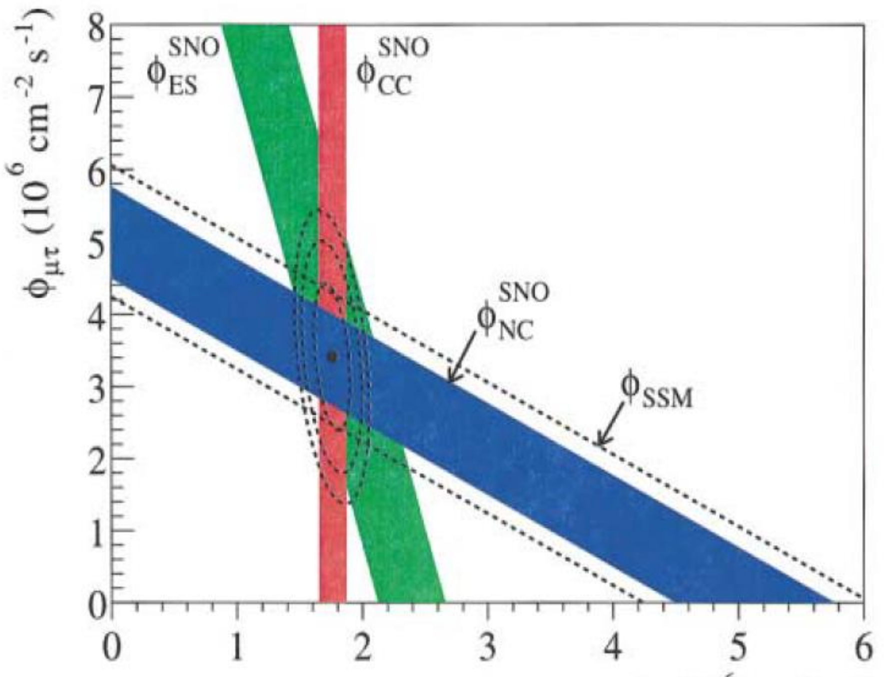
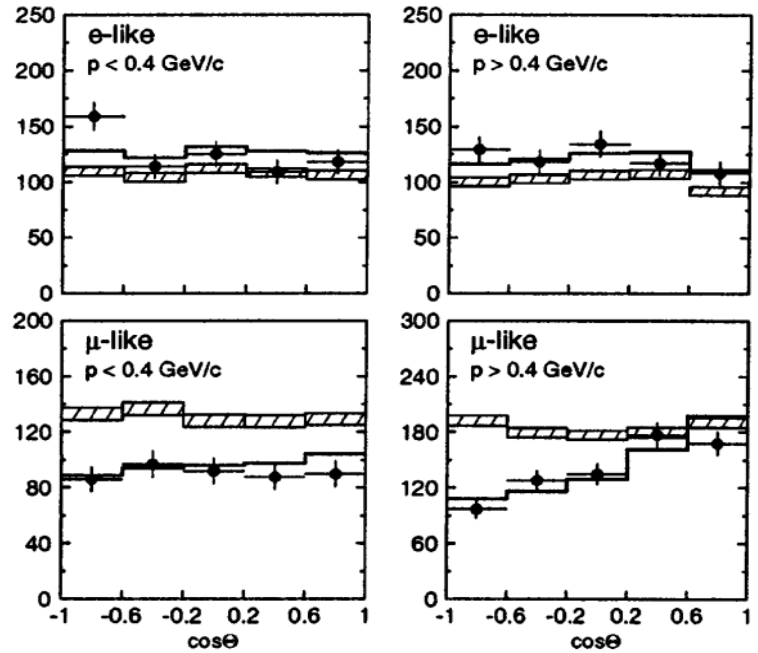
Solar neutrino oscillations



PhysRevLett.89.011301(2002)

Atmospheric neutrino oscillations



PhysRevLett.81.1562(1998)

Neutrino Oscillation Parameter Measurements

Zhe Wang

Tsinghua University

Neutrino Oscillation

Flavor eigenstates → $|\nu_\alpha\rangle = \sum_{i=1}^{n} U^*_{\alpha i} |\nu_i\rangle$ → Mass eigenstates

PMNS matrix: θ_{12}, θ_{13}, θ_{23}, δ

$$U = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \cdot \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta_{\mathrm{CP}}} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta_{\mathrm{CP}}} & 0 & c_{13} \end{pmatrix} \cdot \begin{pmatrix} c_{21} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

Transition Prob. → Appearance or Disappearance

$$P_{\alpha\beta} = \delta_{\alpha\beta} - 4\sum_{i<j}^{n} \mathrm{Re}[U_{\alpha i}U^*_{\beta i}U^*_{\alpha j}U_{\beta j}]\sin^2 X_{ij}$$
$$+ 2\sum_{i<j}^{n} \mathrm{Im}[U_{\alpha i}U^*_{\beta i}U^*_{\alpha j}U_{\beta j}]\sin 2X_{ij} \,,$$

Transition phase → $X_{ij} = \frac{(m_i^2 - m_j^2)L}{4E} = 1.267\frac{\Delta m^2_{ij}}{\mathrm{eV}^2}\frac{L/E}{\mathrm{m/MeV}}$

Mass difference: Δm^2_{21}, Δm^2_{31}

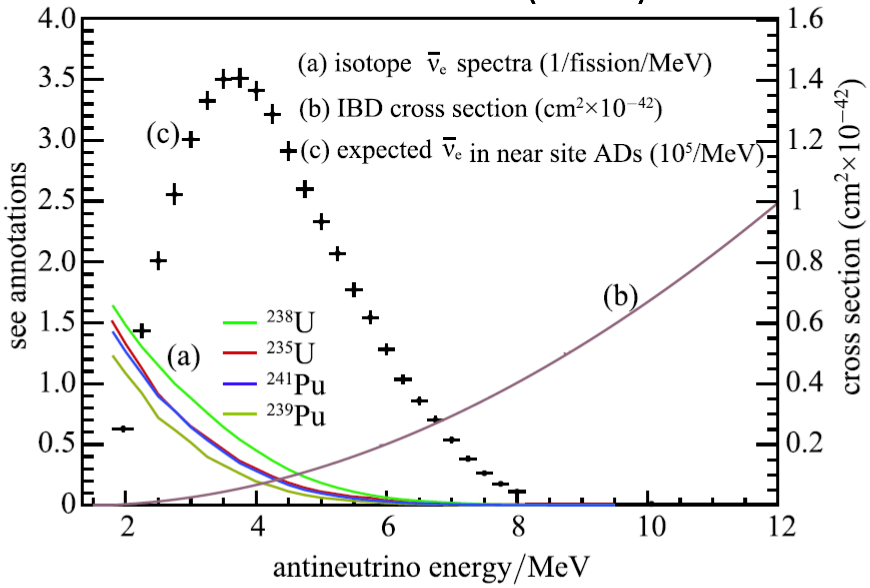
Outlines

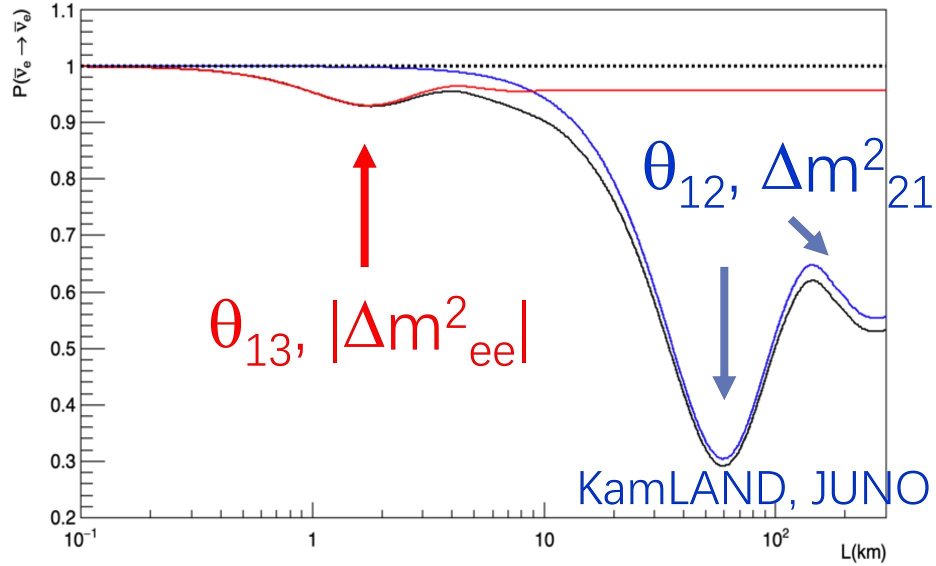
- **Three generations**
  1. Reactor experiments (~1.5 km baseline) θ_{13}, $|\Delta m^2_{ee}|$
  2. Solar+KamLAND θ_{12}, Δm^2_{21}
  3. Accelerator and atmosphere (For Mass ordering and CPV, Atsuko's talk) Disappearance and appearance θ_{23}, Δm^2_{31}, θ_{13}, δ
  4. Global Fit
- **Three+one generations**
  1. Evidence
  2. Status

- High precision
- Octant-symmetry
- Hierarchy
- CP phase
- New Physics

Reactor Experiment Feature (~1.5 km baseline)

CPC 41.013002(2017)





Energy Peak 3-4 MeV

Baseline 1.5 km

$$P_{\mathrm{sur}} = 1 - \boxed{\cos^4\theta_{13}\sin^2 2\theta_{12}\sin^2\Delta_{21}}$$
$$- \boxed{\sin^2 2\theta_{13}}\boxed{(\cos^2\theta_{12}\sin^2\Delta_{31} + \sin^2\theta_{12}\sin^2\Delta_{32})}$$
$$\rightarrow \sin^2 2\theta_{13}\sin^2\Delta_{ee}$$

Measurement of $\bar{\nu}_e$ osci.

