Neutrino Oscillation Experiments - review

Amina Khatun

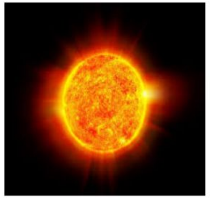
V4 HEP Workshop
Budapest, 12-14 March 2024

Outline

- ❖ History of neutrino oscillation
  - ➢ Solar neutrino anomaly
  - ➢ Atmospheric neutrino anomaly
- ❖ Results from past and ongoing experiments
  - ➢ Solar neutrino experiments
  - ➢ Atmospheric neutrino experiments
  - ➢ Short and long-baseline reactor neutrino experiments
  - ➢ Accelerator-based long-baseline experiments
- ❖ Future roadmap
  - ➢ JUNO in China
  - ➢ DUNE in US
  - ➢ Hyper-K in Japan

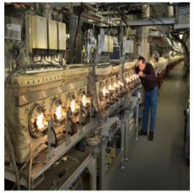
Neutrino sources

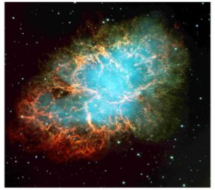
Nuclear Reactors
(E ~ 0.1 - 10 MeV)
Detected (1956)
Cowan, Reines
(nobel Prize 1995)



Sun
(E ~ 0.8 - 15 MeV))
Detected (1968)
Davis, Bahcall

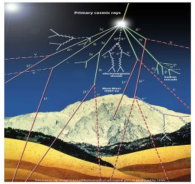
Particle
Accelerators
Detected (1962)
Brookhaven National
Lab, Nobel Prize 1988





Supernovae
(Stellar Collapse)
(E ~ 10 - 30 MeV)
Detected in
1987 SA

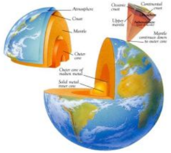
Earth Atmosphere
(Cosmic Rays)
(E ~ MeV - TeV)
Detected (1965)
KGF in India
and south Africa

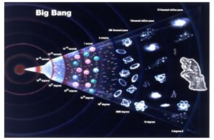


Astrophysical
Accelerators
(E > TeV)

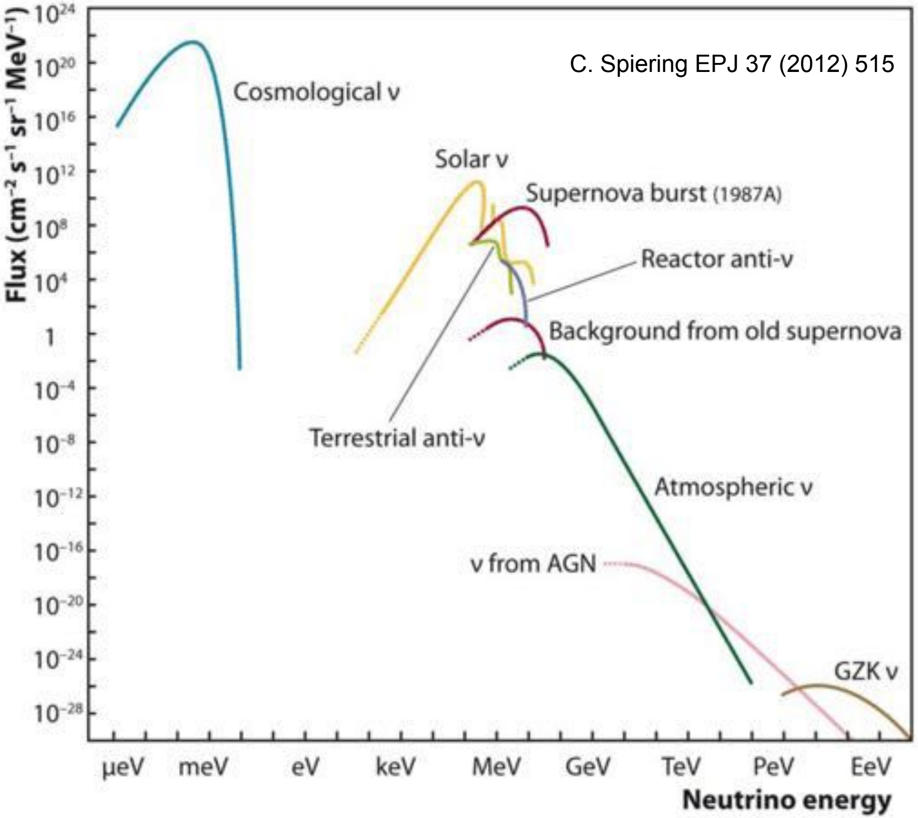
IceCube detected
around 82 events
in 6 years

Earth Crust
Natural Radioactivity
(E ~ 0.1 - 3 MeV)
Detected (2000)

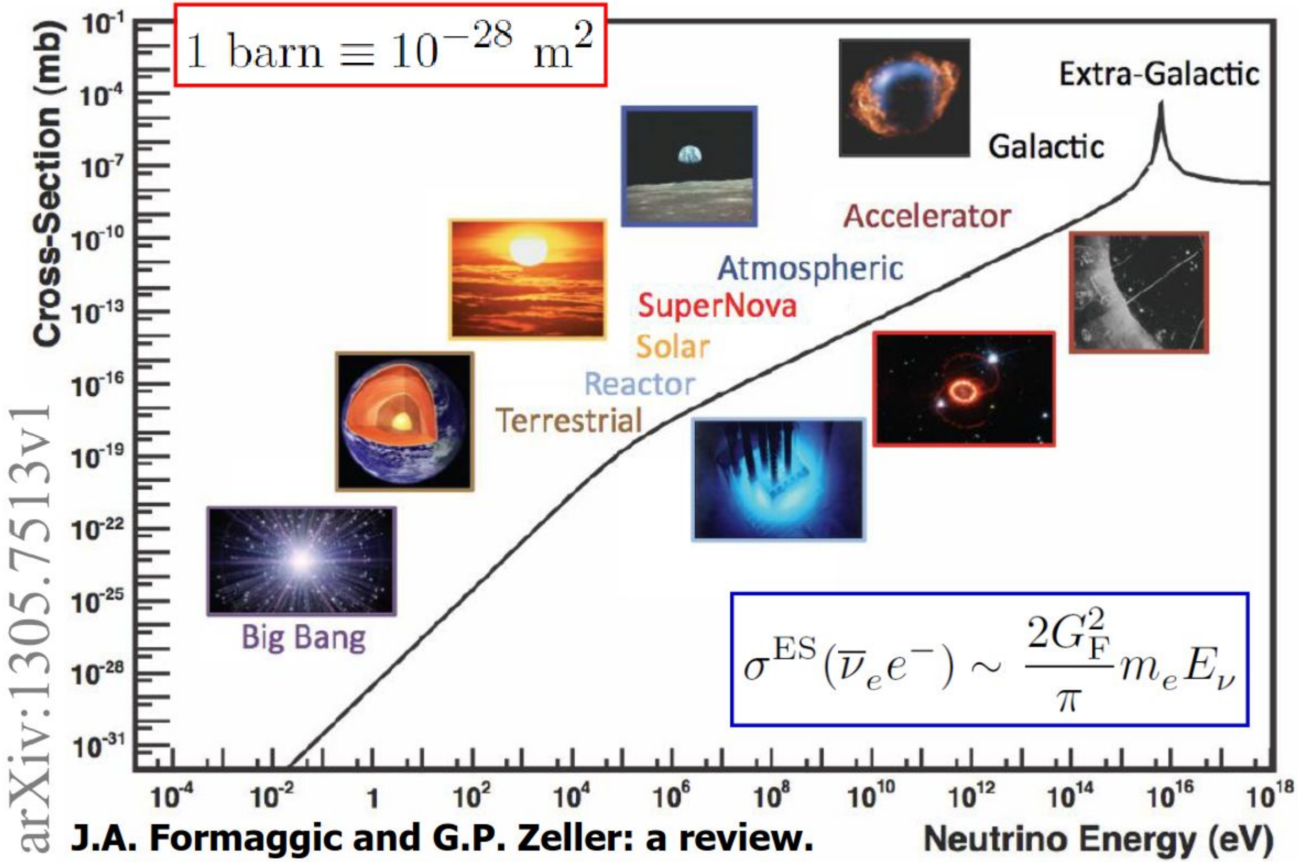




Cosmic Bigbang
(E ~ 0.17 meV)



Neutrinos interact very rarely

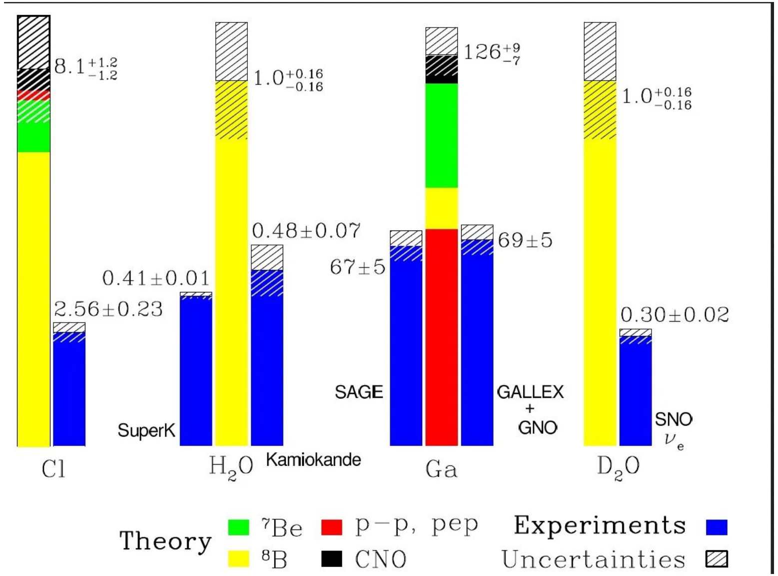


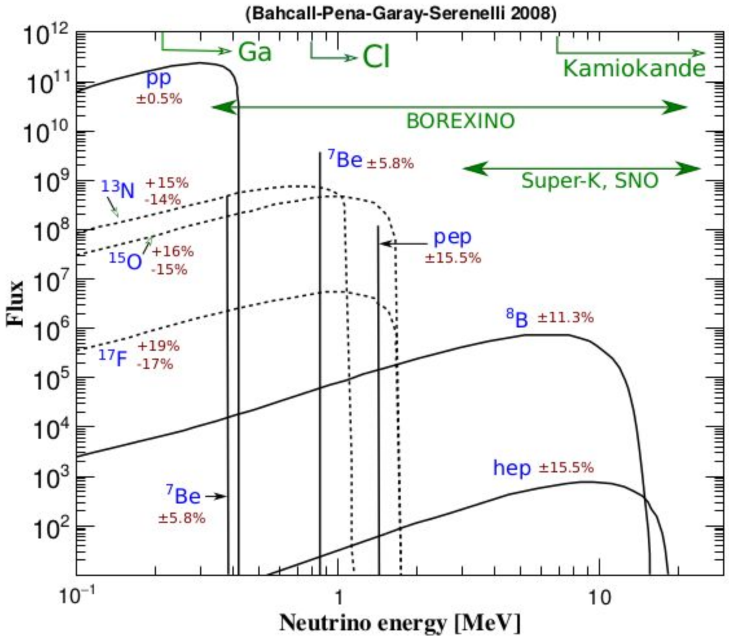
- Large neutrino detectors (kton order) are required
- Cosmogenic muons are the major backgrounds, therefore detectors are placed underground or underwater

Underground Research Facilities

Solar neutrino anomaly

- The observation of solar neutrinos first indicated that there is something about neutrino was unknown that time, which is neutrinos have nonzero mass and mix among each other
- The electron neutrinos reaching at Earth from Sun is around ⅓ of the predicted flux





Solar neutrino detection by radiochemical experiments

1965 ...

