A REVIEW ON THE PRESENT STATUS OF NEUTRINO MIXING AND OSCILLATIONS

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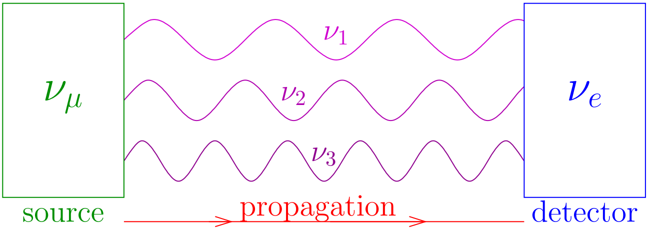
Neutrino Oscillations

- Neutrino Oscillations are Flavor Transitions which oscillate with distance.
- Flavor Neutrinos: ν_e, ν_μ, ν_τ produced in Weak Interactions
- Massive Neutrinos: ν_1, ν_2, ν_3 propagate from Source to Detector
- A Flavor Neutrino is a superposition of Massive Neutrinos

$$
\begin{aligned}
|\nu_e\rangle &= U_{e1}\,|\nu_1\rangle + U_{e2}\,|\nu_2\rangle + U_{e3}\,|\nu_3\rangle \\
|\nu_\mu\rangle &= U_{\mu 1}\,|\nu_1\rangle + U_{\mu 2}\,|\nu_2\rangle + U_{\mu 3}\,|\nu_3\rangle \\
|\nu_\tau\rangle &= U_{\tau 1}\,|\nu_1\rangle + U_{\tau 2}\,|\nu_2\rangle + U_{\tau 3}\,|\nu_3\rangle
\end{aligned}
$$

- U is the 3×3 Neutrino Mixing Matrix

$$|\nu(t=0)\rangle = |\nu_\mu\rangle = U_{\mu 1}\,|\nu_1\rangle + U_{\mu 2}\,|\nu_2\rangle + U_{\mu 3}\,|\nu_3\rangle$$



$$|\nu(t>0)\rangle = U_{\mu 1}\,e^{-iE_1 t}\,|\nu_1\rangle + U_{\mu 2}\,e^{-iE_2 t}\,|\nu_2\rangle + U_{\mu 3}\,e^{-iE_3 t}\,|\nu_3\rangle \neq |\nu_\mu\rangle$$

$$E_k^2 = p^2 + m_k^2$$

$$P_{\nu_\mu \to \nu_e}(t>0) = |\langle \nu_e | \nu(t>0)\rangle|^2 \propto \sin^2\left(\frac{\Delta m^2_{kj} L}{4E}\right)$$

Neutrino Oscillations are Flavor Transitions

$$\nu_e \to \nu_\mu \qquad \nu_e \to \nu_\tau \qquad \nu_\mu \to \nu_e \qquad \nu_\mu \to \nu_\tau$$
$$\bar{\nu}_e \to \bar{\nu}_\mu \qquad \bar{\nu}_e \to \bar{\nu}_\tau \qquad \bar{\nu}_\mu \to \bar{\nu}_e \qquad \bar{\nu}_\mu \to \bar{\nu}_\tau$$

transition probabilities depend on U and $\Delta m^2_{kj} \equiv m_k^2 - m_j^2$

Three-Neutrino Mixing Paradigm

Standard Parameterization of Mixing Matrix

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

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

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

OSCILLATION PARAMETERS

- 3 Mixing Angles: ϑ_{12}, ϑ_{23}, ϑ_{13}
- 1 CPV Dirac Phase: δ_{13}
- 2 independent $\Delta m^2_{kj} \equiv m^2_k - m^2_j$: Δm^2_{21}, Δm^2_{31}

2 CPV Majorana Phases: λ_{21}, λ_{31} $\Longleftrightarrow$ $|\Delta L| = 2$ processes

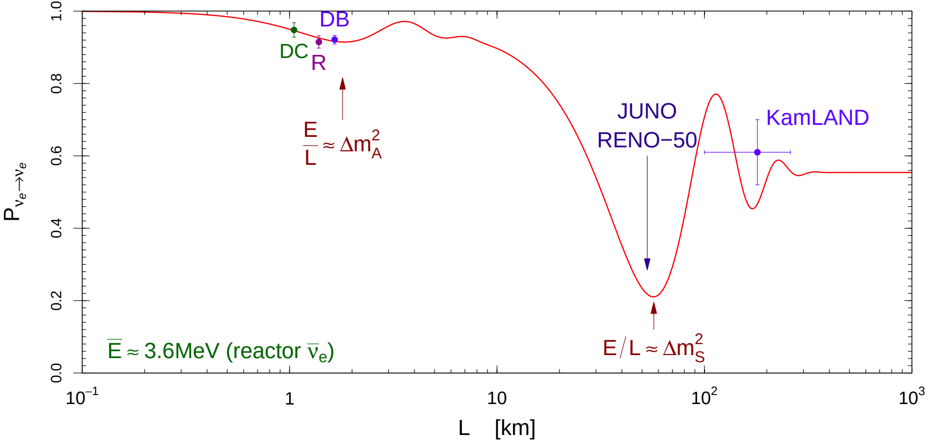
Experimental Evidences of Neutrino Oscillations

Solar $\nu_e \to \nu_\mu, \nu_\tau$	SNO, BOREXino Super-Kamiokande GALLEX/GNO, SAGE Homestake, Kamiokande	$\to$ $\Delta m^2_{\text{S}} = \Delta m^2_{21} \simeq 7.6 \times 10^{-5}\,\text{eV}^2$ $\sin^2\vartheta_{\text{S}} = \sin^2\vartheta_{12} \simeq 0.30$
VLBL Reactor $\bar{\nu}_e$ disappearance	(KamLAND)	
Atmospheric $\nu_\mu \to \nu_\tau$	Super-Kamiokande Kamiokande, IMB MACRO, Soudan-2	$\to$ $\Delta m^2_{\text{A}} = \|\Delta m^2_{31}\| \simeq 2.4 \times 10^{-3}\,\text{eV}^2$ $\sin^2\vartheta_{\text{A}} = \sin^2\vartheta_{23} \simeq 0.50$
LBL Accelerator ν_μ disappearance	K2K, MINOS T2K, NOνA	
LBL Accelerator $\nu_\mu \to \nu_\tau$	(Opera)	
LBL Accelerator $\nu_\mu \to \nu_e$	(T2K, MINOS, NOνA)	$\to$ $\Delta m^2_{\text{A}} = \|\Delta m^2_{31}\|$ $\sin^2\vartheta_{13} \simeq 0.023$
LBL Reactor $\bar{\nu}_e$ disappearance	Daya Bay, RENO Double Chooz	

