The eV-scale Sterile Neutrinos and Neutrino Anomalies: Status

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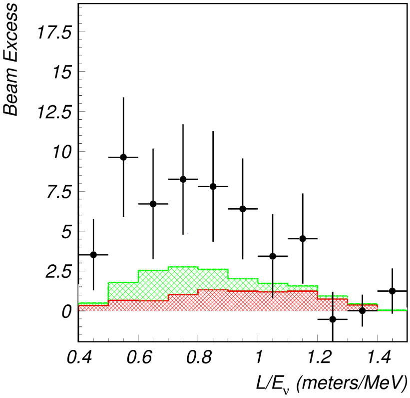
Indications of SBL Oscillations Beyond 3ν

LSND

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

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



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

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

$p + \text{target} \to \pi^+ \xrightarrow{\text{at rest}} \mu^+ + \nu_\mu$

800 MeV

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

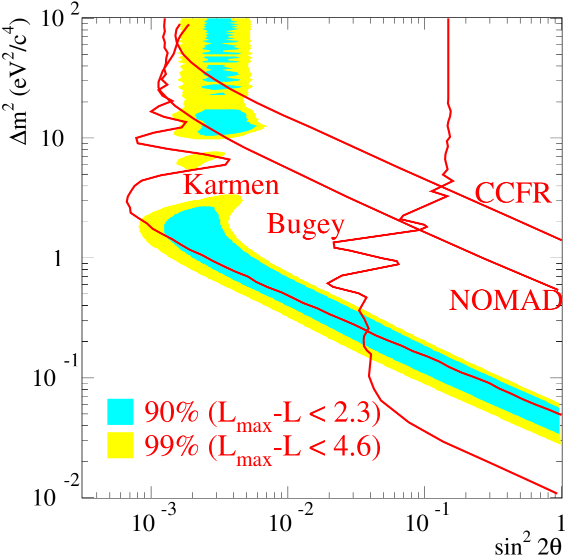
$L \simeq 30\,\text{m}$

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

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

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

[PRD 65 (2002) 112001]



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

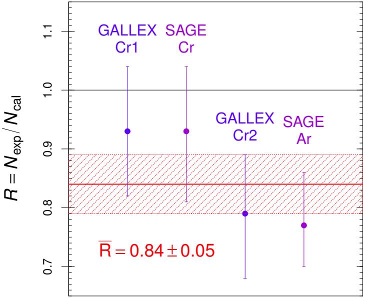
Gallium Anomaly

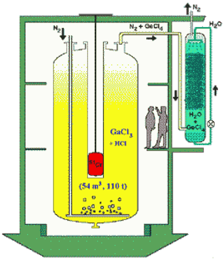
Gallium Radioactive Source Experiments: GALLEX and SAGE

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

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

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

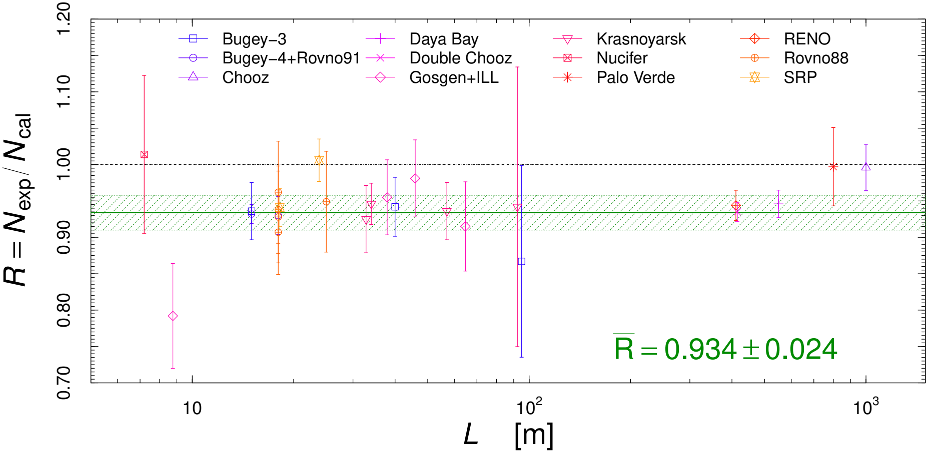
[SAGE, PRC 73 (2006) 045805; PRC 80 (2009) 015807; Laveder et al, Nucl.Phys.Proc.Suppl. 168 (2007) 344, MPLA 22 (2007) 2499, PRD 78 (2008) 073009, PRC 83 (2011) 065504]

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

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 (fourth column)

- 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} $|U_{e4}|^2$ $|U_{\mu 4}|^2$ $(|U_{\tau 4}|^2)$
- 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:

