Phenomenology of Sterile Neutrinos

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Standard Model: Massless Neutrinos

- Standard Model: $\nu_L, \nu_R^c \quad \Longrightarrow \quad$ no Dirac mass term

$$\mathcal{L}^{\mathrm{D}} = m^{\mathrm{D}} \left(\overline{\nu_L} \nu_R + \overline{\nu_R} \nu_L \right)$$

- Majorana Neutrino: $\nu^c = \nu$

- $\nu_R^c = \nu_R \quad \Longrightarrow \quad$ Majorana mass term

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

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

(no Higgs triplet)

- Neutrinos are special in the Standard Model: the only neutral fermions
- In extensions of the SM neutrinos can mix with non-SM fermions

$$L_L = \begin{pmatrix} \nu_{eL} \\ e_L \end{pmatrix} \left(\begin{smallmatrix} I=1/2 \\ Y=-1 \end{smallmatrix} \right) \quad \Phi = \begin{pmatrix} \phi^+ \\ \phi^0 \end{pmatrix} \left(\begin{smallmatrix} I=1/2 \\ Y=+1 \end{smallmatrix} \right) \quad \widetilde{\Phi} = i\tau_2 \, \Phi^* \left(\begin{smallmatrix} I=1/2 \\ Y=-1 \end{smallmatrix} \right)$$

new non-SM chiral fermion field $f_R \left(\begin{smallmatrix} I=0 \\ Y=0 \end{smallmatrix} \right)$

Dirac mass term $\sim \overline{L_L} \widetilde{\Phi} f_R \quad + \quad$ Majorana mass term $\sim \overline{f_R^C} f_R$

f_R is often called Right-Handed Neutrino: $f_R \to \nu_R$

- If these non-SM fermions are light, they are called Sterile Neutrinos:

$$\nu_{sL} = \nu_R^C$$

- Active Neutrinos $(\nu_e, \nu_\mu, \nu_\tau)$ can oscillate into Sterile Neutrinos (ν_s)
- Extremely interesting window on Physics Beyond the SM
- Observable: Disappearance of Active Neutrinos or indirect evidence through combined fit of data

Sterile Neutrinos

- Sterile means No Standard Model Interactions
- Obviously no electromagnetic interactions as normal active neutrinos
- Thus Sterile means No Standard Weak Interactions
- But Sterile Neutrinos are not absolutely sterile:
  - Gravitational Interactions
  - New Non-Standard Interactions of the Physics Beyond the Standard Model which generates the masses of sterile neutrinos

Experimental Evidences of Neutrino Oscillations

Solar

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

Reactor

$\bar{\nu}_e$ disappearance

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

(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

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

Accelerator

ν_μ disappearance

(
Kamiokande
IMB
Super-Kamiokande
MACRO
Soudan-2
)

(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: $\Delta m^2_{\text{ATM}} \simeq 30\,\Delta m^2_{\text{SOL}}$

Large mixings: $\vartheta_{\text{ATM}} \simeq 45^\circ$, $\vartheta_{\text{SOL}} \simeq 34^\circ$

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

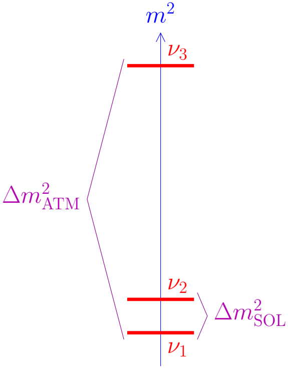
three massive fields: ν_1, ν_2, ν_3

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

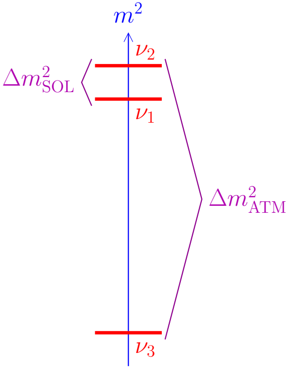
$$\Delta m^2_{\text{SOL}} = \Delta m^2_{21} \simeq 7.6 \times 10^{-5}\, \text{eV}^2$$

