Nuclear Reactor Neutrinos for BSM Physics

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Atomic nuclei as laboratories for BSM physics
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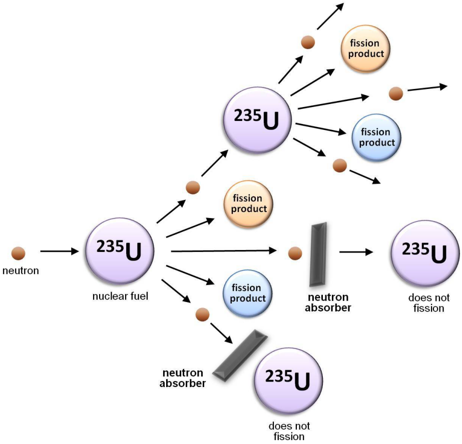
Reactor Neutrinos

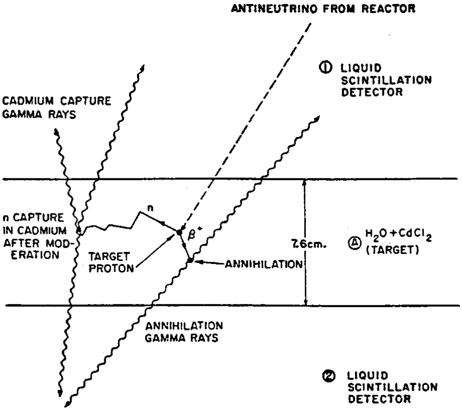
- Nuclear reactors are the most intense terrestrial sources of electron antineutrinos $\bar{\nu}_e$



- $n + {}^{235}\text{U} \to A + B + 2.5n + 6e^{-} + 6\bar{\nu}_e + 200\,\text{MeV}$

- $N_{\bar{\nu}_e} \simeq 2 \times 10^{20}\,\mathrm{s}^{-1}\,\mathrm{GW}_{\mathrm{th}}^{-1}$
- $\Phi_{\bar{\nu}_e} \simeq 1.6 \times 10^{13}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}\,\mathrm{GW}_{\mathrm{th}}^{-1}$ at 10 m
- Comparison: $\Phi_{\nu_e}^{\mathrm{Sun}} \simeq 6.4 \times 10^{10}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$ on Earth.
- Reactor Neutrinos are a great opportunity for Neutrino Physics!
- Indeed neutrinos were detected for the first time by Cowan and Reines in 1956 at the Savannah River nuclear reactor.
- Further advantages:
  - The $\bar{\nu}_e$ flux is under control: background measurement when reactor is off.
  - The $\bar{\nu}_e$ detection cross section is well-known.

Detection: Inverse beta Decay



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

Cowan and Reines 1956

- The delayed ($\lesssim 200\,\mu$s) neutron capture signal is crucial for the background suppression.
- Well-known cross section obtained by crossing from the neutron lifetime.
- Neutrino energy measurement: $E_{\bar{\nu}_e} \simeq T_e + 1.8\,\text{MeV}$

$$T_e = E_{\text{prompt}} - 2m_e$$

E_{prompt} is total visible prompt energy from positron annihilation

Nuclear Fuel

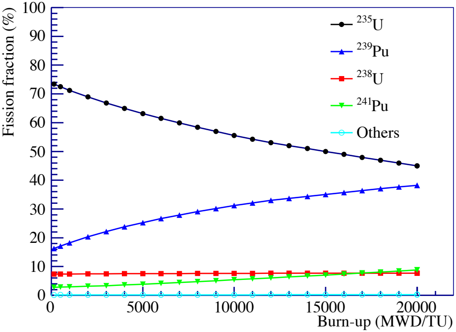
- Nuclear reactor energy is produced by the fissions of

  $$^{235}\mathrm{U} \qquad ^{238}\mathrm{U} \qquad ^{239}\mathrm{Pu} \qquad ^{241}\mathrm{Pu}$$

- ^{235}U, ^{239}Pu, and ^{241}Pu are fissile nuclides, i.e capable of sustaining a nuclear fission chain reaction.
- They have large fission cross section and small neutron capture cross section for slow "thermal" neutrons ($E_n \approx 0.025\,\mathrm{eV}$).
- ^{238}U can be fissioned by the fast neutrons ($E_n \approx 2\,\mathrm{MeV}$) emitted in fissions but it has a small fission cross section and a large neutron capture cross section.
- ^{235}U is the only natural fissile nuclide. Natural Uranium: 0.72% of ^{235}U.
- Neutrons are slowed down by the moderator (H_2O, D_2O, C).
- In typical light water reactors (LWR) the moderator is H_2O that has a significant neutron capture cross section.
- LWR use Low Enriched Uranium (LEU) with 3-5% of ^{235}U to sustain the nuclear chain reactions.

Commercial Light Water Reactors

- In a commercial LWR nuclear power plant as Daya Bay a reactor burning cycle (18 months) starts with the replacement of 1/3 of the fuel elements with fresh LEU.



[Daya Bay, Chin. Phys. C 41 (2017) 013002]

- ^{239}Pu is generated from ^{238}U:

$$\begin{array}{l} n + {}^{238}\mathrm{U} \to {}^{239}\mathrm{U} + \gamma \\ \qquad\qquad\qquad\ \downarrow \\ \qquad\qquad\qquad {}^{239}\mathrm{Np} + e^- + \bar{\nu}_e \\ \qquad\qquad\qquad\ \downarrow \\ \qquad\qquad\qquad {}^{239}\mathrm{Pu} + e^- + \bar{\nu}_e \end{array}$$

- ^{241}Pu is generated from ^{239}Pu:

$$n + {}^{239}\mathrm{Pu} \to {}^{240}\mathrm{Pu} + \gamma$$
$$n + {}^{240}\mathrm{Pu} \to {}^{241}\mathrm{Pu} + \gamma$$

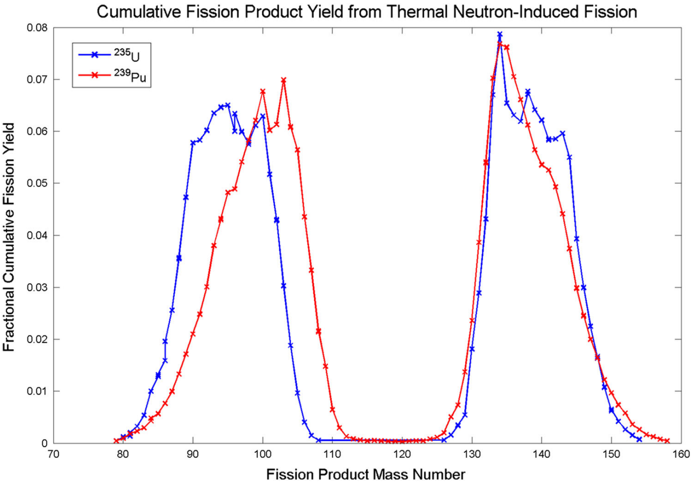
Research Reactors

- Optimized as neutron sources for testing of materials and production of radioisotopes.
- Use Highly Enriched Uranium (HEU): about 93% of $^{235}\mathrm{U}$ (weapons grade).
- The burning cycle is short (about 1 month), minimizing the production of $^{239}\mathrm{Pu}$ and $^{241}\mathrm{Pu}$.
- The $^{235}\mathrm{U}$ fission fraction is larger than 99%.
- Small core sizes (good for neutrino oscillation measurements).
- The frequent reactor-off periods during refueling allow a precise background determination.

