Review of Sterile Neutrino Searches

Carlo Giunti

INFN, Sezione di Torino
and
Dipartimento di Fisica Teorica, Università di Torino

giunti@to.infn.it

Neutrino Unbound: http://www.nu.to.infn.it

NNN15
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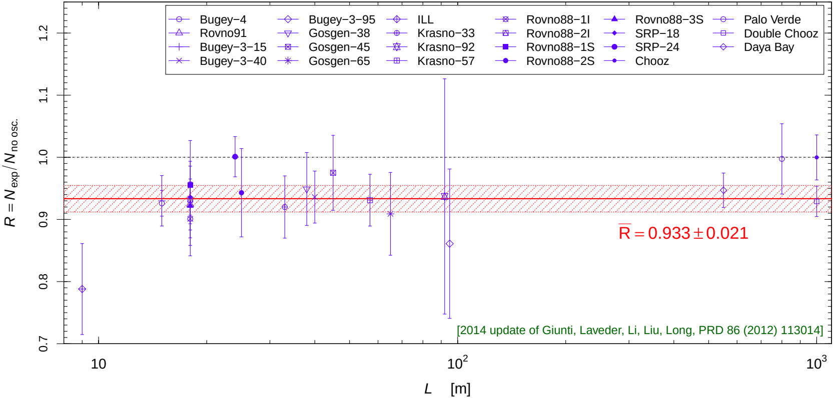
Reactor Electron Antineutrino Anomaly

[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]



$\bar{\nu}_e \to \bar{\nu}_e$ $\quad L \sim 10 - 100\,\mathrm{m}$ $\quad E \sim 4\,\mathrm{MeV}$

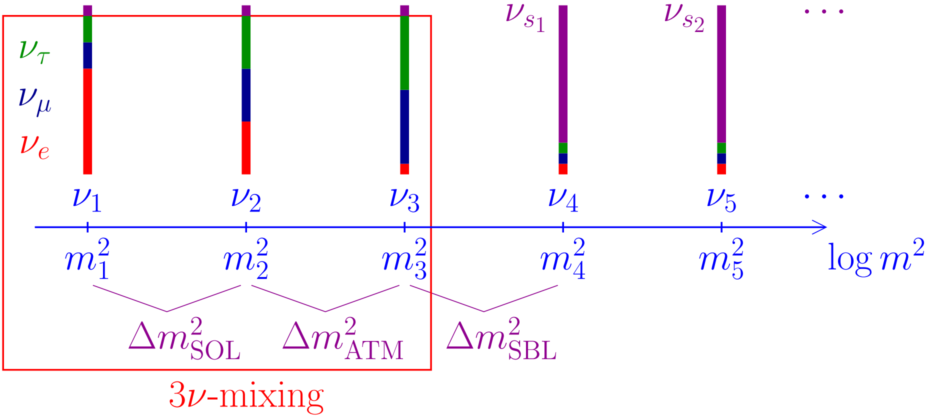
Nominal $\approx 3.1\sigma$ deficit $\quad \Delta m^2 \gtrsim 0.5\,\mathrm{eV}^2$ $\quad (\gg \Delta m^2_{\mathrm{A}} \gg \Delta m^2_{\mathrm{S}})$

[see also: Sinev, arXiv:1103.2452; Ciuffoli, Evslin, Li, JHEP 12 (2012) 110; Zhang, Qian, Vogel, PRD 87 (2013) 073018; Kopp, Machado, Maltoni, Schwetz, JHEP 1305 (2013) 050; Ivanov et al, PRC 88 (2013) 055501]

Problem: unknown $\bar{\nu}_e$ flux uncertainties?

