Phenomenology of Light Sterile Neutrinos

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NIAPP 2014
Neutrinos in Astro and Particle Physics

MIAPP, Munich, Germany

15 July 2014

Sterile Neutrinos

- I consider sterile neutrinos with mass scale $\sim 1\,\text{eV}$ in light of short-baseline Reactor Anomaly, Gallium Anomaly, LSND.
- Other possibilities (not incompatible):
  - Very light sterile neutrinos with mass scale $\ll 1\,\text{eV}$: important for solar neutrino phenomenology

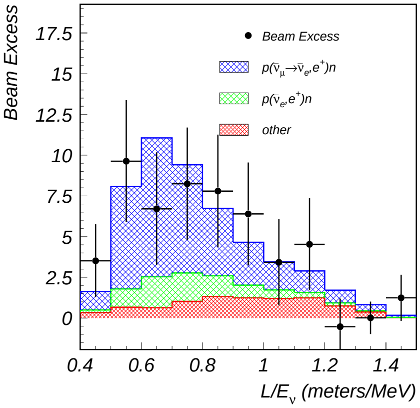
    [Das, Pulido, Picariello, PRD 79 (2009) 073010]
    [de Holanda, Smirnov, PRD 83 (2011) 113011]
  - Heavy sterile neutrinos with mass scale $\gg 1\,\text{eV}$: could be Warm Dark Matter

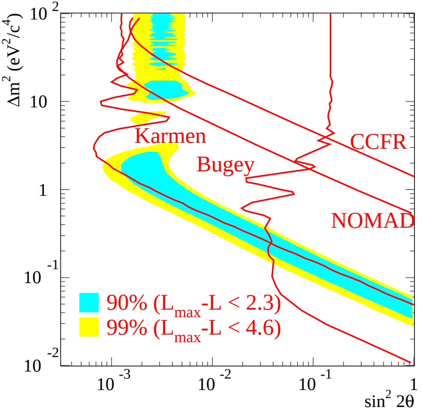
    [Kusenko, Phys. Rept. 481 (2009) 1]
    [Boyarsky, Ruchayskiy, Shaposhnikov, Ann. Rev. Nucl. Part. Sci. 59 (2009) 191]
    [Drewes, IJMPE, 22 (2013) 1330019]

LSND

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

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



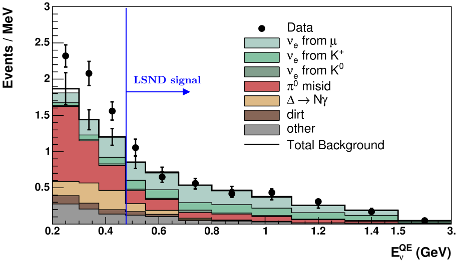


3.8σ excess $\quad \Delta m^2_{\text{LSND}} \gtrsim 0.2\,\mathrm{eV}^2 \quad (\gg \Delta m^2_{\text{A}} \gg \Delta m^2_{\text{S}})$

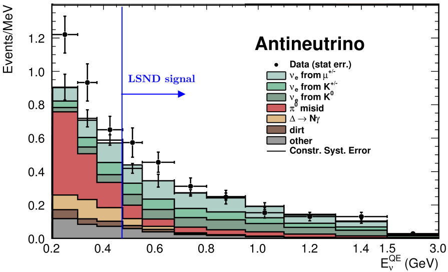
MiniBooNE

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

$\nu_\mu \to \nu_e$ [PRL 102 (2009) 101802]



$\bar{\nu}_\mu \to \bar{\nu}_e$ [PRL 110 (2013) 161801]



- Purpose: check LSND signal.
- Different L and E.
- Similar L/E (oscillations).
- LSND signal: $E > 475\,\text{MeV}$.

- Agreement with LSND signal?
- CP violation?
- Low-energy anomaly!

Reactor Electron Antineutrino Anomaly

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

[update in White Paper, arXiv:1204.5379]

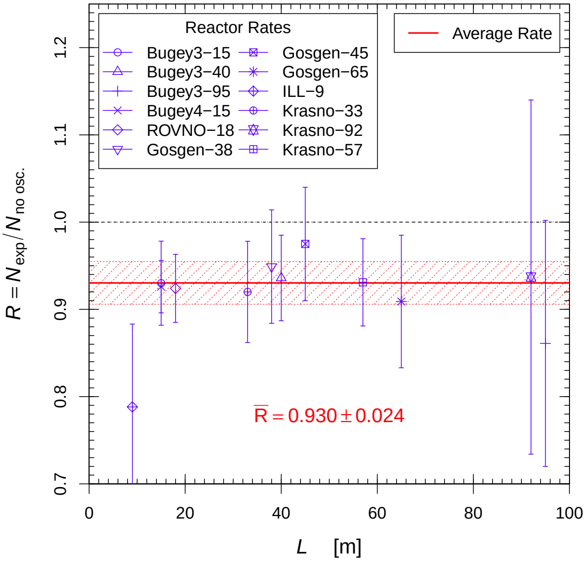
new reactor $\bar{\nu}_e$ fluxes

[Mueller et al, PRC 83 (2011) 054615]

[Huber, PRC 84 (2011) 024617]

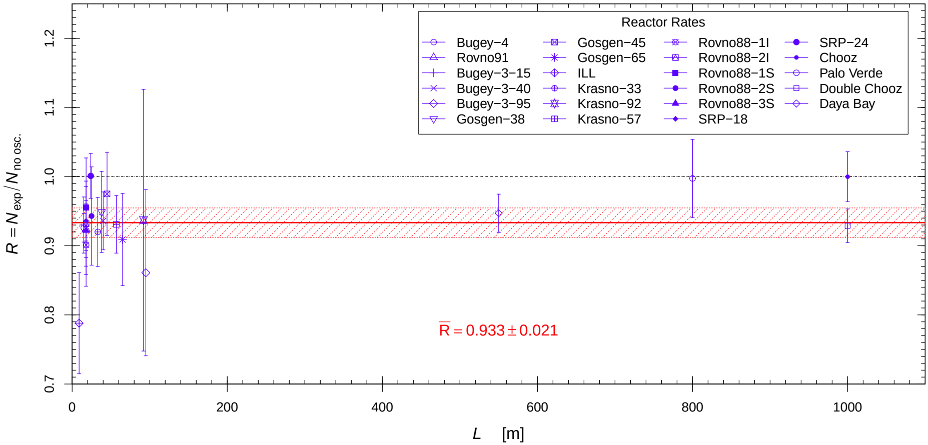
$\sim 2.8\sigma$ anomaly

[see also:
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]



[Giunti, Laveder, Y.F. Li, Q.Y. Liu, H.W. Long, PRD 86 (2012) 113014]

