Neutrino Masses

Carlo Giunti

INFN, Sezione di Torino, and Dipartimento di Fisica, Università di Torino

`mailto://giunti@to.infn.it`

Neutrino Unbound: `http://www.nu.to.infn.it`

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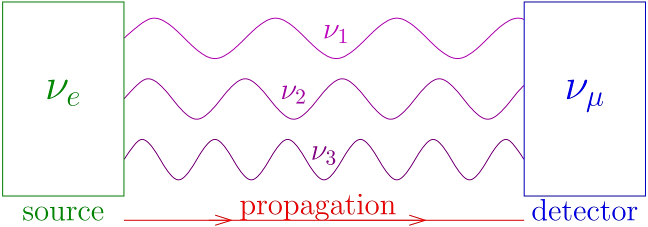
Neutrino Oscillations

- 1957: Bruno Pontecorvo proposed Neutrino Oscillations in analogy with $K^0 \leftrightarrows \bar{K}^0$ oscillations (Gell-Mann and Pais, 1955)
- 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

$$
\begin{aligned}
|\nu_e\rangle &= U_{e1}\,|\nu_1\rangle + U_{e2}\,|\nu_2\rangle + U_{e3}\,|\nu_3\rangle \\
|\nu_\mu\rangle &= U_{\mu1}\,|\nu_1\rangle + U_{\mu2}\,|\nu_2\rangle + U_{\mu3}\,|\nu_3\rangle \\
|\nu_\tau\rangle &= U_{\tau1}\,|\nu_1\rangle + U_{\tau2}\,|\nu_2\rangle + U_{\tau3}\,|\nu_3\rangle
\end{aligned}
$$

- U is the 3×3 Neutrino Mixing Matrix

$$|\nu(t=0)\rangle = |\nu_e\rangle = U_{e1}\,|\nu_1\rangle + U_{e2}\,|\nu_2\rangle + U_{e3}\,|\nu_3\rangle$$



$$|\nu(t>0)\rangle = U_{e1}\,e^{-iE_1 t}\,|\nu_1\rangle + U_{e2}\,e^{-iE_2 t}\,|\nu_2\rangle + U_{e3}\,e^{-iE_3 t}\,|\nu_3\rangle \neq |\nu_e\rangle$$

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

at the detector there is a probability > 0 to see the neutrino as a ν_μ

Neutrino Oscillations are Flavor Transitions $\propto \sin^2\left(\frac{\Delta m_{kj}^2 L}{4E}\right)$

$$\begin{array}{cccc} \nu_e \to \nu_\mu & \nu_e \to \nu_\tau & \nu_\mu \to \nu_e & \nu_\mu \to \nu_\tau \\ \bar\nu_e \to \bar\nu_\mu & \bar\nu_e \to \bar\nu_\tau & \bar\nu_\mu \to \bar\nu_e & \bar\nu_\mu \to \bar\nu_\tau \end{array}$$

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

Experimental Evidences of Neutrino Oscillations

Solar
$\nu_e \to \nu_\mu, \nu_\tau$

SNO, BOREXino
Super-Kamiokande
GALLEX/GNO, SAGE
Homestake, Kamiokande

VLBL Reactor
$\bar{\nu}_e$ disappearance

(KamLAND)

$$\to \begin{cases} \Delta m^2_{\text{S}} \simeq 7.6 \times 10^{-5}\,\text{eV}^2 \\ \sin^2\vartheta_{\text{S}} \simeq 0.30 \end{cases}$$

Atmospheric
$\nu_\mu \to \nu_\tau$

Super-Kamiokande
Kamiokande, IMB
MACRO, Soudan-2

LBL Accelerator
ν_μ disappearance

(K2K, MINOS, T2K)

LBL Accelerator
$\nu_\mu \to \nu_\tau$

(Opera)

$$\to \begin{cases} \Delta m^2_{\text{A}} \simeq 2.4 \times 10^{-3}\,\text{eV}^2 \\ \sin^2\vartheta_{\text{A}} \simeq 0.50 \end{cases}$$