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

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

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



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

- For each allowed β decay the electron spectrum is

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

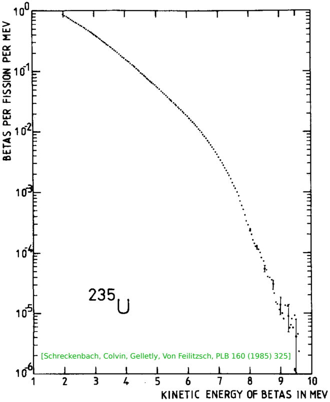
$$S_\nu(E_\nu) = K \sqrt{(E_0 - E_e)^2 - m_e^2}\,(E_0 - E_e)\, E_\nu^2 F(Z, E_e)$$

- Aggregate reactor spectrum (electron or neutrino):

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

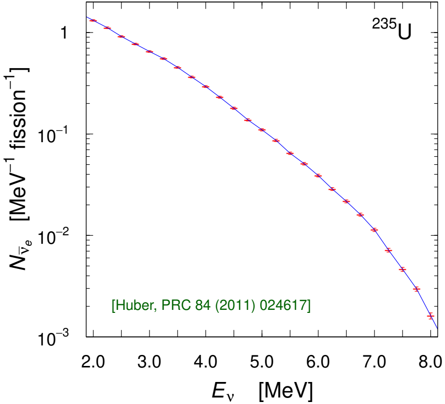
$$S_k(E) = \sum_n \underset{\substack{\uparrow \\ \text{cumulative} \\ \text{fission yield}}}{Y_n^k} \sum_b \text{BR}_n^b\, S_n^b(E)$$

- 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.



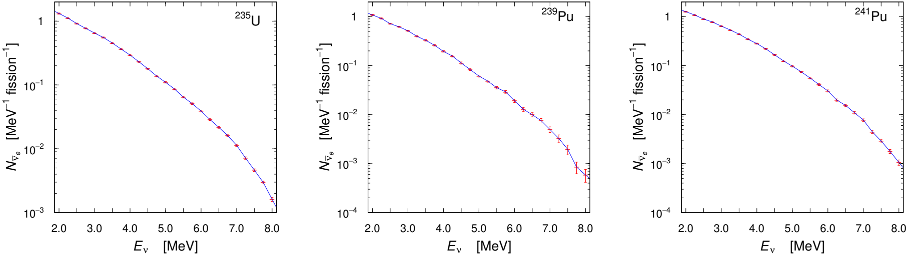
[Schreckenbach, Colvin, Gelletly, Von Feilitzsch, PLB 160 (1985) 325]

$\Longrightarrow$



[Huber, PRC 84 (2011) 024617]

- 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]

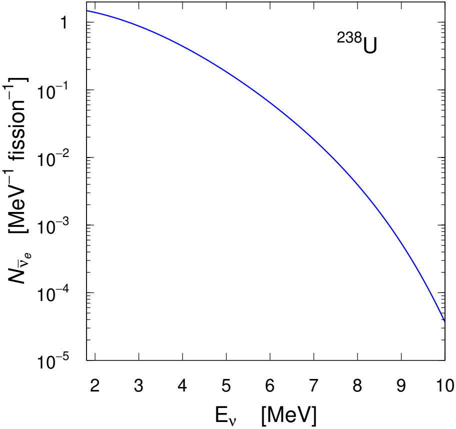
- Estimated total uncertainties on the neutrino detection rates:

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

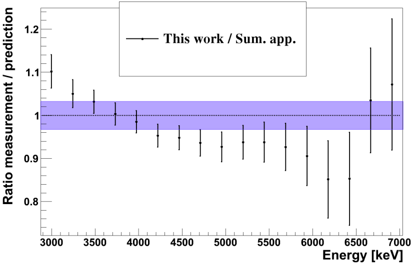
- The ^{238}U $\bar{\nu}_e$ flux was calculated ab initio with estimated 8% uncertainty.

  [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]



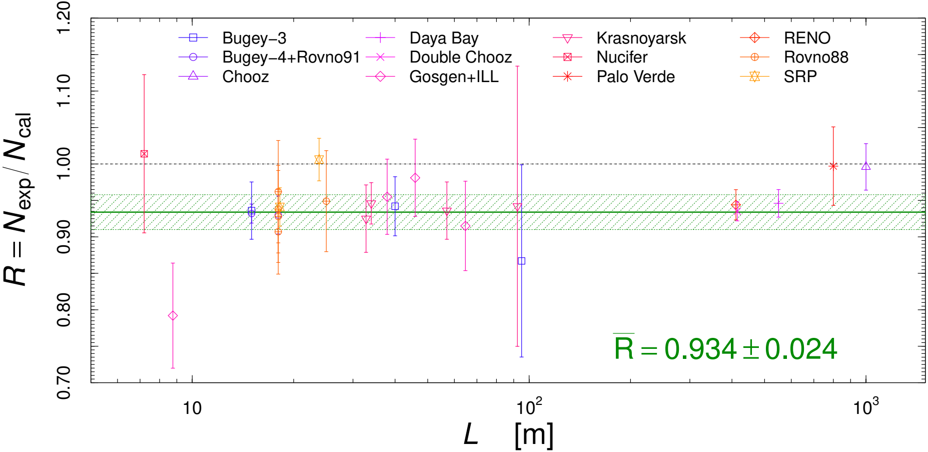
[Haag et al, PRL 112 (2014) 122501]

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

- The Reactor Electron Antineutrino Anomaly can be due to Neutrino Oscillations that generate the disappearance of reactor $\bar{\nu}_e$.