[Hayes, Friar, Garvey, Jonkmans, PRL 112 (2014) 202501; Dwyer, Langford, PRL 114 (2015) 012502]

Beyond Three-Neutrino Mixing: Sterile Neutrinos



Terminology: a eV-scale sterile neutrino

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

Effective SBL Oscillation Probabilities in 3+1 Schemes

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

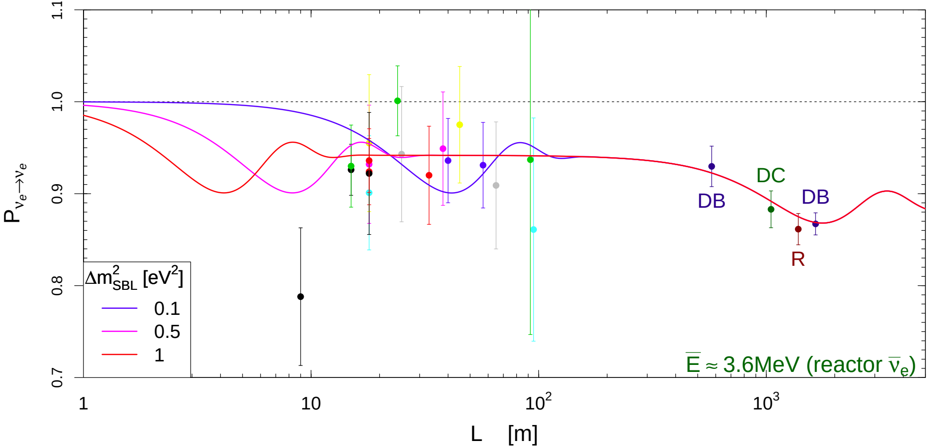
$$P^{\text{SBL}}_{\overset{(-)}{\nu}_\alpha \to \overset{(-)}{\nu}_\alpha} \simeq 1 - \sin^2 2\vartheta_{\alpha\alpha} \sin^2\left(\frac{\Delta m^2_{41} L}{4E}\right) \qquad \sin^2 2\vartheta_{\alpha\alpha} = 4|U_{\alpha 4}|^2 \left(1 - |U_{\alpha 4}|^2\right)$$

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, PRD 92 (2015) 073012, Palazzo, arXiv:1509.03148] and solar exp. sensitive to Δm^2_{SOL} [Long, Li, Giunti, PRD 87, 113004 (2013) 113004]



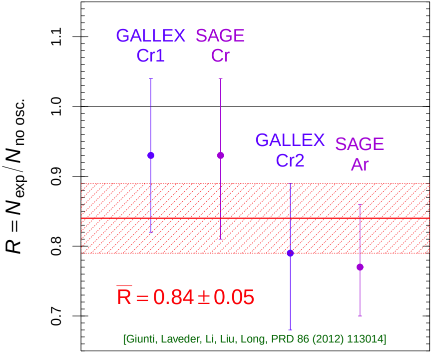
$P_{\nu_e \to \nu_e}$
1.1
1.0
0.9
0.8
0.7
1
10
10^2
10^3
L [m]
Δm^2_{SBL} [eV^2]
0.1
0.5
1
DB
DC
DB
R
$\overline{E} \approx 3.6$MeV (reactor $\bar{\nu}_e$)

Gallium Anomaly

Gallium Radioactive Source Experiments: GALLEX and SAGE

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

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



$\bar{\nu}_e \to \bar{\nu}_e$ $\quad E \sim 0.7\,\text{MeV}$

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

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

Nominal $\approx 2.9\sigma$ anomaly

$\Delta m^2 \gtrsim 1\,\text{eV}^2 \quad (\gg \Delta m^2_{\text{A}} \gg \Delta m^2_{\text{S}})$

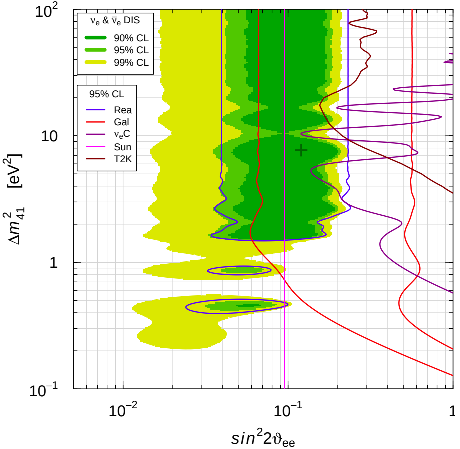
[SAGE, PRC 73 (2006) 045805; PRC 80 (2009) 015807]

