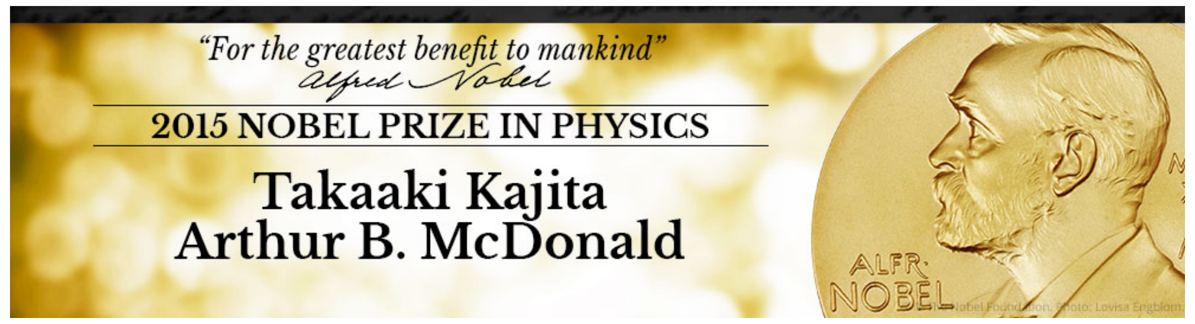
EuCAPT Astroneutrino Theory Workshop 2024

Prague, Czech Republic, Sept. 2024

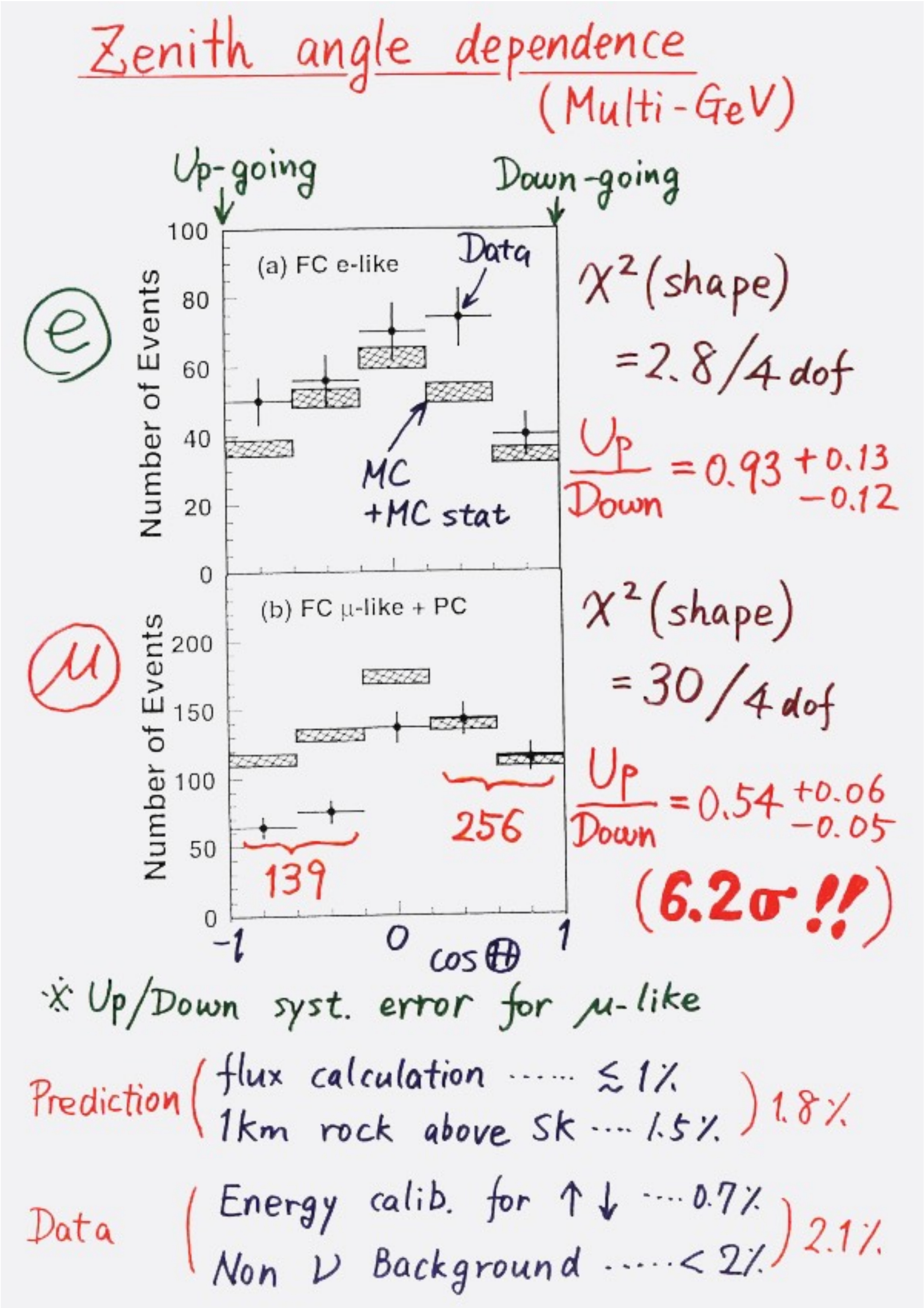
Overview about short-baseline anomalies: no clear hint for eV sterile neutrino oscillations

Thomas Schwetz
Karlsruhe Institute of Technology, Institute for Astroparticle Physics

