Status of PMNS and Impact of Large ϑ_{13} for Sterile Neutrino Phenomenology

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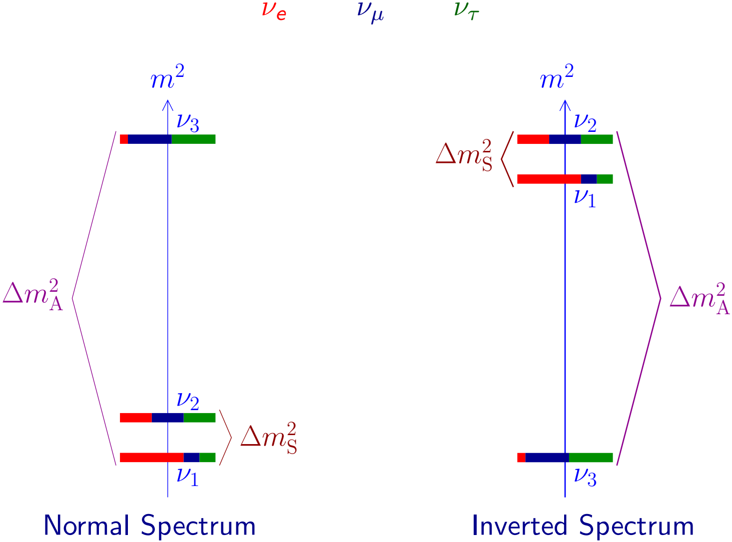
GDR Neutrino

20-21 June 2012, APC, Paris, France

Three-Neutrino Mixing Paradigm



$$\Delta m^2_{\mathrm{S}} = \Delta m^2_{21} = (7.54^{+0.26}_{-0.22}) \times 10^{-5}\,\mathrm{eV}^2$$

$$\Delta m^2_{\mathrm{A}} = \begin{cases} \Delta m^2_{31} = (2.47^{+0.07}_{-0.09}) \times 10^{-3}\,\mathrm{eV}^2 & \text{Normal Spectrum} \\ \Delta m^2_{23} = (2.46^{+0.07}_{-0.10}) \times 10^{-3}\,\mathrm{eV}^2 & \text{Inverted Spectrum} \end{cases}$$

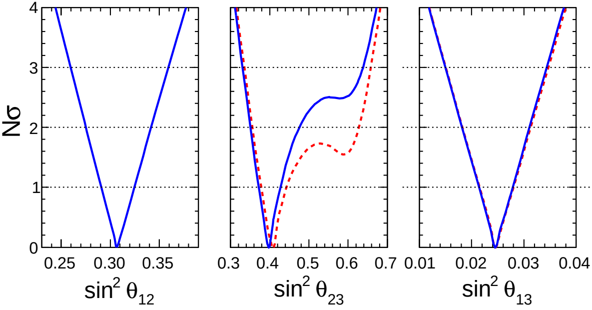
$$\frac{\delta \Delta m^2_{\mathrm{S}}}{\Delta m^2_{\mathrm{S}}} \simeq 3\% \qquad\qquad \frac{\delta \Delta m^2_{\mathrm{A}}}{\Delta m^2_{\mathrm{A}}} \simeq 4\%$$

[Fogli, Lisi, Marrone, Montanino, Palazzo, Rotunno, arXiv:1205.5254v2]

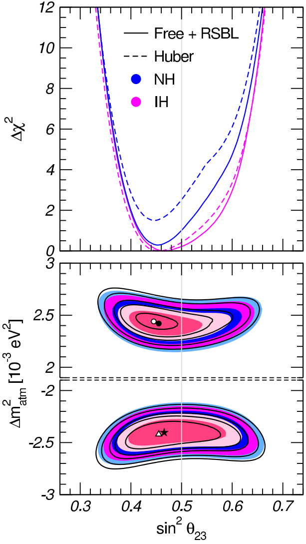
$$U = \begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta_{13}} \\ -s_{12}c_{23}-c_{12}s_{23}s_{13}e^{i\delta_{13}} & c_{12}c_{23}-s_{12}s_{23}s_{13}e^{i\delta_{13}} & s_{23}c_{13} \\ s_{12}s_{23}-c_{12}c_{23}s_{13}e^{i\delta_{13}} & -c_{12}s_{23}-s_{12}c_{23}s_{13}e^{i\delta_{13}} & c_{23}c_{13}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

$$= \underbrace{\begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix}}_{\substack{\vartheta_{23} \simeq \vartheta_{\text{A}} \\ \vartheta_{23} \simeq 45^\circ \pm 5^\circ}} \underbrace{\begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta_{13}} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta_{13}} & 0 & c_{13} \end{pmatrix}}_{\substack{\text{Chooz, Palo Verde} \\ \text{T2K, MINOS} \\ \text{Daya Bay, RENO} \\ \vartheta_{13} \simeq 8.7^\circ \pm 0.5^\circ}} \underbrace{\begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}}_{\substack{\vartheta_{12} \simeq \vartheta_{\text{S}} \\ \vartheta_{12} \simeq 34^\circ \pm 1^\circ}} \underbrace{\begin{pmatrix} 1 & 0 & 0 \\ 0 & e^{i\lambda_2} & 0 \\ 0 & 0 & e^{i\lambda_3} \end{pmatrix}}_{\beta\beta_{0\nu}}$$

$$\frac{\delta\vartheta_{12}}{\vartheta_{12}} \simeq 3\% \qquad \frac{\delta\vartheta_{23}}{\vartheta_{23}} \simeq 10\% \qquad \frac{\delta\vartheta_{13}}{\vartheta_{13}} \simeq 6\%$$