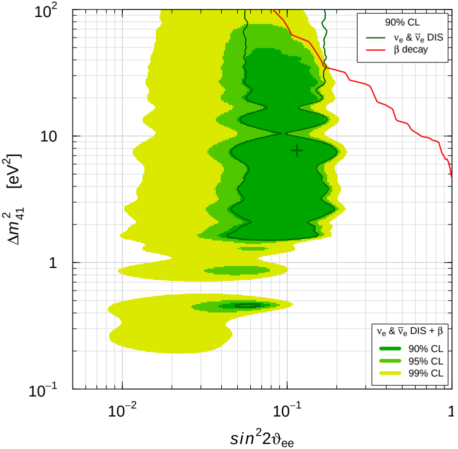
[Laveder et al, Nucl.Phys.Proc.Suppl. 168 (2007) 344; MPLA 22 (2007) 2499; PRD 78 (2008) 073009; PRC 83 (2011) 065504]

[Mention et al, PRD 83 (2011) 073006]

- ${}^{3}\text{He} + {}^{71}\text{Ga} \to {}^{71}\text{Ge} + {}^{3}\text{H}$ cross section measurement [Frekers et al., PLB 706 (2011) 134]
- $E_{\text{th}}(\nu_e + {}^{71}\text{Ga} \to {}^{71}\text{Ge} + e^-) = 233.5 \pm 1.2\,\text{keV}$ [Frekers et al., PLB 722 (2013) 233]

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]

solar ν_e + KamLAND $\bar{\nu}_e$ + ϑ_{13}

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

[Palazzo, PRD 83 (2011) 113013; PRD 85 (2012) 077301]

[Giunti, Laveder, Li, Liu, Long, PRD 86 (2012) 113014]

T2K Near Detector ν_e disappearance

[T2K, PRD 91 (2015) 051102]

Mainz + Troitsk Tritium β decay

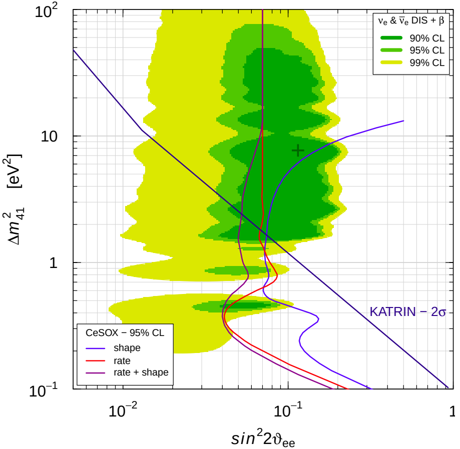
[Mainz, EPJC 73 (2013) 2323]

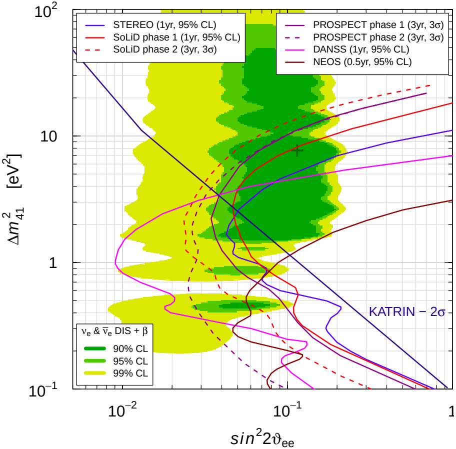
[Troitsk, JETPL 97 (2013) 67; JPG 41 (2014) 015001]

