Neutrino parameters and open questions in neutrino physics

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HIDDeν

Hunting Invisibles: Dark sectors, Dark matter and Neutrinos

Neutrino mass parameters

$$\begin{bmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{bmatrix} = U_{PMNS} \cdot \begin{bmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{bmatrix}$$

$$m_1 \; m_2 \; m_3$$

Mixing parameters

$$U_{PMNS} = O_{23} O_{13} O_{12} \Phi$$

$$O_{23} = \begin{bmatrix} 1 & 0 & 0 \\ 0 & \cos\theta_{23} & \sin\theta_{23} \\ 0 & -\sin\theta_{23} & \cos\theta_{23} \end{bmatrix}$$

$$O_{13} = \begin{bmatrix} \cos\theta_{13} & 0 & \sin\theta_{13} e^{i\delta} \\ 0 & 1 & 0 \\ -\sin\theta_{13} e^{-i\delta} & 0 & \cos\theta_{13} \end{bmatrix}$$

$$O_{12} = \begin{bmatrix} \cos\theta_{12} & \sin\theta_{12} & 0 \\ -\sin\theta_{12} & \cos\theta_{12} & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

$$\Phi = \mathrm{Diag}[e^{i\phi_1}, e^{i\phi_2}, e^{i\phi_3}]$$

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Are ϕ_i observable?

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$$O_{12} = \begin{bmatrix} \cos\theta_{12} & \sin\theta_{12} & 0 \\ -\sin\theta_{12} & \cos\theta_{12} & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

$$\Phi = \mathrm{Diag}[e^{i\phi_1}, e^{i\phi_2}, e^{i\phi_3}]$$

Are ϕ_i observable?

We shall discuss later.

Compact form

$$U_{PMNS} = O_{23} O_{13} O_{12} \Phi$$

$$\begin{bmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta} & s_{23}c_{13} \\ s_{12}s_{23} - c_{12}c_{23}s_{13}e^{i\delta} & -c_{12}s_{23} - s_{12}c_{23}s_{13}e^{i\delta} & c_{23}c_{13} \end{bmatrix}$$

Neutrino oscillation in matter

$$P(\nu_\alpha \to \nu_\beta) = |\ \langle \nu_\beta | \nu_\alpha ; t \rangle\ |^2 = \sum_{i,j} U_{\beta i} U^*_{\alpha i} U^*_{\beta j} U_{\alpha j} e^{i \frac{\Delta m^2_{ji}}{2p} t}$$

$$P(\bar{\nu}_\alpha \to \bar{\nu}_\beta) = |\ \langle \bar{\nu}_\beta | \bar{\nu}_\alpha ; t \rangle\ |^2 = \sum_{i,j} U^*_{\beta i} U_{\alpha i} U_{\beta j} U^*_{\alpha j} e^{i \frac{\Delta m^2_{ji}}{2p} t}$$

$$\Delta m^2_{ji} \equiv m^2_j - m^2_i$$

- Oscillation depends only on mass square difference both in vacuum and in matter.

$$\frac{m_\nu^2}{2E} + V_{eff} =$$

$$\frac{m_1^2}{2E}\begin{bmatrix}1 & 0 & 0\\ 0 & 1 & 0\\ 0 & 0 & 1\end{bmatrix} + U_{PMNS}\cdot\begin{bmatrix}0 & 0 & 0\\ 0 & \frac{\Delta m_{21}^2}{2E} & 0\\ 0 & 0 & \frac{\Delta m_{31}^2}{2E}\end{bmatrix}\cdot U_{PMNS}^T + \begin{bmatrix}V_{NC}+V_{CC} & 0 & 0\\ 0 & V_{NC} & 0\\ 0 & 0 & V_{NC}\end{bmatrix}$$

Oscillation depends only on mass square difference both in vacuum and in matter.

$$\frac{m_\nu^2}{2E} + V_{eff} =$$

$$\frac{m_1^2}{2E}\begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix} + U_{PMNS} \cdot \begin{bmatrix} 0 & 0 & 0 \\ 0 & \frac{\Delta m_{21}^2}{2E} & 0 \\ 0 & 0 & \frac{\Delta m_{31}^2}{2E} \end{bmatrix} \cdot U_{PMNS}^T + \begin{bmatrix} V_{NC} + V_{CC} & 0 & 0 \\ 0 & V_{NC} & 0 \\ 0 & 0 & V_{NC} \end{bmatrix}$$

$$i\frac{d}{dt}\begin{bmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{bmatrix} = (\frac{m_\nu^2}{2E} + V_{eff})\begin{bmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{bmatrix}$$

$$\boxed{\begin{bmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{bmatrix} \rightarrow e^{im_1^2/(2E)L}\begin{bmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{bmatrix}}$$

How to measure neutrino mass scale?

$$N \rightarrow N' \bar{\nu}_e e^-$$

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

Shift of endpoint

$$E_e^{max} = Q - m_{\nu_e} \qquad Q = m_N - m_{N'}$$

$$E_e^{max} = Q - m_{\nu_e}$$

To be precise

$$E_e^{max} = Q - \sum_i m_i |U_{ei}|^2$$

On the effective mass of the electron neutrino in beta decay,
Phys. Lett. B 557 (2003)
YF and Smirnov

Mainz experiment

$$m_\nu < 2.2 \text{ eV}$$

Cosmology $\Rightarrow$ stronger bounds on $\sum_i m_{\nu_i}$

KATRIN experiment

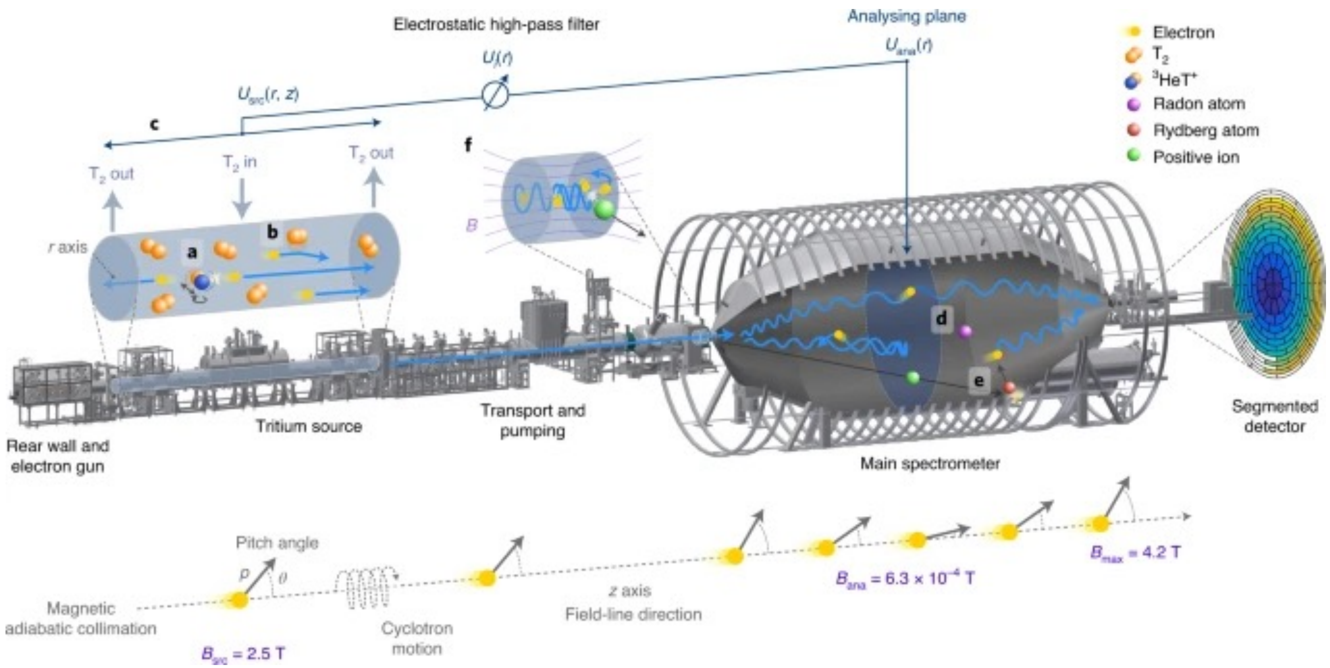
KArlsruhe TRItium Neutrino

Down to 0.2 eV

Present bound:
Aker et al (KATRIN), 2105.08533

$$m_\nu < 0.8 \text{ eV } 90\% \text{ C.L.}$$

KATRIN Bounds



KATRIN collaboration, Nature Physics 18 (2022) 160

$m_\nu < 0.8$ MeV 90 % C.L

Neutrino mass parameters

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$$m_1 \; m_2 \; m_3$$

Pontecorvo-Maki-Nakagawa-Sakata

Mixing parameters

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Knowns parameters

Solar and KamLAND

$$\theta_{12},\ m_2^2 - m_1^2$$

Atmospheric and long baseline

$$\theta_{23},\ |m_3^2 - m_1^2|$$

Chooz: $\theta_{13} < 10^\circ$ $\theta_{13}??$

Daya Bay, RENO05, double CHOOZ θ_{13}

Long baseline

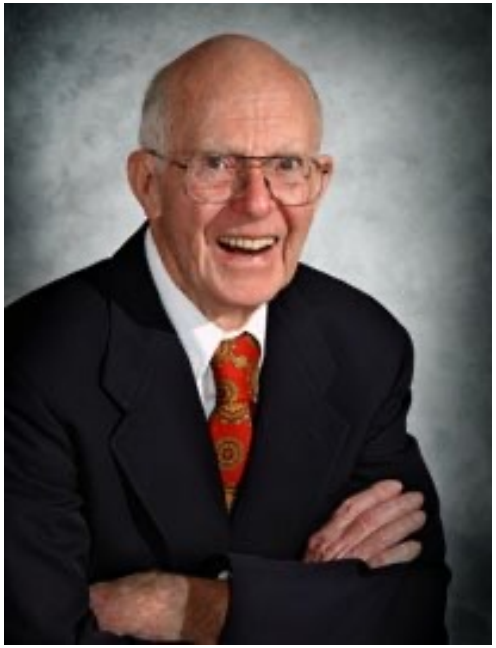
Solar neutrinos

Homestake: 1968-1994

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

Neutrino oscillation appears as deficit. $\nu_e \longrightarrow \nu_\mu, \nu_\tau$

Raymond Davis



2002 Nobel prize

	BP00	BP04	BSB05(GS98)	BSB05(AGS05)
$\Phi_{pp} / 10^{10}$	$5.95\,(1 \pm 0.01)$	$5.94\,(1 \pm 0.01)$	$5.99\,(1 \pm 0.009)$	$6.06\,(1 \pm 0.007)$
$\Phi_{pep} / 10^{8}$	$1.40\,(1 \pm 0.015)$	$1.40\,(1 \pm 0.02)$	$1.42\,(1 \pm 0.015)$	$1.45\,(1 \pm 0.011)$
$\Phi_{hep} / 10^{3}$	9.3	$7.88\,(1 \pm 0.16)$	$7.93\,(1 \pm 0.155)$	$8.25\,(1 \pm 0.155)$
$\Phi_{^7\mathrm{Be}} / 10^{9}$	$4.77\,(1 \pm 0.10)$	$4.86\,(1 \pm 0.12)$	$4.84\,(1 \pm 0.105)$	$4.34\,(1 \pm 0.093)$
$\Phi_{^8\mathrm{B}} / 10^{6}$	$5.05\,(1\,^{+0.20}_{-0.16})$	$5.79\,(1 \pm 0.23)$	$5.69\,(1\,^{+0.173}_{-0.147})$	$4.51\,(1\,^{+0.127}_{-0.113})$
$\Phi_{^{13}\mathrm{N}} / 10^{8}$	$5.48\,(1\,^{+0.21}_{-0.17})$	$5.71\,(1\,^{+0.37}_{-0.35})$	$3.05\,(1\,^{+0.366}_{-0.268})$	$2.00\,(1\,^{+0.145}_{-0.127})$
$\Phi_{^{15}\mathrm{O}} / 10^{8}$	$4.80\,(1\,^{+0.25}_{-0.19})$	$5.03\,(1\,^{+0.43}_{-0.39})$	$2.31\,(1\,^{+0.374}_{-0.272})$	$1.44\,(1\,^{+0.165}_{-0.142})$
$\Phi_{^{17}\mathrm{F}} / 10^{6}$	$5.63\,(1 \pm 0.25)$	$5.91\,(1\,^{+0.44}_{-0.44})$	$5.83\,(1\,^{+0.724}_{-0.420})$	$3.25\,(1\,^{+0.166}_{-0.142})$

C. Giunti and C. W. Kim
Fundamentals of neutrino physics and astrophysics

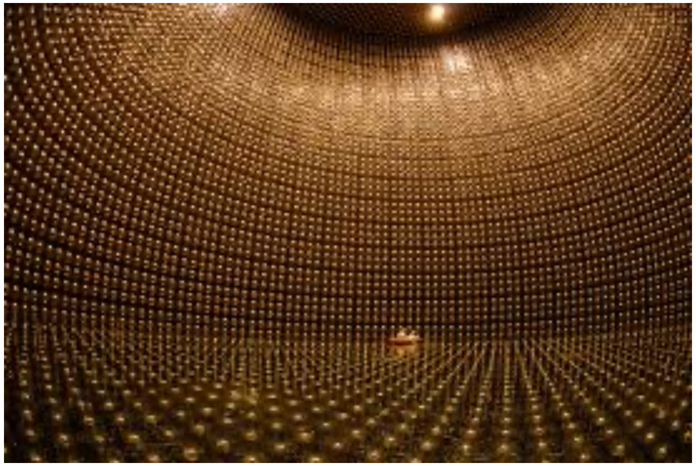
observation= (1/3) of expected

Davis, Harmer and Hoffman, PRL (1968)

Water Cherenkov experiments

- Like super-kamiokande in Japan
- And its predecessor Kamiokande

IMB in the USA



KOSHIBA

Designed Kamiokande to search for Proton decay

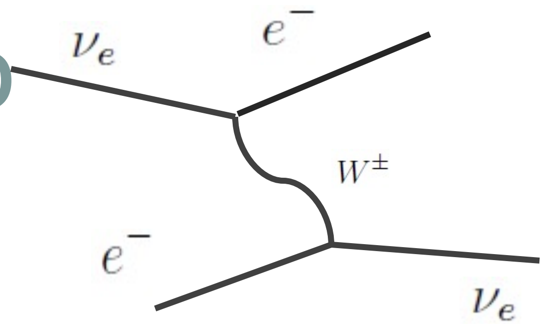
KOSHIBA and DAVIS

2002 Nobel prize

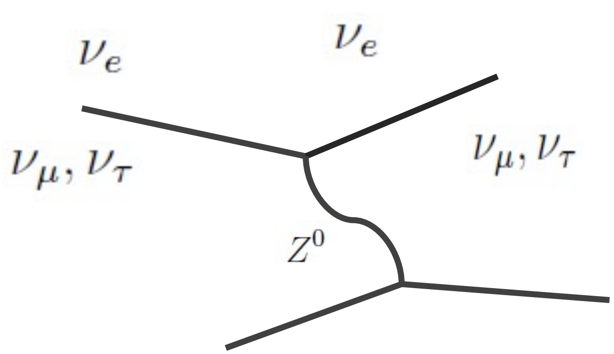
for pioneering contributions to astrophysics, in particular for the detection of cosmic neutrinos

Solar neutrino

Super-Kamiokande:



