New Physics beyond three neutrino mixing: Status of Reactor and Gallium anomalies

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Three Neutrino Paradigm

➢ **See Talk by Prof. Karsten Heeger**

Standard Parameterization of Mixing Matrix

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

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

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

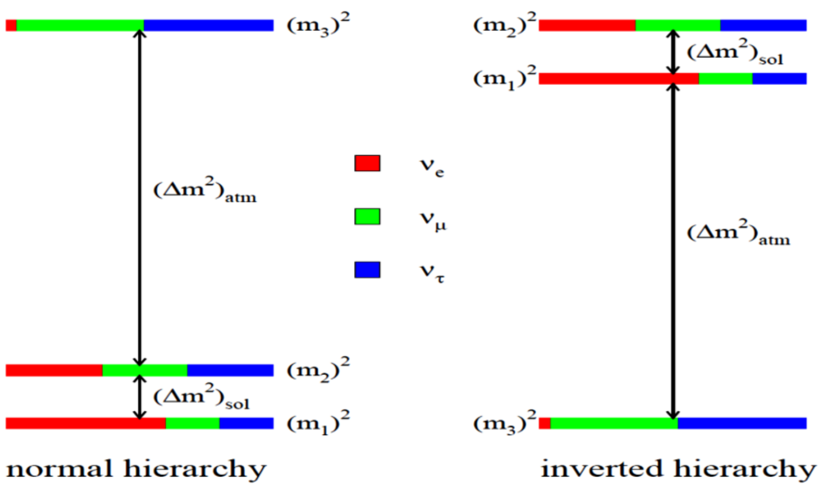
3 Mixing Angles: ϑ_{12}, ϑ_{23}, ϑ_{13}

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}

➢ **Absolute Neutrino Masses**

➢ **Two CPV Majorana Phases**



New Physics Beyond Three Neutrino Mixing

- **Light sterile neutrinos at the eV scale**

  Anomalies-driven sterile neutrino model

  Giunti, YFL, Ternes and Xin, 2212.09722, 2209.00916, 2110.06820

- **New neutrino interactions (Nonstandard Interactions)**

  Coloma et al, arXiv:2305.07698

- **Unitarity Violation of Neutrino Mixing Matrix**

  Blennow et al, arXiv:2306.01040

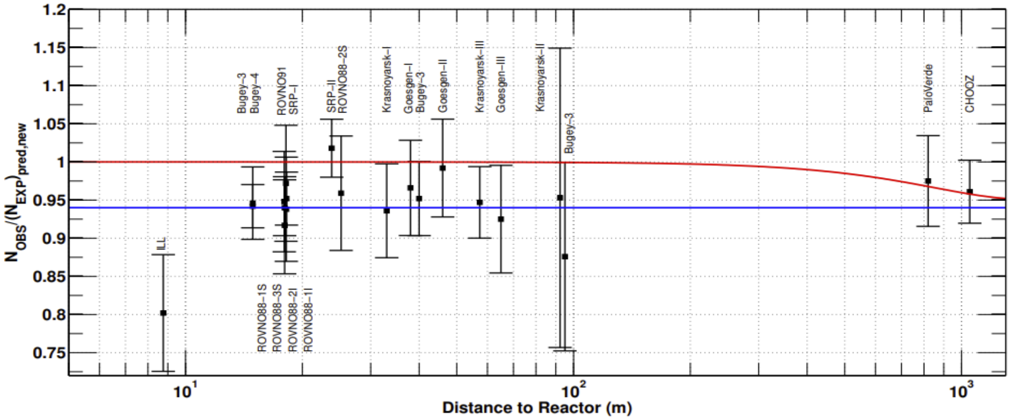
- **Neutrino Electromagnetic Properties**

  Atzori Corona et al, 2205.09484

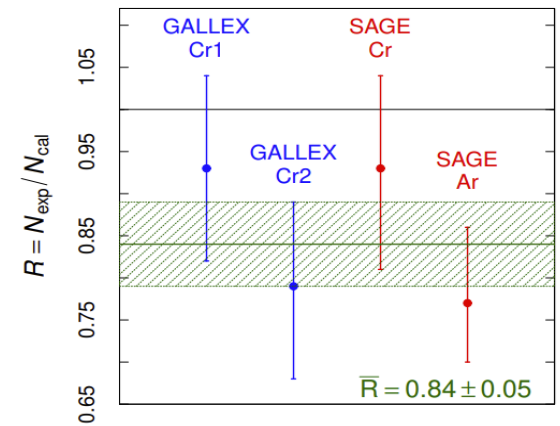
  See also the talk by Yingying Li

Historical Short-Baseline Anomalies

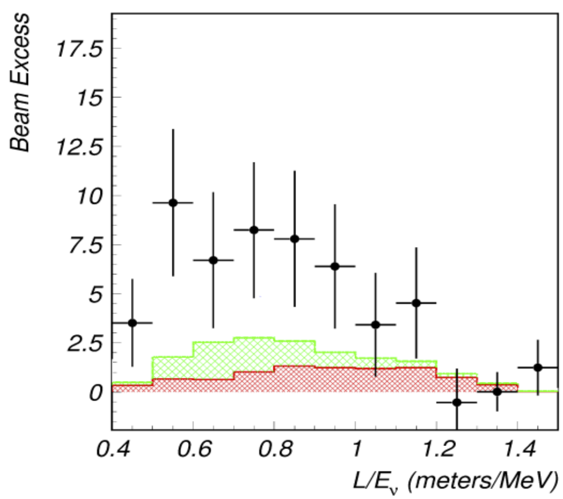
2011 Reactor Anomaly: $\bar{\nu}_e \to \bar{\nu}_x$ (2.5σ)



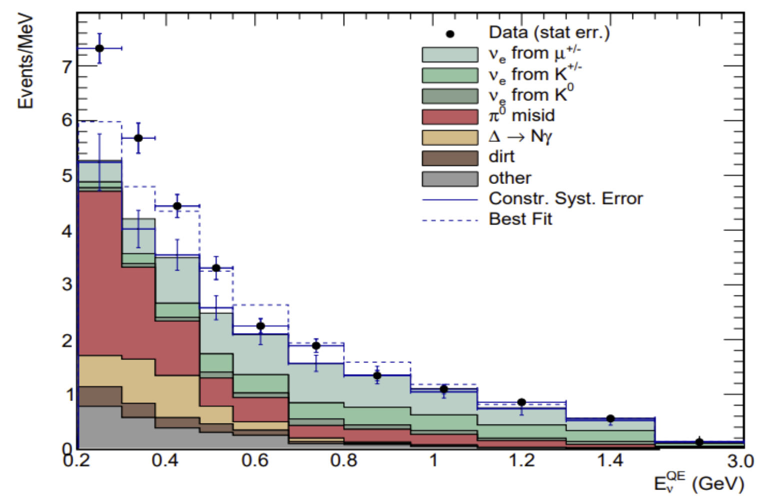
2005 Gallium Anomaly: $\nu_e \to \nu_x$ (2.9σ)



1995 LSND Anomaly: $\bar{\nu}_\mu \to \bar{\nu}_e$ ($\sim 4\sigma$)

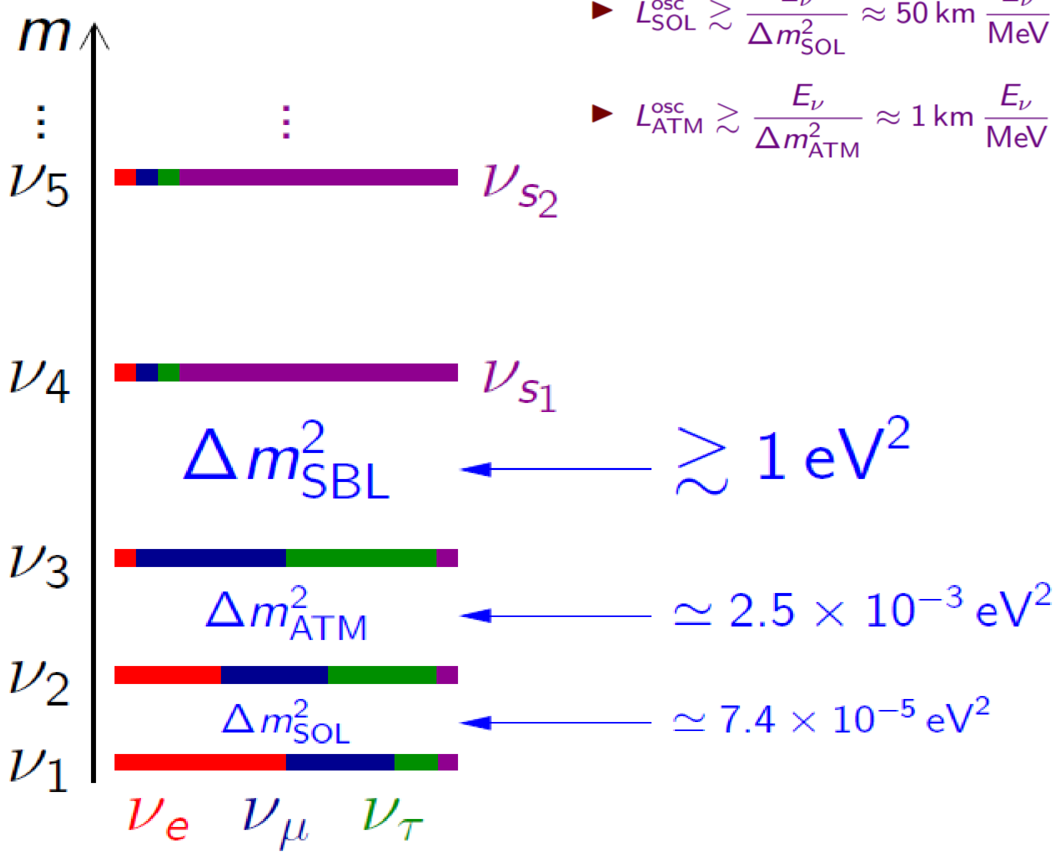


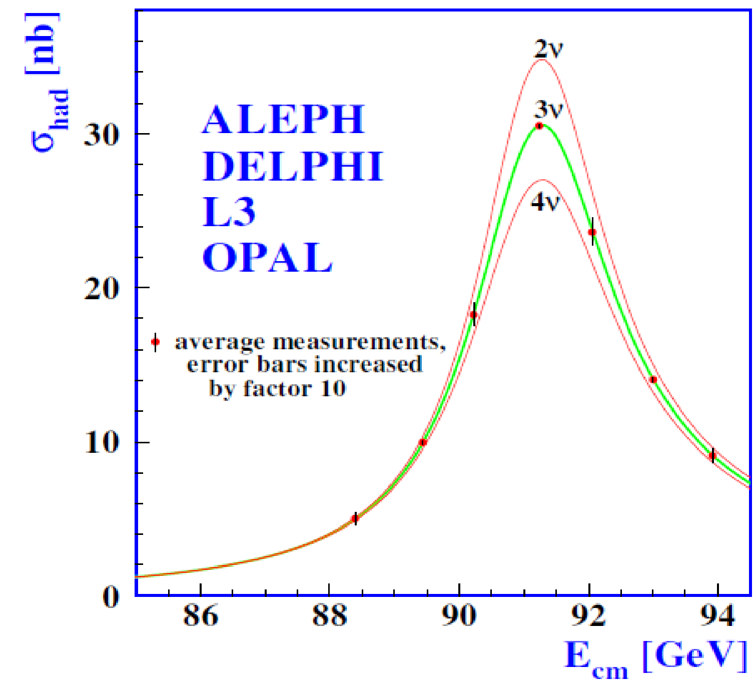
2008 MiniBooNE Anomaly: $\overset{(-)}{\nu}_\mu \to \overset{(-)}{\nu}_e$ (4.8σ)



Beyond 3-ν oscillation: Sterile neutrinos

- $L^{\text{osc}}_{\text{SOL}} \gtrsim \frac{E_\nu}{\Delta m^2_{\text{SOL}}} \approx 50\,\text{km}\,\frac{E_\nu}{\text{MeV}}$
- $L^{\text{osc}}_{\text{ATM}} \gtrsim \frac{E_\nu}{\Delta m^2_{\text{ATM}}} \approx 1\,\text{km}\,\frac{E_\nu}{\text{MeV}}$





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

Explanation of short baseline oscillations:

eV-scale sterile neutrinos (which have mixing with active mass eigenstates)

Parameterization and SBL Oscillations

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

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

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

$$U = \begin{pmatrix} c_{12}c_{13}c_{14} & s_{12}c_{13}c_{14} & c_{14}s_{13}e^{-i\delta_{13}} & s_{14}e^{-i\delta_{14}} \\ \cdots & \cdots & \cdots & c_{14}s_{24} \\ \cdots & \cdots & \cdots & c_{14}c_{24}s_{34}e^{-i\delta_{34}} \\ \cdots & \cdots & \cdots & c_{14}c_{24}c_{34} \end{pmatrix}$$

$$\Delta m^2_{\text{SBL}} = \Delta m^2_{41} \simeq \Delta m^2_{42} \simeq \Delta m^2_{43}$$

Different Notations

Effective short-baseline survival probability of ν_e (Gallium) and $\bar{\nu}_e$ (reactor):

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

with different notations in the literature:

$$\vartheta_{ee} = \vartheta_{14} = \vartheta_{\text{new}} = \vartheta$$

and

$$\Delta m_{41}^2 = \Delta m_{\text{SBL}}^2 = \Delta m_{\text{new}}^2 = \Delta m^2$$

Reactor Antineutrino Anomaly

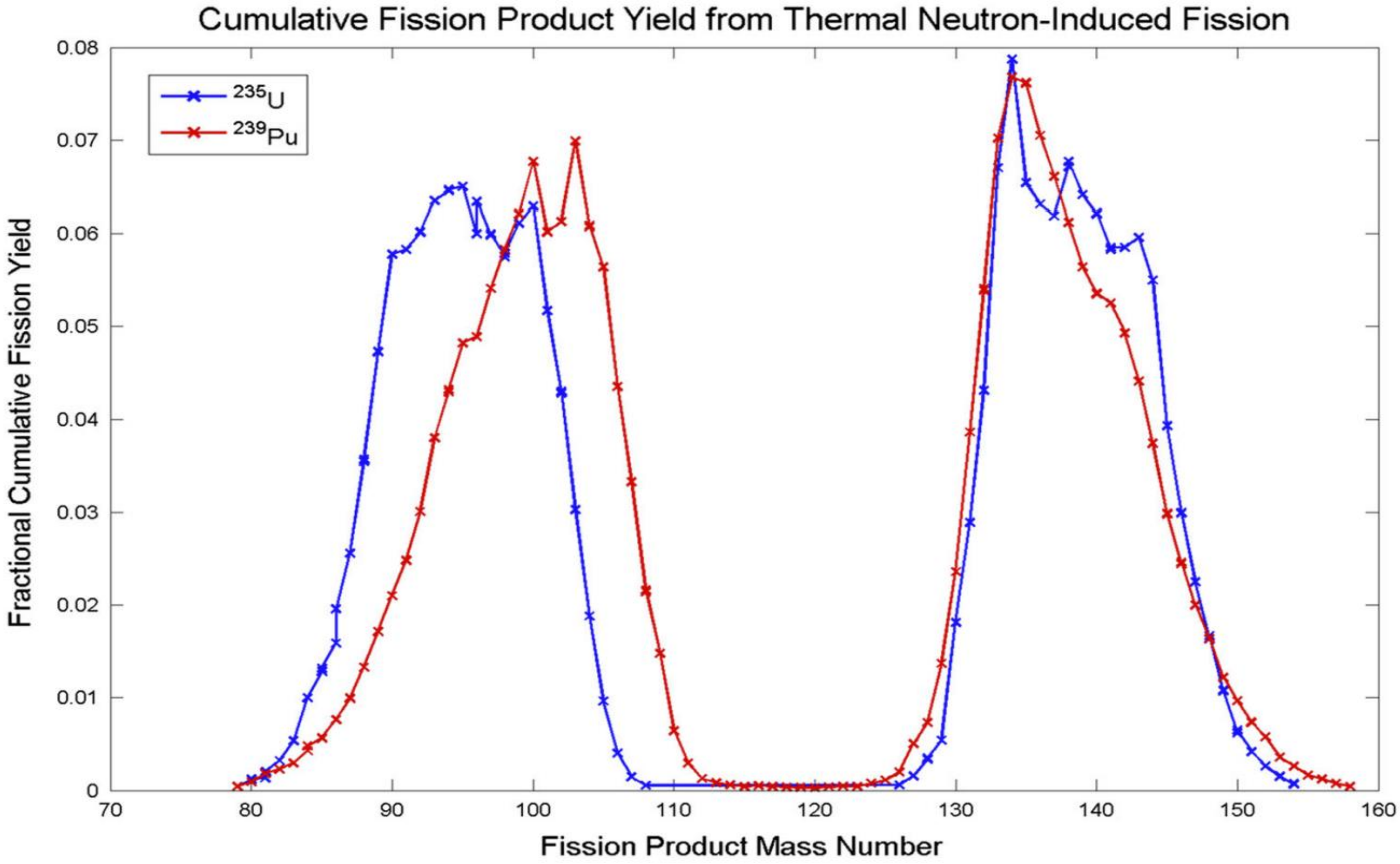
Reactor Flux Calculations

Two methods:

- Summation method (*ab initio*)
- Conversion method

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]

Summation (*ab initio*) Method

- Aggregate reactor spectrum (electron or neutrino):

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

$F_k(t)$ ↑ fission fractions

$$S_k(E) = \sum_n Y_n^k \sum_b \mathrm{BR}_n^b \; S_n^b(E)$$

Y_n^k ↑ cumulative fission yield

BR_n^b ↑ branching ratio

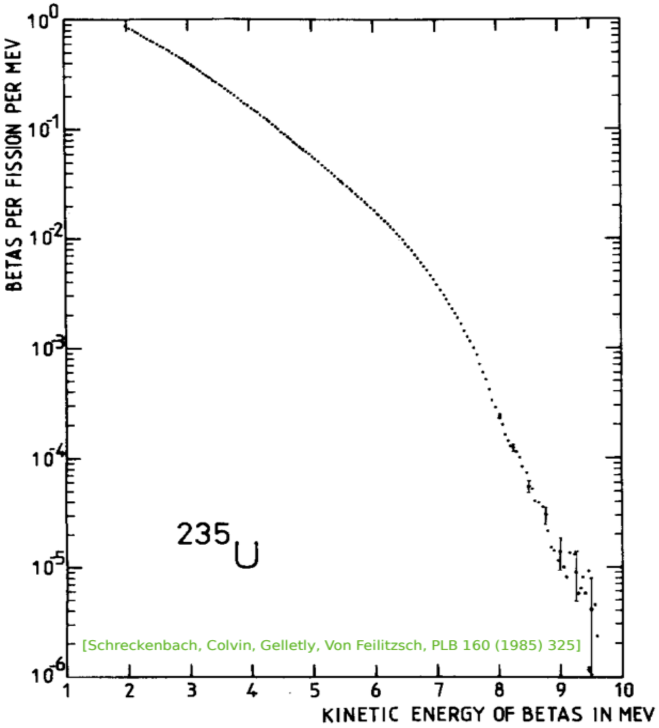
$S_n^b(E)$ ← allowed or forbidden decay spectrum

- The calculation of each $S_k(E)$ requires knowledge of about 1000 spectra and branching ratios.

