Phenomenology of Sterile Neutrinos

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Neutrini in Cosmologia

Scuola di Formazione Professionale INFN

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Three-Neutrino Mixing Paradigm

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

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

Reactor
$\bar{\nu}_e$ disappearance

(KamLAND)

$$\to \begin{cases} \Delta m^2_{\text{SOL}} \simeq 7.6 \times 10^{-5}\,\text{eV}^2 \\ \sin^2\vartheta_{\text{SOL}} \simeq 0.32 \end{cases}$$

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

Kamiokande
IMB
Super-Kamiokande
MACRO
Soudan-2

Accelerator
ν_μ disappearance

(K2K & MINOS)

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

Two scales of Δm^2 $\Longleftrightarrow$ Three-Neutrino Mixing

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

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

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

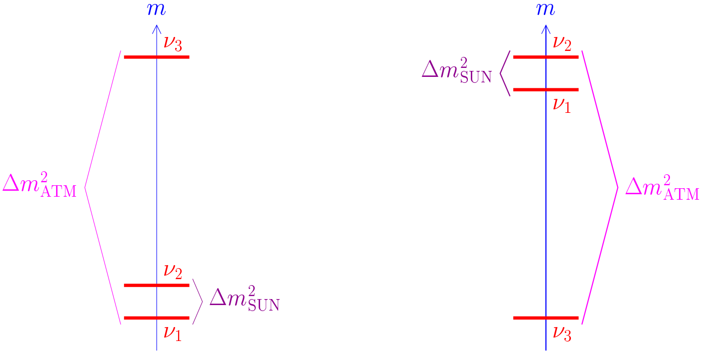
three massive fields: ν_1, ν_2, ν_3

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

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

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

Allowed Three-Neutrino Schemes



"normal" "inverted"

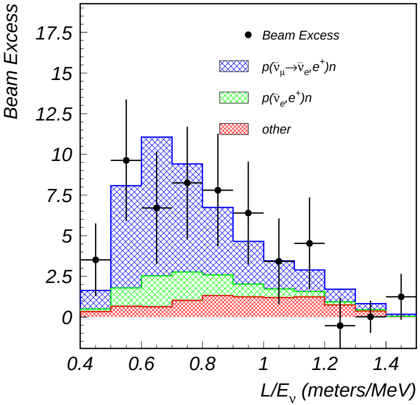
different signs of $\Delta m^2_{31} \simeq \Delta m^2_{32}$

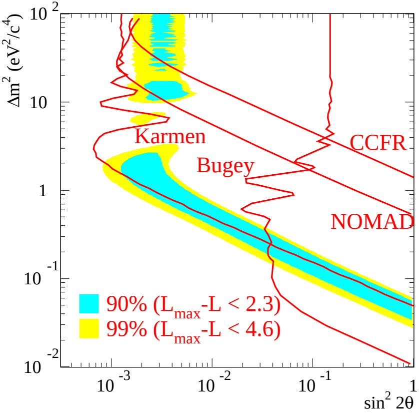
absolute scale is not determined by neutrino oscillation data

LSND

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

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



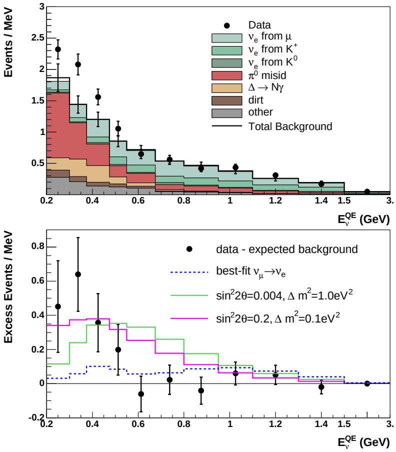


$$\Delta m^2_{\text{LSND}} \gtrsim 0.2\,\text{eV}^2 \qquad (\gg \Delta m^2_{\text{ATM}} \gg \Delta m^2_{\text{SOL}})$$

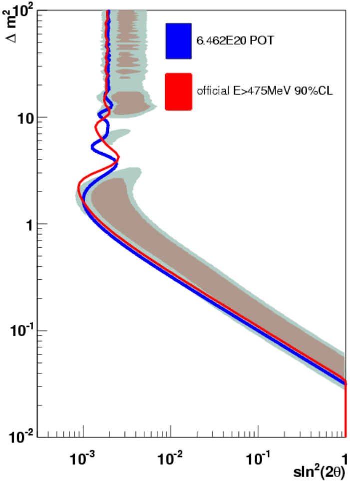
MiniBooNE Neutrinos

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

$\nu_\mu \to \nu_e$ $\qquad L \simeq 541\,\text{m}$ $\qquad 475\,\text{MeV} \leq E \lesssim 3\,\text{GeV}$



[MiniBooNE, PRL 102 (2009) 101802, arXiv:0812.2243]



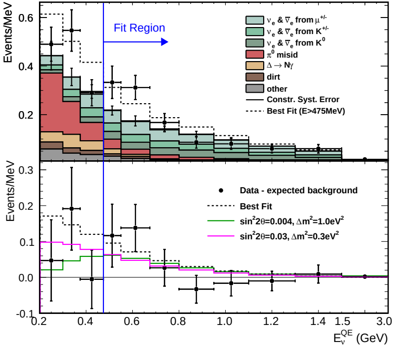
[Djurcic, arXiv:0901.1648]

Low-Energy Anomaly!

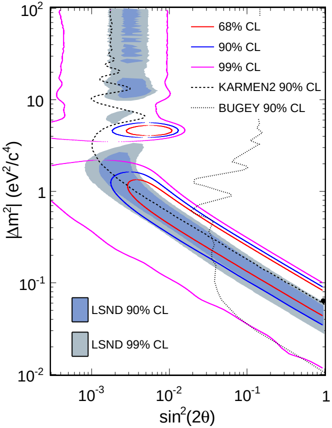
MiniBooNE Antineutrinos

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

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



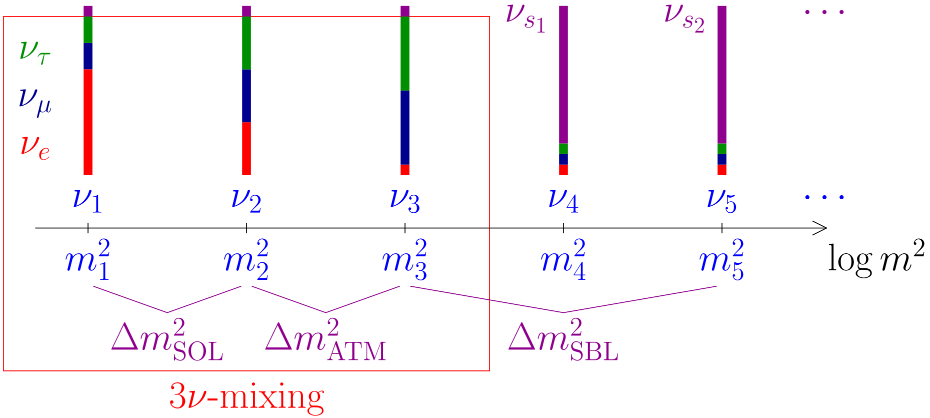
[MiniBooNE, PRL 105 (2010) 181801, arXiv:1007.1150]



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



Standard Model

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

Extension of the SM: Massive Neutrinos

- Simplest extension: introduce right-handed component ν_R
- Dirac mass $m_{\text{D}}\overline{\nu_R}\nu_L$ + Majorana mass $m_{\text{M}}\overline{\nu_R^c}\nu_R$
- $\nu_{eL}\,,\ \nu_{\mu L}\,,\ \nu_{\tau L}\ +\ \nu_{eR}\,,\ \nu_{\mu R}\,,\ \nu_{\tau R}\quad\Longrightarrow$ 6 massive Majorana neutrinos

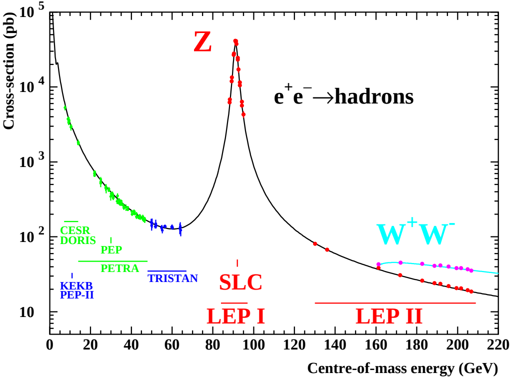
Sterile Neutrinos

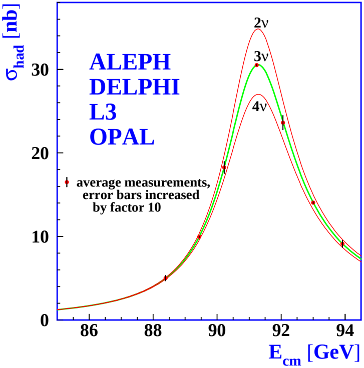
- Light anti-ν_R are called sterile neutrinos

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

- 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
    - Indirect evidence through combined fit of data (current indication)
- Powerful window on new physics beyond the Standard Model

Number of Flavor and Massive Neutrinos?