Reactor Anomaly: 2014 Update

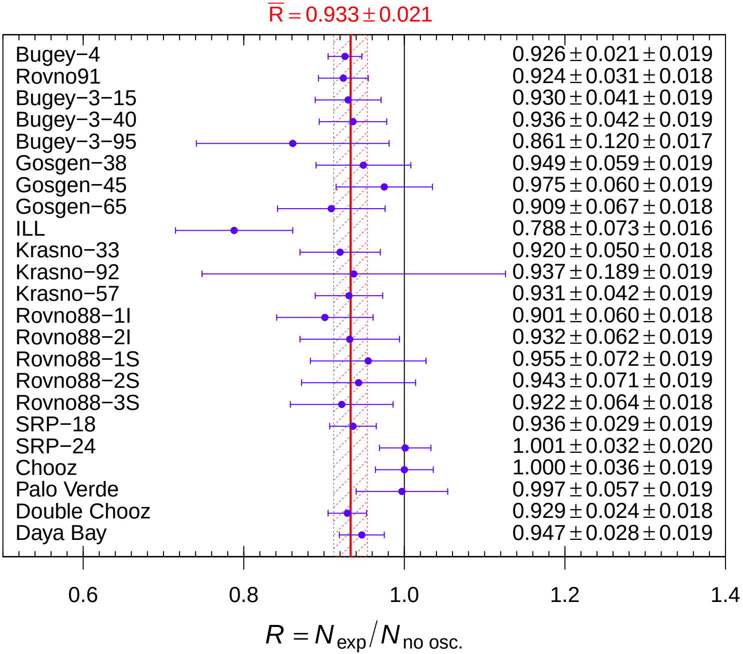


Added: Rovno88, SRP, Chooz, Palo Verde

and the new 2014 experimental results:

$R_{\text{Daya Bay}} = 0.947 \pm 0.022$ [Neutrino 2014]

$R_{\text{Double Chooz}} = 0.929 \pm 0.032$ [Extracted from arXiv:1406.7763]



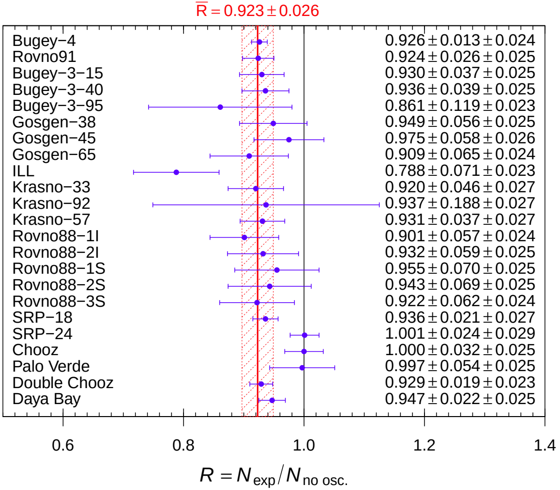
$\overline{R} = 0.933 \pm 0.021$
Bugey−4 0.926 ± 0.021 ± 0.019
Rovno91 0.924 ± 0.031 ± 0.018
Bugey−3−15 0.930 ± 0.041 ± 0.019
Bugey−3−40 0.936 ± 0.042 ± 0.019
Bugey−3−95 0.861 ± 0.120 ± 0.017
Gosgen−38 0.949 ± 0.059 ± 0.019
Gosgen−45 0.975 ± 0.060 ± 0.019
Gosgen−65 0.909 ± 0.067 ± 0.018
ILL 0.788 ± 0.073 ± 0.016
Krasno−33 0.920 ± 0.050 ± 0.018
Krasno−92 0.937 ± 0.189 ± 0.019
Krasno−57 0.931 ± 0.042 ± 0.019
Rovno88−1I 0.901 ± 0.060 ± 0.018
Rovno88−2I 0.932 ± 0.062 ± 0.019
Rovno88−1S 0.955 ± 0.072 ± 0.019
Rovno88−2S 0.943 ± 0.071 ± 0.019
Rovno88−3S 0.922 ± 0.064 ± 0.018
SRP−18 0.936 ± 0.029 ± 0.019
SRP−24 1.001 ± 0.032 ± 0.020
Chooz 1.000 ± 0.036 ± 0.019
Palo Verde 0.997 ± 0.057 ± 0.019
Double Chooz 0.929 ± 0.024 ± 0.018
Daya Bay 0.947 ± 0.028 ± 0.019
0.6
0.8
1.0
1.2
1.4
$R = N_{\text{exp}} / N_{\text{no osc.}}$

	Exp	$\overline{R}$	σ
	SBL	0.928 ± 0.023	3.2σ
$+$	Chooz + Palo Verde	0.935 ± 0.022	2.9σ
$+$	Double Chooz	0.933 ± 0.022	3.1σ
$+$	Daya Bay	0.933 ± 0.021	3.1σ

SBL: Bugey-3 + Bugey-4 + Rovno91 + Gosgen + ILL
+ Krasnoyarsk + Rovno88 + SRP

2.0% fully correlated uncertainty
[Following Mention et al, PRD 83 (2011) 073006]

Fully Correlated 2.7% Total Flux Uncertainty?



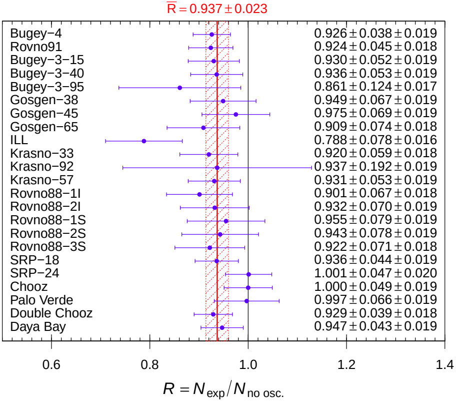
3.0σ Anomaly

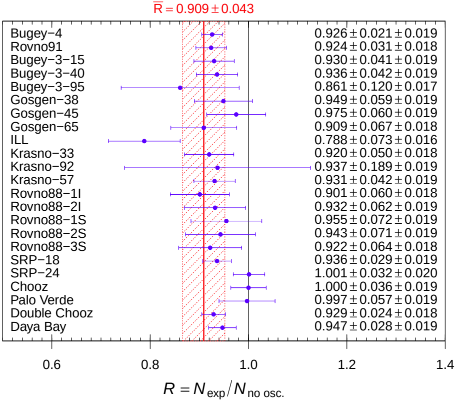
Standard Analysis: $\overline{R} = 0.933 \pm 0.021 \quad (3.1\sigma)$

What About a 4% Uncertainty?

