Status of Light Sterile Neutrinos

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Indications of Short-Baseline Oscillations

- Reactor Electron Antineutrino Anomaly: $\bar{\nu}_e \to \bar{\nu}_e$ $\approx 3\sigma$ deficit

  $L \simeq 10 - 100\,\mathrm{m}$ $E \simeq 4\,\mathrm{MeV}$ $\Delta m^2 \gtrsim 0.5\,\mathrm{eV}^2$

  [Mention et al, PRD 83 (2011) 073006; Mueller et al, PRC 83 (2011) 054615; Huber, PRC 84 (2011) 024617; Sinev, arXiv:1103.2452; Ciuffoli, Evslin, Li, JHEP 12 (2012) 110; Zhang, Qian, Vogel, PRD 87 (2013) 073018; Ivanov et al, PRC 88 (2013) 055501]

- Gallium Anomaly: $\nu_e \to \nu_e$ $\approx 3\sigma$ deficit

  $L \simeq 1\,\mathrm{m}$ $E \simeq 1\,\mathrm{MeV}$ $\Delta m^2 \gtrsim 1\,\mathrm{eV}^2$

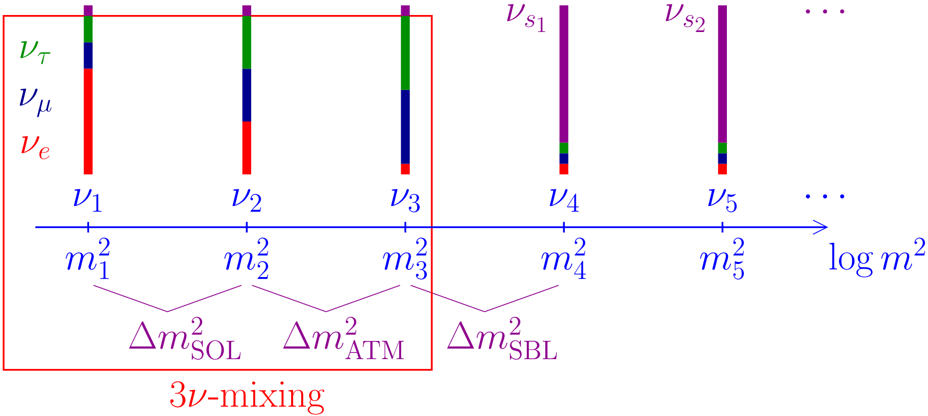
  [SAGE, PRC 73 (2006) 045805, PRC 80 (2009) 015807; Laveder et al, Nucl.Phys.Proc.Suppl. 168 (2007) 344, MPLA 22 (2007) 2499, PRD 78 (2008) 073009, PRC 83 (2011) 065504]

- LSND: Accelerator $\bar{\nu}_\mu \to \bar{\nu}_e$ $\approx 4\sigma$ excess

  $L \simeq 30\,\mathrm{m}$ $E \simeq 50\,\mathrm{MeV}$ $\Delta m^2 \gtrsim 0.2\,\mathrm{eV}^2$

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

Beyond Three-Neutrino Mixing: Sterile Neutrinos



Terminology: a eV-scale sterile neutrino

means: a eV-scale massive neutrino which is mainly sterile

Sterile Neutrinos from Physics Beyond the SM

- Neutrinos are special in the Standard Model: the only neutral fermions
- Active left-handed neutrinos can mix with non-SM singlet fermions often called right-handed neutrinos ⟹ Neutrino Portal [A. Smirnov, arXiv:1502.04530]
- Light anti-ν_R are light sterile neutrinos

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

- Sterile means no standard model interactions

[Pontecorvo, Sov. Phys. JETP 26 (1968) 984]

- Active neutrinos $(\nu_e, \nu_\mu, \nu_\tau)$ can oscillate into light sterile neutrinos (ν_s)
- Observables:
  - Disappearance of active neutrinos (neutral current deficit)
  - Indirect evidence through combined fit of data (current indication)
- Short-baseline anomalies + 3ν-mixing:

$$\Delta m^2_{21} \ll |\Delta m^2_{31}| \ll |\Delta m^2_{41}| \leq \ldots$$

ν_1	ν_2	ν_3	ν_4	$\ldots$
ν_e	ν_μ	ν_τ	ν_{s_1}	$\ldots$

Effective SBL Oscillation Probabilities in 3+1 Schemes

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

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

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

$$U = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} & U_{e4} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} & U_{\mu 4} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} & U_{\tau 4} \\ U_{s1} & U_{s2} & U_{s3} & U_{s4} \end{pmatrix}$$

