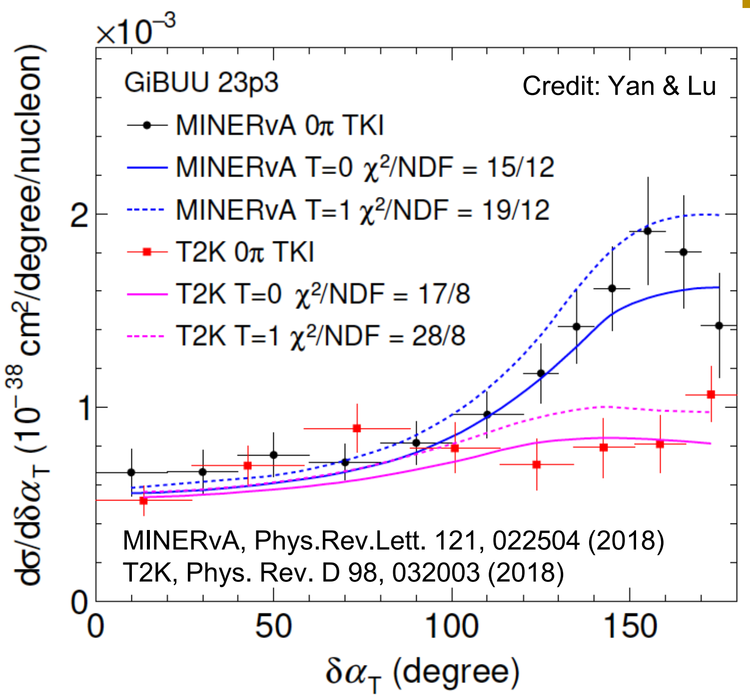




Systematics: Interaction Cross sections

- A lot of measurement of cross sections
  - ν experiments and their prototypes: T2K, NOνA, MicroBooNE, MiniBooNE, MINERvA, …
  - Dedicated experiments
    - ✓ FASERn, SND, and FPF at LHC for high-E ν
    - ✓ CLAS, e4ν... for medium-E ν
- Theoretic calculations and Monte Carlo modelling
  - Generators: GENIE, NuWro, GiBUU, NEUT

Also see *Qiyu's talk @ FB23*



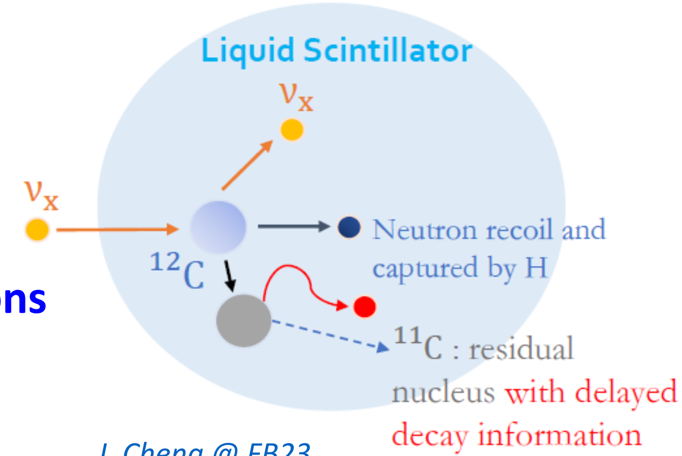
X. Lu @ FB23

More discussions on theoretical predictions of ν-nucleon interactions :

J. Liang @ FB23
D.L. Yao @ FB23

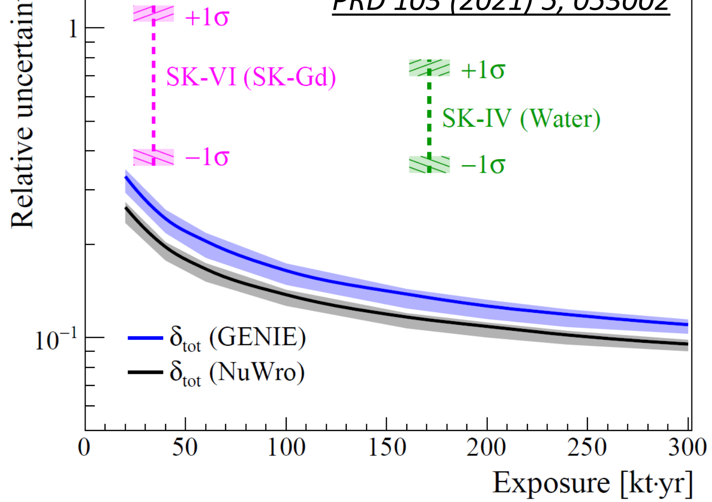
- Possible to have ***in situ* measurement to constrain the NC model prediction** in large detectors like JUNO
  - De-excitation γ's, & neutron tagging