[Claimed by Hayes, Friar, Garvey, Jonkmans, PRL 112 (2014) 202501]

Only 2% Fully Correlated (2.7σ) | All 4% Fully Correlated (2.1σ)





Standard Analysis: $\overline{R} = 0.933 \pm 0.021$ (3.1σ)

Gallium Anomaly

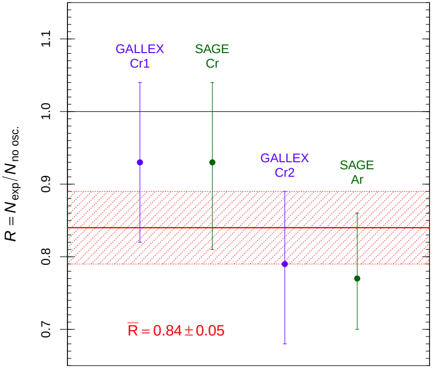
Gallium Radioactive Source Experiments: GALLEX and SAGE

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

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

Anomaly supported by new ${}^{71}\text{Ga}({}^{3}\text{He}, {}^{3}\text{H}){}^{71}\text{Ge}$ cross section measurement

[Frekers et al., PLB 706 (2011) 134]



$E \sim 0.7\,\text{MeV}$

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

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

$\sim 2.9\sigma$ anomaly

[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; PRD 86 (2012) 113014]

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

Light Sterile Neutrinos

- Physics Beyond the SM $\Longrightarrow$ right-handed sterile neutrinos
- 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:

$$\begin{array}{ccccc} & \Delta m^2_{21} \ll & |\Delta m^2_{31}| \ll & |\Delta m^2_{41}| \leq & \ldots \\ \nu_1 & \nu_2 & \nu_3 & \nu_4 & \ldots \\ \nu_e & \nu_\mu & \nu_\tau & \nu_{s_1} & \ldots \end{array}$$

Effective SBL Oscillation Probabilities in 3+1 Schemes

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

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

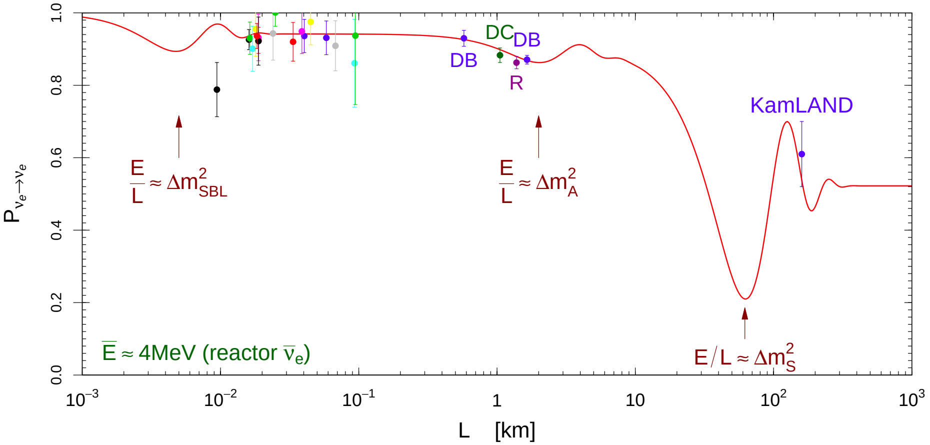
Perturbation of 3ν Mixing: $|U_{e4}|^2 \ll 1\,,\ |U_{\mu 4}|^2 \ll 1\,,\ |U_{\tau 4}|^2 \ll 1\,,\ |U_{s4}|^2 \simeq 1$

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

↑ SBL

- 6 mixing angles
- 3 Dirac CP phases
- 3 Majorana CP phases

but CP violation is not observable in SBL experiments!



$$P^{\text{LBL}}_{\overset{(-)}{\nu_e}\to\overset{(-)}{\nu_e}} \simeq 1 - \frac{1}{2}\sin^2 2\vartheta_{14} - \cos^4\vartheta_{14}\sin^2 2\vartheta_{13}\sin^2\left(\frac{\Delta m^2_{31} L}{4E}\right)$$

Effective SBL Oscillation Probabilities in 3+2 Schemes

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

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

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

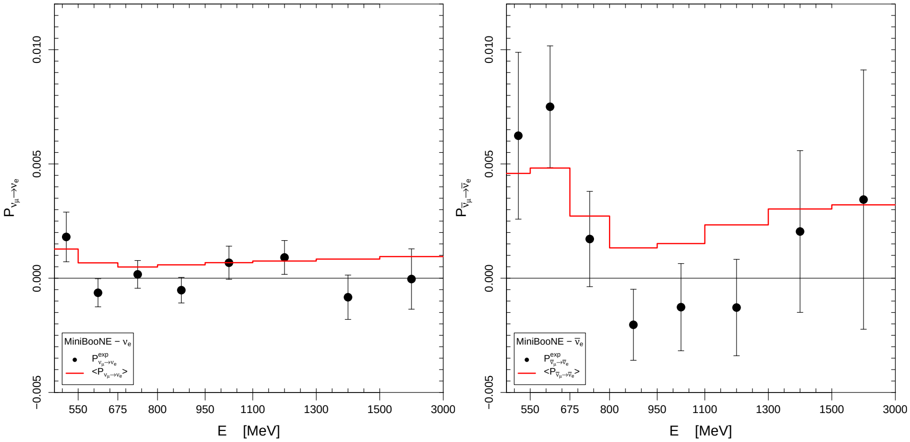
$$P_{\overset{(-)}{\nu}_\alpha \to \overset{(-)}{\nu}_\alpha} = 1 - 4(1 - |U_{\alpha 4}|^2 - |U_{\alpha 5}|^2)(|U_{\alpha 4}|^2 \sin^2\phi_{41} + |U_{\alpha 5}|^2 \sin^2\phi_{51}) - 4|U_{\alpha 4}|^2 |U_{\alpha 5}|^2 \sin^2\phi_{54}$$

[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, JHEP 07 (2012) 161; Archidiacono et al, PRD 86 (2012) 065028; Conrad et al, AHEP 2013 (2013) 163897; Archidiacono et al, PRD 87 (2013) 125034; Kopp, Machado, Maltoni, Schwetz, JHEP 1305 (2013) 050; Giunti, Laveder, Y.F. Li, H.W. Long, PRD 88 (2013) 073008; Girardi, Meroni, Petcov, JHEP 1311 (2013) 146]

- Good: CP violation
- Bad: Two massive sterile neutrinos at the eV scale!

  4 more parameters: $\underbrace{\Delta m^2_{41}, |U_{e4}|^2, |U_{\mu 4}|^2}_{3+1}, \Delta m^2_{51}, |U_{e5}|^2, |U_{\mu 5}|^2, \eta$

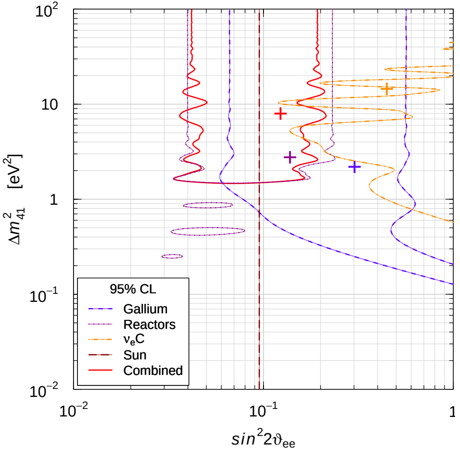
3+2: 2010 MiniBooNE $\nu_\mu \to \nu_e$ and $\bar{\nu}_\mu \to \bar{\nu}_e$