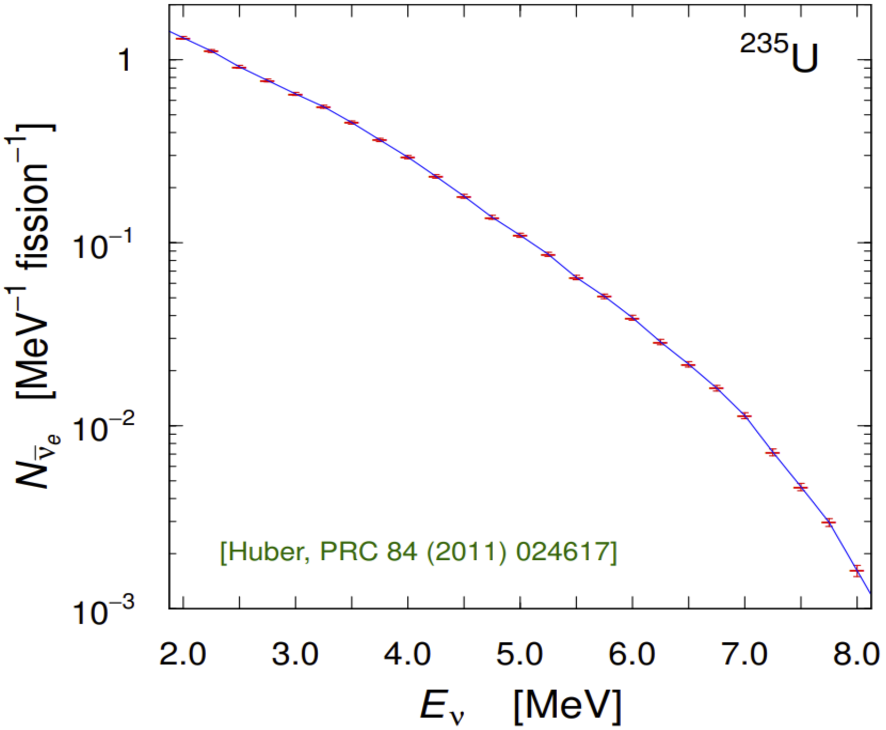
- Large uncertainties, because nuclear databases are incomplete and sometimes inexact.

Conversion Method

- 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.
- Semi-empirical method: conversion $S_k^e(E_e) \rightarrow S_k^\nu(E_\nu)$ considering ~ 30 virtual allowed β decay spectra. $(k = 235, 239, 241)$

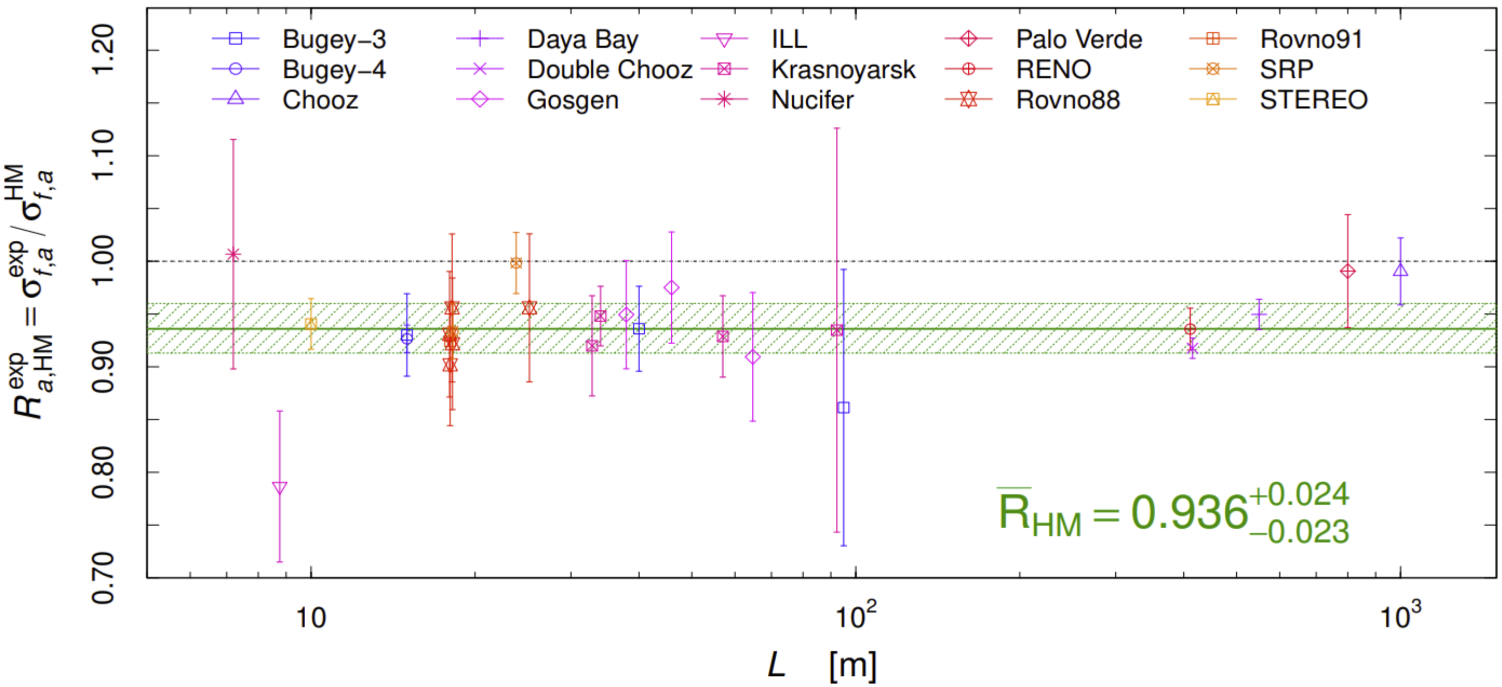


$\Longrightarrow$



2011: HM fluxes (conversion method)

[Mueller et al, arXiv:1101.2663], Huber, arXiv:1106.0687]



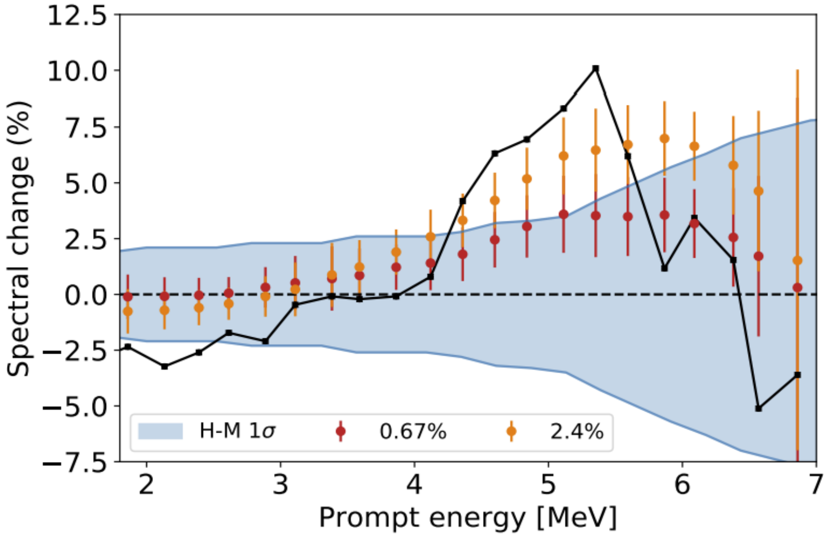
$2.5\,\sigma$ deficit $\Longrightarrow$ Anomaly!

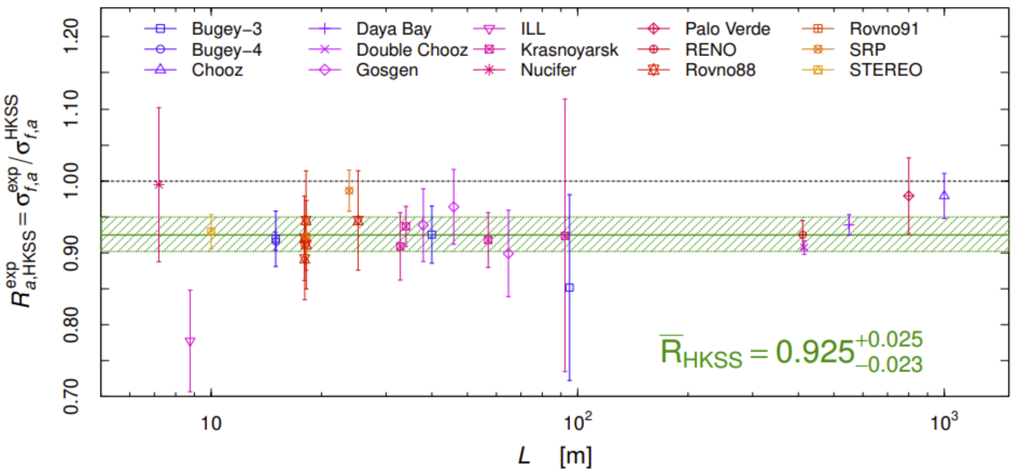
Giunti, YFL,Ternes, Xin, arXiv: 2110.06820

- Original 2011 Reactor Antineutrino Anomaly: 2.5σ [Mention et al, arXiv:1101.2755]

2019: HKSS fluxes (conversion method)

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





Giunti, YFL,Ternes, Xin, arXiv: 2110.06820

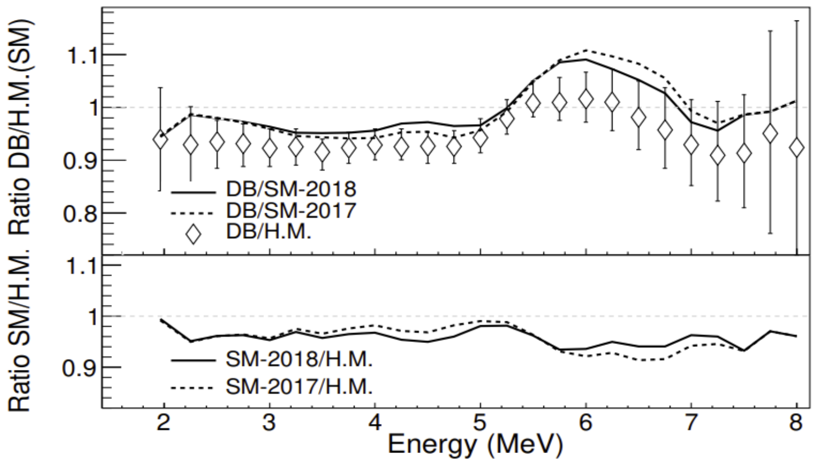
2.9 σ deficit $\Longrightarrow$ Anomaly larger than the 2.5 σ HM anomaly!

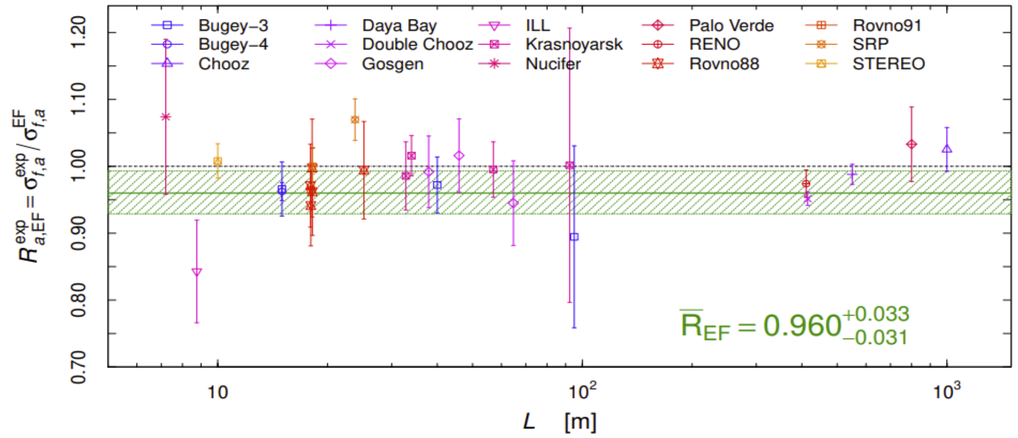
[See also: Berryman, Huber, arXiv:1909.09267, arXiv:2005.01756]

- HM + HKSS uncertainties.

2019: EF fluxes (summation method)

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





Giunti, YFL,Ternes, Xin, arXiv: 2110.06820

$1.2\,\sigma$ deficit $\Longrightarrow$ No Anomaly!

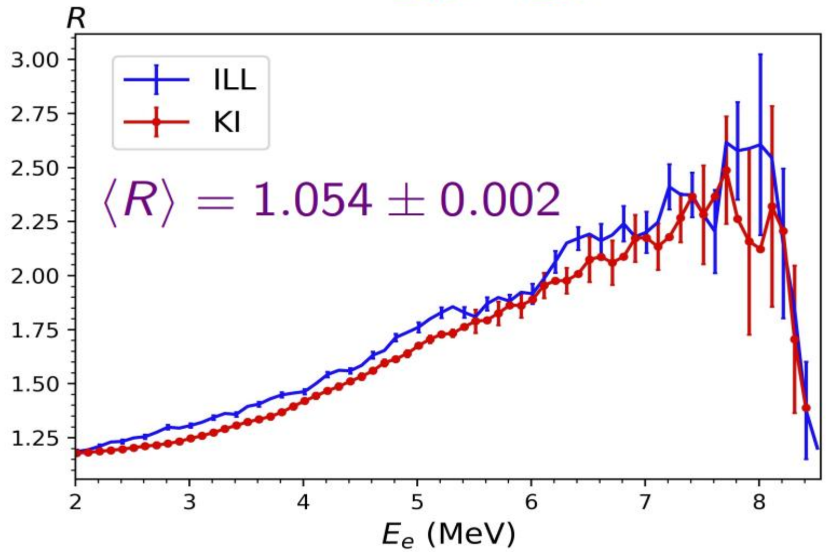
[See also: Berryman, Huber, arXiv:1909.09267, arXiv:2005.01756]

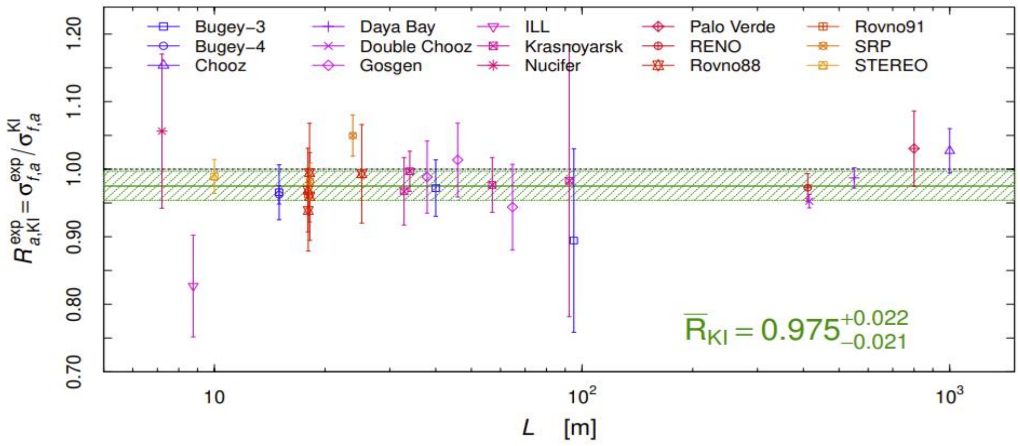
- UNKNOWN UNCERTAINTIES!
- Rough estimation used in our calculations: 5% for ^{235}U, ^{239}Pu, ^{241}Pu and 10% for ^{238}U. [Hayes, Jungman, McCutchan, Sonzogni, Garvey, Wang, arXiv:1707.07728]

2021: KI fluxes (conversion method)

[Kurchatov Institute: Kopeikin, Skorokhvatov, Titov, arXiv:2103.01684]

$$R = S_{235}^{(e)} / S_{239}^{(e)}$$





Giunti, YFL,Ternes, Xin, arXiv: 2110.06820

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

Approximate agreement with ab initio EF fluxes!

- HM + KI uncertainties.