SNO:



$$F(\nu_e) + F(\nu_\mu) + F(\nu_\tau)|_{observed} = F(\nu_e)|_{predicted}$$

SNO in Canada

SNO

1000 tones D_2O

$$\mathrm{CC}: \quad \nu_e + d \to p + p + e^-$$

$$\mathrm{NC}: \quad \nu_\alpha + d \to p + n + \nu_\alpha$$

$$\mathrm{ES}: \quad \nu_\alpha + e^- \to \nu_\alpha + e^-$$

SNO in Canada

SNO

1000 tones D_2O

$$\mathrm{CC:} \quad \nu_e + d \to p + p + e^-$$

$$\mathrm{NC:} \quad \nu_\alpha + d \to p + n + \nu_\alpha$$

$$\mathrm{ES:} \quad \nu_\alpha + e^- \to \nu_\alpha + e^-$$

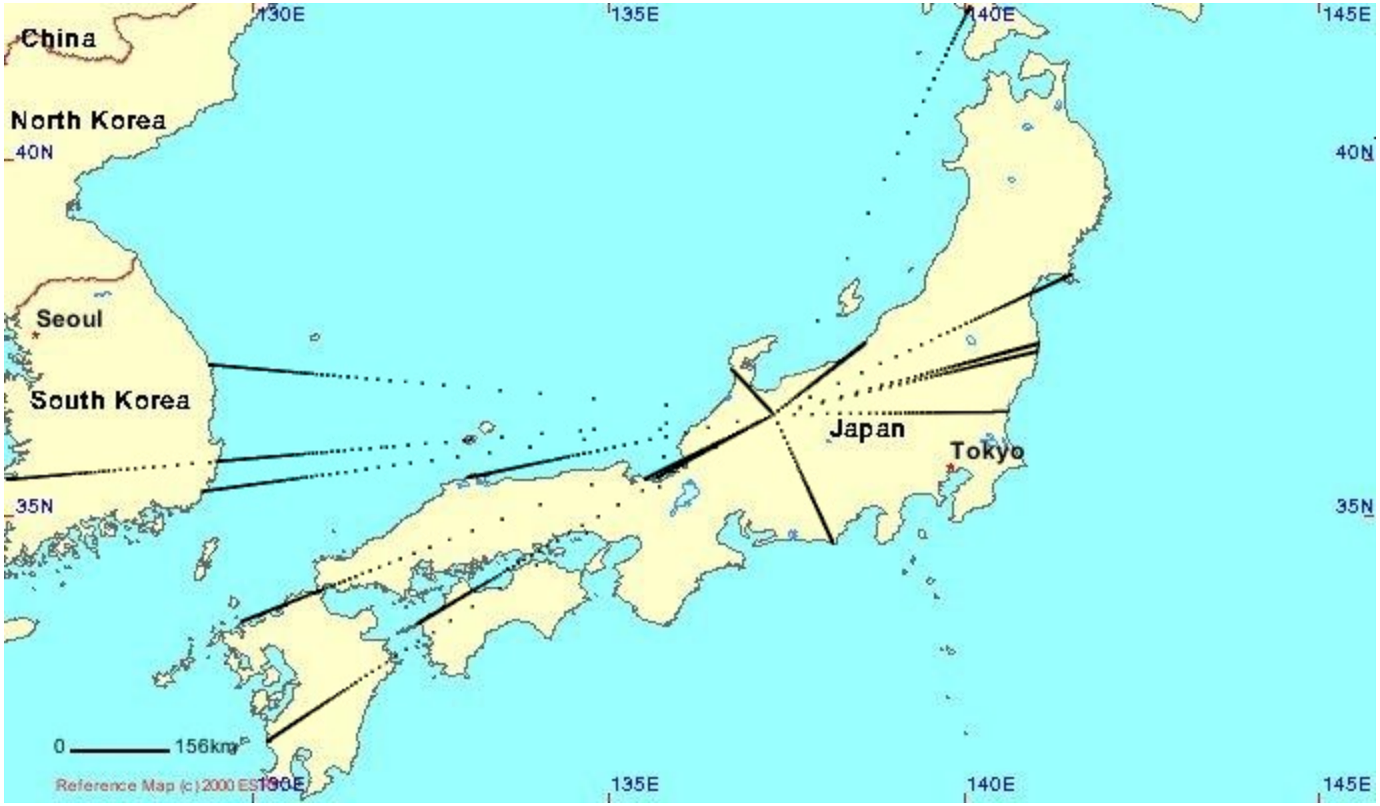
$$F(\nu_e) + F(\nu_\mu) + F(\nu_\tau)|_{observed} = F(\nu_e)|_{predicted}$$

Arthur McDonald

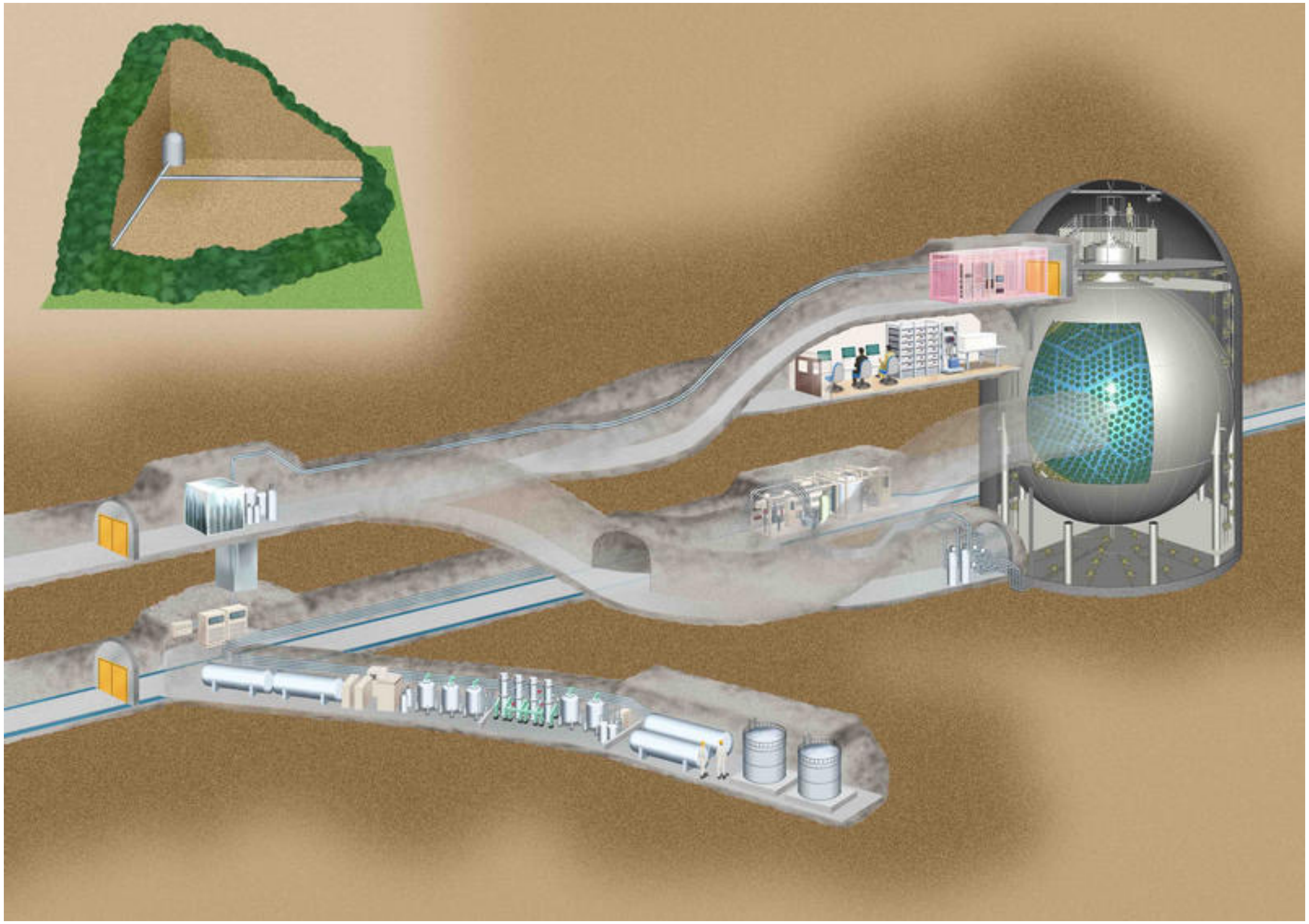
KamLAND

$\bar{\nu}_e \to \bar{\nu}_\mu, \bar{\nu}_\tau$

$\bar{\nu}_e$ deficit

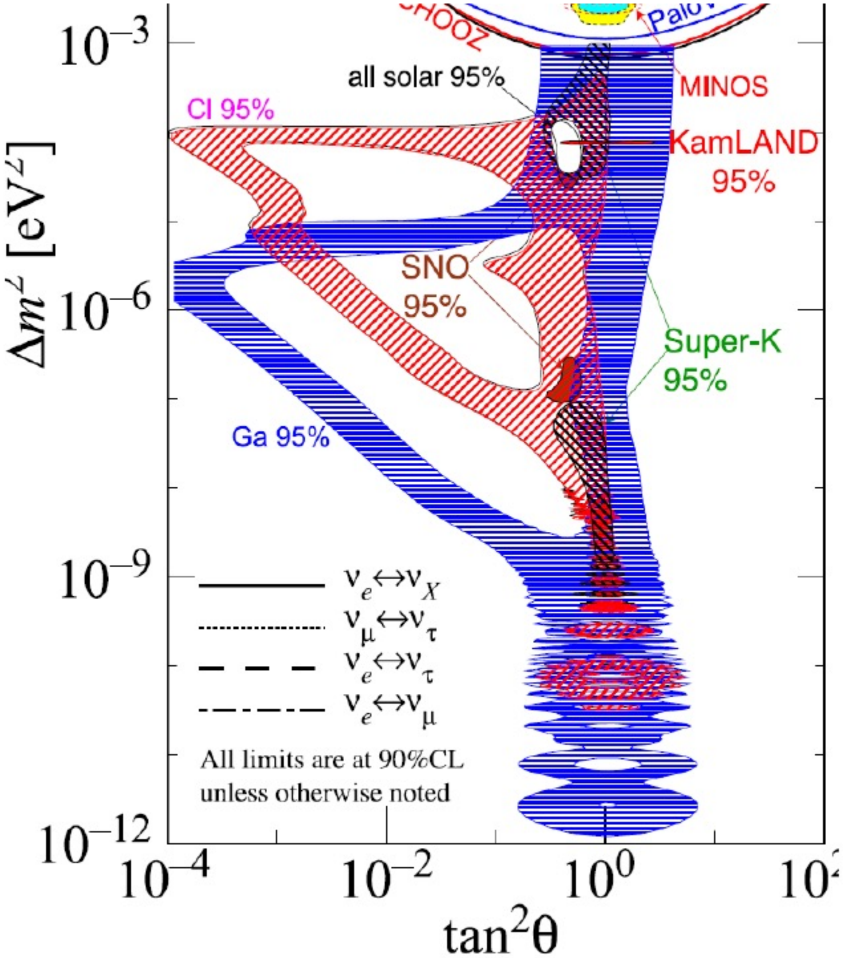


KamLAND

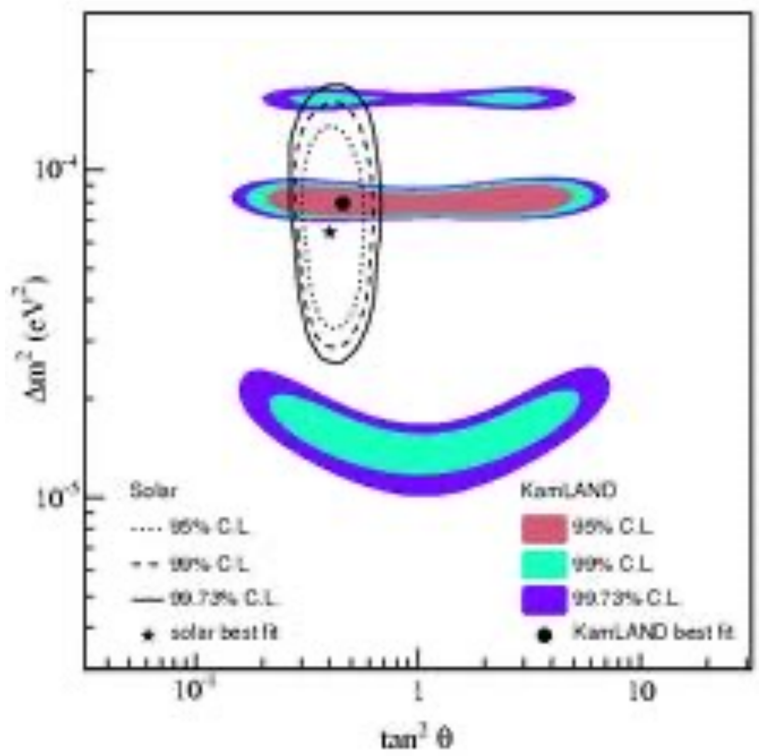


KamLAND massacre!

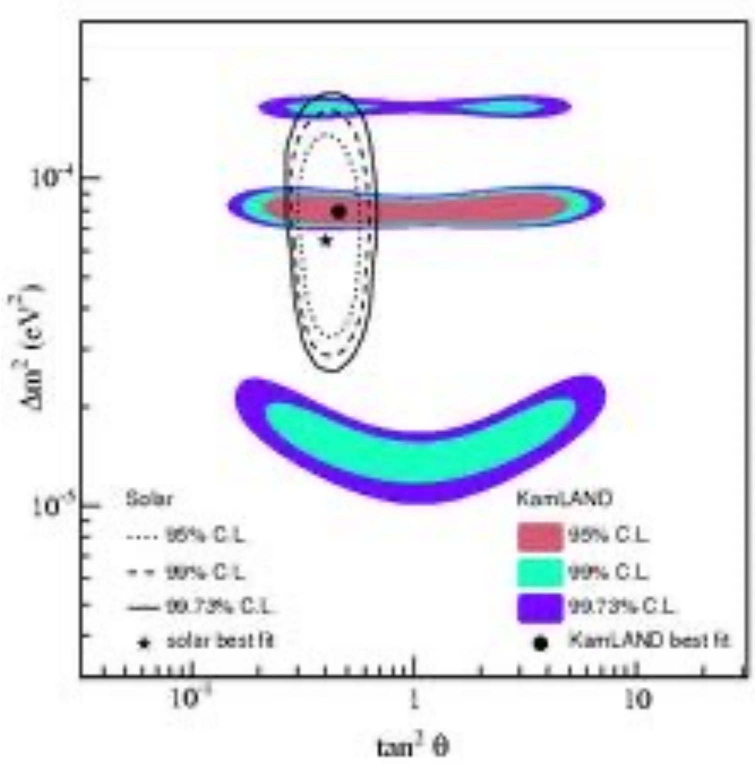
~~Magnetic transition moment solution~~



CLOWN Diagram



CLOWN Diagram



Maskara in turkish!

Pagliaccio in Italian.

