

Neutrino Physics

Part III: Phenomenology of Massive Neutrinos

Carlo Giunti

INFN, Torino, Italy

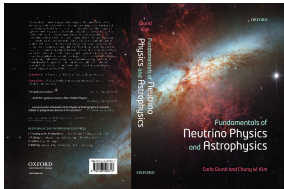
giunti@to.infn.it

Neutrino Unbound: <http://www.nu.to.infn.it>

Torino Graduate School in Physics and Astrophysics

Torino, May 2019

<http://personalpages.to.infn.it/~giunti/slides/2018/>



C. Giunti and C.W. Kim

Fundamentals of Neutrino Physics and
Astrophysics

Oxford University Press

15 March 2007 – 728 pages

Three-Neutrino Mixing Paradigm

$$\nu_{\alpha L} = \sum_{k=1}^3 U_{\alpha k} \nu_{kL}$$

$$\alpha = e, \mu, \tau$$

$$P_{\nu_{\alpha} \rightarrow \nu_{\beta}}(L, E) = \delta_{\alpha\beta} - 4 \underbrace{\sum_{k>j} \text{Re} [U_{\alpha k}^* U_{\beta k} U_{\alpha j} U_{\beta j}^*]}_{\text{CP conserving}} \sin^2 \left(\frac{\Delta m_{kj}^2 L}{4E} \right)$$

$$+ 2 \underbrace{\sum_{k>j} \text{Im} [U_{\alpha k}^* U_{\beta k} U_{\alpha j} U_{\beta j}^*]}_{\text{CP violating}} \sin \left(\frac{\Delta m_{kj}^2 L}{2E} \right)$$

- ▶ Squared-mass differences: $\Delta m_{kj}^2 = m_k^2 - m_j^2$
- ▶ Mixing: $U_{\alpha k}^* U_{\beta k} U_{\alpha j} U_{\beta j}^*$ quartic rephasing invariants
- ▶ Jarlskog invariant: $J_{\text{CP}} = \text{Im} [U_{\alpha k}^* U_{\beta k} U_{\alpha j} U_{\beta j}^*]$

Standard Parameterization of Mixing Matrix

$$U = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta_{13}} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta_{13}} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} 1 & 0 & 0 \\ 0 & e^{i\lambda_{21}} & 0 \\ 0 & 0 & e^{i\lambda_{31}} \end{pmatrix}$$

ATM
Rea LBL $\bar{\nu}_e \rightarrow \bar{\nu}_e$
SOL
 $\beta\beta_{0\nu}$

Acc LBL $\nu_\mu \rightarrow \nu_\mu$
Acc LBL $\nu_\mu \rightarrow \nu_e$
KamLAND

$$= \begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta_{13}} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta_{13}} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta_{13}} & s_{23}c_{13} \\ s_{12}s_{23} - c_{12}c_{23}s_{13}e^{i\delta_{13}} & -c_{12}s_{23} - s_{12}c_{23}s_{13}e^{i\delta_{13}} & c_{23}c_{13} \end{pmatrix} \begin{pmatrix} 1 & 0 & 0 \\ 0 & e^{i\lambda_{21}} & 0 \\ 0 & 0 & e^{i\lambda_{31}} \end{pmatrix}$$

$$c_{ab} \equiv \cos \vartheta_{ab} \quad s_{ab} \equiv \sin \vartheta_{ab} \quad 0 \leq \vartheta_{ab} \leq \frac{\pi}{2} \quad 0 \leq \delta_{13}, \lambda_{21}, \lambda_{31} < 2\pi$$

OSCILLATION
PARAMETERS:

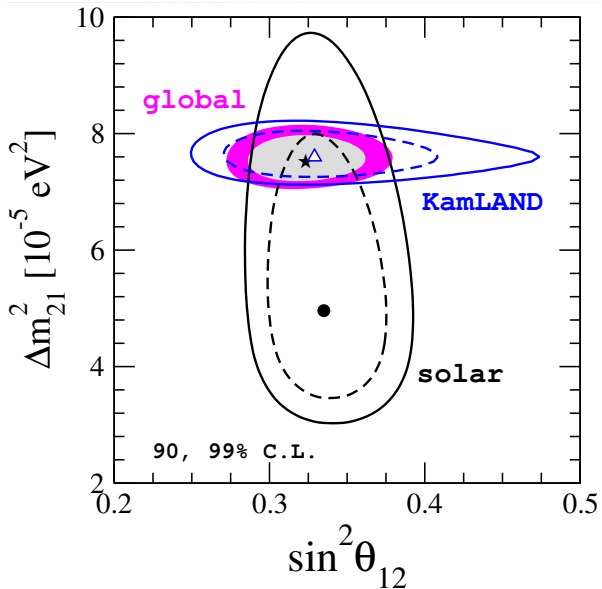
$$\left\{ \begin{array}{l} 3 \text{ Mixing Angles: } \vartheta_{12}, \vartheta_{23}, \vartheta_{13} \\ 1 \text{ CPV Dirac Phase: } \delta_{13} \\ 2 \text{ independent } \Delta m_{kj}^2: \Delta m_{21}^2, \Delta m_{31}^2 \end{array} \right.$$

2 CPV Majorana Phases: $\lambda_{21}, \lambda_{31} \iff |\Delta L| = 2$ processes ($\beta\beta_{0\nu}$)

Three-Neutrino Mixing Ingredients

$$U = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta_{13}} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta_{13}} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} 1 & 0 & 0 \\ 0 & e^{i\lambda_{21}} & 0 \\ 0 & 0 & e^{i\lambda_{31}} \end{pmatrix}$$

Solar $\nu_e \rightarrow \nu_\mu, \nu_\tau$	$\left(\begin{array}{c} \text{SNO, Borexino} \\ \text{Super-Kamiokande} \\ \text{GALLEX/GNO, SAGE} \\ \text{Homestake, Kamiokande} \end{array} \right)$	$\left. \vphantom{\begin{array}{c} \text{SNO, Borexino} \\ \text{Super-Kamiokande} \\ \text{GALLEX/GNO, SAGE} \\ \text{Homestake, Kamiokande} \end{array}} \right\} \rightarrow \left\{ \begin{array}{l} \Delta m_S^2 = \Delta m_{21}^2 \simeq 7.4 \times 10^{-5} \text{ eV}^2 \\ \sin^2 \vartheta_S = \sin^2 \vartheta_{12} \simeq 0.30 \end{array} \right.$
VLBL Reactor $\bar{\nu}_e$ disappearance	(KamLAND)	



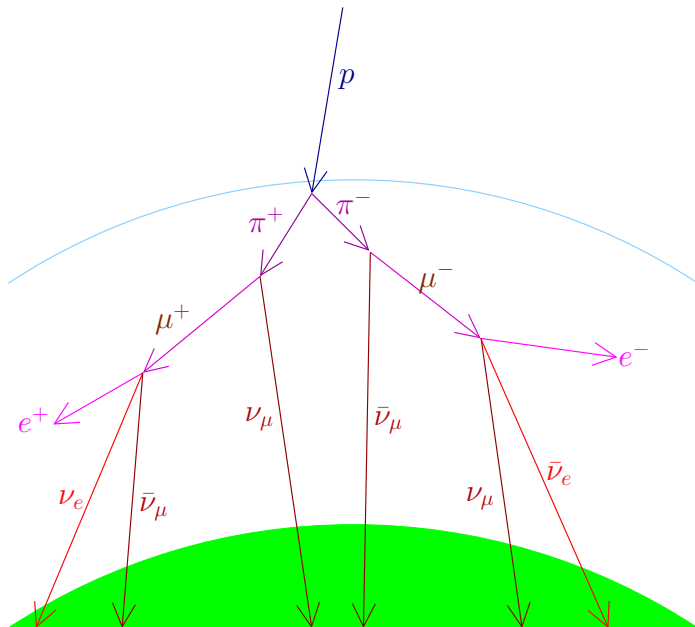
[M. Tortola © Neutrino 2018]

Three-Neutrino Mixing Ingredients

$$U = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta_{13}} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta_{13}} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} 1 & 0 & 0 \\ 0 & e^{i\lambda_{21}} & 0 \\ 0 & 0 & e^{i\lambda_{31}} \end{pmatrix}$$

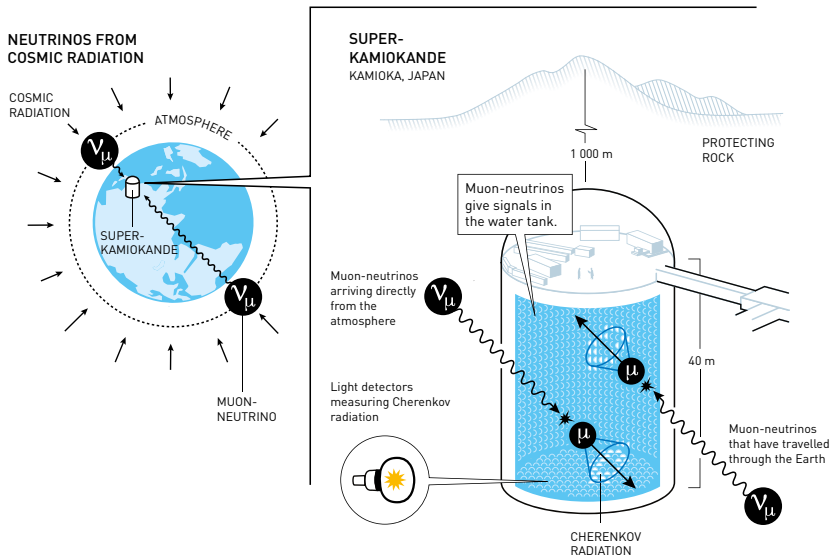
<p>Atmospheric $\nu_\mu \rightarrow \nu_\tau$</p>	$\left(\begin{array}{l} \text{Super-Kamiokande} \\ \text{Kamiokande, IMB} \\ \text{MACRO, Soudan-2} \\ \text{IceCube, ANTARES} \end{array} \right)$	}	→	{	$\Delta m_A^2 \simeq \Delta m_{31}^2 \simeq 2.5 \times 10^{-3} \text{ eV}^2$
<p>LBL Accelerator ν_μ disappearance</p>	$\left(\begin{array}{l} \text{K2K, MINOS} \\ \text{T2K, NO}\nu\text{A} \end{array} \right)$				$\sin^2 \vartheta_A = \sin^2 \vartheta_{23} \simeq 0.50$
<p>LBL Accelerator $\nu_\mu \rightarrow \nu_\tau$</p>	<p>(OPERA)</p>				

Atmospheric Neutrinos

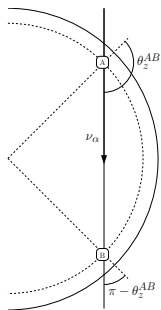


The Super-Kamiokande Experiment

50 ktons of water, Cherenkov detector, 1000 m underground



The Super-Kamiokande Up-Down Asymmetry



$E_\nu \gtrsim 1 \text{ GeV} \Rightarrow$ isotropic flux of cosmic rays

$$\phi_{\nu_\alpha}^{(A)}(\theta_z^{AB}) = \phi_{\nu_\alpha}^{(B)}(\theta_z^{AB})$$

$$\phi_{\nu_\alpha}^{(A)}(\theta_z^{AB}) = \phi_{\nu_\alpha}^{(B)}(\pi - \theta_z^{AB})$$

$$\Downarrow$$
$$\phi_{\nu_\alpha}^{(B)}(\theta_z) = \phi_{\nu_\alpha}^{(B)}(\pi - \theta_z)$$

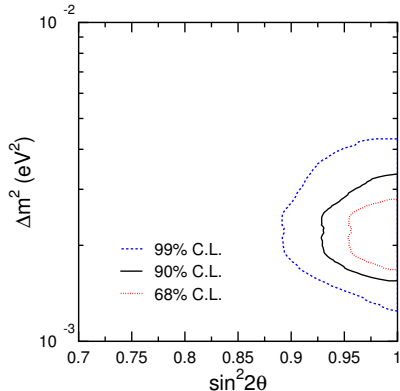
$$A_{\nu_\mu}^{\text{up-down}}(\text{SK}) = \left(\frac{N_{\nu_\mu}^{\text{up}} - N_{\nu_\mu}^{\text{down}}}{N_{\nu_\mu}^{\text{up}} + N_{\nu_\mu}^{\text{down}}} \right) = -0.296 \pm 0.048 \pm 0.01$$

[Super-Kamiokande, Phys. Rev. Lett. 81 (1998) 1562, hep-ex/9807003]

6 σ MODEL INDEPENDENT EVIDENCE OF ν_μ DISAPPEARANCE!