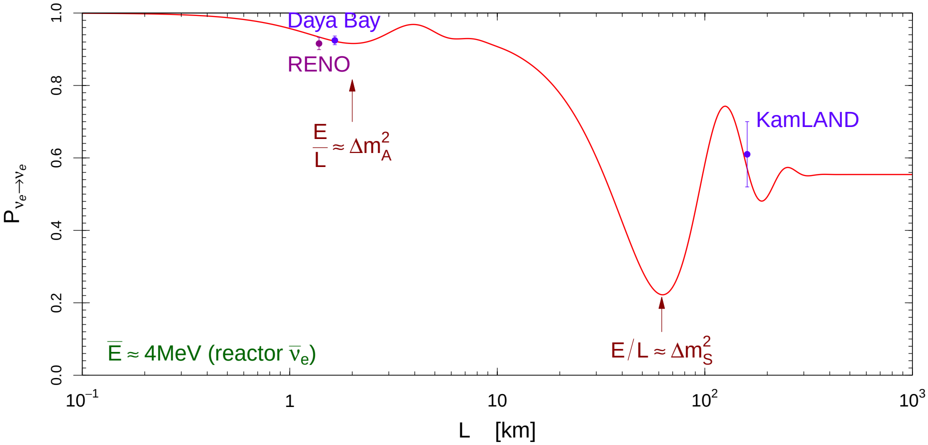
LBL Accelerator
$\nu_\mu \to \nu_e$

(T2K, MINOS)

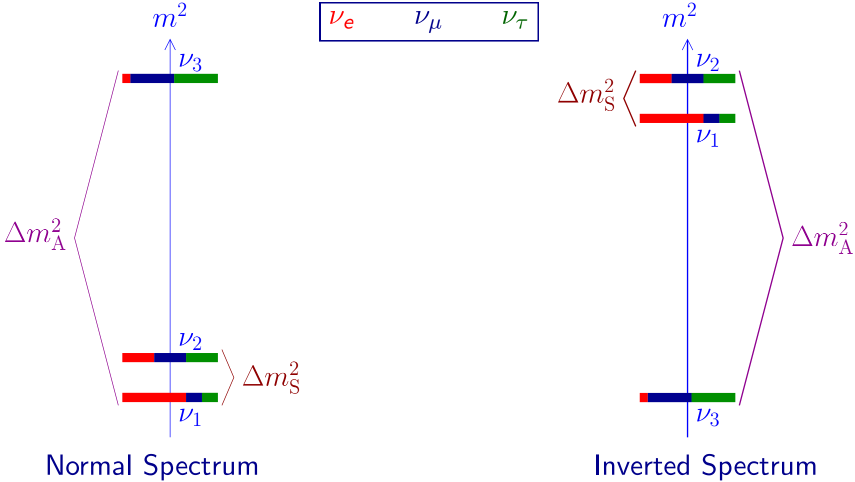
LBL Reactor
$\bar{\nu}_e$ disappearance

Daya Bay, RENO
Double Chooz

$$\to \begin{cases} \Delta m^2_{\text{A}} \\ \sin^2\vartheta_{13} \simeq 0.023 \end{cases}$$


Daya Bay
RENO
KamLAND
$\frac{E}{L} \approx \Delta m^2_A$
$E/L \approx \Delta m^2_S$
$\overline{E} \approx 4\text{MeV}$ (reactor $\overline{\nu}_e$)
$P_{\nu_e \to \nu_e}$
0.0
0.2
0.4
0.6
0.8
1.0
10^{-1}
1
10
10^2
10^3
L [km]

Three-Neutrino Mixing Paradigm



Recent Global Fits

Gonzalez Garcia, Maltoni, Schwetz, Salvado, NuFIT-v1.2 [http://www.nu-fit.org/]

Capozzi, Fogli, Lisi, Marrone, Montanino, Palazzo, arXiv:1312.2878

$$\Delta m^2_{\rm S} = \Delta m^2_{21} \simeq 7.5^{+0.3}_{-0.2} \times 10^{-5}\,{\rm eV}^2 \qquad \text{uncertainty} \simeq 3\%$$

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

$$U = \begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta_{13}} \\ -s_{12}c_{23}-c_{12}s_{23}s_{13}e^{i\delta_{13}} & c_{12}c_{23}-s_{12}s_{23}s_{13}e^{i\delta_{13}} & s_{23}c_{13} \\ s_{12}s_{23}-c_{12}c_{23}s_{13}e^{i\delta_{13}} & -c_{12}s_{23}-s_{12}c_{23}s_{13}e^{i\delta_{13}} & c_{23}c_{13} \end{pmatrix} \begin{pmatrix} 1 & 0 & 0 \\ 0 & e^{i\lambda_2} & 0 \\ 0 & 0 & e^{i\lambda_3} \end{pmatrix}$$

$$= \underbrace{\begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix}}_{\vartheta_{23} = \vartheta_{\rm A}} \underbrace{\begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta_{13}} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta_{13}} & 0 & c_{13} \end{pmatrix}}_{\text{Chooz, Palo Verde}} \underbrace{\begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}}_{\vartheta_{12} = \vartheta_{\rm S}} \underbrace{\begin{pmatrix} 1 & 0 & 0 \\ 0 & e^{i\lambda_2} & 0 \\ 0 & 0 & e^{i\lambda_3} \end{pmatrix}}_{\beta\beta_{0\nu}}$$