Reactor Fuel Evolution

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

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

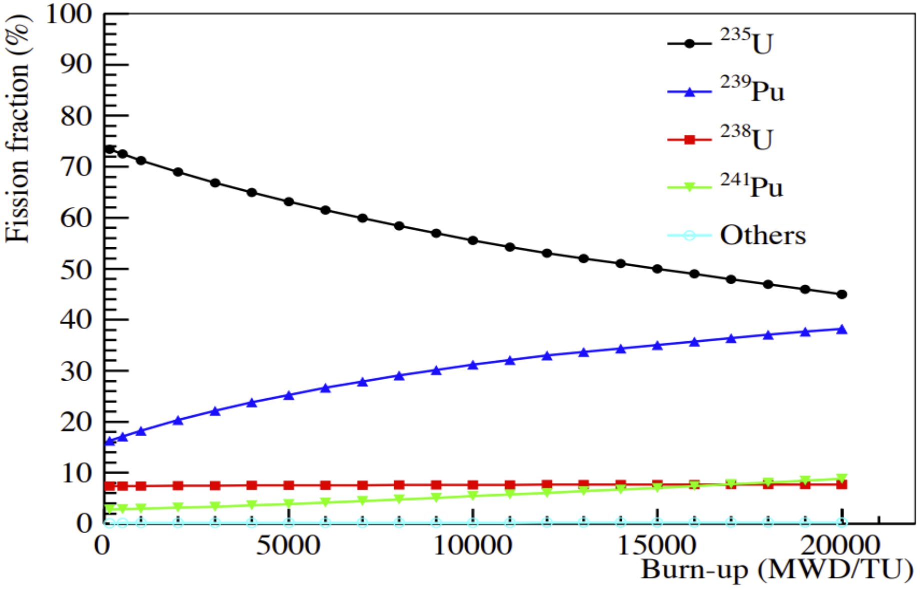
- Effective fission fractions:

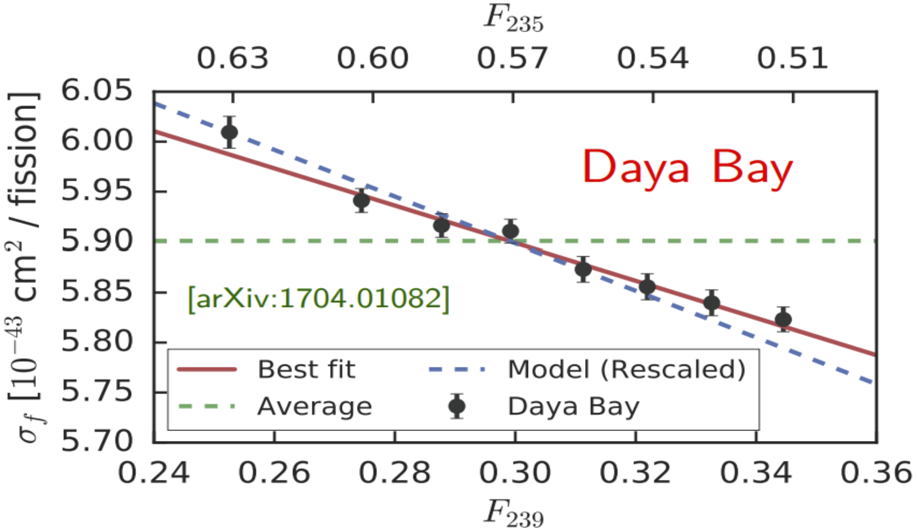
  F_{235} F_{238} F_{239} F_{241}

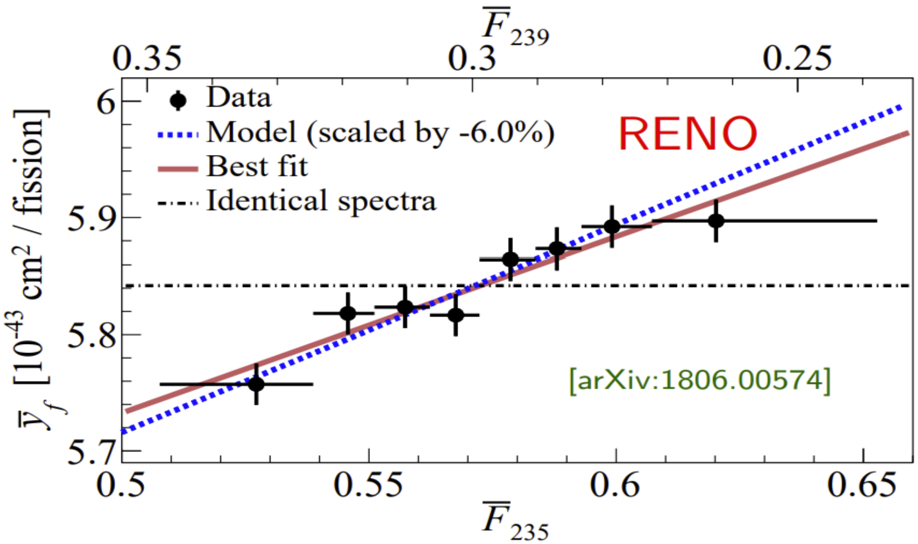
- Cross section per fission (IBD yield):

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

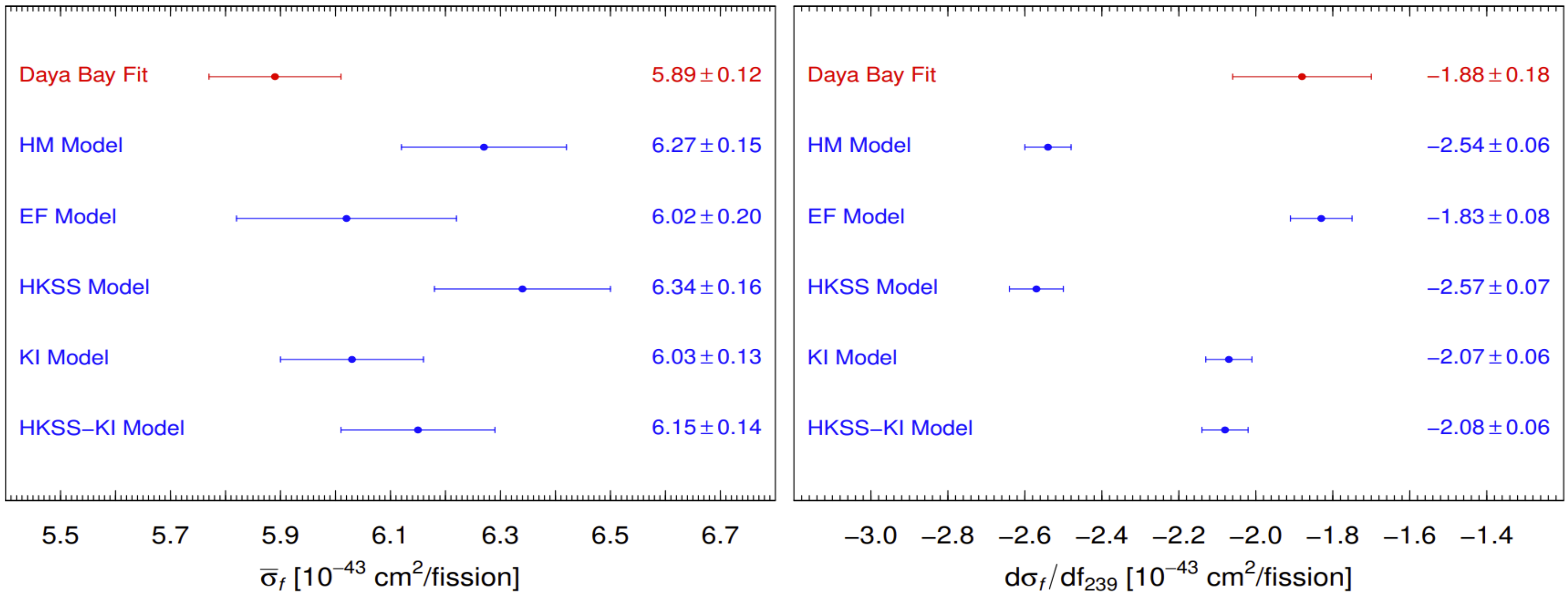
for $k = 235, 238, 239, 241$







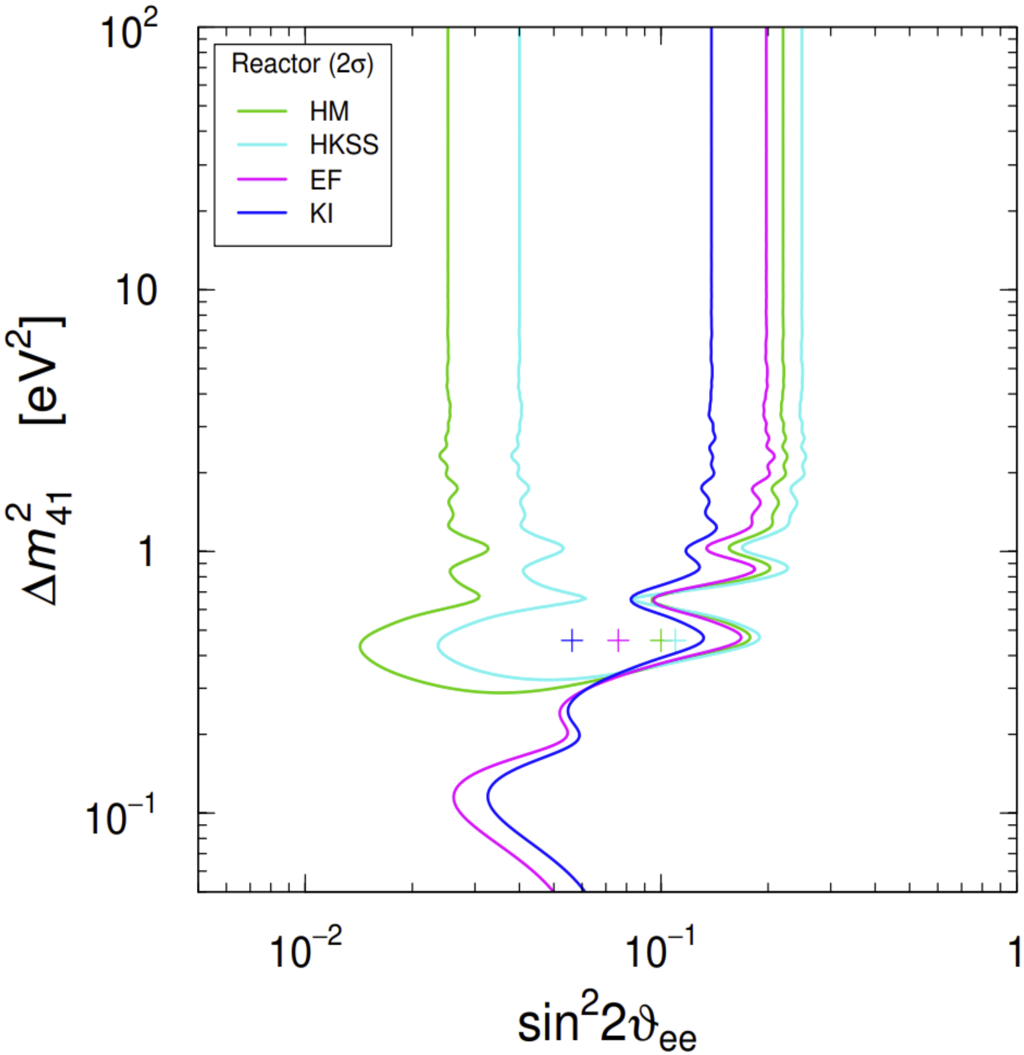
Model v.s. Data Comparison



Giunti, YFL,Ternes, Xin, arXiv: 2110.06820

- Tension with HM ($2.6\,\sigma$), HKSS ($2.8\,\sigma$), and HKSS-KI ($1.9\,\sigma$).
- Agreement with EF ($0.8\,\sigma$) and KI ($1.2\,\sigma$).

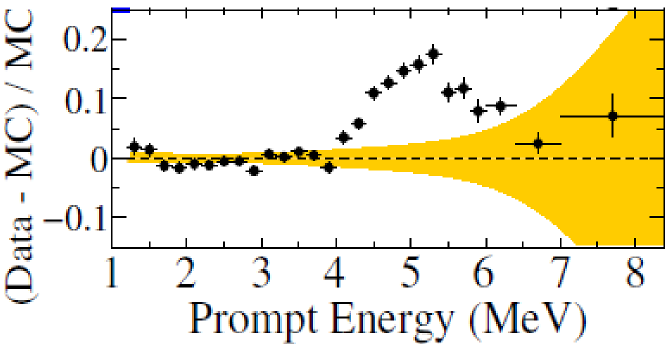
Limits on the SBL mixing



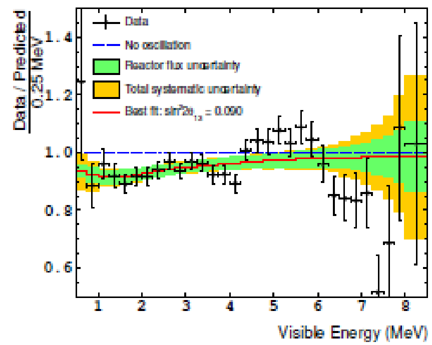
- The favored KI and EF models are compatible with the absence of SBL oscillations and give only 2σ upper bounds on the effective mixing parameter $\sin^2 2\vartheta_{ee} = \sin^2 2\vartheta_{14}$.
- Independently from the reactor neutrino flux model, we have

$$\sin^2 2\vartheta_{ee} \lesssim 0.25 \text{ at } 2\sigma.$$

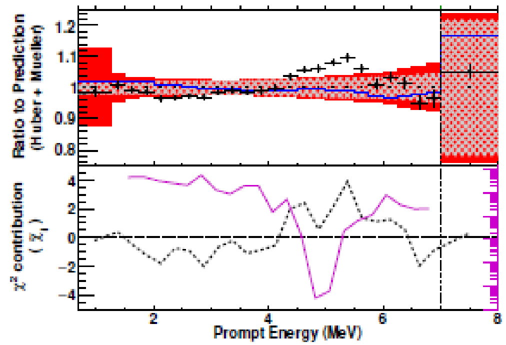
Reactor Antineutrino 5 MeV Bump (Shoulder)



[RENO, arXiv:1511.05849]



[Double Chooz, arXiv:1406.7763]



[Daya Bay, arXiv:1508.04233]

(1) The "5 MeV bump" cannot be explained by neutrino oscillations (SBL oscillations are averaged in RENO, Double Chooz and Daya Bay)

(2) Most of recent studies (a hot topic) attribute to the nuclear physics calculations

(3) Theoretical miscalculation of the spectrum → same for the rate ?

(4) Still NO complete calculation of the neutrino flux, spectrum and associated uncertainty: ***e.g., recent attempt in 2304.14992***

Gallium Anomaly

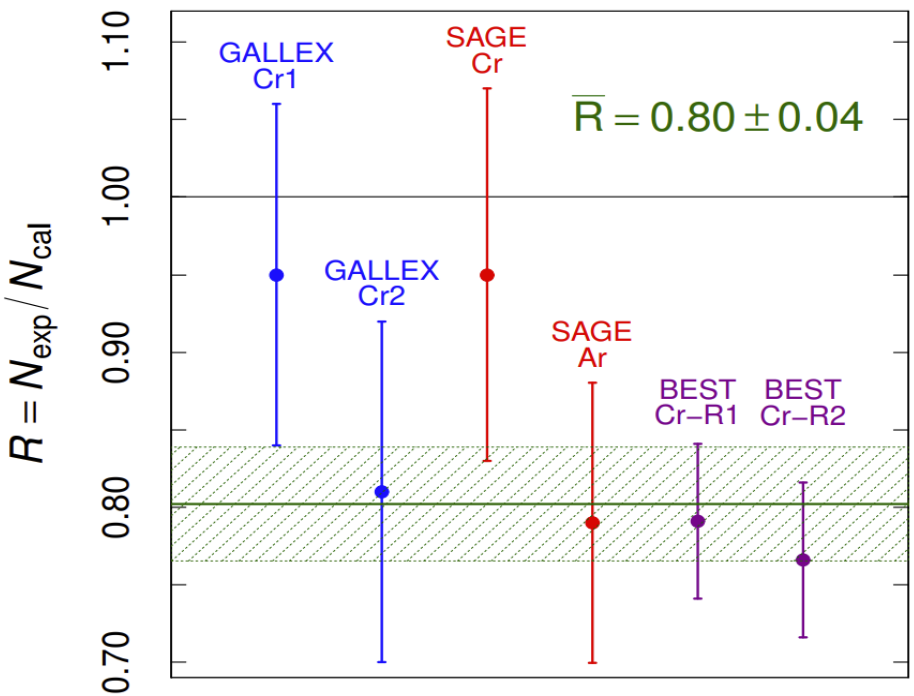
Gallium Anomaly

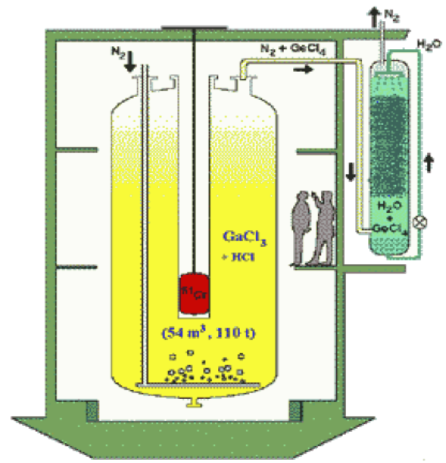
Gallium Radioactive Source Experiments: GALLEX, SAGE, BEST (2021)

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

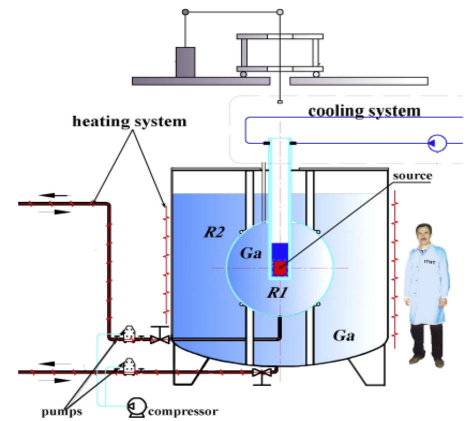
$E \simeq 0.75\,\text{MeV}$ $\quad E \simeq 0.81\,\text{MeV}$

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





GALLEX



BEST

$\approx$ 5-6σ deficit $\Longrightarrow$ Anomaly!