No Osc. excluded at 2.9σ

$\Delta\chi^2/\text{NDF} = 11.2/2$

Near-Future Experiments





CeSOX (BOREXINO, Italy)
^{144}Ce – 100 kCi [Vivier@TAUP2015]
rate: 1% normalization uncertainty
8.5 m from detector center
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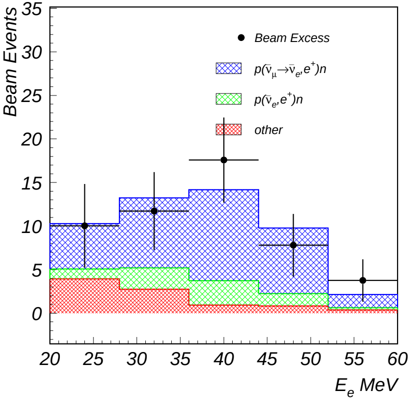
LSND

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

$\bar{\nu}_\mu \to \bar{\nu}_e$ $\qquad L \simeq 30\,\text{m}$ $\qquad 20\,\text{MeV} \leq E \leq 60\,\text{MeV}$



- Well known source of $\bar{\nu}_\mu$:

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

- $\bar{\nu}_\mu \xrightarrow[L \simeq 30\,\text{m}]{} \bar{\nu}_e$

- Well known detection process of $\bar{\nu}_e$:

$$\bar{\nu}_e + p \to n + e^+$$

- But signal not seen by KARMEN with same method at $L \simeq 18\,\text{m}$

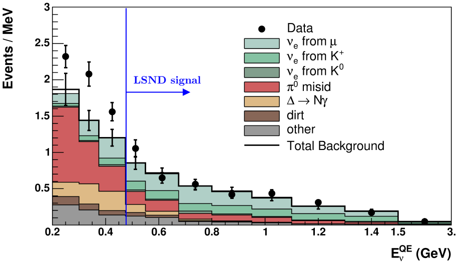
[PRD 65 (2002) 112001]

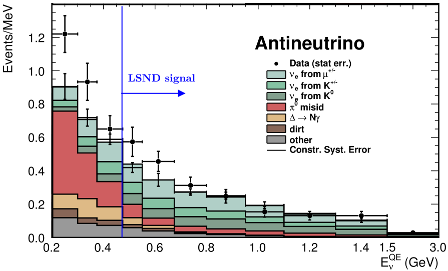
Nominal $\approx 3.8\sigma$ excess $\qquad \Delta m^2 \gtrsim 0.2\,\text{eV}^2 \qquad (\gg \Delta m^2_{\text{A}} \gg \Delta m^2_{\text{S}})$

MiniBooNE

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

$\nu_\mu \to \nu_e$ [PRL 102 (2009) 101802] $\qquad$ $\bar{\nu}_\mu \to \bar{\nu}_e$ [PRL 110 (2013) 161801]





- Purpose: check LSND signal.
- Different L and E.
- Similar L/E (oscillations).
- No money, no Near Detector.
- LSND signal: $E > 475\,\text{MeV}$.
- Agreement with LSND signal?
- CP violation?
- Low-energy anomaly!

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:

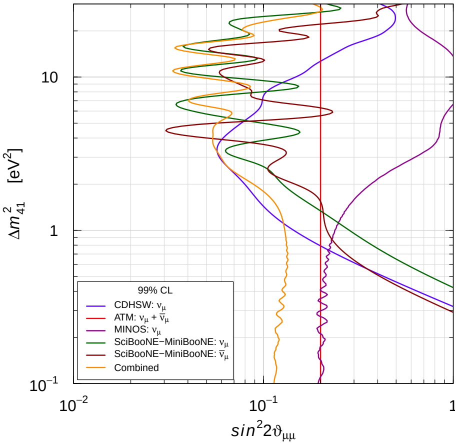
$$\sin^2 2\vartheta_{e\mu} = 4|U_{e4}|^2|U_{\mu4}|^2 \simeq \frac{1}{4} \sin^2 2\vartheta_{ee} \sin^2 2\vartheta_{\mu\mu}$$