Why only $\theta_{12},\ m_2^2 - m_1^2$?

$$\begin{bmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta} & s_{23}c_{13} \\ s_{12}s_{23} - c_{12}c_{23}s_{13}e^{i\delta} & -c_{12}s_{23} - s_{12}c_{23}s_{13}e^{i\delta} & c_{23}c_{13} \end{bmatrix}$$

$$|\nu_e\rangle = c_{12}c_{13}|\nu_1\rangle + s_{12}c_{13}|\nu_2\rangle + c_{12}c_{13}|\nu_1\rangle + s_{13}e^{-i\delta}|\nu_3\rangle$$

Why only $\theta_{12},\ m_2^2 - m_1^2$?

$$|\nu_e\rangle = c_{12}c_{13}|\nu_1\rangle + s_{12}c_{13}|\nu_2\rangle + s_{13}e^{-i\delta}|\nu_3\rangle$$

$$\Downarrow$$

$$|\nu_e\rangle = c_{12}|\nu_1\rangle + s_{12}|\nu_2\rangle$$

$$\mathrm{sgn}(\Delta m^2_{21})$$

- Oscillation in vacuum

$$1 - P(\nu_e \to \nu_e) = \sin^2 2\theta_{12} \sin^2 \frac{\Delta m^2_{21} L}{4E}$$

- Matter effects

$$(\Delta m^2_{21})_{eff} = \sqrt{(\Delta m^2_{21}\cos(2\theta_{12}) - 2V_{CC}E)^2 + (\Delta m^2_{21}\sin(2\theta_{12}))^2}$$

Matter effects inside the Sun makes oscillation sensitive to $\mathrm{sgn}(\Delta m^2_{21})$

Results of global fit

- Gonzalez-Garcia, Maltoni and Salvado, JHEP 2010

$$\Delta m^2_{21} = 7.59 \pm 0.20 \, \left(^{+0.61}_{-0.69}\right) \times 10^{-5} \ \mathrm{eV}^2$$

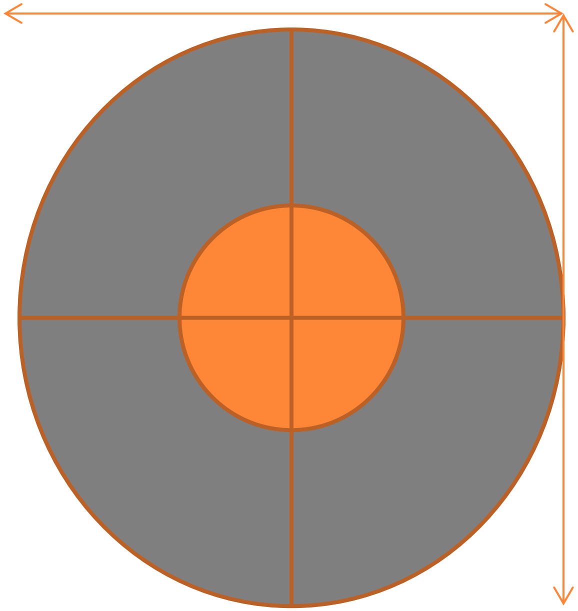
$$\theta_{12} = 34.4 \pm 1.0 \, \left(^{+3.2}_{-2.9}\right)^\circ$$

Atmospheric neutrinos

$$\pi^+ \to \mu^+ \nu_\mu \qquad \mu^+ \to \bar{\nu}_\mu e^+ \nu_e$$

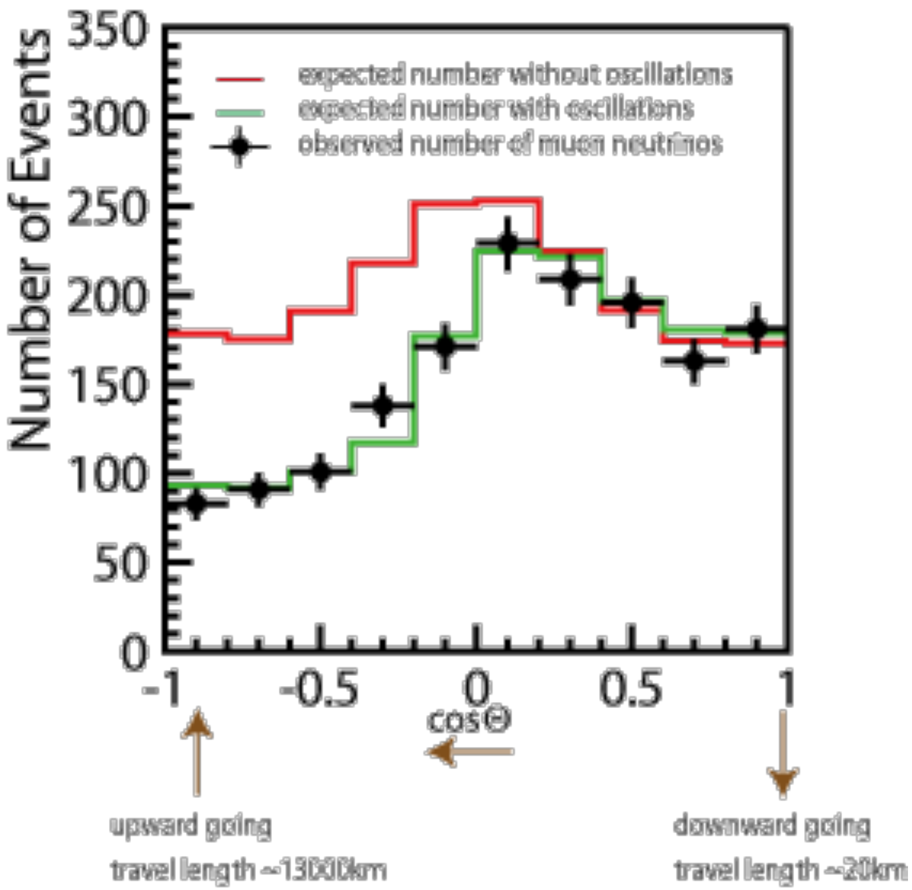
$$\pi^- \to \mu^- \bar{\nu}_\mu \qquad \mu^- \to \nu_\mu e^- \bar{\nu}_e$$

$$E_\nu \gtrsim 1 \text{ GeV}$$



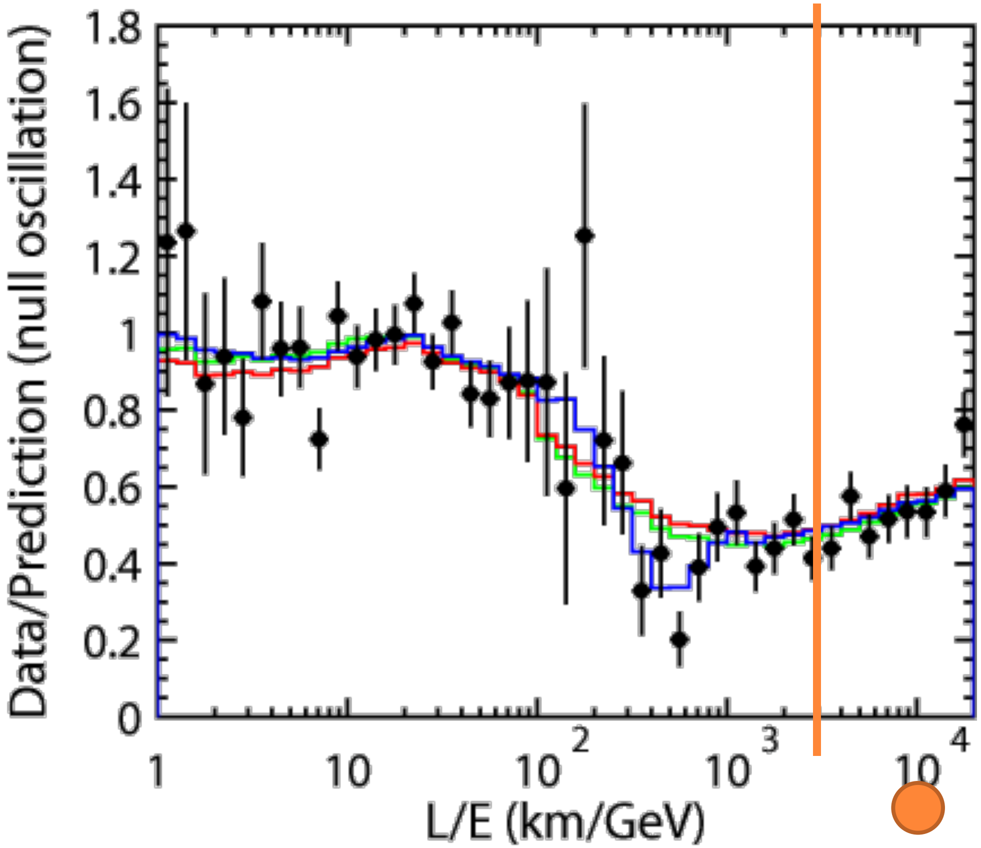
$2R_\oplus$

Muon neutrino events

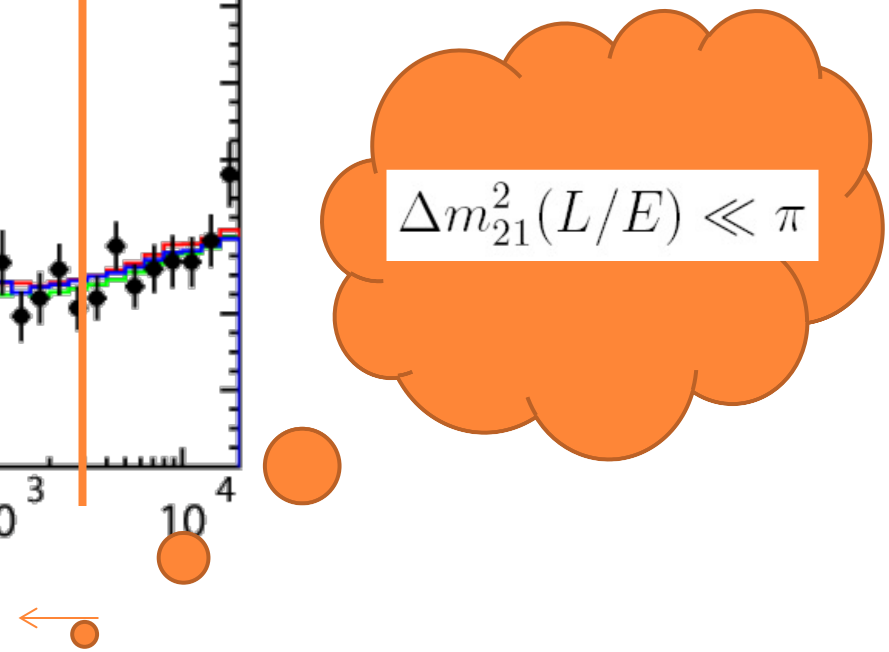


Famous 1998 Super-Kamiokande results

Super-kamiokande homepage



2004 analysis



Leading order

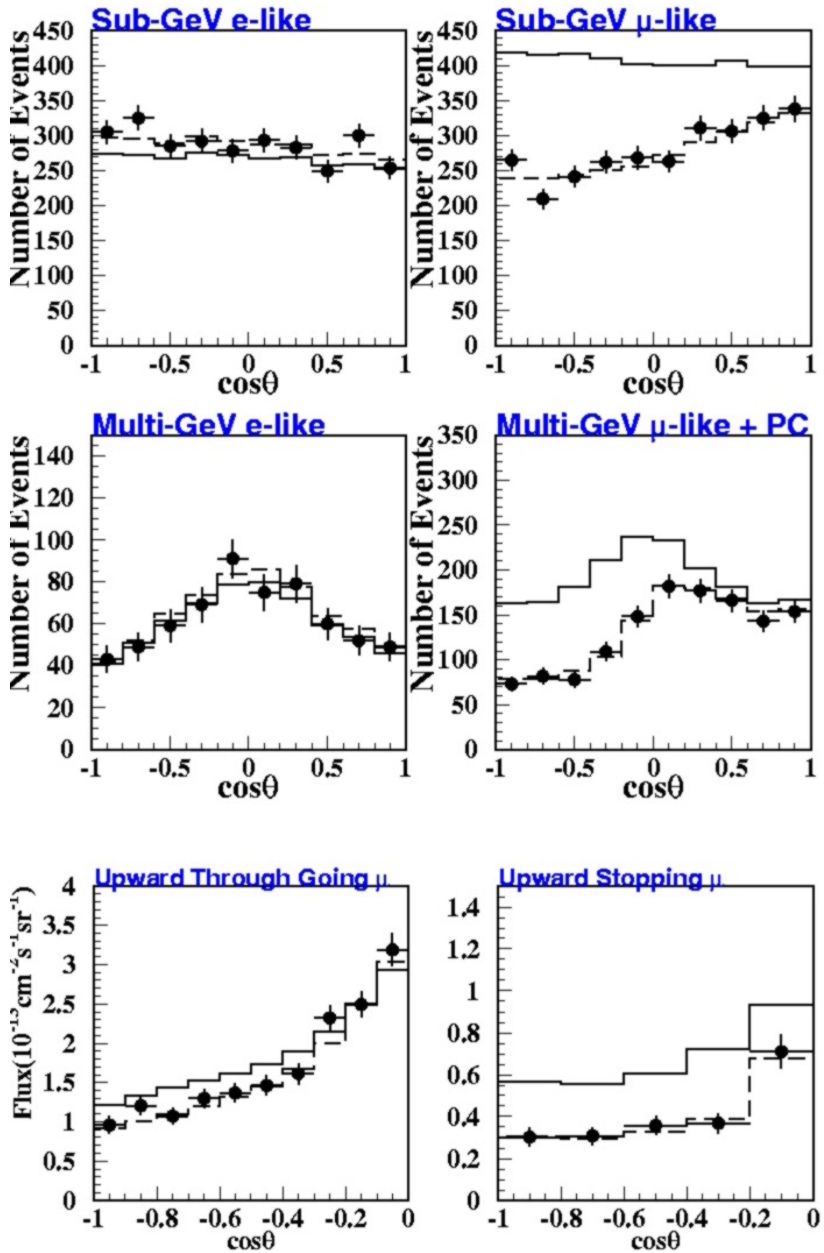
To leading order, we can neglect effects of

$\boxed{V_{CC}}$ $\boxed{\theta_{13}}$ $\boxed{\Delta m^2_{21}}$

Atmospheric neutrino data $\Rightarrow$ $\left|\Delta m^2_{31}\right|$ θ_{23}

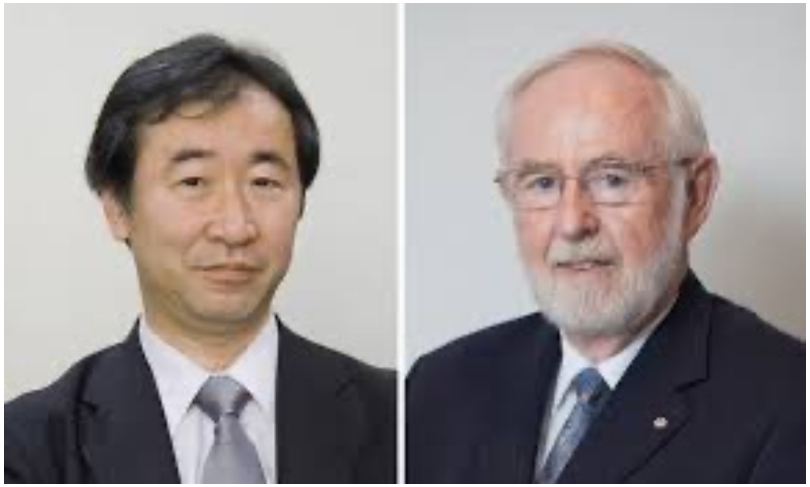
$\boxed{\nu_\mu \longrightarrow \nu_\tau}$

$\boxed{\nu_e \longrightarrow \nu_e}$

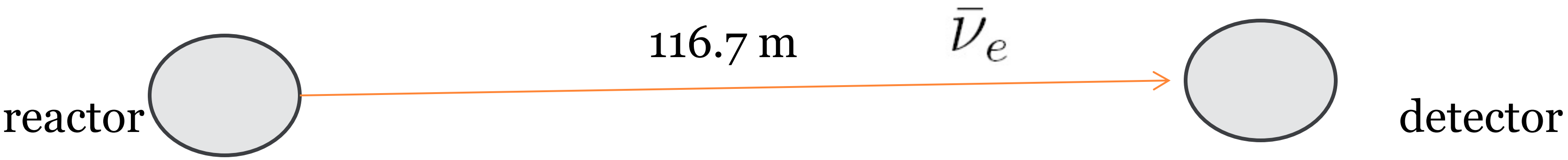


Sub-GeV e-like
Sub-GeV μ-like
Multi-GeV e-like
Multi-GeV μ-like + PC
Upward Through Going μ
Upward Stopping μ
Number of Events
Flux(10⁻¹³cm⁻²s⁻¹sr⁻¹)
cosθ

2015 nobel prize



CHOOZ experiment



$$\boxed{V_{CC} L, \frac{\Delta m_{21}^2 L}{E} \ll \frac{\Delta m_{31}^2 L}{E} \sim 1}$$

$$\boxed{P(\bar{\nu}_e \to \bar{\nu}_e) \simeq 1 - \sin^2 2\theta_{13} \sin^2 \frac{\Delta m_{31}^2 L}{4E}}$$

Observation: $P(\bar{\nu}_e \to \bar{\nu}_e) \simeq 1$ $\Rightarrow$ $\boxed{\theta_{13} < 10^\circ}$

