Neutrino Oscillation Results and Search for Neutrino Sterile States

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Acknowledgements

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- Many thanks to speakers: Yifang Wang, Silvia Pascoli, Joachim Kopp, Matthieu Licciardi, Peter Denton, Carlos Delgado, Steve Elliott, Anne Schukraft, Hanyu Wei and many other contributors

- Special thanks to my colleagues: Maxim Gonchar and Liudmila Kolupaeva who are maintaining the site with new oscillation results and their combinations: https://git.jinr.ru/nu/osc

Neutrino Oscillations in Brief

- Neutrinos are produced by the weak interaction in weak interaction eigenstates: ν_e, ν_μ, ν_τ
- There is no reason for these eigenstates to be identical to the mass eigenstates: ν_1, ν_2, ν_3
- They are related by a unitary transformation:

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

- The mass eigenstates propagate as $e^{-iEt/\hbar}$. Thus, different masses develop different phases with time, resulting in oscillations in the weak eigenstates:
- If we consider only 2 states, then

$$\nu_\alpha = \nu_1 \cos\theta + \nu_2 \sin\theta$$
$$\nu_\beta = -\nu_1 \sin\theta + \nu_2 \cos\theta$$

and

$$P(\nu_\alpha \to \nu_\beta) = \sin^2(2\theta)\sin^2\left(\frac{1.27\Delta m^2 L}{E}\right), \text{ where}$$

$\Delta m^2 \equiv (m_1^2 - m_2^2)$ is in $(\mathrm{eV}/c^2)^2$, L is in km, and E is in GeV.

- In addition to the vacuum oscillations an important effect due to propagation in matter was pointed out by Mikheev, Smirnov and Wolfenstein (MSW).

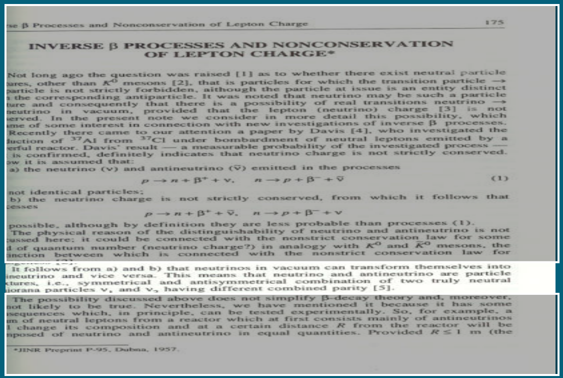
Genesis of Neutrino Oscillations

1957-1958 First proposal by Pontecorvo

1962 Maki, Nakagawa and Sakata

1968-1969 Pontecorvo and Gribov

Since 1970 Pontecorvo and Bilenky carefully and systematically studied possible oscillation scenarios and suggested their experimental tests



se β Processes and Nonconservation of Lepton Charge 175

INVERSE β PROCESSES AND NONCONSERVATION OF LEPTON CHARGE*

Not long ago the question was raised [1] as to whether there exist neutral particle ures, other than K^0 mesons [2], that is particles for which the transition particle → particle is not strictly forbidden, although the particle at issue is an entity distinct the corresponding antiparticle. It was noted that neutrino may be such a particle ture and consequently that there is a possibility of real transitions neutrino → neutrino in vacuum, provided that the lepton (neutrino) charge [3] is not served. In the present note we consider in more detail this possibility, which me of some interest in connection with new investigations of inverse β processes. Recently there came to our attention a paper by Davis [4], who investigated the duction of ^{37}Al from ^{37}Cl under bombardment of neutral leptons emitted by a erful reactor. Davis' result — a measurable probability of the investigated process — is confirmed, definitely indicates that neutrino charge is not strictly conserved. ow it is assumed that:

a) the neutrino (ν) and antineutrino ($\tilde{\nu}$) emitted in the processes

$$p \to n + \beta^+ + \nu, \quad n \to p + \beta^- + \tilde{\nu} \qquad (1)$$

not identical particles;

b) the neutrino charge is not strictly conserved, from which it follows that cesses

$$p \to n + \beta^+ + \tilde{\nu}, \quad n \to p + \beta^- + \nu$$

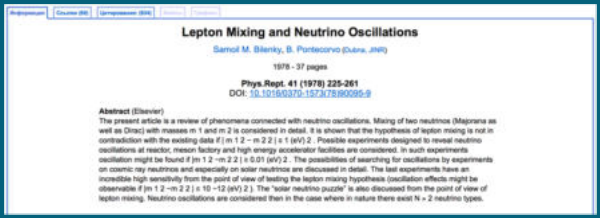
possible, although by definition they are less probable than processes (1).

The physical reason of the distinguishability of neutrino and antineutrino is not cussed here; it could be connected with the nonstrict conservation law for some d of quantum number (neutrino charge?) in analogy with K^0 and $\tilde{K}^0$ mesons, the tinction between which is connected with the nonstrict conservation law for

It follows from a) and b) that neutrinos in vacuum can transform themselves into ineutrino and vice versa. This means that neutrino and antineutrino are particle xtures, i.e., symmetrical and antisymmetrical combination of two truly neutral iorana particles ν_1 and ν_2 having different combined parity [5].

The possibility discussed above does not simplify β-decay theory and, moreover, not likely to be true. Nevertheless, we have mentioned it because it has some sequences which, in principle, can be tested experimentally. So, for example, a m of neutral leptons from a reactor which at first consists mainly of antineutrinos l change its composition and at a certain distance R from the reactor will be nposed of neutrino and antineutrino in equal quantities. Provided $R \leq 1$ m (the

*JINR Preprint P-95, Dubna, 1957.



Lepton Mixing and Neutrino Oscillations

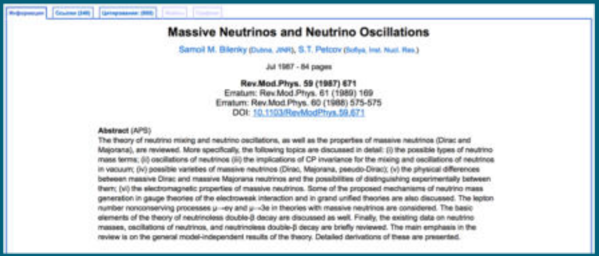
Samoil M. Bilenky, B. Pontecorvo (Dubna, JINR)

1978 - 37 pages

Phys.Rept. 41 (1978) 225-261
DOI: 10.1016/0370-1573(78)90095-9

Abstract (Elsevier)
The present article is a review of phenomena connected with neutrino oscillations. Mixing of two neutrinos (Majorana as well as Dirac) with masses m_1 and m_2 is considered in detail. It is shown that the hypothesis of lepton mixing is not in contradiction with the existing data if $|m_1^2 - m_2^2| \lesssim 1\ (eV)^2$. Possible experiments designed to reveal neutrino oscillations at reactor, meson factory and high energy accelerator facilities are considered. In such experiments oscillation might be found if $|m_1^2 - m_2^2| \gtrsim 0.01\ (eV)^2$. The possibilities of searching for oscillations by experiments on cosmic ray neutrinos and especially on solar neutrinos are discussed in detail. The last experiments have an incredible high sensitivity from the point of view of testing the lepton mixing hypothesis (oscillation effects might be observable if $|m_1^2 - m_2^2| \gtrsim 10^{-12}\ (eV)^2$). The "solar neutrino puzzle" is also discussed from the point of view of lepton mixing. Neutrino oscillations are considered then in the case where in nature there exist N > 2 neutrino types.

1978
Review by
Bilenky and
Pontecorvo
(500+)



Massive Neutrinos and Neutrino Oscillations

Samoil M. Bilenky (Dubna, JINR), S.T. Petcov (Sofiya, Inst. Nucl. Res.)

Jul 1987 - 84 pages

Rev.Mod.Phys. 59 (1987) 671
Erratum: Rev.Mod.Phys. 61 (1989) 169
Erratum: Rev.Mod.Phys. 60 (1988) 575-575
DOI: 10.1103/RevModPhys.59.671

Abstract (APS)
The theory of neutrino mixing and neutrino oscillations, as well as the properties of massive neutrinos (Dirac and Majorana), are reviewed. More specifically, the following topics are discussed in detail: (i) the possible types of neutrino mass terms; (ii) oscillations of neutrinos (iii) the implications of CP invariance for the mixing and oscillations of neutrinos in vacuum; (iv) possible varieties of massive neutrinos (Dirac, Majorana, pseudo-Dirac); (v) the physical differences between massive Dirac and massive Majorana neutrinos and the possibilities of distinguishing experimentally between them; (vi) the electromagnetic properties of massive neutrinos. Some of the proposed mechanisms of neutrino mass generation in gauge theories of the electroweak interaction and in grand unified theories are also discussed. The lepton number nonconserving processes $\mu \to e\gamma$ and $\mu \to 3e$ in theories with massive neutrinos are considered. The basic elements of the theory of neutrinoless double-β decay are discussed as well. Finally, the existing data on neutrino masses, oscillations of neutrinos, and neutrinoless double-β decay are briefly reviewed. The main emphasis in the review is on the general model-independent results of the theory. Detailed derivations of these are presented.

1987
Review by
Bilenky and
Petcov
(500+)

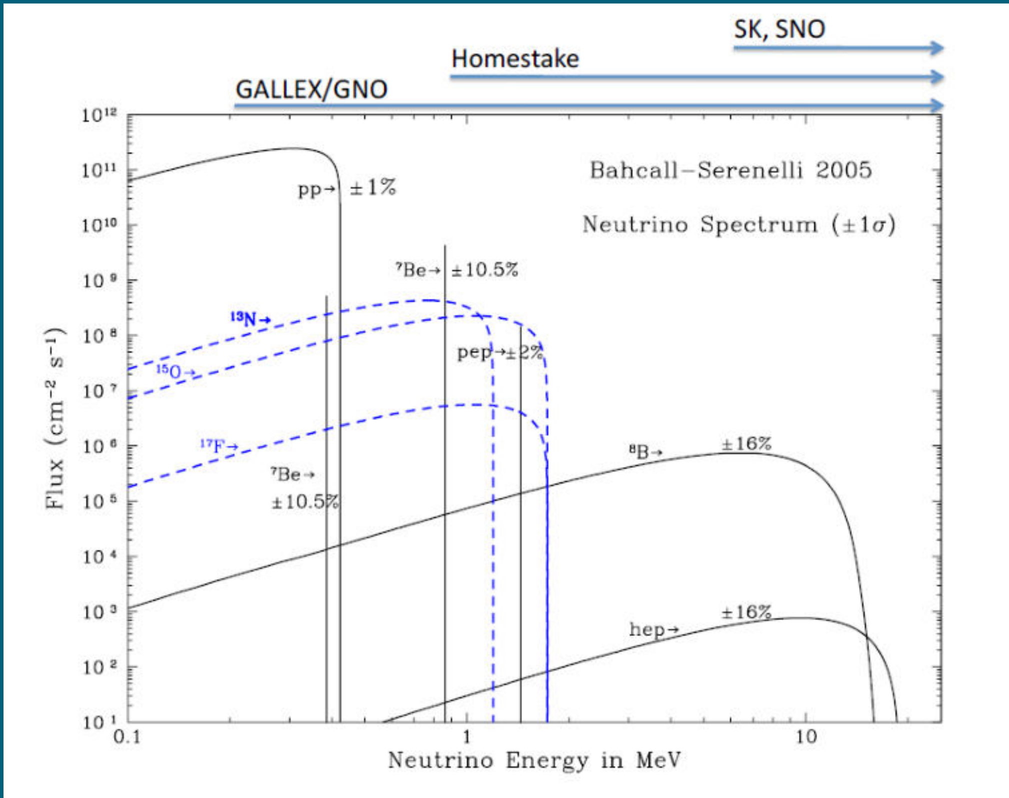
Discovery of Neutrino Oscillations

Deficit of the Solar neutrino flux was observed using radiochemical methods:

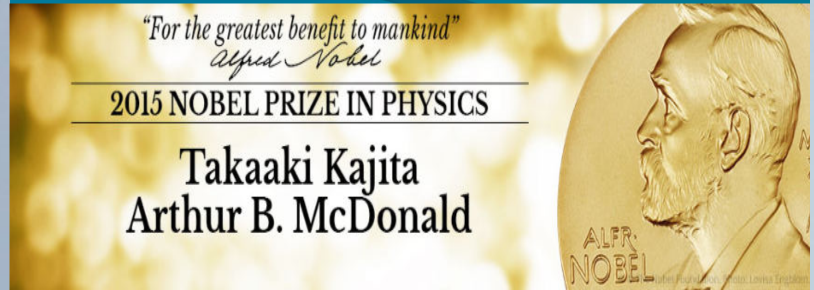
(neutrino + Cl → Ar + electron) – proposed by B.Pontecorvo and used by R.Davis in Homestake