(T. Kajita: 2015 Physics Nobel Prize)

Fit of Super-Kamiokande Atmospheric Data



Best Fit: $\left\{ \begin{array}{l} \nu_{\mu} \rightarrow \nu_{\tau} \\ \Delta m^2 = 2.1 \times 10^{-3} \text{ eV}^2 \\ \sin^2 2\theta = 1.0 \end{array} \right.$
1489.2 live-days (Apr 1996 – Jul 2001)

[Super-Kamiokande, PRD 71 (2005) 112005, hep-ex/0501064]

Measure of ν_{τ} CC Int. is Difficult:

- ▶ $E_{\text{th}} = 3.5 \text{ GeV} \Rightarrow \sim 20 \text{ events/yr}$
- ▶ τ -Decay \Rightarrow Many Final States

ν_{τ} -Enriched Sample

$$N_{\nu_{\tau}}^{\text{the}} = 78 \pm 26 @ \Delta m^2 = 2.4 \times 10^{-3} \text{ eV}^2$$

$$N_{\nu_{\tau}}^{\text{exp}} = 138^{+50}_{-58}$$

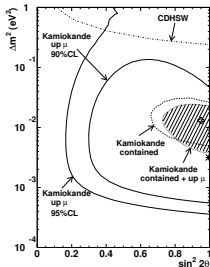
$$N_{\nu_{\tau}} > 0 @ 2.4\sigma$$

[Super-Kamiokande, PRL 97(2006) 171801, hep-ex/0607059]

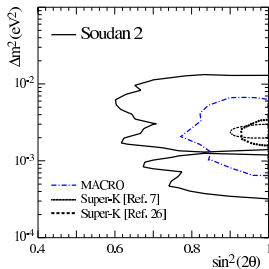
Check: OPERA ($\nu_{\mu} \rightarrow \nu_{\tau}$)
CERN to Gran Sasso (CNCS)
 $L \simeq 732 \text{ km}$ $\langle E \rangle \simeq 18 \text{ GeV}$

[NJP 8 (2006) 303, hep-ex/0611023]

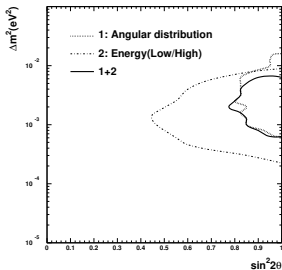
Kamiokande, Soudan-2, MACRO and MINOS



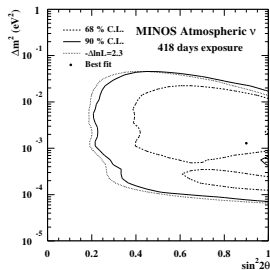
[Kamiokande, hep-ex/9806038]



[Soudan 2, hep-ex/0507068]



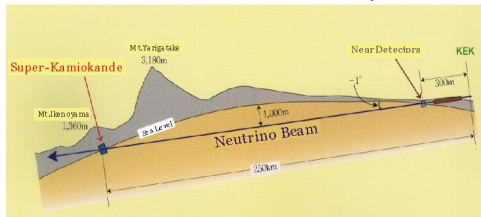
[MACRO, hep-ex/0304037]



[MINOS, hep-ex/0512036]

K2K

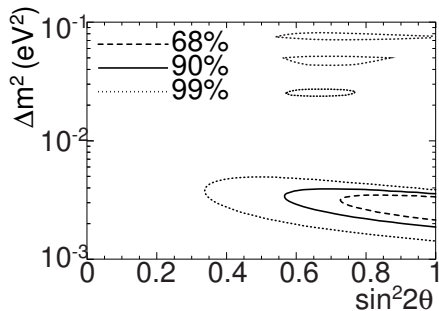
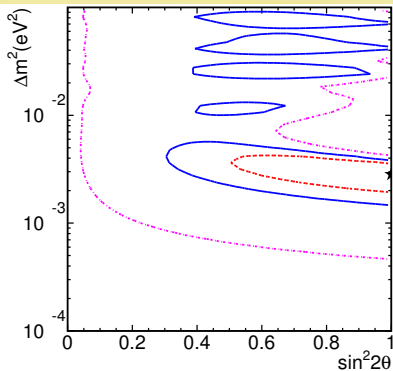
confirmation of atmospheric allowed region (June 2002)



KEK to Kamioka
(Super-Kamiokande)

250 km

$\nu_\mu \rightarrow \nu_\mu$

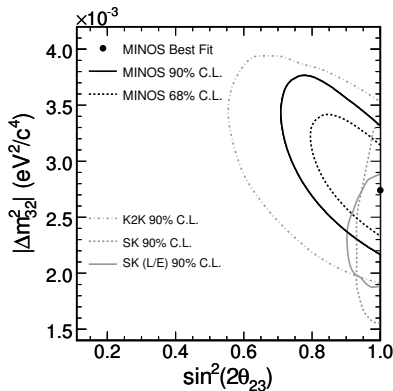


[K2K, Phys. Rev. Lett. 90 (2003) 041801]

[K2K, PRL 94 (2005) 081802, hep-ex/0411038]



Near Detector: 1 km



$\nu_\mu \rightarrow \nu_\mu$

$$\Delta m^2 = 2.74^{+0.44}_{-0.26} \times 10^{-3} \text{ eV}^2$$

$$\sin^2 2\vartheta > 0.87 @ 68\% CL$$

[MINOS, PRL 97 (2006) 191801, hep-ex/0607088]



Discovery of τ Neutrino Appearance in the CNGS Neutrino Beam with the OPERA Experiment

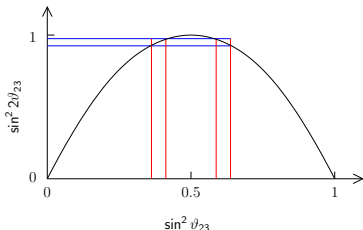
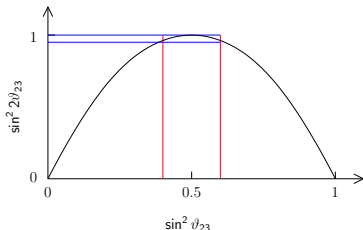
The OPERA experiment was designed to search for $\nu_\mu \rightarrow \nu_\tau$ oscillations in appearance mode, i.e., by detecting the τ leptons produced in charged current ν_τ interactions. The experiment took data from 2008 to 2012 in the CERN Neutrinos to Gran Sasso beam. The observation of the $\nu_\mu \rightarrow \nu_\tau$ appearance, achieved with four candidate events in a subsample of the data, was previously reported. In this Letter, a fifth ν_τ candidate event, found in an enlarged data sample, is described. Together with a further reduction of the expected background, the candidate events detected so far allow us to assess the discovery of $\nu_\mu \rightarrow \nu_\tau$ oscillations in appearance mode with a significance larger than 5σ .

Channel	Expected background			Expected signal	Observed
	Charm	Had. reinterac.	Large μ scat.		
$\tau \rightarrow 1h$	0.017 ± 0.003	0.022 ± 0.006		0.04 ± 0.01	3
$\tau \rightarrow 3h$	0.17 ± 0.03	0.003 ± 0.001		0.17 ± 0.03	1
$\tau \rightarrow \mu$	0.004 ± 0.001		0.0002 ± 0.0001	0.004 ± 0.001	1
$\tau \rightarrow e$	0.03 ± 0.01			0.03 ± 0.01	0
Total	0.22 ± 0.04	0.02 ± 0.01	0.0002 ± 0.0001	0.25 ± 0.05	5

Difficulty of measuring precisely ϑ_{23}

$$P_{\nu_\mu \rightarrow \nu_\mu}^{\text{LBL}} \simeq 1 - \sin^2 2\vartheta_{23} \sin^2 \left(\frac{\Delta m_{31}^2 L}{4E} \right)$$

$$\sin^2 2\vartheta_{23} = 4 \sin^2 \vartheta_{23} (1 - \sin^2 \vartheta_{23})$$



The octant degeneracy is resolved by small ϑ_{13} effects:

$$P_{\nu_\mu \rightarrow \nu_\mu}^{\text{LBL}} \simeq 1 - \left[\sin^2 2\vartheta_{23} \cos^2 \vartheta_{13} + \sin^4 \vartheta_{23} \sin^2 2\vartheta_{13} \right] \sin^2 \left(\frac{\Delta m_{31}^2 L}{4E} \right)$$

$$P_{\nu_\mu \rightarrow \nu_e}^{\text{LBL}} \simeq \sin^2 \vartheta_{23} \sin^2 2\vartheta_{13} \sin^2 \left(\frac{\Delta m_{31}^2 L}{4E} \right)$$

Three-Neutrino Mixing Ingredients

$$U = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta_{13}} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta_{13}} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} 1 & 0 & 0 \\ 0 & e^{i\lambda_{21}} & 0 \\ 0 & 0 & e^{i\lambda_{31}} \end{pmatrix}$$

LBL Accelerator

$$\nu_\mu \rightarrow \nu_e$$

(T2K, MINOS, NO ν A)

LBL Reactor

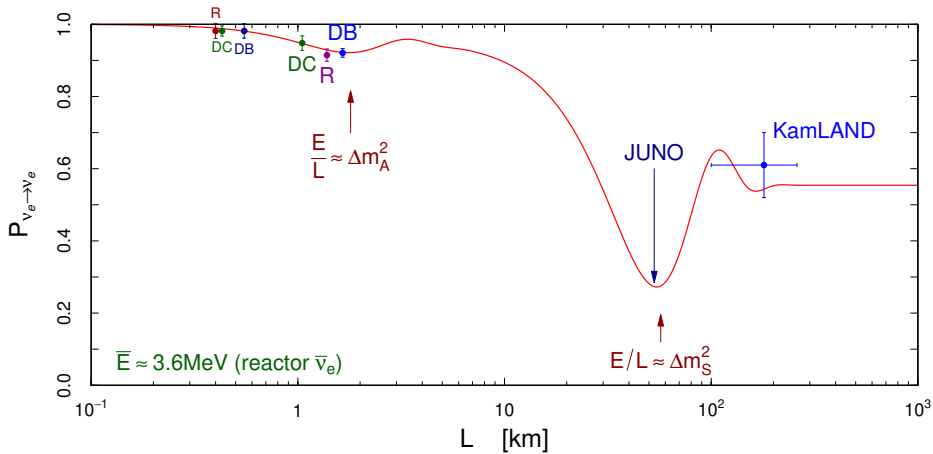
$\bar{\nu}_e$ disappearance

(Daya Bay, RENO
Double Chooz)

\rightarrow

$$\Delta m_A^2 \simeq |\Delta m_{31}^2| \simeq 2.5 \times 10^{-3} \text{ eV}^2$$

$$\sin^2 \vartheta_{13} \simeq 0.022$$



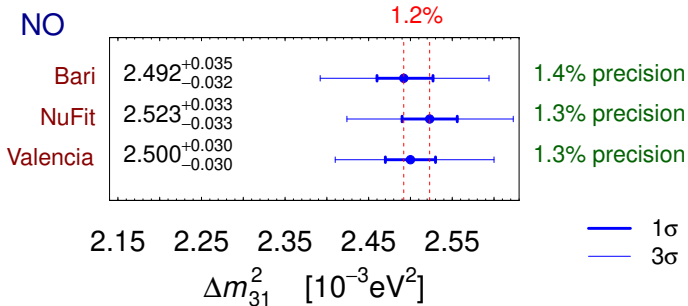
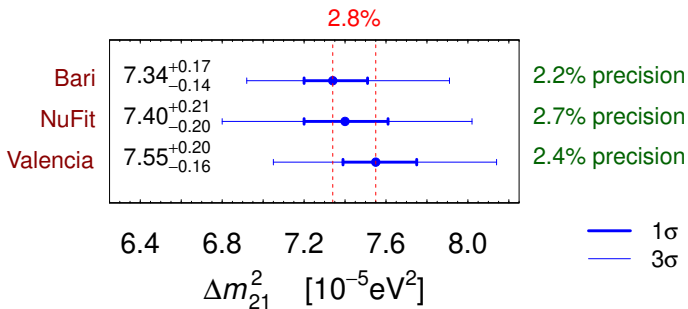
Towards a precise determination of neutrino mixing

$$U = \begin{pmatrix} \boxed{c_{12}c_{13}} & \boxed{s_{12}c_{13}} & \boxed{s_{13}e^{-i\delta_{13}}} \\ \boxed{-s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta_{13}}} & \boxed{c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta_{13}}} & \boxed{s_{23}c_{13}} \\ \boxed{s_{12}s_{23} - c_{12}c_{23}s_{13}e^{i\delta_{13}}} & \boxed{-c_{12}s_{23} - s_{12}c_{23}s_{13}e^{i\delta_{13}}} & \boxed{c_{23}c_{13}} \end{pmatrix} \begin{pmatrix} 1 & 0 & 0 \\ 0 & e^{i\lambda_{21}} & 0 \\ 0 & 0 & e^{i\lambda_{31}} \end{pmatrix}$$

well determined
large uncertainty due to ϑ_{23} and δ_{13}
medium uncertainty due to ϑ_{23}
totally unknown