Recent Experimental Results

- OPERA observed a fifth ν_τ candidate event:
  5σ evidence of long-baseline $\nu_\mu \to \nu_\tau$ transitions!
  arXiv:1507.01417

- NOνA observed first long-baseline neutrino events:
  ν_μ disappearance (33 ν_μ events vs 201 without oscillations)
  and
  ν_e appearance (6 ν_e events with 1 background).
  7 August 2015 Press Release


1.0
0.8
0.6
0.4
0.2
0.0
$P_{\nu_e \to \nu_e}$
DB
DC
R
$\frac{E}{L} \approx \Delta m^2_A$
JUNO
RENO−50
KamLAND
$\overline{E} \approx 3.6$MeV (reactor $\overline{\nu}_e$)
$E/L \approx \Delta m^2_S$
10^{-1}
1
10
10^2
10^3
L [km]

Recent Global Fits

- Capozzi, Fogli, Lisi, Marrone, Montanino, Palazzo
  Status of three-neutrino oscillation parameters, circa 2013
  Phys.Rev. D89 (2014) 093018, arXiv:1312.2878

- Forero, Tortola, Valle
  Neutrino oscillations refitted
  Phys.Rev. D90 (2014) 093006, arXiv:1405.7540

- Gonzalez-Garcia, Maltoni, Schwetz
  Updated fit to three neutrino mixing: status of leptonic CP violation
  JHEP 1411 (2014) 052, arXiv:1409.5439

- Bergstrom, Gonzalez-Garcia, Maltoni, Schwetz
  Bayesian global analysis of neutrino oscillation data
  arXiv:1507.04366

www.nu-fit.org

$$\Delta m^2_{\rm S} = \Delta m^2_{21} \simeq 7.5 \pm 0.3 \times 10^{-5}\,{\rm eV}^2 \qquad \text{uncertainty} \simeq 3\%$$

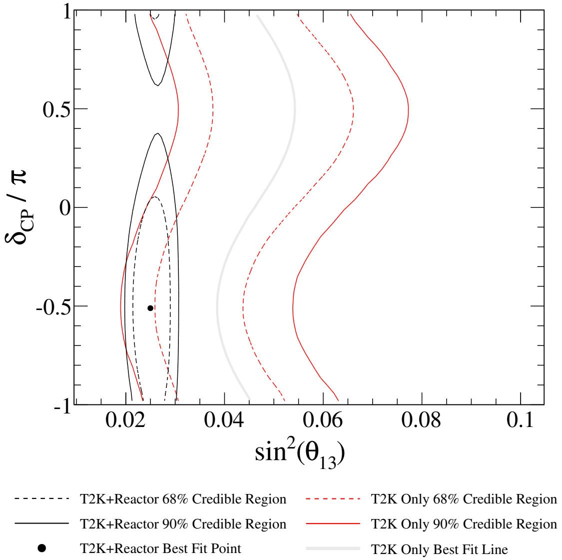
$$\Delta m^2_{\rm A} = |\Delta m^2_{31}| \simeq |\Delta m^2_{32}| \simeq 2.4 \pm 0.1 \times 10^{-3}\,{\rm eV}^2 \qquad \text{uncertainty} \simeq 4\%$$

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

$\vartheta_{23} = \vartheta_{\rm A}$	Daya Bay, RENO	$\vartheta_{12} = \vartheta_{\rm S}$	$\beta\beta_{0\nu}$
$\sin^2\vartheta_{23} \simeq 0.4 - 0.6$	Double Chooz	$\sin^2\vartheta_{12} \simeq 0.30 \pm 0.01$	
$P_{\rm osc} \propto \sin^2 2\vartheta_{23}$	T2K, MINOS		
maximal and flat	$\sin^2\vartheta_{13} \simeq 0.023 \pm 0.002$		
at $\vartheta_{23} = 45^\circ$	$\delta_{13} \approx 3\pi/2?$		

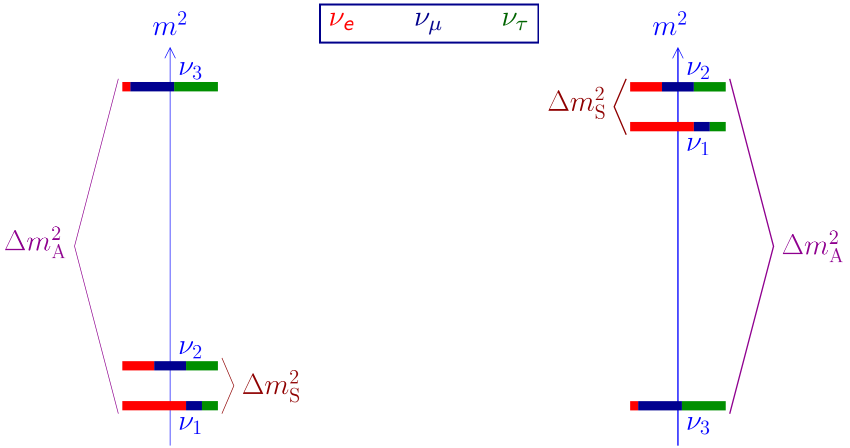
$$\frac{\delta \sin^2\vartheta_{23}}{\sin^2\vartheta_{23}} \approx 40\% \qquad \frac{\delta \sin^2\vartheta_{13}}{\sin^2\vartheta_{13}} \approx 10\% \qquad \frac{\delta \sin^2\vartheta_{12}}{\sin^2\vartheta_{12}} \approx 5\%$$

Maximal CP Violation?