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

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

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

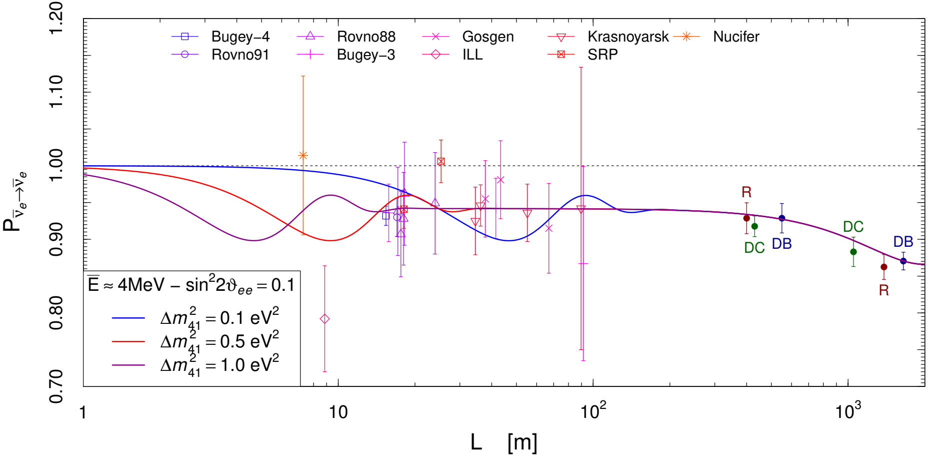
quadratically suppressed for small $|U_{e4}|^2$ and $|U_{\mu 4}|^2$

$\Downarrow$

Appearance-Disappearance Tension

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

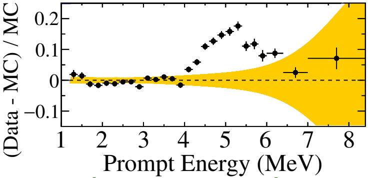
Short-Baseline Reactor Neutrino Oscillations



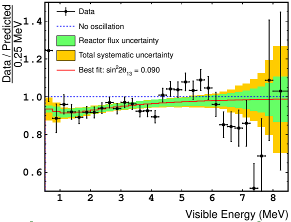
$$\Delta m^2_{\text{SBL}} \gtrsim 0.5\,\text{eV}^2 \gg \Delta m^2_{\text{ATM}}$$

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

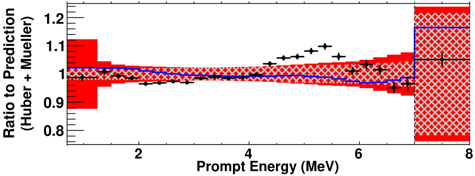
Reactor Antineutrino 5 MeV Bump



[RENO, arXiv:1511.05849]



[Double Chooz, arXiv:1406.7763]



[Daya Bay, arXiv:1508.04233]

[See P. Huber Talk]

[Berryman, Huber, arXiv:1909.09267]

- 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.
  For example:
  - If it is a 4-6 MeV excess it increases the anomaly.
  - If it is a 1-4 MeV suppression it decreases the anomaly.

Reactor Fuel Evolution

- Reactor $\bar{\nu}_e$ flux produced by the β decays of the fission products of

  ^{235}U ^{238}U ^{239}Pu ^{241}Pu

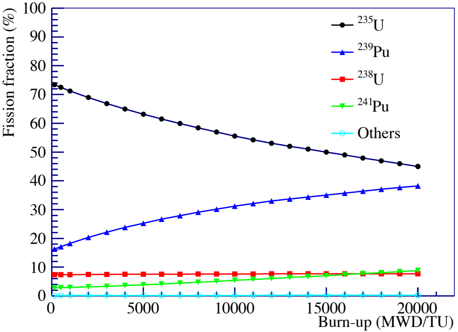
- Effective fission fractions:

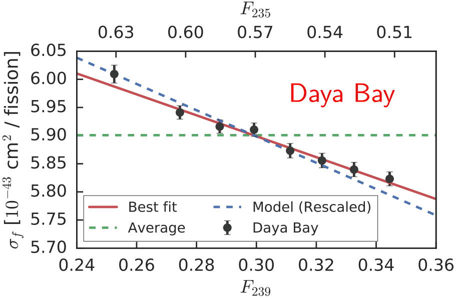
  F_{235} F_{238} F_{239} F_{241}

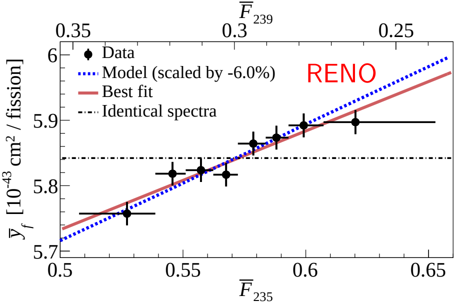
- Cross section per fission (IBD yield):