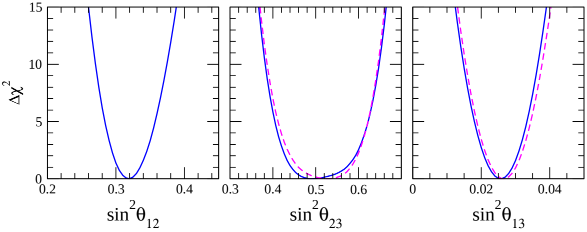


[Fogli, Lisi, Marrone, Montanino, Palazzo, Rotunno, arXiv:1205.5254v2]



[Maltoni@CIPANP2012, with

Gonzalez-Garcia, Salvado, Schwetz]



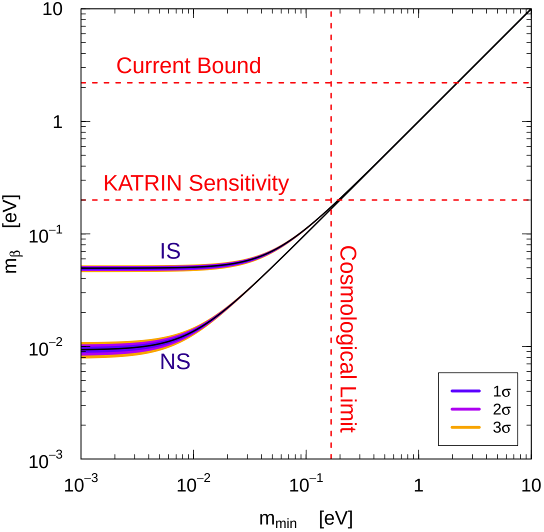
[Forero, Tortola, Valle, arXiv:1205.4018v2]

Open Problems

- $\vartheta_{23} < 45^\circ$?
    - Atmospheric Neutrinos, ...
- $\delta_{13} =$?
    - Nova, LAGUNA, CERN-GS, HyperK, ...
- Mass Hierarchy ?
    - Nova, Atmospheric Neutrinos, Day Bay II, Supernova Neutrinos, ...
- Absolute Mass Scale ?
    - β Decay, Neutrinoless Double-β Decay, Cosmology, ...
- Dirac or Majorana ?
    - Neutrinoless Double-β Decay, ...

β Decay

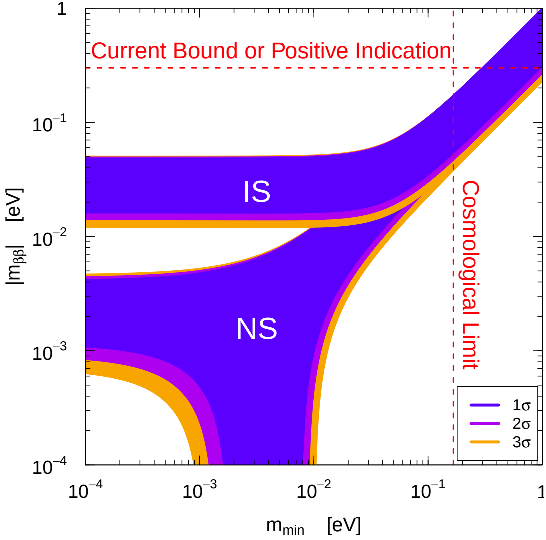
$$m_\beta^2 = |U_{e1}|^2\, m_1^2 + |U_{e2}|^2\, m_2^2 + |U_{e3}|^2\, m_3^2$$



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

Neutrinoless Double-β Decay

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



- Positive indication: tension with cosmology
- Quasi-Degenerate:

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

- Inverted Hierarchy:

$$|m_{\beta\beta}| \simeq \sqrt{\Delta m^2_{\text{A}} (1 - s^2_{2\vartheta_{12}} s^2_{\alpha_2})}$$

- Normal Hierarchy:

$$|m_{\beta\beta}| \simeq |s^2_{12} \sqrt{\Delta m^2_{\text{S}}} + e^{i\alpha} s^2_{13} \sqrt{\Delta m^2_{\text{A}}}|$$

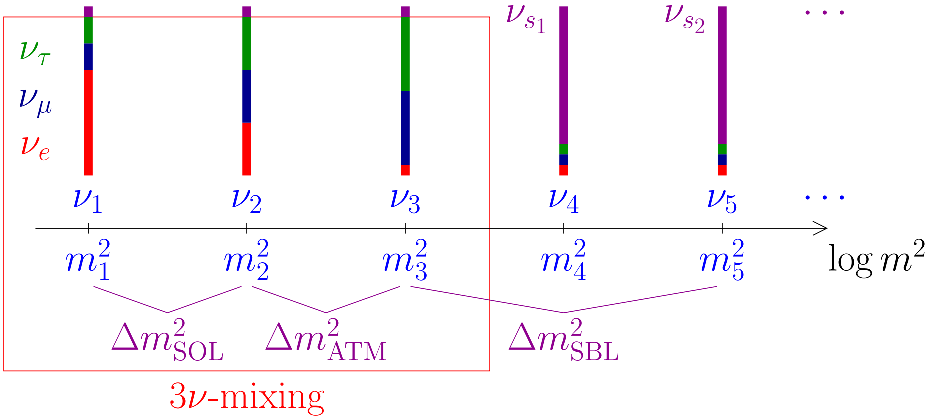
$$\simeq |2.7 + 1.2 e^{i\alpha}| \times 10^{-3}\, \text{eV}$$

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

$$\Downarrow$$

Normal Spectrum

Beyond Three-Neutrino Mixing



Standard Model

- Neutrinos are the only massless fermions
- Neutrinos are the only fermions with only left-handed component ν_L
- Neutrinos are the only neutral fermions

