Phenomenology of light sterile neutrinos

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Determination of the Effective Electron (anti)-neutrino Mass

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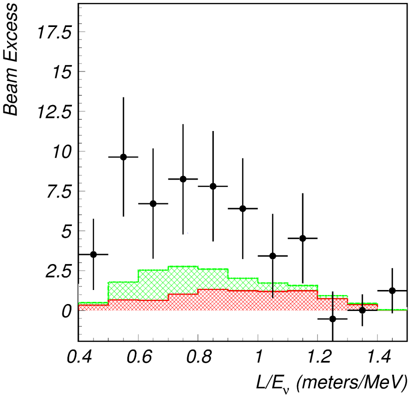
Indications of SBL Oscillations Beyond 3ν

LSND

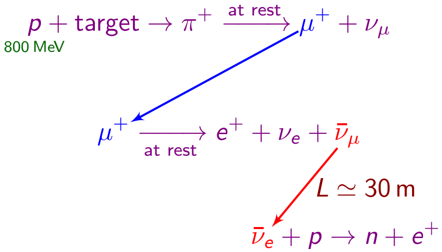
[PRL 75 (1995) 2650; PRC 54 (1996) 2685; PRL 77 (1996) 3082; PRD 64 (2001) 112007]

$\bar{\nu}_\mu \to \bar{\nu}_e$ $\qquad$ $20\,\mathrm{MeV} \leq E \leq 52.8\,\mathrm{MeV}$



$$\Delta m^2_{\mathrm{SBL}} \gtrsim 0.1\,\mathrm{eV}^2 \gg \Delta m^2_{\mathrm{ATM}}$$

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



$$\underset{800\,\mathrm{MeV}}{p} + \mathrm{target} \to \pi^+ \xrightarrow{\text{at rest}} \mu^+ + \nu_\mu$$

$$\mu^+ \xrightarrow[\text{at rest}]{} e^+ + \nu_e + \bar{\nu}_\mu$$

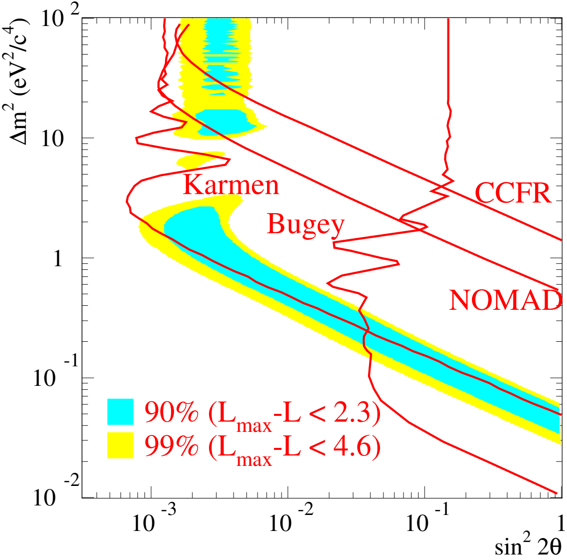
$L \simeq 30\,\mathrm{m}$

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

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

- $\approx 3.8\sigma$ excess
- But signal not seen by KARMEN at $L \simeq 18\,\mathrm{m}$ with the same method

[PRD 65 (2002) 112001]



$$\Delta m^2_{\text{SBL}} \gtrsim 3 \times 10^{-2}\,\text{eV}^2 \gg \Delta m^2_{\text{ATM}} \simeq 2.5 \times 10^{-3}\,\text{eV}^2 \gg \Delta m^2_{\text{SOL}}$$

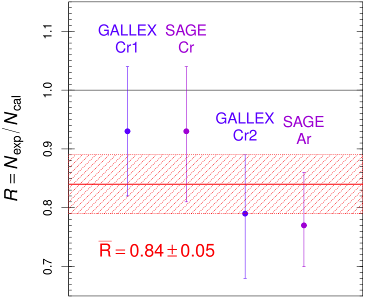
Gallium Anomaly

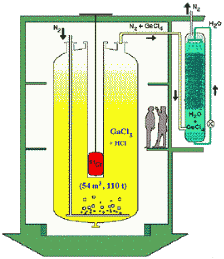
Gallium Radioactive Source Experiments: GALLEX and SAGE

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

$E \simeq 0.75\,\text{MeV}$ $\quad E \simeq 0.81\,\text{MeV}$

Test of Solar ν_e Detection: $\nu_e + {}^{71}\text{Ga} \to {}^{71}\text{Ge} + e^-$





$\approx 2.9\sigma$ deficit

$\langle L \rangle_{\text{GALLEX}} = 1.9\,\text{m} \quad \langle L \rangle_{\text{SAGE}} = 0.6\,\text{m}$

$\Delta m^2_{\text{SBL}} \gtrsim 1\,\text{eV}^2 \gg \Delta m^2_{\text{ATM}}$

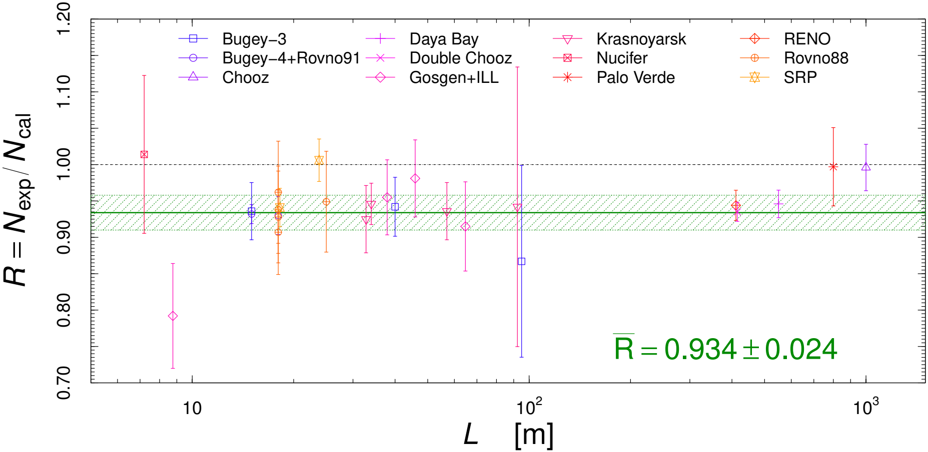
[SAGE, PRC 73 (2006) 045805; PRC 80 (2009) 015807;
Laveder et al, Nucl.Phys.Proc.Suppl. 168 (2007) 344,
MPLA 22 (2007) 2499, PRD 78 (2008) 073009,
PRC 83 (2011) 065504]

Reactor Electron Antineutrino Anomaly

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

New reactor $\bar{\nu}_e$ fluxes: Huber-Mueller (HM)