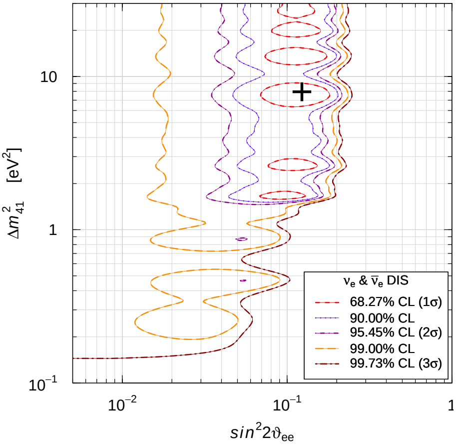


$$P_{\overset{(-)}{\nu}_\mu \to \overset{(-)}{\nu}_e} = 4|U_{e4}|^2|U_{\mu4}|^2 \sin^2\phi_{41} + 4|U_{e5}|^2|U_{\mu5}|^2 \sin^2\phi_{51}$$
$$+ 4|U_{e4}U_{\mu4}U_{e5}U_{\mu5}| \cos\eta \left[\sin^2\phi_{41} + \sin^2\phi_{51} - \sin^2\phi_{54}\right]$$
$$\overset{(+)}{-} 2|U_{e4}U_{\mu4}U_{e5}U_{\mu5}| \sin\eta \left[\sin(2\phi_{41}) - \sin(2\phi_{51}) + \sin(2\phi_{54})\right]$$

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

[Preliminary 2014 Update]





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

KARMEN + LSND

[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]

improved fit of Bugey-3 spectrum

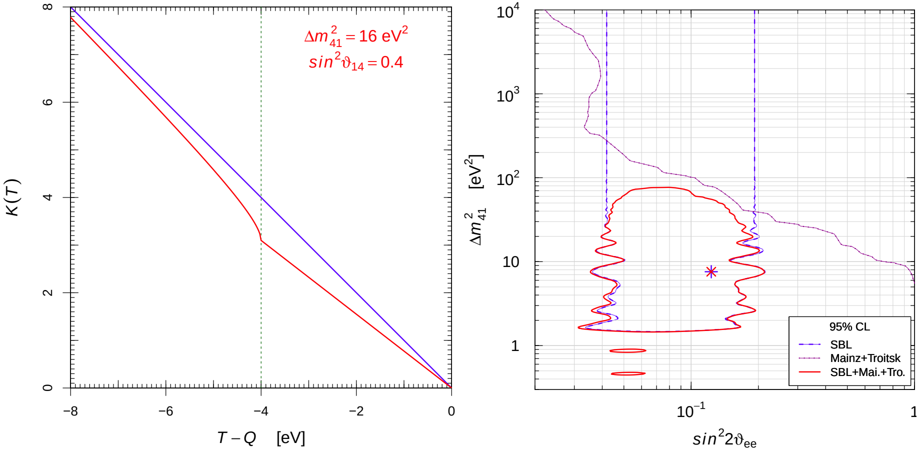
GoF = 53%   PGoF = 4%

No Osc. excluded at 3.0σ

$\Delta\chi^2/\mathrm{NDF} = 11.9/2$

Mainz and Troitsk Limit on m_4^2

[Kraus, Singer, Valerius, Weinheimer, EPJC 73 (2013) 2323] [Belesev et al, JETP Lett. 97 (2013) 67; JPG 41 (2014) 015001]

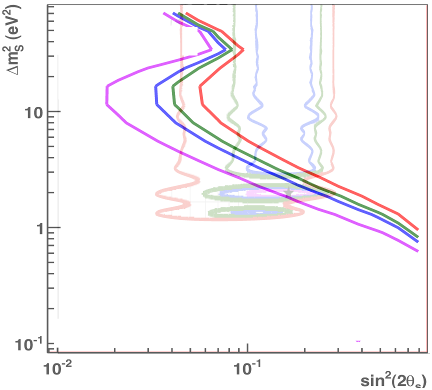


$$m_4 \gg m_1, m_2, m_3 \quad \Longrightarrow \quad \Delta m^2_{41} \equiv m_4^2 - m_1^2 \simeq m_4^2$$

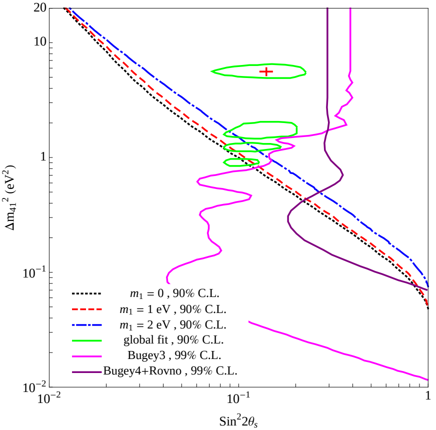
$$2\sigma: \quad 1.5 \lesssim \Delta m^2_{41} \lesssim 37\,\text{eV}^2 \quad \Longrightarrow \quad 7\,\text{cm} \lesssim \frac{L_{41}^{\text{OSC}}}{E\,[\text{MeV}]} \lesssim 2\,\text{m}$$

[Preliminary 2014 Update]

KATRIN Sensitivity



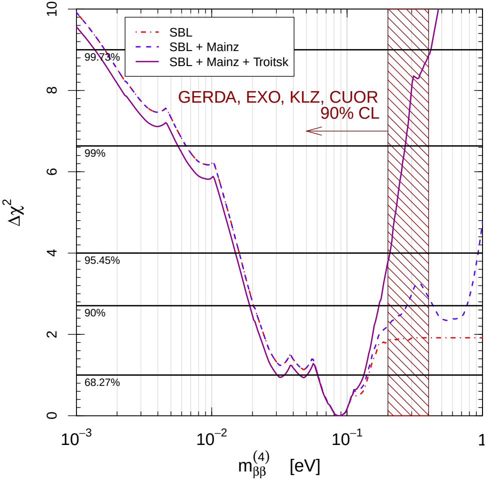
[Formaggio, Barrett, PLB 706 (2011) 68]



[Esmaili, Peres, PRD 85 (2012) 117301]

[see also: Sejersen Riis, Hannestad, JCAP (2011) 1475; Sejersen Riis, Hannestad, Weinheimer, PRC 84 (2011) 045503]

Neutrinoless Double-β Decay



$$|m_{\beta\beta}| = \left| \sum_{k=1}^{4} U_{ek}^2 \, m_k \right|$$

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

caveat:

possible cancellation with $m_{\beta\beta}^{(3\nu-IH)}$

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

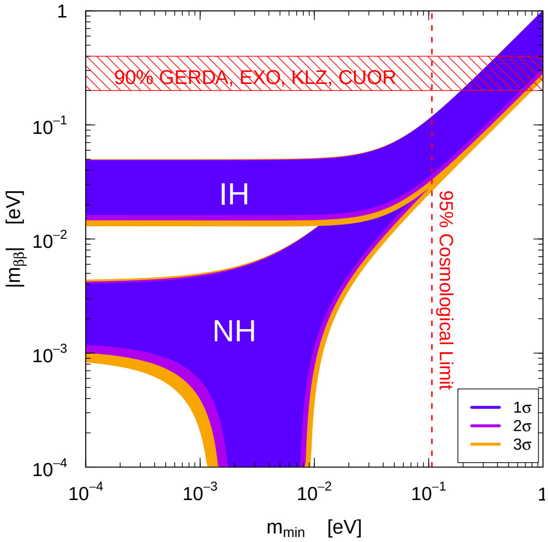
[Li, Liu, PLB 706 (2012) 406]

[Rodejohann, JPG 39 (2012) 124008]

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

3ν-Mixing

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



- 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:

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

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

$m_1 \gtrsim 10^{-3}$ eV $\Rightarrow$ cancellation?