T2K, Phys.Rev. D91 (2015) 072010, arXiv:1502.01550

Mass Ordering



Normal Ordering

$\Delta m^2_{31} > \Delta m^2_{32} > 0$

Inverted Ordering

$\Delta m^2_{32} < \Delta m^2_{31} < 0$

absolute scale is not determined by neutrino oscillation data

Determination of Mass Ordering

1. Matter Effects: Atmospheric (PINGU, ORCA), Long-Baseline, Supernova Experiments
   - $\nu_e \leftrightarrows \nu_\mu$ MSW resonance: $V = \dfrac{\Delta m^2_{13} \cos 2\vartheta_{13}}{2E} \Leftrightarrow \Delta m^2_{13} > 0$ NO
   - $\bar{\nu}_e \leftrightarrows \bar{\nu}_\mu$ MSW resonance: $V = -\dfrac{\Delta m^2_{13} \cos 2\vartheta_{13}}{2E} \Leftrightarrow \Delta m^2_{13} < 0$ IO
2. Phase Difference: Reactor $\bar{\nu}_e \to \bar{\nu}_e$ (JUNO, RENO-50)

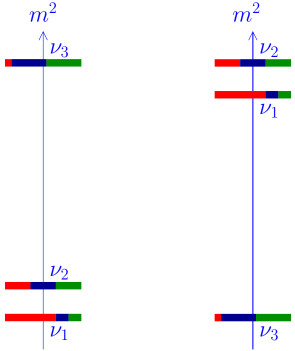
Normal Ordering

$|\Delta m^2_{31}|$

$=$

$|\Delta m^2_{32}| + |\Delta m^2_{21}|$

$|\Delta m^2_{31}| > |\Delta m^2_{32}|$



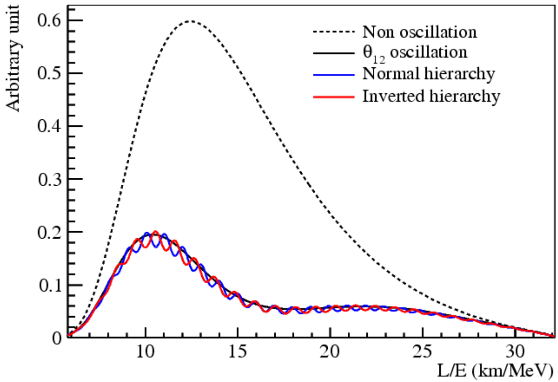
Inverted Ordering

$|\Delta m^2_{31}|$

$=$

$|\Delta m^2_{32}| - |\Delta m^2_{21}|$

$|\Delta m^2_{31}| < |\Delta m^2_{32}|$



Neutrino Physics with JUNO, arXiv:1507.05613

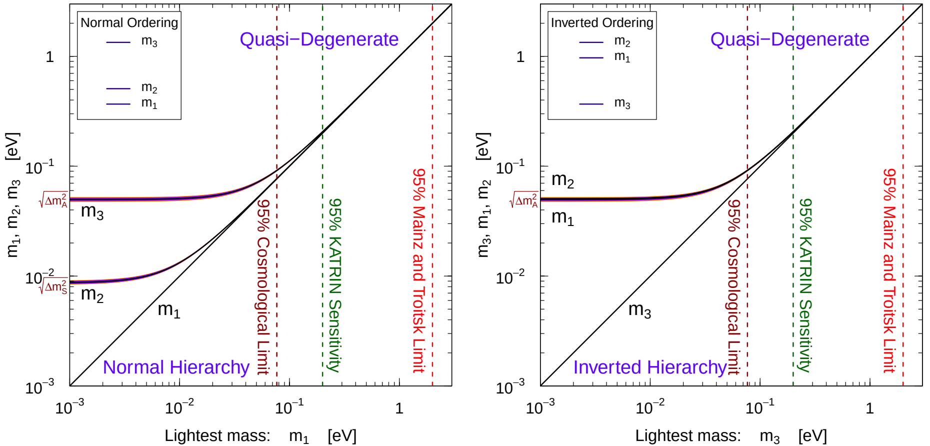
$$
\begin{aligned}
P_{\overset{(-)}{\nu}_e \to \overset{(-)}{\nu}_e} = 1 \; & - \cos^4\vartheta_{13} \sin^2 2\vartheta_{12} \sin^2\left(\Delta m^2_{21} L/4E\right) \\
& - \cos^2\vartheta_{12} \sin^2 2\vartheta_{13} \sin^2\left(\Delta m^2_{31} L/4E\right) \\
& - \sin^2\vartheta_{12} \sin^2 2\vartheta_{13} \sin^2\left(\Delta m^2_{32} L/4E\right)
\end{aligned}
$$

[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]

Open Problems

- $\vartheta_{23} \lesseqgtr 45^\circ$?
  - T2K (Japan), NOνA (USA), PINGU (Antarctica), ORCA (EU), INO (India), ...
- Mass Ordering (Hierarchy) ?
  - NOνA (USA), JUNO (China), RENO-50 (Korea), PINGU (Antarctica), ORCA (EU), INO (India), ...
- CP violation ? $\delta_{13} \approx 3\pi/2$?
  - T2K (Japan), NOνA (USA), DUNE (USA), HyperK (Japan), ...
- Absolute Mass Scale ?
  - β Decay, Neutrinoless Double-β Decay, Cosmology, ...
- Dirac or Majorana ?
  - Neutrinoless Double-β Decay, ...
- Beyond Three-Neutrino Mixing ? Sterile Neutrinos ?

Absolute Scale of Neutrino Masses



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

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

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

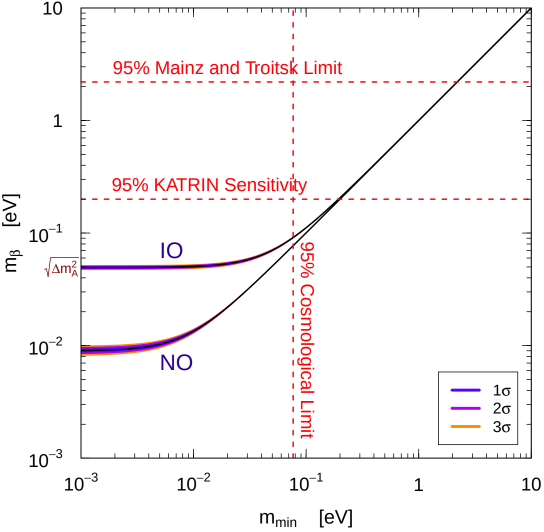
$$m_2^2 = m_1^2 + \Delta m_{21}^2 \simeq m_3^2 + \Delta m_A^2$$

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

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

Neutrino Masses in β decay

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



- Quasi-Degenerate:
  $m_\beta^2 \simeq m_\nu^2 \sum_k |U_{ek}|^2 = m_\nu^2$
- Inverted Hierarchy:
  $m_\beta^2 \simeq (1 - s_{13}^2)\Delta m^2_{\text{A}} \simeq \Delta m^2_{\text{A}}$
- Normal Hierarchy:
  $m_\beta^2 \simeq s_{12}^2 c_{13}^2 \Delta m^2_{\text{S}} + s_{13}^2 \Delta m^2_{\text{A}}$
  $\simeq 2 \times 10^{-5} + 6 \times 10^{-5}\,\text{eV}^2$
- $m_\beta \lesssim 4 \times 10^{-2}\,\text{eV}$