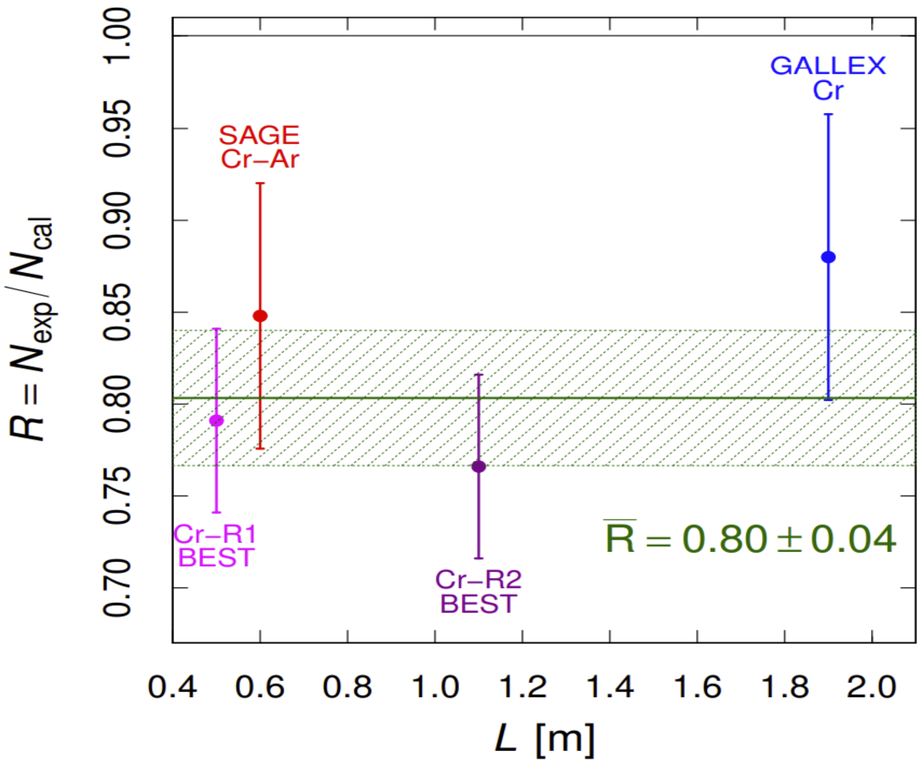
$\langle L \rangle_{\text{GALLEX}} \simeq 1.9\,\text{m}$ $\quad \langle L \rangle_{\text{SAGE}} \simeq 0.6\,\text{m}$

$\langle L \rangle^{\text{R1}}_{\text{BEST}} \simeq 0.7\,\text{m}$ $\quad \langle L \rangle^{\text{R2}}_{\text{BEST}} \simeq 1.1\,\text{m}$

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

[SAGE, arXiv:nucl-ex/0512041, arXiv:0901.2200; Laveder et al, NPPS 168 (2007) 344, arXiv:hep-ph/0610352, arXiv:0711.4222, arXiv:1006.3244; Kostensalo et al, arXiv:1906.10980; BEST, arXiv:2109.11482, arXiv:2109.14654; Berryman et al, arXiv:2111.12530]

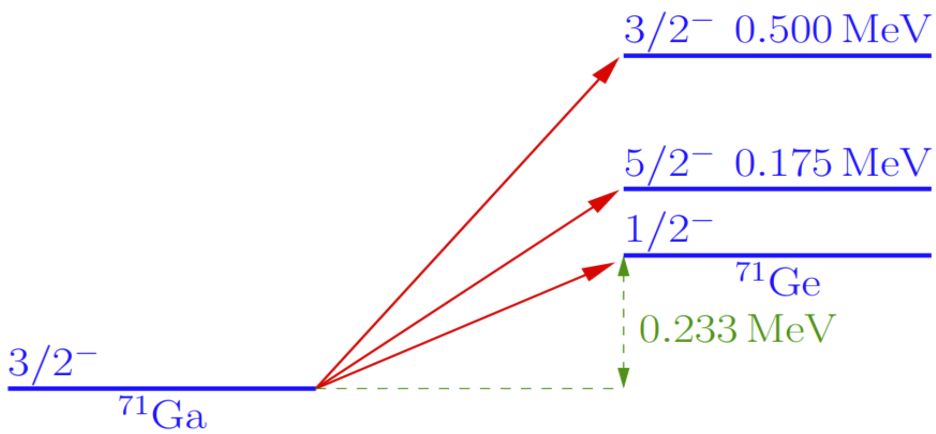
Gallium Anomaly



- No clear model-independent anomaly from different path lengths.
- Puzzling quasi-equality of the two BEST measurements at different distances.
- After the BEST measurements, the Gallium Anomaly is still an anomaly based on the absolute comparison of observed and predicted rates.

Cross section?

- A 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, hep-ph/9710491



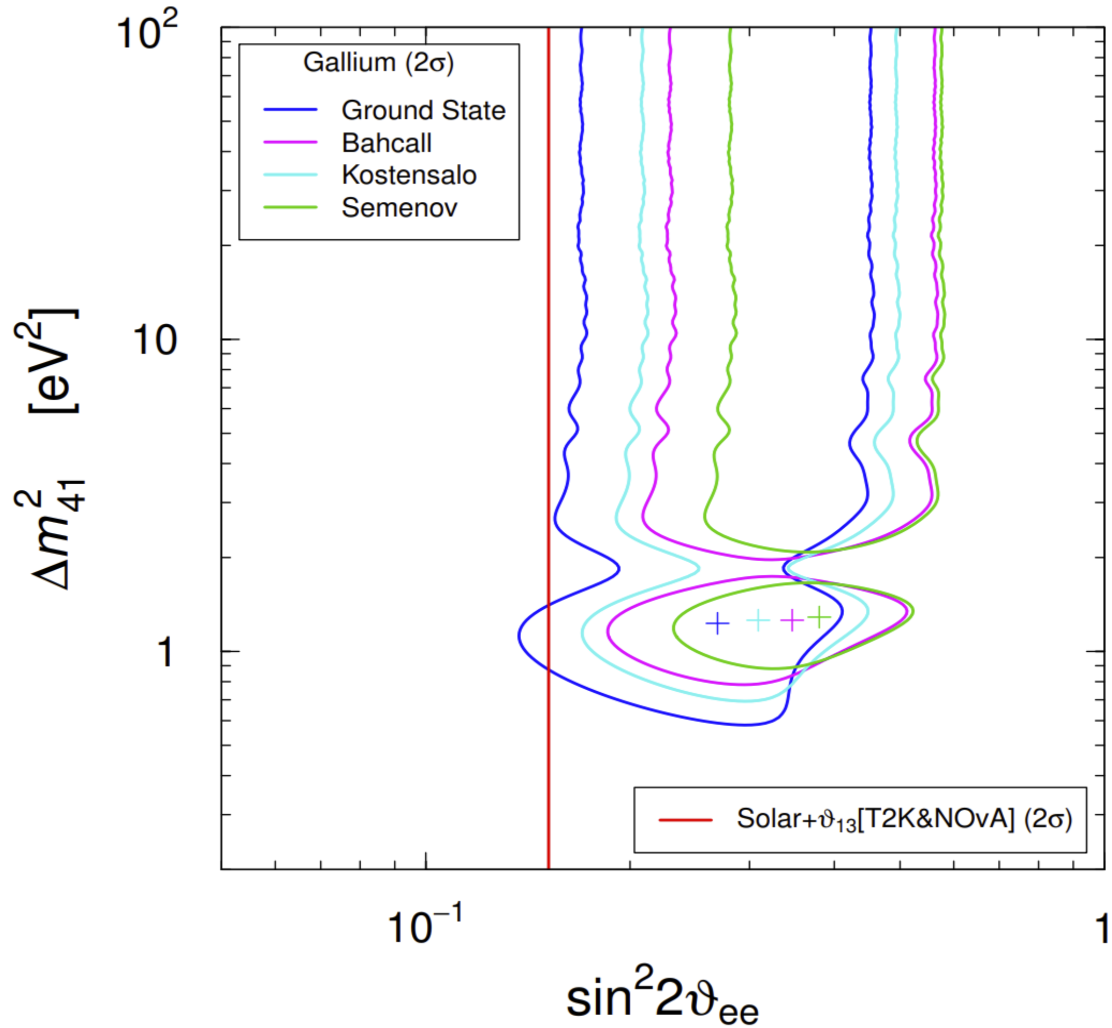
- $\sigma_{\text{G.S.}}$ from $T_{1/2}({}^{71}\text{Ge}) = 11.43 \pm 0.03\,\text{days}$ [Hampel, Remsberg, PRC 31 (1985) 666]
$$\sigma_{\text{G.S.}}({}^{51}\text{Cr}) = (5.54 \pm 0.02) \times 10^{-45}\,\text{cm}^2$$
- $$\sigma({}^{51}\text{Cr}) = \sigma_{\text{G.S.}}({}^{51}\text{Cr}) \left(1 + 0.669\,\frac{\text{BGT}_{175}}{\text{BGT}_{\text{G.S.}}} + 0.220\,\frac{\text{BGT}_{500}}{\text{BGT}_{\text{G.S.}}}\right)$$
- The contribution of excited states is only $\sim 5\%$! [Bahcall, hep-ph/9710491]

Cross section?

$\nu_e + {}^{71}\text{Ga} \to {}^{71}\text{Ge} + e^-$ cross sections in units of 10^{-45} cm^2:

		^{51}Cr		^{37}Ar			
		σ_{tot}	δ_{exc}	σ_{tot}	δ_{exc}	$\overline{R}$	GA
Ground State [Phys.Atom.Nucl. 83 (2020) 1549]	$T_{1/2}({}^{71}\text{Ge})$	5.539 ± 0.019	—	6.625 ± 0.023	—	0.844 ± 0.031	5.0σ
Bahcall [hep-ph/9710491]	${}^{71}\text{Ga}(p,n){}^{71}\text{Ge}$	5.81 ± 0.16	4.7%	7.00 ± 0.21	5.4%	0.802 ± 0.037	5.4σ
Kostensalo et al. [arXiv:1906.10980]	Shell Model	5.67 ± 0.06	2.3%	6.80 ± 0.08	2.6%	0.824 ± 0.031	5.6σ
Semenov [Phys.Atom.Nucl. 83 (2020) 1549]	${}^{71}\text{Ga}({}^{3}\text{He},{}^{3}\text{H}){}^{71}\text{Ge}$	5.938 ± 0.116	6.7%	7.169 ± 0.147	7.6%	0.786 ± 0.033	6.6σ

Gallium – Solar neutrino tension



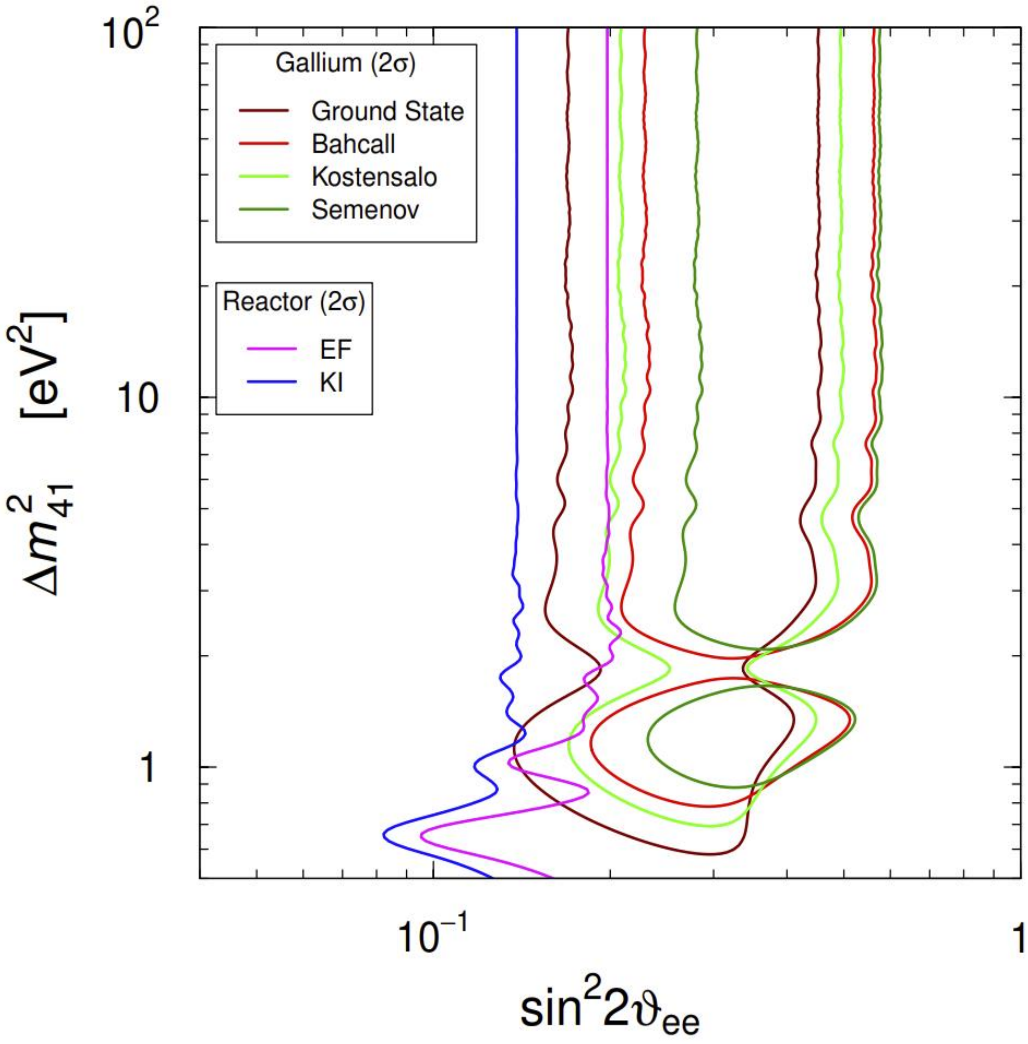
	Solar neutrinos + ϑ_{13}[T2K&NOvA]	
	$\Delta\chi^2_{PG}$	GoF_{PG}
Ground State	10.65	0.49%
Bahcall	14.14	0.085%
Kostensalo	12.79	0.17%
Semenov	17.24	0.018%

Giunti, YFL,Ternes, Tyagi, Xin, arXiv: 2209.00916

- Both Gallium and solar experiments detect neutrinos.
- No CPT-violating solution of the tension!

[see also: Goldhagen, Maltoni, Reichard, Schwetz, arXiv:2109.14898; Berryman, Coloma, Huber, Schwetz, Zhou, arXiv:2111.12530]

Gallium – Reactor rates tension



	EF		KI	
	$\Delta\chi^2_{PG}$	GoF_{PG}	$\Delta\chi^2_{PG}$	GoF_{PG}
Ground State	9.1	1.1%	11.9	0.26%
Bahcall	12.9	0.16%	16.3	0.029%
Kostensalo	11.5	0.31%	15.3	0.049%
Semenov	17.0	0.02%	22.5	0.0013%

Giunti, YFL,Ternes, Tyagi, Xin, arXiv: 2209.00916

Nuclear effects for Gallium Anomaly ?

