Karlsruher Institut für Technologie

HIDDeν
Hunting Invisibles: Dark sectors, Dark matter and Neutrinos

The sterile neutrino hypothesis and short-baseline anomalies

Thomas Schwetz
Karlsruhe Institute of Technology, Institute for Astroparticle Physics

PASCOS
PARTICLES
STRINGS
COSMOLOGY
25-29 JULY 2022 - MPIK - HEIDELBERG - GERMANY

Sterile neutrinos — a very simple extension of the SM

- fermionic singlets under the SM gauge group:
  „sterile neutrinos“, „right-handed neutrinos“, „heavy neutral leptons“

Yukawa term:

$$\mathcal{L}_Y = -y \bar{L}_L \tilde{\phi} N_R + \mathrm{h.c.}$$

bare Majorana mass term:

$$\frac{1}{2} N_R^T C^{-1} M_R^* N_R + \mathrm{h.c.}$$

- generically present in models for neutrino mass (e.g. seesaw)

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bare Majorana mass term:

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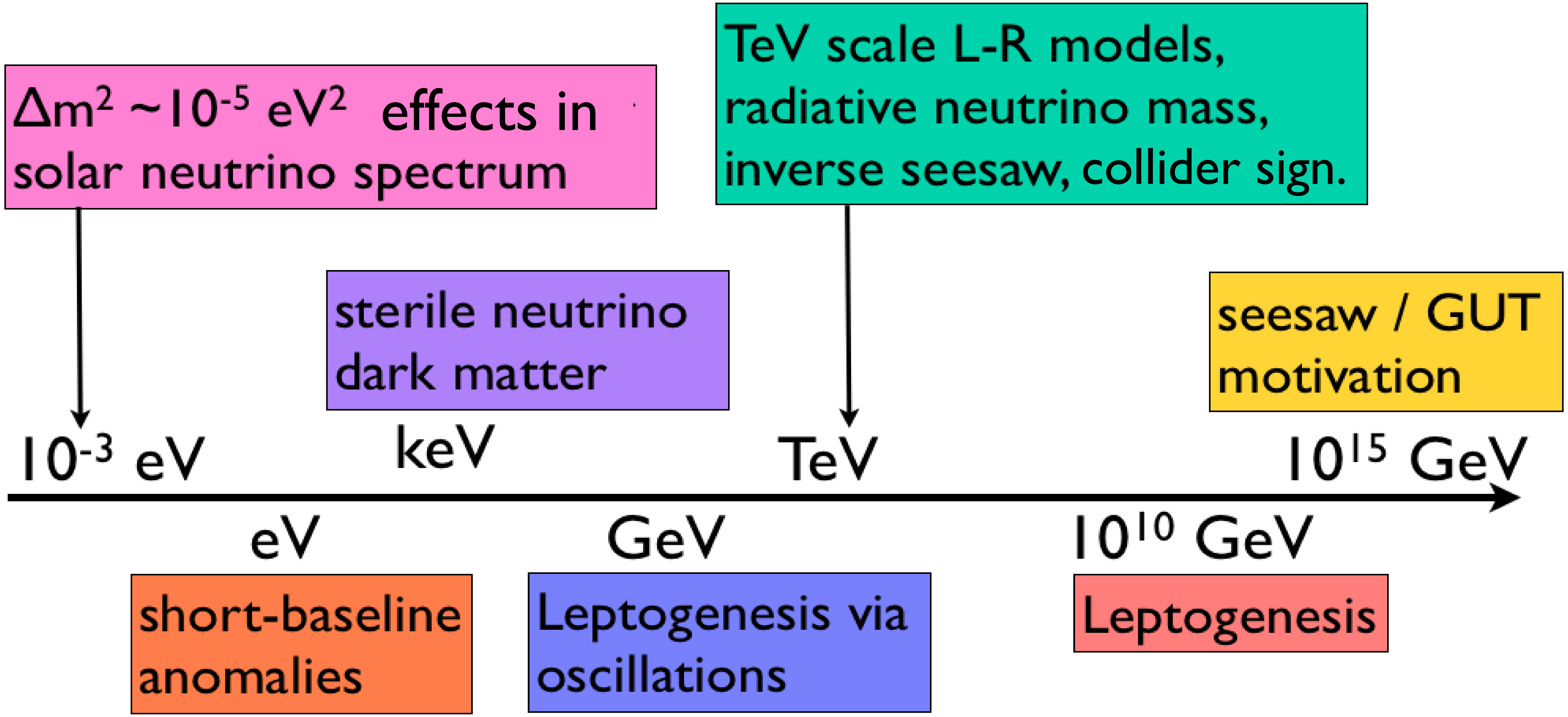
At which mass scale?
(M_R not related to Higgs vev)

- generically present in models for neutrino mass (e.g. seesaw)

Sterile neutrinos at which mass scale?



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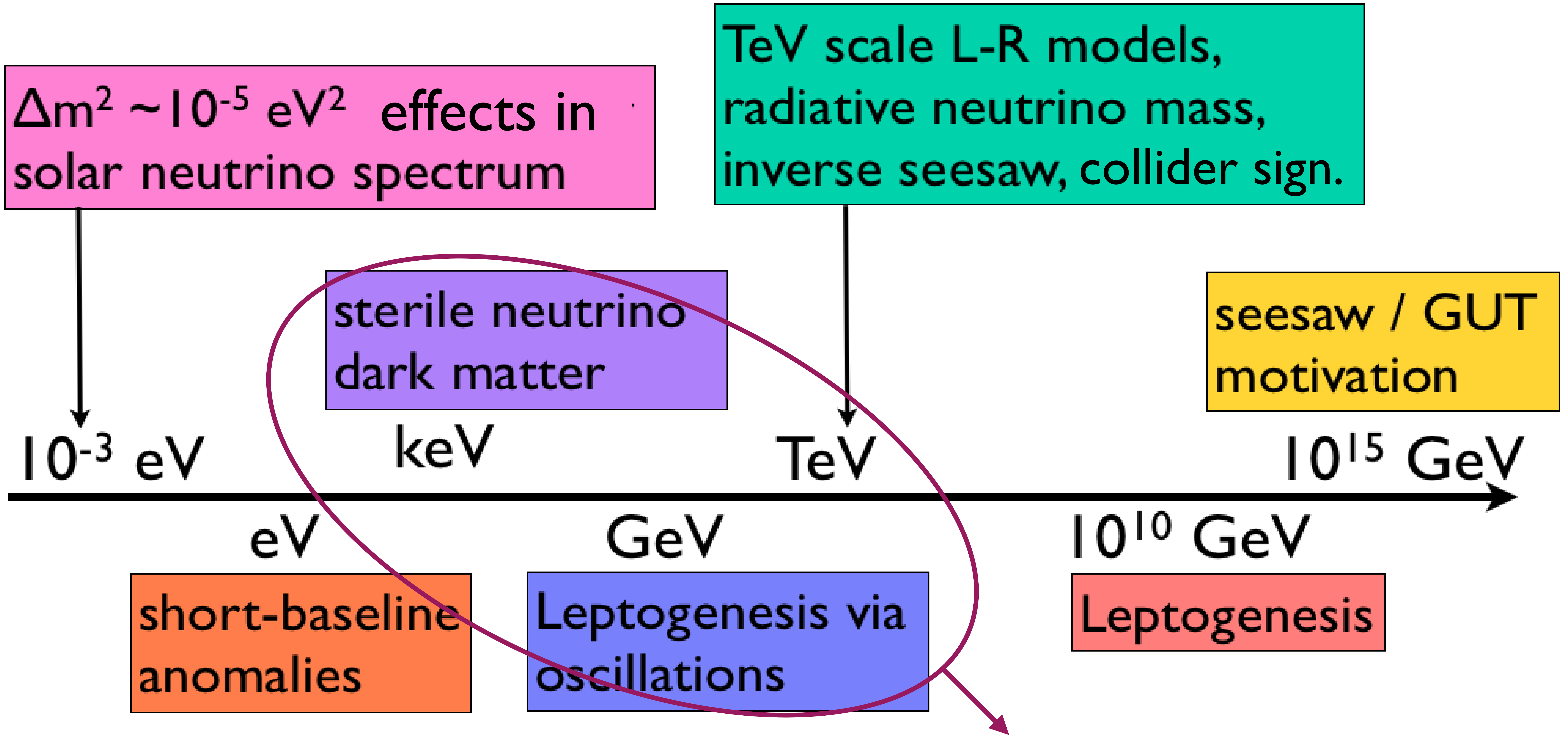
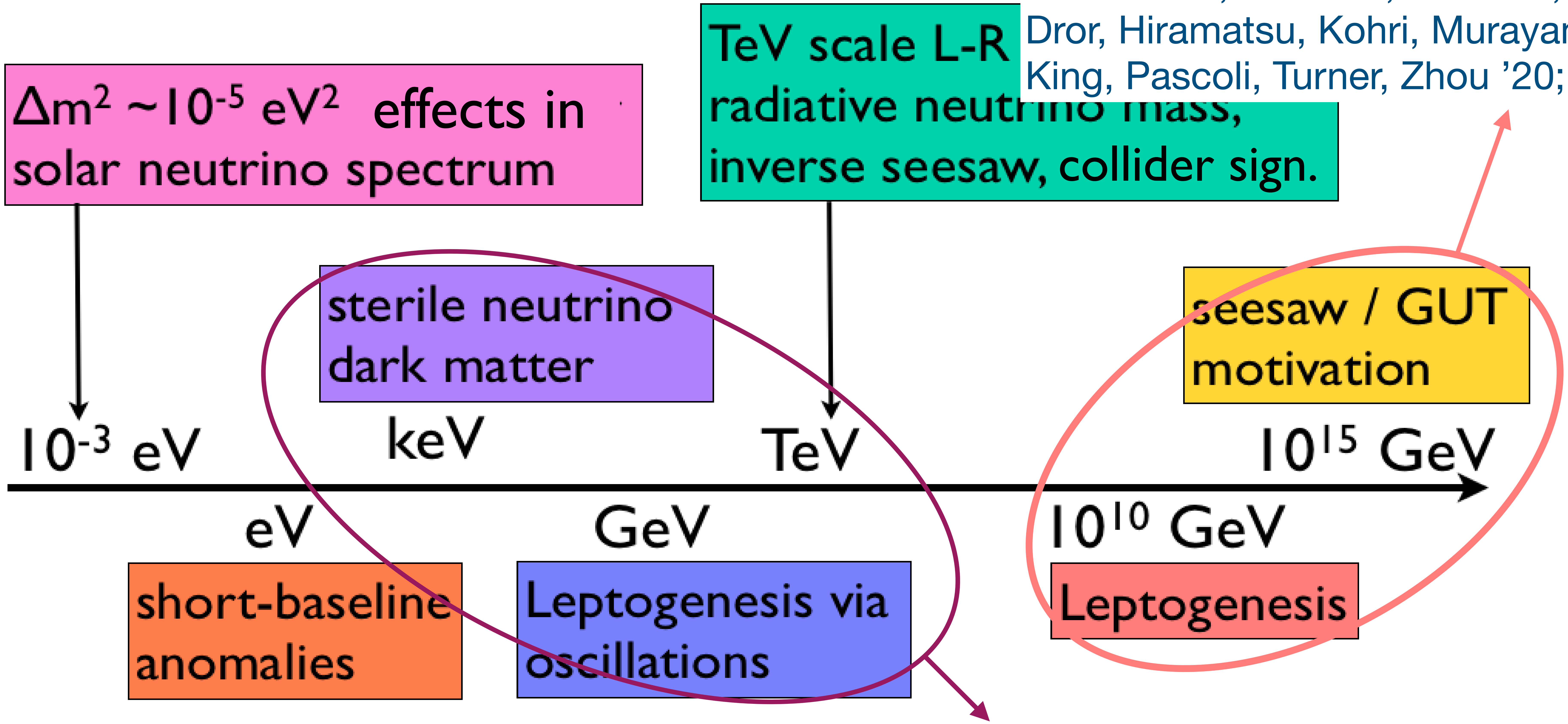


predictive minimal scenario (νMSM):
Asaka, Shaposhnikov ’05; Hernandez et al.,’16; Drewes et al.,’16,…

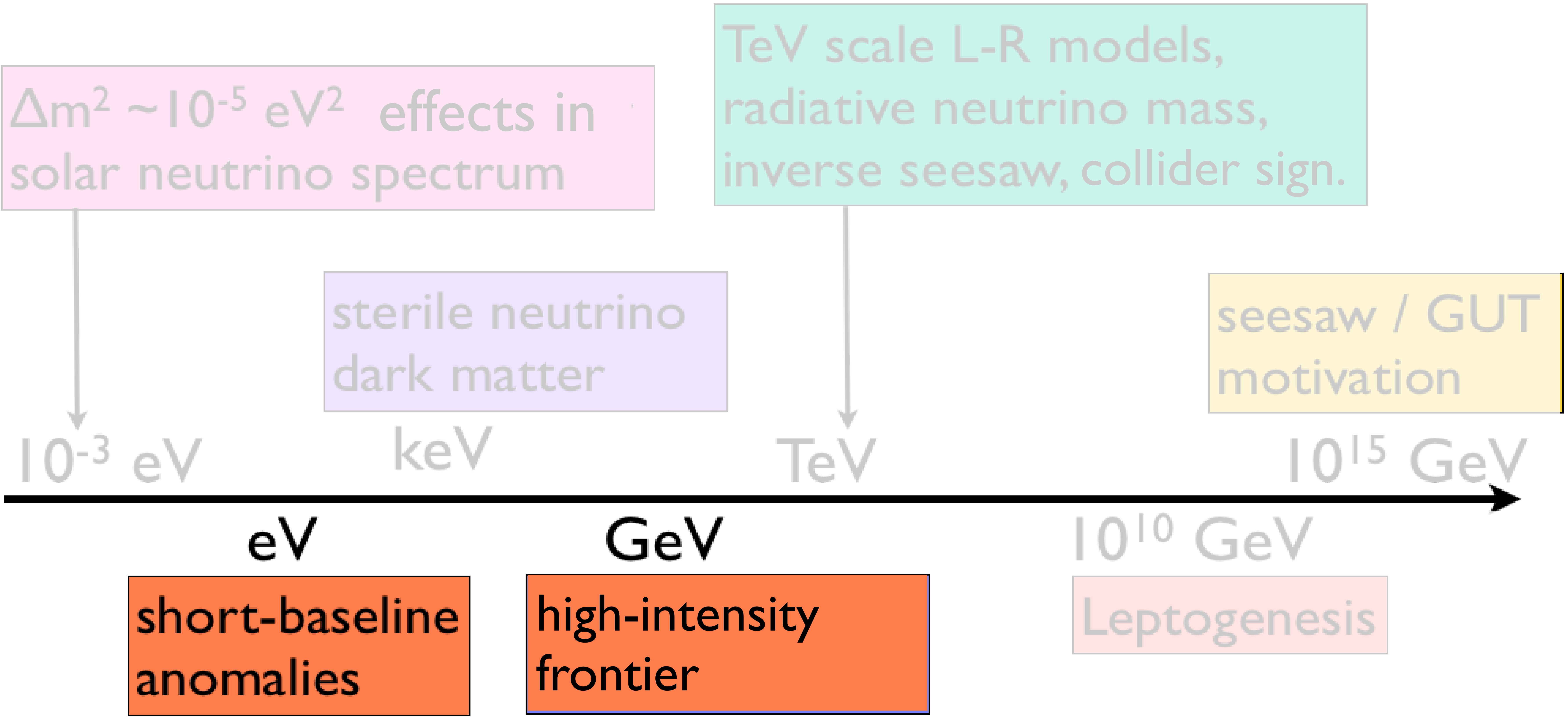
Sterile neutrinos at which mass scale?



possible gravitational wave signature:
Buchmüller, Domcke, Kamada, Schmitz ’13;
Dror, Hiramatsu, Kohri, Murayama, White ’19;
King, Pascoli, Turner, Zhou ’20;…

predictive minimal scenario (νMSM):
Asaka, Shaposhnikov ’05; Hernandez et al.,’16;
Drewes et al.,’16,…

This talk:



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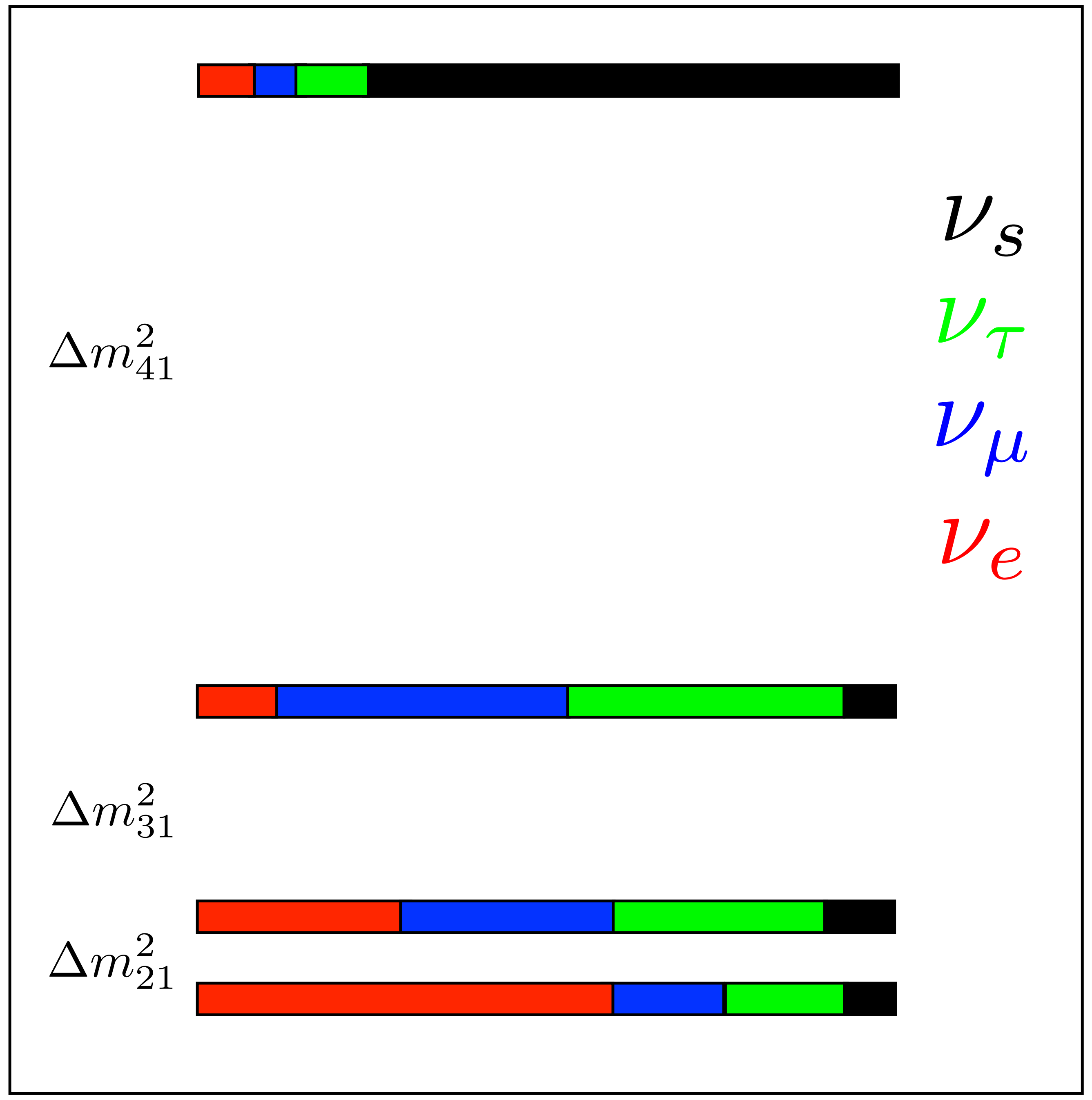
Sterile neutrinos at the eV scale?

- Reactor anomaly ($\bar{\nu}_e$ disappearance)
  - predicted vs measured rate
  - distance dependent spectral distortions
- Gallium anomaly (ν_e disappearance)
- LSND ($\bar{\nu}_\mu \to \bar{\nu}_e$ appearance)
- MiniBooNE ($\nu_\mu \to \nu_e, \bar{\nu}_\mu \to \bar{\nu}_e$ appearance)



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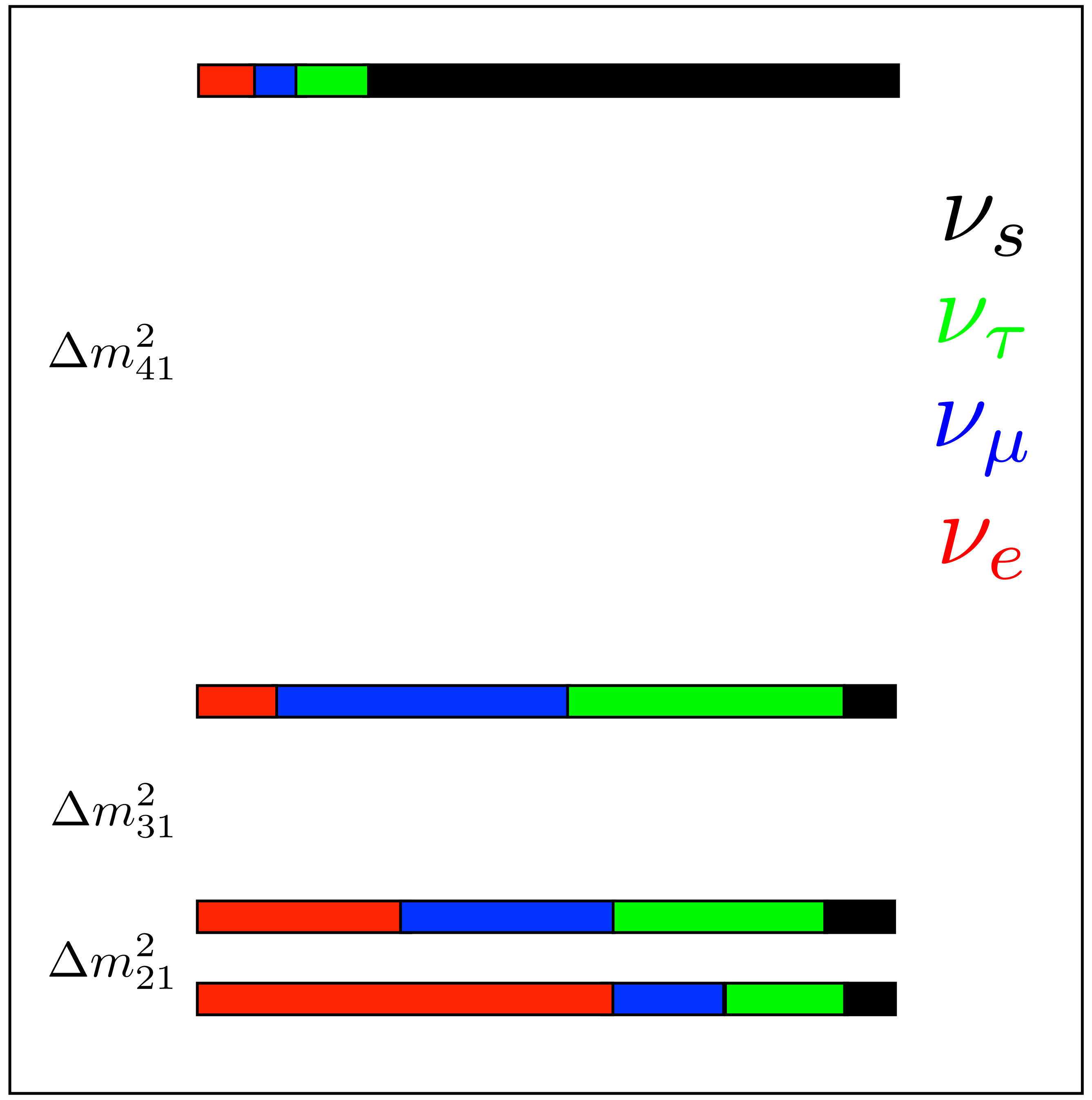
Electron-neutrino disappearance

- Reactor anomaly ($\bar{\nu}_e$ disappearance)
  - predicted vs measured rate
  - distance dependent spectral distortions
- Gallium anomaly (ν_e disappearance)

mixing parameter $|U_{e4}|^2 = \sin^2\theta_{ee}$



Reactor reactor neutrino fluxes

- need to fit measured beta-spectra from ^{235}U, ^{239}Pu, ^{241}Pu [Schreckenbach et al., 80s], ^{238}U [Haag et al., 1312.5601] and predict the corresponding neutrino spectra
- difficult nuclear physics calculations, uncertainties difficult to estimate
- two methods:
  - conversion method using „virtual beta branches“
  - ab initio calculations using nuclear data tables
    problem of „forbidden“-decays