$\Downarrow$

Normal Spectrum

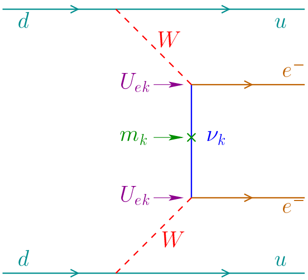
Neutrinoless Double-β Decay

$$\Delta L = 2$$

$$\mathcal{N}(A,Z) \to \mathcal{N}(A,Z+2) + e^- + e^-$$

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

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

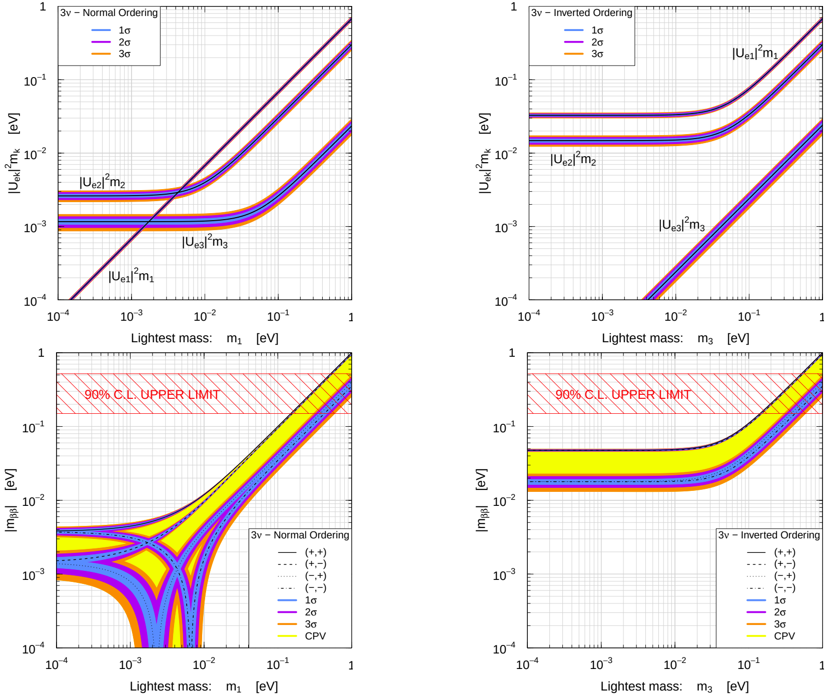


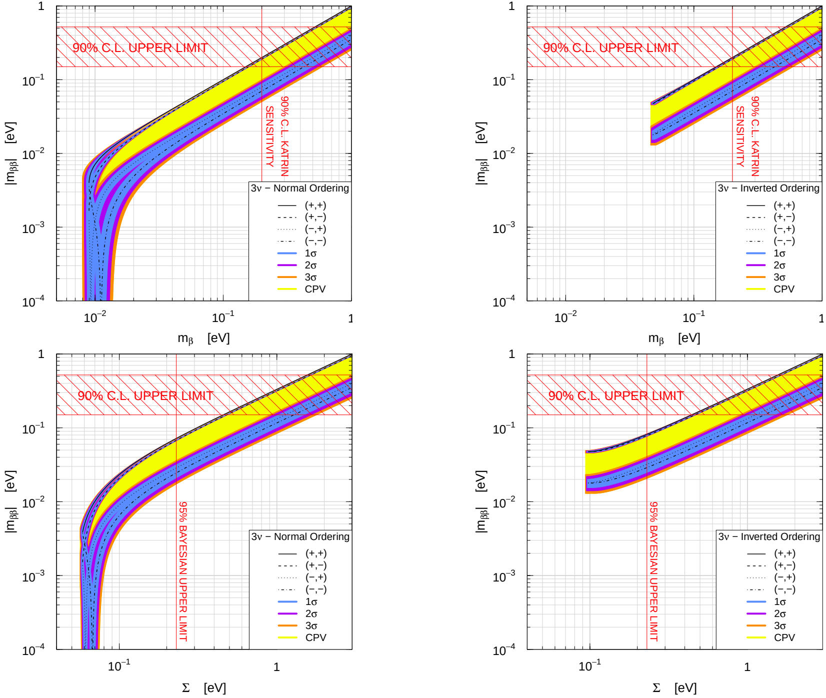
Effective Majorana Neutrino Mass

$$m_{\beta\beta} = |U_{e1}|^2\,m_1 + |U_{e2}|^2\,e^{i\alpha_{21}}\,m_2 + |U_{e3}|^2\,e^{i\alpha_{31}}\,m_3$$

$$\alpha_{21} = 2\lambda_{21} \qquad \alpha_{31} = 2\,(\lambda_{31} - \delta_{13})$$

possible cancellations between the three mass contributions


3ν − Normal Ordering
1σ
2σ
3σ
|Ue2|²m2
|Ue3|²m3
|Ue1|²m1
|Uek|²mk [eV]
Lightest mass: m1 [eV]
3ν − Inverted Ordering
1σ
2σ
3σ
|Ue1|²m1
|Ue2|²m2
|Ue3|²m3
|Uek|²mk [eV]
Lightest mass: m3 [eV]
90% C.L. UPPER LIMIT
|mββ| [eV]
3ν − Normal Ordering
(+,+)
(+,−)
(−,+)
(−,−)
1σ
2σ
3σ
CPV
Lightest mass: m1 [eV]
90% C.L. UPPER LIMIT
|mββ| [eV]
3ν − Inverted Ordering
(+,+)
(+,−)
(−,+)
(−,−)
1σ
2σ
3σ
CPV
Lightest mass: m3 [eV]