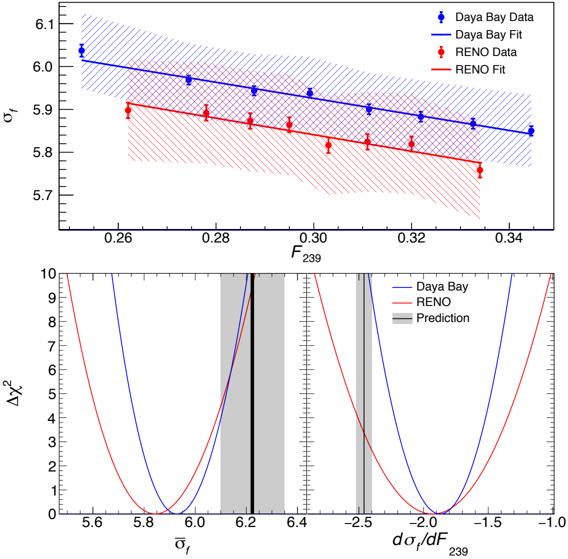
$$\sigma_f = \sum_k F_k \, \sigma_{f,k}$$

for $k = 235, 238, 239, 241$



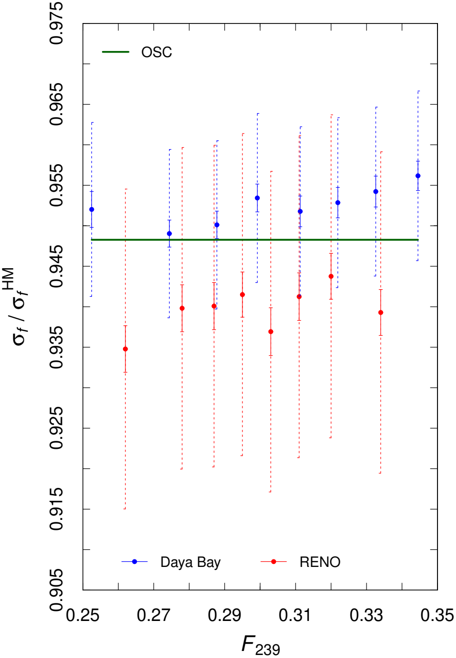






$$\sigma_f(F_{239}) = \bar{\sigma}_f + \frac{d\sigma_f}{dF_{239}} \left(F_{239} - \overline{F}_{239}\right)$$

Giunti, Li, Littlejohn, Surukuchi, PRD 99 (2019) 073005, arXiv:1901.01807

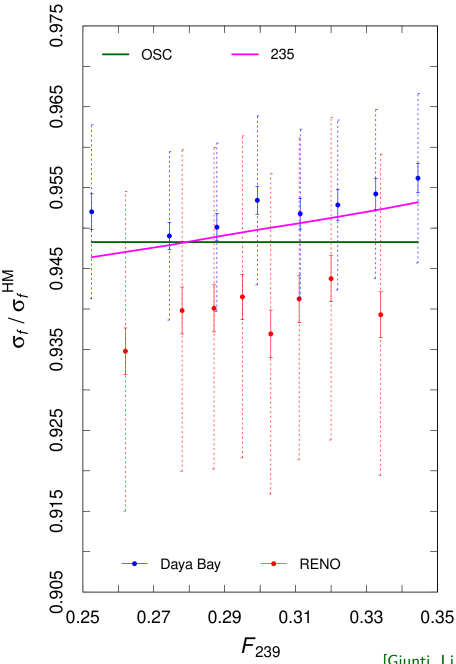


- OSC: $\sigma_f = P_{ee} \sum_k F_k \, \sigma_{f,k}^{HM}$

$$P_{ee} = 0.939 \pm 0.024$$

$$\chi^2/\mathrm{NDF} = 16.3/15 \quad \mathrm{GoF} = 37\%$$

[Giunti, Li, Littlejohn, Surukuchi, PRD 99 (2019) 073005, arXiv:1901.01807



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$$P_{ee} = 0.939 \pm 0.024$$

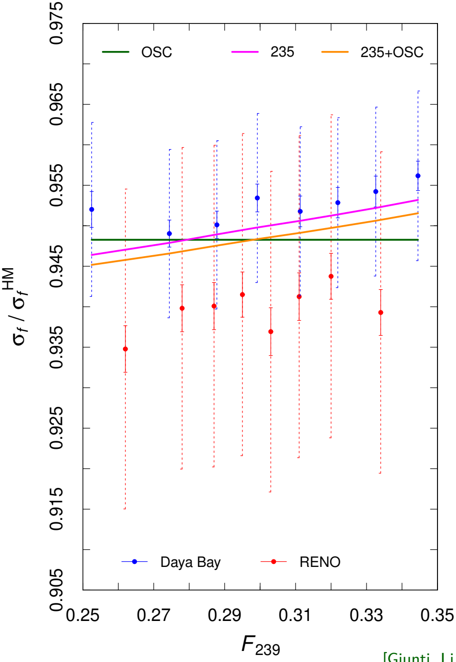
$$\chi^2/\text{NDF} = 16.3/15 \quad \text{GoF} = 37\%$$

- 235: $\sigma_f = \sum_k r_k \, F_k \, \sigma_{f,k}^{HM}$

$$r_{235} = 0.985 \pm 0.015$$

$$\chi^2/\text{NDF} = 9.0/15 \quad \text{GoF} = 88\%$$

[Giunti, Li, Littlejohn, Surukuchi, PRD 99 (2019) 073005, arXiv:1901.01807]