40 years of reactor neutrinos physics rest on the ILL measurments

Anti-neutrino Spectra From ^{241}Pu and ^{239}Pu Thermal Neutron Fission Products #1

A.A. Hahn (UC, Irvine), K. Schreckenbach (Laue-Langevin Inst.), G. Colvin (Laue-Langevin Inst.), B. Krusche (Laue-Langevin Inst.), W. Gelletly (Manchester U.) et al. (1989)

Published in: *Phys.Lett.B* 218 (1989) 365-368

DOI cite 413 citations

DETERMINATION OF THE ANTI-NEUTRINO SPECTRUM FROM U-235 THERMAL NEUTRON FISSION PRODUCTS UP TO 9.5-MEV #2

K. Schreckenbach (Laue-Langevin Inst.), G. Colvin (Laue-Langevin Inst.), W. Gelletly (Manchester U.), F. Von Feilitzsch (Munich, Tech. U.) (1985)

Published in: *Phys.Lett.B* 160 (1985) 325-330

DOI cite 482 citations

EXPERIMENTAL BETA SPECTRA FROM PU-239 AND U-235 THERMAL NEUTRON FISSION PRODUCTS AND THEIR CORRELATED ANTI-NEUTRINOS SPECTRA #3

F. Von Feilitzsch (Munich, Tech. U.), A.A. Hahn (Caltech), K. Schreckenbach (Laue-Langevin Inst.) (1982)

Published in: *Phys.Lett.B* 118 (1982) 162-166

DOI cite 287 citations

The reactor rate anomaly 2011

- tension between „predicted“ and observed neutrino rates at nuclear reactors

Improved Predictions of Reactor Antineutrino Spectra #2

Th.A. Mueller (DAPNIA, Saclay), D. Lhuillier (DAPNIA, Saclay), M. Fallot (SUBATECH, Nantes), A. Letourneau (DSM, DAPNIA, Saclay), S. Cormon (SUBATECH, Nantes) et al. (Jan, 2011)

Published in: *Phys.Rev.C* 83 (2011) 054615 • e-Print: 1101.2663 [hep-ex]

pdf DOI cite 1,105 citations

On the determination of anti-neutrino spectra from nuclear reactors #1

Patrick Huber (Virginia Tech.) (Jun, 2011)

Published in: *Phys.Rev.C* 84 (2011) 024617, *Phys.Rev.C* 85 (2012) 029901 (erratum) • e-Print: 1106.0687 [hep-ph]

pdf DOI cite 922 citations

The Reactor Antineutrino Anomaly #5

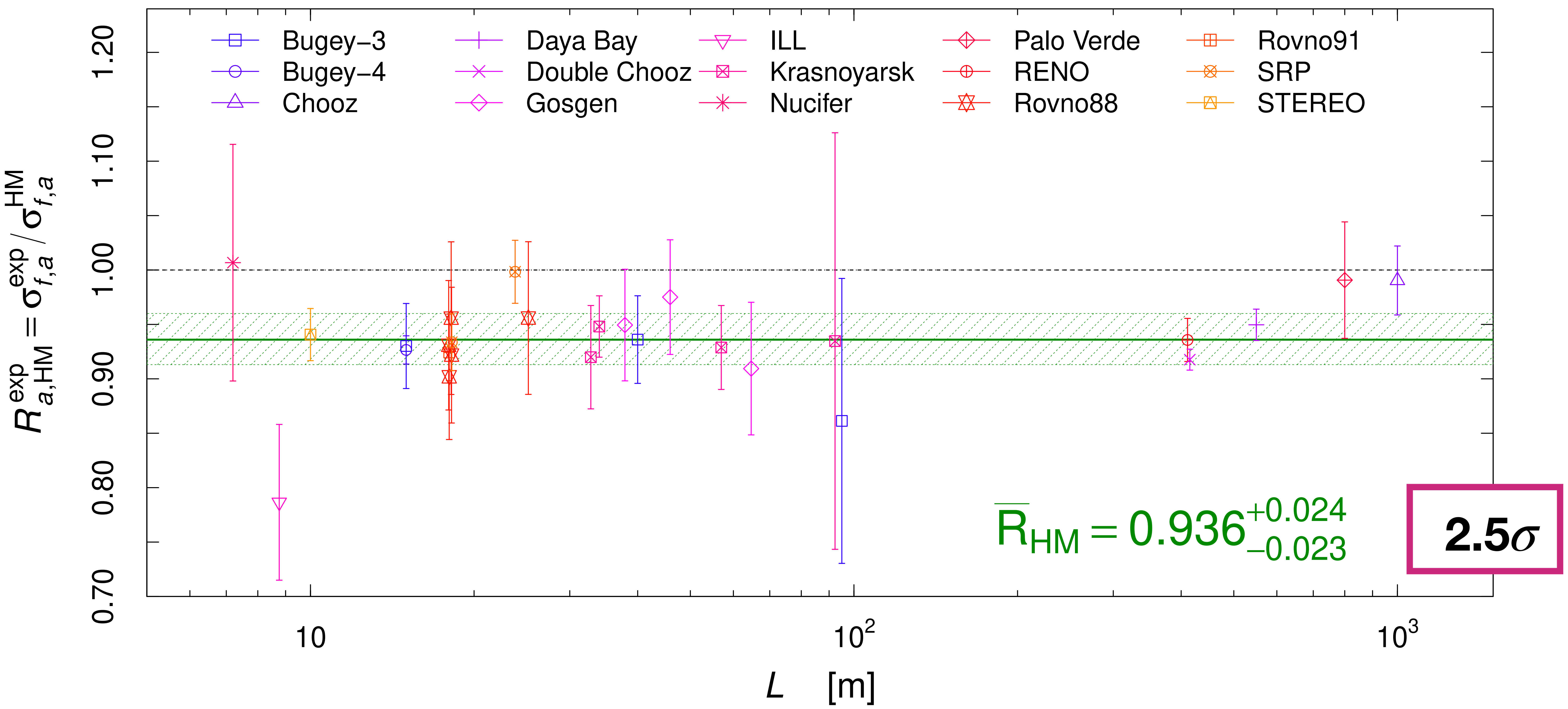
G. Mention (DAPNIA, Saclay), M. Fechner (DAPNIA, Saclay), Th. Lasserre (DAPNIA, Saclay and APC, Paris), Th.A. Mueller (DAPNIA, Saclay), D. Lhuillier (DAPNIA, Saclay) et al. (Jan, 2011)

Published in: *Phys.Rev.D* 83 (2011) 073006 • e-Print: 1101.2755 [hep-ex]

pdf DOI cite 1,510 citations

The reactor rate anomaly 2011

- tension between „predicted“ and observed neutrino rates at nuclear reactors



Giunti, Li, Ternes, Xin, 2110.06820

Reactor anomaly — recent updates on calculations

- new ab initio calculations [Estienne et al., 1904.09358] find decrease in ^{235}U flux, better agreement with DayaBay
- new conversion [Hayen et al., 1908.08302] including forbidden decay shapes via shell model calc., better fit to 5 MeV region

Berryman, Huber, 1909.09267

Huber, Muller, 2011 → HM Rates
Estienne et al., 1904.09358 → Ab Initio Rates
Hayen et al., 1908.08302 → HKSS Rates

Analysis	$\chi^2_{3\nu}$	$\chi^2_{\rm min}$	$n_{\rm data}$	p	$n\sigma$
HM Rates	41.4	33.5	40	2.0×10^{-2}	2.3
Ab Initio Rates	39.2	37.0	40	0.34	0.95
HKSS Rates	58.1	47.5	40	5.0×10^{-3}	2.8
Spectra	184.9	172.2	212	1.8×10^{-3}	3.1
DANSS + NEOS	98.9	84.7	84	8.1×10^{-4}	3.3

The end of the reactor rate anomaly?

… after 40 years of Schreckenbach et al. ILL measurements …
… and 10 years of anomaly …

PHYSICAL REVIEW D **104,** L071301 (2021)

Letter | Editors' Suggestion

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

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

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

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

(Received 5 March 2021; revised 25 May 2021; accepted 20 August 2021; published 25 October 2021)

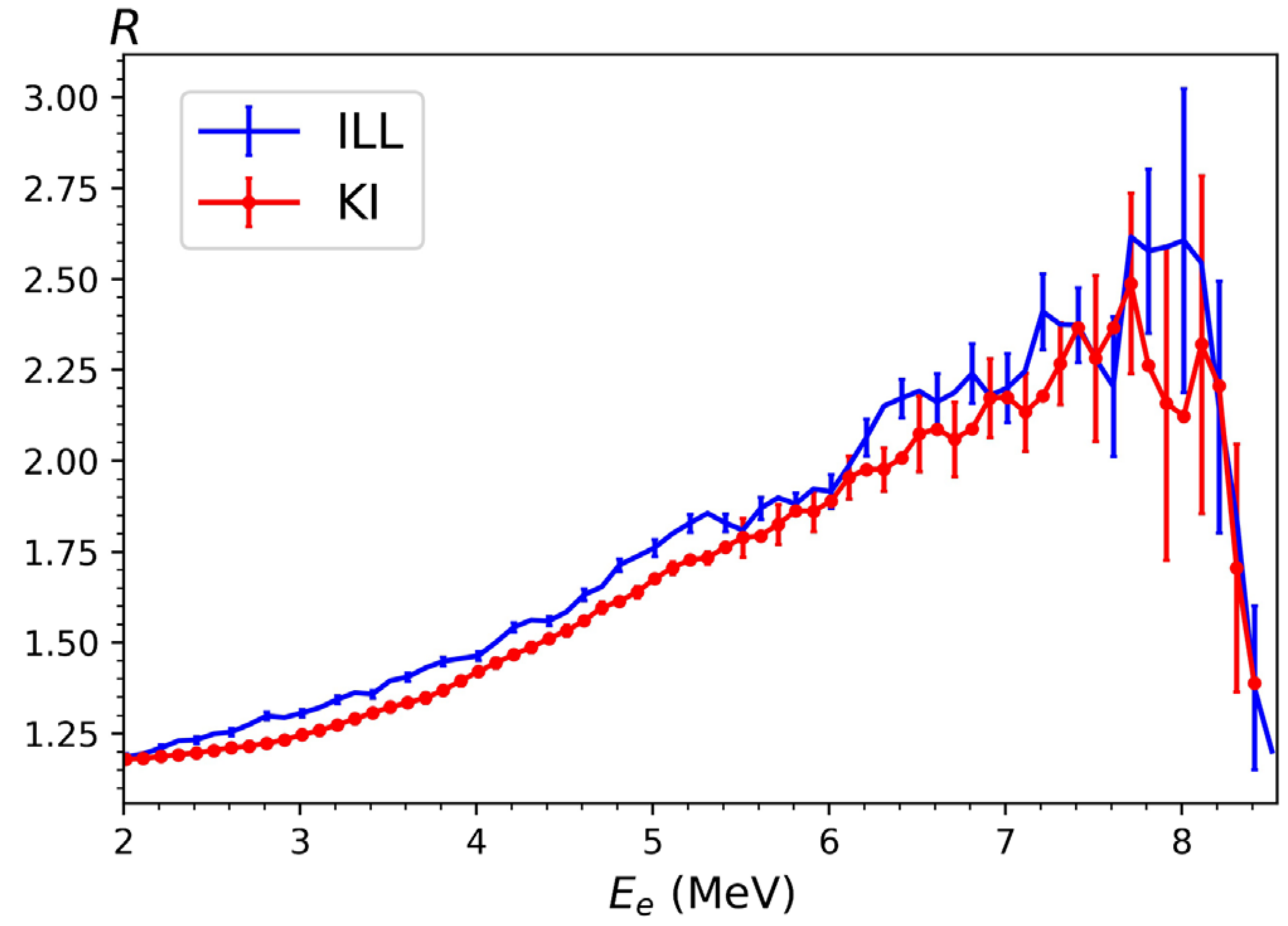


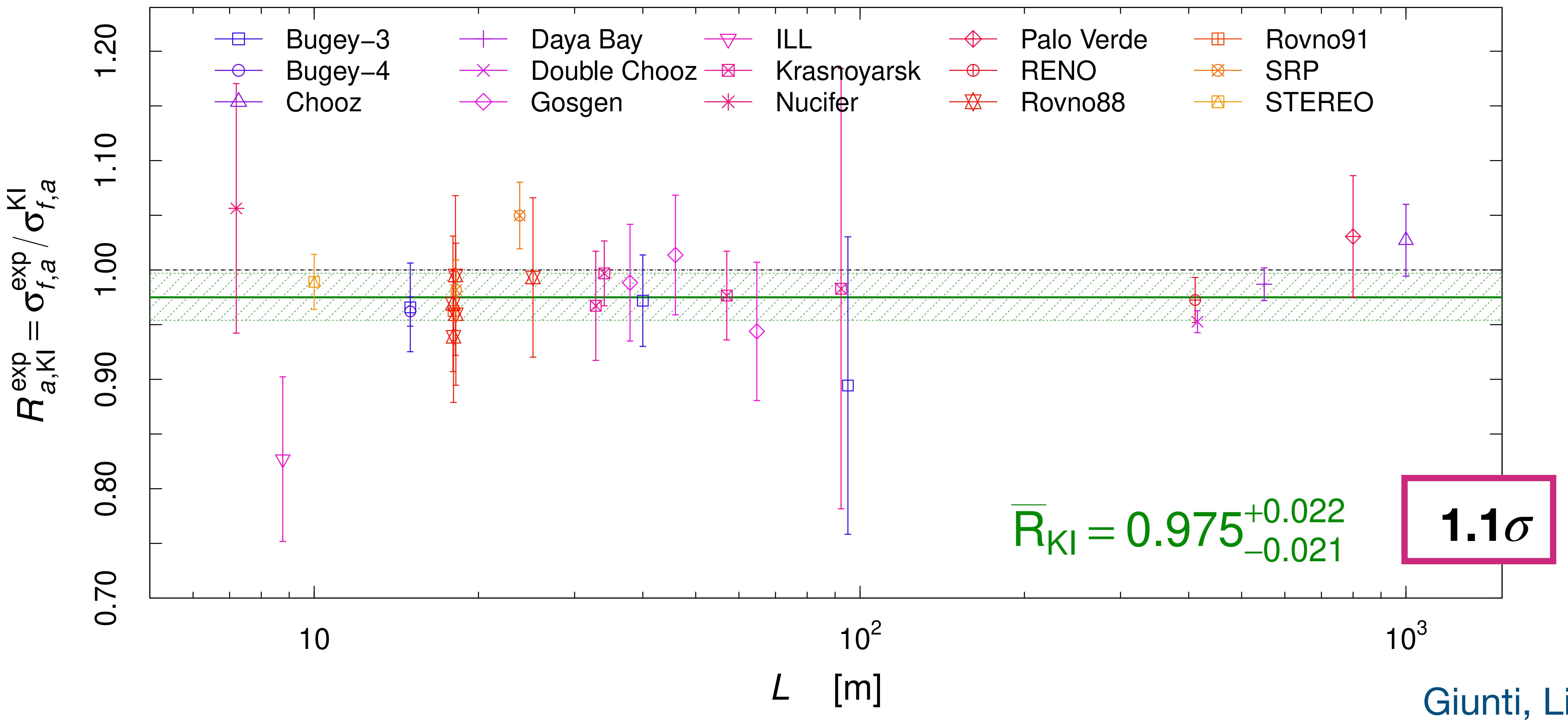
FIG. 1. Ratios $R = {}^eS_5/{}^eS_9$ between cumulative β spectra from ^{235}U and ^{239}Pu from ILL data [11] (the upper curve, blue) and KI data [10] (the lower curve, red). Total electron energies are given. Only statistical errors are shown.

- new measurment of ^{253}U / ^{239}Pu electron spectra ratio
- factor 1.054 lower than ILL measurements!!

The end of the reactor rate anomaly?

…after 40 years of Schreckenbach et al. ILL measurements…

new beta spectrum measurement from Kurchatov Institute:



Giunti, Li, Ternes, Xin, 2110.06820

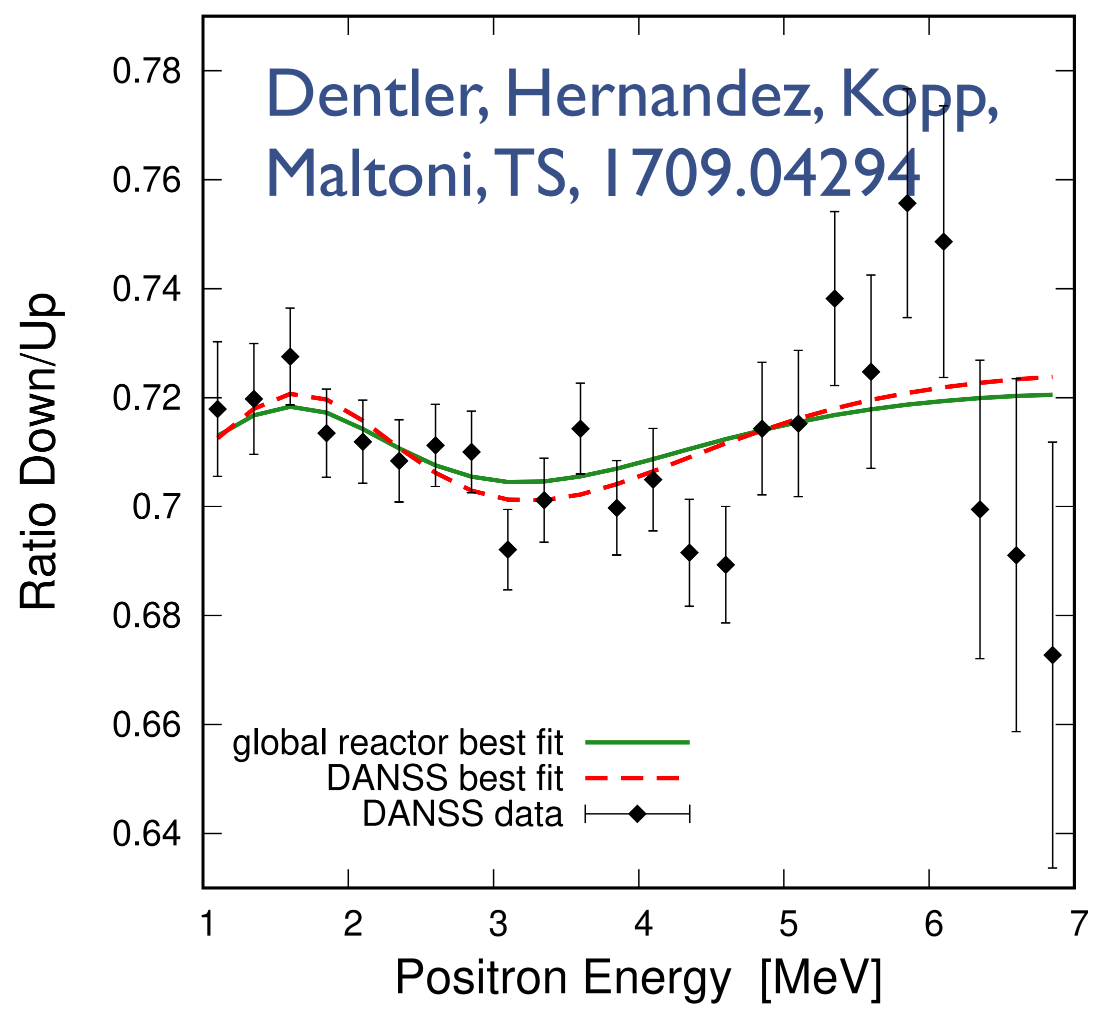
Reactor shape anomaly

- relative measurements at different baselines (near-far comparison, θ_{13} determination)

- spectral distortions in energy spectrum ratios

- segmented detectors, doubly-binned L and E_ν analysis

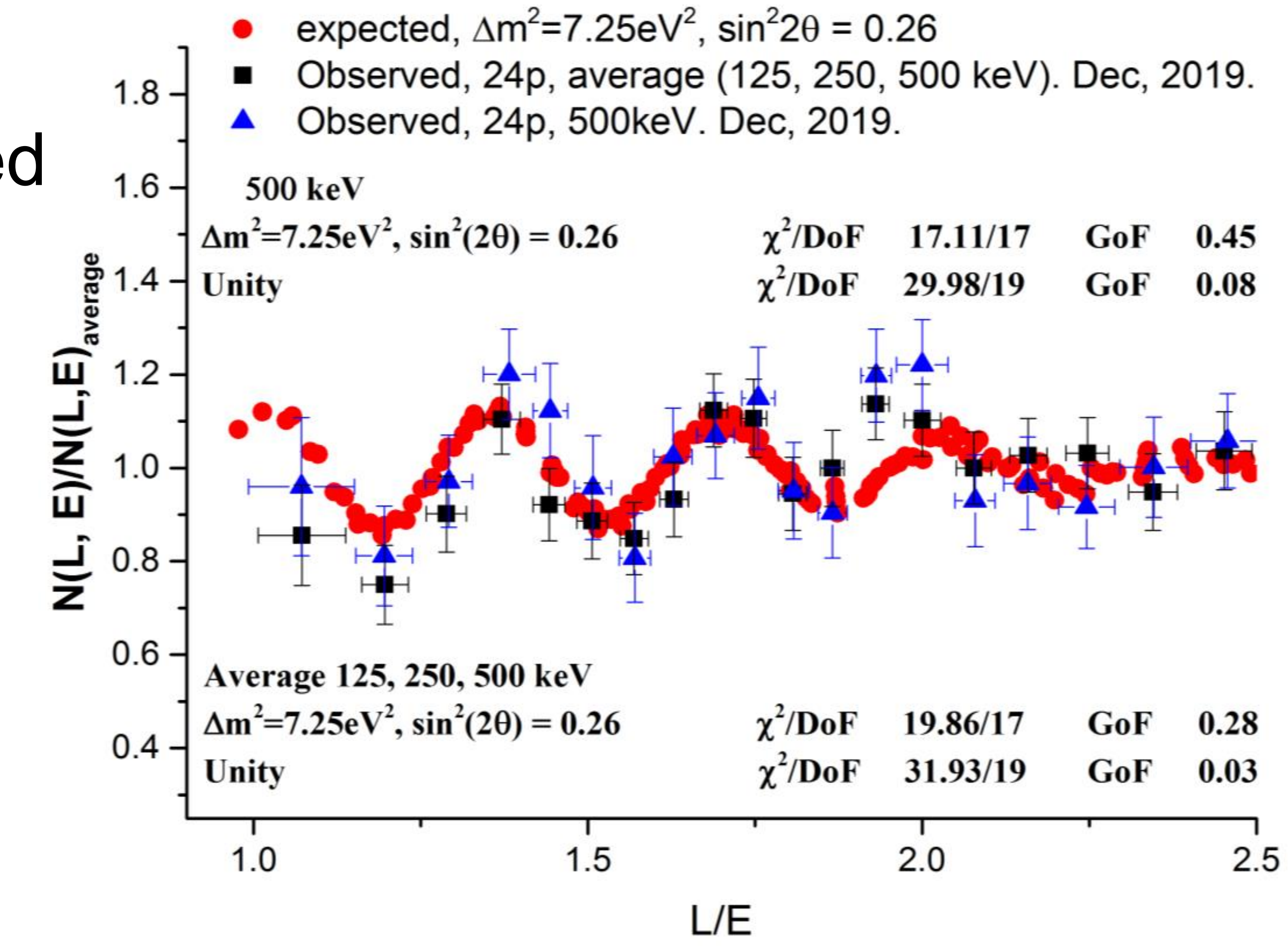
Recent relative spectral measurments



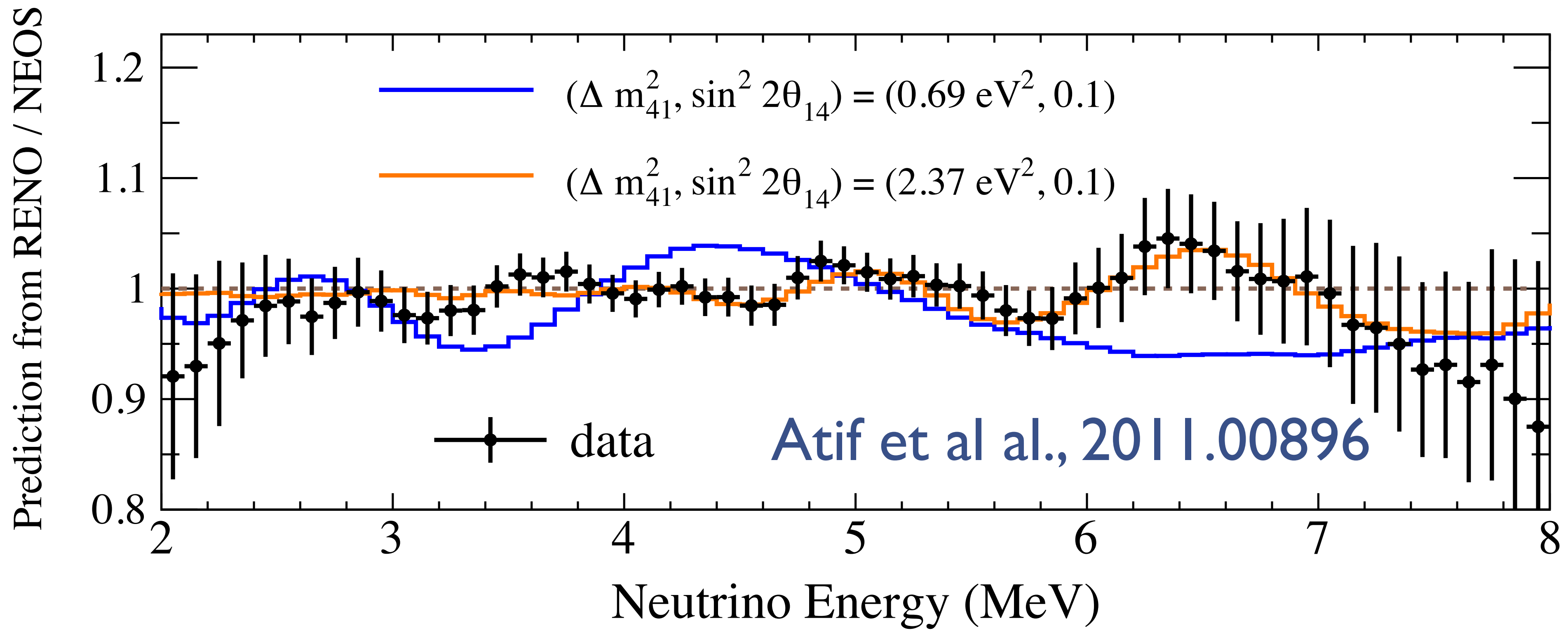
DANSS: relative spectra @ L = 10.7 and 12.7 m
prev. ~ 2σ hint decr. ~1.5σ
DANSS talk @ ICHEP20