[LEP, Phys. Rept. 427 (2006) 257, arXiv:hep-ex/0509008]

$$\Gamma_Z = \sum_{\ell=e,\mu,\tau} \Gamma_{Z\to\ell\bar{\ell}} + \sum_{q\neq t} \Gamma_{Z\to q\bar{q}} + \Gamma_{\text{inv}} \qquad \Gamma_{\text{inv}} = N_\nu \, \Gamma_{Z\to\nu\bar{\nu}}$$

$$\boxed{N_\nu = 2.9840 \pm 0.0082}$$

$$e^+e^- \to Z \xrightarrow{\text{invisible}} \sum_{a=\text{active}} \nu_a \bar{\nu}_a \quad \Longrightarrow \quad \nu_e \ \nu_\mu \ \nu_\tau$$

3 light active flavor neutrinos

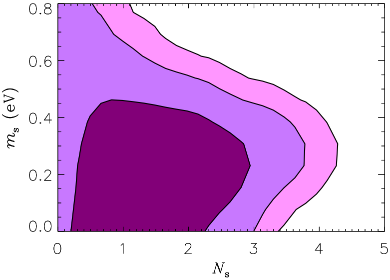
mixing $\Rightarrow$ $$\nu_{\alpha L} = \sum_{k=1}^{N} U_{\alpha k} \nu_{kL} \qquad \alpha = e, \mu, \tau$$

$N \geq 3$
no upper limit!

Mass Basis:	ν_1	ν_2	ν_3	ν_4	ν_5	$\cdots$
Flavor Basis:	ν_e	ν_μ	ν_τ	ν_{s_1}	ν_{s_2}	$\cdots$
	ACTIVE			STERILE		

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]

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

[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]

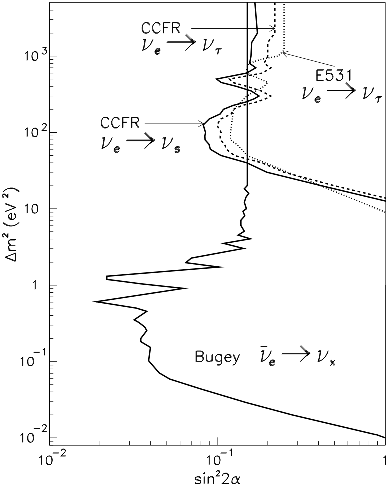
$$N_s = 0.64^{+0.40}_{-0.35}$$

[Izotov, Thuan, ApJL 710 (2010) L67, arXiv:1001.4440]

Direct Searches of Active-Sterile Transitions

CCFR

[PRD 59 (1999) 031101, arXiv:hep-ex/9809023]



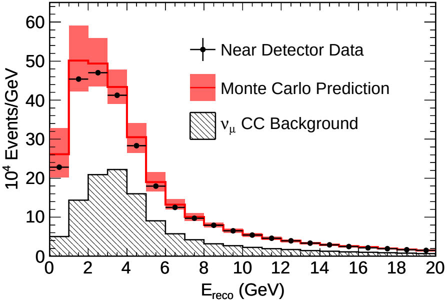
NC interactions $E \sim 100\,\text{GeV}$ $L \simeq 1.4\,\text{km}$

MINOS

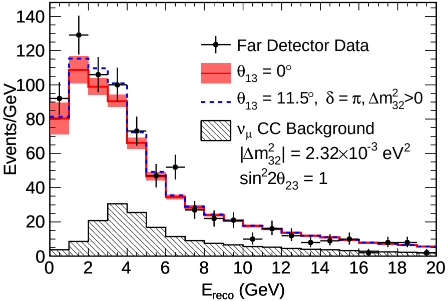
NC sample: 89% efficiency and 61% purity

97% of ν_e-induced CC events misidentified as NC

[arXiv:1104.3922]



$L_{ND} = 1.04\,\mathrm{km}$



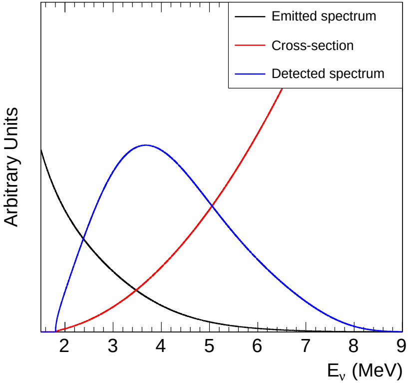
$L_{FD} = 735\,\mathrm{km}$

Model	ϑ_{13}	χ^2/D.O.F.	ϑ_{23}	ϑ_{24}	ϑ_{34}	f_s
$m_4 = m_1$	0	130.4/123	45.0^{+7}_{-7}	-	$0.0^{+17}_{-0.0}$	0.22
	11.5	128.5/123	45.6^{+7}_{-7}	-	$0.0^{+25}_{-0.0}$	0.40
$m_4 \gg m_3$	0	130.4/122	45.0^{+7}_{-7}	$0.0^{+5}_{-0.0}$	$0.0^{+17}_{-0.0}$	0.22
	11.5	128.5/122	45.6^{+7}_{-7}	$0.0^{+5}_{-0.0}$	$0.0^{+25}_{-0.0}$	0.40

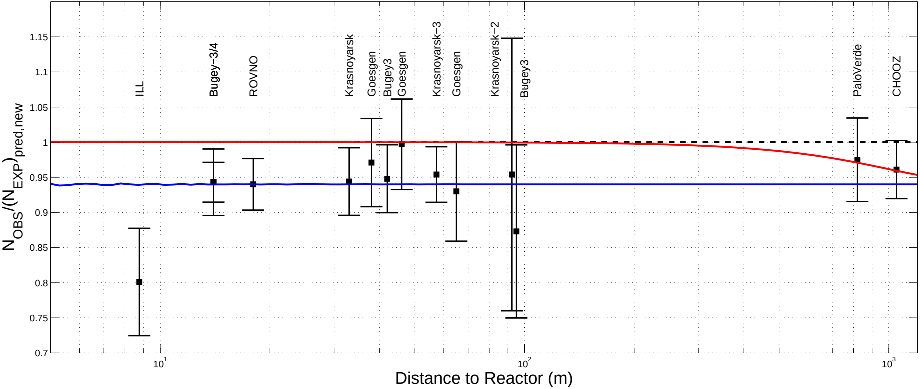
90% C.L.

New Calculation of Reactor $\bar{\nu}_e$ Flux

- Th. A. Mueller, D. Lhuillier, M. Fallot, A. Letourneau, S. Cormon, M. Fechner, L. Giot, T. Lasserre, J. Martino, G. Mention, A. Porta, F. Yermia, Improved Predictions of Reactor Antineutrino Spectra, arXiv:1101.2663
- detected flux normalization is increased by about 3%



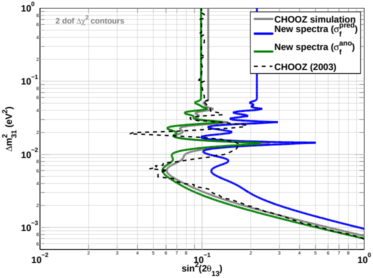
- G. Mention, M. Fechner, Th. Lasserre, Th. A. Mueller, D. Lhuillier, M. Cribier, A. Letourneau, The Reactor Antineutrino Anomaly, arXiv:1101.2755
- ratio of observed and predicted event rates: 0.937 ± 0.027
- deviation from unity at 98.4% C.L.: reactor antineutrino anomaly



- New reactor neutrino flux has several implications: fit of solar and KamLAND data, determination of ϑ_{13}, short-baseline $\bar{\nu}_e$ disappearance, ...

