Sterile neutrino review (theory)

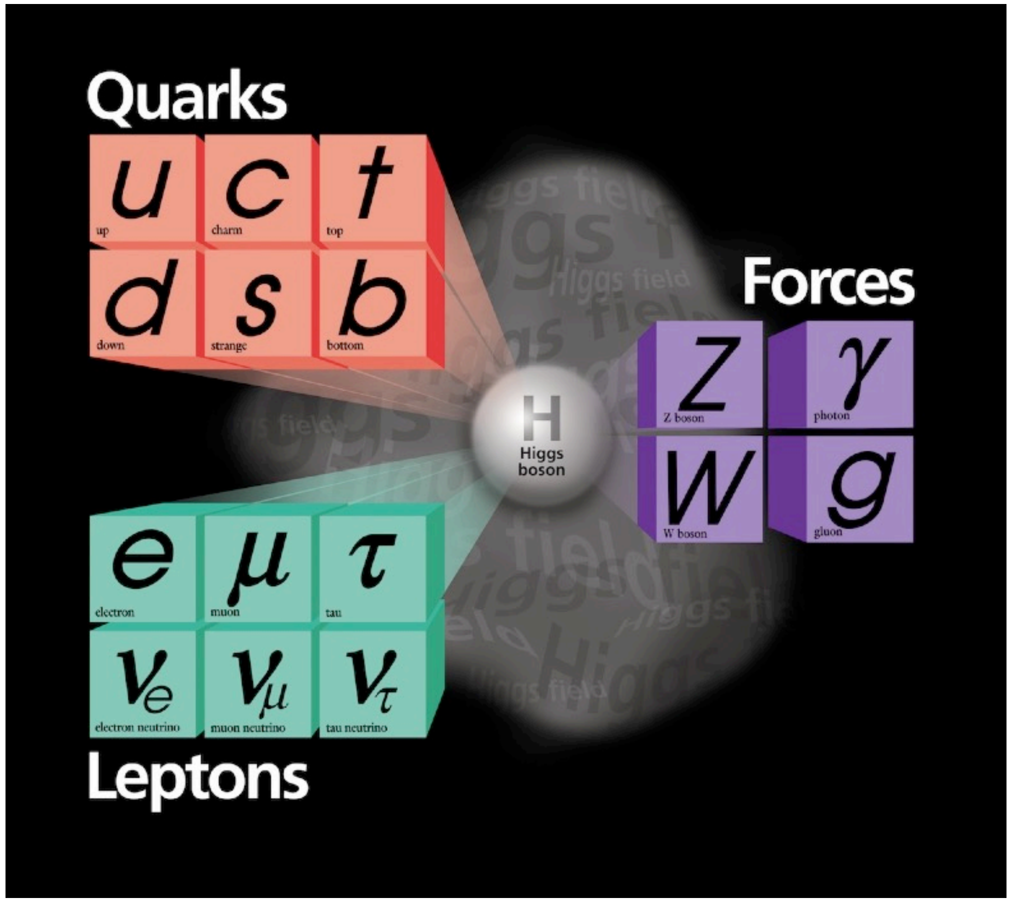
Thomas Schwetz

GDR neutrino — 23 Nov 2020

In memory of

Samoil Bilenky 1923 — 2020

The Standard Model



fermions of one generation:

quarks: $Q_L = \begin{pmatrix} u_L \\ d_L \end{pmatrix}, \; u_R, \; d_R$

leptons: $L_L = \begin{pmatrix} \nu_L \\ e_L \end{pmatrix}, \; e_R$

right-handed neutrinos missing

complete singlets under SM gauge group
→ „sterile neutrinos“

In the Standard Model neutrinos are massless

- absence of right-handed neutrinos
  no Dirac mass for neutrinos

- lepton-number is an accidental symmetry at the renormalizable level
  given SM fields and gauge symmetry, lepton number cannot be violated at dim. 4 $\rightarrow$ no Majorana mass can be generated

a simple way (but not the only one!) to extend the SM in order to give mass to neutrinos is the addition of right-handed neutrinos

Adding right-handed neutrinos to the SM

a very simple extension:

Yukawa term:

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

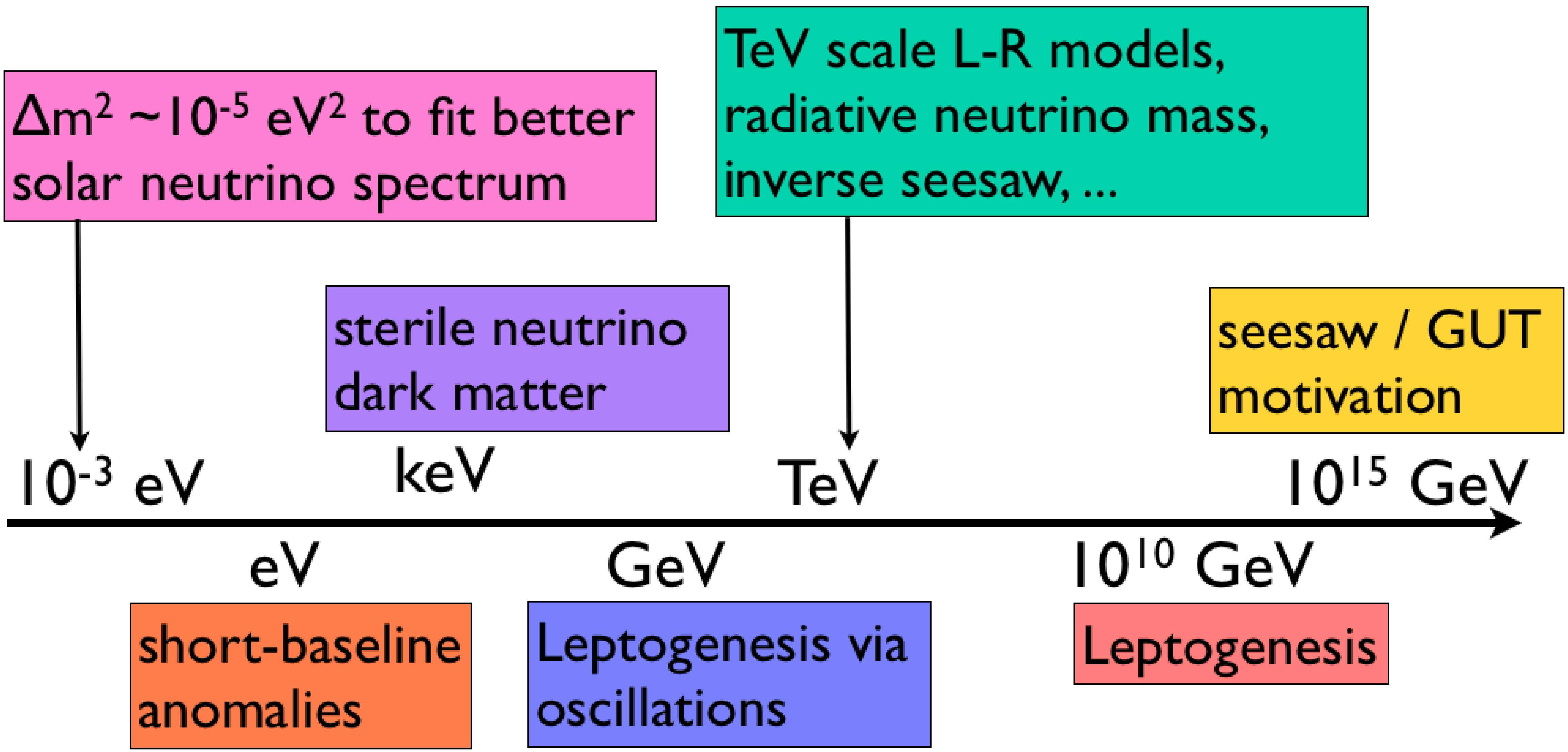
bare Majorana mass term:

lepton number is no longer an accidental symmetry!

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

- can have any number of them
  (no requirement from anomaly cancellation for true singlets)
- we have no (very little) guidance about their mass (y and M_R)
  M_R is not related to the Higgs VEV (unlike for charged fermions)
  $\Rightarrow$ new scale in the theory

Sterile neutrinos at which mass scale?