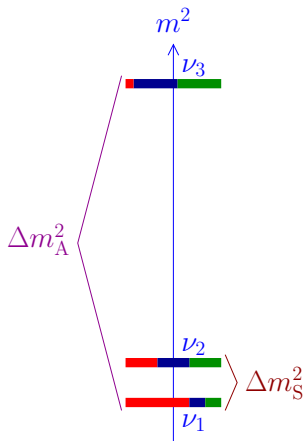
$$|U|_{3\sigma} = \begin{pmatrix} \text{---} & \text{---} & \text{---} \\ \text{=====} & \text{=====} & \text{=====} \\ \text{=====} & \text{=====} & \text{=====} \end{pmatrix}$$

only the mass composition of ν_e is well determined



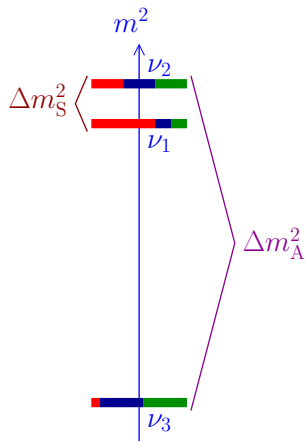
Mass Ordering

ν_e	ν_μ	ν_τ
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Normal Ordering

$$\Delta m_{31}^2 > \Delta m_{32}^2 > 0$$



Inverted Ordering

$$\Delta m_{32}^2 < \Delta m_{31}^2 < 0$$

absolute scale is not determined by neutrino oscillation data

Open Problems

- ▶ $\vartheta_{23} \stackrel{\leq}{\geq} 45^\circ$?
 - ▶ T2K (Japan), NO ν A (USA), ...
- ▶ CP violation ? $\delta_{13} \approx 3\pi/2$?
 - ▶ T2K (Japan), NO ν A (USA), DUNE (USA), HyperK (Japan), ...
- ▶ Mass Ordering ?
 - ▶ JUNO (China), PINGU (Antarctica), ORCA (EU), INO (India), ...
- ▶ Absolute Mass Scale ?
 - ▶ β Decay, Neutrinoless Double- β Decay, Cosmology, ...
- ▶ Dirac or Majorana ?
 - ▶ Neutrinoless Double- β Decay, ...
- ▶ Beyond Three-Neutrino Mixing ? Sterile Neutrinos ?

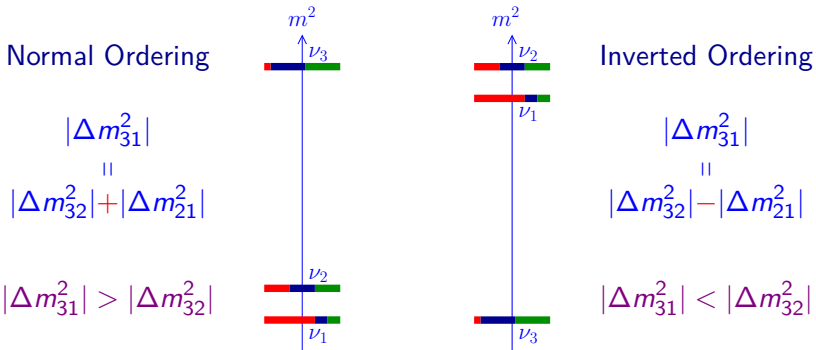
Determination of Mass Ordering

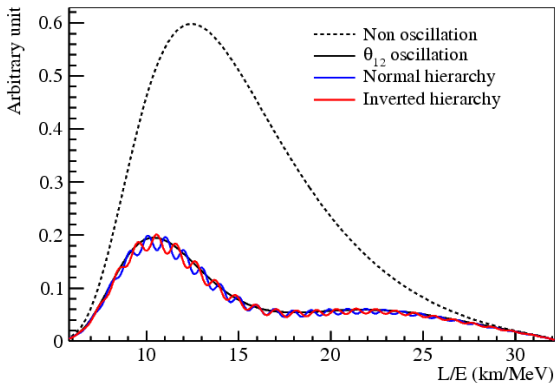
1. Matter Effects: Atmospheric (PINGU, ORCA), Long-Baseline, Supernova Experiments

► $\nu_e \leftrightarrow \nu_\mu$ MSW resonance: $V = \frac{\Delta m_{31}^2 \cos 2\vartheta_{13}}{2E} \Leftrightarrow \Delta m_{31}^2 > 0$ NO

► $\bar{\nu}_e \leftrightarrow \bar{\nu}_\mu$ MSW resonance: $V = -\frac{\Delta m_{31}^2 \cos 2\vartheta_{13}}{2E} \Leftrightarrow \Delta m_{31}^2 < 0$ IO

2. Phase Difference: Reactor $\bar{\nu}_e \rightarrow \bar{\nu}_e$ (JUNO)





Neutrino Physics with JUNO, arXiv:1507.05613

$$\begin{aligned}
 P_{\nu_e \rightarrow \nu_e}^{(-)} = & 1 - \cos^4 \vartheta_{13} \sin^2 2\vartheta_{12} \sin^2 (\Delta m_{21}^2 L/4E) \\
 & - \cos^2 \vartheta_{12} \sin^2 2\vartheta_{13} \sin^2 (\Delta m_{31}^2 L/4E) \\
 & - \sin^2 \vartheta_{12} \sin^2 2\vartheta_{13} \sin^2 (\Delta m_{32}^2 L/4E)
 \end{aligned}$$

[Petcov, Piai, PLB 533 (2002) 94; Choubey, Petcov, Piai, PRD 68 (2003) 113006; Learned, Dye, Pakvasa, Svoboda, PRD 78 (2008) 071302; Zhan, Wang, Cao, Wen, PRD 78 (2008) 111103, PRD 79 (2009) 073007]

CP Violation?

$$\begin{aligned} A_{\alpha\beta}^{\text{CP}} &= P_{\nu_\alpha \rightarrow \nu_\beta} - P_{\bar{\nu}_\alpha \rightarrow \bar{\nu}_\beta} \\ &= -16 J_{\alpha\beta} \sin\left(\frac{\Delta m_{21}^2 L}{4E}\right) \sin\left(\frac{\Delta m_{31}^2 L}{4E}\right) \sin\left(\frac{\Delta m_{32}^2 L}{4E}\right) \end{aligned}$$

$$J_{\alpha\beta} = \text{Im}(U_{\alpha 1} U_{\alpha 2}^* U_{\beta 1}^* U_{\beta 2}) = \pm J$$

$$J = s_{12} c_{12} s_{23} c_{23} s_{13} c_{13}^2 \sin \delta_{13}$$

Necessary conditions for observation of CP violation:

- ▶ Sensitivity to all mixing angles, including small ϑ_{13}
- ▶ Sensitivity to oscillations due to Δm_{21}^2 and Δm_{31}^2

LBL $\nu_\mu \rightarrow \nu_e$ and $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$

$$\Delta = \frac{\Delta m_{31}^2 L}{4E} \quad A = \frac{2EV}{\Delta m_{31}^2} \quad V = \sqrt{2} G_F N_e$$

$$\sin \theta_{13} \ll 1 \quad \Delta m_{21}^2 / \Delta m_{31}^2 \ll 1$$

$$P_{\nu_\mu \rightarrow \nu_e}^{\text{LBL}} \simeq \overset{\vartheta_{13}}{\downarrow} \sin^2 2\vartheta_{13} \overset{\vartheta_{23} \text{ octant}}{\downarrow} \sin^2 \vartheta_{23} \frac{\sin^2[(1-A)\Delta]}{(1-A)^2} \\ + \frac{\Delta m_{21}^2}{\Delta m_{31}^2} \sin 2\vartheta_{13} \sin 2\vartheta_{12} \sin 2\vartheta_{23} \cos(\Delta + \overset{\text{CPV}}{\uparrow} \delta_{13}) \frac{\sin(A\Delta)}{A} \frac{\sin[(1-A)\Delta]}{1-A} \\ + \left(\frac{\Delta m_{21}^2}{\Delta m_{31}^2} \right)^2 \sin^2 2\vartheta_{12} \cos^2 \vartheta_{23} \frac{\sin^2(A\Delta)}{A^2}$$

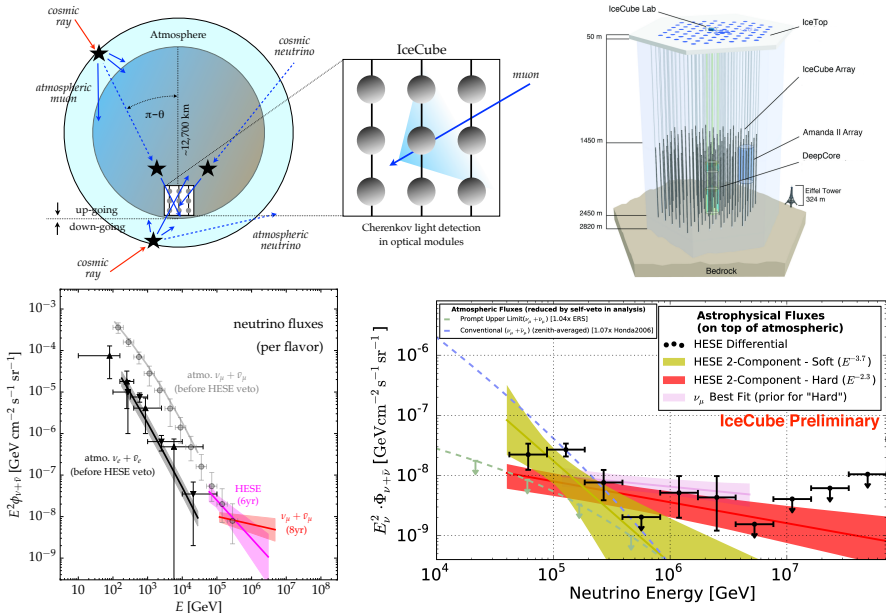
$$\text{NO: } \Delta m_{31}^2 > 0 \quad \text{IO: } \Delta m_{31}^2 < 0$$

For antineutrinos: $\delta_{13} \rightarrow -\delta_{13}$ (CPV) and $A \rightarrow -A$ (Matter Effect)

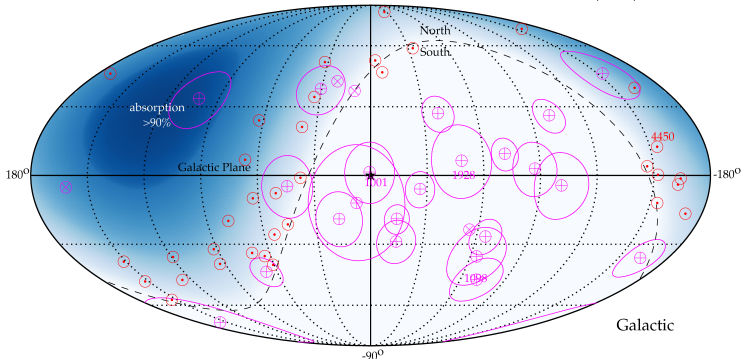
Why it is important to measure accurately the neutrino mixing parameters?

- ▶ They are fundamental parameters.
- ▶ They lead to selection in huge model space. Examples:
 - ▶ Deviation from Tribimaximal Mixing $U \simeq \begin{pmatrix} \sqrt{2/3} & 1/\sqrt{3} & 0 \\ -1/\sqrt{6} & 1/\sqrt{3} & 1/\sqrt{2} \\ 1/\sqrt{6} & -1/\sqrt{3} & 1/\sqrt{2} \end{pmatrix}$
 - ▶ Violation of μ - τ symmetry ($|U_{\mu k}| = |U_{\tau k}|$)
- ▶ They have phenomenological usefulness (e.g. to determine the initial flavor composition of high-energy astrophysical neutrinos).
- ▶ CP:
 - ▶ CP conservation would need an explanation (a new symmetry?).
 - ▶ CP violation may be linked to the CP violation in the sector of heavy neutrinos which generate the matter-antimatter asymmetry in the Universe through leptogenesis (CP-violating decay of heavy neutrinos).