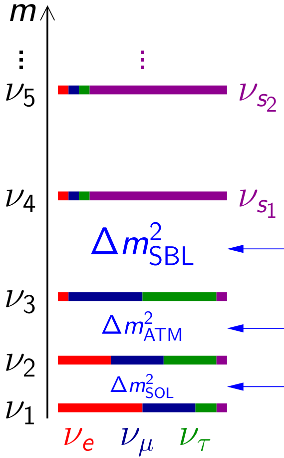
[Mueller et al, PRC 83 (2011) 054615; Huber, PRC 84 (2011) 024617]



$\approx 2.8\sigma$ deficit

Beyond Three-Neutrino Mixing: Sterile Neutrinos

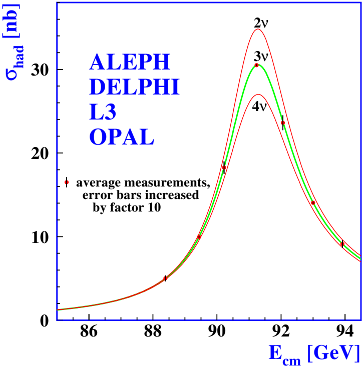
$$L^{\text{osc}} = \frac{4\pi E}{\Delta m^2}$$



Δm^2_{SBL} ← $\gtrsim 1\,\text{eV}^2$

Δm^2_{ATM} ← $\simeq 2.5 \times 10^{-3}\,\text{eV}^2$

Δm^2_{SOL} ← $\simeq 7.4 \times 10^{-5}\,\text{eV}^2$



$$N^{\text{LEP}}_{\nu_{\text{active}}} = 2.9840 \pm 0.0082$$

- Perturbation of 3ν mixing: effective $3{+}1$ with $|U_{e4}|, |U_{\mu4}|, |U_{\tau4}| \ll 1$

Effective 3+1 SBL Oscillation Probabilities

Appearance $(\alpha \neq \beta)$

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

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

Disappearance

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

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

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

SBL

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

- $\Delta m^2_{\text{SBL}} = \Delta m^2_{41} \simeq \Delta m^2_{42} \simeq \Delta m^2_{43}$
- CP violation is not observable in SBL experiments!
- Observable in LBL accelerator exp. sensitive to Δm^2_{ATM} [de Gouvea et al, PRD 91 (2015) 053005, PRD 92 (2015) 073012, arXiv:1605.09376; Palazzo et al, PRD 91 (2015) 073017, PLB 757 (2016) 142; Kayser et al, JHEP 1511 (2015) 039, JHEP 1611 (2016) 122] and solar exp. sensitive to Δm^2_{SOL} [Long, Li, Giunti, PRD 87, 113004 (2013) 113004]

3+1: Appearance vs Disappearance

- SBL Oscillation parameters: Δm^2_{41} $|U_{e4}|^2$ $|U_{\mu4}|^2$ $(|U_{\tau4}|^2)$
- 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:

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

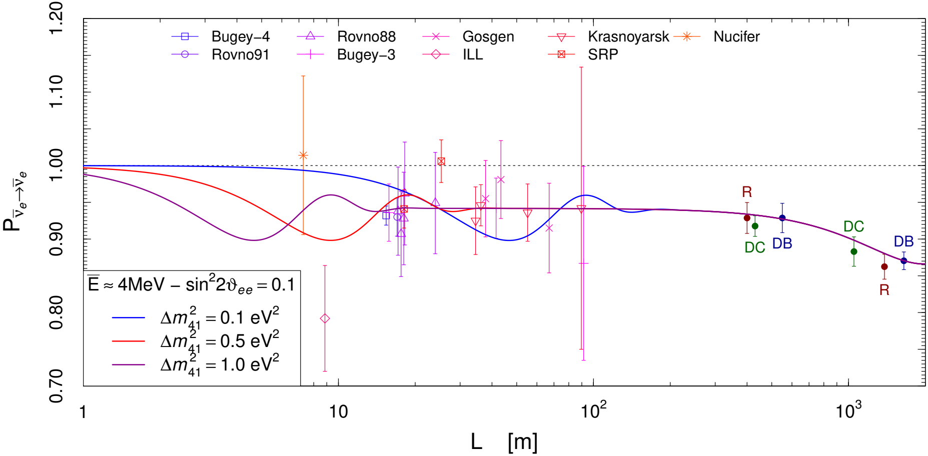
quadratically suppressed for small $|U_{e4}|^2$ and $|U_{\mu4}|^2$

$\Downarrow$

Appearance-Disappearance Tension

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

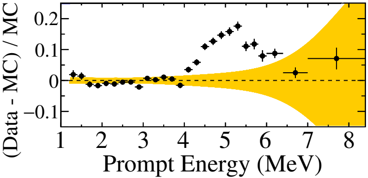
Short-Baseline Reactor Neutrino Oscillations



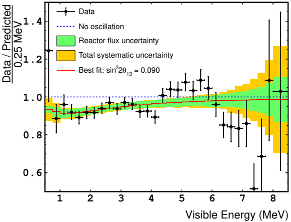
$$\Delta m^2_{\text{SBL}} \gtrsim 0.5\,\text{eV}^2 \gg \Delta m^2_{\text{ATM}}$$

- SBL oscillations are averaged at the Daya Bay, RENO, and Double Chooz near detectors $\Longrightarrow$ no spectral distortion

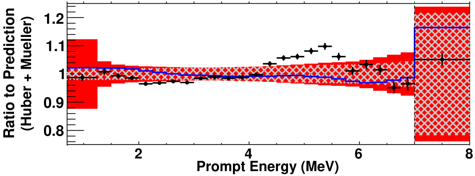
Reactor Antineutrino 5 MeV Bump



[RENO, arXiv:1511.05849]



[Double Chooz, arXiv:1406.7763]



[Daya Bay, arXiv:1508.04233]

- Cannot be explained by neutrino oscillations (SBL oscillations are averaged in RENO, DC, DB).
- If it is due to a theoretical miscalculation of the spectrum, it can have opposite effects on the anomaly:

  [see: Berryman, Huber, arXiv:1909.09267]

  - If it is a 4-6 MeV excess it increases the anomaly: new HKSS flux calculation

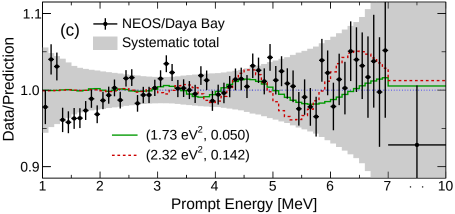
  [Hayen, Kostensalo, Severijns, Suhonen, arXiv:1908.08302]

