Towards the Solutions of Reactor and Gallium Anomalies

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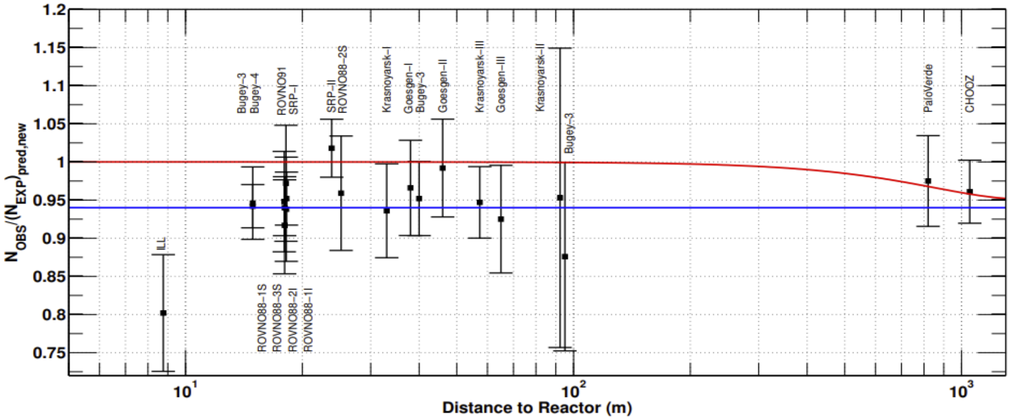
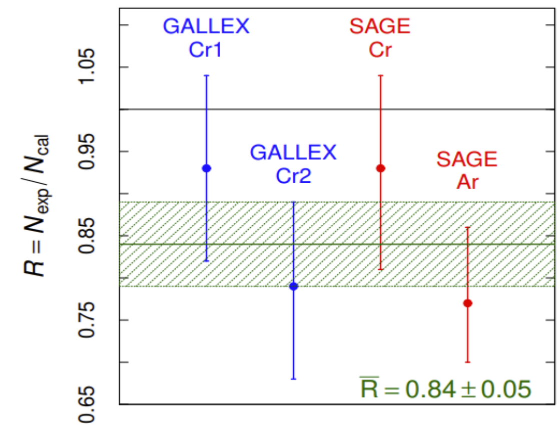
Historical Short-Baseline Anomalies

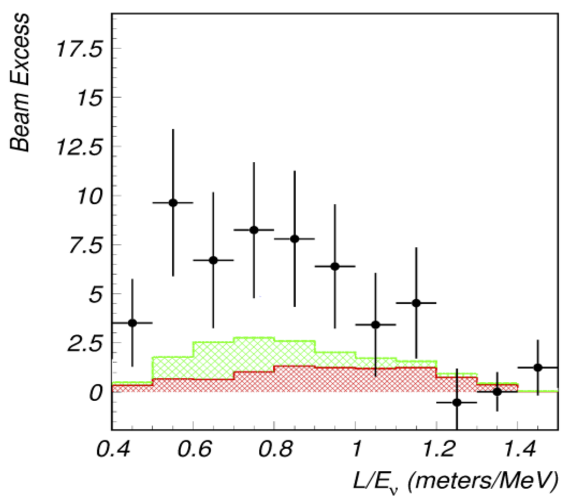
2011 Reactor Anomaly: $\bar{\nu}_e \rightarrow \bar{\nu}_x$ (2.5σ)



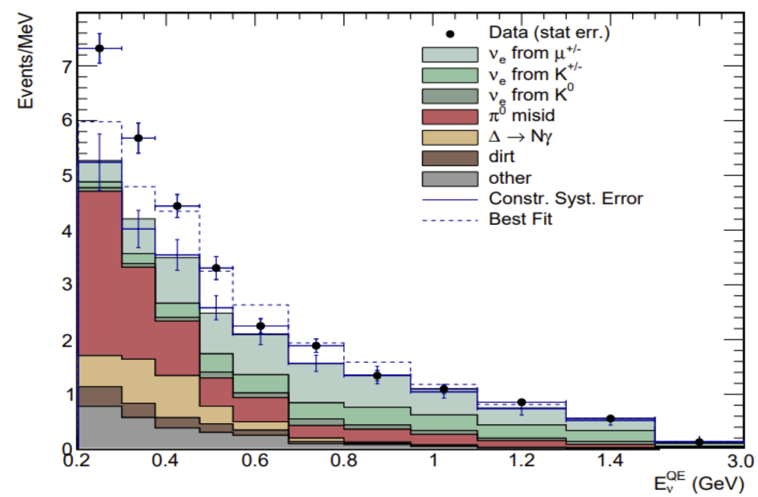
2005 Gallium Anomaly: $\nu_e \rightarrow \nu_x$ (2.9σ)



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

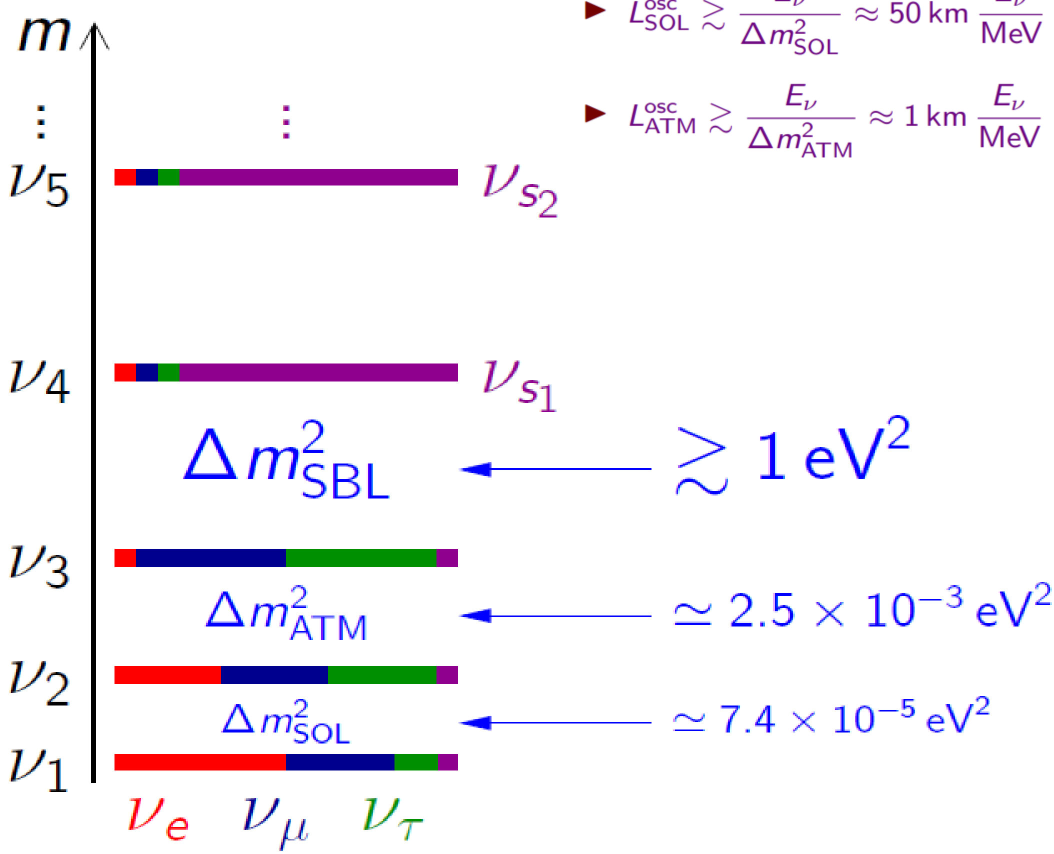


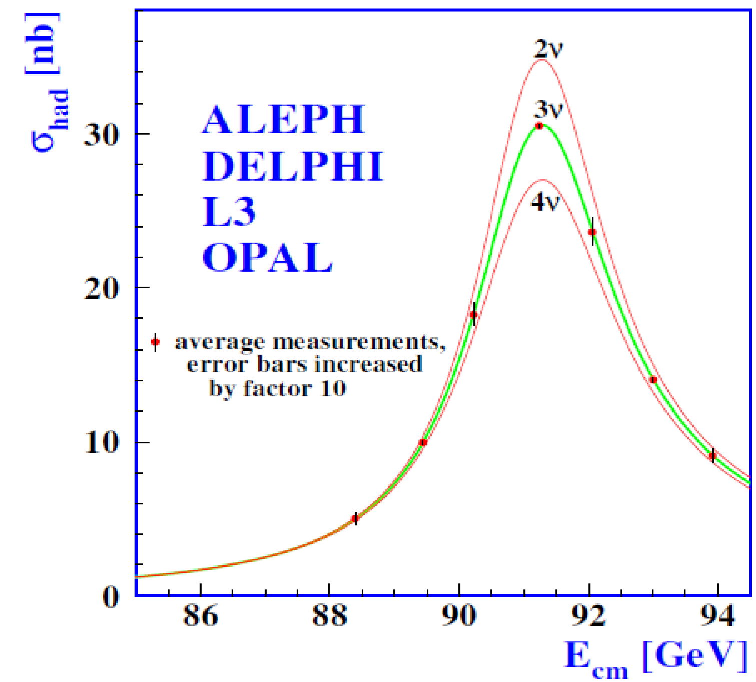
2008 MiniBooNE Anomaly: $\overset{(-)}{\nu}_\mu \rightarrow \overset{(-)}{\nu}_e$ (4.8σ)



Beyond 3-ν oscillation: Sterile neutrinos

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





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

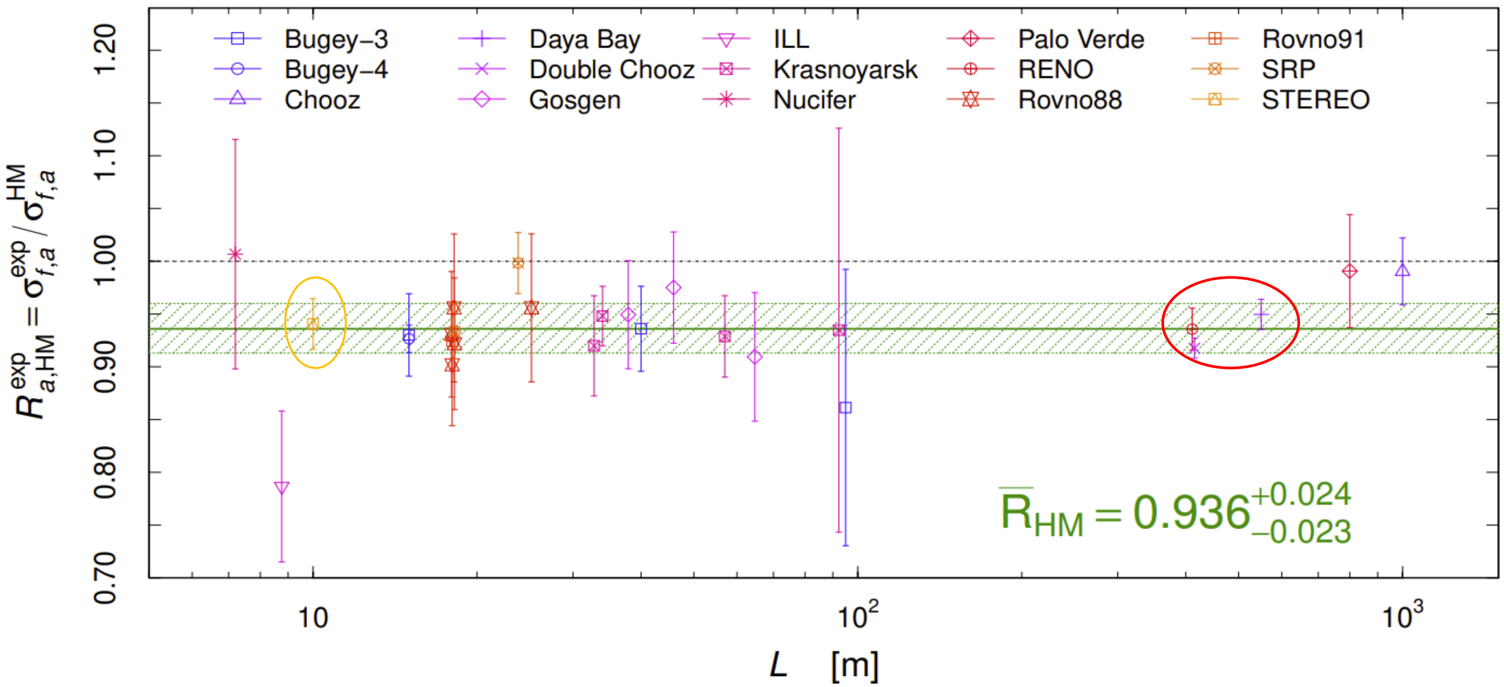
Explanation of short baseline oscillations:

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

Reactor Antineutrino Anomaly

HM fluxes (conversion method) v.s. data

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

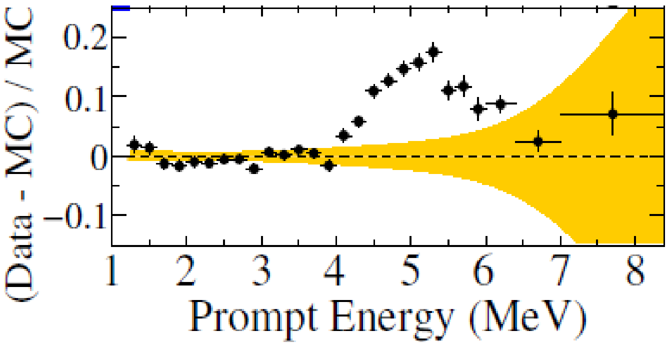


$2.5\,\sigma$ deficit $\Longrightarrow$ Anomaly!

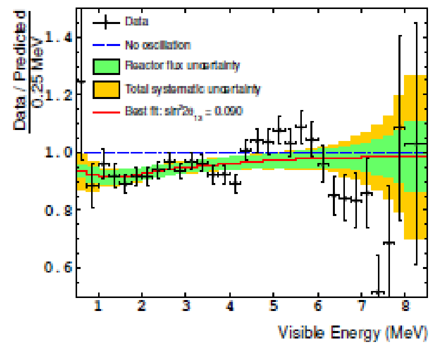
Giunti, YFL,Ternes, Xin, arXiv: 2110.06820

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

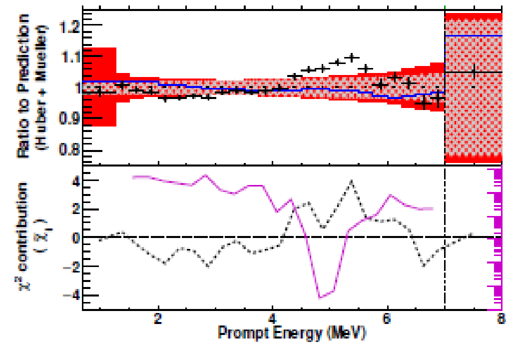
Recent developments



[RENO, arXiv:1511.05849]



[Double Chooz, arXiv:1406.7763]



[Daya Bay, arXiv:1508.04233]

(1) "5 MeV bump" (cannot be explained by oscillation) questioned the theoretical reactor model (HM model).

(2) New development in theoretical models

- **New summation model**
- **KI (Kurchatov Institute) correction to the conversion model**

(3) New development in experimental measurements

- **Fission evolution data from Daya Bay & RENO**

New reactor flux models

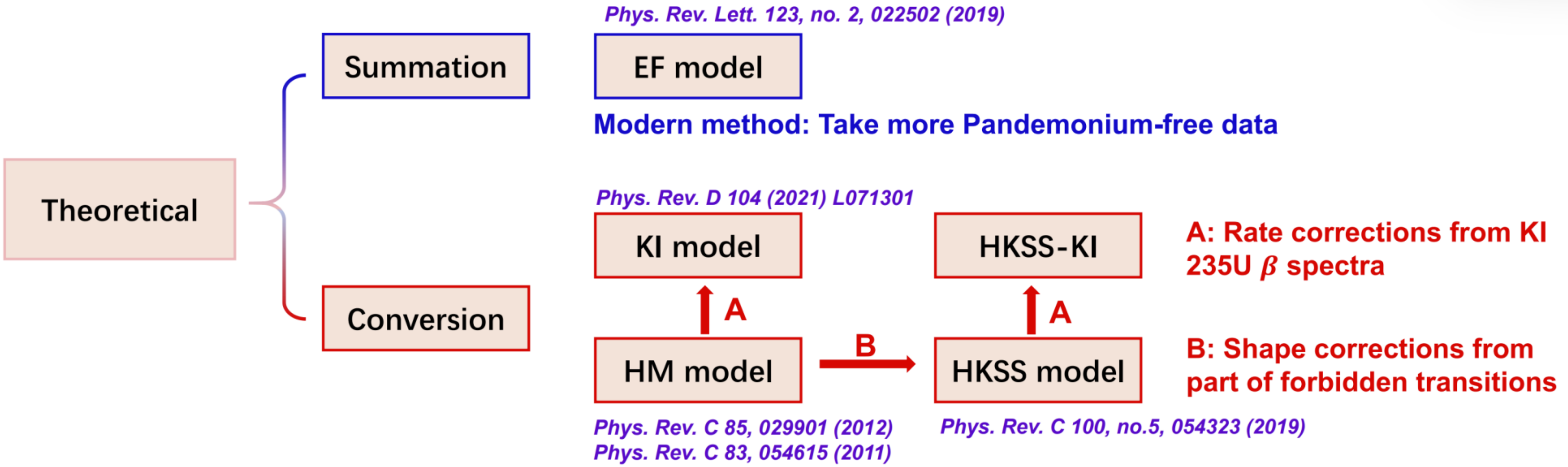
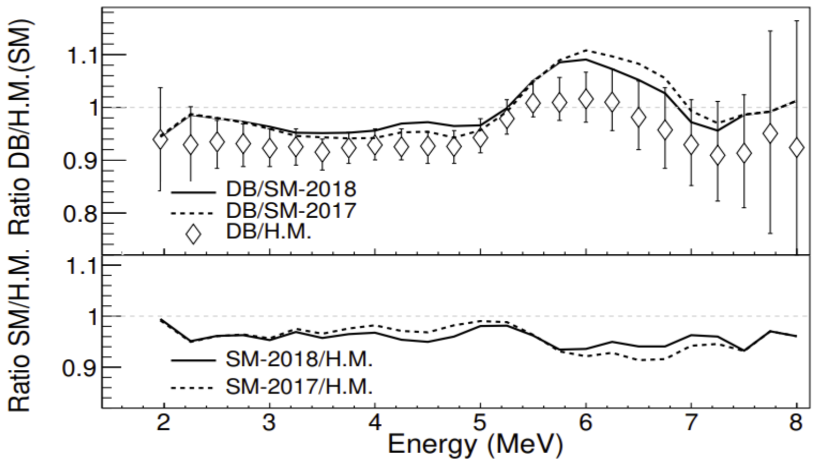
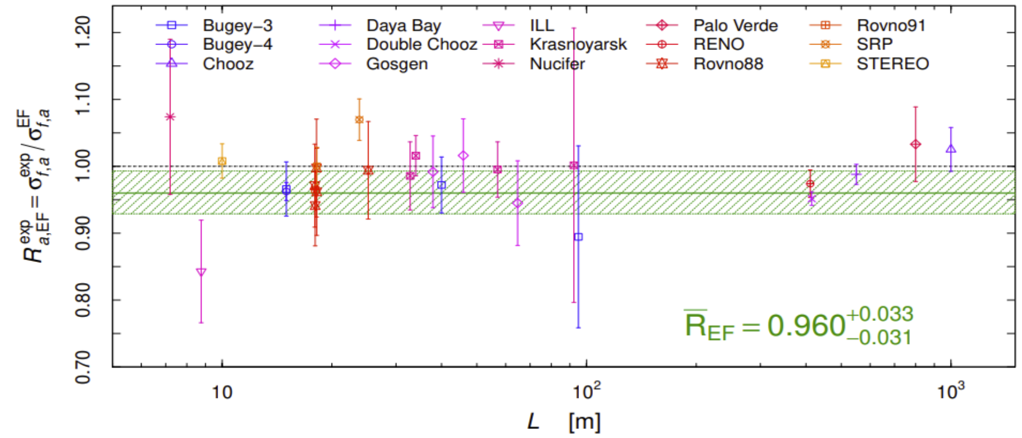


Diagram Courtesy: XIN Zhao

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!

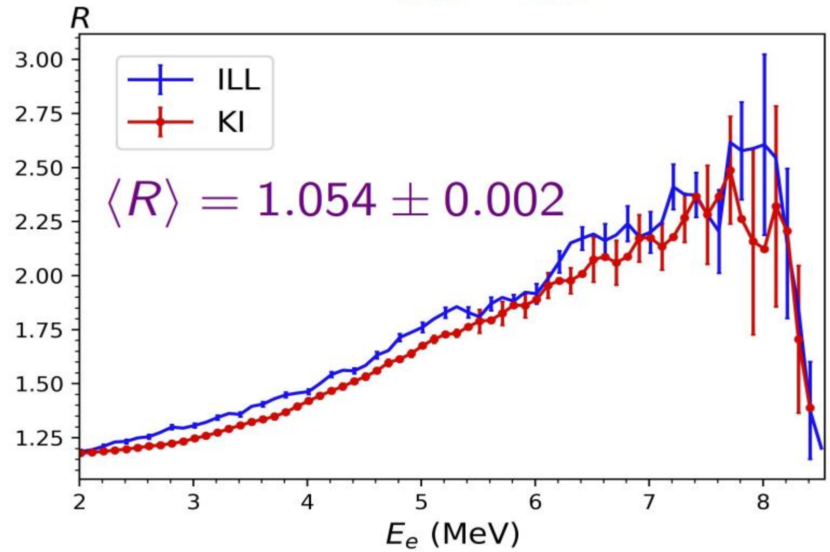
[See also: Berryman, Huber, arXiv:1909.09267, arXiv:2005.01756]

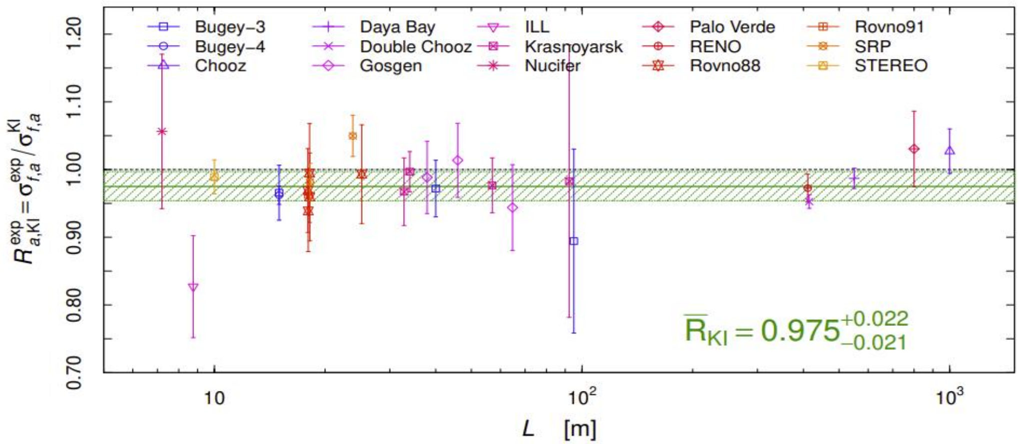
- UNKNOWN UNCERTAINTIES!
- Rough estimation used in our calculations: 5% for ^{235}U, ^{239}Pu, ^{241}Pu and 10% for ^{238}U. [Hayes, Jungman, McCutchan, Sonzogni, Garvey, Wang, arXiv:1707.07728]

