La Fisica dei Neutrini: Stato e Prospettive

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IFAE2011

Incontri di Fisica delle Alte Energie

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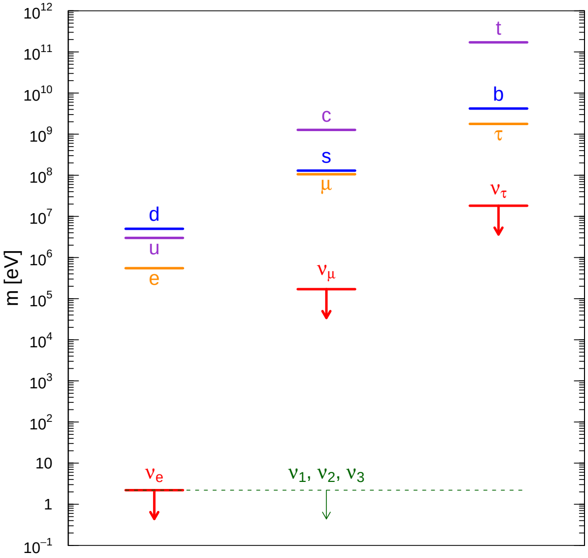
Fermion Mass Spectrum



Standard Model: Massless Neutrinos

left-handed neutrino — boost $V > v$ — right-handed neutrino

Standard Model: $\nu_L \quad \Longrightarrow \quad$ no Dirac mass term

$$\mathcal{L}^{\mathrm{D}} = -m^{\mathrm{D}} \left(\overline{\nu_R} \nu_L + \overline{\nu_L} \nu_R \right) \qquad \text{(no } \nu_R\text{)}$$

Majorana Neutrino: $\nu = \nu^c \Longrightarrow \nu_R = \nu_L^c \Longrightarrow$ Majorana mass term

$$\mathcal{L}^{\mathrm{M}} = -\frac{1}{2} m^{\mathrm{M}} \left(\overline{\nu_L^c} \nu_L + \overline{\nu_L} \nu_L^c \right)$$

Standard Model: Majorana mass term not allowed by $SU(2)_L \times U(1)_Y$

(no Higgs triplet)

Extension of the SM: Massive Neutrinos

Standard Model can be extended with ν_R

Dirac neutrino mass term $\mathcal{L}^{\text{D}} = -m^{\text{D}} \left(\overline{\nu_R} \nu_L + \overline{\nu_L} \nu_R \right) \Rightarrow m^{\text{D}} \lesssim 100\,\text{GeV}$

surprise: Majorana neutrino mass for ν_R is allowed!

$$\mathcal{L}^{\text{M}}_R = -\frac{1}{2} m^{\text{M}}_R \left(\overline{\nu^c_R} \nu_R + \overline{\nu_R} \nu^c_R \right)$$

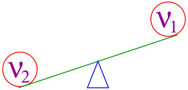
total neutrino mass term $\quad \mathcal{L}^{\text{D+M}} = -\frac{1}{2} \begin{pmatrix} \overline{\nu^c_L} & \overline{\nu_R} \end{pmatrix} \begin{pmatrix} 0 & m^{\text{D}} \\ m^{\text{D}} & m^{\text{M}}_R \end{pmatrix} \begin{pmatrix} \nu_L \\ \nu^c_R \end{pmatrix} + \text{H.c.}$

m^{M}_R can be arbitrarily large (not protected by SM symmetries)

$m^{\text{M}}_R \sim$ scale of new physics beyond Standard Model $\Rightarrow m^{\text{M}}_R \gg m^{\text{D}}$

diagonalization of $\begin{pmatrix} 0 & m^{\text{D}} \\ m^{\text{D}} & m^{\text{M}}_R \end{pmatrix} \quad \Rightarrow \quad m_1 \simeq \frac{(m^{\text{D}})^2}{m^{\text{M}}_R}, \quad m_2 \simeq m^{\text{M}}_R$

natural explanation of smallness
of light neutrino masses



see-saw mechanism

massive neutrinos are Majorana!