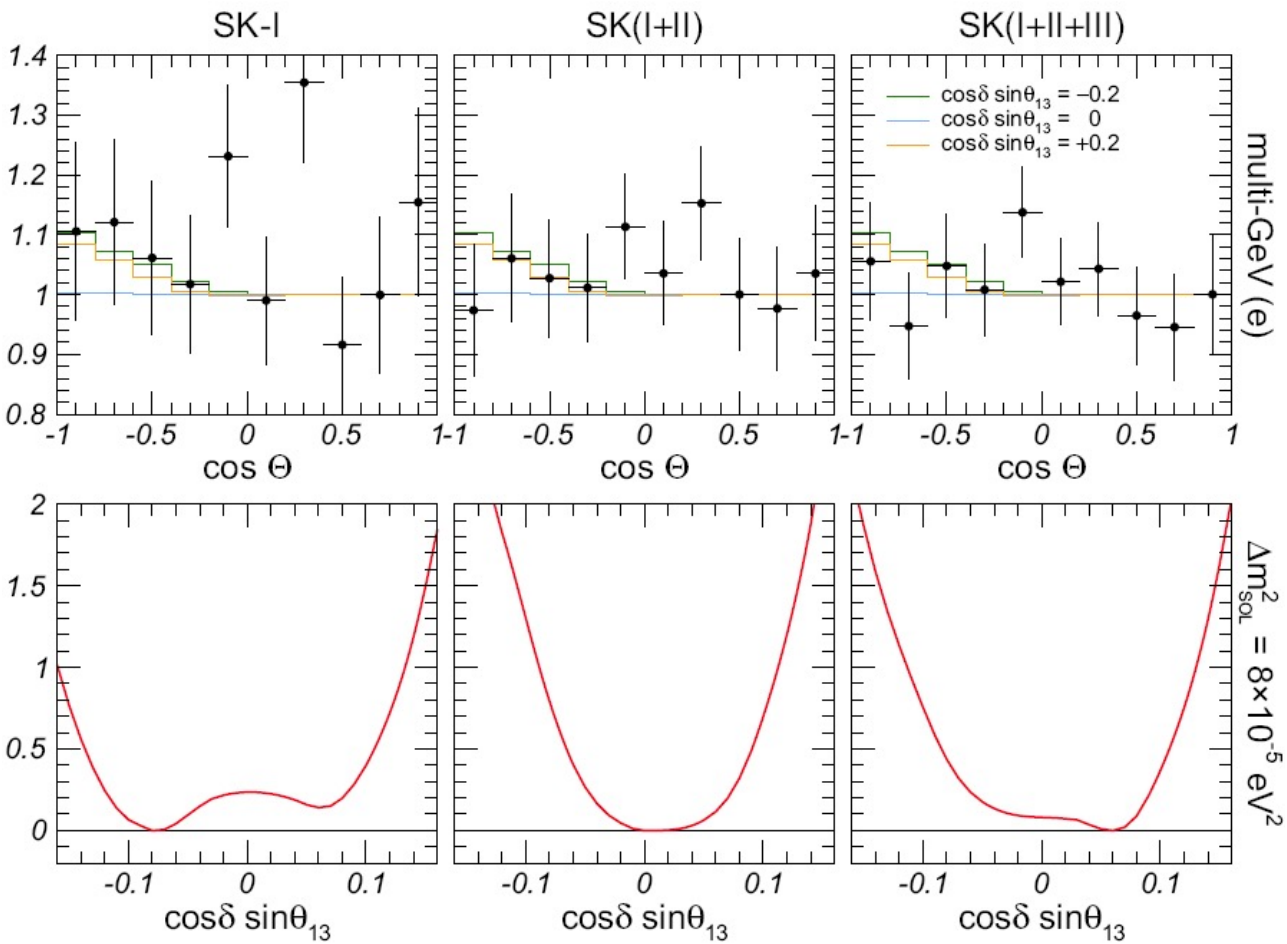
Long baseline experiments

- K2K, MINOS, CERN to Gran Sasso, T2K

$\Downarrow$

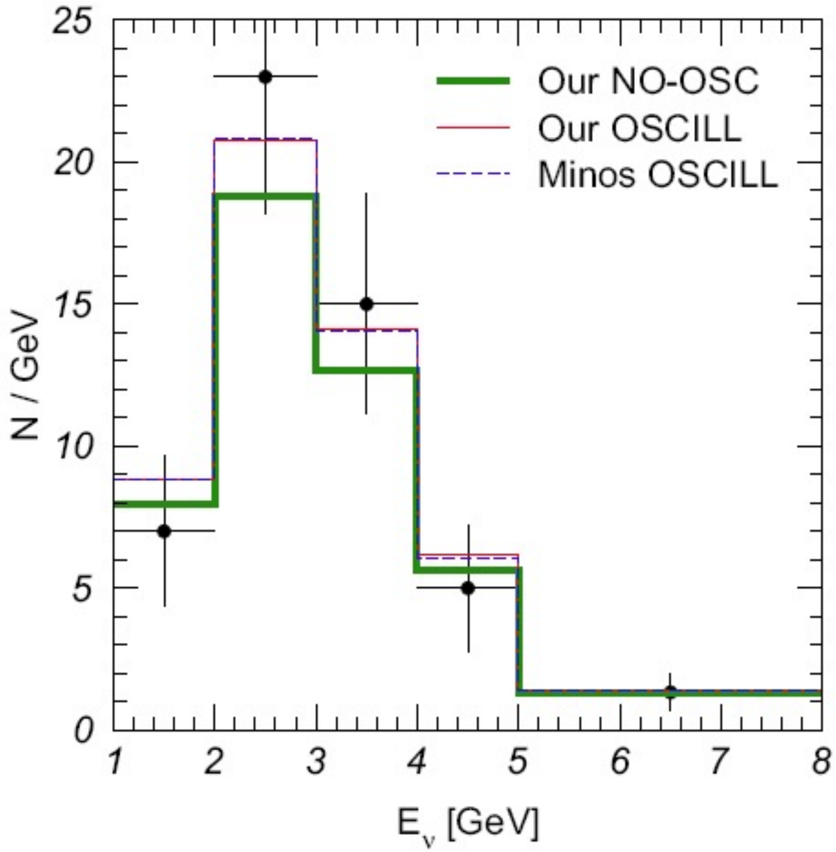
Δm^2_{31} θ_{23}

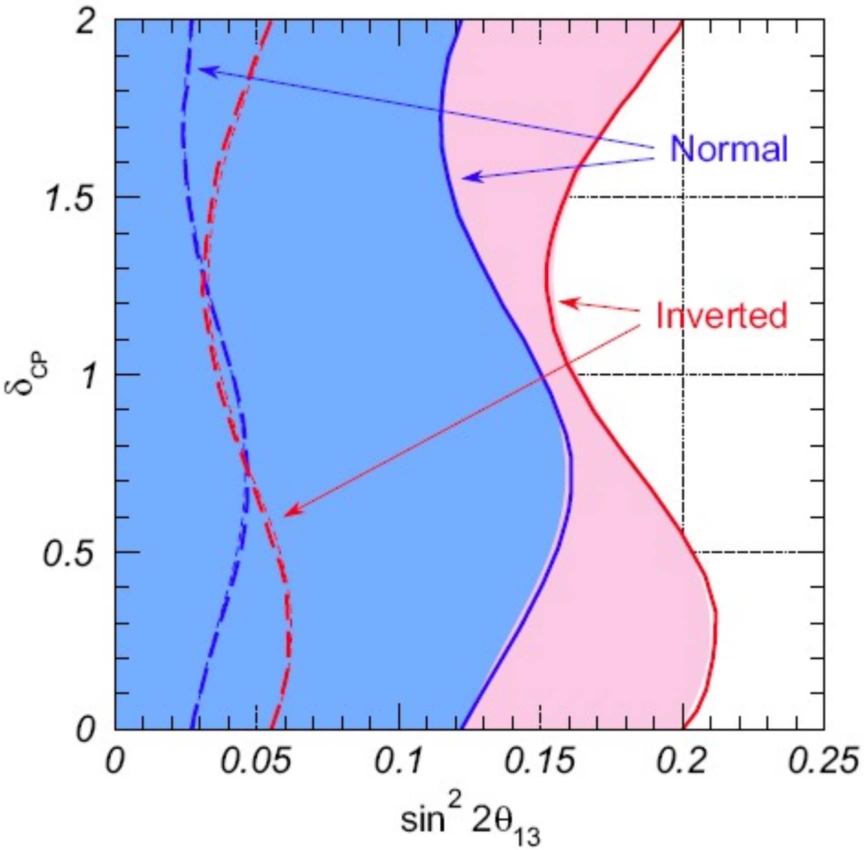
Sub-leading effects-global analysis



Gonzalez-Garcia
Maltoni
Salvado

JHEP 2010





$\sin^2 2\theta_{13} = 0.115$ and $\delta_{\mathrm{CP}} = 0$.

MINOS

$\tan^2\theta_{12} = 0.45$, maximal θ_{23}, $\Delta m^2_{21} = 7.6 \times 10^{-5}\ \mathrm{eV}^2$ and $|\Delta m^2_{32}| = 2.43 \times 10^{-3}\ \mathrm{eV}^2$.

GS98 with Gallium cross-section from [24]	AGSS09 with modified Gallium cross-section [16]
$\Delta m^2_{21} = 7.59 \pm 0.20 \ \left({}^{+0.61}_{-0.69}\right) \times 10^{-5}\ \text{eV}^2$	Same
$\Delta m^2_{31} = \begin{cases} -2.36 \pm 0.11\ (\pm 0.37) \times 10^{-3}\ \text{eV}^2 \\ +2.46 \pm 0.12\ (\pm 0.37) \times 10^{-3}\ \text{eV}^2 \end{cases}$	Same
$\theta_{12} = 34.4 \pm 1.0\ \left({}^{+3.2}_{-2.9}\right)^\circ$	$34.5 \pm 1.0\ \left({}^{+3.2}_{-2.8}\right)^\circ$
$\theta_{23} = 42.8\,{}^{+4.7}_{-2.9}\ \left({}^{+10.7}_{-7.3}\right)^\circ$	Same
$\theta_{13} = 5.6\,{}^{+3.0}_{-2.7}\ (\leq 12.5)^\circ$	$5.1\,{}^{+3.0}_{-3.3}\ (\leq 12.0)^\circ$
$\left[\sin^2\theta_{13} = 0.0095\,{}^{+0.013}_{-0.007}\ (\leq 0.047)\right]$	$\left[0.008\,{}^{+0.012}_{-0.007}\ (\leq 0.043)\right]$
$\delta_{\text{CP}} \in [0,\ 360]$	Same

T2K+MINOS

$$0.03 < \sin^2 2\theta_{13} < 0.219 \quad 3\sigma$$

Abe et al., (T2K), PRL 107 (2011)

Adamson et al., (MINOS) PRL 107 (2011)

Double CHOOZ

Double CHOOZ results

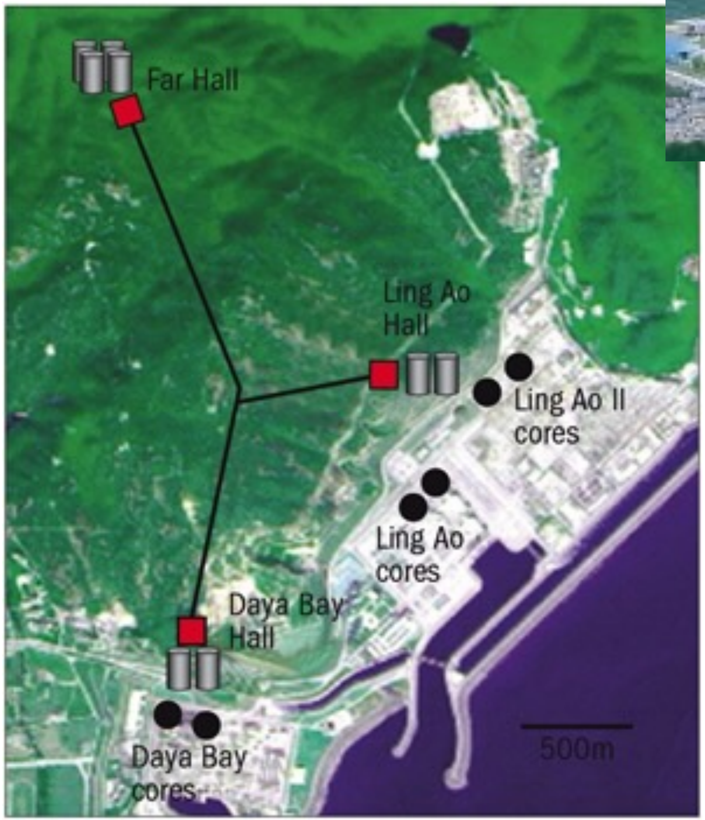
$$\sin^2 2\theta_{13} = 0.086 \pm 0.041\ (stat)\ \pm 0.030\ (sys)$$

Abe, Double CHOOZ collaboration, (2011)

~~No oscillation~~

Ruled out at $94.6\ \%$ C.L.

Daya Bay and RENO



Daya Bay, An et al, PRL 108 (2012) 171803

RENO, Ahn et al, PRL 108 (2012) 191802

NuFIT 4.1 (2019)

		Normal Ordering (best fit)		Inverted Ordering ($\Delta\chi^2 = 6.2$)	
		bfp $\pm 1\sigma$	3σ range	bfp $\pm 1\sigma$	3σ range
without SK atmospheric data	$\sin^2\theta_{12}$	$0.310^{+0.013}_{-0.012}$	$0.275 \to 0.350$	$0.310^{+0.013}_{-0.012}$	$0.275 \to 0.350$
	$\theta_{12}/^\circ$	$33.82^{+0.78}_{-0.76}$	$31.61 \to 36.27$	$33.82^{+0.78}_{-0.76}$	$31.61 \to 36.27$
	$\sin^2\theta_{23}$	$0.558^{+0.020}_{-0.033}$	$0.427 \to 0.609$	$0.563^{+0.019}_{-0.026}$	$0.430 \to 0.612$
	$\theta_{23}/^\circ$	$48.3^{+1.1}_{-1.9}$	$40.8 \to 51.3$	$48.6^{+1.1}_{-1.5}$	$41.0 \to 51.5$
	$\sin^2\theta_{13}$	$0.02241^{+0.00066}_{-0.00065}$	$0.02046 \to 0.02440$	$0.02261^{+0.00067}_{-0.00064}$	$0.02066 \to 0.02461$
	$\theta_{13}/^\circ$	$8.61^{+0.13}_{-0.13}$	$8.22 \to 8.99$	$8.65^{+0.13}_{-0.12}$	$8.26 \to 9.02$
	$\delta_{CP}/^\circ$	222^{+38}_{-28}	$141 \to 370$	285^{+24}_{-26}	$205 \to 354$
	$\frac{\Delta m^2_{21}}{10^{-5}\ \mathrm{eV}^2}$	$7.39^{+0.21}_{-0.20}$	$6.79 \to 8.01$	$7.39^{+0.21}_{-0.20}$	$6.79 \to 8.01$
	$\frac{\Delta m^2_{3\ell}}{10^{-3}\ \mathrm{eV}^2}$	$+2.523^{+0.032}_{-0.030}$	$+2.432 \to +2.618$	$-2.509^{+0.032}_{-0.030}$	$-2.603 \to -2.416$

		Normal Ordering (best fit)		Inverted Ordering ($\Delta\chi^2 = 10.4$)	
		bfp $\pm 1\sigma$	3σ range	bfp $\pm 1\sigma$	3σ range
with SK atmospheric data	$\sin^2\theta_{12}$	$0.310^{+0.013}_{-0.012}$	$0.275 \to 0.350$	$0.310^{+0.013}_{-0.012}$	$0.275 \to 0.350$
	$\theta_{12}/^\circ$	$33.82^{+0.78}_{-0.76}$	$31.61 \to 36.27$	$33.82^{+0.78}_{-0.75}$	$31.61 \to 36.27$
	$\sin^2\theta_{23}$	$0.563^{+0.018}_{-0.024}$	$0.433 \to 0.609$	$0.565^{+0.017}_{-0.022}$	$0.436 \to 0.610$
	$\theta_{23}/^\circ$	$48.6^{+1.0}_{-1.4}$	$41.1 \to 51.3$	$48.8^{+1.0}_{-1.2}$	$41.4 \to 51.3$
	$\sin^2\theta_{13}$	$0.02237^{+0.00066}_{-0.00065}$	$0.02044 \to 0.02435$	$0.02259^{+0.00065}_{-0.00065}$	$0.02064 \to 0.02457$
	$\theta_{13}/^\circ$	$8.60^{+0.13}_{-0.13}$	$8.22 \to 8.98$	$8.64^{+0.12}_{-0.13}$	$8.26 \to 9.02$
	$\delta_{CP}/^\circ$	221^{+39}_{-28}	$144 \to 357$	282^{+23}_{-25}	$205 \to 348$
	$\frac{\Delta m^2_{21}}{10^{-5}\ \mathrm{eV}^2}$	$7.39^{+0.21}_{-0.20}$	$6.79 \to 8.01$	$7.39^{+0.21}_{-0.20}$	$6.79 \to 8.01$
	$\frac{\Delta m^2_{3\ell}}{10^{-3}\ \mathrm{eV}^2}$	$+2.528^{+0.029}_{-0.031}$	$+2.436 \to +2.618$	$-2.510^{+0.030}_{-0.031}$	$-2.601 \to -2.419$

www.nu-fit.org

NuFIT 5.2 (2022)