$\sin^2\vartheta_{23} \simeq 0.4 - 0.6$

T2K, MINOS

Daya Bay, RENO

$\sin^2\vartheta_{13} \simeq 0.023 \pm 0.002$

$\sin^2\vartheta_{12} \simeq 0.30 \pm 0.01$

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

Open Problems

- $\vartheta_{23} \lesseqgtr 45^\circ$?
  - T2K (Japan), NOνA (USA), IceCube-PINGU, INO (India), ...

- Mass Hierarchy ?
  - NOνA (USA), JUNO (China), RENO-50 (Korea), IceCube-PINGU, INO (India), ...

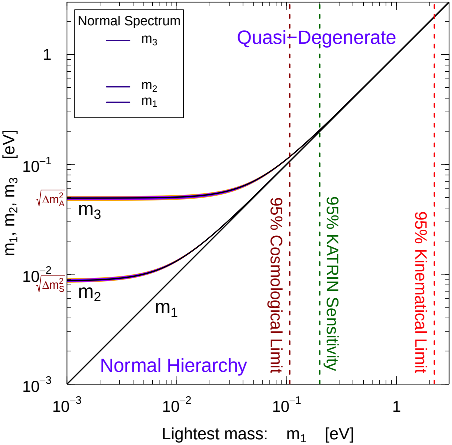
- CP violation ?
  - NOνA (USA), LBNE (USA), LAGUNA-LBNO (EU), HyperK (Japan), ...

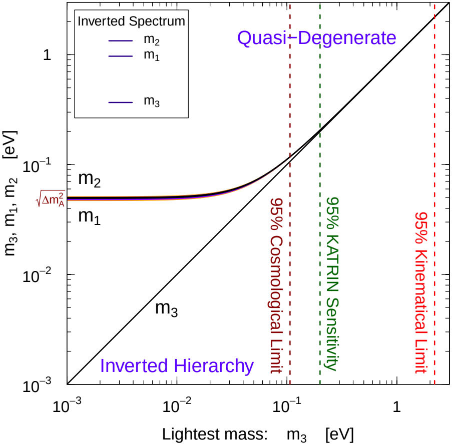
- Absolute Mass Scale ?
  - β Decay, Neutrinoless Double-β Decay, Cosmology, ...

- Dirac or Majorana ?
  - Neutrinoless Double-β Decay, ...

- Beyond Three-Neutrino Mixing ? Sterile Neutrinos ?

Absolute Scale of Neutrino Masses





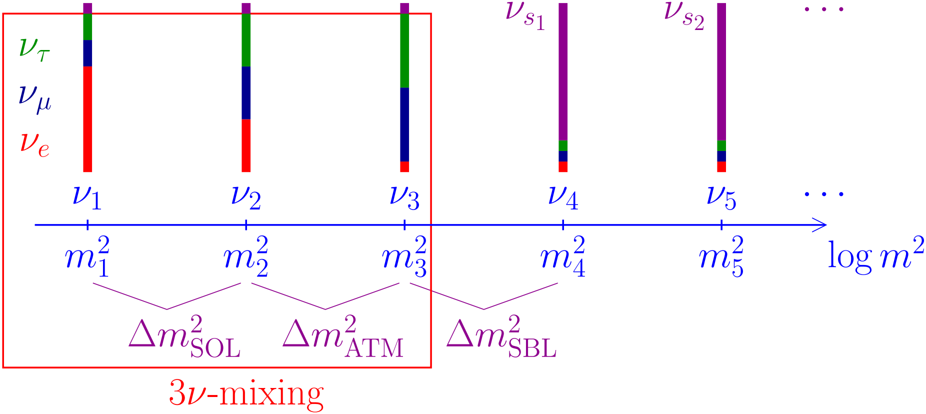
$$m_2^2 = m_1^2 + \Delta m_{21}^2 = m_1^2 + \Delta m_S^2$$
$$m_3^2 = m_1^2 + \Delta m_{31}^2 = m_1^2 + \Delta m_A^2$$

$$m_1^2 = m_3^2 - \Delta m_{31}^2 = m_3^2 + \Delta m_A^2$$
$$m_2^2 = m_1^2 + \Delta m_{21}^2 \simeq m_3^2 + \Delta m_A^2$$