Neutrino Energy measurement

$$\bar{\nu}_e + p \rightarrow e^+ + n$$

$$\quad \rightarrow + p \rightarrow D + \gamma\,(2.2\ MeV) \quad (200\ \mu s)$$

$$\quad \rightarrow + Gd \rightarrow Gd^* \rightarrow Gd + \gamma\text{'s}\ (8\ MeV) \quad (30\ \mu s)$$

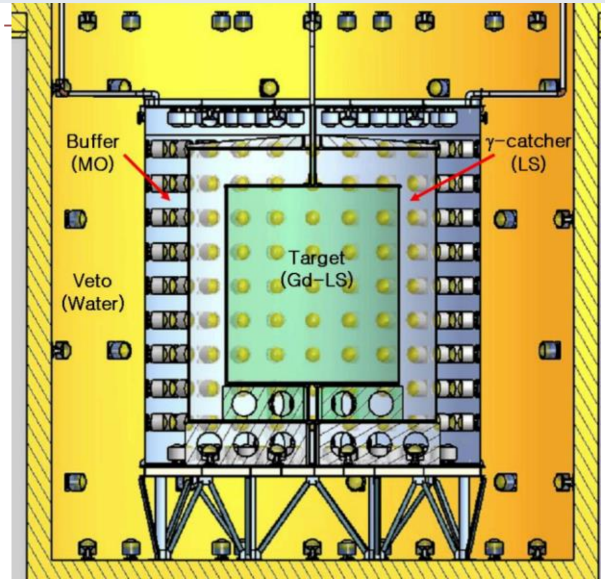
$$E_{\bar{\nu}_e} = E_{\rm prompt} + \bar{E}_n + 0.78\ {\rm MeV}$$

Near-Far cancellation

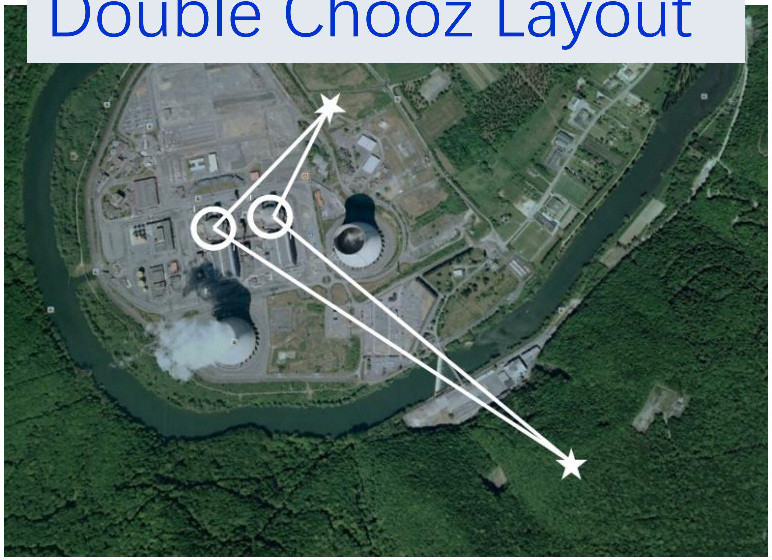
$$\frac{N_{\rm f}}{N_{\rm n}} = \left(\frac{N_{\rm p,f}}{N_{\rm p,n}}\right)\left(\frac{L_{\rm n}}{L_{\rm f}}\right)^2\left(\frac{\epsilon_{\rm f}}{\epsilon_{\rm n}}\right)\left[\frac{P_{\rm sur}(E_\nu, L_{\rm f})}{P_{\rm sur}(E_\nu, L_{\rm n})}\right]$$

=> Relative event rate and spectrum measurements are also used in accelerator experiments.