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

Allowed Three-Neutrino Schemes



"normal"



"inverted"

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

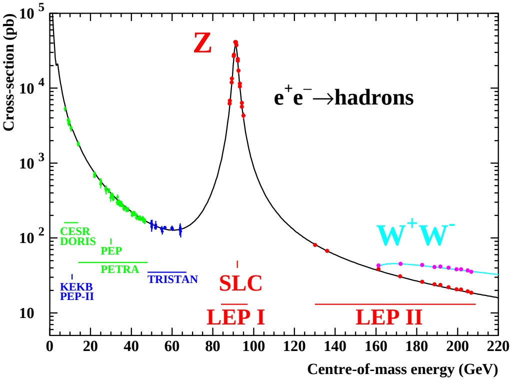
absolute scale is not determined by neutrino oscillation data

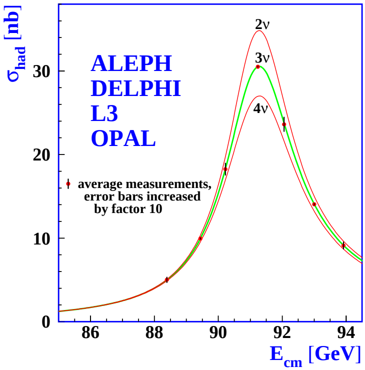
- Interesting possibility: a new $\Delta m^2 \gtrsim 1\,\text{eV}^2$

- It has been studied in connection with searches of neutrino oscillations in Short-BaseLine experiments

- Necessary introduction of at least one new massive neutrino: 4-ν Mixing

Number of Flavor and Massive Neutrinos?





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

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

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

$e^+e^- \to Z \to \nu\bar{\nu} \quad \Rightarrow \quad \nu_e \; \nu_\mu \; \nu_\tau$ 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		

STERILE NEUTRINOS

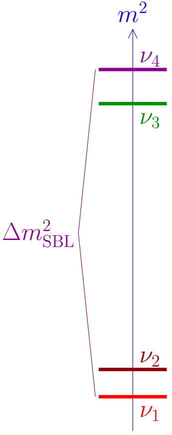
singlets of SM $\Longrightarrow$ no interactions!

active → sterile transitions are possible if $\nu_4, \ldots$ are light

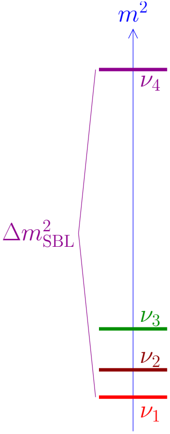
$\Downarrow$

disappearance of active neutrinos

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



"2+2"

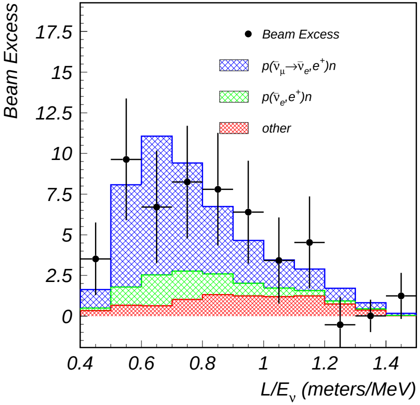


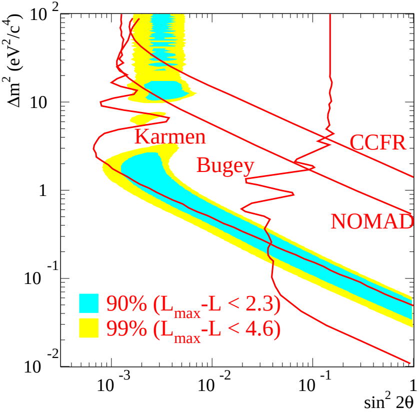
"3+1"