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 + WMAP9 + highL + BAO [arXiv:1303.5076]

Beyond Three-Neutrino Mixing: Sterile Neutrinos



Light Sterile Neutrinos

- Physics Beyond the SM $\Longrightarrow$ right-handed sterile neutrinos
- Sterile means no standard model interactions
  [Pontecorvo, Sov. Phys. JETP 26 (1968) 984]
- Active neutrinos $(\nu_e, \nu_\mu, \nu_\tau)$ can oscillate into light sterile neutrinos (ν_s)
- Observables:
  - Disappearance of active neutrinos (neutral current deficit)
  - Indirect evidence through combined fit of data (current indication)
- Short-baseline anomalies + 3ν-mixing:

$$
\begin{array}{ccccc}
 & \Delta m^2_{21} \ll & |\Delta m^2_{31}| \ll & |\Delta m^2_{41}| \leq & \ldots \\
\nu_1 & \nu_2 & \nu_3 & \nu_4 & \ldots \\
\nu_e & \nu_\mu & \nu_\tau & \nu_{s_1} & \ldots
\end{array}
$$

- In this talk I consider sterile neutrinos with mass scale $\sim 1\,\text{eV}$ in light of short-baseline Reactor Anomaly, Gallium Anomaly, LSND.
- Other possibilities (not incompatible):
    - Very light sterile neutrinos with mass scale $\ll 1\,\text{eV}$: important for solar neutrino phenomenology

      [Das, Pulido, Picariello, PRD 79 (2009) 073010]
      [de Holanda, Smirnov, PRD 83 (2011) 113011]

    - Heavy sterile neutrinos with mass scale $\gg 1\,\text{eV}$: could be Warm Dark Matter

      [Kusenko, Phys. Rept. 481 (2009) 1]
      [Boyarsky, Ruchayskiy, Shaposhnikov, Ann. Rev. Nucl. Part. Sci. 59 (2009) 191]
      [Drewes, IJMPE, 22 (2013) 1330019]

Experimental Indications of Sterile Neutrinos

- LSND: Accelerator $\bar{\nu}_\mu \to \bar{\nu}_e$

$$L \simeq 30\,\text{m} \qquad E \simeq 50\,\text{MeV}$$

3.8σ excess $\quad \Delta m^2 \gtrsim 0.2\,\text{eV}^2 \quad (\gg \Delta m^2_\text{A} \gg \Delta m^2_\text{S})$ [PRD 64 (2001) 112007]

- Reactor Electron Antineutrino Anomaly: $\bar{\nu}_e \to \bar{\nu}_e$

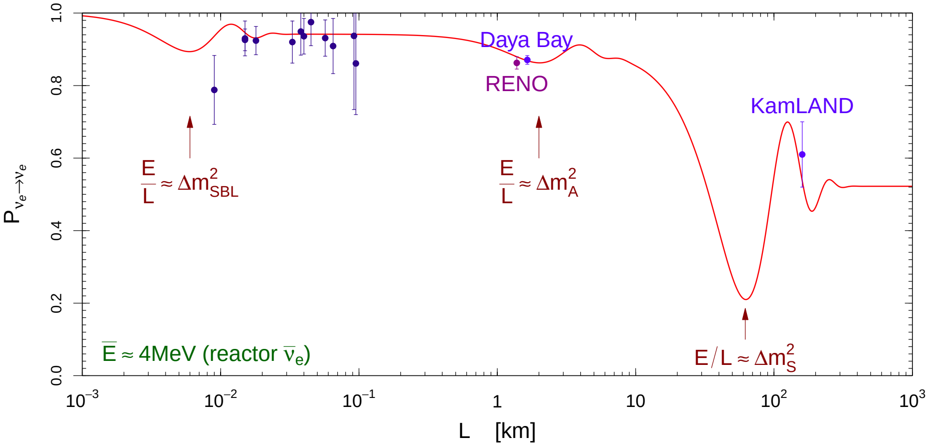
$$L \simeq 10 - 100\,\text{m} \qquad E \simeq 4\,\text{MeV}$$

2.8σ deficit $\quad \Delta m^2 \gtrsim 0.5\,\text{eV}^2$ [Mention et al, PRD 83 (2011) 073006]