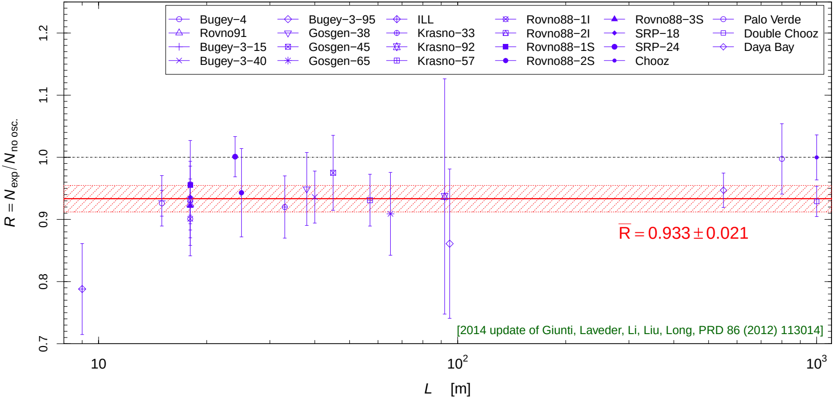

90% C.L. UPPER LIMIT
90% C.L. KATRIN SENSITIVITY
3ν − Normal Ordering
3ν − Inverted Ordering
(+,+)
(+,−)
(−,+)
(−,−)
1σ
2σ
3σ
CPV
95% BAYESIAN UPPER LIMIT
$|m_{\beta\beta}|$ [eV]
m_β [eV]
Σ [eV]

Indications of SBL Oscillations Beyond 3ν

Reactor Electron Antineutrino Anomaly

[Mention et al, PRD 83 (2011) 073006; update in White Paper, arXiv:1204.5379]

New reactor $\bar{\nu}_e$ fluxes [Mueller et al, PRC 83 (2011) 054615; Huber, PRC 84 (2011) 024617]



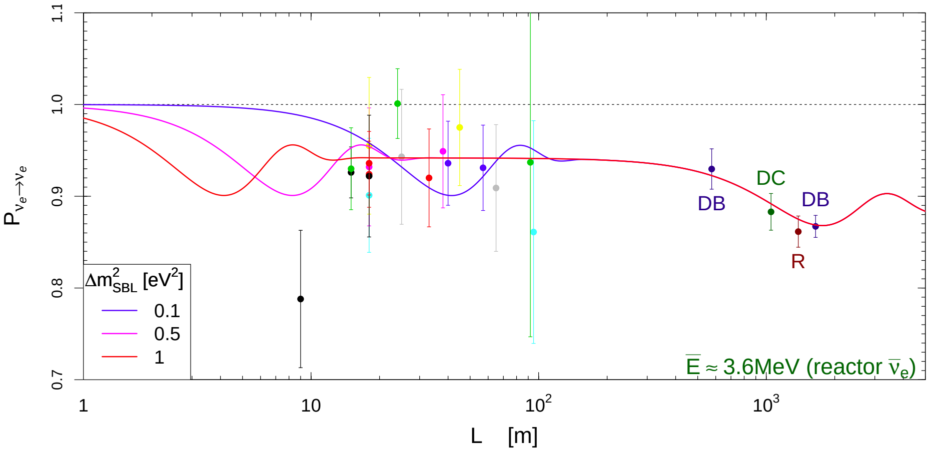
$\bar{\nu}_e \to \bar{\nu}_e$ $\quad L \sim 10 - 100\,\mathrm{m}$ $\quad E \sim 4\,\mathrm{MeV}$

Nominal $\approx 3.1\sigma$ deficit $\quad \Delta m^2 \gtrsim 0.5\,\mathrm{eV}^2$ $\quad (\gg \Delta m^2_{\mathrm{A}} \gg \Delta m^2_{\mathrm{S}})$

[see also: Sinev, arXiv:1103.2452; Ciuffoli, Evslin, Li, JHEP 12 (2012) 110; Zhang, Qian, Vogel, PRD 87 (2013) 073018; Kopp, Machado, Maltoni, Schwetz, JHEP 1305 (2013) 050; Ivanov et al, PRC 88 (2013) 055501]

Problem: unknown $\bar{\nu}_e$ flux uncertainties?

[Hayes, Friar, Garvey, Jonkmans, PRL 112 (2014) 202501; Dwyer, Langford, PRL 114 (2015) 012502]



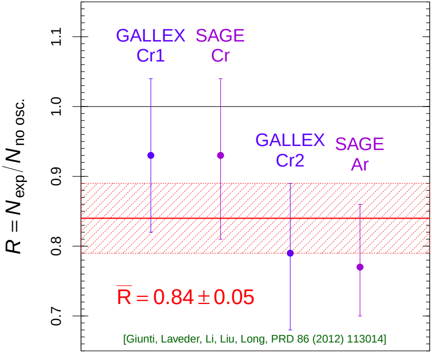
$P_{\nu_e \to \nu_e}$
1.1
1.0
0.9
0.8
0.7
1
10
10^2
10^3
L [m]
Δm^2_{SBL} [eV^2]
0.1
0.5
1
DB
DC
DB
R
$\overline{E} \approx 3.6$MeV (reactor $\bar{\nu}_e$)

Gallium Anomaly

Gallium Radioactive Source Experiments: GALLEX and SAGE

Detection Process: $\nu_e + {}^{71}\text{Ga} \to {}^{71}\text{Ge} + e^-$

ν_e Sources: $e^- + {}^{51}\text{Cr} \to {}^{51}\text{V} + \nu_e$ $\quad e^- + {}^{37}\text{Ar} \to {}^{37}\text{Cl} + \nu_e$



$\bar{\nu}_e \to \bar{\nu}_e \qquad E \sim 0.7\,\text{MeV}$

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

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

Nominal $\approx 2.9\sigma$ anomaly

$\Delta m^2 \gtrsim 1\,\text{eV}^2 \qquad (\gg \Delta m^2_{\text{A}} \gg \Delta m^2_{\text{S}})$

[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]

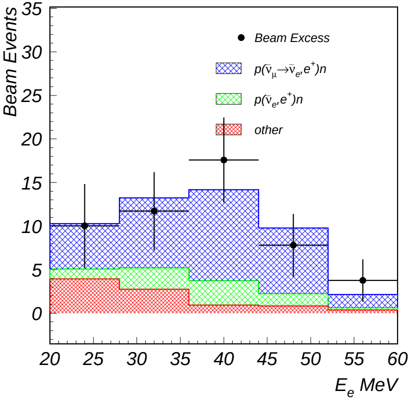
[Mention et al, PRD 83 (2011) 073006]

- ${}^3\text{He} + {}^{71}\text{Ga} \to {}^{71}\text{Ge} + {}^3\text{H}$ cross section measurement [Frekers et al., PLB 706 (2011) 134]
- $E_{\text{th}}(\nu_e + {}^{71}\text{Ga} \to {}^{71}\text{Ge} + e^-) = 233.5 \pm 1.2\,\text{keV}$ [Frekers et al., PLB 722 (2013) 233]