3-GEN $\Rightarrow$ effective low-energy 3-ν mixing

[Minkowski, PLB 67 (1977) 42]

[Yanagida (1979); Gell-Mann, Ramond, Slansky (1979); Mohapatra, Senjanovic, PRL 44 (1980) 912]

Three-Neutrino Mixing

$$\mathcal{L}_{\text{mass}} \sim \begin{pmatrix} \overline{\nu_e} & \overline{\nu_\mu} & \overline{\nu_\tau} \end{pmatrix} \begin{pmatrix} m_{ee} & m_{e\mu} & m_{e\tau} \\ m_{\mu e} & m_{\mu\mu} & m_{\mu\tau} \\ m_{\tau e} & m_{\tau\mu} & m_{\tau\tau} \end{pmatrix} \begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix}$$

diagonalization of mass matrix

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

$$\nu_\alpha = \sum_{k=1}^{3} U_{\alpha k} \nu_k \qquad\qquad (\alpha = e, \mu, \tau)$$

$$\mathcal{L}_{\text{mass}} \sim \begin{pmatrix} \overline{\nu_1} & \overline{\nu_2} & \overline{\nu_3} \end{pmatrix} \begin{pmatrix} m_1 & 0 & 0 \\ 0 & m_2 & 0 \\ 0 & 0 & m_3 \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix} = \sum_{k=1}^{3} m_k \overline{\nu_k} \nu_k$$

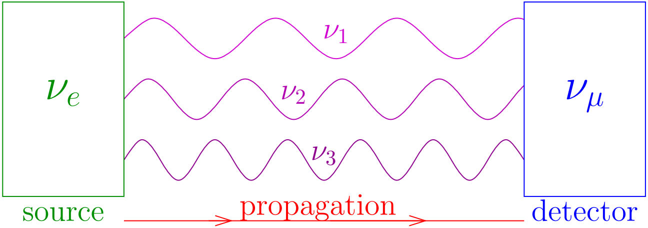
Neutrino Oscillations

- 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

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



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

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

Neutrino Oscillations are Flavor Transitions

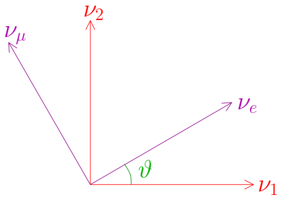
$$\nu_e \to \nu_\mu \qquad \nu_e \to \nu_\tau \qquad \nu_\mu \to \nu_e \qquad \nu_\mu \to \nu_\tau$$

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

$$\Delta L_e, \Delta L_\mu, \Delta L_\tau = \pm 1 \qquad \Delta L = 0$$

Two-Neutrino Mixing and Oscillations

$$|\nu_\alpha\rangle = \sum_{k=1}^{2} U_{\alpha k}\,|\nu_k\rangle \qquad (\alpha = e, \mu)$$



$$U = \begin{pmatrix} \cos\vartheta & \sin\vartheta \\ -\sin\vartheta & \cos\vartheta \end{pmatrix}$$

$$\boxed{\begin{aligned} |\nu_e\rangle &= \cos\vartheta\,|\nu_1\rangle + \sin\vartheta\,|\nu_2\rangle \\ |\nu_\mu\rangle &= -\sin\vartheta\,|\nu_1\rangle + \cos\vartheta\,|\nu_2\rangle \end{aligned}}$$

$$\Delta m^2 \equiv \Delta m^2_{21} \equiv m^2_2 - m^2_1$$

Transition Probability: $$P_{\nu_e\to\nu_\mu} = P_{\nu_\mu\to\nu_e} = \sin^2 2\vartheta \sin^2\left(\frac{\Delta m^2 L}{4E}\right)$$

