Status of the reactor antineutrino anomalies and implications for active-sterile neutrino mixing

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Mainstream 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

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

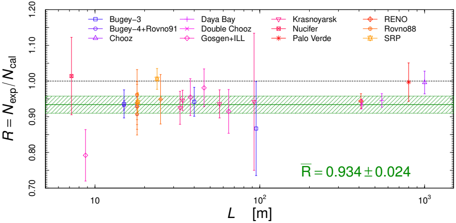
- U is the 3×3 unitary Neutrino Mixing Matrix
- $$P_{\nu_\alpha \to \nu_\beta}(L) = \sum_{k,j} U_{\beta k} U_{\alpha k}^* U_{\beta j}^* U_{\alpha j} \exp\left(-i \frac{\Delta m_{kj}^2 L}{2E}\right) \qquad (\alpha, \beta = e, \mu, \tau)$$
- The oscillation probabilities depend on

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

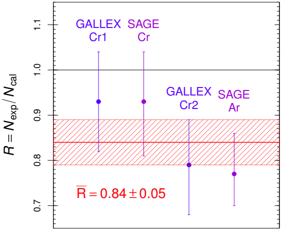
- In the mainstream 3ν mixing paradigm there are two independent Δm^2's:
  - $\Delta m^2_{\text{SOL}} = \Delta m^2_{21} \simeq 7.4 \times 10^{-5}\,\text{eV}^2$ Solar Mass Splitting
  - $\Delta m^2_{\text{ATM}} \simeq |\Delta m^2_{31}| \simeq 2.5 \times 10^{-3}\,\text{eV}^2$ Atmospheric Mass Splitting
- 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 flavor neutrino transitions at shorter distances.

Short-Baseline Neutrino Oscillation Anomalies

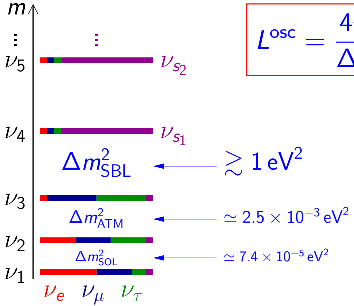
Reactor Anomaly: $\bar{\nu}_e \to \bar{\nu}_x$ ($\sim 3\sigma$)



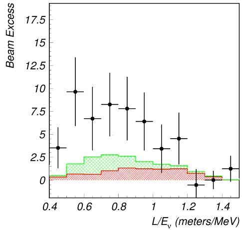
Gallium Anomaly: $\nu_e \to \nu_x$ ($\sim 3\sigma$)



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



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



Minimal perturbation of 3ν mixing: effective 3+1 with $|U_{e4}|, |U_{\mu 4}|, |U_{\tau 4}| \ll 1$

Effective 3+1 SBL Oscillation Probabilities

Appearance ($\alpha \neq \beta$)

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

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

Disappearance

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

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

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

SBL

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

- $\Delta m^2_{\text{SBL}} = \Delta m^2_{41} \simeq \Delta m^2_{42} \simeq \Delta m^2_{43}$
- CP violation is not observable in SBL experiments!
- Observable in LBL accelerator exp. sensitive to Δm^2_{ATM} [de Gouvea et al, 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, Giunti, arXiv:1304.2207]

Common Parameterization of 4ν Mixing

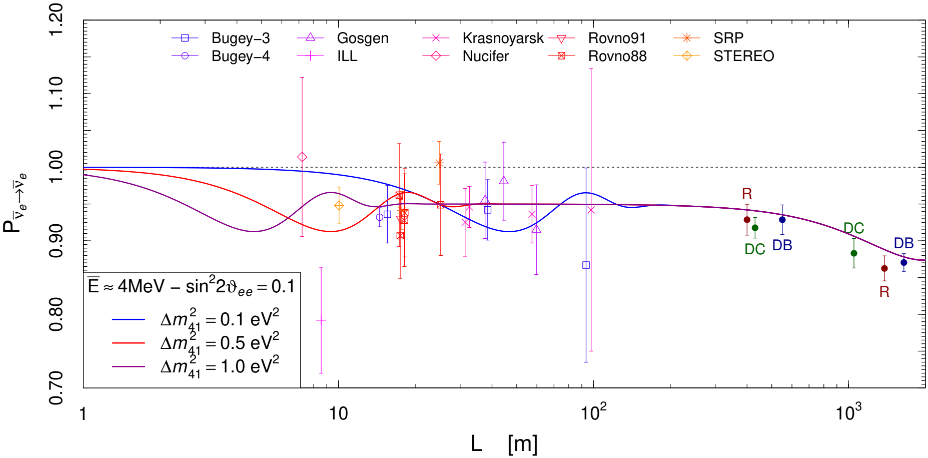
$$U = \left[W^{34} R^{24} W^{14} R^{23} W^{13} R^{12}\right] \mathrm{diag}\left(1, e^{i\lambda_{21}}, e^{i\lambda_{31}}, e^{i\lambda_{41}}\right)$$

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

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

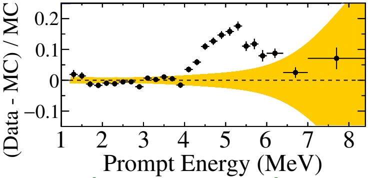
$$|U_{\mu4}|^2 = \cos^2\vartheta_{14}\sin^2\vartheta_{24} \simeq \sin^2\vartheta_{24} \Rightarrow \sin^2 2\vartheta_{\mu\mu} = 4|U_{\mu4}|^2\left(1 - |U_{\mu4}|^2\right) \simeq \sin^2 2\vartheta_{24}$$

Short-Baseline Reactor Neutrino Oscillations

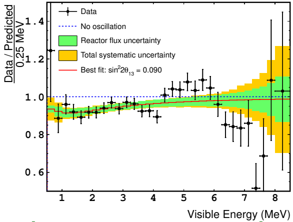


- $\Delta m^2_{\text{SBL}} \gtrsim 0.5\,\text{eV}^2 \gg \Delta m^2_{\text{ATM}}$
- SBL oscillations are averaged at the Daya Bay, RENO, and Double Chooz near detectors $\Longrightarrow$ no spectral distortion
- The reactor antineutrino anomaly is model dependent (depends on the theoretical reactor neutrino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