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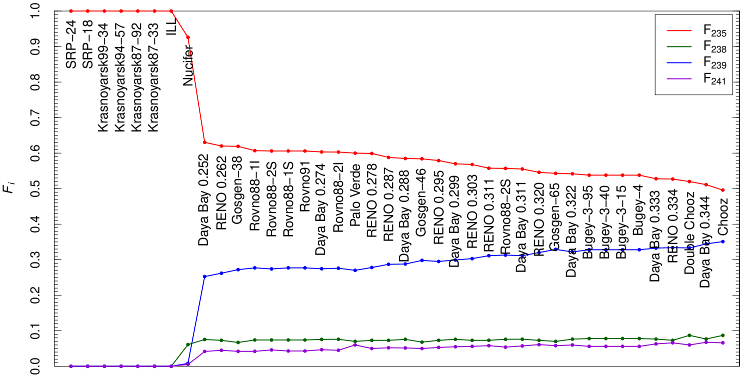
  $$r_{235} = 0.985 \pm 0.015$$
  $$\chi^2/\text{NDF} = 9.0/15 \quad \text{GoF} = 88\%$$

- 235+OSC: $$\sigma_f = P_{ee} \sum_k r_k F_k \sigma_{f,k}^{HM}$$
  $$P_{ee} = 0.986 \pm 0.022$$
  $$r_{235} = 0.938 \pm 0.029$$
  $$\chi^2/\text{NDF} = 8.8/14 \quad \text{GoF} = 85\%$$

[Giunti, Li, Littlejohn, Surukuchi, PRD 99 (2019) 073005, arXiv:1901.01807]

- Daya Bay and RENO favor a suppression of the ^{235}U flux (235) over oscillations (OSC).
- However, a practically equally good fit is obtained with the hybrid model 235+OSC.
- Moreover, the addition of other reactor data favors oscillations or, better, ^{235}U and/or ^{239}U flux suppression plus oscillations.

[Giunti, Ji, Laveder, Li, Littlejohn, JHEP 1710 (2017) 143, arXiv:1708.01133]



- All reactor experiments:

	235	OSC	235+OSC	239+OSC
χ^2_{min}	34.6	33.1	29.5	26.9
NDF	39	38	37	37
GoF	67%	69%	80%	89%

- Even if there are short-baseline neutrino oscillations, it is likely that the reactor antineutrino flux calculations must be corrected (most likely the ^{235}U flux) to fit:
  - The 5 MeV bump
  - The fuel evolution data

- The search for short-baseline neutrino oscillations needs

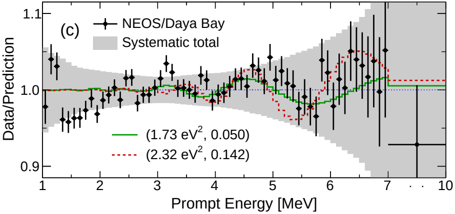
model-independent information

⇑

ratios of spectra at different distances

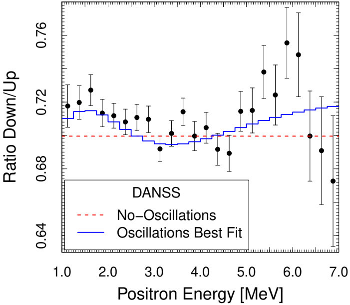
Reactor Spectral Ratios

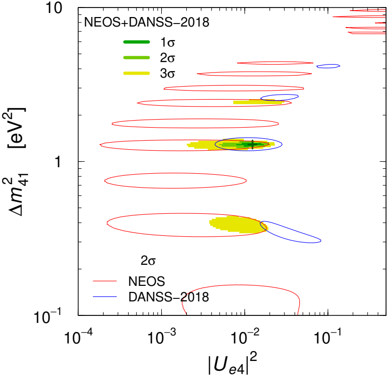
NEOS [PRL 118 (2017) 121802 (arXiv:1610.05134)]



DANSS-2018

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





2018 model independent indication in favor of SBL oscillations

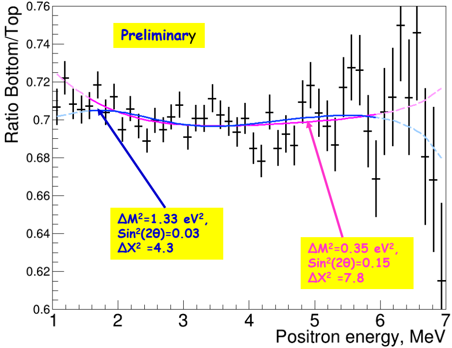
NEOS: $\sim 1.7\sigma$

DANSS-2018: $\sim 2.7\sigma$

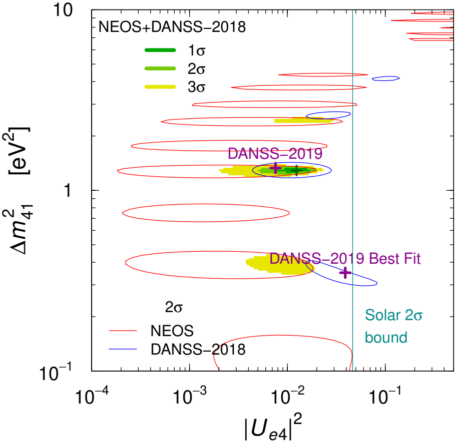
Combined: $\sim 3.5\sigma$

[Gariazzo, Giunti, Laveder, Li, arXiv:1801.06467]
[Dentler, Hernandez-Cabezudo, Kopp, Machado, Maltoni, Martinez-Soler, Schwetz, arXiv:1803.10661]

