Anomalies in Neutrino Oscillation Experiments

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ISAPP 2021 Valencia, 21–30 July 2021

Standard Three Neutrino Mixing Paradigm

- Supported by robust, abundant, and consistent solar, atmospheric and long-baseline (accelerator and reactor) neutrino oscillation data.
- Flavor Neutrinos: ν_e, ν_μ, ν_τ produced in Weak Interactions.
- Massive Neutrinos: ν_1, ν_2, ν_3 propagate from Source to Detector.
- Neutrino Mixing: a Flavor Neutrino is a superposition of Massive Neutrinos:

$$\begin{pmatrix} |\nu_e\rangle \\ |\nu_\mu\rangle \\ |\nu_\tau\rangle \end{pmatrix} = \begin{pmatrix} U_{e1}^* & U_{e2}^* & U_{e3}^* \\ U_{\mu 1}^* & U_{\mu 2}^* & U_{\mu 3}^* \\ U_{\tau 1}^* & U_{\tau 2}^* & U_{\tau 3}^* \end{pmatrix} \begin{pmatrix} |\nu_1\rangle \\ |\nu_2\rangle \\ |\nu_3\rangle \end{pmatrix}$$

- U is the 3×3 unitary Neutrino Mixing Matrix.
- $P_{\nu_\alpha \to \nu_\beta}(L) = \sum_{k,j} U_{\beta k} U_{\alpha k}^* U_{\beta j}^* U_{\alpha j} \exp\left(-i \frac{\Delta m_{kj}^2 L}{2E}\right) \qquad (\alpha, \beta = e, \mu, \tau)$
- The oscillation probabilities depend on:

$$U \text{ (osc. amplitude)} \quad \text{and} \quad \Delta m_{kj}^2 \equiv m_k^2 - m_j^2 \text{ (osc. phase)}$$

Three-Neutrino Mixing Parameters

Standard Parameterization of Mixing Matrix (as CKM)

$$U = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta_{13}} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta_{13}} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} 1 & 0 & 0 \\ 0 & e^{i\lambda_{21}} & 0 \\ 0 & 0 & e^{i\lambda_{31}} \end{pmatrix}$$

$$= \begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta_{13}} \\ -s_{12}c_{23}-c_{12}s_{23}s_{13}e^{i\delta_{13}} & c_{12}c_{23}-s_{12}s_{23}s_{13}e^{i\delta_{13}} & s_{23}c_{13} \\ s_{12}s_{23}-c_{12}c_{23}s_{13}e^{i\delta_{13}} & -c_{12}s_{23}-s_{12}c_{23}s_{13}e^{i\delta_{13}} & c_{23}c_{13} \end{pmatrix} \begin{pmatrix} 1 & 0 & 0 \\ 0 & e^{i\lambda_{21}} & 0 \\ 0 & 0 & e^{i\lambda_{31}} \end{pmatrix}$$

$c_{ab} \equiv \cos\vartheta_{ab}$ $\quad$ $s_{ab} \equiv \sin\vartheta_{ab}$ $\quad$ $0 \leq \vartheta_{ab} \leq \frac{\pi}{2}$ $\quad$ $0 \leq \delta_{13}, \lambda_{21}, \lambda_{31} < 2\pi$

OSCILLATION PARAMETERS $\left\{\right.$

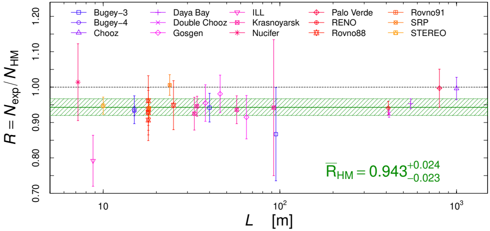
- 3 Mixing Angles: ϑ_{12}, ϑ_{23}, ϑ_{13}
- 1 CPV Dirac Phase: δ_{13}
- 2 independent $\Delta m^2_{kj} \equiv m^2_k - m^2_j$: Δm^2_{21}, Δm^2_{31}

2 CPV Majorana Phases: λ_{21}, λ_{31} $\Longleftrightarrow$ $|\Delta L| = 2$ processes

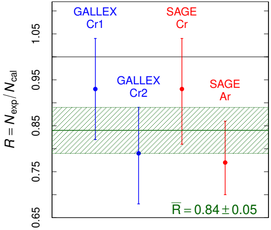
- In the standard 3ν mixing paradigm there are two independent Δm^2's:
  - $\Delta m^2_{\text{SOL}} = \Delta m^2_{21} \simeq 7.4 \times 10^{-5}\,\text{eV}^2$ Solar Mass Splitting
  - $\Delta m^2_{\text{ATM}} \simeq |\Delta m^2_{31}| \simeq 2.5 \times 10^{-3}\,\text{eV}^2$ Atmospheric Mass Splitting
- The solar and atmospheric mass splittings generate oscillations that are detectable at the distances
  - $L^{\text{osc}}_{\text{SOL}} \gtrsim \dfrac{E_\nu}{\Delta m^2_{\text{SOL}}} \approx 50\,\text{km}\,\dfrac{E_\nu}{\text{MeV}}$
  - $L^{\text{osc}}_{\text{ATM}} \gtrsim \dfrac{E_\nu}{\Delta m^2_{\text{ATM}}} \approx 1\,\text{km}\,\dfrac{E_\nu}{\text{MeV}}$
- The solar and atmospheric mass splittings cannot explain neutrino oscillations at shorter distances.
- A neutrino oscillation explanation of short-baseline anomalies needs the existence of larger Δm^2's.

Short-Baseline Anomalies

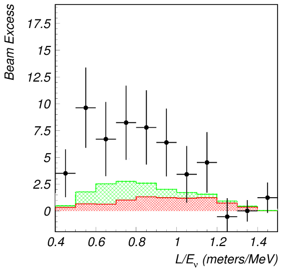
Reactor Anomaly: $\bar{\nu}_e \to \bar{\nu}_x$ ($\approx 2.4\sigma$)



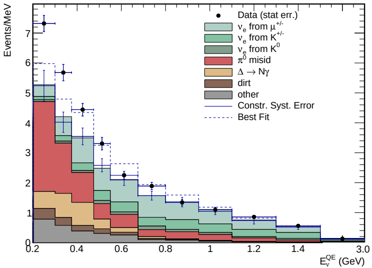
Gallium Anomaly: $\nu_e \to \nu_x$ ($\approx 2.9\sigma$)



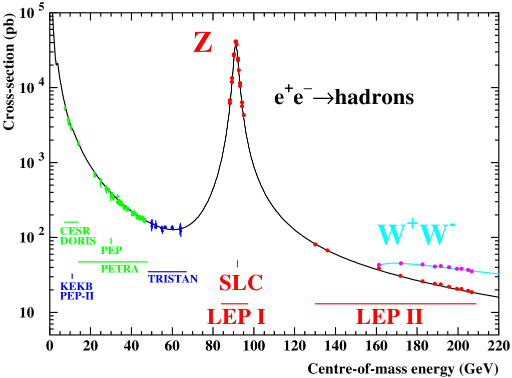
LSND Anomaly: $\bar{\nu}_\mu \to \bar{\nu}_e$ ($\sim 4\sigma$)

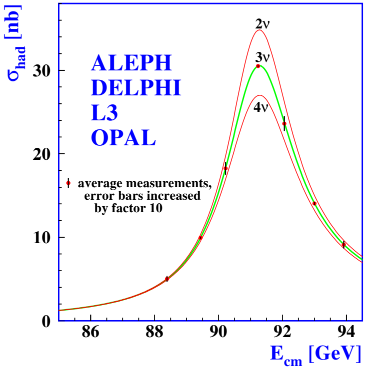


MiniBooNE Anomaly: $\overset{(-)}{\nu}_\mu \to \overset{(-)}{\nu}_e$ (4.8σ)



Number of Flavor and Massive Neutrinos?





[LEP, Phys. Rept. 427 (2006) 257, arXiv:hep-ex/0509008]

$$\Gamma_Z = \sum_{\ell=e,\mu,\tau} \Gamma_{Z\to\ell\bar{\ell}} + \sum_{q\neq t} \Gamma_{Z\to q\bar{q}} + \Gamma_{\text{inv}} \qquad \Gamma_{\text{inv}} = N_\nu \, \Gamma_{Z\to\nu\bar{\nu}}$$

$$\boxed{N_\nu = 2.9840 \pm 0.0082}$$

Improved cross section: $N_\nu = 2.9975 \pm 0.0074$ [Janot, Jadach, arXiv:1912.02067]

$$e^+ e^- \to Z \xrightarrow{\text{invisible}} \sum_{a=\text{active}} \nu_a \bar{\nu}_a \quad \Longrightarrow \quad \nu_e \; \nu_\mu \; \nu_\tau$$

- We know that there are 3 light active flavor neutrinos
- We do not know the number of massive neutrinos

mixing $\Rightarrow$ $\nu_{\alpha L} = \sum_{k=1}^{N} U_{\alpha k} \nu_{kL} \qquad \alpha = e, \mu, \tau$

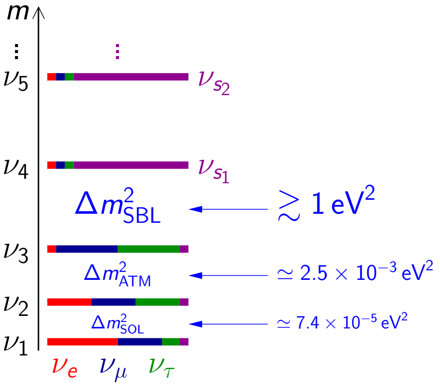
$N \geq 3$
no upper limit!

U: unitary $N \times N$ mixing matrix

Mass Basis:	ν_1	ν_2	ν_3	ν_4	ν_5	$\cdots$
Flavor Basis:	ν_e	ν_μ	ν_τ	ν_{s_1}	ν_{s_2}	$\cdots$
	ACTIVE			STERILE		

$$\boxed{\nu_{\alpha L} = \sum_{k=1}^{N} U_{\alpha k} \nu_{kL} \qquad \alpha = e, \mu, \tau, s_1, s_2, \ldots}$$

Light Sterile Neutrinos



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

Terminology: a eV-scale sterile neutrino

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

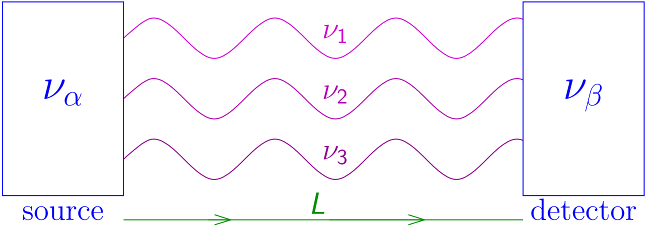
- Minimal perturbation of successfull 3ν mixing:

  effective 4ν mixing with $|U_{e4}|, |U_{\mu4}|, |U_{\tau4}| \ll 1$

Short-Baseline Neutrino Oscillations?