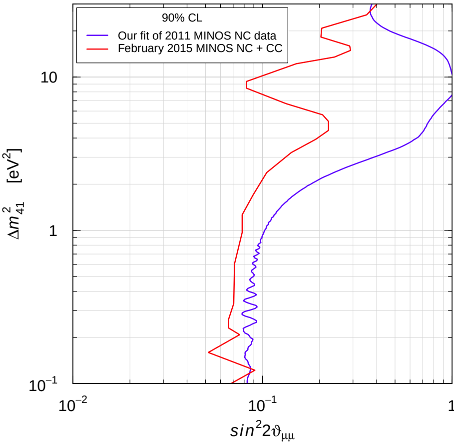
- Upper bounds on ν_e and ν_μ disappearance $\Rightarrow$ strong limit on $\nu_\mu \to \nu_e$

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

- Similar constraint in 3+2, 3+3, . . . , 3+N_s! [Giunti, Zavanin, arXiv:1508.03172]

ν_μ and $\bar{\nu}_\mu$ Disappearance





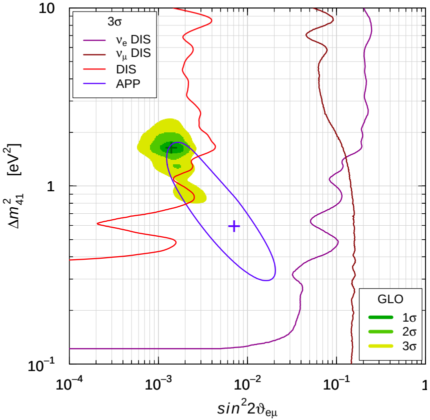
MINOS: $L_{\text{decay}} \simeq 0.675\,\text{km}$ $L_{\text{ND}} \simeq 1.04\,\text{km}$ $L_{\text{FD}} \simeq 735\,\text{km}$

$$E \approx 4\,\text{GeV} \Longrightarrow \frac{L_{\text{osc}}}{L_{\text{ND}}} \approx \frac{10}{\Delta m^2_{41}\,[\text{eV}^2]}$$

[see Whitehead talk]

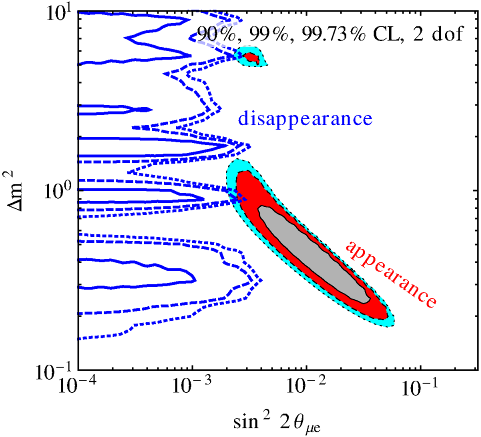
Global 3+1 Fit

Our Fit



GoF = 5% PGoF = 0.1%

Kopp, Machado, Maltoni, Schwetz

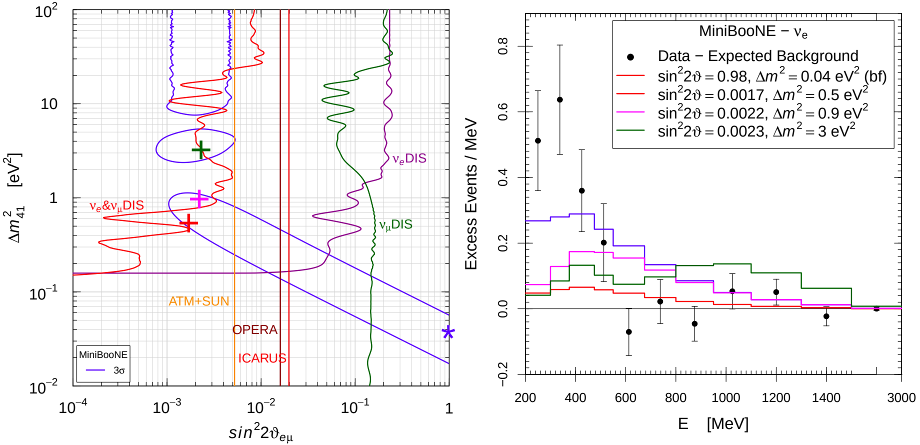


GoF = 19% PGoF = 0.01%

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

There is no globally allowed region in this paper!