Chooz limit on ϑ_{13}

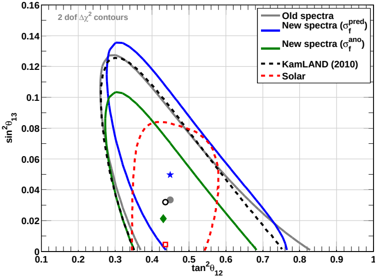
[Chooz, EPJC 27 (2003) 331]



[Mention et al., arXiv:1101.2755]

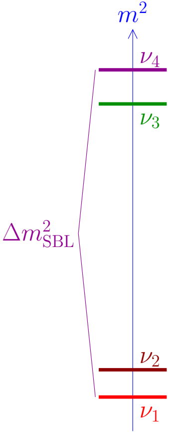
Hint of $\vartheta_{13} > 0$

[Fogli et al., PRL 101 (2008) 141801]

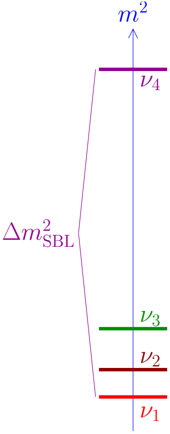


[Mention et al., arXiv:1101.2755]

Four-Neutrino Schemes: 2+2 and 3+1

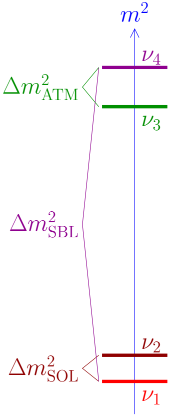


"2+2"

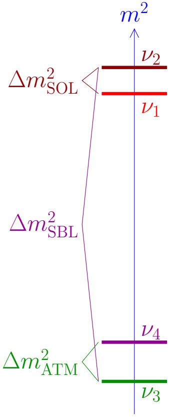


"3+1"

2+2 Four-Neutrino Schemes

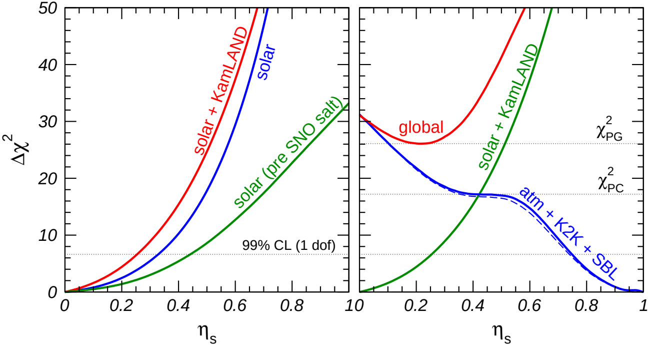


"normal"



"inverted"

2+2 Schemes are strongly disfavored by solar and atmospheric data



matter effects + SNO NC

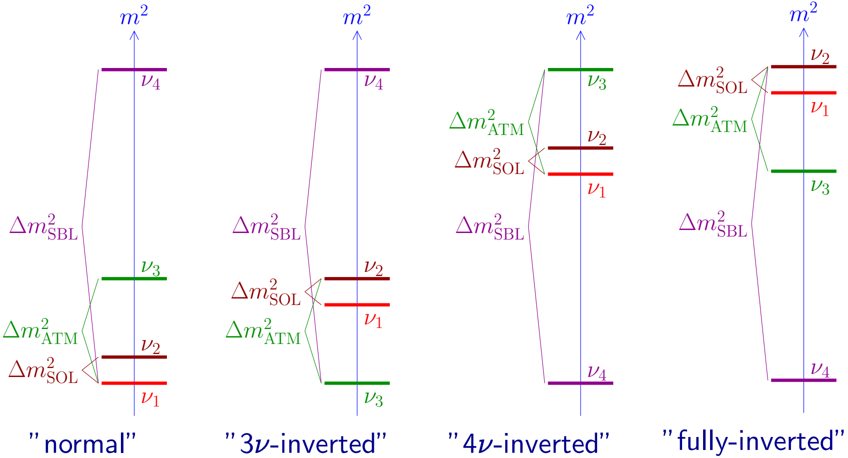
matter effects

$$\eta_s = |U_{s1}|^2 + |U_{s2}|^2$$
$$1 - \eta_s = |U_{s3}|^2 + |U_{s4}|^2$$

$$\text{99\% CL:} \quad \begin{cases} \eta_s < 0.25 & \text{(solar + KamLAND)} \\ \eta_s > 0.75 & \text{(atmospheric + K2K)} \end{cases}$$

[Maltoni, Schwetz, Tortola, Valle, New J. Phys. 6 (2004) 122, arXiv:hep-ph/0405172]

3+1 Four-Neutrino Schemes



Perturbation of 3-ν Mixing

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

Effective SBL Oscillation Probabilities in 3+1 Schemes

$$P_{\nu_\alpha\to\nu_\beta} = \left|\sum_{k=1}^{4} U_{\alpha k}^{*} U_{\beta k} e^{-iE_k t}\right|^2 * \left|e^{iE_1 t}\right|^2$$

$$= \left|\sum_{k=1}^{4} U_{\alpha k}^{*} U_{\beta k} e^{-i(E_k-E_1)t}\right|^2 \to \left|\sum_{k=1}^{4} U_{\alpha k}^{*} U_{\beta k} \exp\left(\frac{\Delta m_{k1}^2 L}{2E}\right)\right|^2$$

$$E_k \simeq p + \frac{m_k^2}{2p} \qquad \frac{\Delta m_{21}^2 L}{2E} \ll 1 \qquad \frac{\Delta m_{31}^2 L}{2E} \ll 1 \qquad \Delta m_{41}^2 \to \Delta m^2$$

$$P_{\nu_\alpha\to\nu_\beta} = \left|U_{\alpha 1}^{*} U_{\beta 1} + U_{\alpha 2}^{*} U_{\beta 2} + U_{\alpha 3}^{*} U_{\beta 3} + U_{\alpha 4}^{*} U_{\beta 4} \exp\left(\frac{\Delta m^2 L}{2E}\right)\right|^2$$

$$U_{\alpha 1}^{*} U_{\beta 1} + U_{\alpha 2}^{*} U_{\beta 2} + U_{\alpha 3}^{*} U_{\beta 3} = \delta_{\alpha\beta} - U_{\alpha 4}^{*} U_{\beta 4}$$

$$
\begin{aligned}
P_{\nu_\alpha\to\nu_\beta} &= \left|\delta_{\alpha\beta} - U_{\alpha4}^{*} U_{\beta4}\left[1-\exp\left(\frac{\Delta m^2 L}{2E}\right)\right]\right|^2 \\
&= \delta_{\alpha\beta} + |U_{\alpha4}|^2 |U_{\beta4}|^2 \left(2 - 2\cos\frac{\Delta m^2 L}{2E}\right) \\
&\qquad - 2\delta_{\alpha\beta} |U_{\alpha4}|^2 \left(1 - \cos\frac{\Delta m^2 L}{2E}\right) \\
&= \delta_{\alpha\beta} - 2|U_{\alpha4}|^2 \left(\delta_{\alpha\beta} - |U_{\beta4}|^2\right) \left(1 - \cos\frac{\Delta m^2 L}{2E}\right) \\
&= \delta_{\alpha\beta} - 4|U_{\alpha4}|^2 \left(\delta_{\alpha\beta} - |U_{\beta4}|^2\right) \sin^2\frac{\Delta m^2 L}{2E}
\end{aligned}
$$

$$\alpha \neq \beta \quad \Longrightarrow \quad P_{\nu_\alpha\to\nu_\beta} = 4|U_{\alpha4}|^2 |U_{\beta4}|^2 \sin^2\left(\frac{\Delta m^2 L}{4E}\right)$$

$$\alpha = \beta \quad \Longrightarrow \quad P_{\nu_\alpha\to\nu_\alpha} = 4|U_{\alpha4}|^2 \left(1 - |U_{\alpha4}|^2\right) \sin^2\left(\frac{\Delta m^2 L}{4E}\right)$$

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

No CP Violation!

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

Perturbation of 3ν Mixing

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

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

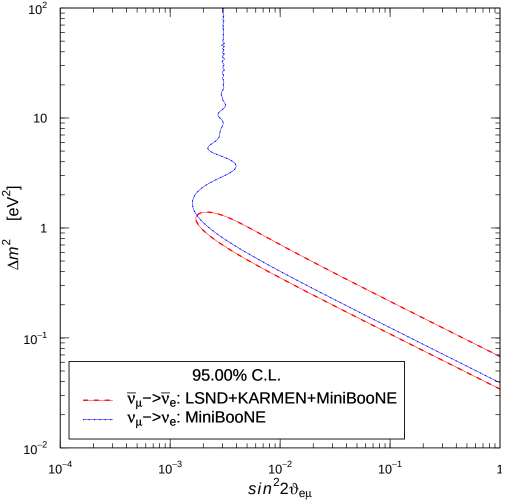
$\uparrow$

SBL

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

$$\Downarrow$$

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



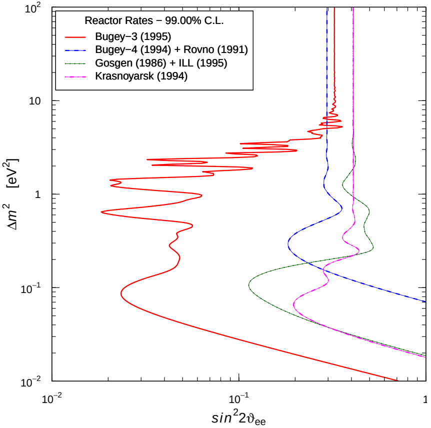
3+1 Schemes

GoF = 32%

PGoF = 0.89%

- Tension between LSND + KARMEN + MiniBooNE $\bar{\nu}_\mu \to \bar{\nu}_e$ and MiniBooNE $\nu_\mu \to \nu_e \Longrightarrow$ CP Violation?
- 3+2 $\Longrightarrow$ CP Violation OK [Sorel, Conrad, Shaevitz, PRD 70 (2004) 073004, hep-ph/0305255; Maltoni, Schwetz, PRD 76, 093005 (2007), arXiv:0705.0107; Karagiorgi et al, PRD 80 (2009) 073001, arXiv:0906.1997]
- 3+1+NSI $\Longrightarrow$ CP Violation OK [Akhmedov, Schwetz, JHEP 10 (2010) 115, arXiv:1007.4171]