Three-Neutrino Mixing

$$|\nu_{\text{source}}\rangle = |\nu_\alpha\rangle = U_{\alpha 1}^* |\nu_1\rangle + U_{\alpha 2}^* |\nu_2\rangle + U_{\alpha 3}^* |\nu_3\rangle$$



$$|\nu_{\text{detector}}\rangle \simeq U_{\alpha 1}^* e^{-iEL} |\nu_1\rangle + U_{\alpha 2}^* e^{-iEL} |\nu_2\rangle + U_{\alpha 3}^* e^{-iEL} |\nu_3\rangle$$

$$= e^{-iEL} \left(U_{\alpha 1}^* |\nu_1\rangle + U_{\alpha 2}^* |\nu_2\rangle + U_{\alpha 3}^* |\nu_3\rangle \right) = e^{-iEL} |\nu_\alpha\rangle$$

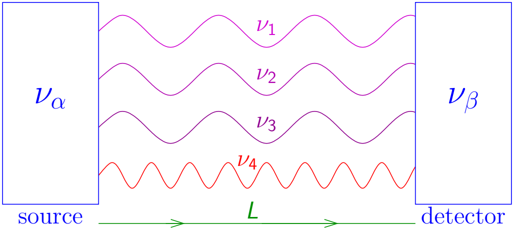
$$P_{\nu_\alpha \to \nu_\beta}(L) = |\langle \nu_\beta | \nu_{\text{detector}} \rangle|^2 \simeq |e^{-iEL} \langle \nu_\beta | \nu_\alpha \rangle|^2 = \delta_{\alpha\beta}$$

No Short-Baseline Neutrino Oscillations!

Short-Baseline Neutrino Oscillations?

3+1 Neutrino Mixing

$$|\nu_{\text{source}}\rangle = |\nu_\alpha\rangle = U_{\alpha 1}^* |\nu_1\rangle + U_{\alpha 2}^* |\nu_2\rangle + U_{\alpha 3}^* |\nu_3\rangle + U_{\alpha 4}^* |\nu_4\rangle$$



$$|\nu_{\text{detector}}\rangle \simeq e^{-iEL} \left(U_{\alpha 1}^* |\nu_1\rangle + U_{\alpha 2}^* |\nu_2\rangle + U_{\alpha 3}^* |\nu_3\rangle \right) + U_{\alpha 4}^* \, e^{-iE_4 L} |\nu_3\rangle \not\propto |\nu_\alpha\rangle$$

$$P_{\nu_\alpha \to \nu_\beta}(L) = |\langle \nu_\beta | \nu_{\text{detector}} \rangle|^2 \neq \delta_{\alpha\beta}$$

Short-Baseline Neutrino Oscillations!

The oscillation probabilities depend on U and
$\Delta m^2_{\text{SBL}} = \Delta m^2_{41} \simeq \Delta m^2_{42} \simeq \Delta m^2_{43}$

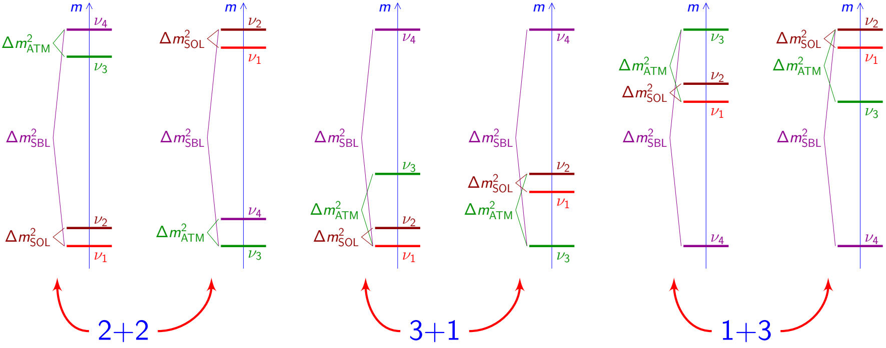
- Some authors that probably did not think about the quantum mechanics of neutrino oscillations present $\nu_\mu \to \nu_e$ short-baseline transitions due to sterile neutrinos as

$$\nu_\mu \to \nu_s \to \nu_e$$

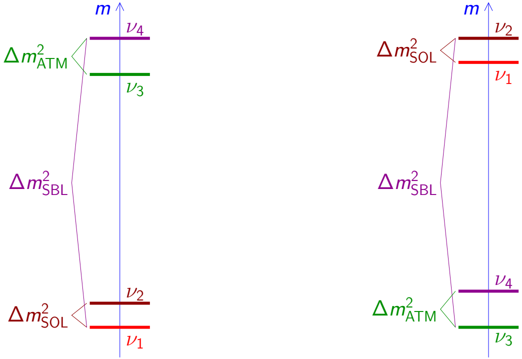
- This is wrong!

THERE IS NO INTERMEDIATE ν_s !

Four-Neutrino Schemes: 2+2, 3+1 and 1+3



2+2 Four-Neutrino Schemes

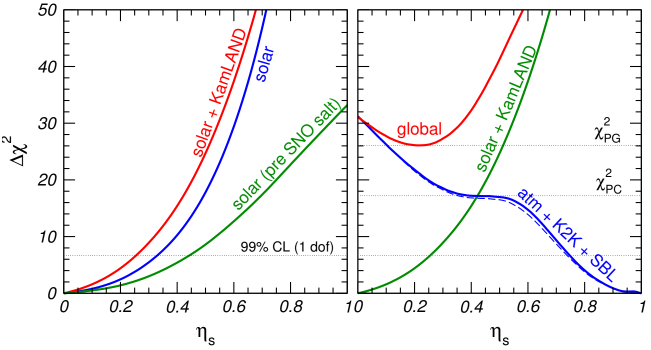


- After LSND (1995) 2+2 was preferred to 3+1, because of the 3+1 appearance-disappearance tension

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

- This is not a perturbation of 3-ν Mixing $\Longrightarrow$ Large active–sterile oscillations for solar or atmospheric neutrinos!

2+2 Schemes are Strongly Disfavored



Solar: Matter Effects + SNO NC

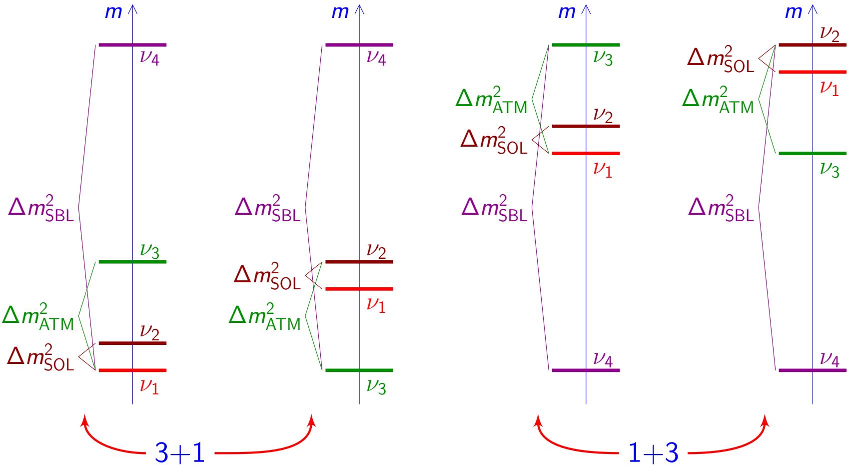
Atmospheric: Matter Effects

$$\eta_s = |U_{s1}|^2 + |U_{s2}|^2 = 1 - |U_{s3}|^2 + |U_{s4}|^2$$

$$99\%\ \text{CL:} \quad \begin{cases} \eta_s < 0.25 & \text{(Solar + KamLAND)} \\ \eta_s > 0.75 & \text{(Atmospheric + K2K)} \end{cases}$$

[Maltoni, Schwetz, Tortola, Valle, New J. Phys. 6 (2004) 122]

3+1 and 1+3 Four-Neutrino Schemes



- Perturbation of 3-ν Mixing: $|U_{e4}|^2, |U_{\mu4}|^2, |U_{\tau4}|^2 \ll 1 \quad |U_{s4}|^2 \simeq 1$
- 1+3 schemes are disfavored by cosmology (ΛCDM):

$$\sum_{k=1}^{3} m_k \lesssim 0.12\,\text{eV} \qquad (95\%\ \text{CL})$$ [Planck, arXiv:1807.06209]

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, arXiv:1412.1479, arXiv:1507.03986, arXiv:1605.09376; Palazzo et al, arXiv:1412.7524, arXiv:1509.03148; Kayser et al, arXiv:1508.06275, arXiv:1607.02152] and solar exp. sensitive to Δm^2_{SOL} [Long, Li, CG, arXiv:1304.2207]

Common Parameterization of 4ν Mixing

$$U = \left[W^{34} R^{24} W^{14} R^{23} W^{13} R^{12}\right] \mathrm{diag}\left(1, e^{i\lambda_{21}}, e^{i\lambda_{31}}, e^{i\lambda_{41}}\right)$$

$$= \begin{pmatrix} c_{12}c_{13}c_{14} & s_{12}c_{13}c_{14} & c_{14}s_{13}e^{-i\delta_{13}} & s_{14}e^{-i\delta_{14}} \\ \cdots & \cdots & \cdots & c_{14}s_{24} \\ \cdots & \cdots & \cdots & c_{14}c_{24}s_{34}e^{-i\delta_{34}} \\ \cdots & \cdots & \cdots & c_{14}c_{24}c_{34} \end{pmatrix} \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & e^{i\lambda_{21}} & 0 & 0 \\ 0 & 0 & e^{i\lambda_{31}} & 0 \\ 0 & 0 & 0 & e^{i\lambda_{41}} \end{pmatrix}$$

$$|U_{e4}|^2 = \sin^2\vartheta_{14} \quad \Rightarrow \quad \sin^2 2\vartheta_{ee} = 4|U_{e4}|^2\left(1 - |U_{e4}|^2\right) = \sin^2 2\vartheta_{14}$$

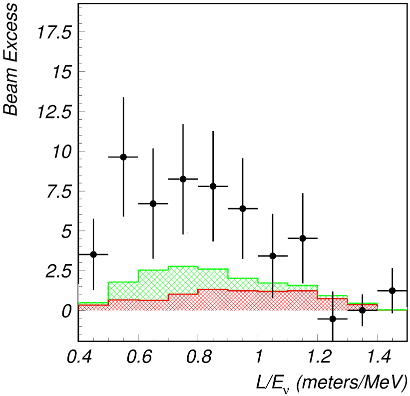
$$|U_{\mu4}|^2 = \cos^2\vartheta_{14}\sin^2\vartheta_{24} \simeq \sin^2\vartheta_{24} \Rightarrow \sin^2 2\vartheta_{\mu\mu} = 4|U_{\mu4}|^2\left(1 - |U_{\mu4}|^2\right) \simeq \sin^2 2\vartheta_{24}$$

Short-Baseline Neutrino Oscillation Anomalies

LSND

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

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



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

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

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

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

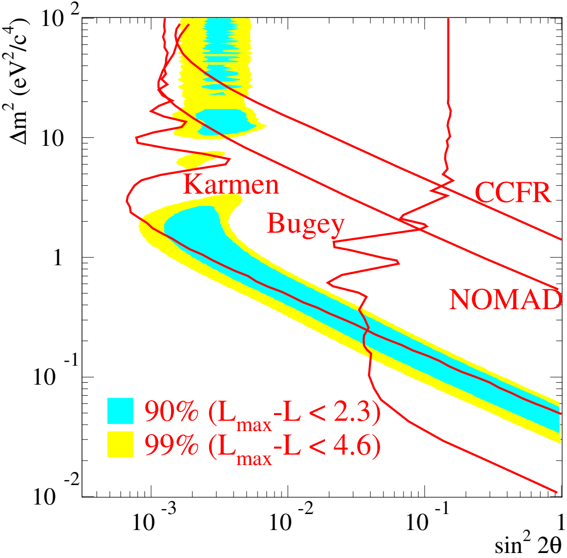
$L \simeq 30\,\text{m}$

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

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

- $\sim 4\sigma$ excess
- But signal not seen by KARMEN at $L \simeq 18\,\text{m}$ with the same method