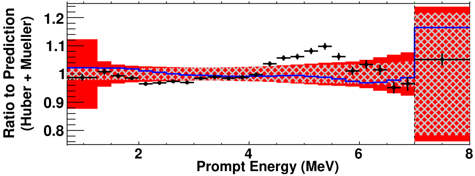
Reactor Antineutrino 5 MeV Bump



[RENO, arXiv:1511.05849]



[Double Chooz, arXiv:1406.7763]



[Daya Bay, arXiv:1508.04233]

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

  [see: Berryman, Huber, arXiv:1909.09267]

  - If it is a 4-6 MeV excess it increases the anomaly: 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]

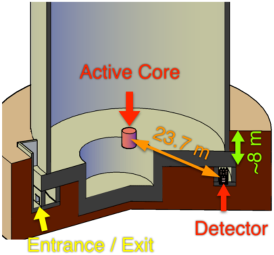
    new KI ^{235}U flux renormalization

    [Kopeikin, Skorokhvatov, Titov, arXiv:2103.01684]

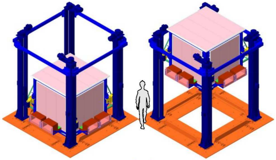
Model Indep. Measurements of Reactor ν Osc.

Ratios of spectra at different distances

NEOS

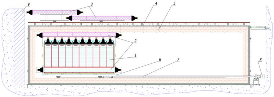


DANSS

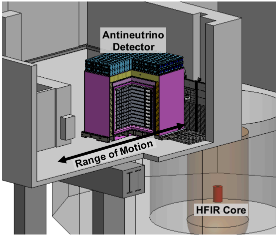


DANSS on a lifting platform

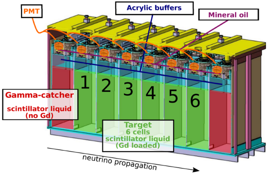
Neutrino-4



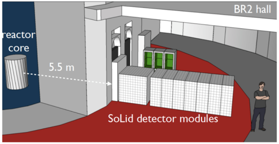
PROSPECT

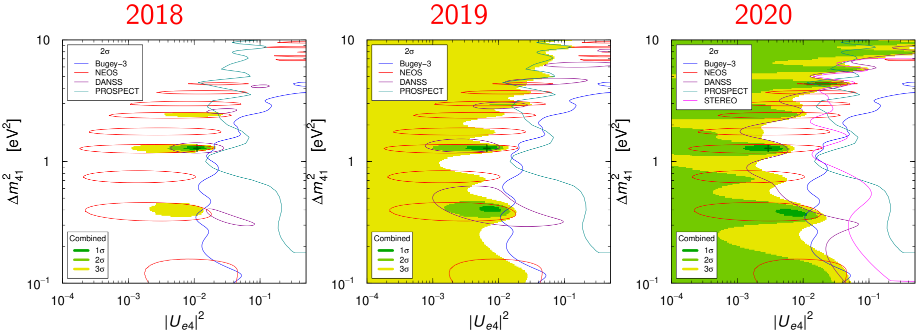


STEREO



SoLid





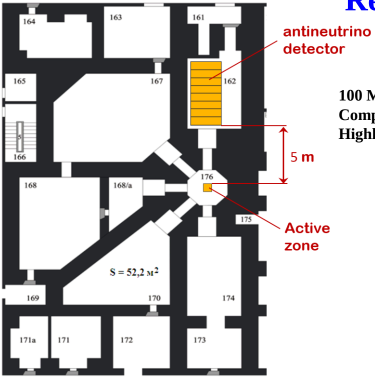
- 2018: remarkable agreement of the DANSS and NEOS best-fit regions at $\Delta m^2_{41} \approx 1.3\,\mathrm{eV}^2 \Longrightarrow$ model independent indication in favor of SBL oscillations.
  [Gariazzo, Giunti, Laveder, Li, arXiv:1801.06467]
  [Dentler, Hernandez-Cabezudo, Kopp, Machado, Maltoni, Martinez-Soler, 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

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

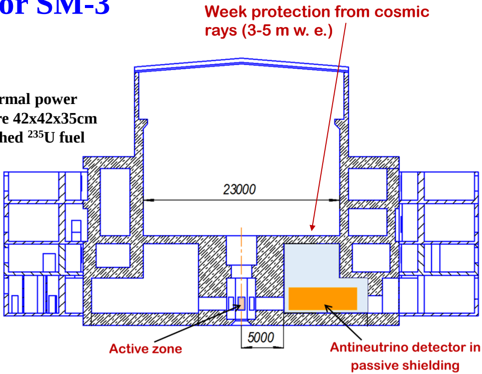
Neutrino-4

[arXiv:1708.00421, arXiv:1809.10561, arXiv:2003.03199, arXiv:2005.05301, arXiv:2006.13639]

Reactor SM-3



100 MW thermal power
Compact core 42x42x35cm
Highly enriched ^{235}U fuel



Due to some peculiar characteristics of its construction, reactor SM-3 provides the most favorable conditions to search for neutrino oscillations at short distances. However, SM-3 reactor, as well as other research reactors, is located on the Earth's surface, hence, cosmic background is the major difficulty in considered experiment.

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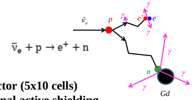
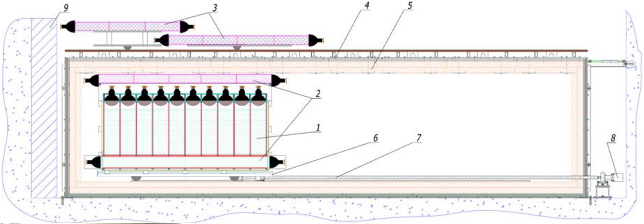
[A. Serebrov, 17 September 2020]

Movable and spectrum sensitive antineutrino detector at SM-3 reactor





1. detector (5x10 cells)
2. internal active shielding
3. external active shielding
4. steel and lead
5. borated polyethylene
6. moveable platform
7. feed screw
8. step motor
9. shielding