LSND

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

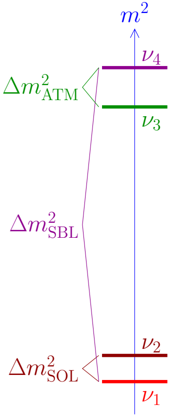
$\bar{\nu}_\mu \to \bar{\nu}_e \qquad L \simeq 30\,\mathrm{m} \qquad 20\,\mathrm{MeV} \leq E \leq 200\,\mathrm{MeV}$



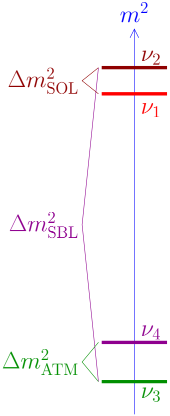


$$\Delta m^2_{\mathrm{LSND}} \gtrsim 0.2\,\mathrm{eV}^2 \qquad (\gg \Delta m^2_{\mathrm{ATM}} \gg \Delta m^2_{\mathrm{SOL}})$$

2+2 Four-Neutrino Schemes

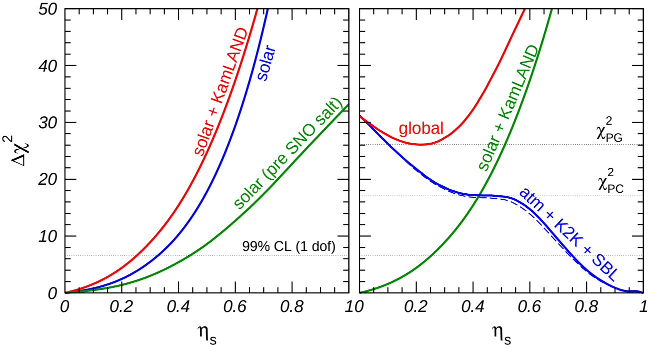


”normal”



”inverted”

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

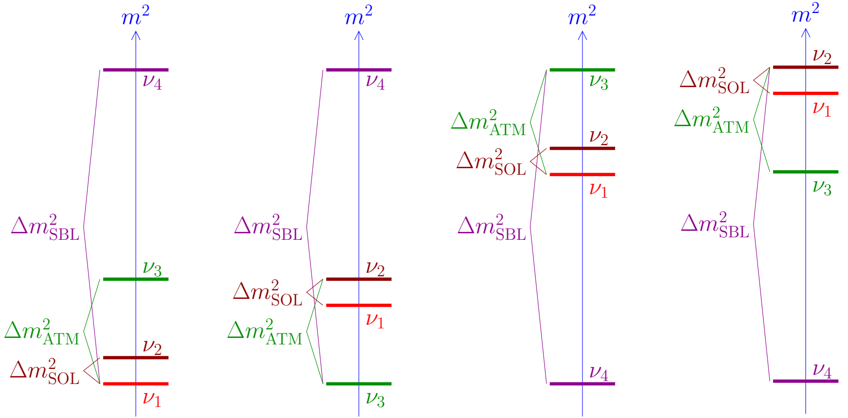


[Maltoni, Schwetz, Tortola, Valle, New J. Phys. 6 (2004) 122, arXiv:hep-ph/0405172]

$\eta_s = |U_{s1}|^2 + |U_{s2}|^2$

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

3+1 Four-Neutrino Schemes



"normal" "3ν-inverted" "4ν-inverted" "fully-inverted"

Perturbation of 3-ν Mixing

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

Effective SBL Oscillation Probability in 3+1 Schemes

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

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

$$\frac{\Delta m_{21}^2 L}{2E} \ll 1 \qquad \frac{\Delta m_{31}^2 L}{2E} \ll 1 \qquad \Delta m_{41}^2 \to \Delta m^2$$

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

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

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

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

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

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

$$\sin^2 2\vartheta_{\alpha\beta} = 4|U_{\alpha 4}|^2 |U_{\beta 4}|^2$$

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

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

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

$\uparrow$

SBL

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

$$\Downarrow$$

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

- 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:

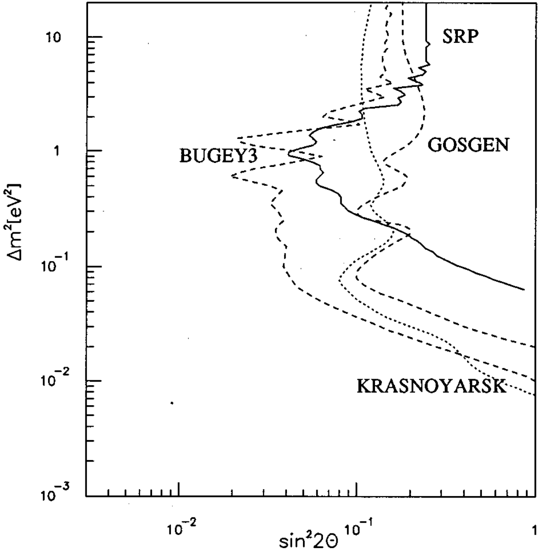
$$\sin^2 2\vartheta_{\mu\mu} = 4|U_{\mu4}|^2 \left(1 - |U_{\mu4}|^2\right) \simeq 4|U_{\mu4}|^2$$

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

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

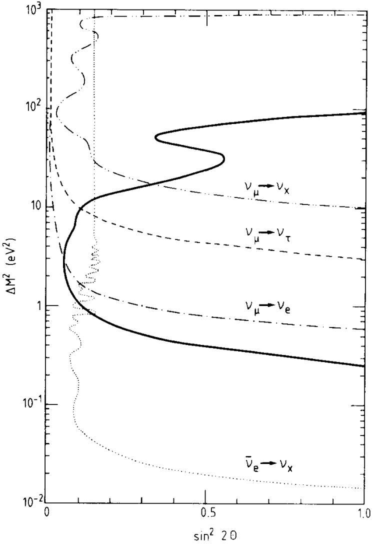
- Upper bounds on $\sin^2 2\vartheta_{ee}$ and $\sin^2 2\vartheta_{\mu\mu}$ imply strong limit on $\sin^2 2\vartheta_{\mu e}$

ν_e Disappearance

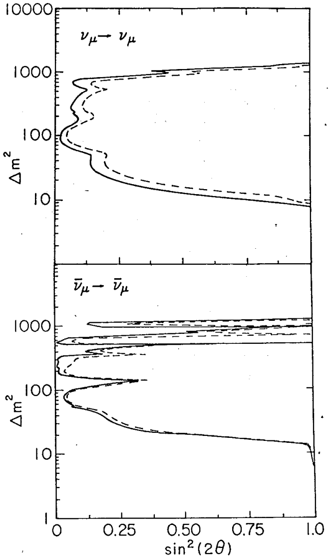


[Savannah River (SRP), PRD 53 (1996) 6054]

ν_μ Disappearance

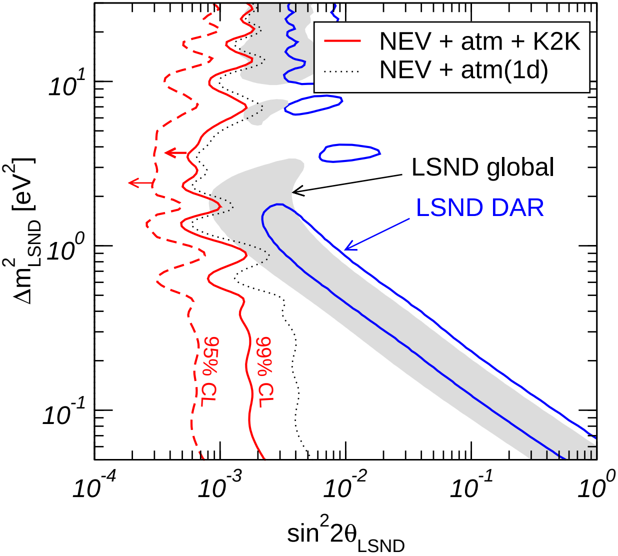


[CDHSW, PLB 134 (1984) 281]



[CCFR, Z. Phys. C 27 (1985) 53]