$\bar{\nu}_e$ Disappearance

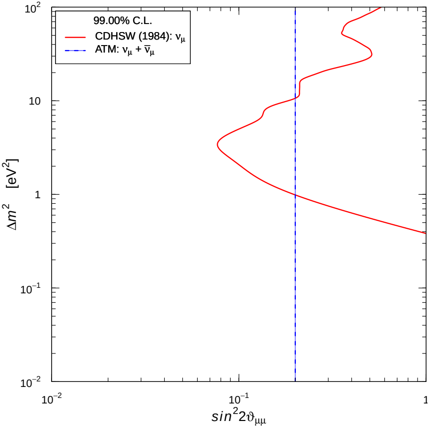


New Reactor $\bar{\nu}_e$ Fluxes

[Mueller et al., arXiv:1101.2663]

[Mention et al., arXiv:1101.2755]

ν_μ and $\bar{\nu}_\mu$ Disappearance



ATM constraint on $|U_{\mu 4}|^2$

[Maltoni, Schwetz, PRD 76 (2007) 093005, arXiv:0705.0107]

- 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:

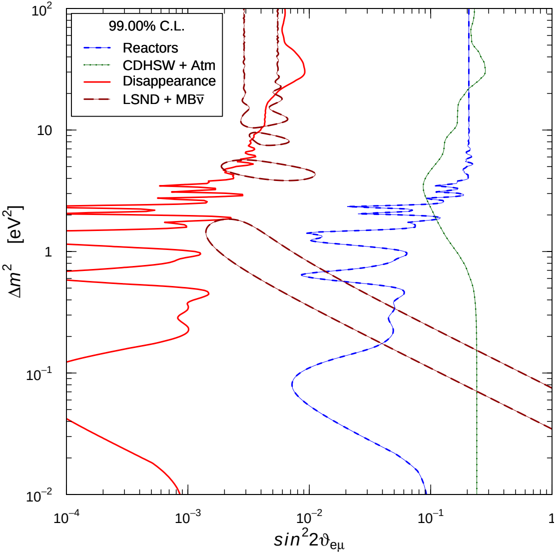
$$\sin^2 2\vartheta_{e\mu} = 4|U_{e4}|^2|U_{\mu4}|^2 \simeq \frac{1}{4}\sin^2 2\vartheta_{ee}\sin^2 2\vartheta_{\mu\mu}$$

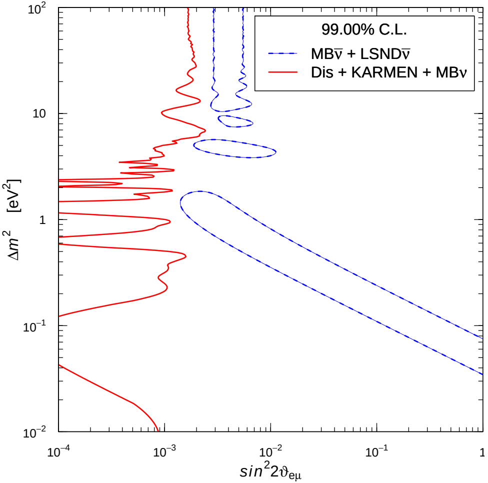
- Upper bounds on $\sin^2 2\vartheta_{ee}$ and $\sin^2 2\vartheta_{\mu\mu}$ $\Longrightarrow$ strong limit on $\sin^2 2\vartheta_{e\mu}$

[Okada, Yasuda, Int. J. Mod. Phys. A12 (1997) 3669-3694, arXiv:hep-ph/9606411]

[Bilenky, Giunti, Grimus, Eur. Phys. J. C1 (1998) 247, arXiv:hep-ph/9607372]

3+1 Schemes


99.00% C.L.
Reactors
CDHSW + Atm
Disappearance
LSND + MB$\bar{\nu}$
Δm^2 [eV^2]
10^2
10
1
10^{-1}
10^{-2}
10^{-4}
10^{-3}
10^{-2}
10^{-1}
1
$sin^2 2\vartheta_{e\mu}$

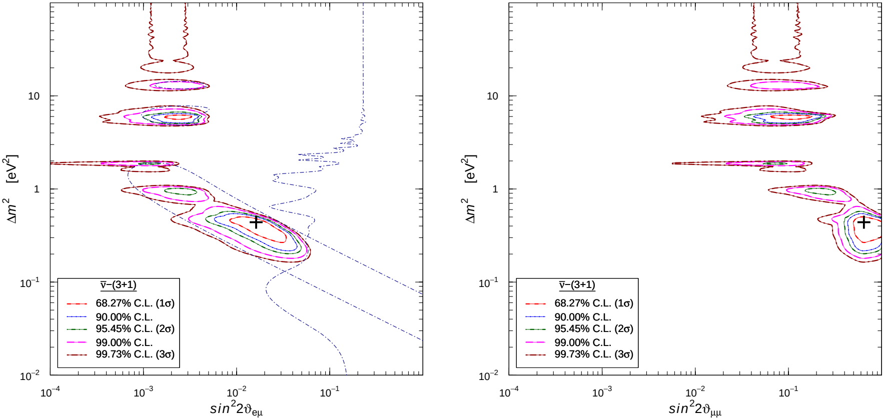


PGoF = 0.006%

- Strong tension between $\bar{\nu}_\mu \to \bar{\nu}_e$ appearance and disappearance limits ($\bar{\nu}_e \to \bar{\nu}_e$ and mainly $\nu_\mu \to \nu_\mu$)
- Tension reduced in 3+2, 3+1+NSI
- CPT Violation?

[Barger, Marfatia, Whisnant, PLB 576 (2003) 303]
[Giunti, Laveder, PRD 82 (2010) 093016, PRD 83 (2011) 053006]

Antineutrino Oscillations in 3+1 Schemes



$\chi^2_{\text{min}} = 87.0 \qquad \text{NdF} = 83 \qquad \text{GoF} = 36\%$

$\Delta m^2 = 0.42\,\text{eV}^2 \quad \sin^2 2\vartheta_{e\mu} = 0.016 \quad \sin^2 2\vartheta_{ee} = 0.020 \quad \sin^2 2\vartheta_{\mu\mu} = 0.65$

Prediction: large SBL $\bar{\nu}_\mu$ disappearance at $\Delta m^2 \gtrsim 0.1\,\text{eV}^2$

[Giunti, Laveder, PRD 83 (2011) 053006, arXiv:1012.0267]

Gallium Anomaly

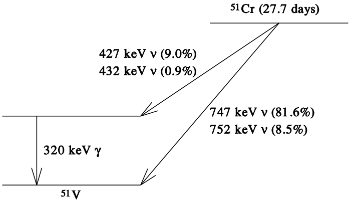
Gallium Radioactive Source Experiments

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

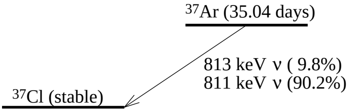
Detection Process: $\nu_e + {}^{71}\text{Ga} \to {}^{71}\text{Ge} + e^-$

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

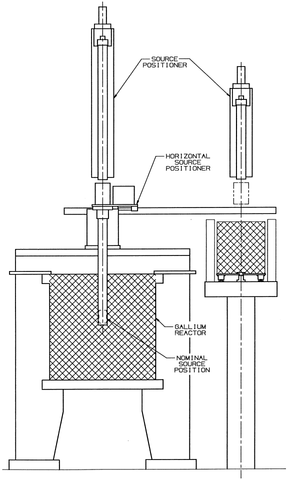
	^{51}Cr				^{37}Ar	
E [keV]	747	752	427	432	811	813
B.R.	0.8163	0.0849	0.0895	0.0093	0.902	0.098



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



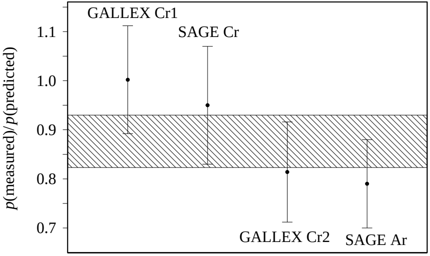
[SAGE, PRC 73 (2006) 045805, nucl-ex/0512041]



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

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

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



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

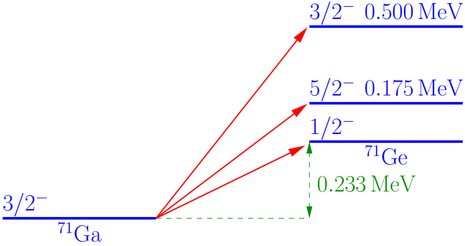
$$\begin{aligned} R_{\text{B}}^{\text{Gallex-Cr1}} &= 0.953 \pm 0.11 \\ R_{\text{B}}^{\text{Gallex-Cr2}} &= 0.812^{+0.10}_{-0.11} \\ R_{\text{B}}^{\text{SAGE-Cr}} &= 0.95 \pm 0.12 \\ R_{\text{B}}^{\text{SAGE-Ar}} &= 0.791^{+0.084}_{-0.078} \end{aligned}$$

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

Bahcall cross section

Only exp uncertainties!