High-Energy Astrophysical Neutrinos



[Ahlers, Halzen, arXiv:1805.11112]

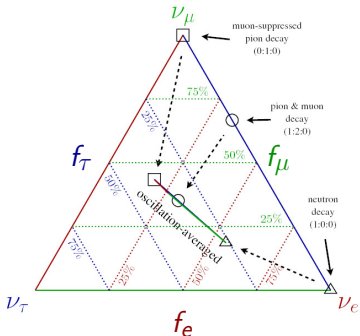


- ⊙ High-energy ($E \gtrsim 200 \text{ TeV}$) ongoing tracks: $\text{CC}(\nu_\mu, \bar{\nu}_\mu)$.
- ⊗&⊕ HESE (High-Energy Starting Events): high-energy neutrinos ($E \gtrsim 100 \text{ TeV}$) interacting inside the detector (all-sky directions).
 - ⊗ Tracks: $\text{CC}(\nu_\mu, \bar{\nu}_\mu)$. ⊕ Cascades: $\text{CC}(\nu_e, \bar{\nu}_e, \nu_\tau, \bar{\nu}_\tau) + \text{NC}$. The thin circles indicate the median angular resolution of the cascade events.
- ▶ The blue-shaded region indicates the zenith-dependent range where Earth absorption of 100 TeV neutrinos becomes important, reaching more than 90% close to the nadir.
- ▶ Dashed line: horizon. Star: Galactic Center.
- ▶ The numbers give the energies of the four most energetic events.

Neutrino Flavor Composition

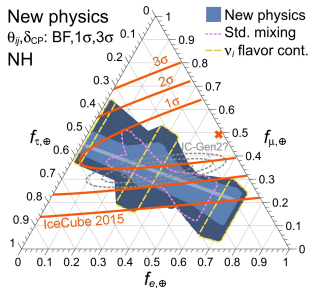
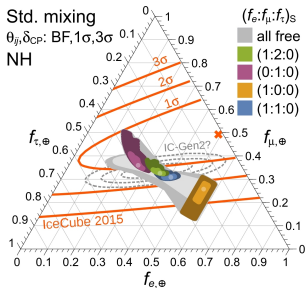
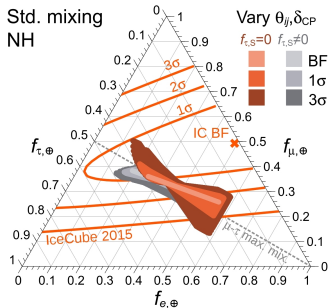
Source: $(f_{e,S} : f_{\mu,S} : f_{\tau,S}) \rightarrow$ Earth: $(f_{e,\oplus} : f_{\mu,\oplus} : f_{\tau,\oplus})$

	$f_{e,S}$	$f_{\mu,S}$	$f_{\tau,S}$	\rightarrow	$f_{e,\oplus}$	$f_{\mu,\oplus}$	$f_{\tau,\oplus}$
Pion and Muon Decay	1/3	2/3	0		1/3	1/3	1/3
Pion only Decay	0	1	0		4/18	7/18	7/18
Charmed Meson Decay	1/2	1/2	0		14/36	11/36	11/36
Neutron Decay	1	0	0		5/9	2/9	2/9



$$f_{\beta,\oplus} = \sum_{\alpha=e,\mu,\tau} f_{\alpha,S} \langle P_{\nu_\alpha \rightarrow \nu_\beta} \rangle$$

$$\langle P_{\nu_\alpha \rightarrow \nu_\beta} \rangle = \sum_{k=1}^3 |U_{\alpha k}|^2 |U_{\beta k}|^2 \simeq \frac{1}{18} \begin{pmatrix} 10 & 4 & 4 \\ 4 & 7 & 7 \\ 4 & 7 & 7 \end{pmatrix}$$



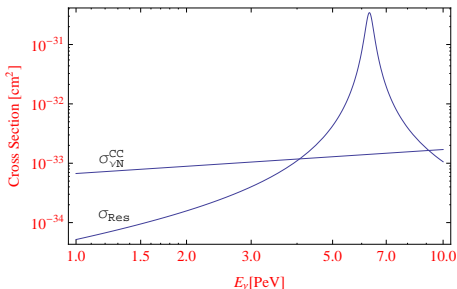
[Bustamante, Beacom, Winter, PRL 115 (2015) 161302 (arXiv:1506.02645)]

The Glashow Resonance

$\bar{\nu}_e + e^- \rightarrow W^- \rightarrow \text{anything}$ at $E_\nu = \frac{m_W^2}{2m_e} = 6.32 \text{ PeV}$ [Glashow, Phys. Rev. 118 (1960) 316]

	$f_{e,S}$	$f_{\mu,S}$	$f_{\tau,S}$	\rightarrow	$f_{e,\oplus}$	$f_{\mu,\oplus}$	$f_{\tau,\oplus}$	$R_{\bar{\nu}_e}$
Pion and Muon Decay	1/3	2/3	0		1/3	1/3	1/3	0.17
Pion only Decay	0	1	0		4/18	7/18	7/18	0.11
Charmed Meson Decay	1/2	1/2	0		14/36	11/36	11/36	0.19
Neutron Decay	1	0	0		5/9	2/9	2/9	0.56

[Barger, Fu, Learned, Marfatia, Pakvasa, Weiler, PRD 90 (2014) 121301 (arXiv:1407.3255)]

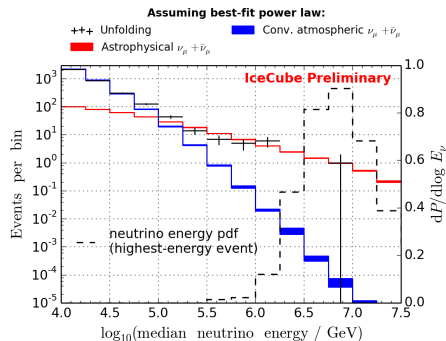


- ▶ $\Phi_\nu \propto E_\nu^{-\gamma}$
- ▶ Standard Fermi shock-acceleration mechanism: $\gamma = 2.0$.
- ▶ 2014 IceCube data: events with $E_\nu \lesssim 2 \text{ PeV}$.
- ▶ $\gamma \geq 2.3$ at 90% CL.

[Anchordoqui et al, PRD 89 (2014) 083003]

- ▶ PeV Energy Partially-contained Events (PEPE) search, with special focus on the Glashow resonance.

[IceCube, arXiv:1710.01191]



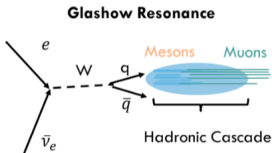
[Ahlers, Halzen, arXiv:1805.11112]

- ▶ For the highest energy event the median energy of the parent neutrino is about 7 PeV.
- ▶ The energy lost by the muon inside the instrumented detector volume is 2.6 ± 0.3 PeV.
- ▶ The calculation of the probability density function takes into account the additional tracks from charged current interactions of $\nu_\tau + \bar{\nu}_\tau$ and resonant interactions of $\bar{\nu}_e$ with electrons (Glashow resonance).

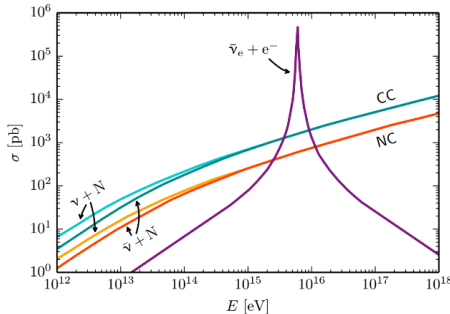
- ▶ Assumption: a democratic composition of neutrino and antineutrino flavors.
- ▶ The cosmic neutrino flux is well described by a power law with a spectral index $\gamma = 2.19 \pm 0.10$ and a normalization at 100 TeV neutrino energy of

$$(1.01^{+0.26}_{-0.23}) \times 10^{-18} \text{ GeV}^{-1} \text{ cm}^{-2} \text{ sr}^{-1}$$

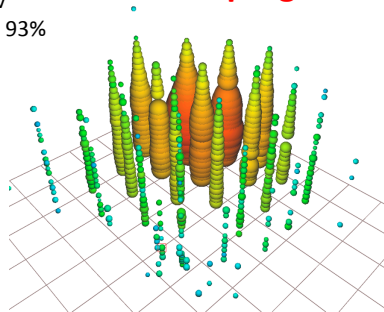
A 5.9 PeV event in IceCube



Resonance: $E_\nu = 6.3 \text{ PeV}$
 Typical visible energy is 93%



Work in progress



Event identified in a partially-contained PeV search (PEPE)

Deposited energy: $5.9 \pm 0.18 \text{ PeV}$ (stat only)

[ICRC 2017 arXiv:1710.01191](#)

Potential hadronic nature of this event under study

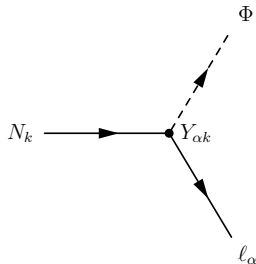
Why it is important to measure accurately the neutrino mixing parameters?

- ▶ They are fundamental parameters.
- ▶ They lead to selection in huge model space. Examples:
 - ▶ Deviation from Tribimaximal Mixing $U \simeq \begin{pmatrix} \sqrt{2/3} & 1/\sqrt{3} & 0 \\ -1/\sqrt{6} & 1/\sqrt{3} & 1/\sqrt{2} \\ 1/\sqrt{6} & -1/\sqrt{3} & 1/\sqrt{2} \end{pmatrix}$
 - ▶ Violation of μ - τ symmetry ($|U_{\mu k}| = |U_{\tau k}|$)
- ▶ They have phenomenological usefulness (e.g. to determine the initial flavor composition of high-energy astrophysical neutrinos).
- ▶ CP:
 - ▶ CP conservation would need an explanation (a new symmetry?).
 - ▶ CP violation may be linked to the CP violation in the sector of heavy neutrinos which generate the matter-antimatter asymmetry in the Universe through leptogenesis (CP-violating decay of heavy neutrinos).

Leptogenesis

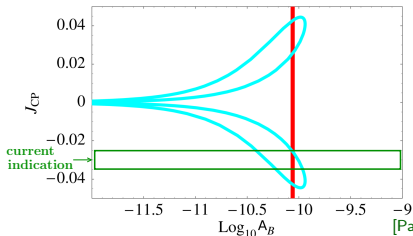
$$\mathcal{L}_I \sim \bar{L}_L \Phi^\dagger Y N_R$$

$$A_L \sim \frac{\sum_{k,\alpha} [\Gamma(N_k \rightarrow \Phi l_\alpha) - \Gamma(N_k \rightarrow \bar{\Phi} \bar{l}_\alpha)]}{\sum_{k,\alpha} [\Gamma(N_k \rightarrow \Phi l_\alpha) + \Gamma(N_k \rightarrow \bar{\Phi} \bar{l}_\alpha)]}$$



$$\text{Seesaw} \implies Y \sim \frac{1}{v} \underbrace{M_R^{1/2} R}_{\text{inaccessible}} \underbrace{m_\nu^{1/2} U_{3 \times 3}}_{\text{measurable}} \quad (RR^T = \mathbb{1})$$

CP-violating $U_{3 \times 3} \implies$ plausible CP-violating Y



$$M_{R1} = 5 \times 10^{11} \text{ GeV}$$

$$M_{R1} \ll M_{R2} \ll M_{R3}$$

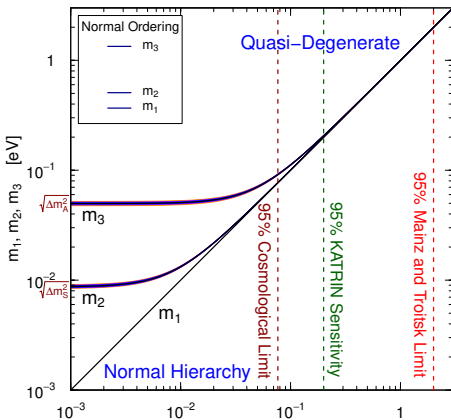
$$R_{12} = 0.86$$

$$R_{13} = 0.5$$

[Pascoli, Petcov, Riotto, PRD 75 (2007) 083511, arXiv:hep-ph/0609125]

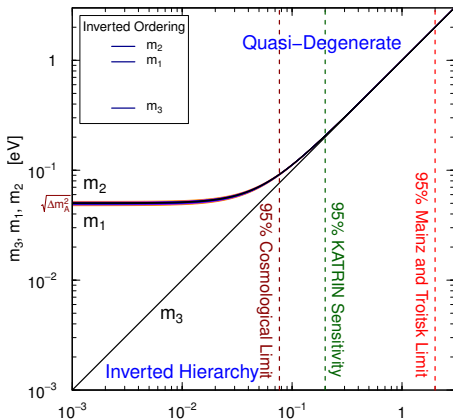
Absolute Scale of Neutrino Masses

Mass Hierarchy or Degeneracy?



$$m_2^2 = m_1^2 + \Delta m_{21}^2 = m_1^2 + \Delta m_S^2$$

$$m_3^2 = m_1^2 + \Delta m_{31}^2 = m_1^2 + \Delta m_A^2$$



$$m_1^2 = m_3^2 - \Delta m_{31}^2 = m_3^2 + \Delta m_A^2$$

$$m_2^2 = m_3^2 + \Delta m_{21}^2 \simeq m_3^2 + \Delta m_A^2$$

Quasi-Degenerate for $m_1 \simeq m_2 \simeq m_3 \simeq m_\nu \gtrsim \sqrt{\Delta m_A^2} \simeq 5 \times 10^{-2}$ eV