SBL (fourth column)

- 6 mixing angles
- 3 Dirac CP phases
- 3 Majorana CP phases
- But CP violation is not observable in current SBL experiments!
- Observable in LBL accelerator exp. sensitive to Δm^2_{ATM} [de Gouvea, Kelly, Kobach, PRD 91 (2015) 053005; Klop, Palazzo, PRD 91 (2015) 073017; Berryman, de Gouvea, Kelly, Kobach, arXiv:1507.03986] and solar exp. sensitive to Δm^2_{SOL} [Long, Li, Giunti, PRD 87, 113004 (2013) 113004]

3+1: Appearance vs Disappearance

- Amplitude of ν_e disappearance:

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

- Amplitude of ν_μ disappearance:

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

- Amplitude of $\nu_\mu \to \nu_e$ transitions:

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

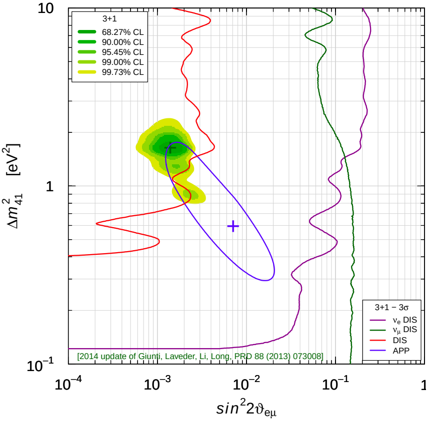
- Upper bounds on ν_e and ν_μ disappearance $\Rightarrow$ strong limit on $\nu_\mu \to \nu_e$

[Okada, Yasuda, IJMPA 12 (1997) 3669; Bilenky, Giunti, Grimus, EPJC 1 (1998) 247]

- Similar constraint in 3+2, 3+3, ..., 3+N_s !