  - If it is a 1-4 MeV suppression it decreases the anomaly: new EF flux calculation

  [Estienne, Fallot, et al, arXiv:1904.09358]

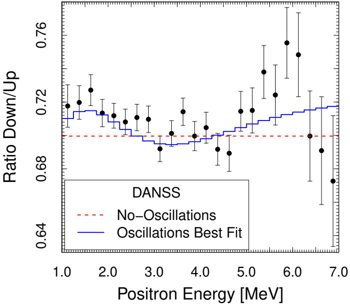
Reactor Spectral Ratios

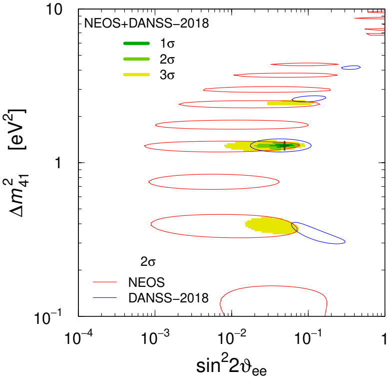
NEOS [PRL 118 (2017) 121802 (arXiv:1610.05134)]



DANSS-2018

[PLB 787 (2018) 56, arXiv:1804.04046]





2018 model independent indication in favor of SBL oscillations

NEOS: $\sim 2.0\sigma$

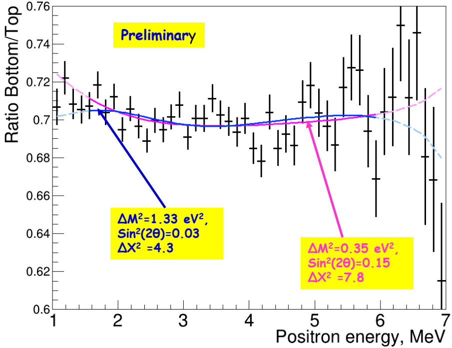
DANSS-2018: $\sim 2.7\sigma$

Combined: $\sim 3.5\sigma$

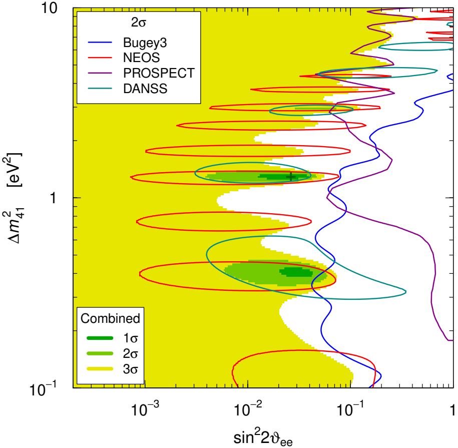
[Gariazzo, Giunti, Laveder, Li, arXiv:1801.06467]

[Dentler, Hernandez-Cabezudo, Kopp, Machado, Maltoni, Martinez-Soler, Schwetz, arXiv:1803.10661]

2019 DANSS Results



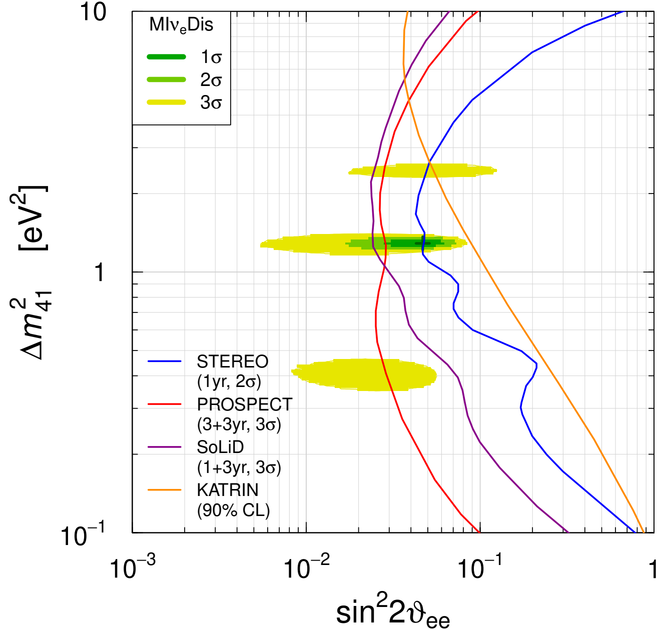
[Danilov @ EPS-HEP 2019, arXiv:1911.10140]



[Giunti, Y.F. Li, Y.Y. Zhang, arXiv:1912.12956]

- The agreement between NEOS and DANSS has diminished.
- We wait independent checks of PROSPECT, STEREO, SoLiD ...

Sensitivities of New Experiments



Tritium Beta-Decay: $^3\mathrm{H} \to {}^3\mathrm{He} + e^- + \bar{\nu}_e$

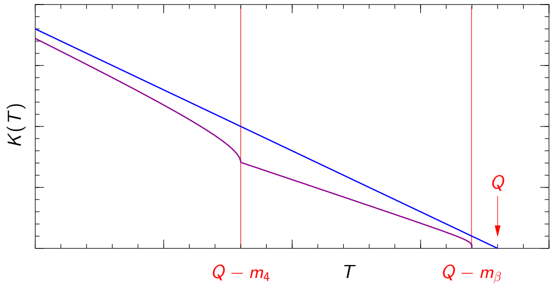
$$Q = M_{^3\mathrm{H}} - M_{^3\mathrm{He}} - m_e = 18.58\,\mathrm{keV}$$

$$\frac{d\Gamma}{dT} = \frac{(\cos\vartheta_C G_F)^2}{2\pi^3} |\mathcal{M}|^2 F(E)\, p\, E\, K^2(T)$$

$$\frac{K^2(T)}{Q-T} = \sum_k |U_{ek}|^2 \sqrt{(Q-T)^2 - m_k^2}\, \theta(Q-T-m_k)$$

$$m_4 \gg m_{1,2,3} \Rightarrow \simeq \left(1 - |U_{e4}|^2\right) \sqrt{(Q-T)^2 - m_\beta^2}\, \theta(Q-T-m_\beta)$$

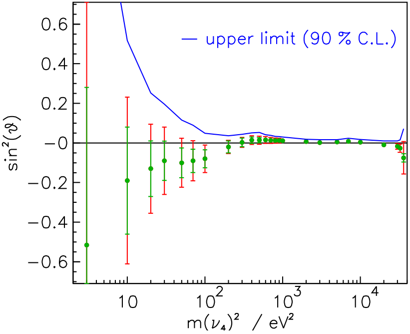
$$+ |U_{e4}|^2 \sqrt{(Q-T)^2 - m_4^2}\, \theta(Q-T-m_4)$$