Standard Three Neutrino Mixing

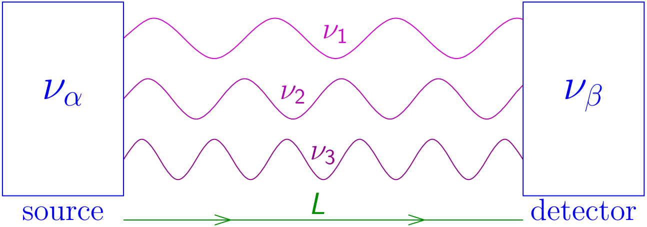
- Flavor Neutrinos: ν_e, ν_μ, ν_τ produced in Weak Interactions
- Massive Neutrinos: ν_1, ν_2, ν_3 propagate from Source to Detector
- Neutrino Mixing: a Flavor Neutrino is a superposition of Massive Neutrinos

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

- U is the 3×3 unitary Neutrino Mixing Matrix

Neutrino Oscillations

$$|\nu(t=0)\rangle = |\nu_\alpha\rangle = U_{\alpha 1}\,|\nu_1\rangle + U_{\alpha 2}\,|\nu_2\rangle + U_{\alpha 3}\,|\nu_3\rangle$$



$$|\nu(t>0)\rangle = U_{\alpha 1}\,e^{-iE_1 t}\,|\nu_1\rangle + U_{\alpha 2}\,e^{-iE_2 t}\,|\nu_2\rangle + U_{\alpha 3}\,e^{-iE_3 t}\,|\nu_3\rangle \neq |\nu_\alpha\rangle$$

$$E_k^2 = p^2 + m_k^2 \qquad\qquad t = L$$

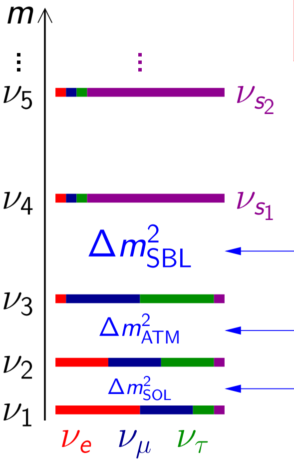
$$P_{\nu_\alpha\to\nu_\beta}(L) = |\langle\nu_\beta|\nu(L)\rangle|^2 = \sum_{k,j} U_{\beta k}\,U_{\alpha k}^*\,U_{\beta j}^*\,U_{\alpha j}\,\exp\left(-i\frac{\Delta m_{kj}^2 L}{2E}\right)$$

The oscillation probabilities depend on U and $\Delta m_{kj}^2 \equiv m_k^2 - m_j^2$

- In the standard framework of three-neutrino mixing there are two independent Δm^2's:
  - $\Delta m^2_{\text{SOL}} = \Delta m^2_{21} \simeq 7.4 \times 10^{-5}\,\text{eV}^2$
  - $\Delta m^2_{\text{ATM}} \simeq |\Delta m^2_{31}| \simeq 2.5 \times 10^{-3}\,\text{eV}^2$
- For a typical reactor neutrino energy of a few MeV atmospheric and solar neutrino oscillations are detectable at the distances
  - $L^{\text{osc}}_{\text{ATM}} \approx \dfrac{E_\nu}{\Delta m^2_{\text{ATM}}} \approx 1\,\text{km}$
  - $L^{\text{osc}}_{\text{SOL}} \approx \dfrac{E_\nu}{\Delta m^2_{\text{SOL}}} \approx 50\,\text{km}$
- The atmospheric and solar neutrino oscillations cannot explain the Reactor Antineutrino Anomaly deficit that is observed at $L \approx 10\,\text{m}$.

Beyond Three-Neutrino Mixing: Sterile Neutrinos

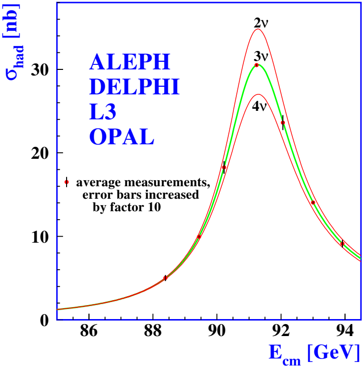
$$\boxed{L^{\text{osc}} = \frac{4\pi E}{\Delta m^2}}$$



$\gtrsim 1\,\text{eV}^2$

$\simeq 2.5 \times 10^{-3}\,\text{eV}^2$

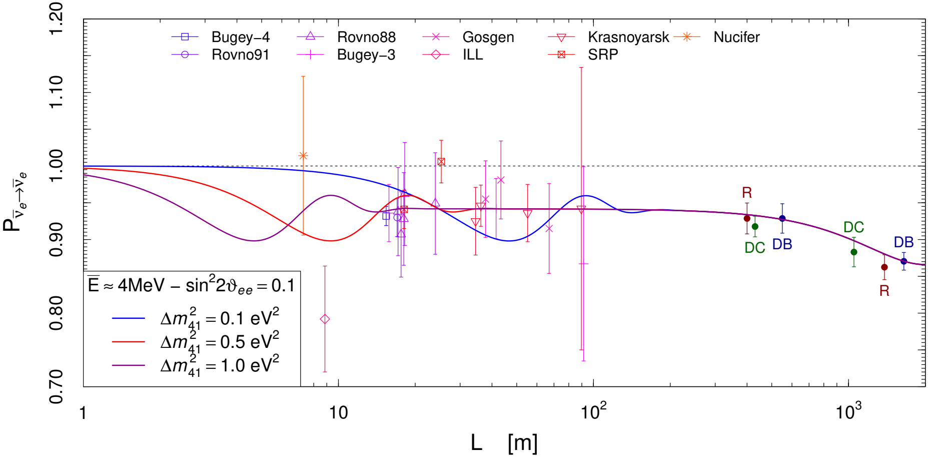
$\simeq 7.4 \times 10^{-5}\,\text{eV}^2$



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

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

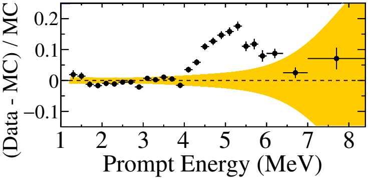
Short-Baseline Reactor Neutrino Oscillations



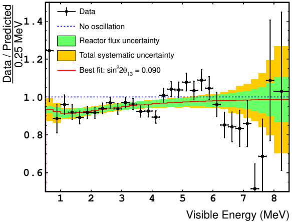
$$\Delta m^2_{\text{SBL}} \gtrsim 0.5\,\text{eV}^2 \gg \Delta m^2_{\text{ATM}}$$

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

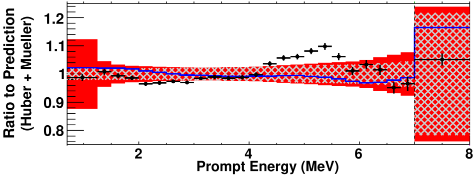
Reactor Antineutrino 5 MeV Bump



[RENO, arXiv:1511.05849]



[Double Chooz, arXiv:1406.7763]



[Daya Bay, arXiv:1508.04233]

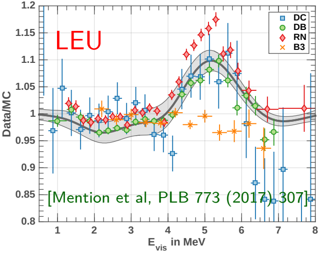
- Cannot be explained by neutrino oscillations (SBL oscillations are averaged in RENO, DC, DB).
- It is likely due to a theoretical miscalculation of the spectrum.
- Heretic solution: detector energy nonlinearity. [Mention et al, PLB 773 (2017) 307]

- $\sim 3\%$ effect on total flux, but if it is an excess it increases the anomaly!
- No post-bump complete calculation of the neutrino fluxes.
- Nominal Huber-Mueller flux calculation uncertainty: $\sim 2.7\%$.
- Post-bump estimate of the flux uncertainty due to unknown forbidden decays: $\sim 5\%$.