New DANSS results @ EPS-HEP 2019

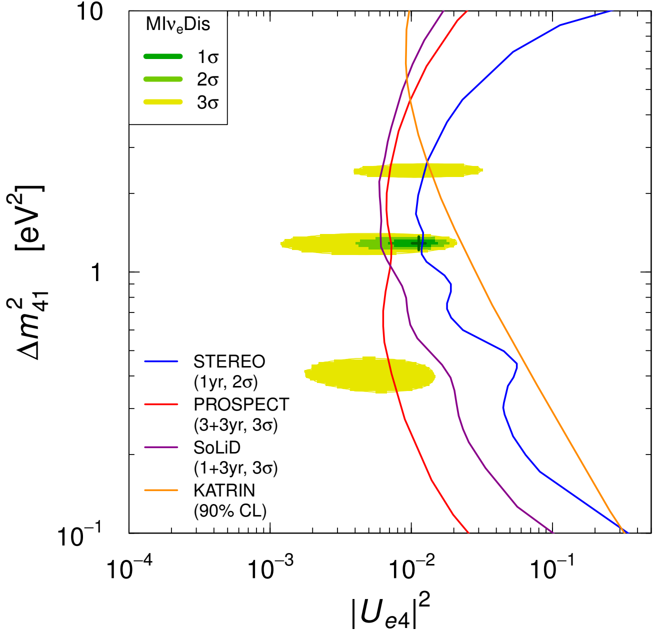


[Danilov @ EPS-HEP 2019]



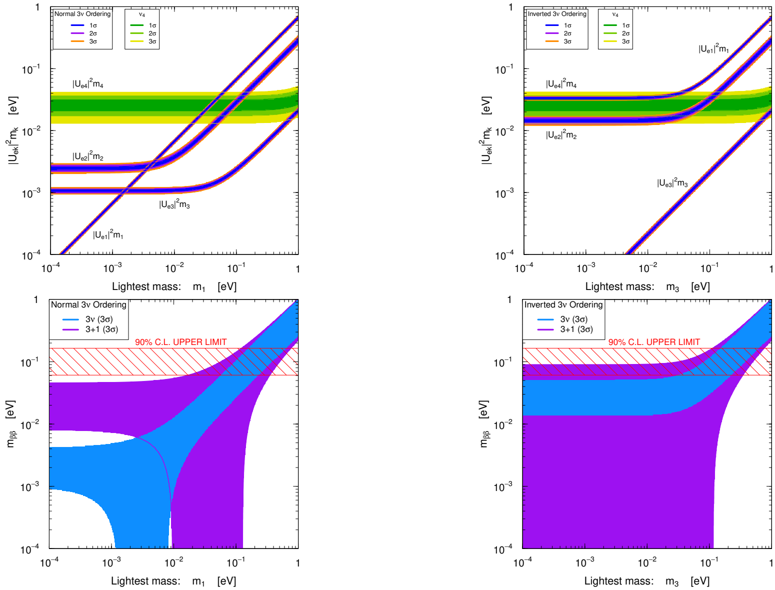
- The agreement between NEOS and DANSS has diminished.
- Reactor indications in favor of SBL oscillations may be fading away.
- We wait independent checks of PROSPECT, STEREO and SoLiD.

Sensitivities of New Experiments



Neutrinoless Double-Beta Decay

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

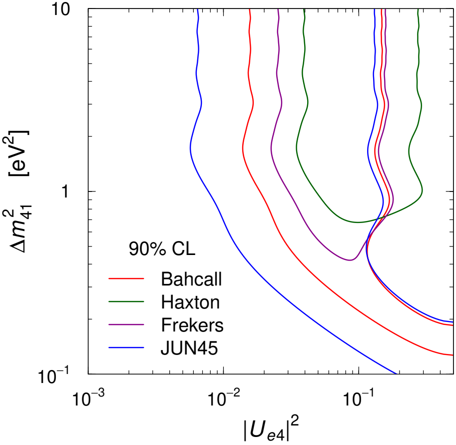


The Gallium Anomaly Revisited

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

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

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



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

	$\sigma(^{51}\mathrm{Cr})$	$\sigma(^{37}\mathrm{Ar})$
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

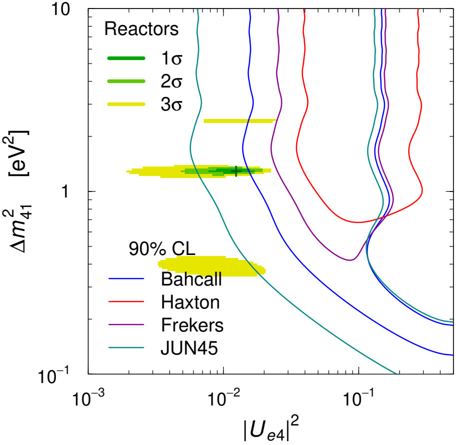
- The statistical significance of the gallium anomaly is reduced from 2.9σ (Frekers) to 2.3σ (JUN45).