[PRD 65 (2002) 112001]



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

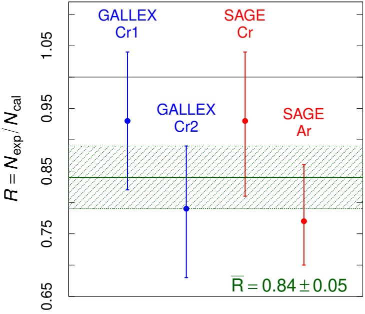
Gallium Anomaly

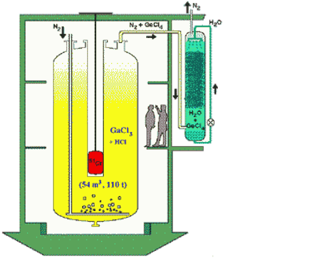
Gallium Radioactive Source Experiments: GALLEX and SAGE

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

$E \simeq 0.75\,\mathrm{MeV}$ $\qquad$ $E \simeq 0.81\,\mathrm{MeV}$

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





$\approx 2.9\sigma$ deficit

$\langle L \rangle_{\mathrm{GALLEX}} = 1.9\,\mathrm{m}$ $\qquad$ $\langle L \rangle_{\mathrm{SAGE}} = 0.6\,\mathrm{m}$

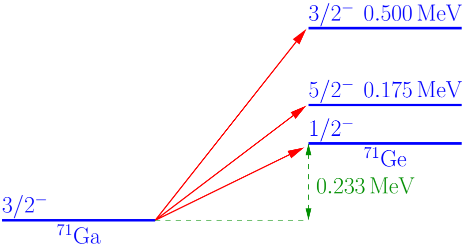
$\Delta m^2_{\mathrm{SBL}} \gtrsim 1\,\mathrm{eV}^2 \gg \Delta m^2_{\mathrm{ATM}}$

[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]

- Deficit could be due to an overestimate of

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

- First calculation: Bahcall, PRC 56 (1997) 3391

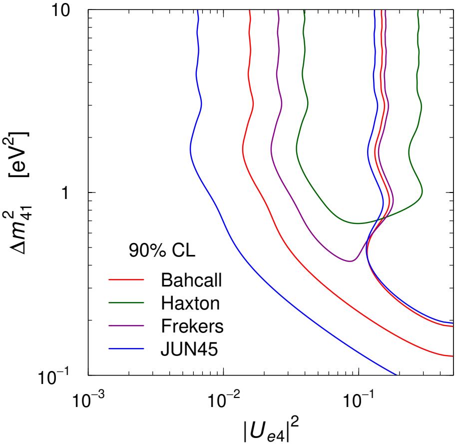


- $\sigma_{\text{G.S.}}$ from $T_{1/2}({}^{71}\text{Ge}) = 11.43 \pm 0.03\,\text{days}$ [Hampel, Remsberg, PRC 31 (1985) 666]

$$\sigma_{\text{G.S.}}({}^{51}\text{Cr}) = 55.3 \times 10^{-46}\,\text{cm}^2\,(1 \pm 0.004)_{3\sigma}$$

- $\sigma({}^{51}\text{Cr}) = \sigma_{\text{G.S.}}({}^{51}\text{Cr}) \left(1 + 0.669\,\frac{\text{BGT}_{175}}{\text{BGT}_{\text{G.S.}}} + 0.220\,\frac{\text{BGT}_{500}}{\text{BGT}_{\text{G.S.}}}\right)$

- The contribution of excited states is only $\sim 5\%$, but it is crucial for the size of the Gallium anomaly!



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

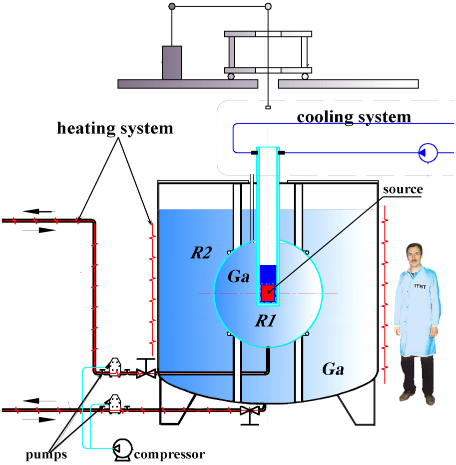
	$\sigma(^{51}\mathrm{Cr})$	$\sigma(^{37}\mathrm{Ar})$
Bahcall	5.81 ± 0.16	7.00 ± 0.21
Haxton	6.39 ± 0.65	7.72 ± 0.81
Frekers	5.92 ± 0.11	7.15 ± 0.14
JUN45	5.67 ± 0.06	6.80 ± 0.08

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

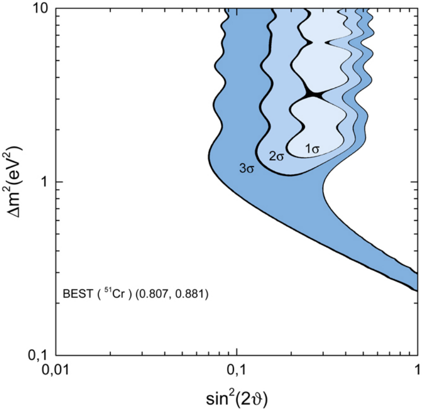
BEST

[arXiv:1006.2103, arXiv:1602.03826, arXiv:1710.06326, arXiv:1807.02977, arXiv:1905.07437]

Direct test of the Gallium anomaly with ^{51}Cr source.



$$R_1 = 0.66\,\mathrm{m}, \quad R_2 = 1.096\,\mathrm{m}$$



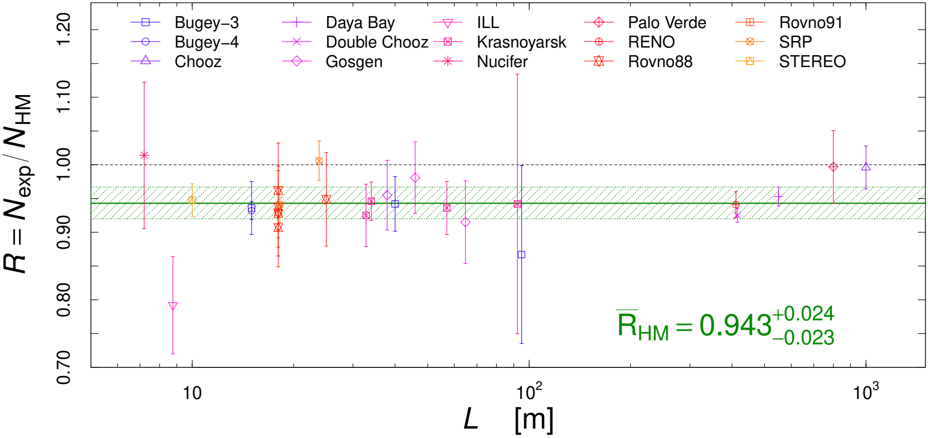
Allowed regions of oscillations parameters if the result of the BEST experiment corresponds to the best fit point for combining the SAGE + GALLEX. The numbers in parentheses indicate the most probable ratios R of observed-to-expected without sterile neutrinos germanium atoms in the two vessels.

Reactor Electron Antineutrino Anomaly

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

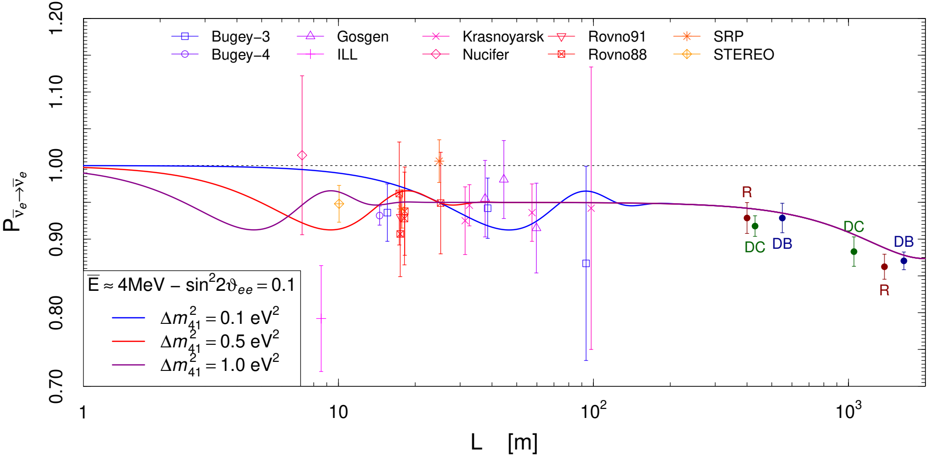
2011: new reactor $\bar{\nu}_e$ fluxes: Huber-Mueller (HM)

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



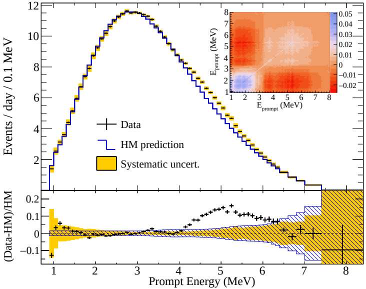
$\approx 2.4\,\sigma$ deficit $\Longrightarrow$ Anomaly!

Short-Baseline Reactor Neutrino Oscillations

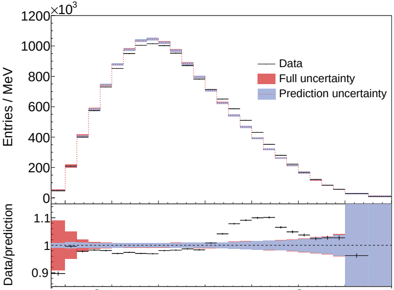


- $\Delta m^2_{\mathrm{SBL}} \gtrsim 0.5\,\mathrm{eV}^2 \gg \Delta m^2_{\mathrm{ATM}}$
- SBL oscillations are averaged at the Daya Bay, RENO, and Double Chooz near detectors $\Longrightarrow$ no spectral distortion
- The reactor antineutrino anomaly is model dependent (depends on the theoretical reactor neutrino flux calculation; is it reliable?).