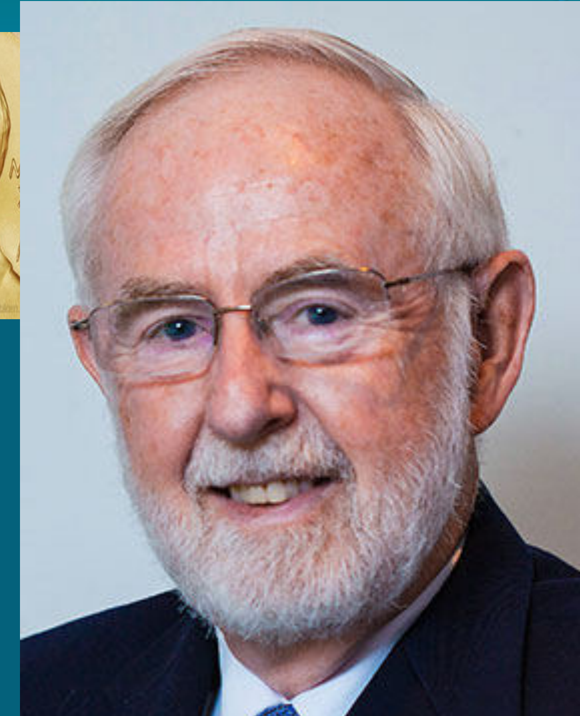
(neutrino + Ga → Ge + electron) – suggested by V.Kuzmin and applied in SAGE at Baksan and GALLEX/GNO at Gran Sasso

also, Water Cherenkov detectors Kamiokande and SK observed this effect

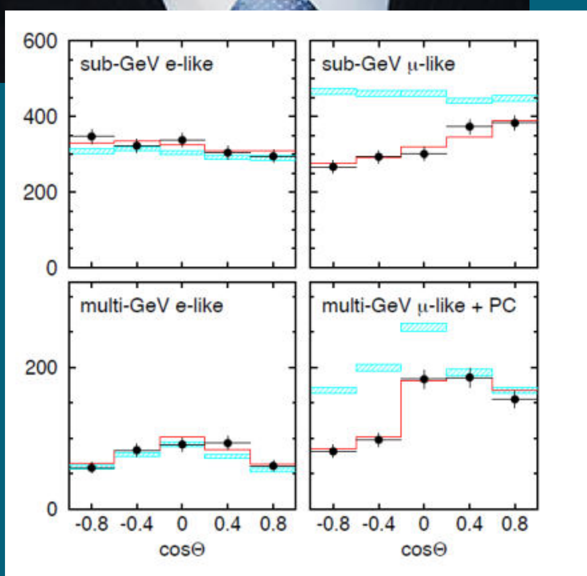


Oscillations were the most plausible explanation of the deficit but there was a suspicion in the theoretical uncertainties of the Solar neutrino flux prediction





for the discovery of ***neutrino oscillations,*** *which shows that* ***neutrinos have mass***

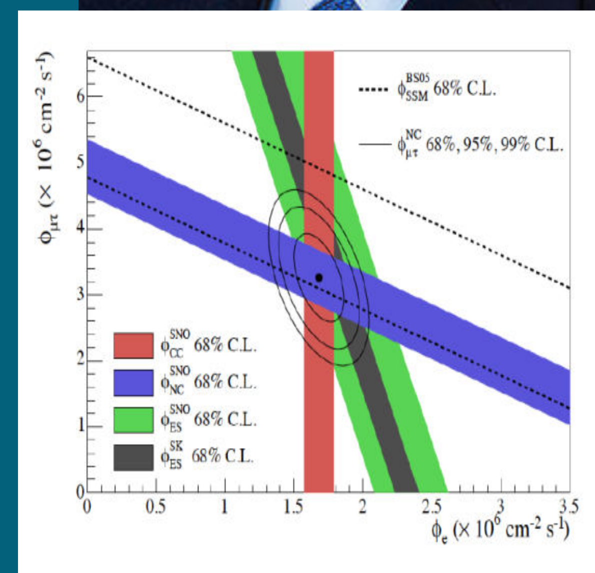


Super Kamiokande

Macroscopic proof of quantum effects

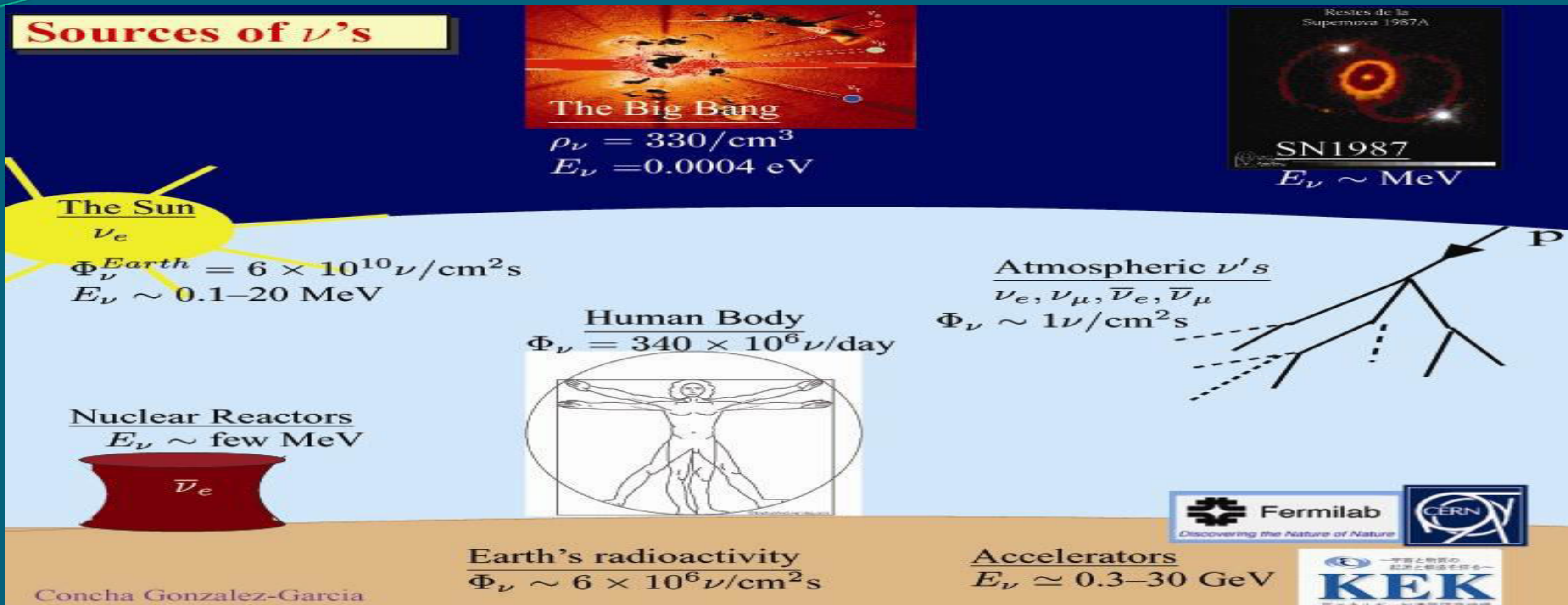
Fundamental information for understanding symmetries in Nature

Possible source of lepton CP, which might be important for baryon asymmetry of the Universe



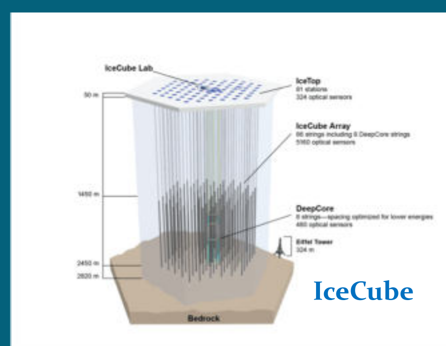
S N O

Neutrino Sources and Detectors

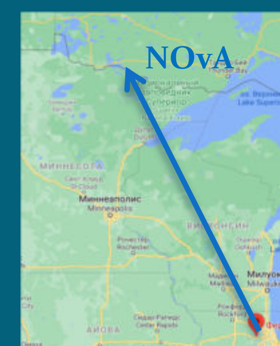


Reactor

Atmospheric



Accelerator



PMNS today

What We Know

atmospheric accelerator ν_μ	short baseline reactor accelerator ν_e	solar long baseline reactor

Flavor

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

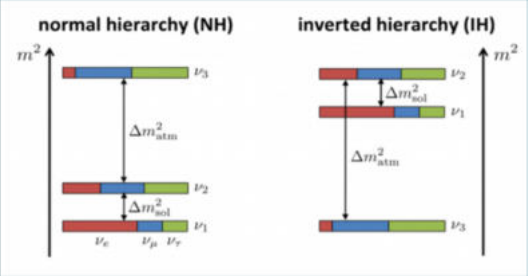
Mass

$\theta_{23} \approx 45^\circ$ $\theta_{13} \approx 9^\circ$ $\theta_{12} \approx 34^\circ$

$\Delta m^2_{\text{atm}} \approx 2 \times 10^{-3}\ \text{eV}^2$

$\Delta m^2_{\text{sol}} \approx 8 \times 10^{-5}\ \text{eV}^2$

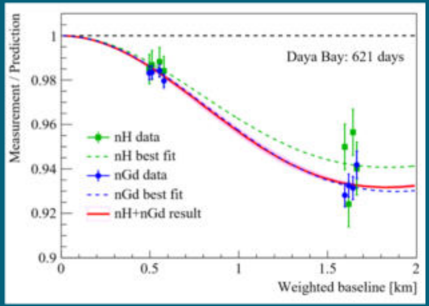
But we are missing:



- ν Mass Ordering
- CP phase (δ_{CP}) measurement
- θ_{23} octant

Also, general refinement of neutrino oscillation parameters is desirable

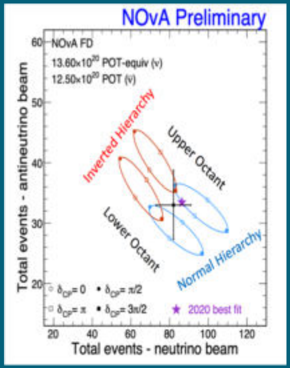
How to measure θ_{13} ?



- Disappearance probability at reactors:

$$P(\overline{\nu}_e \rightarrow \overline{\nu}_e) = 1 - \sin^2 2\theta_{13}$$

Clean θ_{13} measurement, best at a distance of ~ 1.8 km



- Appearance probability at accelerators:

$$P(\nu_\mu \rightarrow \nu_e) \sim \frac{\sin^2\theta_{23}\sin^2 2\theta_{13}}{(1-\rho_m L)^2} - 0.04\frac{\sin 2\theta_{13}}{(1-\rho_m L)}\sin\delta_{CP}$$

Very rich - apart from θ_{13} sensitive to θ_{23}, δ_{CP} and MO, but this introduce degeneracy of these parameters

- Clear strategy for complementary measurements at reactors and accelerators.

Results on θ_{13}

- New results from Daya Bay nGd capture:

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

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

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

(2.3% precision)

- Expect final results from Daya Bay on combined nGd+nH analysis: 2.6% for $\sin^2 2\theta_{13}$?
- RENO reported new results(up to 2019)

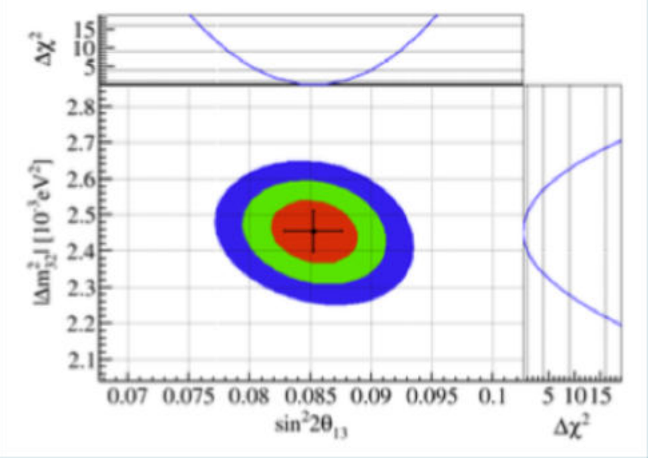
$$\sin^2 2\theta_{13} = 0.0892 \pm 0.0044(\text{stat.}) \pm 0.0045(\text{sys.}) \quad (\pm\ 7.0\ \%)$$

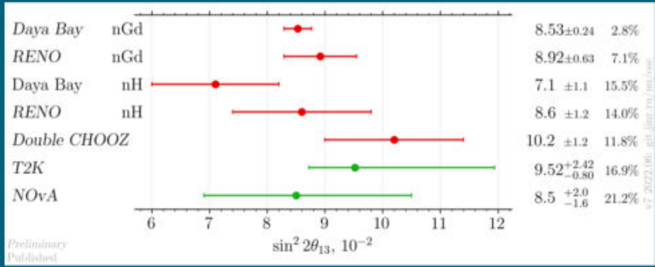
$$|\Delta m^2_{ee}| = 2.74 \pm 0.10(\text{stat.}) \pm 0.06(\text{sys.})(\times 10^{-3}\text{eV}^2) \quad (\pm\ 4.4\ \%)$$

- RENO will continue for another ~3 years(up to 4400 d)

$\sin^2 2\theta_{13}$: 6.4%; Δm^2_{ee}: 4.1%

- DUNE can measure $\sin^2 2\theta_{13}$ in appearance channel, to a precision of ~ 5%