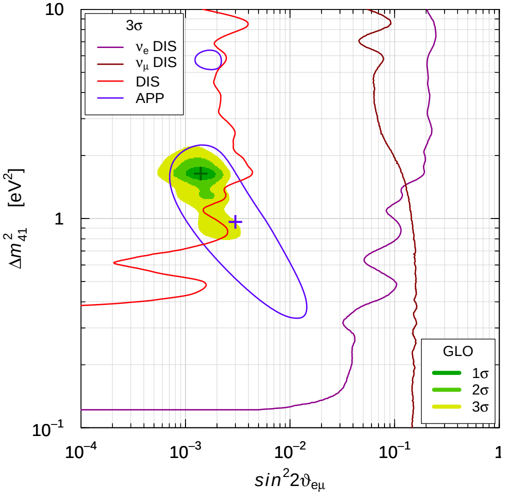
MiniBooNE Low-Energy Excess?



- 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 Global 3+1 Fit

[PRD 88 (2013) 073008; arXiv:1507.08204]



- 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~~)

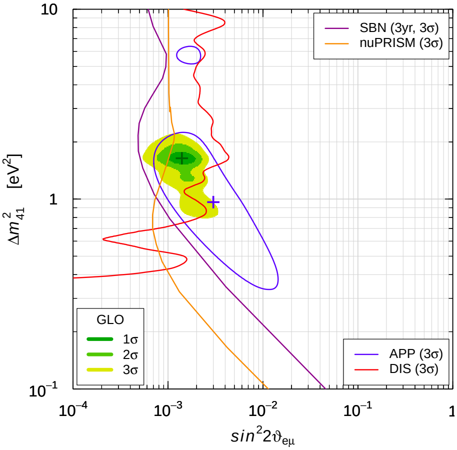
MiniBooNE $E > 475\,\text{MeV}$

GoF = 26% PGoF = 7%

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

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

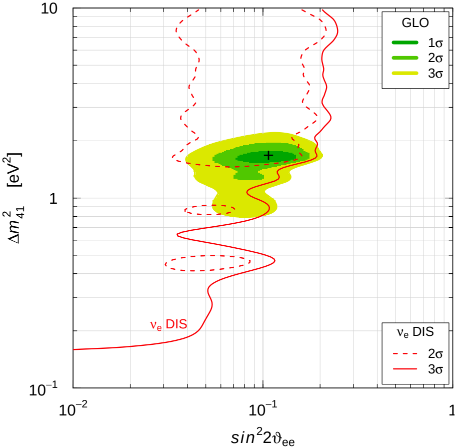
Future Experiments

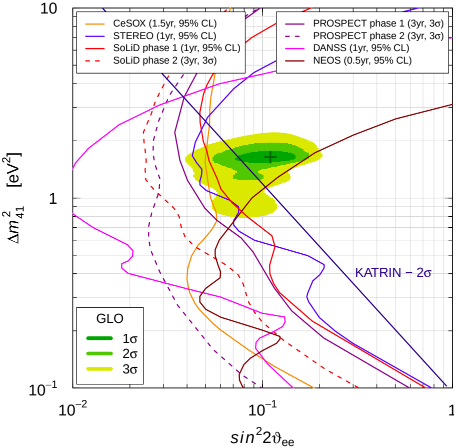


SBN (FNAL, USA)
[arXiv:1503.01520]
3 Liquid Argon TPCs
LAr1-ND $L \simeq 100\,\mathrm{m}$
MicroBooNE $L \simeq 470\,\mathrm{m}$
ICARUS T600 $L \simeq 600\,\mathrm{m}$

nuPRISM (J-PARC, Japan)
[Wilking@NNN2015]
$L \simeq 1\,\mathrm{km}$
50 m tall water Cherenkov detector
$1^\circ - 4^\circ$ off-axis
can be improved with T2K ND