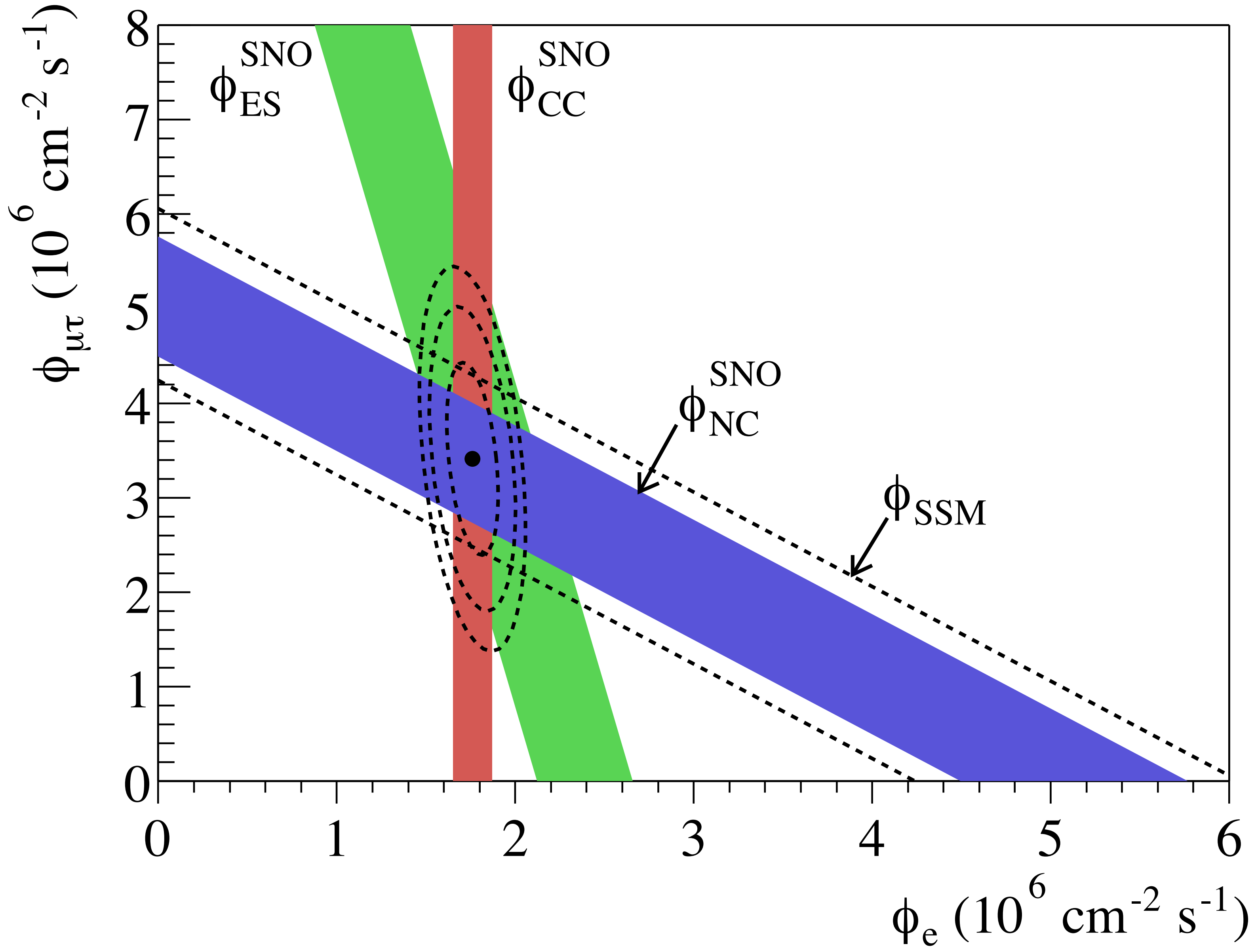
Neutrinos oscillate…



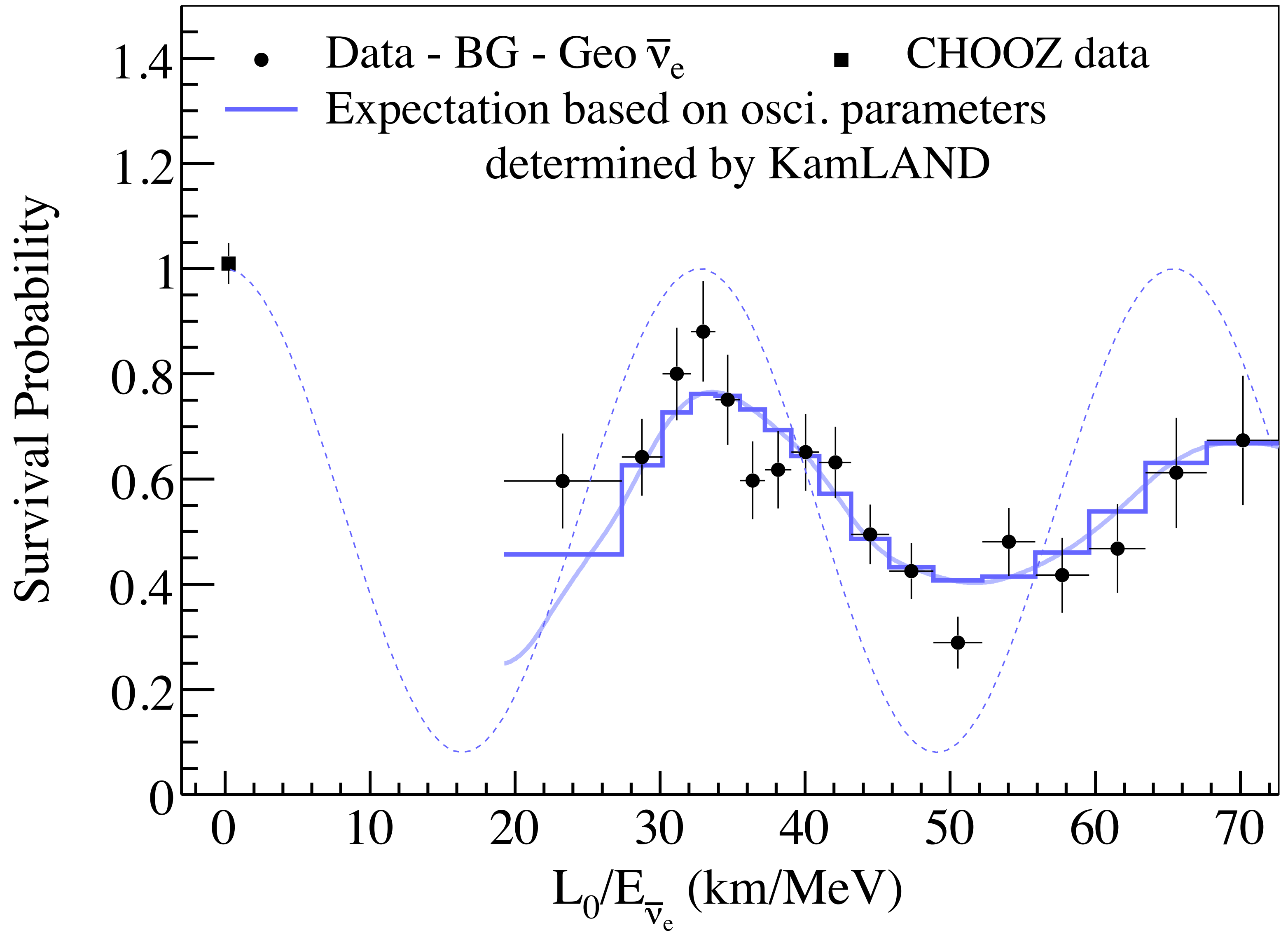
SuperK 1998 atmospheric neutrinos



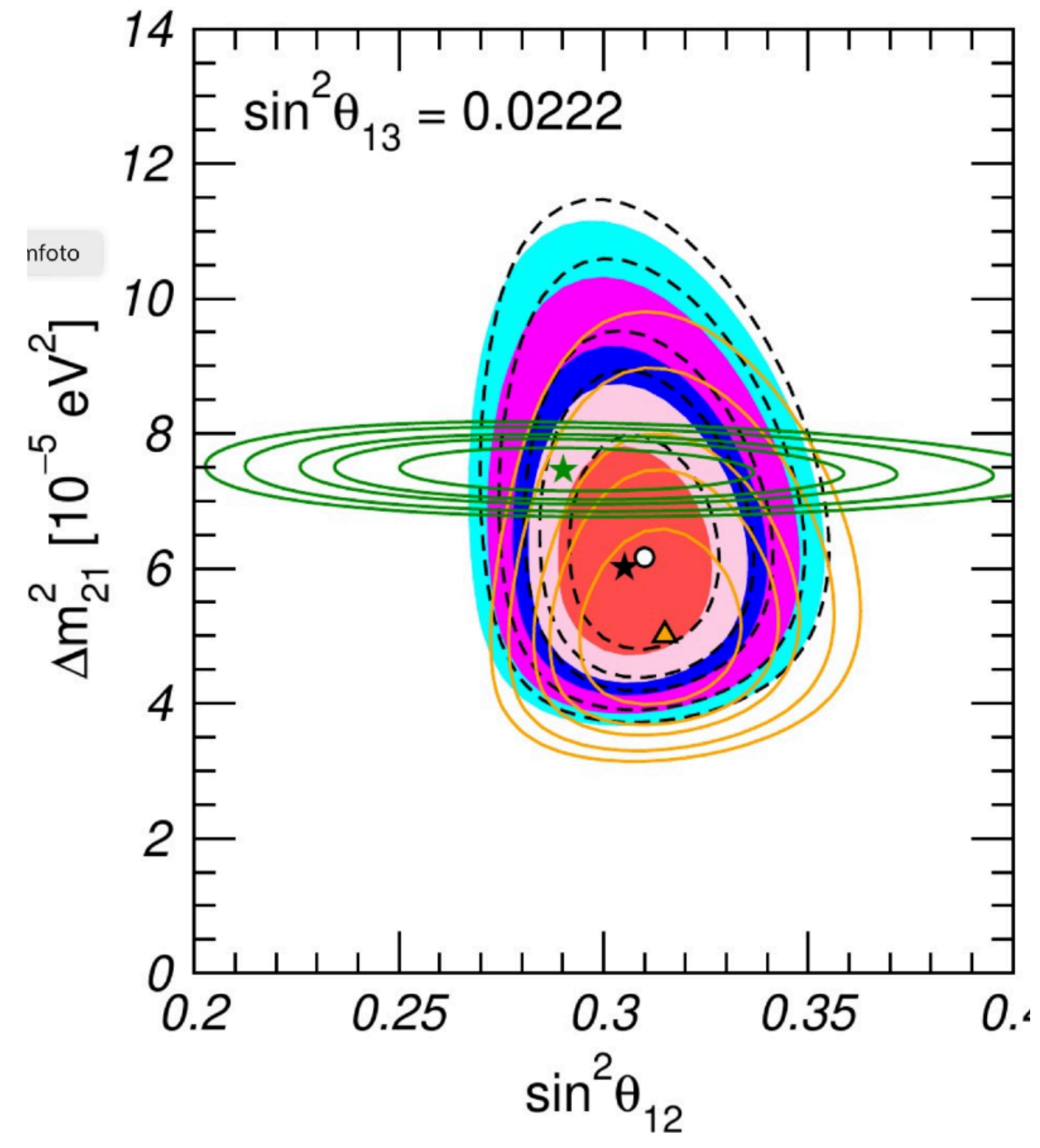
SNO 2002 solar neutrinos

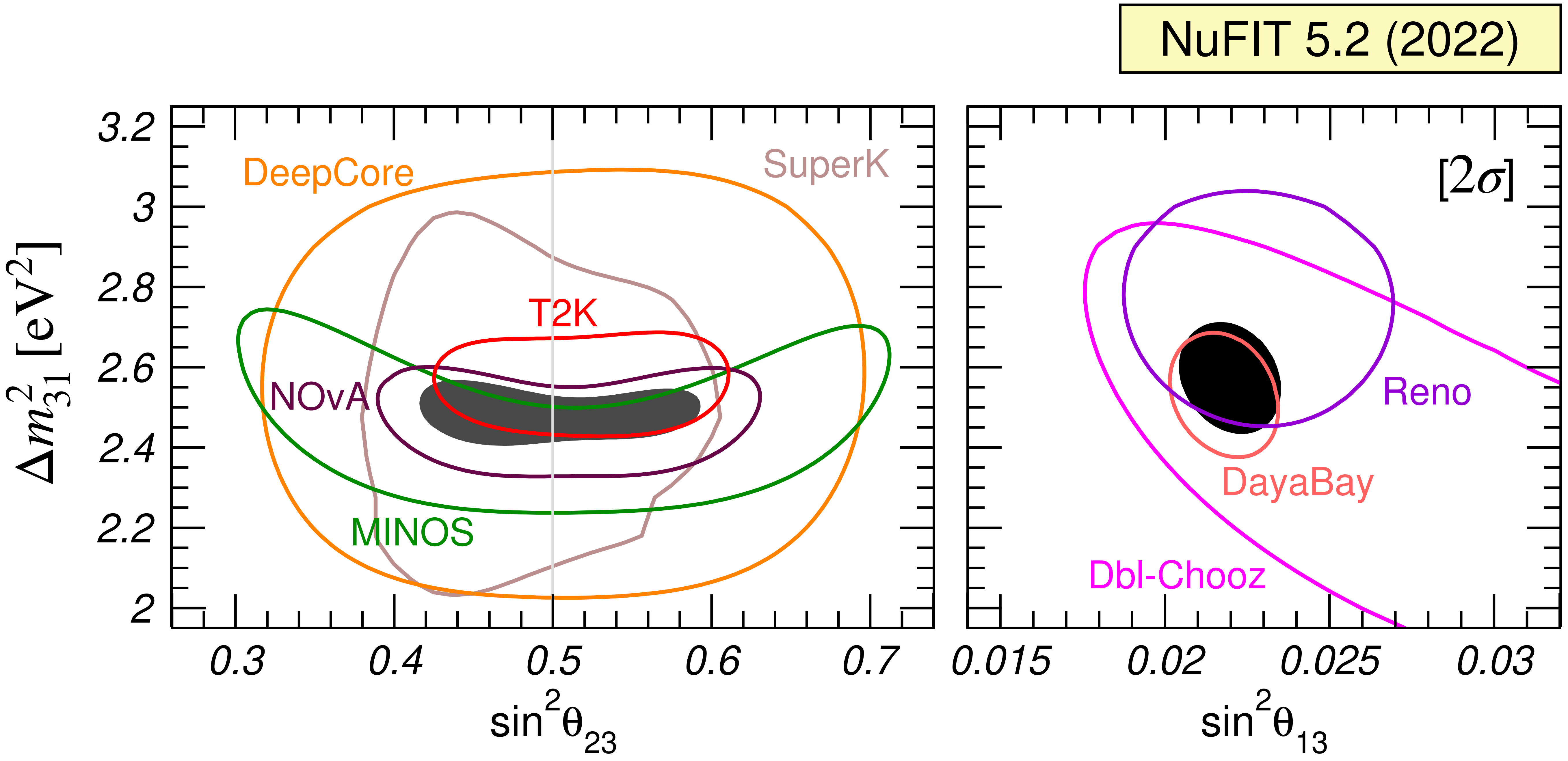


KamLAND 2006 reactor neutrinos



Big success of 3-neutrino framework



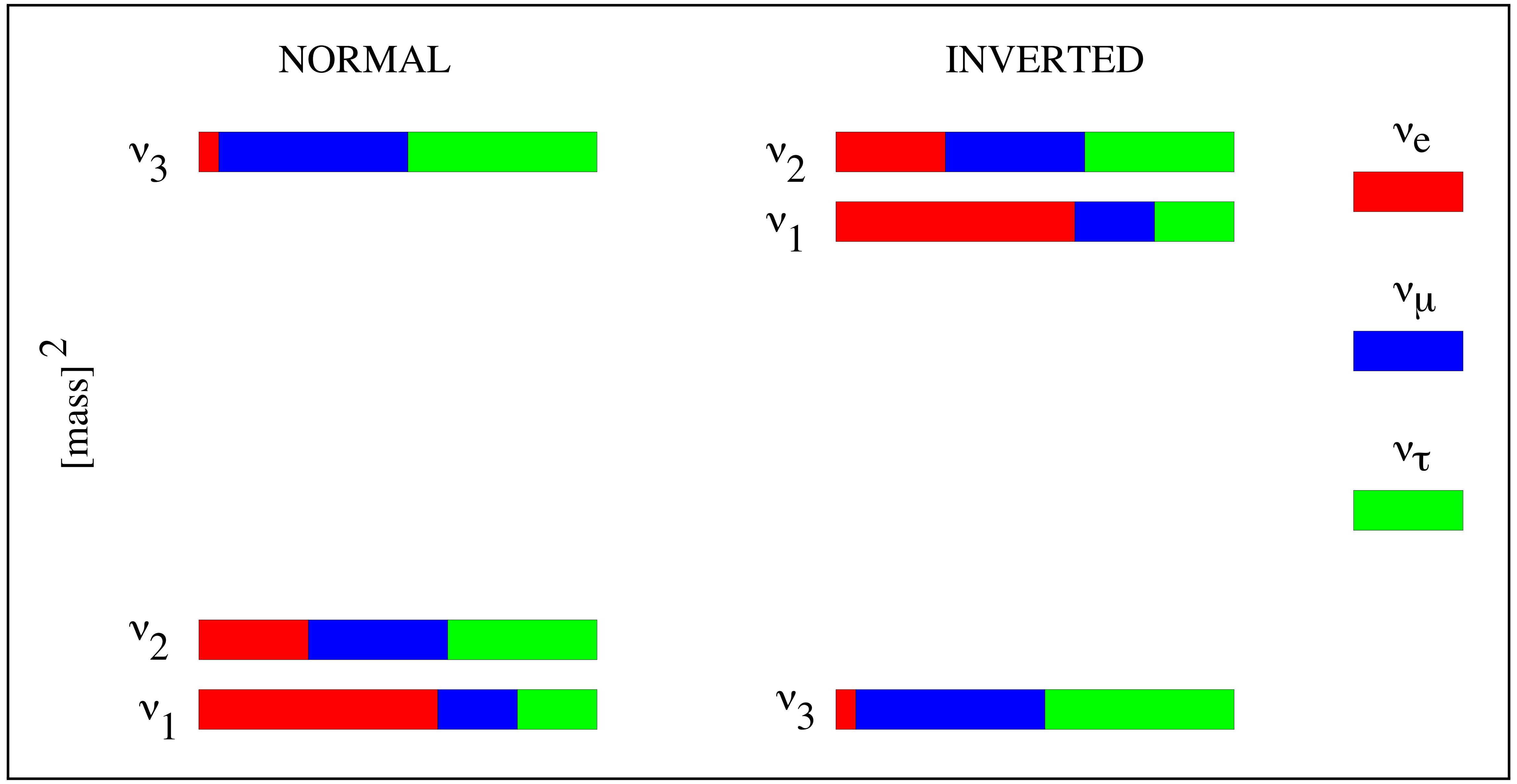


www.nu-fit.org

Big success of 3-neutrino framework

$$|m_3^2 - m_1^2| \approx (2.5 \pm 0.03) \times 10^{-3}\,\mathrm{eV}^2$$
$$m_2^2 - m_1^2 = (7.42 \pm 0.21) \times 10^{-5}\,\mathrm{eV}^2$$

$$\theta_{12} \approx 33^\circ$$
$$\theta_{23} \approx 45^\circ$$
$$\theta_{13} \approx 9^\circ$$



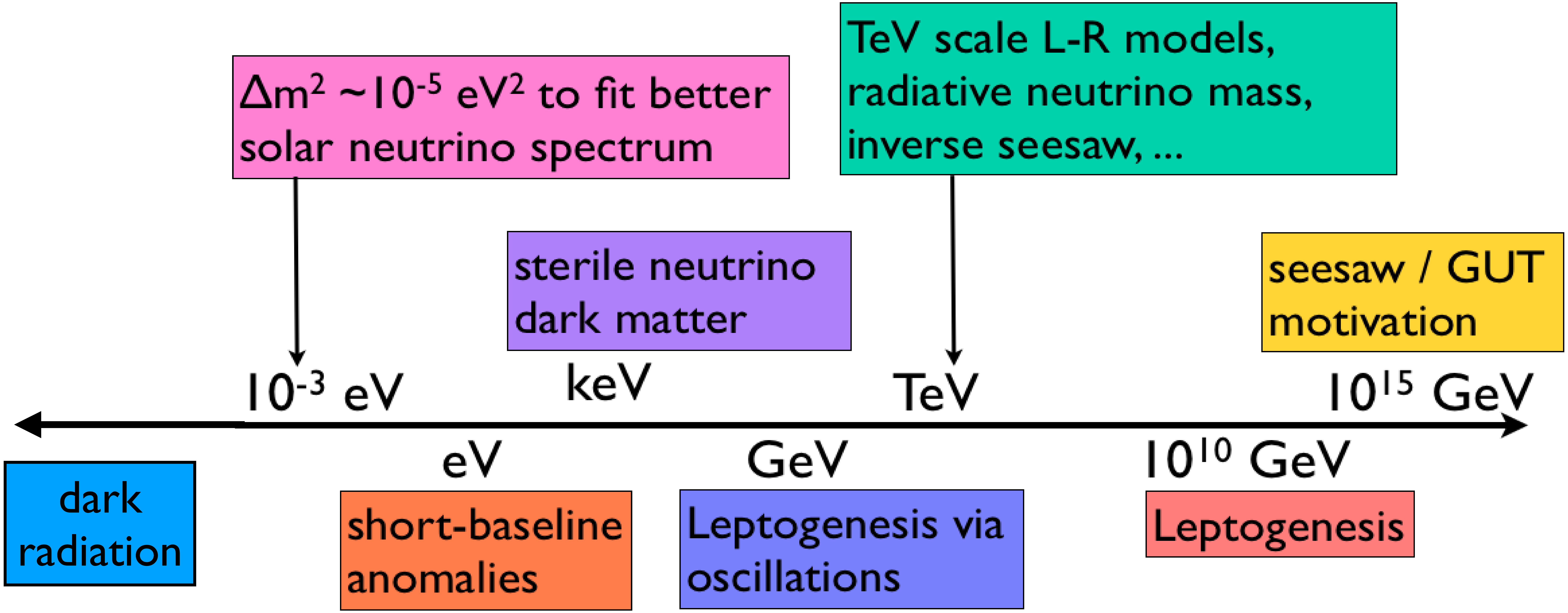
www.nu-fit.org

Sterile neutrinos — right-handed neutrinos — heavy neutral leptons

- fermion, singlet under the SM gauge group
- renormalizable interaction with SM: $\mathscr{L}_Y = y\bar{L}\tilde{H}N + \mathrm{h.c.}$
- appear in many extensions of the SM, models for neutrino mass (seesaw)
- „portal“ to a dark sector, e.g. $\mathscr{L}_{\mathrm{dark}} = g\phi\bar{N}^c N + \ldots$
- Majorana mass term $\mathscr{L}_M = M_N \bar{N}^c N$ unrelated to Higgs VEV, scale of new physics

Lecture by M. Malinsky on Monday

Sterile neutrino at which mass scale?



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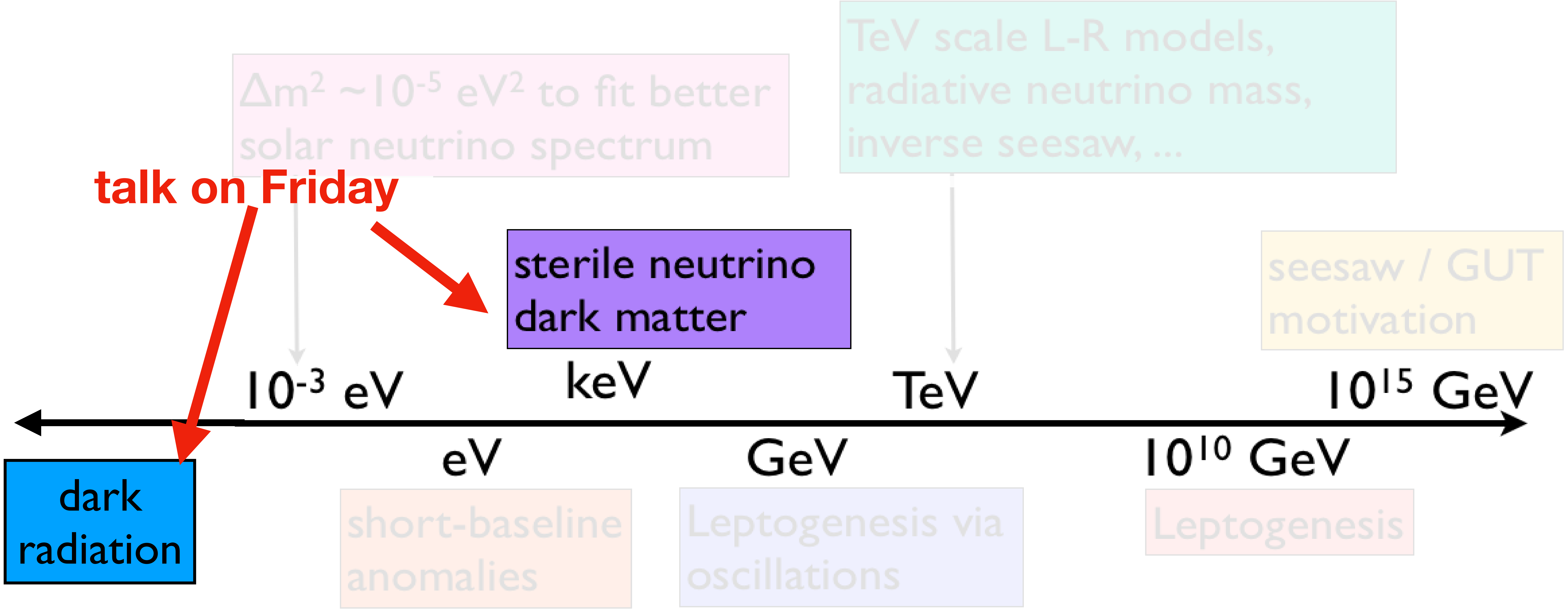

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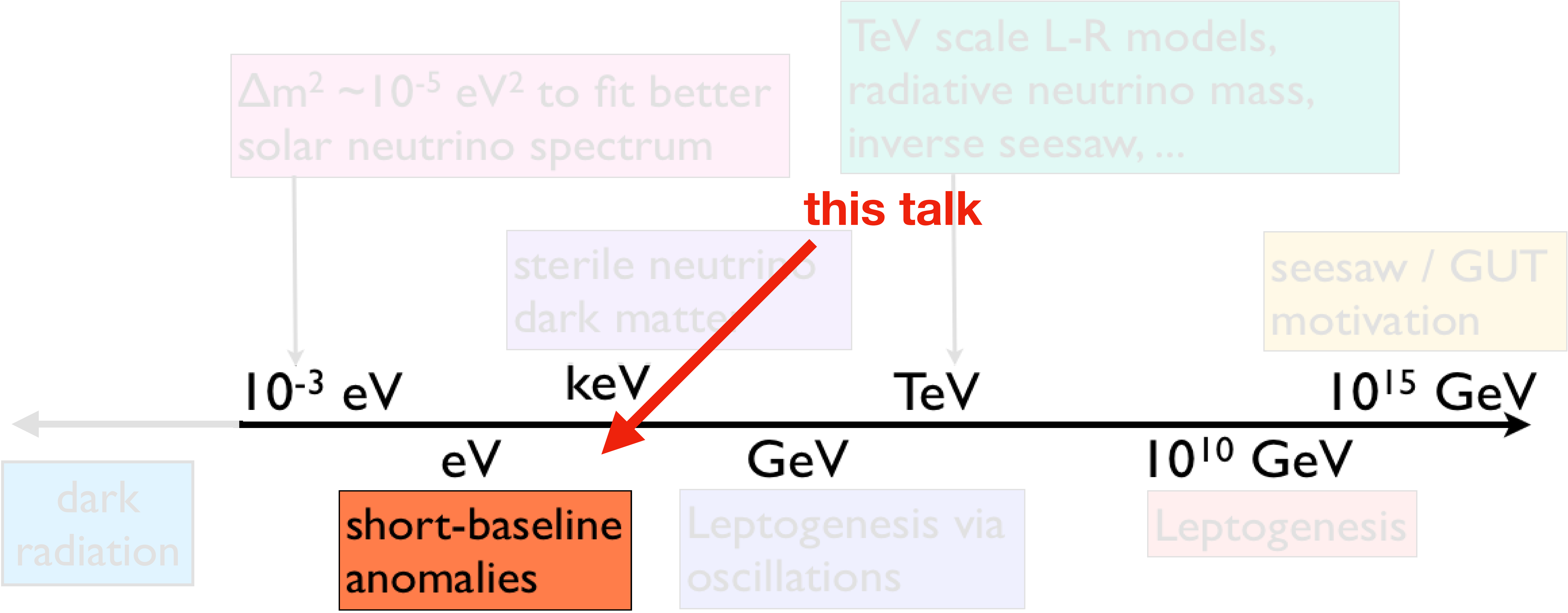
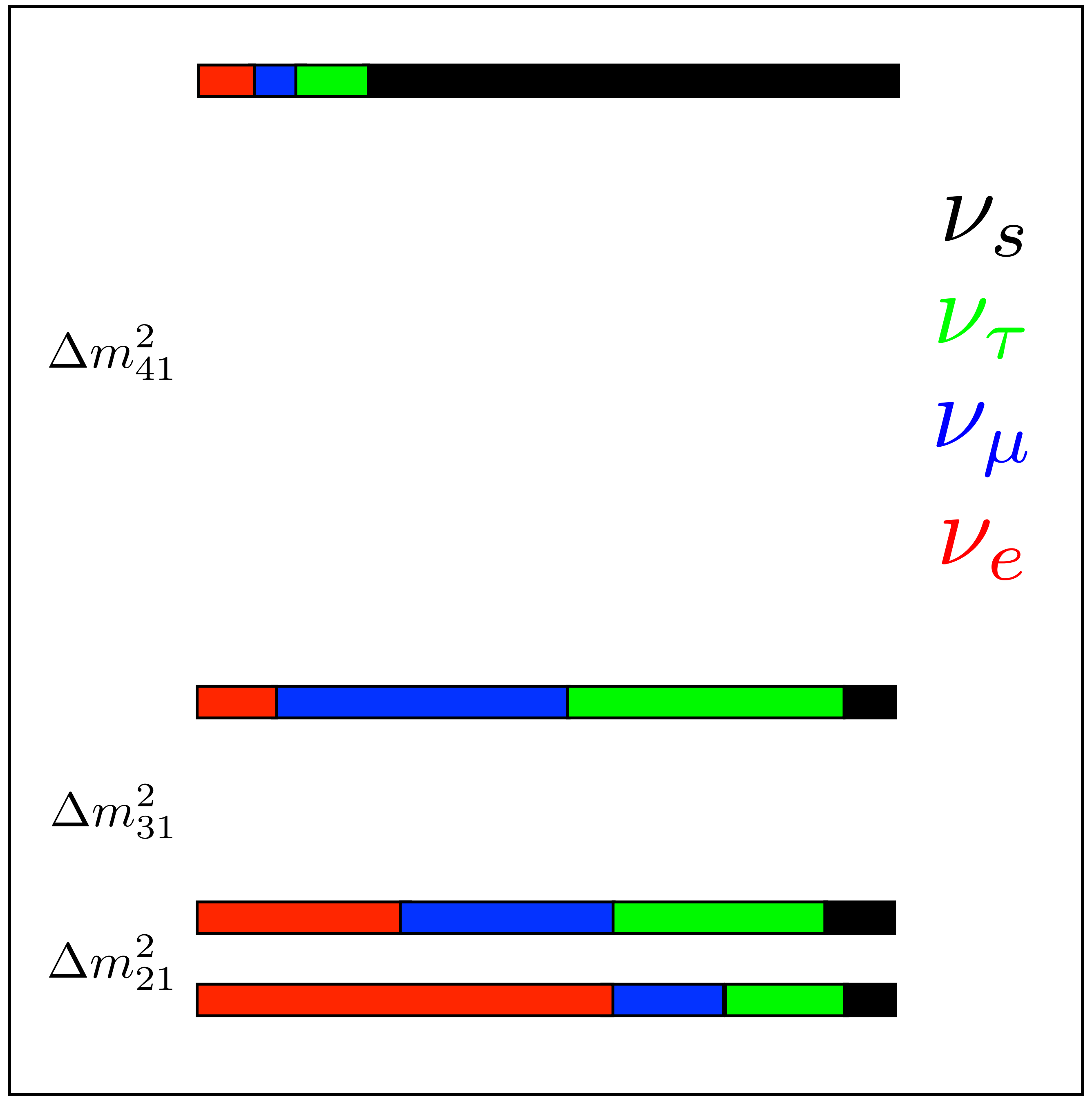


Sterile neutrinos at the eV scale?

- 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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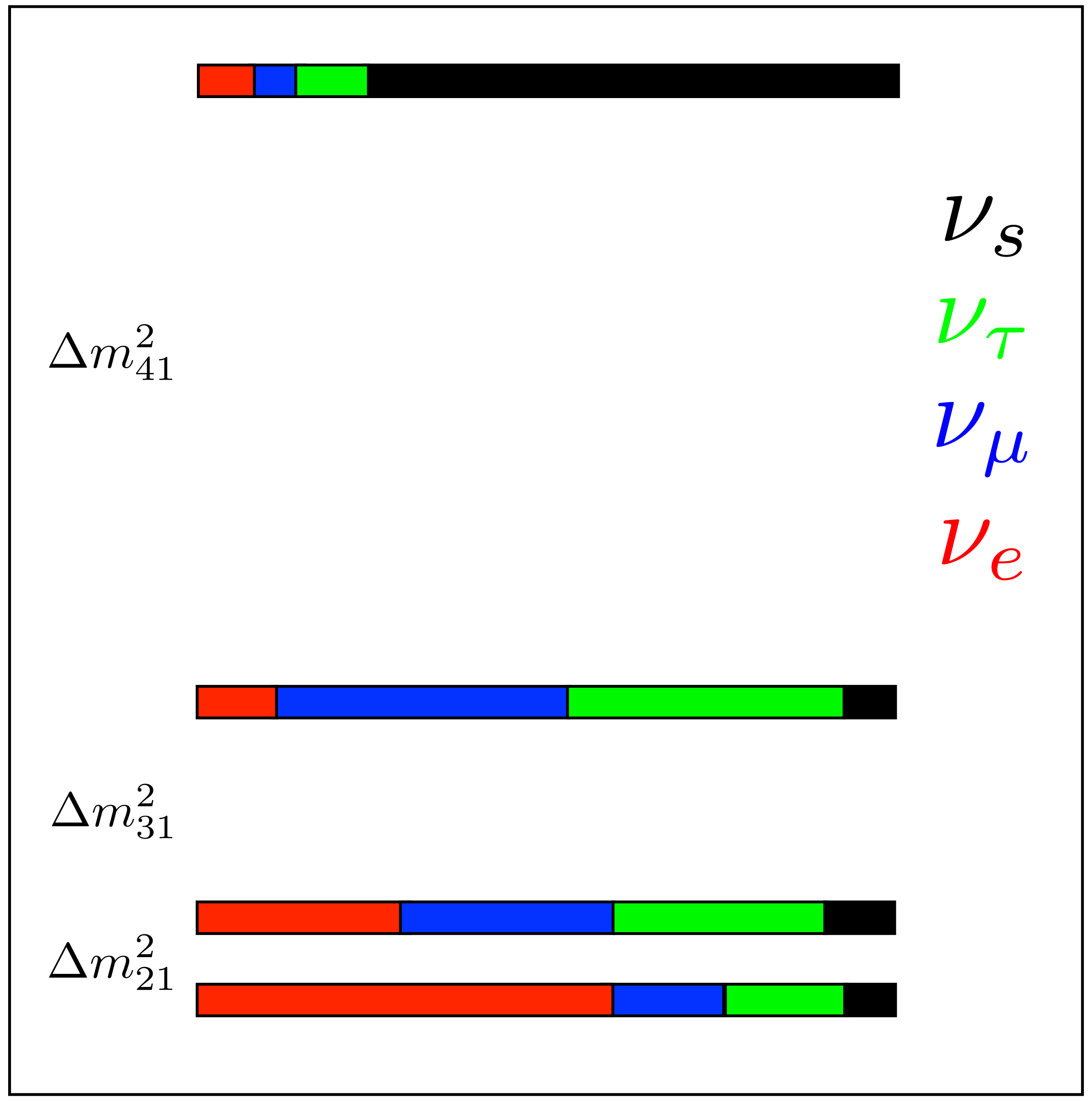