$\nu_\mu \to \nu_e$

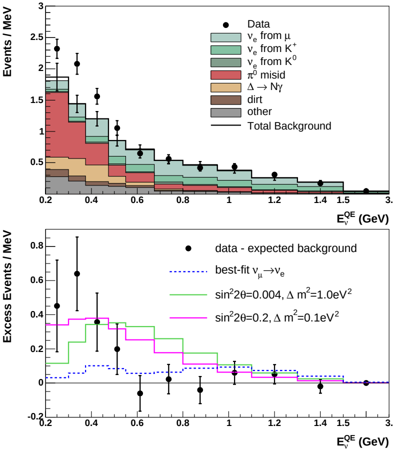


[Maltoni, Schwetz, Tortola, Valle, New J. Phys. 6 (2004) 122, arXiv:hep-ph/0405172]

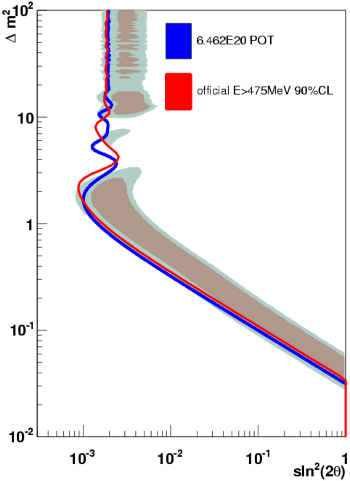
MiniBooNE

[PRL 98 (2007) 231801]

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



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



[arXiv:0901.1648]

Low-Energy Anomaly!

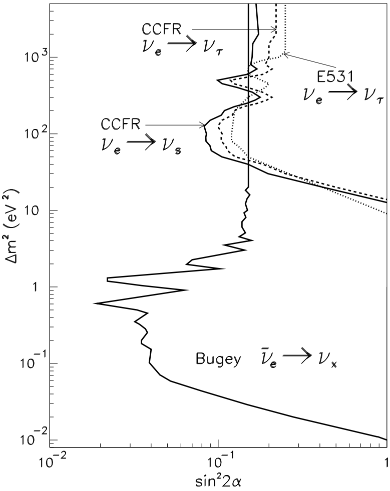
- The LSND signal is strongly disfavored:
  - Not seen by other $\bar{\nu}_\mu \to \bar{\nu}_e$ and $\nu_\mu \to \nu_e$ experiments
  - Disfavored by combined fit of data

- Possibility of a $\Delta m^2 \gtrsim 1\,\text{eV}^2$ relevant for SBL experiments independent of LSND signal remains interesting: chance to discover Sterile Neutrinos and open powerful window on New Physics

- There are also direct searches of active-sterile transitions:
  - Solar + KamLAND: mixing smaller than 0.25 at 99% CL (constrained by matter effects and by SNO NC measurement)
  - Atmospheric + K2K: mixing smaller than 0.25 at 99% CL (constrained by matter effects)
  - Bounds from observation of NC interactions in SBL (CCFR) and LBL (MINOS) experiments

CCFR

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



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

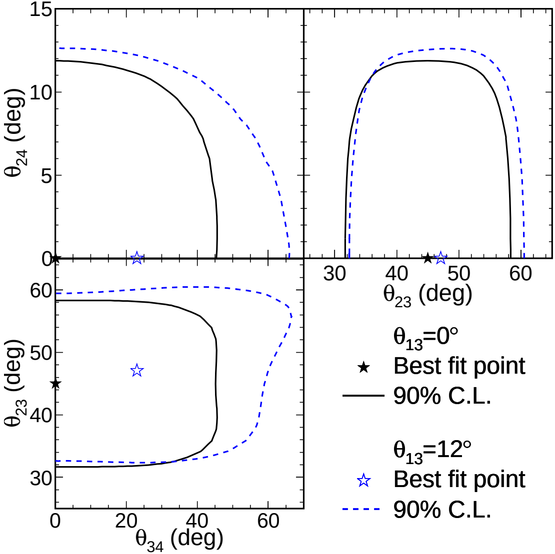
MINOS

[PRD 81 (2010) 052004, arXiv:1001.0336]