➔ T2K: Measure NCQE by deexcitation γ-rays
➔ Super-K: Measure by deexcitation γ-rays & **neutrons**
➔ JUNO: possibly constrains to ~15% w/ 10 yrs data



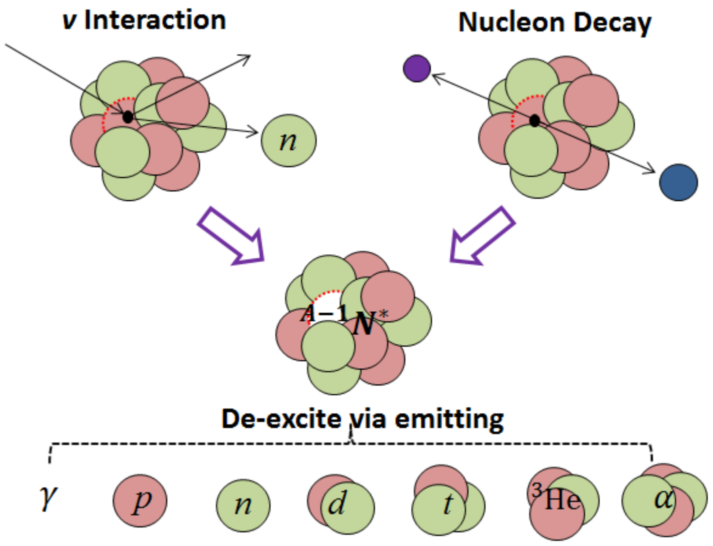
J. Cheng @ FB23

Modified from
PRD 103 (2021) 5, 053002



Systematics: Nuclear de-excitations

De-excitations: An increasingly significant role associated with

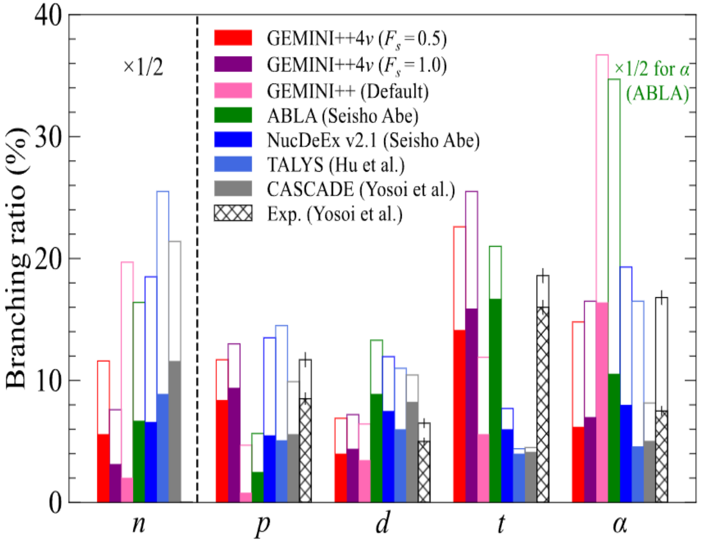


- neutrons
- unstable isotopes
- Mono-energetic γ
- …

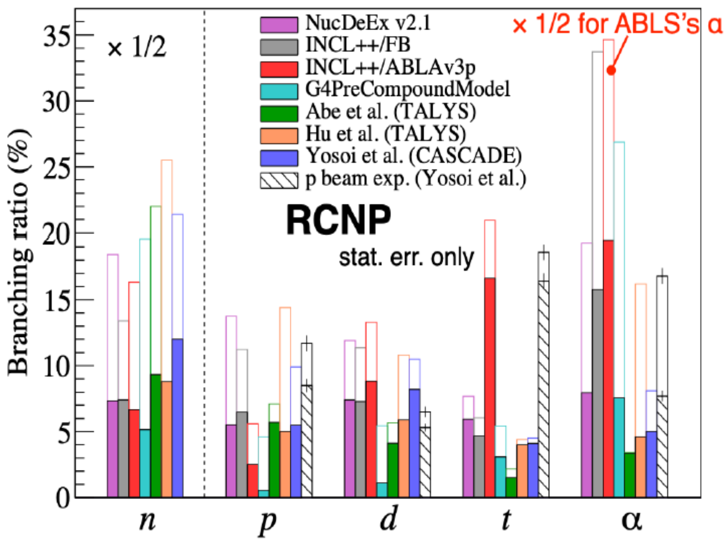
However, no universally adopted and quantitatively accurate models to describe de-excitation cascades!