- Deficit could be due to overestimate of
$$\sigma(\nu_e + {}^{71}\mathrm{Ga} \to {}^{71}\mathrm{Ge} + e^-)$$
- Calculation: Bahcall, PRC 56 (1997) 3391, hep-ph/9710491



- $\sigma_{\mathrm{G.S.}}$ related to measured $\sigma(e^- + {}^{71}\mathrm{Ge} \to {}^{71}\mathrm{Ga} + \nu_e)$:
$$\sigma_{\mathrm{G.S.}}({}^{51}\mathrm{Cr}) = 55.3 \times 10^{-46}\,\mathrm{cm}^2\,(1 \pm 0.004)_{3\sigma}$$
- $\sigma({}^{51}\mathrm{Cr}) = \sigma_{\mathrm{G.S.}}({}^{51}\mathrm{Cr}) \left(1 + 0.669\,\frac{\mathrm{BGT}_{175\,\mathrm{keV}}}{\mathrm{BGT}_{\mathrm{G.S.}}} + 0.220\,\frac{\mathrm{BGT}_{500\,\mathrm{keV}}}{\mathrm{BGT}_{\mathrm{G.S.}}}\right)$
- Contribution of Excited States only 5%!

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

  from $p + {}^{71}\mathrm{Ga} \to {}^{71}\mathrm{Ge} + n$ measurements [Krofcheck et al., PRL 55 (1985) 1051]

  $$\frac{\mathrm{BGT}_{175\,\mathrm{keV}}}{\mathrm{BGT}_{\mathrm{G.S.}}} < 0.056 \Rightarrow \frac{\mathrm{BGT}_{175\,\mathrm{keV}}}{\mathrm{BGT}_{\mathrm{G.S.}}} = \frac{0.056}{2} \qquad \frac{\mathrm{BGT}_{500\,\mathrm{keV}}}{\mathrm{BGT}_{\mathrm{G.S.}}} = 0.146$$

  3σ lower limit: $\dfrac{\mathrm{BGT}_{175\,\mathrm{keV}}}{\mathrm{BGT}_{\mathrm{G.S.}}} = \dfrac{\mathrm{BGT}_{500\,\mathrm{keV}}}{\mathrm{BGT}_{\mathrm{G.S.}}} = 0$

  3σ upper limit: $\dfrac{\mathrm{BGT}_{175\,\mathrm{keV}}}{\mathrm{BGT}_{\mathrm{G.S.}}} < 0.056 \times 2 \qquad \dfrac{\mathrm{BGT}_{500\,\mathrm{keV}}}{\mathrm{BGT}_{\mathrm{G.S.}}} = 0.146 \times 2$

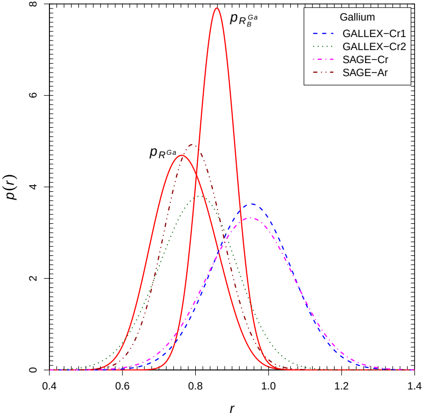
  $$\sigma({}^{51}\mathrm{Cr}) = 58.1 \times 10^{-46}\,\mathrm{cm}^2 \left(1^{+0.036}_{-0.028}\right)_{1\sigma} \quad \Longrightarrow \quad \boxed{R_{\mathrm{B}}^{\mathrm{Ga}} = 0.86 \pm 0.06}$$

- Haxton: [Hata, Haxton, PLB 353 (1995) 422, nucl-th/9503017; Haxton, PLB 431 (1998) 110, nucl-th/9804011]

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

  $$\sigma({}^{51}\mathrm{Cr}) = 63.9 \times 10^{-46}\,\mathrm{cm}^2 \,(1 \pm 0.106)_{1\sigma} \quad \Longrightarrow \quad \boxed{R_{\mathrm{H}}^{\mathrm{Ga}} = 0.78 \pm 0.13}$$

- $R^{\text{Ga}}_{\text{H}} = 0.78 \pm 0.13$ exp and the uncertainties added in quadrature
- $R^{\text{Ga}} = R^{\text{Ga}}_{\text{exp}} / R^{\text{Ga}}_{\text{the}}$ probability distribution of ratio is not Gaussian



$$p_{R^{\text{Ga}}}(r) = \int_{R^{\text{Ga}}_{\text{gs}}}^{\infty} p_{R^{\text{Ga}}_{\text{exp}}}(rs)\, p_{R^{\text{Ga}}_{\text{the}}}(s)\, s\, \mathrm{d}s$$

$$\boxed{R^{\text{Ga}} = 0.76^{+0.09}_{-0.08}}$$

$$\begin{aligned} R^{\text{Gallex-Cr1}} &= 0.84^{+0.13}_{-0.12} \\ R^{\text{Gallex-Cr2}} &= 0.71^{+0.12}_{-0.11} \\ R^{\text{SAGE-Cr}} &= 0.84^{+0.14}_{-0.13} \\ R^{\text{SAGE-Ar}} &= 0.70^{+0.10}_{-0.09} \end{aligned}$$

[Giunti, Laveder, arXiv:1006.3244]

Gallium Radioactive Source Experiments
are
Short-BaseLine Neutrino Oscillation Experiments

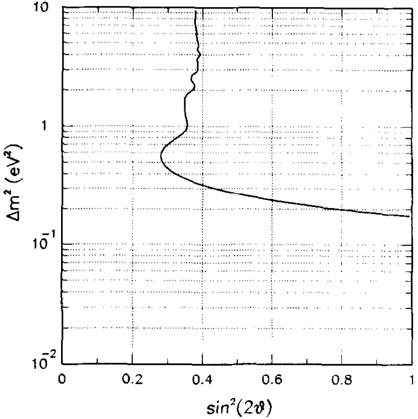


Fig. 1. Region of electron neutrino oscillation parameters ruled out at 90% C.L. by the GALLEX ^{51}Cr source experiment.

[Bahcall, Krastev, Lisi, PLB 348 (1995) 121]

$$P^{\mathrm{SBL}}_{\nu_e\to\nu_e}(L,E) = 1 - \sin^2 2\vartheta \, \sin^2\left(\frac{\Delta m^2 L}{4E}\right)$$

$$R^k(\sin^2 2\vartheta, \Delta m^2) = \frac{\int_k \mathrm{d}V \, L^{-2} \sum_i b_i^k \, \sigma_i^k \, P^{\mathrm{SBL}}_{\nu_e\to\nu_e}(L,E_i)}{\sum_i b_i^k \, \sigma_i^k \int_k \mathrm{d}V \, L^{-2}}$$

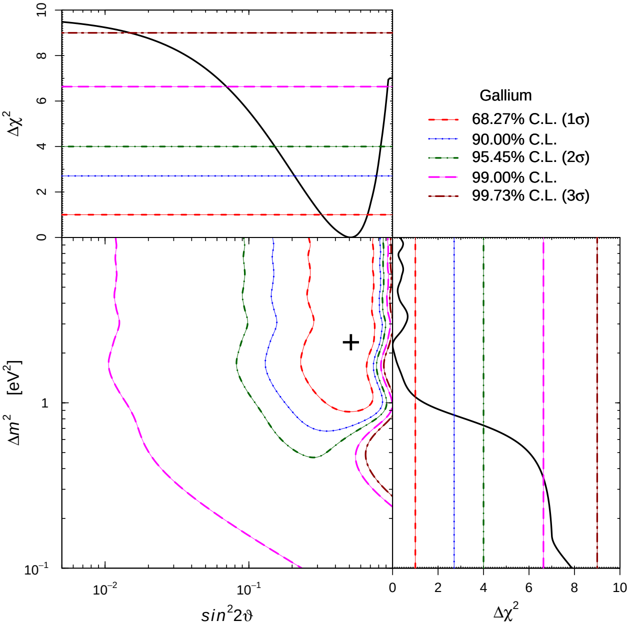
$k =$ GALLEX-Cr1 , GALLEX-Cr2 , SAGE-Cr , SAGE-Ar