Passive shielding - 60 tons

Neutrino channel outside and inside

Range of measurements is 6 – 12 meters

Detector prototype

Full-scale detector

Liquid scintillator detector
50 sections 0.235x0.235x0.85м³

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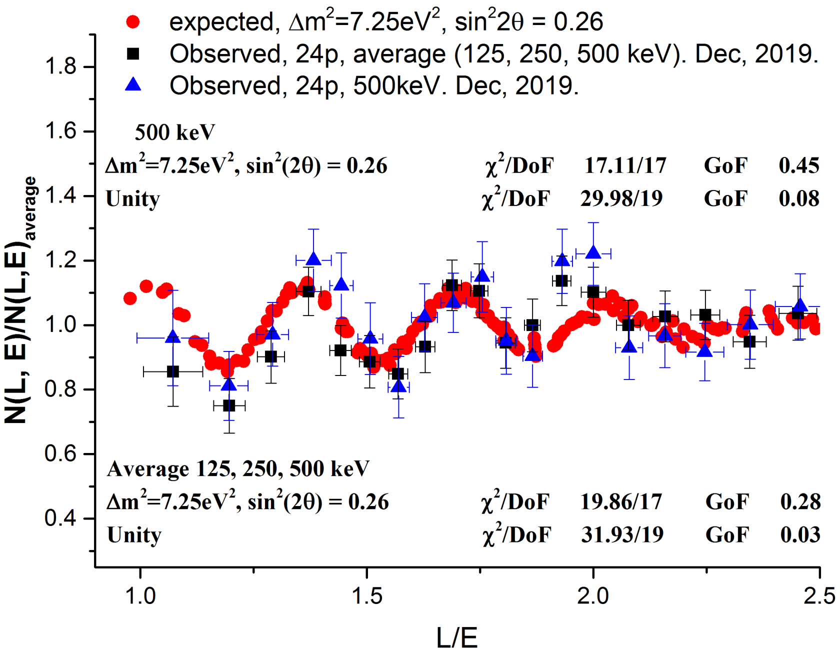
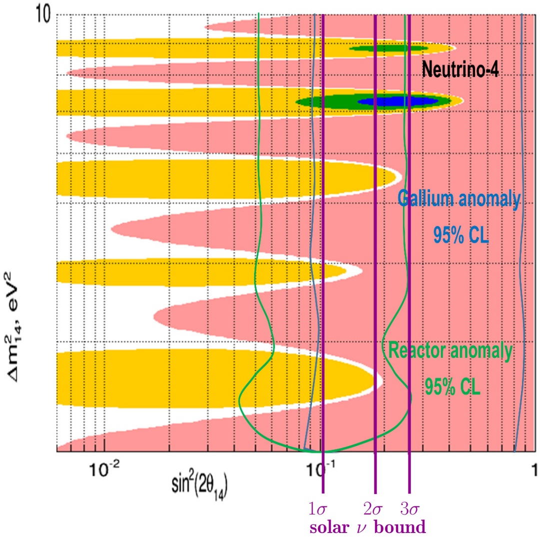
[A. Serebrov, 17 September 2020]



expected, Δm²=7.25eV², sin²2θ = 0.26
Observed, 24p, average (125, 250, 500 keV). Dec, 2019.
Observed, 24p, 500keV. Dec, 2019.
500 keV
Δm²=7.25eV², sin²(2θ) = 0.26 χ²/DoF 17.11/17 GoF 0.45
Unity χ²/DoF 29.98/19 GoF 0.08
Average 125, 250, 500 keV
Δm²=7.25eV², sin²(2θ) = 0.26 χ²/DoF 19.86/17 GoF 0.28
Unity χ²/DoF 31.93/19 GoF 0.03
N(L, E)/N(L,E)average
L/E
1.8
1.6
1.4
1.2
1.0
0.8
0.6
0.4
1.0
1.5
2.0
2.5



- Neutrino-4 best fit:

$$\sin^2 2\vartheta_{ee} = 0.26$$

$$\Delta m^2_{41} = 7.25\,\text{eV}^2$$

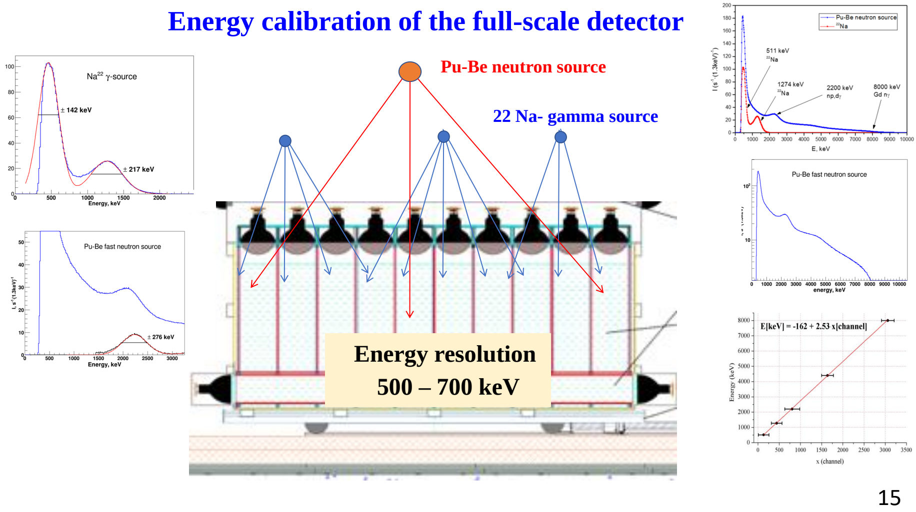
- Very large mixing!
- Not a small perturbation of 3ν mixing.
- Tension with solar neutrino bound.