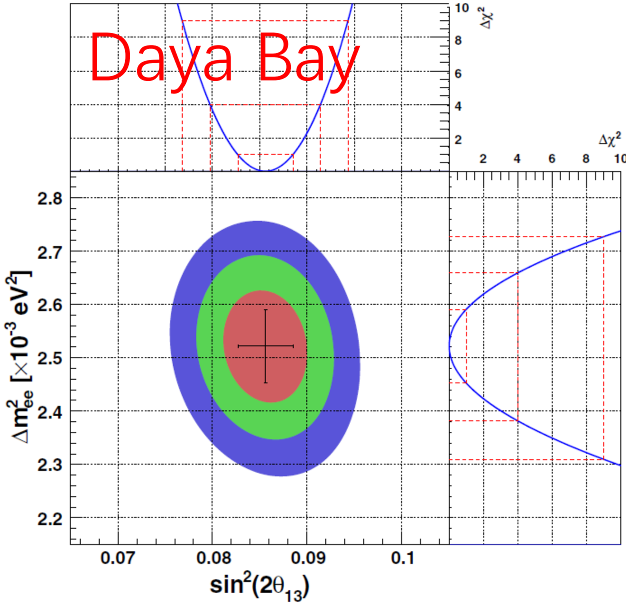
RENO anti-ν_e detector

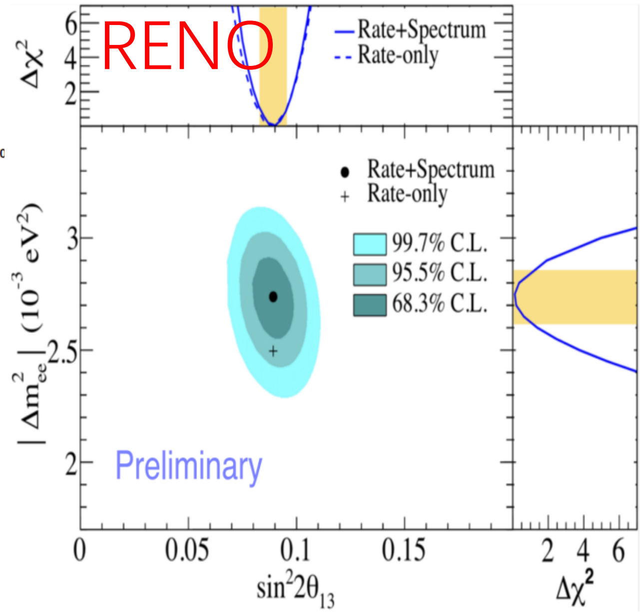


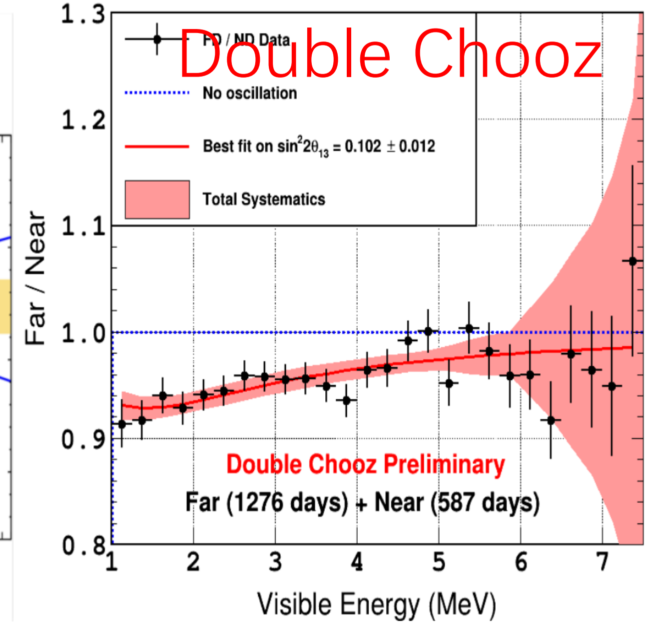
Double Chooz Layout



Recent θ_{13} and $|\Delta m^2_{ee}|$ Results







Gd-capture

$$\boxed{\sin^2 2\theta_{13} = 0.0856 \pm 0.0029}$$

$$|\Delta m^2_{ee}| = (2.52 \pm 0.07) \times 10^{-3}\ \mathrm{eV}^2$$

*PRL **121** 241805 (2018)*

H-capture

$$\sin^2 2\theta_{13} = 0.071 \pm 0.011$$

*PRD **93** 072011 (2016)*

Gd-capture

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

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

@ICHEP 2020

H-capture

$$\sin^2 2\theta_{13} = 0.086 \pm 0.008(stat.) \pm 0.014(sys.)$$

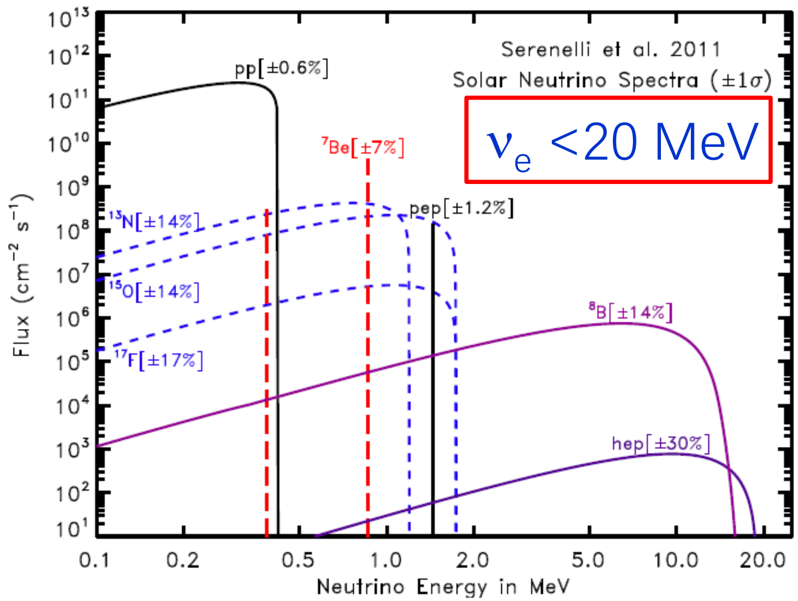
JHEP 04 (2020) 029

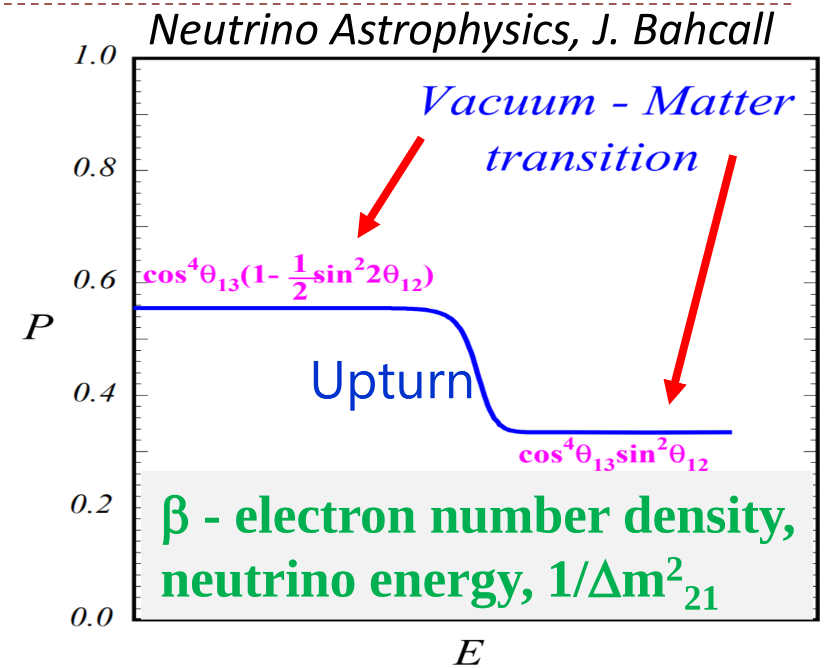
Total-capture

$\sin^2 2\theta_{13} = 0.102 \pm 0.011$ (syst.) $\pm$ 0.004 (stat.)

@Neutrino 2020

Neutrinos from the Sun





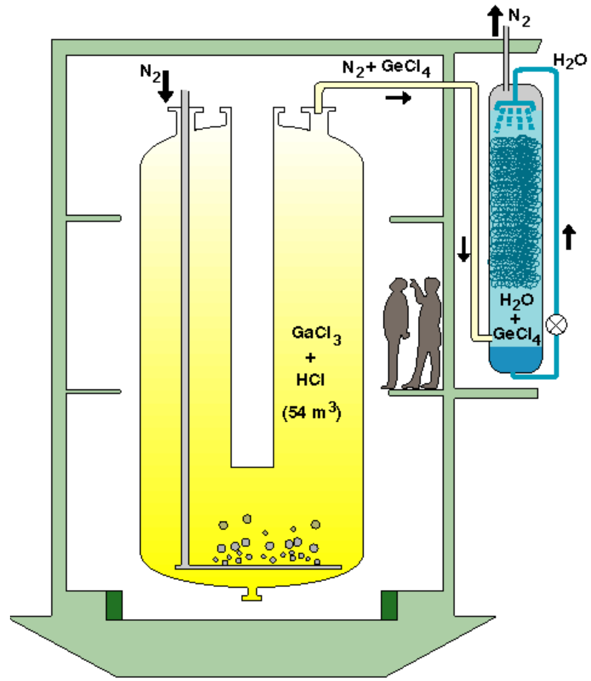
Neutrino survival prob. → $P_{ee}^{\odot} = \cos^4\theta_{13}\left(\frac{1}{2} + \frac{1}{2}\cos 2\theta_{12}^{M}\cos 2\theta_{12}\right)$

$$\cos 2\theta_{12}^{M} = \frac{\cos 2\theta_{12} - \beta}{\sqrt{(\cos 2\theta_{12} - \beta)^2 + \sin^2 2\theta_{12}}} \qquad \beta = \frac{2\sqrt{2}G_F\cos^2\theta_{13} n_e E_\nu}{\Delta m^2_{21}}$$

The sign of Δm^2_{21} can be determined.

Solar Experiments - Chemical

Homestake



GALLEX/GNO

SAGE

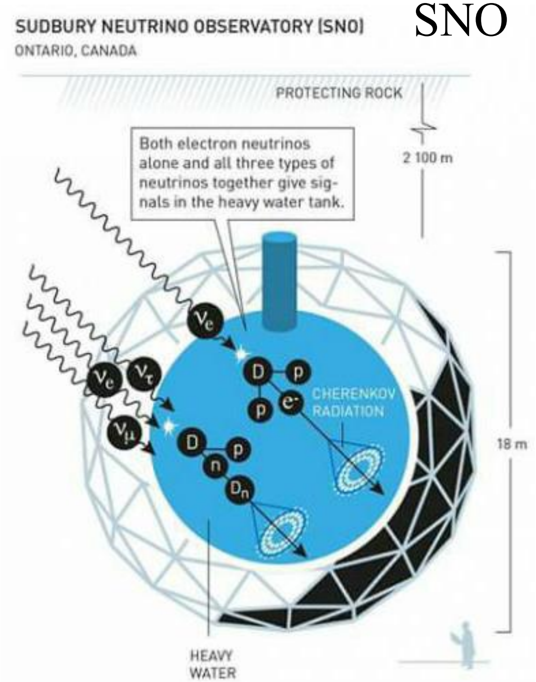
- Charged current, ν_e only

$$\nu_e + {}^{37}Cl \rightarrow {}^{37}Ar + e^-$$

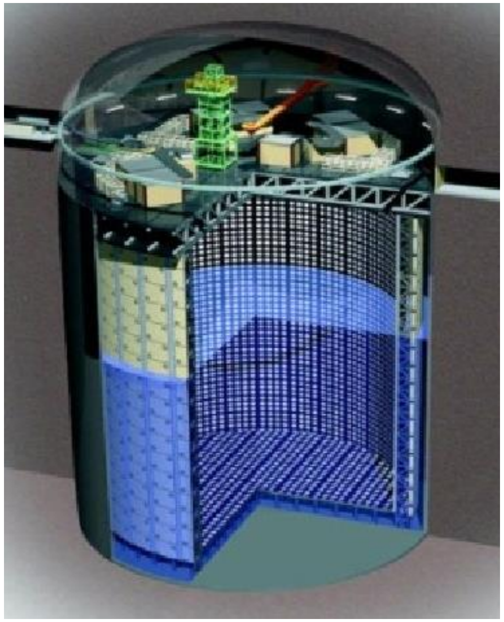
$$\nu_e + {}^{71}Ga \rightarrow {}^{71}Ge + e^-$$

Solar Experiments – Realtime Counting

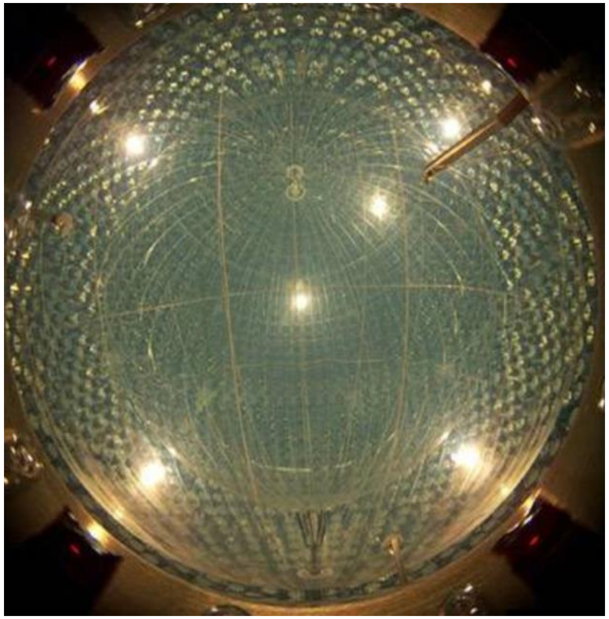
SNO



SK



Borexino



- Neutral current + Charged current

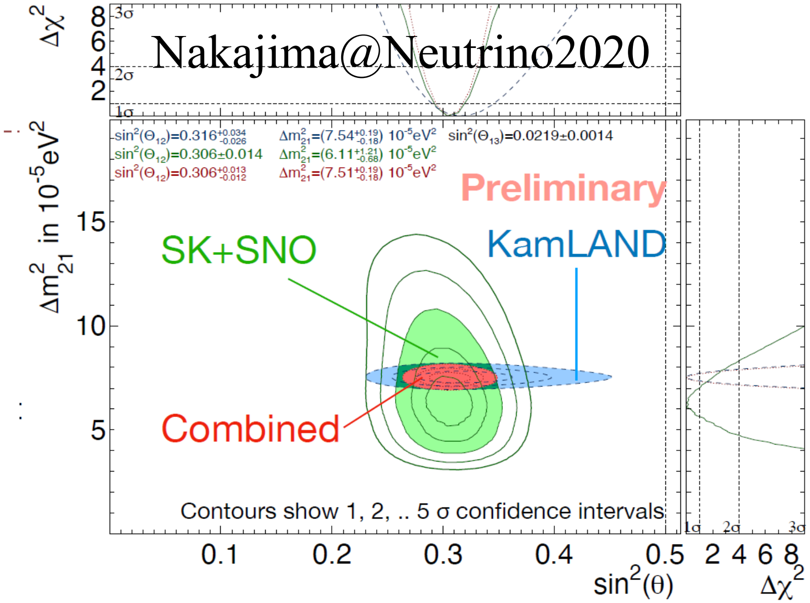
$$\nu_x + e^- \rightarrow \nu_x + e^- \quad \text{(ES)},$$