$R^k = R^k_{\mathrm{exp}}/R^k_{\mathrm{the}}$ fully correlated theoretical uncertainty!

$$p_{\vec{R}}(\vec{r}) = \int_{R^k_{\mathrm{gs}}}^{\infty} \left[\prod_k p_{R^k_{\mathrm{exp}}}(r^k s)\right] p_{R^k_{\mathrm{the}}}(s)\, s^4 \, \mathrm{d}s$$

$$\mathcal{L}(\sin^2 2\vartheta, \Delta m^2) = p_{\vec{R}}(\vec{R}(\sin^2 2\vartheta, \Delta m^2))$$

$$\chi^2(\sin^2 2\vartheta, \Delta m^2) = -2 \ln \mathcal{L}(\sin^2 2\vartheta, \Delta m^2) + \text{constant}$$



$\Delta\chi^2_{\text{No Osc.}} = 9.7$

No Osc. disfavored
at 99.23 % C.L
(2.7σ)

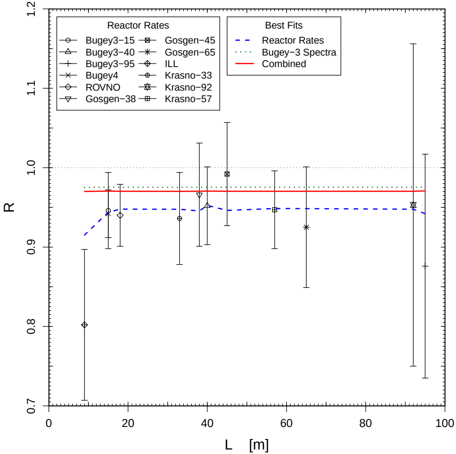
Osc.

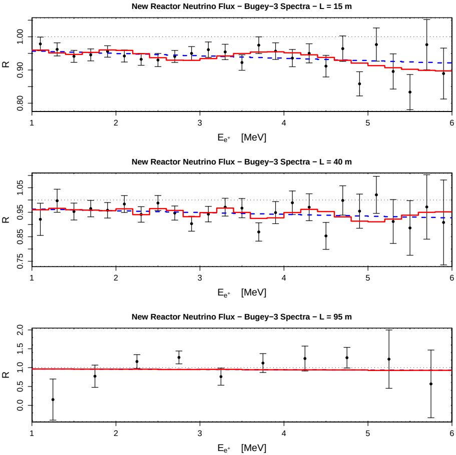
$\sin^2 2\vartheta_{\text{bf}} = 0.51$

$\Delta m^2_{\text{bf}} = 2.24\,\text{eV}^2$

[Giunti, Laveder, arXiv:1006.3244]

Reactor Antineutrino Anomaly




New Reactor Neutrino Flux − Bugey−3 Spectra − L = 15 m

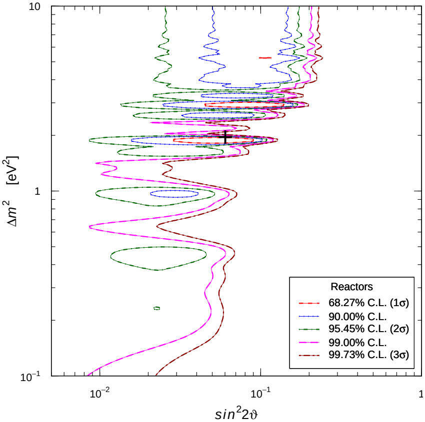
New Reactor Neutrino Flux − Bugey−3 Spectra − L = 40 m

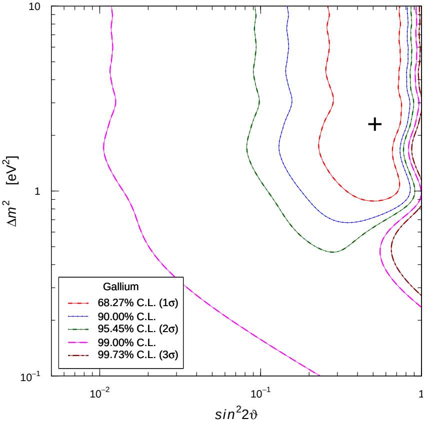
New Reactor Neutrino Flux − Bugey−3 Spectra − L = 95 m

- $\overline{R}_{\text{rates}} = 0.946 \pm 0.024$
- Improved hint of oscillations given by Bugey energy spectrum with old reactor fluxes [Acero, Giunti, Laveder, PRD 78 (2008) 073009, arXiv:0711.4222]
- $\sin^2 2\vartheta_{\text{bf}} = 0.059 \qquad \Delta m^2_{\text{bf}} = 1.89\,\text{eV}^2$

Reactor Antineutrino Anomaly

Gallium Neutrino Anomaly





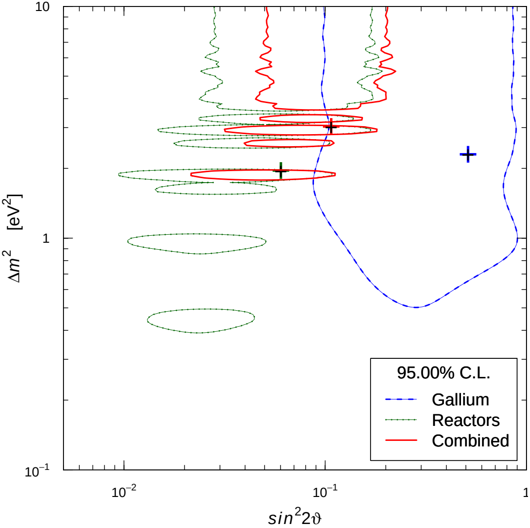
$$\sin^2 2\vartheta_{\text{bf}} = 0.059$$

$$\Delta m^2_{\text{bf}} = 1.89\,\text{eV}^2$$

$$\sin^2 2\vartheta_{\text{bf}} = 0.51$$

$$\Delta m^2_{\text{bf}} = 2.24\,\text{eV}^2$$

Gallium Anomaly + Reactor Anomaly



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

$\text{NdF} = 71$

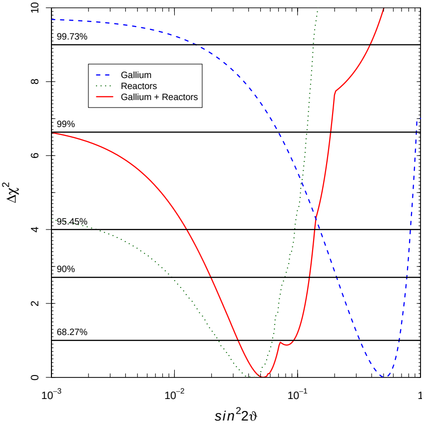
$\text{GoF} = 83\%$

$\sin^2 2\vartheta = 0.11$

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

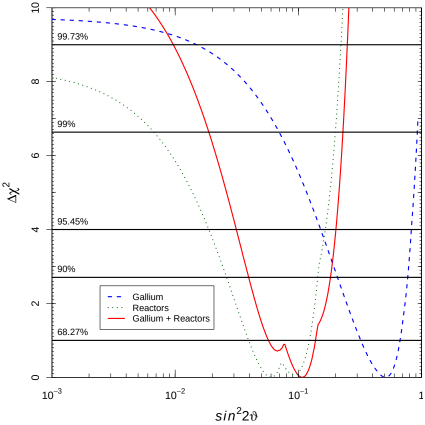
$\text{PGoF} = 4.6\%$

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



PGoF = 2.3%

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



PGoF = 4.6%

Tritium Beta-Decay

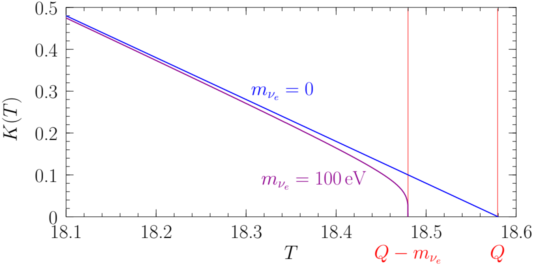
$^3H \to {}^3He + e^- + \bar{\nu}_e$

$$\frac{d\Gamma}{dT} = \frac{(\cos\vartheta_C G_F)^2}{2\pi^3} |\mathcal{M}|^2 F(E)\, pE\, (Q - T) \sqrt{(Q-T)^2 - m_{\nu_e}^2}$$

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

Kurie plot

$$K(T) = \sqrt{\frac{d\Gamma/dT}{\frac{(\cos\vartheta_C G_F)^2}{2\pi^3} |\mathcal{M}|^2 F(E)\, pE}} = \left[(Q - T)\sqrt{(Q-T)^2 - m_{\nu_e}^2}\right]^{1/2}$$