Survival Probabilities: $$P_{\nu_e\to\nu_e} = P_{\nu_\mu\to\nu_\mu} = 1 - P_{\nu_e\to\nu_\mu}$$

Solar and Atmospheric Neutrino Oscillations

Solar $\nu_e \to \nu_\mu, \nu_\tau$	Homestake, Kamiokande, GALLEX/GNO & SAGE, Super-Kamiokande, SNO, BOREXino	$\to$ $\Delta m^2_{\text{SOL}} \simeq 7.6 \times 10^{-5}\,\text{eV}^2$, $\sin^2\vartheta_{\text{SOL}} \simeq 0.30$
Reactor $\bar{\nu}_e$ disappearance	(KamLAND)	
Atmospheric $\nu_\mu \to \nu_\tau$	Kamiokande, IMB, Super-Kamiokande, MACRO, Soudan-2	$\to$ $\Delta m^2_{\text{ATM}} \simeq 2.4 \times 10^{-3}\,\text{eV}^2$, $\sin^2\vartheta_{\text{ATM}} \simeq 0.50$
Accelerator ν_μ disappearance	(K2K & MINOS)	

Two scales of Δm^2: $\Delta m^2_{\text{ATM}} \simeq 30\,\Delta m^2_{\text{SOL}}$

Large mixings: $\vartheta_{\text{ATM}} \simeq 45^\circ$, $\quad \vartheta_{\text{SOL}} \simeq 33^\circ$

Three-Neutrino Mixing

$$\nu_{\alpha L} = \sum_{k=1}^{3} U_{\alpha k}\, \nu_{kL} \qquad (\alpha = e, \mu, \tau)$$

three flavor fields: ν_e, ν_μ, ν_τ

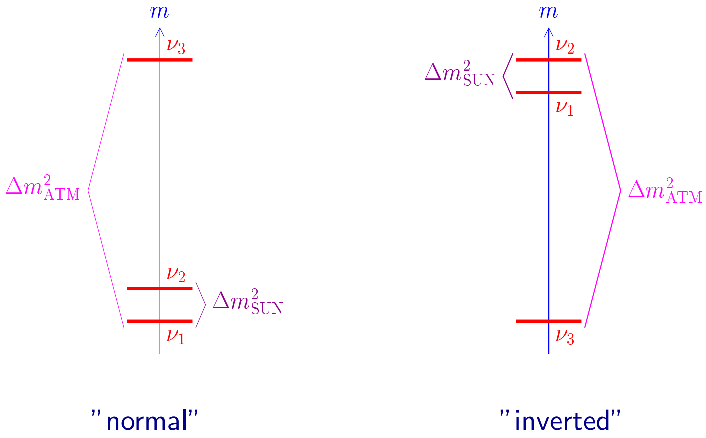
three massive fields: ν_1, ν_2, ν_3

$$\Delta m^2_{21} + \Delta m^2_{32} + \Delta m^2_{13} = m^2_2 - m^2_1 + m^2_3 - m^2_2 + m^2_1 - m^2_3 = 0$$

$$\Delta m^2_{\text{SOL}} = \Delta m^2_{21} \simeq 7.6 \times 10^{-5}\,\text{eV}^2$$

$$\Delta m^2_{\text{ATM}} \simeq |\Delta m^2_{31}| \simeq |\Delta m^2_{32}| \simeq 2.4 \times 10^{-3}\,\text{eV}^2$$

Allowed Three-Neutrino Schemes



different signs of $\Delta m^2_{31} \simeq \Delta m^2_{32}$

absolute scale is not determined by neutrino oscillation data

Mixing Matrix

$$\boxed{\Delta m^2_{21} \ll |\Delta m^2_{31}|}$$

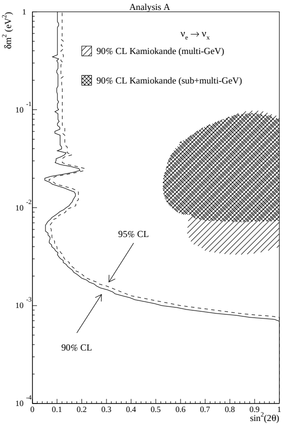
$$\begin{array}{rc} \text{SOL} \rightarrow & \\ U = & \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu1} & U_{\mu2} & U_{\mu3} \\ U_{\tau1} & U_{\tau2} & U_{\tau3} \end{pmatrix} \\ & \uparrow \\ & \text{ATM \& LBL} \end{array}$$