[Hayes and Vogel, ARNPS 66 (2016) 219]

Further Bump Puzzles

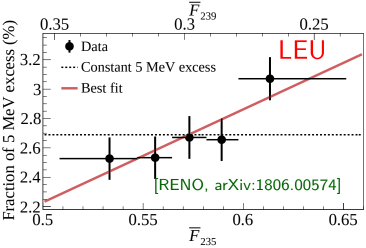
Not seen at Bugey-3 (1995)



LEU

[Mention et al, PLB 773 (2017) 307]

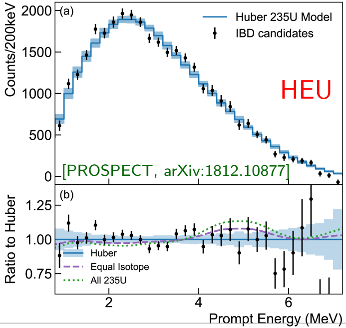
RENO: correlated with F_{235}?



LEU

[RENO, arXiv:1806.00574]

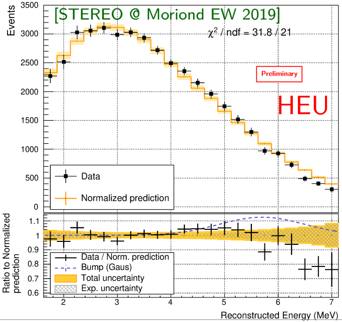
PROSPECT: bump or no bump?



HEU

[PROSPECT, arXiv:1812.10877]

STEREO: no bump



[STEREO @ Moriond EW 2019]

HEU

Reactor Fuel Evolution

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

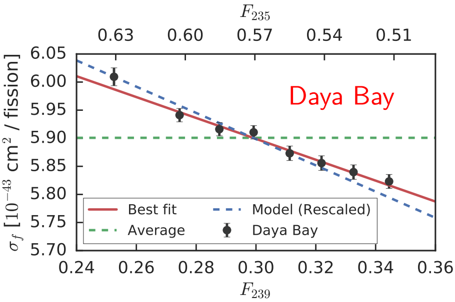
  ^{235}U ^{238}U ^{239}Pu ^{241}Pu

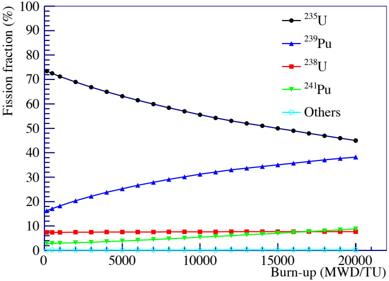
- Effective fission fractions:

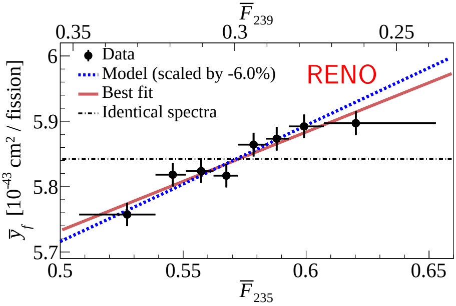
  F_{235} F_{238} F_{239} F_{241}

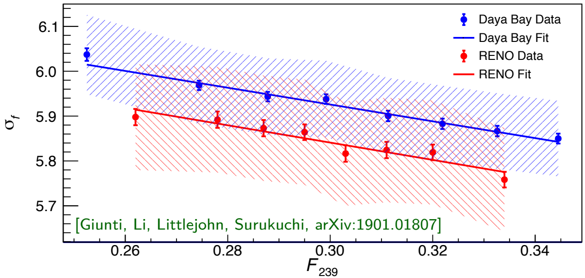
- Cross section per fission (IBD yield):

$$\sigma_f = \sum_{k=235,238,239,241} F_k \, \sigma_{f,k}$$

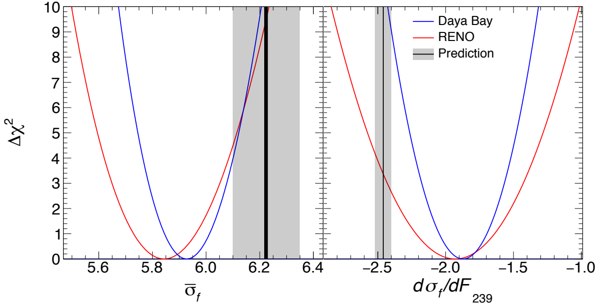




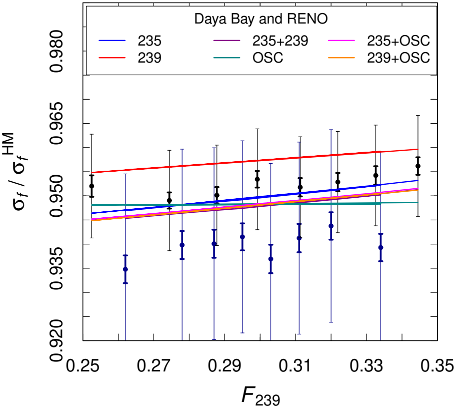


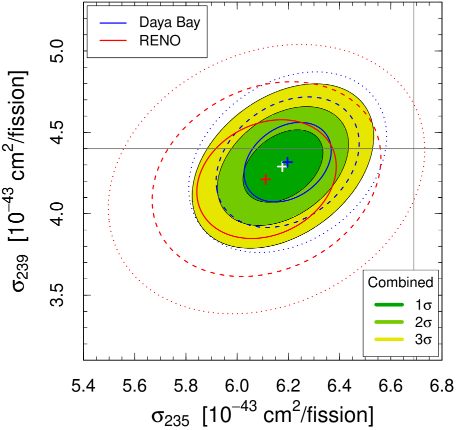


[Giunti, Li, Littlejohn, Surukuchi, arXiv:1901.01807]



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





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

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

OSC: $P_{\bar{\nu}_e \to \bar{\nu}_e} = 0.939 \pm 0.024$

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

$$235{+}239: \begin{cases} r_{235} = 0.923 \pm 0.015 \\ r_{239} = 0.975 \pm 0.032 \end{cases}$$

$\chi^2/\text{NDF} = 8.7/14 \quad \text{GoF} = 85\%$

$$235{+}\text{OSC}: \begin{cases} r_{235} = 0.938 \pm 0.029 \\ P_{\bar{\nu}_e \to \bar{\nu}_e} = 0.986 \pm 0.022 \end{cases}$$

$\chi^2/\text{NDF} = 8.8/14 \quad \text{GoF} = 85\%$

[Giunti, Li, Littlejohn, Surukuchi, arXiv:1901.01807]

- Daya Bay and RENO favor a suppression of the ^{235}U flux (235) over oscillations (OSC).