Extension of the SM: Massive Neutrinos

- Simplest extension: introduce right-handed component ν_R (singlet of $SU(2)_L \times U(1)_Y$)
- One generation: Dirac mass $m_{\text{D}} \overline{\nu_R} \nu_L$ + Majorana mass $m_{\text{M}} \overline{\nu_R^c} \nu_R$
  $\Longrightarrow$ 2 massive Majorana neutrinos
- Three left-handed fields + N_R right-handed fields:
  $\nu_{eL} \, , \; \nu_{\mu L} \, , \; \nu_{\tau L} \; + \; \nu_{1R} \, , \; \ldots \, , \; \nu_{N_R R}$
  $\Longrightarrow$ $3 + N_R$ massive Majorana neutrinos

Sterile Neutrinos

- Light anti-ν_R are called sterile neutrinos

$$\nu_R^c \to \nu_{sL} \qquad \text{(left-handed)}$$

- 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 (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 LSND, MiniBooNE, Reactor Anomaly, Gallium Anomaly.

- Other possibilities (not incompatible):
  - Very light sterile neutrinos with mass scale $\ll 1\,\text{eV}$: important for solar neutrino phenomenology

    [de Holanda, Smirnov, PRD 83 (2011) 113011, arXiv:1012.5627]

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

    [Kusenko, Phys. Rept. 481 (2009) 1, arXiv:0906.2968]

    [Boyarsky, Ruchayskiy, Shaposhnikov, Ann. Rev. Nucl. Part. Sci. 59 (2009) 191, arXiv:0901.0011]

Effective SBL Oscillation Probabilities in 3+1 Schemes

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

No CP Violation!

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

Perturbation of 3ν Mixing

$$|U_{e4}|^2 \ll 1 \,, \quad |U_{\mu 4}|^2 \ll 1 \,, \quad |U_{\tau 4}|^2 \ll 1 \,, \quad |U_{s4}|^2 \simeq 1$$

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

$$\uparrow$$

SBL

$$\sin^2 2\vartheta_{\alpha\alpha} \ll 1$$

$$\Downarrow$$

$$|U_{\alpha 4}|^2 \simeq \frac{\sin^2 2\vartheta_{\alpha\alpha}}{4}$$

Effective SBL Oscillation Probabilities in 3+2 Schemes

$$\phi_{kj} = \Delta m^2_{kj} L / 4E$$

$$\eta = \arg[U^*_{e4} U_{\mu 4} U_{e5} U^*_{\mu 5}]$$

$$\begin{aligned} P_{\overset{(-)}{\nu}_\mu \to \overset{(-)}{\nu}_e} = {} & 4|U_{e4}|^2|U_{\mu 4}|^2 \sin^2\phi_{41} + 4|U_{e5}|^2|U_{\mu 5}|^2 \sin^2\phi_{51} \\ & + 8|U_{\mu 4} U_{e4} U_{\mu 5} U_{e5}| \sin\phi_{41} \sin\phi_{51} \cos(\phi_{54} \overset{(+)}{-} \eta) \end{aligned}$$

$$\begin{aligned} P_{\overset{(-)}{\nu}_\alpha \to \overset{(-)}{\nu}_\alpha} = {} & 1 - 4(1 - |U_{\alpha 4}|^2 - |U_{\alpha 5}|^2)(|U_{\alpha 4}|^2 \sin^2\phi_{41} + |U_{\alpha 5}|^2 \sin^2\phi_{51}) \\ & - 4|U_{\alpha 4}|^2|U_{\alpha 5}|^2 \sin^2\phi_{54} \end{aligned}$$

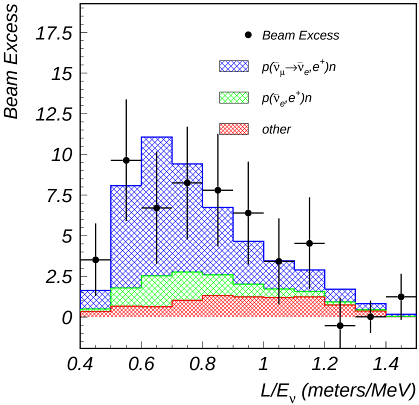
- More parameters: 7 (vs 3 in 3+1)
- CP violation

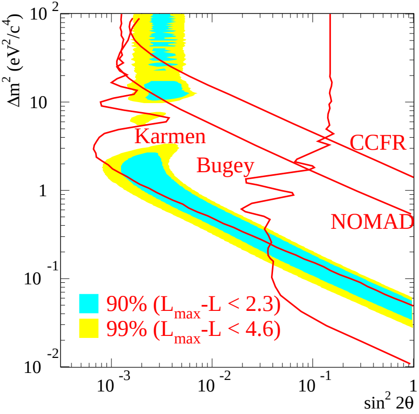
[Sorel, Conrad, Shaevitz, PRD 70 (2004) 073004; Maltoni, Schwetz, PRD 76 (2007) 093005; Karagiorgi et al, PRD 80 (2009) 073001; Kopp, Maltoni, Schwetz, PRL 107 (2011) 091801; Giunti, Laveder, PRD 84 (2011) 073008; Donini et al, arXiv:1205.5230]