ν_e Disappearance





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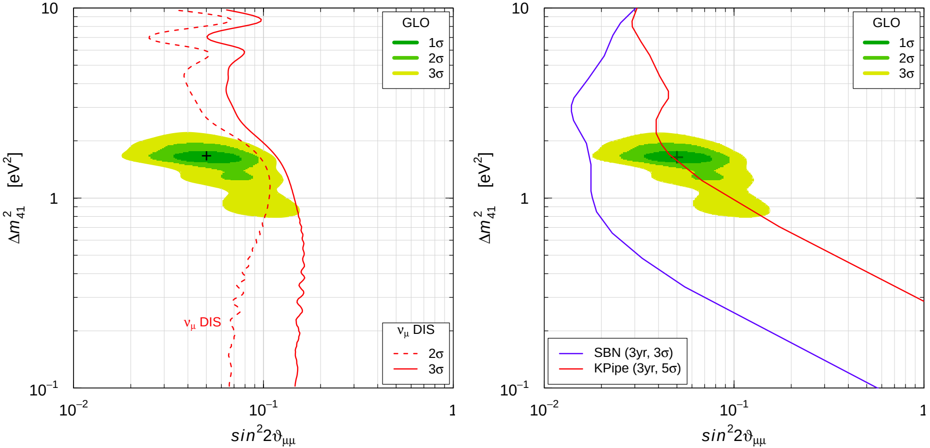
ν_μ Disappearance



SBN (USA) [arXiv:1503.01520]

LAr1-ND $L \simeq$ 100m

MicroBooNE $L \simeq$ 470m

ICARUS T600 $L \simeq$ 600m

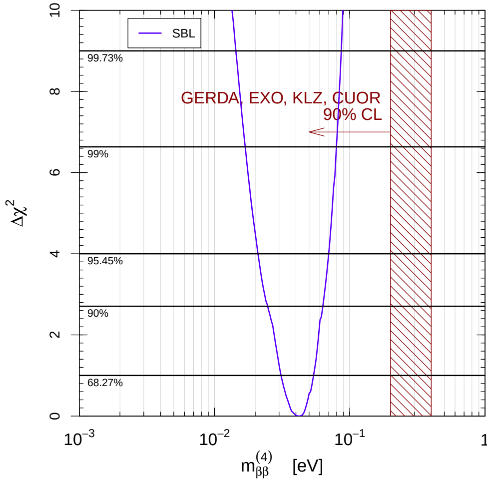
KPipe (Japan) [arXiv:1510.06994]

$L \simeq$ 30-150m

120 m long detector!

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

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

$$m_1 \ll m_4$$

$$\Downarrow$$

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

surprise:

possible cancellation

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

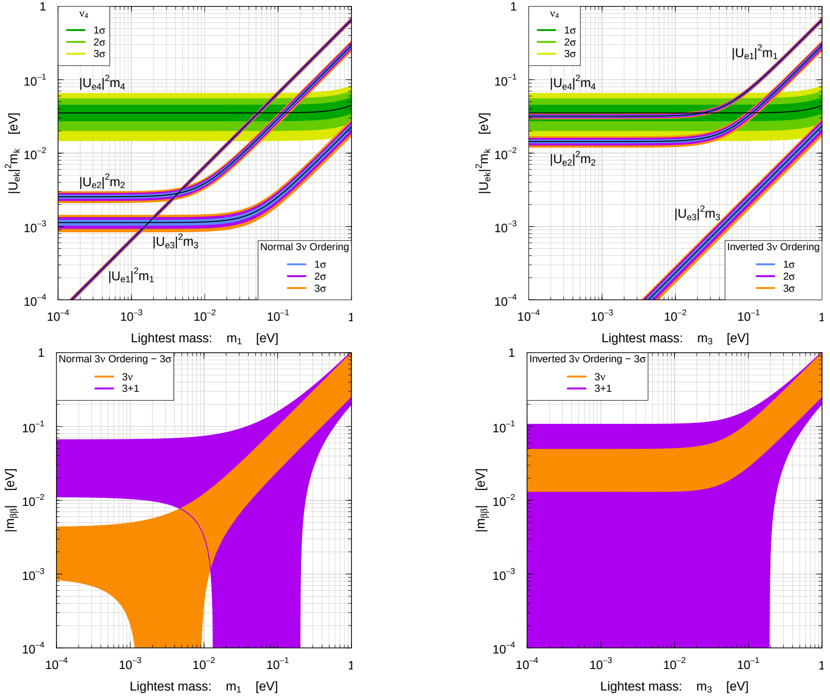
[Barry et al, JHEP 07 (2011) 091]