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

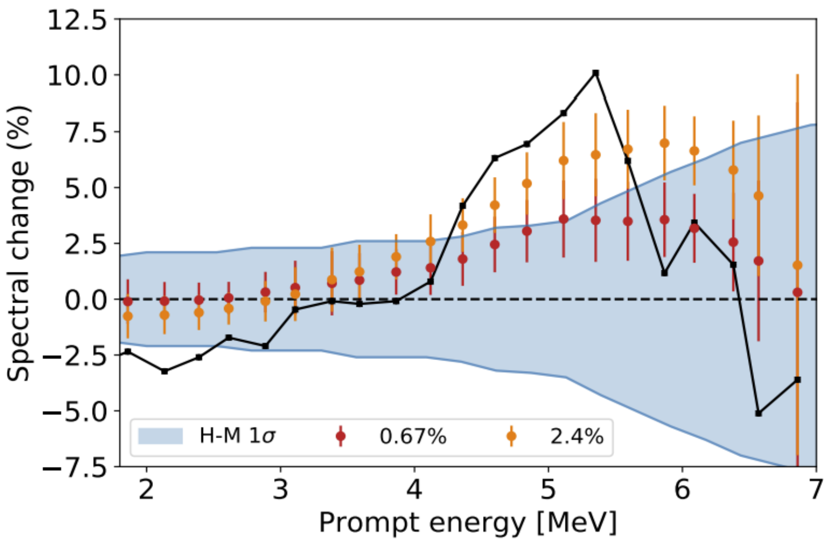
$1.1\,\sigma$ deficit $\Longrightarrow$ No Anomaly!

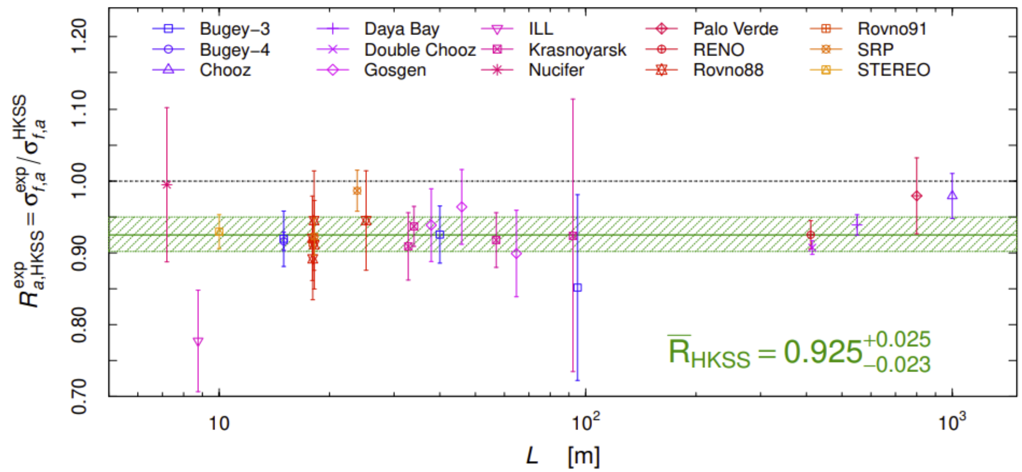
Approximate agreement with ab initio EF fluxes!

- HM + KI uncertainties.

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]

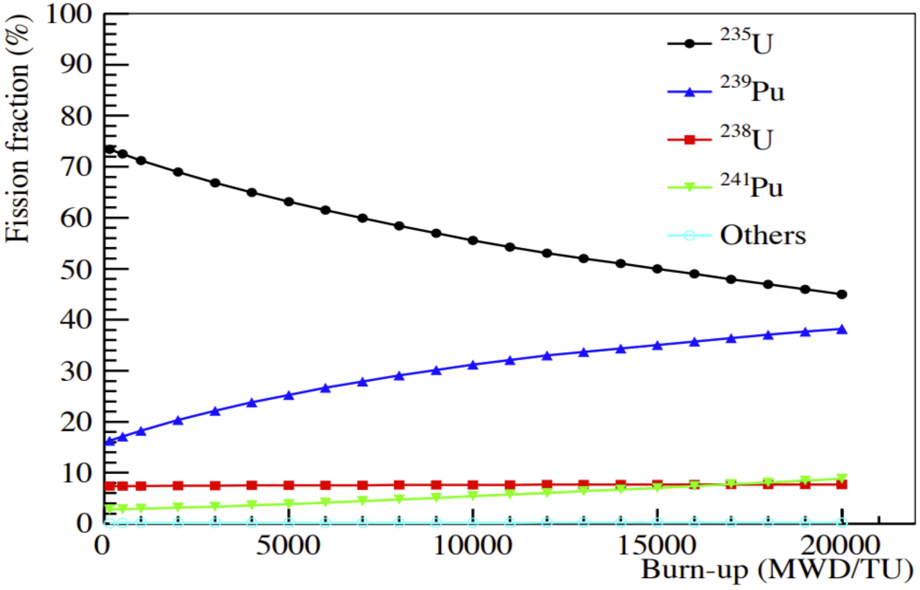
- HM + HKSS uncertainties.

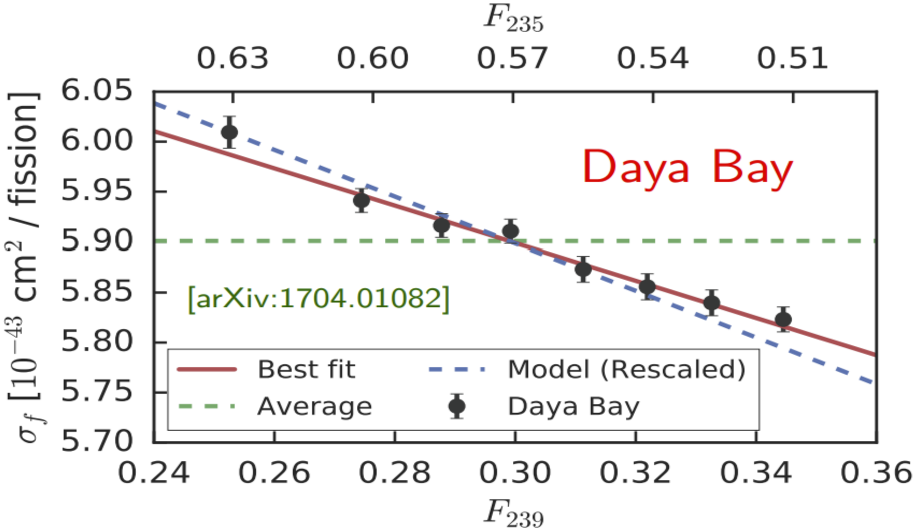
Reactor fuel evolution data

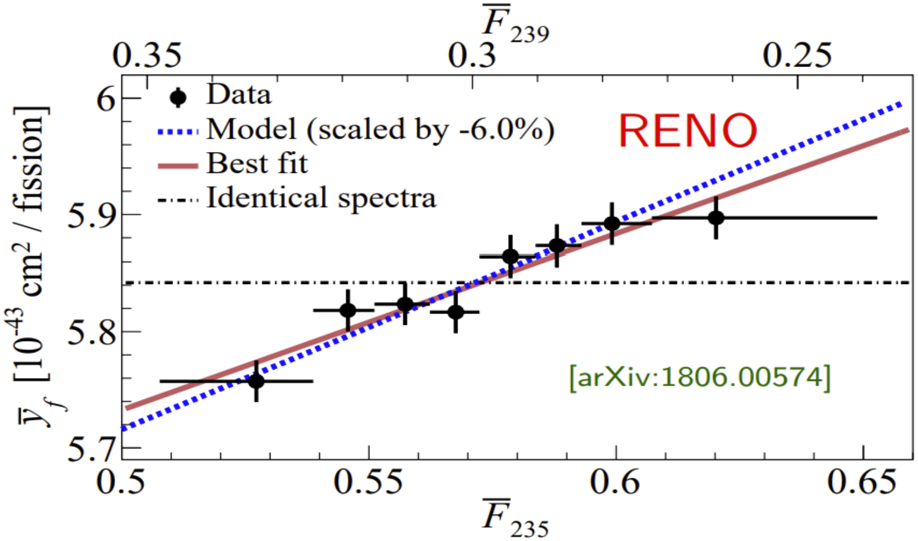
- Reactor $\bar{\nu}_e$ flux produced by the β decays of the fission products of
  ^{235}U ^{238}U ^{239}Pu ^{241}Pu
- Effective fission fractions:
  F_{235} F_{238} F_{239} F_{241}
- Cross section per fission (IBD yield):