Neutrino4: segmented detector, L = 6.25 to 11.9 m, 216 bins in L/E „3σ“ indication

Neutrino4 2005.05301

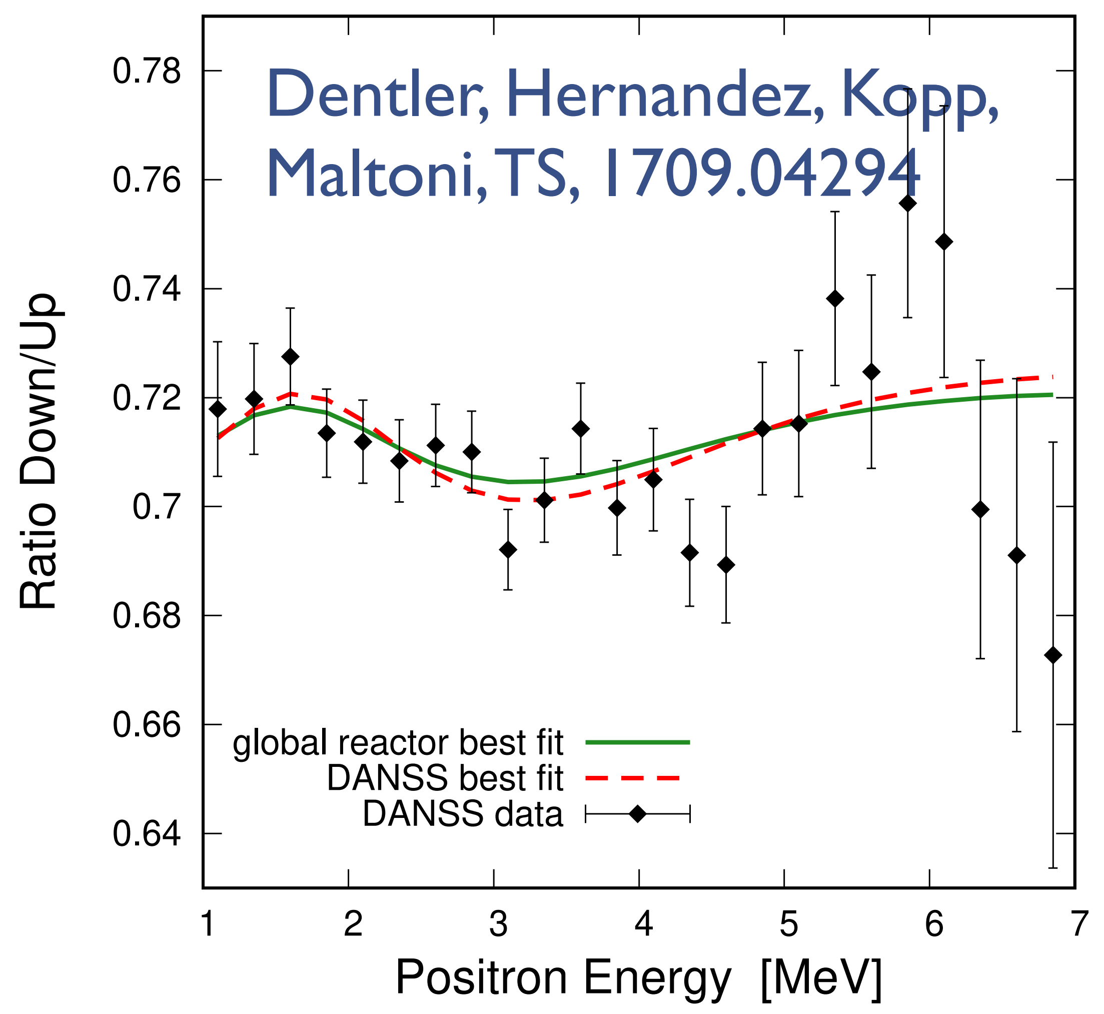


segmented detectors:
STEREO [arXiv:1912.06582]
L = 9 to 11 m $\Delta\chi^2$(no osc) ≈ 9
PROSPECT [arXiv:2006.11210]
L = 6.7 to 9.2 m



NEOS: spectrum at L = 24 m, relative to RENO (or DayaBay) near detectors: $\Delta\chi^2$(no osc) = 11.7

Recent relative spectral measurments



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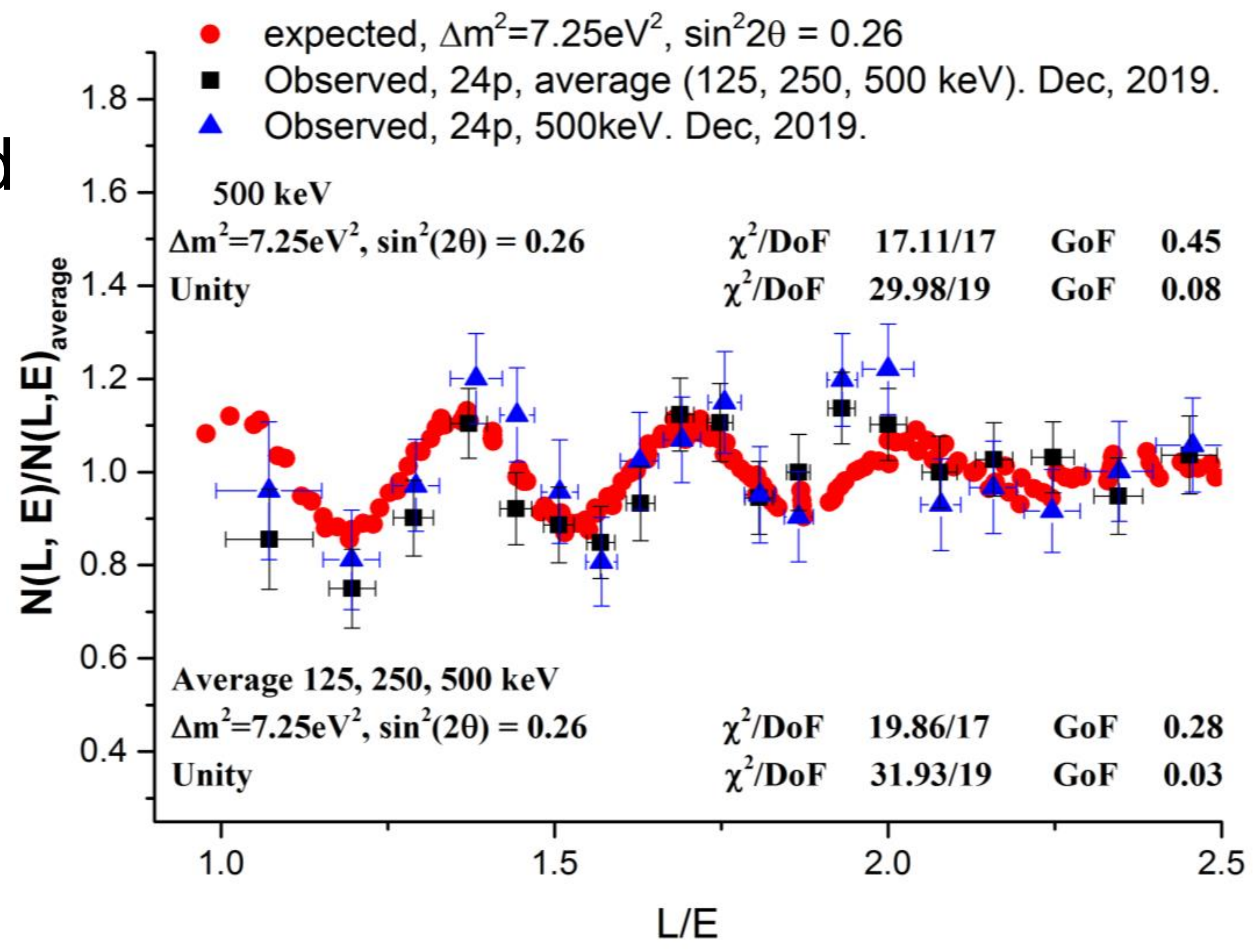

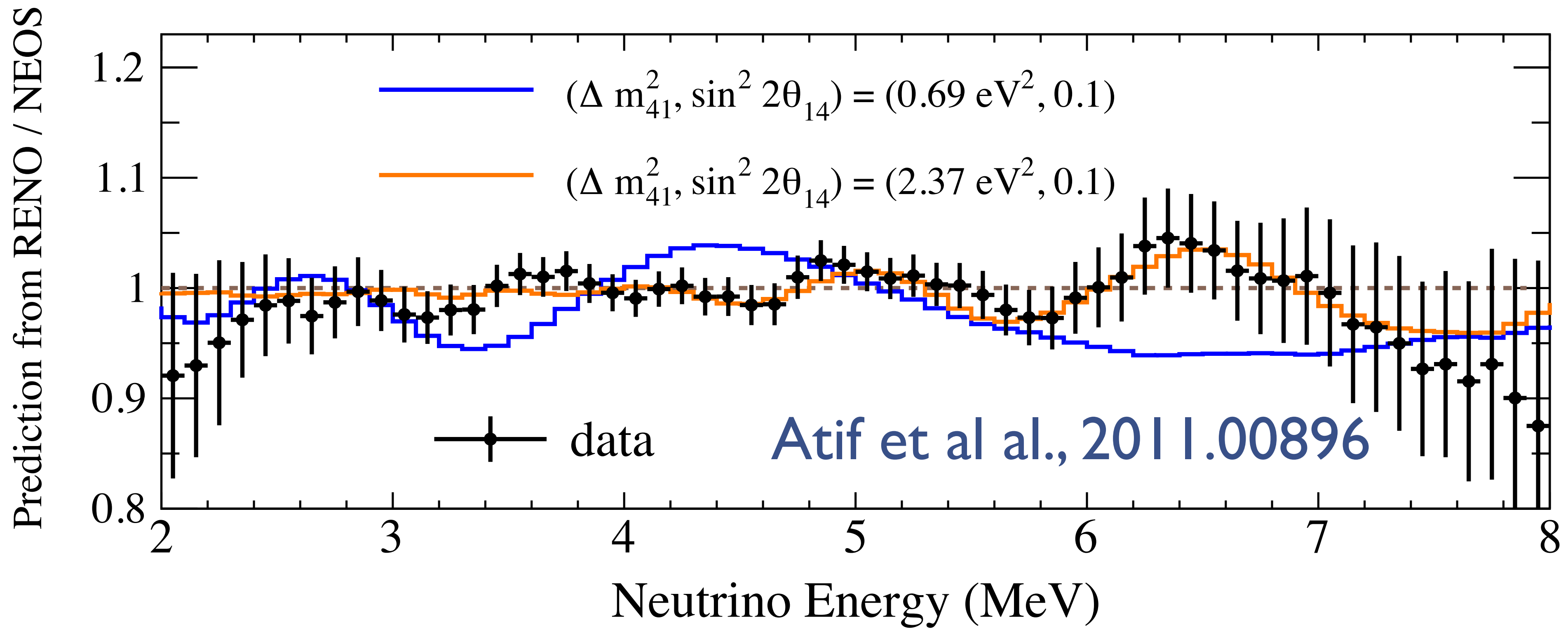

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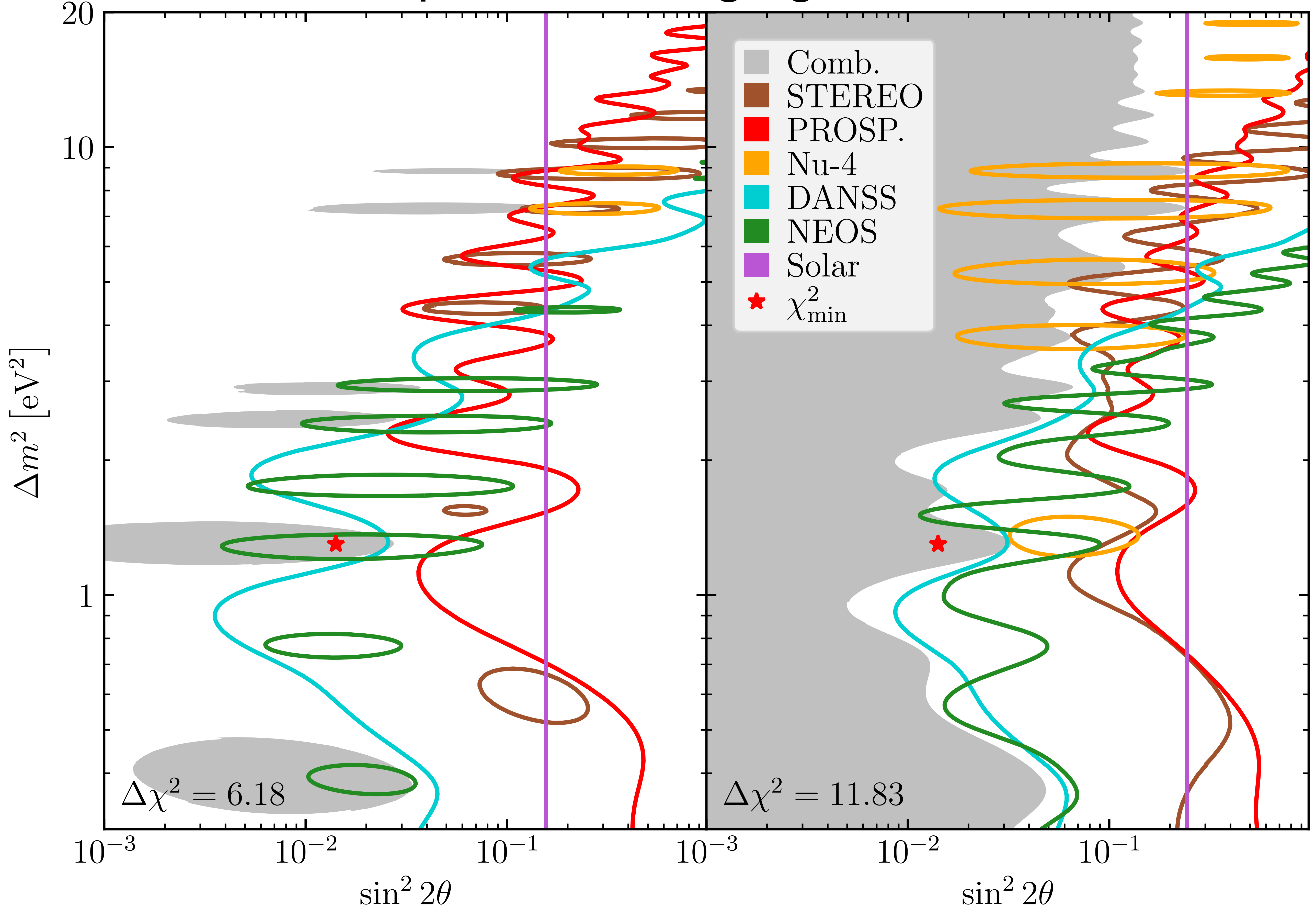
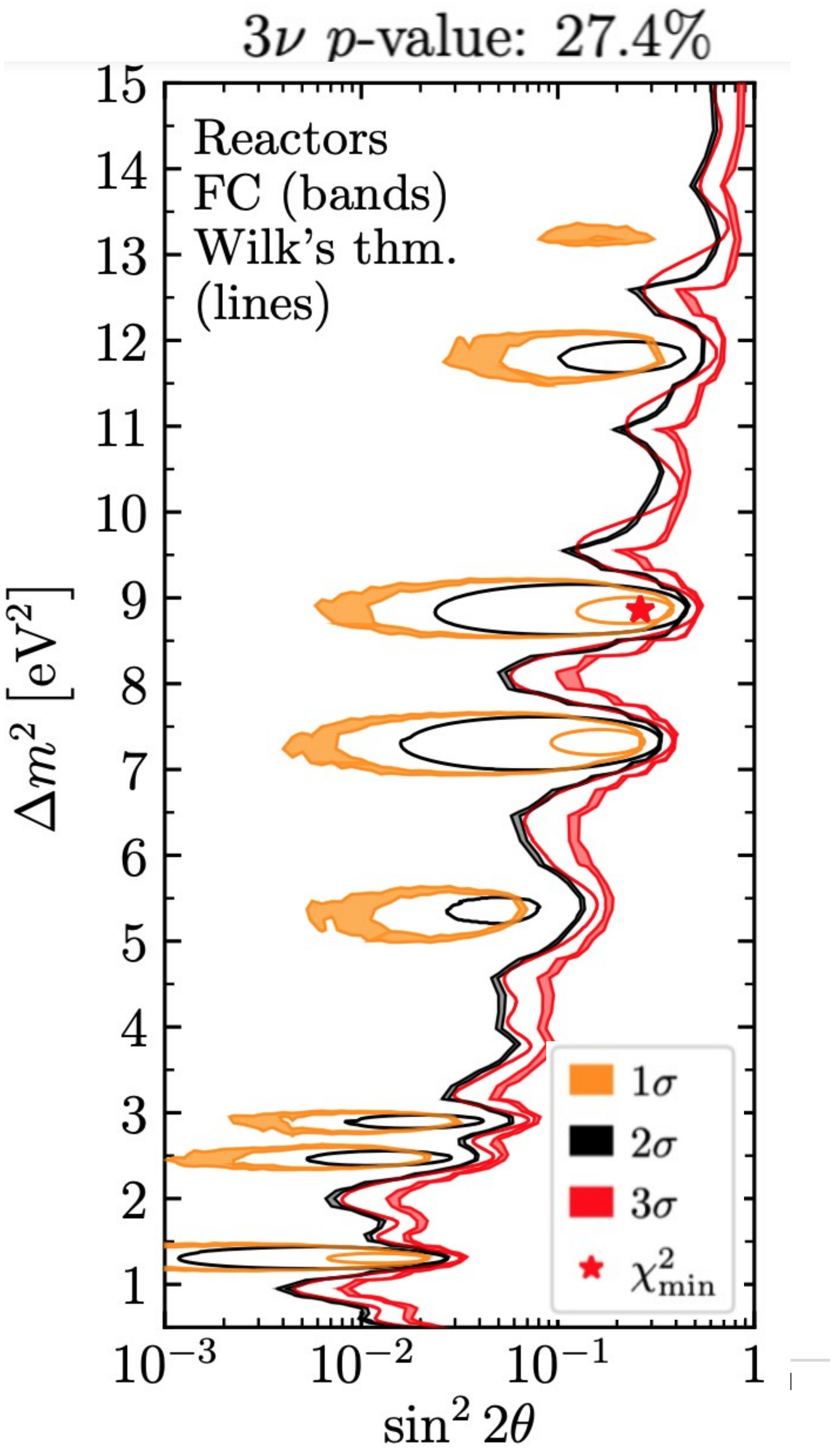
Global analysis of relative reactor data

Berryman, Coloma, Huber, Schwetz, Zhou, 2111.12530

No coherent picture emerging:

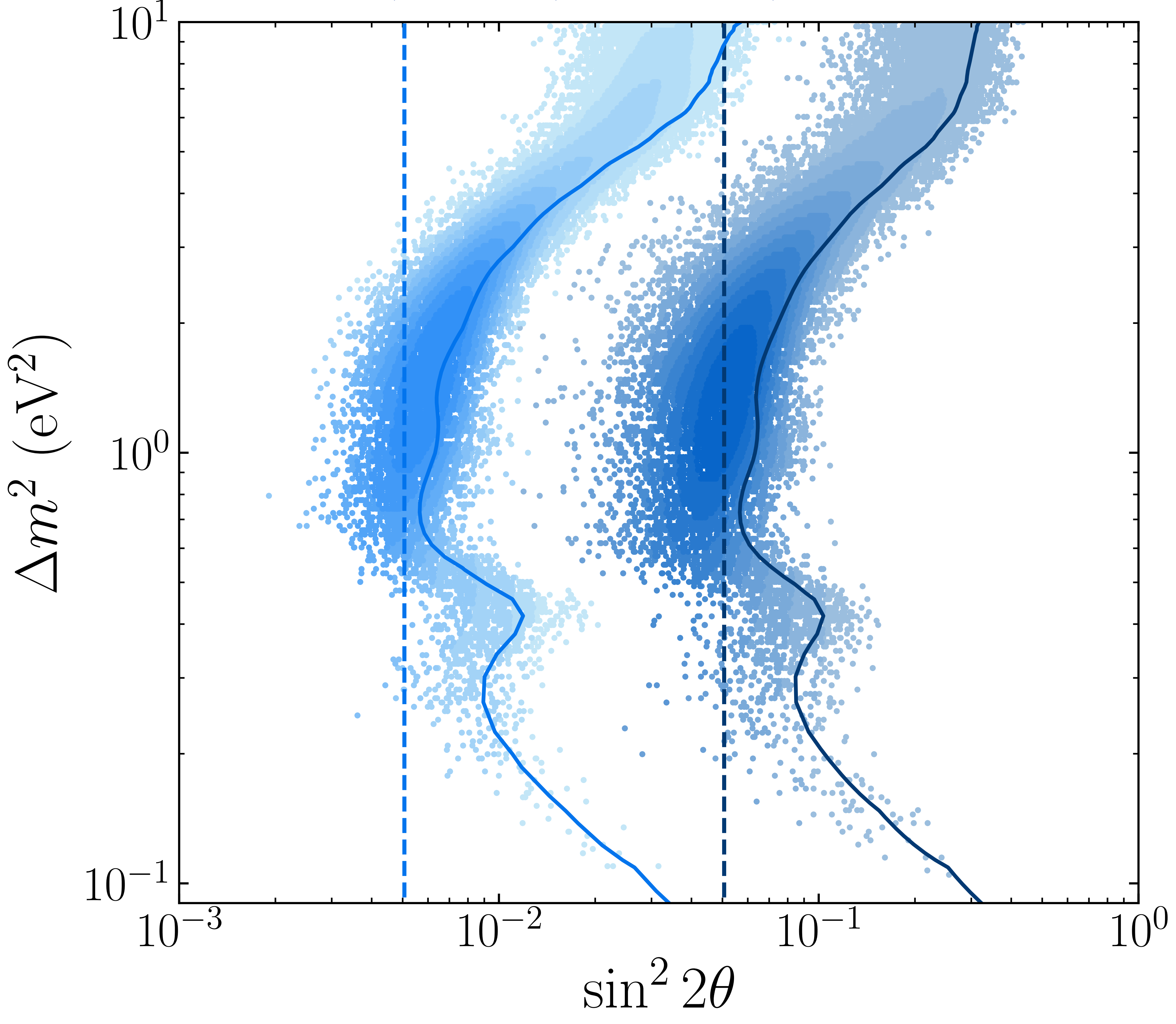




Global analysis of relative reactor data

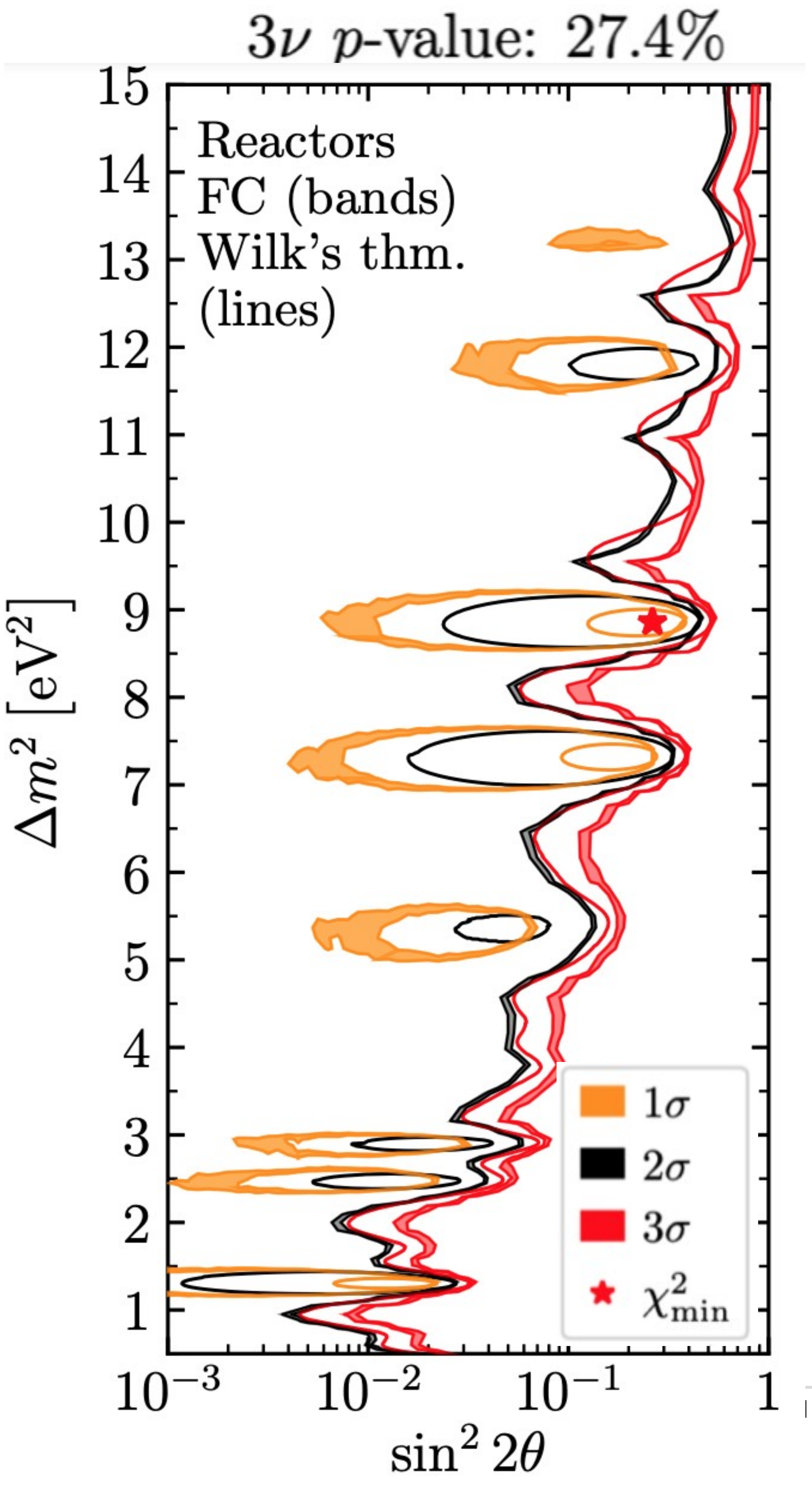
Berryman, Coloma, Huber, Schwetz, Zhou, 2111.12530

Coloma, Huber, Schwetz, 2008.06083



Wilks theorem does not apply

see also,
Feldman, Cousins, 98;
Agostini, Neumair, 1906.11854;
Giunti, 2004.07577;
PROSPECT&STEREO colls. 2006.13147

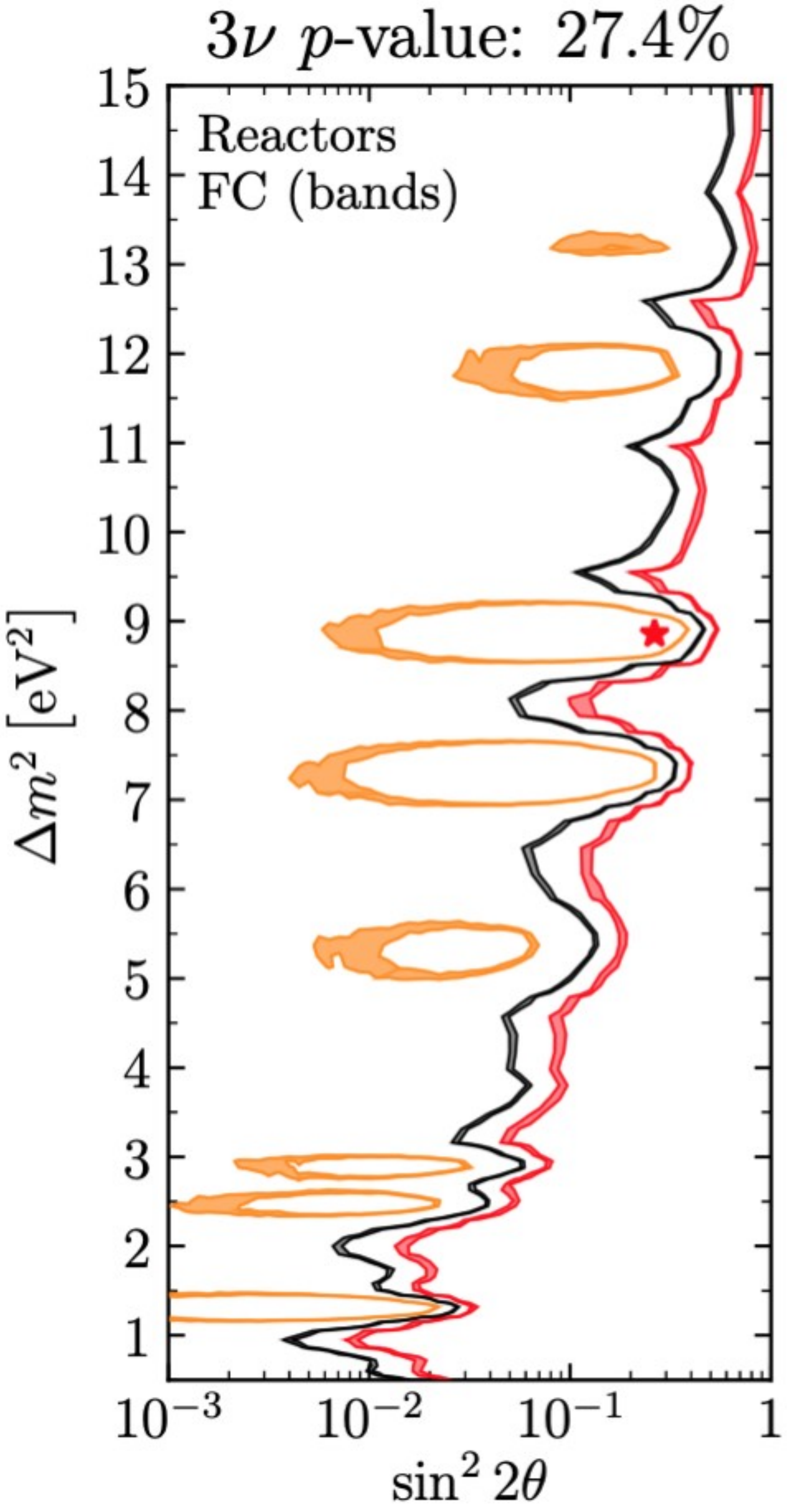


Global analysis of relative reactor data

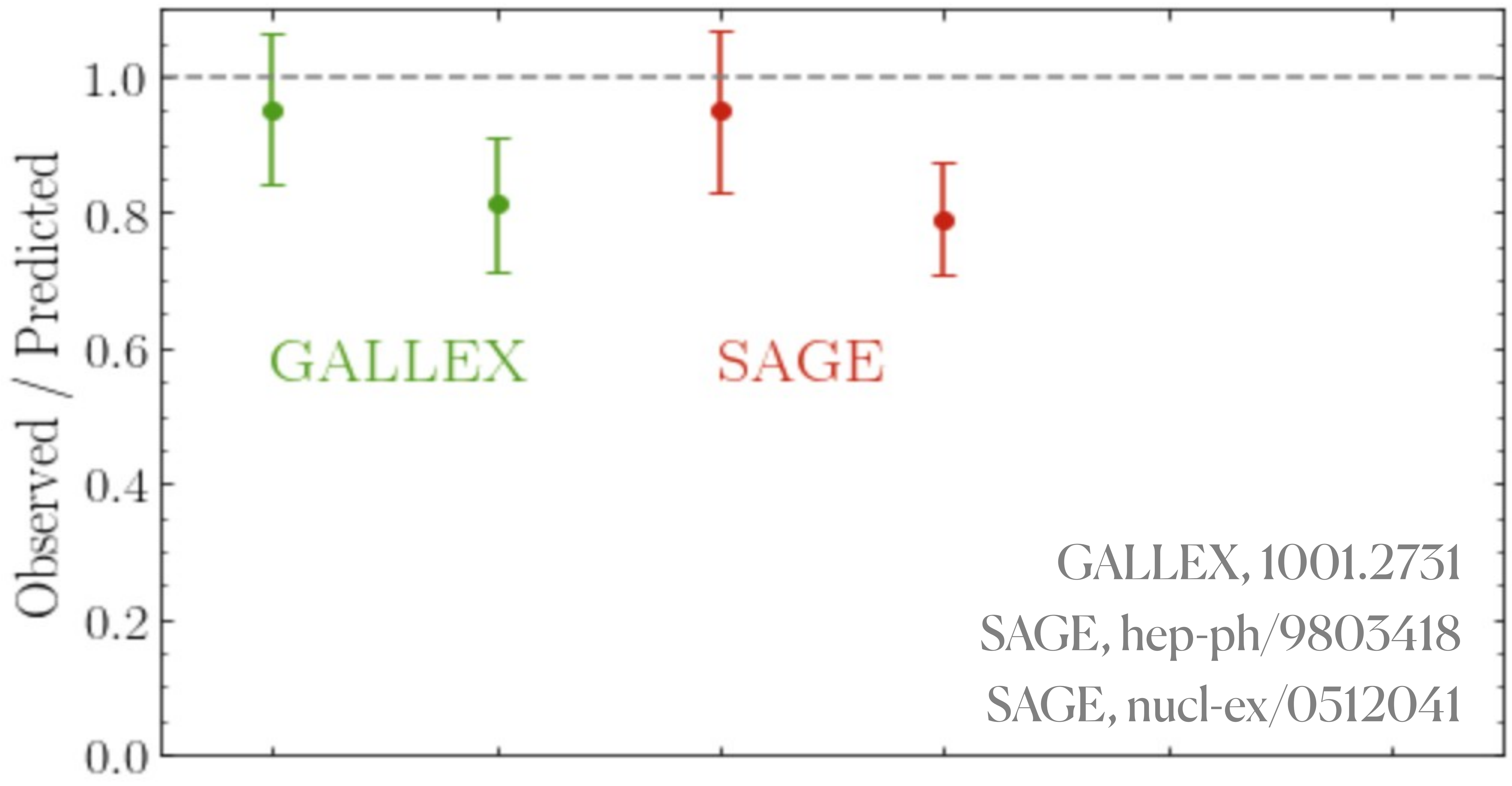
Berryman, Coloma, Huber, Schwetz, Zhou, 2111.12530

no significant indication for sterile neutrino oscillations from reactor data:

p-value: 27.4% (1.1σ)



Gallium radioactive source experiments — BEST



$$\nu_e + {}^{71}\mathrm{Ga} \rightarrow {}^{71}\mathrm{Ge} + e^-$$

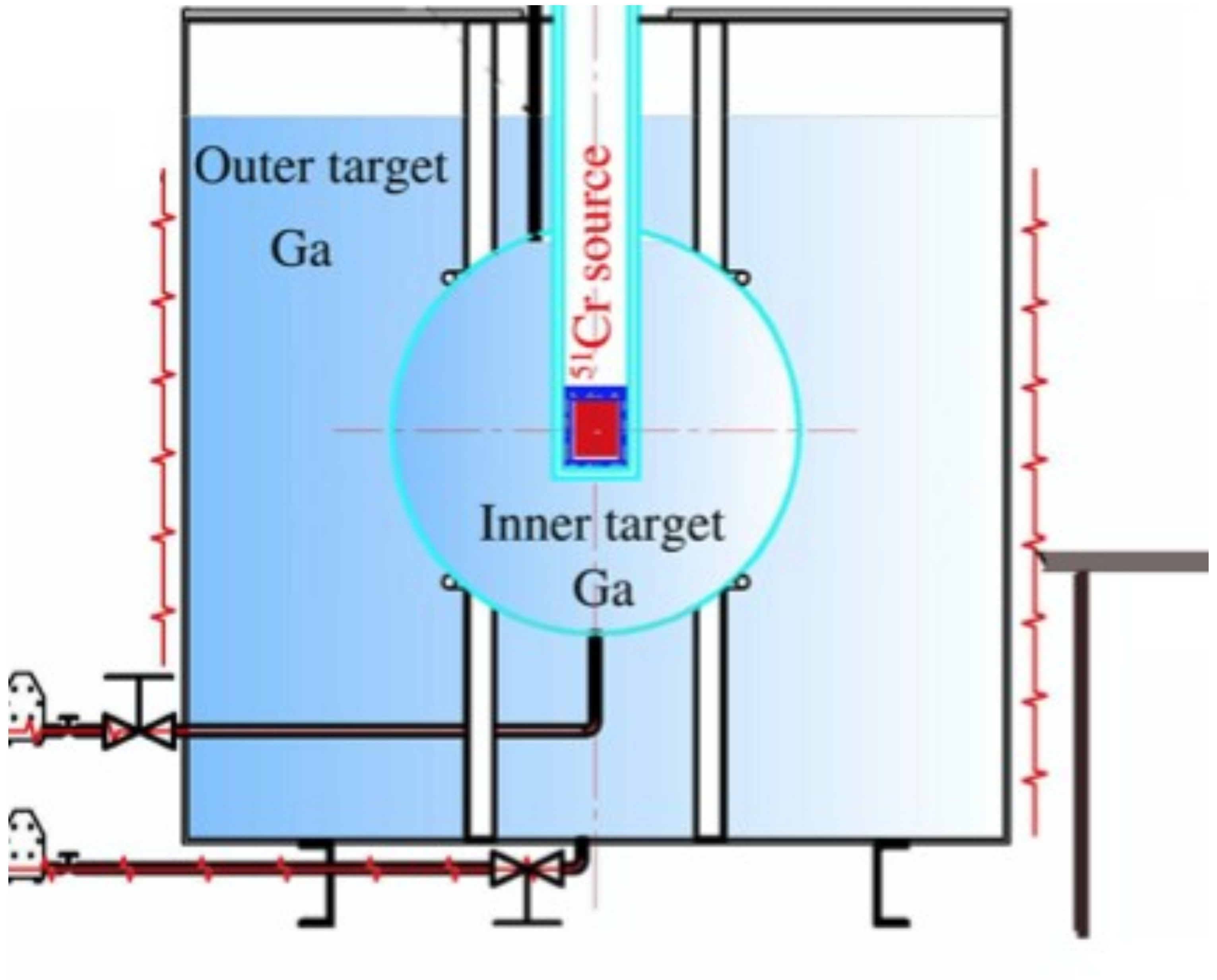
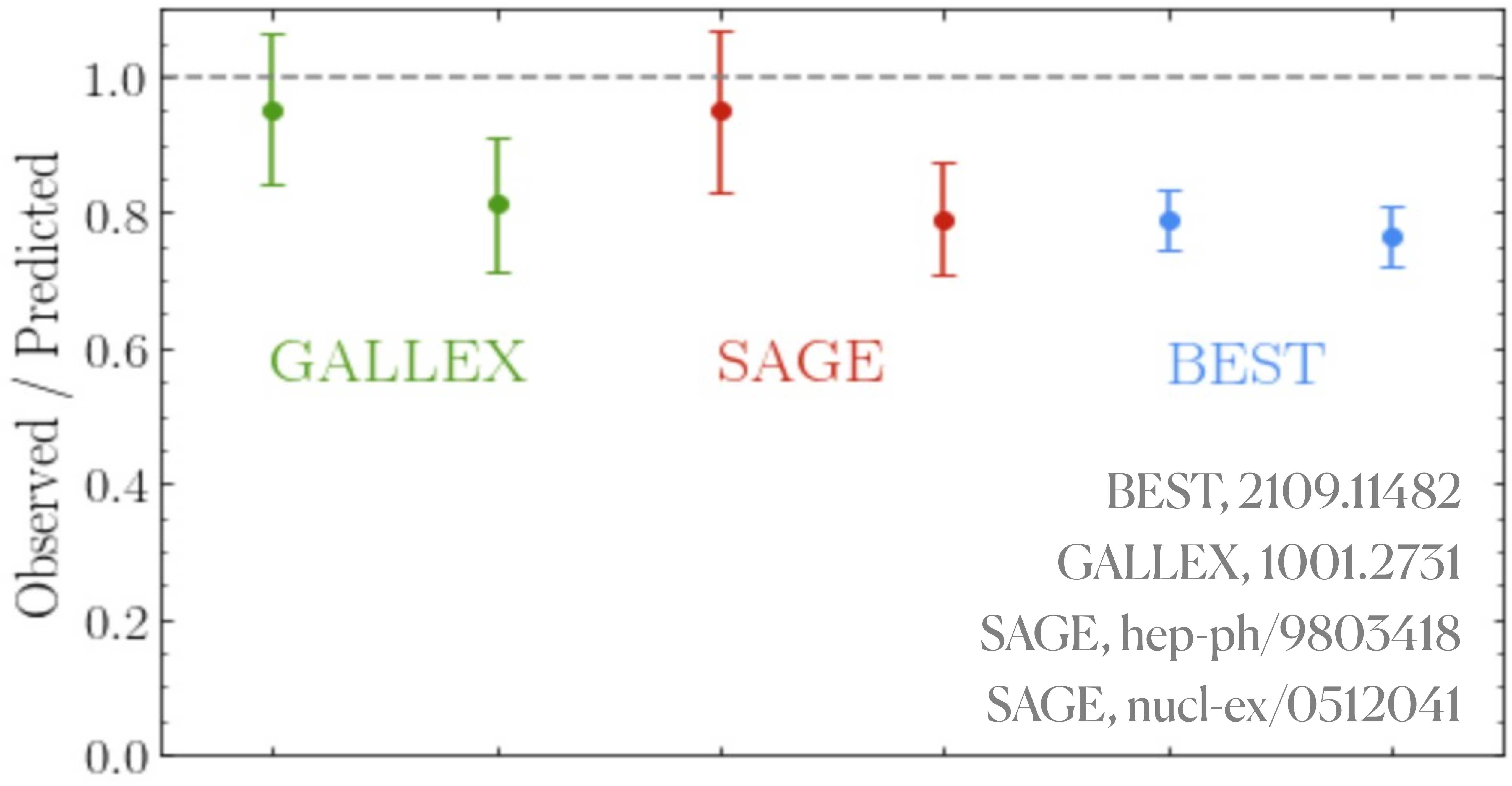


Figure from 2109.11482

Gallium radioactive source experiments — BEST



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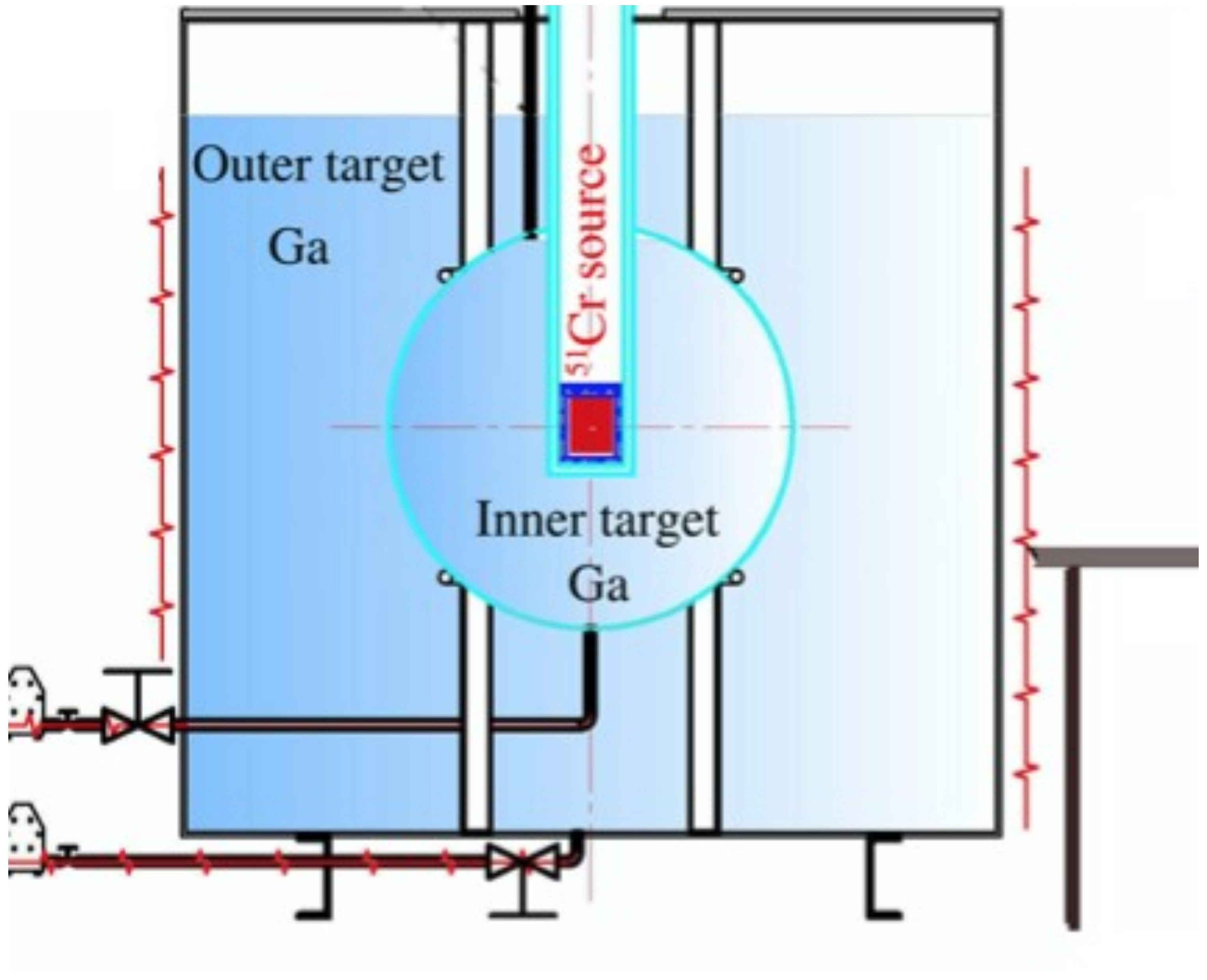