The Gallium Anomaly Revisited

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

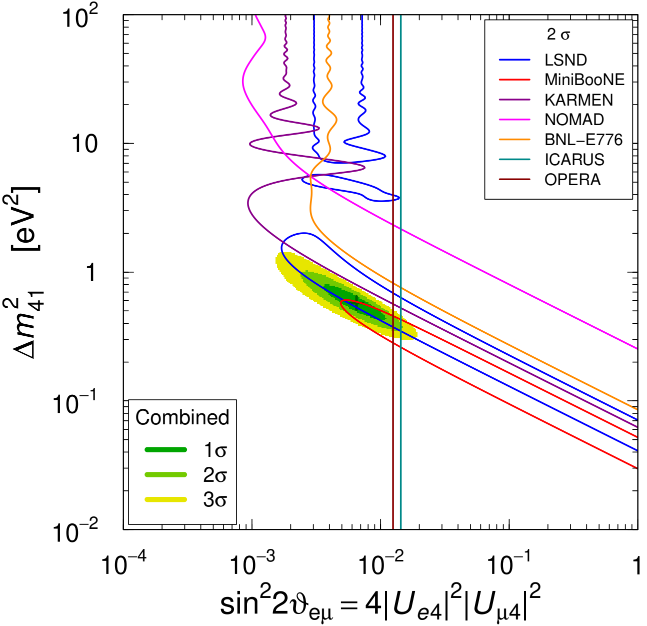
- New JUN45 shell-model calculation of the cross section of

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



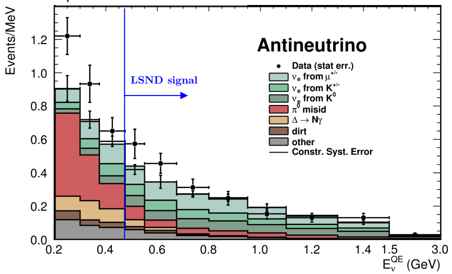
- With the new JUN45 shell-model calculation the Gallium anomaly is more compatible with small-mixing SBL oscillations.

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

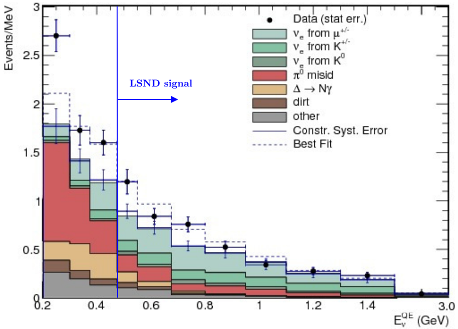


MiniBooNE

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



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



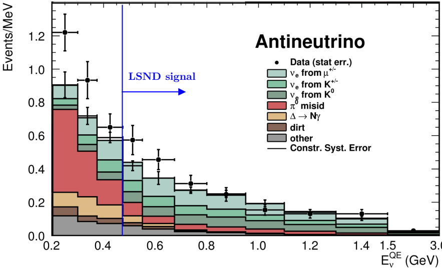
- Purpose: check the LSND signal
- Different $L \simeq 541\,\text{m}$
- Different $200\,\text{MeV} \leq E \lesssim 3\,\text{GeV}$
- Similar $L/E \Longleftrightarrow$ oscillations
- No money, no Near Detector
- LSND signal expected for

  $E \gtrsim 475\,\text{MeV}$
- New low-energy anomaly for

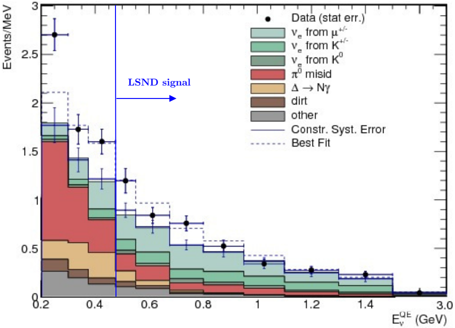
  $E < 475\,\text{MeV}$

MiniBooNE

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

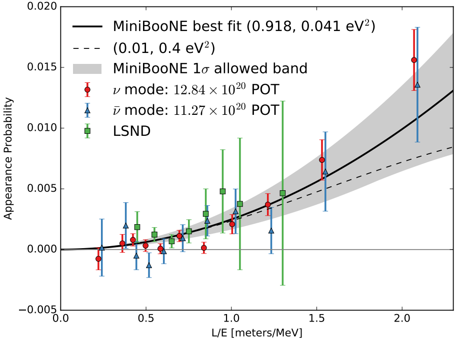


$\nu_\mu \to \nu_e$ [PRL 121 (2018) 221801]



- LSND: excess for $\dfrac{L}{E} \lesssim 1.2\,\dfrac{\text{m}}{\text{MeV}}$
- MiniBooNE: the LSND excess should be at