$$\nu_e + d \rightarrow p + p + e^- \quad \text{(CC)},$$

$$\nu_x + d \rightarrow p + n + \nu_x \quad \text{(NC)}.$$

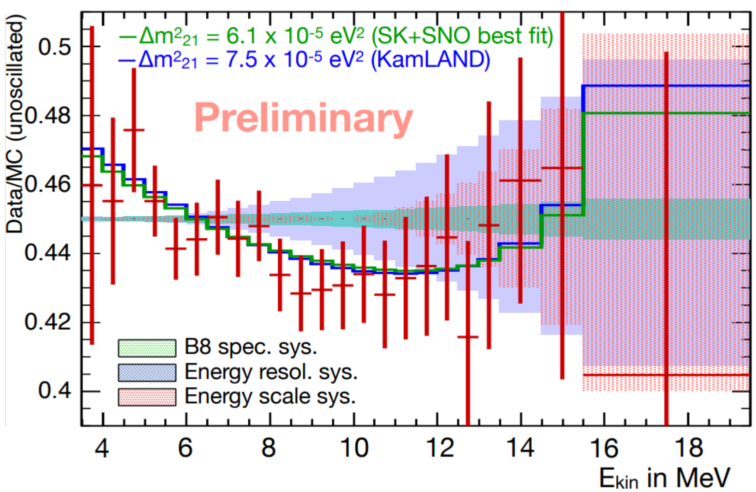
Super-Kamiokande Results

	$\sin^2(\theta_{12})$	Δm^2_{21} [10^{-5} eV^2]
KamLAND	$0.316^{+0.034}_{-0.026}$	$7.54^{+0.19}_{-0.18}$
SK+SNO	0.306 ± 0.014	$6.11^{+1.21}_{-0.68}$
Combined	$0.306^{+0.013}_{-0.012}$	$7.51^{+0.19}_{-0.18}$

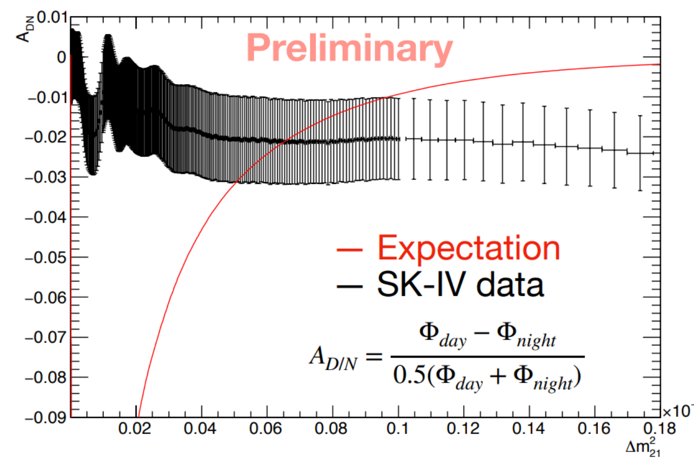


SK+SNO fit disfavors the KamLAND best fit value at ~1.4σ (was ~2σ)

Energy spectrum fit (SK-IV)



Day/Night amplitude fit (SK-IV)



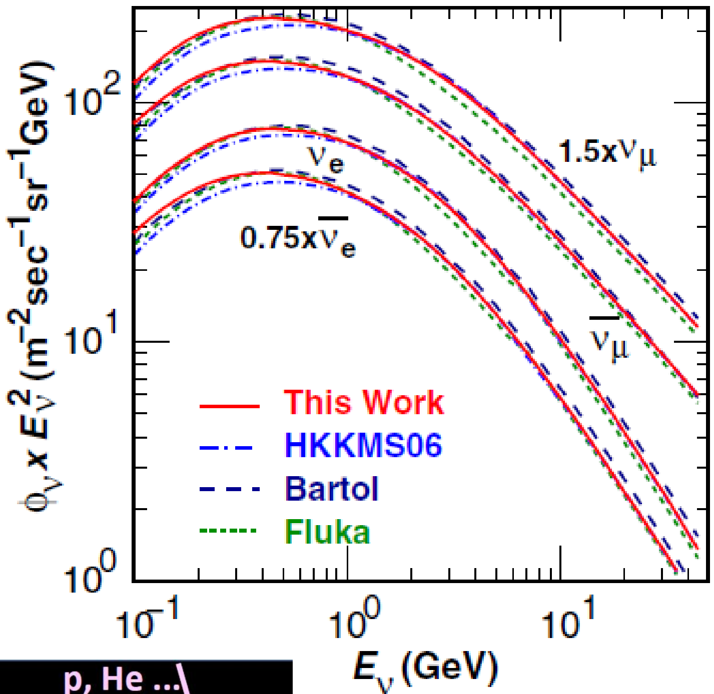
Disfavors flat oscillation probability by ~1σ

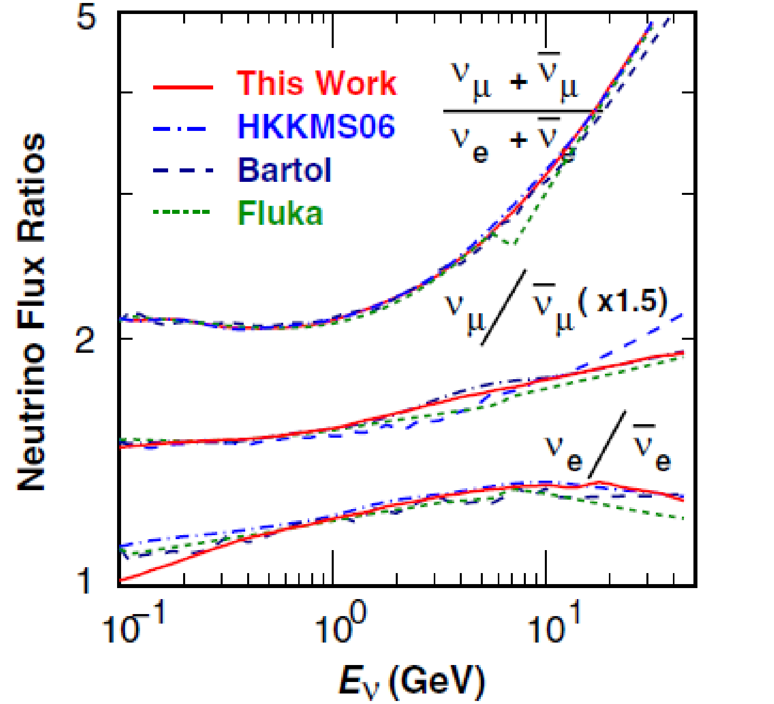
$A^{Fit}_{DN} = (-2.1 \pm 1.1)\,\%$ [3.5 < E < 19.5 (MeV)]

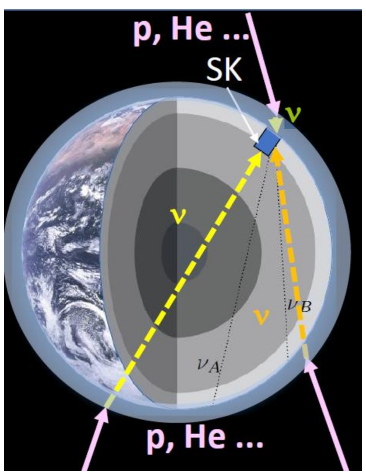
BTW, Borexino reported a first CNO neutrino measurement.

Atmosphere Neutrinos

M. Honda et. al. PRDD 83, 123001 (2011)







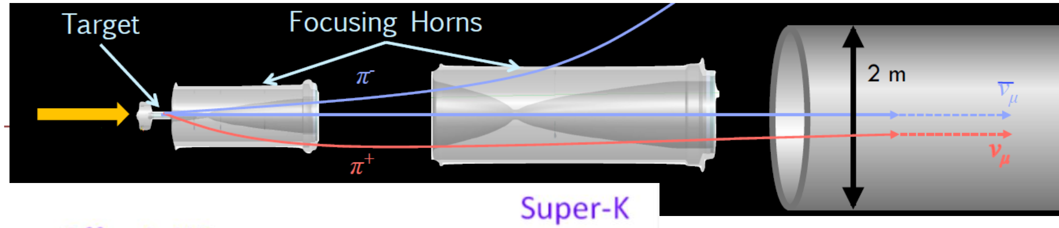
$\pi^- \rightarrow \mu^- + \bar{\nu}_\mu;\ \mu^- \rightarrow e^- + \bar{\nu}_e + \nu_\mu.$

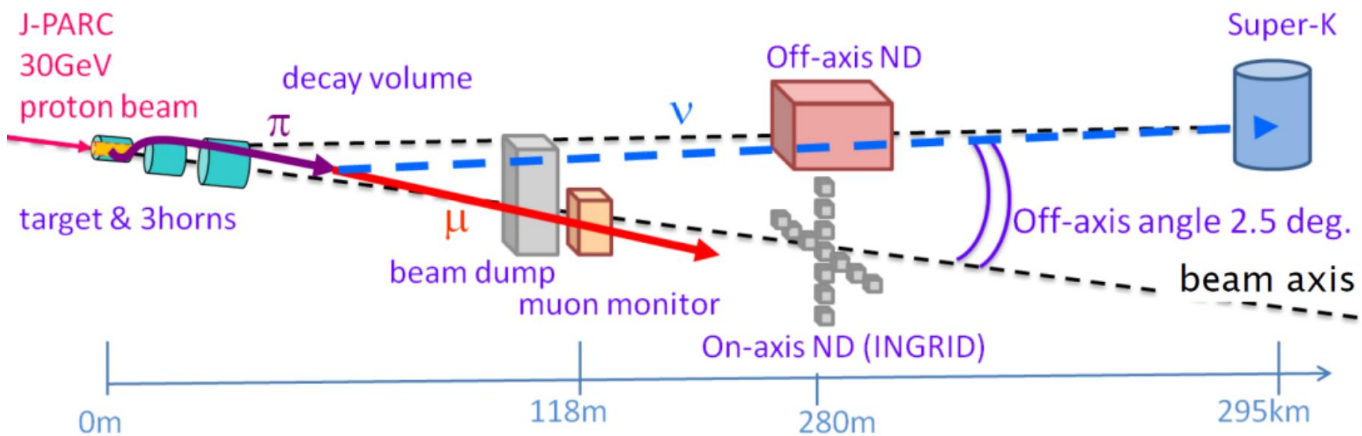
$=> (\bar{\nu}_\mu + \nu_\mu)/(\bar{\nu}_e + \nu_e) \approx 2$