Homestake experiment: Raymond Davis first time observed solar neutrinos in

Target: 615 ton C_2Cl_4

Ar atoms are counted by observing their decay to have solar neutrino flux

$^{37}Cl(\nu_e,e)^{37}Ar$ (E_{thr} = 813 keV)

K_{shell} **EC** τ = 50.5 d

^{37}Cl + 2.82 keV (*Auger e⁻, X*)

Observed much smaller (⅓) than the predicted flux

SAGE in BAKSAN, 1989 - contd.

Gallex/GNO In LNGS 1991 - 2003

Target: ^{71}Ga

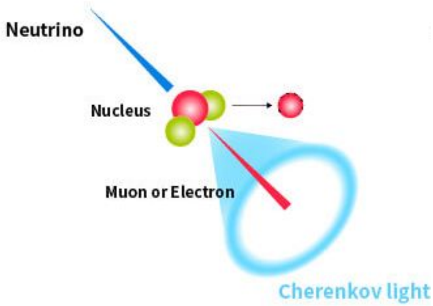
$^{71}Ga(\nu_e,e)^{71}Ge$ (E_{thr} = 233 keV)

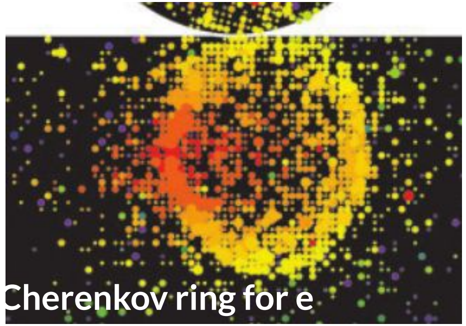
K,L shell **EC** τ = 16.5 d

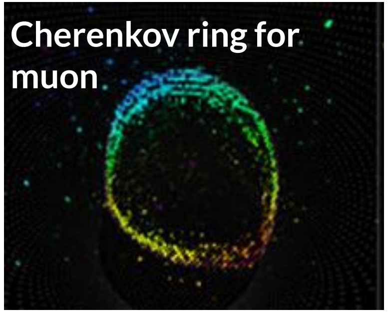
^{71}Ga + 10 keV, 1 keV (Auger e⁻, X)

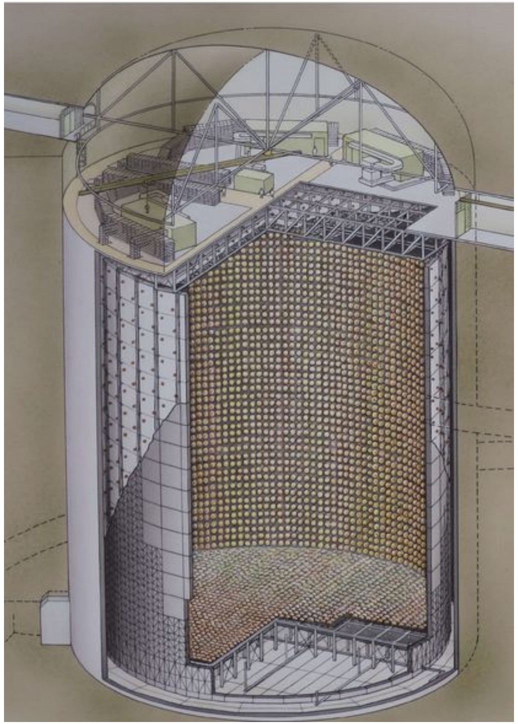
Super-Kamiokande (Super-K) in Japan

- **50 kiloton water Cherenkov detector**
  - ❖ Detect neutrinos from various sources
    - ➢ Sun
    - ➢ Earth's atmosphere
    - ➢ particle accelerators
  - ❖ Real-time measurement of energy spectra of neutrinos

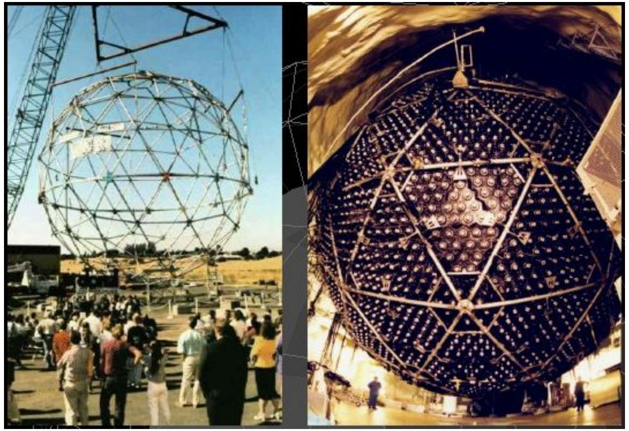








Sudbury Neutrino Observatory, Canada, 1999-2006

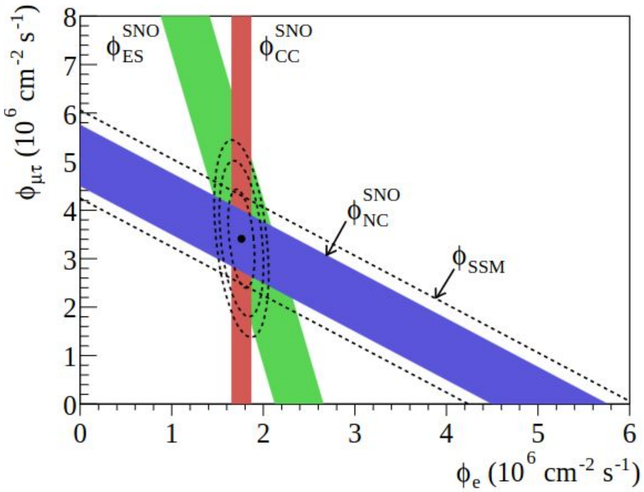


Heavy water detector, D_2O (1000 tons)

How it can do more than water?

$$\nu_e + d \rightarrow p + p + e^- \quad \text{(CC)}$$
$$\nu_x + d \rightarrow p + n + \nu_x \quad \text{(NC)}$$
$$\nu_x + e^- \rightarrow \nu_x + e^- \quad \text{(ES)}$$

NC events in agreement with the predicted total solar event: proves that electron neutrinos are not lost, just converted to other flavors

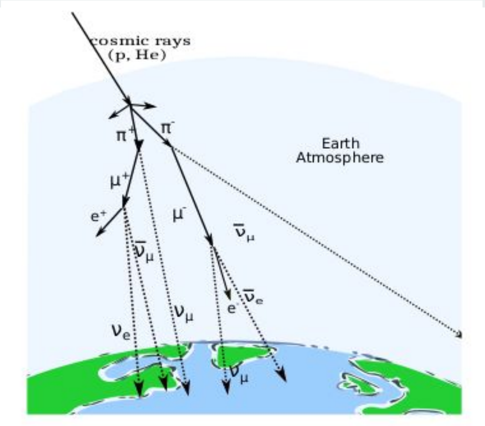


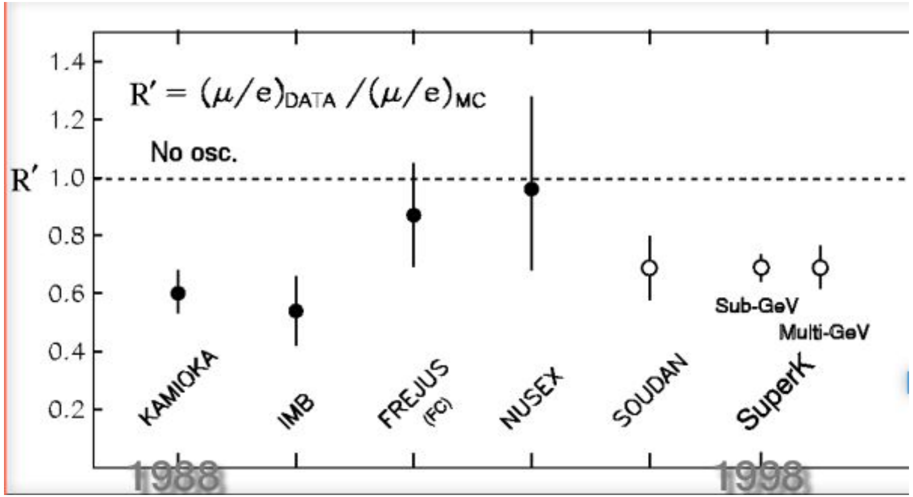
Solar neutrino data agrees with the solution of Large mixing angle with MSW effect (Mikheyev-Smirnov-Wolfenstein) due to matter potential

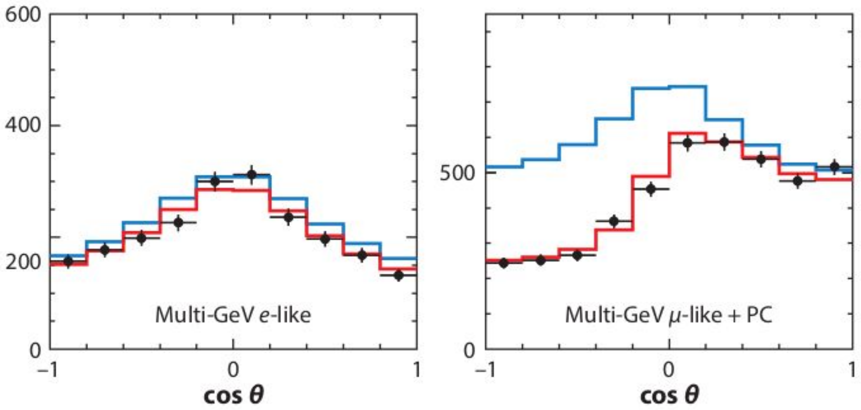
Atmospheric neutrino anomaly

- The hint of the atmospheric neutrino anomaly was found in the relative number of muon neutrino to electron neutrinos