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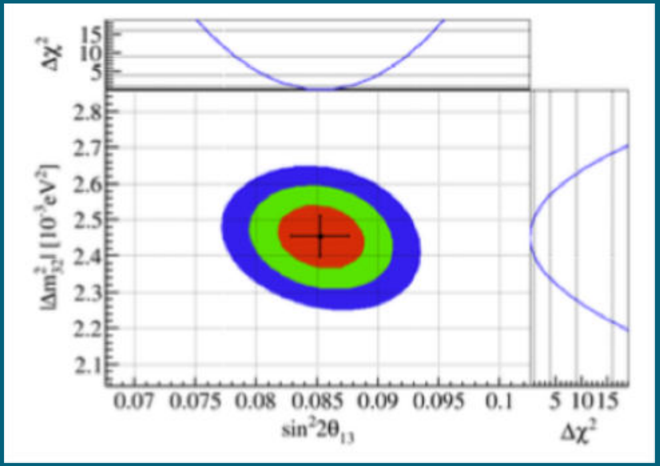
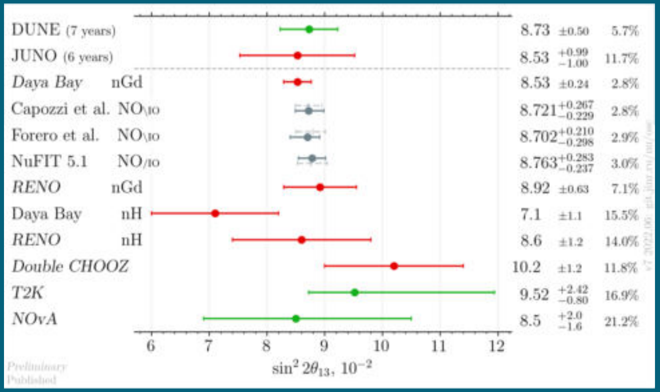
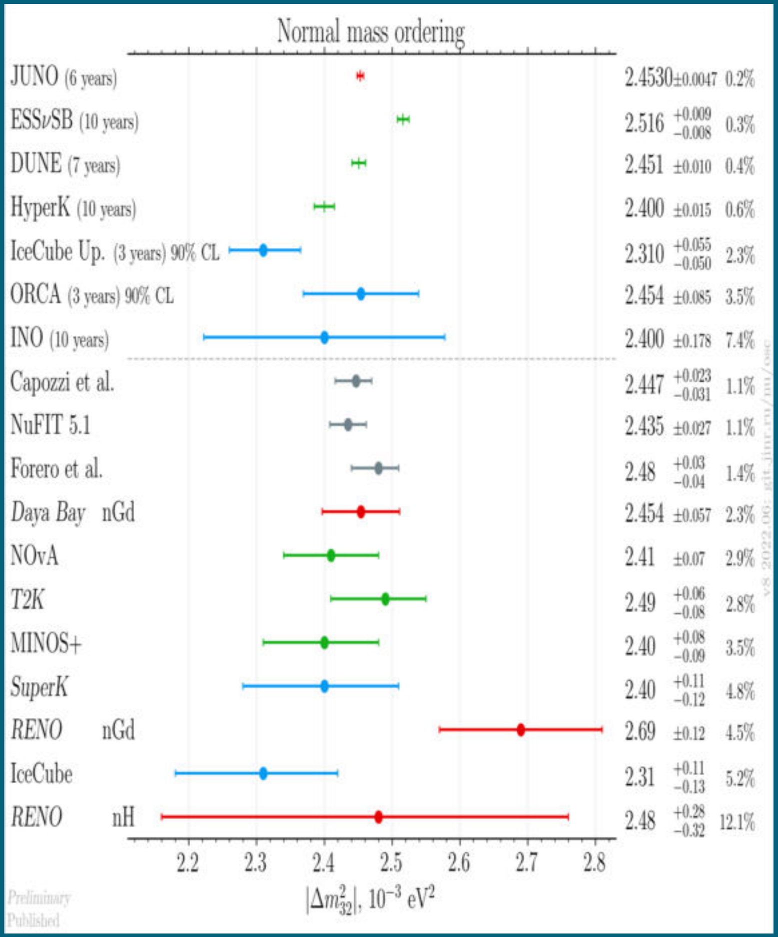
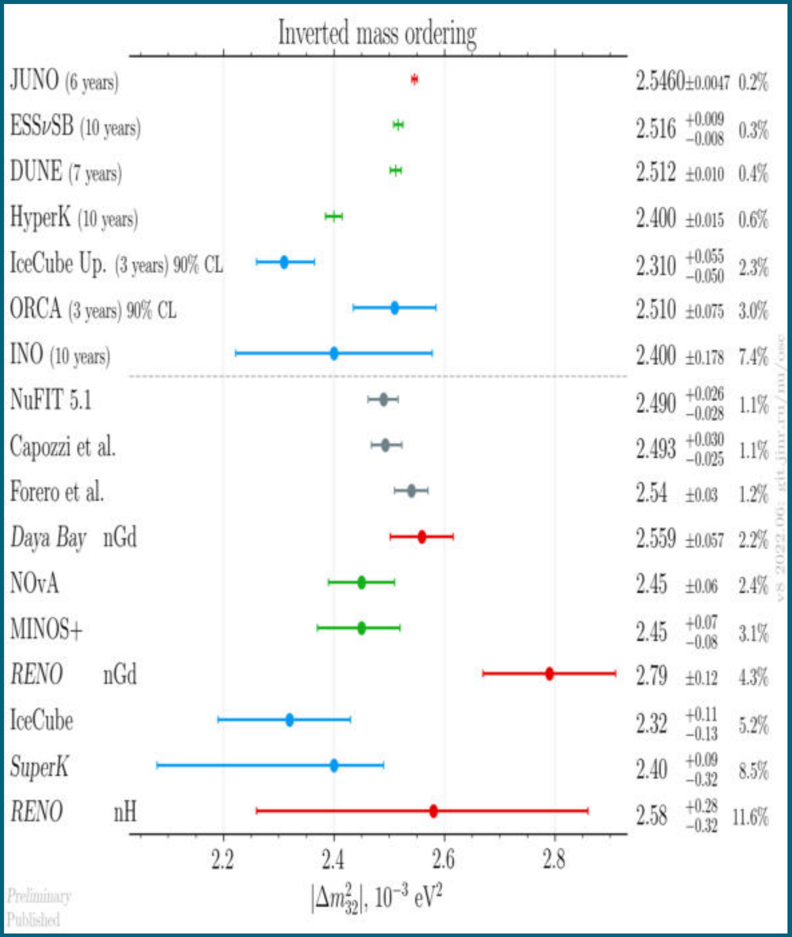