- Gallium Anomaly: $\nu_e \to \nu_e$

$$L \simeq 1\,\text{m} \qquad E \simeq 1\,\text{MeV}$$

2.9σ deficit $\quad \Delta m^2 \gtrsim 1\,\text{eV}^2$ [SAGE, PRC 73 (2006) 045805]



$P_{\nu_e \to \nu_e}$
1.0
0.8
0.6
0.4
0.2
0.0
10^{-3}
10^{-2}
10^{-1}
1
10
10^{2}
10^{3}
L [km]
Daya Bay
RENO
KamLAND
$\frac{E}{L} \approx \Delta m^2_{SBL}$
$\frac{E}{L} \approx \Delta m^2_{A}$
$E/L \approx \Delta m^2_{S}$
$\overline{E} \approx$ 4MeV (reactor $\overline{\nu}_e$)

Effective SBL Oscillation Probabilities in 3+1 Schemes

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

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

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

$$U = \left(\begin{array}{ccc|c|} \cline{4-4} U_{e1} & U_{e2} & U_{e3} & U_{e4} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} & U_{\mu 4} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} & U_{\tau 4} \\ U_{s1} & U_{s2} & U_{s3} & U_{s4} \\ \cline{4-4} \end{array}\right)$$

$\uparrow$

SBL

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

but CP violation is not observable
in SBL experiments!

3+1: Appearance vs Disappearance

- ν_e disappearance experiments:

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

- ν_μ disappearance experiments:

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

- $\nu_\mu \to \nu_e$ experiments:

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

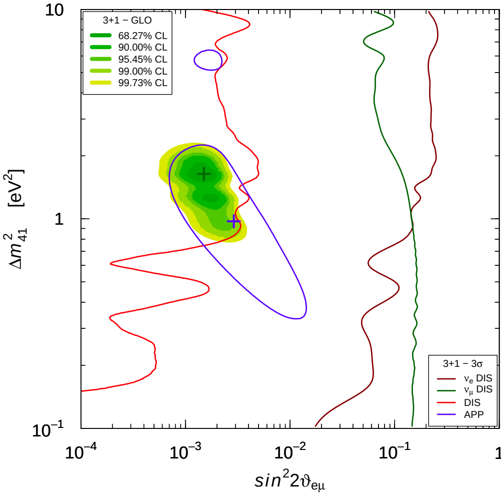
- Upper bounds on $\sin^2 2\vartheta_{ee}$ and $\sin^2 2\vartheta_{\mu\mu} \Longrightarrow$ strong limit on $\sin^2 2\vartheta_{e\mu}$

[Okada, Yasuda, IJMPA 12 (1997) 3669-3694]

[Bilenky, Giunti, Grimus, EPJC 1 (1998) 247]

3+1 Global Fit

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



- APP $\nu_\mu \to \nu_e$ & $\bar{\nu}_\mu \to \bar{\nu}_e$: LSND (Y), MiniBooNE (?), OPERA (N), ICARUS (N), KARMEN (N), NOMAD (N), BNL-E776 (N)
- DIS ν_e & $\bar{\nu}_e$: Reactors (Y), Gallium (Y), ν_eC (N), Solar (N)
- DIS ν_μ & $\bar{\nu}_\mu$: CDHSW (N), MINOS (N), Atmospheric (N), MiniBooNE/SciBooNE (N)