Reactor Antineutrino 5 MeV Bump (Shoulder)



[RENO, arXiv:2010.14989]



[Daya Bay, arXiv:1904.07812]

- Discovered in 2014 by RENO, Double Chooz, Daya Bay.
- 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:

    recent HKSS flux calculation

    [Hayen, Kostensalo, Severijns, Suhonen, arXiv:1908.08302]
  - If it is a 1-4 MeV suppression it decreases the anomaly:

    recent EF flux calculation

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

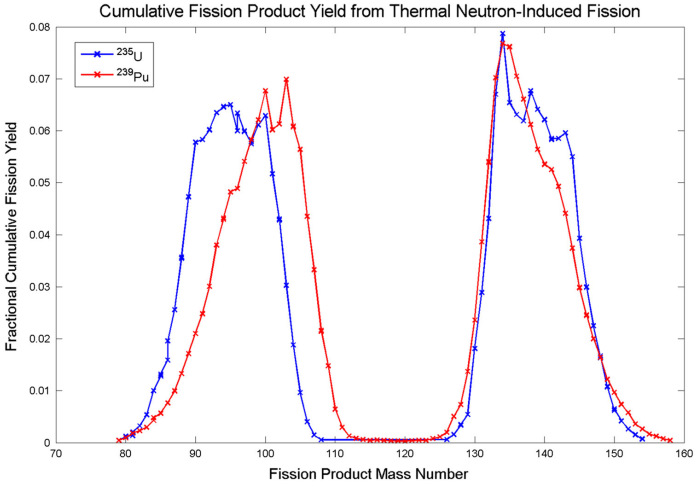
    new KI ^{235}U flux renormalization

    [Kopeikin, Skorokhvatov, Titov, arXiv:2103.01684]

Reactor $\bar{\nu}_e$ Flux Calculation

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

^{235}U $\quad$ ^{238}U $\quad$ ^{239}Pu $\quad$ ^{241}Pu



[Dayman, Biegalski, Haas, Rad. Nucl. Chem. 305 (2015) 213]

- For each allowed β decay the electron spectrum is

$$S_\beta(E_e) = K p_e E_e (E_e - E_0)^2 F(Z, E_e) \qquad (E_\nu = E_0 - E_e)$$

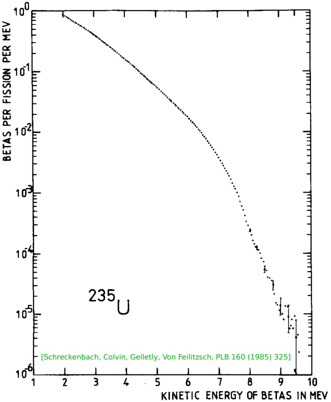
$$S_\nu(E_\nu) = K \sqrt{(E_0 - E_e)^2 - m_e^2}\,(E_0 - E_e)\, E_\nu^2 F(Z, E_e)$$

- Aggregate reactor spectrum (electron or neutrino):

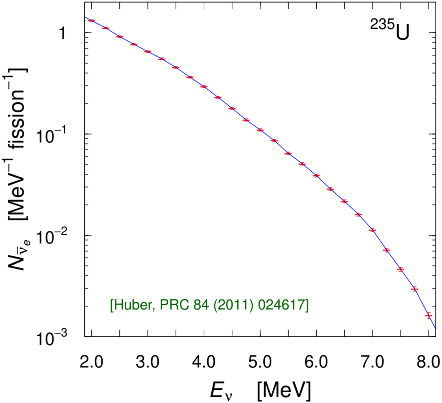
$$S_{\mathrm{tot}}(E, t) = \sum_k \underset{\substack{\uparrow \\ \text{fission fractions}}}{F_k(t)}\, S_k(E) \qquad (k = 235, 238, 239, 241)$$

$$S_k(E) = \sum_n \underset{\substack{\uparrow \\ \text{cumulative} \\ \text{fission} \\ \text{yield}}}{Y_n^k} \sum_b \underset{\substack{\uparrow \\ \text{branching} \\ \text{ratio}}}{\mathrm{BR}_n^b}\; S_n^b(E) \leftarrow \begin{array}{c}\text{allowed or} \\ \text{forbidden} \\ \text{decay} \\ \text{spectrum}\end{array}$$

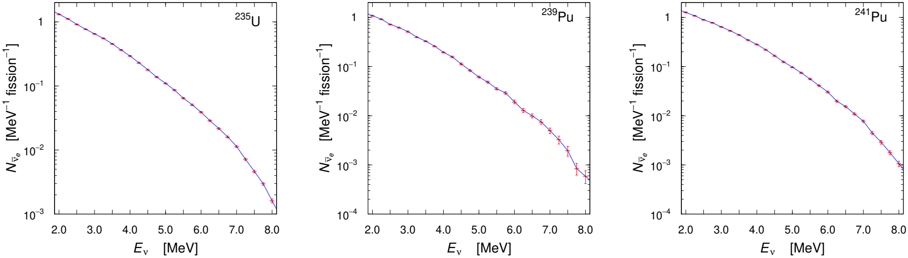
- The *ab initio* calculation of each $S_k^{\nu}(E_{\nu})$ requires knowledge of about 1000 spectra and branching ratios $(k = 235, 238, 239, 241)$.
- Nuclear data tables are incomplete and sometimes inexact.
- Semi-empirical method: conversion of the aggregate β spectra $S_k^{\beta}(E_e)$ measured at ILL in the 80's with ~ 30 virtual β branches.



$\Longrightarrow$



- In the 80's Schreckenbach et al. measured the aggregate β spectra of ^{235}U, ^{239}Pu, and ^{241}Pu exposing thin foils to the thermal neutron flux of the ILL reactor in Grenoble.
- The standard reactor $\bar{\nu}_e$ fluxes and spectra from ^{235}U, ^{239}Pu, and ^{241}Pu were obtained with the virtual-branches conversion method:



[Huber, PRC 84 (2011) 024617]

- The conversion method was estimated to have about 1% uncertainty.

[Vogel, PRC 76 (2007) 025504]

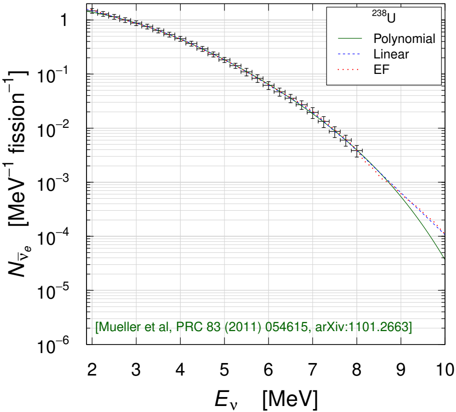
- Estimated total uncertainties on the neutrino detection rates:

$$2.4\%(^{235}\mathrm{U}) \qquad 2.9\%(^{239}\mathrm{Pu}) \qquad 2.6\%(^{241}\mathrm{Pu})$$

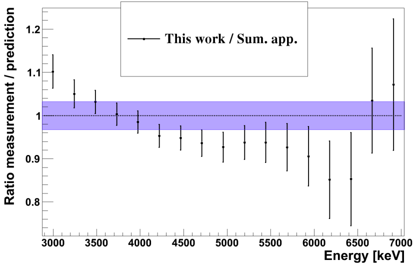
- The ^{238}U $\bar{\nu}_e$ flux was calculated ab initio with estimated 8% uncertainty.

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

- Approximate agreement with the 2014 β spectrum measurement at FRM II in Garching using a fast neutron beam. [Haag et al, PRL 112 (2014) 122501]



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



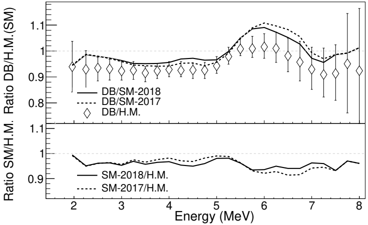
[Haag et al, PRL 112 (2014) 122501]

Updated Summation Model: An Improved Agreement with the Daya Bay Antineutrino Fluxes

M. Estienne,[1,*] M. Fallot,[1] A. Algora,[2,3] J. Briz-Monago,[1] V. M. Bui,[1] S. Cormon,[1] W. Gelletly,[4] L. Giot,[1] V. Guadilla,[1] D. Jordan,[2] L. Le Meur,[1] A. Porta,[1] S. Rice,[4] B. Rubio,[2] J. L. Taín,[2] E. Valencia,[2] and A.-A. Zakari-Issoufou[1]

[1]*SUBATECH, IMT Atlantique, Université de Nantes, CNRS-IN2P3, F-44307 Nantes, France*
[2]*Instituto de Física Corpuscular, CSIC-Universitat de València, E-46071 València, Spain*
[3]*Institute of Nuclear Research of the Hungarian Academy of Sciences, H-4026 Debrecen, Hungary*
[4]*Department of Physics, University of Surrey, GU2 7XH Guildford, United Kingdom*

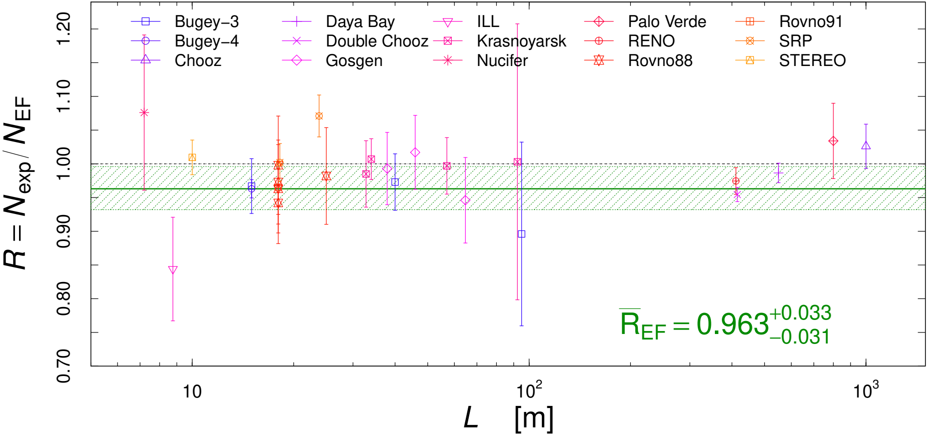
A new summation method model of the reactor antineutrino energy spectrum is presented. It is updated with the most recent evaluated decay databases and with our total absorption gamma-ray spectroscopy measurements performed during the last decade. For the first time, the spectral measurements from the Daya Bay experiment are compared with the antineutrino energy spectrum computed with the updated summation method without any renormalization. The results exhibit a better agreement than is obtained with the Huber-Mueller model in the 2–5 MeV range, the region that dominates the detected flux. A systematic trend is found in which the antineutrino flux computed with the summation model decreases with the inclusion of more pandemonium-free data. The calculated flux obtained now lies only 1.9% above that detected in the Daya Bay experiment, a value that may be reduced with forthcoming new pandemonium-free data, leaving less room for a reactor anomaly. Eventually, the new predictions of individual antineutrino spectra for the ^{235}U, ^{239}Pu, ^{241}Pu, and ^{238}U are used to compute the dependence of the reactor antineutrino spectral shape on the fission fractions.



[arXiv:1904.09358]

2019: new ab initio reactor $\bar{\nu}_e$ fluxes: Estienne, Fallot, et al (EF)

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

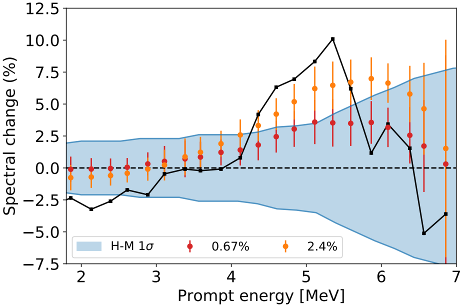


$\approx 1.1\,\sigma$ deficit $\Longrightarrow$ No Anomaly!