LSND

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

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



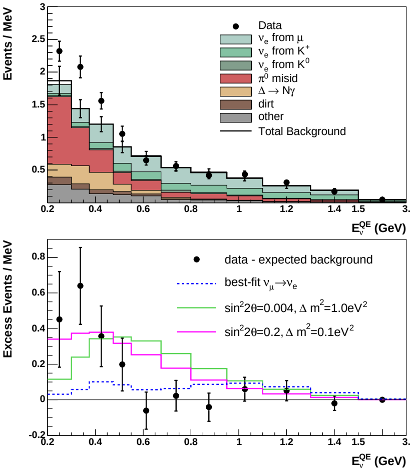


$$\Delta m^2_{\mathrm{LSND}} \gtrsim 0.2\,\mathrm{eV}^2 \qquad (\gg \Delta m^2_{\mathrm{A}} \gg \Delta m^2_{\mathrm{S}})$$

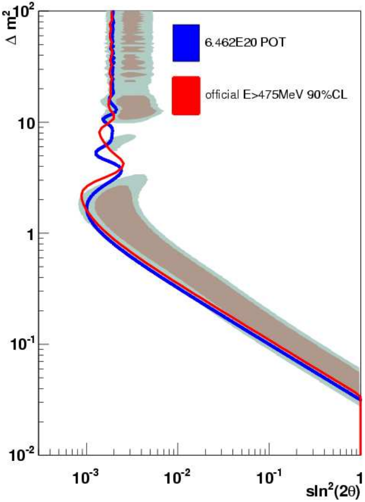
MiniBooNE Neutrinos

[PRL 98 (2007) 231801; PRL 102 (2009) 101802]

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



[MiniBooNE, PRL 102 (2009) 101802]



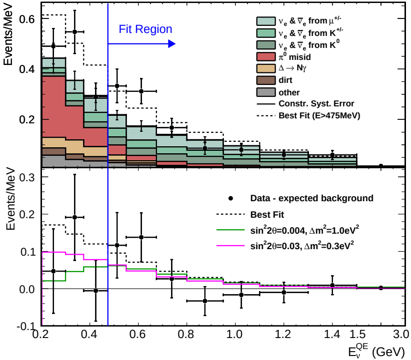
[Djurcic, arXiv:0901.1648]

- no $\nu_\mu \to \nu_e$ signal corresponding to LSND $\bar{\nu}_\mu \to \bar{\nu}_e$ signal ($E > 475\,\text{MeV}$)
- low-energy anomaly

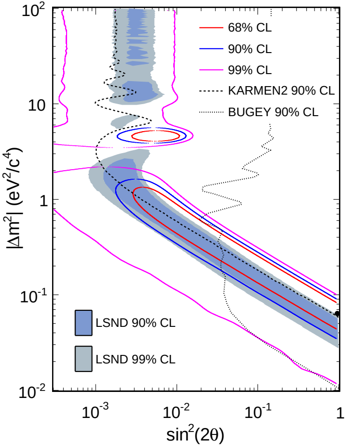
MiniBooNE Antineutrinos - 2009-2010

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

$\bar{\nu}_\mu \to \bar{\nu}_e$ $L \simeq 541\,\text{m}$ $200\,\text{MeV} \le E \lesssim 3\,\text{GeV}$

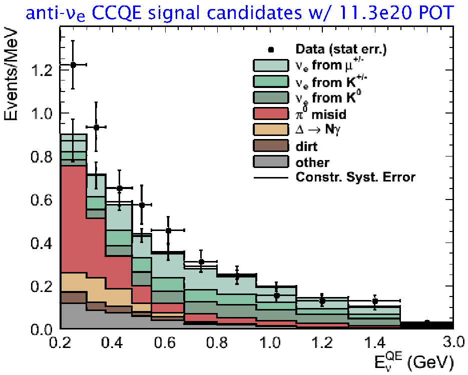


[MiniBooNE, PRL 105 (2010) 181801]



- 5.7e20 POT: agreement with LSND $\bar{\nu}_\mu \to \bar{\nu}_e$ signal ($E > 475\,\text{MeV}$)
- similar L/E but different L and $E \Longrightarrow$ oscillations

MiniBooNE $\bar{\nu}$ - Neutrino 2012 - 6 June



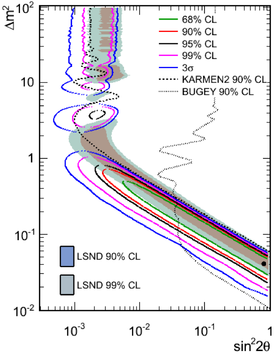
Higher stat anti-neutrino data is now much more consistent with what was observed in the data taken with a neutrino beam

* Systematic error after all other data constraints applied, e.g. ν_μ CCQE, NC π^0 , dirt events, SciBooNE K^+

		1st half			2nd half	
	data	mc	excess	data	mc	excess
200-475	119	100.5±14.3	18.5 (1.3s)	138	100.0±14.1	38 (2.7s)
475-1250	120	99.1±14.0	20.9 (1.5s)	101	103.1±14.4	-2.2 (-0.2s)

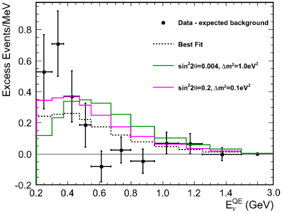
agreement with LSND signal is sadly vanishing

MiniBooNE ν and $\bar{\nu}$ - Neutrino 2012 - 6 June



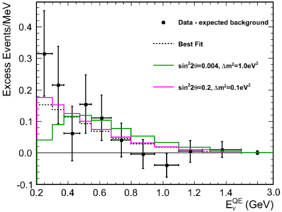
fit of low-energy excesses is excluded by reactor bound!