Figure from 2109.11482

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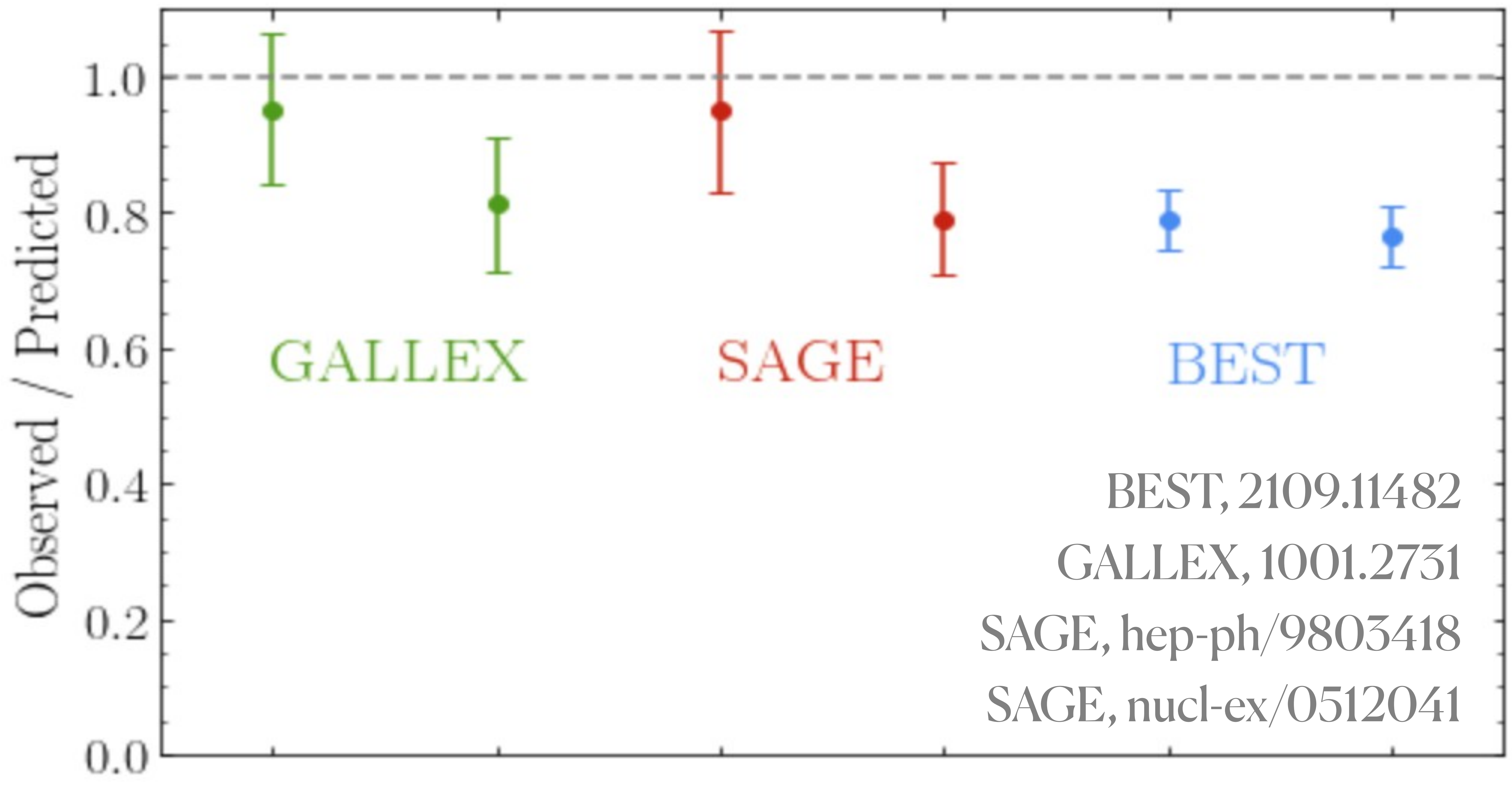
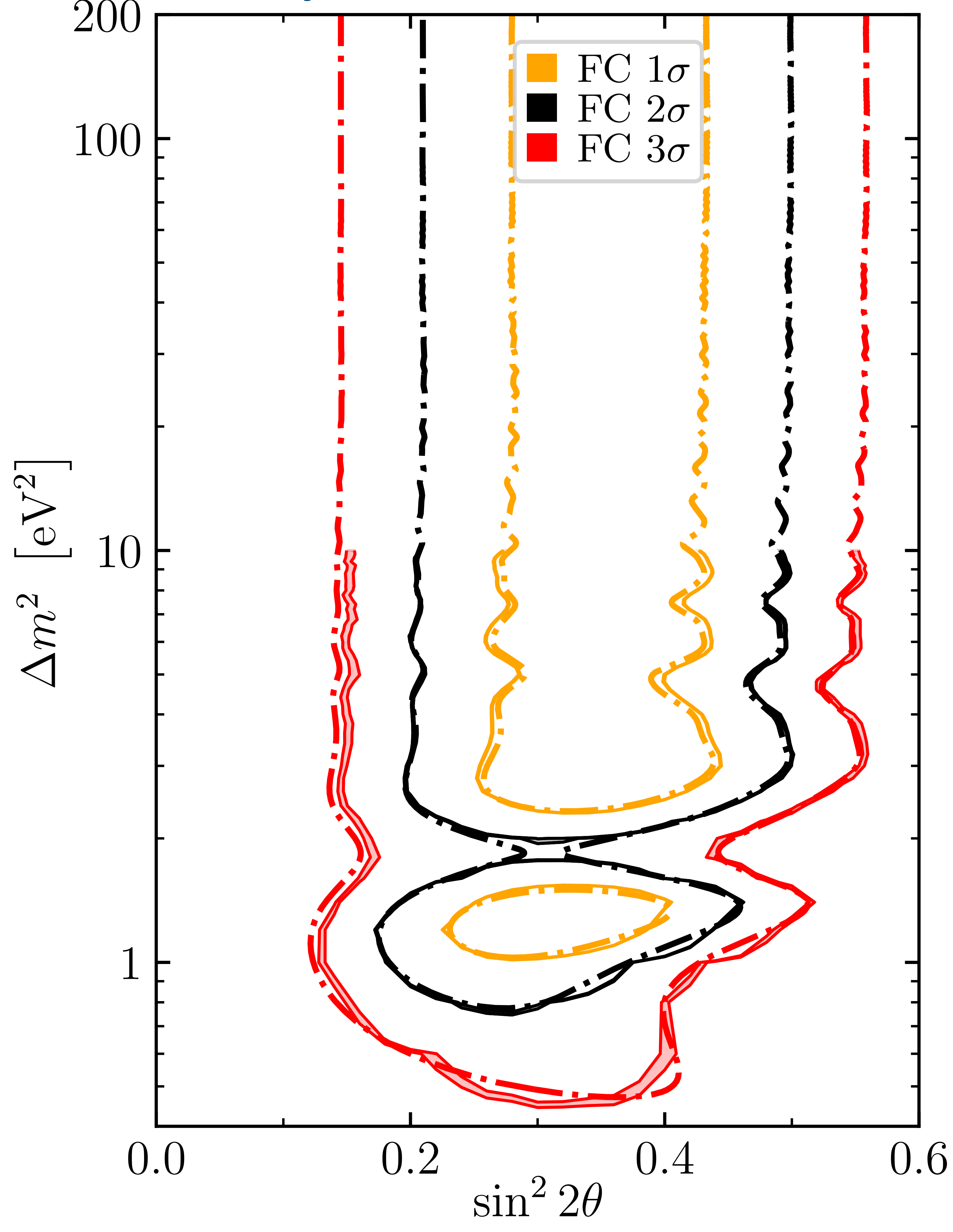
Gallium radioactive source experiments



$p_0 \approx 2.7 \times 10^{-8} \quad (5.6\sigma)$ from MC estimate

Berryman et al., 2111.12530



Gallium radioactive source experiments

robust wrt to cross section modelling $\nu_e + {}^{71}\mathrm{Ga} \rightarrow {}^{71}\mathrm{Ge} + e^-$

	GALLEX & SAGE		BEST		All gallium combined			
Cross section	$\Delta\chi^2_{3\nu}$	$\#\sigma^{(W)}$	$\Delta\chi^2_{3\nu}$	$\#\sigma^{(W)}$	$\sin^2 2\theta_{\rm min}$	$\Delta m^2_{\rm min}$	$\Delta\chi^2_{3\nu}$	$\#\sigma^{(W)}$
Bahcall [56]	3.7	1.4	31.3	5.2	0.35	$1.3\,\mathrm{eV}^2$	31.7	5.3
Kostensalo [54]	4.9	1.7	31.5	5.2	0.32	$1.3\,\mathrm{eV}^2$	32.9	5.4
Semenov [57]	9.4	2.6	42.4	6.2	0.39	$1.3\,\mathrm{eV}^2$	44.7	6.4
Ground state	3.4	1.3	29.7	5.1	0.29	$1.3\,\mathrm{eV}^2$	31.5	5.3

Berryman et al., 2111.12530

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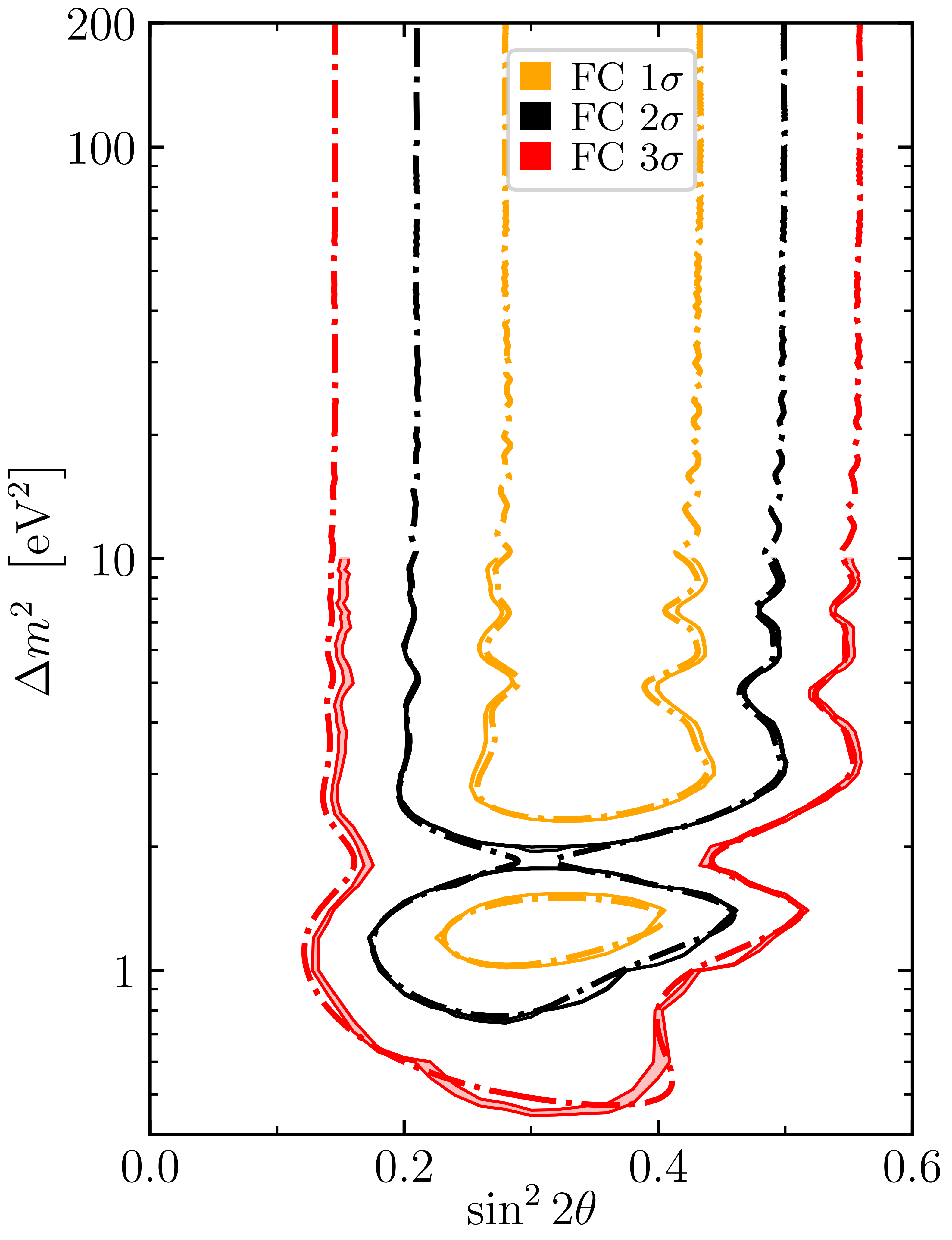
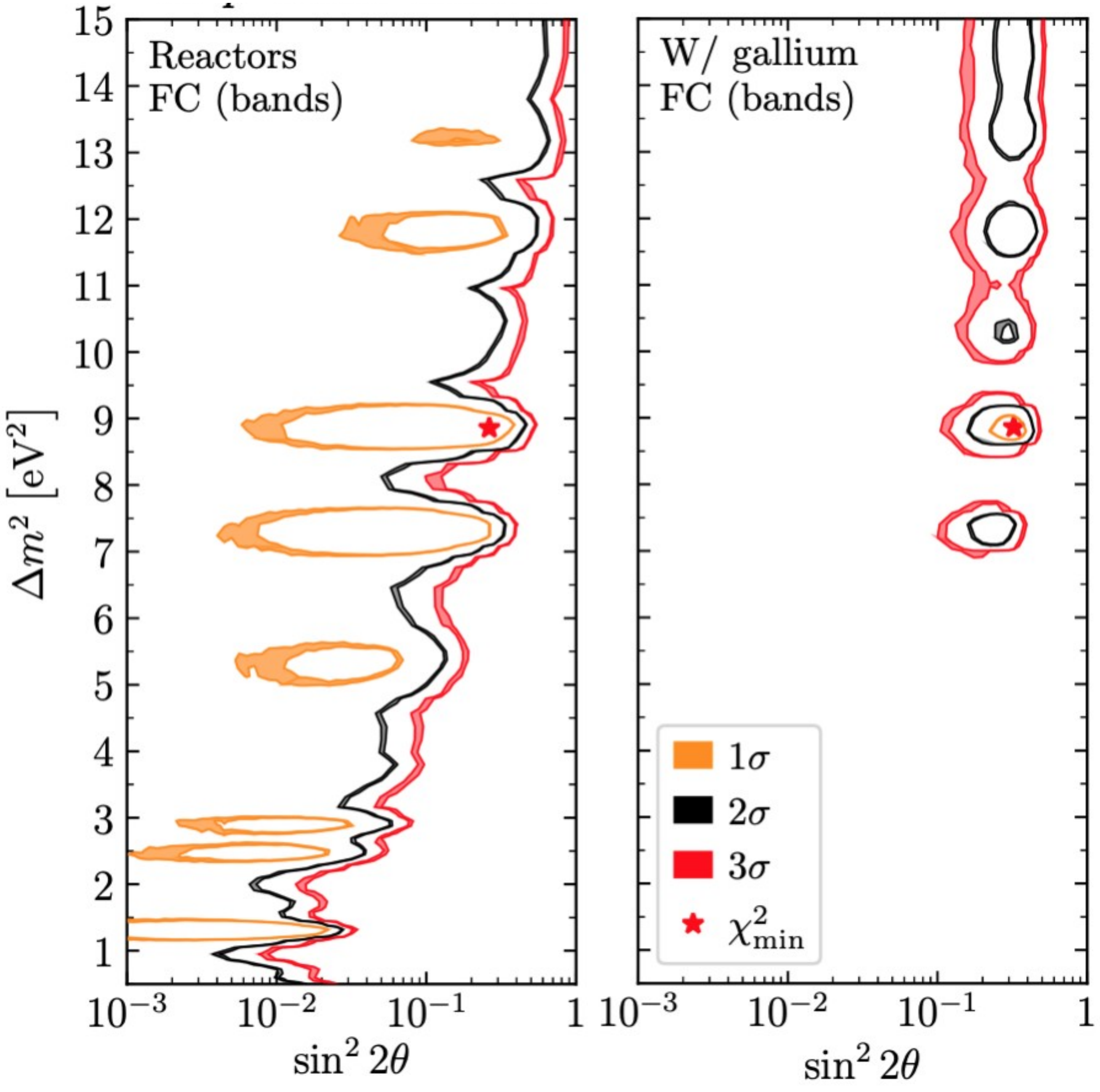


Gallium evidence…

- consistent with reactor shape-only data

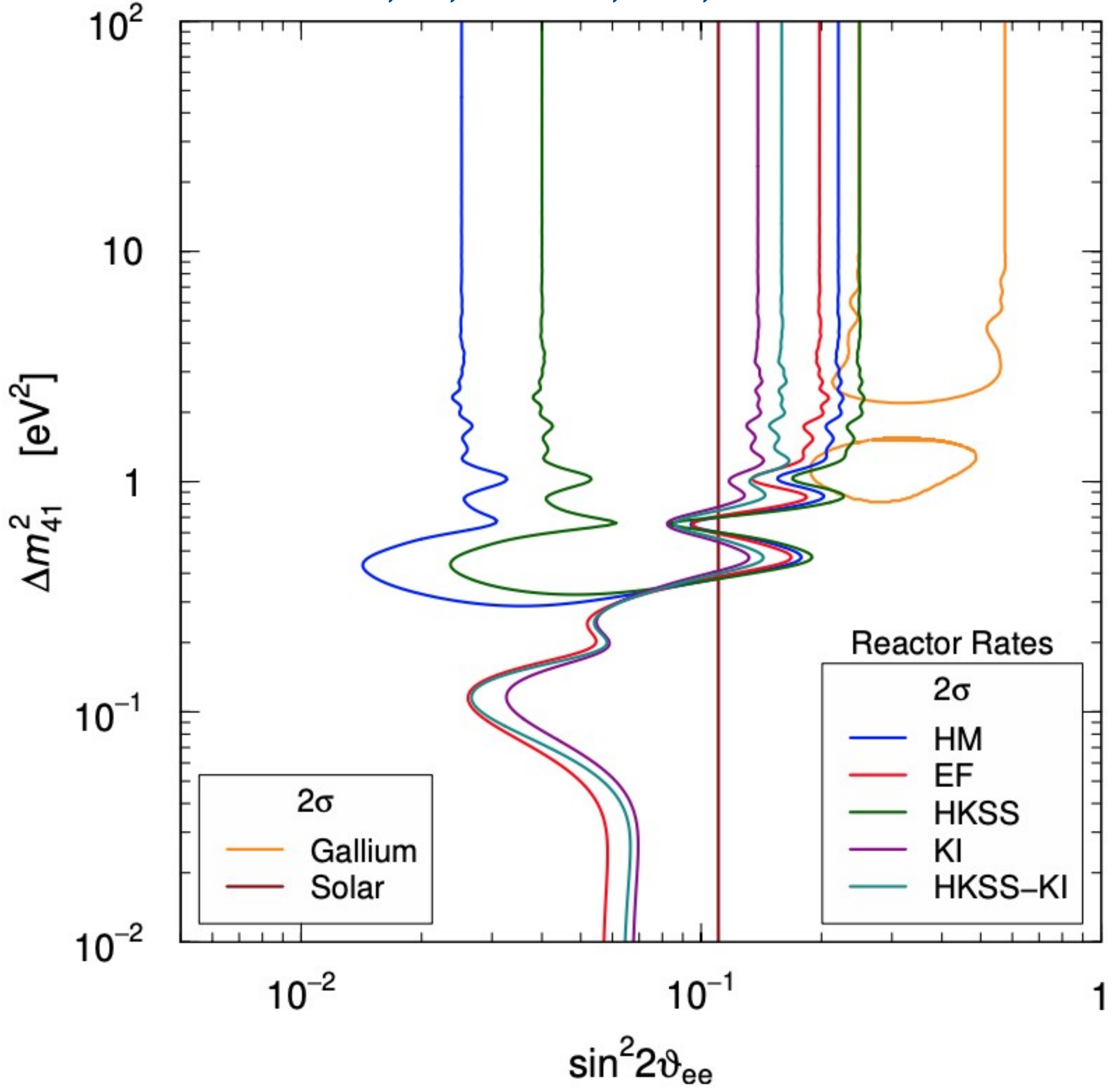
Berryman, Coloma, Huber, Schwetz, Zhou, 2111.12530



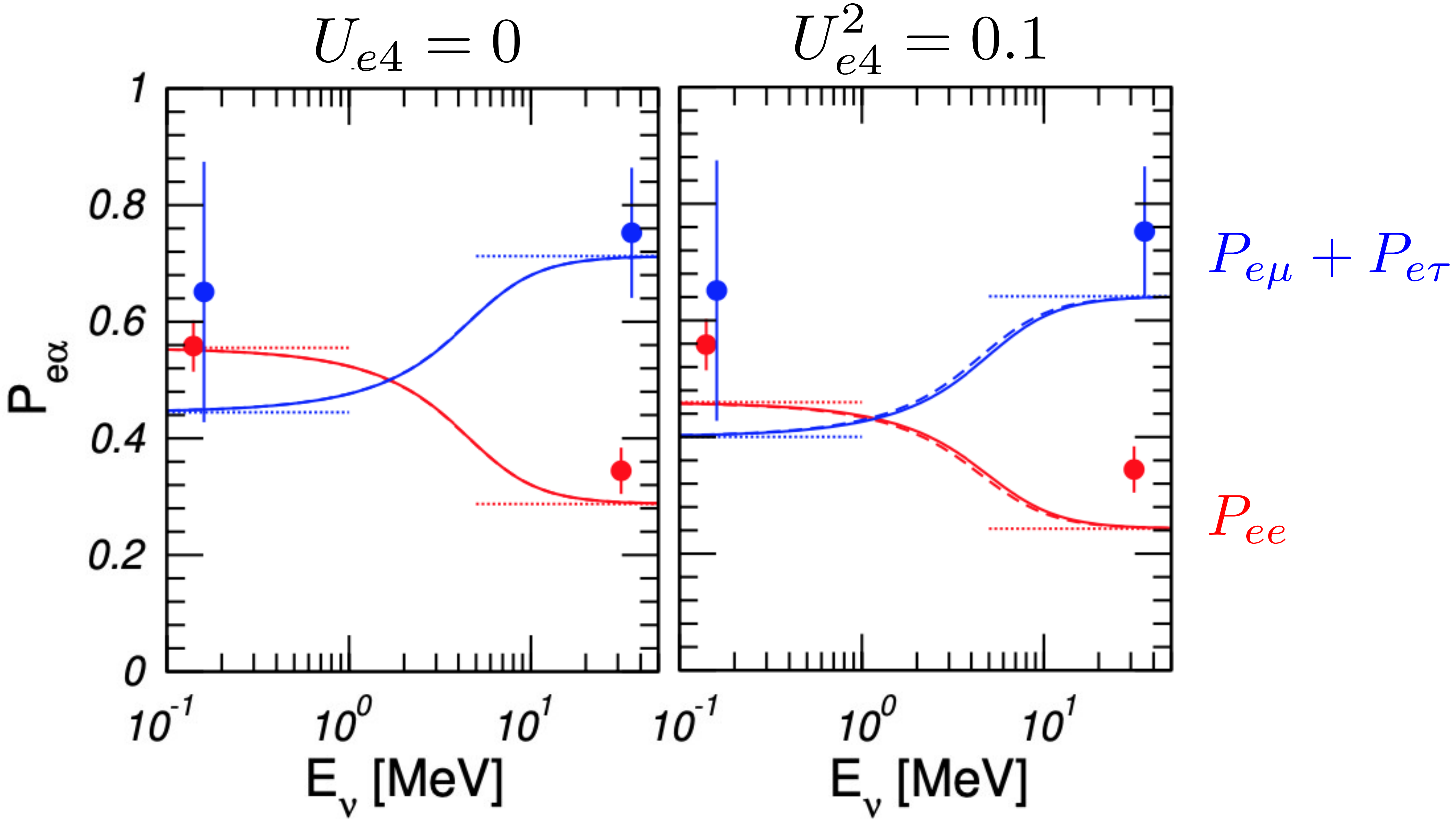
Gallium evidence…

- consistent with reactor shape-only data
- but in tension with reactor rate measurments