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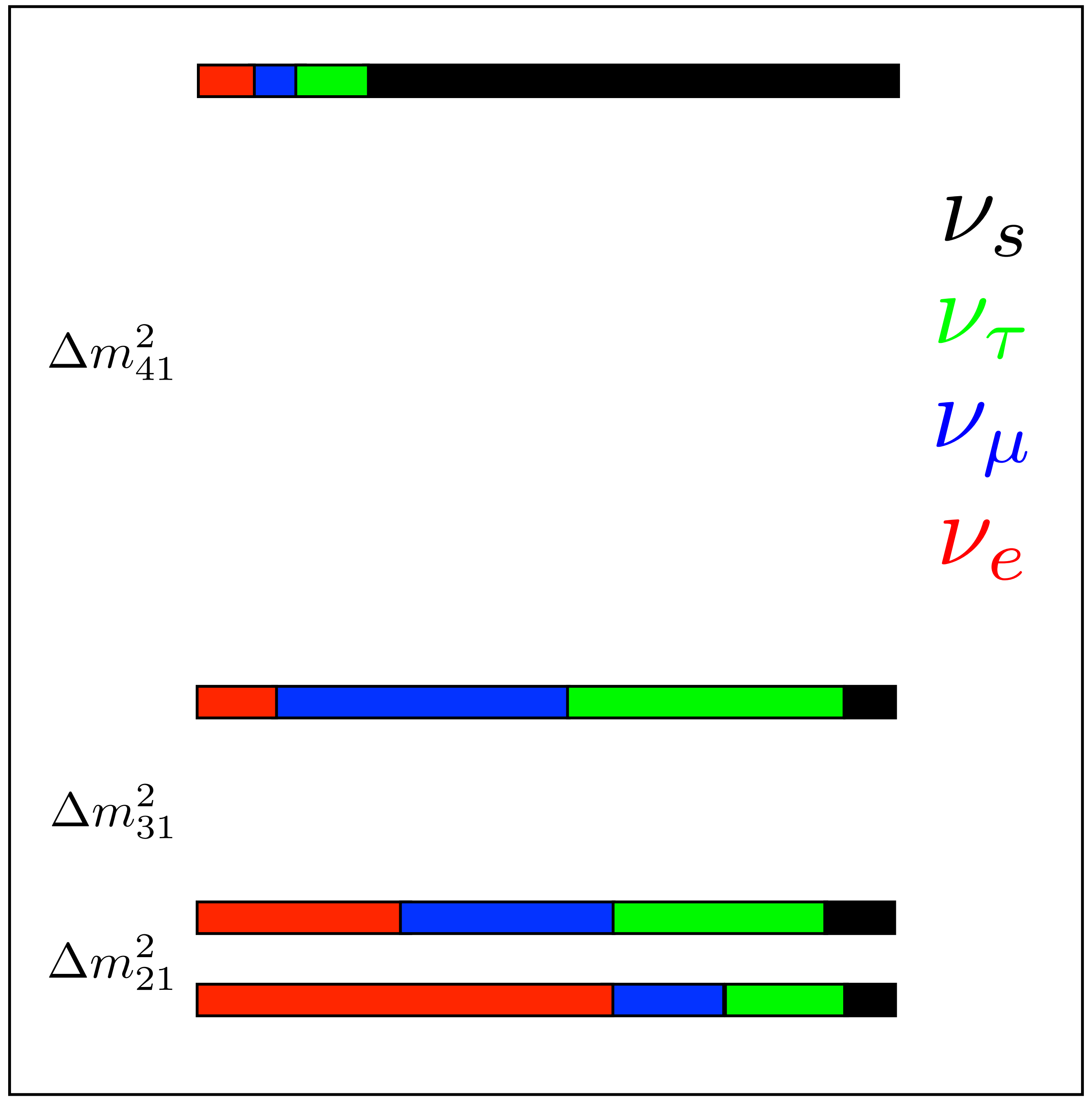
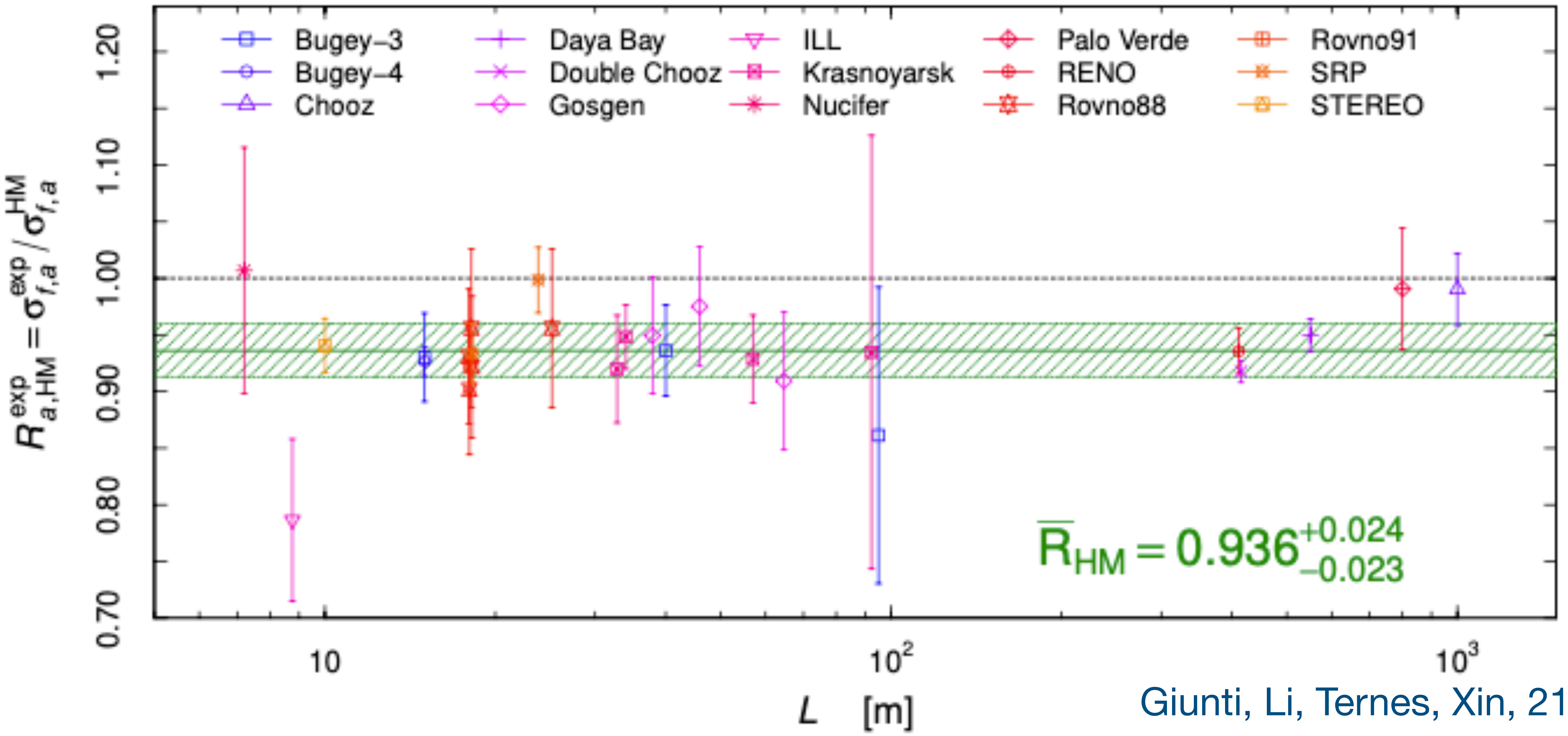


Reactor anomaly

- tension between „predicted“ and observed neutrino rates at reactors
- dominated by systematic/theoretical uncertainty



Giunti, Li, Ternes, Xin, 2110.06820

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

Berryman, Huber, 1909.09267

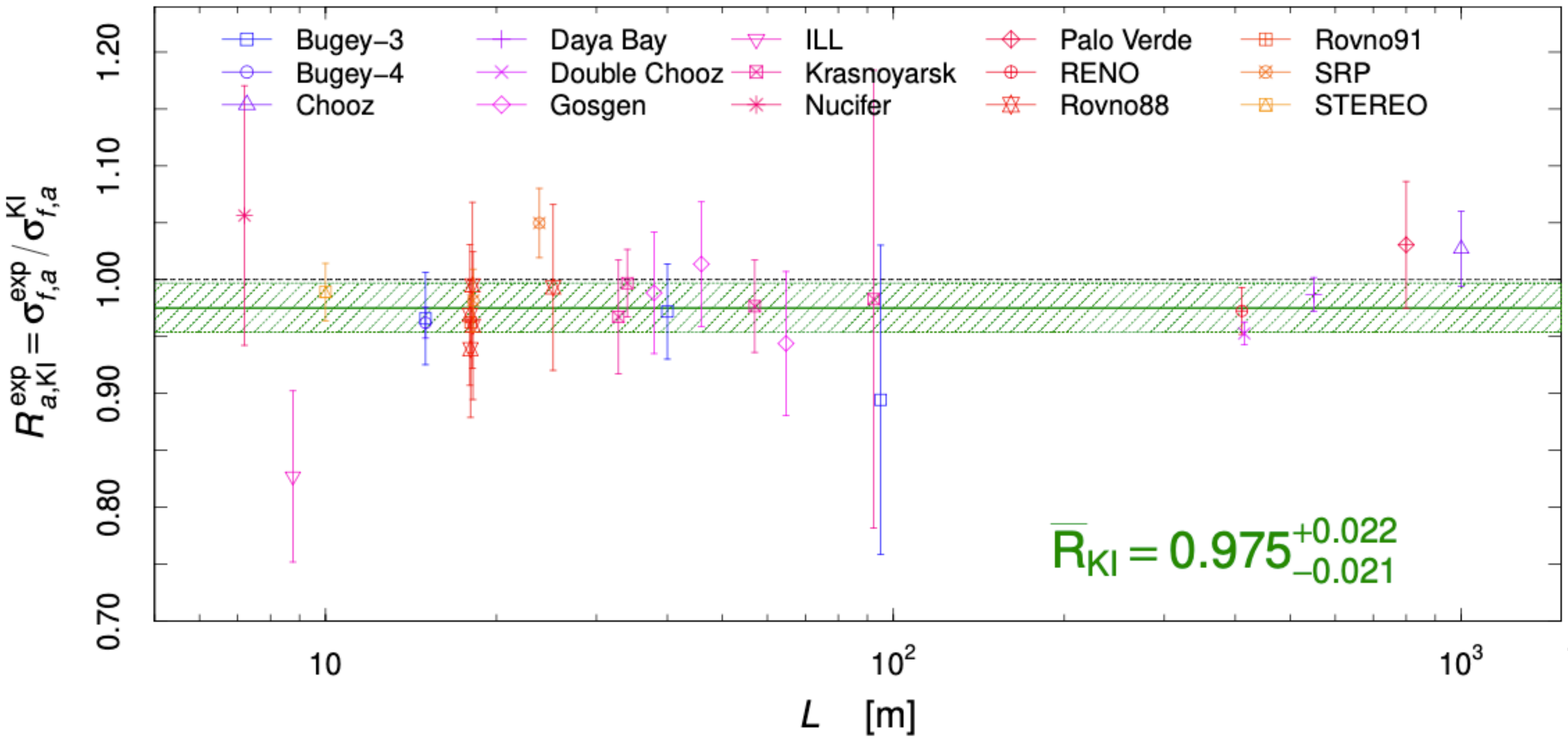
Analysis	$\chi^2_{3\nu}$	χ^2_{min}	n_{data}	p	$n\sigma$
HM Rates	41.4	33.5	40	2.0×10^{-2}	2.3
Ab Initio Rates	39.2	37.0	40	0.34	0.95
HKSS Rates	58.1	47.5	40	5.0×10^{-3}	2.8
Spectra	184.9	172.2	212	1.8×10^{-3}	3.1
DANSS + NEOS	98.9	84.7	84	8.1×10^{-4}	3.3

see also Perissé, Onillon, Mougeot, Vivier, Lasserre et al. 2304.14992

Reactor anomaly

- all reactor neutrino spectra predictions (till 2021) were based on electron spectra measured by Schreckenbach et al., 1981-89 @ ILL

- 2021: measurement of $^{235}U/^{239}Pu$ beta-sepctra @ Kurchatov Inst. (KI)
  Kopeikin, Skorokhvatov, Titov, PRD21 [2103.01684]
  5.4% smaller than ILL → suggests bias in ^{235}U ILL spectrum



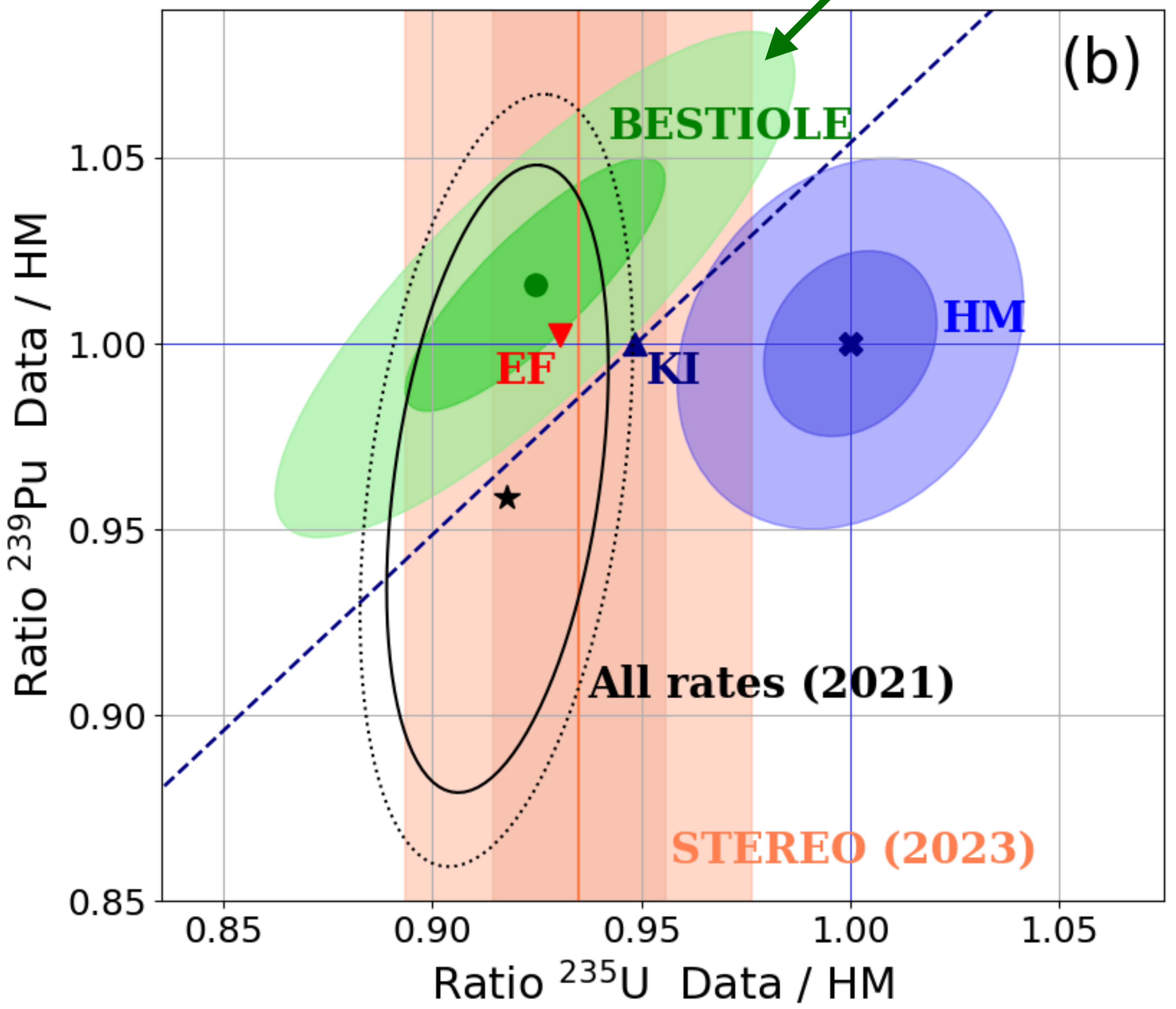
consistent within 1.1σ

Giunti, Li, Ternes, Xin, 2110.06820

Reactor anomaly

- Recent „ad-initio“ calculation of reactor neutrino spectrum
  Perissé, Onillon, Mougeot, Vivier, Lasserre et al. 2304.14992