Global 3+1 Fit

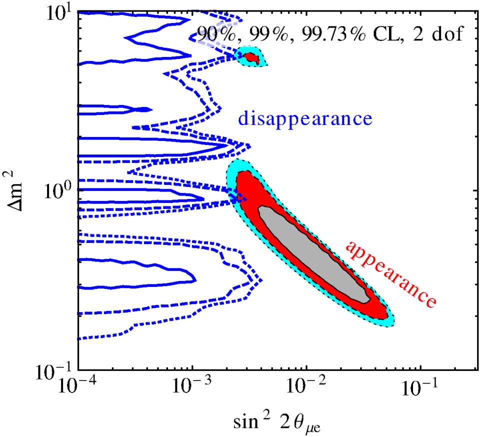
Our Fit



GoF = 5%

PGoF = 0.1%

Kopp, Machado, Maltoni, Schwetz

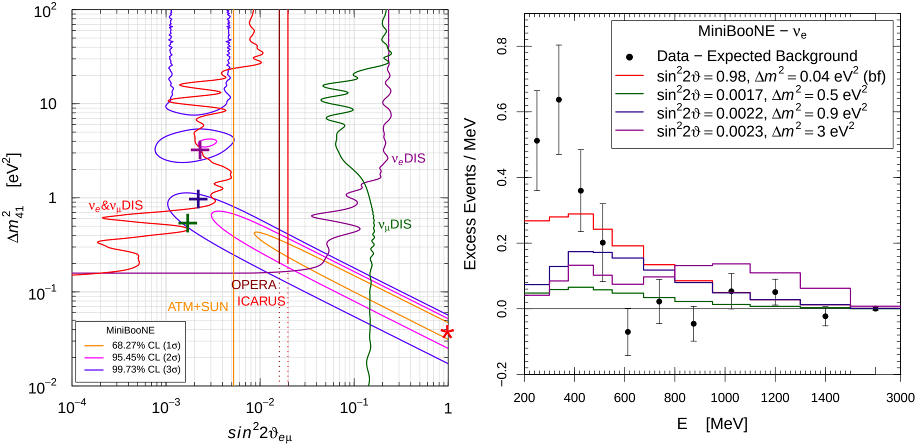


GoF = 19%

PGoF = 0.01%

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

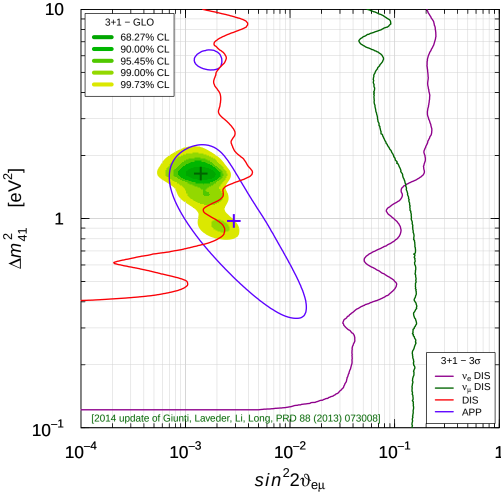
MiniBooNE Low-Energy Excess?



- No fit of low-energy excess for realistic $\sin^2 2\vartheta_{e\mu} \lesssim 3 \times 10^{-3}$
- Neutrino energy reconstruction problem? [Martini, Ericson, Chanfray, PRD 87 (2013) 013009]
- MB low-energy excess is the main cause of bad APP-DIS PGoF = 0.1%
- Pragmatic Approach: discard the Low-Energy Excess because it is very likely not due to oscillations

Pragmatic 3+1 Fit

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



MiniBooNE $E > 475\,\text{MeV}$

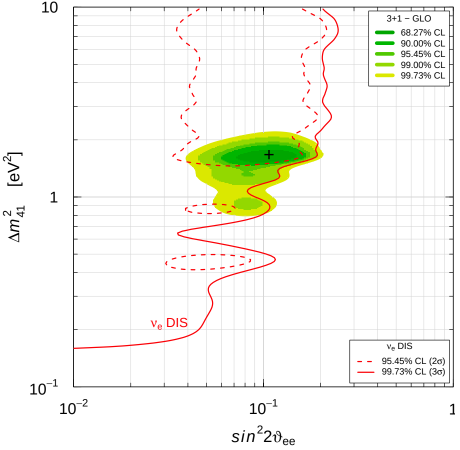
GoF $= 26\%$ PGoF $= 7\%$

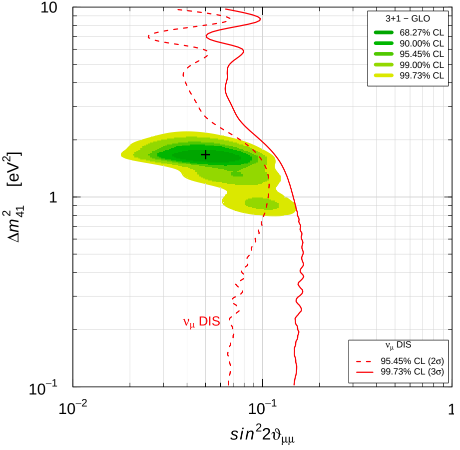
- APP $\nu_\mu \to \nu_e$ & $\bar{\nu}_\mu \to \bar{\nu}_e$: LSND ($\nu_s$), MiniBooNE (?), OPERA (~~ν_s~~), ICARUS (~~ν_s~~), KARMEN (~~ν_s~~), NOMAD (~~ν_s~~), BNL-E776 (~~ν_s~~)
- DIS ν_e & $\bar{\nu}_e$: Reactors (ν_s), Gallium (ν_s), ν_eC (~~ν_s~~), Solar (~~ν_s~~)
- DIS ν_μ & $\bar{\nu}_\mu$: CDHSW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

No Osc. nominally disfavored at $\approx 6.3\sigma$

$\Delta\chi^2/\text{NDF} = 47.7/3$

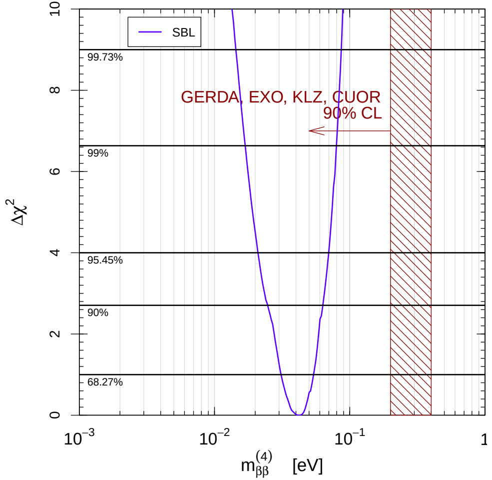
ν_e and ν_μ Disappearance





Neutrinoless Double-β Decay

$$m_{\beta\beta} = |U_{e1}|^2\, m_1 + |U_{e2}|^2\, e^{i\alpha_{21}}\, m_2 + |U_{e3}|^2\, e^{i\alpha_{31}}\, m_3 + |U_{e4}|^2\, e^{i\alpha_{41}}\, m_4$$