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

Mainz & Troitsk

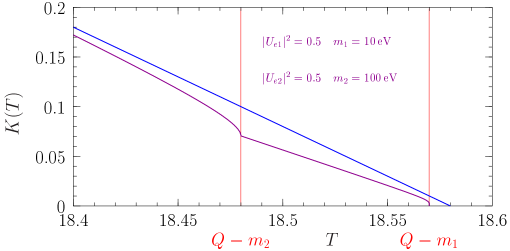
[Weinheimer, hep-ex/0210050]

future: KATRIN (start 2010)

[hep-ex/0109033] [hep-ex/0309007]

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

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



analysis of data is different from the no-mixing case: $2N-1$ parameters

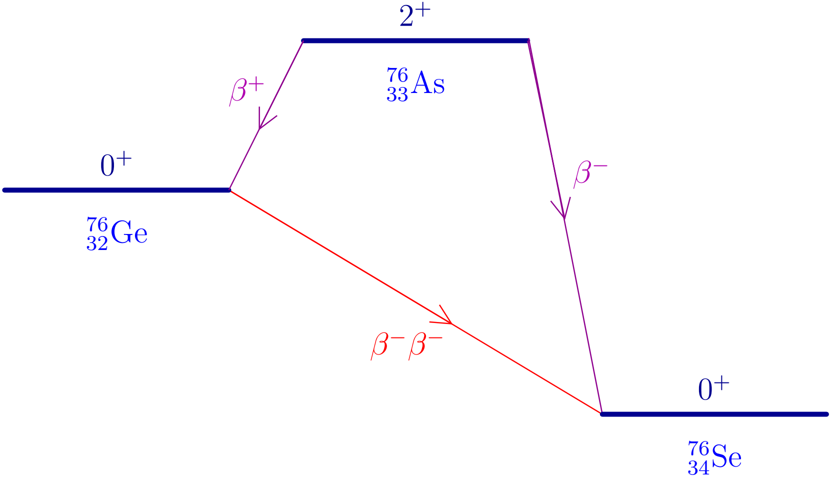
$$\left(\sum_k |U_{ek}|^2 = 1 \right)$$

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

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

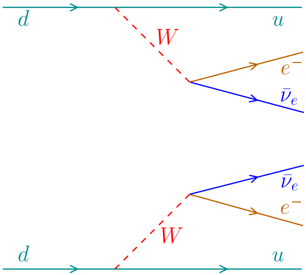
$$
\begin{aligned}
K^2 &= (Q-T)^2 \sum_k |U_{ek}|^2 \sqrt{1 - \frac{m_k^2}{(Q-T)^2}} \simeq (Q-T)^2 \sum_k |U_{ek}|^2 \left[1 - \frac{1}{2} \frac{m_k^2}{(Q-T)^2} \right] \\
&= (Q-T)^2 \left[1 - \frac{1}{2} \frac{m_\beta^2}{(Q-T)^2} \right] \simeq (Q-T) \sqrt{(Q-T)^2 - m_\beta^2}
\end{aligned}
$$

Neutrinoless Double-Beta Decay



Effective Majorana Neutrino Mass: $m_{\beta\beta} = \sum_k U_{ek}^2 \, m_k$

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

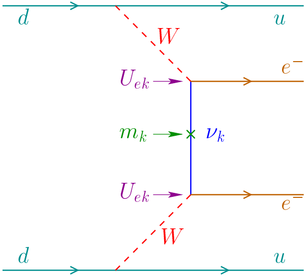


$$\mathcal{N}(A, Z) \to \mathcal{N}(A, Z+2) + e^- + e^- + \bar{\nu}_e + \bar{\nu}_e$$

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

second order weak interaction process
in the Standard Model

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



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

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

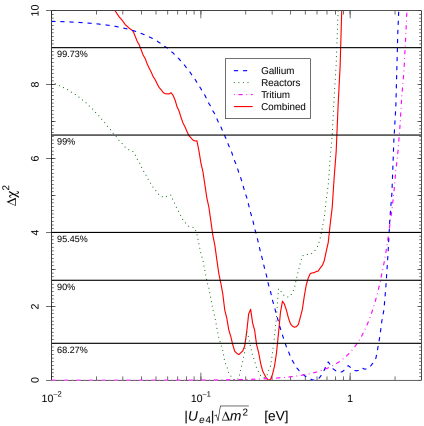
effective
Majorana
mass

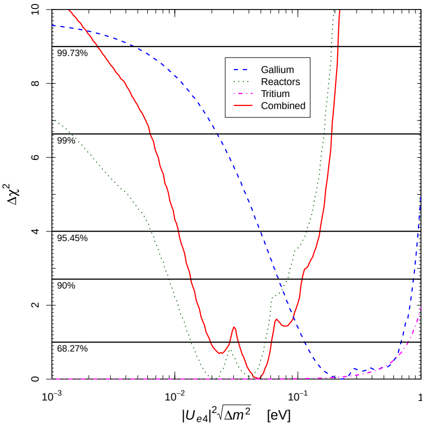
$$m_{\beta\beta} = \sum_k U_{ek}^2 \, m_k$$

Implications of Gallium and Reactor Anomalies

β Decay

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



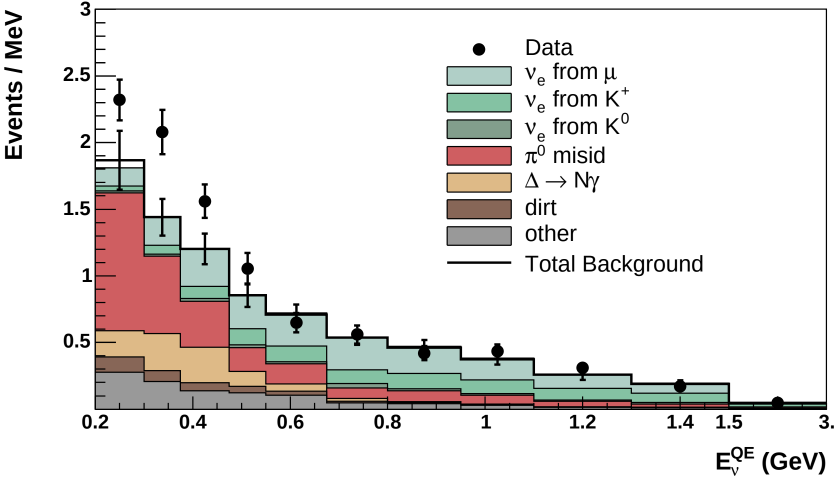


$$m_\beta^2 = \sum_k |U_{ek}|^2 m_k^2$$

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

[Giunti, Laveder, In Preparation]

MiniBooNE Low-Energy Anomaly



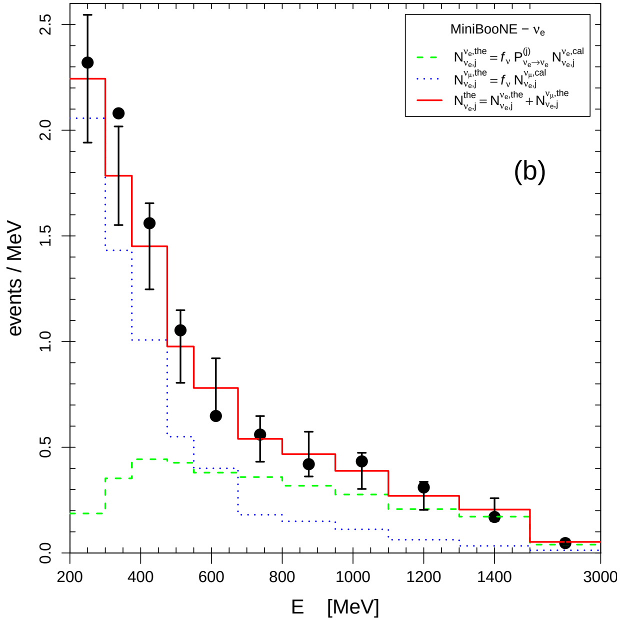
[PRL 102 (2009) 101802, arXiv:0812.2243]

Our Hypothesis: $N^{\text{the}}_{\nu,j} = f_\nu \left(P_{\nu_e\to\nu_e} N^{\text{cal}}_{\nu_e,j} + N^{\text{cal}}_{\nu_\mu,j} \right)$

[Giunti, Laveder, PRD 77 (2008) 093002, arXiv:0707.4593; PRD 80 (2009) 013005, arXiv:0902.1992]

$$\boxed{N^{\text{the}}_{\nu,j} = f_\nu \left(P_{\nu_e\to\nu_e} N^{\text{cal}}_{\nu_e,j} + N^{\text{cal}}_{\nu_\mu,j} \right)}$$