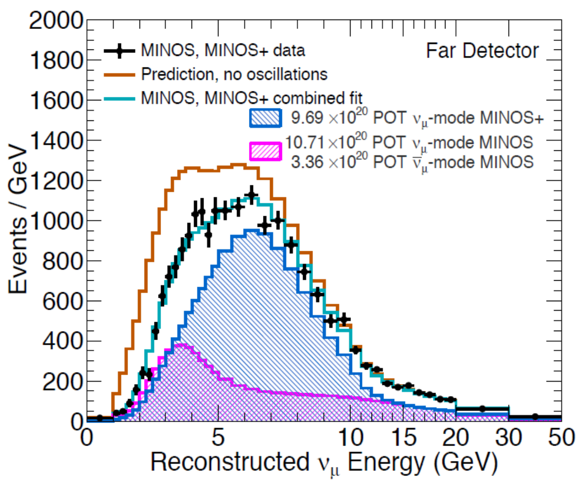
Baseline: $L \sim L(cos\theta_{zenith})$

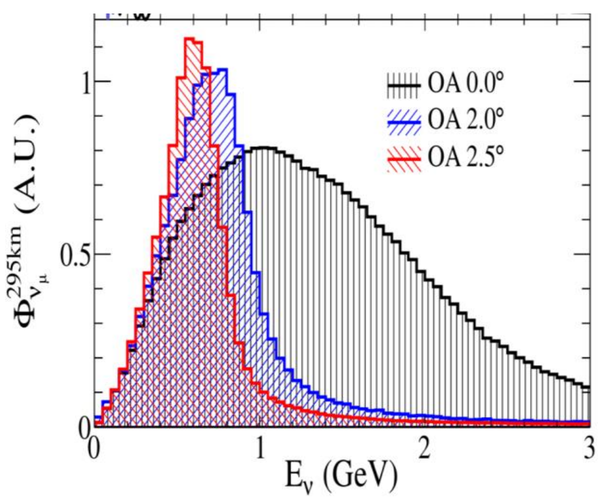
Neutrinos travel 10~12000 km

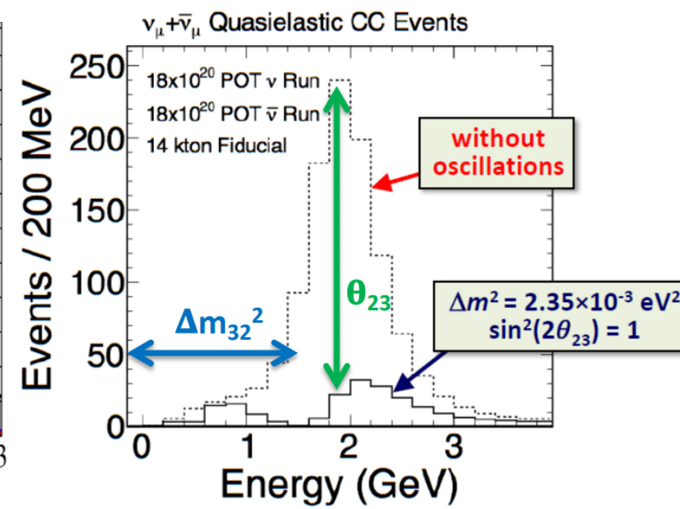
Accelerator Neutrinos











Minos/Minos+ 735 km

T2K 295 km

NOvA 810 km

Atmospheric/Accelerator Neutrino Oscillation

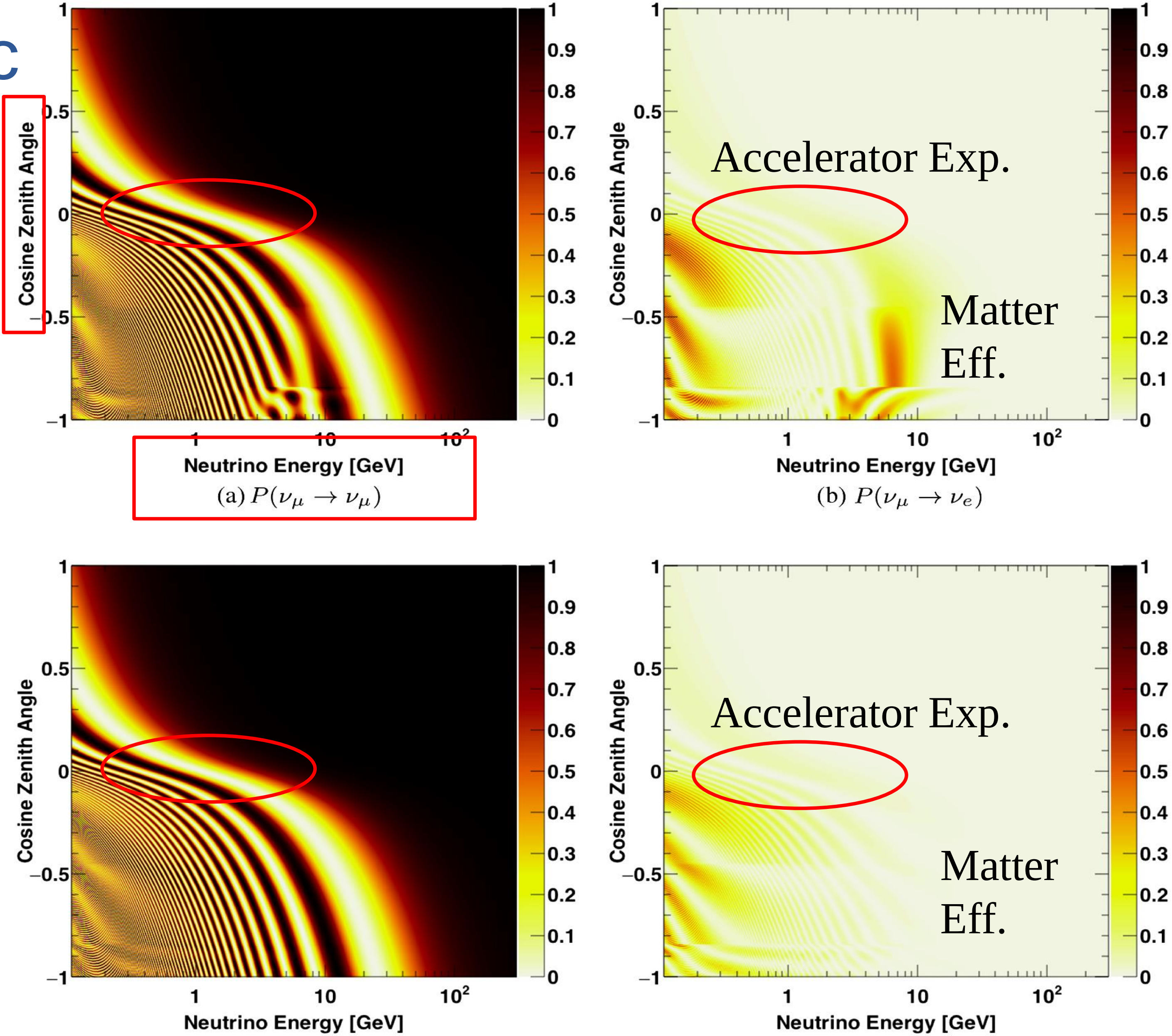
Disappearance:

$$P_{\nu_\mu \to \nu_\mu} \approx 1 - \cos^2\theta_{13}\sin^2(2\theta_{23})\sin^2\frac{\Delta m^2_{32}L}{4E_\nu}$$

Appearance:

$$P_{\nu_\mu \to \nu_e} = \frac{1}{(A-1)^2}\sin^2 2\theta_{13}\sin^2\theta_{23}\sin^2[(A-1)\Delta]$$
$$-(+)\frac{\alpha}{A(1-A)}\cos\theta_{13}\sin 2\theta_{12}\sin 2\theta_{23}\sin 2\theta_{13}$$
$$\times\sin\delta_{CP}\sin\Delta\sin A\Delta\sin[(1-A)\Delta] + \frac{\alpha}{A(1-A)}$$
$$\times\cos\theta_{13}\sin 2\theta_{12}\sin 2\theta_{23}\sin 2\theta_{13}$$
$$\times\cos\delta_{CP}\cos\Delta\sin A\Delta\sin[(1-A)\Delta]$$
$$+\frac{\alpha^2}{A^2}\cos^2\theta_{23}\sin^2 2\theta_{12}\sin^2 A\Delta.$$