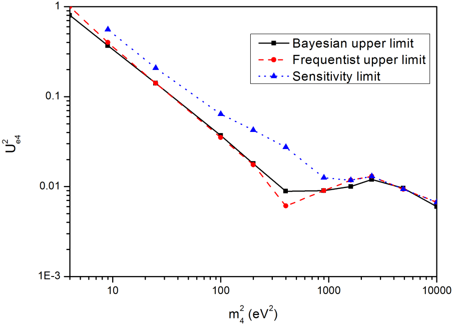
$$m_\beta^2 = \sum_{k=1}^{3} |U_{ek}|^2 m_k^2$$

Mainz and Troitsk Limit on $\Delta m^2_{41} \simeq m^2_4$

$$m_4 \gg m_{1,2,3} \quad \Longrightarrow \quad \Delta m^2_{41} \equiv m^2_4 - m^2_1 \simeq m^2_4$$

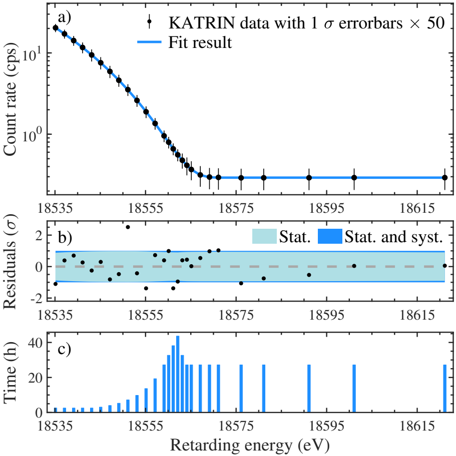


[Kraus, Singer, Valerius, Weinheimer, EPJC 73 (2013) 2323]



[Belesev et al, JPG 41 (2014) 015001]

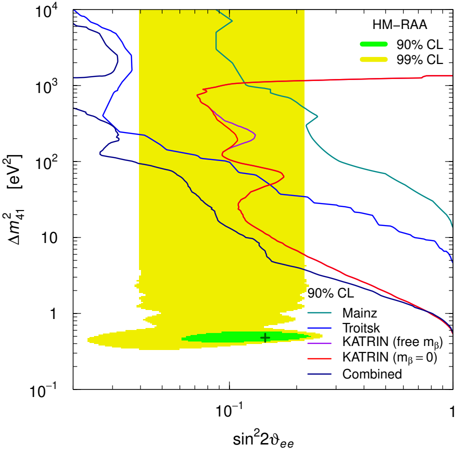
Bound from first KATRIN data



[KATRIN, arXiv:1909.06048]

$$m_\beta^2 = \sum_{k=1}^{3} |U_{ek}|^2 m_k^2$$

- $T_2 \to {}^3\text{HeT}^+ + e^- + \bar{\nu}_e$
- Electron spectrum measurement until $\approx Q - 40\,\text{eV}$
- We can probe the mixing of ν_4 with $m_4 \lesssim 40\,\text{eV}$
- $$R_\beta(E) = (1 - |U_{e4}|^2)\, R_\beta(E, m_\beta) + |U_{e4}|^2\, R_\beta(E, m_4)$$
- $$R_\beta(E, m_\nu) \propto \sum_{i,j} |U_{ei}|^2 \zeta_j \varepsilon_j \times \sqrt{\varepsilon_j^2 - m_\nu^2}\, \Theta(\varepsilon_j - m_\nu)$$
- $\varepsilon_j = E_0 - E - V_j$



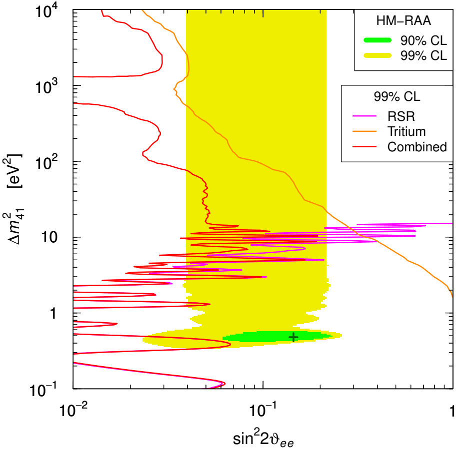
[Giunti, Y.F. Li, Y.Y. Zhang, arXiv:1912.12956]

$$P_{ee}^{\text{SBL}} = 1 - \sin^2 2\vartheta_{ee} \sin^2\left(\frac{\Delta m^2_{41} L}{4E}\right)$$

- $\sin^2 2\vartheta_{ee} = 4|U_{e4}|^2(1 - |U_{e4}|^2)$
- $\Delta m^2_{41} \simeq m^2_4 - m^2_\beta$
- Shape analysis with
  - free endpoint E_0,
  - free signal amplitude,
  - free background rate.
- The KATRIN bounds with
  - free m^2_β
  - $m^2_\beta = 0$

  are practically equivalent.
- KATRIN extends the region excluded by Mainz and Troitsk to smaller value of Δm^2_{41} at large mixing.
- Only the large-Δm^2_{41} part of the HM-RAA is excluded by the KATRIN+Mainz+Troitsk bound.

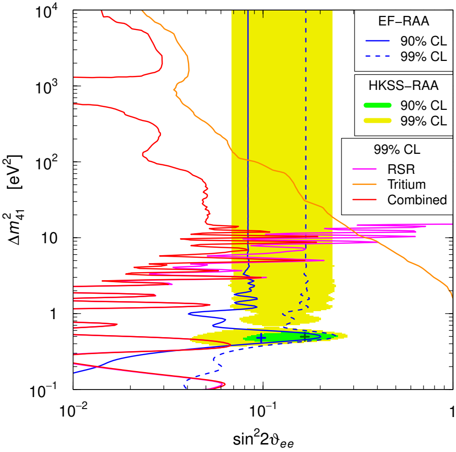
Tension of Tritium+RSR with HM-RAA



- RSR: Reactor Spectral Ratio
- Tritium: KATRIN+Mainz+Troitsk

- Model-independent RSR bounds:
  - Bugey-3 (1995)
  - NEOS (2016)
  - PROSPECT (2018)
  - DANSS (2019)
- The Tritium+RSR bound at large values of Δm^2_{41} is much more stringent than the Tritium bound, because the global χ^2 has a minimum at $\Delta m^2_{41} \approx 1.3\,\text{eV}^2$ and $\sin^2 2\vartheta_{ee} \approx 0.025$ that corresponds to the RSR best fit.
- The Tritium+RSR 99% CL exclusion curve disfavors most of the 99% CL HM-RAA region.