CHOOZ: $\begin{cases} \Delta m^2_{\text{CHOOZ}} = \Delta m^2_{31} = \Delta m^2_{\text{ATM}} \\ \sin^2 2\vartheta_{\text{CHOOZ}} = 4|U_{e3}|^2(1-|U_{e3}|^2) \end{cases}$

$$\Downarrow$$

$$\boxed{|U_{e3}|^2 \lesssim 5 \times 10^{-2}}$$

SOLAR AND ATMOSPHERIC ν OSCILLATIONS ARE PRACTICALLY DECOUPLED!



[CHOOZ, PLB 466 (1999) 415]

[Palo Verde, PRD 64 (2001) 112001]

$$|U_{e1}|^2 \simeq \cos^2\vartheta_{\text{SOL}} \qquad |U_{e2}|^2 \simeq \sin^2\vartheta_{\text{SOL}}$$

$$|U_{\mu3}|^2 \simeq \sin^2\vartheta_{\text{ATM}} \qquad |U_{\tau3}|^2 \simeq \cos^2\vartheta_{\text{ATM}}$$

$$U = \underbrace{\begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix}}_{\vartheta_{23} \simeq \vartheta_{\text{ATM}}} \begin{pmatrix} c_{13} & 0 & s_{13} e^{-i\delta_{13}} \\ 0 & 1 & 0 \\ -s_{13} e^{i\delta_{13}} & 0 & c_{13} \end{pmatrix} \underbrace{\begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}}_{\vartheta_{12} \simeq \vartheta_{\text{SOL}}} \underbrace{\begin{pmatrix} 1 & 0 & 0 \\ 0 & e^{i\lambda_2} & 0 \\ 0 & 0 & e^{i\lambda_3} \end{pmatrix}}_{\beta\beta_{0\nu}}$$

$$\Delta m^2_{21} = \left(7.65^{+0.23}_{-0.20}\right) \times 10^{-5}\,\text{eV}^2 \qquad |\Delta m^2_{31}| = \left(2.40^{+0.12}_{-0.11}\right) \times 10^{-3}\,\text{eV}^2$$

$$\sin^2\vartheta_{12} = 0.304^{+0.022}_{-0.016} \qquad \sin^2\vartheta_{23} = 0.50^{+0.07}_{-0.06}$$

$$\sin^2\vartheta_{13} < 0.035 \quad (90\%\ \text{C.L.})$$

[Schwetz, Tortola, Valle, arXiv:0808.2016v3, 11 Feb 2010]

$$U \simeq \begin{pmatrix} \sqrt{2/3} & 1/\sqrt{3} & 0 \\ -1/\sqrt{6} & 1/\sqrt{3} & 1/\sqrt{2} \\ 1/\sqrt{6} & -1/\sqrt{3} & 1/\sqrt{2} \end{pmatrix}$$

Tri-Bimaximal Mixing

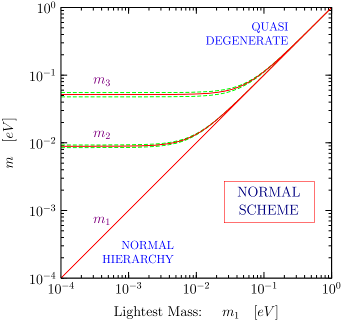
[Harrison, Perkins, Scott, PLB 530 (2002) 167]