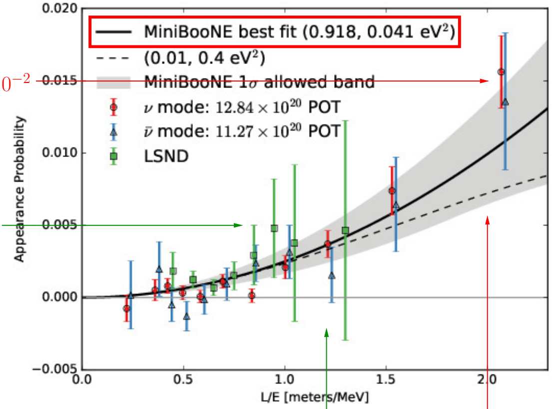
$$E \gtrsim \frac{541\,\text{m}}{1.2\,\text{m}}\,\text{MeV} \simeq 451\,\text{MeV}$$



[MiniBooNE, PRL 121 (2018) 221801]

$\sin^2 2\vartheta_{\mu e} \simeq 1.5 \times 10^{-2}$

$\sin^2 2\vartheta_{\mu e} \simeq 5 \times 10^{-3}$

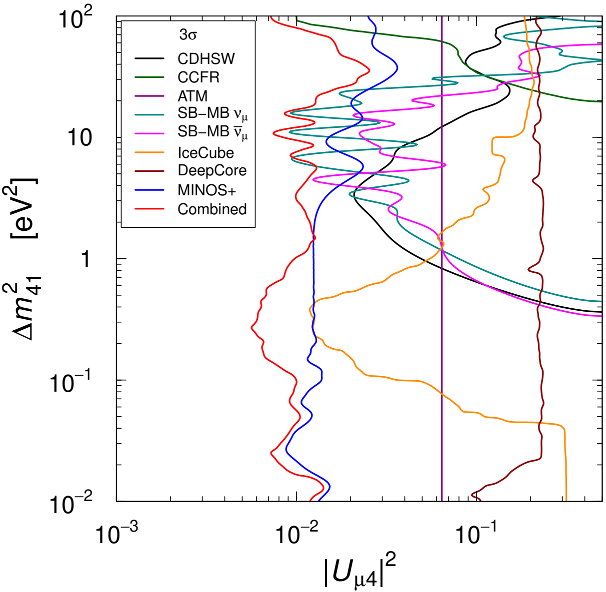


$\Delta m^2_{41} \simeq 1\,\mathrm{eV}^2$ $\Delta m^2_{41} \simeq 0.6\,\mathrm{eV}^2$

$$P_{\nu_\mu \to \nu_e} = \sin^2 2\vartheta_{\mu e} \sin^2\left(\frac{\Delta m^2_{41} L}{4E}\right) \quad \Longrightarrow \quad P^{\max}_{\nu_\mu \to \nu_e} = \sin^2 2\vartheta_{\mu e}$$

$$\text{for} \quad \frac{\Delta m^2_{41} L}{4E} = \frac{\pi}{2} \quad \Longrightarrow \quad \frac{L\,[\mathrm{m}]}{E\,[\mathrm{MeV}]} \simeq \frac{1.2}{\Delta m^2_{41}\,[\mathrm{eV}^2]}$$

ν_μ and $\bar{\nu}_\mu$ Disappearance



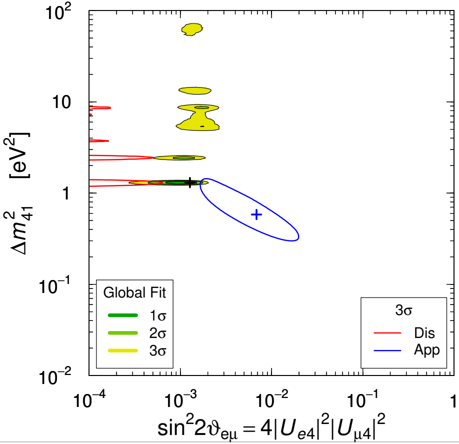
[Gariazzo, Giunti, Ternes, in preparation]

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:

  $\chi^2/\text{NDF} = 831.7/797$

  GoF = 19%

  $\chi^2_{\text{PG}}/\text{NDF}_{\text{PG}} = 42.8/2$

  $\text{GoF}_{\text{PG}} = 5 \times 10^{-10}$ ← ☹
- Similar tension in

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

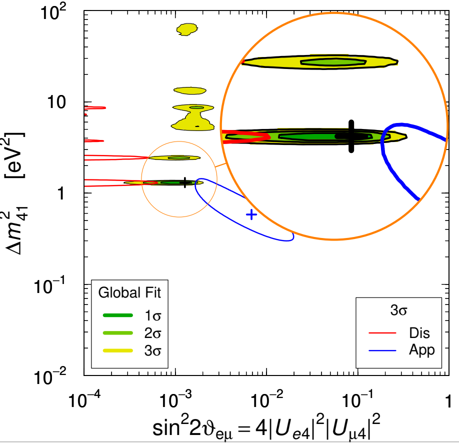
[Giunti, Zavanin, MPLA 31 (2015) 1650003]