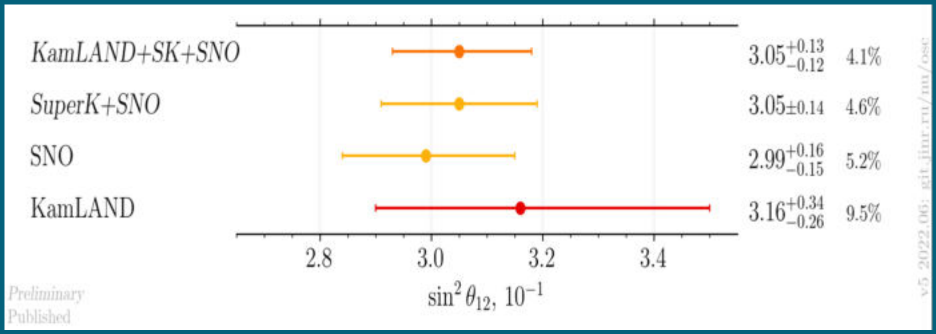


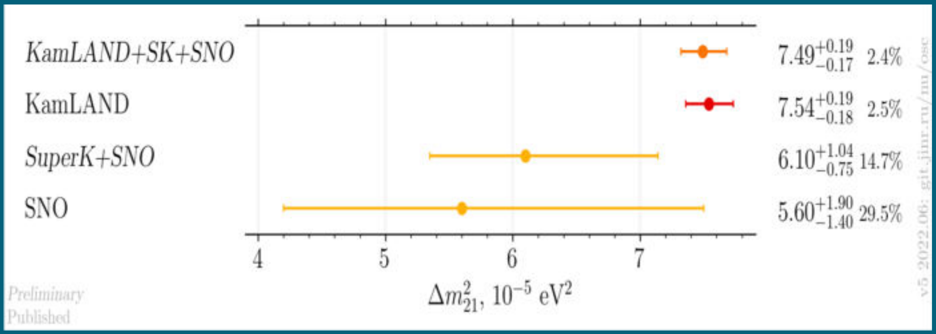
… and Δm^2_{32}

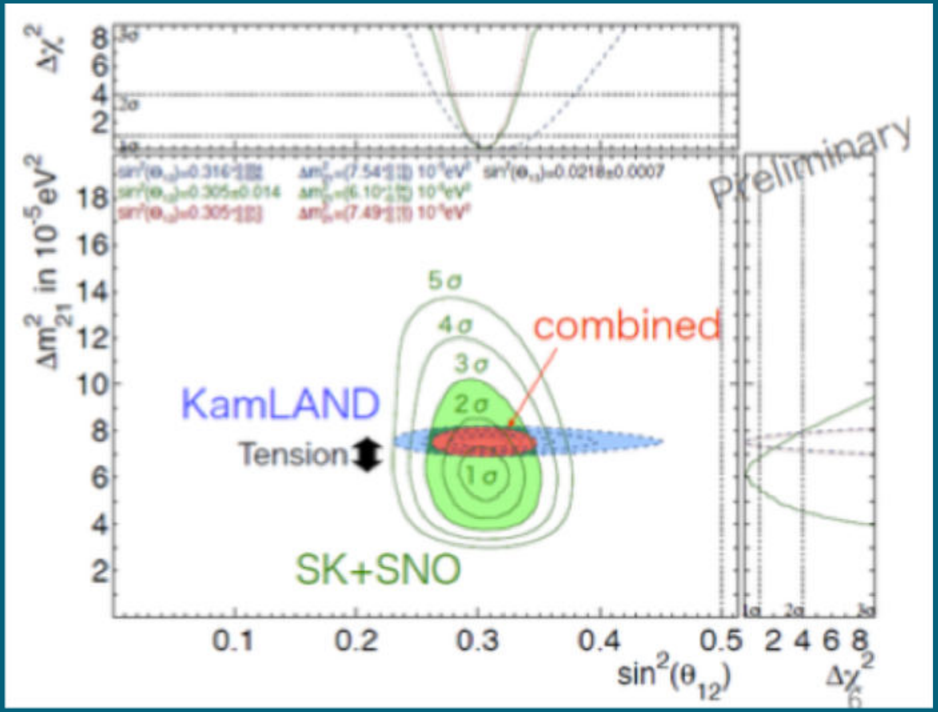




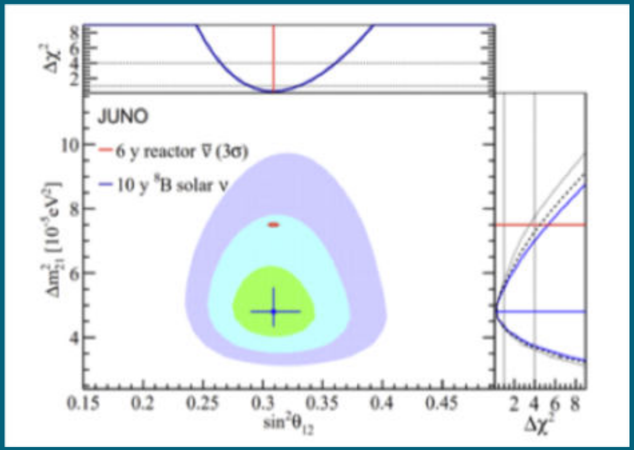
Results on θ_{12} and Δm^2_{21}



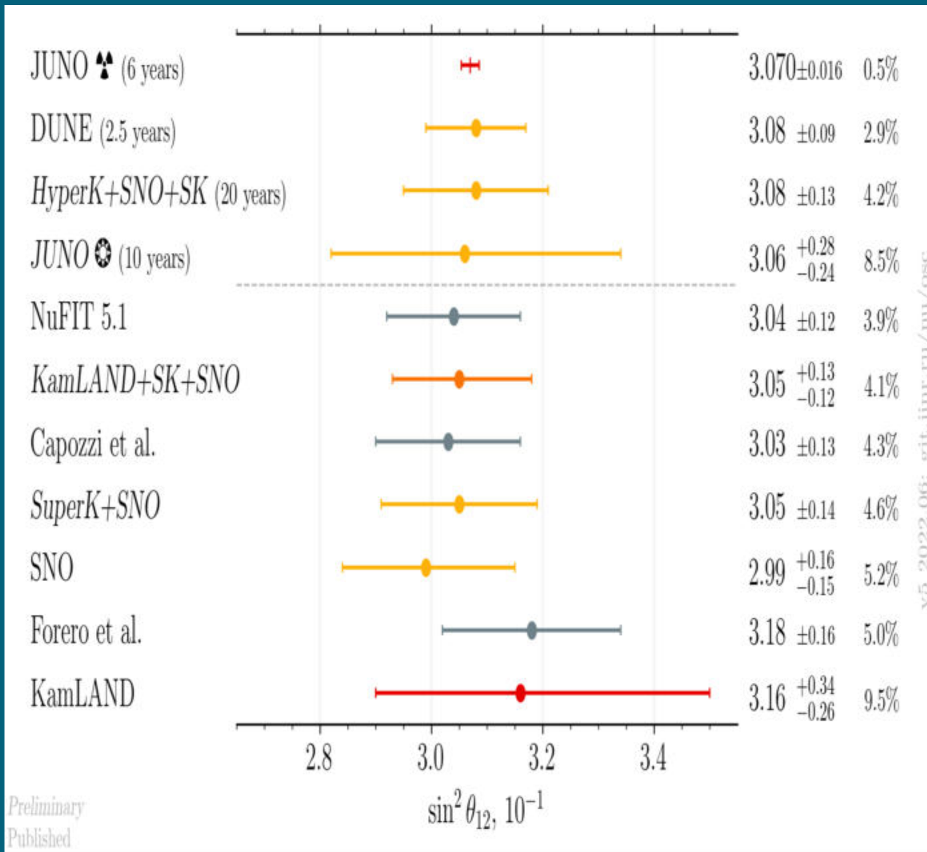


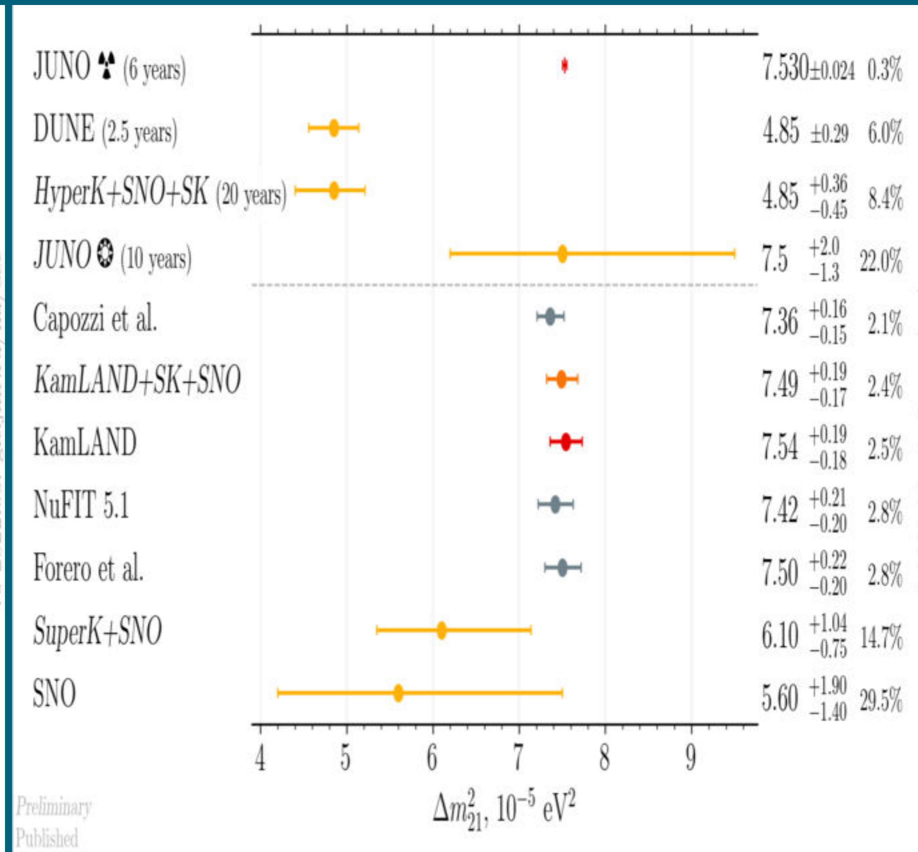


Possible tension (1.5σ) in Δm^2_{21} between solar and reactor results can be resolved with significant improvement by JUNO.

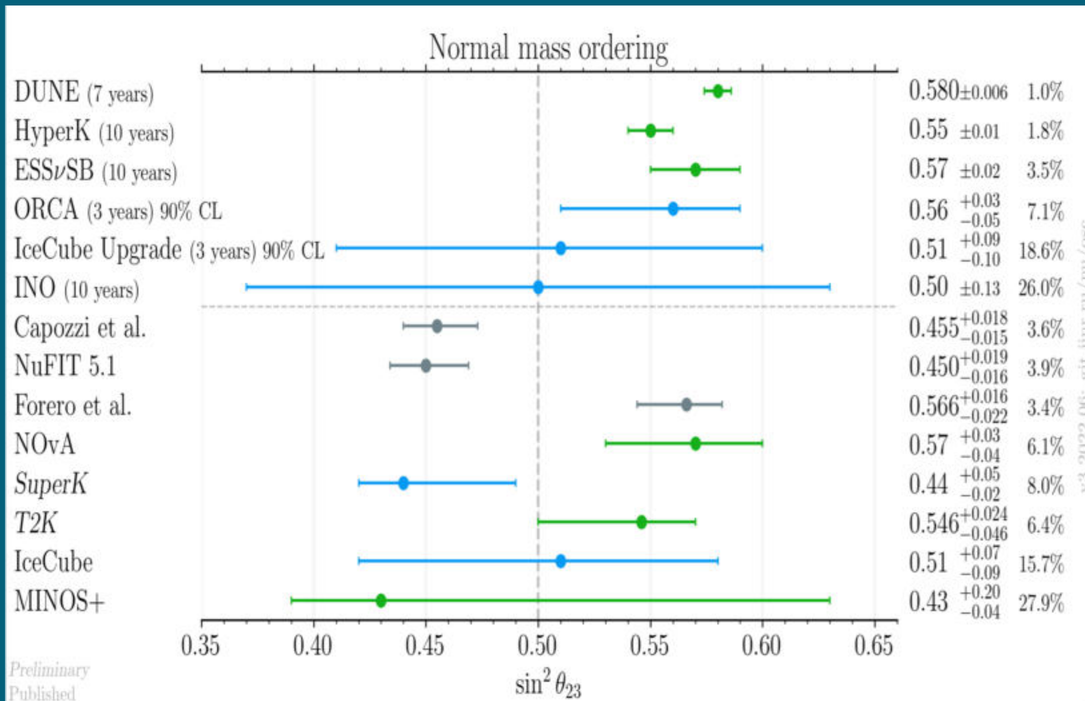


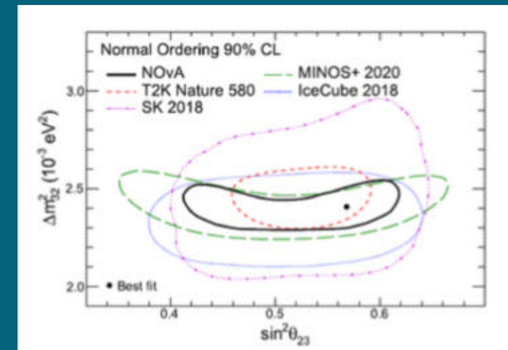
Results on θ_{12} and Δm^2_{21}

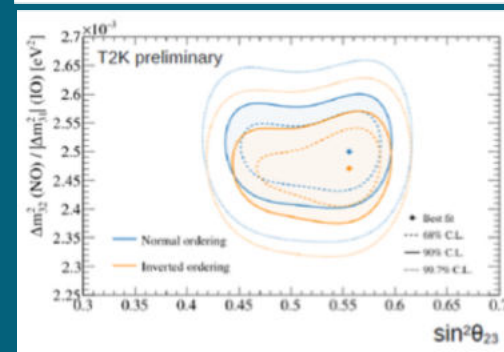




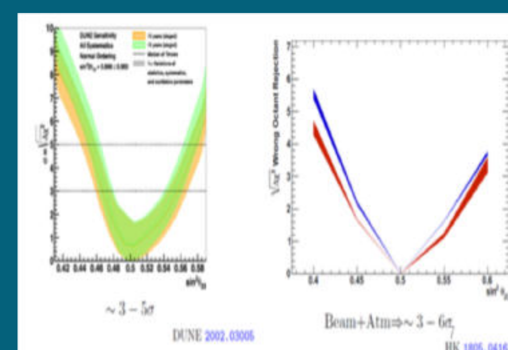
Results on θ_{23} and its octant





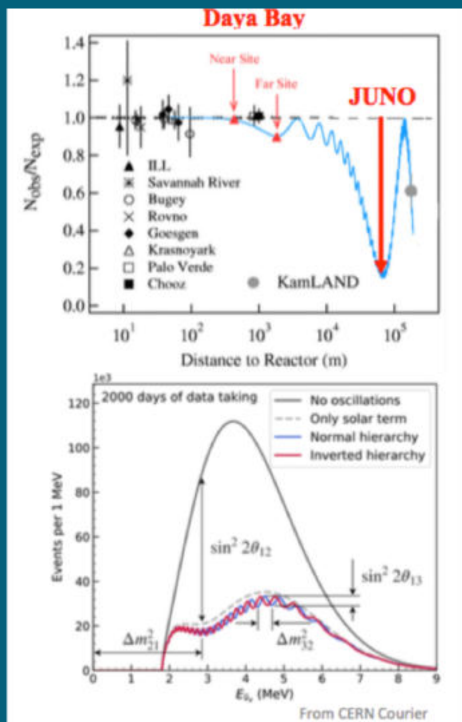


- T2K and NOvA will further slightly improve $\sin^2\theta_{23}$
- New results (down to ~1%) will come from ORCA, IceCube, DUNE and HK
- θ_{23} octant can be probed with a good precision



Mass Ordering Measurement

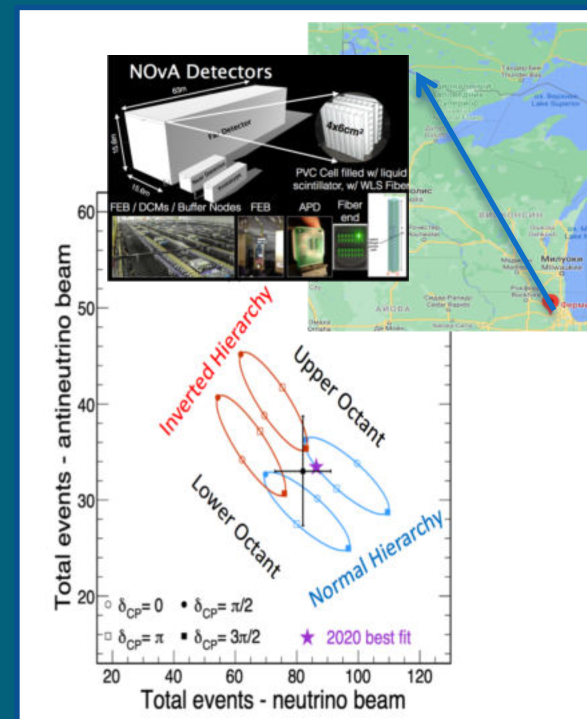
Disappearance at reactors
(S.Bilenky and S.Petcov)
(early 2000's)



JUNO

Complementary
to each other

Appearance at accelerators
θ_{23}, δ_{CP} and MO
(degeneracy)

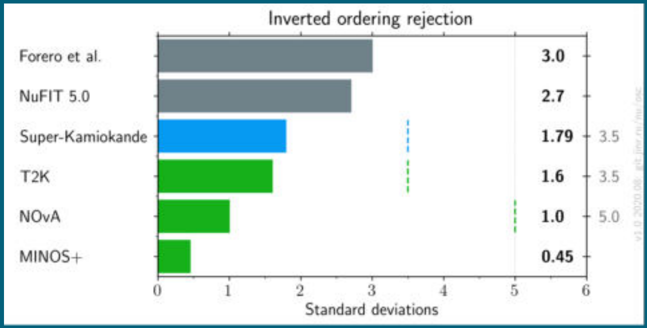


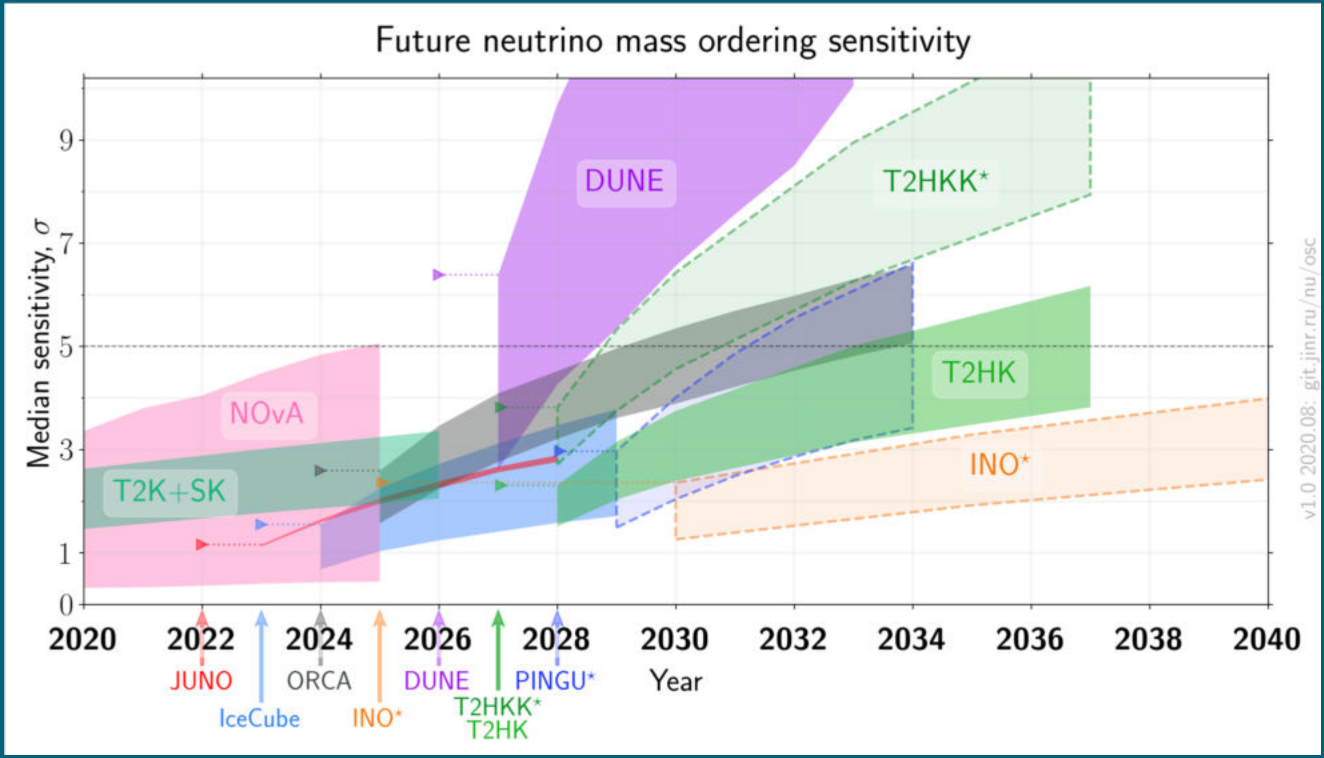
T2K, NOvA (T2HK, DUNE)