Two good and easy-to-use codes are available

GEMINI++4ν W.L. Guo @ FB23



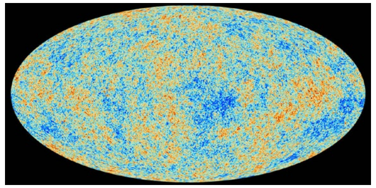
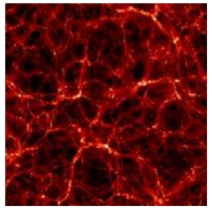
NucDeEx S. Abe @ FB23



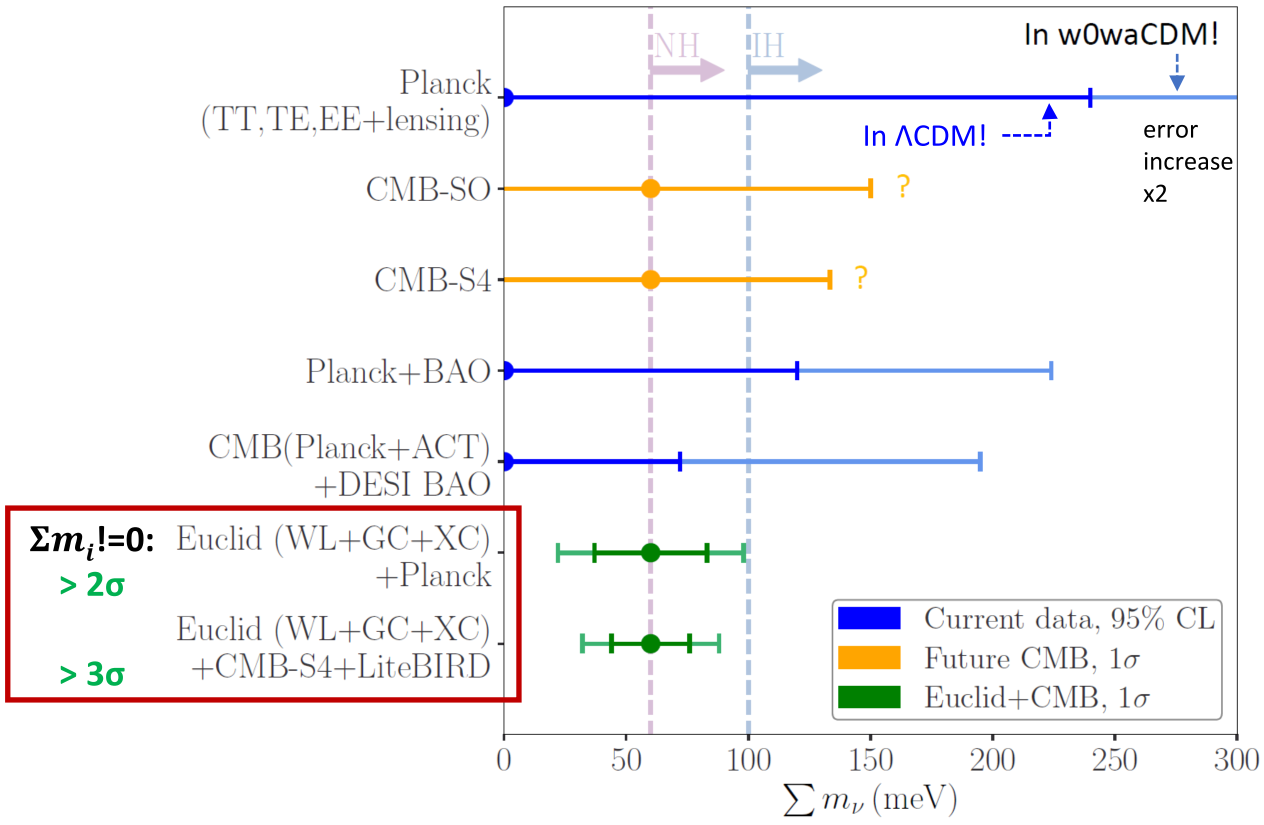
Code	GEMINI++4ν	NucDeEx
Kernel	GEMINI++	TALYS
Model	Weisskopf-Ewing	Hauser-Feshbach
Open source	github.com/NiuYJ1999/GEMINI_4nu	github.com/SeishoAbe/NucDeEx
Paper	Y.J. Niu et al, arXiv:2408.14955	S. Abe, PRD 109 (2024) 036009
Advantage	Best predictions for $^{11}B^*$ and $^{15}N^*$	Good predictions; γ emission;Geant4