[Palazzo, arXiv:1105.1705, arXiv:1201.4280]
[Giunti, Laveder, Li, Liu, Long, arXiv:1210.5715]
[Gariazzo, Giunti, Laveder, Li, arXiv:1703.00860]

Oscillations of Last Neutrino-4 Results

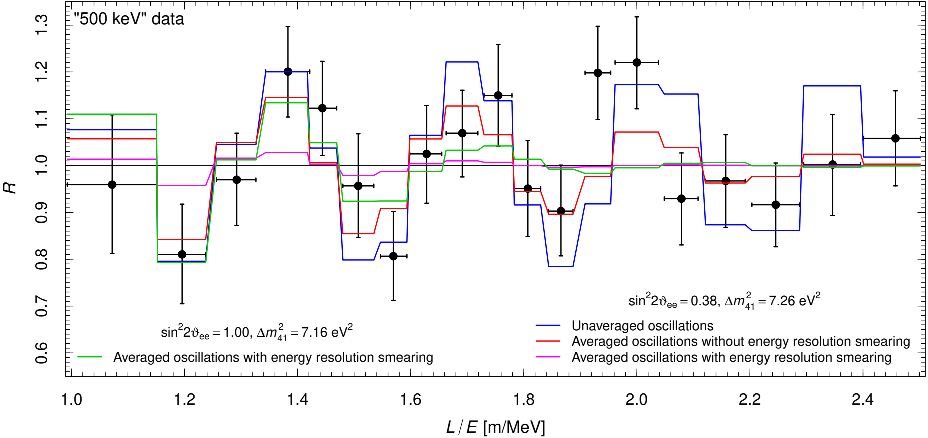
[arXiv:2005.05301]

version	date	$(\Delta m^2_{41})_{\text{bf}}$	$(\sin^2 2\vartheta_{ee})_{\text{bf}}$	statistical significance
v1	9 May 2020	7.25 ± 1.0	0.26 ± 0.09	2.8σ
v2	18 Jun 2020	7.25 ± 1.0	0.26 ± 0.09	2.8σ
v3	31 Jul 2020	7.25 ± 1.09	0.26 ± 0.09	2.9σ
v4	16 Aug 2020	7.25 ± 1.09	0.26 ± 0.09	2.9σ
v5	14 Feb 2021	7.2 ± 1.13	0.29 ± 0.12	2.4σ
v6	21 Feb 2021	7.2 ± 1.13	0.26 ± 0.08	3.2σ
v7	5 Apr 2021	7.3 ± 1.17	0.36 ± 0.12	2.9σ



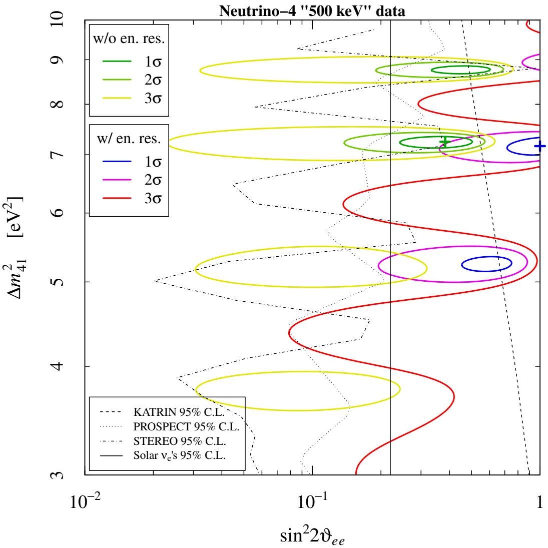
- We approximate the energy resolution with the function

$$R(E_{\rm p}, E_{\rm p}') = \frac{1}{\sqrt{2\pi}\sigma_{E_p}} \exp\left(- \frac{(E_{\rm p} - E_{\rm p}')^2}{2\sigma_{E_p}^2} \right) \quad \text{with} \quad \sigma_{E_p} = 0.19 \sqrt{\frac{E_p}{\text{MeV}}}\ \text{MeV}$$



$$\left\langle \sin^2\left(\frac{\Delta m^2_{41} L}{4E}\right)\right\rangle_{ik} = \frac{\int_{L_k^{\min}}^{L_k^{\max}} dL\, L^{-2} \int_{E_i^{\min}}^{E_i^{\max}} dE'_{\mathrm{p}} \int dE_{\mathrm{p}}\, R(E_{\mathrm{p}}, E'_{\mathrm{p}})\, \sin^2\left(\frac{\Delta m^2_{41} L}{4E}\right)\, \phi_{\bar{\nu}_e}(E)\, \sigma_{\bar{\nu}_e p}(E)}{\int_{L_k^{\min}}^{L_k^{\max}} dL\, L^{-2} \int_{E_i^{\min}}^{E_i^{\max}} dE'_{\mathrm{p}} \int dE_{\mathrm{p}}\, R(E_{\mathrm{p}}, E'_{\mathrm{p}})\, \phi_{\bar{\nu}_e}(E)\, \sigma_{\bar{\nu}_e p}(E)}$$

[CG, Li, Ternes, Zhang, arXiv:2101.06785]



$$\chi^2 = \sum_{j=1}^{19} \left(\frac{R_j^{\text{the}} - R_j^{\text{exp}}}{\Delta R_j^{\text{exp}}} \right)^2$$

	without en. res.	with en. res.
χ^2_{min}	14.9	18.2
GoF	60%	37%
$(\sin^2 2\vartheta_{ee})_{\text{bf}}$	0.38	1.0
$(\Delta m^2_{41})_{\text{bf}}$	7.2	7.2
$\Delta\chi^2_{\text{NO}}$	13.1	9.8
p-value	0.0014	0.0075
σ-value	3.2	2.7

[CG, Li, Ternes, Zhang, arXiv:2101.06785]

- Disconcerting comment in arXiv:2005.05301v7: The simultaneous usage of energy interval $\Delta E = 500\,\mathrm{keV}$ and energy resolution $\sigma = 250\,\mathrm{keV}$ is incorrect, because it includes into the analysis the resolution of the detector twice as it was done in the work [Giunti, Li, Ternes, Zhang, arXiv:2101.06785].

- The Neutrino-4 collaboration thinks that energy binning takes into account the energy resolution.

- It is obvious that an event with an unknown true energy in an unknown energy bin can be counted in another bin because of the energy resolution.

- This effect is obviously not taken into account by the binning.

- This effect can be neglected if the energy resolution is much smaller than the bin width.

- This effect cannot be neglected in the Neutrino-4 experiment, where the the bin width is only twice of the energy resolution.

Wilks Theorem (1938)

THE LARGE-SAMPLE DISTRIBUTION OF THE LIKELIHOOD RATIO FOR TESTING COMPOSITE HYPOTHESES[1]

BY S. S. WILKS

. . . .