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

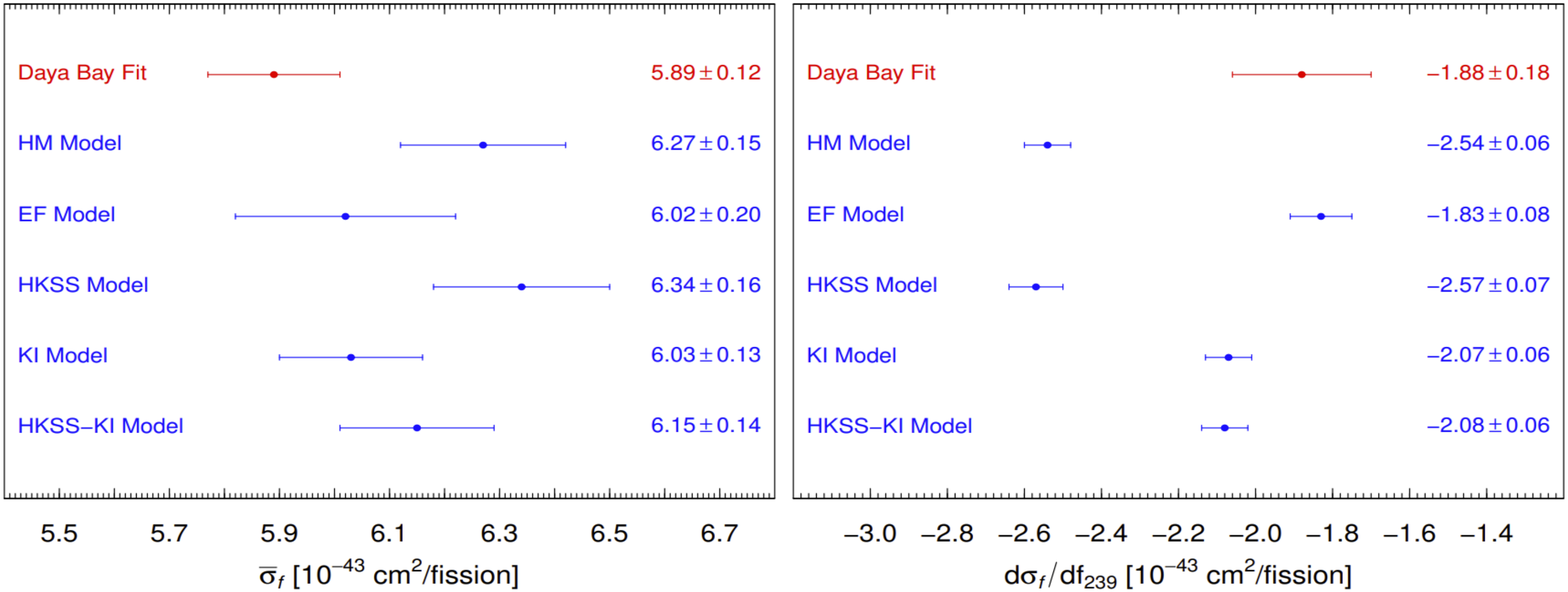
for $k = 235, 238, 239, 241$







Model v.s. Data Comparison



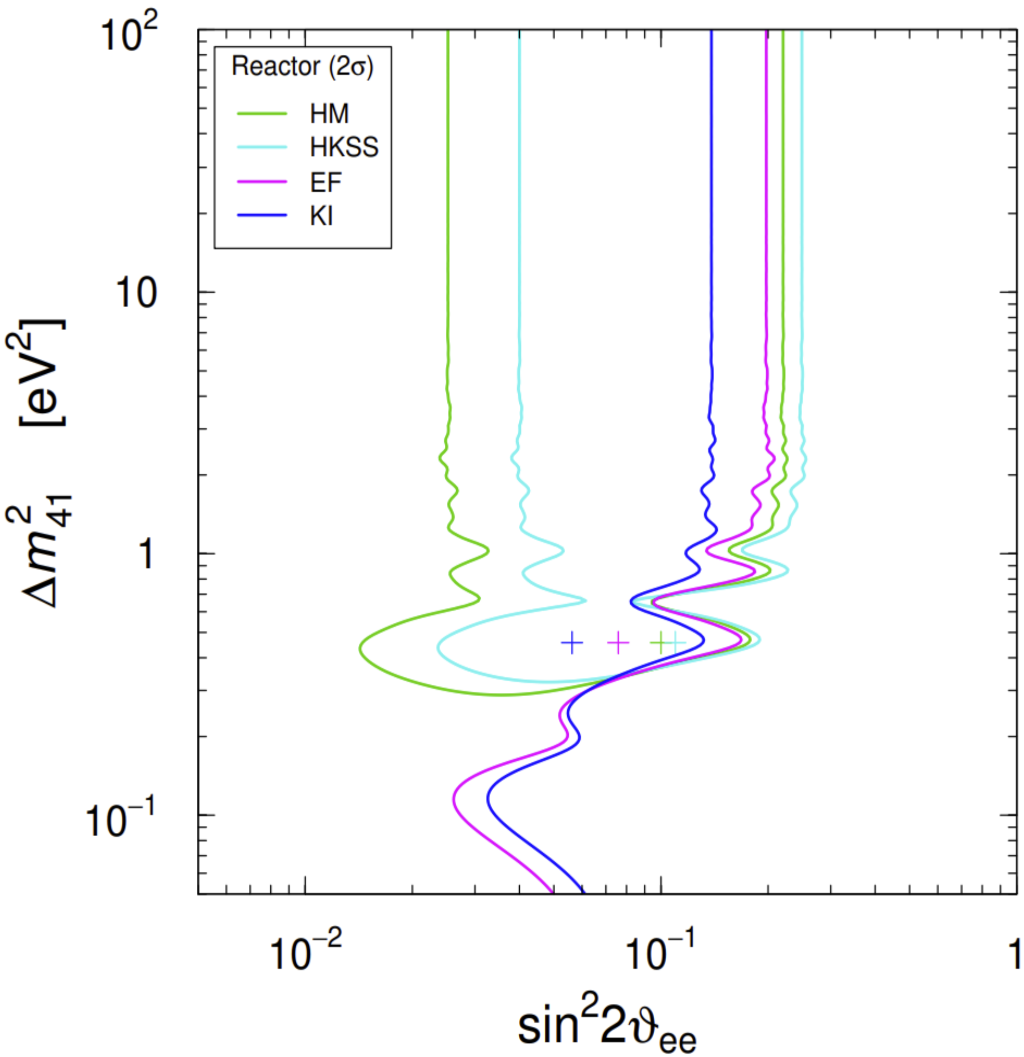
Giunti, YFL,Ternes, Xin, arXiv: 2110.06820

A global fit of all reactor rates + evolution data shows

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

The EF (summation model) and KI (conversion) models are the best ones!

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

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

Gallium Anomaly

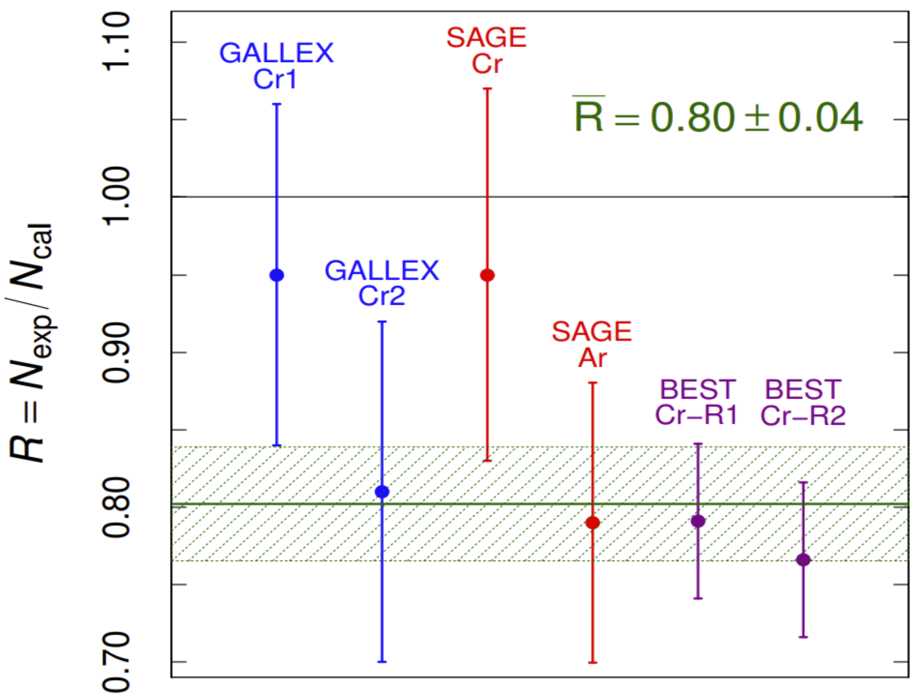
Gallium Anomaly

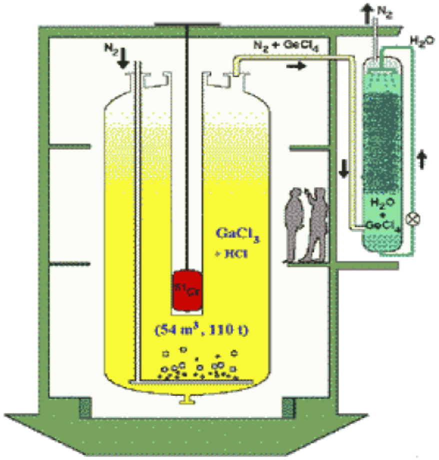
Gallium Radioactive Source Experiments: GALLEX, SAGE, BEST (2021)

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

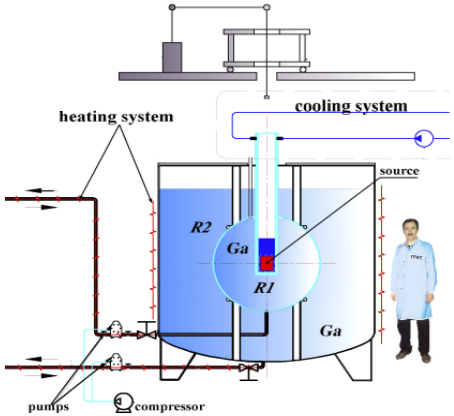
$E \simeq 0.75\,\text{MeV}$ $\quad E \simeq 0.81\,\text{MeV}$

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





GALLEX



BEST

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

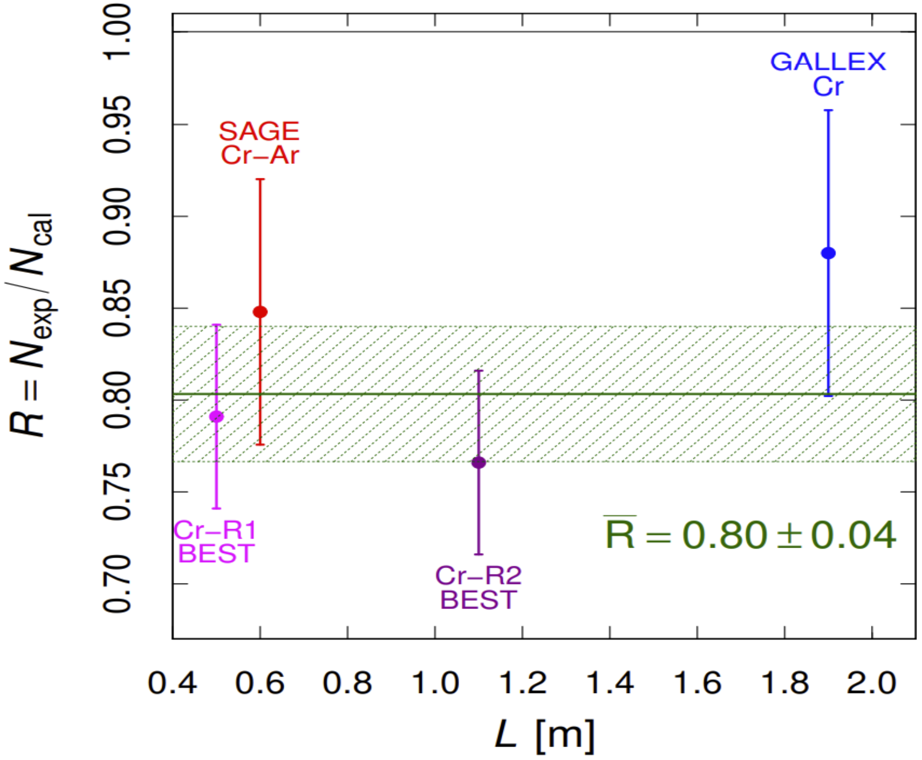
$\langle L \rangle_{\text{GALLEX}} \simeq 1.9\,\text{m}$ $\quad \langle L \rangle_{\text{SAGE}} \simeq 0.6\,\text{m}$

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

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

[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

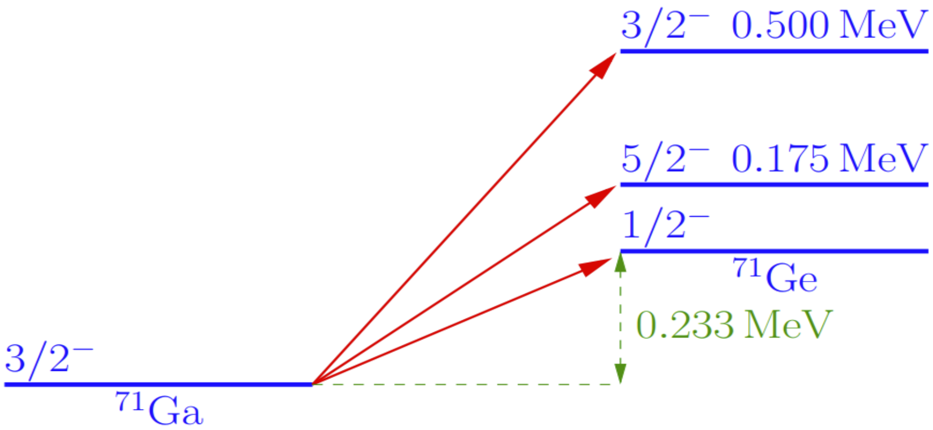


- No clear model-independent anomaly from different path lengths.
- Puzzling quasi-equality of the two BEST measurements at different distances.
- After the BEST measurements, the Gallium Anomaly is still an anomaly based on the absolute comparison of observed and predicted rates.

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: contribution of excited states?