Neutrino mass: cosmology, β-decay, 0νββ

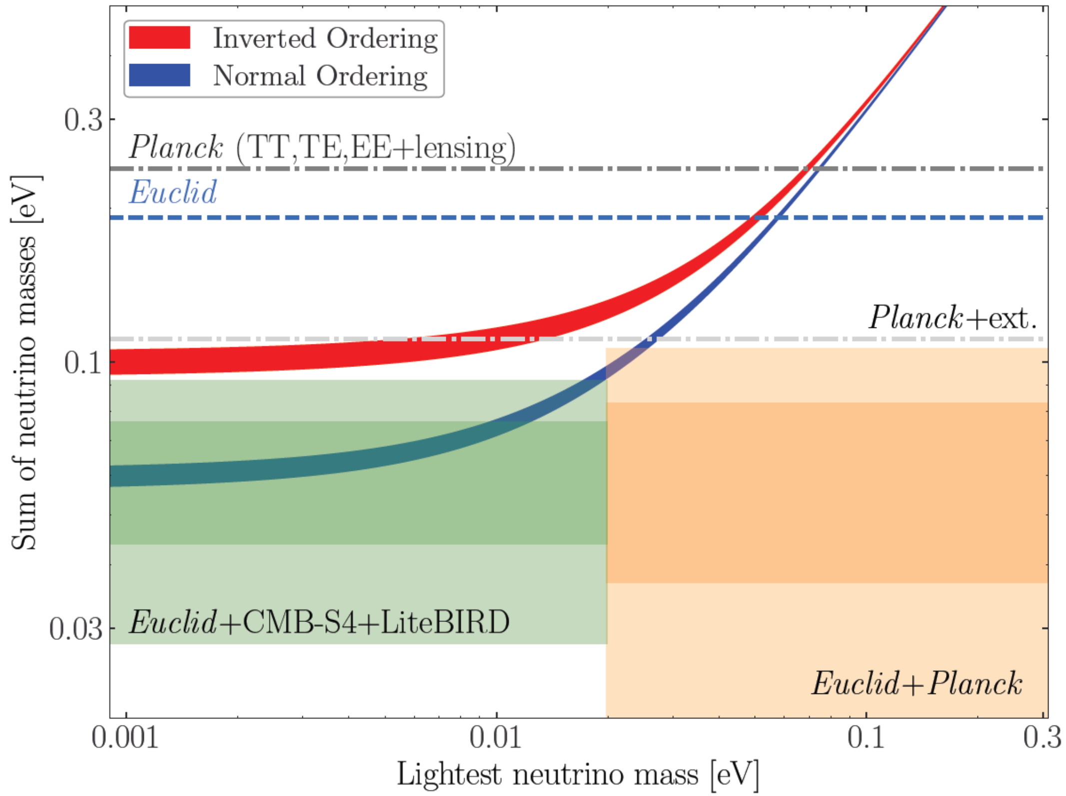
Footprints of **ν** in cosmological observables: CMB + LSS

- Not directly sensitive to the neutrino mass ordering, it constrains Σm_i
- **Model dependent**, and it requires that **systematic effects** are under control
- Not sensitive to the Dirac/Majorana nature, mixing angles
- Still open question: in case of tension between the Cosmos and the Lab



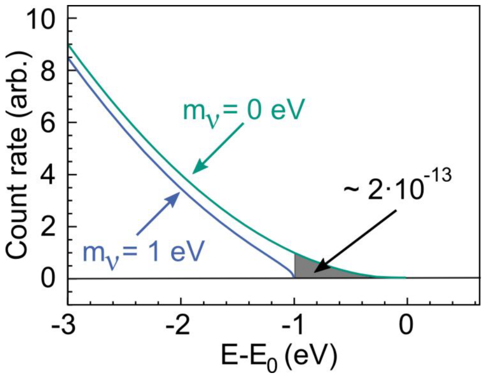
Euclid Collaboration: Archidiacono et al. (2024)