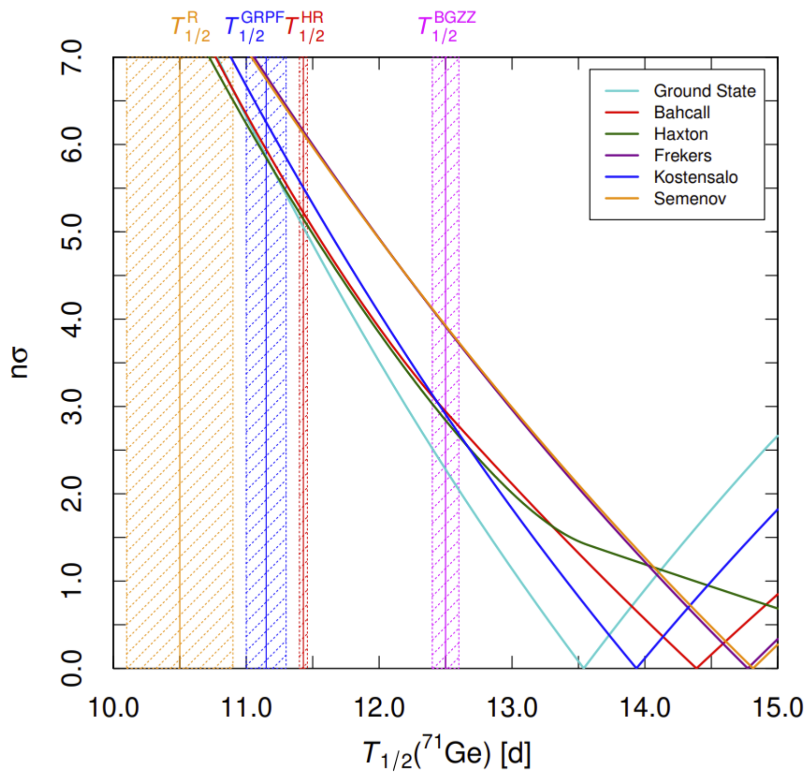
$$T_{1/2}^{\mathrm{BGZZ}}(^{71}\mathrm{Ge}) = 12.5 \pm 0.1\,\mathrm{d} \quad \text{(Bisi, Germagnoli, Zappa, and Zimmer, 1955) [39]},$$

$$T_{1/2}^{\mathrm{R}}(^{71}\mathrm{Ge}) = 10.5 \pm 0.4\,\mathrm{d} \quad \text{(Rudstam, 1956) [40]},$$

Giunti, YFL,Ternes, Xin, arXiv: 2212.09722

$$T_{1/2}^{\mathrm{GRPF}}(^{71}\mathrm{Ge}) = 11.15 \pm 0.15\,\mathrm{d} \quad \text{(Genz, Renier, Pengra, and Fink, 1971) [41]},$$

$$T_{1/2}^{\mathrm{HR}}(^{71}\mathrm{Ge}) = 11.43 \pm 0.03\,\mathrm{d} \quad \text{(Hampel and Remsberg, 1985) [42]}.$$



See also in Brdar, Gehrlein, Kopp, 2303.05528

a) Enlarged life time of Ge71

b) New excited states

c) Changes of branching ratios

scenario	comments	our rating
Explanations within the Standard Model		
increased ^{71}Ge half-life (Section 2.1 and Ref. [39])	would lead to smaller matrix element for $\nu + {}^{71}$Ga; but the ^{71}Ge half-life has been measured many times with different methods in [38], all of which yield consistent results. So it is hard to imagine a bias in these measurements.	★★☆☆☆
new ^{71}Ga excited state (Section 2.2)	would imply a bias in the extraction of the $\nu + {}^{71}$Ga matrix element from the measured ^{71}Ge half-life. Some very old experiments claim the existence of such a state, but this has not been confirmed in more recent observations.	★★☆☆☆
increased BR(^{51}Cr → ^{51}V*) (Section 3)	would cause a bias in translating the heat output of the source to a neutrino production rate. Measurements of BR(^{51}Cr → ^{51}V*) show some tension, but it is far less than the shift required to explain the gallium anomaly.	★★★☆☆
^{71}Ge extraction efficiency (Section 4)	one of SAGE's calibration runs has revealed a large bias. Could a small, unnoticed, bias have been present in all gallium experiments?	★★★★☆

Beyond Simple 3+1 mixing scheme

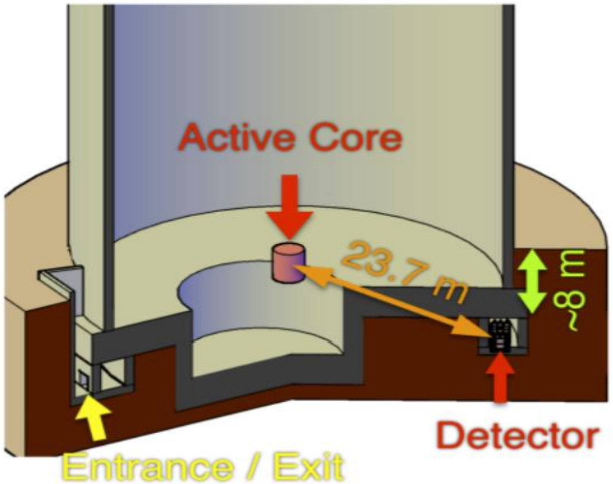
Explanations beyond the Standard Model		
ν_s coupled to ultralight DM (MSW resonance, Sec. 5.1.1)	several exotic ingredients; somewhat tuned MSW resonance; new ν_4 decay channel required for cosmology.	★★★★☆
ν_s coupled to dark energy (MSW resonance, Sec. 5.1.2)	several exotic ingredients; somewhat tuned MSW resonance; cosmology similar to the previous scenario.	★★★☆☆
ν_s coupled to ultralight DM (param. resonance, Sec. 5.1.3)	several exotic ingredients; somewhat tuned parametric resonance; cosmology requires post-BBN DM production via misalignment.	★★★★☆
decaying ν_s (Section 5.2)	difficult to reconcile with reactor and solar data; regeneration of active neutrinos in ν_s decays alleviates tension, but does not resolve it.	★★☆☆☆
vanilla eV-scale ν_s (Refs. [17, 18])	preferred parameter space is strongly disfavored by solar and reactor data.	★☆☆☆☆
ν_s with CPT violation (Refs. [130])	avoids constraints from reactor experiments, but those from solar neutrinos cannot be alleviated.	
extra dimensions (Refs. [131–133])	neutrinos oscillate into sterile Kaluza–Klein modes that propagate in extra dimensions; in tension with reactor data.	
stochastic neutrino mixing (Ref. [134])	based on a difference between sterile neutrino mixing angles at production and detection (see also [135, 136]); fit worse than for vanilla ν_s.	
decoherence (Refs. [137, 138])	non-standard source of decoherence needed; known experimental energy resolutions constrain wave packet length, making an explanation by wave packet separation alone challenging.	
ν_s coupled to ultralight scalar (Ref. [139])	ultralight scalar coupling to ν_s and to ordinary matter affects sterile neutrino parameters; can not avoid reactor constraints	

Status of light sterile neutrinos

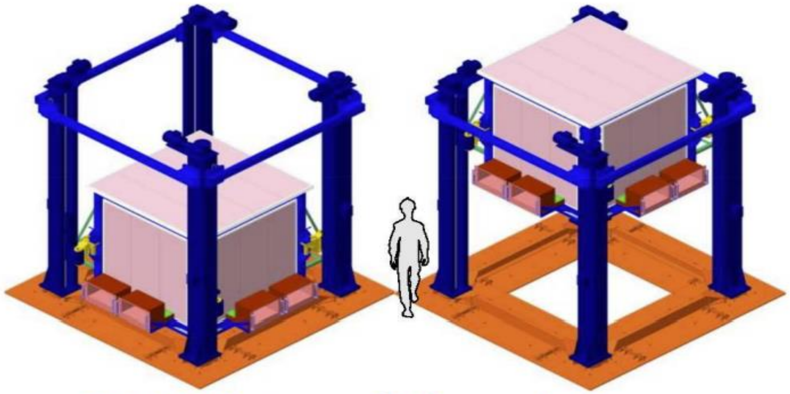
Model Indep. Measurements at Reactors

Ratios of spectra at different distances

NEOS

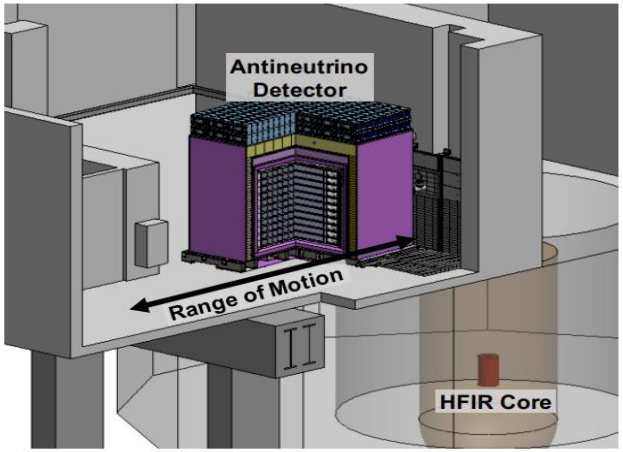


DANSS [Alekseev @ NOW 2022]

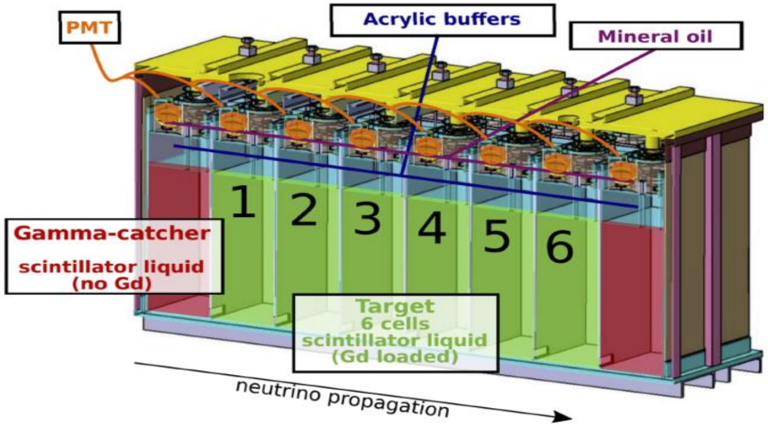


DANSS on a lifting platform

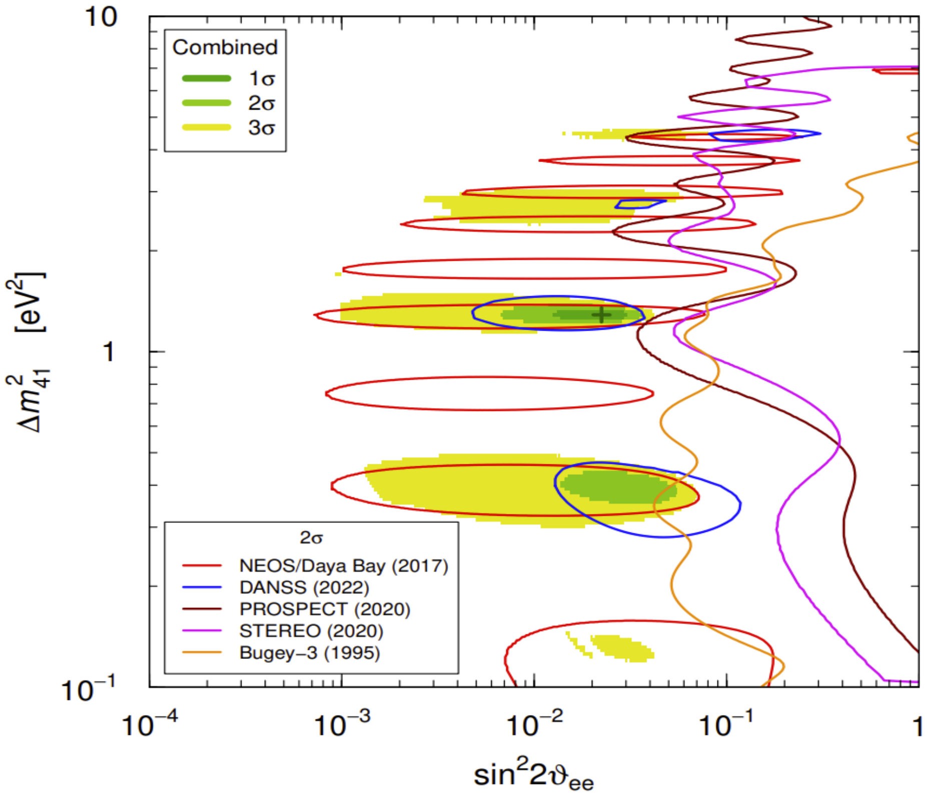
PROSPECT [Roca Catala @ NOW 2022]

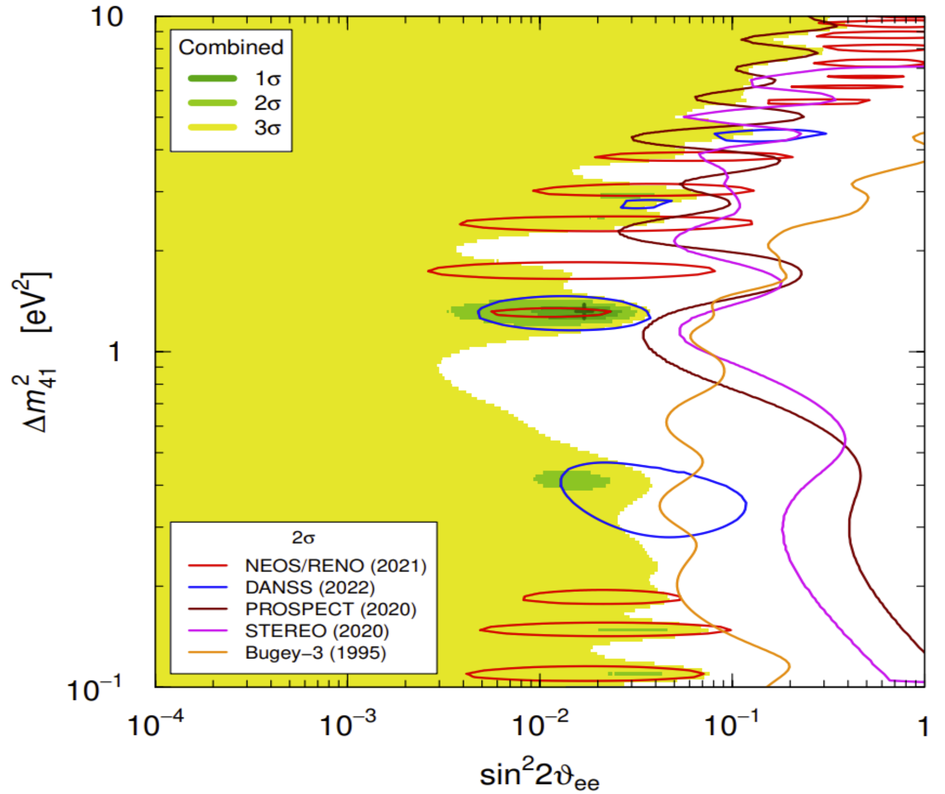


STEREO [del Amo Sanchez @ NOW 2022]



Model Indep. Measurements at Reactors

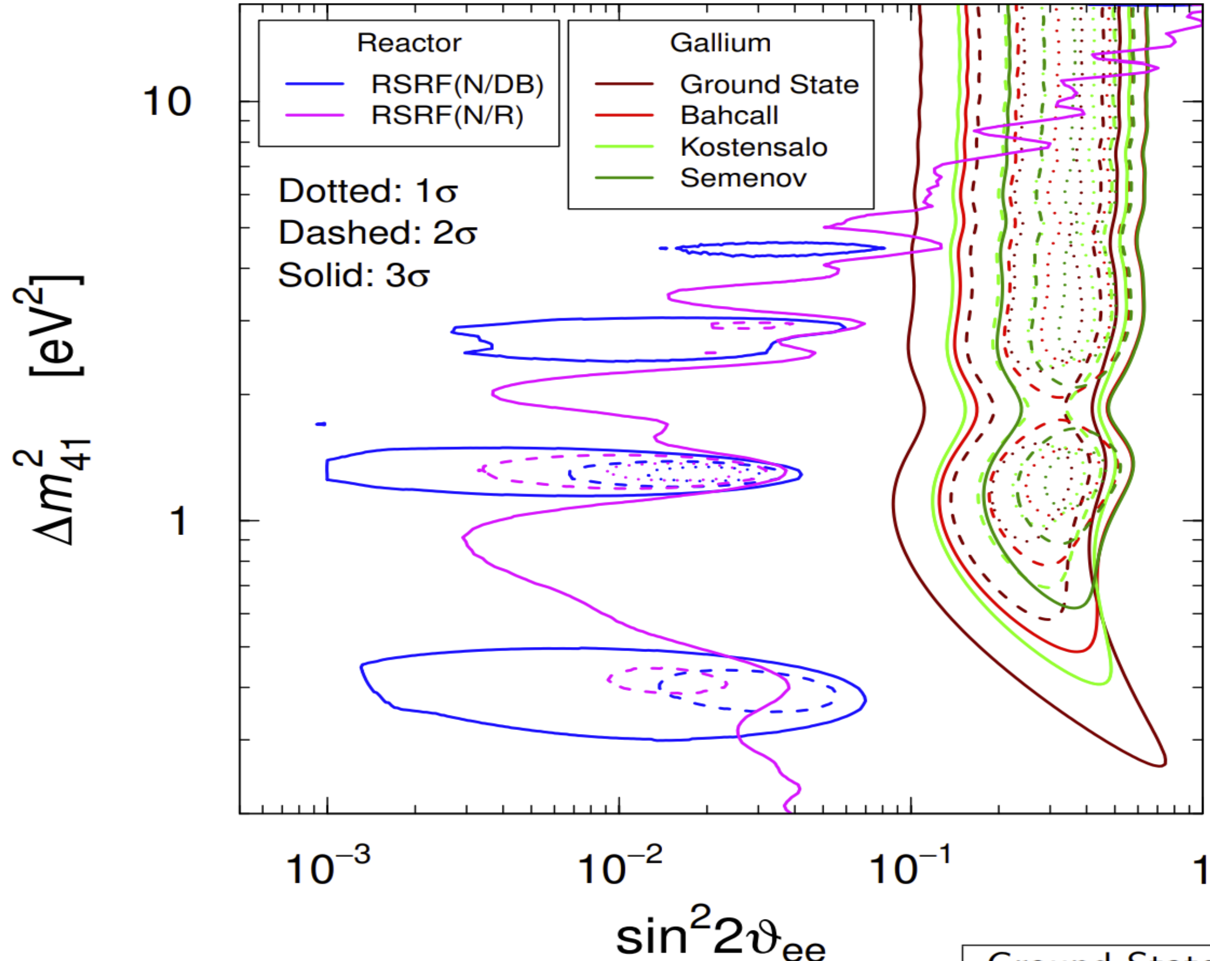




Giunti, YFL,Ternes, Tyagi, Xin, arXiv: 2209.00916

- Fit with NEOS/Daya Bay: $\Delta\chi^2_{3\nu-4\nu} = 12.6 \Longrightarrow 3.1\ \sigma$
- Fit with NEOS/RENO: $\Delta\chi^2_{3\nu-4\nu} = 9.1 \Longrightarrow 2.6\ \sigma$

Gallium – Reactor spectral-ratio tension



- The Reactor Spectral Ratio Fits (RSRF) prefer SBL oscillations with small mixing ($\sin^2 2\vartheta_{ee} \approx 0.02$).
- Tension with the Gallium Anomaly!