good agreement with measured neutrino rates



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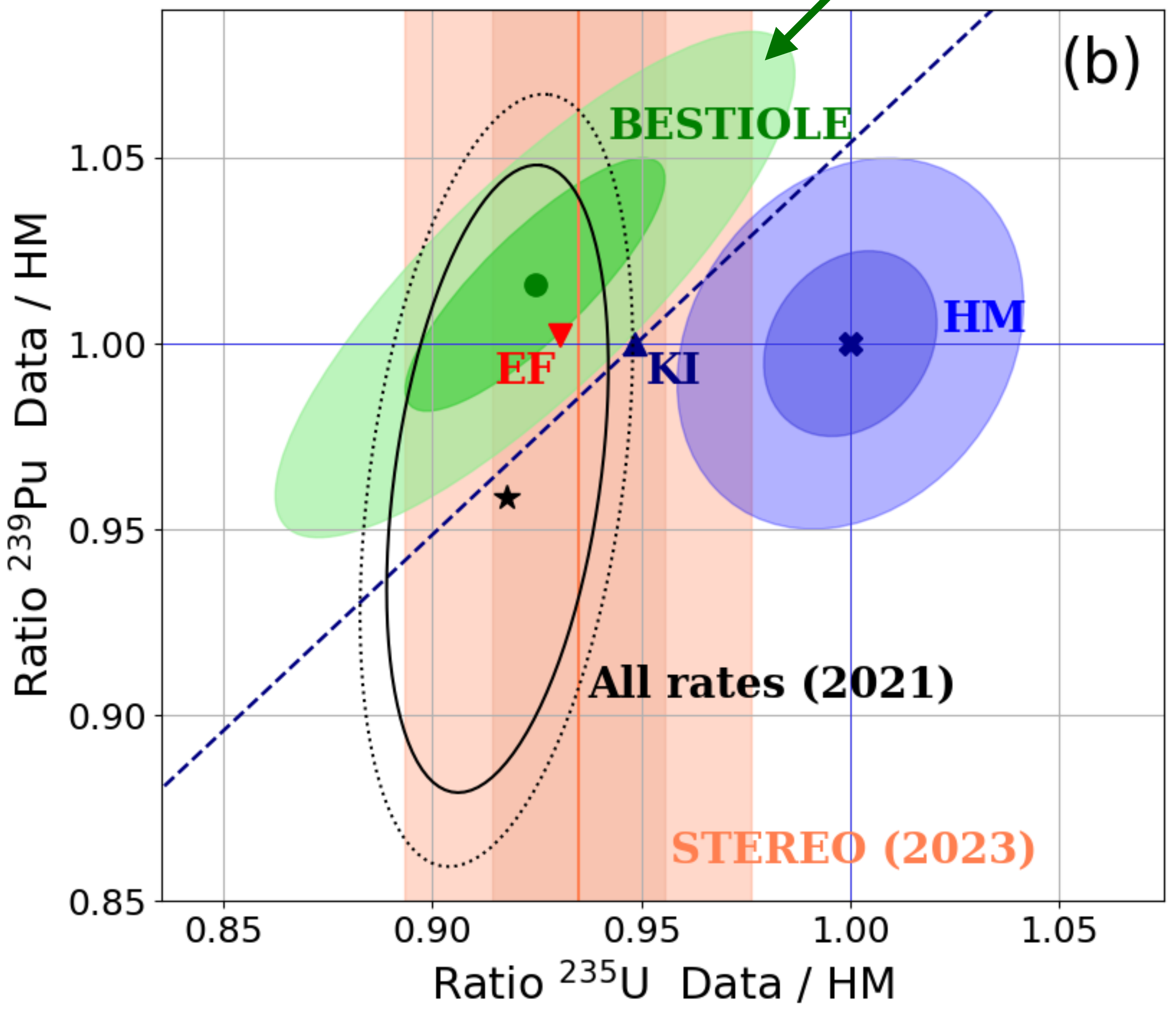
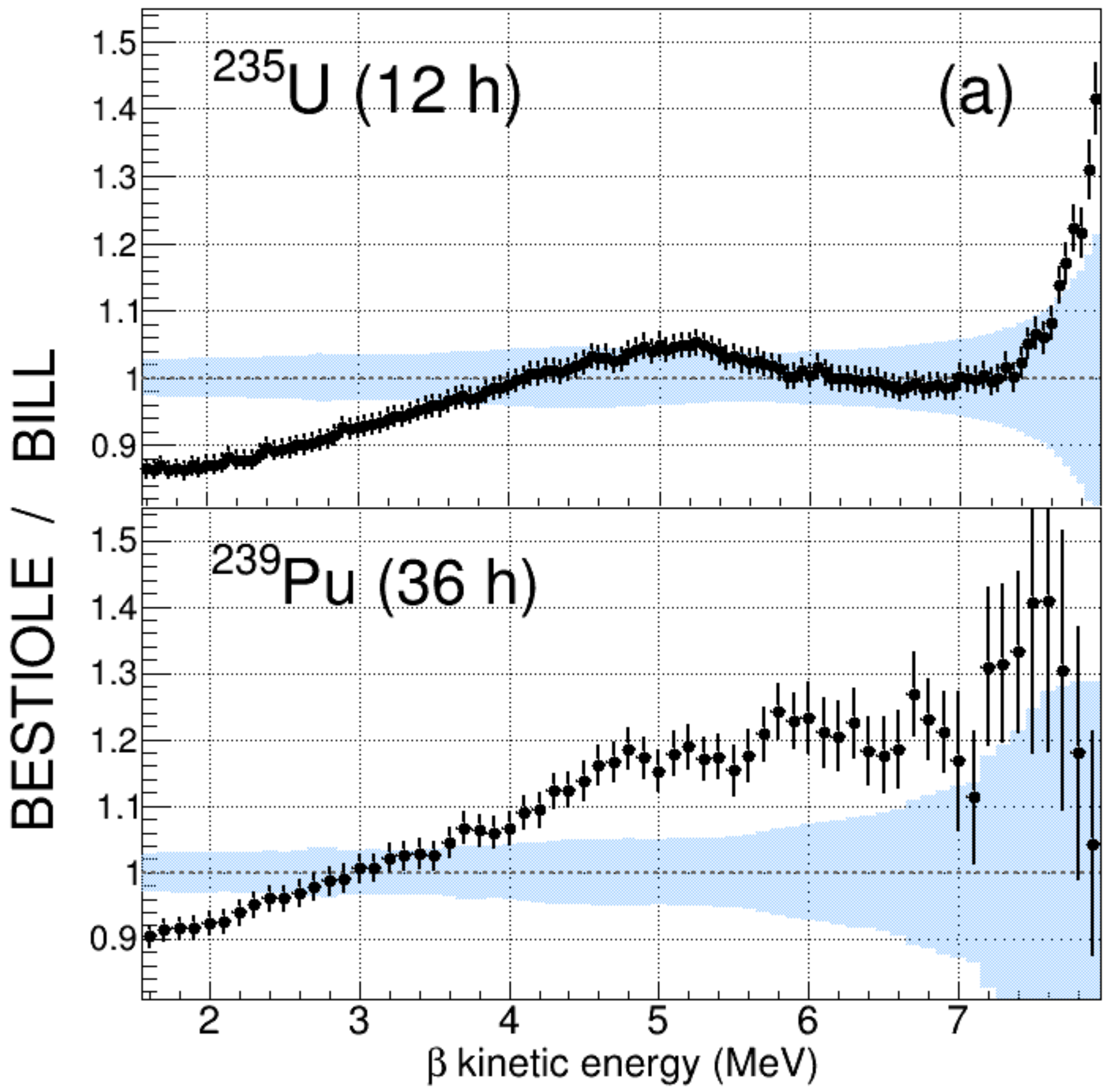
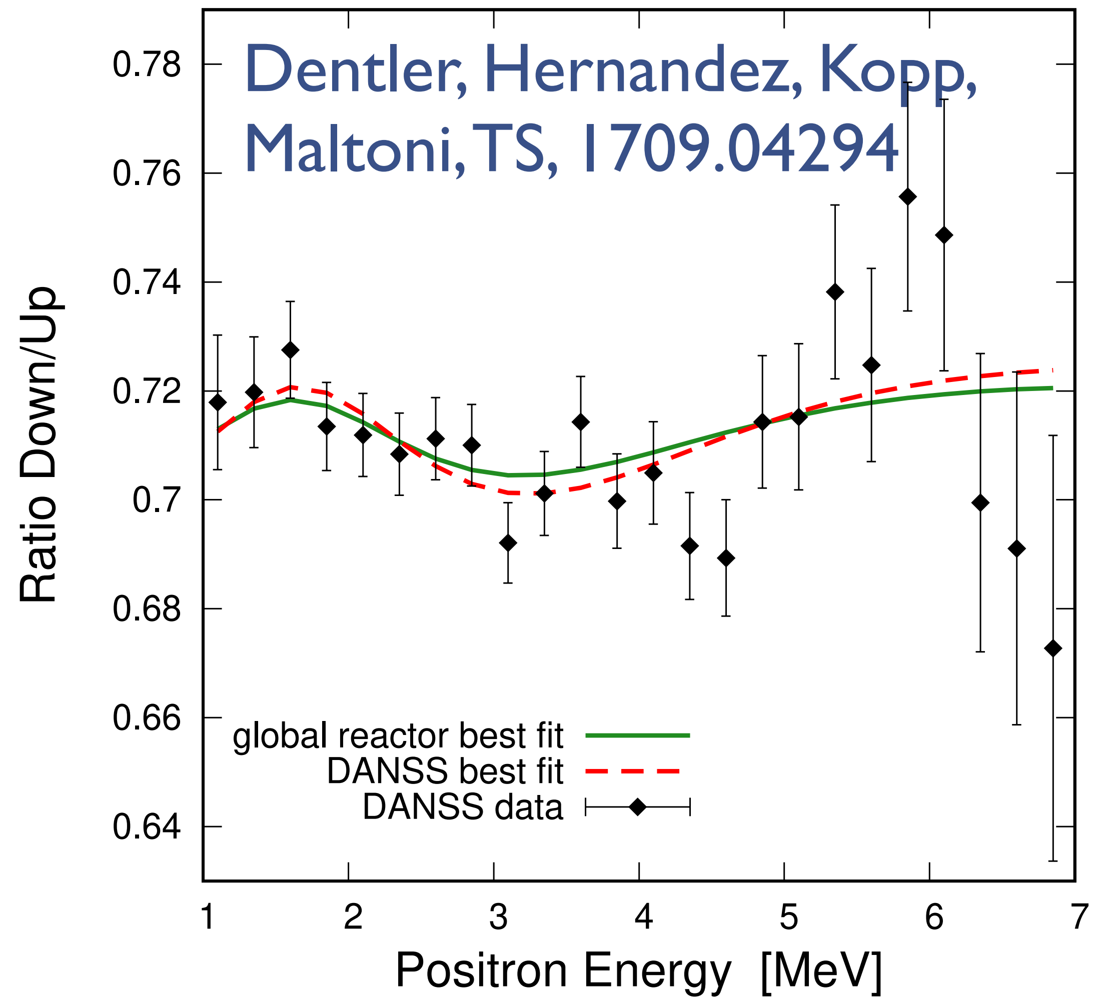


ILL β spectra not well reproduced



Reactor shape anomaly

relative spectral measurments:



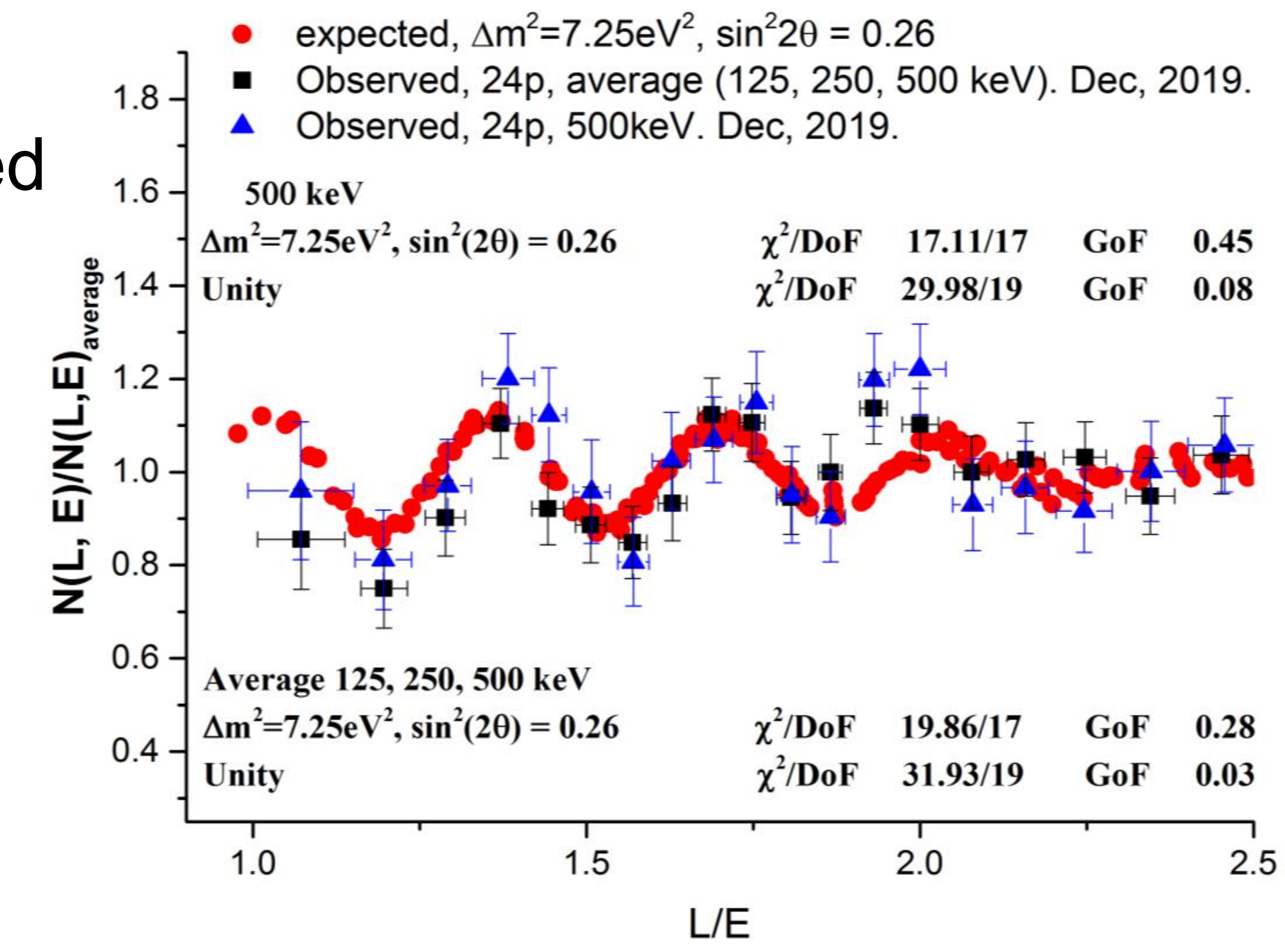
DANSS: relative spectra @ L = 10.7 and 12.7 m
prev. ~ 2σ hint decr. ~1.5σ
DANSS talk @ ICHEP20

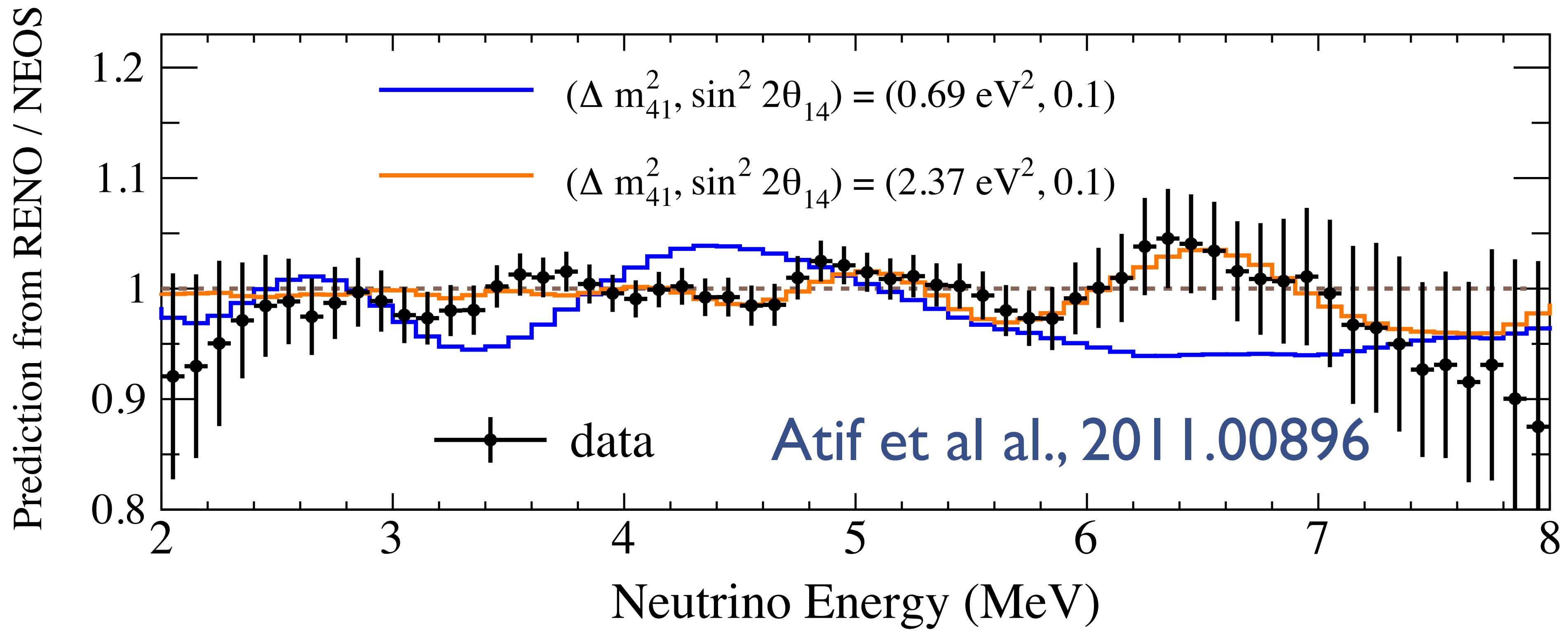
segmented detectors:
STEREO [arXiv:1912.06582]
L = 9 to 11 m $\Delta\chi^2$(no osc) ≈ 9

PROSPECT [arXiv:2006.11210]
L = 6.7 to 9.2 m

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

Neutrino4 2005.05301

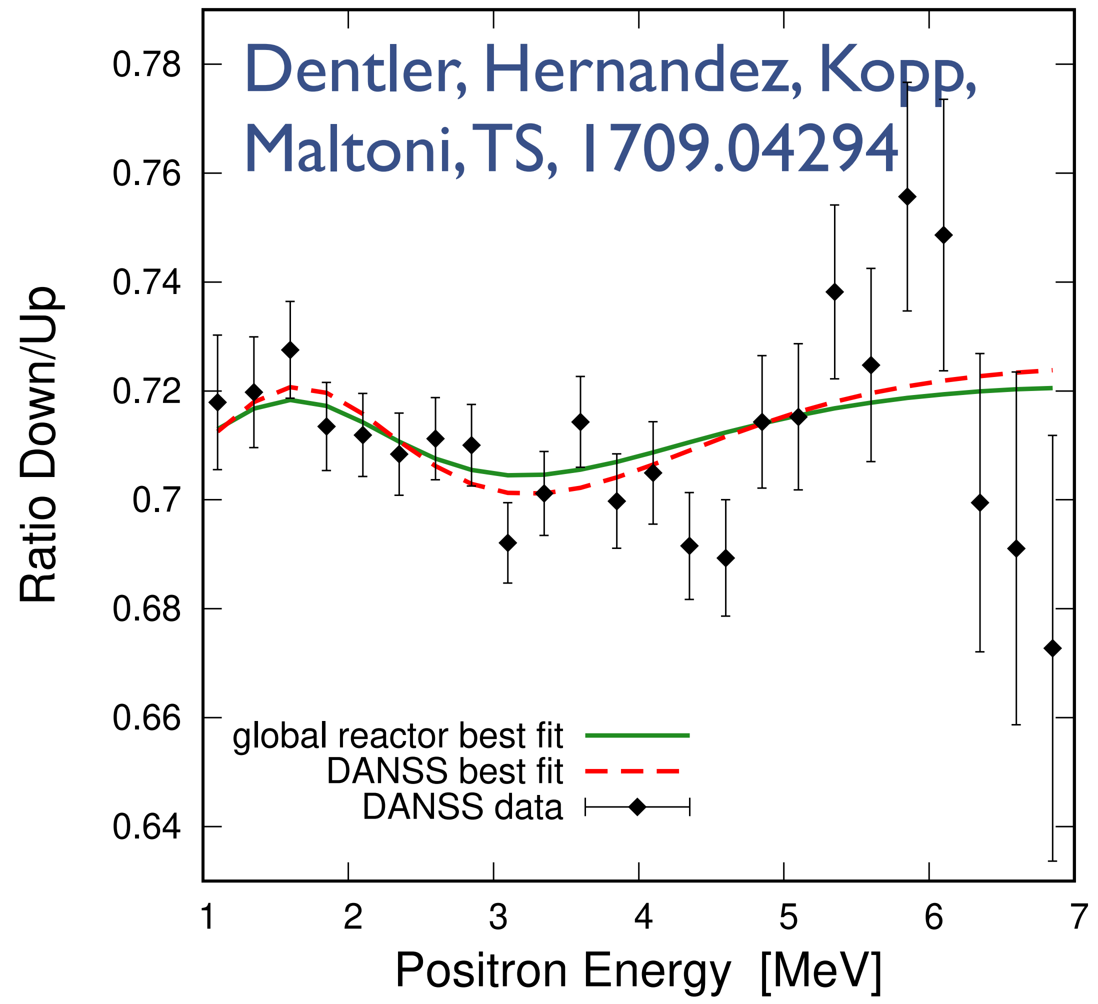




NEOS: spectrum at L = 24 m, relative to RENO (or DayaBay) near detectors: $\Delta\chi^2$(no osc) = 11.7

Reactor shape anomaly

relative spectral measurments:



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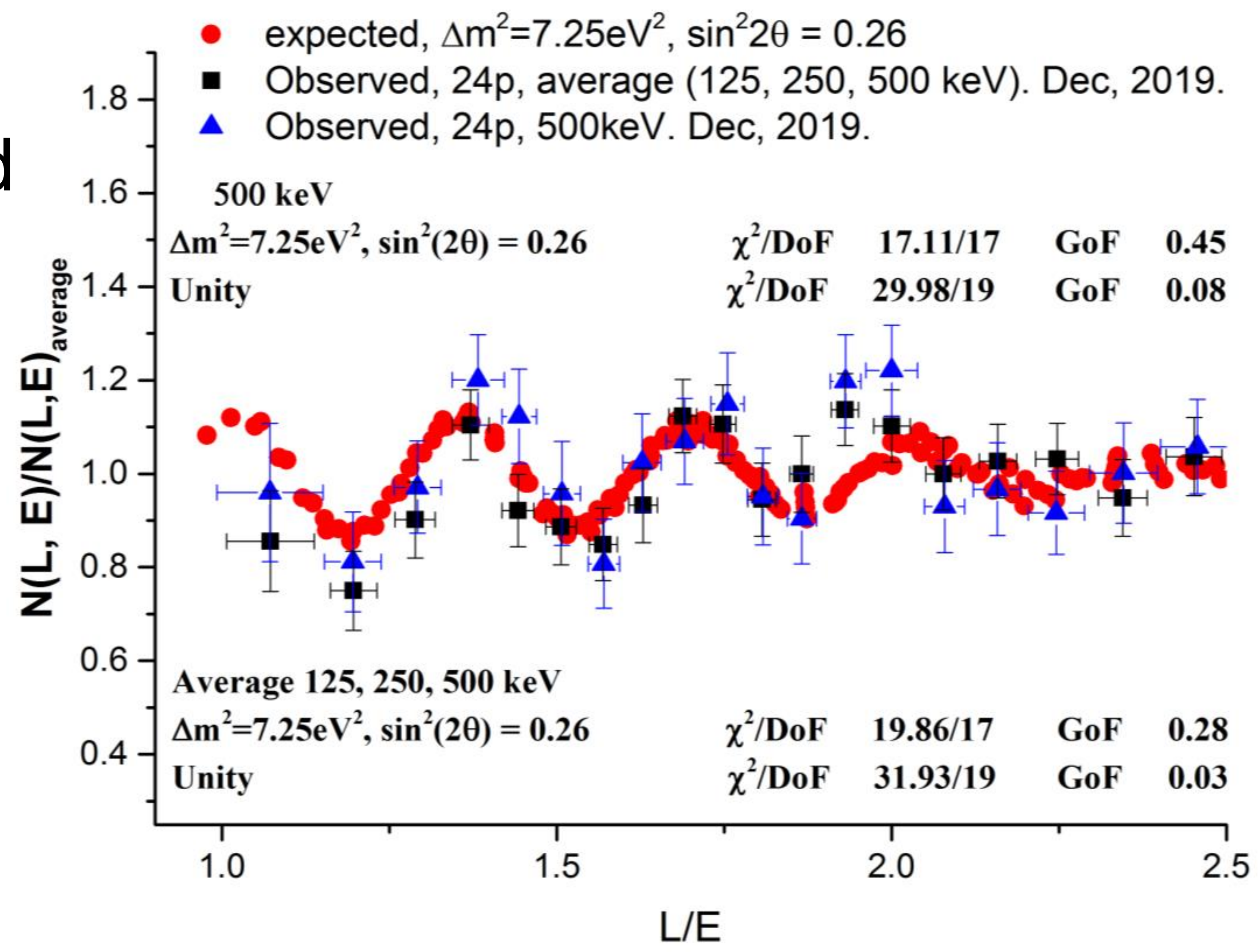