Total Excess: 240.3 +/- 34.5 +/- 52.6



* Simultaneous fit (E>200 MeV) with fully-correlated systematic to entire MB neutrino and anti-neutrino data

combined	E > 200 MeV	E > 475 MeV
χ^2(null)	42.53	12.87
Prob(null)	0.1%	35.8%
χ^2(bf)	24.72	10.67
Prob(bf)	6.7%	35.8%

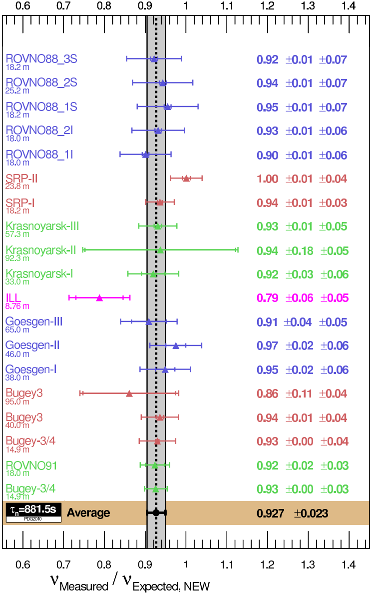


Neutrino energy reconstruction problem?

[Martini, Ericson, Chanfray, arXiv:1202.4745]

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]

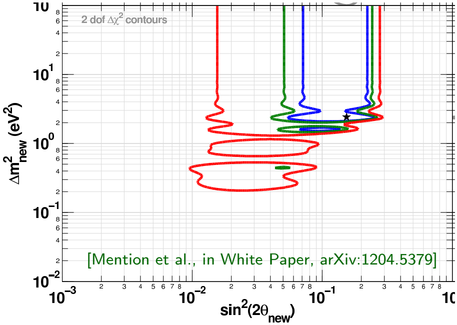
Detection: $\sigma(\bar{\nu}_e + p \to n + e^+) \propto \tau_n^{-1}$

PDG	neutron lifetime τ_n
1995	887.0 ± 2.0 sec
1998	886.7 ± 1.9 sec
2002	885.7 ± 0.8 sec
2011	881.5 ± 1.5 sec

change of predicted event rates

^{235}U	^{238}U	^{239}Pu	^{241}Pu
$+3.7\%$	$+9.8\%$	$+4.2\%$	$+4.7\%$

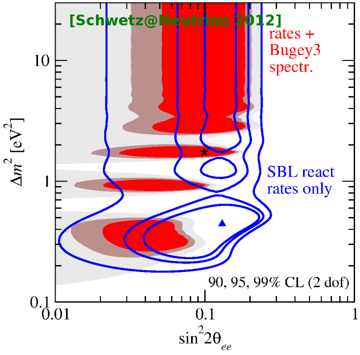
Reactor $\bar{\nu}_e$ Disappearance



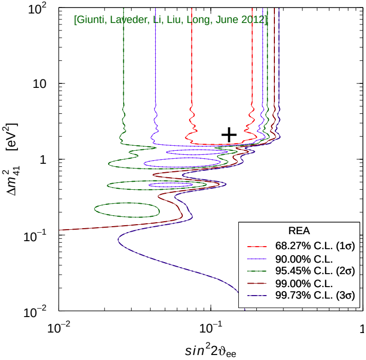
[Mention et al., in White Paper, arXiv:1204.5379]

$$P_{\nu_e \to \nu_e} = 1 - \sin^2 2\vartheta_{ee} \sin^2 \left(\frac{\Delta m^2_{41} L}{4E} \right)$$

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



[Schwetz@Neutrino 2012]



[Giunti, Laveder, Li, Liu, Long, June 2012]

Gallium Anomaly

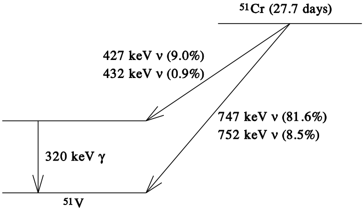
Gallium Radioactive Source Experiments

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

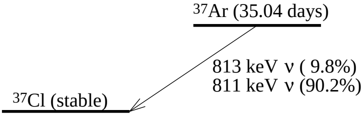
Detection Process: $\nu_e + {}^{71}\text{Ga} \to {}^{71}\text{Ge} + e^-$

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

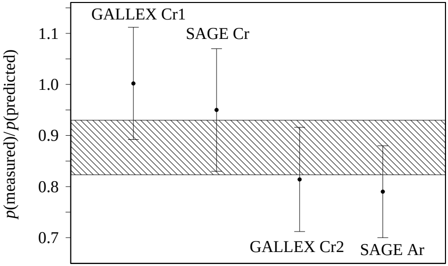
	${}^{51}\text{Cr}$				${}^{37}\text{Ar}$	
E [keV]	747	752	427	432	811	813
B.R.	0.8163	0.0849	0.0895	0.0093	0.902	0.098



[SAGE, PRC 59 (1999) 2246, hep-ph/9803418]



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



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

$$R_{\mathrm{B}}^{\text{GALLEX-Cr1}} = 0.953 \pm 0.11$$
$$R_{\mathrm{B}}^{\text{GALLEX-Cr2}} = 0.812^{+0.10}_{-0.11}$$
$$R_{\mathrm{B}}^{\text{SAGE-Cr}} = 0.95 \pm 0.12$$
$$R_{\mathrm{B}}^{\text{SAGE-Ar}} = 0.791^{+0.084}_{-0.078}$$