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

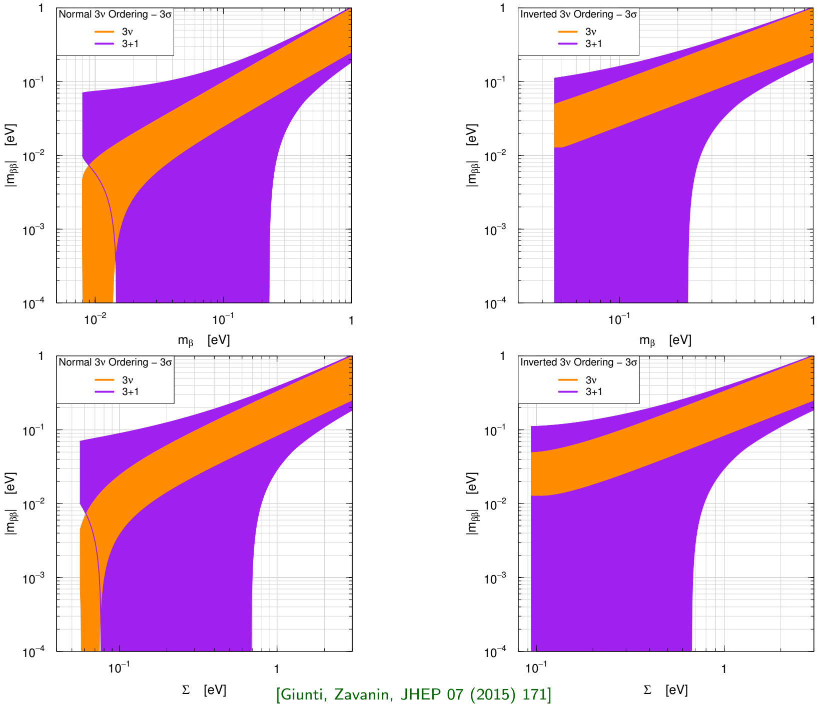
[Rodejohann, JPG 39 (2012) 124008]

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

[Giunti, Zavanin, JHEP 07 (2015) 171]



ν4
1σ
2σ
3σ
$|U_{e4}|^2 m_4$
$|U_{e2}|^2 m_2$
$|U_{e3}|^2 m_3$
$|U_{e1}|^2 m_1$
Normal 3ν Ordering
Inverted 3ν Ordering
$|U_{ek}|^2 m_k$ [eV]
Lightest mass: m_1 [eV]
Lightest mass: m_3 [eV]
Normal 3ν Ordering − 3σ
Inverted 3ν Ordering − 3σ
3ν
3+1
$|m_{\beta\beta}|$ [eV]



[Giunti, Zavanin, JHEP 07 (2015) 171]

Conclusions

- Short-Baseline ν_e and $\bar{\nu}_e$ Disappearance:
  - Experimental data agree on Reactor $\bar{\nu}_e$ and Gallium ν_e disappearance.
  - Problem: total rates may have unknown systematic uncertainties.
  - 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!
  - Promising Fermilab program aimed at a conclusive solution of the mystery: a near detector (LAr1-ND), an intermediate detector (MicroBooNE) and a far detector (ICARUS-T600), all Liquid Argon Time Projection Chambers.
- Pragmatic 3+1 Fit is fine: moderate APP-DIS tension.
- 3+2 is not needed: same APP-DIS tension and no exp. CP violation.
- Cosmology [see Y. Wong talk]:
  - 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.