Giunti, Li, Ternes, Xin, 2110.06820

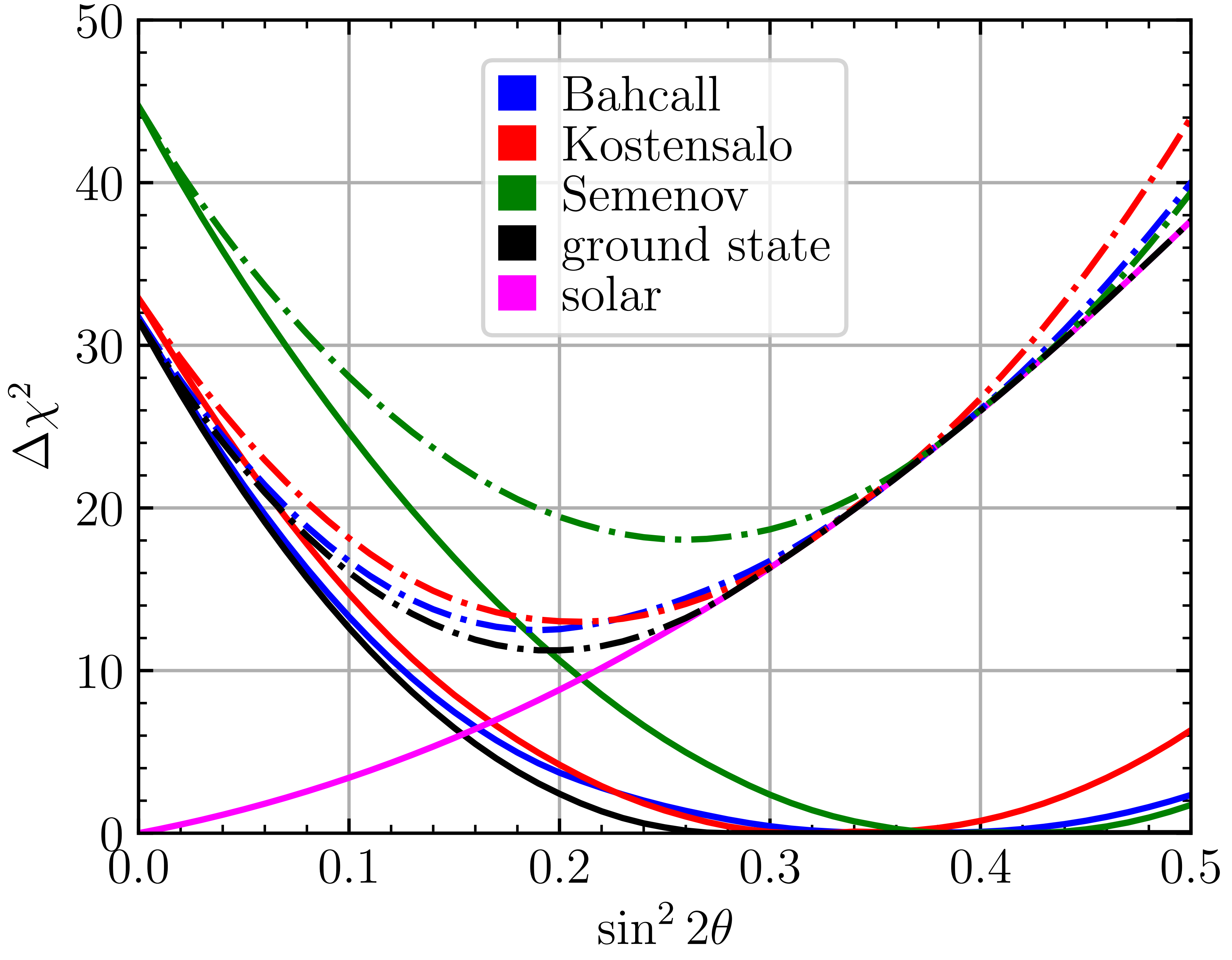


Gallium evidence…tension with solar data



Goldhagen, Maltoni, Reichard, Schwetz, 2109.14898

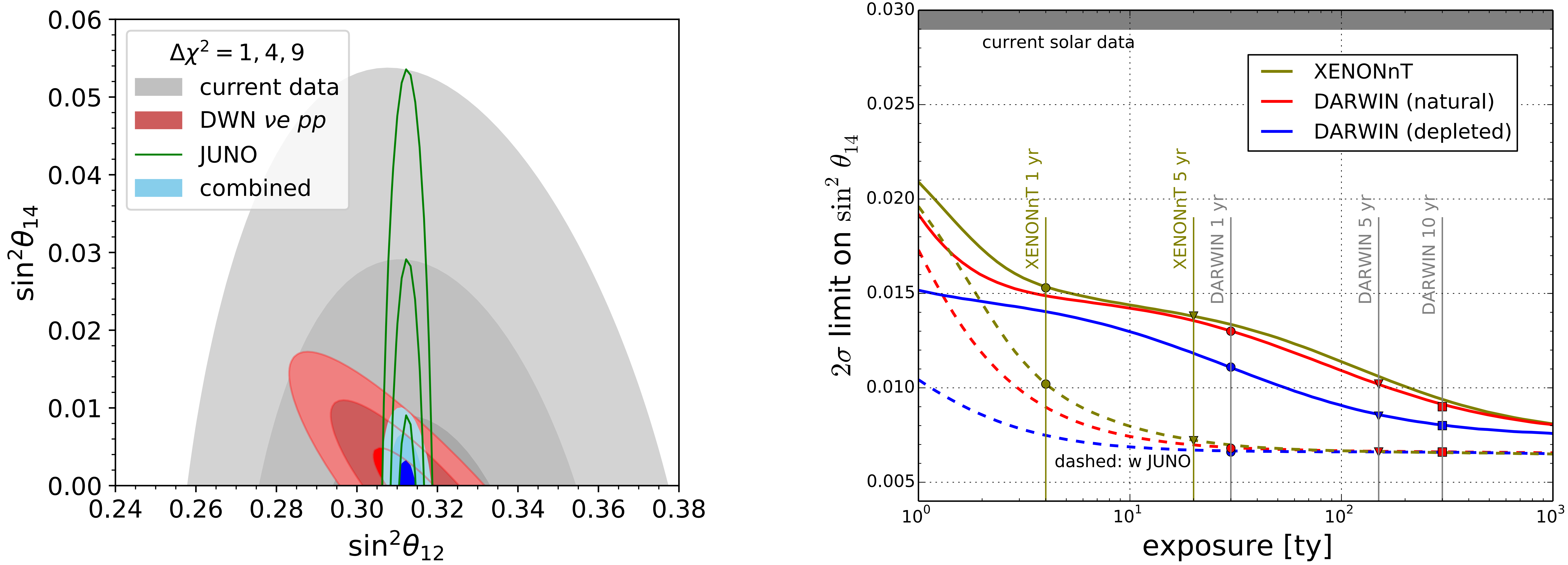
Berryman et al., 2111.12530



tension at more than 3σ

Sterile neutrino sensitivity from solar neutrinos in Dark Matter experiments

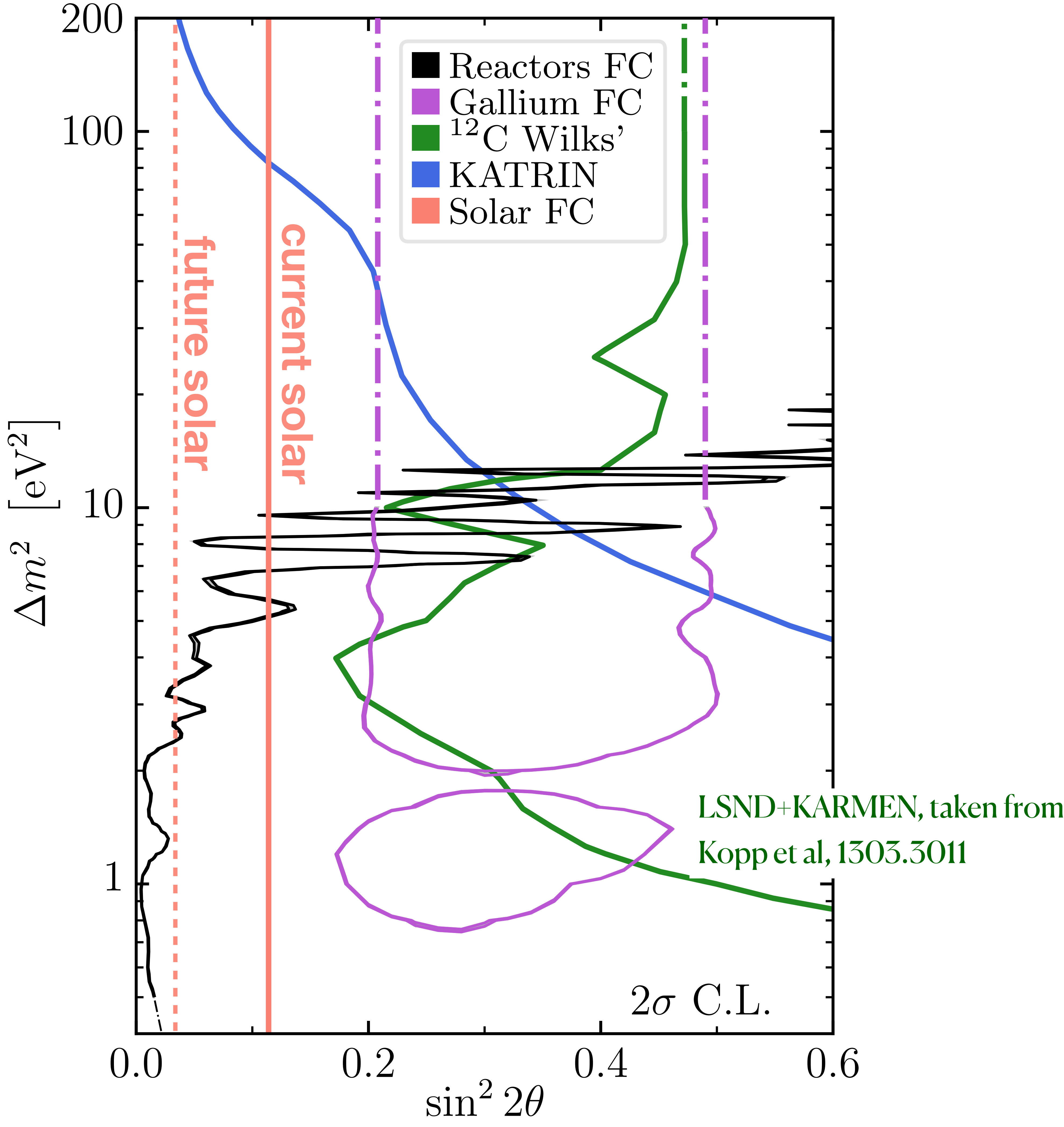
Goldhagen, Maltoni, Reichard, Schwetz, 2109.14898



s. also deGouvea et al., 2111.02421

Gallium evidence…

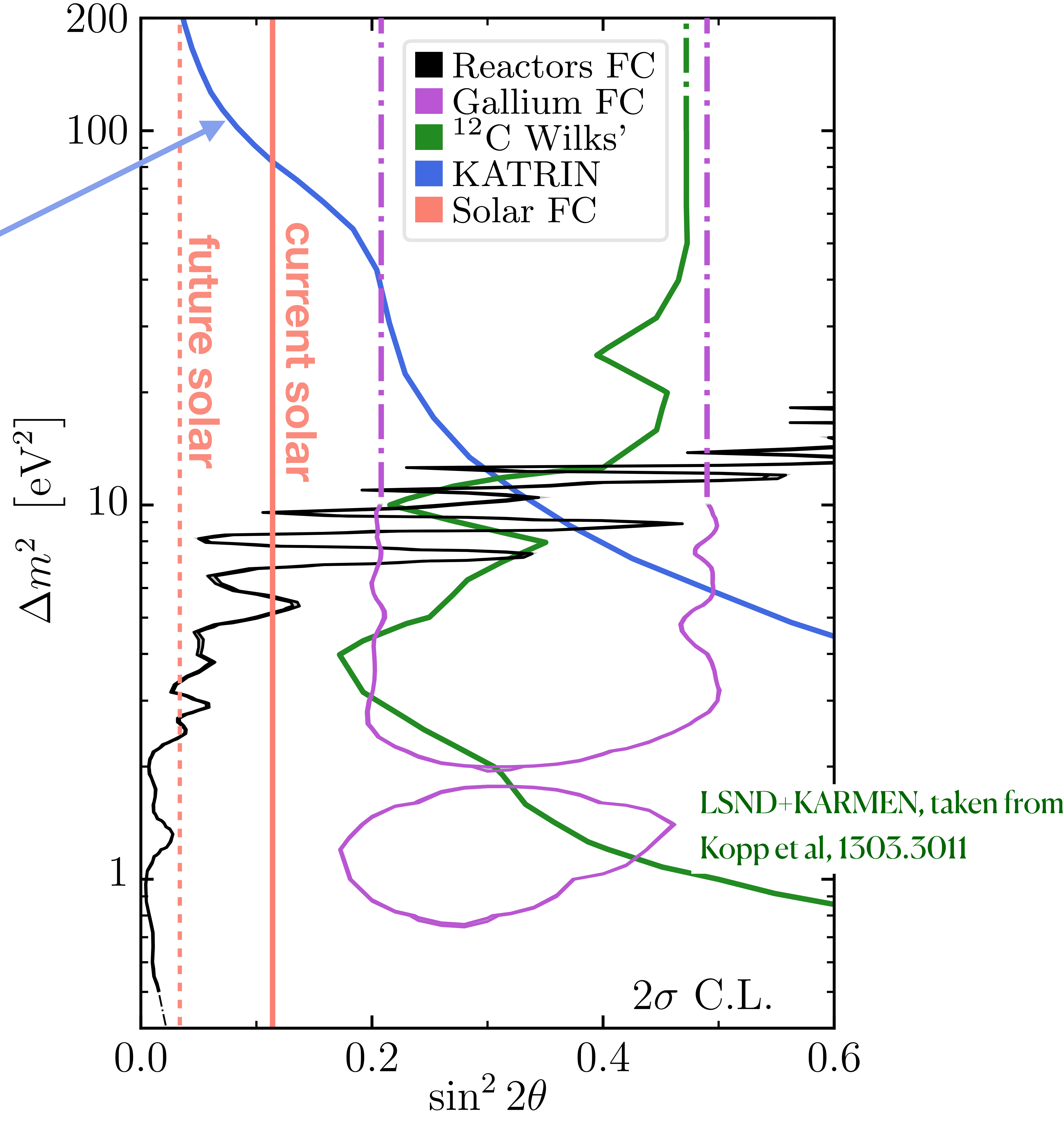
A. Zhou, PhD thesis, updated from Berryman et al., 2111.12530



Gallium evidence…

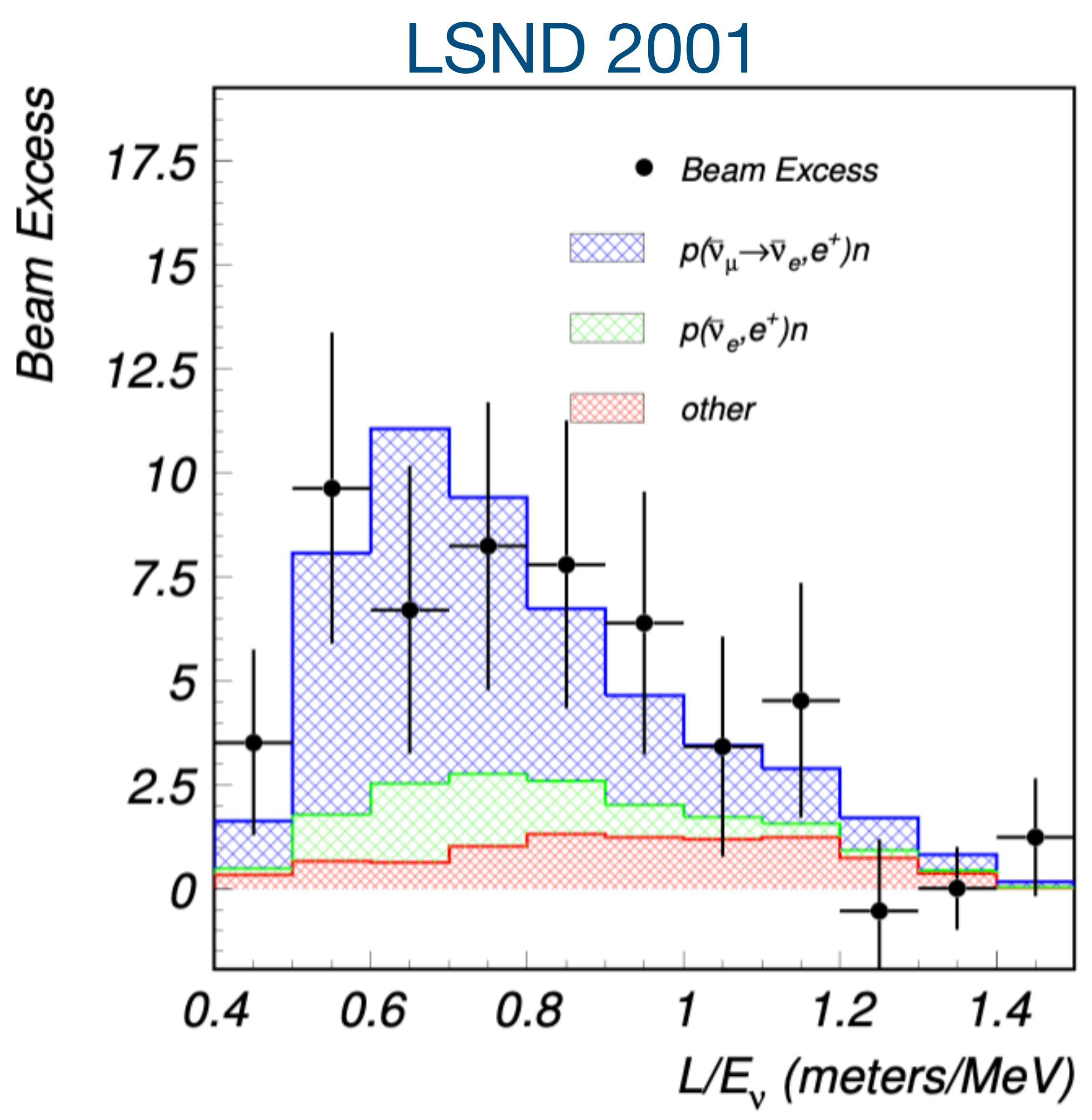
- additionally constrained by KATRIN [2201.11593]
- contribution of eV mass state to beta-decay spectrum

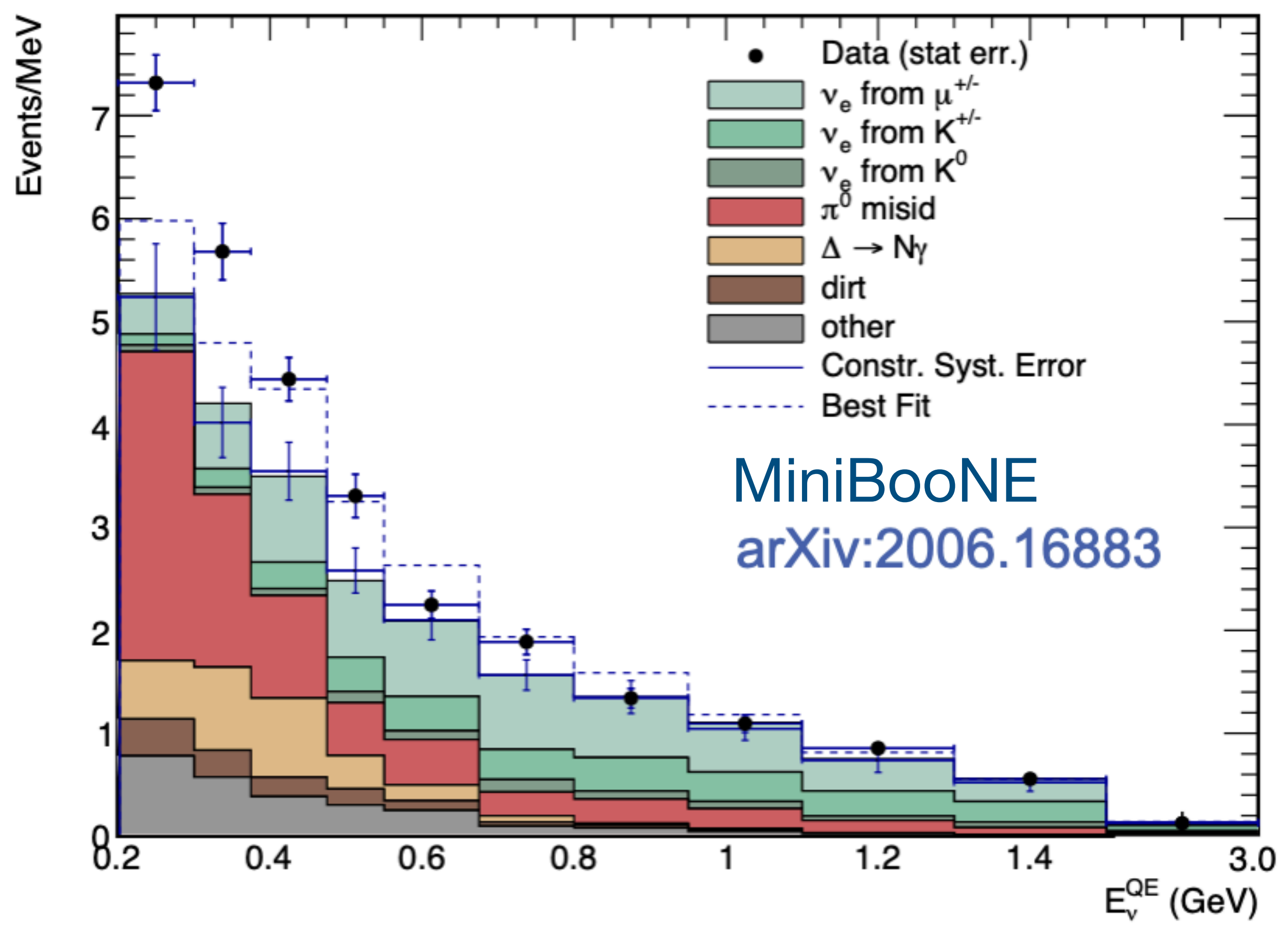
A. Zhou, PhD thesis, updated from Berryman et al., 2111.12530



Hints for $\nu_\mu \to \nu_e$ appearance

- LSND ($\bar{\nu}_\mu \to \bar{\nu}_e$ appearance) (3.8σ)
- MiniBooNE ($\nu_\mu \to \nu_e, \bar{\nu}_\mu \to \bar{\nu}_e$ appearance)
  excess: 638.0±132.8 events (4.8σ)





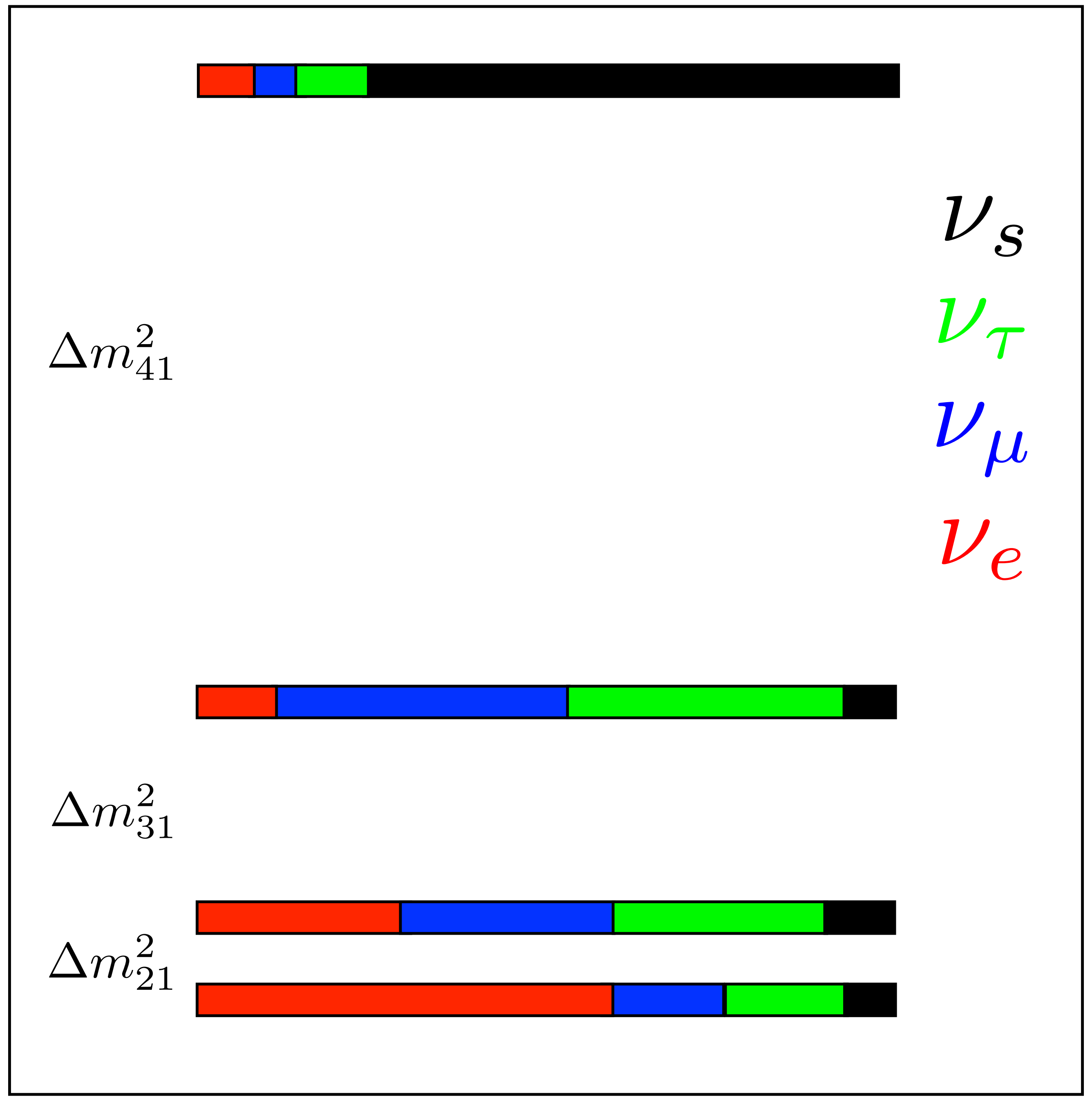
appearance signal not (yet) directly excluded nor confirmed independently
MicroBooNE, 2110.00409 & talk @ Neutrino22
Arguelles et al., 2111.10359
SBN / ICARUS @ FNL