First-forbidden transitions in the reactor anomaly

L. Hayen,[1,*] J. Kostensalo,[2] N. Severijns,[1] and J. Suhonen[2]
[1]*Instituut voor Kern- en Stralingsfysica, KU Leuven, Celestijnenlaan 200D, B-3001 Leuven, Belgium*
[2]*Department of Physics, University of Jyväskylä, P.O. Box 35, FI-40014 University of Jyväskylä, Finland*

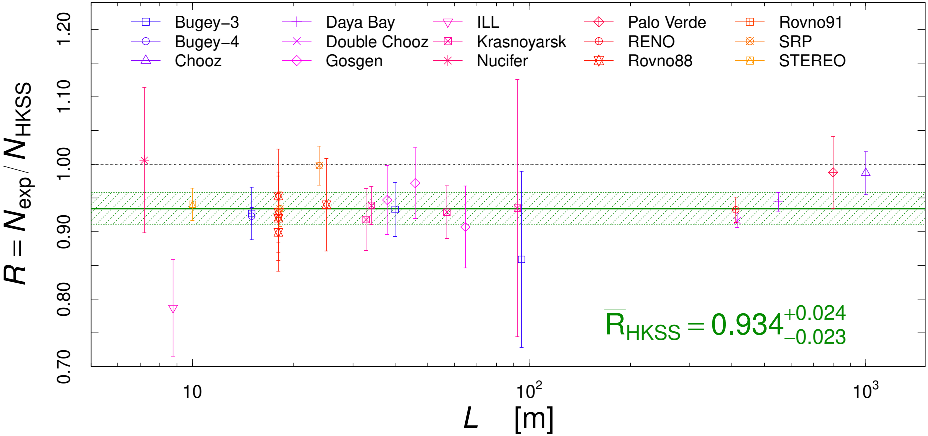
We describe here microscopic calculations performed on the dominant forbidden transitions in reactor antineutrino spectra above 4 MeV using the nuclear shell model. By taking into account Coulomb corrections in the most complete way, we calculate the shape factor with the highest fidelity and show strong deviations from allowed approximations and previously published results. Despite small differences in the *ab initio* electron cumulative spectra, large differences on the order of several percent are found in the antineutrino spectra. Based on the behavior of the numerically calculated shape factors we propose a parametrization of forbidden spectra. Using Monte Carlo techniques we derive an estimated spectral correction and uncertainty due to forbidden transitions. We establish the dominance and importance of forbidden transitions in both the reactor anomaly and spectral shoulder analysis with their respective uncertainties. Based on these results, we conclude that a correct treatment of forbidden transitions is indispensable in both the normalization anomaly and spectral shoulder.



[arXiv:1908.08302]

2019: new conversion reactor $\bar{\nu}_e$ fluxes: Hayen, Kostensalo, Severijns, Suhonen (HKSS)

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



$\approx 2.7\,\sigma$ deficit $\Longrightarrow$ Anomaly larger than the $\approx 2.4\,\sigma$ HM anomaly!

Reevaluating reactor antineutrino spectra with new measurements of the ratio between ^{235}U and ^{239}Pu β spectra

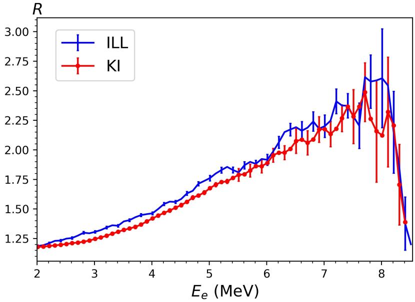
V. Kopeikin,[1] M. Skorokhvatov,[1,2] and O. Titov[1,*]

[1] *National Research Centre Kurchatov Institute, 123182, Moscow, Russia*

[2] *National Research Nuclear University MEPhI (Moscow Engineering Physics Institute), 115409, Moscow, Russia*

(Dated: March 3, 2021)

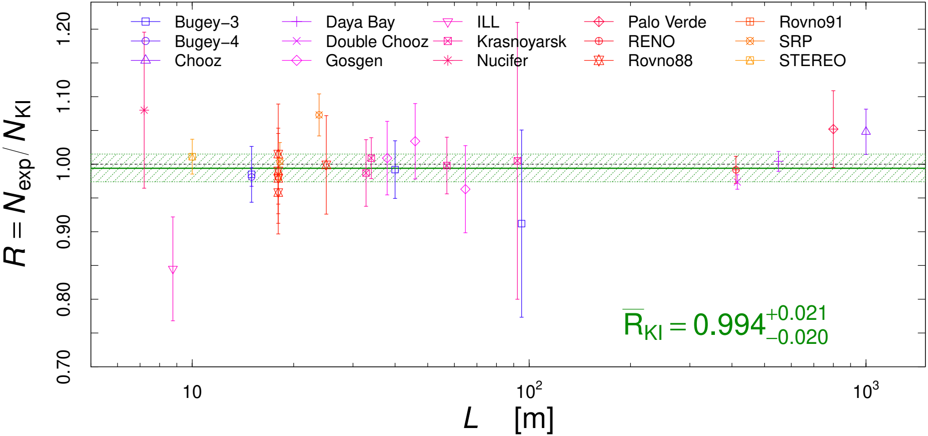
We report a reanalysis of the reactor antineutrino energy spectra based on the new relative measurements of the ratio $R = ^eS_5/^eS_9$ between cumulative β spectra from ^{235}U and ^{239}Pu, performed at a research reactor in National Research Centre Kurchatov Institute (KI). A discrepancy with the β spectra measured at Institut Laue-Langevin (ILL) was observed, indicating a steady excess of the ILL ratio by the factor of 1.054 ± 0.002. We find a value of the ratio between inverse beta decay cross section per fission for ^{235}U and ^{239}Pu: $(^5\sigma_f/^9\sigma_f)_{KI} = 1.45 \pm 0.03$, and then we reevaluate the converted antineutrino spectra for ^{235}U and ^{238}U. We conclude that the new predictions are consistent with the results of Daya Bay and STEREO experiments.



[arXiv:2103.01684]

2021: new converted reactor $\bar{\nu}_e$ fluxes: Kurchatov Institute (KI)

[Kopeikin, Skorokhvatov, Titov, arXiv:2103.01684]



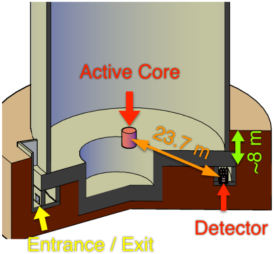
$\approx 0.3\,\sigma$ deficit $\Longrightarrow$ No Anomaly!

Approximate agreement with ab initio EF fluxes!

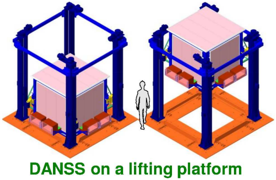
Model Indep. Measurements of Reactor ν Osc.

Ratios of spectra at different distances

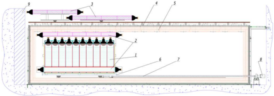
NEOS



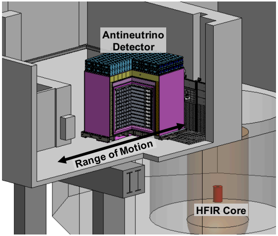
DANSS



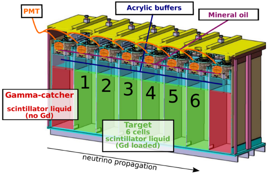
Neutrino-4



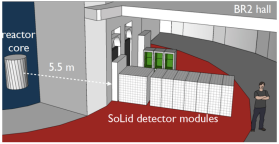
PROSPECT

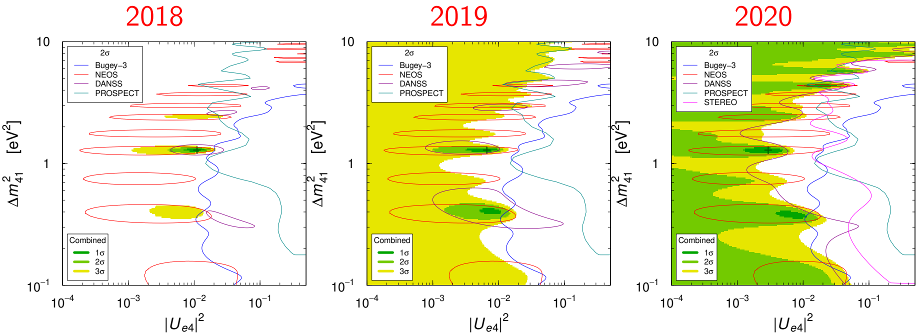


STEREO



SoLid





- 2018: remarkable agreement of the DANSS and NEOS best-fit regions at $\Delta m^2_{41} \approx 1.3\,\text{eV}^2 \Longrightarrow$ model independent indication in favor of SBL oscillations.

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

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

- 2019: decreased agreement between NEOS and DANSS allowed regions.

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

- 2020: No 2σ DANSS allowed regions (exclusion curve).
  No compelling indication of oscillations.
  In practice these reactor experiments exclude large values of $|U_{e4}|^2$ for

$$0.1 \lesssim \Delta m^2_{41} \lesssim 10\,\text{eV}^2$$

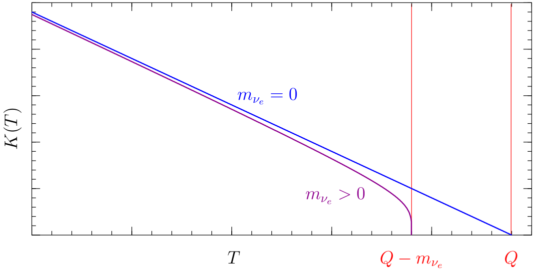
Tritium Beta-Decay

$$^3\text{H} \to {}^3\text{He} + e^- + \bar{\nu}_e$$

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

Kurie function: $K(T) = \left[(Q-T) \sqrt{(Q-T)^2 - m_{\nu_e}^2} \right]^{1/2}$

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



KATRIN

$\boxed{m_{\nu_e} < 1.1\,\text{eV} \quad (90\%\ \text{C.L.})}$

[arXiv:1909.06048]

$\boxed{m_{\nu_e} < 0.8\,\text{eV} \quad (90\%\ \text{C.L.})}$

[arXiv:2105.08533]

Expected final sensitivity:

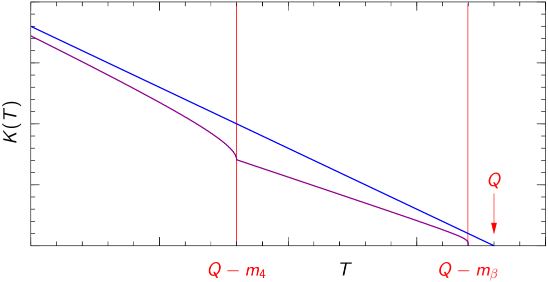
$m_{\nu_e} \approx 0.2\,\text{eV}$

Robust kinematical probe of $\nu_e - \nu_s$ mixing

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

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

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



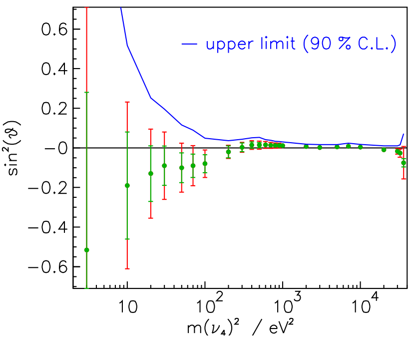
$$Q = M_{^3\mathrm{H}} - M_{^3\mathrm{He}} - m_e$$
$$= 18.58\,\mathrm{keV}$$

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

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

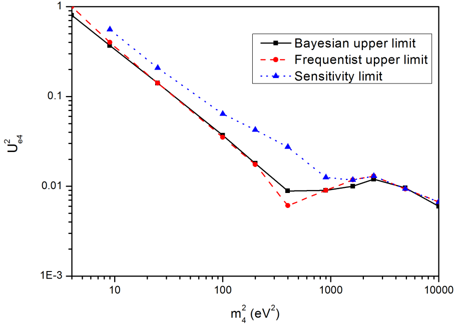
$$m_4 \gg m_{1,2,3} \quad \Longrightarrow \quad \Delta m^2_{41} \equiv m^2_4 - m^2_1 \simeq m^2_4$$