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:

  $\chi^2/\mathrm{NDF} = 831.7/797$

  $\mathrm{GoF} = 19\%$

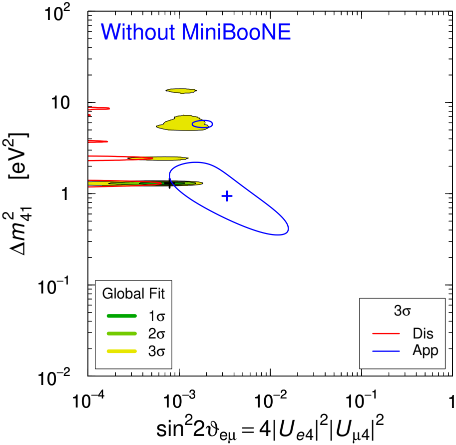
  $\chi^2_{\mathrm{PG}}/\mathrm{NDF}_{\mathrm{PG}} = 42.8/2$

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

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

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

Global Fit Without MiniBooNE



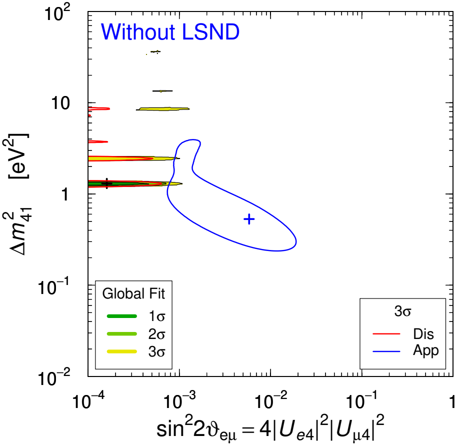
$\chi^2/\mathrm{NDF} = 768.9/763$

$\mathrm{GoF} = 43\%$

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

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

Global Fit Without LSND



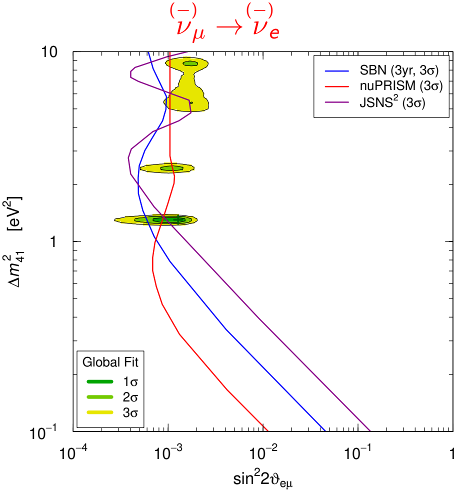
$\chi^2/\text{NDF} = 802.9/793$

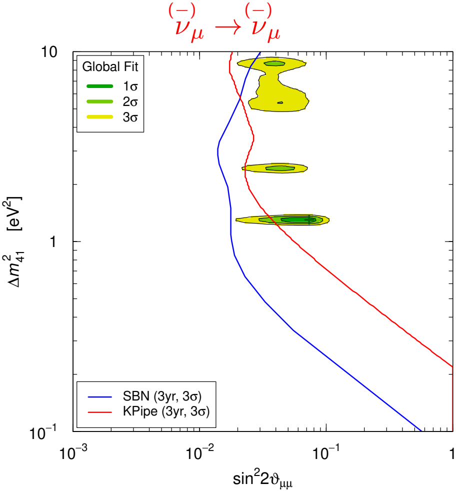
$\text{GoF} = 40\%$

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

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

New Dedicated Experiments





Conclusions I

- 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.
- Exciting 2018 model-independent indication of light sterile neutrinos at the eV scale from the NEOS and DANSS experiments in approximate agreement with the reactor and Gallium anomalies.
- 2019 DANSS data do not confirm the 2018 indication and the reactor indications in favor of SBL oscillations seem to be fading away.
- Important checks in the near future by the reactor experiments PROSPECT, STEREO, SoLid. (Neutrino-4?)
- Independent tests through the effect of m_4 in β-decay (KATRIN), electron-capture (ECHo, HOLMES) and $\beta\beta_{0\nu}$-decay experiments.

Conclusions II

- In principle, the simplest explanation of the LSND and MiniBooNE ν_e-like excesses is neutrino oscillations, that requires a new Δm^2_{SBL} associated with a light sterile neutrino.
- Unfortunately, the LSND and MiniBooNE ν_e-like excesses are too large to be compatible with the existing bounds on ν_e and ν_μ disappearance in the framework of $3 + N_s$ active-sterile neutrino mixing:

  APPEARANCE-DISAPPEARANCE TENSION

- Alternative explanations exist with a heavy sterile neutrino produced and decayed in the detector.
- Promising Fermilab SBN program aimed at a conclusive solution of the mystery with three Liquid Argon Time Projection Chamber (LArTPC): a near detector (LAr1-ND), an intermediate detector (MicroBooNE) and a far detector (ICARUS-T600).
- It is important that LArTPC detectors can distinguish a single ν_e-induced electron from a γ or a collimated e^+e^- pair.