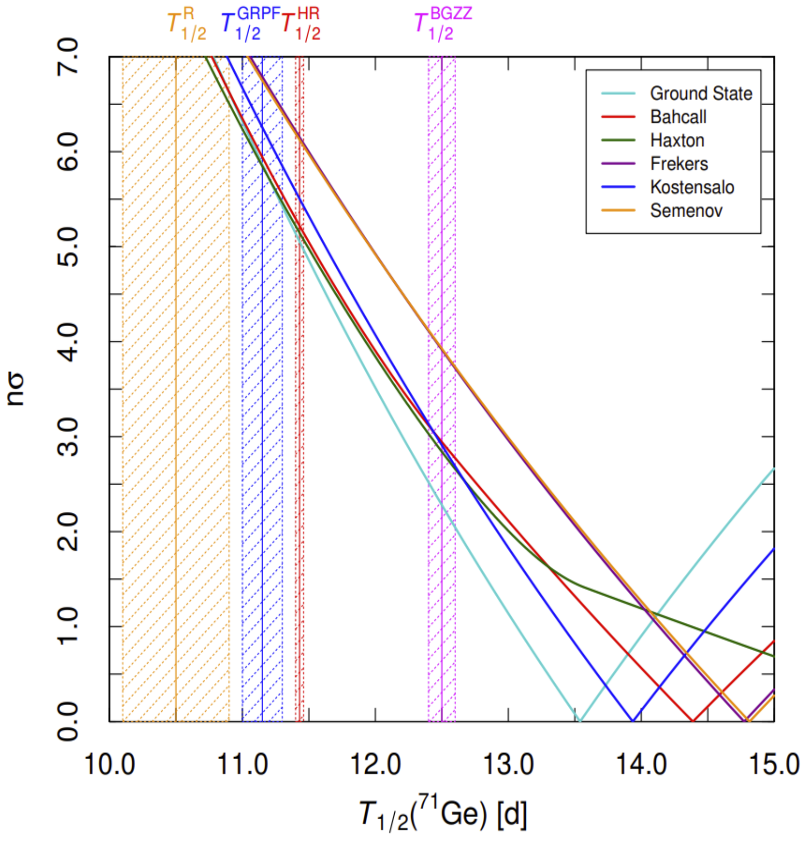
$\nu_e + {}^{71}\mathrm{Ga} \rightarrow {}^{71}\mathrm{Ge} + e^-$ cross sections in units of 10^{-45} cm^2:

		^{51}Cr		^{37}Ar			
		σ_{tot}	δ_{exc}	σ_{tot}	δ_{exc}	$\overline{R}$	GA
Ground State [Phys.Atom.Nucl. 83 (2020) 1549]	$T_{1/2}({}^{71}\mathrm{Ge})$	5.539 ± 0.019	–	6.625 ± 0.023	–	0.844 ± 0.031	5.0σ
Bahcall [hep-ph/9710491]	${}^{71}\mathrm{Ga}(p,n){}^{71}\mathrm{Ge}$	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]	${}^{71}\mathrm{Ga}({}^{3}\mathrm{He},{}^{3}\mathrm{H}){}^{71}\mathrm{Ge}$	5.938 ± 0.116	6.7%	7.169 ± 0.147	7.6%	0.786 ± 0.033	6.6σ

Cross section: ^{71}Ge decays

$$T_{1/2}^{\rm BGZZ}(^{71}{\rm Ge}) = 12.5 \pm 0.1\,{\rm d} \quad \text{(Bisi, Germagnoli, Zappa, and Zimmer, 1955) [39]},$$
$$T_{1/2}^{\rm R}(^{71}{\rm Ge}) = 10.5 \pm 0.4\,{\rm d} \quad \text{(Rudstam, 1956) [40]},$$
$$T_{1/2}^{\rm GRPF}(^{71}{\rm Ge}) = 11.15 \pm 0.15\,{\rm d} \quad \text{(Genz, Renier, Pengra, and Fink, 1971) [41]},$$
$$T_{1/2}^{\rm HR}(^{71}{\rm Ge}) = 11.43 \pm 0.03\,{\rm d} \quad \text{(Hampel and Remsberg, 1985) [42]}.$$

Giunti, YFL, Ternes, Xin, arXiv: 2212.09722

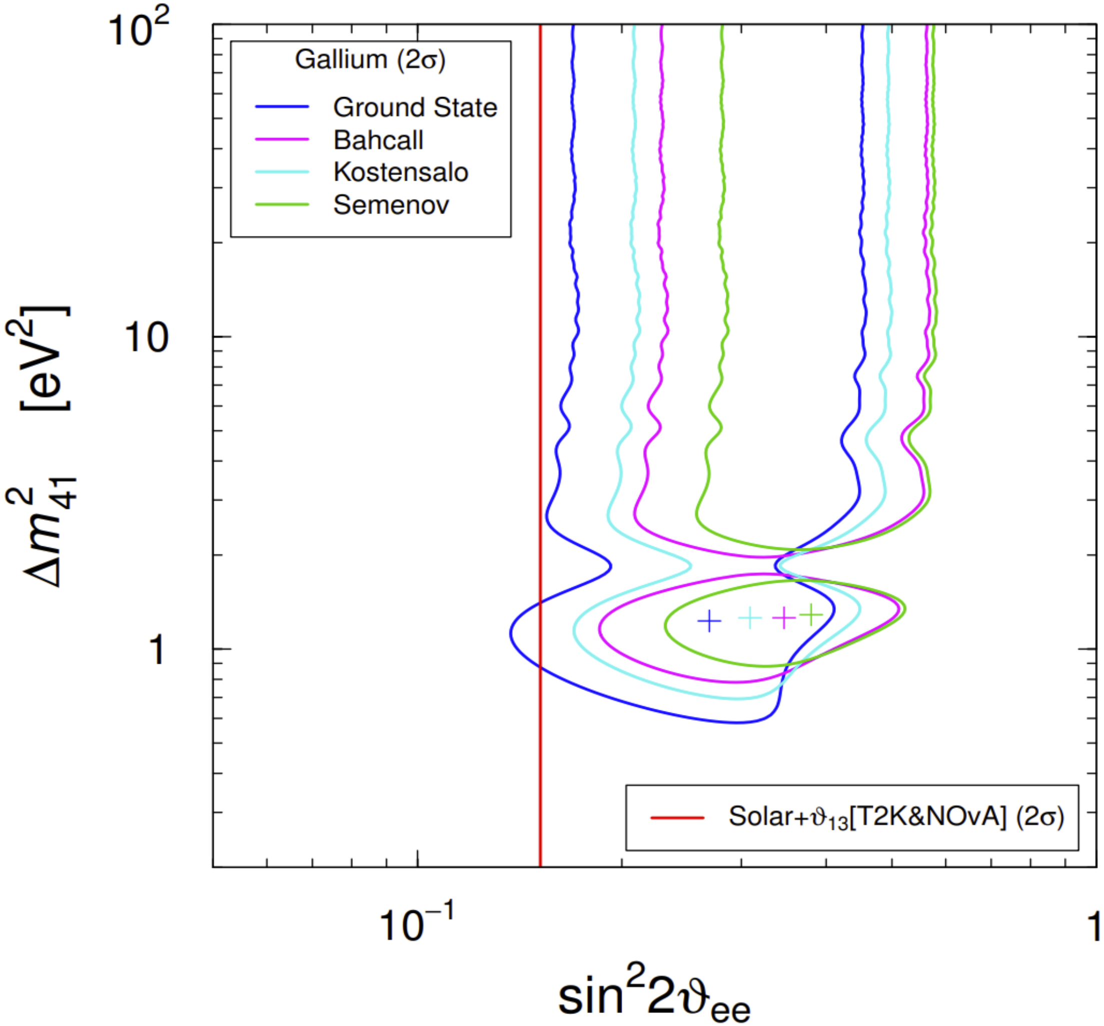


See a similar study in
Brdar, Gehrlein, Kopp, 2303.05528

- **New measurement of ^{71}Ge life time:** *Collar, Yoon, 2307.05353*
  11.46 ± 0.04 **days**
- **New decay branch to unknown ^{71}Ga states:**
  < 0.4% BR (v.s. 10% BR for GA)
- **Relative EC rates from different atomic shells:**
  PL/PK = 0.125±0.008 (v.s. 0.117)

All nuclear aspects of Ge are NOT viable!

Gallium – Solar neutrino tension



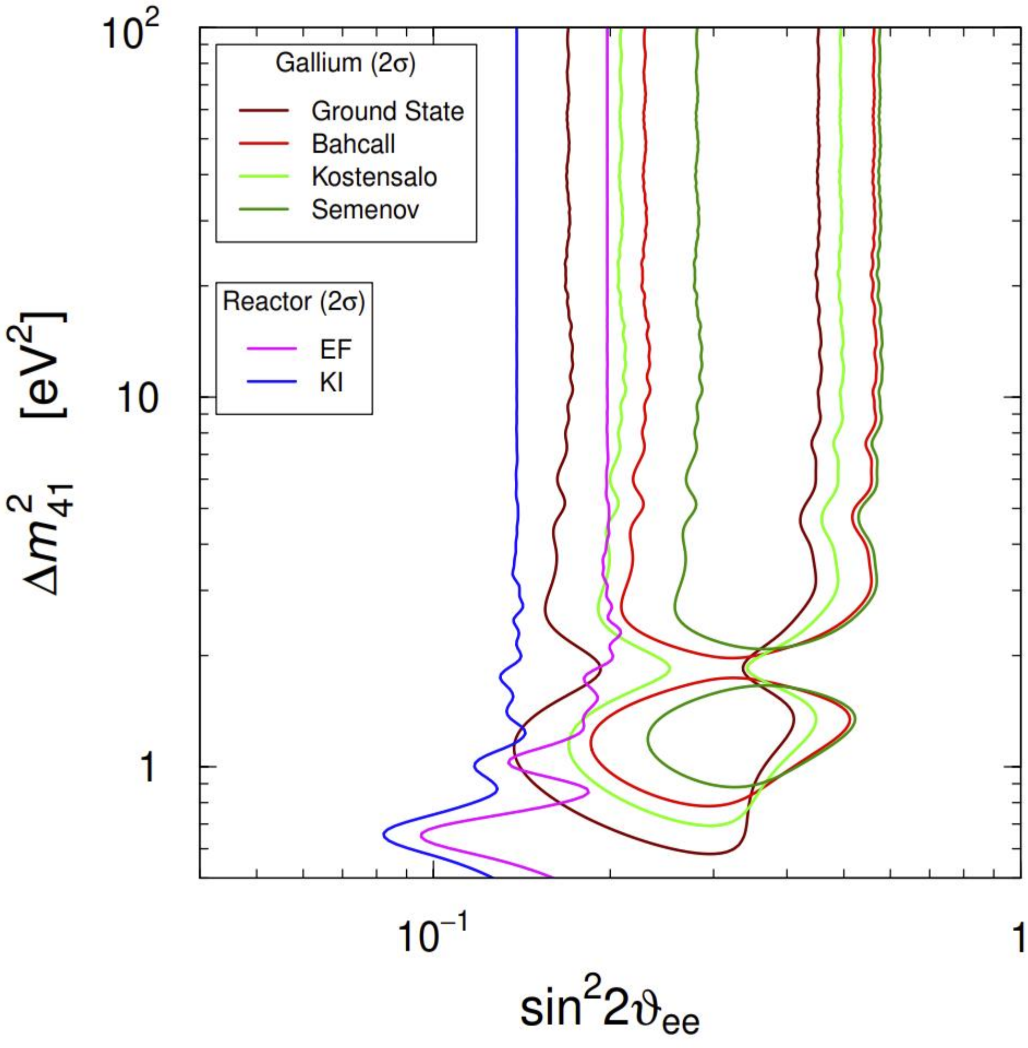
	Solar neutrinos + ϑ_{13}[T2K&NOvA]	
	$\Delta\chi^2_{PG}$	GoF_{PG}
Ground State	10.65	0.49%
Bahcall	14.14	0.085%
Kostensalo	12.79	0.17%
Semenov	17.24	0.018%

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]