\+ Super Kamiokande
Sensitivity to MO in Atmospheric data

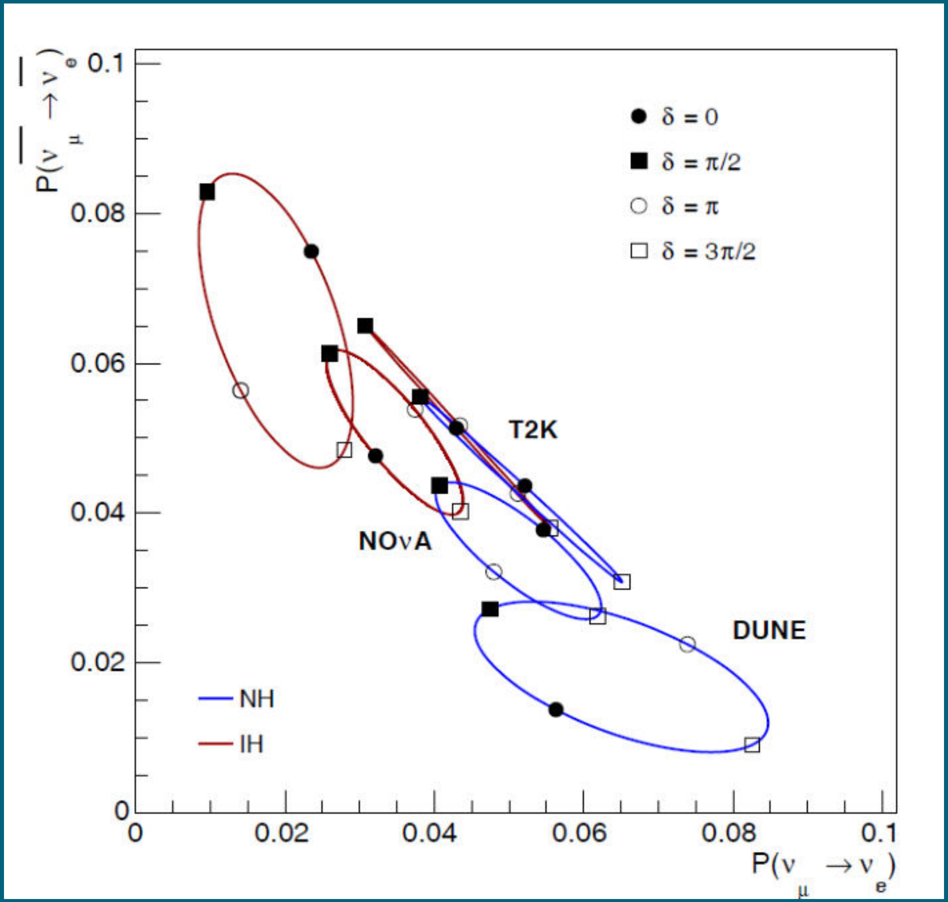
Mass Ordering Results

- No concrete evidence of MO from individual experiment (T2K, Nova and SuperK)
- Global fit seems slightly prefer NO(<3σ)
- Definite answer will come from DUNE, JUNO, HyperK, ORCA and Icecube.





CP phase (δ_{CP}) measurement



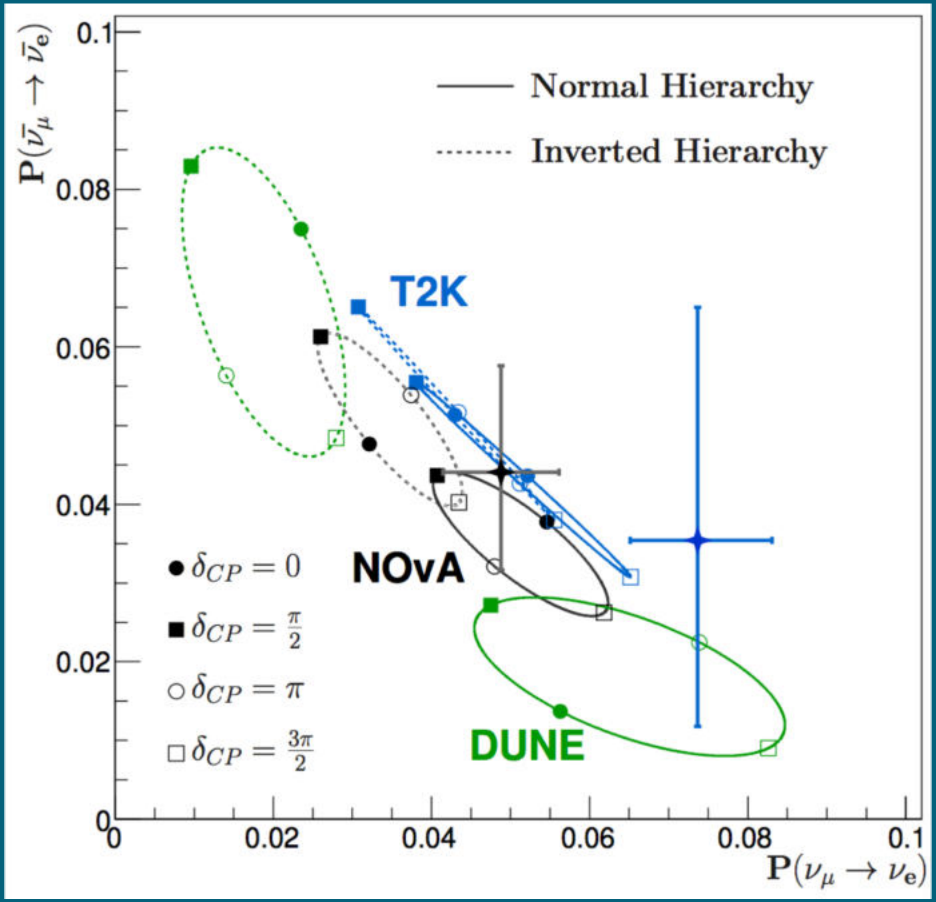
T2K: baseline ~300 km
energy ~0.6 GeV
500->750 kW

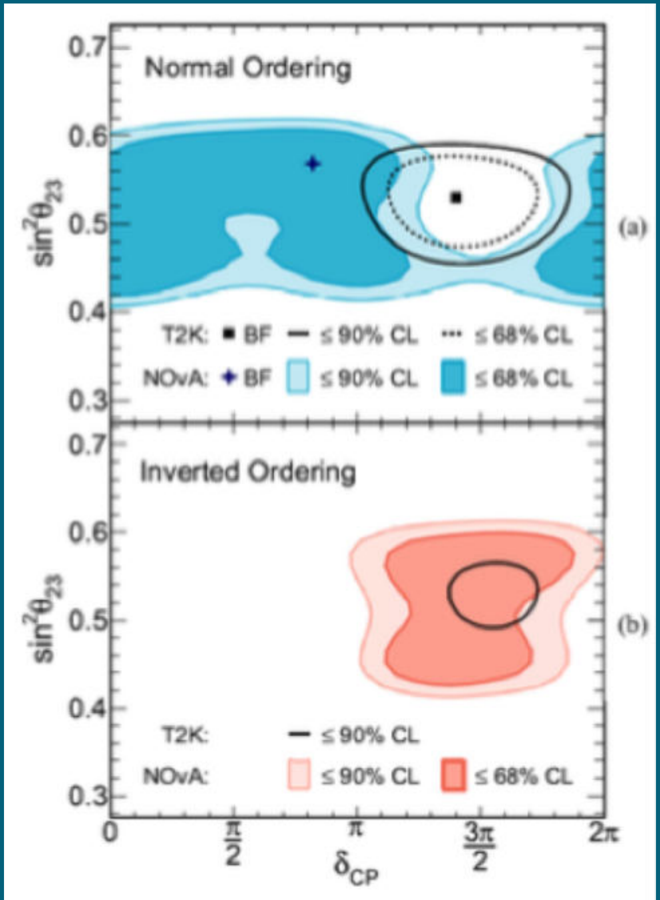
NOvA: baseline ~800 km
energy ~2.0 GeV
900 kW

so, nearly the same oscillation phase (L/E) , but :

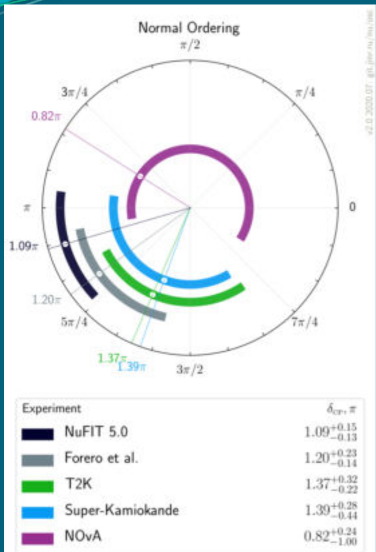
- significantly different sensitivity due to matter effects
- different ν energy and interaction x-section systematics

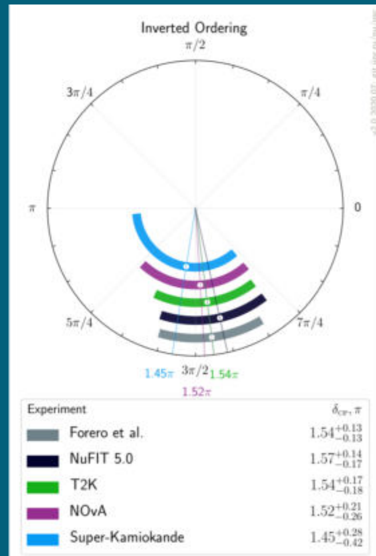
CP phase (δ_{CP}) measurement





CP phase (δ_{CP}) measurement



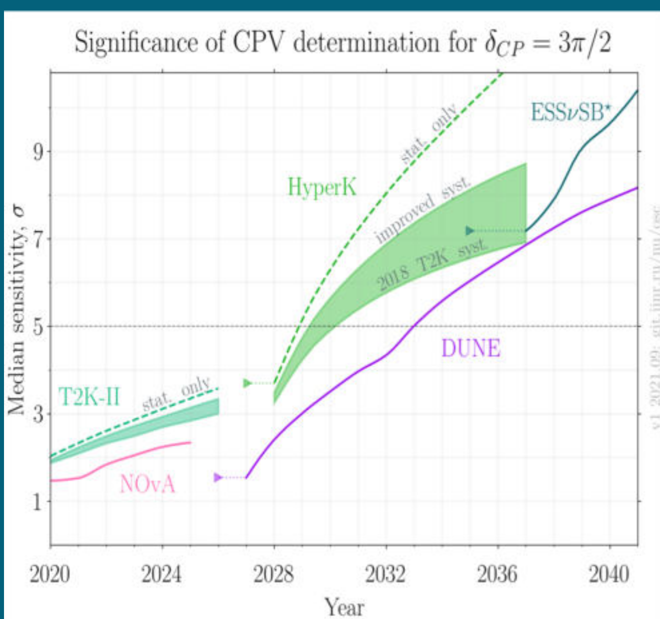


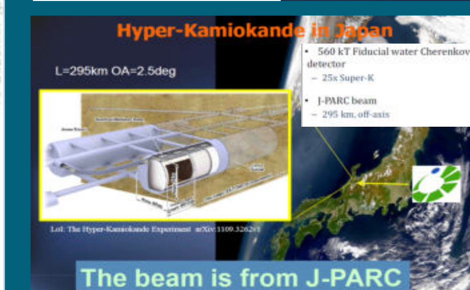
- ~270° (-90°) seems slightly favored by many exp.s (< 3σ)
- Combined analysis may give more preference, but not stable yet
- DUNE & HyperK can give a more definite answer
- Further improvement may come from KNO, ESSnuSB, and THEIA