- LBL ν_μ disappearance and $\nu_\mu \to \nu_e$ experiment with $E \sim 3\,\text{GeV}$ and
  - Near Detector at 1.04 km
  - Far Detector at 734 km
- Events classified in two groups: CC and NC
- Information on $\nu_\mu \to \nu_s$ from difference between near and far NC energy spectrum
- Analysis complicated because there are five contributions to NC sample:
  1. Genuine NC interactions
  2. Misidentified ν_μ CC interactions
  3. ν_τ CC interactions
  4. Possible ν_e CC interactions originating from $\nu_\mu \to \nu_e$ oscillations
  5. CC interactions of ν_e beam component
- Assumed 4-ν Mixing with Mixing Matrix

$$U = R_{34}(\theta_{34}) R_{24}(\theta_{24}, \delta_2) R_{14}(\theta_{14}) R_{23}(\theta_{23}) R_{13}(\theta_{13}, \delta_1) R_{12}(\theta_{12}, \delta_3)$$

3+1 Schemes



[MINOS, PRD 81 (2010) 052004, arXiv:1001.0336]

Gallium Anomaly

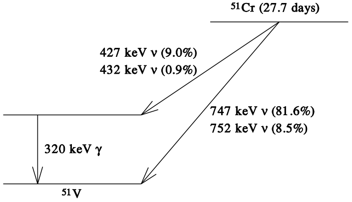
Gallium Radioactive Source Experiments

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

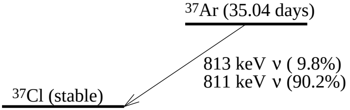
Detection Process: $\nu_e + {}^{71}\text{Ga} \to {}^{71}\text{Ge} + e^-$

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

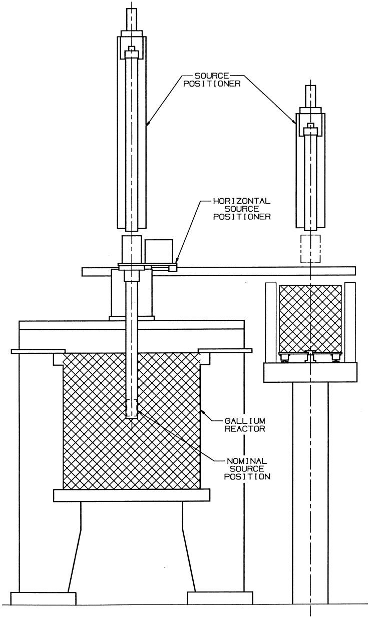
	^{51}Cr				^{37}Ar	
E [keV]	747	752	427	432	811	813
B.R.	0.8163	0.0849	0.0895	0.0093	0.902	0.098



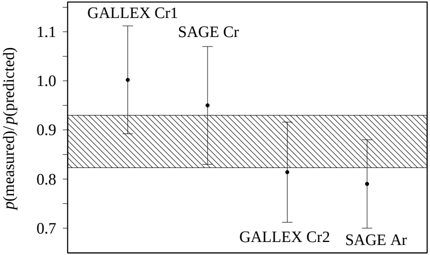
[SAGE, PRC 59 (1999) 2246, hep-ph/9803418]



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



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



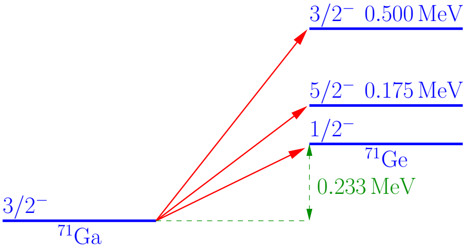
[SAGE, PRC 73 (2006) 045805, nucl-ex/0512041]

$$\boxed{R_{\text{Ga}} = 0.88 \pm 0.05}$$

- Deficit could be partly due to overestimate of

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

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



- $\sigma_{\text{G.S.}}$ related to measured $\sigma(e^- + {}^{71}\text{Ge} \to {}^{71}\text{Ga} + \nu_e)$:

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

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

- Contribution of Excited States only 5%!