95% Cosmological Limit: Planck TT + lowP + BAO [arXiv:1502.01589]

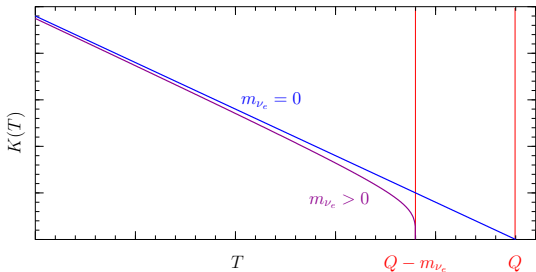
Tritium Beta-Decay



$$\frac{d\Gamma}{dT} = \frac{(\cos\vartheta_C G_F)^2}{2\pi^3} |\mathcal{M}|^2 F(E) p E K^2(T)$$

Kurie function:
$$K(T) = \left[(Q - T) \sqrt{(Q - T)^2 - m_{\nu_e}^2} \right]^{1/2}$$

$$Q = M_{{}^3\text{H}} - M_{{}^3\text{He}} - m_e = 18.58 \text{ keV}$$



$$m_{\nu_e} < 2.2 \text{ eV} \quad (95\% \text{ C.L.})$$

Mainz & Troitsk

[Weinheimer, hep-ex/0210050]

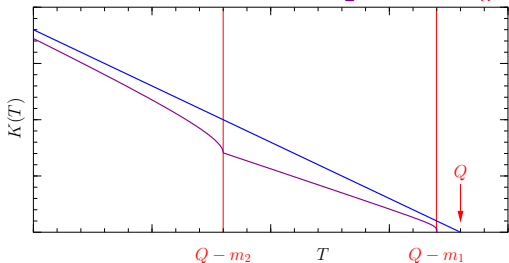
future: KATRIN

[www.katrin.kit.edu]

started data taking 2018

sensitivity: $m_{\nu_e} \simeq 0.2 \text{ eV}$

$$\text{Neutrino Mixing} \implies K(T) = \left[(Q - T) \sum_k |U_{ek}|^2 \sqrt{(Q - T)^2 - m_k^2} \right]^{1/2}$$



analysis of data is different from the no-mixing case:

$2N - 1$ parameters

$$\left(\sum_k |U_{ek}|^2 = 1 \right)$$

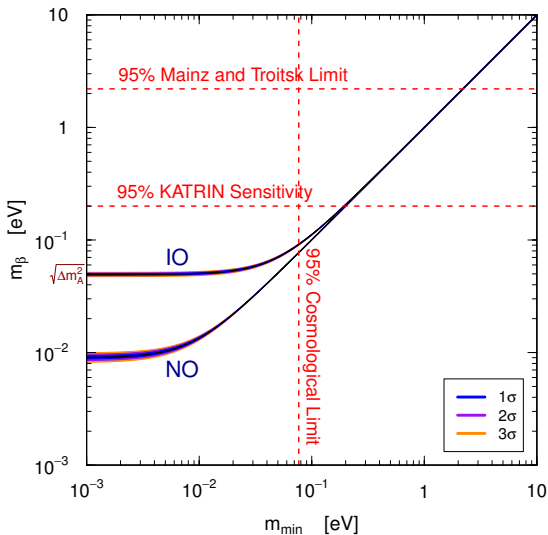
if experiment is not sensitive to masses ($m_k \ll Q - T$)

effective mass:
$$m_\beta^2 = \sum_k |U_{ek}|^2 m_k^2$$

$$\begin{aligned} K^2 &= (Q - T)^2 \sum_k |U_{ek}|^2 \sqrt{1 - \frac{m_k^2}{(Q - T)^2}} \simeq (Q - T)^2 \sum_k |U_{ek}|^2 \left[1 - \frac{1}{2} \frac{m_k^2}{(Q - T)^2} \right] \\ &= (Q - T)^2 \left[1 - \frac{1}{2} \frac{m_\beta^2}{(Q - T)^2} \right] \simeq (Q - T) \sqrt{(Q - T)^2 - m_\beta^2} \end{aligned}$$

Predictions of 3ν -Mixing Paradigm

$$m_\beta^2 = |U_{e1}|^2 m_1^2 + |U_{e2}|^2 m_2^2 + |U_{e3}|^2 m_3^2$$



▶ Quasi-Degenerate:

$$m_\beta^2 \simeq m_\nu^2 \sum_k |U_{ek}|^2 = m_\nu^2$$

▶ Inverted Hierarchy:

$$m_\beta^2 \simeq (1 - s_{13}^2) \Delta m_A^2 \simeq \Delta m_A^2$$

▶ Normal Hierarchy:

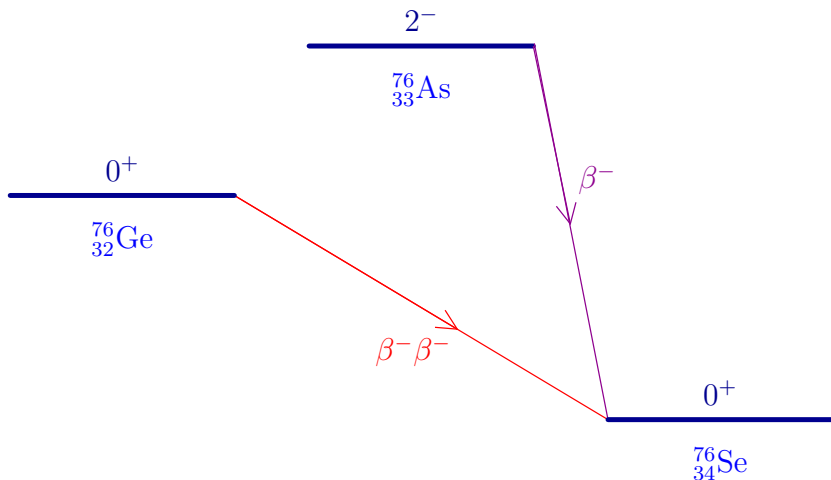
$$m_\beta^2 \simeq s_{12}^2 c_{13}^2 \Delta m_S^2 + s_{13}^2 \Delta m_A^2 \\ \simeq 2 \times 10^{-5} + 6 \times 10^{-5} \text{ eV}^2$$

▶ If $m_\beta \lesssim 4 \times 10^{-2} \text{ eV}$



Normal Spectrum

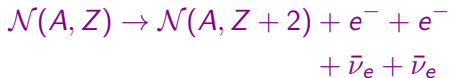
Neutrinoless Double-Beta Decay



Effective Majorana Neutrino Mass:

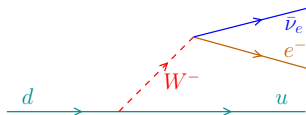
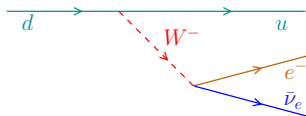
$$m_{\beta\beta} = \sum_k U_{ek}^2 m_k$$

Two-Neutrino Double- β Decay: $\Delta L = 0$



$$(T_{1/2}^{2\nu})^{-1} = G_{2\nu} |\mathcal{M}_{2\nu}|^2$$

second order weak interaction
process
in the Standard Model



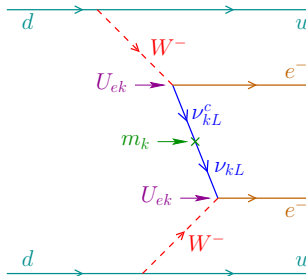
Neutrinoless Double- β Decay: $\Delta L = 2$

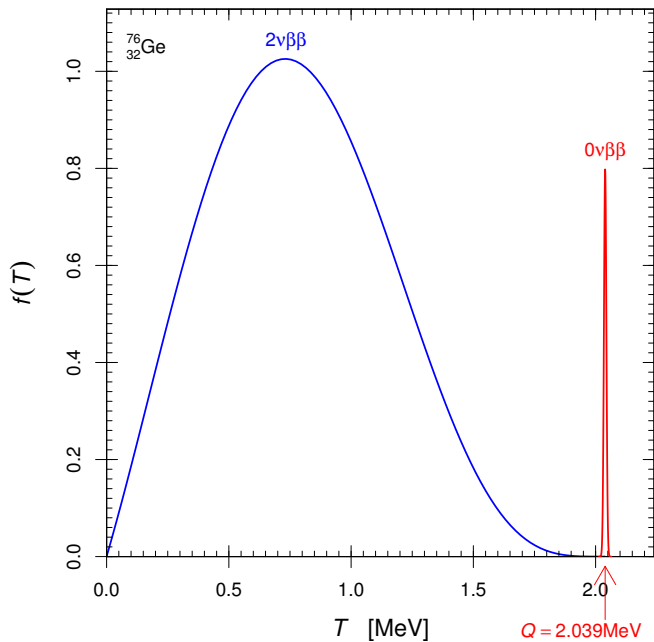


$$(T_{1/2}^{0\nu})^{-1} = G_{0\nu} |\mathcal{M}_{0\nu}|^2 |m_{\beta\beta}|^2$$

effective
Majorana
mass

$$|m_{\beta\beta}| = \left| \sum_k U_{ek}^2 m_k \right|$$



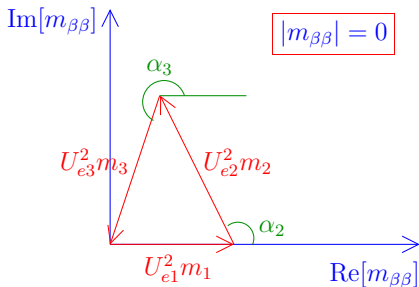
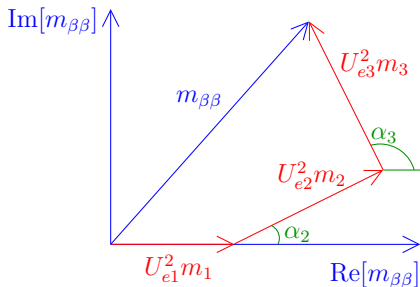


Effective Majorana Neutrino Mass

$$m_{\beta\beta} = \sum_k U_{ek}^2 m_k \quad \text{complex } U_{ek} \Rightarrow \text{possible cancellations}$$

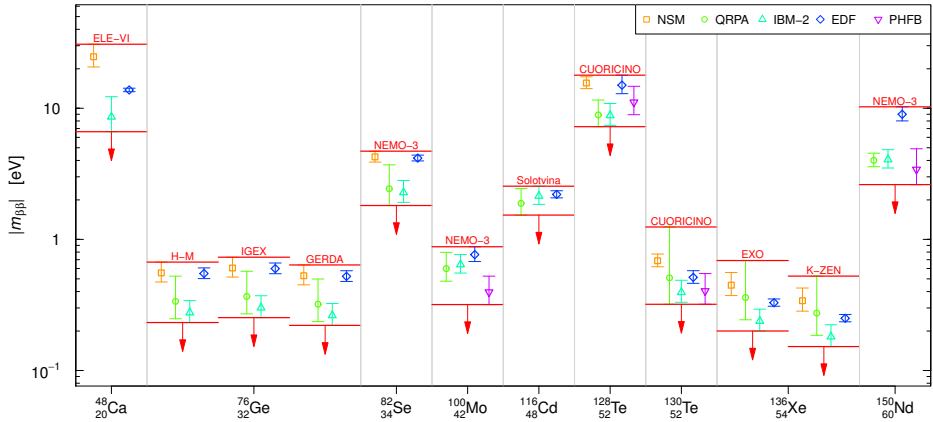
$$m_{\beta\beta} = |U_{e1}|^2 m_1 + |U_{e2}|^2 e^{i\alpha_2} m_2 + |U_{e3}|^2 e^{i\alpha_3} m_3$$