Test of Two New Reactor ν Flux Calculations



- EF-RAA:
  - Only upper bound on mixing at $\gtrsim 90\%$ CL.
  - The EF-RAA is not statistically significant.
  - Compatible with the Tritium+RSR bound.

- HKSS-RAA:
  - HKSS-RAA is larger than HM-RAA.
  - Small mixing is more restricted than in HM-RAA.
  - More tension with the Tritium+RSR bound.

EF: Estienne, Fallot, et al, arXiv:1904.09358

HKSS: Hayen, Kostensalo, Severijns, Suhonen, arXiv:1908.08302

Neutrino-4

[JETPL 109 (2019) 213, arXiv:1809.10561]

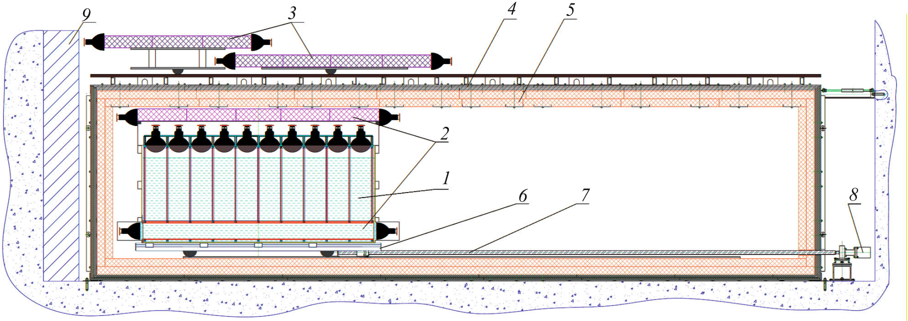
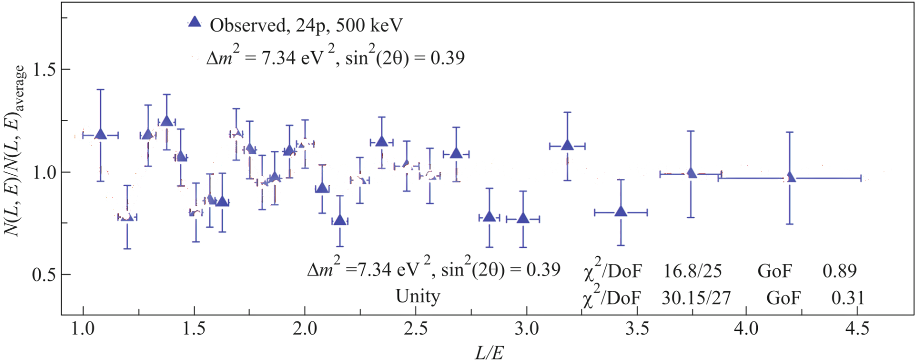


Fig. 1. (Color online) General scheme of the experimental setup: (*1*) detector of reactor antineutrino, (*2*) internal active shielding, (*3*) external active shielding (umbrella), (*4*) steel and lead passive shielding, (*5*) borated polyethylene passive shielding, (*6*) moveable platform, (*7*) feed screw, (*8*) step motor, (*9*) shielding against fast neutrons from iron shot.

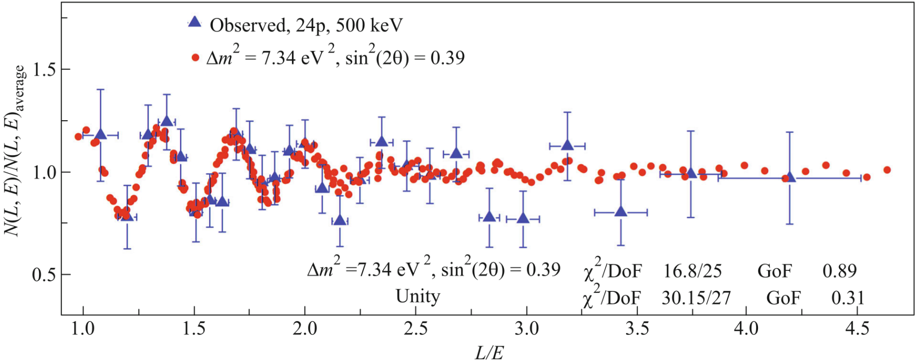
Neutrino-4

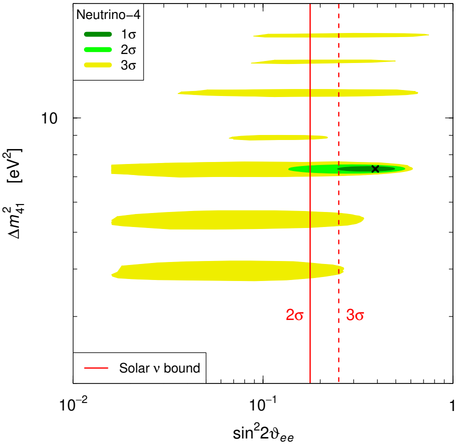
[JETPL 109 (2019) 213, arXiv:1809.10561]



Neutrino-4

[JETPL 109 (2019) 213, arXiv:1809.10561]





- Neutrino-4 best fit:

$$\sin^2 2\vartheta_{ee} = 0.39$$

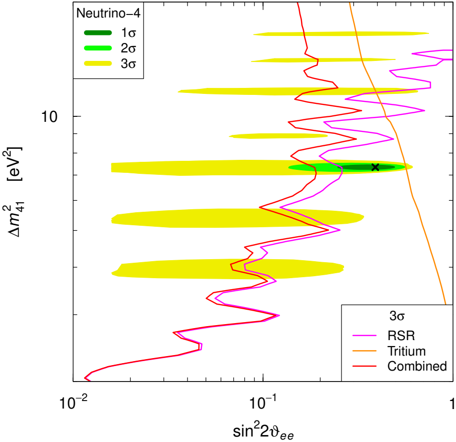
$$\Delta m^2_{41} = 7.34\,\text{eV}^2$$

- Too large mixing!
- Not a perturbation of 3ν mixing.
- Tension with solar neutrino bound.

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

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

[Gariazzo, Giunti, Laveder, Li JHEP 1706 (2017) 135]



- Neutrino-4 best fit:

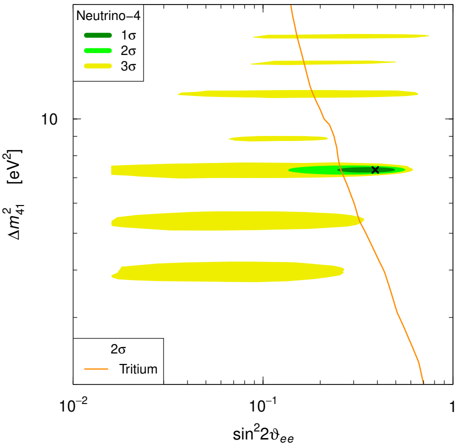
$$\sin^2 2\vartheta_{ee} = 0.39$$
$$\Delta m^2_{41} = 7.34\,\mathrm{eV}^2$$

- Too large mixing!