- However the best fit is obtained for 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)]

- 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:

  1. The 5 MeV bump
  2. The fuel evolution data

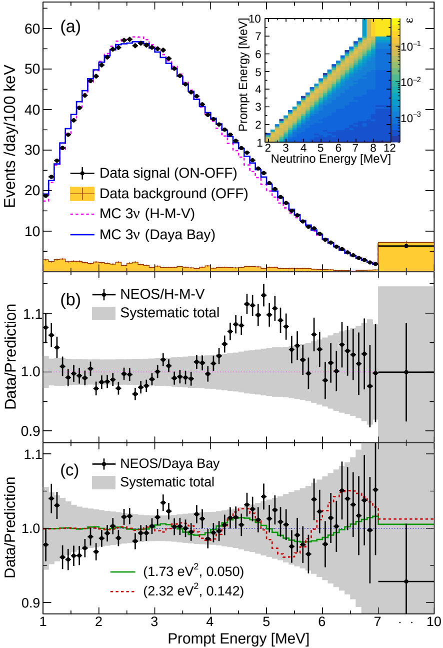
- The search for short-baseline neutrino oscillations needs

model-independent information

$\Uparrow$

ratios of spectra at different distances

NEOS



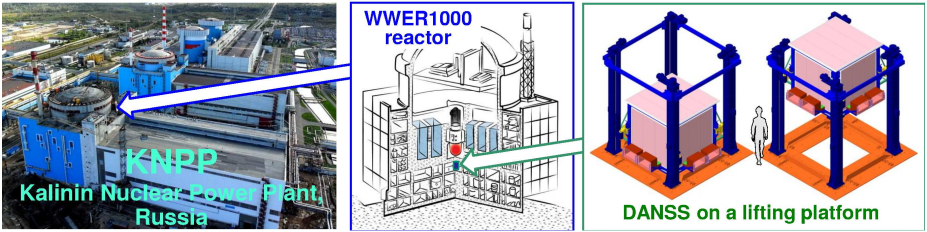
[PRL 118 (2017) 121802, arXiv:1610.05134]

- Hanbit Nuclear Power Complex in Yeong-gwang, Korea.
- Thermal power of 2.8 GW.
- Detector: a ton of Gd-loaded liquid scintillator in a gallery approximately 24 m from the reactor core.
- The measured antineutrino event rate is 1976 per day with a signal to background ratio of about 22.

DANSS

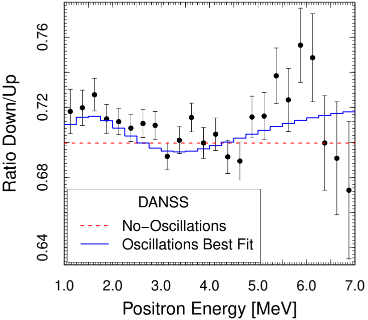
[PLB 787 (2018) 56, arXiv:1804.04046]

Detector of reactor AntiNeutrino based on Solid Scintillator



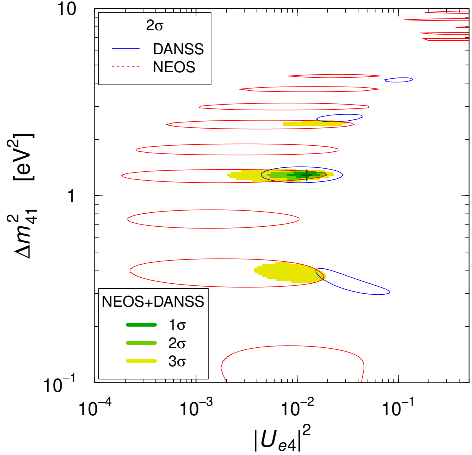
- Installed on a movable platform under a 3 GW reactor.
- Large neutrino flux.
- Reactor shielding of cosmic rays.
- Variable source-detector distance with the same detector!

$$\text{Down} = 12.7\,\text{m}$$
$$\text{Up} = 10.7\,\text{m}$$



Model-Independent $\bar{\nu}_e$ SBL Oscillations

[Gariazzo, Giunti, Laveder, Li, PLB 782 (2018) 13, arXiv:1801.06467]



$\sim 3.7\sigma$

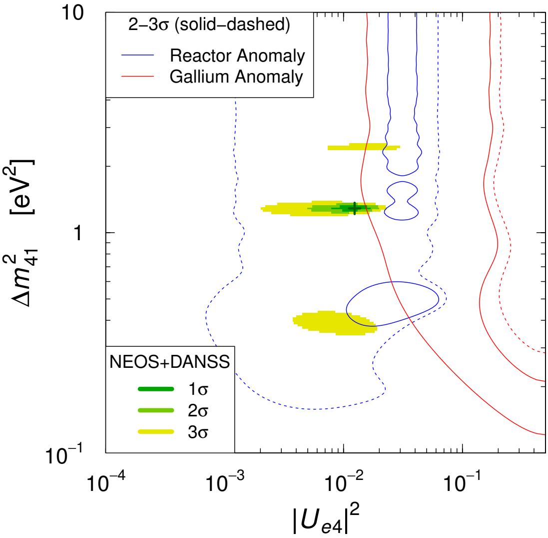
$$\Delta m^2_{41} = 1.29 \pm 0.03$$

$$|U_{e4}|^2 = 0.012 \pm 0.003$$

$$|U_{e3}|^2 = 0.022 \pm 0.001$$

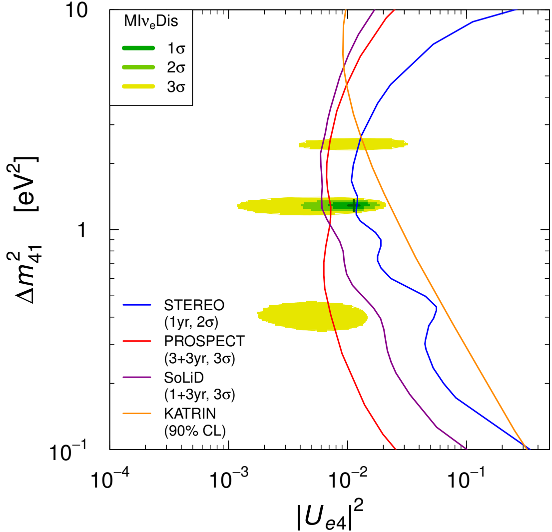
[See also Dentler, Hernandez-Cabezudo, Kopp, Machado, Maltoni, Martinez-Soler, Schwetz, arXiv:1803.10661]

Comparison with the Reactor and Gallium Anomalies



- 3σ agreement.
- 2σ tension.
- Small overestimate of the reactor fluxes.
- Small overestimate of the GALLEX and SAGE efficiencies.