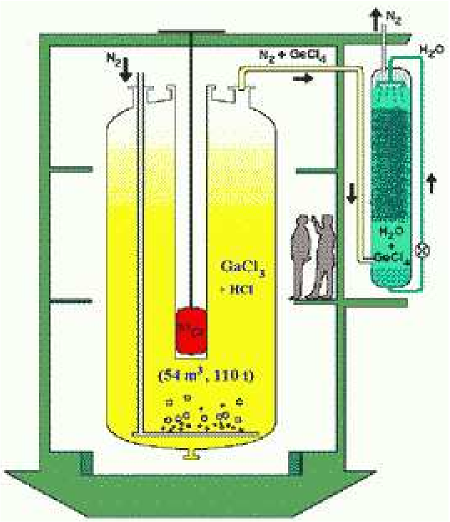
$$\boxed{R_{\mathrm{B}}^{\mathrm{Ga}} = 0.86 \pm 0.05}$$

Bahcall cross section without uncertainty

[Bahcall, PRC 56 (1997) 3391, hep-ph/9710491]

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

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

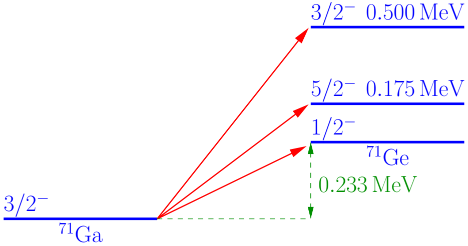


[GALLEX]

- Deficit could be due to overestimate of

$$\sigma(\nu_e + {}^{71}\text{Ga} \to {}^{71}\text{Ge} + e^-)$$

- Calculation: Bahcall, PRC 56 (1997) 3391



- $\sigma_{\text{G.S.}}$ from $T_{1/2}({}^{71}\text{Ge}) = 11.43 \pm 0.03\,\text{days}$ [Hampel, Remsberg, PRC 31 (1985) 666]

$$\sigma_{\text{G.S.}}({}^{51}\text{Cr}) = 55.3 \times 10^{-46}\,\text{cm}^2\,(1 \pm 0.004)_{3\sigma}$$

- $\sigma({}^{51}\text{Cr}) = \sigma_{\text{G.S.}}({}^{51}\text{Cr}) \left(1 + 0.669\,\frac{\text{BGT}_{175}}{\text{BGT}_{\text{G.S.}}} + 0.220\,\frac{\text{BGT}_{500}}{\text{BGT}_{\text{G.S.}}}\right)$

- Contribution of Excited States only 5%!

		$\frac{\text{BGT}_{175}}{\text{BGT}_{\text{G.S.}}}$	$\frac{\text{BGT}_{500}}{\text{BGT}_{\text{G.S.}}}$
Krofcheck et al. PRL 55 (1985) 1051	$^{71}\text{Ga}(p,n)^{71}\text{Ge}$	< 0.056	0.13 ± 0.02
Haxton PLB 431 (1998) 110	Shell Model	0.19 ± 0.18	
Frekers et al. PLB 706 (2011) 134	$^{71}\text{Ga}(^{3}\text{He},{}^{3}\text{H})^{71}\text{Ge}$	0.039 ± 0.030	0.202 ± 0.016

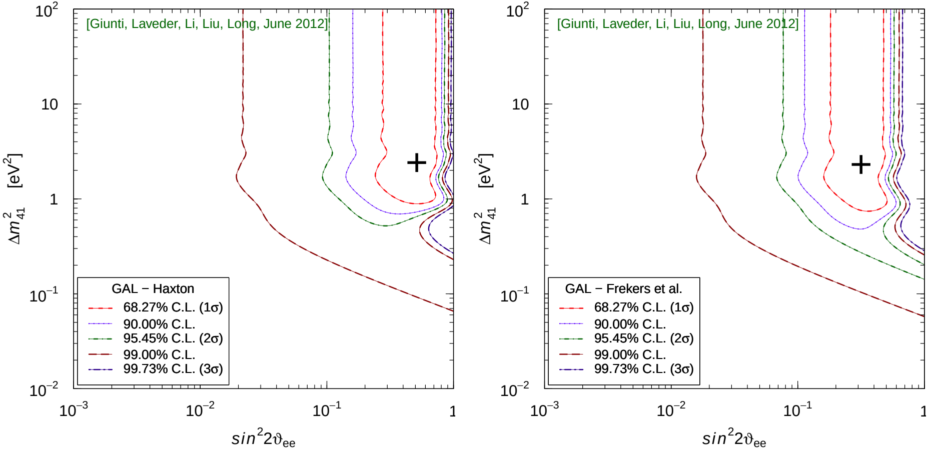
- Haxton: [Haxton, PLB 431 (1998) 110]

  "a sophisticated shell model calculation is performed ... for the transition to the first excited state in ^{71}Ge. The calculation predicts destructive interference between the (p, n) spin and spin-tensor matrix elements"

- 2.7σ discrepancy of $\text{BGT}_{500}/\text{BGT}_{\text{G.S.}}$ measurements

- Anyhow, new $^{71}\text{Ga}(^{3}\text{He},{}^{3}\text{H})^{71}\text{Ge}$ data support Gallium Anomaly!