Let $P_\Omega(O_n)$ be the least upper bound of P for the simple hypotheses in Ω, and $P_\omega(O_n)$ the least upper bound of P for those in ω. Then

$$\lambda = \frac{P_\omega(O_n)}{P_\Omega(O_n)} \tag{2}$$

. . . .

which *optimum* estimates of the θ's exist. That is, we shall assume the existence of functions $\bar{\theta}_i(x_1, \cdots x_n)$(maximum likelihood estimates of the θ_i) such that[3] their distribution is

$$\frac{|c_{ij}|^{\frac{1}{2}}}{(2\pi)^{h/2}} e^{-\frac{1}{2}\sum_{i,j=1}^{h} c_{ij} z_i z_j} (1 + \phi)\, dz_1 \cdots dz_h \tag{3}$$

where $z_i = (\bar{\theta}_i - \theta_i)\sqrt{n}$, $c_{ij} = -E\left(\dfrac{\partial^2 \log f}{\partial\theta_i\, \partial\theta_j}\right)$, E denoting mathematical expectation, and ϕ is of order $1/\sqrt{n}$ and $||c_{ij}||$ is positive definite. Denoting (3) by

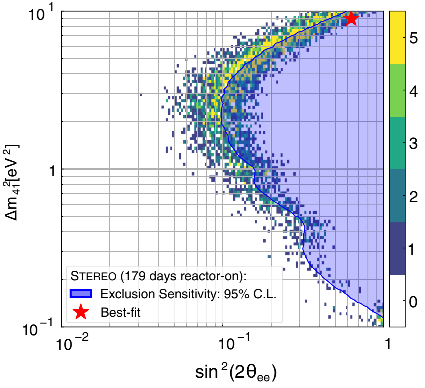
. . . .

Theorem: If a population with a variate x is distributed according to the probability function $f(x, \theta_1, \theta_2 \cdots \theta_h)$, such that optimum estimates $\bar{\theta}_i$ of the θ_i exist which are distributed in large samples according to (3), then when the hypothesis H is true that $\theta_i = \theta_{0i}$, $i = m+1, m+2, \cdots h$, the distribution of $-2\log\lambda$, where λ is given by (2) is, except for terms of order $1/\sqrt{n}$, distributed like χ^2 with $h - m$ degrees of freedom.

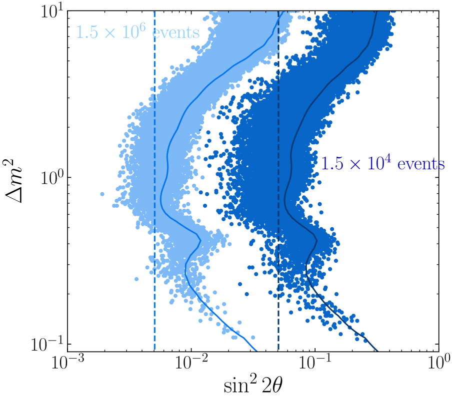
Deviations from χ^2 Distribution (Wilks' Theorem)

[Agostini, Neumair, arXiv:1906.11854; Silaeva, Sinev, arXiv:2001.10752; Giunti, arXiv:2004.07577]
[PROSPECT+STEREO, arXiv:2006.13147; Coloma, Huber, Schwetz, arXiv:2008.06083]

Even in the absence of real oscillations, binned data can often be fitted better by oscillations that reproduce the statistical fluctuations of the bins.

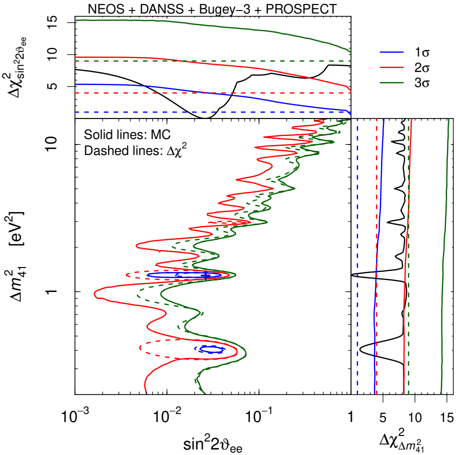


[STEREO, arXiv:1912.06582]



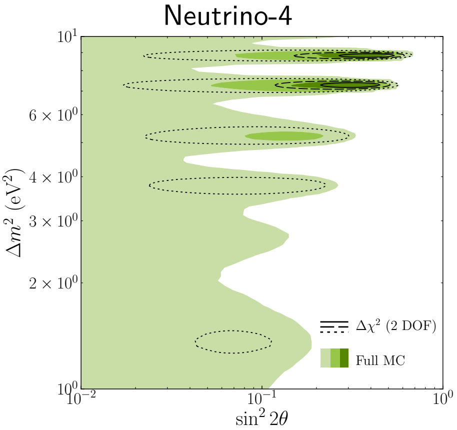
[Coloma, Huber, Schwetz, arXiv:2008.06083]

MC evaluation of test statistic distribution



$2.4\sigma\,(\Delta\chi^2) \longrightarrow 1.8\sigma\,(\text{MC})$

[Giunti, arXiv:2004.07577]



$3.2\sigma\,(\Delta\chi^2) \longrightarrow 2.6\sigma\,(\text{MC})$

[Coloma, Huber, Schwetz, arXiv:2008.06083]

- MC calculations are unfortunately difficult and require a lot of computer time.
- They must be completely redone for each combination of experiments.

Monte Carlo confidence intervals

- For each point on a grid in the $(\sin^2 2\vartheta_{ee}, \Delta m^2_{41})$ plane we generated a large number of random data sets (of the order of 10^5) with the uncertainties of the Neutrino-4 data set.

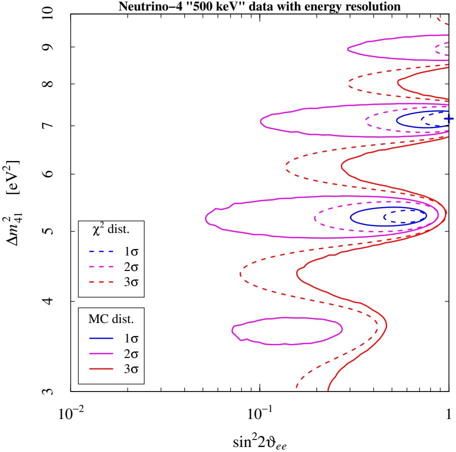
- For each random data set:

  - We calculated the value of χ^2 corresponding to the generating values of $\sin^2 2\vartheta_{ee}$ and Δm^2_{41}: $\chi^2_{\text{MC}}(\sin^2 2\vartheta_{ee}, \Delta m^2_{41})$.