Current Research

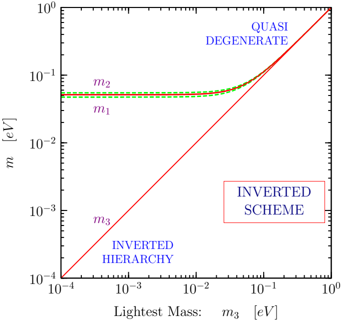
measure $\vartheta_{13} \neq 0 \Longrightarrow$ CP violation, matter effects, mass hierarchy

Absolute Scale of Neutrino Masses

normal scheme



inverted scheme



$$m_2^2 = m_1^2 + \Delta m_{21}^2 = m_1^2 + \Delta m_{\mathrm{SOL}}^2$$
$$m_3^2 = m_1^2 + \Delta m_{31}^2 = m_1^2 + \Delta m_{\mathrm{ATM}}^2$$

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

Quasi-Degenerate for $m_1 \simeq m_2 \simeq m_3 \simeq m_\nu \gg \sqrt{\Delta m_{\mathrm{ATM}}^2} \simeq 5 \times 10^{-2}\,\mathrm{eV}$

- Tritium Beta-Decay

  $m_\nu < 2.2\,\mathrm{eV} \quad (95\%\ \mathrm{C.L.})$ Mainz & Troitsk [hep-ex/0210050]

  KATRIN sensitivity: $m_\nu \simeq 0.2\,\mathrm{eV}$ [hep-ex/0109033, hep-ex/0309007]

- Neutrinoless Double-Beta Decay

  $|m_{\beta\beta}| \lesssim 0.3 - 0.7\,\mathrm{eV} \quad (90\%\ \mathrm{C.L.})$ CUORICINO [arXiv:1012.3266]

- Cosmology

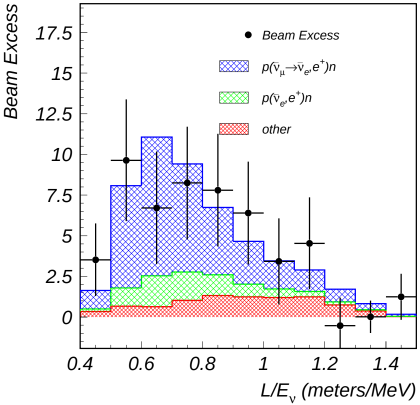
  $m_\nu \lesssim 0.07 - 0.2\,\mathrm{eV} \quad (95\%\ \mathrm{C.L.})$ [hep-ph/0805.2517, arXiv:1006.3795]

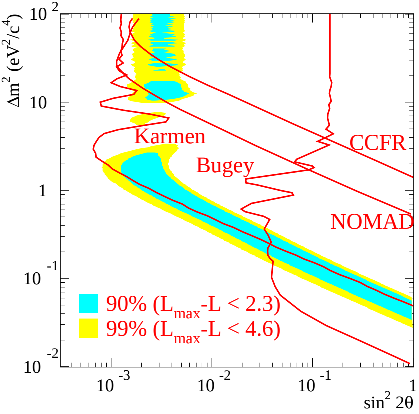
Anomalies Beyond 3-ν Mixing

LSND

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

$\bar{\nu}_\mu \to \bar{\nu}_e \qquad L \simeq 30\,\text{m} \qquad 20\,\text{MeV} \leq E \leq 200\,\text{MeV}$



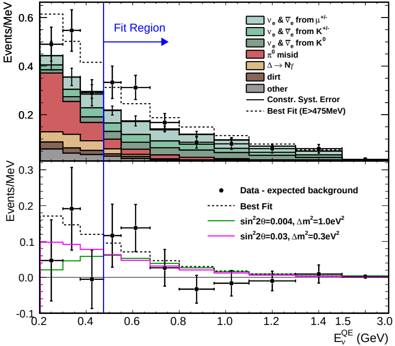


$\Delta m^2_{\text{LSND}} \gtrsim 0.2\,\text{eV}^2 \qquad (\gg \Delta m^2_{\text{ATM}} \gg \Delta m^2_{\text{SOL}})$