- Electron neutrinos are in agreement with prediction, however, muon neutrinos are less by half of the predicted

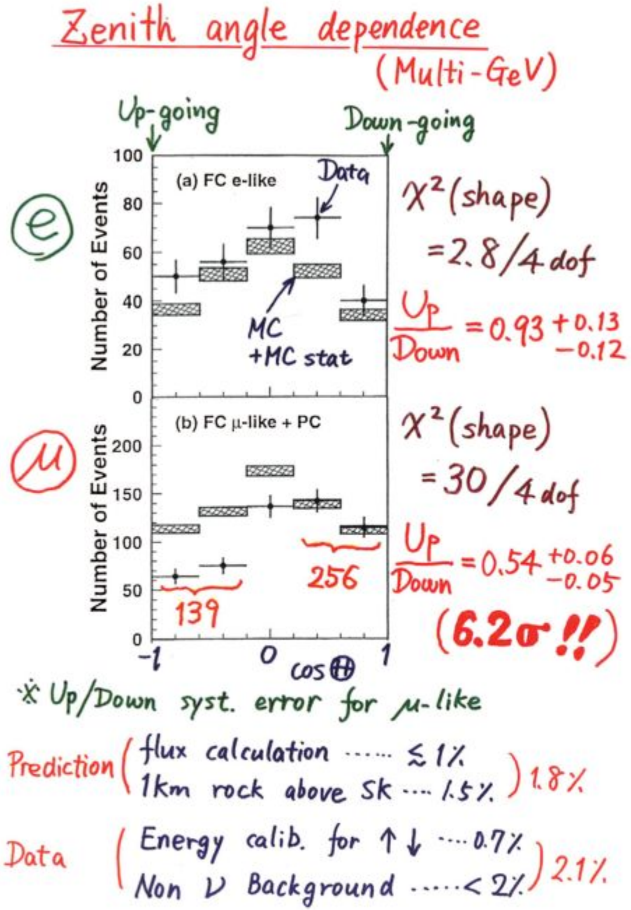


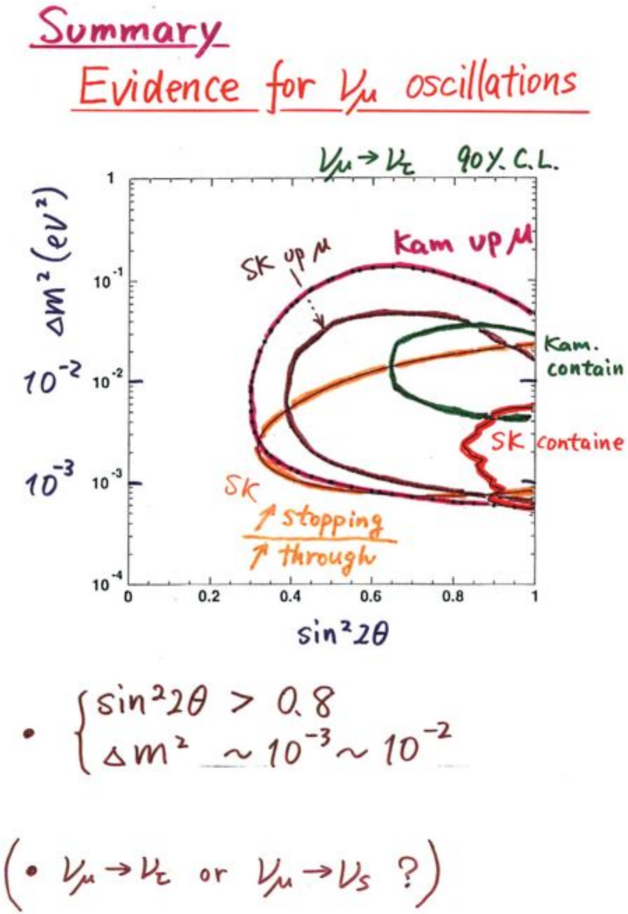


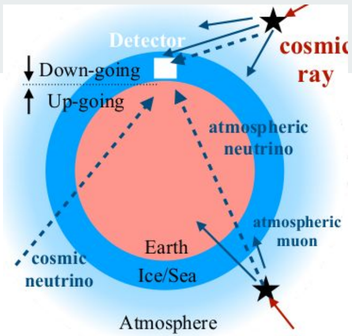


Annu. Rev. Nucl. Part. Sci. 2014. 64:343–62

Discovery of neutrino Oscillation in 1998







Nobel prize lecture by Takaaki Kajita
REV. Of Mod. Phys., V 88

Three-neutrino mixing paradigm

Flavor neutrinos (ν_α) are superposition of neutrinos with definite masses

At source : $|\nu_\alpha\rangle\,(t=0) = \sum_{i=1}^{3} U^*_{\alpha i}\,|\nu_i\rangle$

At Detector: $|\nu_\alpha\rangle\,(t>0) = \sum_{i=1}^{3} U^*_{\alpha i}\; e^{-iEt}\,|\nu_i\rangle$

Probability of transition

$$P(\nu_\alpha \to \nu_\beta) = |\langle \nu_\beta | \nu_\alpha(t)\rangle|^2 = \sum_{k,j} U^*_{\alpha k} U_{\beta k} U_{\alpha j} U^*_{\beta j}\, \exp\left(-i\frac{\Delta m^2_{kj} L}{2E}\right)$$

$$\Delta m^2_{kj} = m^2_k - m^2_j$$

Pontecorvo - Maki - Nakagawa -Sakata (PMNS) Matrix

$$U = \underbrace{\begin{pmatrix} 1 & 0 & 0 \\ 0 & C_{23} & S_{23} \\ 0 & -S_{23} & C_{23} \end{pmatrix}}_{\text{Atmospheric sector}} \underbrace{\begin{pmatrix} C_{13} & 0 & S_{13}\,e^{-i\delta} \\ 0 & 1 & 0 \\ -S_{13}\,e^{i\delta} & 0 & C_{13} \end{pmatrix}}_{\text{Reactor sector}} \underbrace{\begin{pmatrix} C_{12} & S_{12} & 0 \\ -S_{12} & C_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}}_{\text{Solar sector}}$$

$C_{ij} = \cos\theta_{ij},\ S_{ij} = \sin\theta_{ij}$

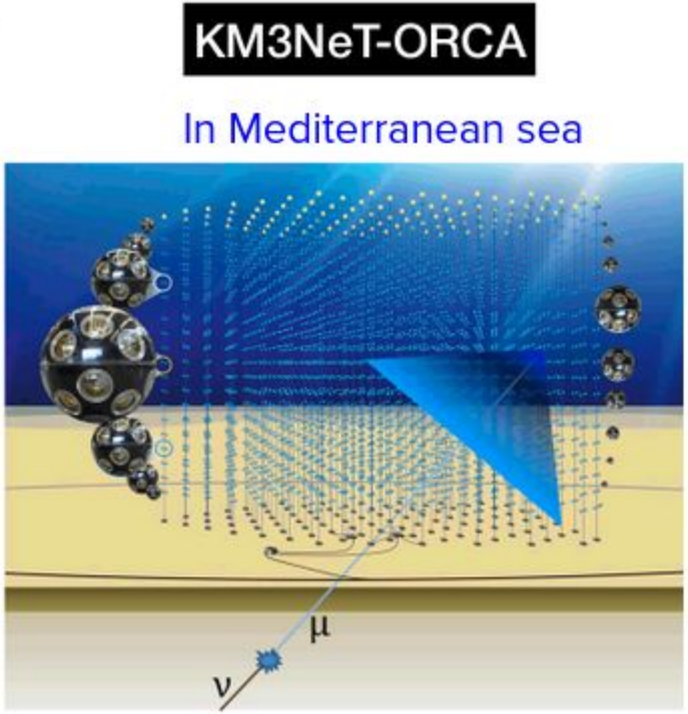
2ν mixing

$$P_{\nu_\alpha \to \nu_\alpha}(L,E) = 1 - \sin^2 2\theta\ \sin^2\left(1.27\frac{\Delta m^2_{ij}[\mathrm{eV}^2]\ L\,[\mathrm{m}]}{E\,[\mathrm{MeV}]}\right)$$

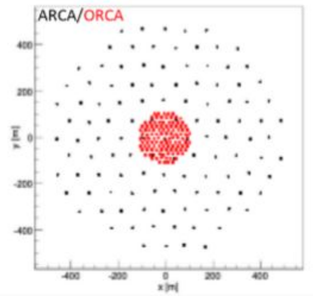
Independent osc. par. : $\theta_{23},\ \theta_{12},\ \theta_{13},\ \delta,\ \Delta m^2_{21} \equiv m^2_2 - m^2_1,\ \Delta m^2_{31} \equiv m^2_3 - m^2_1.$

Atmospheric neutrino oscillation experiments

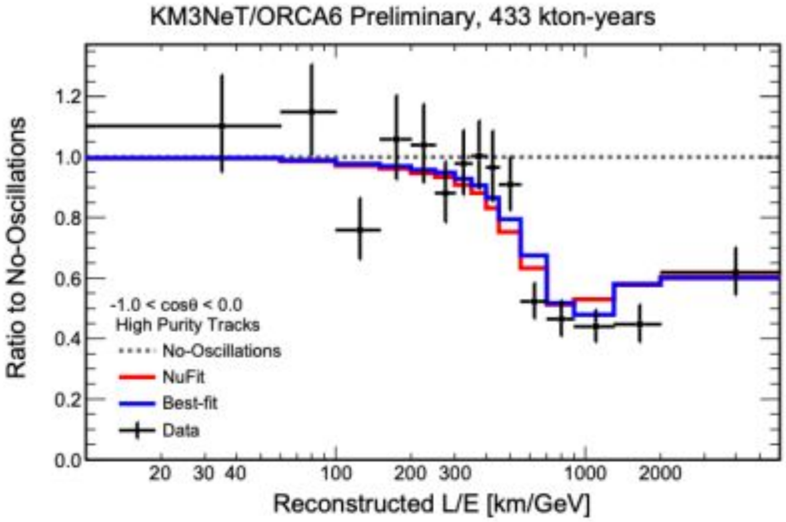
➢ Wide range of L/E: Atmospheric neutrino has wide range of energies and travels through a few km to thousands of km distance through Earth's matter