IF $|m_{\beta\beta}| \lesssim 10^{-2}$ eV $\Longrightarrow$ Normal Spectrum

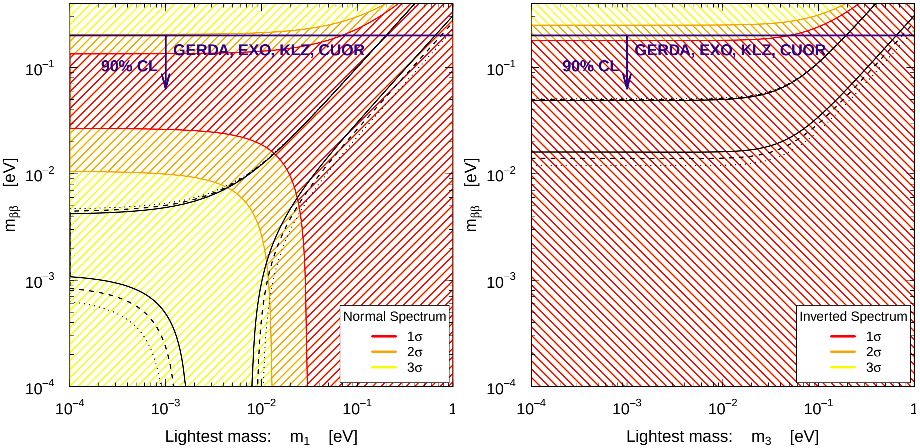
Cancellation with $m_{\beta\beta}^{(\text{light})}$?

[Barry, Rodejohann, Zhang, JHEP 07 (2011) 091]; Li, Liu, PLB 706 (2012) 406; Rodejohann, arXiv:1206.2560]

$$m_{\beta\beta}^{(\text{light})} = \left| \sum_{k=1}^{3} U_{ek}^2 \, m_k \right| \qquad m_{\beta\beta}^{(4)} = |U_{e4}|^2 \sqrt{\Delta m_{41}^2}$$

$$m_{\beta\beta} = m_{\beta\beta}^{(\text{light})} + e^{i\alpha_4} m_{\beta\beta}^{(4)} \qquad m_{\beta\beta}^{(4)} \gtrsim 10^{-2}\,\text{eV}$$

- **Normal Hierarchy:** $m_{\beta\beta}^{(\text{light})} \lesssim 4.5 \times 10^{-3}\,\text{eV}$ (95% CL)
  no cancellation is possible
- **Inverted Hierarchy:** $1.4 \times 10^{-2} \lesssim m_{\beta\beta}^{(\text{light})} \lesssim 5.0 \times 10^{-2}\,\text{eV}$ (95% CL)
  cancellation is possible
- **Quasi-Degenerate:** $m_{\beta\beta}^{(\text{light})} \gtrsim 5.0 \times 10^{-2}\,\text{eV}$ cancellation is possible


GERDA, EXO, KLZ, CUOR
90% CL
Normal Spectrum
1σ
2σ
3σ
$m_{\beta\beta}$ [eV]
Lightest mass: m_1 [eV]
GERDA, EXO, KLZ, CUOR
90% CL
Inverted Spectrum
1σ
2σ
3σ
$m_{\beta\beta}$ [eV]
Lightest mass: m_3 [eV]

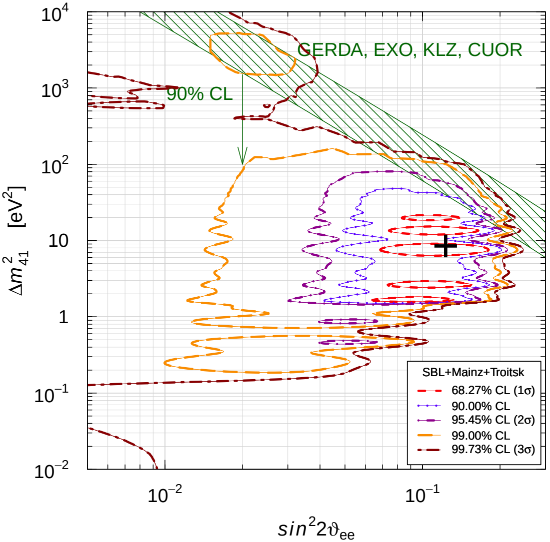
Assumption: no cancellation

$$m_{\beta\beta} \geq m_{\beta\beta}^{(4)}$$

$$= |U_{e4}|^2 \sqrt{\Delta m_{41}^2}$$

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

$$\leq \left(\frac{m_{\beta\beta}}{|U_{e4}|^2} \right)^2$$



3+1: Appearance vs Disappearance

- 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:

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

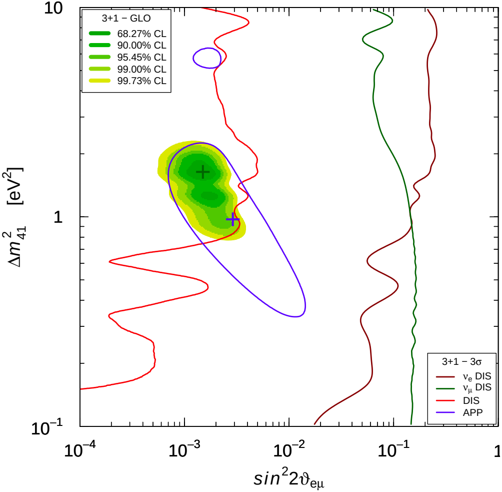
- Upper bounds on $\sin^2 2\vartheta_{ee}$ and $\sin^2 2\vartheta_{\mu\mu}$ $\Longrightarrow$ strong limit on $\sin^2 2\vartheta_{e\mu}$

[Okada, Yasuda, IJMPA 12 (1997) 3669-3694]

[Bilenky, Giunti, Grimus, EPJC 1 (1998) 247]

3+1 Global Fit

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



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

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

GoF = 29% PGoF = 9%

No Osc. excluded at 6.2σ

$\Delta\chi^2/\text{NDF} = 46.2/3$

[different approach and conclusions: Kopp, Machado, Maltoni, Schwetz, JHEP 1305 (2013) 050]