SM explanation? Brdar, Kopp, 2109.08157

Hints for $\nu_\mu \to \nu_e$ appearance — sterile oscillations?

mixing parameter

$$\sin^2 2\theta_{\mu e} = 4\,|U_{e4}|^2\,|U_{\mu 4}|^2$$



- LSND ($\bar\nu_\mu \to \bar\nu_e$ appearance) (3.8σ)
- MiniBooNE ($\nu_\mu \to \nu_e, \bar\nu_\mu \to \bar\nu_e$ appearance)
  excess: 638.0±132.8 events (4.8σ)

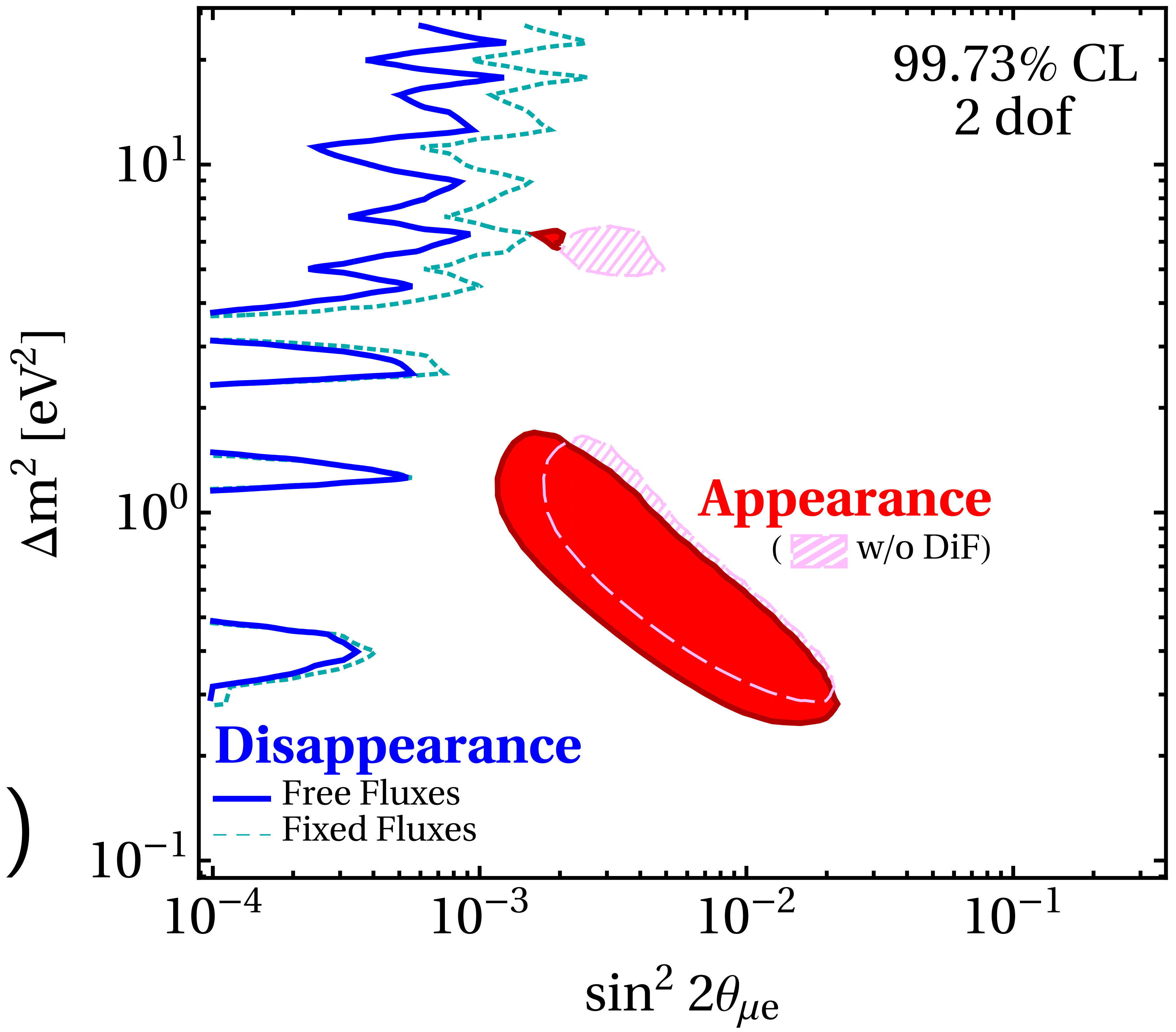
Karlsruher Institut für Technologie

Hints for $\nu_\mu \rightarrow \nu_e$ appearance — sterile oscillations?

mixing parameter

$$\sin^2 2\theta_{\mu e} = 4|U_{e4}|^2|U_{\mu 4}|^2$$

Dentler et al., 1803.10661



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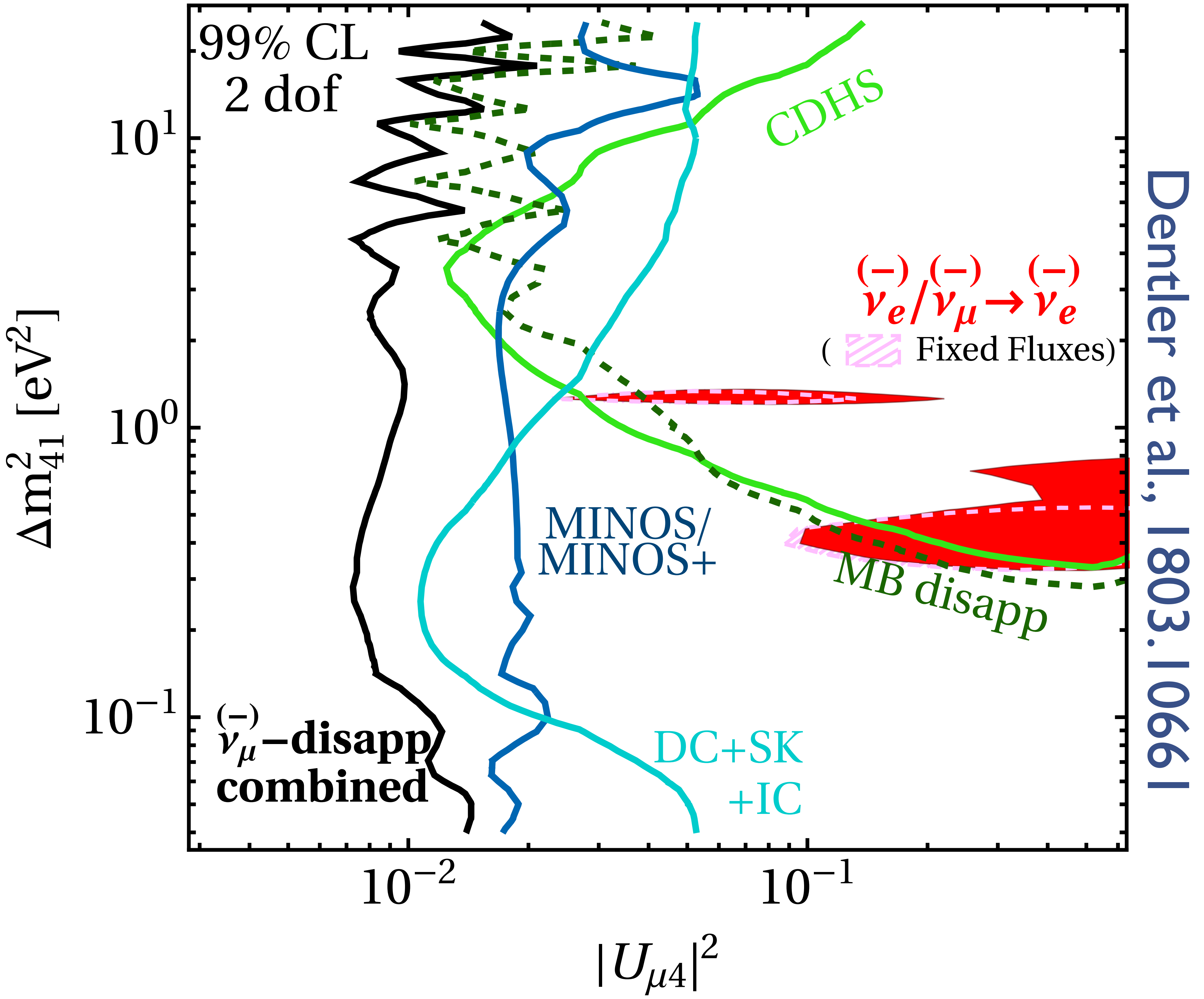
$$\sin^2 2\theta_{\mu e} = 4\,|U_{e4}|^2\,|U_{\mu 4}|^2$$



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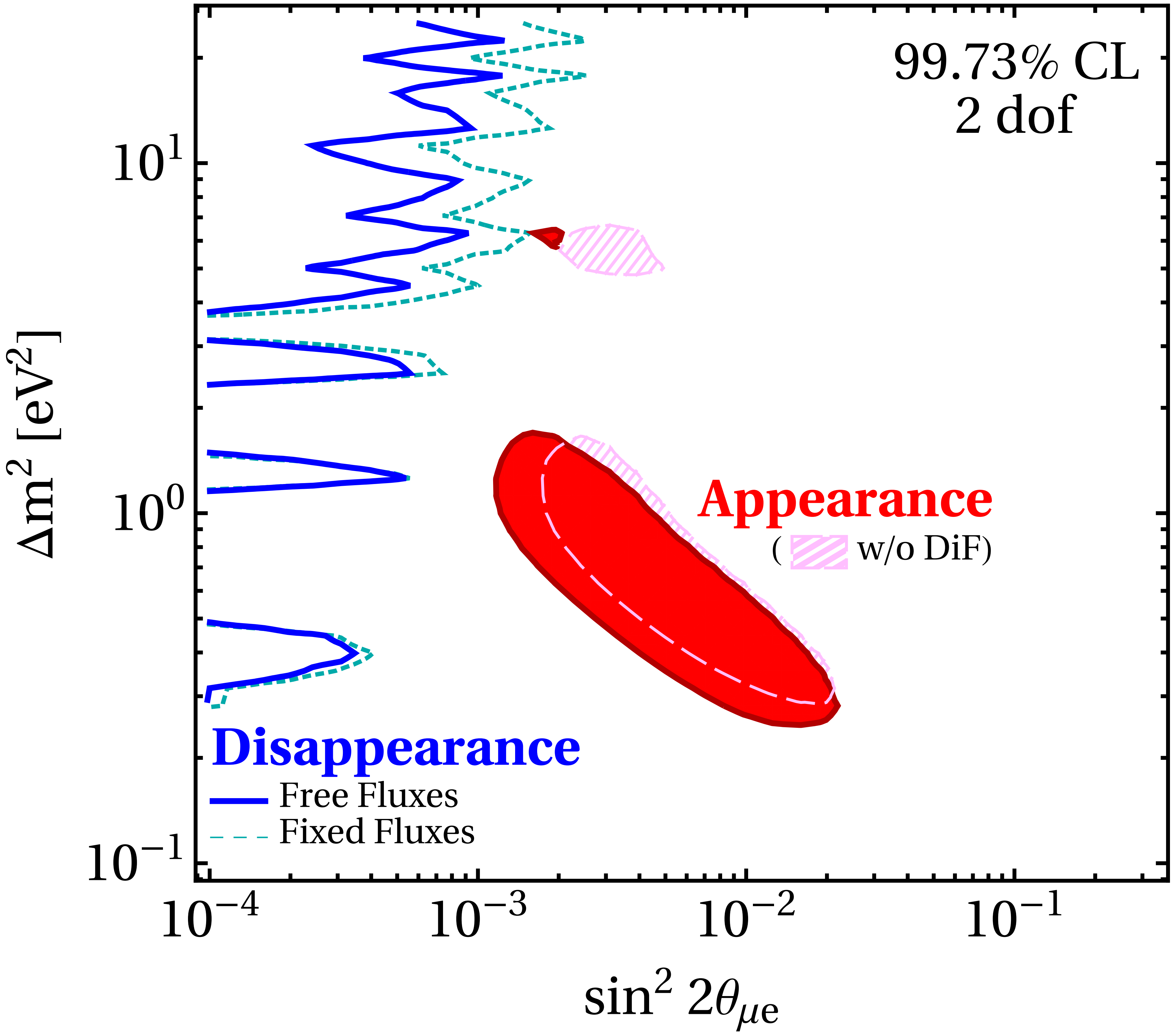
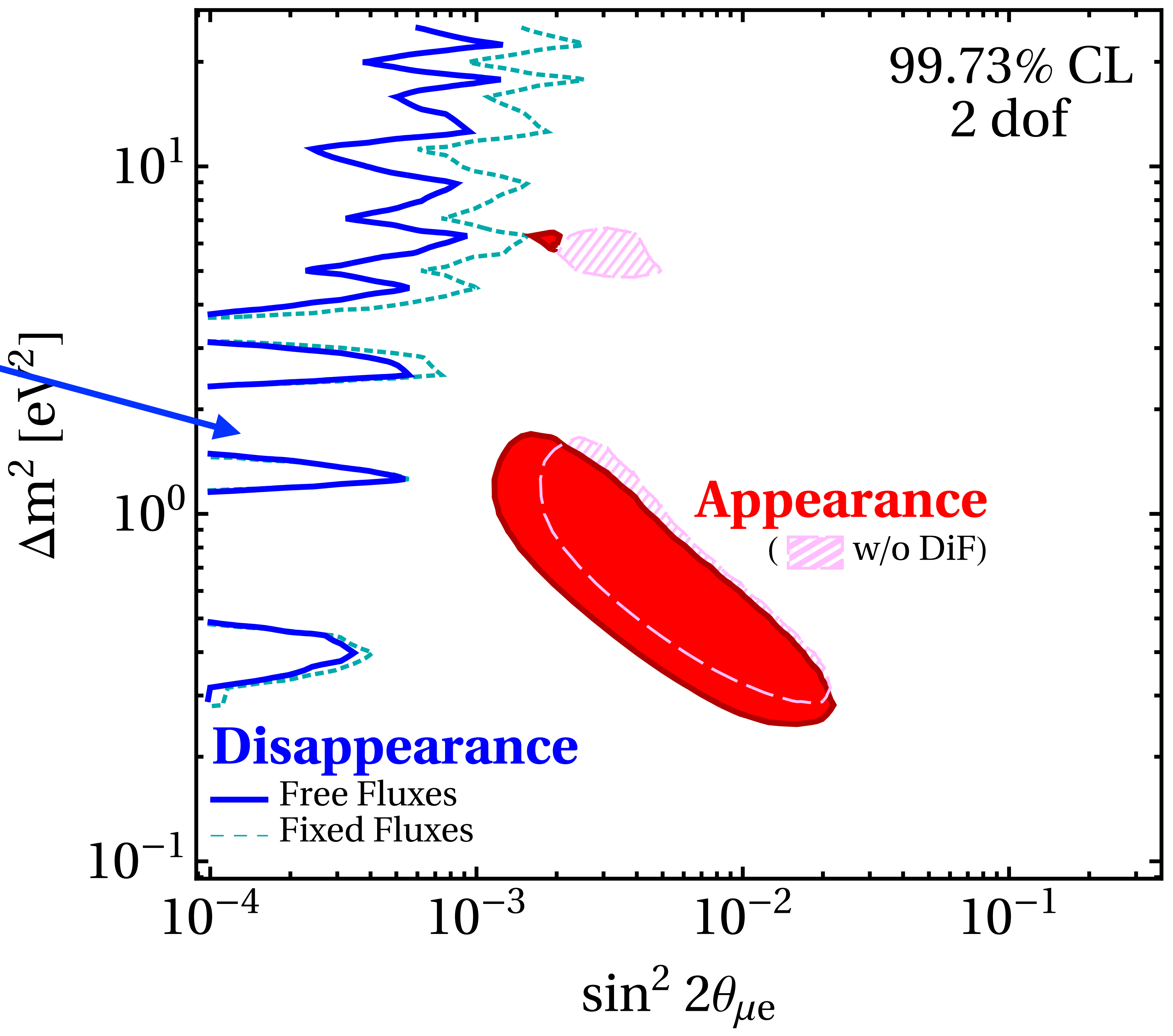


Hints for $\nu_\mu \to \nu_e$ appearance — not sterile ν oscillations!

$$\sin^2 2\theta_{\mu e} = 4\,|U_{e4}|^2\,|U_{\mu4}|^2$$

Dentler et al., 1803.10661



strong tension between appearance and disappearance data in the eV-sterile osc. framework p-value $\lesssim 10^{-5}$

(non-observation of ν_μ disappearance)

sterile oscillation explanation of LSND/MiniB robustly disfavoured

Other BSM explanations?

incomplete and outdated list:

- 3-neutrinos and CPT violation
  Murayama, Yanagida 01; Barenboim, Borissov, Lykken 02; Gonzalez-Garcia, Maltoni, TS 03
- 4-neutrinos and CPT violation Barger, Marfatia, Whisnant 03
- Exotic muon-decay Babu, Pakvasa 02
- CPT viol. quantum decoherence Barenboim, Mavromatos 04
- Lorentz violation Kostelecky et al., 04, 06; Gouvea, Grossman 06
- mass varying ν Kaplan,Nelson,Weiner 04; Zurek 04; Barger,Marfatia,Whisnant 05
- shortcuts of sterile νs in extra dim Paes, Pakvasa, Weiler 05; Doring, Pas, Sicking, Weiler, 18
- decaying sterile neutrino Palomares-Riuz, Pascoli, TS 05; Gninenko 09, 10;
  Bertuzzo, Jana, Machado, Zukanovich, 18; Ballett, Pascoli, Ross-Lonergan, 18; Fischer, Hernandez, TS, 19; Dentler, Esteban, Kopp, Machado, 19; deGouvea, Peres, Prakash, Stenico, 19; Abdallah, Gandhi, Roy, 20, Arguelles et al, 22
- energy dependent quantum decoherence Farzan, TS, Smirnov 07; Bakhti, Farzan, TS, 15
- sterile neutrinos and new gauge boson Nelson, Walsh 07
- sterile ν with energy dependent mass or mixing TS 07
- sterile ν with non-standard interactions
  Akhmedov, TS 10; Conrad, Karagiorgi, Shaevitz, 12; Liao, Marfatia, Whisnant 18

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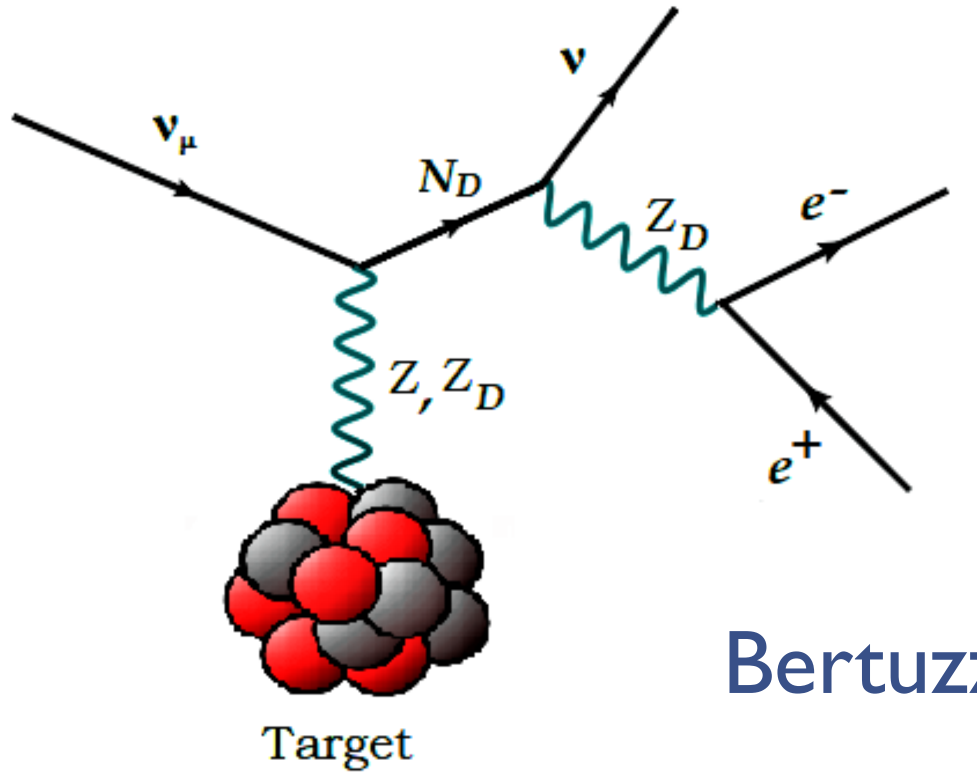
many of them excluded by some data

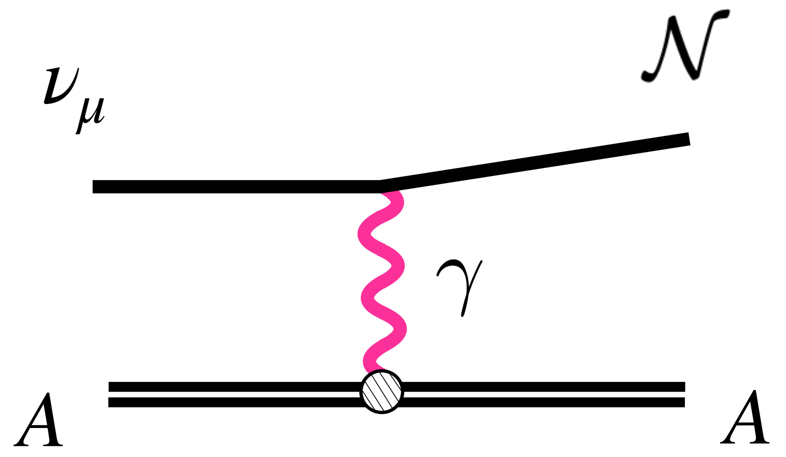
MiniBooNE and a decaying sterile neutrino

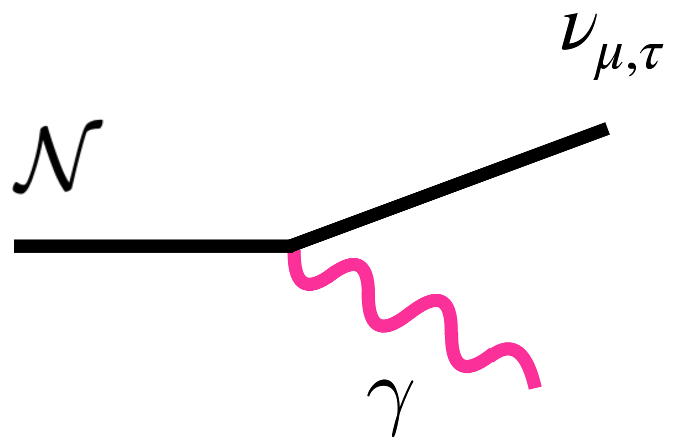
Palomares, Pascoli, TS, hep-ph/0505216; Gninenko, 0902.3802, 1009.5536; Bertuzzo, Jana, Machado, Zukanovich, 1807.09877; Ballett, Pascoli, Ross-Lonergan, 1808.2915; Arguelles, Hostert, Tsai, 1812.08768; Fischer, Hernandez, TS, 1909.09561; Dentler, Esteban, Kopp, Machado, 1911.01427; deGouvea, Peres, Prakash, Stenico, 1911.01447; Brdar, Fischer, Smirnov, 2007.14411; Abdallah, Gandhi, Roy, 2010.06159; Arguelles et al., 2206.07100…

- sterile neutrino N with m_N ~ keV to ~500 MeV
- produce N either by mixing or by up-scattering
- decay:
  - $N \to \phi \, \nu_e$ with standard neutrino interaction in detector
  - electromagn. decay inside MB detector $N \to \nu\gamma / \nu e^{\pm} / \nu\pi^0 / \ldots$ (no LSND)