		Normal Ordering (best fit)		Inverted Ordering ($\Delta\chi^2 = 2.3$)	
		bfp $\pm 1\sigma$	3σ range	bfp $\pm 1\sigma$	3σ range
without SK atmospheric data	$\sin^2\theta_{12}$	$0.303^{+0.012}_{-0.011}$	$0.270 \to 0.341$	$0.303^{+0.012}_{-0.011}$	$0.270 \to 0.341$
	$\theta_{12}/^\circ$	$33.41^{+0.75}_{-0.72}$	$31.31 \to 35.74$	$33.41^{+0.75}_{-0.72}$	$31.31 \to 35.74$
	$\sin^2\theta_{23}$	$0.572^{+0.018}_{-0.023}$	$0.406 \to 0.620$	$0.578^{+0.016}_{-0.021}$	$0.412 \to 0.623$
	$\theta_{23}/^\circ$	$49.1^{+1.0}_{-1.3}$	$39.6 \to 51.9$	$49.5^{+0.9}_{-1.2}$	$39.9 \to 52.1$
	$\sin^2\theta_{13}$	$0.02203^{+0.00056}_{-0.00059}$	$0.02029 \to 0.02391$	$0.02219^{+0.00060}_{-0.00057}$	$0.02047 \to 0.02396$
	$\theta_{13}/^\circ$	$8.54^{+0.11}_{-0.12}$	$8.19 \to 8.89$	$8.57^{+0.12}_{-0.11}$	$8.23 \to 8.90$
	$\delta_{CP}/^\circ$	197^{+42}_{-25}	$108 \to 404$	286^{+27}_{-32}	$192 \to 360$
	$\frac{\Delta m^2_{21}}{10^{-5}\ \mathrm{eV}^2}$	$7.41^{+0.21}_{-0.20}$	$6.82 \to 8.03$	$7.41^{+0.21}_{-0.20}$	$6.82 \to 8.03$
	$\frac{\Delta m^2_{3\ell}}{10^{-3}\ \mathrm{eV}^2}$	$+2.511^{+0.028}_{-0.027}$	$+2.428 \to +2.597$	$-2.498^{+0.032}_{-0.025}$	$-2.581 \to -2.408$
		Normal Ordering (best fit)		Inverted Ordering ($\Delta\chi^2 = 6.4$)	
		bfp $\pm 1\sigma$	3σ range	bfp $\pm 1\sigma$	3σ range
with SK atmospheric data	$\sin^2\theta_{12}$	$0.303^{+0.012}_{-0.012}$	$0.270 \to 0.341$	$0.303^{+0.012}_{-0.011}$	$0.270 \to 0.341$
	$\theta_{12}/^\circ$	$33.41^{+0.75}_{-0.72}$	$31.31 \to 35.74$	$33.41^{+0.75}_{-0.72}$	$31.31 \to 35.74$
	$\sin^2\theta_{23}$	$0.451^{+0.019}_{-0.016}$	$0.408 \to 0.603$	$0.569^{+0.016}_{-0.021}$	$0.412 \to 0.613$
	$\theta_{23}/^\circ$	$42.2^{+1.1}_{-0.9}$	$39.7 \to 51.0$	$49.0^{+1.0}_{-1.2}$	$39.9 \to 51.5$
	$\sin^2\theta_{13}$	$0.02225^{+0.00056}_{-0.00059}$	$0.02052 \to 0.02398$	$0.02223^{+0.00058}_{-0.00058}$	$0.02048 \to 0.02416$
	$\theta_{13}/^\circ$	$8.58^{+0.11}_{-0.11}$	$8.23 \to 8.91$	$8.57^{+0.11}_{-0.11}$	$8.23 \to 8.94$
	$\delta_{CP}/^\circ$	232^{+36}_{-26}	$144 \to 350$	276^{+22}_{-29}	$194 \to 344$
	$\frac{\Delta m^2_{21}}{10^{-5}\ \mathrm{eV}^2}$	$7.41^{+0.21}_{-0.20}$	$6.82 \to 8.03$	$7.41^{+0.21}_{-0.20}$	$6.82 \to 8.03$
	$\frac{\Delta m^2_{3\ell}}{10^{-3}\ \mathrm{eV}^2}$	$+2.507^{+0.026}_{-0.027}$	$+2.427 \to +2.590$	$-2.486^{+0.025}_{-0.028}$	$-2.570 \to -2.406$

Unknown parameters

$\delta??$

$m_1??$

$\mathrm{sgn}(m_3^2 - m_1^2)??$

CP-violation and T-violation

$$P(\nu_\alpha \to \nu_\beta) - P(\bar{\nu}_\alpha \to \bar{\nu}_\beta) \propto \sin\theta_{13} \sin\delta$$

$$P(\nu_\alpha \to \nu_\beta) - P(\nu_\beta \to \nu_\alpha) \propto \sin\theta_{13} \sin\delta$$

Neutrino factory?? MOMENT

Superbeam? DUNE
T2HK
T2HKK

ESSnuSB

Mass terms invariant under Lorentz symmetry

- Dirac mass term

$$m_D(\bar{\nu}_R\nu_L + \bar{\nu}_L\nu_R)$$

- Majorana mass term

$$\frac{m_M}{2}(\nu_L^T c\nu_L - \nu_L^\dagger c\nu_L^*)$$

Mass terms invariant under Lorentz symmetry

- Dirac mass term

$$m_D(\bar{\nu}_R\nu_L + \bar{\nu}_L\nu_R)$$

- Majorana mass term

$$\frac{m_M}{2}(\nu_L^T c\nu_L - \nu_L^\dagger c\nu_L^*)$$

$$c = \begin{pmatrix} 0 & 1 \\ -1 & 0 \end{pmatrix}$$

Lepton number

$U(1) \Rightarrow \quad \nu_L \to e^{i\alpha}\nu_L \qquad \nu_R \to e^{i\alpha}\nu_R$

Invariant: $\quad m_D(\bar{\nu}_R\nu_L + \bar{\nu}_L\nu_R)$

Majorana mass term does not conserve lepton number.

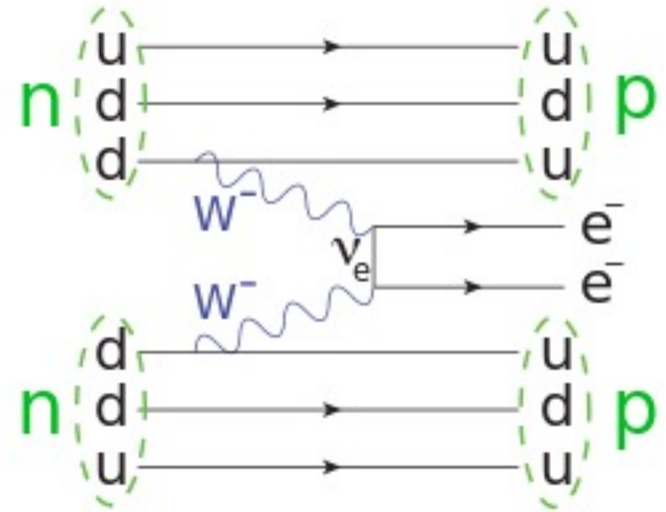
$$\nu_L^T c\nu_L \to e^{2i\alpha}\nu_L^T c\nu_L$$

Lepton number conserved $2\nu 2\beta$

$$N \rightarrow N' + e^- + e^- + \bar{\nu}_e + \bar{\nu}_e$$

Lepton number violated $0\nu 2\beta$

$$N \rightarrow N' + e^- + e^-$$



$$m_{ee} = m_{\beta\beta} = |\sum_{i=1}^{3} m_i U_{ei}^2|$$

Zen) five (EXO-200, SuperNEMO, SNO+ and CUORE) and ten (EXO, full-scale GERDA and MAJORANA) years of measurements is presented. M - mass of isotopes.

Experiment	Isotope	M, kg	Sensitivity $T_{1/2}$, yr	Sensitivity $\langle m_\nu \rangle$, meV	Status
CUORE [34]	^{130}Te	200	9.5×10^{25}	53–200	in progress
GERDA [35]	^{76}Ge	35	1×10^{26}	110–280	current
		1000	6×10^{27}	14–37	R&D
MAJORANA	^{76}Ge	30	1×10^{26}	110–280	current
[36]		1000	6×10^{27}	14-37	R&D
EXO [37]	^{136}Xe	200	4×10^{25}	100–270	current
		5000	$10^{27} - 10^{28}$	6–53	R&D
SuperNEMO	^{82}Se	7	6.5×10^{24}	240–570	in progress
[38]		100–200	$(1\text{–}2) \times 10^{26}$	40–140	R&D
KamLAND-Zen	^{136}Xe	750	2×10^{26}	45–120	in progress
[39]		1000	6×10^{26}	26-69	R&D
SNO+ [40]	^{130}Te	800	9×10^{25}	55–205	in progress
		8000	7×10^{26}	20-73	R&D

Barabash, arXiv: 1702.06340

2. ^{76}Ge: $T_{1/2}(0\nu) > 1.5 \cdot 10^{26}$ yr ($\langle m_\nu \rangle < 0.09 - 0.23$ eV).

This result will be obtained combining GERDA-II ($\sim 10^{26}$ yr) and MAJORANA-DEMONSTRATOR ($\sim 10^{26}$ yr) results.

3. ^{130}Te: $T_{1/2}(0\nu) > 1 \cdot 10^{26}$ yr ($\langle m_\nu \rangle < 0.05 - 0.19$ eV).

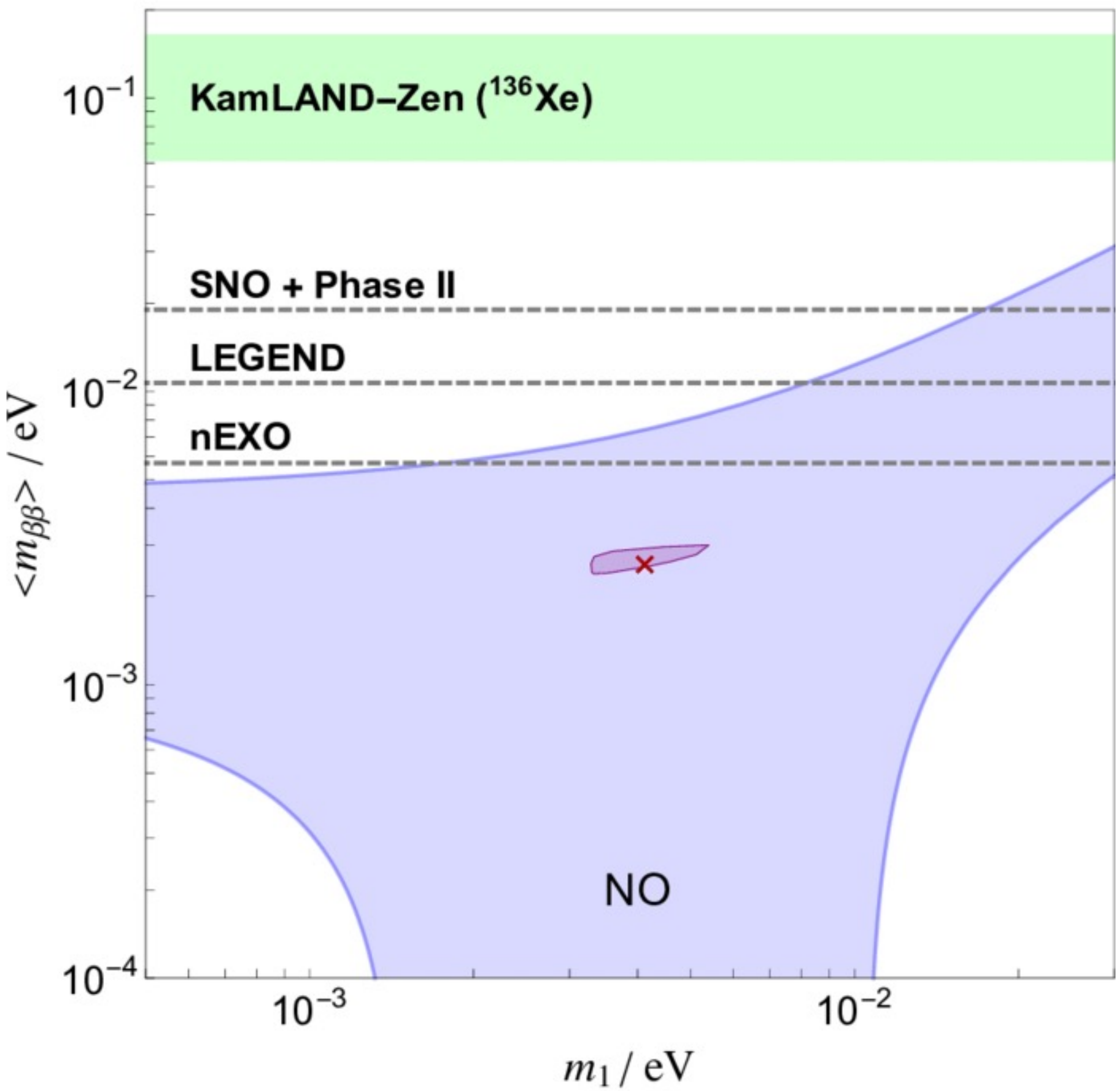
This result will be obtained combining CUORE ($\sim 0.7 \cdot 10^{26}$ yr) and SNO+ ($\sim 0.7 \cdot 10^{26}$ yr) results.