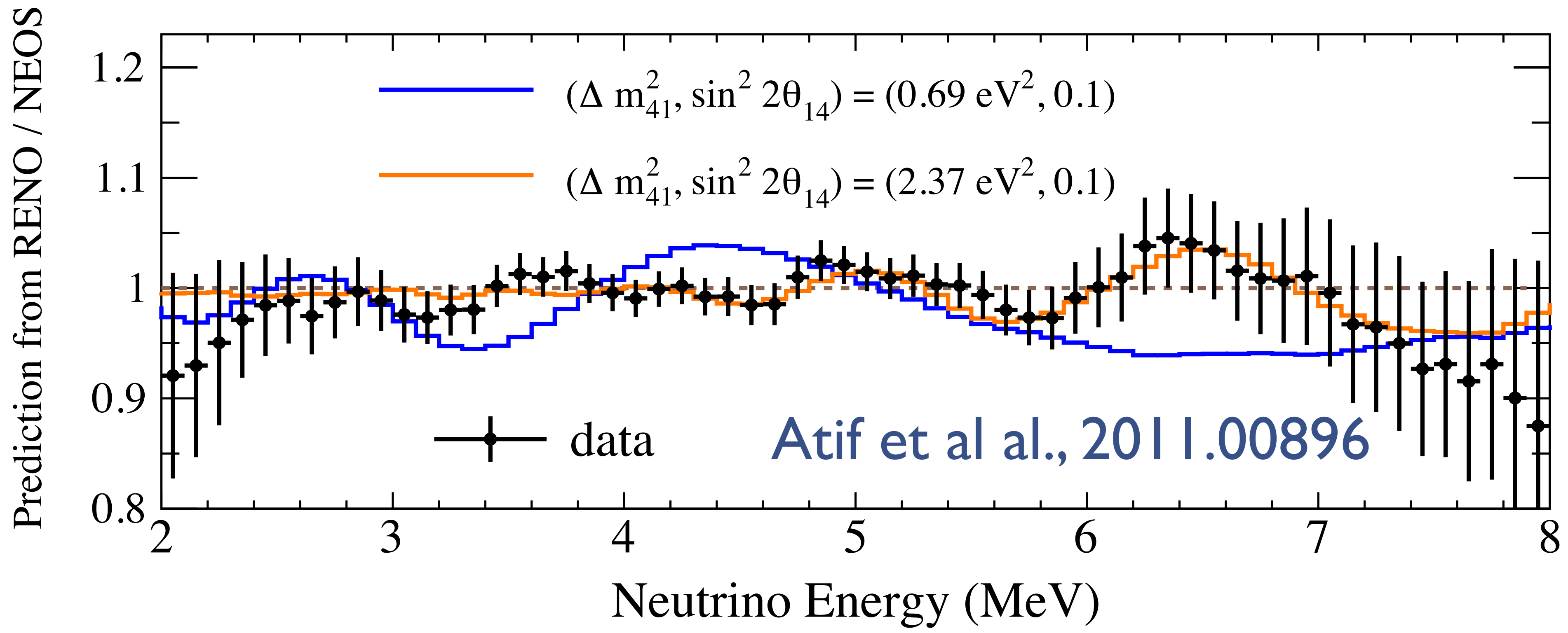

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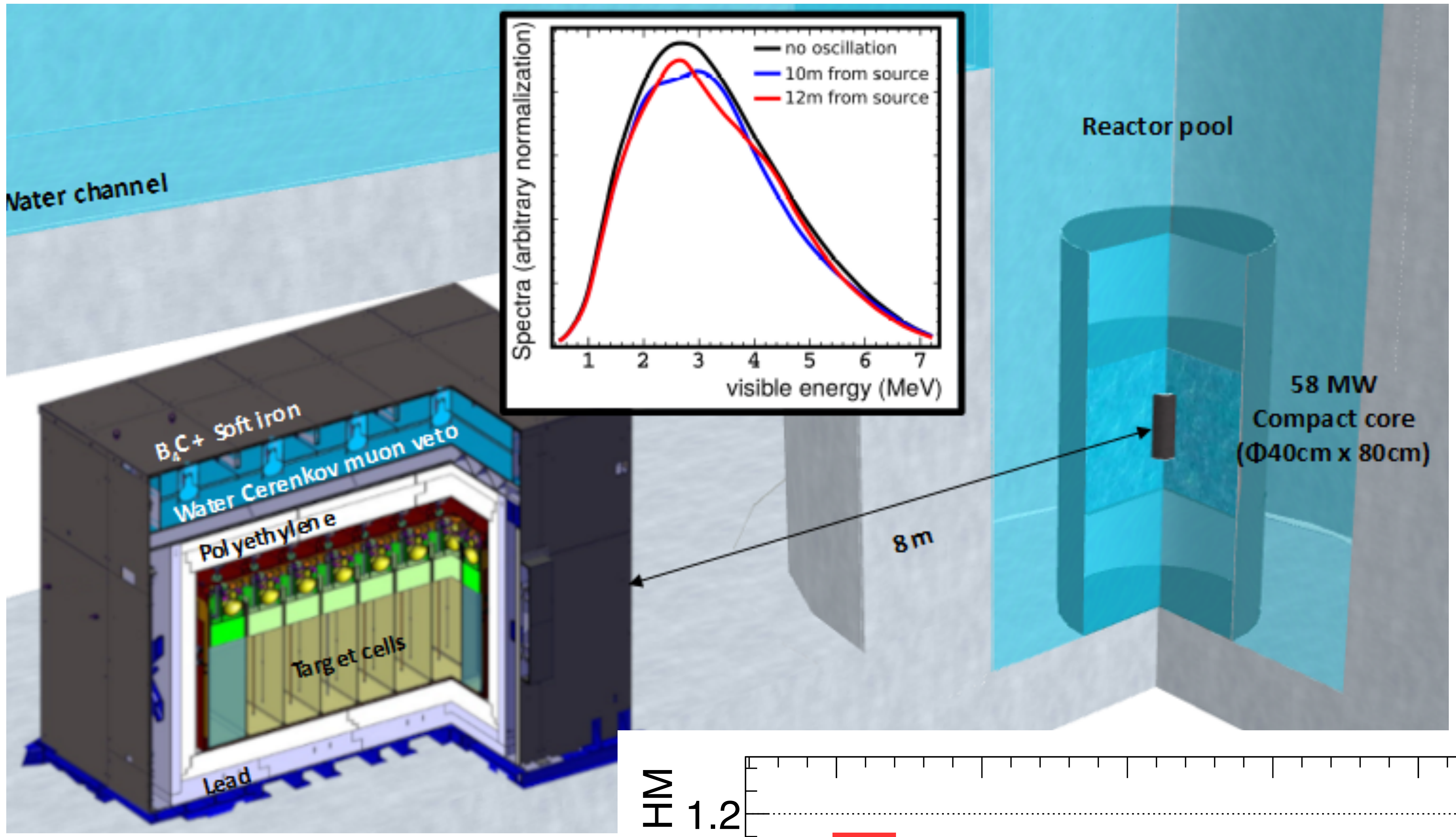
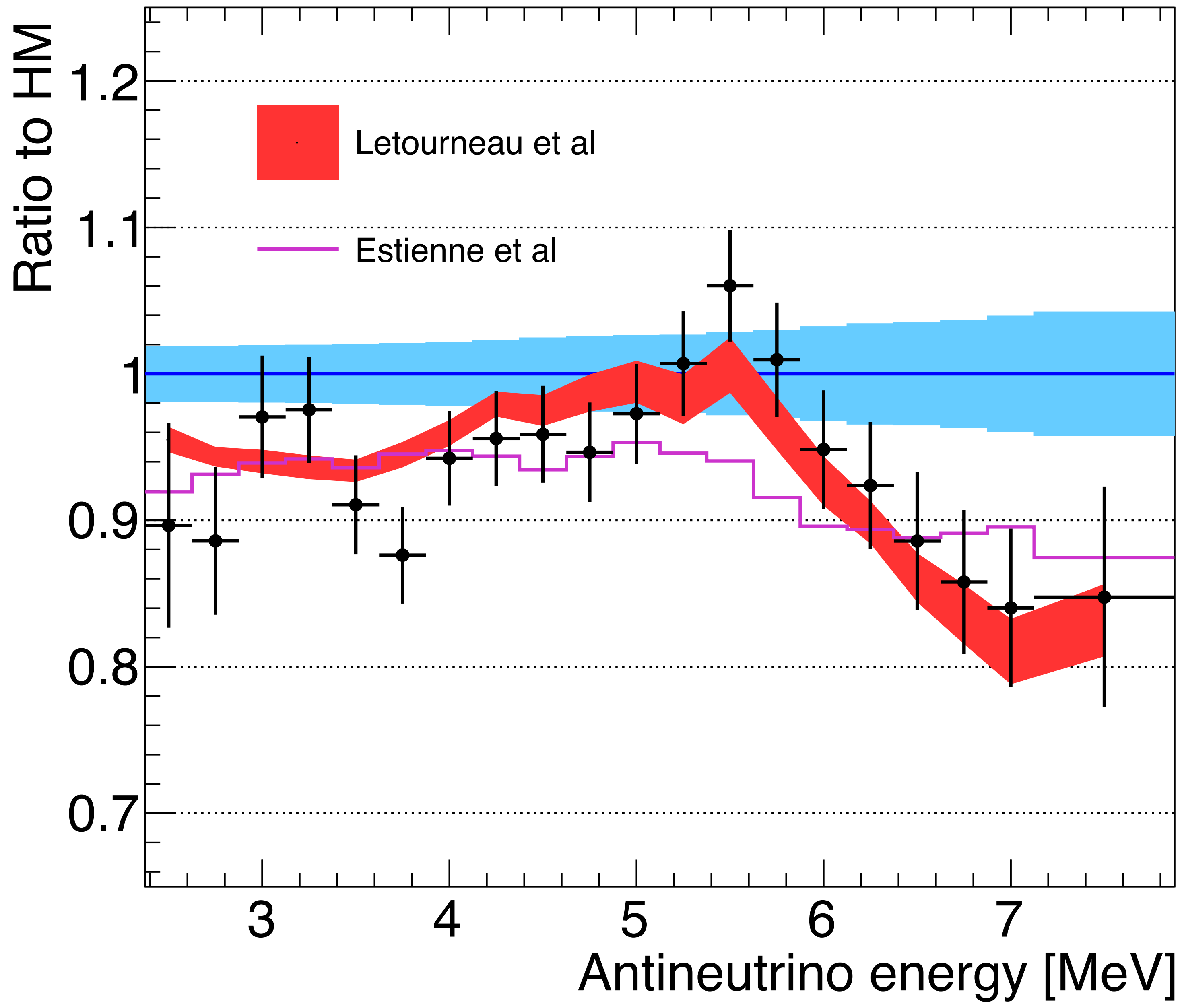
STEREO experiment

STEREO Coll. Nature 613 (2023) 257 [2210.07664]

- 6 detector cells
  9-11m from reactor core
- compare 6 energy spectra at different distances
- neutrino rate consistent with previous measurements
- no (clear) evidence for spectral distortion



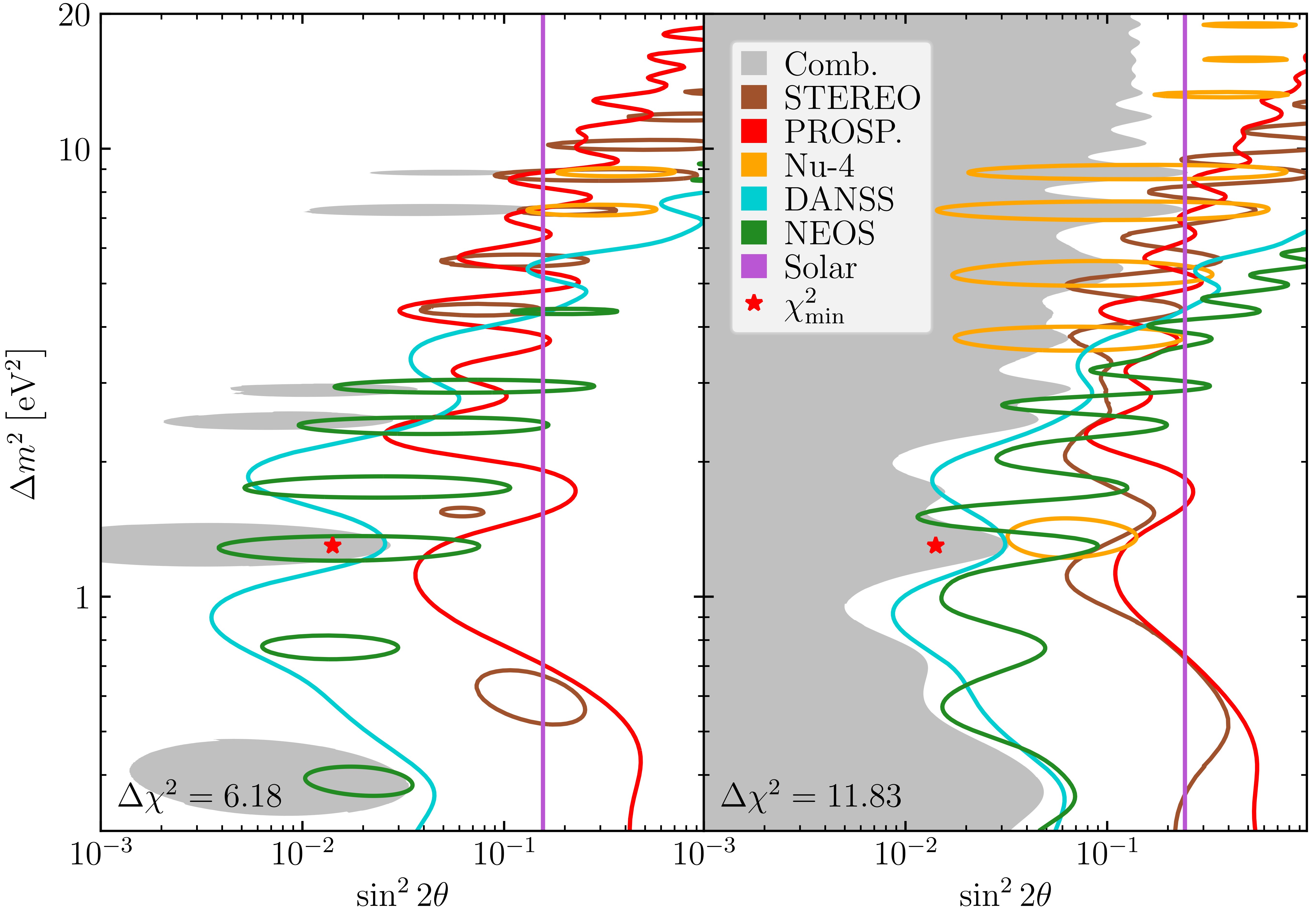


Do the hints add up?

- statistical interpretation not straight forward
  Coloma, Huber, Schwetz, 2008.06083
  see also, Feldman, Cousins, 98;
  Agostini, Neumair, 1906.11854;
  Giunti, 2004.07577;
  PROSPECT&STEREO 2006.13147

- constraint from solar neutrinos for large mixing
  Goldhagen, Maltoni, Reichard, TS, 2109.14898

Berryman, Coloma, Huber, TS, Zhou, 2111.12530



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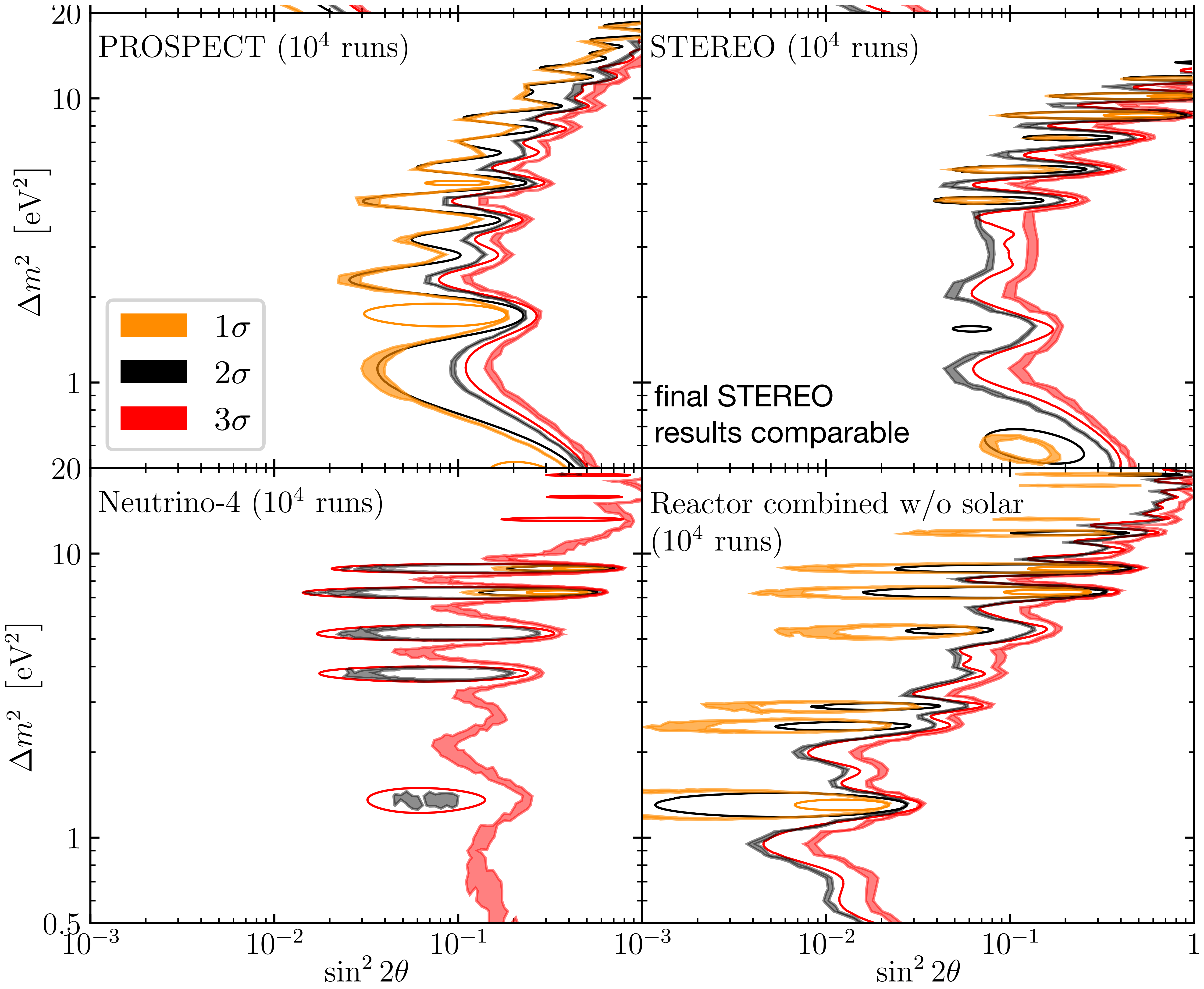

combined significance of sterile neutrino compared to 3ν hypothesis:

1.3σ (2.1σ Gauss)

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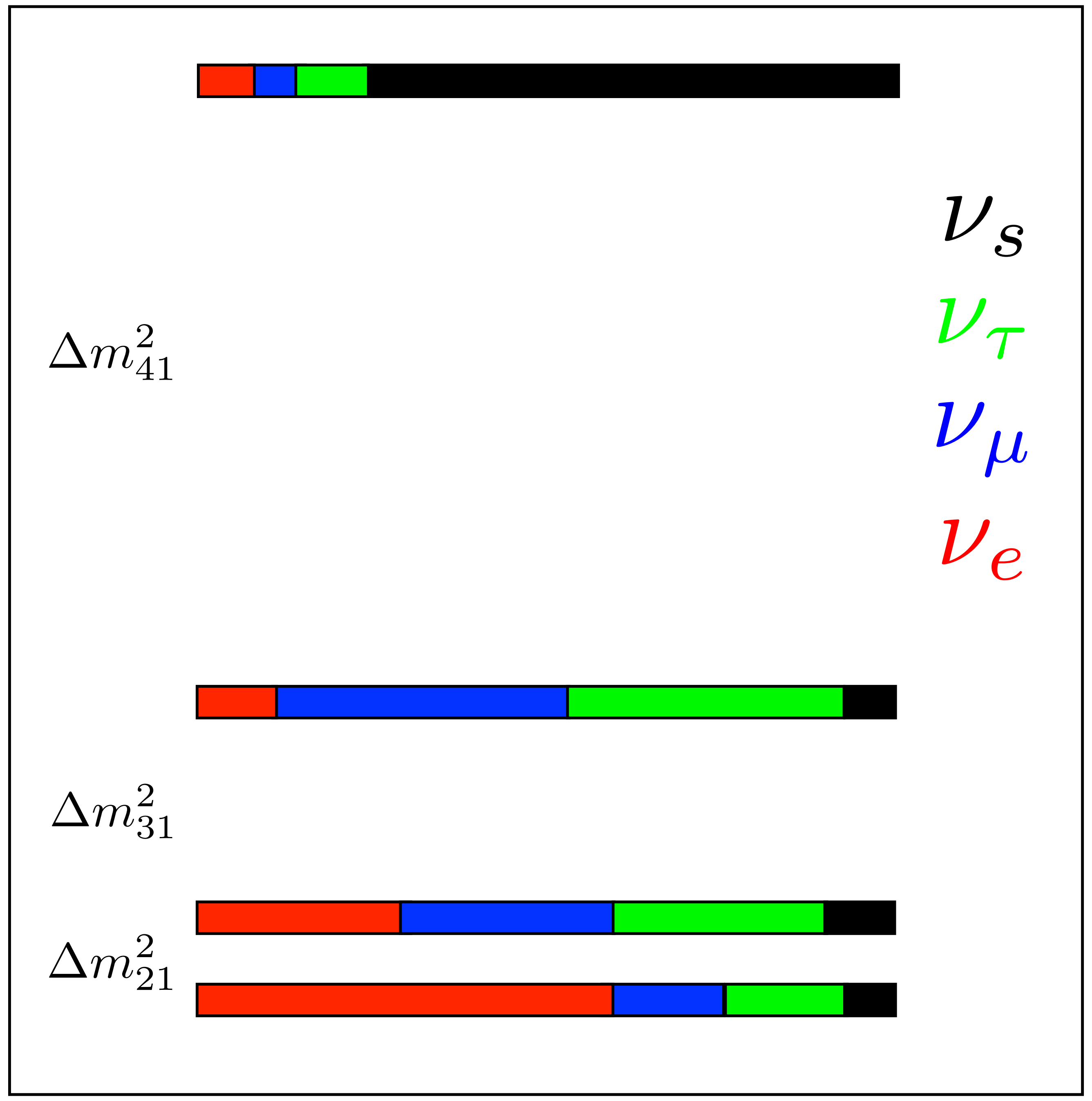