Pragmatic 3+1 Fit

[Giunti, Laveder, Li, Long, 2014]

$$m_{\beta\beta}^{(k)} = |U_{ek}|^2 m_k$$

$$m_1 \ll m_4$$

$$\Downarrow$$

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

surprise:

possible cancellation

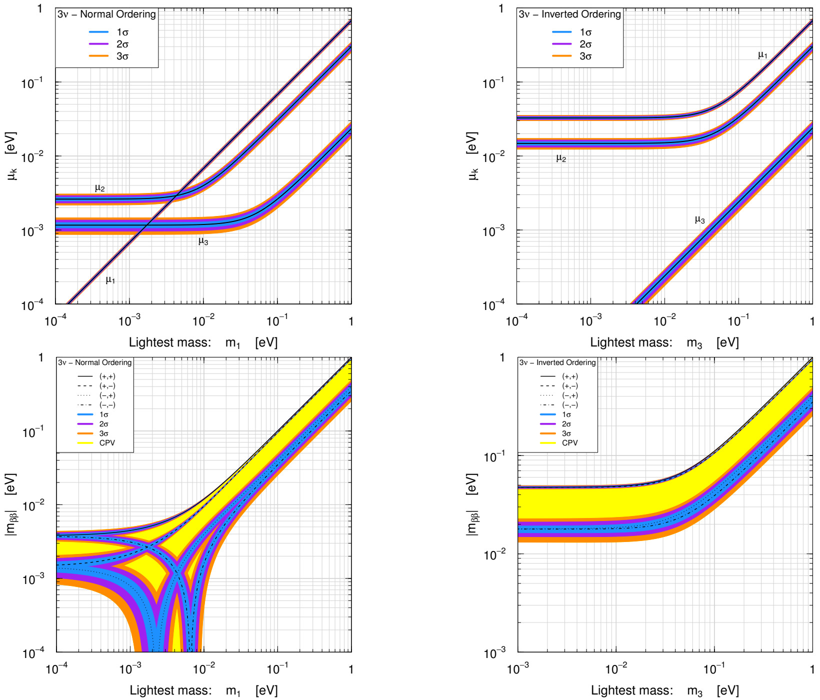
with $m_{\beta\beta}^{(3\nu)}$

[Barry et al, JHEP 07 (2011) 091]

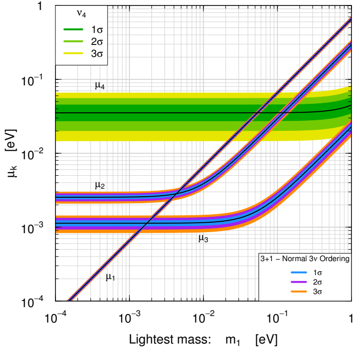
[Li, Liu, PLB 706 (2012) 406]

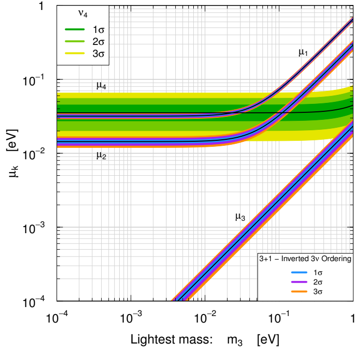
[Rodejohann, JPG 39 (2012) 124008]

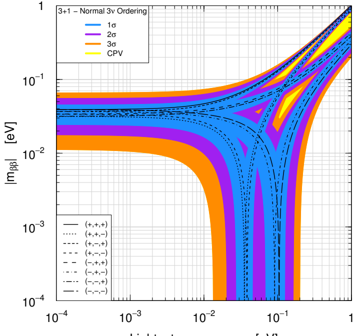
[Girardi, Meroni, Petcov, JHEP 1311 (2013) 146]