Experiment	Start of data taking, yr
KamLAND2-Zen (1000 kg of ^{136}Xe)	$\sim 2020 - 2022$
SNO+ (8000 kg of ^{nat}Te)	$\sim 2020 - 2022$
CUPID (^{100}Mo, ^{82}Se, ^{116}Cd,...)	~ 2022
LEGEND-I (200 kg of ^{76}Ge)	$\sim 2022 - 2025$
LEGEND (1000 kg of ^{76}Ge)	$\sim 2025 - 2030$
nEXO (5000 kg of ^{136}Xe)	$\sim 2025 - 2030$

Barabash, arXiv:1702.06340

-
- *** 2023 long range plan for nuclear science released
- https://science.osti.gov/-/media/np/nsac/pdf/202310/NSAC_LRP_2023.pdf
- RECOMMENDATION 2 is "As the highest priority for new experiment
- construction, we recommend that the US lead an international
- consortium that will undertake a neutrinoless double beta decay
- campaign, featuring the expeditious construction of ton-scale
- experiments, using different isotopes and complementary
- techniques." The plan endorses CUPID, nEXO and LEGEND-1000.
- The report is a vision for nuclear physics for the next 5-10 y.

$$m_{ee} = m_{\beta\beta} = |\sum_{i=1}^{3} m_i U_{ei}^2|$$



De Anda, Valle and Vaquera-Araujo, arXiv:1910.05605

Neutrino mass parameters

$$\begin{bmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{bmatrix} = U_{PMNS} \cdot \begin{bmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{bmatrix}$$

$$m_1 \ m_2 \ m_3$$

Mixing parameters

$$U_{PMNS} = O_{23}O_{13}O_{12}\Phi$$

$$O_{23} = \begin{bmatrix} 1 & 0 & 0 \\ 0 & \cos\theta_{23} & \sin\theta_{23} \\ 0 & -\sin\theta_{23} & \cos\theta_{23} \end{bmatrix}$$

$$O_{13} = \begin{bmatrix} \cos\theta_{13} & 0 & \sin\theta_{13}e^{i\delta} \\ 0 & 1 & 0 \\ -\sin\theta_{13}e^{-i\delta} & 0 & \cos\theta_{13} \end{bmatrix}$$

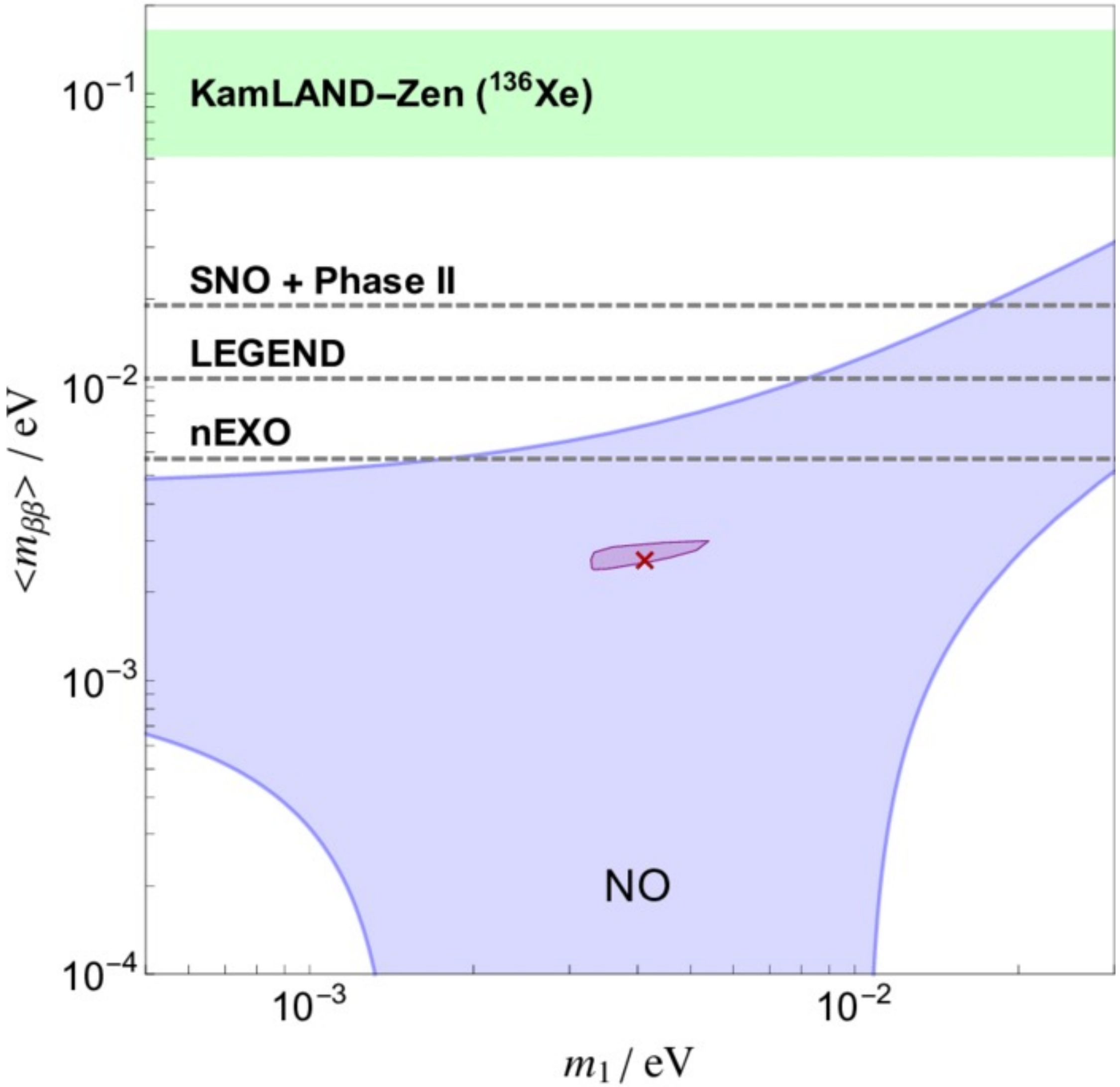
$$O_{12} = \begin{bmatrix} \cos\theta_{12} & \sin\theta_{12} & 0 \\ -\sin\theta_{12} & \cos\theta_{12} & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

$$\Phi = \mathrm{Diag}[e^{i\phi_1}, e^{i\phi_2}, e^{i\phi_3}]$$

Are ϕ_i observable?

$$m_{ee} = m_{\beta\beta} = |\sum_{i=1}^{3} m_i U_{ei}^2|$$

$$m_{ee} = m_{\beta\beta} = |\sum_{i=1}^{3} m_i U_{ei}^2|$$



De Anda, Valle and Vaquera-Araujo, arXiv:1910.05605

Open question:
Is neutrino mass of Dirac type or Majorana type?

Is lepton number conserved?

Invariance under electroweak symmetry

- Yukawa coupling

$$Y_D \bar{\nu}_R \epsilon_{\alpha\beta} H_\alpha L_\beta \qquad L = (\nu \; l^-)$$

Singlet under SU(2) U(1)

- Dirac mass

$$m_D = Y_D \langle H \rangle \qquad Y_D \lesssim \frac{0.1 \text{ eV}}{170 \text{ GeV}} \sim 10^{-12}$$

Majorana mass term

- Rich literature on models for Majorana mass
- Radiative mass
- Seesaw mechanism
- Type I seesaw, Type II seesaw, Type II seesaw

Type I seesaw mechanism

$$\mathcal{L} = -Y_D \epsilon_{\alpha\beta} \bar{N} H_\alpha L_\beta - \frac{m_M}{2} N^T c N$$

$N = \nu_R$

$$\frac{1}{2} \begin{bmatrix} \overline{\nu_L^c} & \overline{\nu_R^c} \end{bmatrix} \begin{bmatrix} 0 & m_D \\ m_D & m_M \end{bmatrix} \begin{bmatrix} \nu_L \\ \nu_R \end{bmatrix}$$

Type I seesaw mechanism

$$\mathcal{L} = -Y_D \epsilon_{\alpha\beta} \bar{N} H_\alpha L_\beta - \frac{m_M}{2} N^T c N$$

$$N = \nu_R$$

$$\frac{1}{2} \begin{bmatrix} \overline{\nu_L^c} & \overline{\nu_R^c} \end{bmatrix} \begin{bmatrix} 0 & m_D \\ m_D & m_M \end{bmatrix} \begin{bmatrix} \nu_L \\ \nu_R \end{bmatrix}$$

Type I seesaw mechanism

$$\mathcal{L} = -Y_D \epsilon_{\alpha\beta} \bar{N} H_\alpha L_\beta - \frac{m_M}{2} N^T c N$$

$$\frac{1}{2} \begin{bmatrix} \overline{\nu_L^c} & \overline{\nu_R^c} \end{bmatrix} \begin{bmatrix} 0 & m_D \\ m_D & m_M \end{bmatrix} \begin{bmatrix} \nu_L \\ \nu_R \end{bmatrix}$$

$$m_D \ll m_M$$

Type I seesaw mechanism

$$\mathcal{L} = -Y_D \epsilon_{\alpha\beta} \bar{N} H_\alpha L_\beta - \frac{m_M}{2} N^T c N$$

$$\frac{1}{2} \begin{bmatrix} \overline{\nu_L^c} & \overline{\nu_R^c} \end{bmatrix} \begin{bmatrix} 0 & m_D \\ m_D & m_M \end{bmatrix} \begin{bmatrix} \nu_L \\ \nu_R \end{bmatrix}$$

$$m_D \ll m_M$$

$$m_1 \simeq -m_D^2/m_M \quad m_2 \simeq m_M$$

Type I seesaw mechanism

$m_D \ll m_M$

$$m_1 \simeq -m_D^2/m_M \quad m_2 \simeq m_M$$

$$m_M \sim 10^{14} \text{ GeV}$$

$$m_D \sim m_{EW} \sim 100 \text{ GeV}$$

$$\boxed{m_1 \simeq m_D^2/m_M \sim 0.1 \text{ eV}}$$

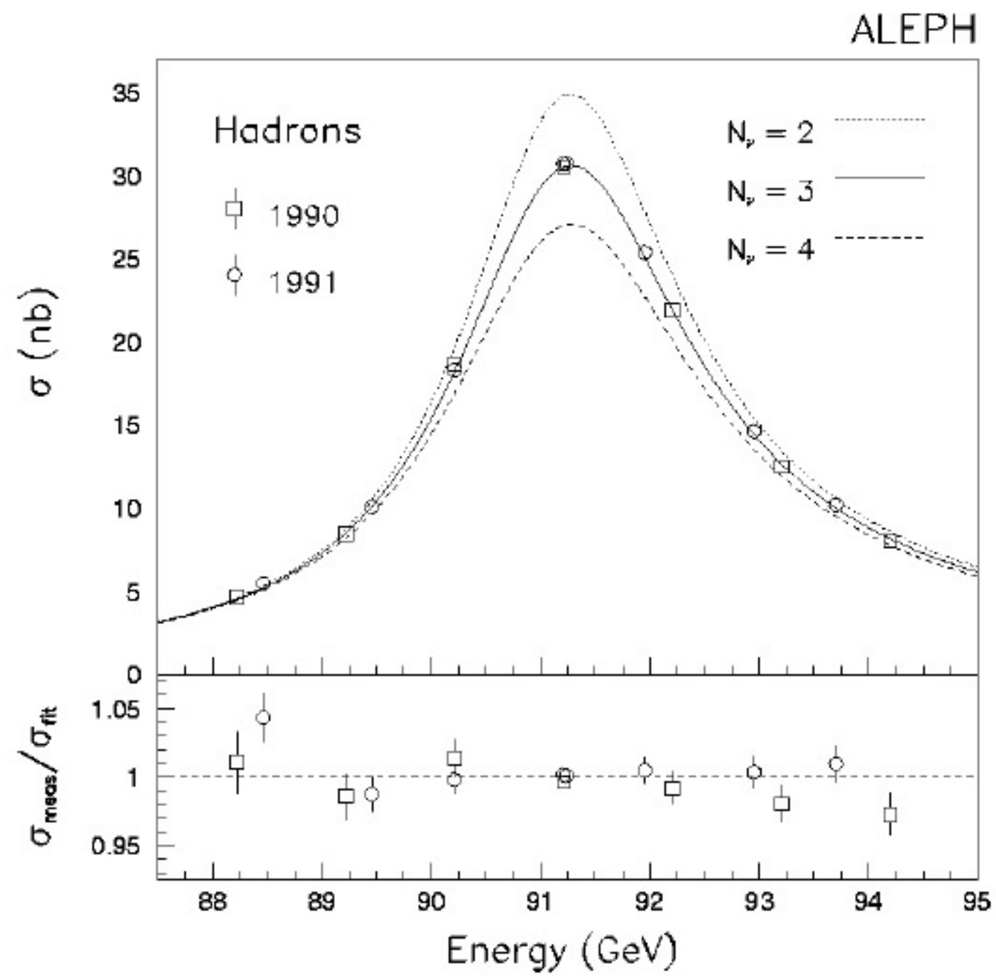
Bonus of type I seesaw mechanism: Explaining matter-antimatter asymmetry

- Baryon (proton, neutron) density in the universe

$$\neq$$

- Anti-baryon (Anti-proton, anti-neutron) density in the universe

Reminder



$$Z \rightarrow \nu_e \bar{\nu}_e$$
$$Z \rightarrow \nu_\mu \bar{\nu}_\mu$$
$$Z \rightarrow \nu_\tau \bar{\nu}_\tau$$

$$Z \rightarrow invisibles$$

How many neutrinos are there?

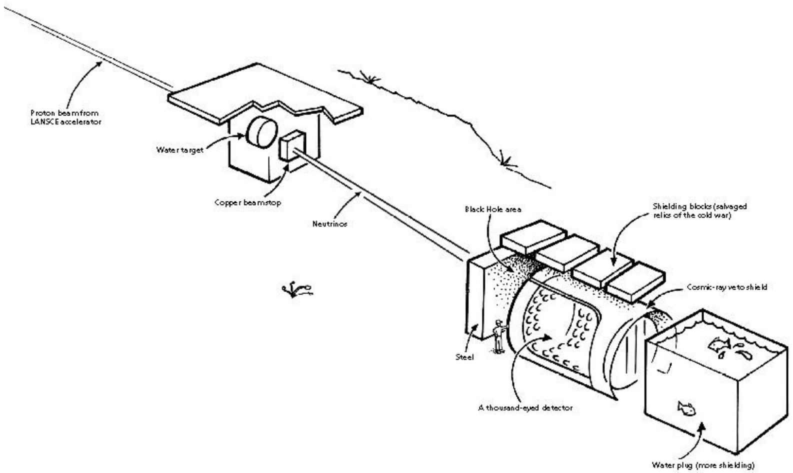
- Fourth generation

$$m > m_Z/2 = 45 \text{ GeV}$$

- Sterile neutrino can be light!

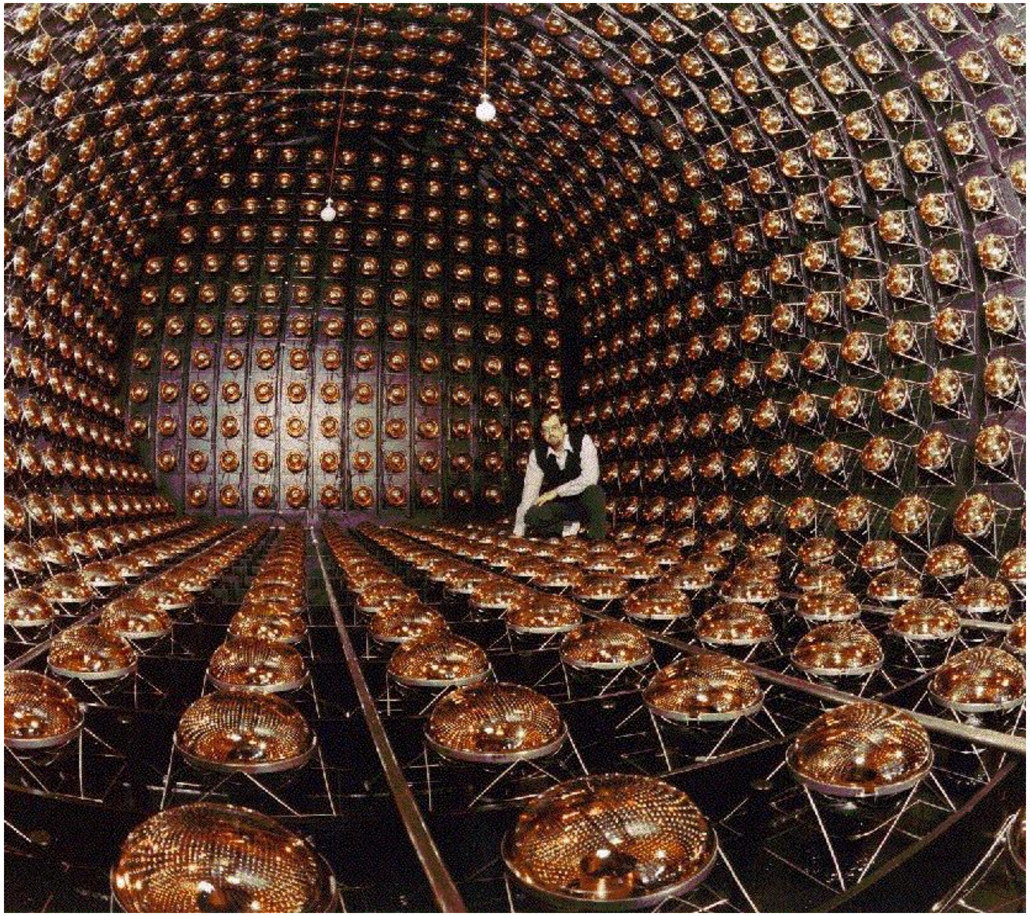
Short baseline experiments

$$\frac{\Delta m_{21}^2 L}{2E} \ll \frac{\Delta m_{31}^2 L}{2E} \ll 1$$



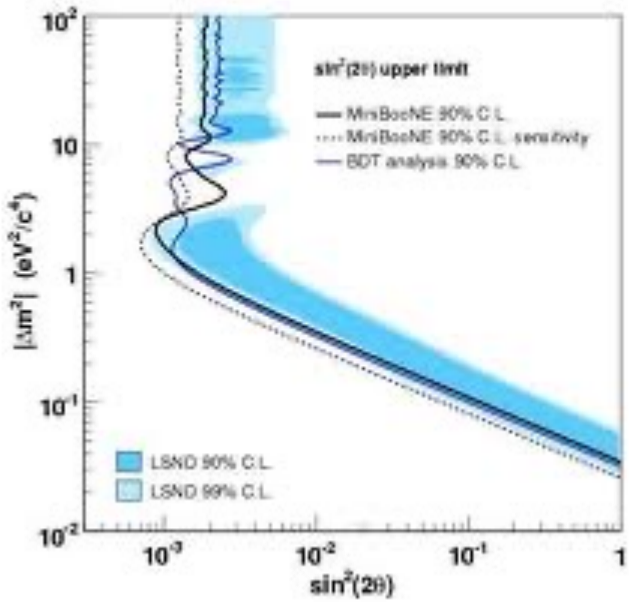
No oscillation is expected.