- The large-mixing parts of the Neutrino-4 allowed regions are excluded by Tritium+RSR.

- Almost all the Neutrino-4 2σ allowed region is excluded at 3σ by Tritium+RSR.

- The Neutrino-4 1σ allowed region is excluded at 3σ by RSR.



- Neutrino-4 best fit:

$$\sin^2 2\vartheta_{ee} = 0.39$$

$$\Delta m^2_{41} = 7.34\,\text{eV}^2$$

- Too large mixing!

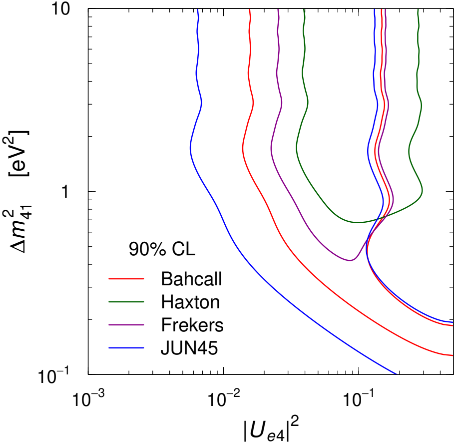
- The Neutrino-4 1σ allowed region is excluded at 2σ by Tritium with dominant KATRIN.

The Gallium Anomaly Revisited

[Kostensalo, Suhonen, Giunti, Srivastava, arXiv:1906.10980]

- New JUN45 shell-model calculation of the cross section of

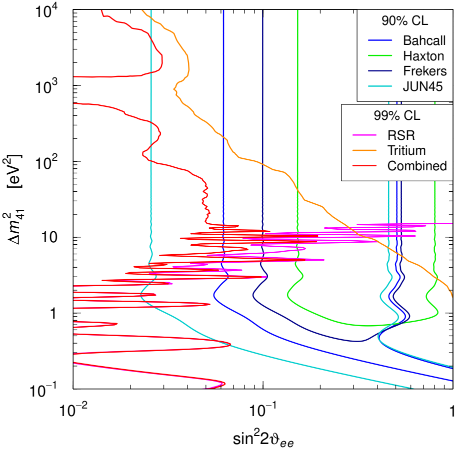
$$\nu_e + {}^{71}\text{Ga} \to {}^{71}\text{Ge} + e^-$$



Cross sections in units of $10^{-45}\,\text{cm}^2$:

	$\sigma(^{51}\text{Cr})$	$\sigma(^{37}\text{Ar})$
Bahcall	5.81 ± 0.16	7.00 ± 0.21
Haxton	6.39 ± 0.65	7.72 ± 0.81
Frekers	5.92 ± 0.11	7.15 ± 0.14
JUN45	5.67 ± 0.06	6.80 ± 0.08

- The statistical significance of the gallium anomaly is reduced from 2.9σ (Frekers) to 2.3σ (JUN45).

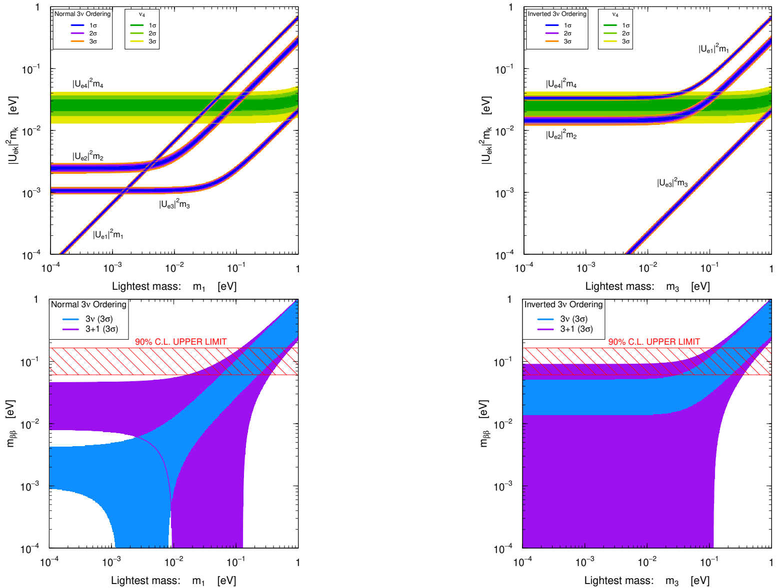


[Giunti, Y.F. Li, Y.Y. Zhang, arXiv:1912.12956]

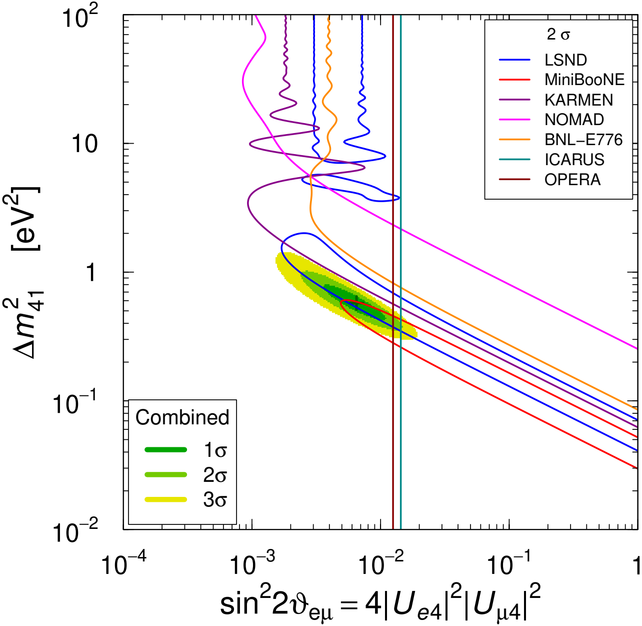
- The large Haxton cross section gives the strongest anomaly, that is in severe tension with Tritium+RSR.
- The smaller Frekers and Bahcall cross sections allow smaller values of the mixing.
  However, their 90% CL allowed regions are in tension with Tritium+RSR.
- The smallest JUN45 cross section allows the smallest mixing.
  It has a large not-excluded area for Δm^2_{41}, between about 5 and 100 eV^2.
  It is favored by Tritium+RSR.