Goodness of Fit

- Assumption or approximation: Gaussian uncertainties and linear model
- χ^2_{min} has χ^2 distribution with Number of Degrees of Freedom

$$\text{NDF} = N_{\text{D}} - N_{\text{P}}$$

N_{D} = Number of Data $\qquad$ N_{P} = Number of Fitted Parameters

- $\langle \chi^2_{\text{min}} \rangle = \text{NDF}$ $\qquad$ $\text{Var}(\chi^2_{\text{min}}) = 2\text{NDF}$
- $\text{GoF} = \int_{\chi^2_{\text{min}}}^{\infty} p_{\chi^2}(z, \text{NDF})\, dz$ $\qquad$ $p_{\chi^2}(z, n) = \dfrac{z^{n/2-1} e^{-z/2}}{2^{n/2}\Gamma(n/2)}$

Parameter Goodness of Fit

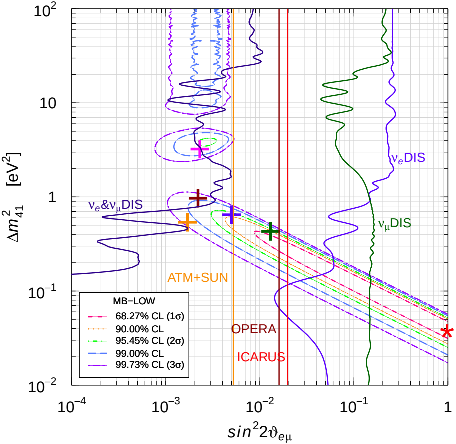
Maltoni, Schwetz, PRD 68 (2003) 033020, arXiv:hep-ph/0304176

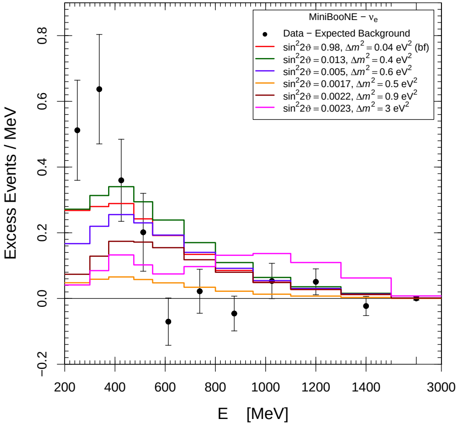
- Measure compatibility of two (or more) sets of data points A and B under fitting model
- $\chi^2_{\text{PGoF}} = (\chi^2_{\text{min}})_{\text{A+B}} - [(\chi^2_{\text{min}})_{\text{A}} + (\chi^2_{\text{min}})_{\text{B}}]$
- χ^2_{PGoF} has χ^2 distribution with Number of Degrees of Freedom

$$\text{NDF}_{\text{PGoF}} = N_{\text{P}}^{\text{A}} + N_{\text{P}}^{\text{B}} - N_{\text{P}}^{\text{A+B}}$$

- $\text{PGoF} = \int_{\chi^2_{\text{PGoF}}}^{\infty} p_{\chi^2}(z, \text{NDF}_{\text{PGoF}})\, dz$

MiniBooNE Low-Energy Excess?

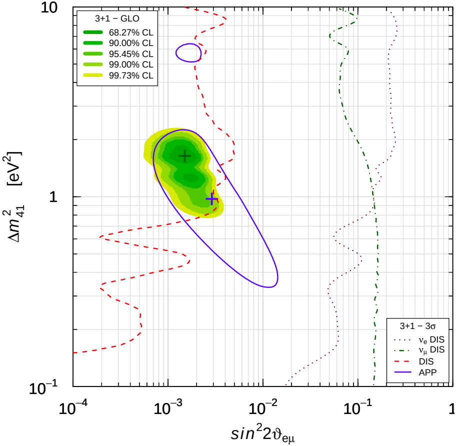




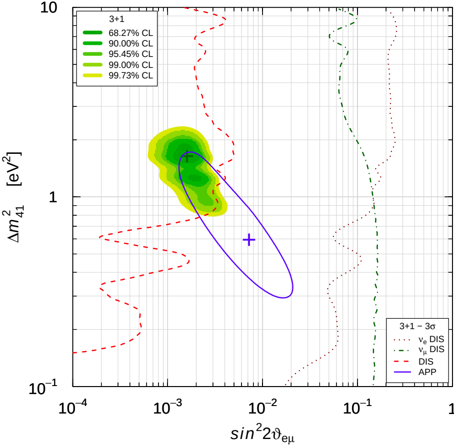
NO FIT OF LOW-ENERGY EXCESS!

3+1 Global Fit with MB Low-Energy Data

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



All MiniBooNE Data

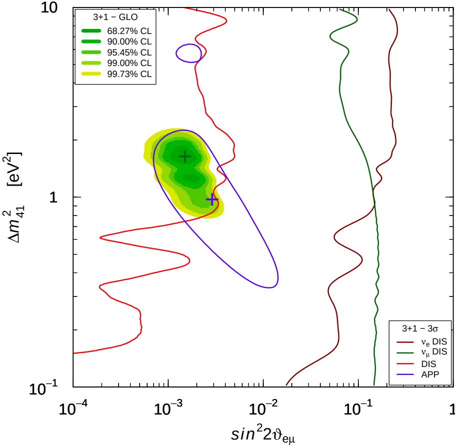


GoF = 29% PGoF = 9% GoF = 6% PGoF = 0.2%

- Allowed region does not change much
- Enhanced appearance-disappearance tension
- Our approach: low-energy excess is not due to oscillations

MiniBooNE Impact on SBL Oscillations?

with MiniBooNE ($E > 475\,\mathrm{MeV}$)

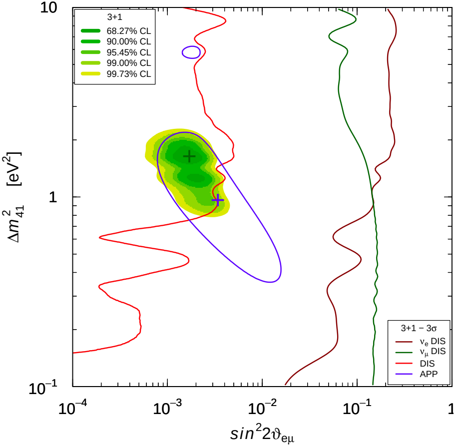


GoF = 29%   PGoF = 9%

No Osc. excluded at 6.2σ

$\Delta\chi^2/\mathrm{NDF} = 46.2/3$

without MiniBooNE



GoF = 19%   PGoF = 8%

No Osc. excluded at 6.3σ

$\Delta\chi^2/\mathrm{NDF} = 47.1/3$

Without LSND: No Osc. excluded only at 2.1σ $\quad(\Delta\chi^2/\mathrm{NDF} = 8.3/3)$

3+2

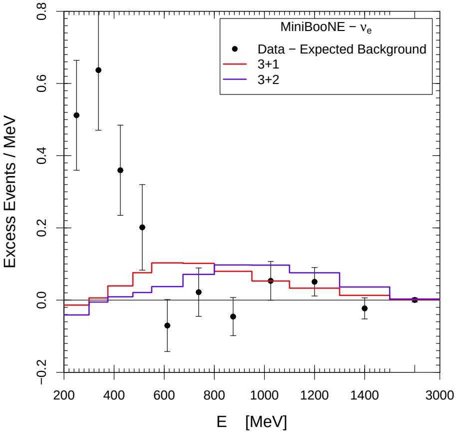
- 3+2 should be preferred to 3+1 only if
  - there is evidence of two peaks of the probability corresponding to two Δm^2's