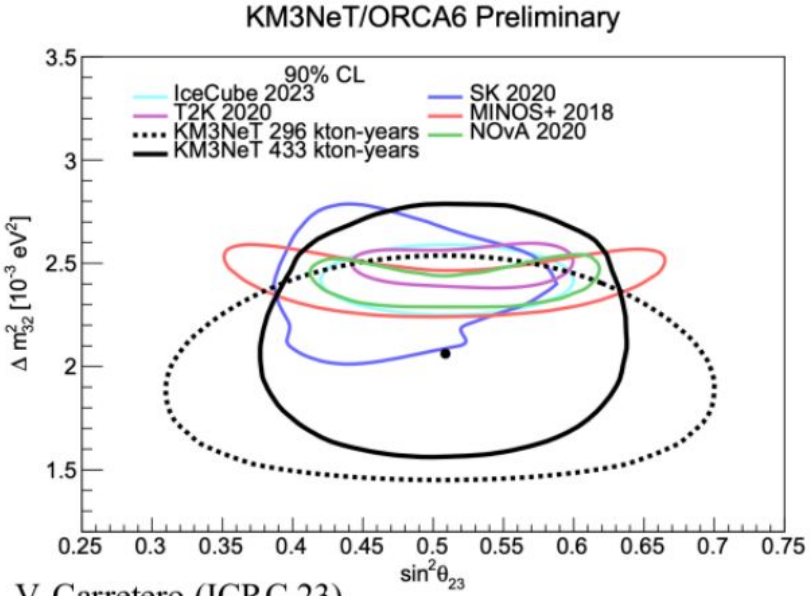
KM3NeT - ORCA Results



- Currently 19 strings are taking data of ORCA (spacing 23m x 9m) and 21 lines of ARCA (spacing 90m x 36 m)
- Dense distribution of lines make ORCA sensitive to GeV neutrinos

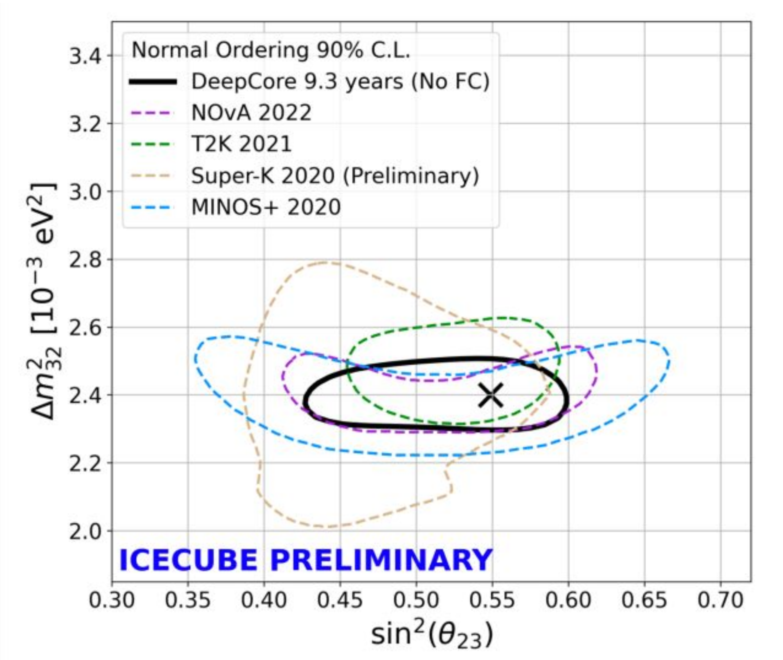


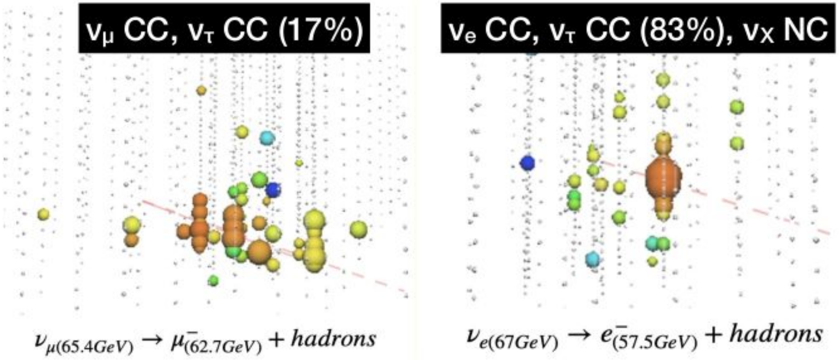
High Purity Tracks

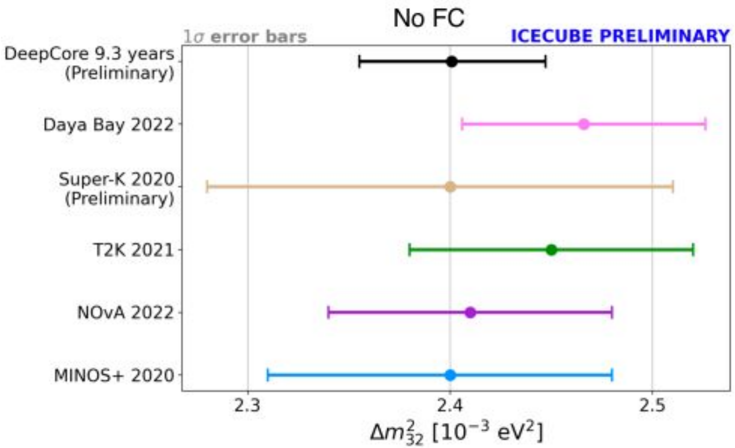


V. Carretero (ICRC 23)

Results from DeepCore : 8 strings in dense configuration







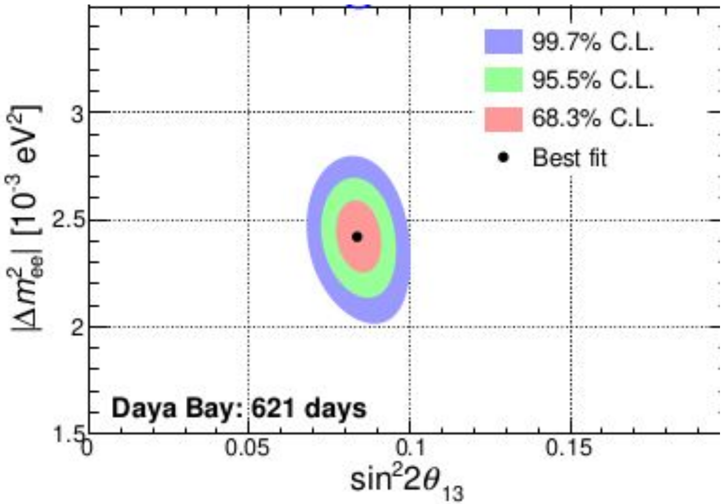
S. Yu and J. Micallef (ICRC 23)

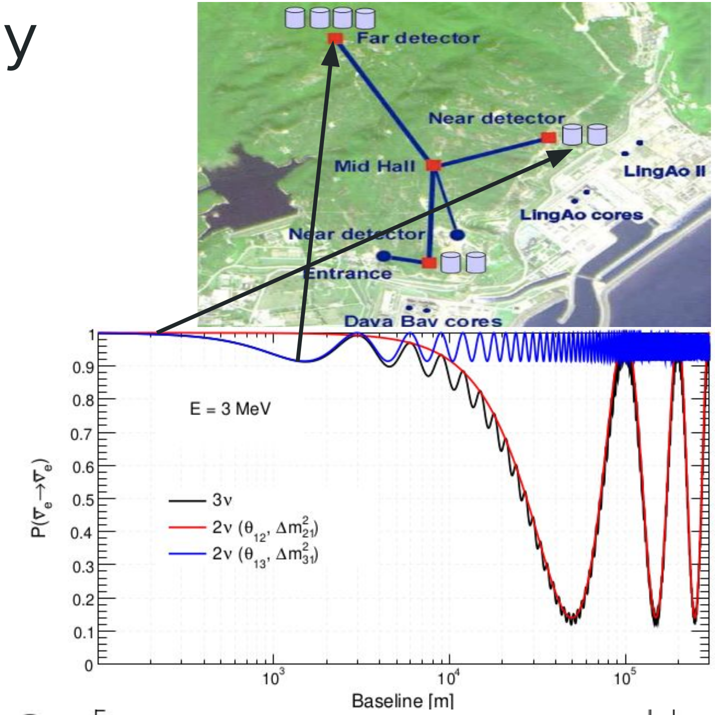
Result of DeepCore is competitive to accelerator-based neutrino experiments

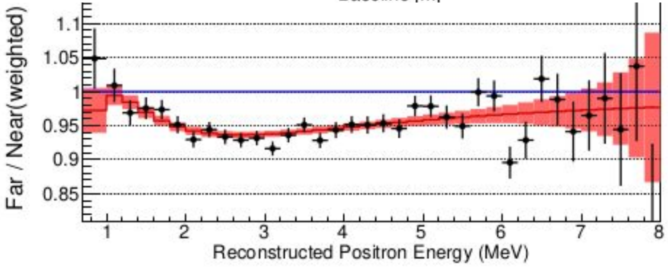
Reactor neutrino experiment: Daya Bay

- High statistics: 80 ton Gd-LS detector, powerful reactors: 17.6 GW_{th}
- Near and far detector in Daya Bay help to reduce systematics due to antineutrino flux from nuclear reactor
- Daya Bay measured 1-3 mixing angle with unprecedented precision