  - We found the minimum value of χ^2 in the $(\sin^2 2\vartheta_{ee}, \Delta m^2_{41})$ plane: $\chi^2_{\text{MC,min}}(\sin^2 2\vartheta_{ee}, \Delta m^2_{41})$.

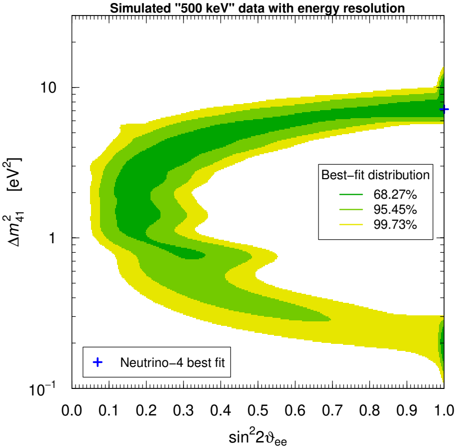
- In this way, we obtained the distribution of $\Delta\chi^2_{\text{MC}}(\sin^2 2\vartheta_{ee}, \Delta m^2_{41}) = \chi^2_{\text{MC}}(\sin^2 2\vartheta_{ee}, \Delta m^2_{41}) - \chi^2_{\text{MC,min}}(\sin^2 2\vartheta_{ee}, \Delta m^2_{41})$.

- This distribution allows us to determine if the value of $\Delta\chi^2(\sin^2 2\vartheta_{ee}, \Delta m^2_{41}) = \chi^2(\sin^2 2\vartheta_{ee}, \Delta m^2_{41}) - \chi^2_{\text{min}}(\sin^2 2\vartheta_{ee}, \Delta m^2_{41})$ obtained with the analysis of the actual Neutrino-4 data is included or not in a region with a fixed confidence level.



	χ^2 dist.	MC dist.
p-value	0.0075	0.028
σ-value	2.7	2.2

Best-fit distribution in absence of oscillations



	probability
$\sin^2 2\vartheta_{ee} < 0.1$	0.008
$0.1 < \sin^2 2\vartheta_{ee} < 0.5$	0.625
$0.5 < \sin^2 2\vartheta_{ee} < 0.9$	0.184
$\sin^2 2\vartheta_{ee} > 0.9$	0.183

Conclusion on Neutrino-4: the claimed indication in favor of short-baseline neutrino oscillations with very large mixing is rather doubtful.

[CG, Li, Ternes, Zhang, arXiv:2101.06785]

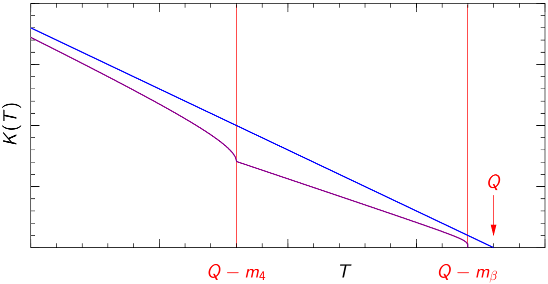
Robust kinematical probe of $\nu_e - \nu_s$ mixing

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

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

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

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



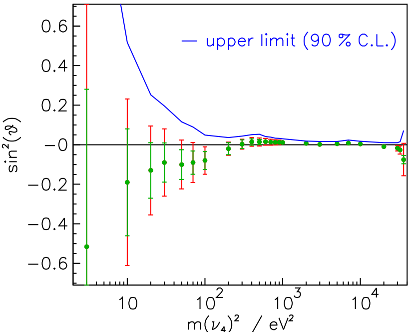
$$Q = M_{^3\text{H}} - M_{^3\text{He}} - m_e = 18.58\,\text{keV}$$

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

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

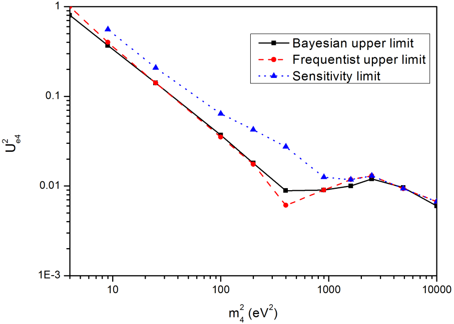
$$m_4 \gg m_{1,2,3} \quad \Longrightarrow \quad \Delta m^2_{41} \equiv m^2_4 - m^2_1 \simeq m^2_4$$

Mainz

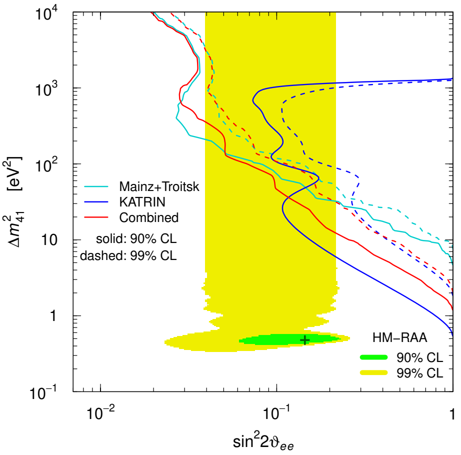


[Kraus, Singer, Valerius, Weinheimer, arXiv:1210.4194]

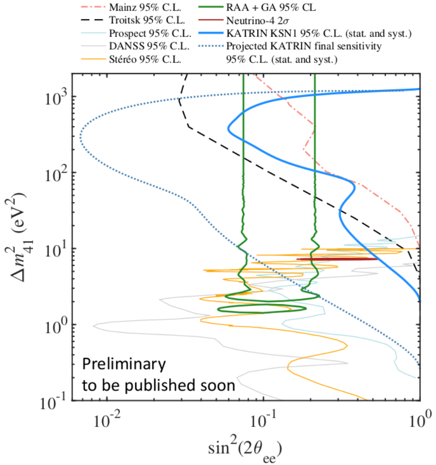
Troitsk



[Belesev et al, arXiv:1307.5687]