- Estimated 15% uncertainty of the calculated neutrino flux [MiniBooNE, PRD 79 (2009) 072002, arXiv:0806.1449] is consistent with measured ratio 1.21 ± 0.24 of detected and predicted charged-current quasi-elastic ν_μ events [MiniBooNE, PRL 100 (2008) 032301, arXiv:0706.0926]
- We fit MiniBooNE ν_e and ν_μ data using the info at `http://www-boone.fnal.gov/for_physicists/data_release/lowe/`



No Osc. & $f_\nu = 1$

$\chi^2_{\text{min}} = 14.3 + 5.4$

$\text{NdF} = 3 + 16$

$\text{GoF} = 41\%$

Our Hypothesis

$\chi^2_{\text{min}} = 2.0 + 7.6$

$\text{NdF} = 16$

$\text{GoF} = 89\%$

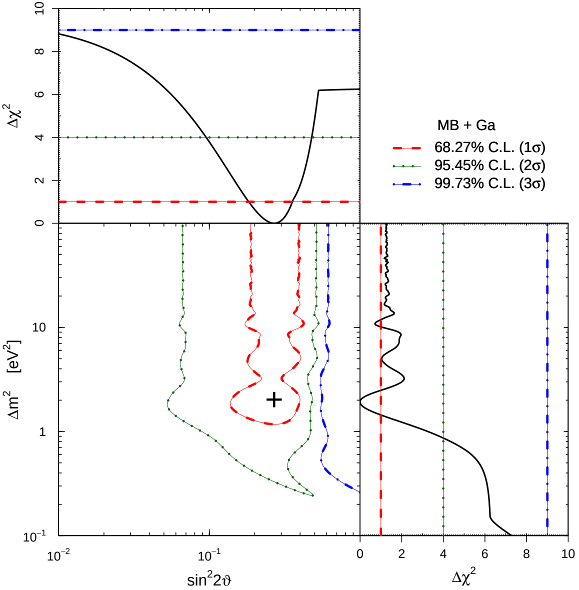
$f_\nu = 1.26$

$\sin^2 2\vartheta = 0.32$

$\Delta m^2 = 1.84\,\text{eV}^2$

[Giunti, Laveder, PRD 82 (2010) 053005, arXiv:1005.4599]

MiniBooNE + Gallium



$\chi^2_{\text{min}} = 2.3 + 9.2$

$\text{NdF} = 20$

$\text{GoF} = 93\%$

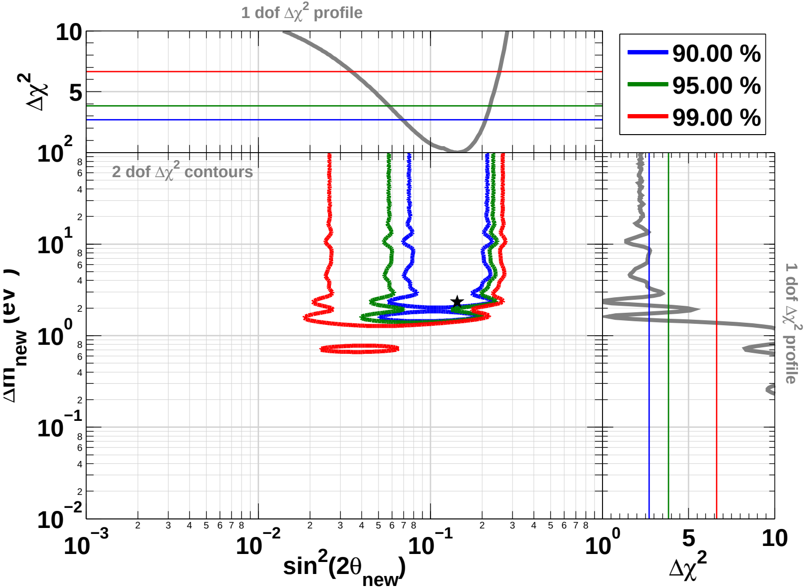
$\sin^2 2\vartheta = 0.27$

$\Delta m^2 = 1.92\,\text{eV}^2$

$\text{PGoF} = 93\%$

[Giunti, Laveder, PRD 82 (2010) 053005, arXiv:1005.4599]

MiniBooNE + Gallium + Reactors



[Mention et al., arXiv:1101.2755]

Future

- MiniBooNE is continuing to take antineutrino data.

$$\bar{\nu}_\mu \to \bar{\nu}_e + \bar{\nu}_\mu \to \bar{\nu}_\mu$$

- ICARUS@CERN-PS: $L \sim 1\text{km}$ $E \sim 1\text{GeV}$ [C. Rubbia et al, CERN-SPSC-2011-012]

$$\overset{(-)}{\nu}_\mu \to \overset{(-)}{\nu}_e + \overset{(-)}{\nu}_\mu \to \overset{(-)}{\nu}_\mu + \overset{(-)}{\nu}_e \to \overset{(-)}{\nu}_e$$

- MicroBooNE will test the MiniBooNE low-energy anomaly by measuring $\pi^0 \to 2\gamma$ background.

- ν_e disappearance: new SAGE Gallium source experiments with 2 spherical shells [Gavrin et al, arXiv:1006.2103]

- CPT test: ν_e and $\bar{\nu}_e$ disappearance

- Beta-Beam experiments: [Antusch, Fernandez-Martinez, PLB 665 (2008) 190, arXiv:0804.2820]

$$N(A,Z) \to N(A,Z+1) + e^- + \bar{\nu}_e \qquad (\beta^-)$$

$$N(A,Z) \to N(A,Z-1) + e^+ + \nu_e \qquad (\beta^+)$$

- Neutrino Factory experiments: [Giunti, Laveder, Winter, PRD 80 (2009) 073005, arXiv:0907.5487]

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

$$\mu^- \to \nu_\mu + e^- + \bar{\nu}_e$$

- New ν_e and $\bar{\nu}_e$ radioactive source experiments with low-threshold neutrino elastic scattering detectors.

- Borexino: $\overset{(-)}{\nu}_e + e^- \to \overset{(-)}{\nu}_e + e^-$ [Pallavicini, talk at BEYOND3NU]

  [Ianni, Montanino, Scioscia, EPJC 8 (1999) 609, arXiv:hep-ex/9901012]

- LENS (Low Energy Neutrino Spectroscopy): [Agarwalla, Raghavan, arXiv:1011.4509]

$$\nu_e + {}^{115}\text{In} \to {}^{115}\text{Sn} + e^- + 2\gamma \qquad E_{\text{th}} = 0.1\,\text{MeV}$$

$$\bar{\nu}_e + p \to n + e^+ \qquad E_{\text{th}} = 1.8\,\text{MeV}$$

- Spherical Gaseous TPC: [Vergados, Giomataris, Novikov, arXiv:1103.5307]
  - Targets: ${}^{131}\text{Xe}$, ${}^{40}\text{Ar}$, ${}^{20}\text{Ne}$, ${}^{4}\text{He}$.
  - Sources: ${}^{37}\text{Ar}$, ${}^{51}\text{Cr}$, ${}^{65}\text{Zn}$, ${}^{32}\text{P}$.

Conclusions 1

- Suggestive LSND and MiniBooNE agreement on SBL $\bar{\nu}_\mu \to \bar{\nu}_e$
- Hint in favor of sterile neutrinos is compatible with cosmological data, but mass is limited
- Two experimental tensions:
  - LSND and MiniBooNE $\bar{\nu}_\mu \to \bar{\nu}_e$ vs MiniBooNE $\nu_\mu \to \nu_e$ (CP violation?)
  - LSND and MiniBooNE $\bar{\nu}_\mu \to \bar{\nu}_e$ vs $\bar{\nu}_e$ and ν_μ disappearance limits
- CPT-invariant 3+1 Four-Neutrino Mixing is strongly disfavored (no CP violation and tension between appearance and disappearance)
- 3+2 can explain CP violation and reduce tension between appearance and disappearance with New Reactor $\bar{\nu}_e$ Fluxes
- 3+1+NSI has CP violation and reduced appearance-disappearance tension
- CPT-violating 3+1 Mixing $\Longrightarrow$ testable large SBL $\bar{\nu}_\mu$ disappearance

Conclusions 2

- Interesting possible agreement of
    - Gallium Anomaly (SBL ν_e disappearance)
    - Reactor Anomaly (SBL $\bar{\nu}_e$ disappearance)
- Testable Predictions:
    - $m_\beta \sim 0.12 - 0.71\,\text{eV} \quad (2\sigma)$
    - $m_{\beta\beta} \sim 0.011 - 0.15\,\text{eV} \quad (2\sigma)$

- Exciting experimental results in favor of sterile neutrinos.

- More work to do because interpretation is not clear:

    - Explanation of all data needs at least two new physical effects.

    - Without CPT violation tensions do not disappear completely.

    - Possible that some experiments are giving misleading information.

- New short-baseline neutrino oscillation experiments are needed!