Atmospheric /accelerator neutrino oscillation

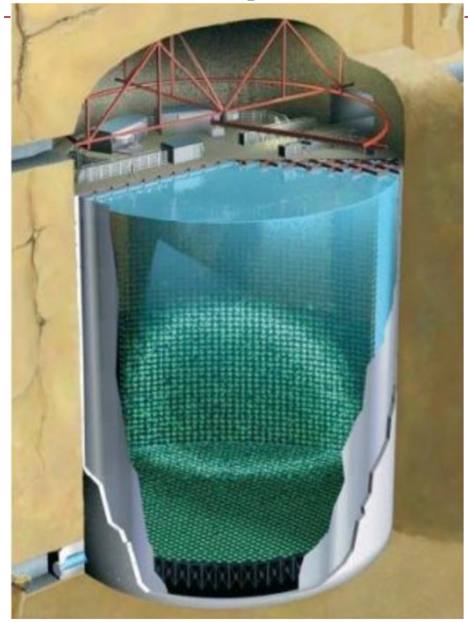


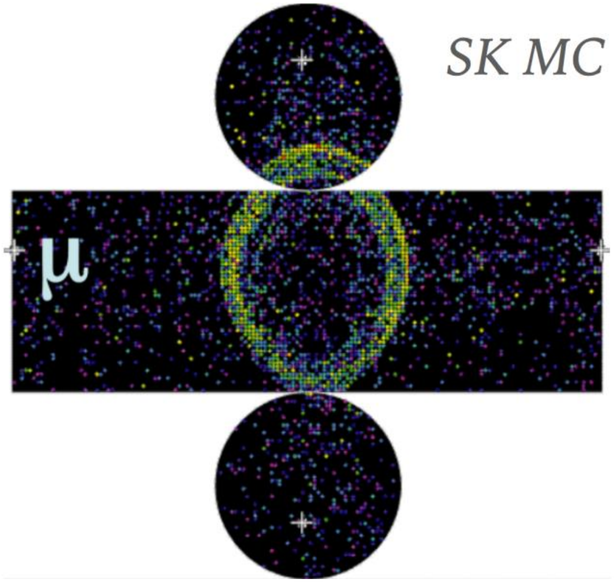
(a) $P(\nu_\mu \to \nu_\mu)$ (b) $P(\nu_\mu \to \nu_e)$

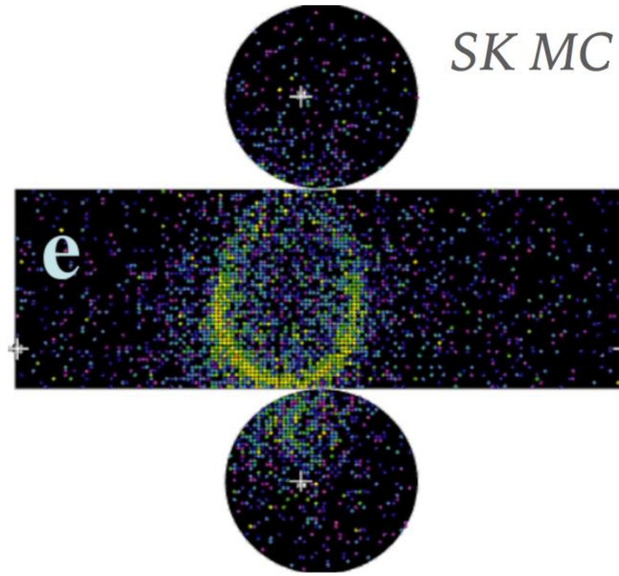
(c) $P(\bar{\nu}_\mu \to \bar{\nu}_\mu)$ (d) $P(\bar{\nu}_\mu \to \bar{\nu}_e)$

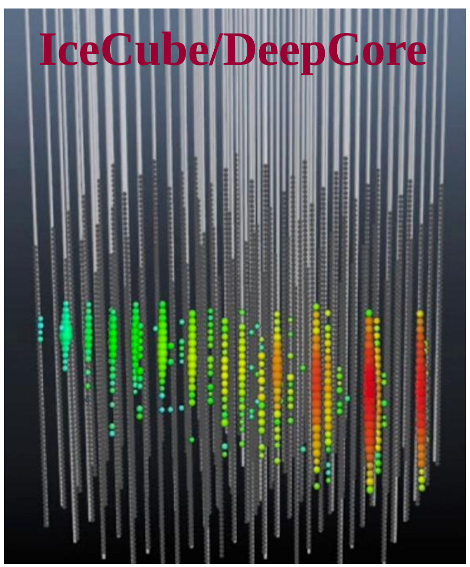
Not easy to separate ν_e or $\bar{\nu}_e$ for Atm. Neu.

Atmospheric/Accelerator Neutrino Detection



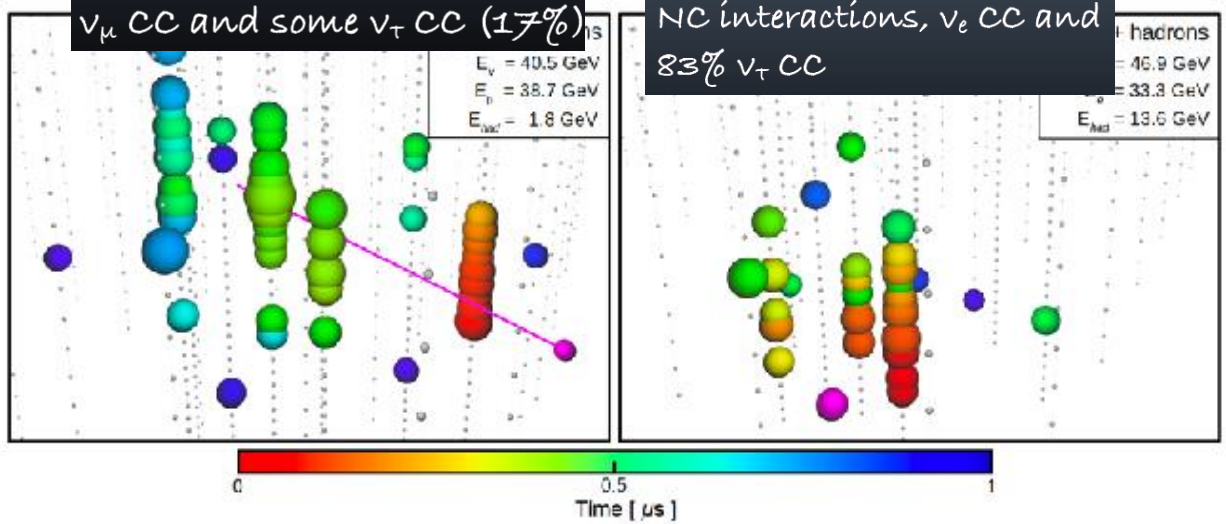






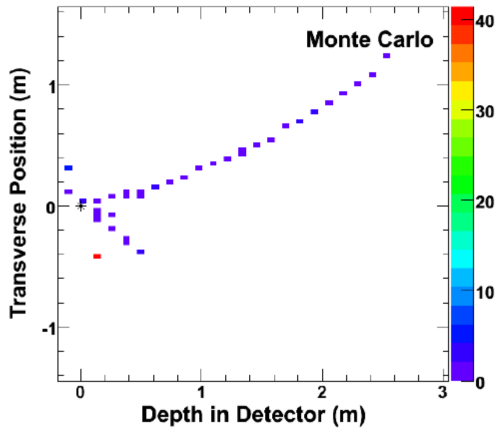
"Track-like":
ν_μ CC and some ν_τ CC (17%)

"Cascade-like":
NC interactions, ν_e CC and 83% ν_τ CC

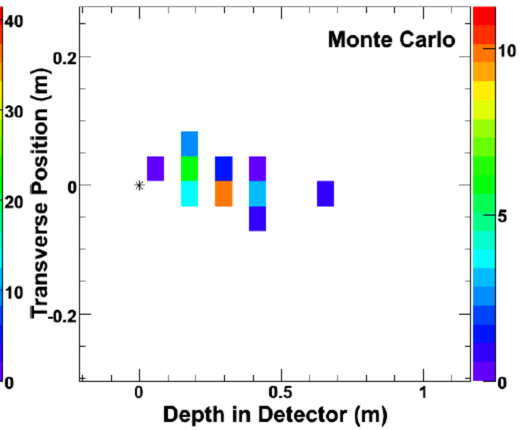


Atmospheric/Accelerator Neutrino Detection

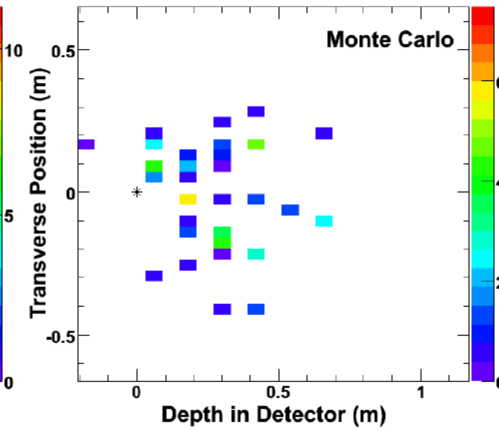
ν_μ-CC event

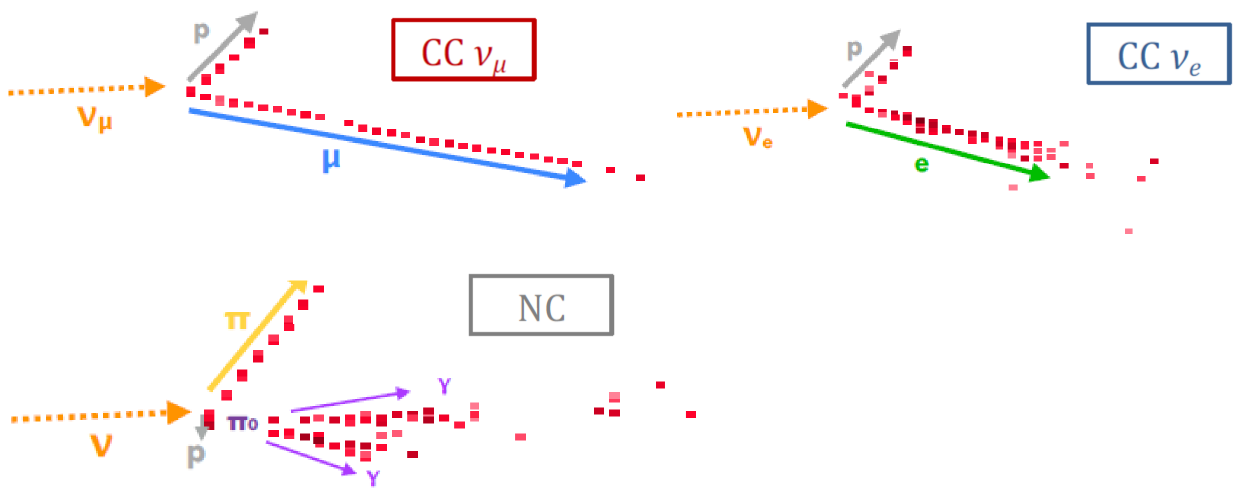


ν_e-CC event



NC event





Atmospheric Neutrino Results

Super Kaminokande

Takhistov@ICHEP2020

930 Bins	$\chi 2$	θ_{13}	δ_{cp}	θ_{23}	Δm_{23} ($x10^{-3}$)
SK (NH)	**1037.5**	0.0218	$4.36^{+0.88}_{-1.39}$	$0.44^{+0.05}_{-0.02}$	$2.40^{+0.11}_{-0.12}$
SK (IH)	**1040.7**	0.0218	$4.54^{+0.88}_{-1.32}$	$0.45^{+0.09}_{-0.03}$	$2.40^{+0.09}_{-0.32}$