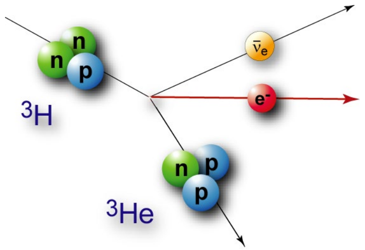


Input fiducial value of the forecast Σm_i = 60 meV

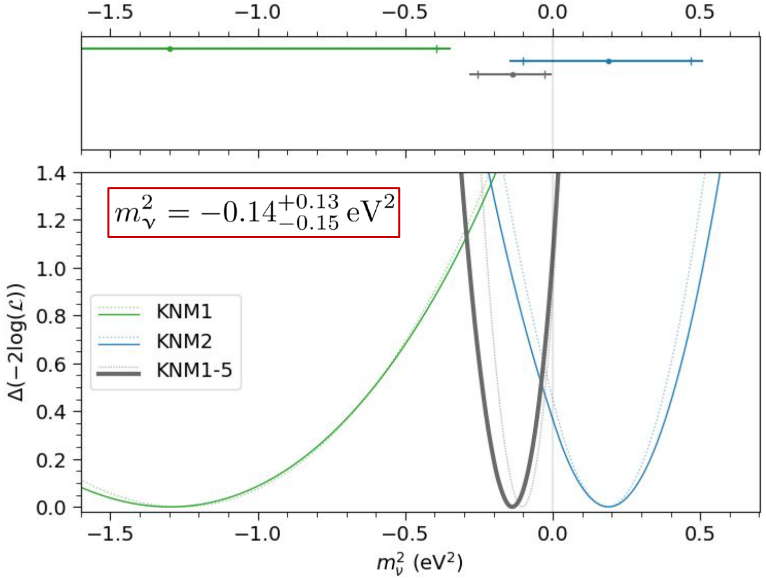
Neutrino mass: cosmology, β-decay, 0νββ

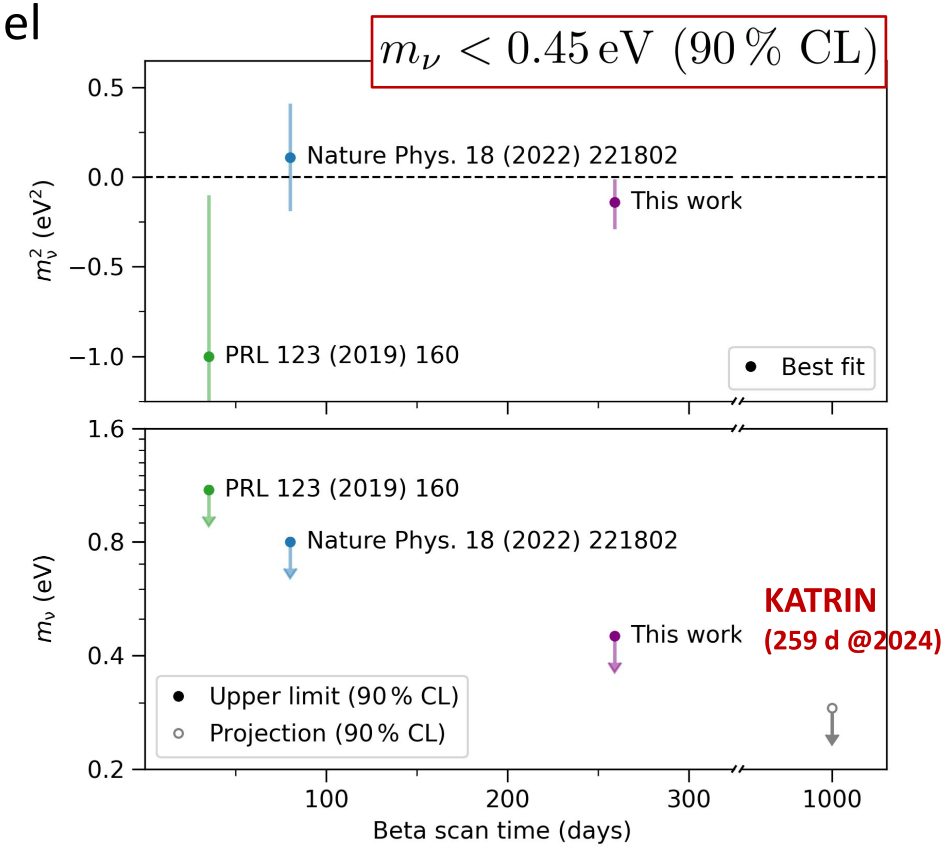
- β decays can measure $m_\beta = \left(\Sigma_i |U_{ei}|^2 m_i^2\right)^{1/2}$
- Experimental challenges:
  - High source activity
  - Excellent energy resolution (~ 1 eV)
  - Low background (≪1 cps)
  - Detector response model

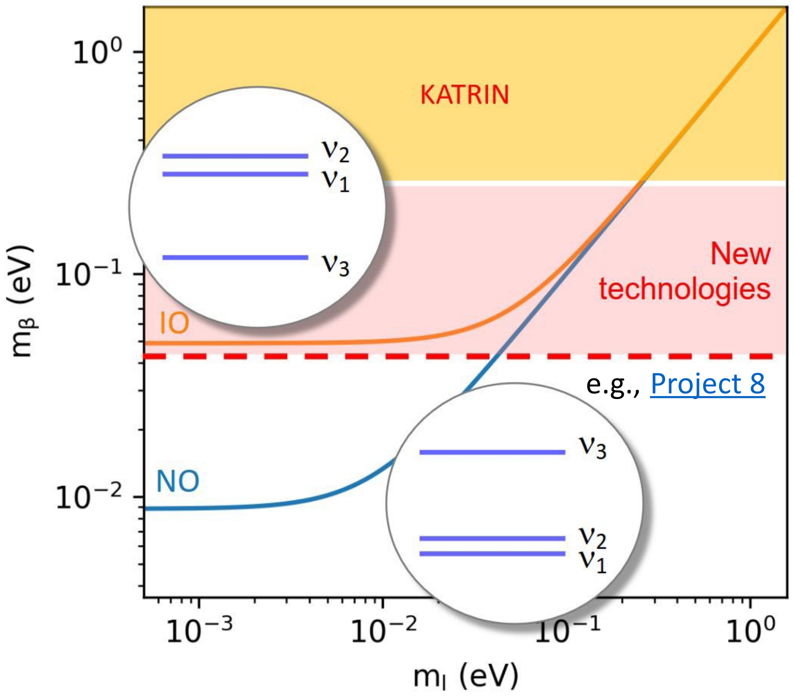




^{3}H: super-allowed β-decay
($T_{1/2}$ ~ 12.3 yrs, E_0 ~ 18.56 keV)