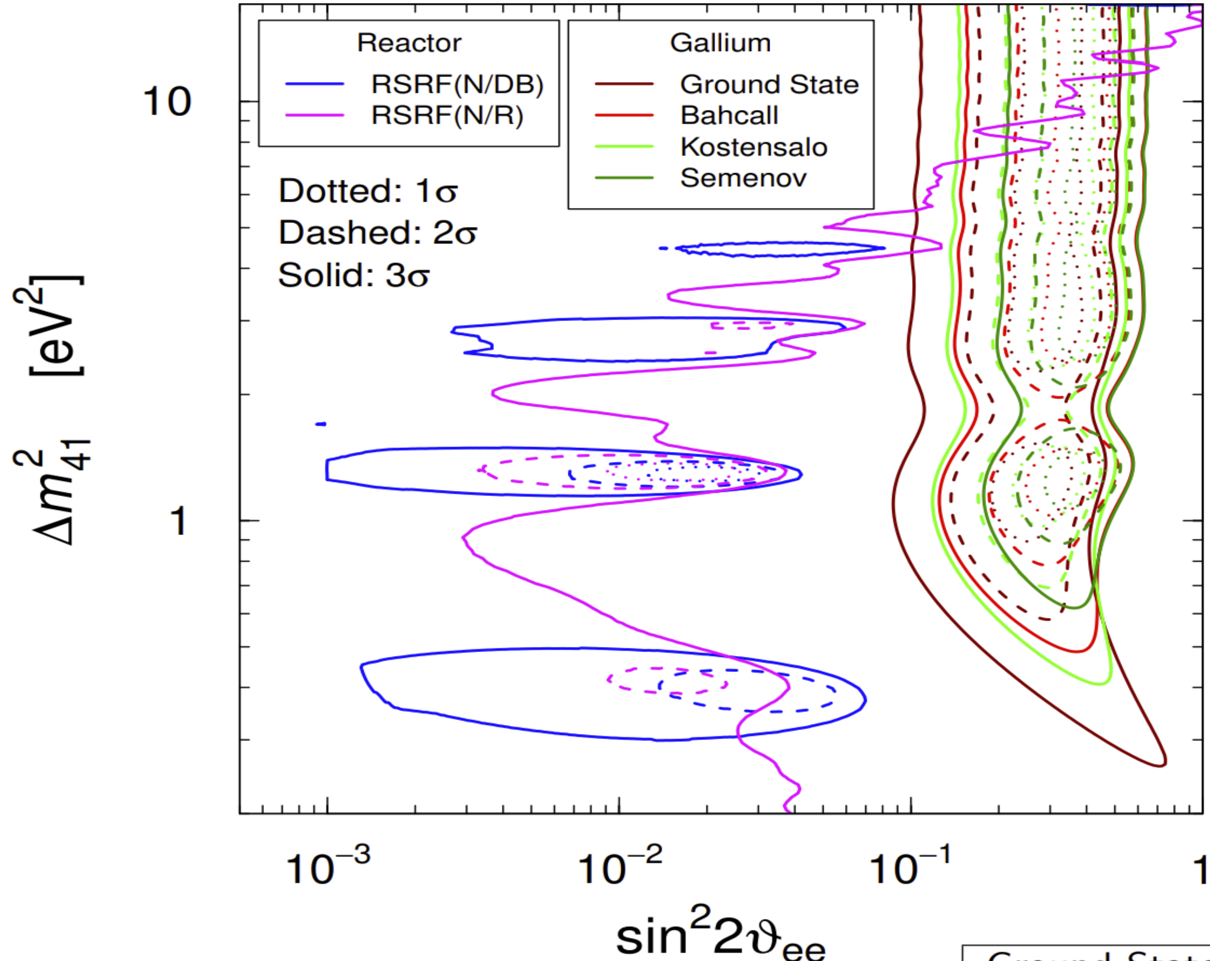
Gallium – Reactor rates tension



	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

Gallium – Reactor spectral-ratio tension



NEOS+PROSPECT+DANSS +STEREO+Bugey-3

- 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

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	

Brdar, Gehrlein, Kopp, 2303.05528

Conclusion

The Reactor Antineutrino Anomaly, discovered in 2011, is practically resolved with a reduction of the ^{235}U flux.

- **This consensus is supported by new summation model, by the KI correction to conversion model, and by global fit of reactor data (including evolution data).**
- **Solution (not yet) to the spectral anomaly may change the game.**

The Gallium Neutrino Anomaly, discovered in 2007, has been revived by the BEST result.

- **No viable solution from nuclear physics yet**
- **Strong tension between Gallium and reactor (solar) data**

The global fit of light sterile neutrinos (see backups)

- **strong disappearance and appearance tension**

Thank you for your attention!

Extras

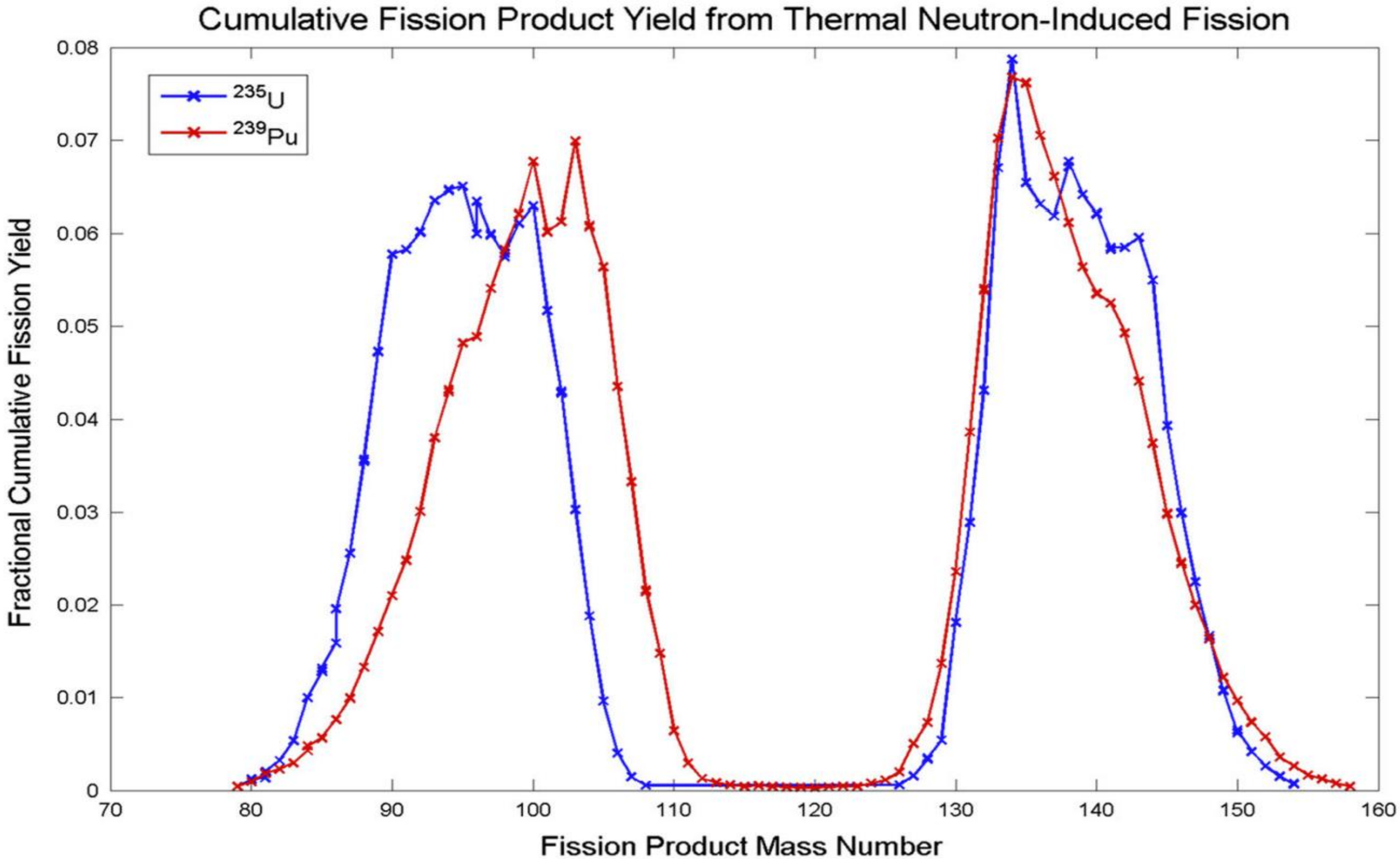
Reactor Flux Calculations

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

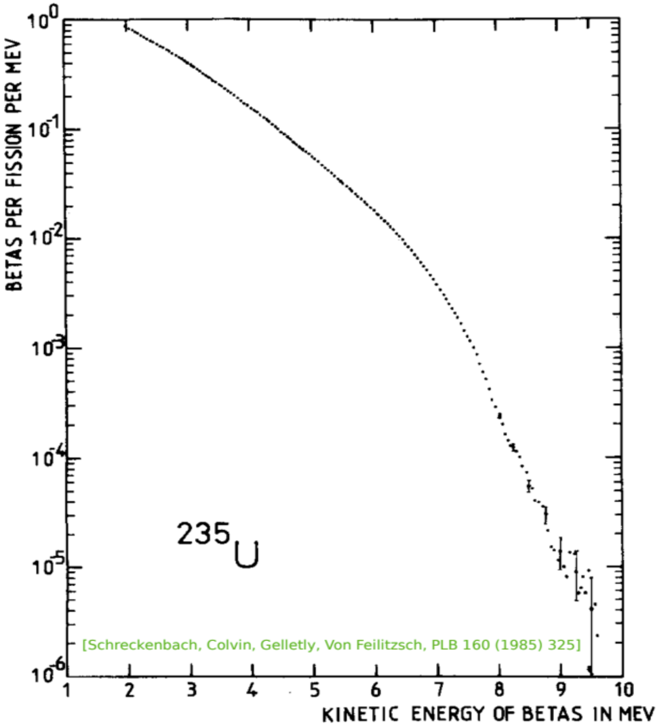
$S_n^b(E)$ ← allowed or forbidden decay spectrum

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

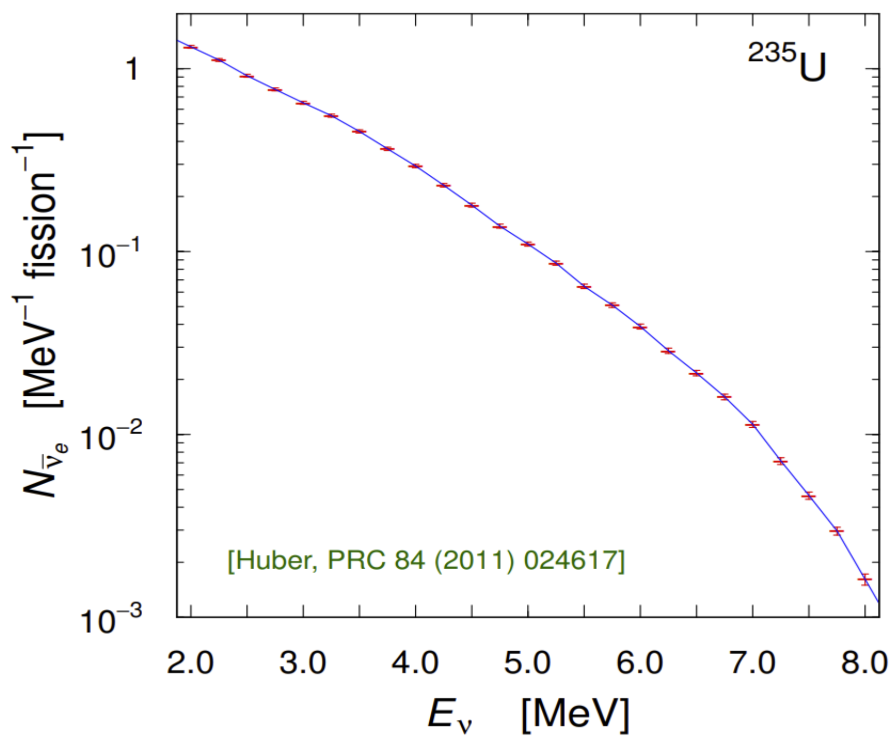
- Large uncertainties, because nuclear databases are incomplete and sometimes inexact.