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

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

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

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

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

  $$\sigma({}^{51}\text{Cr}) = 58.1 \times 10^{-46}\,\text{cm}^2 \left(1^{+0.036}_{-0.028}\right)_{1\sigma}$$

- 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 ${}^{71}\text{Ge}$. The calculation predicts destructive interference between the (p,n) spin and spin-tensor matrix elements."

  $$\sigma({}^{51}\text{Cr}) = 63.9 \times 10^{-46}\,\text{cm}^2\,(1 \pm 0.106)_{1\sigma}$$

Gallium Radioactive Source Experiments
are
Short-BaseLine Neutrino Oscillation Experiments

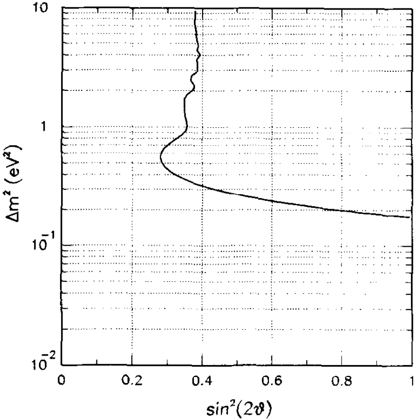


Fig. 1. Region of electron neutrino oscillation parameters ruled out at 90% C.L. by the GALLEX ^{51}Cr source experiment.

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

	GALLEX		SAGE	
	Cr1	Cr2	Cr	Ar
R	0.953 ± 0.11	$0.812^{+0.10}_{-0.11}$	0.95 ± 0.12	$0.79 \pm {}^{+0.09}_{-0.10}$
$\langle L \rangle$	1.9 m		0.6 m	

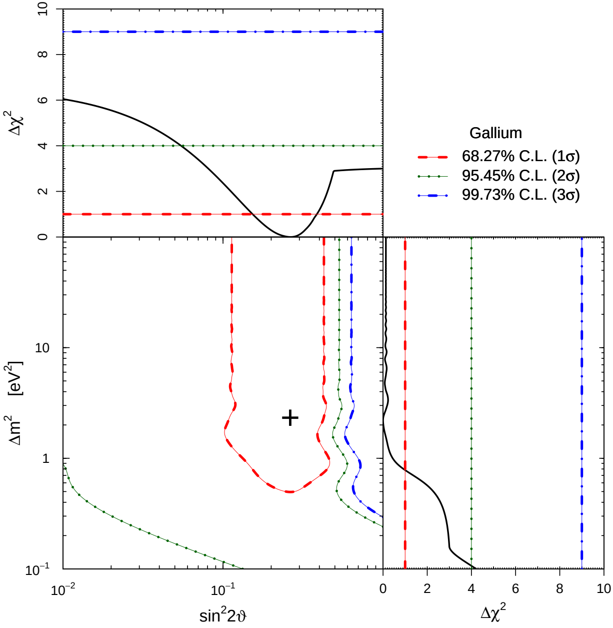
$$\boxed{R_{\text{Ga}} = 0.87 \pm 0.05}$$

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

$$L_{\text{osc}} \lesssim 0.5 \quad \text{m} \quad \Longrightarrow \quad \Delta m^2 \gtrsim 1\,\text{eV}^2 \quad \Longrightarrow \quad \nu_e \to \nu_s$$

$$R = \frac{\int \mathrm{d}V \, L^{-2} \sum_i (\text{B.R.})_i \, \sigma_i \, P_{\nu_e \to \nu_e}(L, E_i)}{\sum_i (\text{B.R.})_i \, \sigma_i \int \mathrm{d}V \, L^{-2}}$$

[Acero, Giunti, Laveder, PRD 78 (2008) 073009, arXiv:0711.4222]



No Osc.

$\chi^2_{\text{min}} = 8.3$

NdF $= 2$

GoF $= 8.1\%$

Osc.