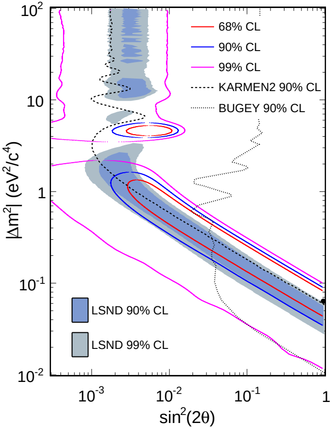
MiniBooNE Antineutrinos

[PRL 103 (2009) 111801; PRL 105 (2010) 181801]

$\bar{\nu}_\mu \to \bar{\nu}_e$ $\quad L \simeq 541\,\text{m}$ $\quad 475\,\text{MeV} \leq E \lesssim 3\,\text{GeV}$



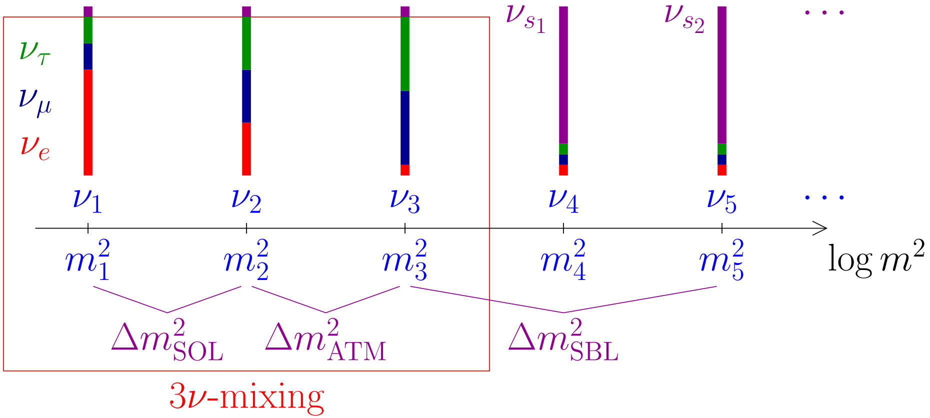
[MiniBooNE, PRL 105 (2010) 181801, arXiv:1007.1150]



Agreement with LSND $\bar{\nu}_\mu \to \bar{\nu}_e$ signal!

Similar L/E but different L and E $\Longrightarrow$ Oscillations!

Beyond Three-Neutrino Mixing



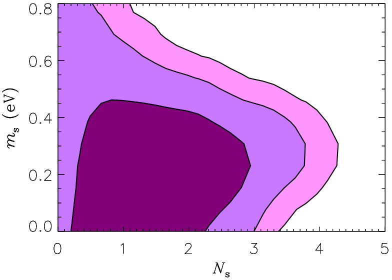
Sterile Neutrinos

- Sterile means no standard model interactions
- Active neutrinos $(\nu_e, \nu_\mu, \nu_\tau)$ can oscillate into sterile neutrinos (ν_s)
- Observables:
  - Disappearance of active neutrinos
  - Indirect evidence through combined fit of data (current indication)
- Powerful window on new physics beyond the Standard Model

Cosmology

- N_s = number of thermalized sterile neutrinos (not necessarily integer)

- CMB and LSS in ΛCDM:



[Hamann, Hannestad, Raffelt, Tamborra, Wong, PRL 105 (2010) 181301, arXiv:1006.5276]

$$N_s = 1.61 \pm 0.92 \qquad\qquad m_{\nu_s} < 0.70\,\text{eV} \quad (95\%\ \text{C.L.})$$

[Giusarma, Corsi, Archidiacono, de Putter, Melchiorri, Mena, Pandolfi, arXiv:1102.4774]

- BBN:

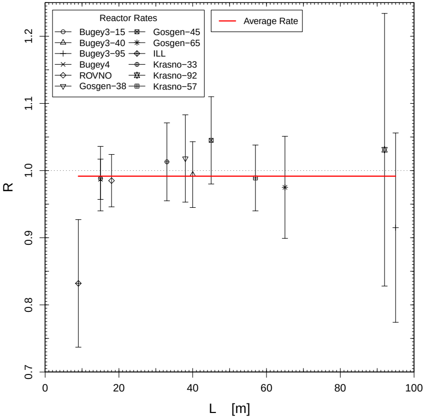
$$N_s = 0.22 \pm 0.59$$ [Cyburt, Fields, Olive, Skillman, AP 23 (2005) 313, astro-ph/0408033]

$$N_s = 0.64^{+0.40}_{-0.35}$$ [Izotov, Thuan, ApJL 710 (2010) L67, arXiv:1001.4440]

Reactor Antineutrino Anomaly

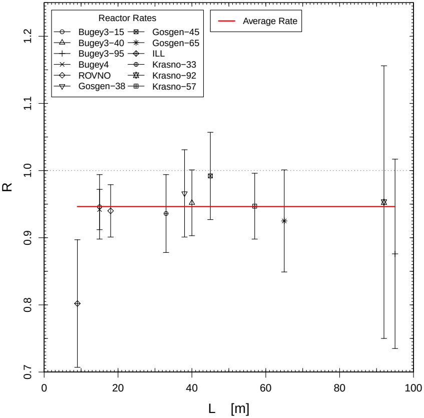
- Improved Predictions of Reactor Antineutrino Spectra, arXiv:1101.2663
- The Reactor Antineutrino Anomaly, arXiv:1101.2755

Standard Reactor $\bar{\nu}_e$ Fluxes



$$\overline{R} = 0.992 \pm 0.024$$

New Reactor $\bar{\nu}_e$ Fluxes



$$\overline{R} = 0.946 \pm 0.024$$

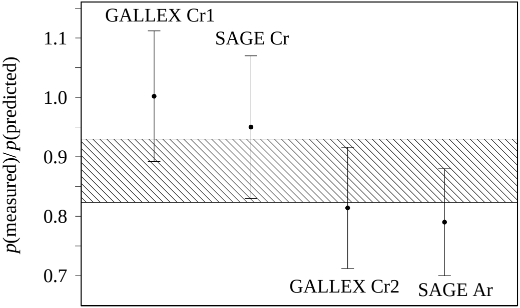
Gallium Anomaly

Gallium Radioactive Source Experiments

Tests of the solar neutrino detectors GALLEX (Cr1, Cr2) and SAGE (Cr, Ar)

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

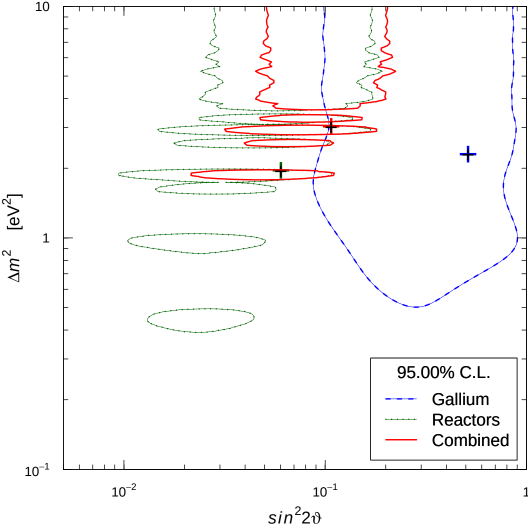
ν_e Sources: $e^- + {}^{51}\text{Cr} \to {}^{51}\text{V} + \nu_e$ $e^- + {}^{37}\text{Ar} \to {}^{37}\text{Cl} + \nu_e$



$\boxed{R_{\text{Ga}} = 0.86 \pm 0.05}$

[SAGE, PRC 73 (2006) 045805, nucl-ex/0512041]