SK data ***disfavors*** **Inverted Hierarchy at 71.4-90.3% C.L.** (SK 2018 published: 81.9-96.1%)

SK data ***prefers*** **1st θ_{23} octant** and **$\delta cp \sim 3\pi/2$**

IceCube/DeepCore

PRD 99, 032007 (2019)

$\Delta m^2_{32} = 2.55^{+0.12}_{-0.11}\ x10^{-3}\ eV^2$ $\sin^2\theta_{23} = 0.58^{+0.04}_{-0.13}$

Norm $\nu_\tau^{(CC+NC)} = 0.73^{+0.34}_{-0.24}$ Reject no-ν_τ with 3.2σ (CC+NC)

Minos/Minos+

Atmospheric Best Fit
Normal Hierarchy

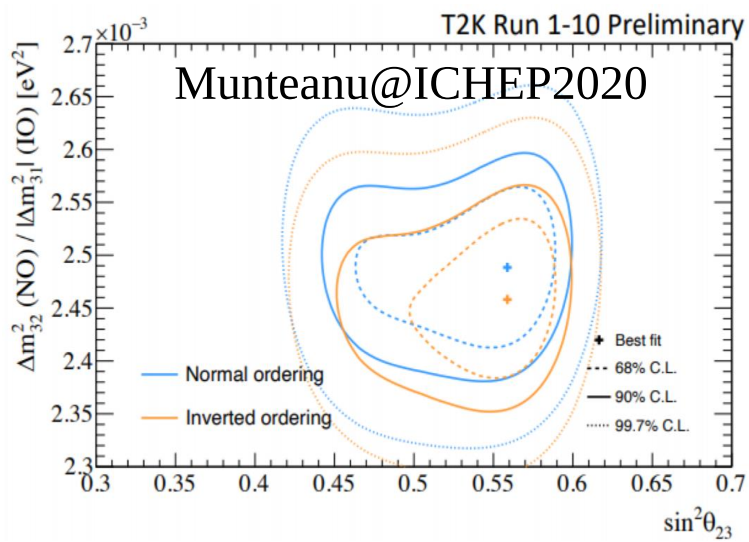
$$\Delta m^2_{32} = 2.11 \times 10^{-3}\ \text{eV}^2$$

$$\sin^2\theta_{23} = 0.52$$

arXiv:2006.15208v2 (2020)

Accelerator Neutrino Results

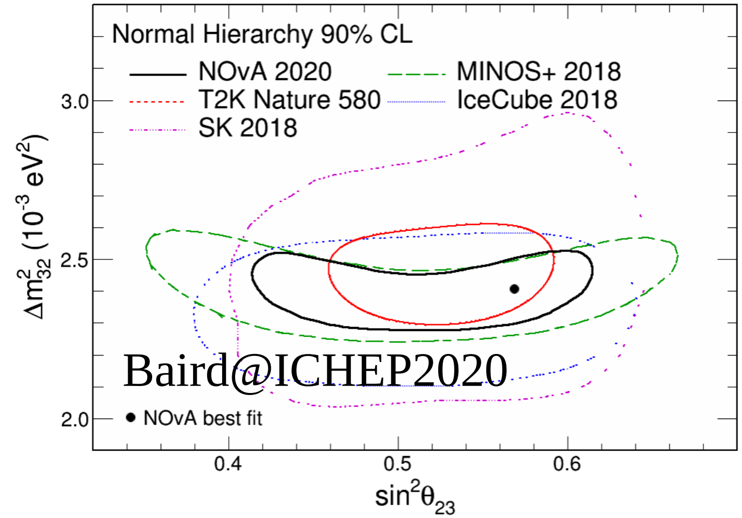
T2K



NOvA

$\Delta m^2_{32} = (2.41 \pm 0.07) \times 10^{-3}$ eV^2

$\sin^2(\theta_{23}) = 0.57^{+0.04}_{-0.03}$ (49°)



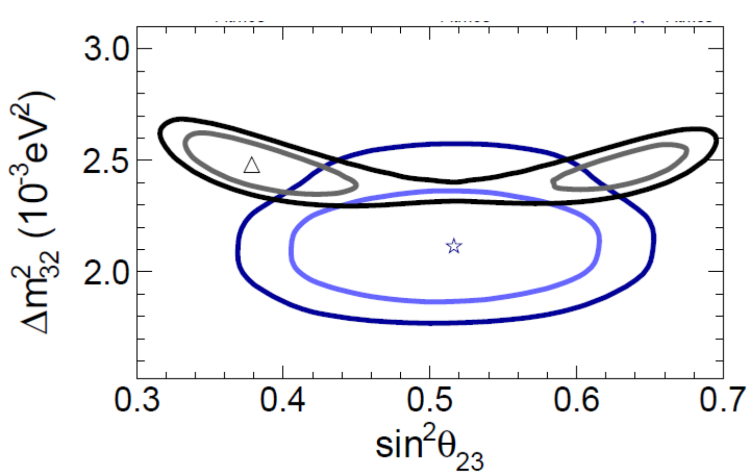
Minos/Minos+

Beam Best Fit

Normal Hierarchy

$$\Delta m^2_{32} = 2.48 \times 10^{-3}\ \mathrm{eV}^2$$

$$\sin^2\theta_{23} = 0.38$$



arXiv:2006.15208v2 (2020)

Global Fit

(pre-Neutrino2020)

JHEP 01 (2019) 106
PRD 101, 116013 (2020)
Tórtola@ICHEP2020

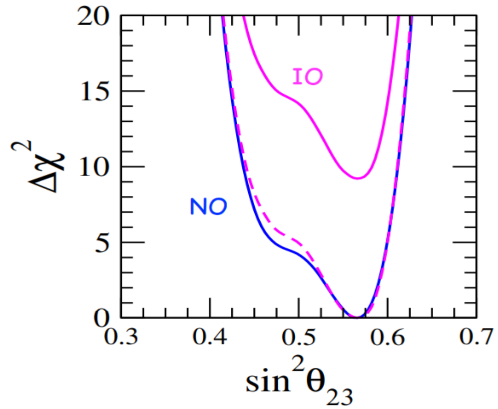
de Salas et al, arXiv:2006.11237

https://globalfit.astroparticles.es/

parameter	best fit $\pm 1\sigma$	3σ range	relative 1σ uncertainty
Δm^2_{21} $[10^{-5}\mathrm{eV}^2]$	$7.50^{+0.22}_{-0.20}$	6.94–8.14	2.7%
$\lvert\Delta m^2_{31}\rvert$ $[10^{-3}\mathrm{eV}^2]$ (NO)	$2.56^{+0.03}_{-0.04}$	2.46–2.65	1.2%
$\lvert\Delta m^2_{31}\rvert$ $[10^{-3}\mathrm{eV}^2]$ (IO)	2.46 ± 0.03	2.37–2.55	
$\sin^2\theta_{12}$ $/10^{-1}$	3.18 ± 0.16	2.71–3.70	5.2%
$\sin^2\theta_{23}$ $/10^{-1}$ (NO)	$5.66^{+0.16}_{-0.22}$	4.41–6.09	4.9%
$\sin^2\theta_{23}$ $/10^{-1}$ (IO)	$5.66^{+0.18}_{-0.23}$	4.46–6.09	4.8%
$\sin^2\theta_{13}$ $/10^{-2}$ (NO)	$2.225^{+0.055}_{-0.078}$	2.015–2.417	3.0%
$\sin^2\theta_{13}$ $/10^{-2}$ (IO)	$2.250^{+0.056}_{-0.076}$	2.039–2.441	
δ/π (NO)	$1.20^{+0.23}_{-0.14}$	0.80–2.00	17%
δ/π (IO)	1.54 ± 0.13	1.14–1.90	8%

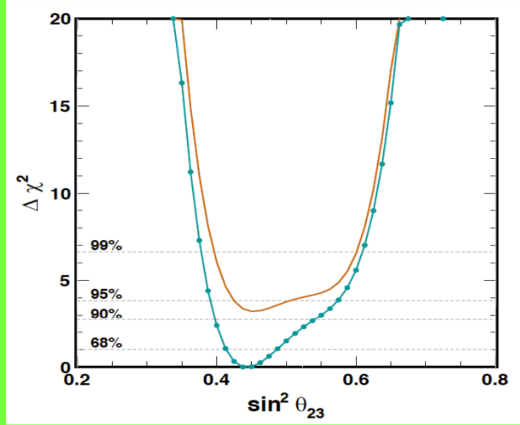
Tension between exp.