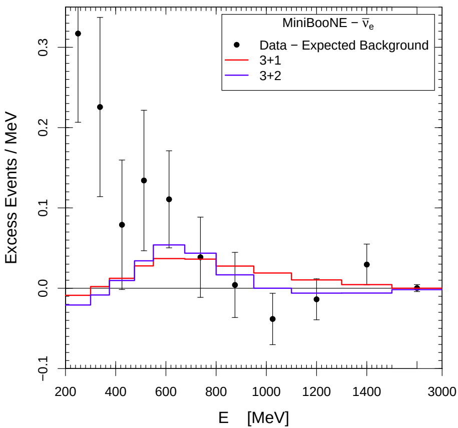
    or
  - there is CP-violating difference of $\nu_\mu \to \nu_e$ and $\bar{\nu}_\mu \to \bar{\nu}_e$ transitions
- 2008 ν + 2010 $\bar{\nu}$ MiniBooNE data indicated ν–$\bar{\nu}$ difference

  $\Downarrow$

  reasonable and useful to consider 3+2
- ν–$\bar{\nu}$ difference almost disappeared with 2012 $\bar{\nu}$ data
- Okkam razor: 3+1 is enough!
- Different approach and conclusions:
  - Kopp, Machado, Maltoni, Schwetz, JHEP 1305 (2013) 050:
    Use all MiniBooNE data. No 3+1 global fit. 3+2 slightly preferred? Small allowed region.
  - Conrad, Ignarra, Karagiorgi, Shaevitz, Spitz, AHEP 2013 (2013) 163897:
    Use all MiniBooNE data. 3+2 strongly preferred. Very small allowed regions.

MiniBooNE Low-Energy Excess?

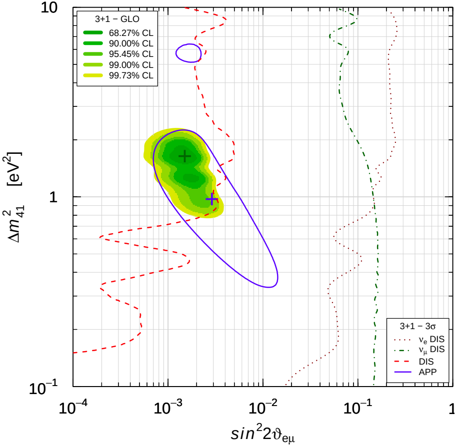




- 3+1: GoF = 6% PGoF = 0.2%
- 3+2: GoF = 8% PGoF = 0.1%

Preliminary 2014 Update of 3+1 Global Fit

OLD

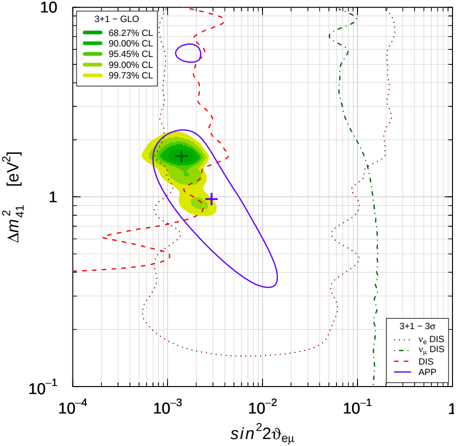


GoF = 29% PGoF = 9%

No Osc. excluded at 6.2σ

$\Delta\chi^2/\text{NDF} = 46.2/3$

NEW

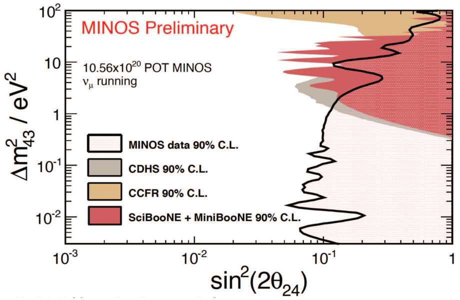


GoF = 26% PGoF = 7%

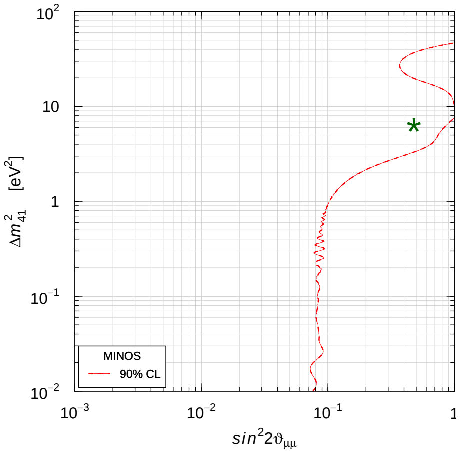
No Osc. excluded at 6.3σ

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

MINOS?



Neutrino 2014



[Giunti, Laveder, PRD 84 (2011) 093006]

IN PRACTICE NO CHANGE!

Cosmology

- Energy density of radiation before photon decoupling (CMB):

$$\rho_R = \left[1 + \frac{7}{8} \left(\frac{4}{11} \right)^{4/3} N_{\text{eff}} \right] \rho_\gamma$$

$$N_{\text{eff}}^{\text{SM}} = 3.046 \qquad\qquad \Delta N_{\text{eff}} = N_{\text{eff}} - N_{\text{eff}}^{\text{SM}}$$

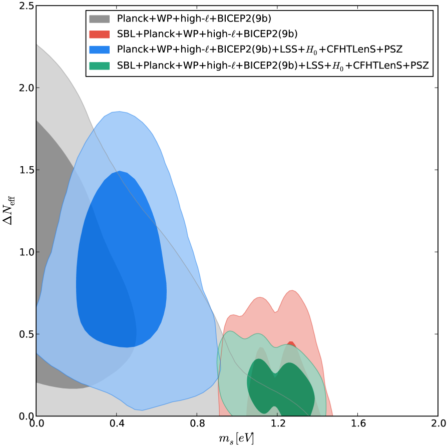
- Sterile neutrino contribution:

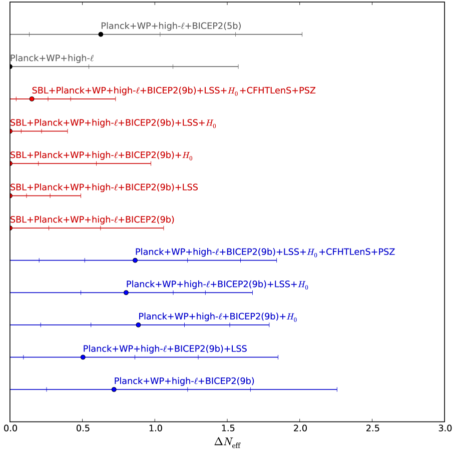
$$\rho_s = (T_s/T_\nu)^4 \rho_\nu \quad \Longrightarrow \quad \Delta N_{\text{eff}} = (T_s/T_\nu)^4$$