Bertuzzo et al. 18





Arguelles et al. 22

MiniBooNE and a decaying sterile neutrino

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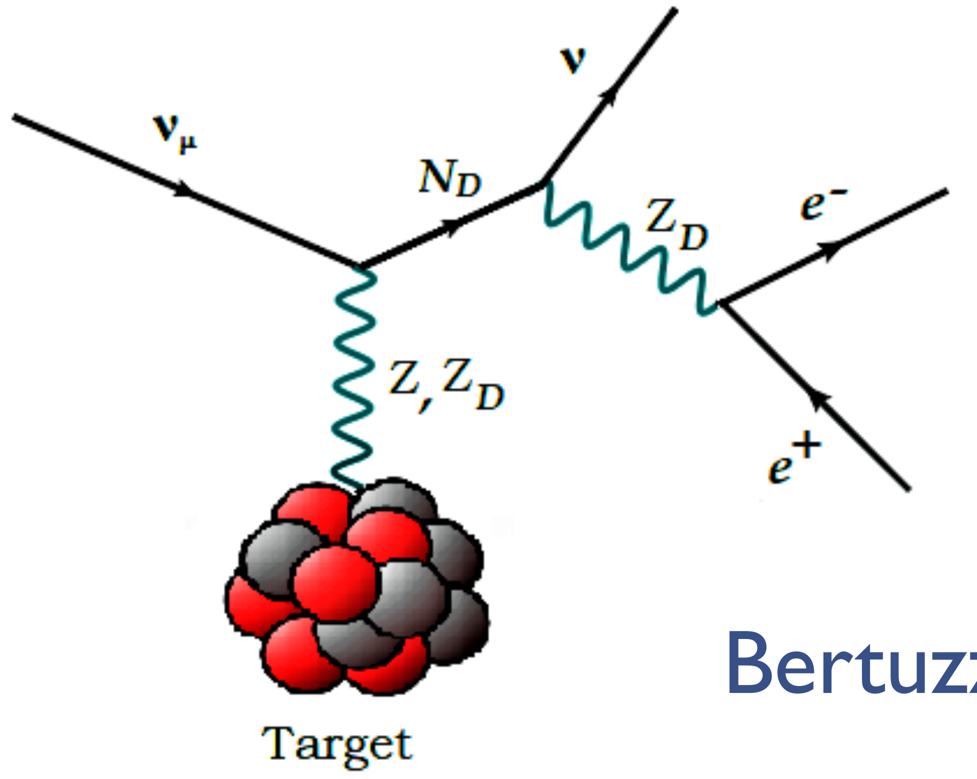
- exciting new physics
- rich phenomenology
  (timing signatures, angular dependence,…)
- predict signatures in existing (near detectors) and/or upcoming experiments
  (e.g., Fermilab SBN, DUNE, HK, IceC)

e.g., Jordan et al., 1810.07185; Arguelles, Hostert, Tsai, 1812.08768; Brdar, Fischer, Smirnov, 2007.14411



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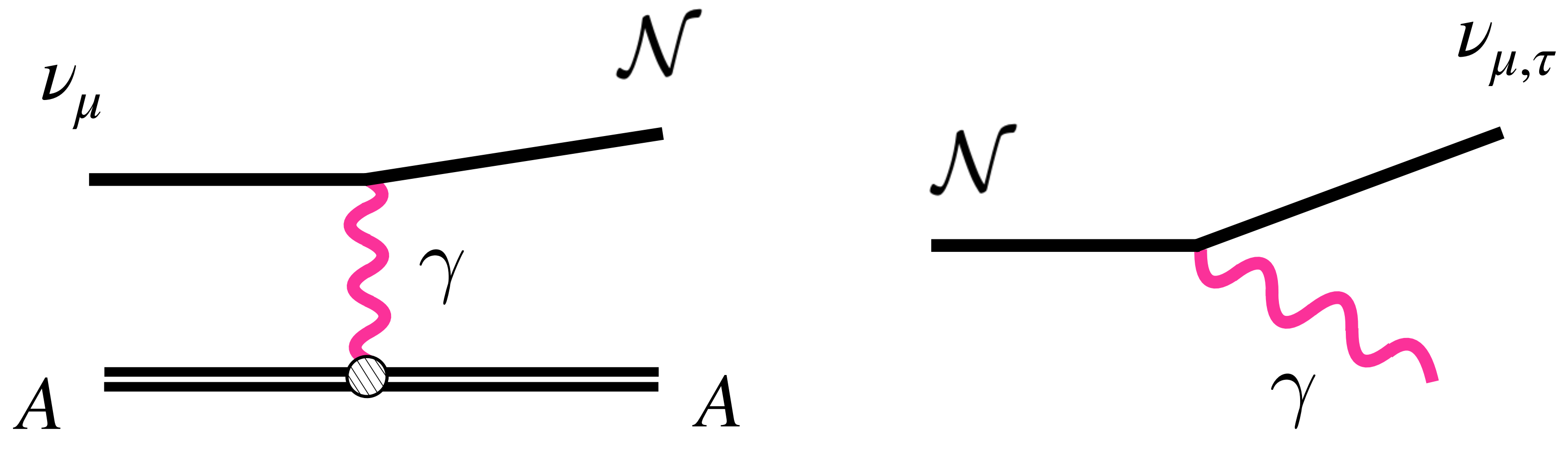


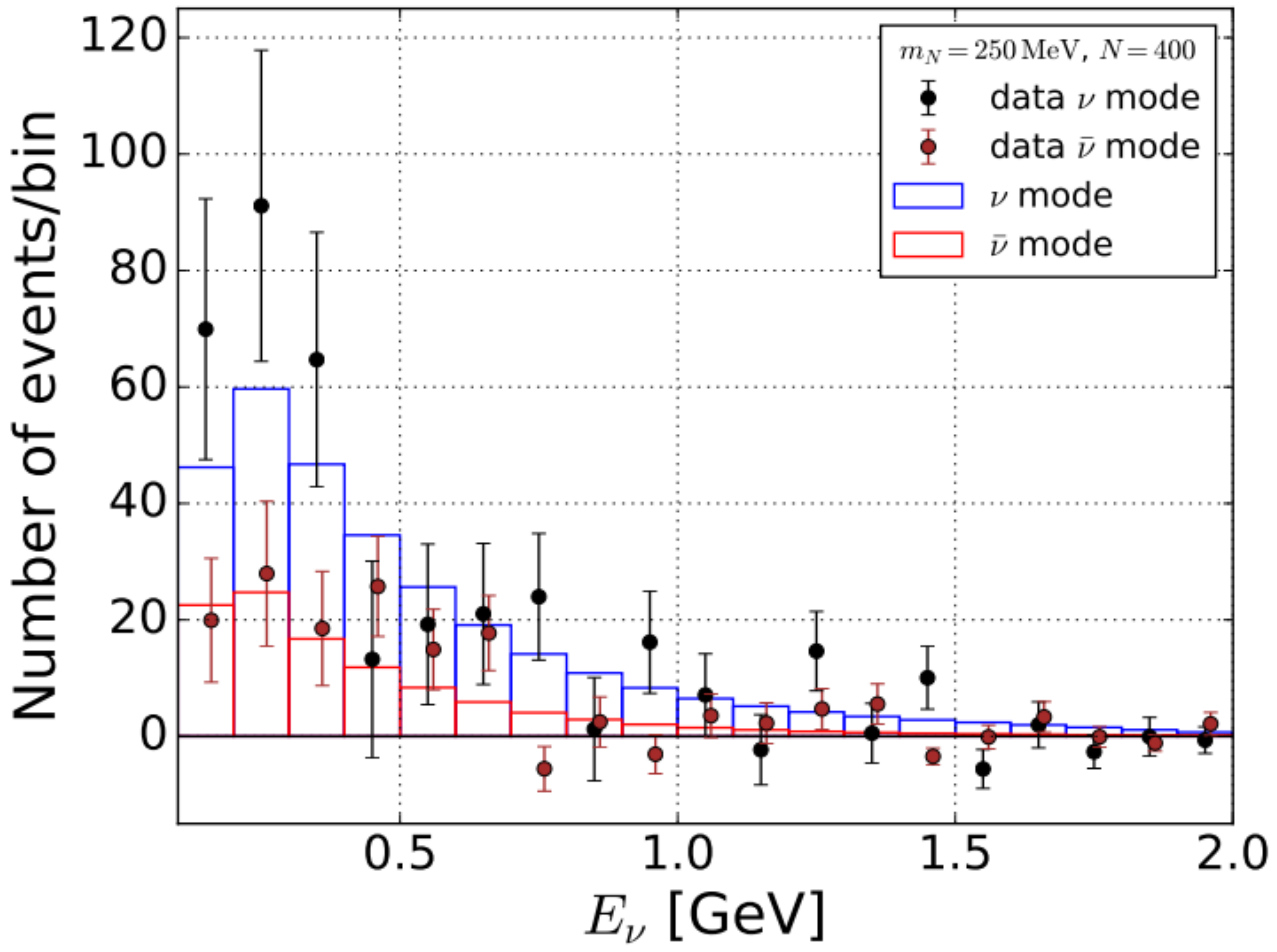
Arguelles et al. 22

MiniBooNE and a decaying sterile neutrino — example:

Fischer, Hernandez, TS, 1909.09561

- sterile neutrino N with $m_N \sim 250$ MeV ($m_\pi < m_N < m_K$)
- produce N in kaon decays via mixing $K \to N\, \mu/e$
- decay inside MB detector $N \to \nu\gamma$ via

$$\mathcal{O}_{N\to\gamma\nu} = \frac{1}{\Lambda}\bar{N}\sigma^{\alpha\beta}\nu F_{\alpha\beta}$$



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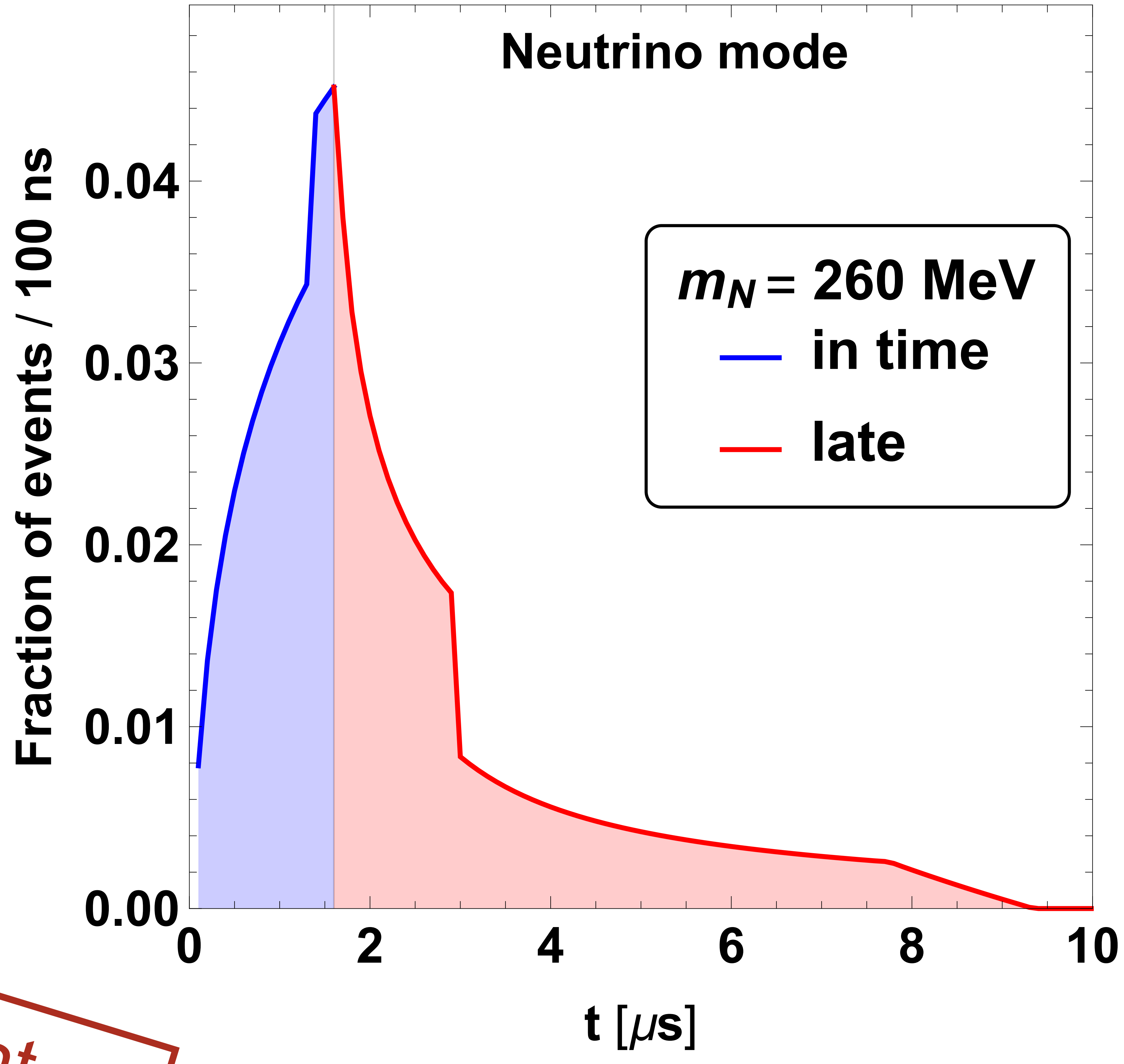
- dec MB detector $N \to \nu\gamma$ via

$$\mathcal{O}_{N\to\gamma\nu} = \quad \Lambda$$

disfavoured (excluded?) by new MiniBooNE event timing analysis [arXiv:2006.16883]



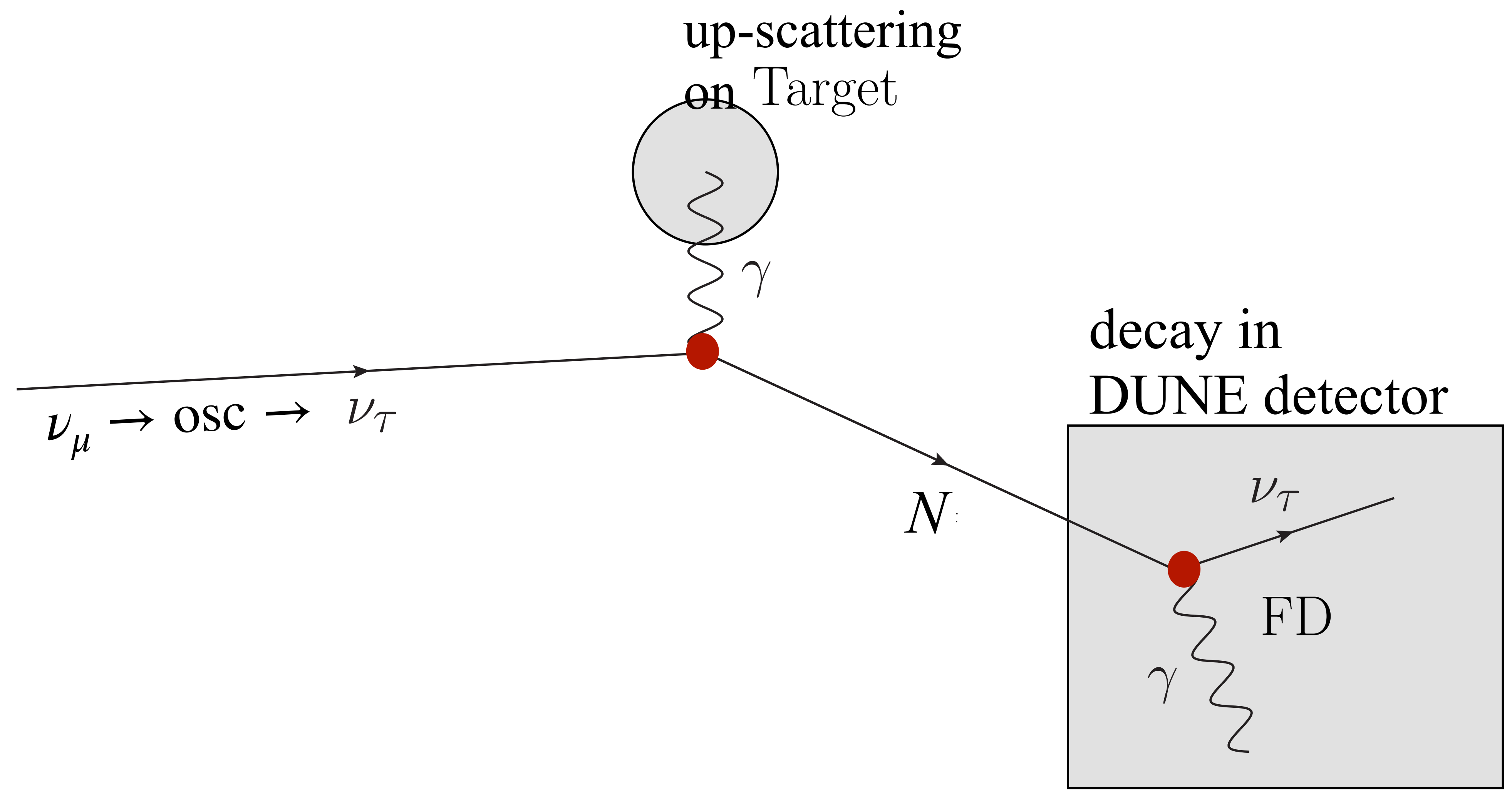
The photon—heavy neutrino (dipole) portal

$$\mathscr{L} = d_\alpha \bar{N} \sigma_{\mu\nu} \nu_\alpha F^{\mu\nu} + \mathrm{hc} \quad (\alpha = e, \mu, \tau)$$

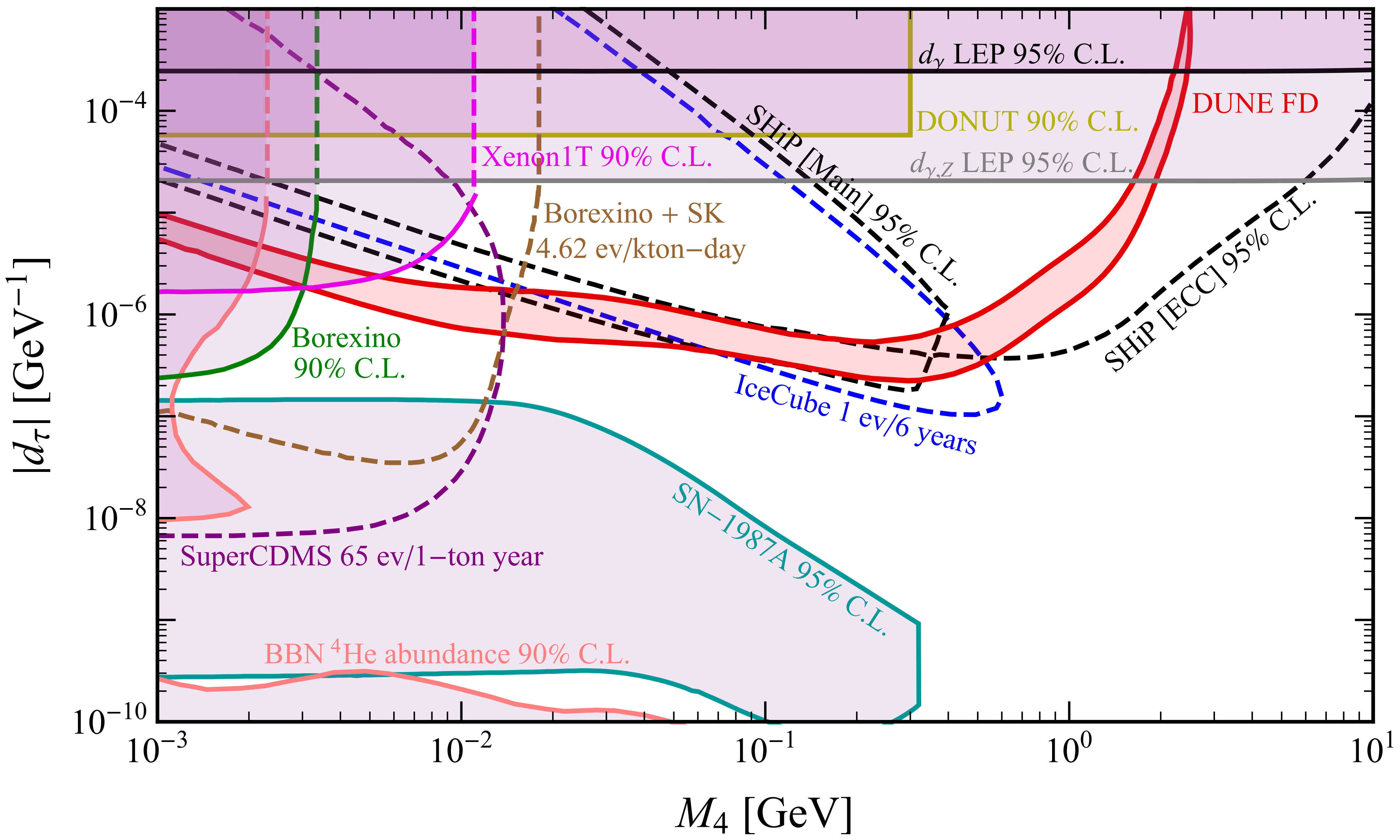
- effective operator $d_\alpha \sim \langle H \rangle / \Lambda^2$, coupling active neutrinos to HNL + photon
- in the context of MiniBooNE anomaly Gninenko, 0902.3802, 1009.5536; Fischer, Hernandez, TS, 1909.09561; Arguelles et al., 2206.07100
- portal to new physics irrespective of anomalies (signatures in beam experiments, atmospheric/solar neutrinos, cosmology,…) Magill, Plestid, Pospelov, Tsai, 1803.03262; Brdar, Greljo, Kopp, Opferkuch, 2007.15563; Shoemaker, Tsai, Wyenberg, 2007.05513; Coloma, Hernandez, Munoz, Shoemaker, 1911.09129; Plestid, 2010.04193; Schwetz, Zhou, Zhu, 2105.09699; Atkinson et al., 2105.09357

Example: tau neutrino dipole portal @ DUNE

$$\mathscr{L} = d_\tau \bar{N}\sigma_{\mu\nu}\nu_\tau F^{\mu\nu} + \text{hc}$$



Schwetz, Zhou, Zhu, 2105.09699



e and μ flavour better probed at near detector

see also Atkinson et al., 2105.09357

Summary

- Reactor rate anomaly: fading away
- Reactor shape anomaly: fading away
- Gallium anomaly: BEST results $> 5\sigma$ significance
  require ~0.1 mixing, in tension with solar neutrinos, reactor rates
- tension with cosmology (talk by L. Verde)
- LSND, MiniBooNE appearance signals
  - cannot be explained by eV-sterile neutrino oscillations
  - maybe sign of other exciting new physics (e.g. decaying HNLs?)
    but no straight-forward explanation

Appearance vs disappearance tension

Analysis	$\chi^2_{\text{min,global}}$	$\chi^2_{\text{min,app}}$	$\Delta\chi^2_{\text{app}}$	$\chi^2_{\text{min,disapp}}$	$\Delta\chi^2_{\text{disapp}}$	$\chi^2_{\text{PG}}/\text{dof}$	PG
Global	1120.9	79.1	11.9	1012.2	17.7	29.6/2	3.71×10^{-7}
Removing anomalous data sets							
w/o LSND	1099.2	86.8	12.8	1012.2	0.1	12.9/2	1.6×10^{-3}
w/o MiniBooNE	1012.2	40.7	8.3	947.2	16.1	24.4/2	5.2×10^{-6}
w/o reactors	925.1	79.1	12.2	833.8	8.1	20.3/2	3.8×10^{-5}
w/o gallium	1116.0	79.1	13.8	1003.1	20.1	33.9/2	4.4×10^{-8}
Removing constraints							
w/o IceCube	920.8	79.1	11.9	812.4	17.5	29.4/2	4.2×10^{-7}
w/o MINOS(+)	1052.1	79.1	15.6	948.6	8.94	24.5/2	4.7×10^{-6}
w/o MB disapp	1054.9	79.1	14.7	947.2	13.9	28.7/2	6.0×10^{-7}
w/o CDHS	1104.8	79.1	11.9	997.5	16.3	28.2/2	7.5×10^{-7}
Removing classes of data							
$\overset{(-)}{\nu}_e$ dis vs app	628.6	79.1	0.8	542.9	5.8	6.6/2	3.6×10^{-2}
$\overset{(-)}{\nu}_\mu$ dis vs app	564.7	79.1	12.0	468.9	4.7	16.7/2	2.3×10^{-4}
$\overset{(-)}{\nu}_\mu$ dis + solar vs app	884.4	79.1	13.9	781.7	9.7	23.6/2	7.4×10^{-6}

Dentler et al., 1803.10661