Global Model-Independent ν_e and $\bar{\nu}_e$ Disappearance

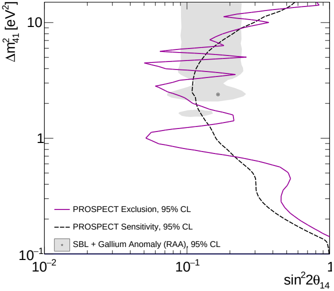


- NEOS and DANSS.
- Reactor rates with free ^{235}U and ^{239}Pu fluxes: r_{235} and r_{239}.
- Gallium data with free GALLEX and SAGE efficiencies: η_G and η_S.
- New reactor experiments: PROSPECT, STEREO, Neutrino-4, SoLiD
- Kinematic ν_4 mass measurement: KATRIN

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

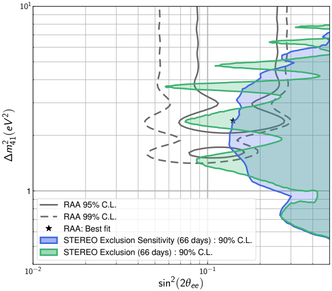
PROSPECT

[PRL 121 (2018) 251802, arXiv:1806.02784]

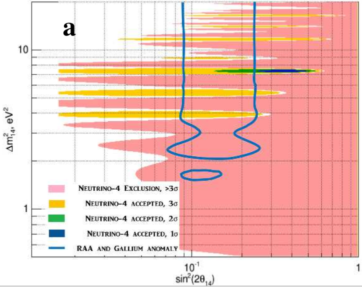


STEREO

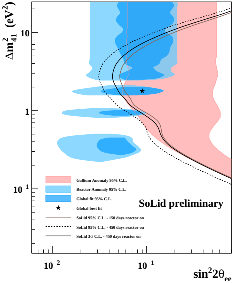
[PRL 121 (2018) 161801, arXiv:1806.02096]

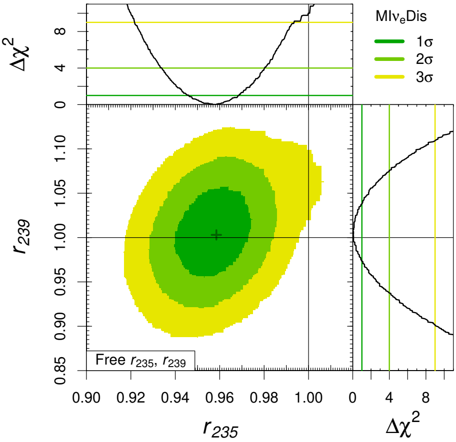


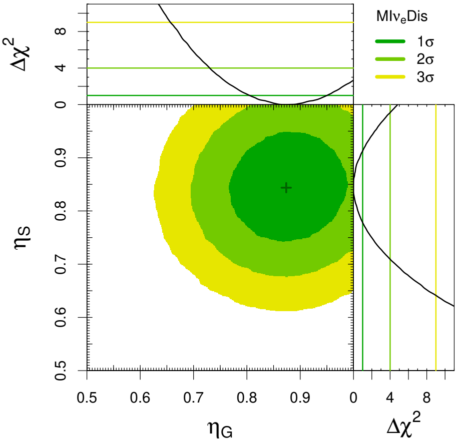
Neutrino-4 [arXiv:1809.10561]



SoLiD sensitivity [arXiv:1710.07933]





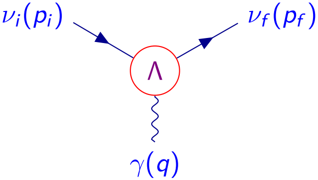


- Indication of $r_{235} < 1$.
- Likely small overestimate of the GALLEX and SAGE efficiencies.

Neutrino Electromagnetic Interactions

- Effective Hamiltonian: $\mathcal{H}_{\text{em}}^{(\nu)}(x) = j_{\mu}^{(\nu)}(x) A^{\mu}(x) = \sum_{k,j=1} \overline{\nu_k}(x) \Lambda_{\mu}^{kj} \nu_j(x) A^{\mu}(x)$

- Effective electromagnetic vertex:



$$\langle \nu_f(p_f) | j_{\mu}^{(\nu)}(0) | \nu_i(p_i) \rangle = \overline{u_f}(p_f) \Lambda_{\mu}^{fi}(q) u_i(p_i)$$

$$q = p_i - p_f$$

- Vertex function:

$$\Lambda_{\mu}(q) = \left(\gamma_{\mu} - q_{\mu} \not{q}/q^2\right) \left[F_Q(q^2) + F_A(q^2) q^2 \gamma_5\right] - i \sigma_{\mu\nu} q^{\nu} \left[F_M(q^2) + i F_E(q^2) \gamma_5\right]$$

Lorentz-invariant form factors: charge (F_Q), anapole (F_A), magnetic (F_M), electric (F_E)

$q^2 = 0 \implies$ $\mathfrak{q}$, a, μ, ε

- Hermitian form factor matrices $\implies$ $\mathfrak{q} = \mathfrak{q}^{\dagger}$ $\quad a = a^{\dagger}$ $\quad \mu = \mu^{\dagger}$ $\quad \varepsilon = \varepsilon^{\dagger}$

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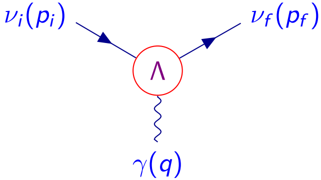

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Lorentz-invariant form factors: charge ↑ anapole ↑ magnetic ↑ electric ↑

$q^2 = 0 \quad \Longrightarrow$ $\mathbb{q}$ $\quad a \quad \mu \quad \varepsilon$

- Majorana neutrinos $\Longrightarrow$ $\mathbb{q} = -\mathbb{q}^T \quad a = a^T \quad \mu = -\mu^T \quad \varepsilon = -\varepsilon^T$

no diagonal charges and electric and magnetic moments

Neutrino Electromagnetic Interactions

- Effective Hamiltonian: $\mathcal{H}_{\text{em}}^{(\nu)}(x) = j_{\mu}^{(\nu)}(x) A^{\mu}(x) = \sum\limits_{k,j=1} \overline{\nu_k}(x) \Lambda_{\mu}^{kj} \nu_j(x) A^{\mu}(x)$

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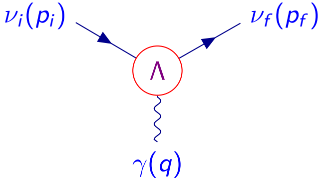

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Lorentz-invariant form factors: charge, anapole, magnetic, electric

$q^2 = 0 \quad \Longrightarrow \quad \mathfrak{q}$, a, μ, ε

- For ultrarelativistic neutrinos $\gamma_5 \to -1 \Rightarrow$ The phenomenology of the charge and anapole moments are similar and the phenomenology of the magnetic and electric moments are similar.

Neutrino Electromagnetic Interactions

- Effective Hamiltonian: $\mathcal{H}_{\text{em}}^{(\nu)}(x) = j_\mu^{(\nu)}(x) A^\mu(x) = \sum_{k,j=1} \overline{\nu_k}(x) \Lambda_\mu^{kj} \nu_j(x) A^\mu(x)$

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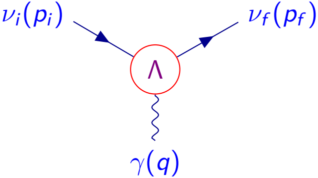

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Lorentz-invariant form factors:	charge	anapole	magnetic	electric
	$\downarrow$	$\downarrow$	$\downarrow$	$\downarrow$
$q^2 = 0 \quad \Longrightarrow$	$\mathfrak{q}$	a	μ	ε

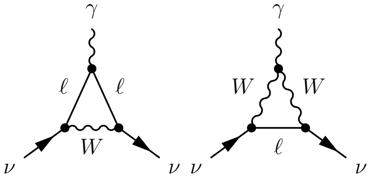
- For ultrarelativistic neutrinos the charge and anapole terms conserve helicity, whereas the magnetic and electric terms invert helicity.