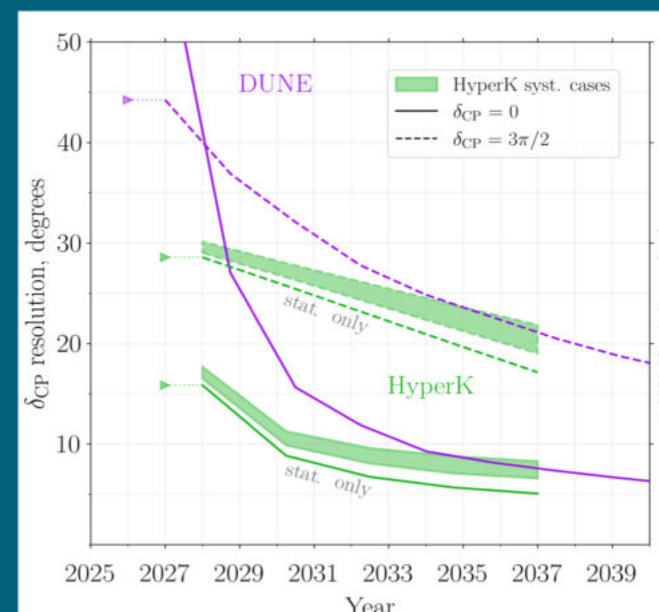
KNO: T2HK + second WC detector in Korea

ESSnuSB: European Spallation Source neutrino Super Beam

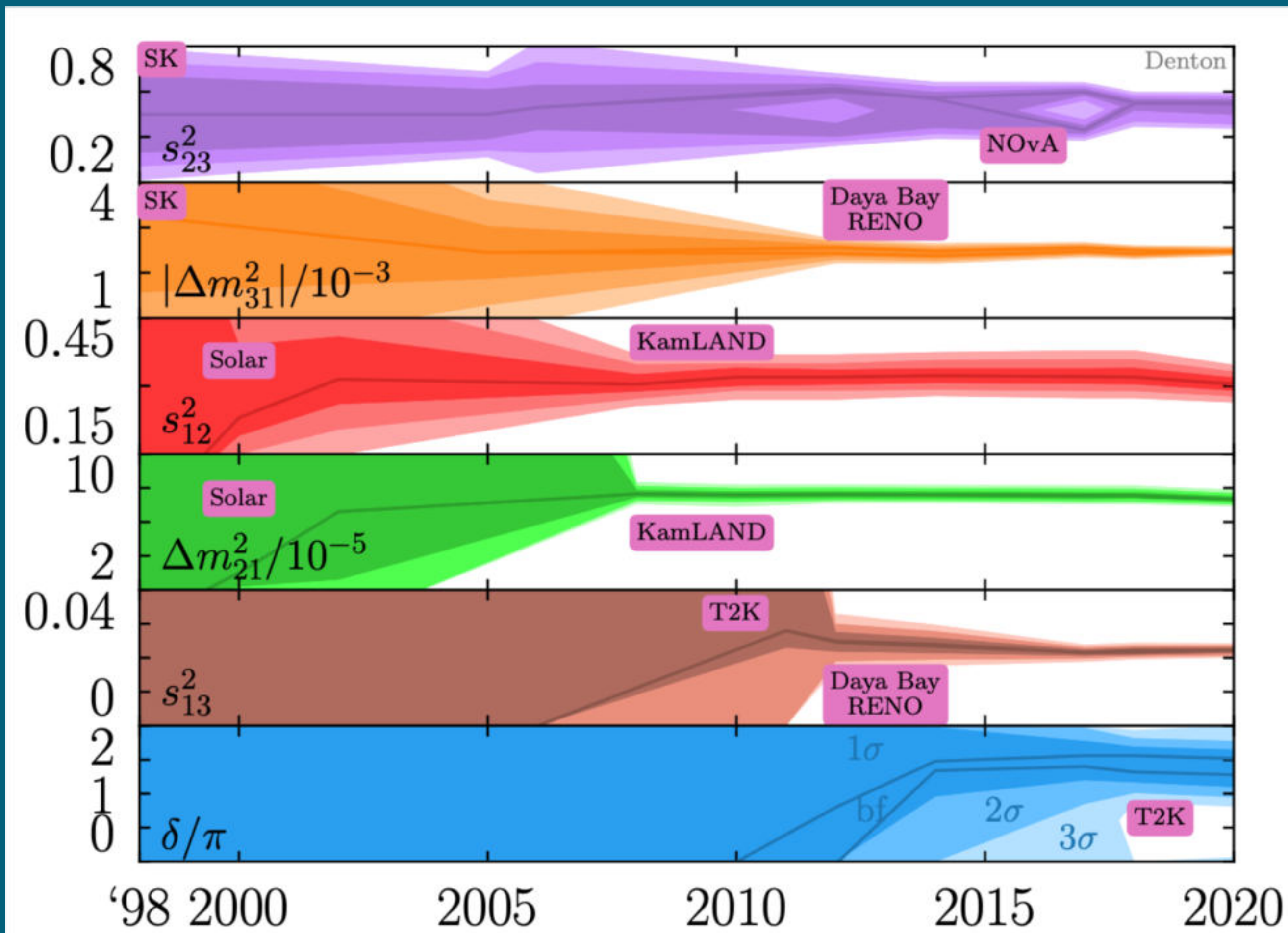
THEIA: 50-100 kt WbLS detector at Sanford







Evolution of Oscillation Parameters Precision



Present	Future
~4%	~1%
~1%	~0.2%
~4%	~0.5%
~2%	~0.3%
~3%	~3%

	Current (PDG2020)
Δm^2_{31} Δm^2_{32}	1.3%
Δm^2_{21}	2.4%
$\sin^2\theta_{12}$	4.2%
$\sin^2\theta_{13}$	3.2%

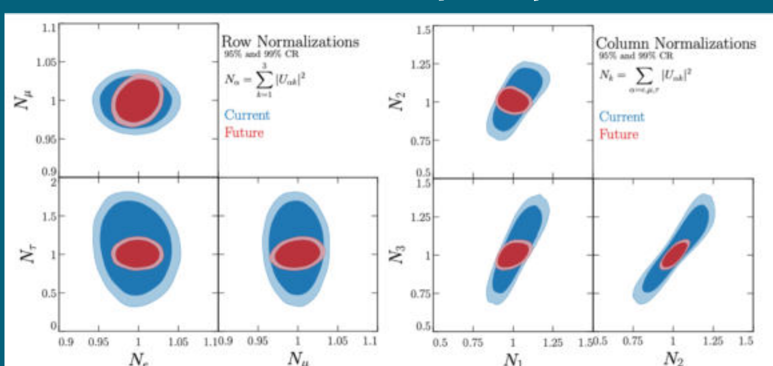
Unitarity of PMNS matrix

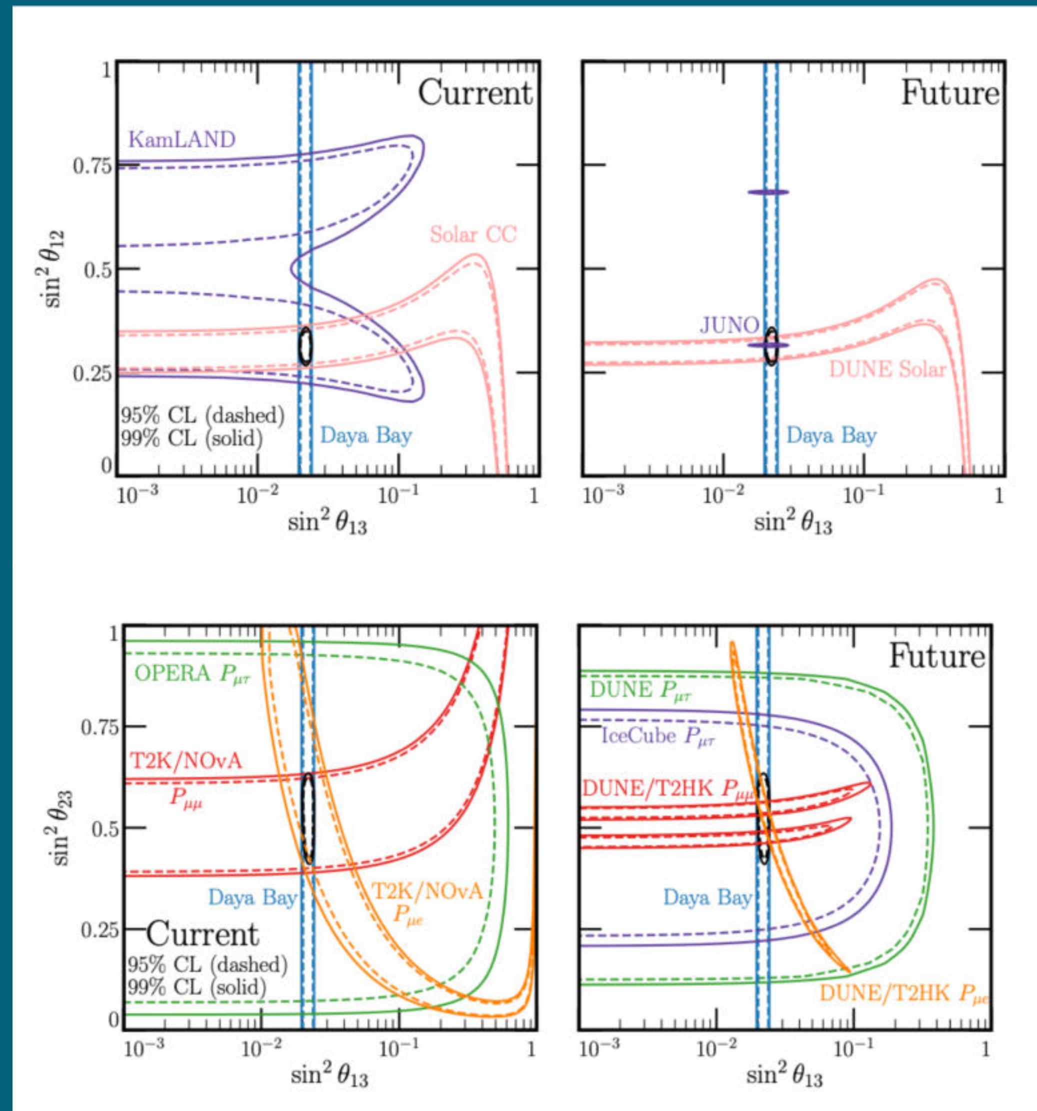
$$U \rightarrow \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} & U_{e4} & \cdots \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} & U_{\mu 4} & \cdots \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} & U_{\tau 4} & \cdots \\ U_{a1} & U_{a2} & U_{a3} & U_{a4} & \cdots \\ \vdots & \vdots & \vdots & \vdots & \ddots \end{pmatrix}$$

3σ deviations from unitarity

$$|U_{\mathrm{PMNS}}|^2 = \begin{pmatrix} 0.677 & 0.302 & 0.022 \\ 0.083 & 0.378 & 0.534 \\ 0.240 & 0.320 & 0.439 \end{pmatrix} \quad \begin{matrix} 0.05 \\ 0.04 \\ 0.82 \end{matrix}$$

$$\begin{matrix} 0.22 & 0.27 & 0.40 \end{matrix}$$

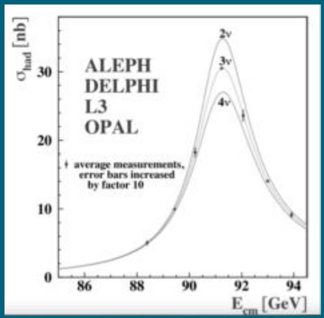




Search for Additional Neutrino States

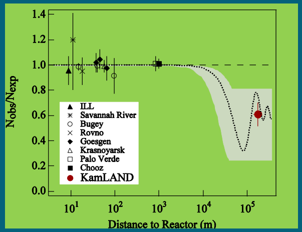
Limits on active neutrinos:

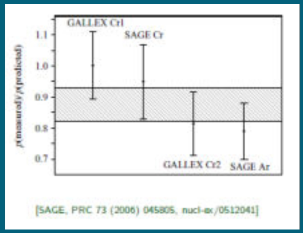
- N = 2.9841 +- 0.0083 from Z invisible width
- N $\lesssim$ 3.16 and $\Sigma m_{\nu i}$ < 0.12 eV from cosmology

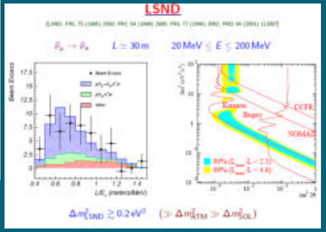


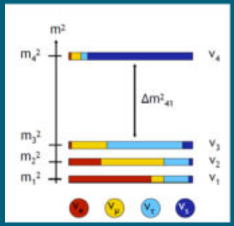
But additional (sterile) states are not excluded:

- Neutrino mass generation (seesaw, > TeV)
- Baryon asymmetry (leptogenesis, >> 100 GeV)
- Dark matter (~ keV)
- **Oscillation anomalies (~ eV)**





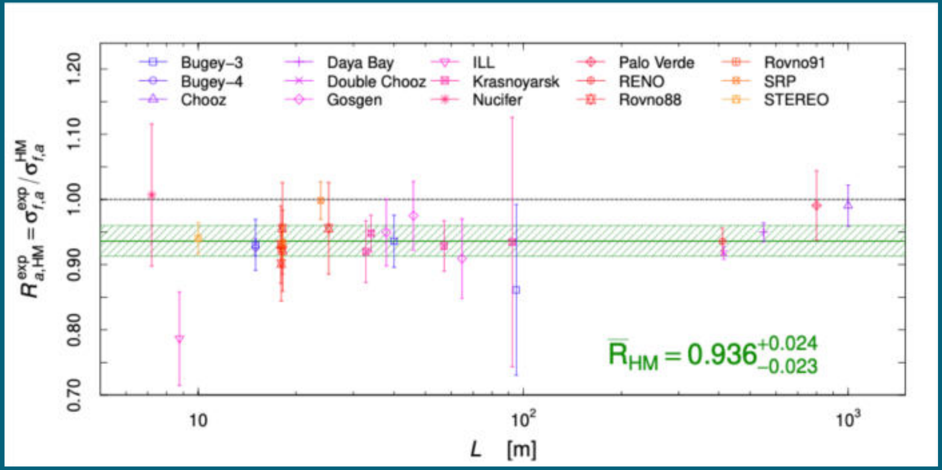




Due to (very) short distance oscillations

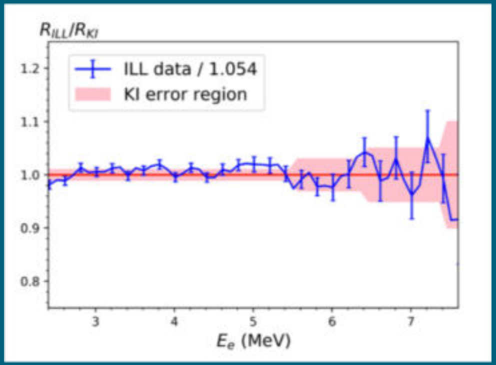
Reactor Antineutrino Anomaly

Flux from reactors was by ~2.7σ below prediction of the HM-model, which was using old ILL data. Plausible explanation by short distance oscillations:



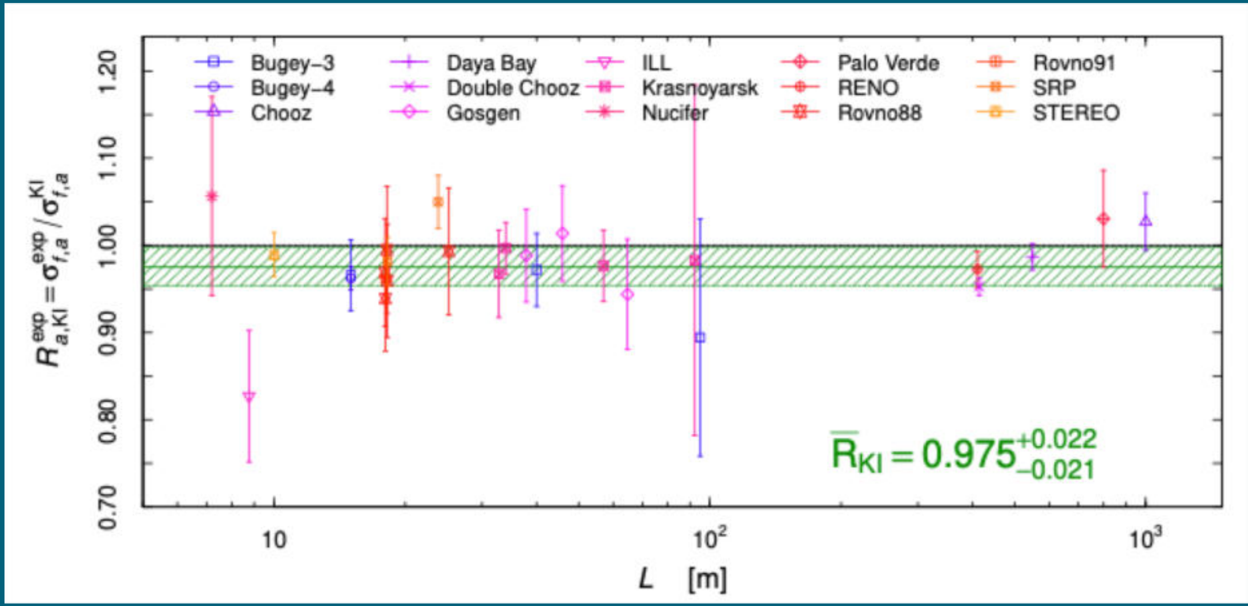
The shape difference studied by different experiments suggested that the problem is in the U235 isotope.

New data were obtained at KI research reactor on the ratio of cumulative beta-spectra of U235 and Pu239 , showing systematic normalization problem with ILL

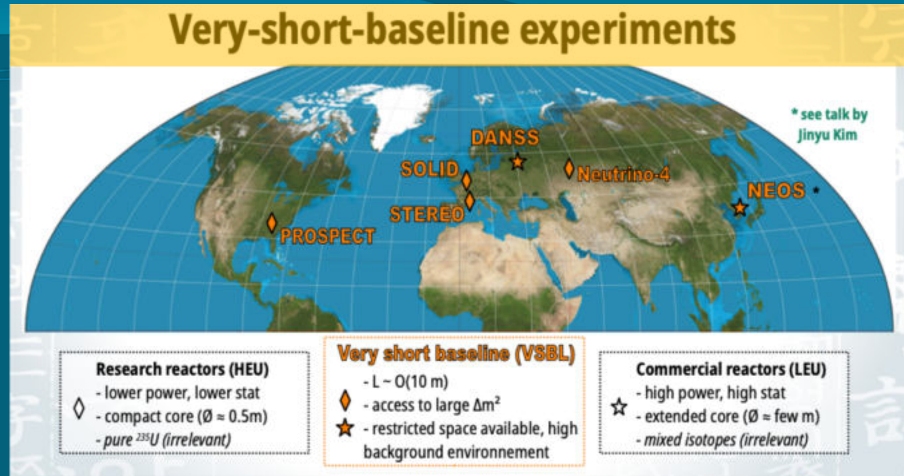


Reactor Antineutrino Anomaly

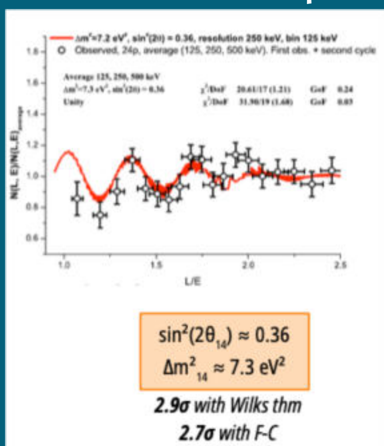
After this is accounted for, the new calculations are much better (~1σ) consistent with the data



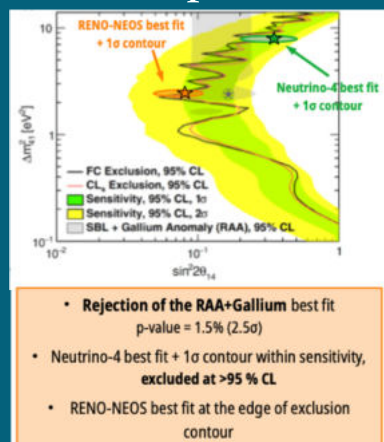
So, the (flux) Reactor Antineutrino Anomaly seems gone, but in the meantime a search for (very) short distance oscillations was performed by many experiments: DANSS, NEOS, PROSPECT, STEREO, Neutrino-4, … , studying IBD rates at different distances from cores of commercial and research reactors



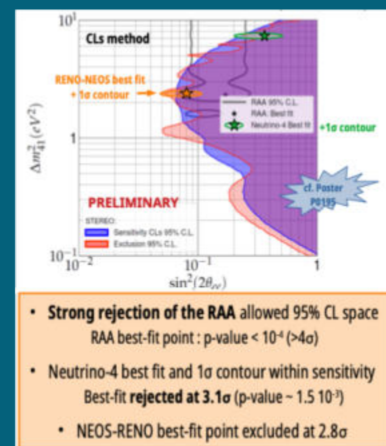
Neutrino-4



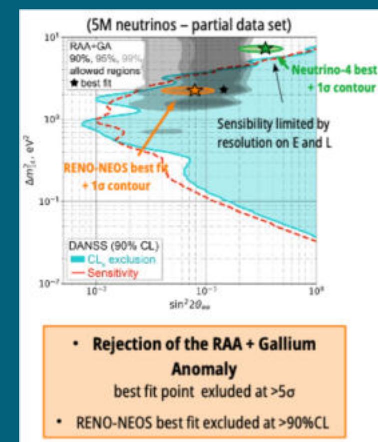
Prospect



Stereo



DANSS



- Reactor Antineutrino Anomaly is excluded at 95 % CL up to $\Delta m^2 \approx 5$ eV^2
- Neutrino-4 hint ($<3\sigma$) at $\Delta m2 = 7.3$ eV^2, $\sin^2 2\theta = 0.36$ exists but is excluded by PROSPECT (>95%CL) and STEREO (>3σ)
- New results, especially after ongoing upgrades of Neutrino-4, PROSPECT and DANSS, are eagerly awaited.

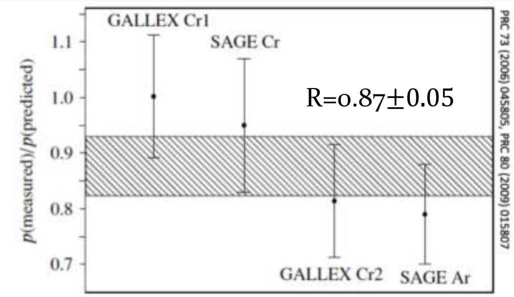
Ga/Ge Detectors Calibration Anomaly

- Neutrino radiochemical detection reaction (ν + Ga $\rightarrow$ Ge + e^-) was applied in SAGE at Baksan and GALLEX/GNO at Gran Sasso.
- Calibration with radioactive sources showed deficit of the neutrino flux.

The Ga Anomaly

Previously measured rates of $^{71}Ga(\nu_e,e)^{71}Ge$ are lower than that predicted from the known cross section and ν_e flux. R=0.87±0.05

The ν_e sources in these experiments were the electron-capture isotopes, ^{51}Cr or ^{37}Ar.



Overview of BEST

- Neutrinos produced at center of Ga by ^{51}Cr decay:

$$^{51}Cr + e^- \rightarrow {}^{51}V + \nu_e$$

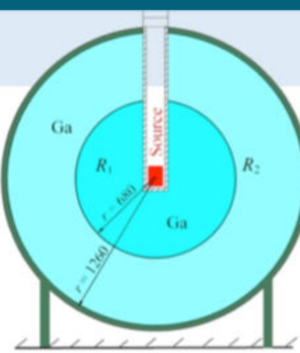
- This is a well-understood monochromatic spectrum of a compact source. The source intensity is well measured.
- These neutrinos are detected via a charged-current (CC) reaction on Ga surrounding the source:

$$\nu_e + {}^{71}Ga \rightarrow {}^{71}Ge + e^-$$

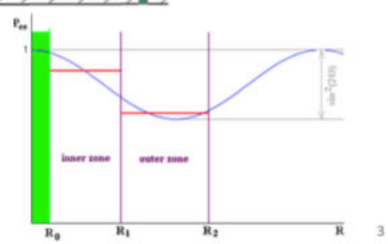
- Very Short Baseline. ~1m, two zone target to measure ν interaction rate at two distances.
- Almost zero background. Mainly from the Sun.

The source, 3.4 MCi, provides a capture rate in the Ga that exceeds the rate from the Sun by several factors of ten.

- Well established experimental procedures for extraction and counting of the ^{71}Ge developed in SAGE solar measurements.
- Simple interpretation of results. (Phys. Part. Nucl. 46 (2015) 131)



Schematic drawing of the BEST neutrino source experiment.



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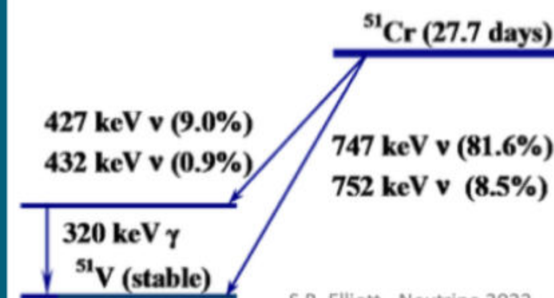
4kg ^{51}Cr ν source

Irradiated for ~100 days with thermal neutrons in the SM-3 reactor (RIAR, Dmitrovgrad) to produce ^{51}Cr neutrino source

Thermal neutron flux density – 5×10^{15} n/(cm^2 s)



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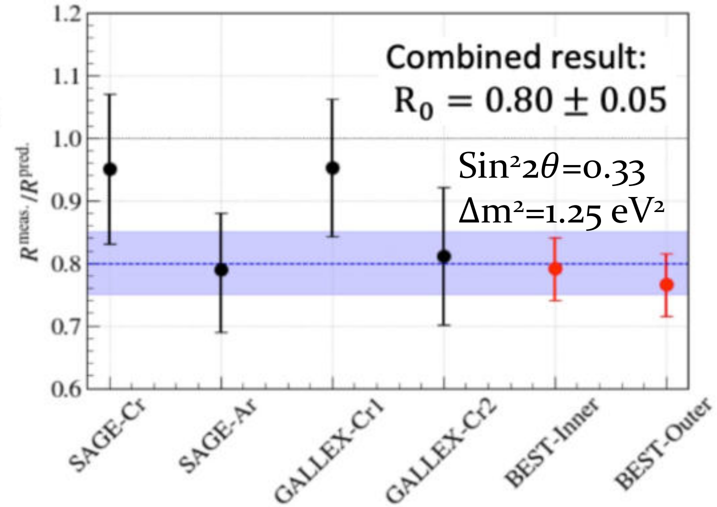
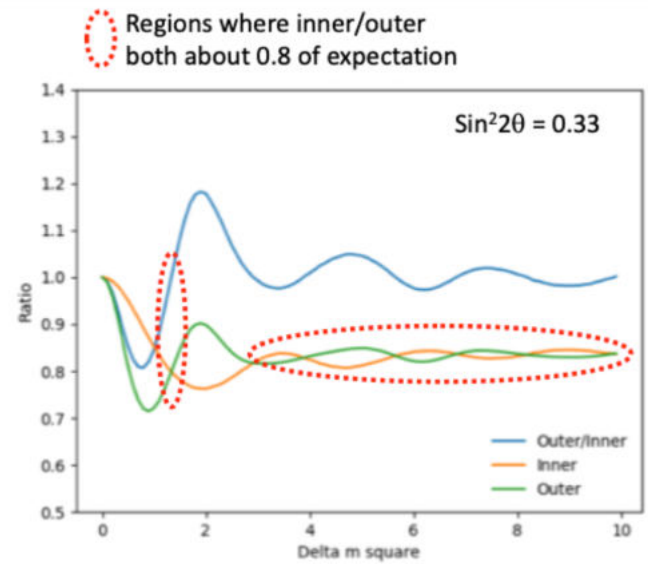
Ga/Ge Detectors Calibration Anomaly

- BEST measured the ^{71}Ge production in Ga from neutrinos emitted by ^{51}Cr at two distances (inner zone: ~40 cm, outer zone: ~96 cm, but both have large spread.)
- The ratio of the measured-to-predicted rates in both the inner and outer zones are depressed by about 20% from unity. The ratio-of-ratios is ~1.
- The Ga Anomaly is reaffirmed.
- No dependence on oscillation length was observed.