Neutrinoless Double-Beta Decay

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

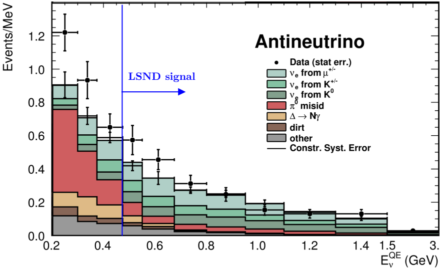


$\bar{\nu}_\mu \to \bar{\nu}_e$ and $\nu_\mu \to \nu_e$ Appearance

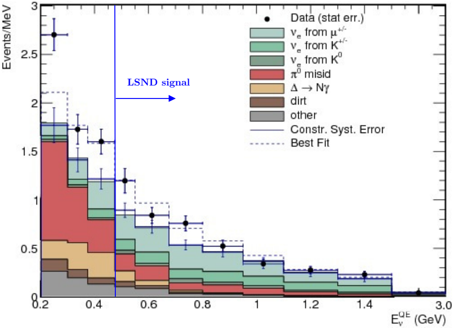


MiniBooNE

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



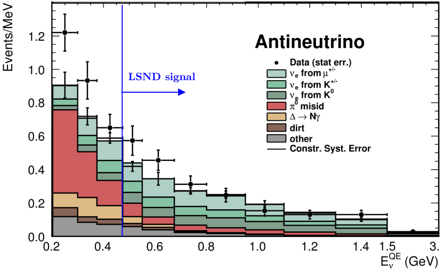
$\nu_\mu \to \nu_e$ [PRL 121 (2018) 221801]



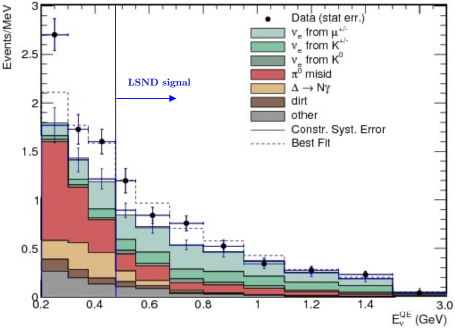
- Purpose: check the LSND signal
- Different $L \simeq 540\,\text{m}$
- Different $200\,\text{MeV} \leq E \lesssim 3\,\text{GeV}$
- Similar $L/E \Longrightarrow$ Oscillations Smoking Gun?
- No money, no Near Detector
- Large beam-related background
- Large flux and cross section uncertainties

MiniBooNE

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



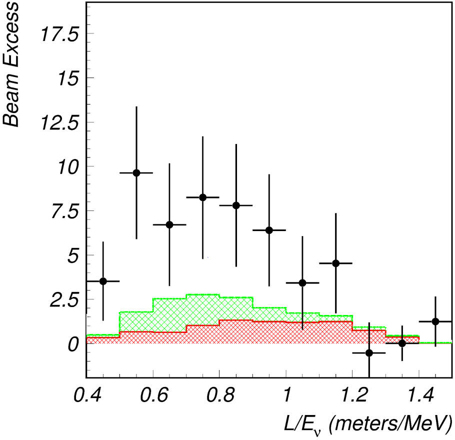
$\nu_\mu \to \nu_e$ [PRL 121 (2018) 221801]



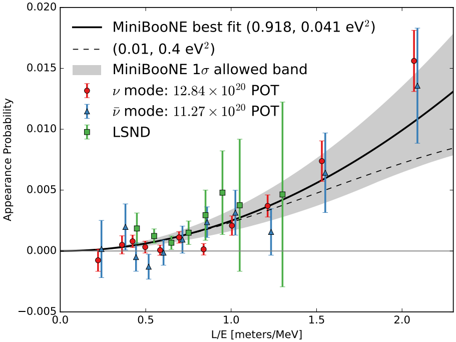
- LSND signal?
- LSND: excess only for
$$\frac{L}{E} \lesssim 1.2\,\frac{m}{\text{MeV}}$$
- MiniBooNE: the LSND excess should be at
$$E \gtrsim \frac{540\,\text{m}}{1.2\,\text{m}}\,\text{MeV} \simeq 450\,\text{MeV}$$
- New large excess for
$$E \lesssim 450\,\text{MeV}$$

MiniBooNE low-energy anomaly

- The MiniBooNE low-energy excess is at larger L/E than LSND.

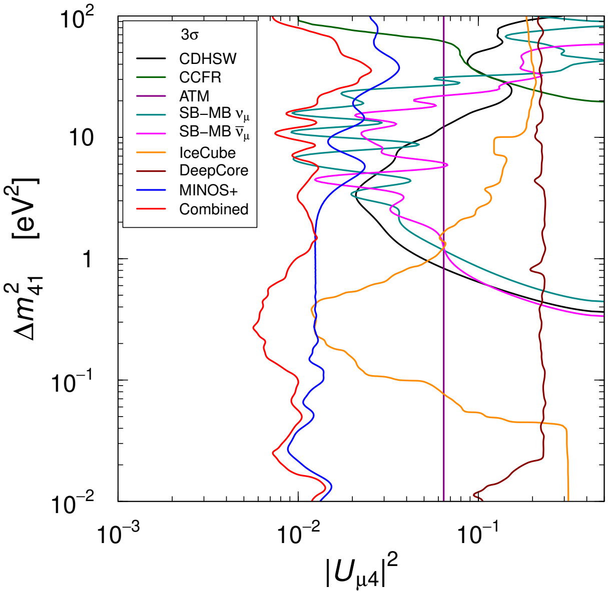


[LSND, PRD 64 (2001) 112007]



[MiniBooNE, PRL 121 (2018) 221801]

ν_μ and $\bar{\nu}_\mu$ Disappearance



[Gariazzo, Giunti, Ternes, in preparation]

Global Appearance-Disappearance Tension

ν_e DIS

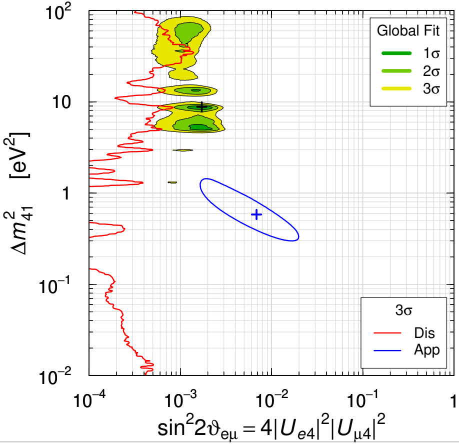
$\sin^2 2\vartheta_{ee} \simeq 4|U_{e4}|^2$

ν_μ DIS

$\sin^2 2\vartheta_{\mu\mu} \simeq 4|U_{\mu4}|^2$

$\nu_\mu \to \nu_e$ APP

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



- $\nu_\mu \to \nu_e$ is quadratically suppressed!
- Global Fit:

  $\chi^2/\text{NDF} = 843.6/794$

  $\text{GoF} = 11\%$

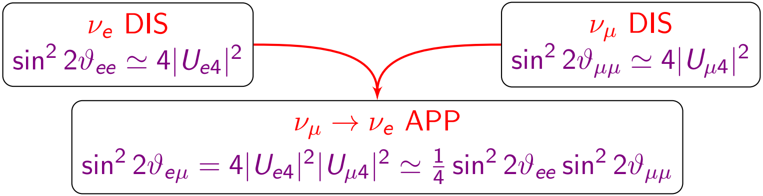
  $\chi^2_{\text{PG}}/\text{NDF}_{\text{PG}} = 46.7/2$

  $\text{GoF}_{\text{PG}} = 7 \times 10^{-11}$ ← ☹
- Similar tension in

  $3+2, \quad 3+3, \quad \ldots, \quad 3+N_s$

[Giunti, Zavanin, MPLA 31 (2015) 1650003]

Global Appearance-Disappearance Tension



ν_e DIS

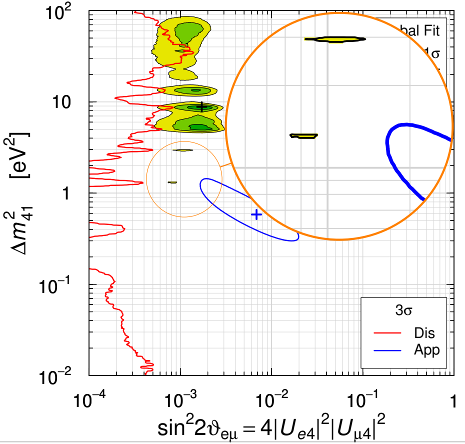
$\sin^2 2\vartheta_{ee} \simeq 4|U_{e4}|^2$

ν_μ DIS

$\sin^2 2\vartheta_{\mu\mu} \simeq 4|U_{\mu4}|^2$

$\nu_\mu \to \nu_e$ APP

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



- $\nu_\mu \to \nu_e$ is quadratically suppressed!

- Global Fit:

  $\chi^2/\text{NDF} = 843.6/794$

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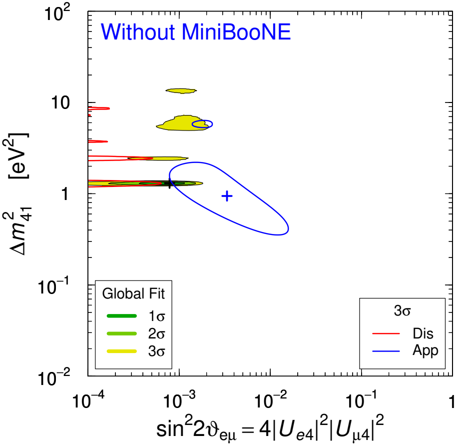
  $\text{GoF}_{\text{PG}} = 7 \times 10^{-11}$ ← ☹

- Similar tension in

  $3+2, \quad 3+3, \quad \ldots, \quad 3+N_s$

[Giunti, Zavanin, MPLA 31 (2015) 1650003]

Global Fit Without MiniBooNE



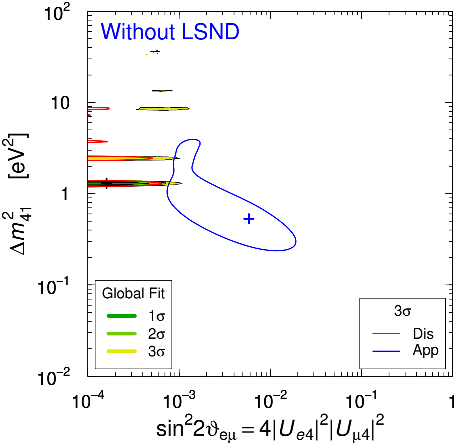
$\chi^2/\mathrm{NDF} = 768.9/763$

$\mathrm{GoF} = 43\%$

$\chi^2_{\mathrm{PG}}/\mathrm{NDF}_{\mathrm{PG}} = 28.7/2$

$\mathrm{GoF}_{\mathrm{PG}} = 6 \times 10^{-7}$ ← ☹

Global Fit Without LSND



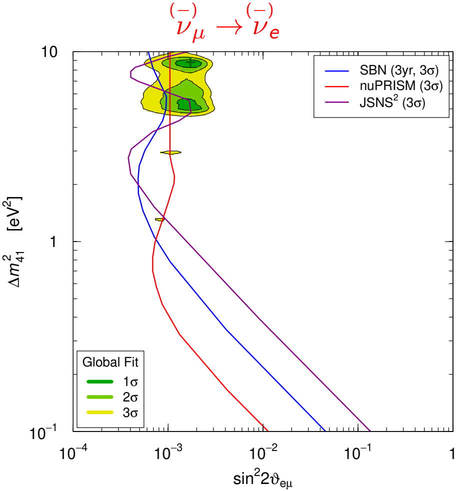
$\chi^2/\mathrm{NDF} = 802.9/793$

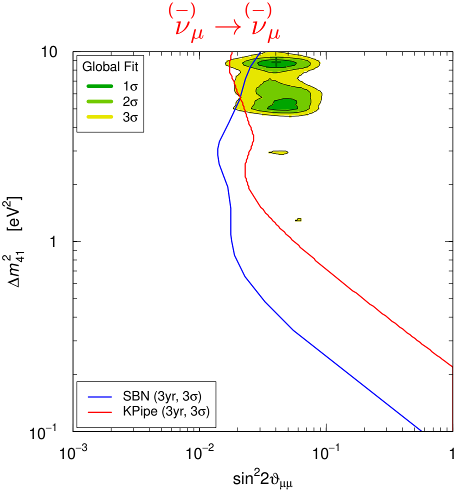
$\mathrm{GoF} = 40\%$

$\chi^2_{\mathrm{PG}}/\mathrm{NDF}_{\mathrm{PG}} = 22.1/2$

$\mathrm{GoF}_{\mathrm{PG}} = 2 \times 10^{-5}$ ← ☹

New Dedicated Experiments





Conclusions

- Neutrinos can be powerful messengers of new physics beyond the SM.
- The existence of light sterile neutrinos beyond the SM is indicated by the Reactor, Gallium and LSND anomalies.
- Some experimental results are confusing, pointing in different directions.
- Therefore, there is no definitive conclusion yet.
- The search must be continued with enthusiasm, because a positive outcome would yield a huge reward.
- The first KATRIN data allowed us to restrict the mixing of ν_e with ν_4.
- Promising future for KATRIN and the electron-capture experiments ECHo, HOLMES.