$\chi^2_{\text{min}} = 1.8$

NdF $= 2$

GoF $= 40\%$

$\sin^2 2\vartheta = 0.26$

$\Delta m^2 = 2.20\,\text{eV}^2$

[Acero, Giunti, Laveder, PRD 78 (2008) 073009, arXiv:0711.4222]

Future Promising Searches of SBL Oscillations

- SAGE is planning a new source experiment (ν_e disappearance)
- Beta-Beam experiments:

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

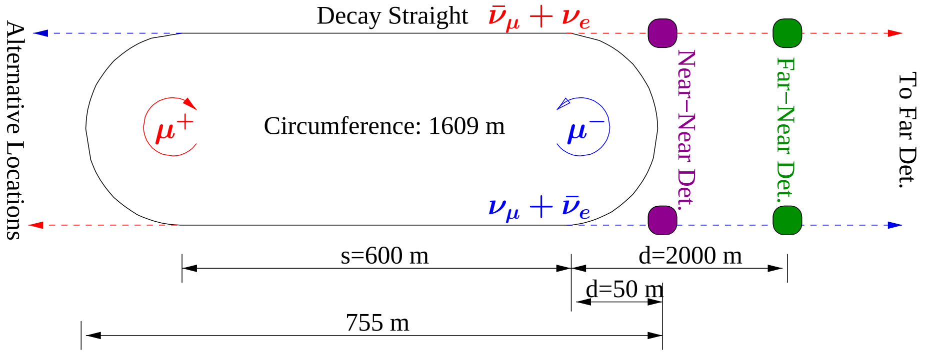
$$N(A,Z) \to N(A,Z-1) + e^+ + \nu_e \qquad (\beta^+)$$

- Neutrino Factory experiments:

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

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

Neutrino Factory

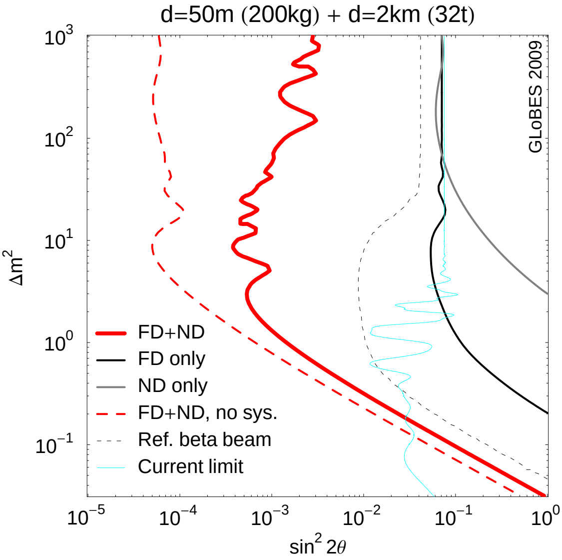


[Giunti, Laveder, Winter, PRD 80 (2009) 073005, arXiv:0907.5487]

Near Detectors: Scintillator or Iron Calorimeter with perfect flavor identification

Systematic Uncertainties: Cross Section, Detector Normalization, Energy Resolution and Calibration, Backgrounds

ν_e Disappearance



[Giunti, Laveder, Winter, PRD 80 (2009) 073005, arXiv:0907.5487]

Conclusions

- Existence of sterile neutrinos is possible
- Likely connected with neutrino mass generation
- Active-Sterile transitions have been searched in several experiments and discussed in global phenomenological analyses of data
- LSND indication of 4-Neutrino Mixing is disfavored
- Gallium Anomaly may be due to $\nu_e \to \nu_s$ oscillations with $\sin^2 2\vartheta \gtrsim 0.1$ and $\Delta m^2 \gtrsim 1\,\text{eV}^2$
- SBL oscillations can be explored with high precision in
  - Beta-Beam experiments (pure ν_e or $\bar{\nu}_e$ beam from nuclear decay)
  - Neutrino Factory experiments (ν_e and $\bar{\nu}_\mu$ from μ^+ decay, or $\bar{\nu}_e$ and ν_μ from μ^- decay)