LSND

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

$\bar{\nu}_\mu \to \bar{\nu}_e$ $\qquad L \simeq 30\,\mathrm{m}$ $\qquad 20\,\mathrm{MeV} \leq E \leq 60\,\mathrm{MeV}$



- Well known source of $\bar{\nu}_\mu$:

$$\mu^+ \text{ at rest} \to e^+ + \nu_e + \bar{\nu}_\mu$$

- $\bar{\nu}_\mu \xrightarrow[L \simeq 30\,\mathrm{m}]{} \bar{\nu}_e$

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

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

- But signal not seen by KARMEN with same method at $L \simeq 18\,\mathrm{m}$

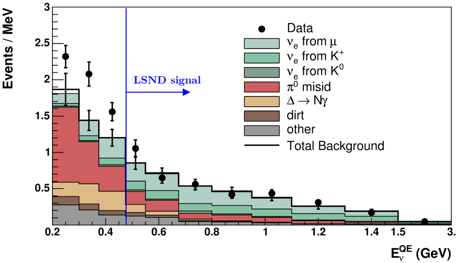
[PRD 65 (2002) 112001]

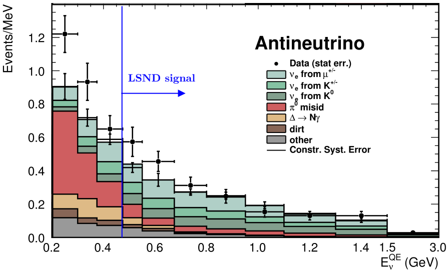
Nominal $\approx 3.8\sigma$ excess $\qquad \Delta m^2 \gtrsim 0.2\,\mathrm{eV}^2 \qquad (\gg \Delta m^2_{\mathrm{A}} \gg \Delta m^2_{\mathrm{S}})$

MiniBooNE

$L \simeq 541\,\text{m}$ $\qquad$ $200\,\text{MeV} \leq E \lesssim 3\,\text{GeV}$

$\nu_\mu \to \nu_e$ [PRL 102 (2009) 101802] $\qquad$ $\bar{\nu}_\mu \to \bar{\nu}_e$ [PRL 110 (2013) 161801]





- Purpose: check LSND signal.
- Different L and E.
- Similar L/E (oscillations).
- No money, no Near Detector.
- LSND signal: $E > 475\,\text{MeV}$.
- Agreement with LSND signal?
- CP violation?
- Low-energy anomaly!

Effective SBL Oscillation Probabilities in 3+1 Schemes

$$P^{\text{SBL}}_{\overset{(-)}{\nu}_\alpha \to \overset{(-)}{\nu}_\beta} \simeq \sin^2 2\vartheta_{\alpha\beta} \sin^2\left(\frac{\Delta m^2_{41} L}{4E}\right) \qquad \sin^2 2\vartheta_{\alpha\beta} = 4|U_{\alpha 4}|^2 |U_{\beta 4}|^2$$

$$P^{\text{SBL}}_{\overset{(-)}{\nu}_\alpha \to \overset{(-)}{\nu}_\alpha} \simeq 1 - \sin^2 2\vartheta_{\alpha\alpha} \sin^2\left(\frac{\Delta m^2_{41} L}{4E}\right) \qquad \sin^2 2\vartheta_{\alpha\alpha} = 4|U_{\alpha 4}|^2 \left(1 - |U_{\alpha 4}|^2\right)$$

Perturbation of 3ν Mixing: $|U_{e4}|^2 \ll 1\,,\ |U_{\mu 4}|^2 \ll 1\,,\ |U_{\tau 4}|^2 \ll 1\,,\ |U_{s4}|^2 \simeq 1$

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

↑ SBL

- 6 mixing angles
- 3 Dirac CP phases
- 3 Majorana CP phases
- But CP violation is not observable in current SBL experiments!
- Observable in LBL accelerator exp. sensitive to Δm^2_{ATM} [de Gouvea, Kelly, Kobach, PRD 91 (2015) 053005; Klop, Palazzo, PRD 91 (2015) 073017; Berryman, de Gouvea, Kelly, Kobach, arXiv:1507.03986] and solar exp. sensitive to Δm^2_{SOL} [Long, Li, Giunti, PRD 87, 113004 (2013) 113004]

3+1: Appearance vs Disappearance

- Amplitude of ν_e disappearance:

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

- Amplitude of ν_μ disappearance:

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

- Amplitude of $\nu_\mu \to \nu_e$ transitions:

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

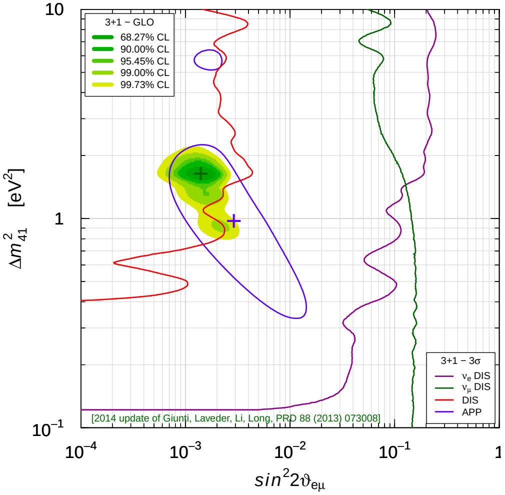
- Upper bounds on ν_e and ν_μ disappearance $\Rightarrow$ strong limit on $\nu_\mu \to \nu_e$

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

- Similar constraint in 3+2, 3+3, ..., 3+N_s! [Giunti, Zavanin, arXiv:1508.03172]

Pragmatic Global 3+1 Fit

[Giunti, Laveder, Y.F. Li, H.W. Long, PRD 88 (2013) 073008]