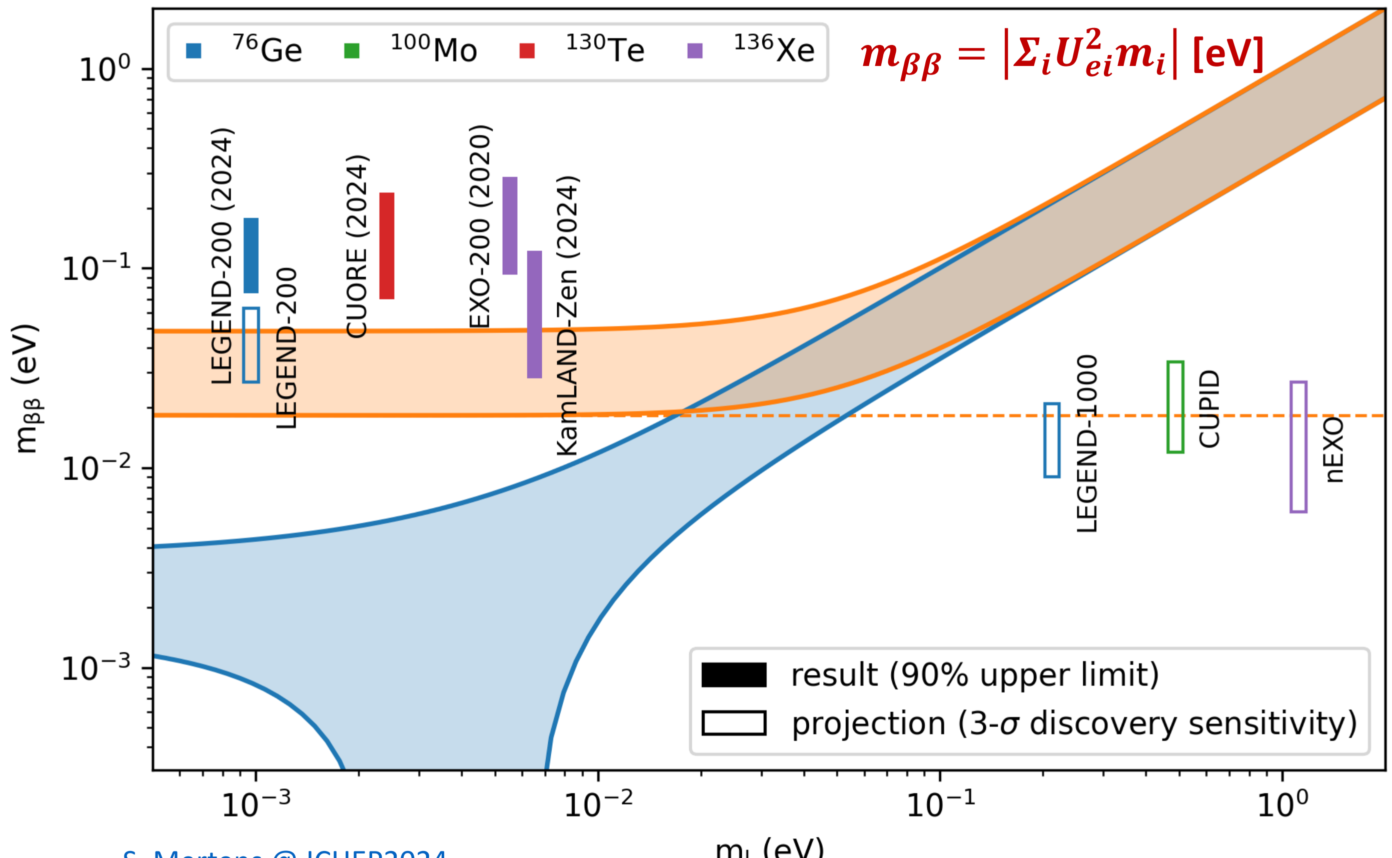




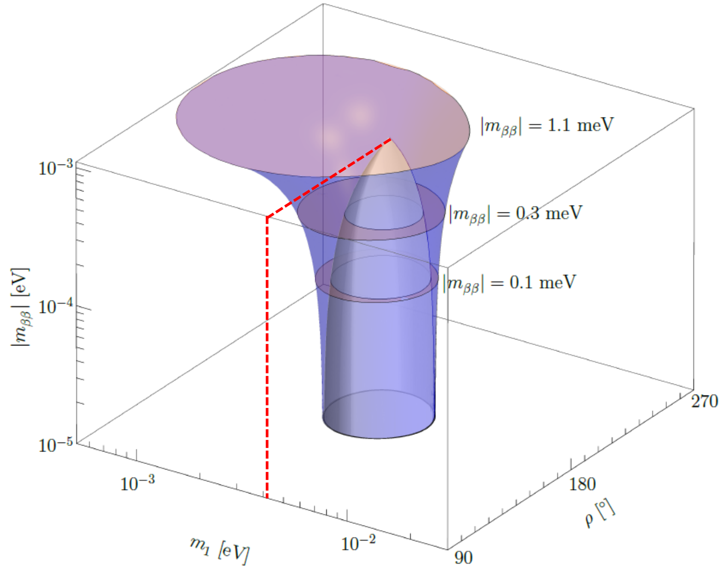
Neutrino mass: cosmology, β-decay, 0νββ

Search for 0νββ decays is a no loss game

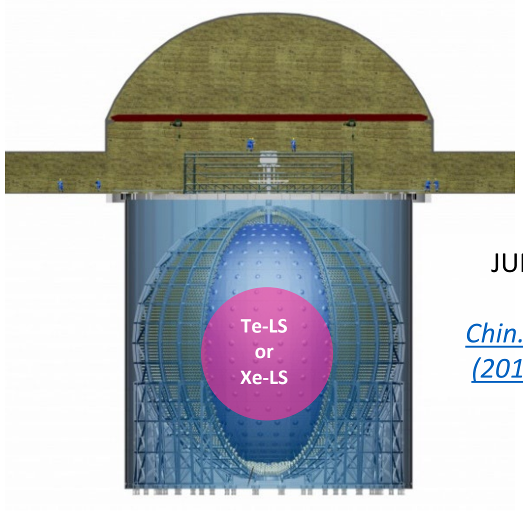
- If 0νββ decays seen ➔ Majorana neutrinos, lepton number violation
- If no 0νββ decays up to ~ 1 meV ➔ determine the lightest neutrino mass (m_1) to be ~ 5 meV, and well constrain Majorana CP-Phases



S. Mertens @ ICHEP2024



J. Cao et al., arXiv:1908.08355 , CPC 44 (2020) 031001

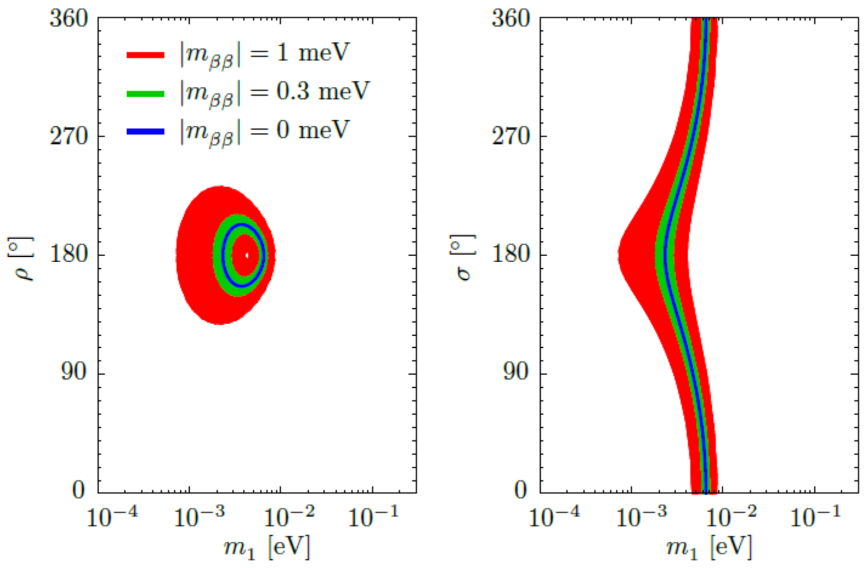


JUNO-0νββ

Chin. Phys. C 41 (2017) 053001

0νββ future prospects

- $m_{\beta\beta}$ sensitivity
  - ~ 10 meV achievable in 10 yrs, ***O****(1 ton)*
  - ~ 1 meV, ***O****(10-100 t)*
  - ~ 0.1 meV, cover almost all parameter space of Majorana neutrinos, ***O****(10^2 - 10^4 t)* target mass



J. Cao et al., arXiv:1908.08355 , [CPC 44 (2020) 031001]

Experimentally to achieve ~ 1 meV sensitivity …

- Increase the target mass while reducing backgrounds
  - Internal backgrounds by purification and/or tagging
  - External backgrounds by tagging, (self-)shielding and/or reduction of the surface-volume ratio
  - ^{8}B solar ν background reduction by directionality

- Technology choices
  - Liquid scintillator detectors need to improve loading
    - ✓ ^{136}Xe: reduce the cost by 1 order
    - ✓ ^{136}Te: increase the loading, reduce internal backgrounds
  - Crystal detectors need to improve shielding and reduce the cost