JHEP 10 (2014) 086

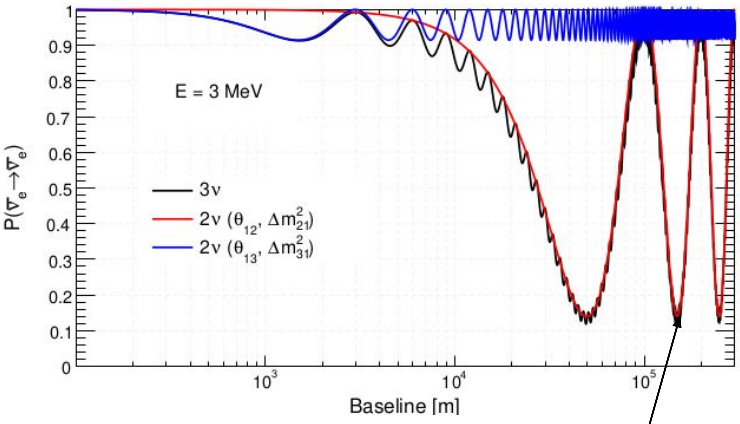






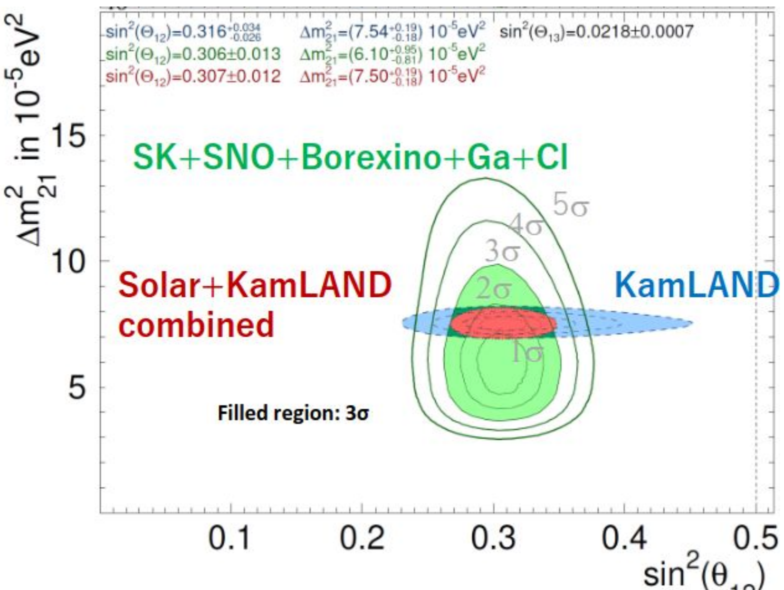
Long baseline Reactor neutrino experiment: KamLAND

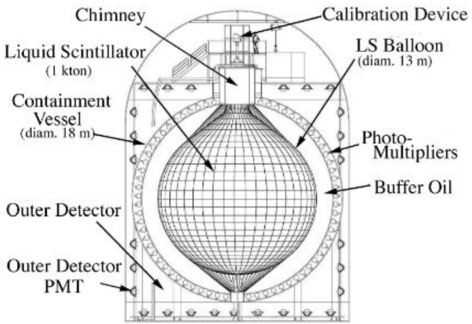
- Oscillation in KamLand is governed by smaller mass-squared difference (solar mass splitting)
- KamLAND provides complementary measurement of solar neutrino oscillation parameters



KamLAND (180 km from reactors)

PRD 100, 082004
CNO: Nature 587, 577





Current knowledge about the oscillation parameters

Mixing of three active neutrinos with at least two massive, fits the data quite well*

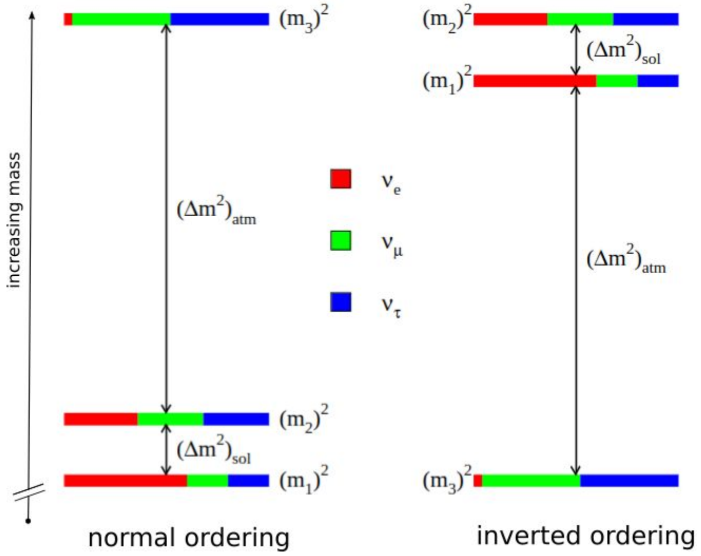
$$\begin{aligned}
\Delta m^2_{21} &= (7.42 \pm 0.21) \times 10^{-5}\ \text{eV}^2 \quad (3\%) \\
|\Delta m^2_{31}| &= (2.50 \pm 0.03) \times 10^{-3}\ \text{eV}^2 \quad (1\%) \\
\sin^2\theta_{12} &= 0.304 \pm 0.013 \quad (4\%) \\
\sin^2\theta_{13} &= 0.02220 \pm 0.00068 \quad (3\%) \\
\sin^2\theta_{23} &= 0.573 \pm 0.023 \quad (5\%) \\
\delta_{CP} &= (105 - 405)^\circ \ (3\sigma) \quad (\text{unknown}) \\
\text{sign}(\Delta m^2_{31}) &= +,\ \text{slightly favored} \quad (\text{unknown})
\end{aligned}$$

http://www.nu-fit.org

But, so much still unknown

Uncharted Realms of Neutrino Mysteries

- ❖ What is neutrino mass ordering (NMO) ?
  - ➢ Vacuum oscillation of reactor antineutrino
  - ➢ Matter effect while passing Earth's matter
- ❖ What is the octant of θ_{23}
  - ➢ Lower octant if >45 degree
  - ➢ Higher octant if < 45 degree



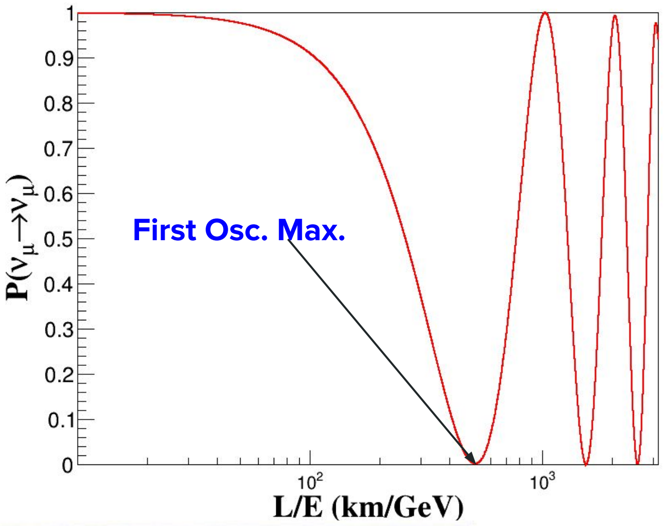
- ❖ What is the particle nature of neutrino ?
- ❖ Is there fourth neutrino state (sterile) ?
- ❖ Is there non-standard Interactions of neutrino
- ❖ Link between neutrino and dark matter

Plethora of neutrino experiments are currently running and many are under construction to pin down these unknowns.

Accelerator-based Long-baseline neutrino Experiments

- ν_μ is produced at accelerators, and in the far detector, ν_μ , ν_e , and ν_τ are detected
- Detectors at source (near det.) and at oscillation maximum (far det.) help in precision measurement

$$ND(\nu_\mu) = \boxed{\Phi(E_\nu) \times \sigma(E_\nu, A)} \times \epsilon_{ND}$$
$$FD(\nu_\mu) = \boxed{\Phi(E_\nu) \times \sigma(E_\nu, A)} \times \epsilon_{FD} \times P_{osc}$$



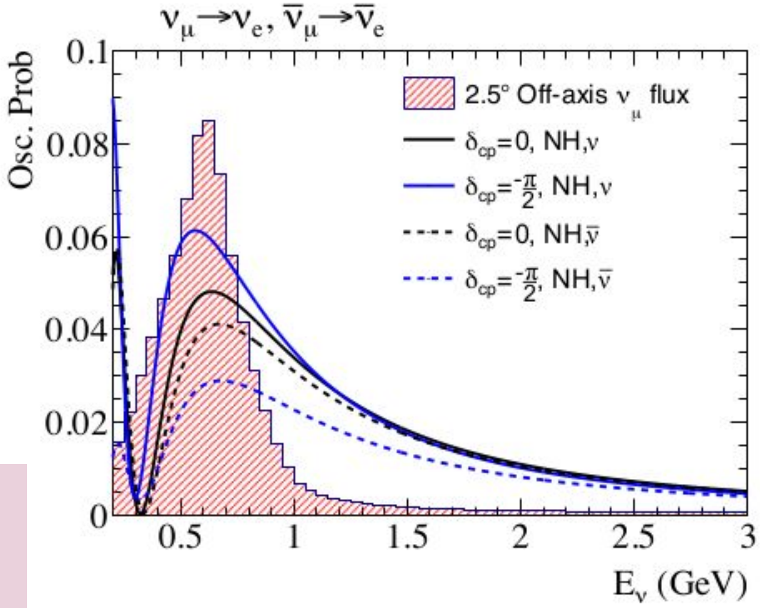
Appearance Probability at far detector (295 km) of T2K

Vacuum like

$$P(\nu_\mu \to \nu_e) \simeq \sin^2(2\theta_{13})\sin^2(\theta_{23})\sin^2\left(1.27\Delta m^2_{32}\frac{L}{E_\nu}\right)$$
$$\mp 1.27\Delta m^2_{32}\frac{L}{E_\nu}8J_{\rm CP}\sin^2\left(1.27\Delta m^2_{32}\frac{L}{E_\nu}\right)$$

$$J_{\rm CP} \equiv \sin\theta_{13}\cos^2\theta_{13}\sin\theta_{12}\cos\theta_{12}\sin\theta_{23}\cos\theta_{23}\sin\delta_{\rm CP}$$

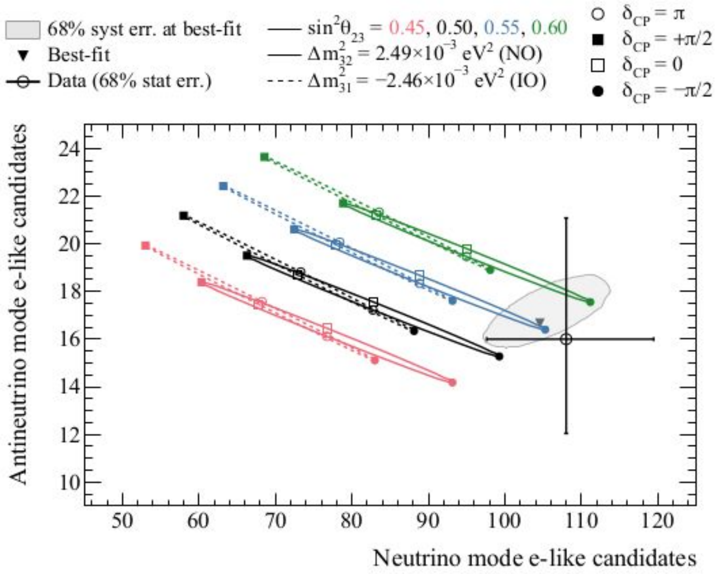
- The leading order depend on $\sin^2\theta_{23}$, therefore can probe the octant of θ_{23},
- Subleading dependence on CP phase, therefore detect CP violation

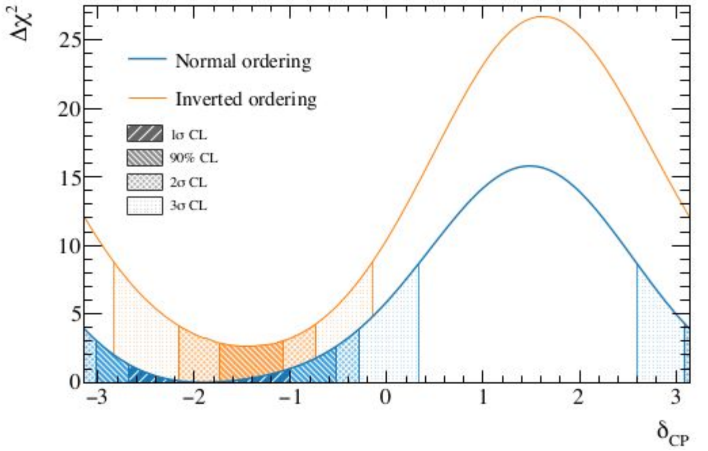


J G Walsh, 20th Conference FP and CPV, 2022

T2K results on Delta CP

- Eightfold degeneracy between Dirac CP phase, octant of θ_{23} and mass ordering
- An asymmetry between neutrino and antineutrino is observed
- Maximal violation of CP is observed for both the mass ordering
  - Normal ordering, and higher octant of θ_{23} with a nearly maximum violation of CP is favored
- Exclude δ_{CP} =0 and π at 90 % C.L.