MiniBooNE $E > 475\,\text{MeV}$

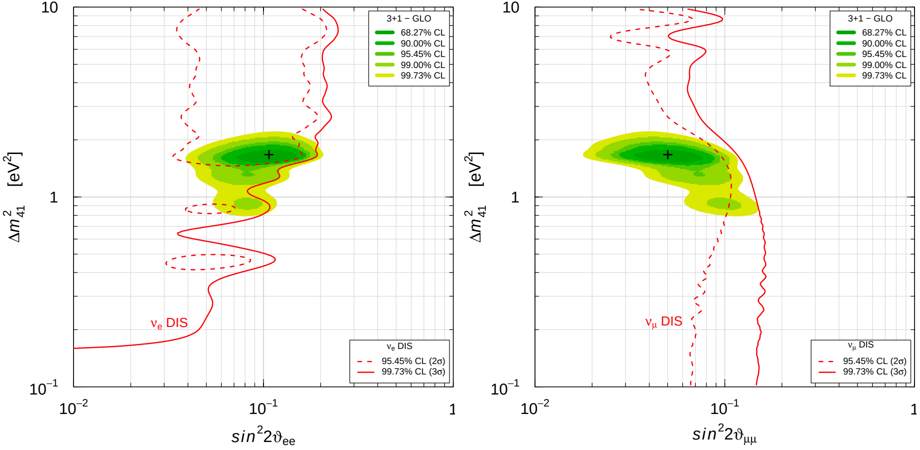
GoF $= 26\%$ PGoF $= 7\%$

- APP $\nu_\mu \to \nu_e$ & $\bar{\nu}_\mu \to \bar{\nu}_e$: LSND ($\nu_s$), MiniBooNE (?), OPERA ($\not{\nu_s}$), ICARUS ($\not{\nu_s}$), KARMEN ($\not{\nu_s}$), NOMAD ($\not{\nu_s}$), BNL-E776 ($\not{\nu_s}$)
- DIS ν_e & $\bar{\nu}_e$: Reactors (ν_s), Gallium (ν_s), ν_eC ($\not{\nu_s}$), Solar ($\not{\nu_s}$)
- DIS ν_μ & $\bar{\nu}_\mu$: CDHSW ($\not{\nu_s}$), MINOS ($\not{\nu_s}$), Atmospheric ($\not{\nu_s}$), MiniBooNE/SciBooNE ($\not{\nu_s}$)

No Osc. nominally disfavored at $\approx 6.3\sigma$

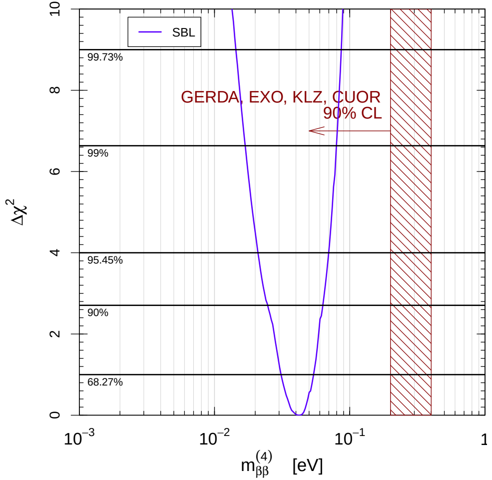
$\Delta\chi^2/\text{NDF} = 47.7/3$

ν_e and ν_μ Disappearance



Neutrinoless Double-β Decay

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



Pragmatic 3+1 Fit

[Giunti, Laveder, Li, Long, 2014]

$$m_{\beta\beta}^{(k)} = |U_{ek}|^2 m_k$$

$$m_1 \ll m_4$$

$$\Downarrow$$

$$m_{\beta\beta}^{(4)} \simeq |U_{e4}|^2 \sqrt{\Delta m_{41}^2}$$

surprise:

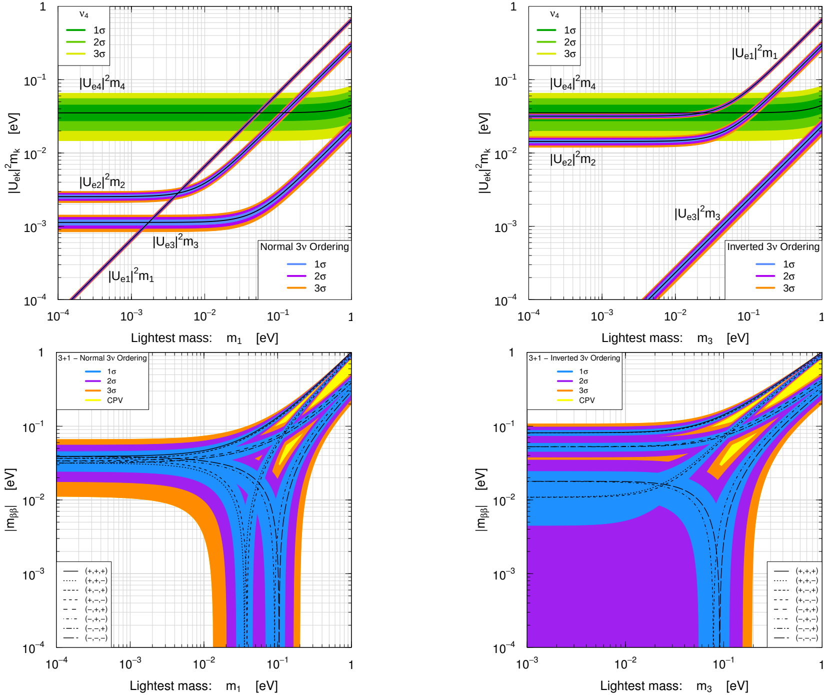
possible cancellation with $m_{\beta\beta}^{(3\nu)}$

[Barry et al, JHEP 07 (2011) 091]

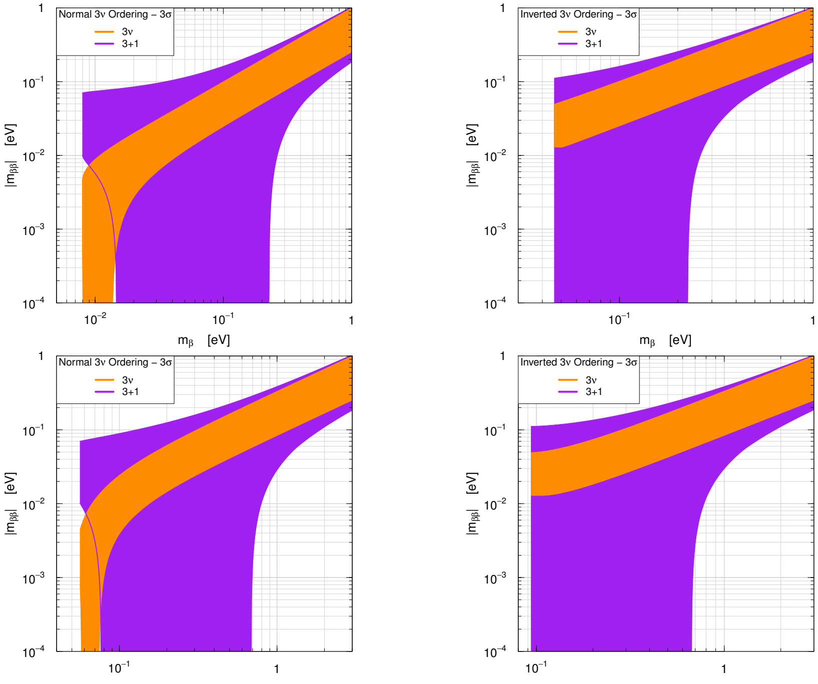
[Li, Liu, PLB 706 (2012) 406]