	RSRF(N/DB)		RSRF(N/R)	
	$\Delta\chi^2_{PG}$	GoF_{PG}	$\Delta\chi^2_{PG}$	GoF_{PG}
Ground State	12.95	0.15%	8.91	1.2%
Bahcall	12.86	0.16%	8.74	1.3%
Kostensalo	12.91	0.16%	8.89	1.2%
Semenov	12.88	0.16%	8.70	1.3%

Giunti, YFL,Ternes, Tyagi, Xin, arXiv: 2209.00916

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:

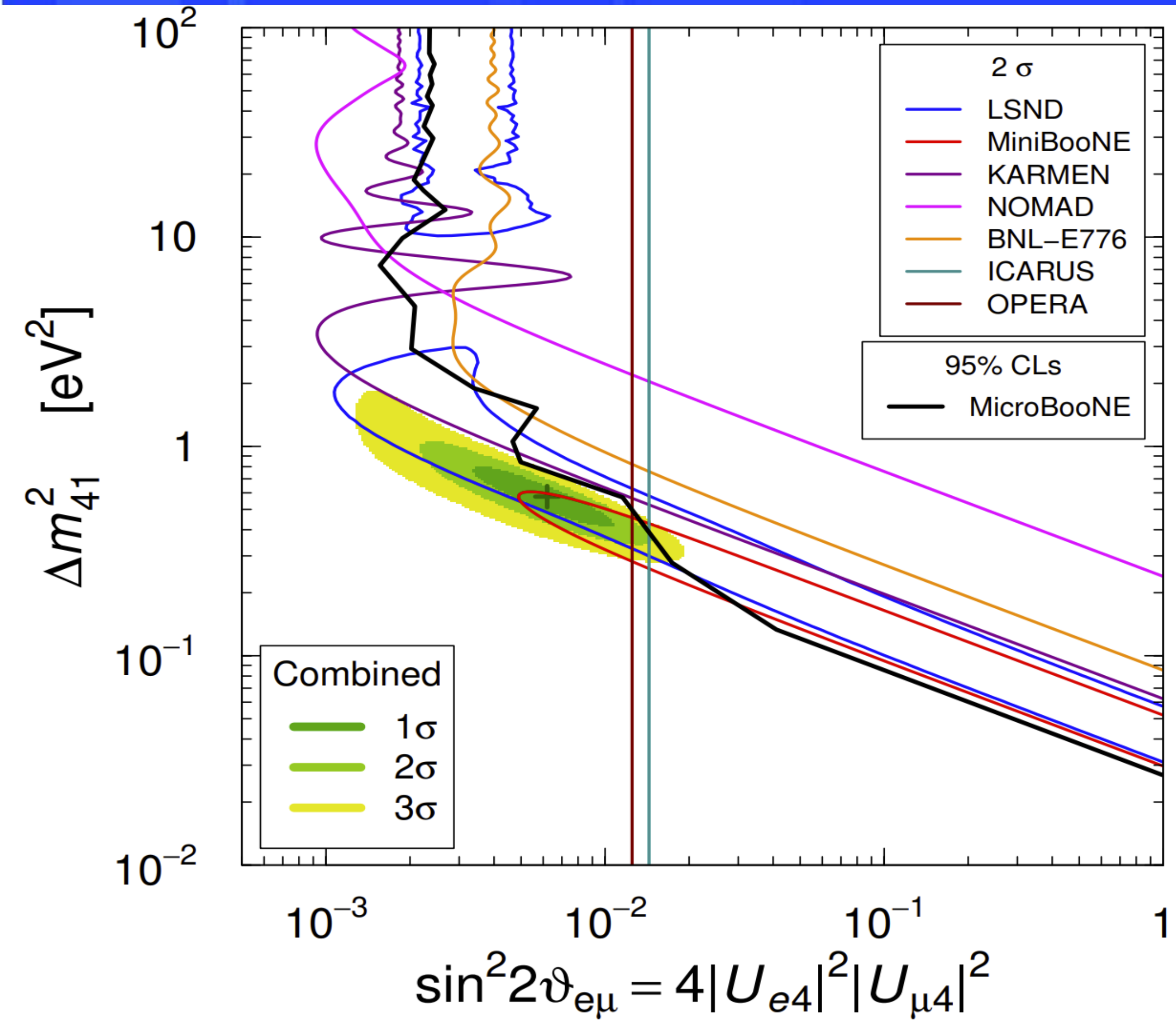
$$\sin^2 2\vartheta_{e\mu} = 4|U_{e4}|^2|U_{\mu 4}|^2 \simeq \frac{1}{4} \sin^2 2\vartheta_{ee} \sin^2 2\vartheta_{\mu\mu}$$

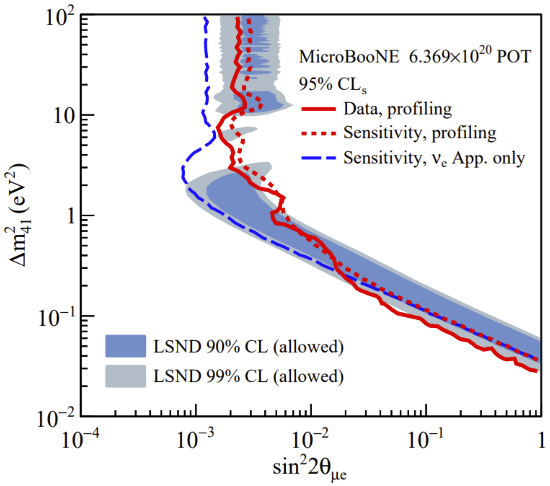
quadratically suppressed for small $|U_{e4}|^2$ and $|U_{\mu 4}|^2$

$\Downarrow$

Appearance-Disappearance Tension

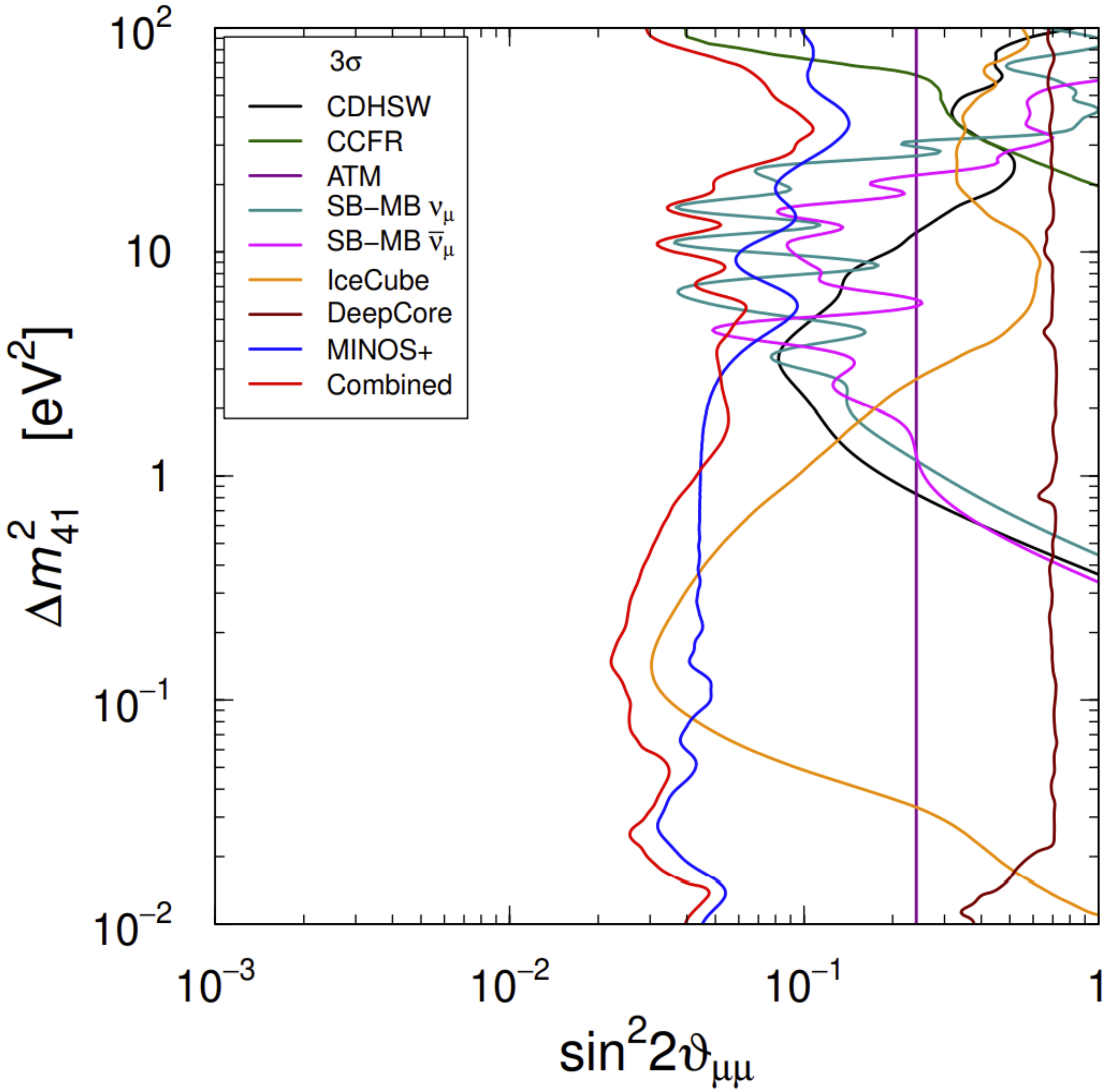
Appearance ($\nu_\mu \rightarrow \nu_e$) channel

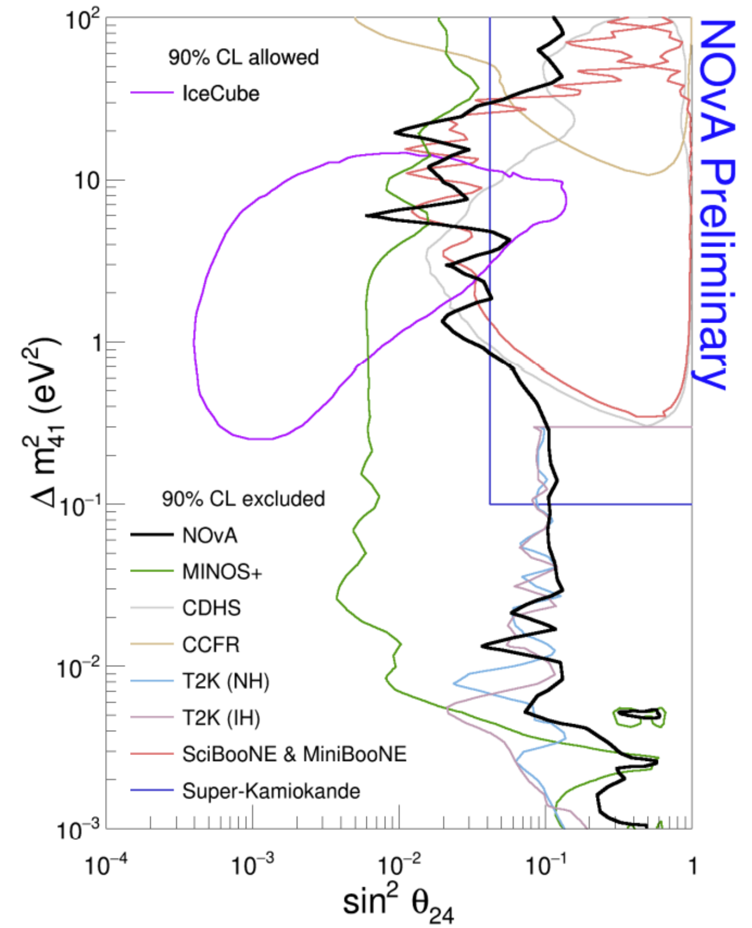




MicroBooNE, 2210.10216,
See also Xiangpan Ji's talk

Disappearance (ν_μ) channel





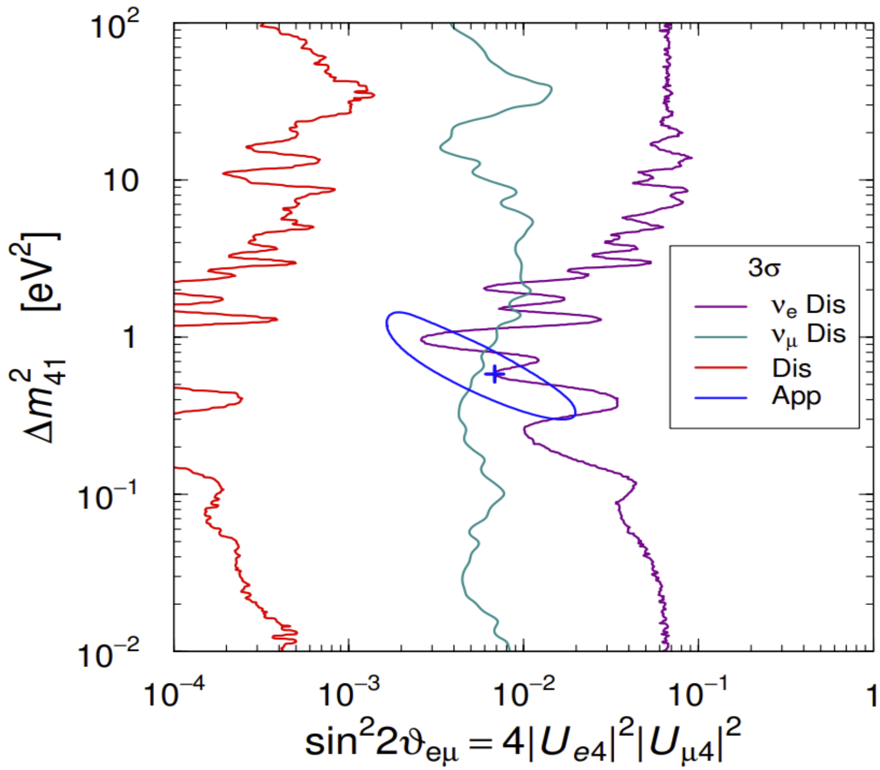
[Aurisano @ NOW 2022]

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!
- 2019 Global Fit:

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

  $\text{GoF} = 11\%$

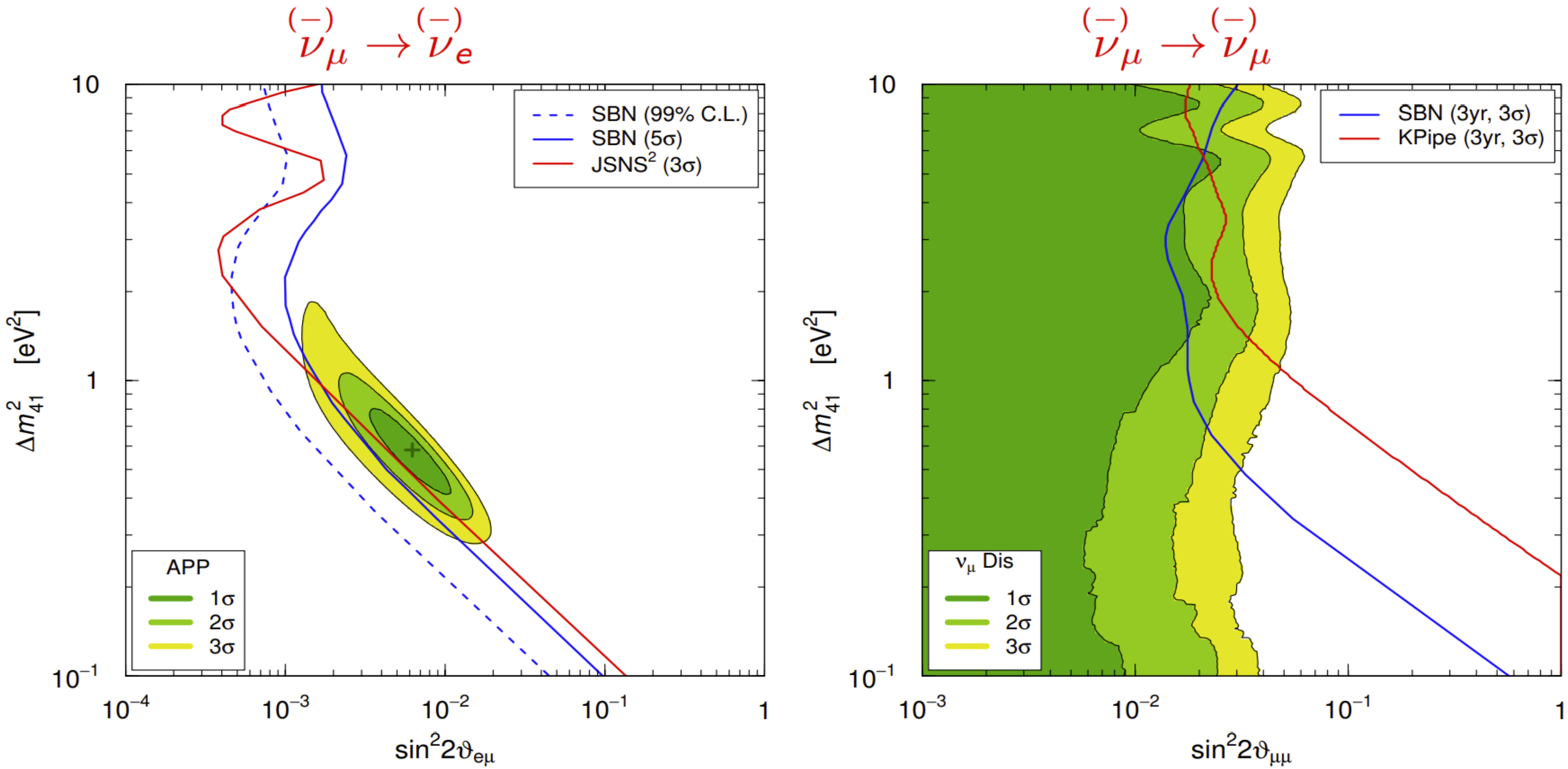
  $\chi^2_{\text{PG}}/\text{NDF}_{\text{PG}} = 46.7/2$

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

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

1508.03172

New Dedicated Experiments



- SBN: Stanco @ NOW 2022 and Karagiorgi @ NOW 2022.
- JSNS^2 : August 2022 Long-Baseline Neutrino News: They are working on the blind analysis of the 1.45×10^{22} POT data taken until June 2021.