Neutrino Charge Radius

- In the Standard Model neutrinos are neutral and there are no electromagnetic interactions at the tree-level.

- Radiative corrections generate an effective electromagnetic interaction vertex

$$\Lambda_\mu(q) = \left(\gamma_\mu - q_\mu \not{q}/q^2\right) F(q^2)$$



- $F(q^2) = \cancel{F(0)} + q^2 \left. \frac{dF(q^2)}{dq^2} \right|_{q^2=0} + \ldots = q^2 \frac{\langle r^2 \rangle}{6} + \ldots$

- In the Standard Model: [Bernabeu et al, PRD 62 (2000) 113012, NPB 680 (2004) 450]

$$\langle r^2_{\nu_\ell} \rangle_{\text{SM}} = -\frac{G_{\text{F}}}{2\sqrt{2}\pi^2} \left[3 - 2 \log\left(\frac{m_\ell^2}{m_W^2} \right) \right]$$

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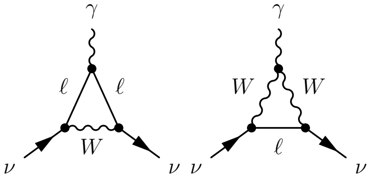


- $F(q^2) = \cancel{F(0)} + q^2 \left.\frac{dF(q^2)}{dq^2}\right|_{q^2=0} + \ldots = q^2 \frac{\langle r^2 \rangle}{6} + \ldots$
- In the Standard Model: [Bernabeu et al, PRD 62 (2000) 113012, NPB 680 (2004) 450]

$$\langle r^2_{\nu_e} \rangle_{\text{SM}} = -8.2 \times 10^{-33}\,\text{cm}^2 \quad \langle r^2_{\nu_\mu} \rangle_{\text{SM}} = -4.8 \times 10^{-33}\,\text{cm}^2 \quad \langle r^2_{\nu_\tau} \rangle_{\text{SM}} = -3.0 \times 10^{-33}\,\text{cm}^2$$

Experimental Bounds

Method	Experiment	Limit $[10^{-32}\text{cm}^2]$	CL	Year
Reactor $\bar{\nu}_e\, e^-$	Krasnoyarsk	$\lvert\langle r^2_{\nu_e}\rangle\rvert < 7.3$	90%	1992
	TEXONO	$-4.2 < \langle r^2_{\nu_e}\rangle < 6.6$	90%	2009
Accelerator $\nu_e\, e^-$	LAMPF	$-7.12 < \langle r^2_{\nu_e}\rangle < 10.88$	90%	1992
	LSND	$-5.94 < \langle r^2_{\nu_e}\rangle < 8.28$	90%	2001
Accelerator $\nu_\mu\, e^-$	BNL-E734	$-5.7 < \langle r^2_{\nu_\mu}\rangle < 1.1$	90%	1990
	CHARM-II	$\lvert\langle r^2_{\nu_\mu}\rangle\rvert < 1.2$	90%	1994

$$\frac{d\sigma_{\bar{\nu}_e e^-}}{dT_e} = \frac{G_F^2 m_e}{2\pi}\left\{(g_V^{\bar{\nu}_e} + g_A^{\bar{\nu}_e})^2 + (g_V^{\bar{\nu}_e} - g_A^{\bar{\nu}_e})^2\left(1 - \frac{T_e}{E_\nu}\right)^2 + \left[(g_A^{\bar{\nu}_e})^2 - (g_V^{\bar{\nu}_e})^2\right]\frac{m_e T_e}{E_\nu^2}\right\}$$

Weak interactions: $g_V^{\bar{\nu}_e} = 2\sin^2\theta_W + 1/2 \qquad g_A^{\bar{\nu}_e} = -1/2$

Neutrino charge radius: $\sin^2\vartheta_W \to \sin^2\vartheta_W\left(1 + \frac{1}{3}m_W^2\langle r^2_{\bar{\nu}_e}\rangle\right)$

[see the review Giunti, Studenikin, RMP 87 (2015) 531, arXiv:1403.6344]

Magnetic and Electric Moments

- Extended Standard Model with right-handed neutrinos and $\Delta L = 0$:

$$\mu^{\text{D}}_{kk} \simeq 3.2 \times 10^{-19} \mu_{\text{B}} \left(\frac{m_k}{\text{eV}} \right) \qquad \varepsilon^{\text{D}}_{kk} = 0$$

$$\left. \begin{array}{r} \mu^{\text{D}}_{kj} \\ i\varepsilon^{\text{D}}_{kj} \end{array} \right\} \simeq -3.9 \times 10^{-23} \mu_{\text{B}} \left(\frac{m_k \pm m_j}{\text{eV}} \right) \sum_{\ell=e,\mu,\tau} U^{*}_{\ell k} U_{\ell j} \left(\frac{m_\ell}{m_\tau} \right)^2$$

off-diagonal moments are GIM-suppressed

[Fujikawa, Shrock, PRL 45 (1980) 963; Pal, Wolfenstein, PRD 25 (1982) 766; Shrock, NPB 206 (1982) 359; Dvornikov, Studenikin, PRD 69 (2004) 073001, JETP 99 (2004) 254]

- Extended Standard Model with Majorana neutrinos ($|\Delta L| = 2$):

$$\mu^{\text{M}}_{kj} \simeq -7.8 \times 10^{-23} \mu_{\text{B}} \, i \, (m_k + m_j) \sum_{\ell=e,\mu,\tau} \text{Im} \left[U^{*}_{\ell k} U_{\ell j} \right] \frac{m^2_\ell}{m^2_W}$$

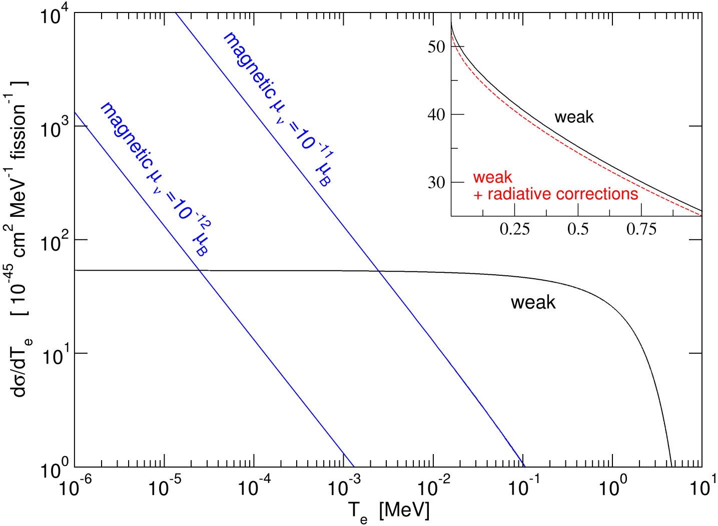
$$\varepsilon^{\text{M}}_{kj} \simeq 7.8 \times 10^{-23} \mu_{\text{B}} \, i \, (m_k - m_j) \sum_{\ell=e,\mu,\tau} \text{Re} \left[U^{*}_{\ell k} U_{\ell j} \right] \frac{m^2_\ell}{m^2_W}$$