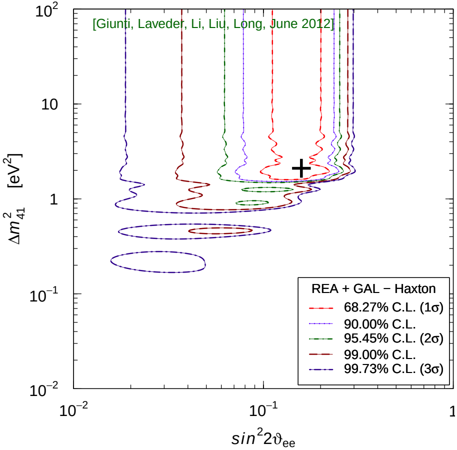
Gallium ν_e Disappearance

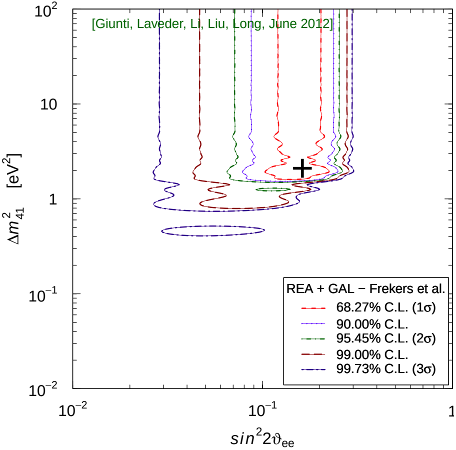


No Osc.	χ^2_{min}	14.9
	NDF	4
	GoF	0.5 %
3+1	χ^2_{min}	4.7
	NDF	2
	GoF	9.5 %
	$\Delta m^2_{41}[\text{eV}^2]$	2.24
	$\sin^2 2\vartheta_{ee}$	0.51

No Osc.	χ^2_{min}	18.2
	NDF	4
	GoF	0.1 %
3+1	χ^2_{min}	7.9
	NDF	2
	GoF	1.9 %
	$\Delta m^2_{41}[\text{eV}^2]$	2.14
	$\sin^2 2\vartheta_{ee}$	0.32

Reactor $\bar{\nu}_e$ and Gallium ν_e Disappearance

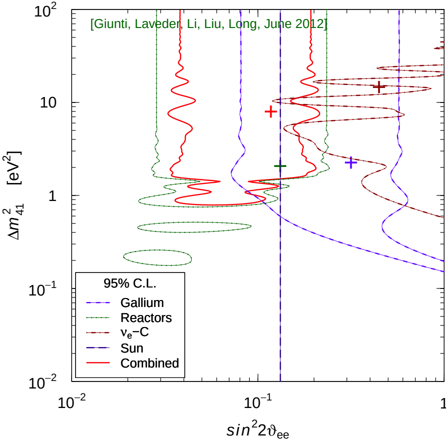


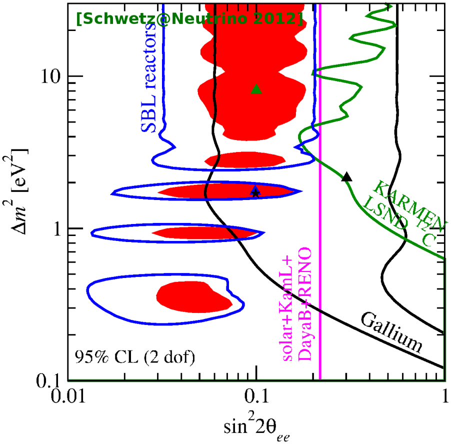


No Osc.	χ^2_{min}	45.6
	NDF	42
	GoF	32.3 %
3+1	χ^2_{min}	30.8
	NDF	40
	GoF	85 %
	Δm^2_{41} [eV^2]	1.95
	$\sin^2 2\vartheta_{ee}$	0.16

No Osc.	χ^2_{min}	48.9
	NDF	42
	GoF	21.5 %
3+1	χ^2_{min}	32.2
	NDF	40
	GoF	80 %
	Δm^2_{41} [eV^2]	1.95
	$\sin^2 2\vartheta_{ee}$	0.16

Global ν_e and $\bar{\nu}_e$ Disappearance





KARMEN + LSND

$\nu_e + {}^{12}\text{C} \to {}^{12}\text{N}_{\text{g.s.}} + e^-$

[Conrad, Shaevitz, PRD 85 (2012) 013017]

[Giunti, Laveder, PLB 706 (2011) 200]

SUN&KamLAND + ϑ_{13}

[Giunti, Li, PRD 80 (2009) 113007]

[Palazzo, PRD 83 (2011) 113013]

[Palazzo, PRD 85 (2012) 077301]

SUN&KamLAND + ϑ_{13} bound on $|U_{e4}|^2$

[Giunti, Li, PRD 80 (2009) 113007; Palazzo, PRD 83 (2011) 113013, PRD 85 (2012) 077301]

3+1 with simplifying assumptions: $U_{\mu 4} = U_{\tau 4} = 0$, no CP violation

$$U_{e1} = c_{12} c_{13} c_{14} \qquad U_{e2} = s_{12} c_{13} c_{14} \qquad U_{e3} = s_{13} c_{14} \qquad U_{e4} = s_{14}$$

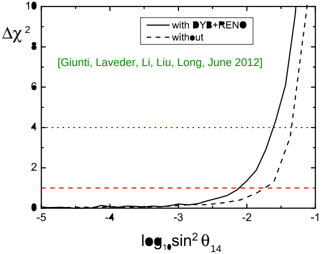
$$U_{s1} = -c_{12} c_{13} s_{14} \quad U_{s2} = -s_{12} c_{13} s_{14} \quad U_{s3} = -s_{13} s_{14} \quad U_{s4} = c_{14}$$

$$P_{\nu_e \to \nu_e} = c_{13}^4 c_{14}^4 P_{\nu_e \to \nu_e}^{2\nu} + s_{13}^4 c_{14}^4 + s_{14}^4$$

$$P_{\nu_e \to \nu_s} = c_{14}^2 s_{14}^2 \left(c_{13}^4 P_{\nu_e \to \nu_s}^{2\nu} + s_{13}^4 + 1 \right)$$