LSND

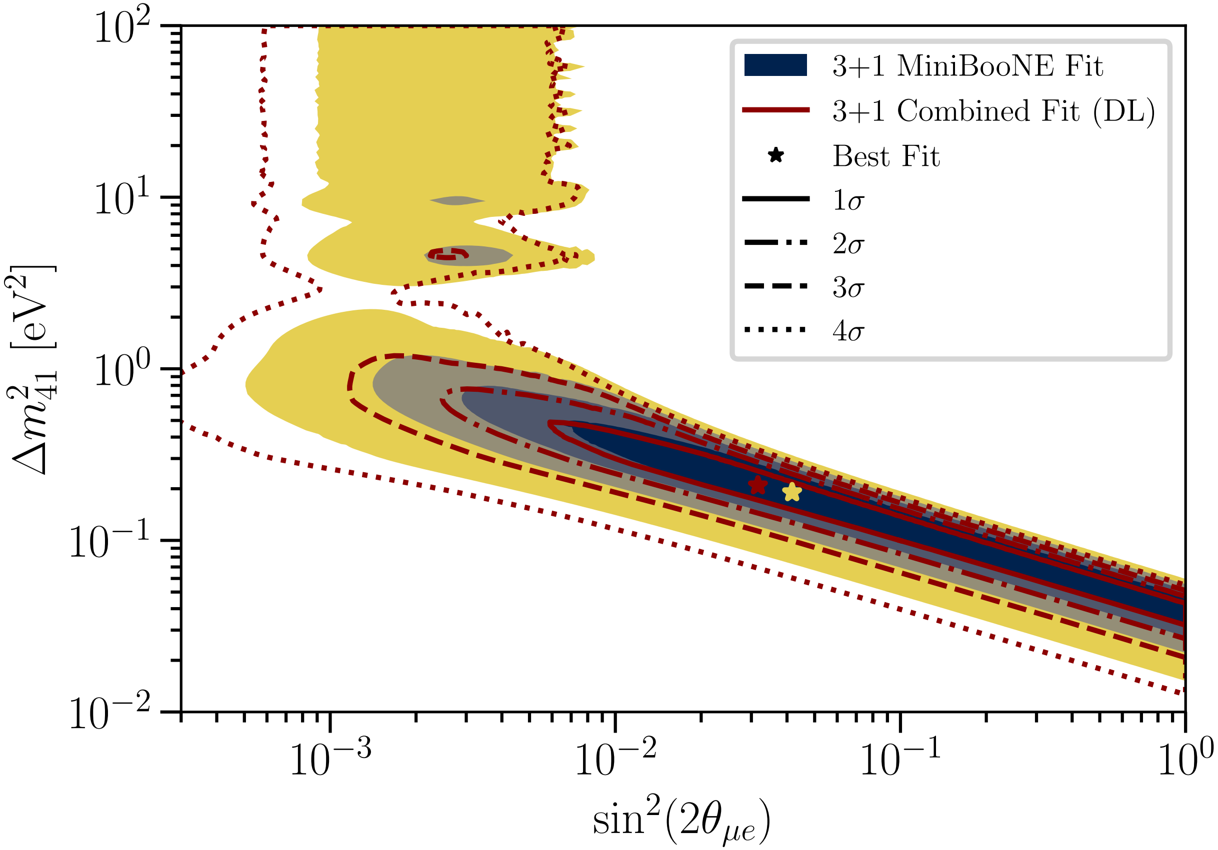


$$\bar{\nu}_\mu \longrightarrow \bar{\nu}_e$$

$$P(\nu_\alpha \to \nu_\beta) = |\langle \nu_\beta | \nu_\alpha ; t\rangle|^2 = \sum_{i,j} U^*_{\beta i} U_{\alpha i} U_{\beta j} U^*_{\alpha j} e^{i\frac{m_j^2 - m_i^2}{2p}t}$$

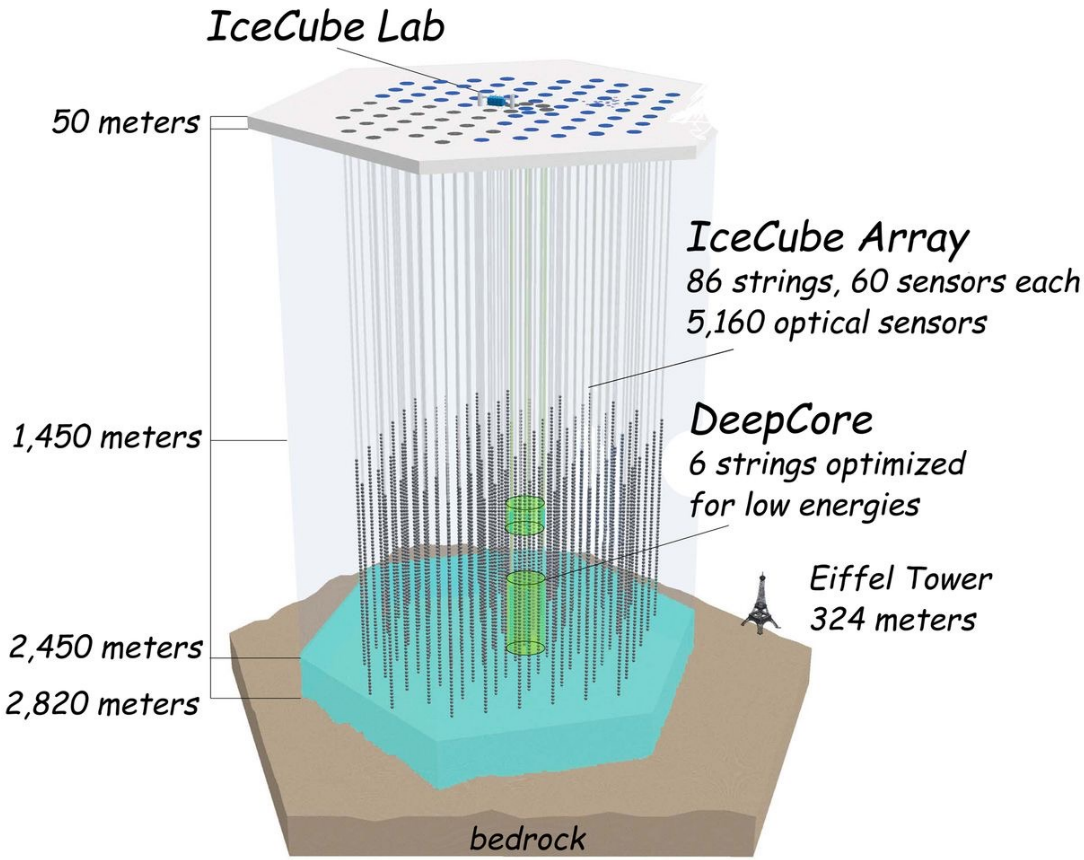


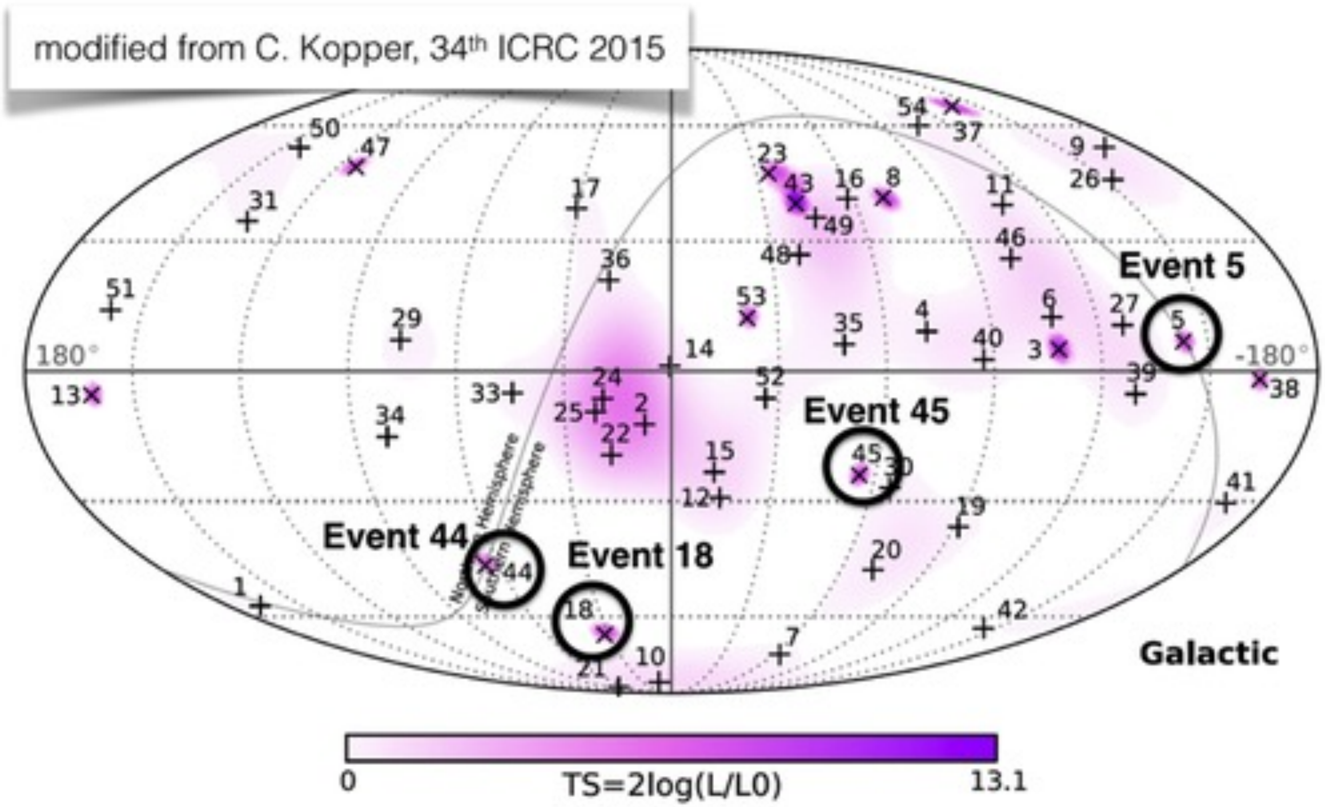
$$\Delta m^2 \sim 1 \text{ eV}^2$$

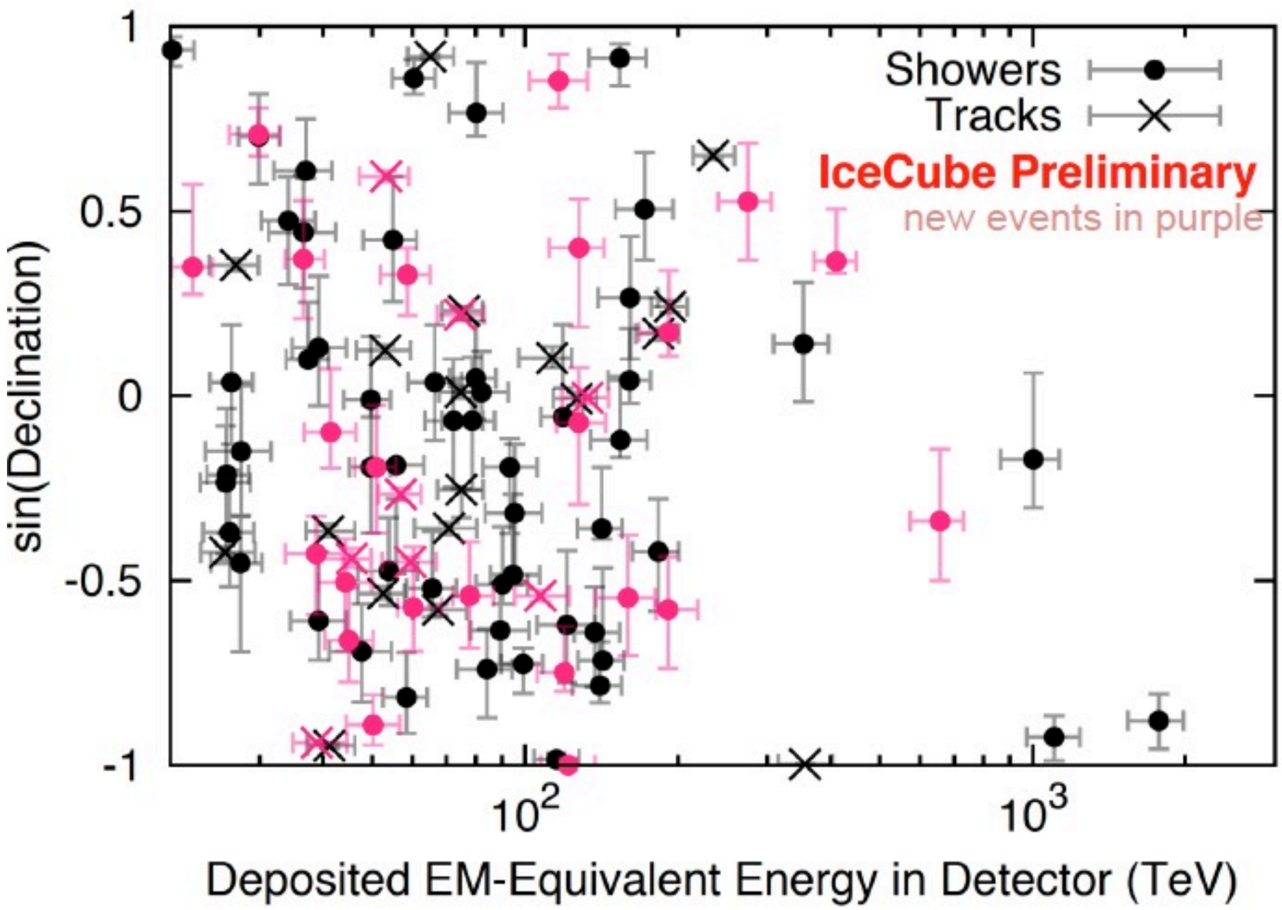


A. A.Aguilar-Arevalo et al. [MiniBooNE], "MiniBooNE and MicroBooNE Combined Fit to a 3+1 Sterile Neutrino Scenario," Phys. Rev. Lett. 129 (2022) no.20, 201801