[Giunti, 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} $|U_{e4}|^2$ $|U_{\mu4}|^2$ $(|U_{\tau4}|^2)$
- Amplitude of ν_e disappearance:

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

- Amplitude of ν_μ disappearance:

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

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

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

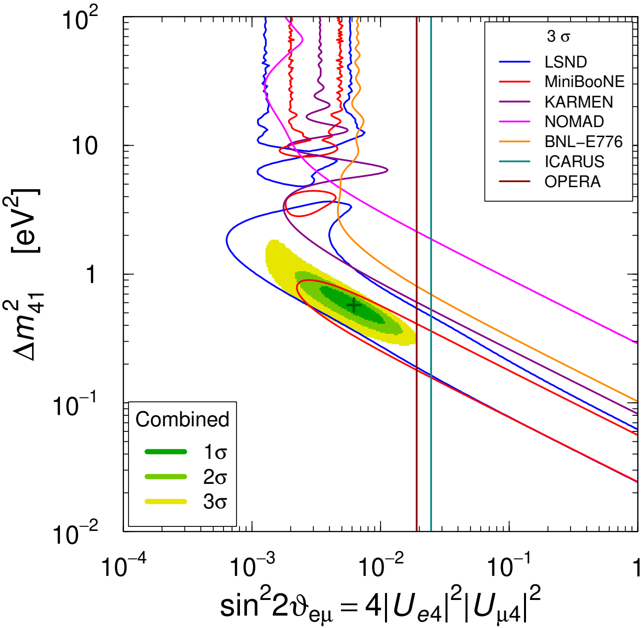
quadratically suppressed for small $|U_{e4}|^2$ and $|U_{\mu4}|^2$

$\Downarrow$

Appearance-Disappearance Tension

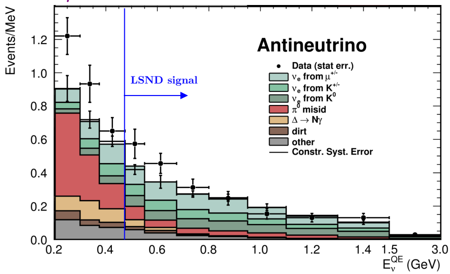
[Okada, Yasuda, IJMPA 12 (1997) 3669; Bilenky, CG, Grimus, EPJC 1 (1998) 247]

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

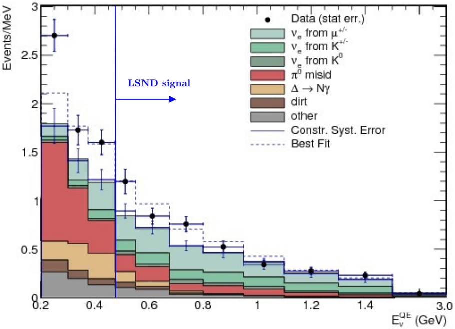


MiniBooNE

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



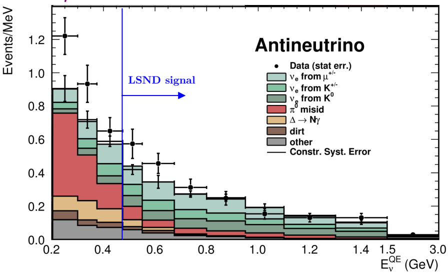
$\nu_\mu \to \nu_e$ [PRL 121 (2018) 221801]



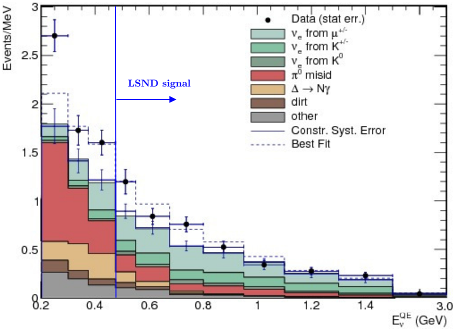
- Purpose: check the LSND signal
- Different $L \simeq 540\,\text{m}$
- Different $200\,\text{MeV} \leq E \lesssim 3\,\text{GeV}$
- Similar $L/E \Longrightarrow$ Oscillations Smoking Gun?
- No money, no Near Detector
- Large beam-related background
- Large flux and cross section uncertainties

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

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

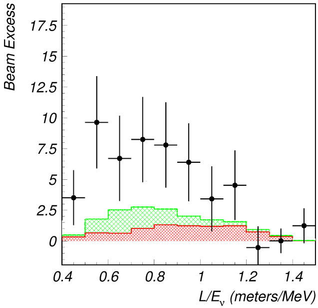
MiniBooNE low-energy anomaly

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

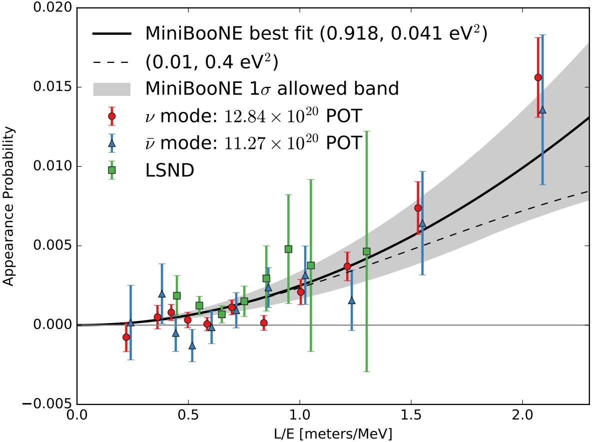
[Ioannisian et al, arXiv:1909.08571, arXiv:1912.01524]

To be checked by MicroBooNE@FNAL?