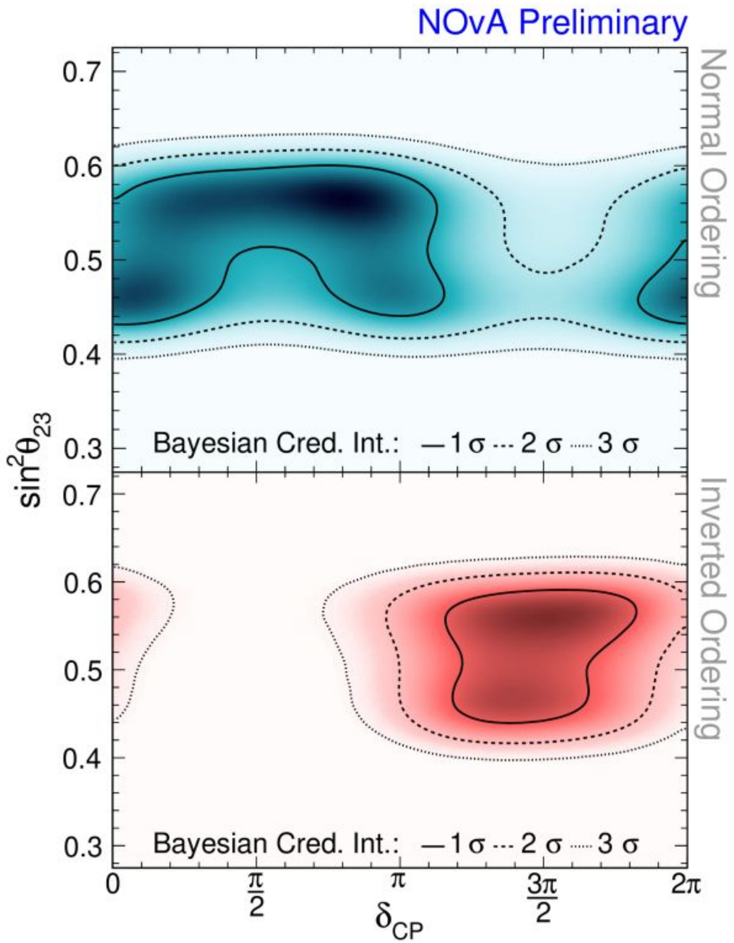


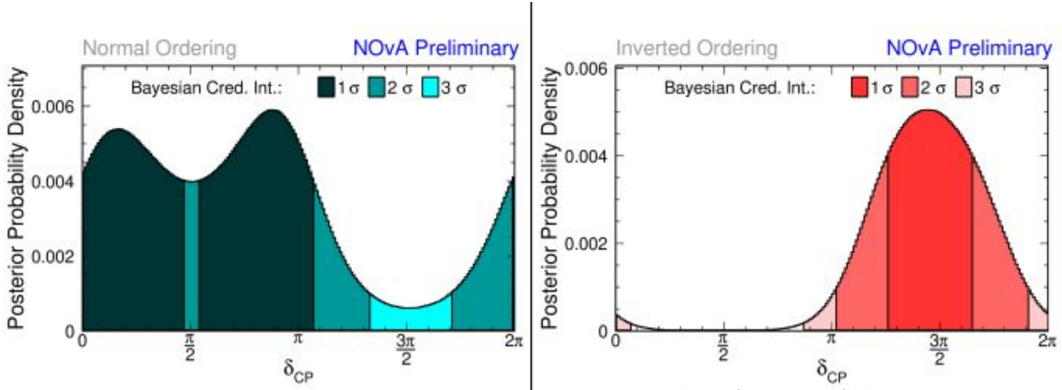


Eur.Phys.J.C 83 (2023) 9, 782

NOvA results on delta CP phase

Mayly Sanchez TAUP2023





Note opposite convention than T2K (3π/2 = - π/2)

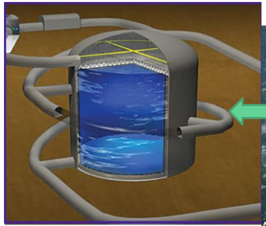
- No asymmetry in electron neutrino vs antineutrino rates of appearance. Disfavoring points that would produce asymmetry

Disfavor NH δ=3π/2 at ~2σ
Exclude IH δ=π/2 at > 3σ

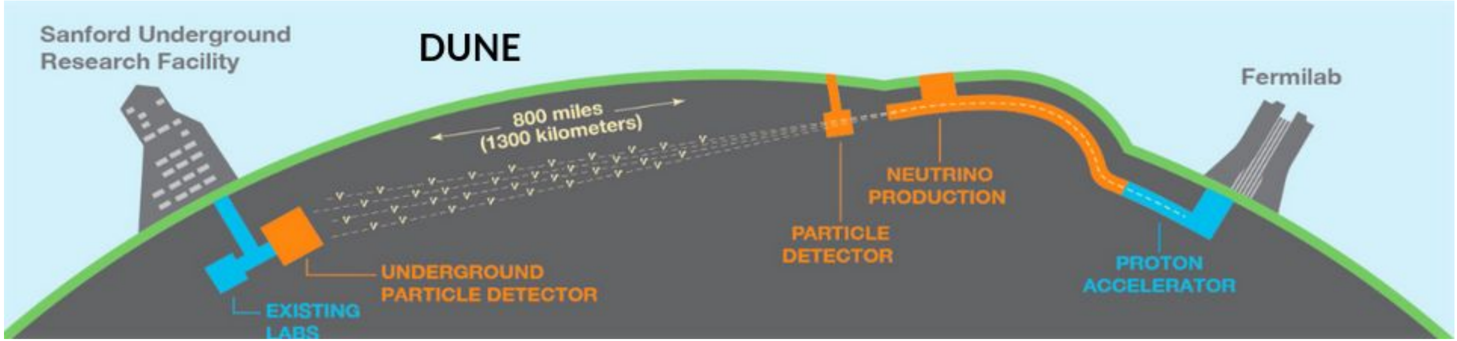
Favored region in T2K and NOvA are opposite for NO, Combined analysis is ongoing

Future Neutrino Oscillation Experiments

Hyper-K



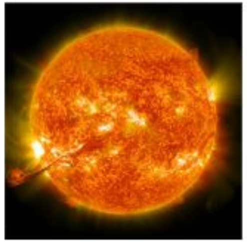
185 kt water



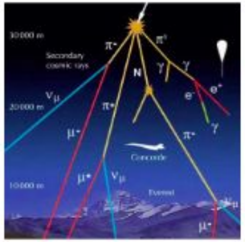
Jiangmen Underground Neutrino Observatory

➢ Primary goal: Neutrino Mass ordering measurement (with vacuum oscillation)

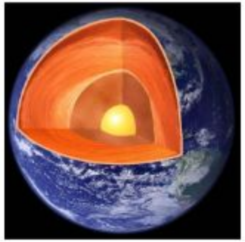
$\sim 50/\text{day}$



$\mathcal{O}(1000)/\text{day}$



$\sim 10/\text{day}$

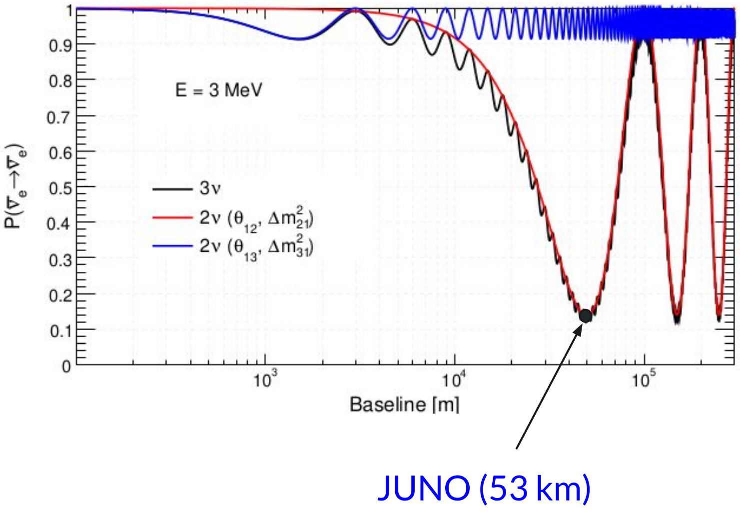


~ 1 - $2/\text{day}$

CCSN @10kpc : $\mathcal{O}(1000)/\text{s}$
DSNB: few/year

New Physics

Proton decay
etc



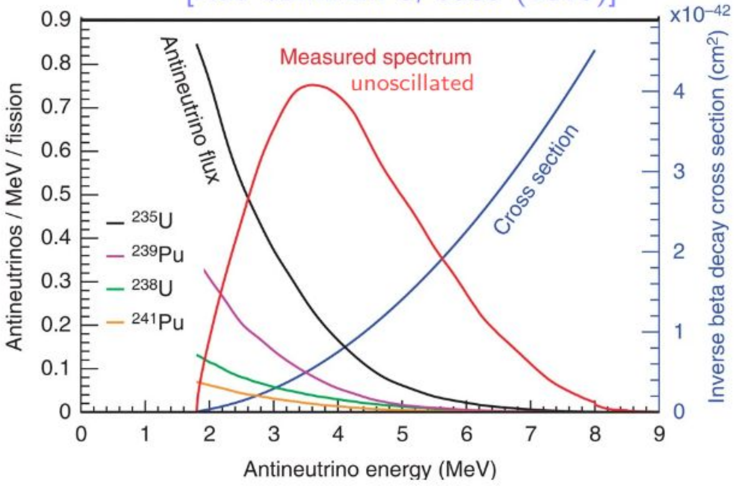
NPP	Yangjiang	Taishan	DayaBay
Power	17.4 GW_{th}	9.2 GW_{th}	17.4 GW_{th}