Mainz



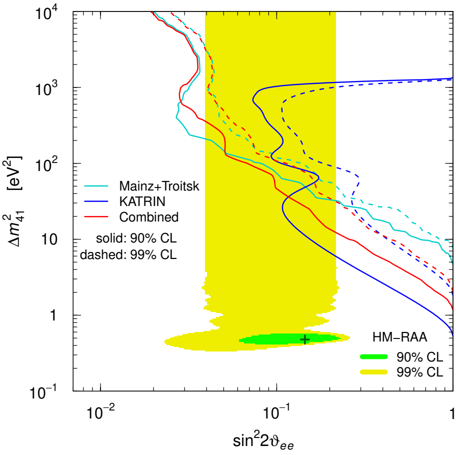
[Kraus, Singer, Valerius, Weinheimer, arXiv:1210.4194]

Troitsk

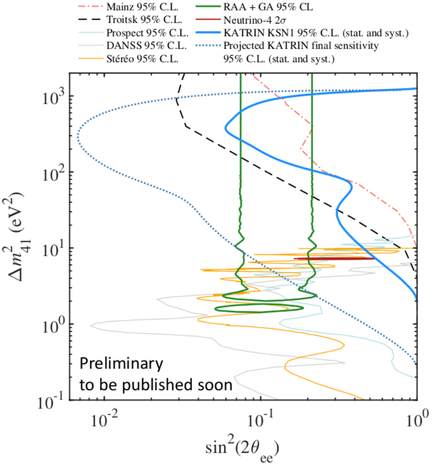


[Belesev et al, arXiv:1307.5687]

Bounds from first KATRIN data



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



[KATRIN @ Neutrino 2020]

[arXiv:2011.05087]

$$\Delta m^2_{41} \simeq m^2_4$$

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

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:

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

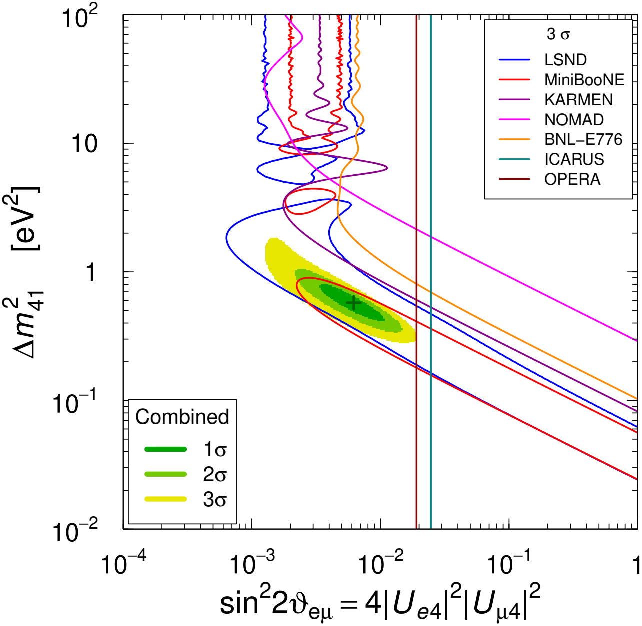
quadratically suppressed for small $|U_{e4}|^2$ and $|U_{\mu 4}|^2$

$\Downarrow$

Appearance-Disappearance Tension

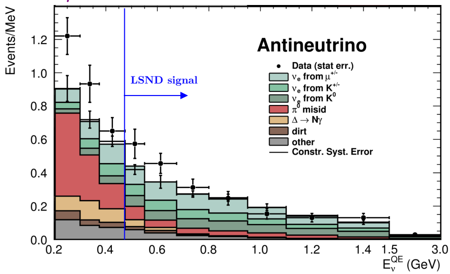
[Okada, Yasuda, IJMPA 12 (1997) 3669; Bilenky, CG, Grimus, EPJC 1 (1998) 247]

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

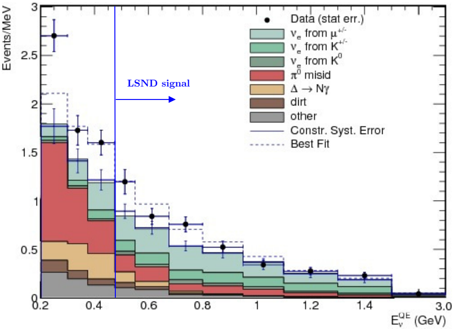


MiniBooNE

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



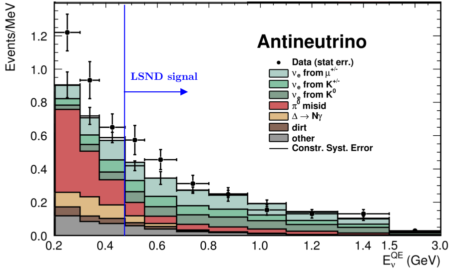
$\nu_\mu \to \nu_e$ [PRL 121 (2018) 221801]



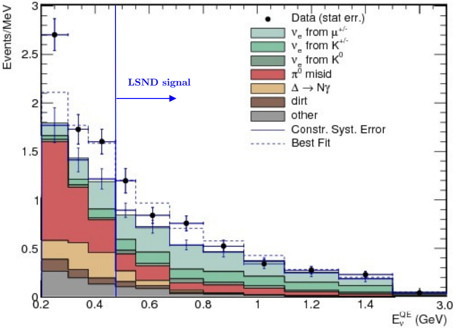
- Purpose: check the LSND signal
- Different $L \simeq 540\,\text{m}$
- Different $200\,\text{MeV} \leq E \lesssim 3\,\text{GeV}$
- Similar $L/E \Longrightarrow$ Oscillations Smoking Gun?
- No money, no Near Detector
- Large beam-related background
- Large flux and cross section uncertainties

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

$$E \lesssim 450\,\text{MeV}$$

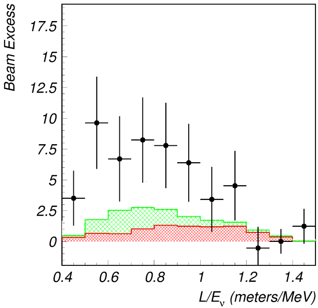
MiniBooNE low-energy anomaly

Maybe due to additional $\Delta \to N\gamma$ background?

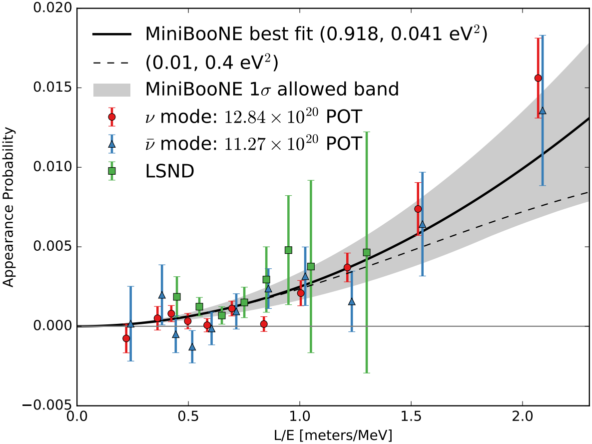
[Ioannisian et al, arXiv:1909.08571, arXiv:1912.01524]

To be checked by MicroBooNE@FNAL?

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

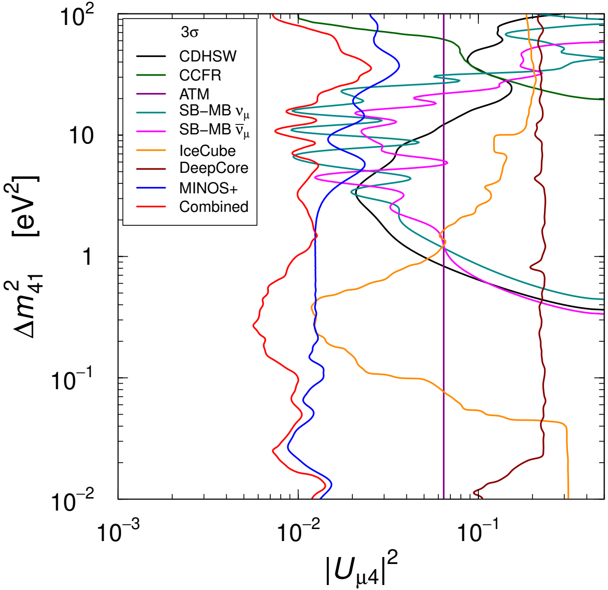


[LSND, PRD 64 (2001) 112007]



[MiniBooNE, PRL 121 (2018) 221801]

ν_μ and $\bar{\nu}_\mu$ Disappearance

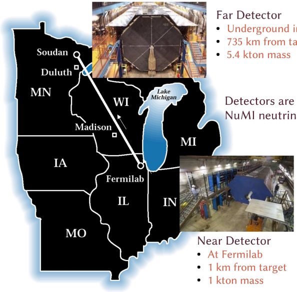


MINOS+

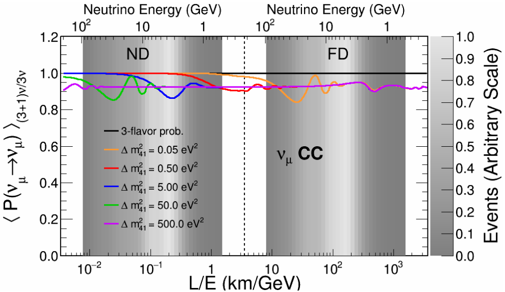
Far Detector
- Underground in Soudan mine
- 735 km from target
- 5.4 kton mass

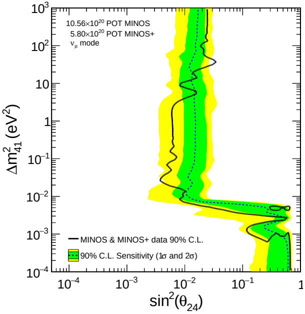
Detectors are on-axis for NuMI neutrino beam

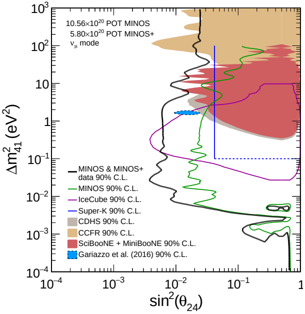
Near Detector
- At Fermilab
- 1 km from target
- 1 kton mass



[PRL 122 (2019) 091803, arXiv:1710.06488]







Global Appearance-Disappearance Tension

ν_e DIS

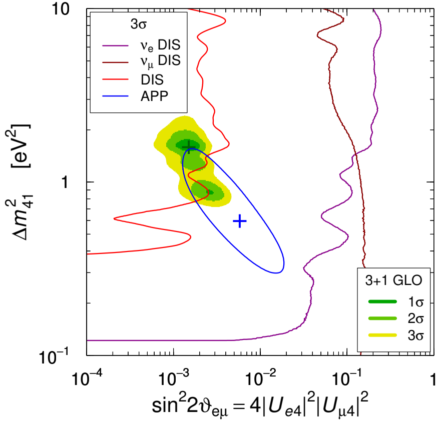
$\sin^2 2\vartheta_{ee} \simeq 4|U_{e4}|^2$

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!
- 2016 Global Fit:

  $\chi^2/\text{NDF} = 304.0/275$

  $\text{GoF} = 11\%$

  $\chi^2_{\text{PG}}/\text{NDF}_{\text{PG}} = 15.0/2$

  $\text{GoF}_{\text{PG}} = 6 \times 10^{-4}$ ← ☹
- Similar tension in

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

[CG, Zavanin, arXiv:1508.03172]

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 $\qquad N_{\text{P}}$ = 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

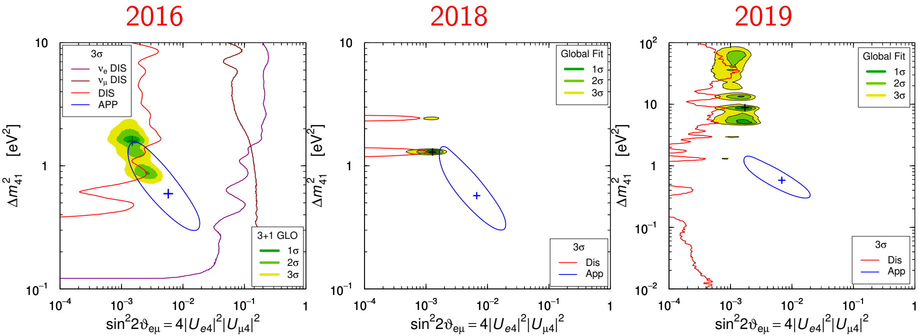
Maltoni, Schwetz, PRD 68 (2003) 033020 (arXiv:hep-ph/0304176)

- 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

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

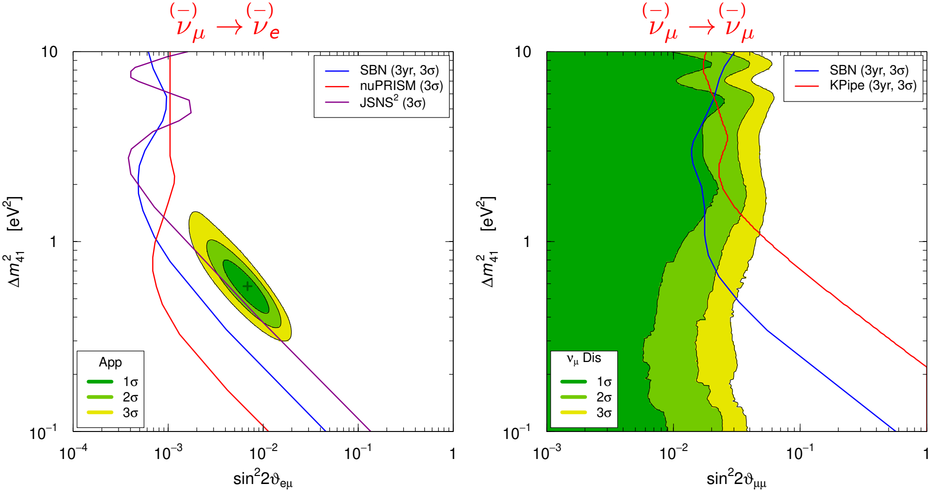
- $\text{PGoF} = \int_{\chi^2_{\text{PGoF}}}^{\infty} p_{\chi^2}(z, \text{NDF}_{\text{PGoF}})\, dz$

Global Appearance-Disappearance Tension



- 2016: Global Fit: $\mathrm{GoF_{PG}} \approx 6 \times 10^{-4}$ [arXiv:1602.01390, arXiv:1606.07673]
- 2018: Global Fit: $\mathrm{GoF_{PG}} \approx 2 \times 10^{-7}$ [arXiv:1801.06467, arXiv:1803.10661, arXiv:1901.08330]
- 2019: Global Fit: $\mathrm{GoF_{PG}} \approx 7 \times 10^{-11}$

New Dedicated Experiments



Effective 3+1 LBL Oscillation Probabilities

[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, JHEP 1602 (2016) 111, JHEP 1609 (2016) 016, PRL 118 (2017) 031804; Kayser et al, JHEP 1511 (2015) 039, JHEP 1611 (2016) 122; Capozzi et al, PRD 95 (2017) 033006]

$$|U_{e3}| \simeq \sin\vartheta_{13} \simeq 0.15 \sim \varepsilon \quad \Longrightarrow \quad \varepsilon^2 \sim 0.03$$

$$|U_{e4}| \simeq \sin\vartheta_{14} \simeq 0.17 \sim \varepsilon$$

$$|U_{\mu 4}| \simeq \sin\vartheta_{24} \simeq 0.11 \sim \varepsilon$$

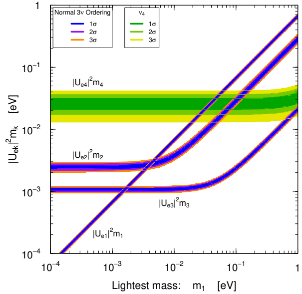
$$\alpha \equiv \frac{\Delta m^2_{21}}{|\Delta m^2_{31}|} \simeq \frac{7 \times 10^{-5}}{2.4 \times 10^{-3}} \simeq 0.031 \sim \varepsilon^2$$

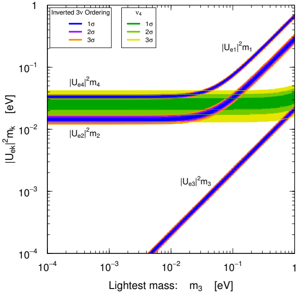
At order ε^3: [Klop, Palazzo, PRD 91 (2015) 073017] $\Delta_{kj} \equiv \Delta m^2_{kj} L/4E$

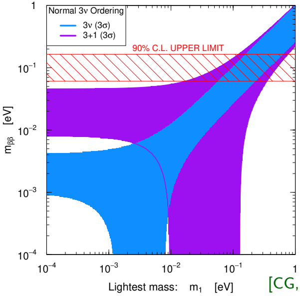
$$\begin{aligned}
P^{\text{LBL}}_{\nu_\mu\to\nu_e} \simeq\ & 4\sin^2\vartheta_{13}\sin^2\vartheta_{23}\sin^2\Delta_{31} && \sim \varepsilon^2 \\
& +2\sin\vartheta_{13}\sin 2\vartheta_{12}\sin 2\vartheta_{23}(\alpha\Delta_{31})\sin\Delta_{31}\cos(\Delta_{32}+\delta_{13}) && \sim \varepsilon^3 \\
& +4\sin\vartheta_{13}\sin\vartheta_{14}\sin\vartheta_{24}\sin\vartheta_{23}\sin\Delta_{31}\sin(\Delta_{31}+\delta_{13}-\delta_{14}) && \sim \varepsilon^3
\end{aligned}$$

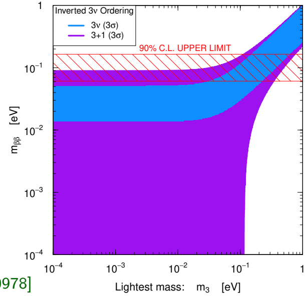
Neutrinoless Double-Beta Decay

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









[CG, Zavanin, arXiv:1505.00978]

2016 (incomplete) list of papers on non-SBL effects of light sterile neutrinos:

- β Decay Experiments
  [Hannestad et al, JCAP 1102 (2011) 011, PRC 84 (2011) 045503; Formaggio, Barrett, PLB 706 (2011) 68; Esmaili, Peres, PRD 85 (2012) 117301; Gastaldo et al, JHEP 1606 (2016) 061]
- Neutrinoless Double-β Decay Experiments
  [Rodejohann et al, JHEP 1107 (2011) 091; Li, Liu, PLB 706 (2012) 406; Meroni et al, JHEP 1311 (2013) 146, PRD 90 (2014) 053002; Pascoli et al, PRD 90 (2014) 093005; CG, Zavanin, JHEP 1507 (2015) 171; Guzowski et al, PRD 92 (2015) 012002]
- Long-baseline Neutrino Oscillation Experiments
  [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, JHEP 1602 (2016) 111, JHEP 1609 (2016) 016, PRL 118 (2017) 031804; Kayser et al, JHEP 1511 (2015) 039, JHEP 1611 (2016) 122; Pant et al, NPB 909 (2016) 1079, Choubey, Pramanik, PLB 764 (2017) 135]
- Solar neutrinos
  [Dooling et al, PRD 61 (2000) 073011, Gonzalez-Garcia et al, PRD 62 (2000) 013005; Palazzo, PRD 83 (2011) 113013, PRD 85 (2012) 077301; Li et al, PRD 80 (2009) 113007, PRD 87, 113004 (2013), JHEP 1308 (2013) 056; Kopp et al, JHEP 1305 (2013) 050]
- Atmospheric neutrinos
  [Goswami, PRD 55 (1997) 2931; Bilenky et al, PRD 60 (1999) 073007; Maltoni et al, NPB 643 (2002) 321, PRD 67 (2003) 013011; Choubey, JHEP 0712 (2007) 014; Razzaque, Smirnov, JHEP 1107 (2011) 084, PRD 85 (2012) 093010; Gandhi, Ghoshal, PRD 86 (2012) 037301; Barger et al, PRD 85 (2012) 011302; Esmaili et al, JCAP 1211 (2012) 041, JCAP 1307 (2013) 048, JHEP 1312 (2013) 014; Rajpoot et al, EPJC 74 (2014) 2936; Lindner et al, JHEP 1601 (2016) 124; Behera et al, arXiv:1605.08607]
- Supernova neutrinos
  [Caldwell, Fuller, Qian, PRD 61 (2000) 123005; Peres, Smirnov, NPB 599 (2001); Sorel, Conrad, PRD 66 (2002) 033009; Tamborra et al, JCAP 1201 (2012) 013; Wu et al, PRD 89 (2014) 061303; Esmaili et al, PRD 90 (2014) 033013]
- Cosmic neutrinos
  [Cirelli et al, NPB 708 (2005) 215; Donini, Yasuda, arXiv:0806.3029; Barry et al, PRD 83 (2011) 113012]
- Indirect dark matter detection [Esmaili, Peres, JCAP 1205 (2012) 002]
- Cosmology [see: Wong, ARNPS 61 (2011) 69; Archidiacono et al, AHEP 2013 (2013) 191047]

Alternative Explanations of MiniBooNE

- Generation by a particle X produced in the MiniBooNE target is excluded by the angular distribution of the ν_e-like events, that is not strongly forward peaked.