Conclusion

- **Light Sterile Neutrinos can be powerful messengers of BSM New Physics.**
- **Historically, the existence of light sterile neutrinos is motivated by the LSND, Gallium, and Reactor Anomalies.**
- **The Reactor Antineutrino Anomaly, discovered in 2011, is practically resolved with new flux models.**
- **The Gallium Neutrino Anomaly, discovered in 2007, has been revived by the BEST results.**
- **Puzzling Gallium-Reactor tension, DIS-APP tension?**
- **Beyond simple 3+1 scheme?**

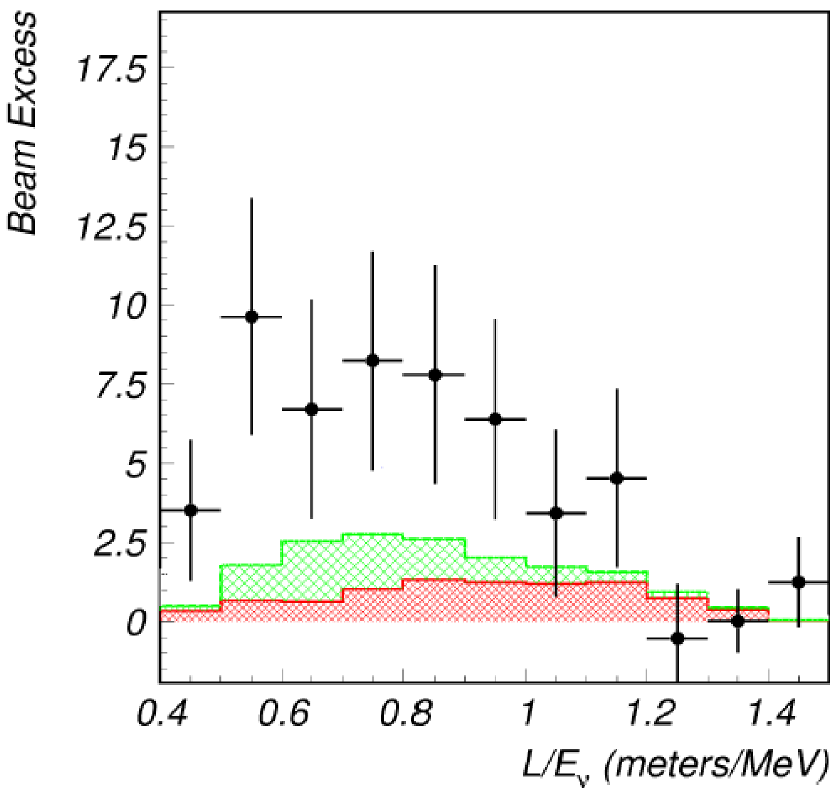
Thank you for your attention!

Backup

LSND

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

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



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

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

800 MeV

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

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

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

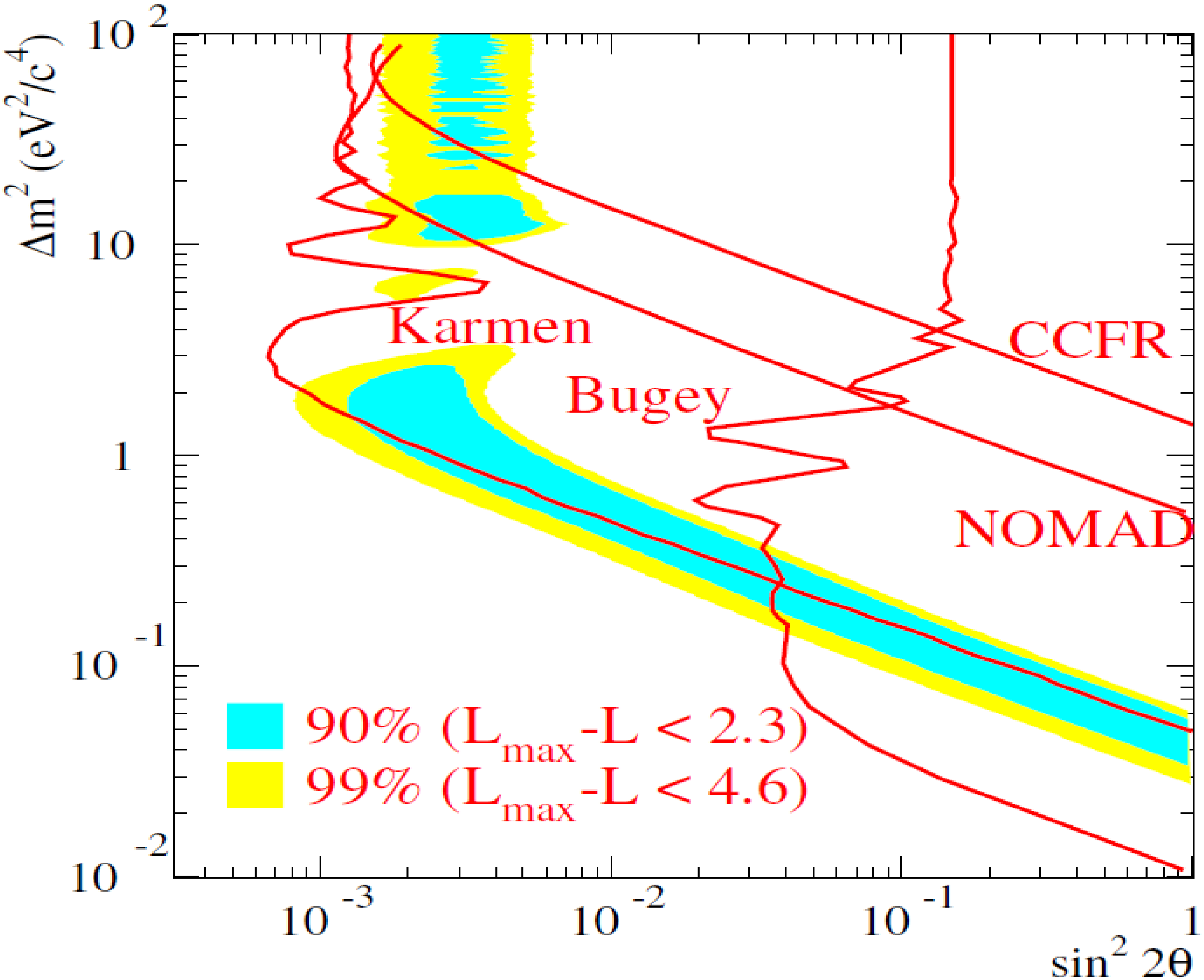
Well-known detection process of $\bar{\nu}_e$

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

[PRD 65 (2002) 112001]

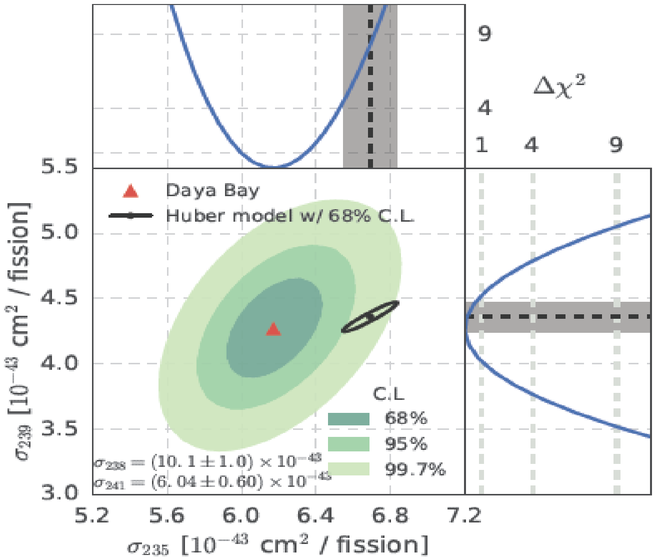
$$\Delta m^2_{\text{SBL}} \gtrsim 0.1\,\text{eV}^2 \gg \Delta m^2_{\text{ATM}}$$

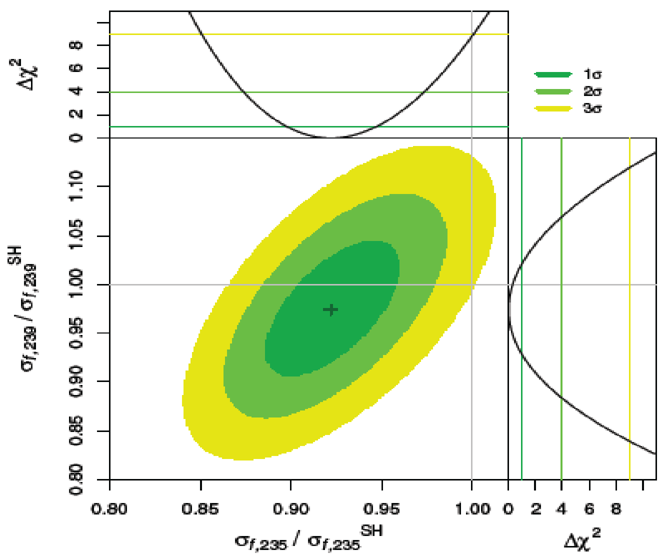
Allowed parameter space



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

Daya Bay fuel evolution data





- Best fit: mainly suppression of $\sigma_{f,235}$
- Equal fluxes suppression:

$$\Delta\chi^2/\text{NDF} = 7.9/1$$

  disfavored at 2.8σ

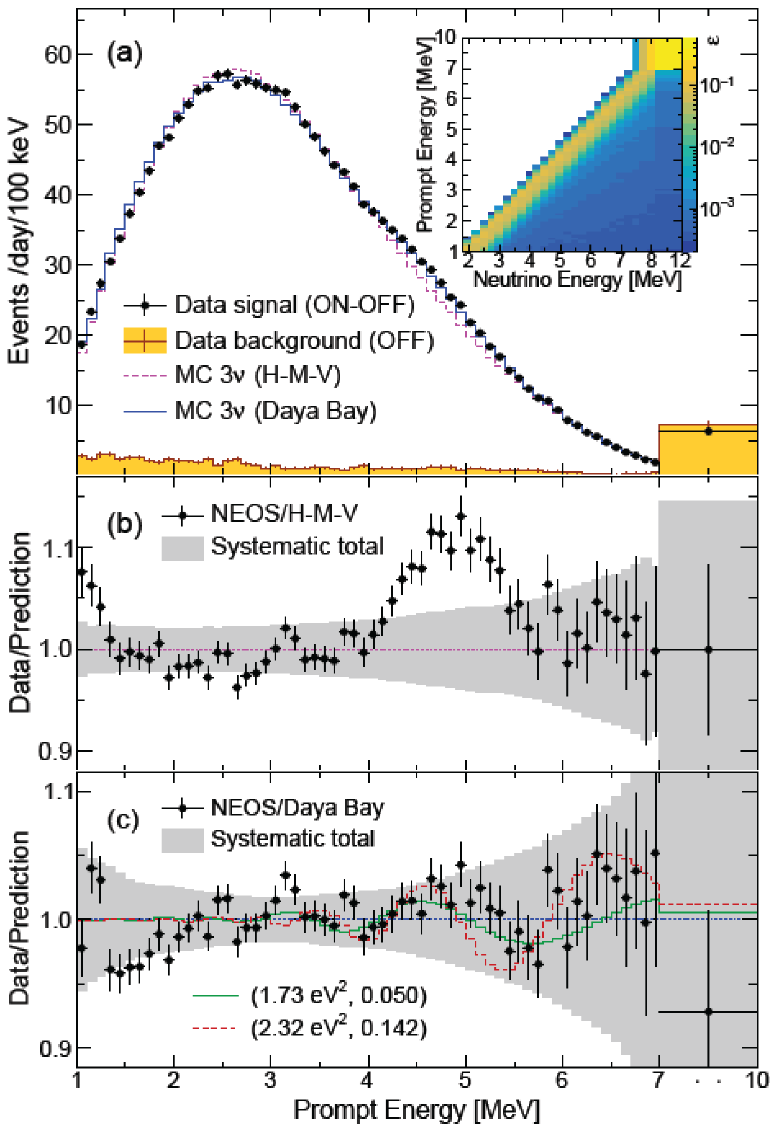
- Equal fluxes suppression corresponds to SBL oscillations, but theoretical flux uncertainties must be taken into account

- With theoretical flux uncertainties:

Daya Bay	^{235}U	OSC
χ^2_{min}	3.8	9.5
NDF	7	7
GoF	80%	22%

- MC: OSC disfavored at 2.6σ

New development: NEOS PRL 118 (2017) 121802

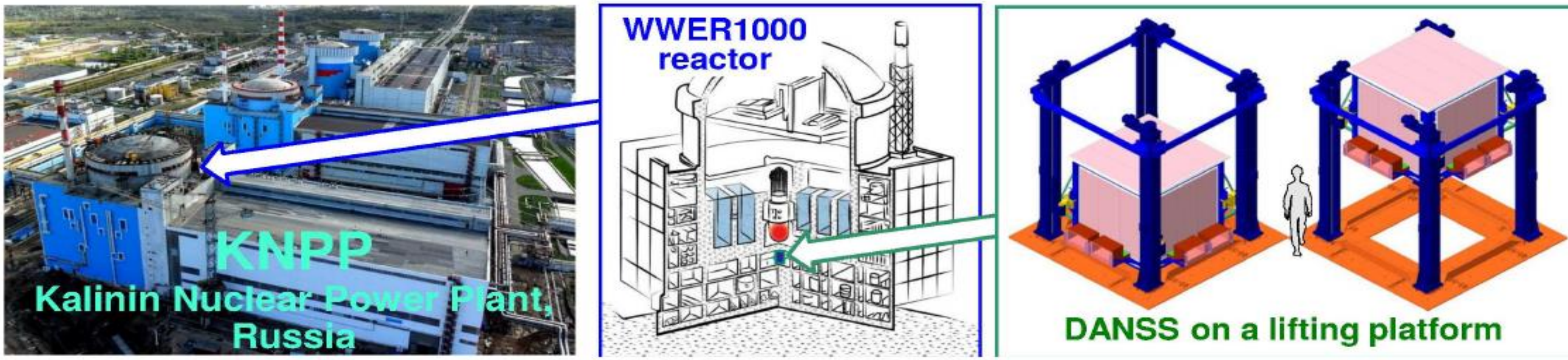


- Hanbit Nuclear Power Complex in Yeong-gwang, Korea.
- Thermal power of 2.8 GW.
- Detector: a ton of Gd-loaded liquid scintillator in a gallery approximately 24 m from the reactor core.
- The measured antineutrino event rate is 1976 per day with a signal to background ratio of about 22.

New development: DANSS

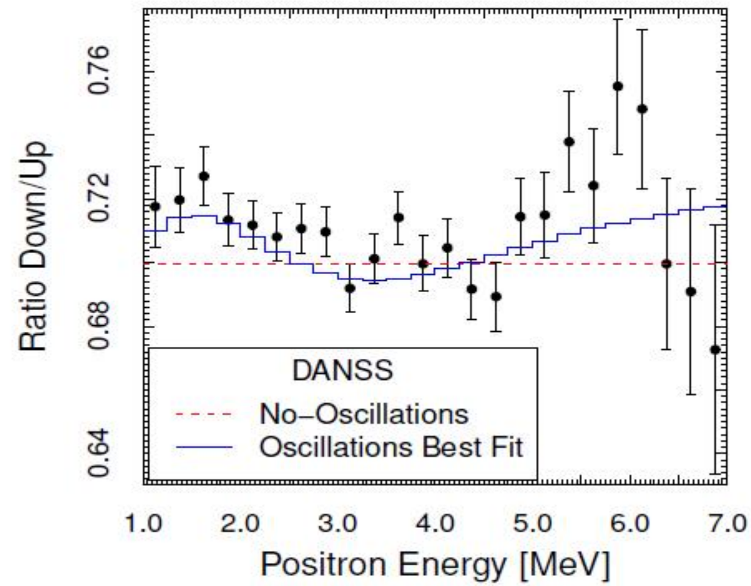
[Solvay Workshop, 1 December 2017; La Thuile 2018, 3 March 2018; Neutrino 2018, 8 June 2018]

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!