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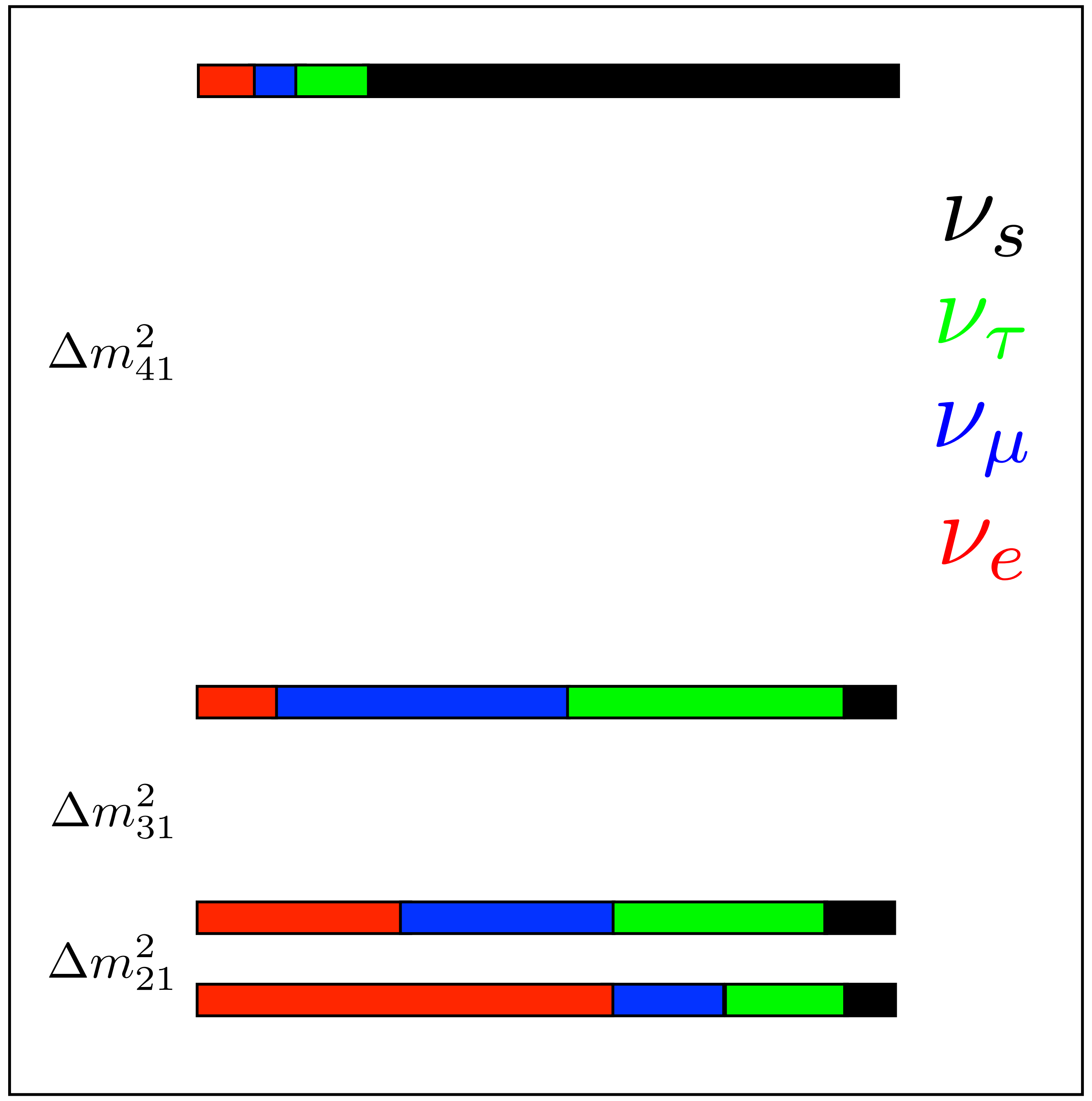


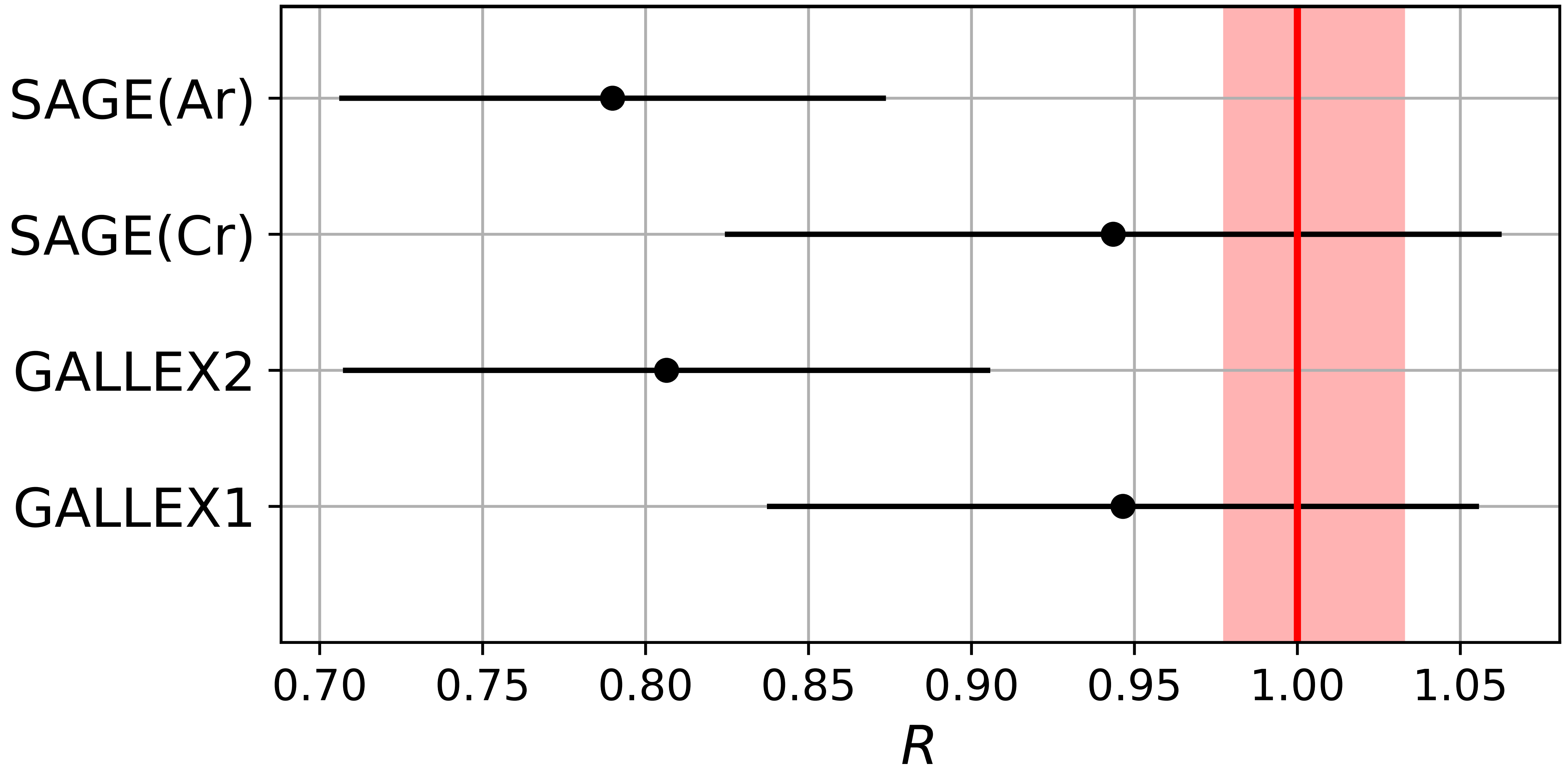
The gallium anomaly

- Measurements of gallium solar neutrino experiments GALLEX and SAGE with radioactive ^{51}Cr or ^{37}Ar sources lead to rates lower than expected ($\sim 2\sigma$)
  e.g. Giunti, Laveder, 2011

- possible explanation due to eV sterile neutrino oscillations?

electron capture decay: $^{51}\mathrm{Cr} \to \ ^{51}\mathrm{V} + \nu_e$

$$E_\nu = 750\,\mathrm{keV}\,(90\%)\,\&\,430\,\mathrm{keV}\,(10\%)$$

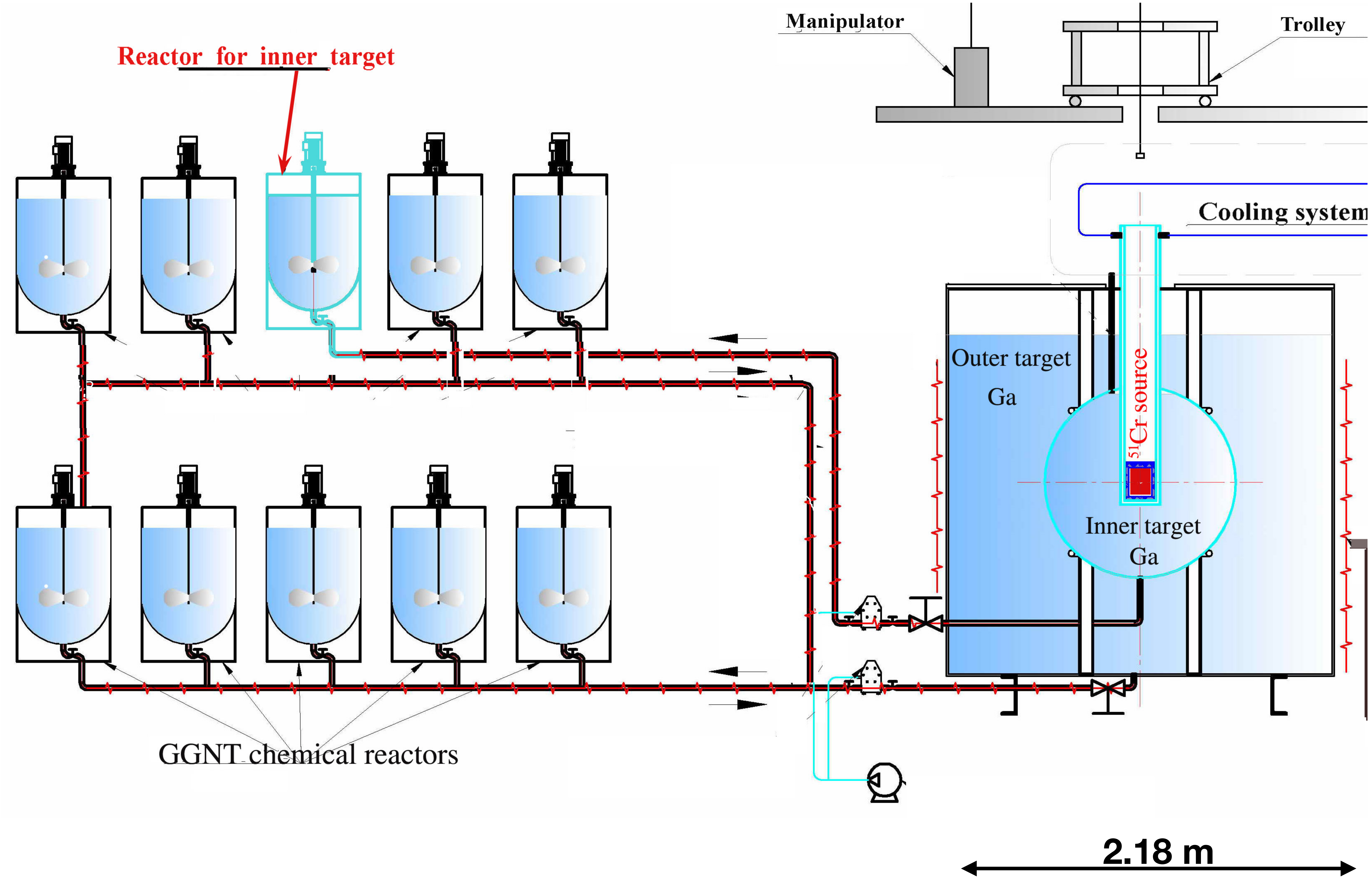


The BEST experiment

V. V. Barinov et al., Phys. Rev. Lett. 128 (2022), no. 23 232501; Phys. Rev. C 105 (2022), no. 6 065502

$$R_{in} = 0.79 \pm 0.05$$

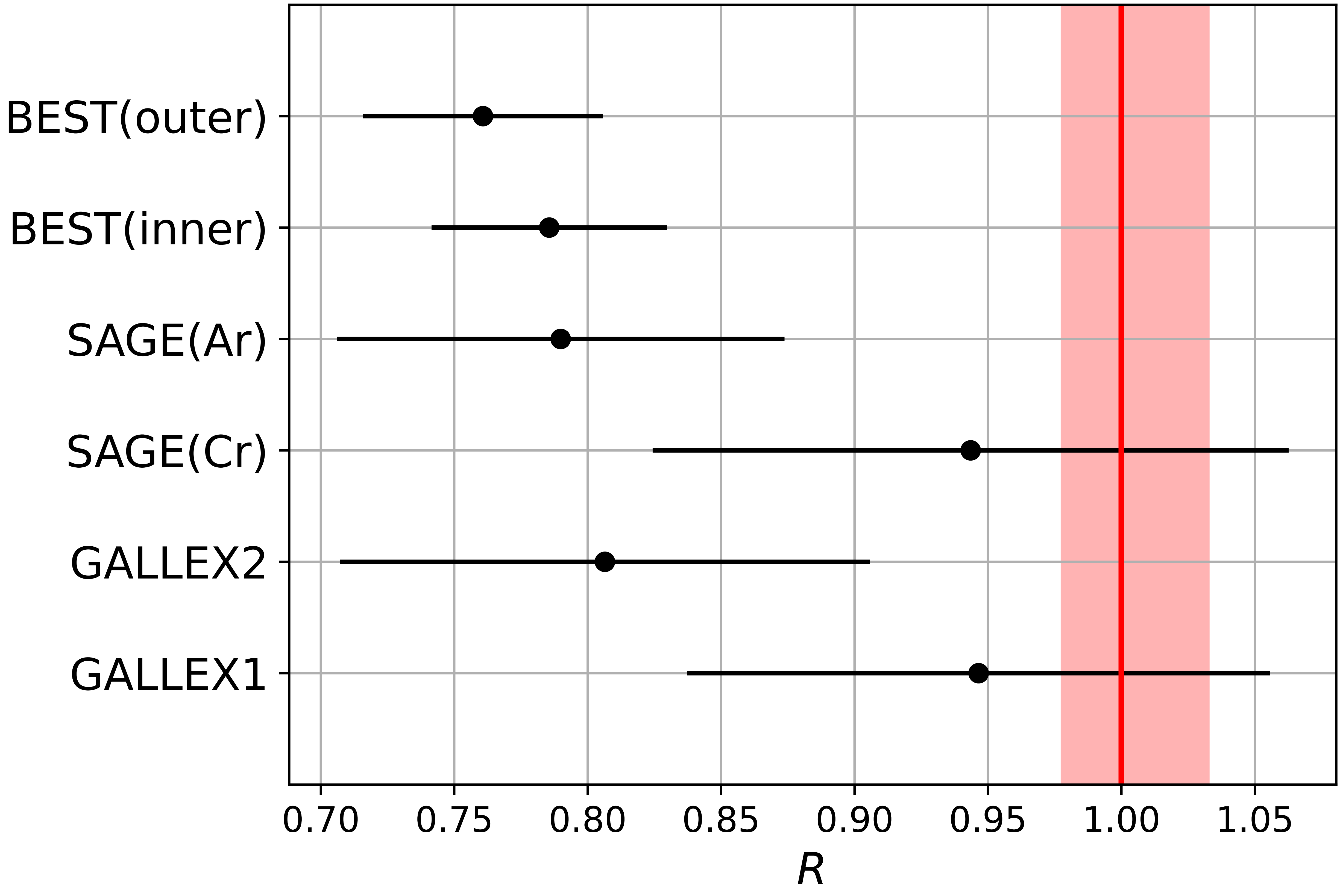
$$R_{out} = 0.77 \pm 0.05$$



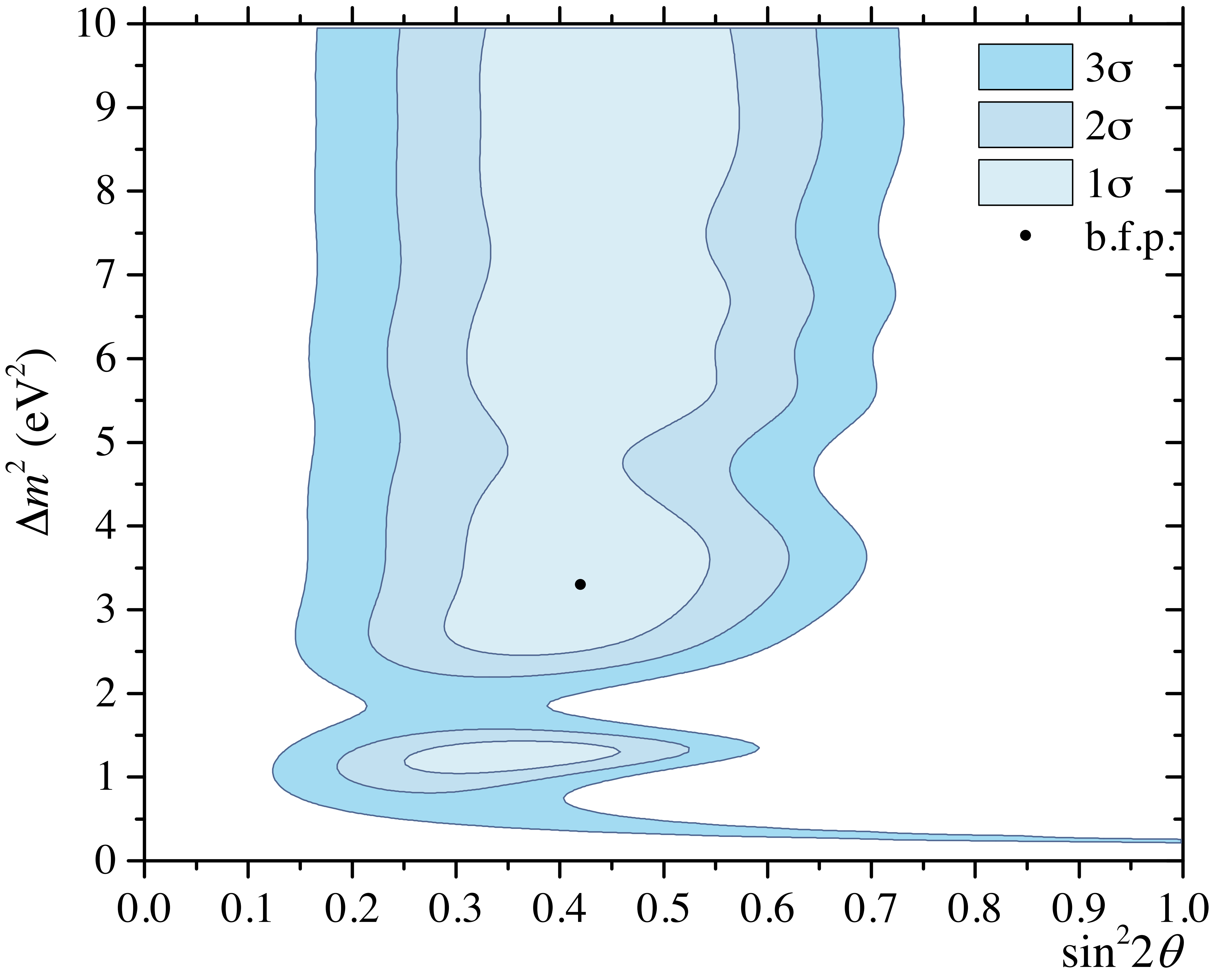
The gallium anomaly

	$\chi^2_{\rm null}/\rm dof$	p-value
CS1, BEST	$32.1/2$	1.1×10^{-7} (5.3σ)
CS1, all	$36.3/6$	2.4×10^{-6} (4.7σ)
CS2, BEST	$34.7/2$	2.9×10^{-8} (5.5σ)
CS2, all	$38.4/6$	9.4×10^{-7} (4.9σ)