Understanding the Nuclear Matrix Element

$$\left(T_{1/2}^{0\nu}\right)^{-1} = \frac{\langle m_{\beta\beta}\rangle^2}{m_e^2} G^{0\nu} g_A^4 |M^{0\nu}|^2$$

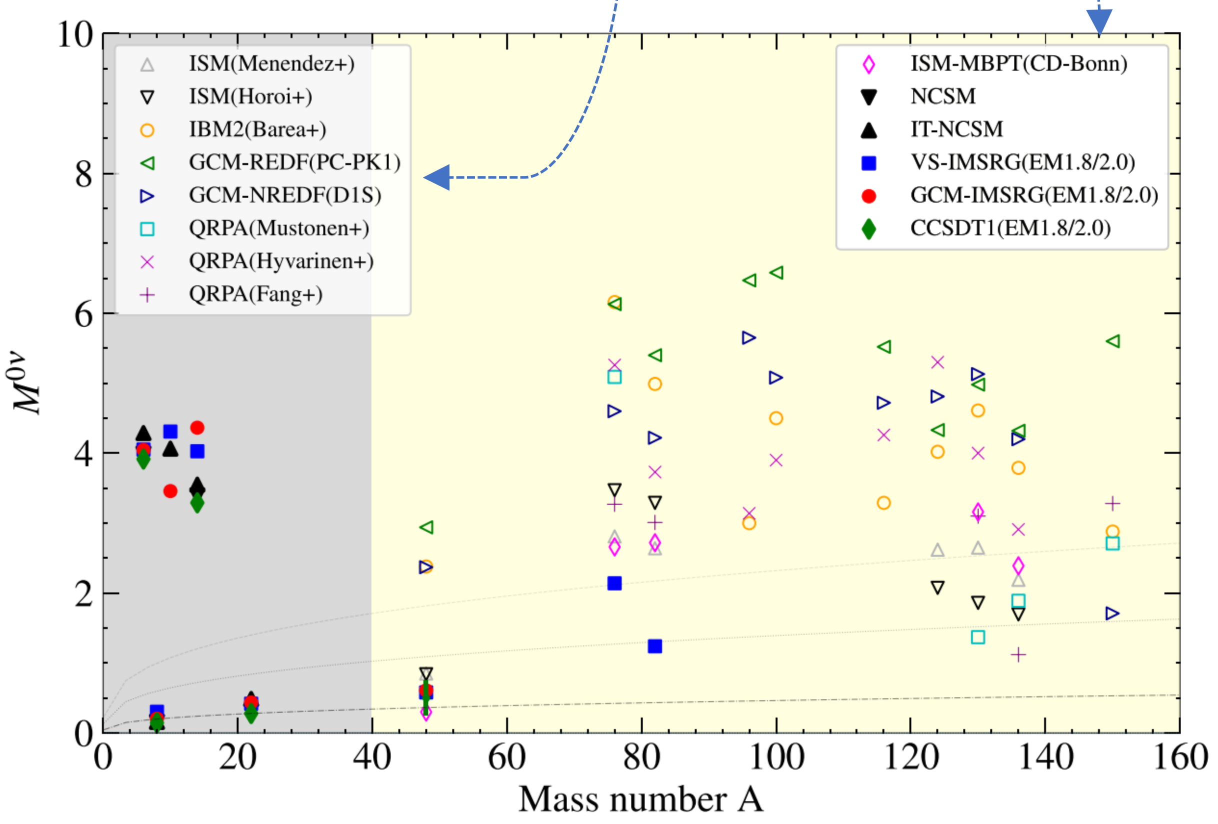
Phase space factor

NME

- Predictions on nuclear matrix element (NME), **$|M^{0\nu}|$,** has large uncertainty, using various **many-body methods**

- Constrain (indirectly) NME with experimental inputs
  - Precision $2\nu\beta\beta$ decay measurement
  - Heavy-ion double charge exchange reactions
  - Ordinary muon capture
  - Double nucleon transfer reaction, e.g., $^{138}\mathrm{Ba}(p,t)$
  - Double gamma decay

- Nuclear many-body approaches based on
  - *ab initio* (realistic) nuclear force
  - phenomenological nuclear force
- **short-range operator**



J. Yao et al, Prog. Part. Nucl. Phys. 126 (2022) 103965

Summary

- Revealing the mysteries of neutrinos are extremely important for understanding the two infinities: particle physics and cosmology
- Neutrino oscillation studies entered a precision era, oscillation will be completely understood in **~10 yrs**: mass ordering and δ_{CP}
- Neutrino absolute masses may be measured in **~20 yrs**, via cosmology, β-decay and 0νββ
- Neutrino's Majorana nature may be determined in **~30 yrs**

- New experiments will be online. Exciting results will come out soon!

Thank you!