Challenges in NMO measurement with reactor antineutrino

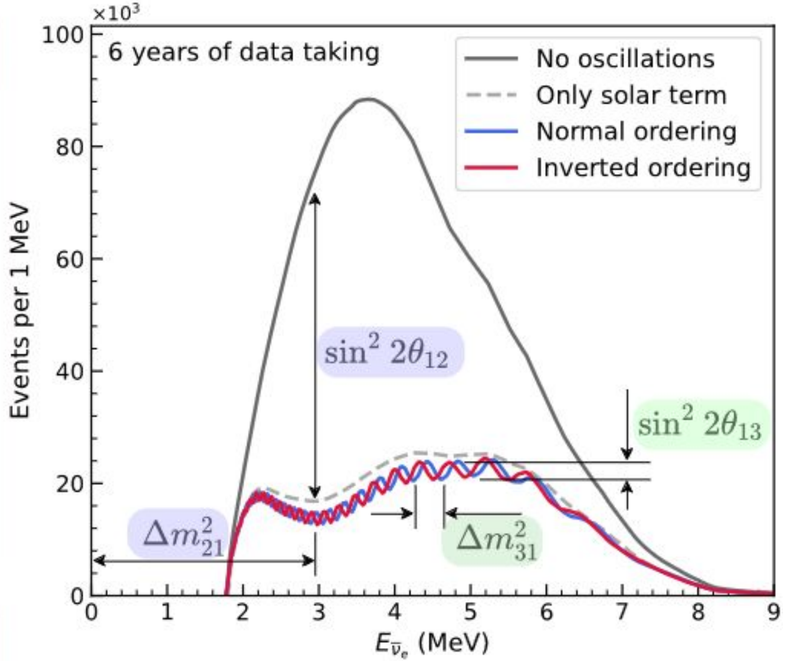
- Survival probability at medium baseline

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

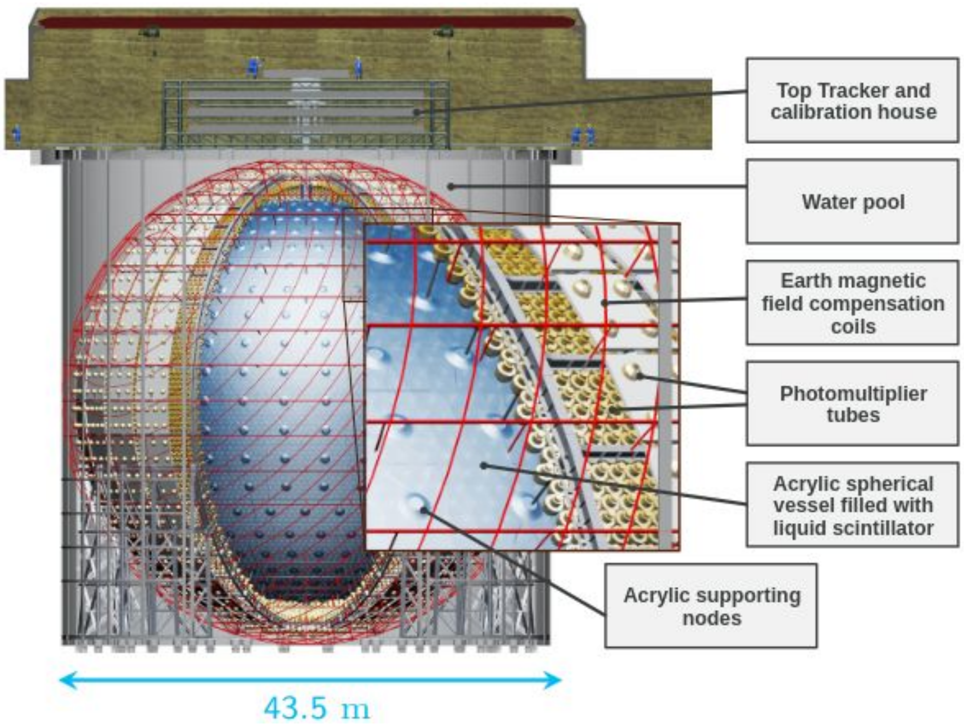
[Nat Commun 6, 6935 (2015)]



$$|\Delta m^2_{32}|_{IO} = |\Delta m^2_{32}|_{NO} + 2\Delta m^2_{21}$$



Overview of JUNO detector



Central detector (CD)

- ★ 20 ktons liquid scintillator (LS) in acrylic sphere of diameter 35.4 m, largest in the world

Unprecedented energy resolution of 3% at 1 MeV

- ★ High light yield of LS (expected 10^4 photons/MeV)
- ★ High Transparency of LS (20 m attenuation length at 430 nm)
- ★ High photocoverage (□78%) : 17,612 large PMTS (20-inch) and 25,600 small PMTs (3-inch)

Water Cherenkov detector (WCD)

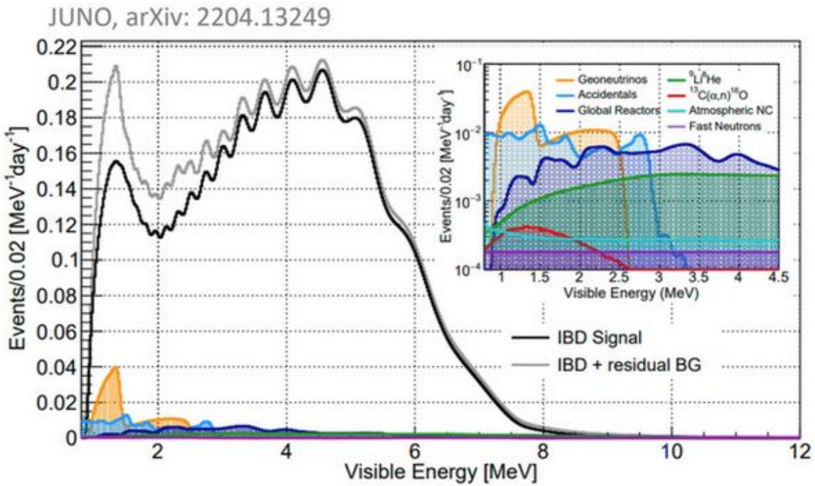
- ★ 35 ktons of ultra-pure water in a cylinder of 43.5 m diameter and 44 m in height
- ★ 2400 large PMTs (20-inch)
- ★ **Veto and shield surrounding radioactivity and outer photons**

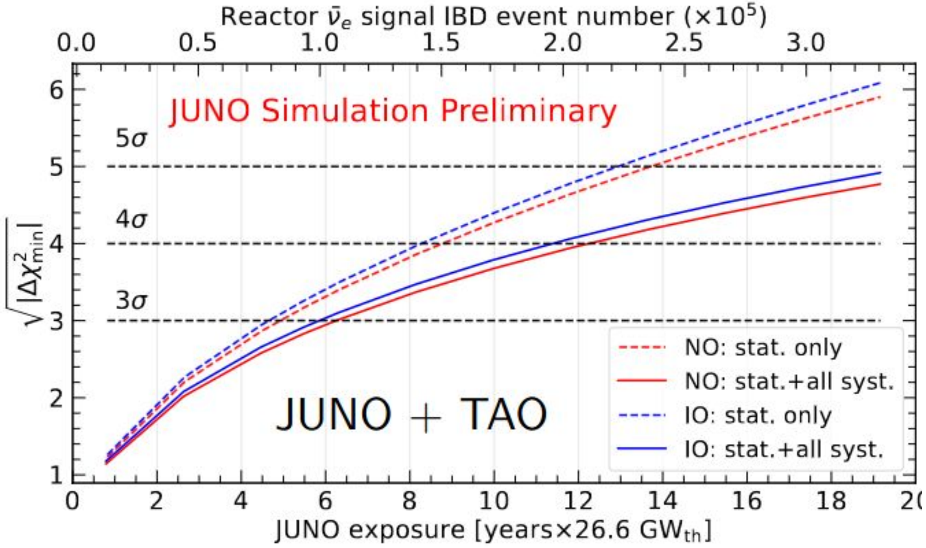
Top Tracker (TT): two planes of plastic scintillator strips, cover about 60% surface above CD, an extra veto for muons from top, reconstruct muon tracks combined with CD or WCD information validate reconstruction algorithm

Current status

- ❖ All civil construction is finished in December 2021
- ❖ Stainless steel supporting structure fully assembled in June 2022
- ❖ All LPMTs and SPMTs have been produced, tested, and instrumented with waterproof potting
- ❖ Around half of the PMTs are already installed
- ❖ JUNO electronics being installed: all the electronics under water are installed,
- ❖ Veto (WCD and TT): installation is well in progress: ultrapure water system for WCD is installed, scintillator panels of OPERA target will be reused for TT and arrived on site in 2019, the TT support bridge is ready for production
- ❖ LS filling and data taking are expected to start in 2024