[Shrock, NPB 206 (1982) 359]

GIM-suppressed, but additional model-dependent contributions of the scalar sector can enhance the Majorana transition dipole moments

[Pal, Wolfenstein, PRD 25 (1982) 766; Barr, Freire, Zee, PRL 65 (1990) 2626; Pal, PRD 44 (1991) 2261]

$$\left(\frac{d\sigma_{\nu e^-}}{dT_e}\right)_{\text{mag}} = \frac{\pi\alpha^2}{m_e^2}\left(\frac{1}{T_e}-\frac{1}{E_\nu}\right)\left(\frac{\mu_\nu}{\mu_B}\right)^2$$



Method	Experiment	Limit $[\mu_{\text{B}}]$	CL	Year
Reactor $\bar{\nu}_e\, e^-$	Krasnoyarsk	$\mu_{\nu_e} < 2.4 \times 10^{-10}$	90%	1992
	Rovno	$\mu_{\nu_e} < 1.9 \times 10^{-10}$	95%	1993
	MUNU	$\mu_{\nu_e} < 9 \times 10^{-11}$	90%	2005
	TEXONO	$\mu_{\nu_e} < 7.4 \times 10^{-11}$	90%	2006
	GEMMA	$\mu_{\nu_e} < 2.9 \times 10^{-11}$	90%	2012
Accelerator $\nu_e\, e^-$	LAMPF	$\mu_{\nu_e} < 1.1 \times 10^{-9}$	90%	1992
Accelerator $(\nu_\mu, \bar{\nu}_\mu)\, e^-$	BNL-E734	$\mu_{\nu_\mu} < 8.5 \times 10^{-10}$	90%	1990
	LAMPF	$\mu_{\nu_\mu} < 7.4 \times 10^{-10}$	90%	1992
	LSND	$\mu_{\nu_\mu} < 6.8 \times 10^{-10}$	90%	2001
Accelerator $(\nu_\tau, \bar{\nu}_\tau)\, e^-$	DONUT	$\mu_{\nu_\tau} < 3.9 \times 10^{-7}$	90%	2001
Solar $\nu_e\, e^-$	Super-Kamiokande	$\mu_{\text{S}}(E_\nu \gtrsim 5\,\text{MeV}) < 1.1 \times 10^{-10}$	90%	2004
	Borexino	$\mu_{\text{S}}(E_\nu \lesssim 1\,\text{MeV}) < 2.8 \times 10^{-11}$	90%	2017

[see the review Giunti, Studenikin, RMP 87 (2015) 531, arXiv:1403.6344]

- Gap of about 8 orders of magnitude between the experimental limits and the $\lesssim 10^{-19}\,\mu_{\text{B}}$ prediction of the minimal Standard Model extensions.
- $\mu_\nu \gg 10^{-19}\,\mu_{\text{B}}$ discovery $\Rightarrow$ non-minimal new physics beyond the SM.
- Neutrino spin-flavor precession in a magnetic field

[Lim, Marciano, PRD 37 (1988) 1368; Akhmedov, PLB 213 (1988) 64]

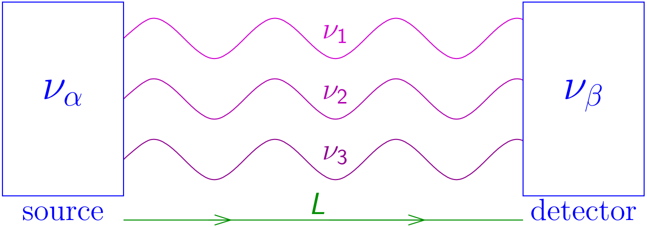
Conclusions

- Exciting model-independent indication of light sterile neutrinos at the eV scale from the NEOS and DANSS experiments $\Longrightarrow$ New Physics beyond the Standard Model!
- Agreement with the Reactor and Gallium Anomalies $\Longrightarrow$ Needed revision of the ^{235}U calculation and small decrease of the GALLEX and SAGE efficiencies.
- Can be checked in the near future by the reactor experiments STEREO, Neutrino-4, SoLid, PROSPECT.
- Independent tests through effect of m_4 in β-decay (KATRIN), EC (ECHo, HOLMES) and $\beta\beta_{0\nu}$-decay.
- The reactor antineutrino 5 MeV bump is a puzzle.
- Reactor antineutrinos can be powerful probes of other neutrino BSM properties as electromagnetic interactions.
- Coherent elastic neutrino-nucleus scattering. [G. Rich talk]

Short-Baseline Neutrino Oscillations

Three-Neutrino Mixing

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



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

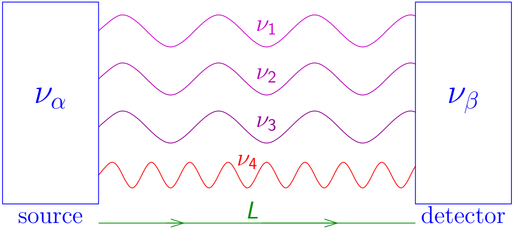
$$P_{\nu_\alpha \to \nu_\beta}(L) = |\langle \nu_\beta | \nu_{\text{detector}} \rangle|^2 \simeq |e^{-iEL} \langle \nu_\beta | \nu_\alpha \rangle|^2 = \delta_{\alpha\beta}$$

No Observable Short-Baseline Neutrino Oscillations!

Short-Baseline Neutrino Oscillations

3+1 Neutrino Mixing

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



$$|\nu_{\text{detector}}\rangle \simeq e^{-iEL}\left(U_{\alpha 1}\,|\nu_1\rangle + U_{\alpha 2}\,|\nu_2\rangle + U_{\alpha 3}\,|\nu_3\rangle\right) + U_{\alpha 4}\,e^{-iE_4 L}\,|\nu_3\rangle \neq |\nu_\alpha\rangle$$

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

Observable Short-Baseline Neutrino Oscillations!

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

Effective 3+1 SBL Oscillation Probabilities

Appearance $(\alpha \neq \beta)$

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

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

Disappearance

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

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

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

SBL

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

- $\Delta m^2_{\rm SBL} = \Delta m^2_{41} \simeq \Delta m^2_{42} \simeq \Delta m^2_{43}$
- CP violation is not observable in SBL experiments!
- Observable in LBL accelerator exp. sensitive to $\Delta m^2_{\rm ATM}$ [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 $\Delta m^2_{\rm SOL}$ [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, Giunti, Grimus, EPJC 1 (1998) 247]