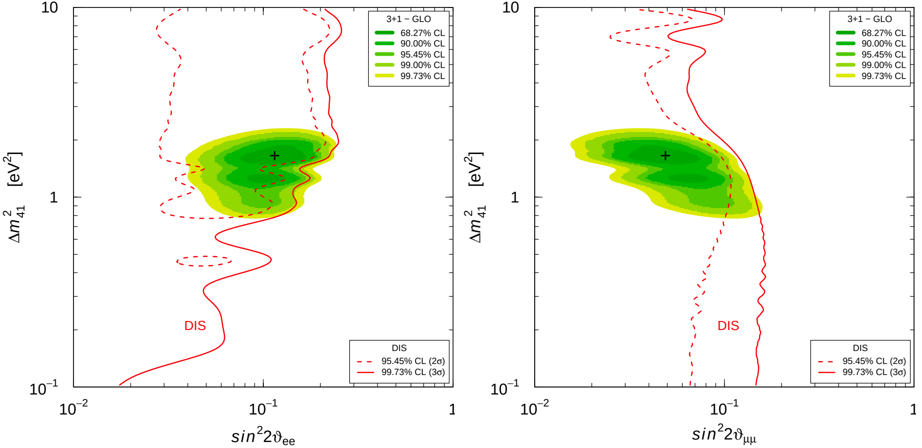
No Osc. excluded at 6.2σ

$\Delta\chi^2/\text{NDF} = 46.2/3$

GoF = 29%   PGoF = 9%

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

ν_e and ν_μ Disappearance



Many Exciting New Experiments and Projects

- Reactor $\bar{\nu}_e$ Disappearance:
  - Nucifer (OSIRIS, Saclay), Stereo (ILL, Grenoble) [arXiv:1204.5379]
  - DANSS (Kalinin Nuclear Power Plant, Russia) [arXiv:1304.3696], POSEIDON (PIK, Gatchina, Russia) [arXiv:1204.2449]
  - SCRAAM (San Onofre, California) [arXiv:1204.5379]
  - CARR (China Advanced Research Reactor) [arXiv:1303.0607]
  - Neutrino-4 (SM-3, Dimitrovgrad, Russia), SOLID (BR2, Belgium), Hanaro (Korea) [D. Lhuillier, EPSHEP 2013]
- Radioactive Source ν_e and $\bar{\nu}_e$ Disappearance:
  - SOX (Borexino, Gran Sasso, Italy) [arXiv:1304.7721]
  - CeLAND (^{144}Ce@KamLAND, Japan) [arXiv:1107.2335]
  - SAGE (Baksan, Russia) [arXiv:1006.2103]
  - IsoDAR (DAEδALUS, USA) [arXiv:1210.4454, arXiv:1307.2949]
  - SNO+, Daya Bay, RENO [T. Lasserre, Neutrino 2012]
- Accelerator $\overset{(-)}{\nu}_\mu \to \overset{(-)}{\nu}_e$ Appearance:
  - ICARUS/NESSIE (CERN) [arXiv:1304.2047, arXiv:1306.3455]
  - nuSTORM [arXiv:1308.0494]
  - OscSNS (Oak Ridge, USA) [arXiv:1305.4189, arXiv:1307.7097]

Effects of light sterile neutrinos can be also seen in:

- Solar neutrinos

  [Dooling et al, PRD 61 (2000) 073011, Gonzalez-Garcia et al, PRD 62 (2000) 013005;
  Palazzo, PRD 83 (2011) 113013, PRD 85 (2012) 077301;
  Li et al, PRD 80 (2009) 113007, PRD 87, 113004 (2013), JHEP 1308 (2013) 056;
  Kopp, Machado, Maltoni, Schwetz, JHEP 1305 (2013) 050]

- Atmospheric neutrinos

  [Goswami, PRD 55 (1997) 2931;
  Bilenky, Giunti, Grimus, Schwetz, PRD 60 (1999) 073007;
  Maltoni, Schwetz, Tortola, Valle, NPB 643 (2002) 321, PRD 67 (2003) 013011;
  Choubey, JHEP 12 (2007) 014;
  Razzaque, Smirnov, JHEP 07 (2011) 084, PRD 85 (2012) 093010;
  Gandhi, Ghoshal, PRD 86 (2012) 037301;
  Esmaili, Halzen, Peres, JCAP 1211 (2012) 041;
  Esmaili, Smirnov, arXiv:1307.6824]

- Supernova neutrinos

  [Caldwell, Fuller, Qian, PRD 61 (2000) 123005;
  Peres, Smirnov, NPB 599 (2001);
  Sorel, Conrad, PRD 66 (2002) 033009;
  Tamborra, Raffelt, Huedepohl, Janka, JCAP 1201 (2012) 013;
  Wu, Fischer, Martinez-Pinedo, Qian, arXiv:1305.2382]

Conclusions

- Robust Three-Neutrino Mixing Paradigm.
  Open problems: $\vartheta_{23} \lesseqgtr 45^\circ$?, Mass Hierarchy, CP Violation, Absolute Mass Scale, Dirac or Majorana?

- Very interesting indications of light sterile neutrinos:
  - LSND $\bar{\nu}_\mu \to \bar{\nu}_e$ signal.
  - Reactor $\bar{\nu}_e$ disappearance.
  - Gallium ν_e disappearance.

- Many promising projects to test in a few years short-baseline ν_e and $\bar{\nu}_e$ disappearance with reactors and radioactive sources.

- More difficult (expensive) projects to check the LSND $\bar{\nu}_\mu \to \bar{\nu}_e$ signal are under discussion.

- Cosmology:
  - Important effects of sterile neutrinos.
  - Implications depend on theoretical framework and considered data set.
  - Cosmological indications must be checked by laboratory experiments.