Farzan, TS, 2306.09422
cross sections CS1, CS2 from
Haxton et al., 2303.13623



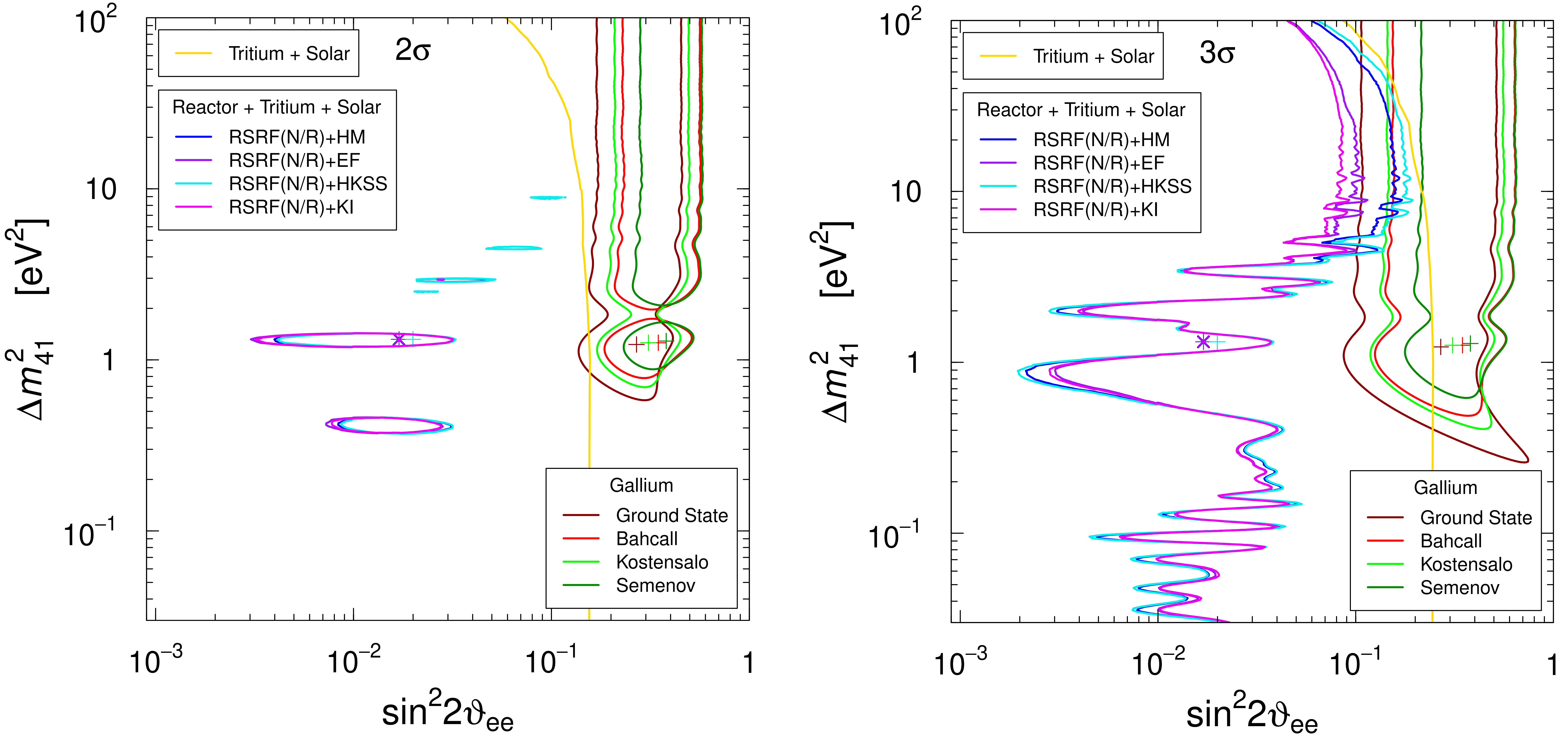
Can it be explained by eV sterile neutrino oscillations?



Barinov et al., PRL(2022)

Can it be explained by eV sterile neutrino oscillations?

- in tension with solar neutrinos, reactor experiments and cosmology!



Giunti, Li, Ternes, Tyagi, Xin, 2209.00916

see also
Berryman, Coloma, Huber, TS, Zhou, 2111.12530;
Goldhagen, Maltoni, Reichard, TS, 2109.14898;

severe tension of $4-5\sigma$

How to explain?

Brdar, Gehrlein, Kopp, 2303.05528

scenario	comments	our rating
Explanations within the Standard Model		
increased ^{71}Ge half-life (Section 2.1 and Ref. [38])	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 [37], 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 $\to$ ^{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 $\to$ ^{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?	★★★★☆

see also Elliott, Gavrin, Haxton [2306.03299]

How to explain?

- New physics explanations?
- 20% ν_e disappearance at the scale of 2m
- difficult to reconcile with vast body of neutrino data
  many ideas do not work
- Ex.: sterile neutrino coupled to a background field, such that an MSW-like resonance happens at $E_\nu \approx 750\,\mathrm{keV}$ Brdar, Gehrlein, Kopp, 2303.05528
- Exotic decoherence effects (three neutrino) Farzan, TS, 2306.09422

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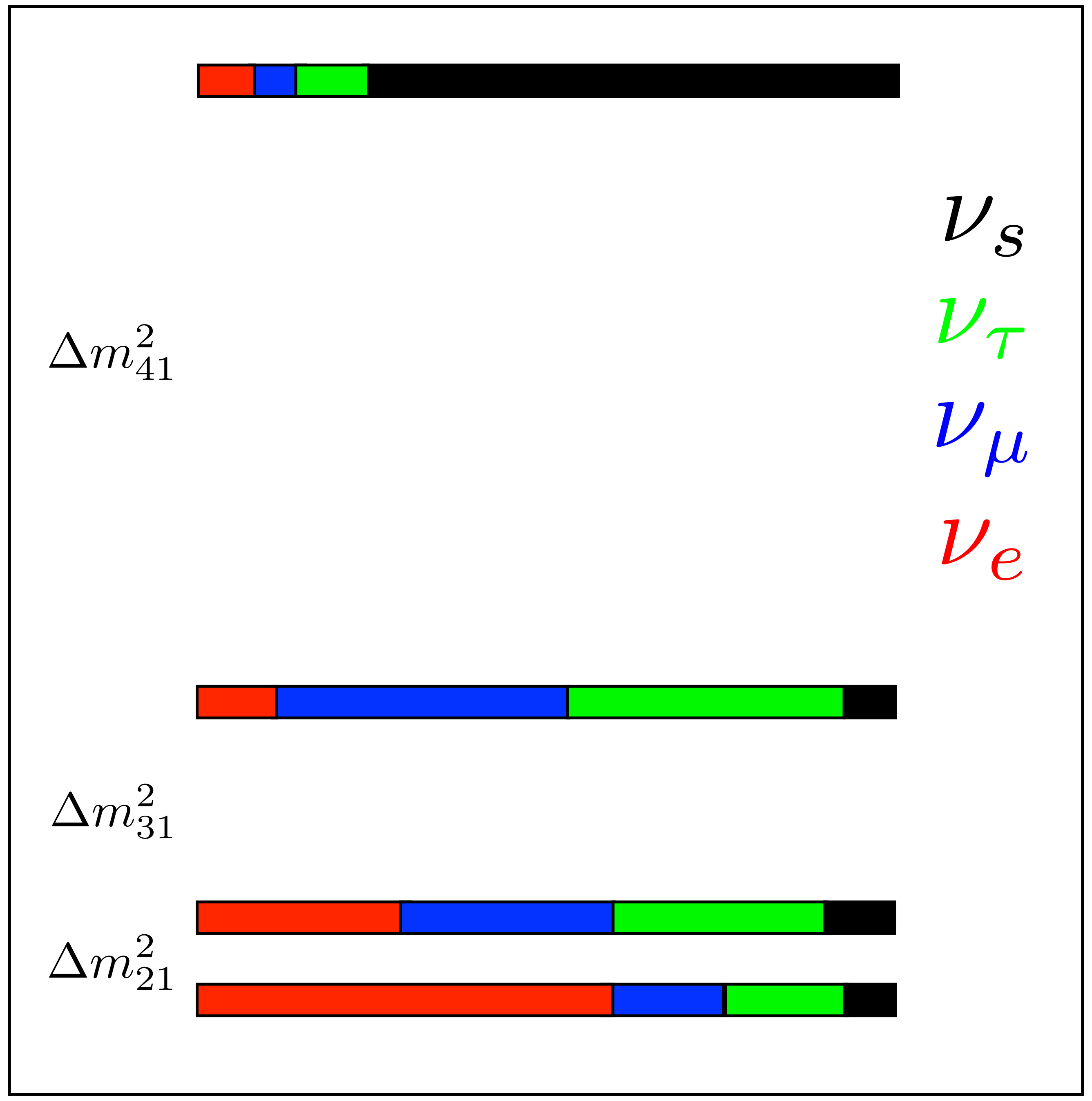

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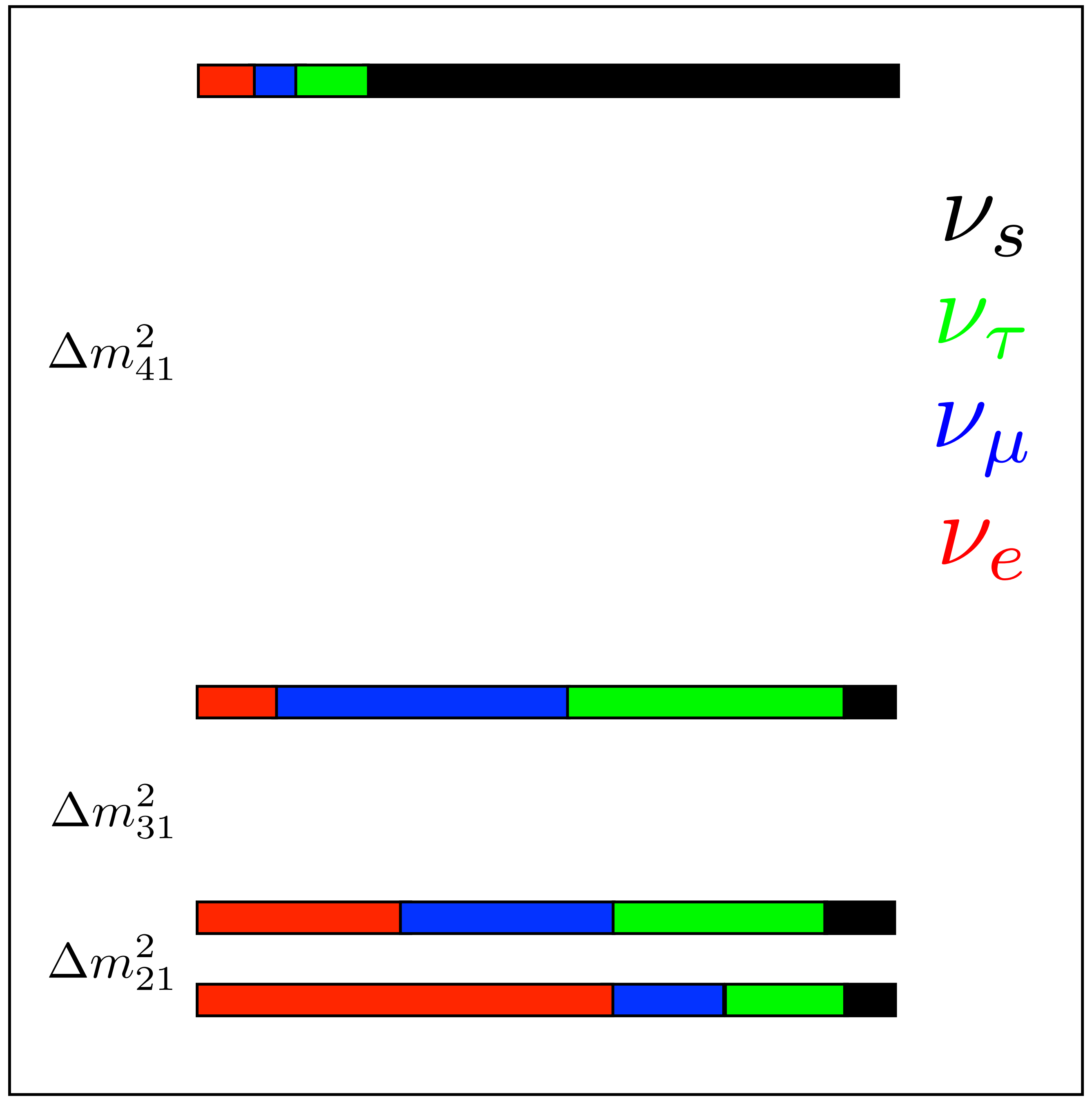
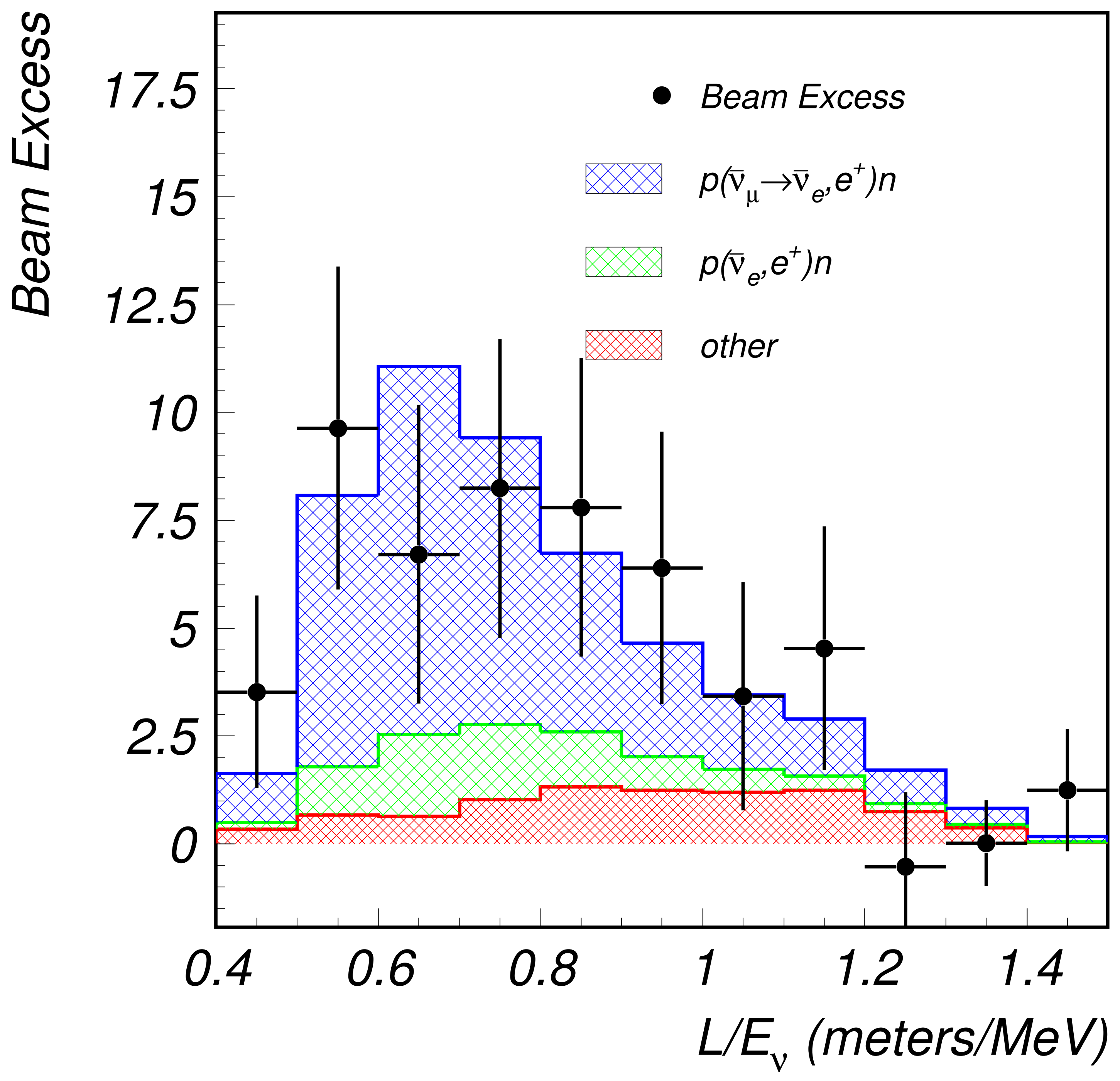
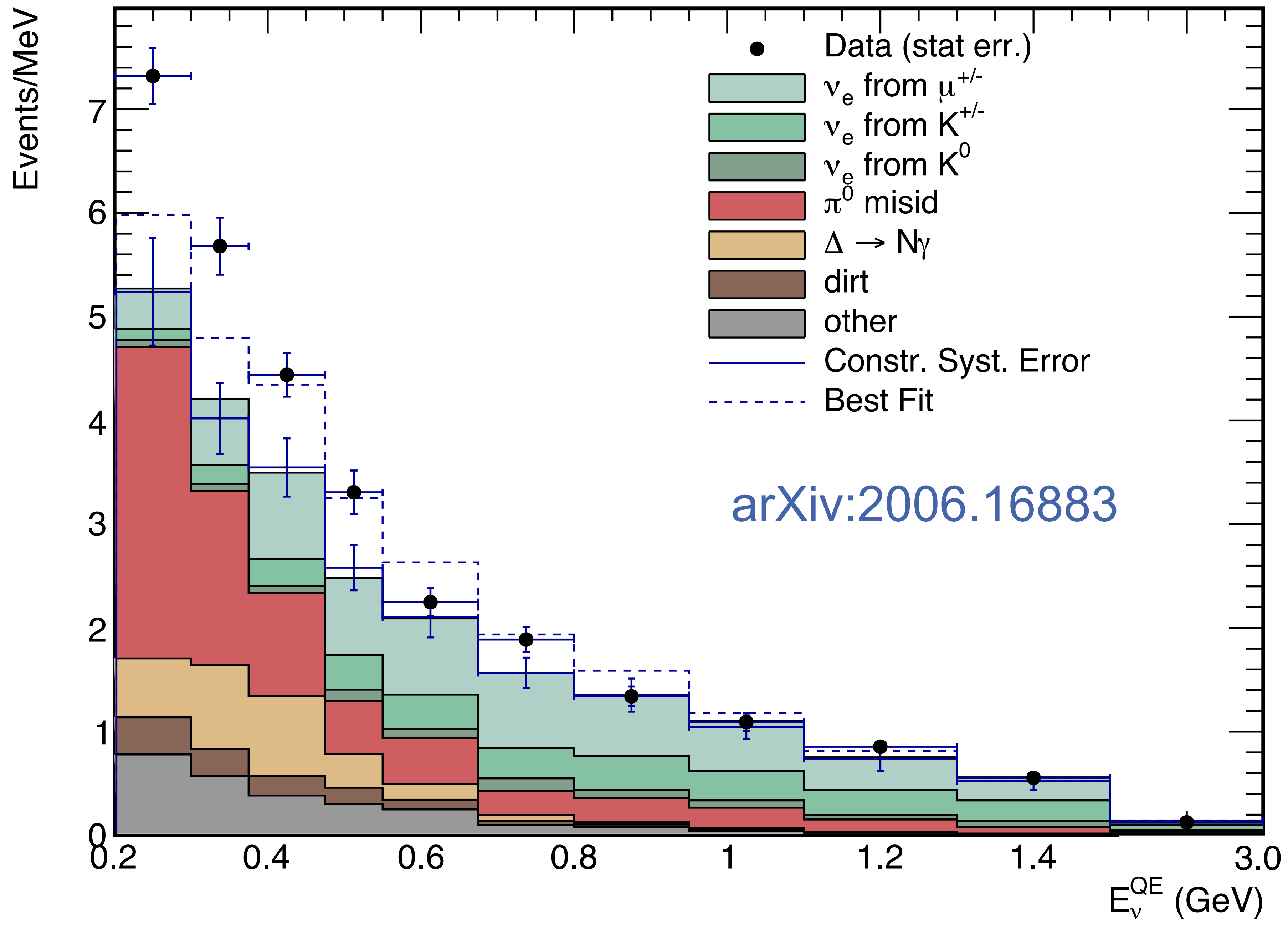


Hints for $\nu_\mu \to \nu_e$ appearance

LSND, 2001



MiniBooNE 2020



- signal for $\bar{\nu}_\mu \to \bar{\nu}_e$ transitions (3.8σ)

combined neutrino+antineutrino excess: 638.0±132.8 events (4.8σ)

Correlation between appearance and disappearance probabilities

appearance

$$P_{\mu e} = \sin^2 2\theta_{\mu e} \sin^2 \frac{\Delta m^2_{41} L}{4E} \qquad \sin^2 2\theta_{\mu e} = 4|U_{e4}|^2 |U_{\mu 4}|^2$$

disappearance $(\alpha = e, \mu)$

$$P_{\alpha\alpha} = 1 - \sin^2 2\theta_{\alpha\alpha} \sin^2 \frac{\Delta m^2_{41} L}{4E} \qquad \sin^2 2\theta_{\alpha\alpha} = 4|U_{\alpha 4}|^2 (1 - |U_{\alpha 4}|^2)$$

$$\boxed{\sin^2 2\theta_{\mu e} \approx \frac{1}{4} \sin^2 2\theta_{ee} \sin^2 2\theta_{\mu\mu}}$$