- Current energy density of sterile neutrinos:

$$\Omega_s = \frac{n_s m_s}{\rho_c} \simeq \frac{1}{h^2} \frac{(T_s/T_\nu)^3 m_s}{94\,\text{eV}} = \frac{1}{h^2} \frac{\Delta N_{\text{eff}}^{3/4} m_s}{94\,\text{eV}} = \frac{1}{h^2} \frac{m_s^{\text{eff}}}{94\,\text{eV}}$$

$$m_s = m_4 \simeq \sqrt{\Delta m_{41}^2}$$





[Archidiacono, Fornengo, Gariazzo, Giunti, Hannestad, Laveder, arXiv:1404.1794]

Without oscillation data:
- [Giusarma, Di Valentino, Lattanzi, Melchiorri, Mena, arXiv:1403.4852]
- [Zhang, Li, Zhang, arXiv:1403.7028]
- [Dvorkin, Wyman, Rudd, Hu, arXiv:1403.8049]
- [Zhang, Li, Zhang, arXiv:1404.3598]

Recent discussion: [Bergstrom, Gonzalez-Garcia, Niro, Salvado, arXiv:1407.3806]

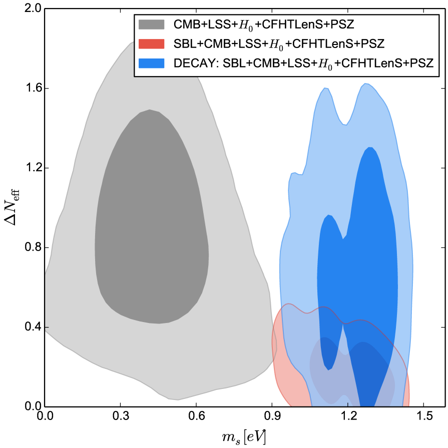
Tension between $\Delta N_{\text{eff}} = 1$ and $m_s \approx 1\,\text{eV}$

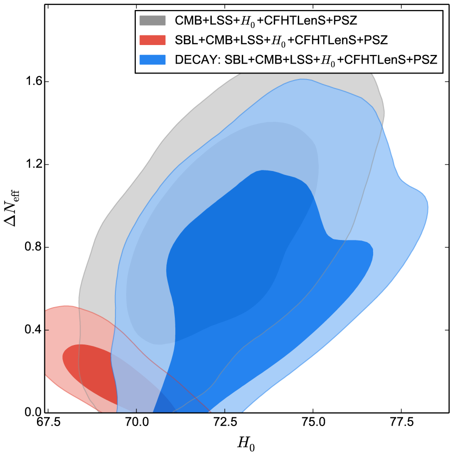
Sterile neutrinos are thermalized $(\Delta N_{\text{eff}} = 1)$ by active-sterile oscillations before neutrino decoupling [Dolgov, Villante, NPB 679 (2004) 261]

Proposed mechanisms to avoid the tension:

- Large lepton asymmetry [Hannestad, Tamborra, Tram, JCAP 1207 (2012) 025; Mirizzi, Saviano, Miele, Serpico, PRD 86 (2012) 053009; Saviano et al., PRD 87 (2013) 073006; Hannestad, Hansen, Tram, JCAP 1304 (2013) 032]
- Enhanced background potential due to interactions in the sterile sector [Hannestad, Hansen, Tram, PRL 112 (2014) 031802; Dasgupta, Kopp, PRL 112 (2014) 031803; Bringmann, Hasenkamp, Kersten, arXiv:1312.4947; Ko, Tang, arXiv:1404.0236; Archidiacono, Hannestad, Hansen,Tram, arXiv:1404.5915]
- a larger cosmic expansion rate at the time of sterile neutrino production [Rehagen, Gelmini JCAP 1406 (2014) 044]
- MeV dark matter annihilation [Ho, Scherrer, PRD 87 (2013) 065016]
- Invisible decay [Gariazzo, Giunti, Laveder, arXiv:1404.6160]

Cosmological Invisible Decay





[Gariazzo, Giunti, Laveder, arXiv:1404.6160]

$$N_s(t) = \Delta N_{\rm eff}\, e^{-t/\tau_s} \qquad \tau_s \sim 10^9 \text{ y}$$

Sketch of Model

- $\mathcal{L}_\mathsf{I} = \sum_{\alpha,\beta} \overline{\nu}_\alpha \left(g^{(\mathsf{s})}_{\alpha\beta} + g^{(\mathsf{p})}_{\alpha\beta} \gamma^5 \right) \nu_\beta \, \phi \qquad \alpha, \beta = e, \mu, \tau, s, s', \ldots$

- $\Gamma_{\nu_s \to \nu_\beta + \phi} \simeq \frac{(g^{(\mathsf{s,p})}_{s\beta})^2}{16\pi} m_s \qquad \beta = e, \mu, \tau, s', \ldots$

- $m_s \sim 1\,\mathrm{eV}, \quad \tau_s \sim 10^9\,\mathrm{y} \quad \Longrightarrow \quad g^{(\mathsf{s,p})}_{s\beta} \sim 10^{-15}$

- Rate of $\nu - \phi$ interactions ($\nu + \bar{\nu} \to \phi + \phi$, $\nu + \phi \to \nu + \phi$, $\ldots$), in a thermal environment of relativistic neutrinos with temperature T_ν:

  $$\Gamma_\mathsf{I} \sim (g^{(\mathsf{s,p})}_{s\beta})^4 \, T_\nu$$ [Hannestad, Raffelt, PRD 72 (2005) 103514]

  $$T_\nu \lesssim 1\,\mathrm{MeV} \quad \Longrightarrow \quad \Gamma_\mathsf{I}^{-1} \gtrsim 10^{31}\,\mathrm{y}$$

- The only effective process is the invisible decay $\nu_s \to \nu_\beta + \phi$

Conclusions

- Short-Baseline ν_e and $\bar{\nu}_e$ 3+1 Disappearance:
  - Reactor $\bar{\nu}_e$ anomaly is alive and exciting.
  - Gallium ν_e anomaly 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.
- Short-Baseline $\bar{\nu}_\mu \to \bar{\nu}_e$ LSND Signal:
  - MiniBooNE experiment has been inconclusive.
  - Better experiments are needed to check LSND signal!
  - If $|U_{e4}| > 0$ why not $|U_{\mu 4}| > 0$? $\Longrightarrow$ Maybe LSND luckily observed a fluctuation of a small $\bar{\nu}_\mu \to \bar{\nu}_e$ transition probability with amplitude $\sin^2 2\vartheta_{e\mu} = 4|U_{e4}|^2|U_{\mu 4}|^2$, which has not been seen by other appearance experiments.
- Cosmology:
  - BICEP2 + Planck indication in favor of $\Delta N_{\text{eff}} \approx 1$.
  - Tension between $\Delta N_{\text{eff}} = 1$ and $m_s \approx 1\,\text{eV}$.
  - Cosmological and oscillation data can be explained by invisible decay of ν_s.