Gallium Anomaly + Reactor Anomaly



$\chi^2_{\text{min}} = 59.6$

$\text{NdF} = 71$

$\text{GoF} = 83\%$

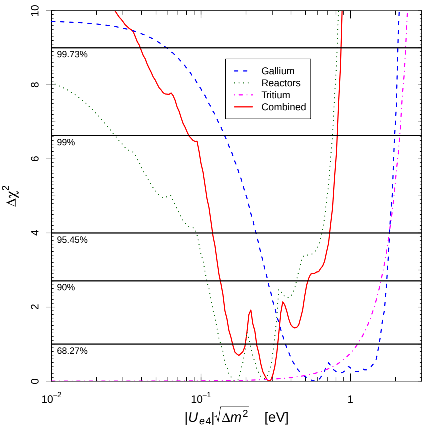
$\sin^2 2\vartheta = 0.11$

$\Delta m^2 = 2.95\,\text{eV}^2$

$\text{PGoF} = 4.6\%$

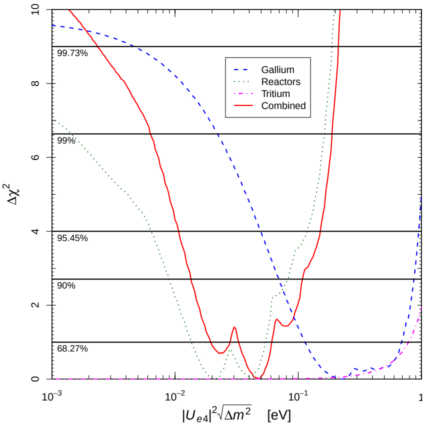
Implications of Gallium and Reactor Anomalies

β Decay



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

$(\beta\beta)_{0\nu}$ Decay



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

[Giunti, Laveder, In Preparation]

Conclusions - Three-Neutrino Mixing

$\nu_e \to \nu_\mu, \nu_\tau$ with $\Delta m^2_{\text{SOL}} \simeq 8.3 \times 10^{-5}\,\text{eV}^2$ (SOL, KamLAND)

$\nu_\mu \to \nu_\tau$ with $\Delta m^2_{\text{ATM}} \simeq 2.4 \times 10^{-3}\,\text{eV}^2$ (ATM, K2K, MINOS)

$\Downarrow$

Bilarge 3ν-Mixing with $|U_{e3}|^2 \ll 1$ (CHOOZ)

β & $\beta\beta_{0\nu}$ Decay and Cosmology $\Longrightarrow$ $m_\nu \lesssim 1\,\text{eV}$

To Do

Theory: Why lepton mixing $\neq$ quark mixing?

(Due to Majorana nature of ν's?)

Why only $|U_{e3}|^2 \ll 1$?

Exp.: Measure $|U_{e3}| > 0 \Rightarrow$ CP viol., matter effects, mass hierarchy.

Find absolute mass scale.

Conclusions - Anomalies

- Existence of sterile neutrinos is a very interesting possibility: powerful window on new physics beyond the Standard Model
- ΛCDM cosmology and BBN hint at $N_s > 0$
- Suggestive LSND and MiniBooNE agreement on SBL $\bar{\nu}_\mu \to \bar{\nu}_e$
- Interesting agreement of
  - Gallium Anomaly (SBL ν_e disappearance)
  - Reactor Anomaly (SBL $\bar{\nu}_e$ disappearance)

  Testable Predictions:
  - $m_\beta \sim 0.12 - 0.71\,\text{eV} \quad (2\sigma)$
  - $m_{\beta\beta} \sim 0.011 - 0.15\,\text{eV} \quad (2\sigma)$
- Phenomenological Work in Progress: combined explanation of LSND and MiniBooNE + Gallium and Reactor Anomalies
- Experimental Work in Progress: study of new short-baseline neutrino oscillation experiments to clarify anomalies