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. $(k = 235, 239, 241)$



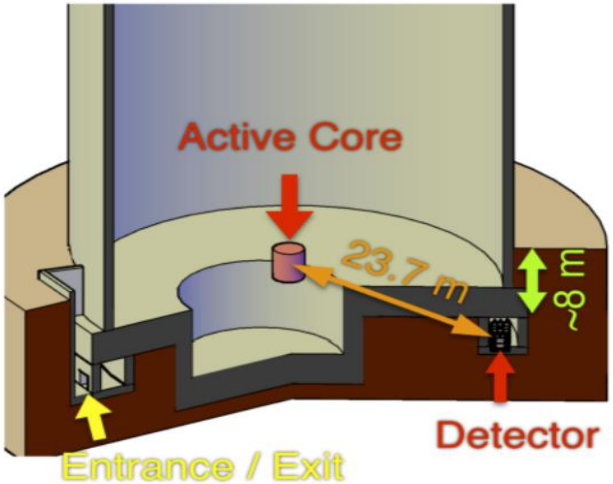
$\Longrightarrow$



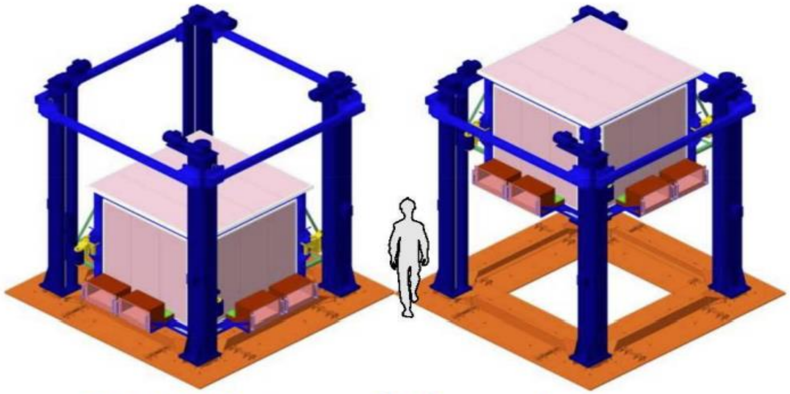
Model Indep. Measurements at Reactors

Ratios of spectra at different distances

NEOS

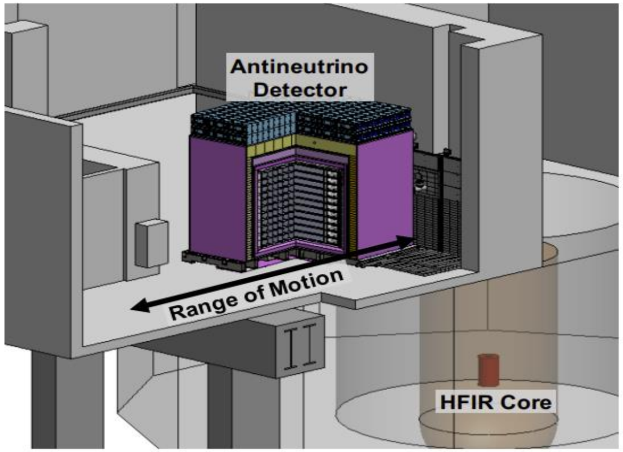


DANSS [Alekseev @ NOW 2022]

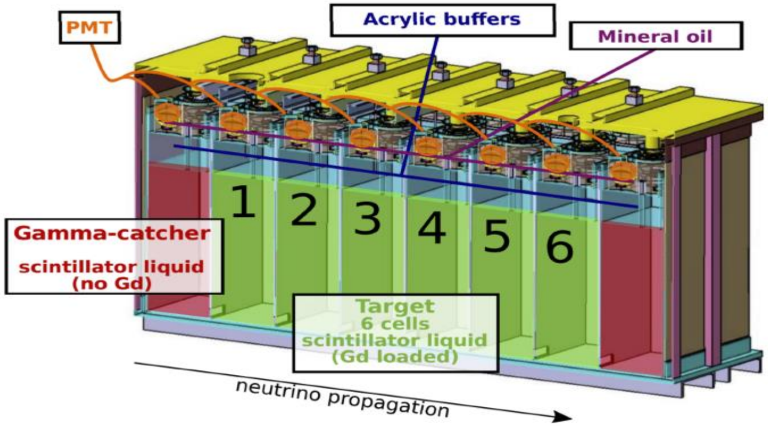


DANSS on a lifting platform

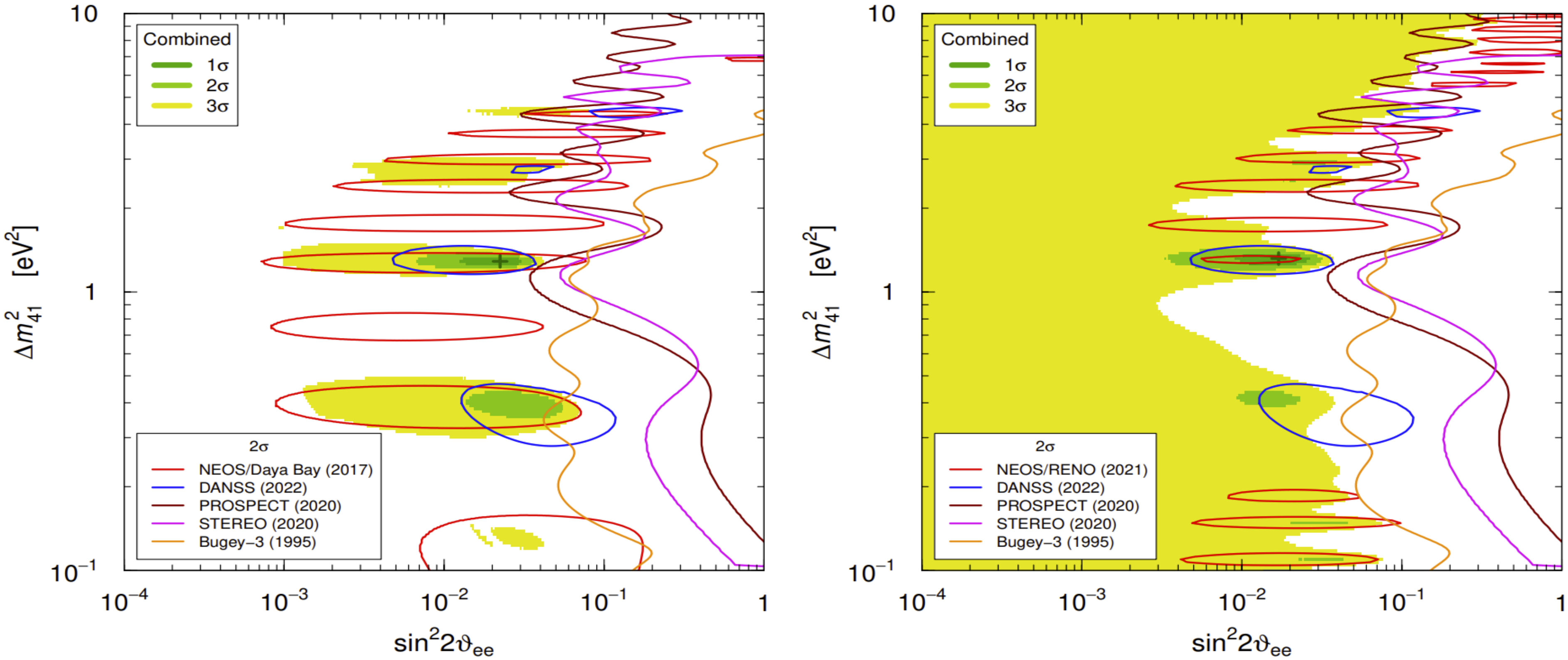
PROSPECT [Roca Catala @ NOW 2022]



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: $\Delta\chi^2_{3\nu-4\nu} = 9.1 \Longrightarrow 2.6\ \sigma$

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:

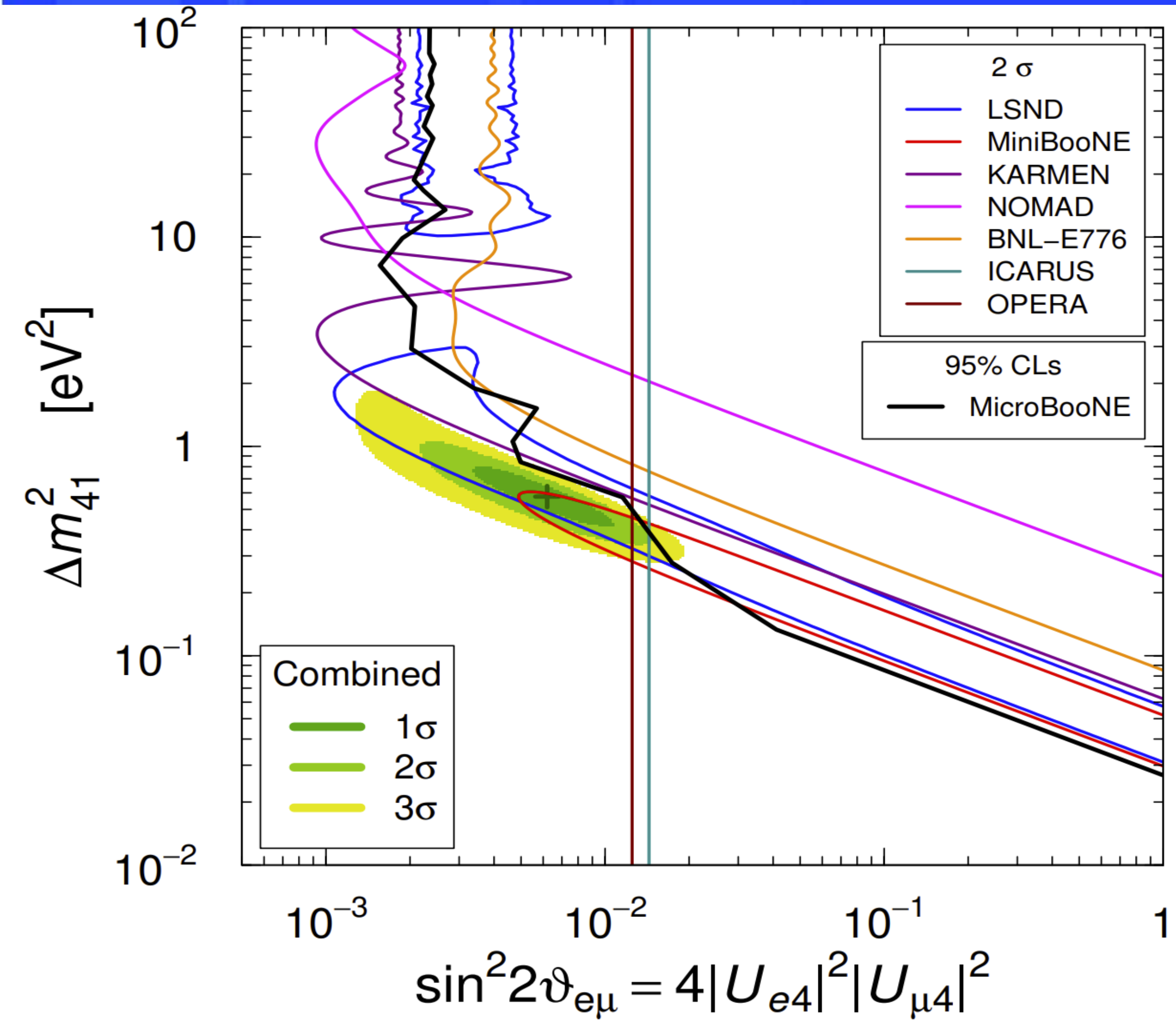
$$\sin^2 2\vartheta_{e\mu} = 4|U_{e4}|^2|U_{\mu4}|^2 \simeq \frac{1}{4}\sin^2 2\vartheta_{ee}\sin^2 2\vartheta_{\mu\mu}$$