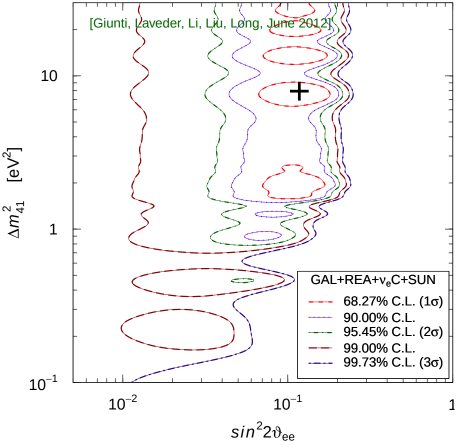
$$V = c_{13}^2 c_{14}^2 V_{\text{CC}} - c_{13}^2 s_{14}^2 V_{\text{NC}} = \left(|U_{e1}|^2 + |U_{e2}|^2 \right) V_{\text{CC}} - \left(|U_{s1}|^2 + |U_{s2}|^2 \right) V_{\text{NC}}$$

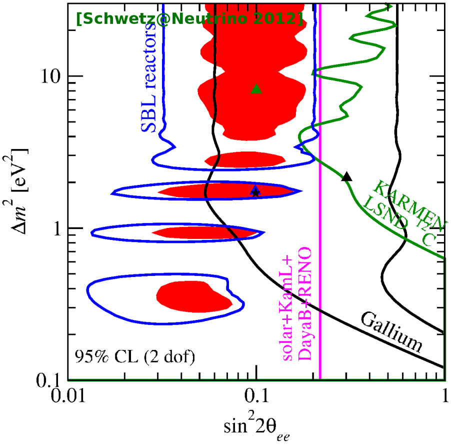
Fit with $U_{\mu 4}$ and $U_{\tau 4}$ free:



[Giunti, Laveder, Li, Liu, Long, June 2012]

Global ν_e and $\bar{\nu}_e$ Disappearance



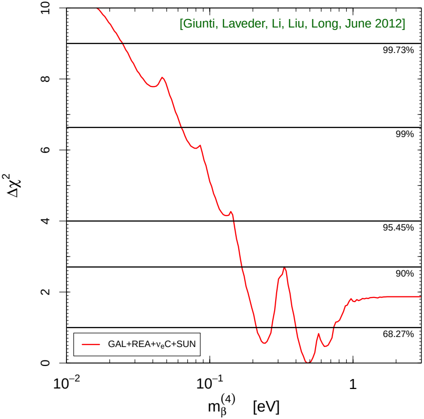


No Osc.	χ^2_{min}	57.1
	NDF	53
	GoF	32.6 %
3+1	χ^2_{min}	46.0
	NDF	51
	GoF	67 %
	Δm^2_{41}[eV^2]	7.59
	$\sin^2 2\vartheta_{ee}$	0.12

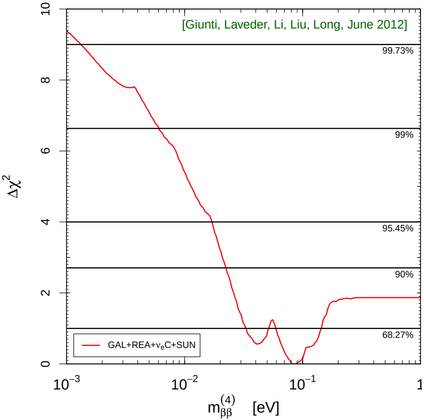
No Osc.	χ^2_{min}	318.4
	NDF	331
	GoF	68%
3+1	χ^2_{min}	306.0
	NDF	329
	GoF	80%
	Δm^2_{41}[eV^2]	1.71
	$\sin^2 2\vartheta_{ee}$	0.099

Testable Implications

β Decay



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



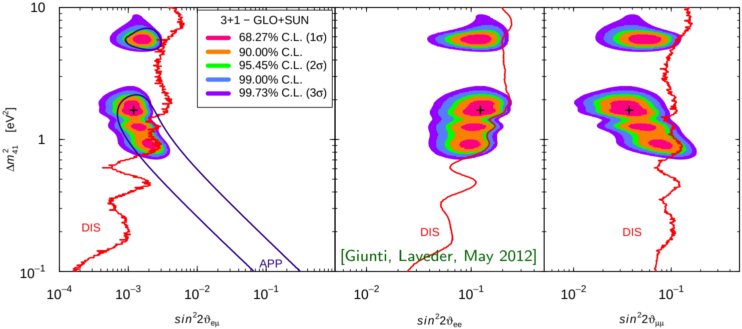
$$m_\beta = \sqrt{\sum_k |U_{ek}|^2 m_k^2}$$

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

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

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

Global 3+1 Fit



[Giunti, Laveder, May 2012]

- MiniBooNE 2011 data ($E > 475\,\text{MeV}$)
- More time is needed to fit MiniBooNE 2012 data

Conclusions

- Three-Neutrino mixing is robust. Open problems: $\vartheta_{23} - 45^\circ$, CP Violation, Mass Hierarchy, Absolute Mass Scale, Dirac or Majorana?
- Short-Baseline $\bar{\nu}_\mu \to \bar{\nu}_e$ Signal is not feeling well:
  - MiniBooNE 2011 antineutrino data were more similar to neutrino data than those of 2010 (LSND signal diminished and low-energy anomaly appeared)
  - MiniBooNE 2012 antineutrino data are even more similar to neutrino data
  - Probably there is no CP violation $\Longrightarrow$ no need of 3+2
  - The decrease of MiniBooNE-LSND agreement is discouraging
  - Better experiments are needed to clarify situation
- Short-Baseline ν_e and $\bar{\nu}_e$ Disappearance is in good health:
  - Reactor $\bar{\nu}_e$ anomaly is alive and exciting
  - Gallium ν_e anomaly has been strengthened by new cross-section measurements
  - Many promising projects to test 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