de Salas et al, arXiv:2006.11237



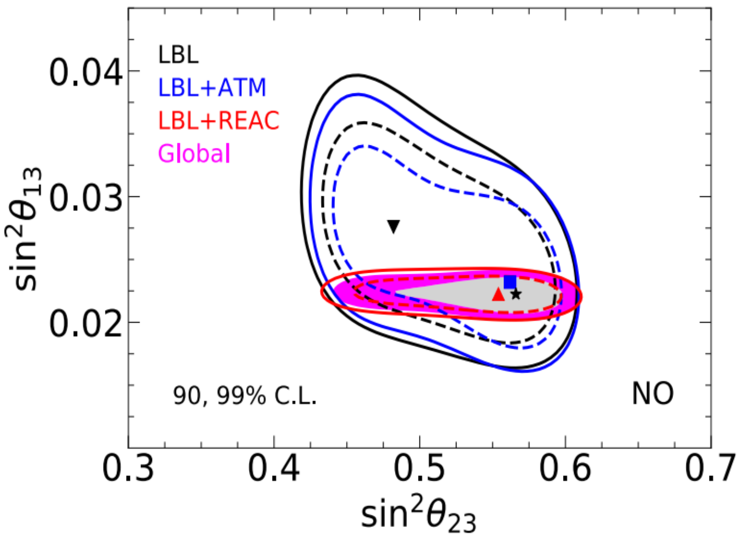
Values at the first octant allowed with $\Delta\chi^2 \geq 4.3$ (5.1) for NO (IO)

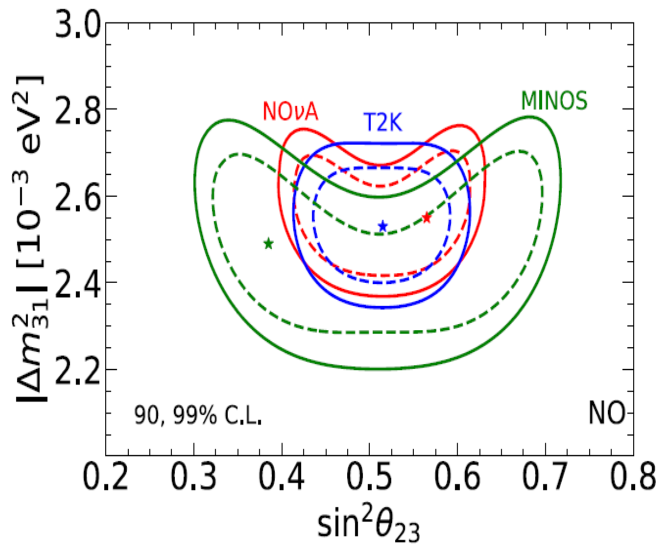
New Super-Kamiokande data



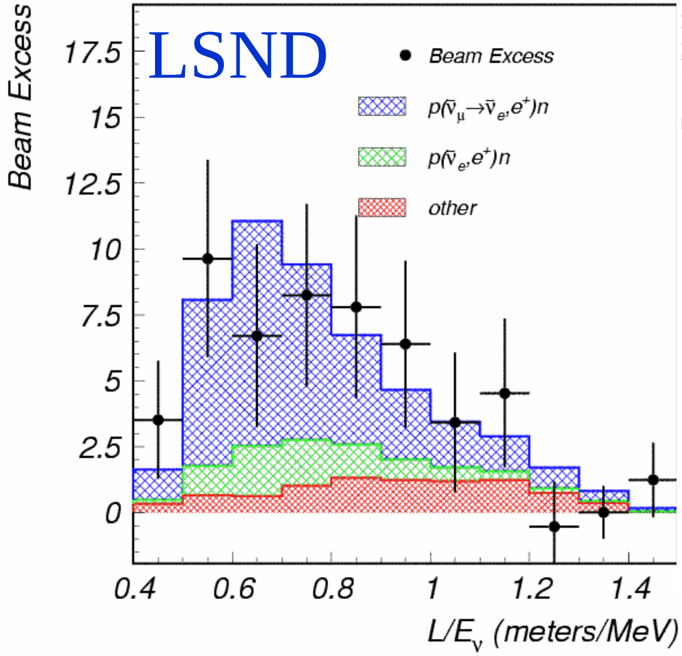
Y. Nakajima, Neutrino 2020

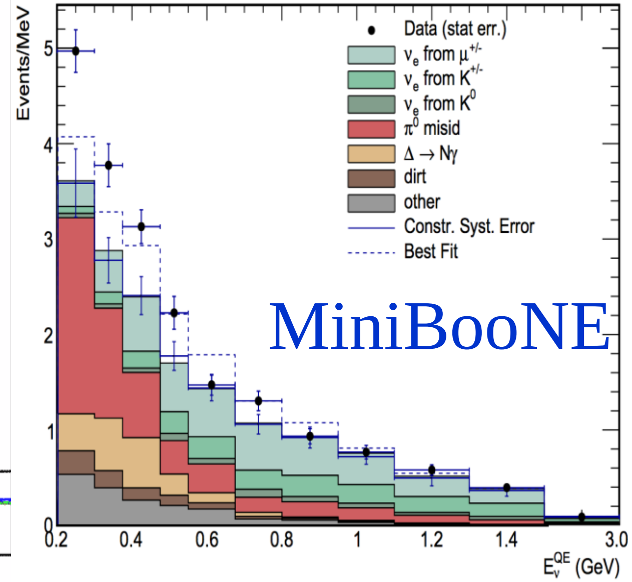
Synergy between exp.

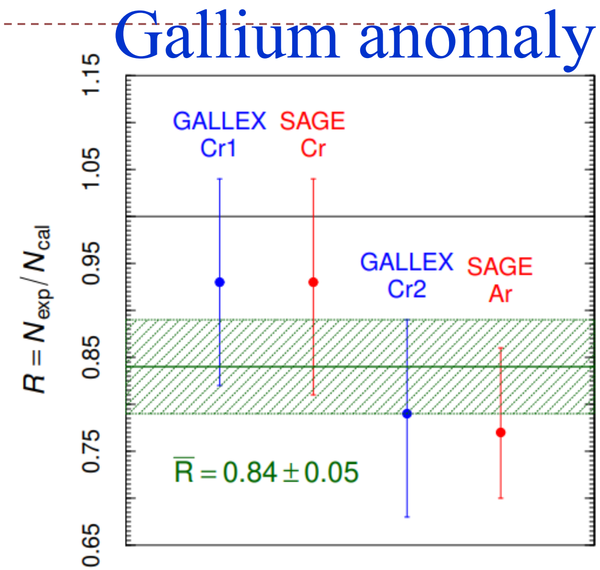


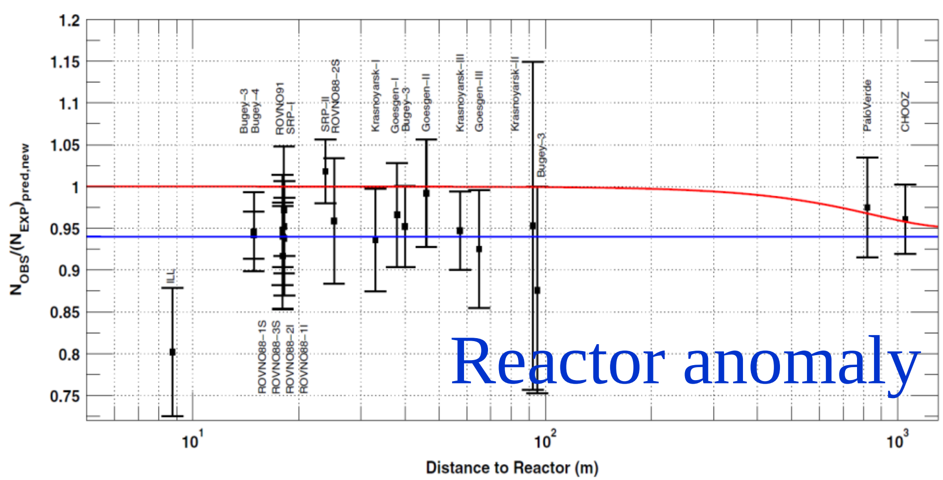


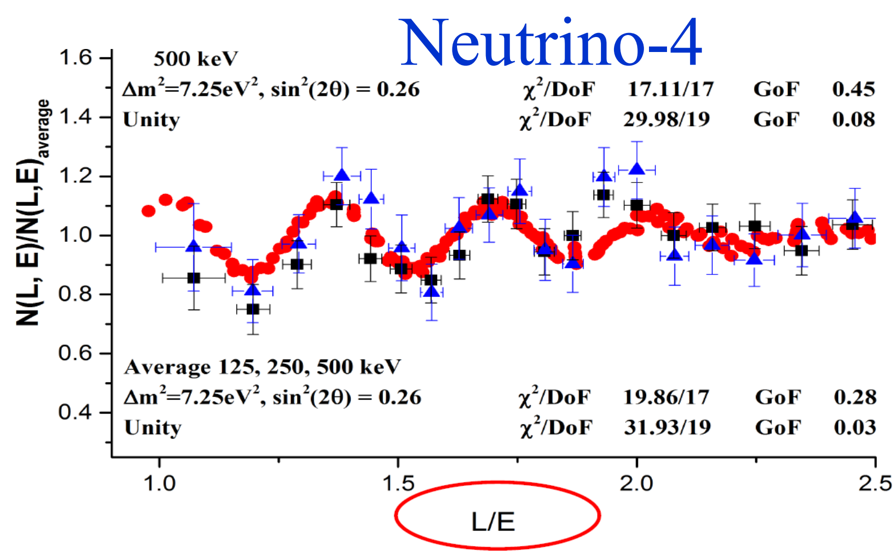
Three+One Generations, Evidence











Theoretical and Experimental Work in Progress

Experiments with the right L/E
Model-independent tests
Some region is excluded
New reactor-related experiment and prediction
New technique to reject background
New technique to explore neutrino interaction
β decay, 0νββ constrains

NEOS, STEREO, PROSPECT, DANSS, SoLid, BEST, SBN, $JSNS^2$, IceCube, ICARUS, MicroBooNE, Daya Bay, Minos+, KATRIN ...

Summary

- We see many progress on
  - Reactor neutrino study
  - Solar neutrino study
  - Atmospheric neutrino study
  - Accelerator neutrino study
- Many efforts on sterile neutrinos, verdict in the near future

Not a comprehensive review. May have mistakes.

Thank you for your attention.