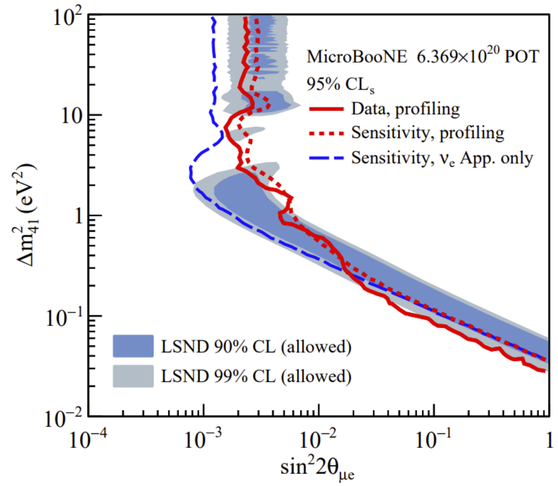
quadratically suppressed for small $|U_{e4}|^2$ and $|U_{\mu4}|^2$

$\Downarrow$

Appearance-Disappearance Tension

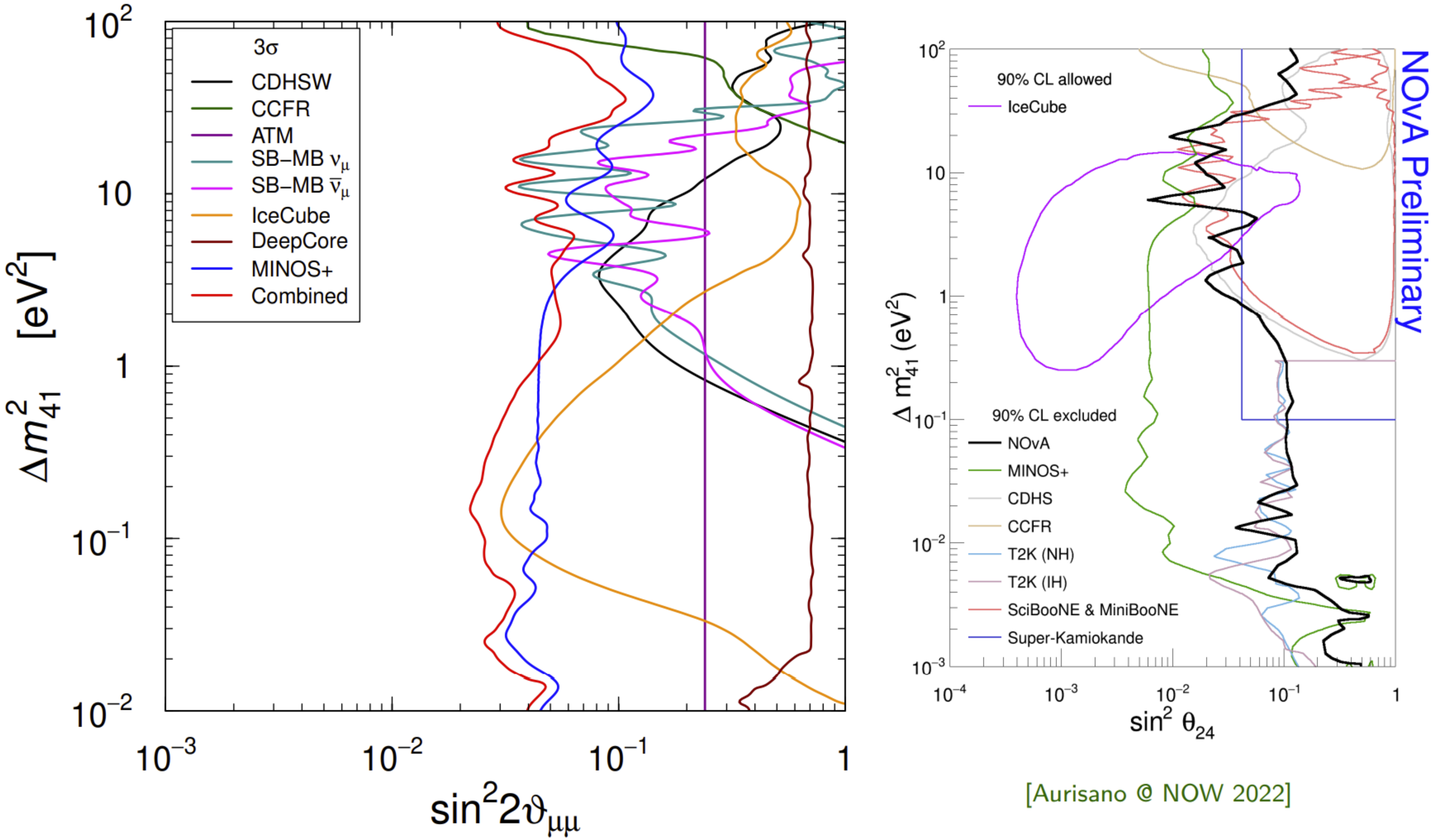
Appearance ($\nu_\mu \to \nu_e$) channel





MicroBooNE, 2210.10216,
See also Xiangpan Ji's talk

Disappearance (ν_μ) channel



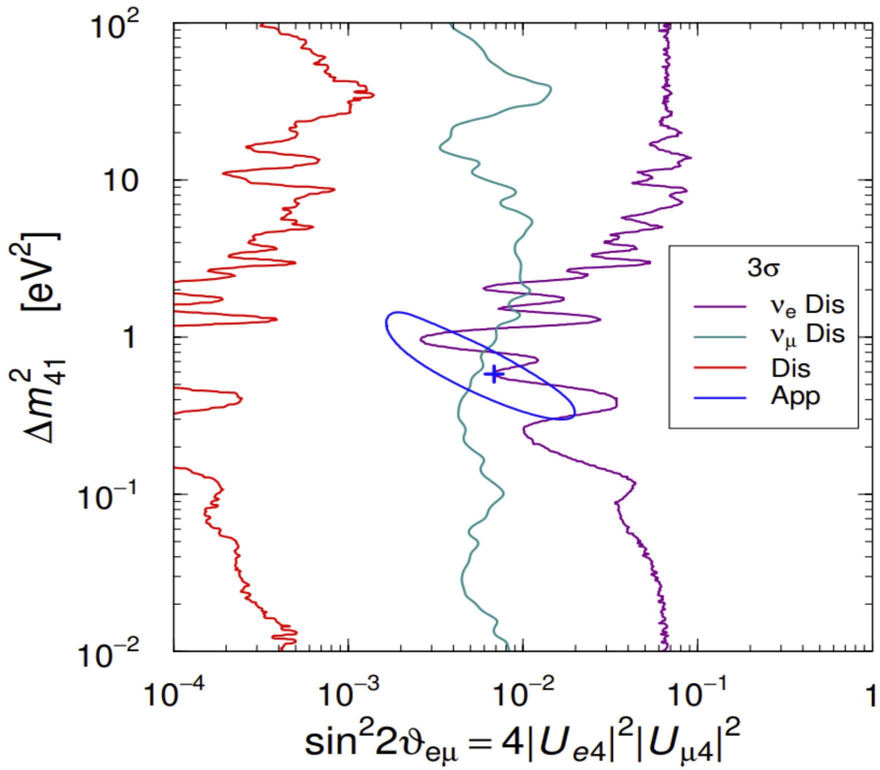
[Aurisano @ NOW 2022]

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:

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

  $\text{GoF} = 11\%$

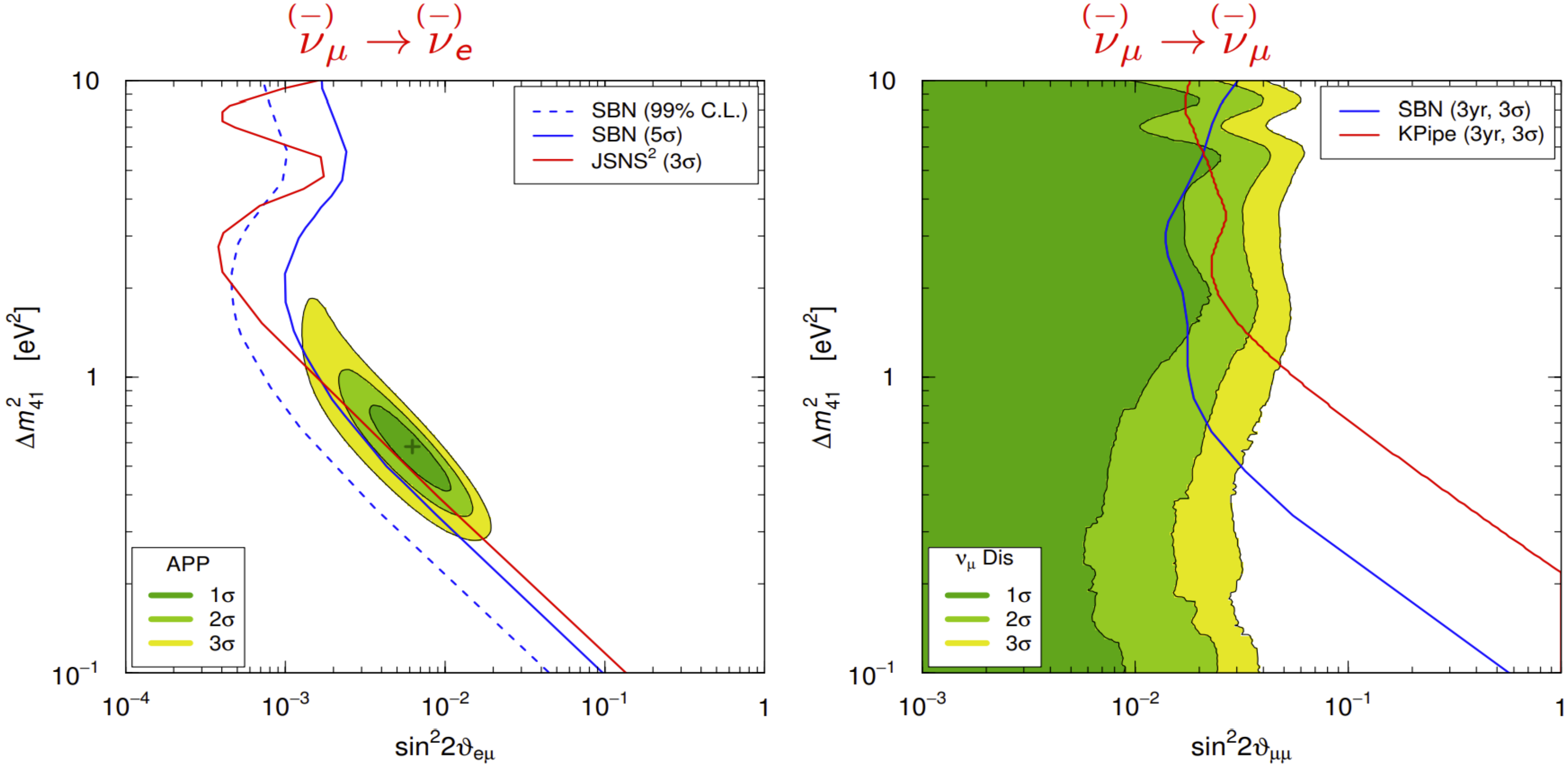
  $\chi^2_{\text{PG}}/\text{NDF}_{\text{PG}} = 46.7/2$

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