[Jordan, Kahn, Krnjaic, Moschella, Spitz, PRL 122 (2019) 081801]

- Visible decays:

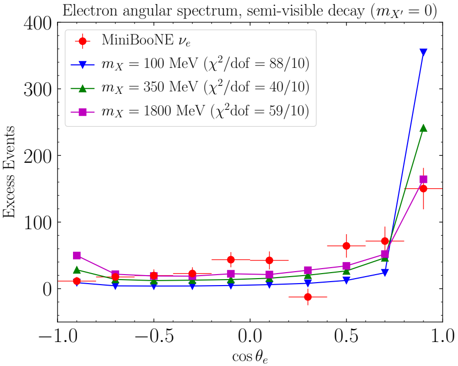
$$X \to e^+ e^- \text{ or } X \to \gamma\gamma$$

$$\cos\theta_e > 0.9999$$

- Semi-visible decay:

$$X \to X' + p_{\text{EM}}$$

$\longrightarrow$



Heavy Neutrino Generation in the Detector

- Neutrino Neutral-Current Weak Interaction Lagrangian:

$$\mathscr{L}_{\text{I}}^{(\text{NC})} = -\frac{g}{2\cos\vartheta_{\text{W}}} Z_\rho \sum_{\alpha=e,\mu,\tau} \overline{\nu_{\alpha L}} \gamma^\rho \nu_{\alpha L}$$

- Sterile neutrinos: $\nu_{\alpha L} = \sum_{k=1}^{3+N_s} U_{\alpha k} \nu_{kL} \qquad (\alpha = e, \mu, \tau, s_1, \ldots, s_{N_s})$

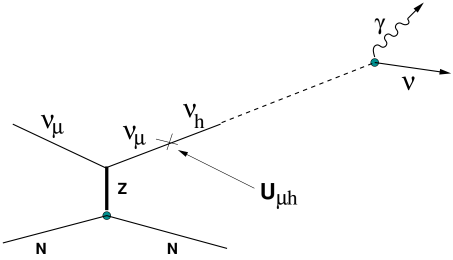
- No GIM: $\mathscr{L}_{\text{I}}^{(\text{NC})} = -\frac{g}{2\cos\vartheta_{\text{W}}} Z_\rho \sum_{j=1}^{3+N_s} \sum_{k=1}^{3+N_s} \overline{\nu_{jL}} \gamma^\rho \nu_{kL} \sum_{\alpha=e,\mu,\tau} U_{\alpha j}^* U_{\alpha k}$

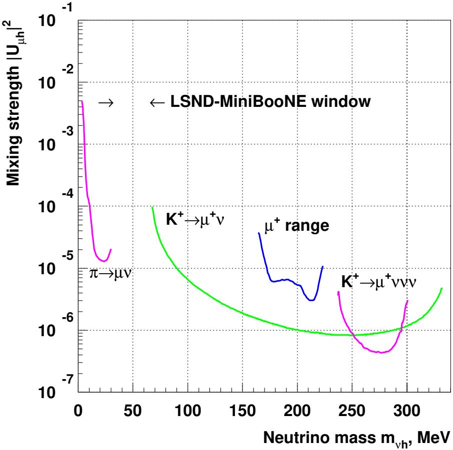
- $\sum_{\alpha=e,\mu,\tau,s_1,\ldots} U_{\alpha j}^* U_{\alpha k} = \delta_{jk}$ but $\sum_{\alpha=e,\mu,\tau} U_{\alpha j}^* U_{\alpha k} \neq \delta_{jk}$

- A heavy neutrino ν_h with $h \geq 4$ can be generated in the detector by neutral-current ν_μ scattering.

Heavy Sterile Neutrino Radiative Decay

[Gninenko, PRL 103 (2009) 241802, PRD 83 (2011) 015015, PRD 83 (2011) 093010, PLB 710 (2012) 86]





It may explain also LSND with

$$m_{\nu_h} \approx 40 - 80\,\text{MeV}$$

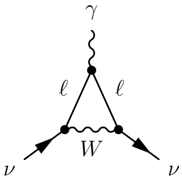
and

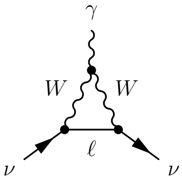
$$|U_{\mu h}|^2 \approx 10^{-3} - 10^{-2}$$

- It needs a fast radiative decay $\tau_{\nu_h} \lesssim 10^{-9}\,\text{s}$ that can be generated by a transition magnetic moment $|\mu_{hi}| \gtrsim 10^{-8}\,\mu_{\text{B}}$:

$$\Gamma_{\nu_h \to \nu_i + \gamma} = \frac{|\mu_{hi}|^2}{8\pi} m_{\nu_h}^3 \left(1 - \frac{m_{\nu_i}^2}{m_{\nu_h}^2}\right)^3$$

- Simplest extensions of the Standard Model:





$$|\mu_{hi}| \sim 10^{-11}\,\mu_{\text{B}} \frac{m_{\nu_h}}{100\,\text{MeV}} |U_{\ell h}| \sim 10^{-12}\,\mu_{\text{B}} \qquad \text{not enough}$$

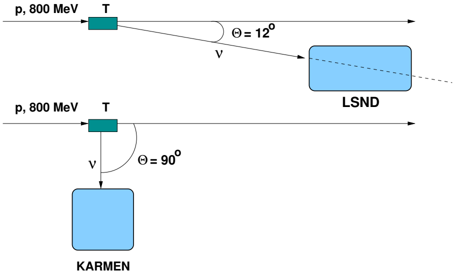
- More exotic extensions of the Standard Model may give the needed

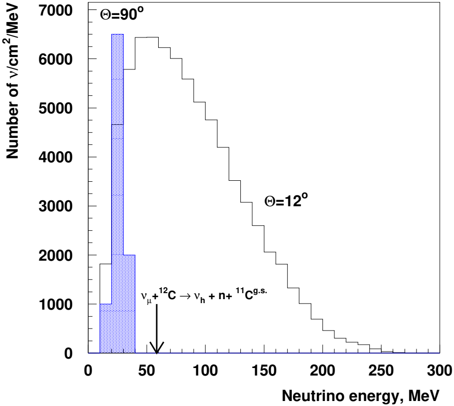
$$|\mu_{hi}| \gtrsim 10^{-8}\,\mu_{\text{B}}$$

- It is interesting that this mechanism can explain why the LSND signal was not observed in KARMEN:

ν_μ from π^+ decay in flight

$$\nu_\mu + {}^{12}\mathrm{C} \to \nu_h + {}^{11}\mathrm{C} + n$$



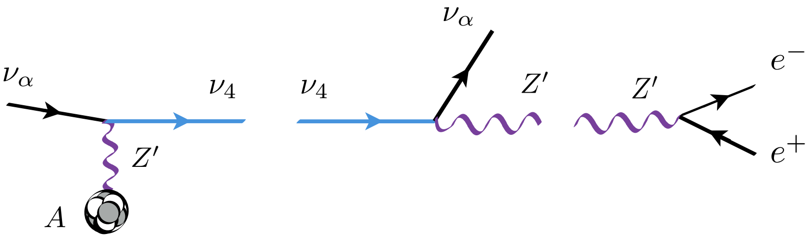


[Gninenko, PRD 83 (2011) 015015]

- This mechanism can be ruled out by Liquid Argon Time Projection Chamber (LArTPC) detectors that distinguish between electrons and photons: MicroBooNE, ICARUS, SBND (Fermilab Short-Baseline Neutrino Oscillation Program).

Interacting Heavy Sterile Neutrino

[Bertuzzo, Jana, Machado, Zukanovich Funchal, PRL 121 (2018) 241801]

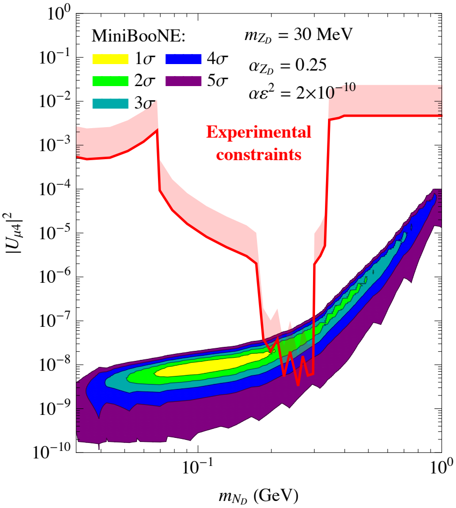


[Arguelles, Hostert, Tsai, arXiv:1812.08768]

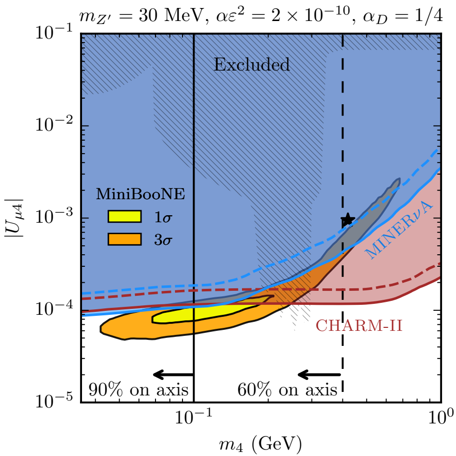
$$\mathcal{L} \supset \frac{m_{Z'}^2}{2} Z'_\mu Z'^\mu + g_\mathcal{D} Z'_\mu \overline{\nu}_s \gamma^\mu \nu_s + e\epsilon\, Z'^\mu\, J_\mu^{\mathrm{em}} + \frac{g}{c_W} \epsilon'\, Z'^\mu\, J_\mu^{\mathrm{Z}}$$

$$\Gamma_{\nu_4 \to Z' + \nu_\mu} = \frac{\alpha_\mathcal{D}}{2} |U_{\mu 4}|^2 \frac{m_{\nu_4}^3}{m_{Z'}^2} \left(1 - \frac{m_{Z'}^2}{m_{\nu_4}^2}\right) \left(1 + \frac{m_{Z'}^2}{m_{\nu_4}^2} - 2\frac{m_{Z'}^4}{m_{\nu_4}^4}\right)$$

$$\Gamma_{Z' \to e^+ e^-} \approx \frac{\alpha\, \epsilon^2}{3}\, m_{Z'}$$



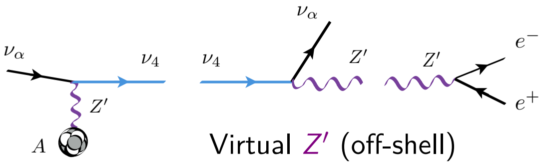
[Bertuzzo et al, PRL 121 (2018) 241801]

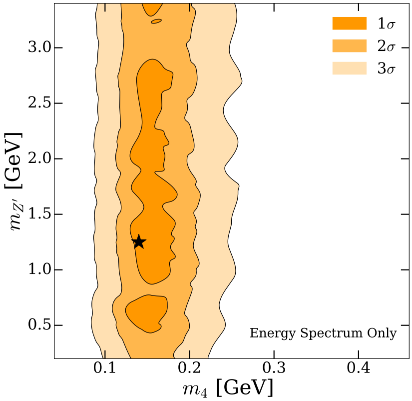


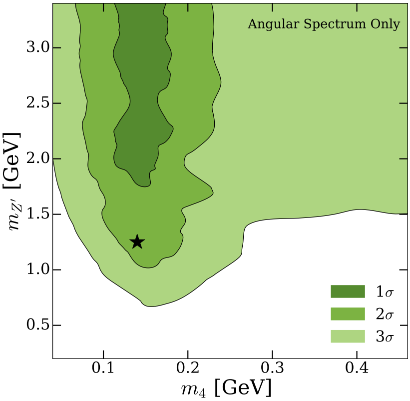
[Arguelles, Hostert, Tsai, arXiv:1812.08768]

Heavy New Gauge Boson

[Ballett, Pascoli, Ross-Lonergan, PRD 99 (2019) 071701]







Conclusions

- Light sterile neutrinos can be powerful messengers of new physics beyond the SM.
- Historically, their existence is motivated by the reactor, Gallium and LSND short-baseline anomalies.
- The reactor antineutrino anomaly, discovered in 2011, seems to be disappearing, because of new neutrino flux calculations and the absence of a clear model-independent signal in the new experiments (DANSS, PROSPECT, STEREO).
- The Gallium neutrino anomaly, discovered in 2007, is uncertain and needs a direct model-independent check.
- Important model-independent tests of the effect of m_4 in β-decay (KATRIN), electron-capture (ECHo, HOLMES) and $\beta\beta_{0\nu}$-decay experiments.

- 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 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 (ad hoc) 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.