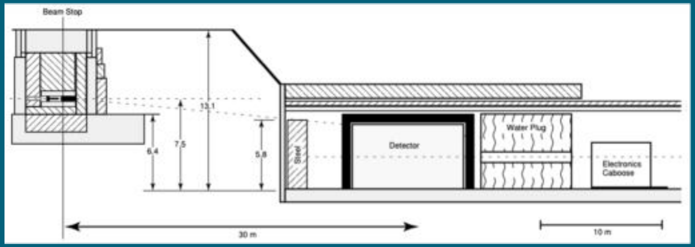
If oscillations, the oscillation length is short (large Δm^2). BEST has poor Δm^2 resolution for values greater than ~2 eV^2.

- Smaller inner volume probably not feasible.
  - Half the radius, need 8x the source strength for same rate.
- ^{65}Zn Source (PRD 97 (2018) 073001)
  - Higher energy source (1.35 MeV vs. 0.75 MeV).
  - Almost twice the cross section.
    - But adds a couple additional excited states.
  - 13-14 kg of 95% enriched ^{64}Zn to produce 0.5 MCi.
  - About 9x longer half life (244 d), many more events even with lower activity.

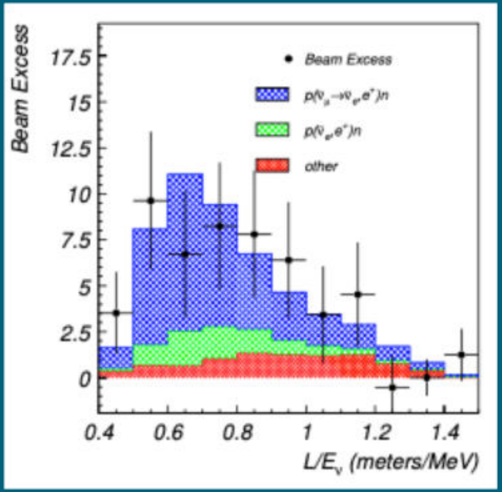


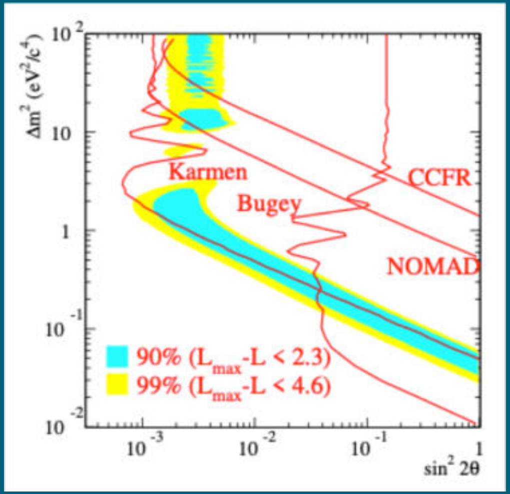
LSND Anomaly

Los Alamos Neutrino Detector - pion decays at rest experiment

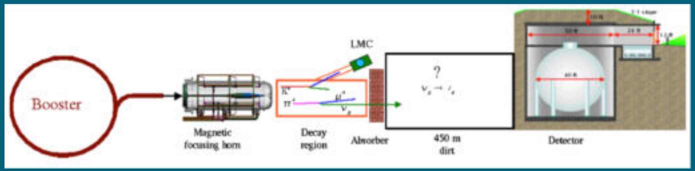


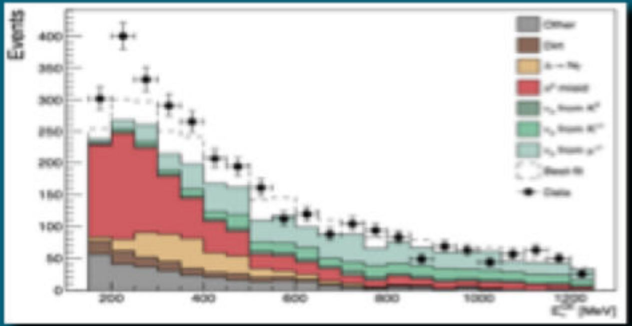
Δm^2=1.2 eV^2, $\sin^2 2\theta$=0.003

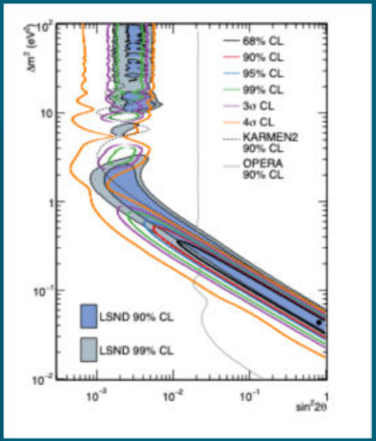




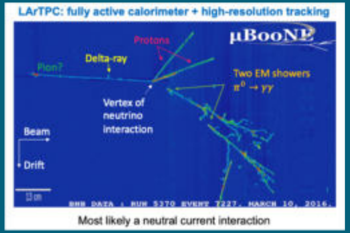
MiniBooNE at Fermilab – pion decays in flight (possible + and -)



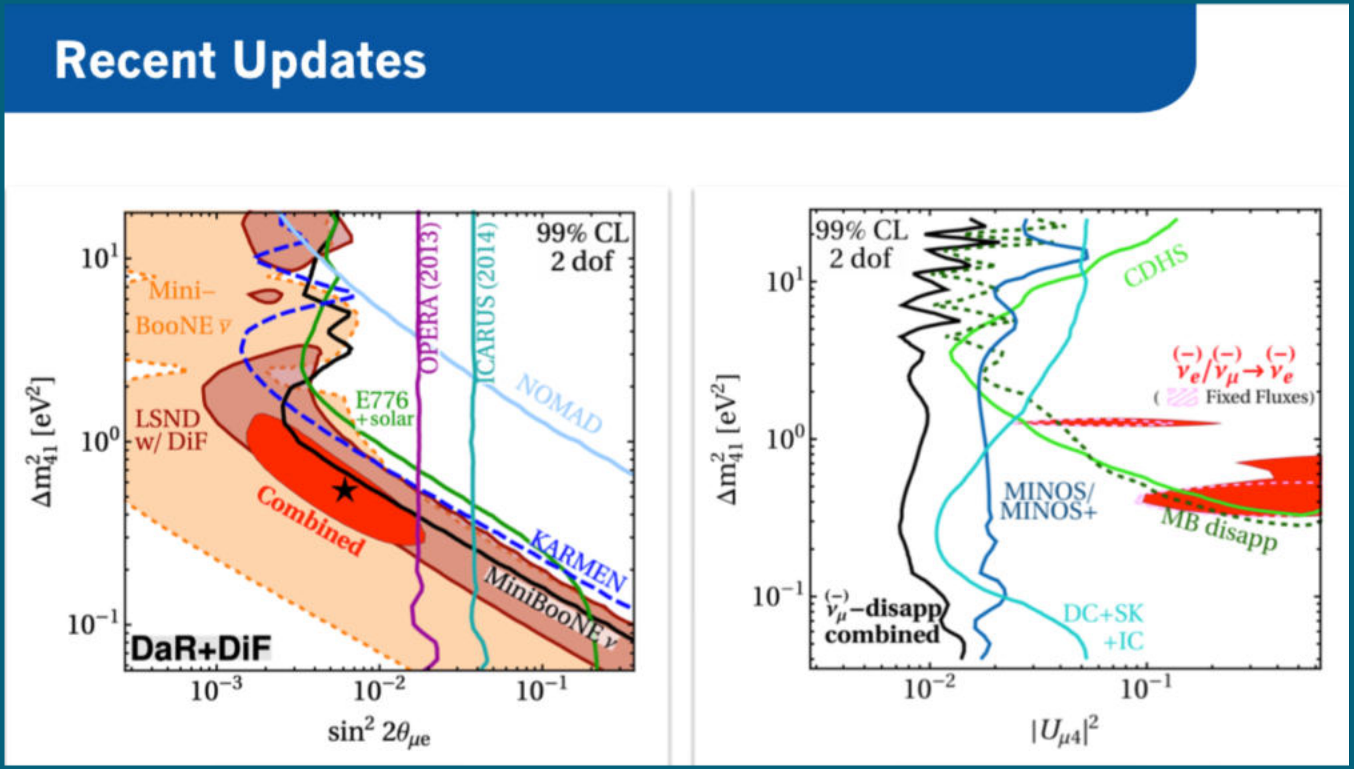




MicroBooNE – precise LAr detector at Fermilab to study neutrino events and possible backgrounds – didn't rule out the MiniBooNE allowed region. More exps are coming (SBND, ICARUS, JSNS^2,…)

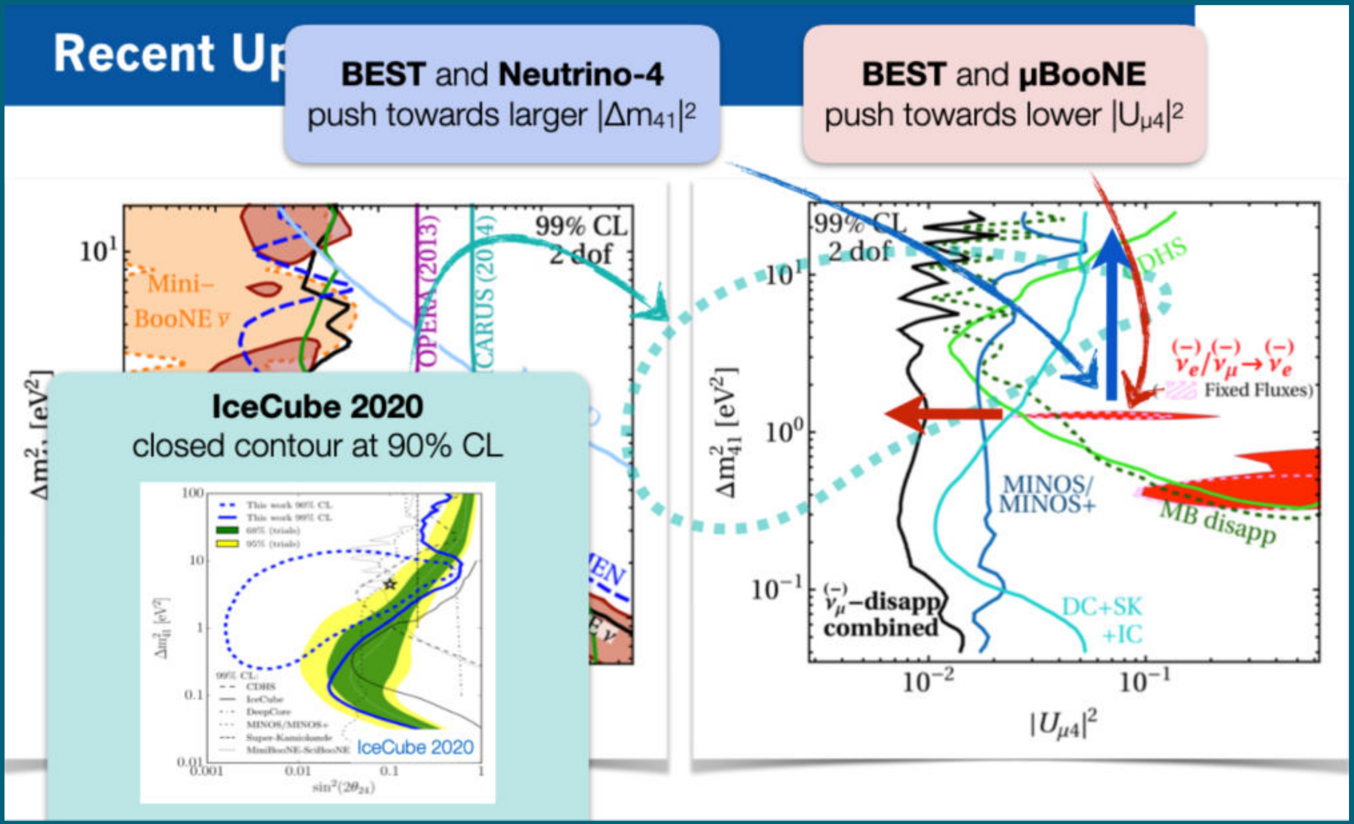


3+1 Scenario



- (3+1) picture describes anomalies better than 3f , but
- it is internally inconsistent (tension between App and Disapp data)
- in addition, trying to introduce decay, decoherence, NSI, …

3+1 Scenario



- (3+1) picture describe data, but an internal consistency is rather low. In addition, trying to improve by adding decays, decoherence, NSI, …
- N $\lesssim$ 3.16 and $\Sigma m_{\nu i} \lesssim$ 0.12 eV from cosmology (Planch measurements)

Summary

- Significant progress in establishing oscillation phenomenon
- Many new fundamental projects running and being prepared: JUNO, IceCube and KM3NET, HyperK and T2HK, DUNE
- Very good chance of getting in ~10 years further improvement of oscillation parameters, including an information on θ_{23} octant, MO and leptonic CP violation
- Present data consistent with the 3f oscillation picture, but several anomalies exist, hinting not necessarily to the existence of sterile states, but certainly to something not yet understood
- Very bright future ahead