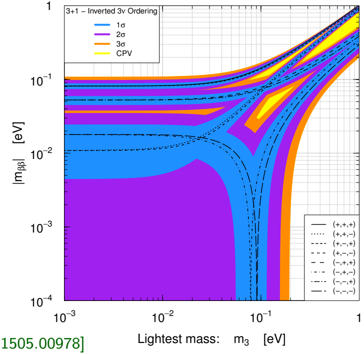
3ν – Normal Ordering
1σ
2σ
3σ
μ2
μ3
μ1
μk [eV]
Lightest mass: m1 [eV]
3ν – Inverted Ordering
1σ
2σ
3σ
μ1
μ2
μ3
μk [eV]
Lightest mass: m3 [eV]
3ν – Normal Ordering
(+,+)
(+,−)
(−,+)
(−,−)
1σ
2σ
3σ
CPV
|mββ| [eV]
Lightest mass: m1 [eV]
3ν – Inverted Ordering
(+,+)
(+,−)
(−,+)
(−,−)
1σ
2σ
3σ
CPV
|mββ| [eV]
Lightest mass: m3 [eV]

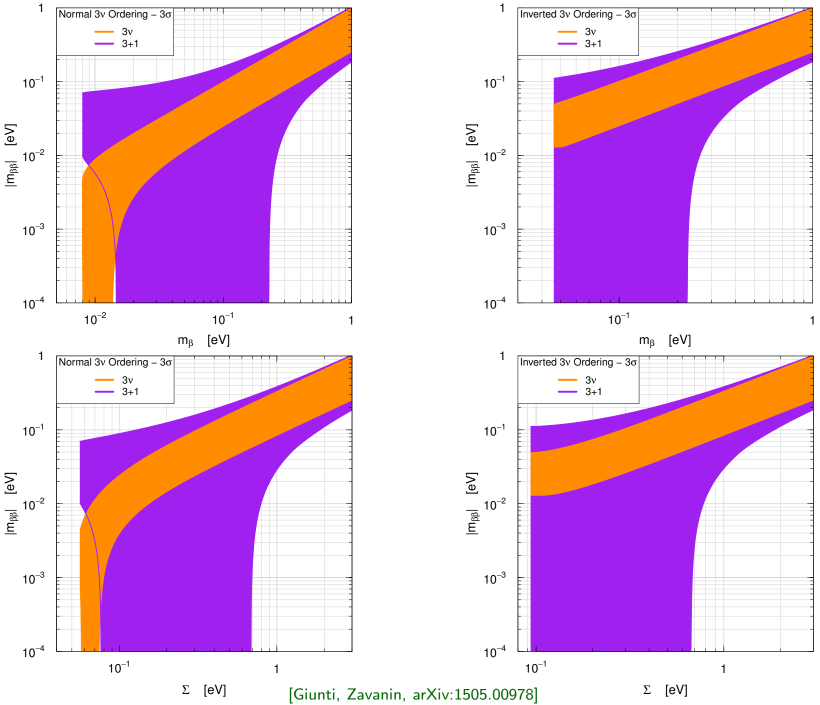






[Giunti, Zavanin, arXiv:1505.00978]





[Giunti, Zavanin, arXiv:1505.00978]

Conclusions

- Short-Baseline ν_e and $\bar{\nu}_e$ Disappearance:
  - Experimental data agree on Reactor $\bar{\nu}_e$ and Gallium ν_e anomalies.
  - Problem: unknown systematic uncertainties (Reactor $\bar{\nu}_e$ flux).
  - Many promising projects to test unambiguously 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.
- Short-Baseline $\bar{\nu}_\mu \to \bar{\nu}_e$ LSND Signal:
  - Not seen by other SBL $\overset{(-)}{\nu}_\mu \to \overset{(-)}{\nu}_e$ experiments.
  - MiniBooNE experiment has been inconclusive.
  - Experiments with near detector are needed to check LSND signal!
  - If $|U_{e4}| > 0$ why not $|U_{\mu4}| > 0$? $\Longrightarrow$ $\sin^2 2\vartheta_{e\mu} = 4|U_{e4}|^2|U_{\mu4}|^2 > 0$
- Pragmatic 3+1 Fit is fine: moderate APP-DIS tension.
- 3+2 is not needed: same APP-DIS tension as 3+1 and no evidence of CP violation.
- Cosmology:
  - Tension between $\Delta N_{\text{eff}} = 1$ and $m_s \approx 1\,\text{eV}$.
  - Cosmological and oscillation data may be reconciled by a non-standard cosmological mechanism.