$$\alpha_2 = 2\lambda_2 \quad \alpha_3 = 2(\lambda_3 - \delta_{13})$$



90% C.L. Experimental Bounds

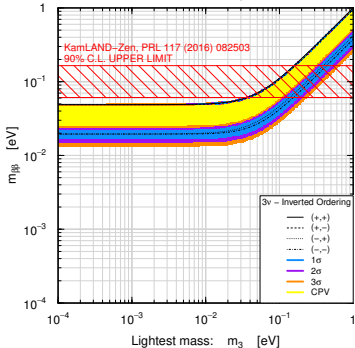
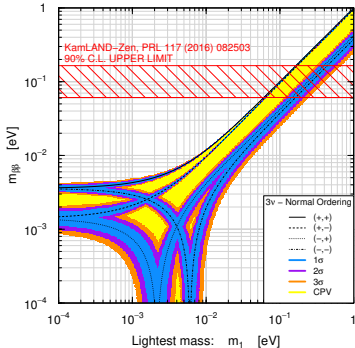
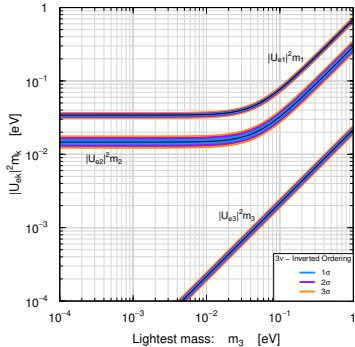
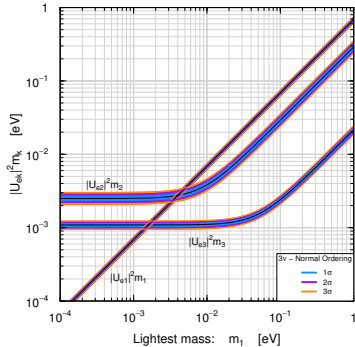
$\beta\beta^-$ decay	experiment	$T_{1/2}^{0\nu}$ [y]	$m_{\beta\beta}$ [eV]
${}^{48}_{20}\text{Ca} \rightarrow {}^{48}_{22}\text{Ti}$	ELEGANT-VI	$> 1.4 \times 10^{22}$	$< 6.6 - 31$
	Heidelberg-Moscow	$> 1.9 \times 10^{25}$	$< 0.23 - 0.67$
${}^{76}_{32}\text{Ge} \rightarrow {}^{76}_{34}\text{Se}$	IGEX	$> 1.6 \times 10^{25}$	$< 0.25 - 0.73$
	Majorana	$> 4.8 \times 10^{25}$	$< 0.20 - 0.43$
	GERDA	$> 8.0 \times 10^{25}$	$< 0.12 - 0.26$
${}^{82}_{34}\text{Se} \rightarrow {}^{82}_{36}\text{Kr}$	NEMO-3	$> 1.0 \times 10^{23}$	$< 1.8 - 4.7$
${}^{100}_{42}\text{Mo} \rightarrow {}^{100}_{44}\text{Ru}$	NEMO-3	$> 2.1 \times 10^{25}$	$< 0.32 - 0.88$
${}^{116}_{48}\text{Cd} \rightarrow {}^{116}_{50}\text{Sn}$	Solotvina	$> 1.7 \times 10^{23}$	$< 1.5 - 2.5$
${}^{128}_{52}\text{Te} \rightarrow {}^{128}_{54}\text{Xe}$	CUORICINO	$> 1.1 \times 10^{23}$	$< 7.2 - 18$
${}^{130}_{52}\text{Te} \rightarrow {}^{130}_{54}\text{Xe}$	CUORE	$> 1.5 \times 10^{25}$	$< 0.11 - 0.52$
${}^{136}_{54}\text{Xe} \rightarrow {}^{136}_{56}\text{Ba}$	EXO	$> 1.1 \times 10^{25}$	$< 0.17 - 0.49$
	KamLAND-Zen	$> 1.1 \times 10^{26}$	$< 0.06 - 0.16$
${}^{150}_{60}\text{Nd} \rightarrow {}^{150}_{62}\text{Sm}$	NEMO-3	$> 2.1 \times 10^{25}$	$< 2.6 - 10$



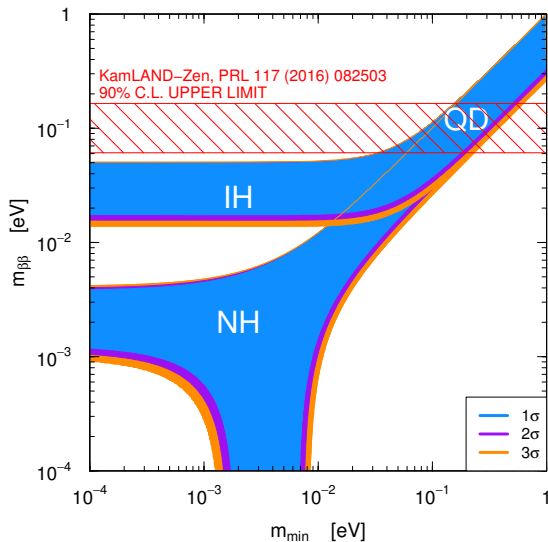
[Bilenky, CG, IJMPA 30 (2015) 0001]

Predictions of 3ν -Mixing Paradigm

$$m_{\beta\beta} = |U_{e1}|^2 m_1 + |U_{e2}|^2 e^{i\alpha_2} m_2 + |U_{e3}|^2 e^{i\alpha_3} m_3$$



$$m_{\beta\beta} = |U_{e1}|^2 m_1 + |U_{e2}|^2 e^{i\alpha_2} m_2 + |U_{e3}|^2 e^{i\alpha_3} m_3$$



▶ Quasi-Degenerate:

$$|m_{\beta\beta}| \simeq m_\nu \sqrt{1 - s_{2\vartheta_{12}}^2 s_{\alpha_2}^2}$$

▶ Inverted Hierarchy:

$$|m_{\beta\beta}| \simeq \sqrt{\Delta m_A^2 (1 - s_{2\vartheta_{12}}^2 s_{\alpha_2}^2)}$$

▶ Normal Hierarchy:

$$|m_{\beta\beta}| \simeq |s_{12}^2 \sqrt{\Delta m_S^2} + e^{i\alpha} s_{13}^2 \sqrt{\Delta m_A^2}|$$

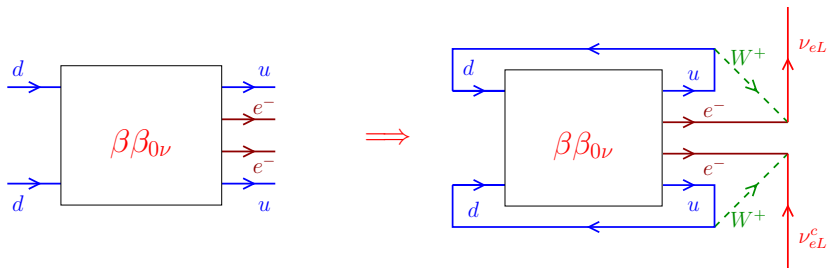
$$\simeq |2.7 + 1.2e^{i\alpha}| \times 10^{-3} \text{ eV}$$

▶ If $|m_{\beta\beta}| \lesssim 10^{-2} \text{ eV}$

↓
Normal Spectrum

$\beta\beta_{0\nu}$ Decay \Leftrightarrow Majorana Neutrino Mass

- ▶ $|m_{\beta\beta}|$ can vanish because of unfortunate cancellations among the ν_1, ν_2, ν_3 contributions or because neutrinos are Dirac particles.
- ▶ However, $\beta\beta_{0\nu}$ decay can be generated by another mechanism beyond the Standard Model.
- ▶ In this case, a Majorana mass for ν_e is generated by radiative corrections:



[Schechter, Valle, PRD 25 (1982) 2951; Takasugi, PLB 149 (1984) 372]

- ▶ Majorana Mass Term:

$$\mathcal{L}_{eL}^M = -\frac{1}{2} m_{ee} (\overline{\nu_{eL}^c} \nu_{eL} + \overline{\nu_{eL}} \nu_{eL}^c)$$

- ▶ Very small four-loop diagram contribution: $m_{ee} \sim 10^{-24} \text{ eV}$

[Duerr, Lindner, Merle, JHEP 06 (2011) 091 (arXiv:1105.0901)]

- ▶ In any case finding $\beta\beta_{0\nu}$ decay is important for
 - ▶ Finding total Lepton number violation ($\Delta L = \pm 2$).
 - ▶ Establishing the Majorana (or pseudo-Dirac) nature of neutrinos.
- ▶ On the other hand, even if $\beta\beta_{0\nu}$ decay is not found, it is not possible to prove experimentally that neutrinos are Dirac particles, because
 - ▶ A Dirac neutrino is equivalent to 2 Majorana neutrinos with the same mass.
 - ▶ It is impossible to prove experimentally that the mass splitting is exactly zero.

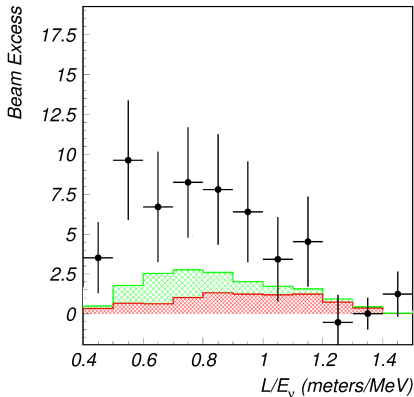
Short-Baseline Neutrino Oscillation Anomalies

LSND

[PRL 75 (1995) 2650; PRC 54 (1996) 2685; PRL 77 (1996) 3082; PRD 64 (2001) 112007]

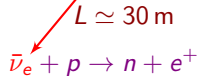
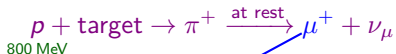
$$\bar{\nu}_\mu \rightarrow \bar{\nu}_e$$

$$20 \text{ MeV} \leq E \leq 52.8 \text{ MeV}$$



$$\Delta m_{\text{SBL}}^2 \gtrsim 0.1 \text{ eV}^2 \gg \Delta m_{\text{ATM}}^2$$

- ▶ Well-known and pure source of $\bar{\nu}_\mu$



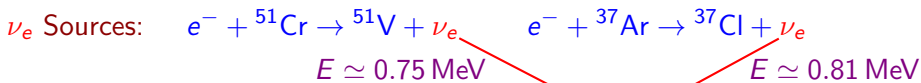
Well-known detection process of $\bar{\nu}_e$

- ▶ $\approx 3.8\sigma$ excess
- ▶ But signal not seen by **KARMEN** at $L \simeq 18 \text{ m}$ with the same method

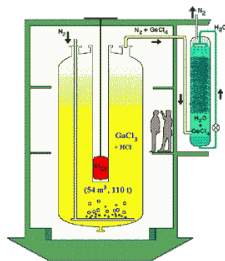
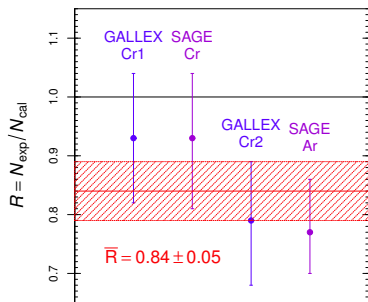
[PRD 65 (2002) 112001]

Gallium Anomaly

Gallium Radioactive Source Experiments: GALLEX and SAGE



Test of Solar ν_e Detection:



$\approx 2.9\sigma$ deficit

$\langle L \rangle_{\text{GALLEX}} = 1.9 \text{ m}$ $\langle L \rangle_{\text{SAGE}} = 0.6 \text{ m}$

$\Delta m_{\text{SBL}}^2 \gtrsim 1 \text{ eV}^2 \gg \Delta m_{\text{ATM}}^2$

[SAGE, PRC 73 (2006) 045805; PRC 80 (2009) 015807;
Laveder et al, Nucl.Phys.Proc.Suppl. 168 (2007) 344,
MPLA 22 (2007) 2499, PRD 78 (2008) 073009,
PRC 83 (2011) 065504]

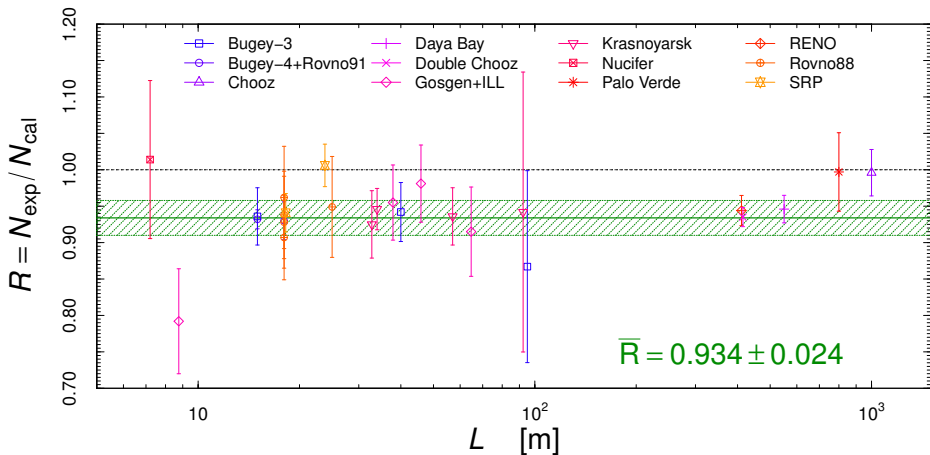
▶ ${}^3\text{He} + {}^{71}\text{Ga} \rightarrow {}^{71}\text{Ge} + {}^3\text{H}$ cross section measurement [Frekers et al., PLB 706 (2011) 134]