$\nu_\mu \to \nu_e$ app. signal requires also signal in both, ν_e and ν_μ disappearance (appearance mixing angle quadratically suppressed)

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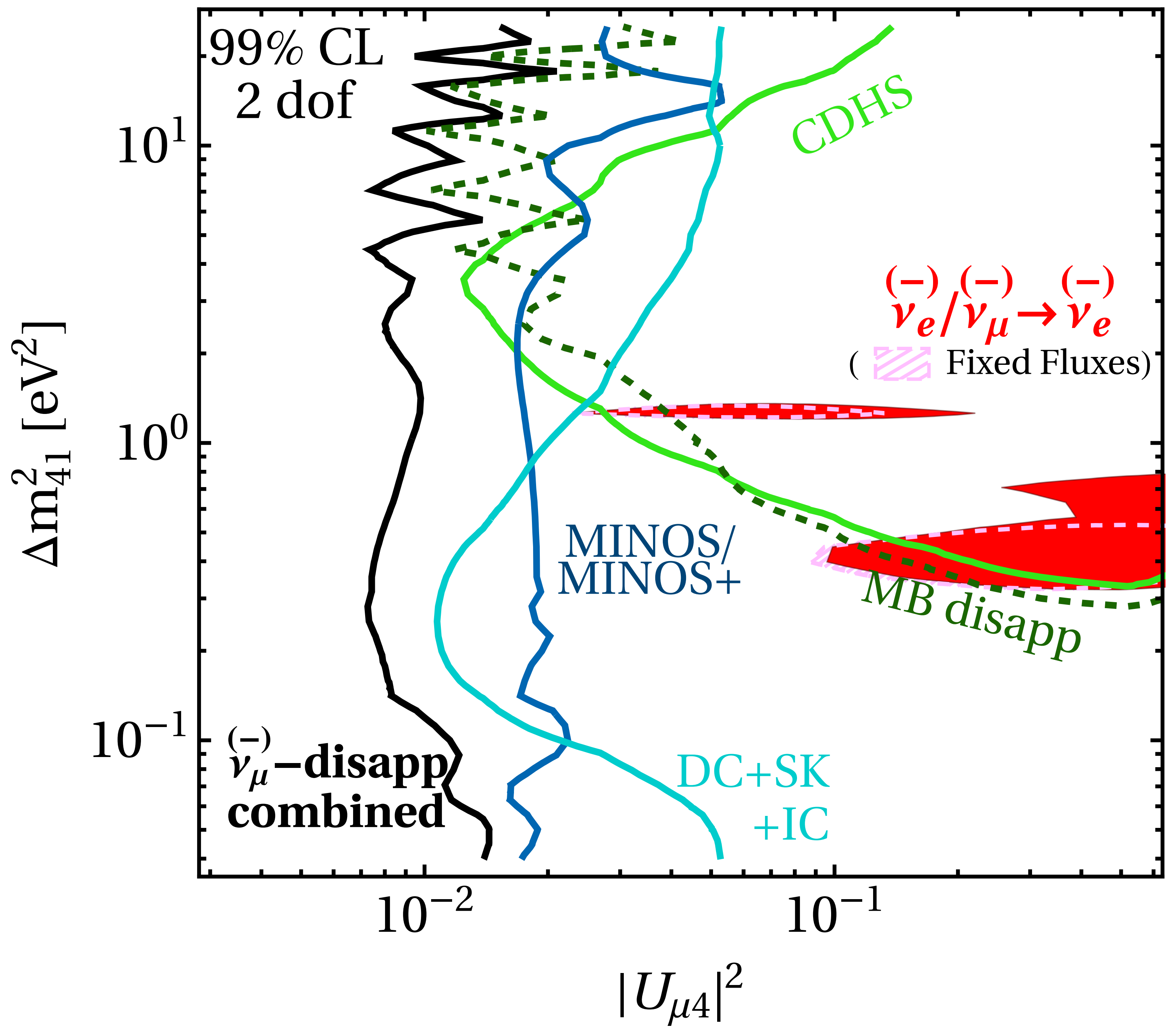
Strong tension btw appearance and disappearance

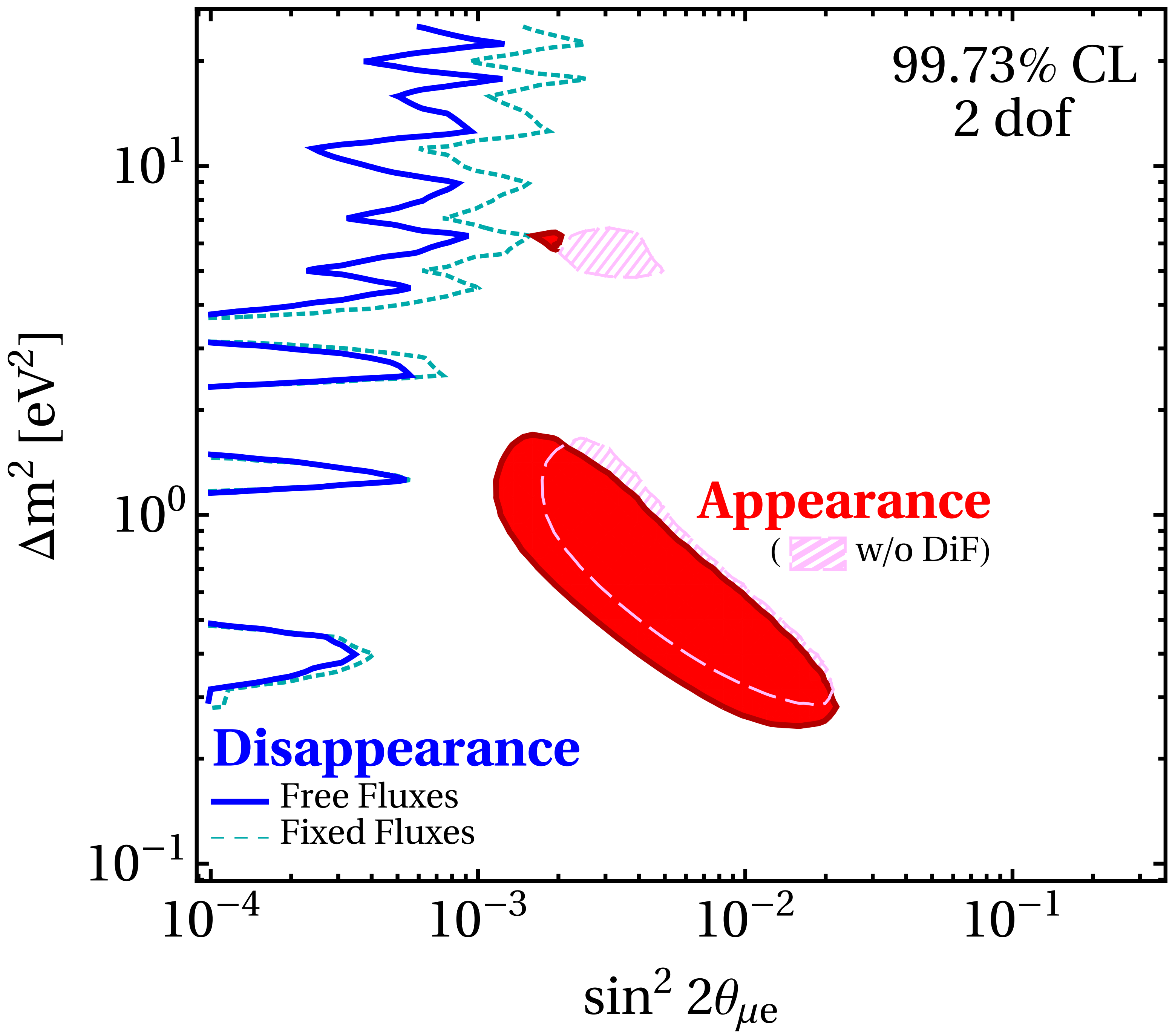
$$\sin^2 2\theta_{\mu e} \approx \frac{1}{4} \sin^2 2\theta_{ee} \sin^2 2\theta_{\mu\mu}$$

sterile oscillation explanation of LSND/MiniB robustly disfavoured



non-observation of oscillations in ν_μ disappearance (CDHS, MiniB, MINOS+, SK, IceCube)

Dentler et al, 1803.10661



consistency of appearance and disapp. data with a p-value $< 10^{-6}$

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
- energy dependent quantum decoherence Farzan, TS, Smirnov 07; Bakhti, Farzan, TS, 15, Farzan TS, 23
- 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
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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; Abdullahi, Hostert, Pascoli, 2007.11813;…

- 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)

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

eV sterile neutrinos are severely constrained by cosmology

Two effects of neutrinos in cosmology:

- sum of neutrino masses

$$\sum m_\nu < 0.12\,\mathrm{eV}$$

- effective number of neutrino species

$$N_{\mathrm{eff}} = 2.99 \pm 0.17$$

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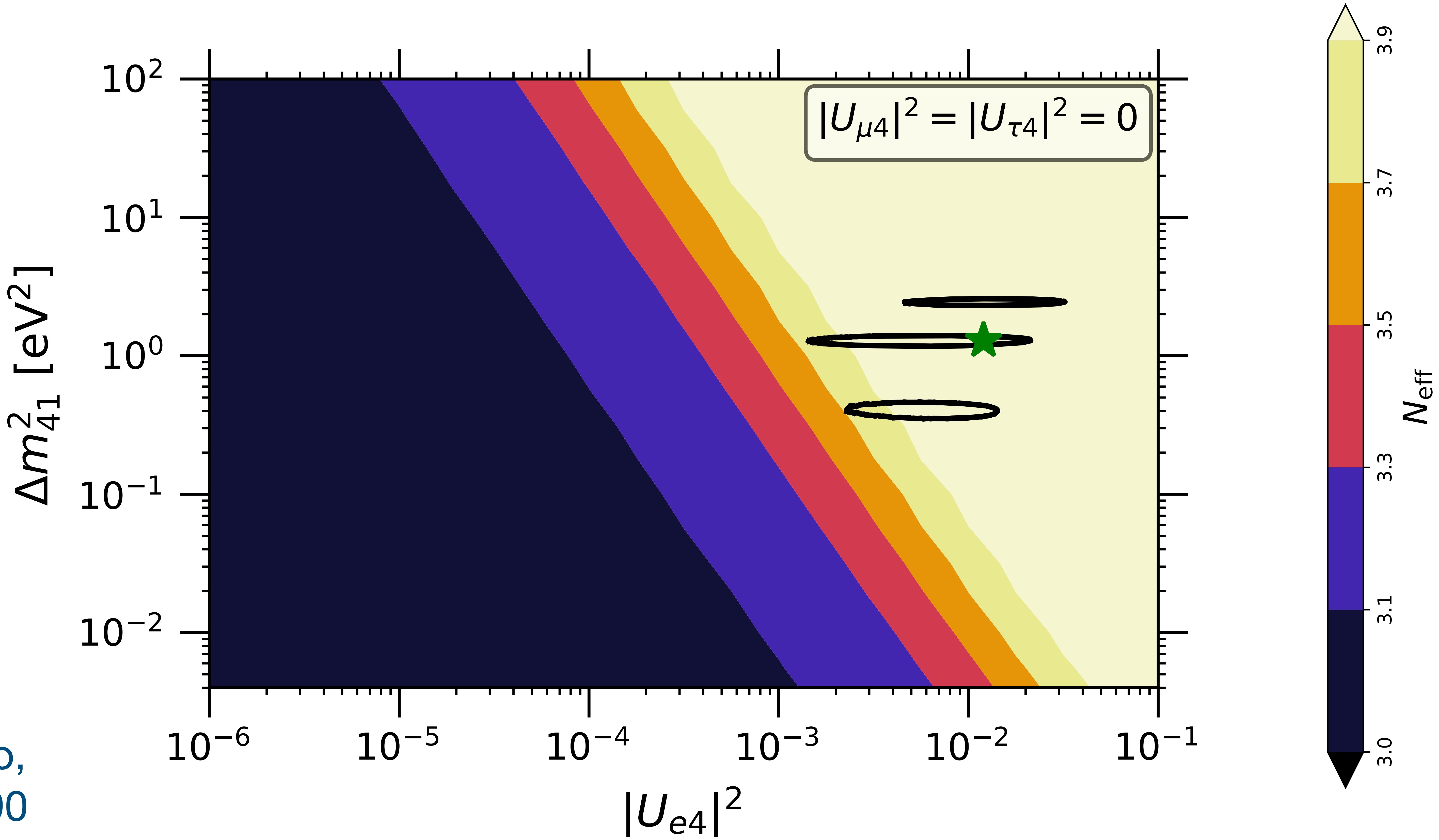
consider a partially thermalized eV-scale neutrino state:

- $N_{\mathrm{eff}} = 3 + \Delta N_{\mathrm{eff}}$

- $\sum m_\nu \approx \sum_{i=1}^{3} m_i + \Delta N_{\mathrm{eff}} m_4$

eV sterile neutrinos are severely constrained by cosmology

for sizeable mixing they are equilibrated and contribute to $N_{\rm eff}$ and $\sum_i m_i$



de Salas, Gariazzo, Pastor, 1905.11290

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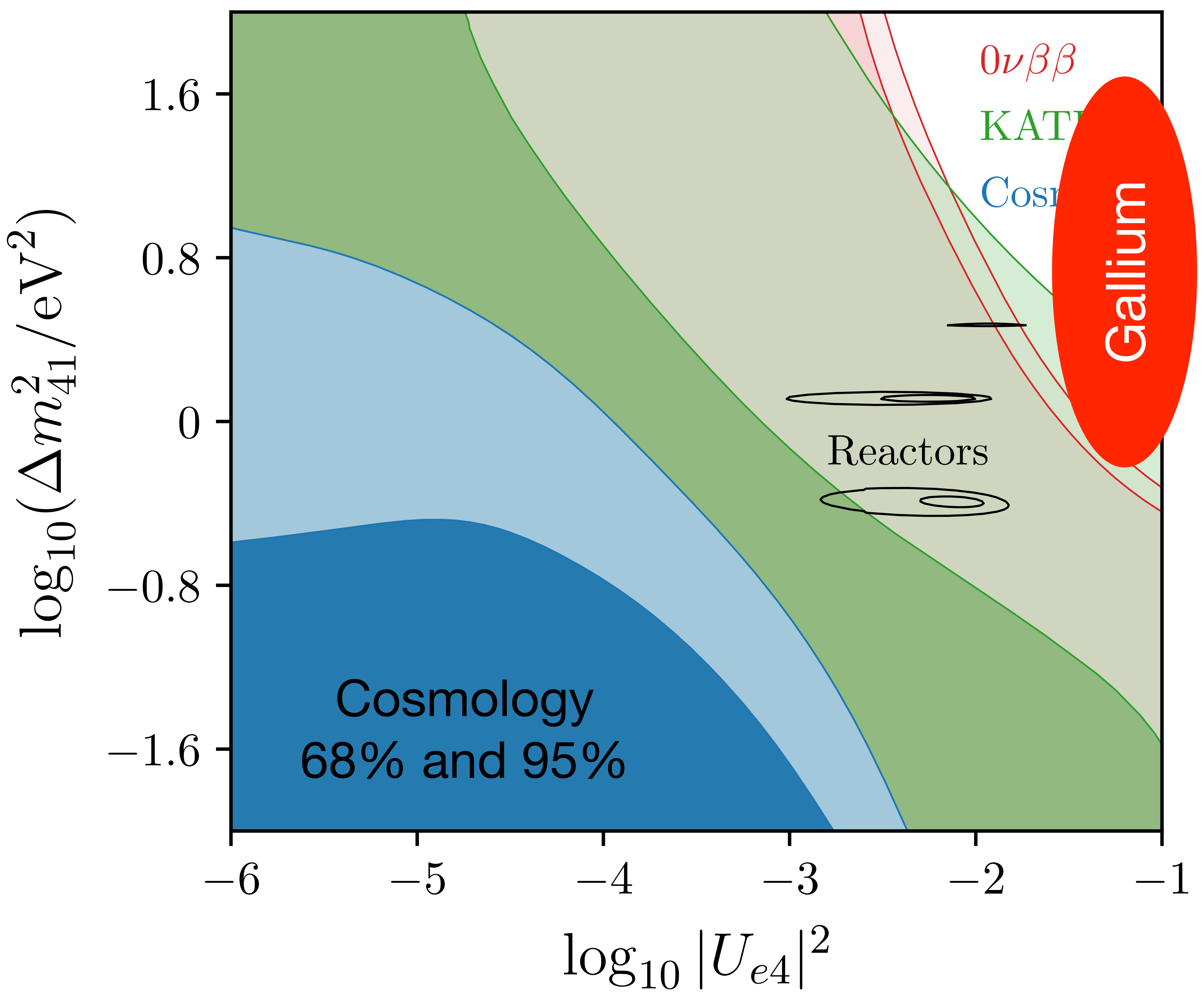

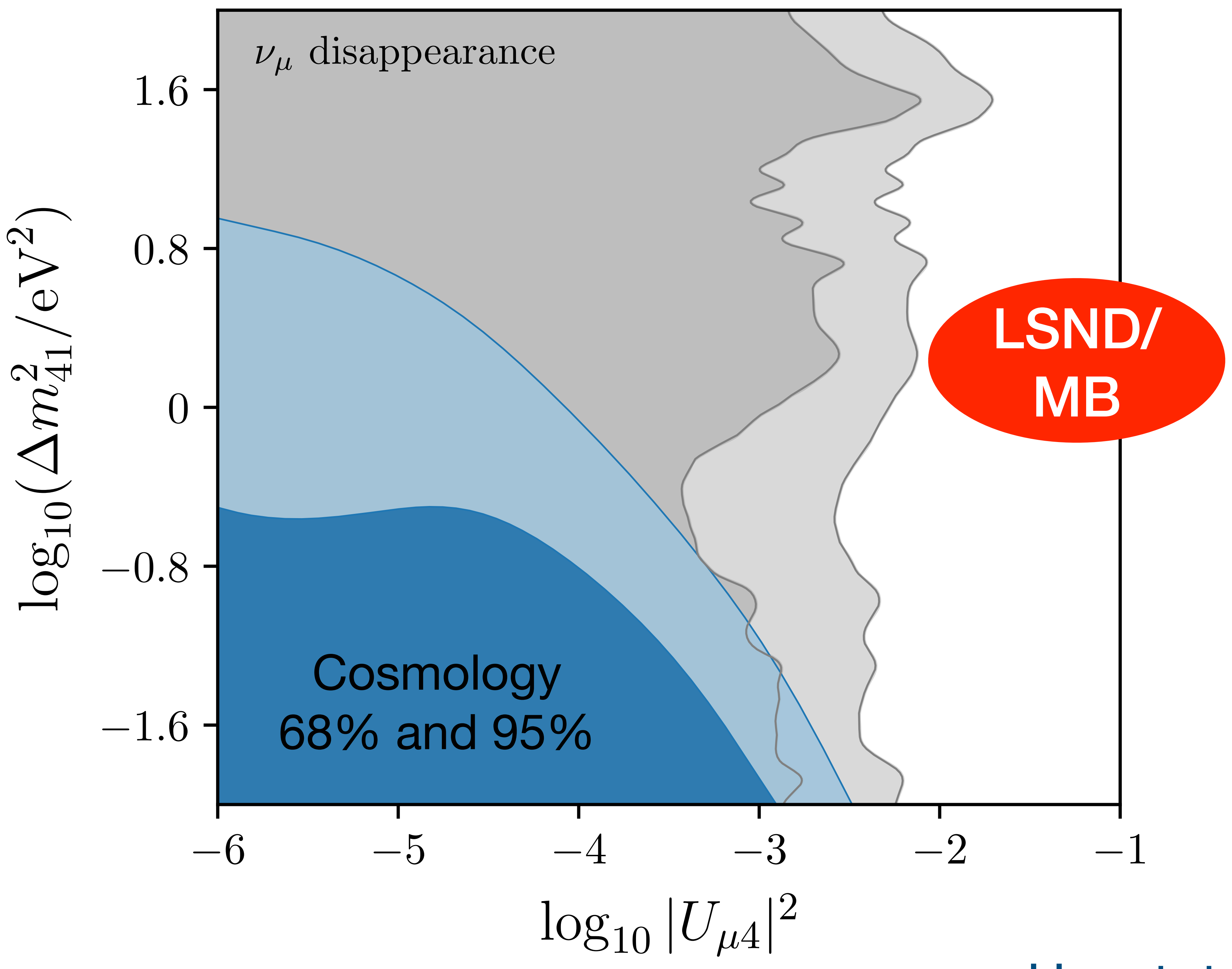

Hagstotz et al., 2003.02289

Summary

Anomaly	Status	Explanation?
Reactor rate and shape	fading away ($< 2\sigma$) systematics dominated	nuclear physics
Gallium / BEST	very significant ($\sim 5\sigma$)	sterile oscillations in strong tension w reactor, solar, cosmology difficult to explain exotic decoherence (?)
LSND	significant (3.8σ) ~25 yr anomaly	sterile oscillations in strong tension w disappearance data, cosmology difficult to explain HNL decay / exotic decoherence (?)
MiniBooNE	very significant (4.8σ) relies on background estimate	

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Thank you for your attention

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