Reactor antineutrino event spectra at JUNO



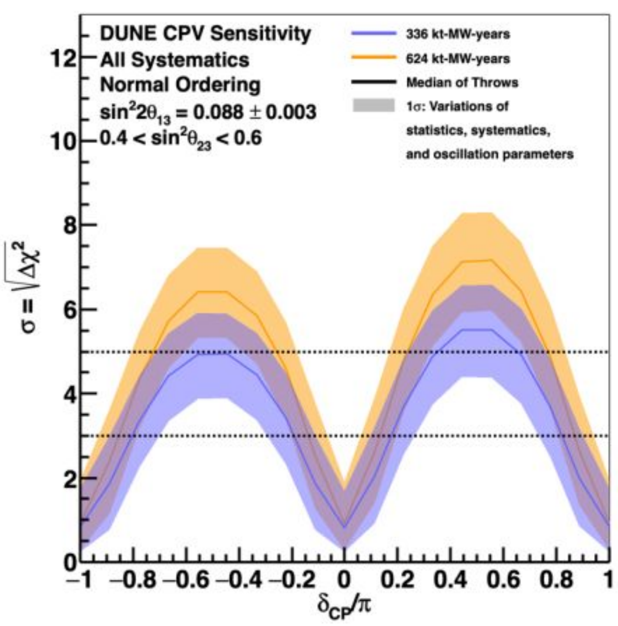


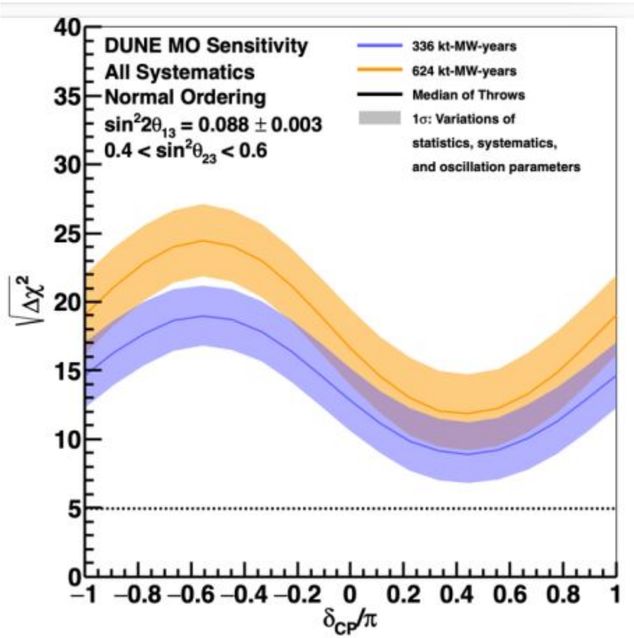
- TAO: 1 ton fiducial volume LS detector @ 30 m from core with high resolution, provide the reference flux from nuclear reactor, eliminate model dependence
- NMO measurement sensitivity do not rely on the matter effect
- Median sensitivity: **3σ at 6 years**

Physics potential of DUNE

Mayly Sanchez TAUP2023

Long baseline (1300 km) and high beam power of 2.4 MW will enable to determine NMO for all values of CP phase with short exposure (3-5 years)





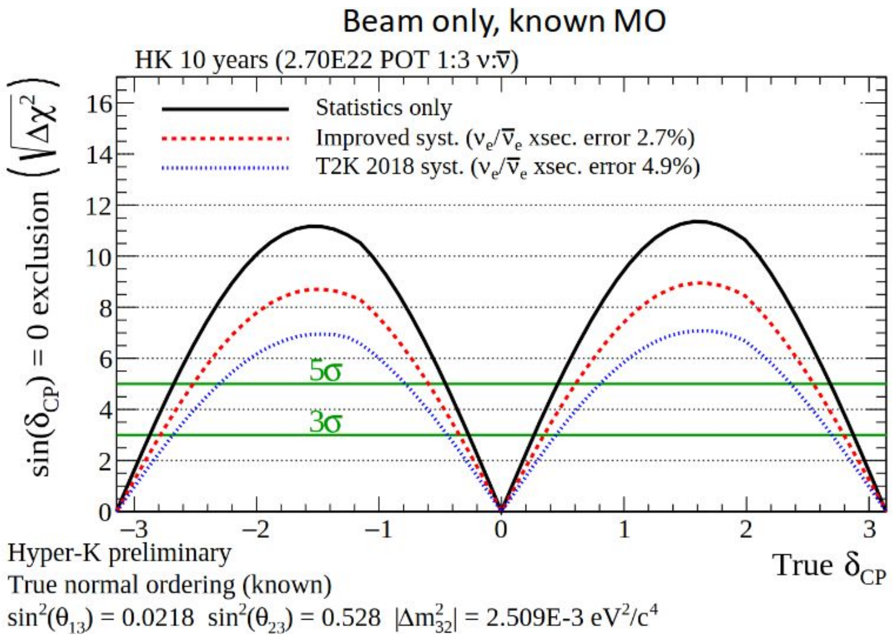
Status

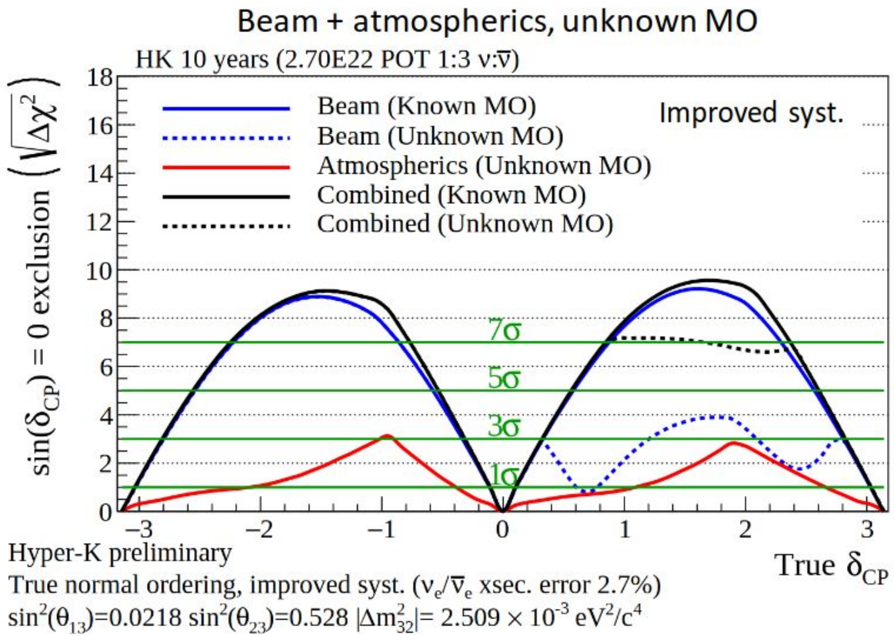
- Excavation to complete in 2024, Far detector module installation in 2026, beam data taking and near detector around 2031

Physics Potential of Hyper-K

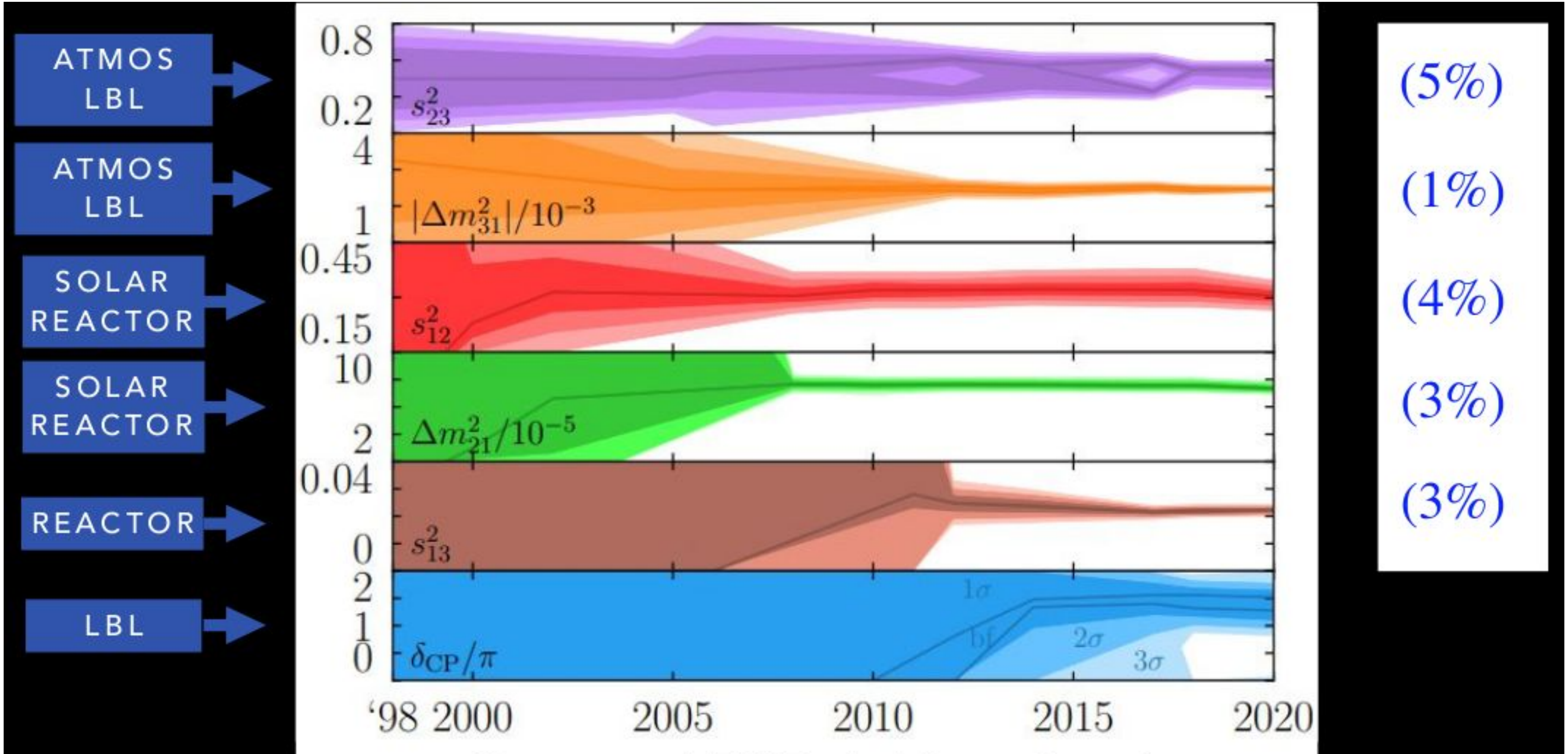
Charlie Nasebie NuFACT 2023

- Beam line at JPARC will be upgraded to reach 1.3 MW, currently at 420 kW, Hyper-K detector with 186 kton (x8 of Super-K) fiducial volume will be built by 2027
- >5σ sensitivity for 60% of CP phase value if MO is known
- Combined with atmospheric data improves the sensitivity if MO is unknown





Summary and Outlook



(Snowmass: NF01 Topical Group Report)

Summary and Outlook

- The current oscillation experiments are pushing the boundaries to provide the complete picture of neutrino mixing
  - The nonzero value of 1-3 angle measured by short-baseline reactor neutrino experiment confirms the three neutrino mixing picture
  - T2K and NOvA favor normal ordering but different CP phase space
  - The measurements from atmospheric neutrino experiments are competitive in 2-3 parameter space, more data from KM3NeT-ORCA, and IceCube-DeepCore can bring exciting results
- The next generation experiments with more detector mass and intense source will allow us to test 3-neutrino mixing framework
  - JUNO will be able to measure NMO by 3σ C.L. with 6 years exposure
  - The future long-baseline experiment will provide precise measurement of the complex part of the mixing matrix