Neutrino telescopes

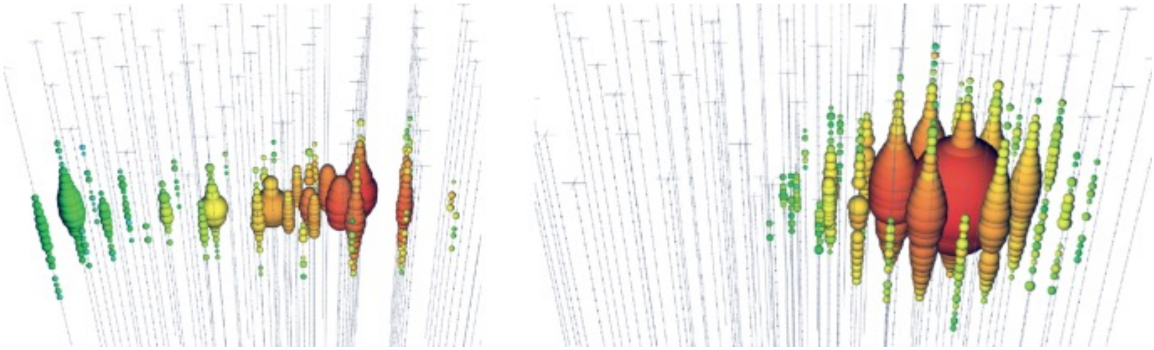



modified from C. Kopper, 34th ICRC 2015
Event 5
Event 45
Event 44
Event 18
Galactic
180°
-180°
0
TS=2log(L/L0)
13.1



Neutrino 2018

Shower vs muon-track



Muon-track

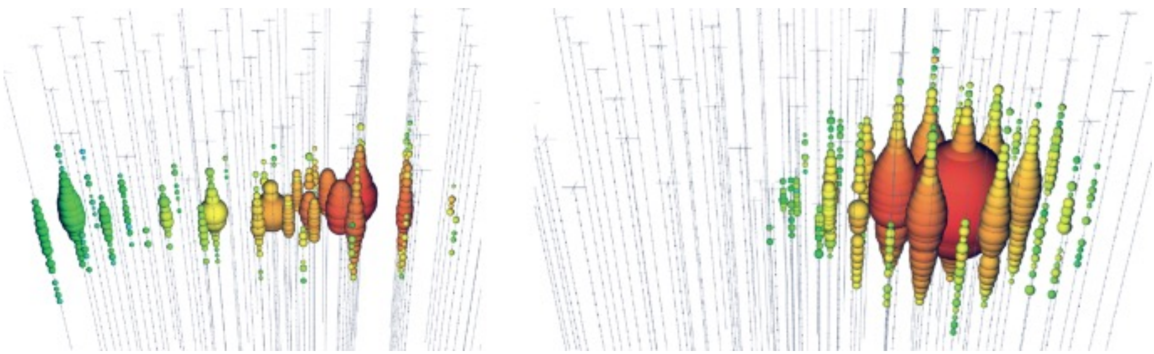
Charged current interaction of muon neutrinos $\nu_\mu + N \rightarrow \mu + X$

Charged current interaction of tau neutrinos and subsequent decay of tau to the muon

$$\nu_\tau + N \rightarrow \tau + X$$

$$\tau \rightarrow \mu \bar{\nu}_\mu \nu_\tau$$

Shower vs muon-track



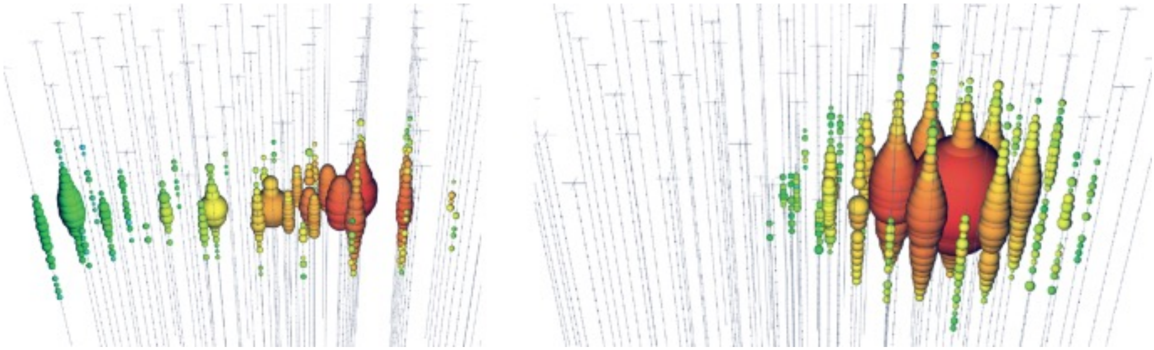
Shower=cascade

Charged current interaction of electron and tau neutrinos

$$\boxed{\nu_e + N \rightarrow e + X}$$

NC interaction of all three flavors

Shower vs muon-track



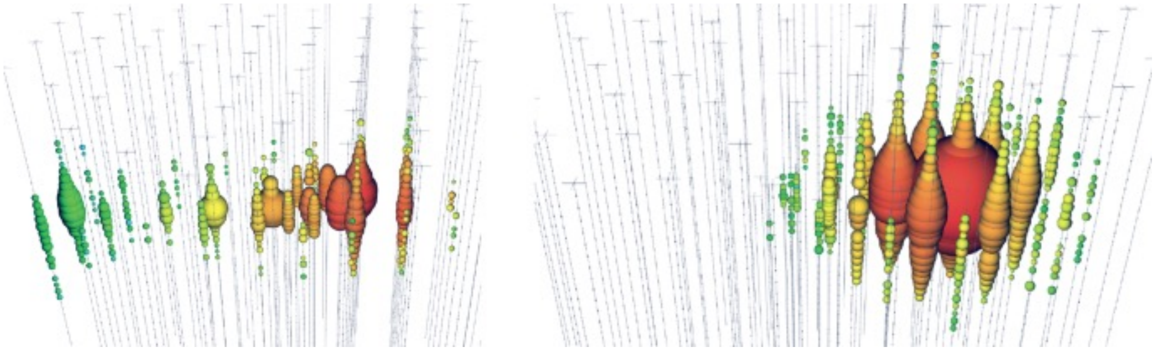
Shower=cascade

Charged current interaction of electron and tau neutrinos

$$\boxed{\begin{aligned} \nu_\tau + N &\rightarrow \tau + X \\ \tau &\rightarrow e\bar{\nu}_e\nu_\tau \\ \tau &\rightarrow \text{hadrons} + \nu_\tau \end{aligned}}$$

NC interaction of all three flavors

Shower vs muon-track



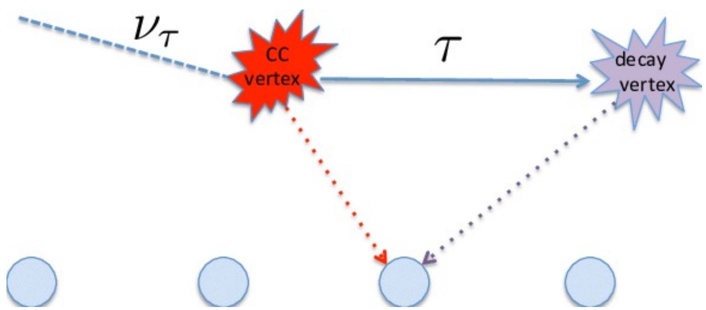
Shower=cascade

Charged current interaction of electron and tau neutrinos

NC interaction of all three flavors $\boxed{\nu_\alpha + N \rightarrow \nu_\alpha + X}$

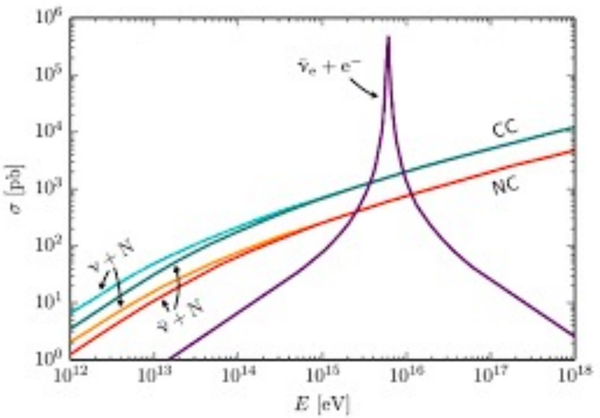
Two other sort of events

- Double bang or elongated track



- Glashow resonance

$$\bar{\nu}_e + e^- \to W^- \to \text{hadrons}$$



Possible sources

- AGN
- Gamma ray bursters

Proton-proton

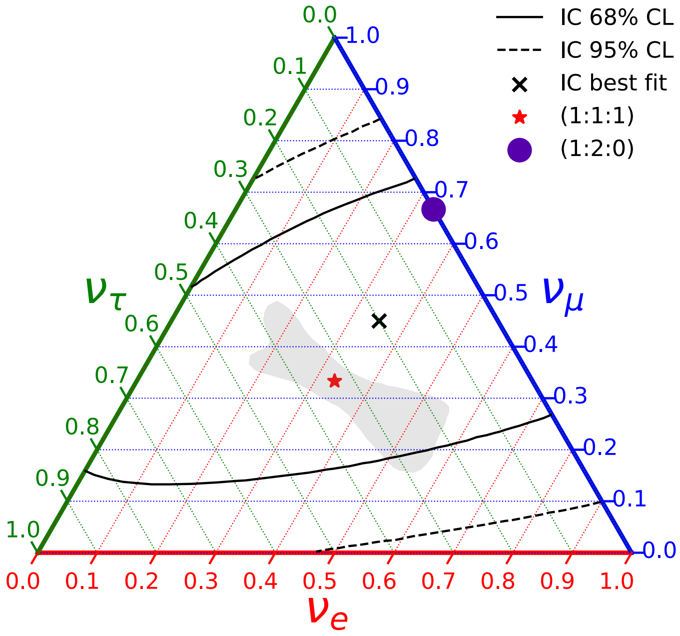
$$\pi^+ \to \mu^+ \nu_\mu \quad \mu^+ \to \bar{\nu}_\mu e^+ \nu_e$$

Proton-gamma

$$\pi^- \to \mu^- \bar{\nu}_\mu \quad \mu^- \to \nu_\mu e^- \bar{\nu}_e$$

$$F_{\nu_e} : F_{\nu_\mu} : F_{\nu_\tau} = 1 : 2 : 0 \xrightarrow{\text{Oscillation}} F^{\oplus}_{\nu_e} : F^{\oplus}_{\nu_\mu} : F^{\oplus}_{\nu_\tau} = 1 : 1 : 1$$

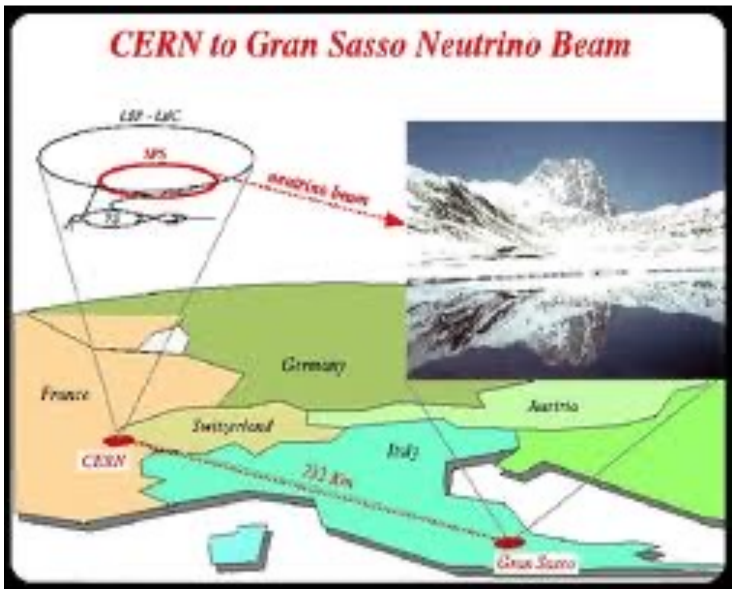
Ternary diagram



$$f_{\nu_e}^{\oplus} + f_{\nu_\mu}^{\oplus} + f_{\nu_\tau}^{\oplus} = 1$$

- In the end let me tell you an old but fascinating story!

OPERA experiment



Prime goal

$$\boxed{\nu_\mu \longrightarrow \nu_\tau}$$


IHE Bruxelles
Sofia
IRB Zagreb
Bari
Bologna
LNF Frascati
L'Aquila
LNGS
Napoli
Padova
Roma
Salerno
LAPP Annecy
IPNL Lyon
IPHC Strasbourg
OPERA is an international collaboration made of ~ 200 physicists from 36 institutions and 13 countries.
Aichi
Toho
Kobe
Nagoya
Utsunomiya
Hamburg
Münster
Rostock
Jinju
Technion Haifa
INR Moscow
NPI Moscow
ITEP Moscow
SINP MSU Moscow
JINR Dubna
Obninsk
Bern
Neuchâtel
ETH Zürich
Tunis
METU Ankara

Opera’s ground-breaking performance

- **Measurement of the neutrino velocity with the OPERA detector in the CNGS beam**

- **arXiv:1109.4897**

Abstract

- Data taking 2009-2010-2011

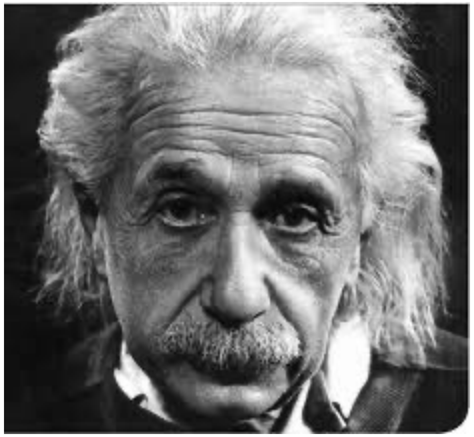
Early arrival: $57.8 \pm 7.8(stat.) + \binom{+8.3}{-5.9} (sys.)\ ns$

-

$$\frac{v-c}{c} = (2.37 \pm 0.32) \times 10^{-5}$$

Public reaction

- Over-excitement



Public reaction

- Over-excitement
- Versus
- Anger

Public reaction

Science : patience until enough evidence is gathered

- Over-excitement
- Versus
- Anger

- Science : patience until enough evidence
- is gathered

- Science: No prejudice

- Let us see what T2K will say.

Literature

- Possible sources of systematic error
- synchronization

Literature

- Possible sources of systematic error
- Neutrinos faster than light can be accommodated
- Wrong
- Field theory by construction does not allow

Literature

- Possible sources of systematic error
- Neutrinos faster than light cannot be accommodated
- Modifying standard picture to accommodate superluminal neutrinos
- Lorentz violation

Literature

- Possible sources of systematic error
- Neutrinos faster than light cannot be accommodated
- Modifying standard picture to accommodate
- Other observational consequences

Literature

- Possible sources of systematic error
- Neutrinos faster than light cannot be accommodated
- Modifying standard picture to accommodate superluminal neutrinos
- Other observational consequences

Few slides on this

Supernova neutrino

- Neutrinos from SN1987 a should have arrived much earlier than light; but they did not.

Interpreting OPERA results on superluminal neutrinos
Giudice, Sibiryakov and Strumia

Energy dependent $\frac{v-c}{c}$

Pair Creation Contraint

$$\nu_\mu \longrightarrow \begin{cases} \nu_\mu + \gamma & (a) \\ \nu_\mu + \nu_e + \overline{\nu}_e & (b) \\ \nu_\mu + e^+ + e^- & (c) \end{cases}$$

Even in vacuum

Glashow and Cohen

Already published in PRL

Energy loss

$$(\nu \to \nu + e^- + e^+).$$

Ideas to avoid this constraint: oscillation to sterile neutrino

Pair production constraints on superluminal Neutrinos
Brodsky and Gardner

Non-standard neutrino propagation and pion decay

Observation & SM prediction
$$\frac{Br(\pi^- \to \bar{\nu}_e e^-)}{Br(\pi^- \to \bar{\nu}_\mu \mu^-)} = 1.2 \times 10^{-4}$$

Distortion of dispersion relation:
$$\frac{Br(\pi^- \to \bar{\nu}_e e^-)}{Br(\pi^- \to \bar{\nu}_\mu \mu^-)} \gg 1.2 \times 10^{-4}$$

Minarelli et al., arXiv:1112.0169

- T2K may disprove OPERA

- However, all these efforts are enriching

- Even wrong papers help us to understand basics better.

Outlook

- There are plenty of open questions in neutrino physics

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- Neutrinos have surprised us so many time

Outlook

- There are plenty of open questions in neutrino physics
- Neutrinos have surprised us so many times!

- Neutrinos will keep us busy for ages even if LHC fails to find anything interesting!