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

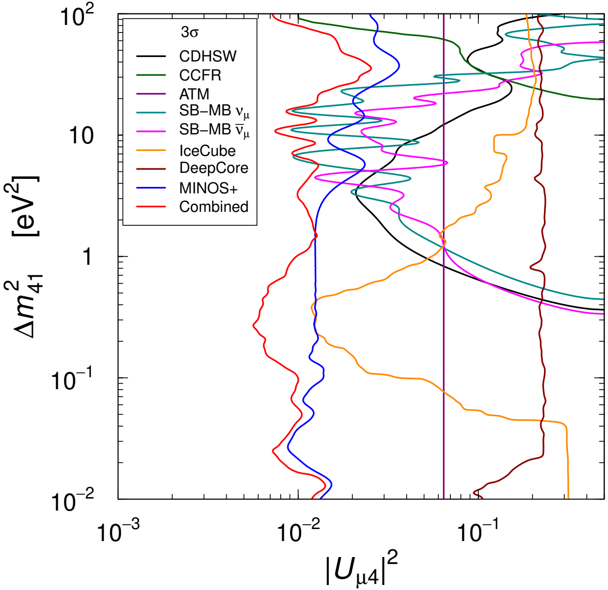


[LSND, PRD 64 (2001) 112007]

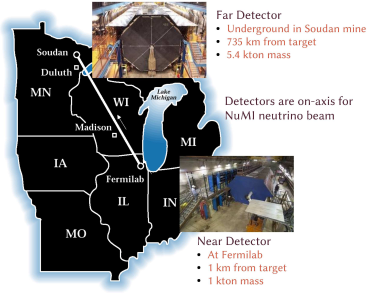


[MiniBooNE, PRL 121 (2018) 221801]

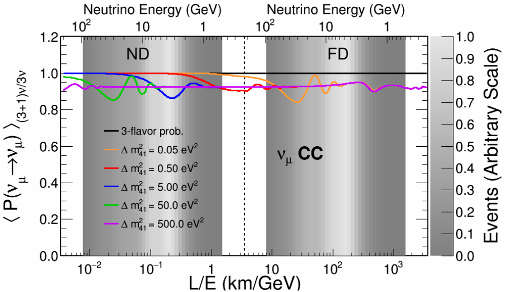
ν_μ and $\bar{\nu}_\mu$ Disappearance

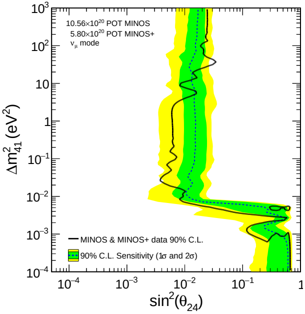


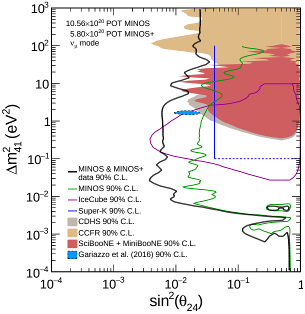
MINOS+



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





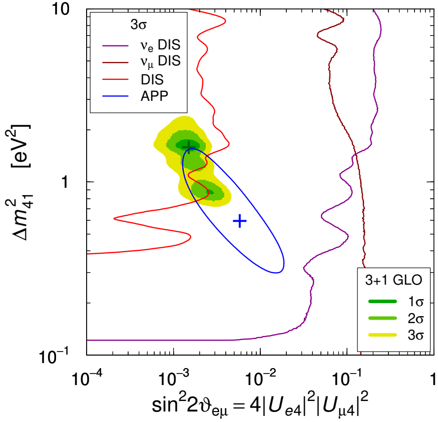


Global Appearance-Disappearance Tension

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:

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

  $\text{GoF} = 11\%$

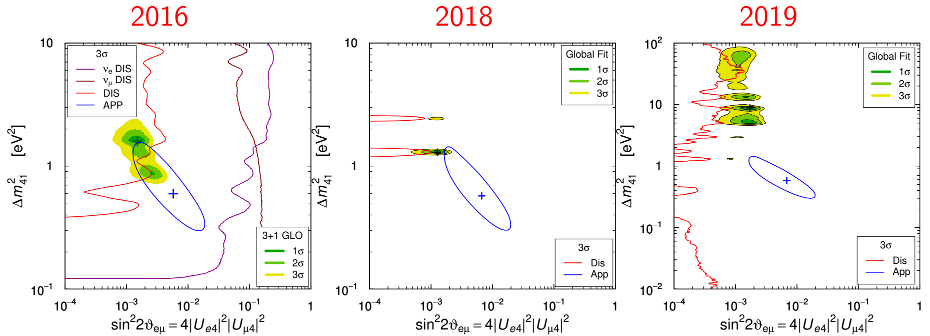
  $\chi^2_{\text{PG}}/\text{NDF}_{\text{PG}} = 15.0/2$

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

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

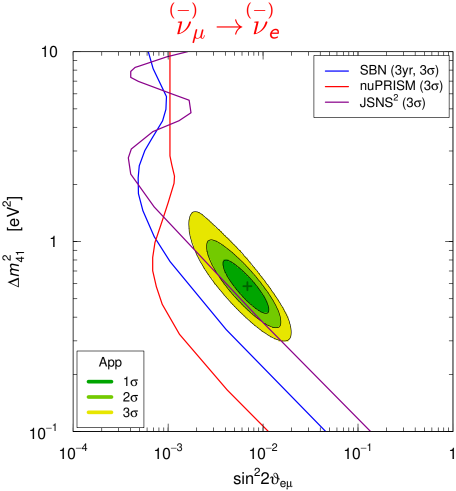
[Giunti, Zavanin, arXiv:1508.03172]

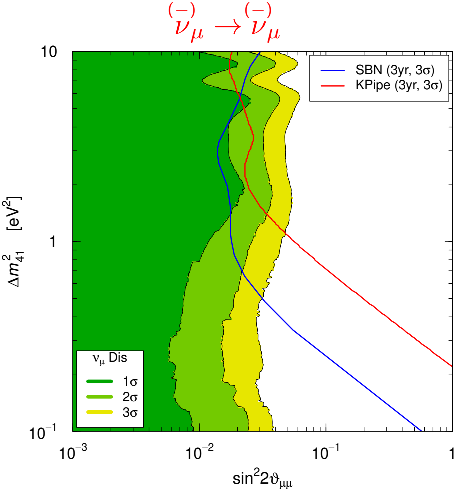
Global Appearance-Disappearance Tension



- 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





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, is disappearing, because of new neutrino flux calculations and the absence of a clear model-independent signal in the new experiments (DANSS, PROSPECT, STEREO).
- The claimed Neutrino-4 indication in favor of short-baseline neutrino oscillations with very large mixing is rather doubtful.
- 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.