Reactor Electron Antineutrino Anomaly

[Mention et al, PRD 83 (2011) 073006]

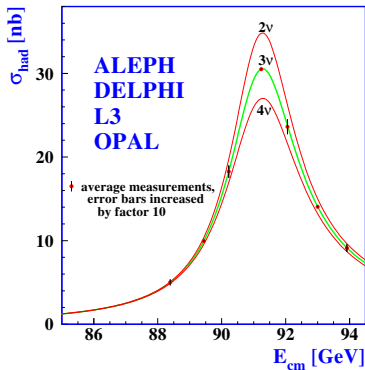
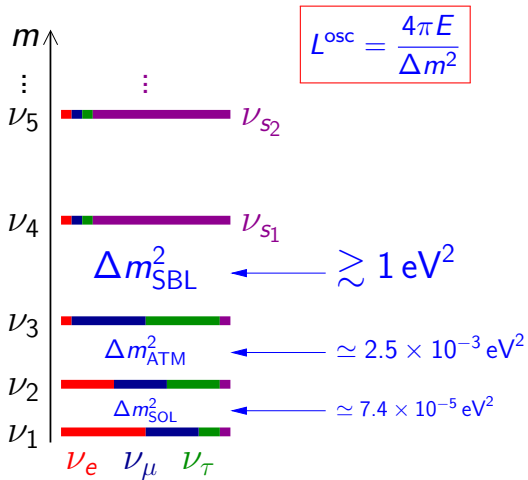
New reactor $\bar{\nu}_e$ fluxes: Huber-Mueller (HM)

[Mueller et al, PRC 83 (2011) 054615; Huber, PRC 84 (2011) 024617]



$\approx 2.8\sigma$ deficit

Beyond Three-Neutrino Mixing: Sterile Neutrinos



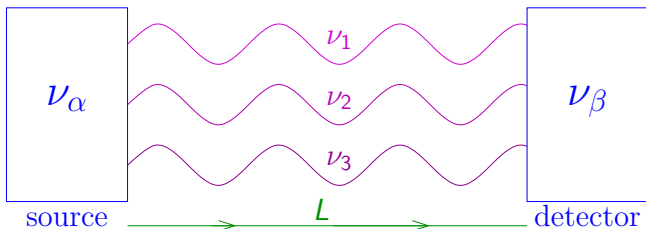
$$N_{\nu_{\text{active}}}^{\text{LEP}} = 2.9840 \pm 0.0082$$

Terminology: a eV-scale sterile neutrino
 means: a eV-scale massive neutrino which is mainly sterile

Short-Baseline Neutrino Oscillations

Three-Neutrino Mixing

$$|\nu_{\text{source}}\rangle = |\nu_{\alpha}\rangle = U_{\alpha 1} |\nu_1\rangle + U_{\alpha 2} |\nu_2\rangle + U_{\alpha 3} |\nu_3\rangle$$



$$|\nu_{\text{detector}}\rangle \simeq U_{\alpha 1} e^{-iEL} |\nu_1\rangle + U_{\alpha 2} e^{-iEL} |\nu_2\rangle + U_{\alpha 3} e^{-iEL} |\nu_3\rangle = e^{-iEL} |\nu_{\alpha}\rangle$$

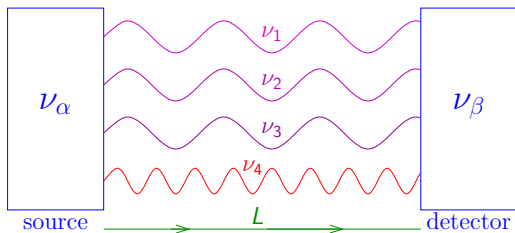
$$P_{\nu_{\alpha} \rightarrow \nu_{\beta}}(L) = |\langle \nu_{\beta} | \nu_{\text{detector}} \rangle|^2 \simeq |e^{-iEL} \langle \nu_{\beta} | \nu_{\alpha} \rangle|^2 = \delta_{\alpha\beta}$$

No Observable Short-Baseline Neutrino Oscillations!

Short-Baseline Neutrino Oscillations

3+1 Neutrino Mixing

$$|\nu_{\text{source}}\rangle = |\nu_{\alpha}\rangle = U_{\alpha 1} |\nu_1\rangle + U_{\alpha 2} |\nu_2\rangle + U_{\alpha 3} |\nu_3\rangle + U_{\alpha 4} |\nu_4\rangle$$



$$|\nu_{\text{detector}}\rangle \simeq e^{-iEL} (U_{\alpha 1} |\nu_1\rangle + U_{\alpha 2} |\nu_2\rangle + U_{\alpha 3} |\nu_3\rangle) + U_{\alpha 4} e^{-iE_4 L} |\nu_4\rangle \neq |\nu_{\alpha}\rangle$$

$$P_{\nu_{\alpha} \rightarrow \nu_{\beta}}(L) = |\langle \nu_{\beta} | \nu_{\text{detector}} \rangle|^2 \neq \delta_{\alpha\beta}$$

Observable Short-Baseline Neutrino Oscillations!

The oscillation probabilities depend on U and

$$\Delta m_{\text{SBL}}^2 = \Delta m_{41}^2 \simeq \Delta m_{42}^2 \simeq \Delta m_{43}^2$$

Effective 3+1 SBL Oscillation Probabilities

Appearance ($\alpha \neq \beta$)

$$P_{\nu_{\alpha} \rightarrow \nu_{\beta}}^{\text{SBL}(-)(-)} \simeq \sin^2 2\vartheta_{\alpha\beta} \sin^2 \left(\frac{\Delta m_{41}^2 L}{4E} \right)$$

$$\sin^2 2\vartheta_{\alpha\beta} = 4|U_{\alpha 4}|^2 |U_{\beta 4}|^2$$

Disappearance

$$P_{\nu_{\alpha} \rightarrow \nu_{\alpha}}^{\text{SBL}(-)(-)} \simeq 1 - \sin^2 2\vartheta_{\alpha\alpha} \sin^2 \left(\frac{\Delta m_{41}^2 L}{4E} \right)$$

$$\sin^2 2\vartheta_{\alpha\alpha} = 4|U_{\alpha 4}|^2 (1 - |U_{\alpha 4}|^2)$$

$$U = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} & U_{e4} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} & U_{\mu 4} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} & U_{\tau 4} \\ U_{s1} & U_{s2} & U_{s3} & U_{s4} \end{pmatrix}$$

SBL

- ▶ 6 mixing angles
- ▶ 3 Dirac CP phases
- ▶ 3 Majorana CP phases

- ▶ $\Delta m_{\text{SBL}}^2 = \Delta m_{41}^2 \simeq \Delta m_{42}^2 \simeq \Delta m_{43}^2$
- ▶ CP violation is not observable in SBL experiments!

- ▶ Observable in LBL accelerator exp. sensitive to Δm_{ATM}^2 [de Gouvea et al, PRD 91 (2015) 053005, PRD 92 (2015) 073012, arXiv:1605.09376; Palazzo et al, PRD 91 (2015) 073017, PLB 757 (2016) 142; Kayser et al, JHEP 1511 (2015) 039, JHEP 1611 (2016) 122] and solar exp. sensitive to Δm_{SOL}^2 [Long, Li, CG, PRD 87, 113004 (2013) 113004]

3+1: Appearance vs Disappearance

▶ SBL Oscillation parameters: Δm_{41}^2 $|U_{e4}|^2$ $|U_{\mu4}|^2$ ($|U_{\tau4}|^2$)

▶ Amplitude of ν_e disappearance:

$$\sin^2 2\vartheta_{ee} = 4|U_{e4}|^2 (1 - |U_{e4}|^2) \simeq 4|U_{e4}|^2$$

▶ Amplitude of ν_μ disappearance:

$$\sin^2 2\vartheta_{\mu\mu} = 4|U_{\mu4}|^2 (1 - |U_{\mu4}|^2) \simeq 4|U_{\mu4}|^2$$

▶ Amplitude of $\nu_\mu \rightarrow \nu_e$ transitions:

$$\sin^2 2\vartheta_{e\mu} = 4|U_{e4}|^2 |U_{\mu4}|^2 \simeq \frac{1}{4} \sin^2 2\vartheta_{ee} \sin^2 2\vartheta_{\mu\mu}$$

quadratically suppressed for small $|U_{e4}|^2$ and $|U_{\mu4}|^2$

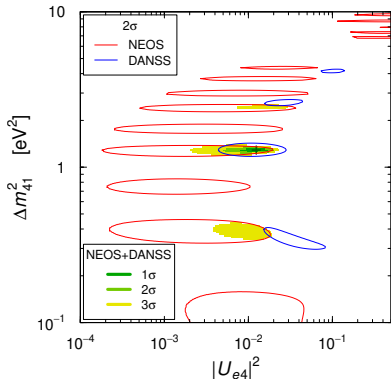
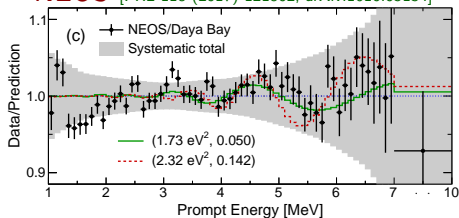


Appearance-Disappearance Tension

[Okada, Yasuda, IJMPA 12 (1997) 3669; Bilenky, CG, Grimus, EPJC 1 (1998) 247]

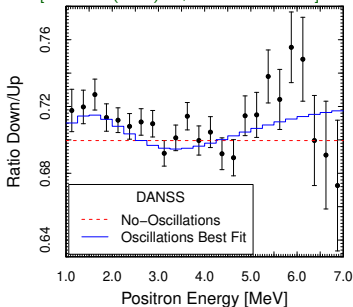
Reactor Spectral Ratios

NEOS [PRL 118 (2017) 121802, arXiv:1610.05134]



DANSS

[PLB 787 (2018) 56, arXiv:1804.04046]



MODEL INDEPENDENT!

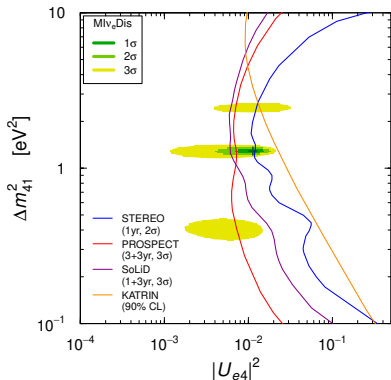
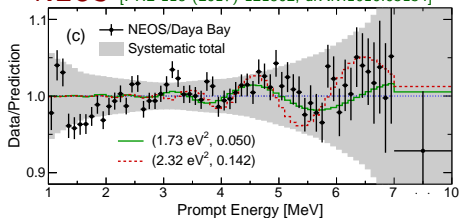
$\sim 3.5\sigma$

[Gariazzo, CG, Laveder, Li, PLB 782 (2018) 13, arXiv:1801.06467]

[See also: Dentler et al, JHEP 1808 (2018) 010, arXiv:1803.10661]

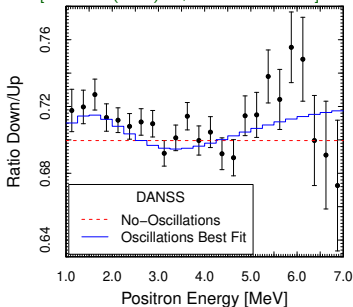
Reactor Spectral Ratios

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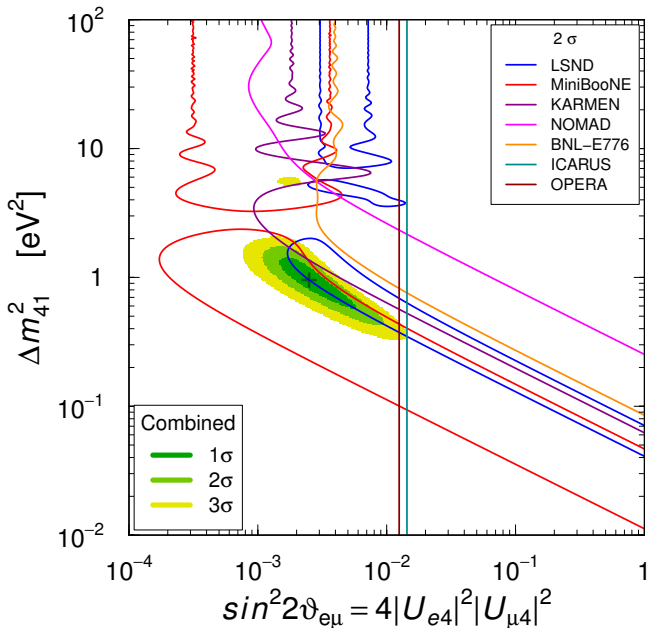
MODEL INDEPENDENT!