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

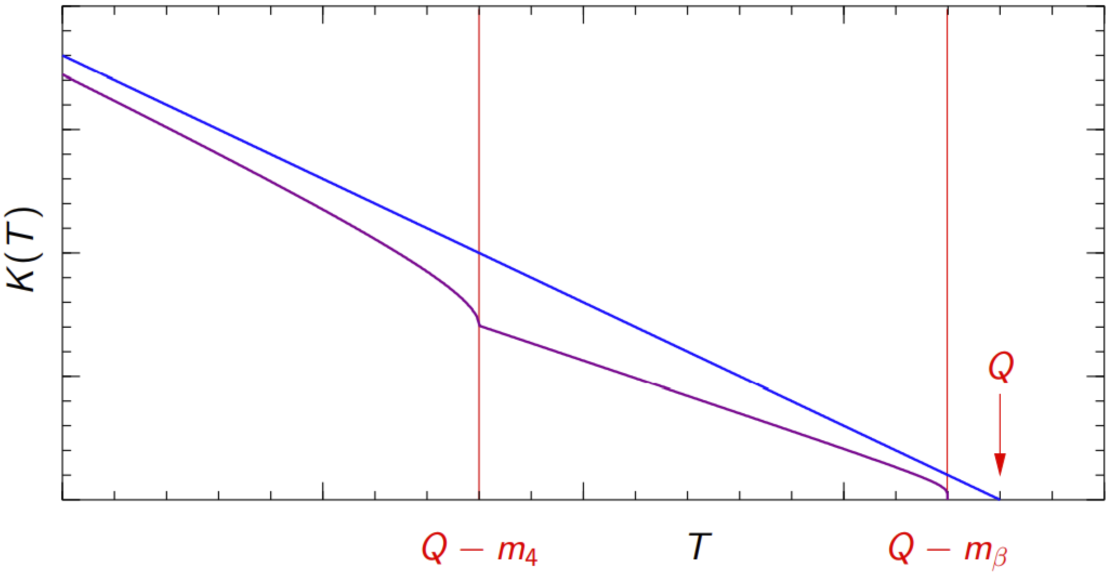


Robust kinematical probe of $\nu_e - \nu_s$ mixing

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

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

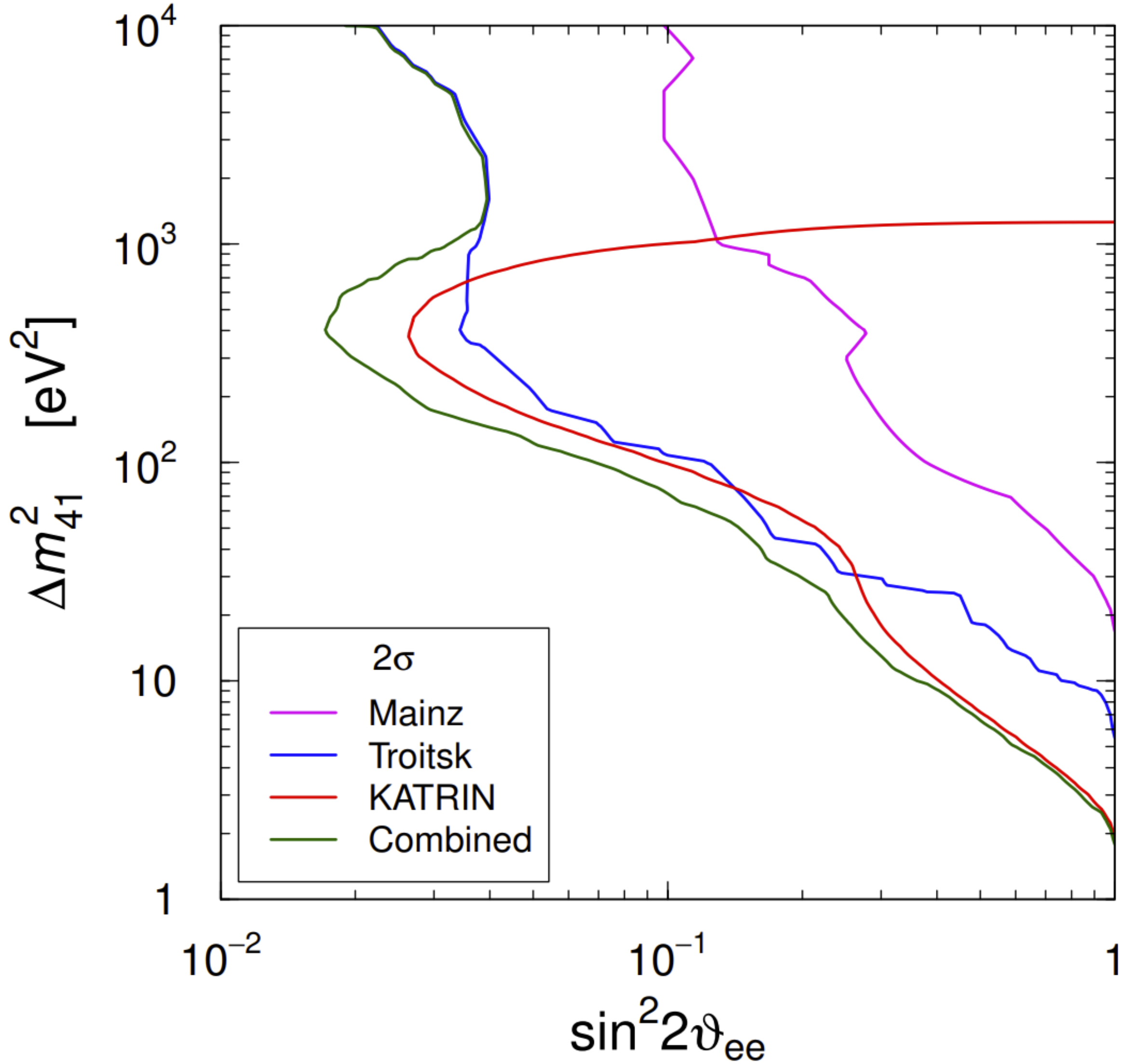
$$+|U_{e4}|^2\sqrt{(Q-T)^2 - m_4^2}\,\theta(Q-T-m_4)$$



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

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

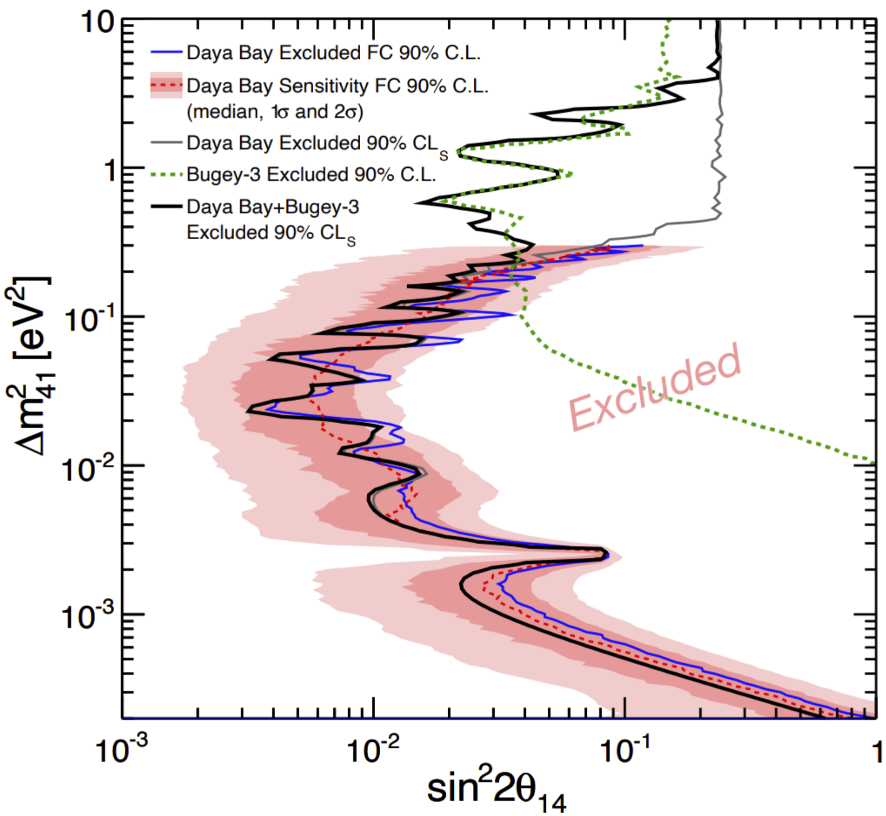
Tritium Neutrino Mass Bound



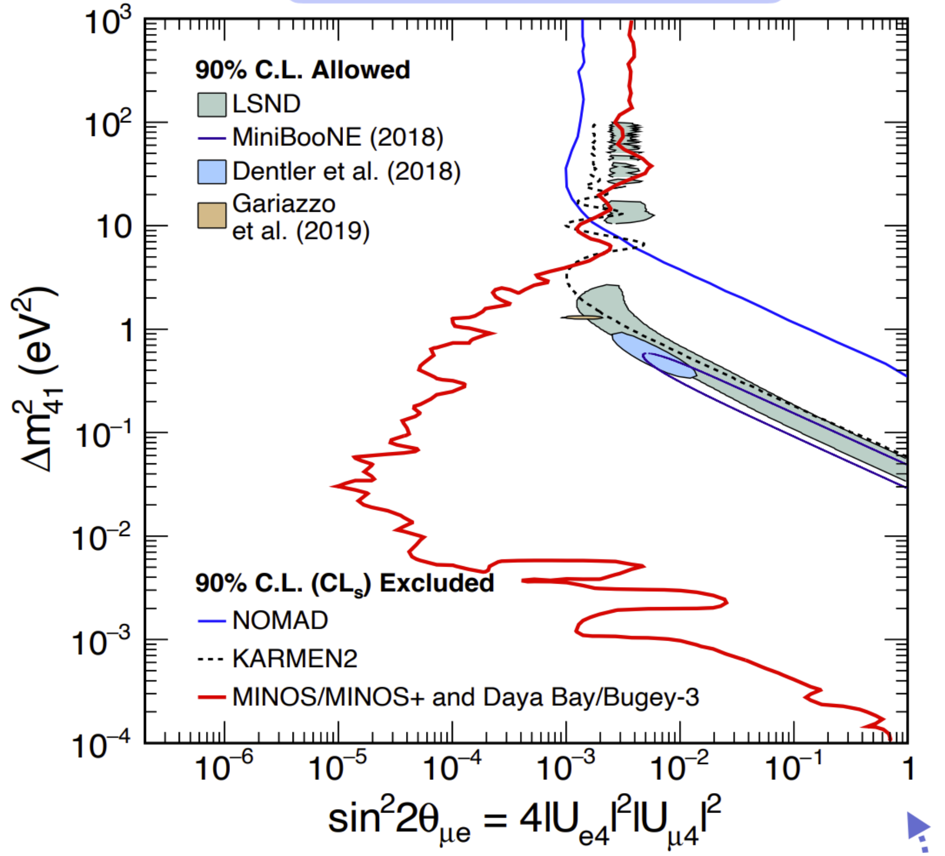
$$m_4 \gg m_{1,2,3} \implies \Delta m^2_{41} \equiv m^2_4 - m^2_1 \simeq m^2_4$$

Model Indep. Measurement at Daya Bay

$\bar{\nu}_e$ disappearance
(Bugey-3 & Daya Bay)



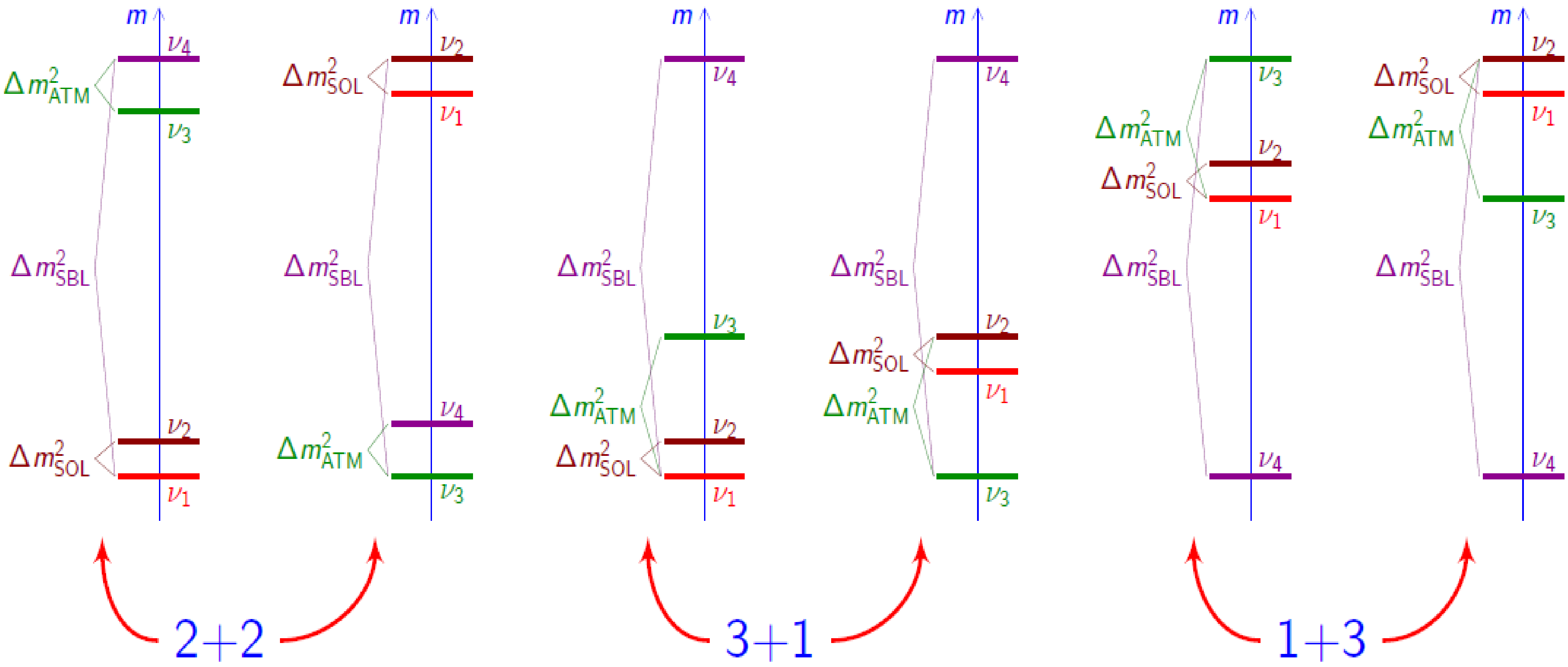
Combined Results
(Bugey-3, Daya Bay,
MINOS & MINOS+)



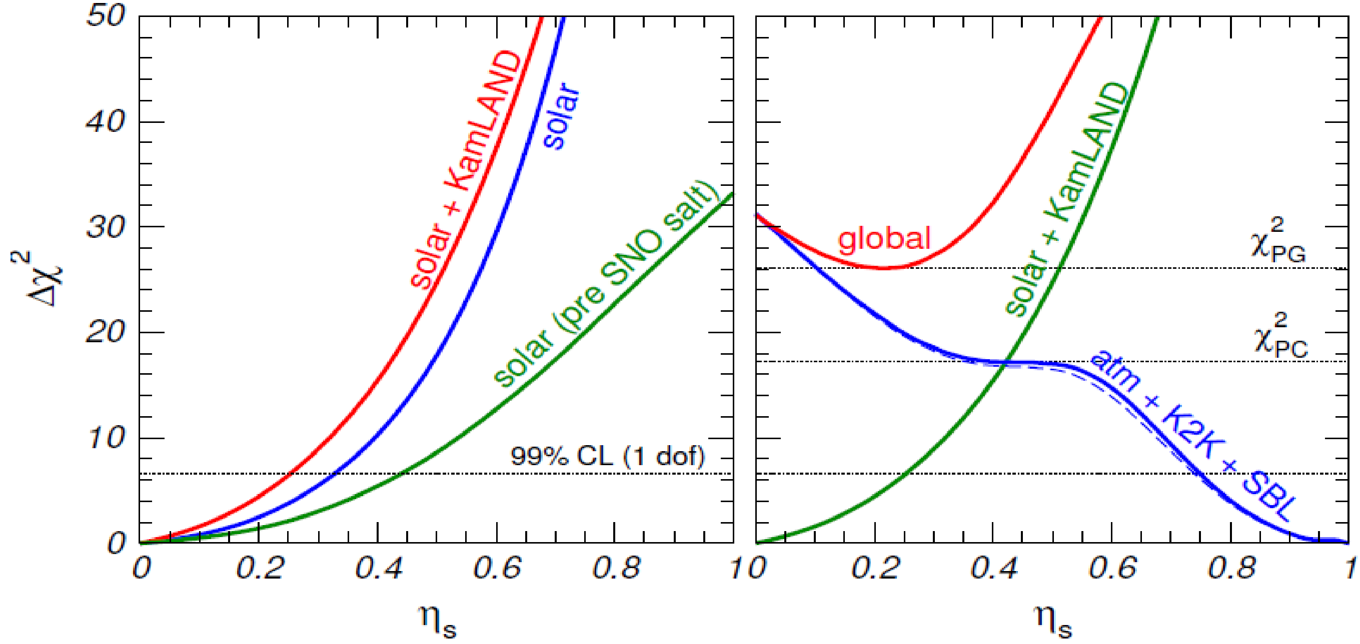
PRL 125,071801 (2020)

Most stringent limits on $\theta_{\mu e}$ to date over 5 orders of magnitude in Δm^2_{41}

Schemes of four neutrino mixing



2+2 Scheme: 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% CL: $\begin{cases} \eta_s < 0.25 & \text{(Solar + KamLAND)} \\ \eta_s > 0.75 & \text{(Atmospheric + K2K)} \end{cases}$

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

Goodness of Fit

- Assumption or approximation: Gaussian uncertainties and linear model
- χ^2_{min} has χ^2 distribution with Number of Degrees of Freedom

$$\text{NDF} = N_{\text{D}} - N_{\text{P}}$$

$$N_{\text{D}} = \text{Number of Data} \qquad N_{\text{P}} = \text{Number of Fitted Parameters}$$

- $\langle \chi^2_{\text{min}} \rangle = \text{NDF} \qquad \text{Var}(\chi^2_{\text{min}}) = 2\text{NDF}$
- $\text{GoF} = \int_{\chi^2_{\text{min}}}^{\infty} p_{\chi^2}(z, \text{NDF})\, \text{d}z \qquad p_{\chi^2}(z, n) = \frac{z^{n/2-1} e^{-z/2}}{2^{n/2}\Gamma(n/2)}$

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

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

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