[Rodejohann, JPG 39 (2012) 124008]

[Girardi, Meroni, Petcov, JHEP 1311 (2013) 146]



ν4
1σ
2σ
3σ
$|U_{e4}|^2m_4$
$|U_{e2}|^2m_2$
$|U_{e3}|^2m_3$
$|U_{e1}|^2m_1$
Normal 3ν Ordering
Inverted 3ν Ordering
$|U_{ek}|^2m_k$ [eV]
Lightest mass: m_1 [eV]
Lightest mass: m_3 [eV]
3+1 – Normal 3ν Ordering
3+1 – Inverted 3ν Ordering
CPV
$|m_{\beta\beta}|$ [eV]
(+,+,+)
(+,+,−)
(+,−,+)
(+,−,−)
(−,+,+)
(−,+,−)
(−,−,+)
(−,−,−)



[Giunti, Zavanin, JHEP 07 (2015) 171]

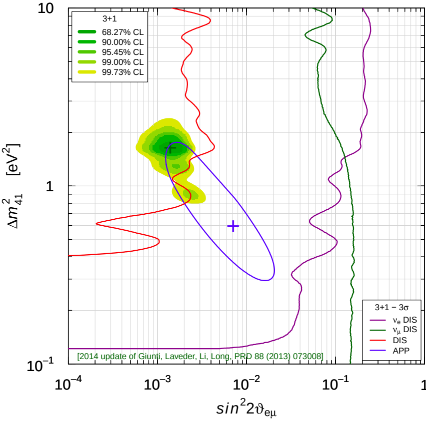
Conclusions

- Robust Three-Neutrino Mixing Paradigm.
  Open problems with exciting experimental program: $\vartheta_{23} \lesseqgtr 45°$?, Mass Ordering, CP Violation, Absolute Mass Scale, Dirac or Majorana?
  Determination of Mass Ordering is very important!
- Short-Baseline ν_e and $\bar{\nu}_e$ Disappearance:
  - Experimental data agree on Reactor $\bar{\nu}_e$ and Gallium ν_e anomalies.
  - Problem: unknown systematic uncertainties (Reactor $\bar{\nu}_e$ flux).
  - Many promising projects to test unambiguously short-baseline ν_e and $\bar{\nu}_e$ disappearance in a few years with reactors and radioactive sources.
  - Independent tests through effect of m_4 in β-decay and $\beta\beta_{0\nu}$-decay.
- Short-Baseline $\bar{\nu}_\mu \to \bar{\nu}_e$ LSND Signal:
  - Not seen by other SBL $\overset{(-)}{\nu}_\mu \to \overset{(-)}{\nu}_e$ experiments.
  - MiniBooNE experiment has been inconclusive.
  - Experiments with near detector are needed to check LSND signal!
- Pragmatic 3+1 Fit is fine: moderate APP-DIS tension.
- Light Sterile Neutrinos in Cosmology: see S. Gariazzo talk.

Backup Slides

Global 3+1 Fit

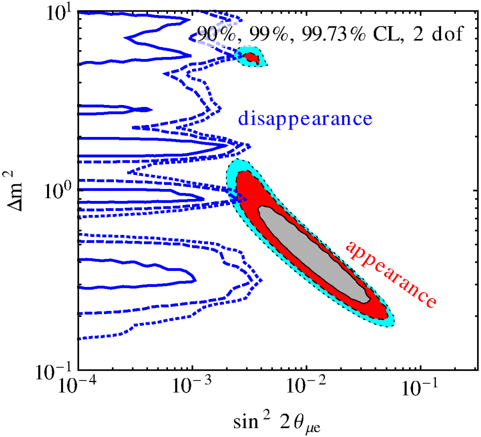
Our Fit



GoF = 5%

PGoF = 0.1%

Kopp, Machado, Maltoni, Schwetz

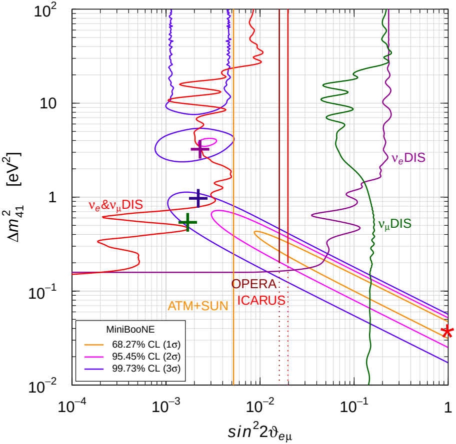


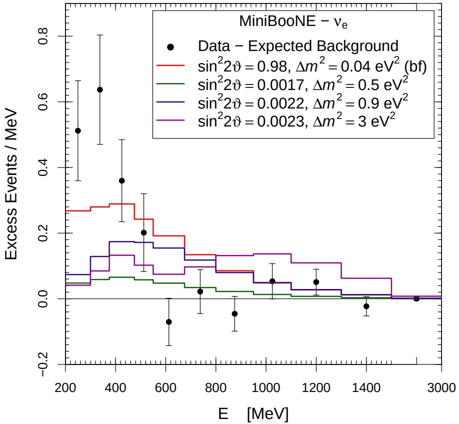
GoF = 19%

PGoF = 0.01%

[Kopp, Machado, Maltoni, Schwetz, JHEP 1305 (2013) 050]

MiniBooNE Low-Energy Excess?





- No fit of low-energy excess for realistic $\sin^2 2\vartheta_{e\mu} \lesssim 3 \times 10^{-3}$
- Neutrino energy reconstruction problem? [Martini, Ericson, Chanfray, PRD 87 (2013) 013009]
- MB low-energy excess is the main cause of bad APP-DIS PGoF = 0.1%
- Pragmatic Approach: discard the Low-Energy Excess because it is very likely not due to oscillations