~ 3.5σ

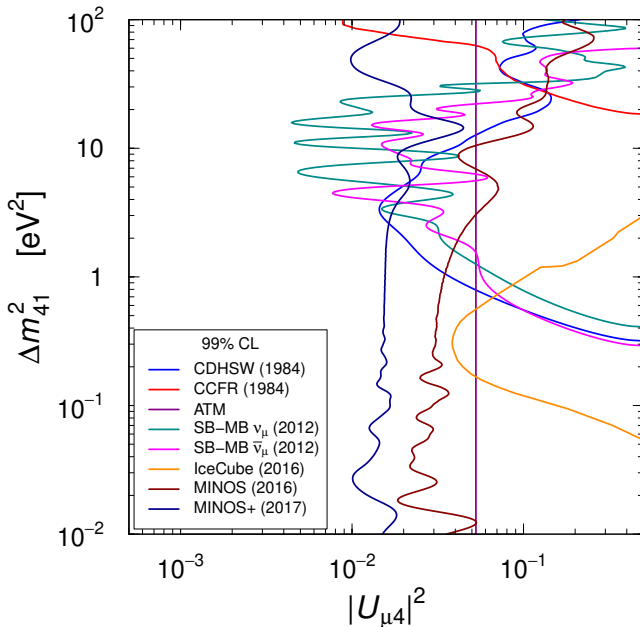
[Gariazzo, CG, Laveder, Li, PLB 782 (2018) 13, arXiv:1801.06467]

[See also: Dentler et al, JHEP 1808 (2018) 010, arXiv:1803.10661]

$\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ and $\nu_\mu \rightarrow \nu_e$ Appearance



ν_μ and $\bar{\nu}_\mu$ Disappearance

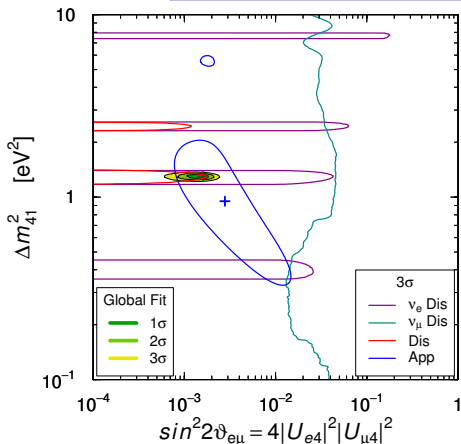


3+1 Appearance-Disappearance Tension

$$\nu_e \text{ DIS} \\ \sin^2 2\vartheta_{ee} \simeq 4|U_{e4}|^2$$

$$\nu_\mu \text{ DIS} \\ \sin^2 2\vartheta_{\mu\mu} \simeq 4|U_{\mu4}|^2$$

$$\nu_\mu \rightarrow \nu_e \text{ APP} \\ \sin^2 2\vartheta_{e\mu} = 4|U_{e4}|^2|U_{\mu4}|^2 \simeq \frac{1}{4} \sin^2 2\vartheta_{ee} \sin^2 2\vartheta_{\mu\mu}$$



▶ $\nu_\mu \rightarrow \nu_e$ is quadratically suppressed!

▶ Global Fit without MINOS+

$$\chi^2_{\text{PG}}/\text{NDF}_{\text{PG}} = 7.8/2 \Rightarrow \text{GoF}_{\text{PG}} = 2\%$$

▶ Similar tension in

$$3 + 2, \quad 3 + 3, \quad \dots, \quad 3 + N_s$$

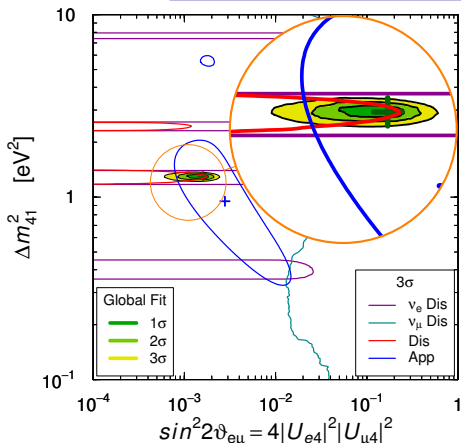
[CG, Zavanin, MPLA 31 (2015) 1650003]

3+1 Appearance-Disappearance Tension

$$\nu_e \text{ DIS} \\ \sin^2 2\vartheta_{ee} \simeq 4|U_{e4}|^2$$

$$\nu_\mu \text{ DIS} \\ \sin^2 2\vartheta_{\mu\mu} \simeq 4|U_{\mu4}|^2$$

$$\nu_\mu \rightarrow \nu_e \text{ APP} \\ \sin^2 2\vartheta_{e\mu} = 4|U_{e4}|^2|U_{\mu4}|^2 \simeq \frac{1}{4} \sin^2 2\vartheta_{ee} \sin^2 2\vartheta_{\mu\mu}$$



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$$\chi_{\text{PG}}^2 / \text{NDF}_{\text{PG}} = 7.8/2 \Rightarrow \text{GoF}_{\text{PG}} = 2\%$$

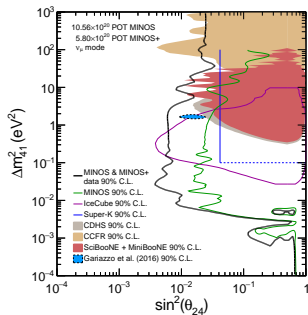
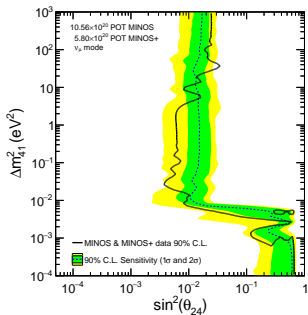
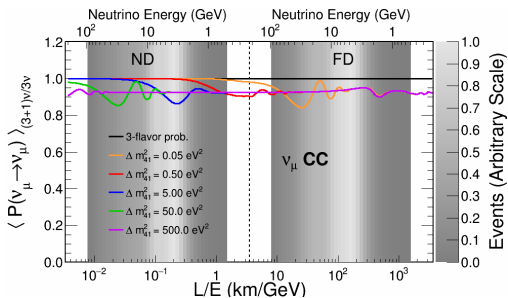
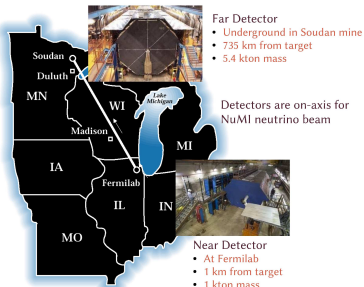
▶ Similar tension in

$$3 + 2, \quad 3 + 3, \quad \dots, \quad 3 + N_s$$

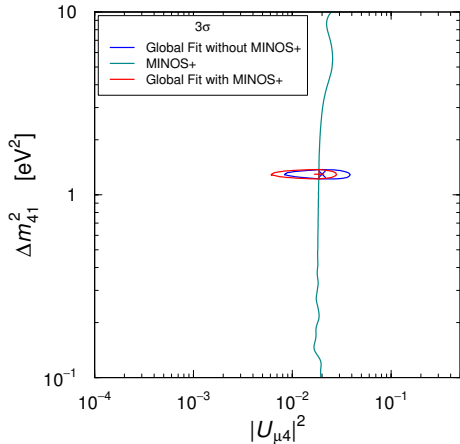
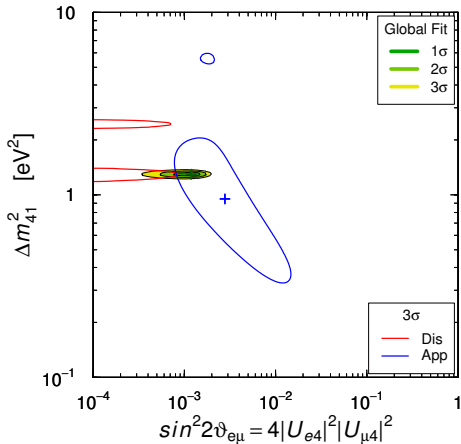
[CG, Zavanin, MPLA 31 (2015) 1650003]

New Bound from MINOS+

[arXiv:1710.06488]



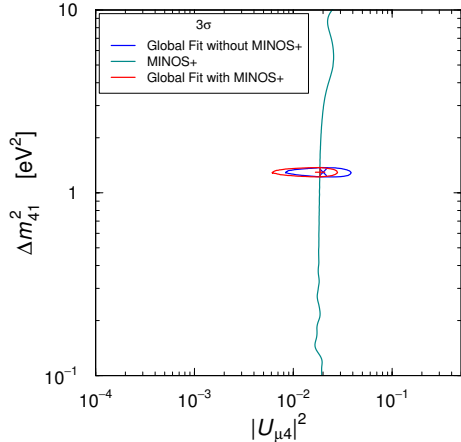
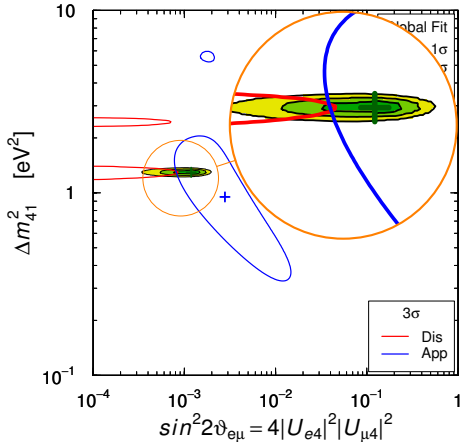
Effects of MINOS+



- ▶ $\chi^2_{\text{PG}}/\text{NDF}_{\text{PG}} = 18.3/2 \Rightarrow \text{GoF}_{\text{PG}} = 0.01\% \leftarrow \text{Intolerable tension!}$
- ▶ The MINOS+ bound (if correct) disfavors the LSND $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ signal.

[See also Dentler, Hernandez-Cabezudo, Kopp, Machado, Maltoni, Martinez-Soler, Schwetz, arXiv:1803.10661]

Effects of MINOS+

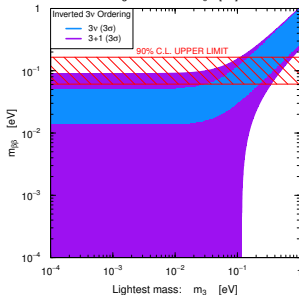
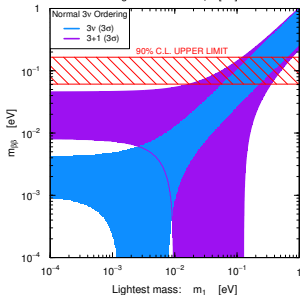
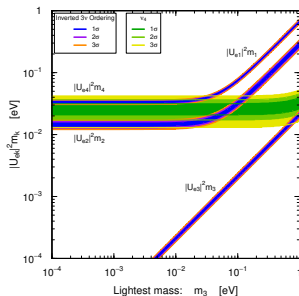
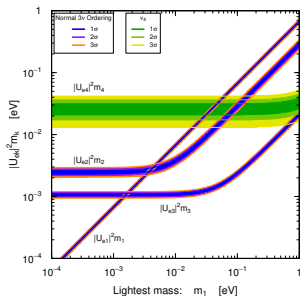


- ▶ $\chi^2_{\text{PG}}/\text{NDF}_{\text{PG}} = 18.3/2 \Rightarrow \text{GoF}_{\text{PG}} = 0.01\% \leftarrow \text{Intolerable tension!}$
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[See also Dentler, Hernandez-Cabezudo, Kopp, Machado, Maltoni, Martinez-Soler, Schwetz, arXiv:1803.10661]

Neutrinoless Double-Beta Decay

$$m_{\beta\beta} = \left| |U_{e1}|^2 m_1 + |U_{e2}|^2 e^{i\alpha_{21}} m_2 + |U_{e3}|^2 e^{i\alpha_{31}} m_3 + |U_{e4}|^2 e^{i\alpha_{41}} m_4 \right|$$



Conclusions

- ▶ Mainstream 3ν -mixing research: precise measurements of masses, mixing angles and CP violating phases with neutrino oscillations, β decay, $\beta\beta_{0\nu}$ decay.
- ▶ Neutrinos provide a Window to the New Physics beyond the Standard Model through:
 - ▶ Small (Majorana) Masses.
 - ▶ Sterile Neutrinos.
 - ▶ Non-Standard Interactions. [see Ohlsson, RPP 76 (2013) 044201, arXiv:1209.2710]
 - ▶ Electromagnetic Interactions. [see CG, Studenikin, RMP 87 (2015) 531, arXiv:1403.6344]
 - ▶ ...
- ▶ Exciting model-independent indication of light sterile neutrinos at the eV scale from the NEOS and DANSS experiments, in agreement with the reactor and Gallium anomalies.
It will be tested soon by several experiments.