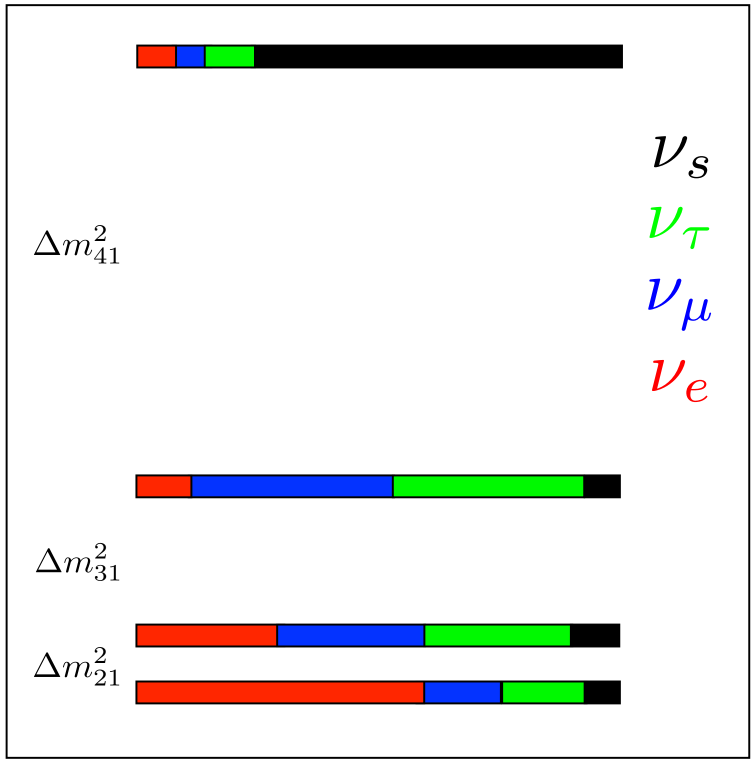


Sterile neutrinos at which mass scale?

- neutrino mass generation does not point to any particular scale
- phenomenological approach: study sterile neutrino phenomenology independent of neutrino mass mechanism
- consider sterile neutrino mass and mixing parameter as independent free parameters

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)



Tension with cosmology

- eV scale sterile neutrinos with mixings relevant for the SBL anomalies are thermalised in the early Universe
  [deSalas, Gariazzo, Pastor, 19; Hannestad Tamborra, Tram 12; diBari, 01;
  Bilenky, Giunti, Grimus, Schwetz, 98; Okada, Yasuda, 96;
  Shi, Schramm, Fields, 93; Enqvist, Kainulainen, Thomson, 92]

→ predict $N_{eff} \approx 4$

↕

$$N_{\rm eff} = 2.9 \pm 0.5 \ , \quad (95\%{\rm CL,\ Helium + Deuterium + BBN})$$

$$N_{\rm eff} = 2.92 \pm 0.37 \ , \quad (95\%{\rm CL,\ CMB{+}\Lambda CDM})$$

Böser et al., 1906.01739

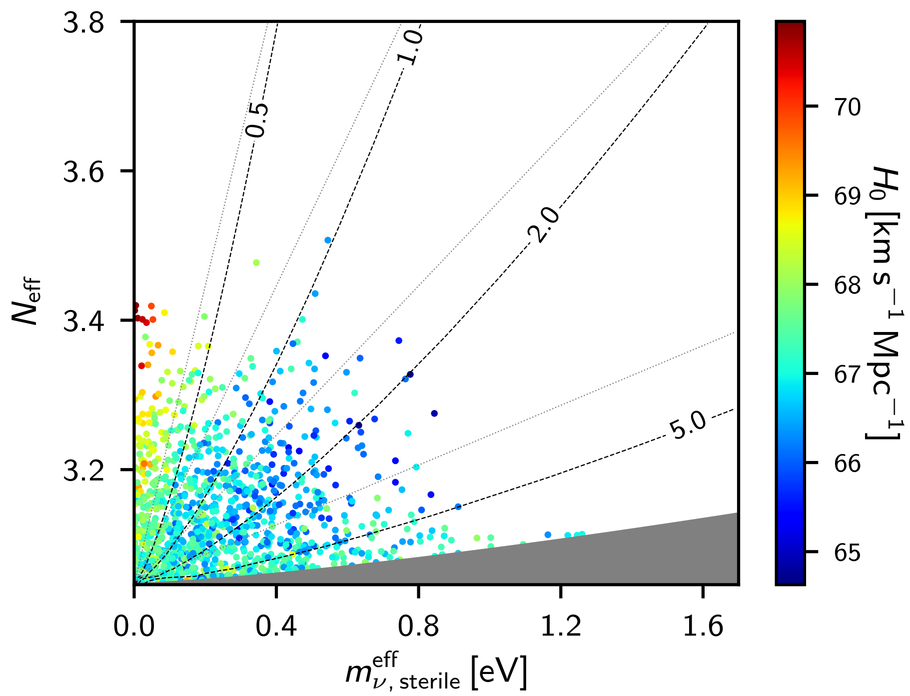
Tension with cosmology

- bound on the sum of neutrino masses:
  for $N_{eff} \approx 4$ we have $\sum m_\nu \gtrsim \sqrt{\Delta m^2_{41}}$

$$\sum m_\nu < 0.24\,\text{eV (CMB)}$$
$$\sum m_\nu < 0.12\,\text{eV (CMB+BAO)}$$

limits at 95% CL

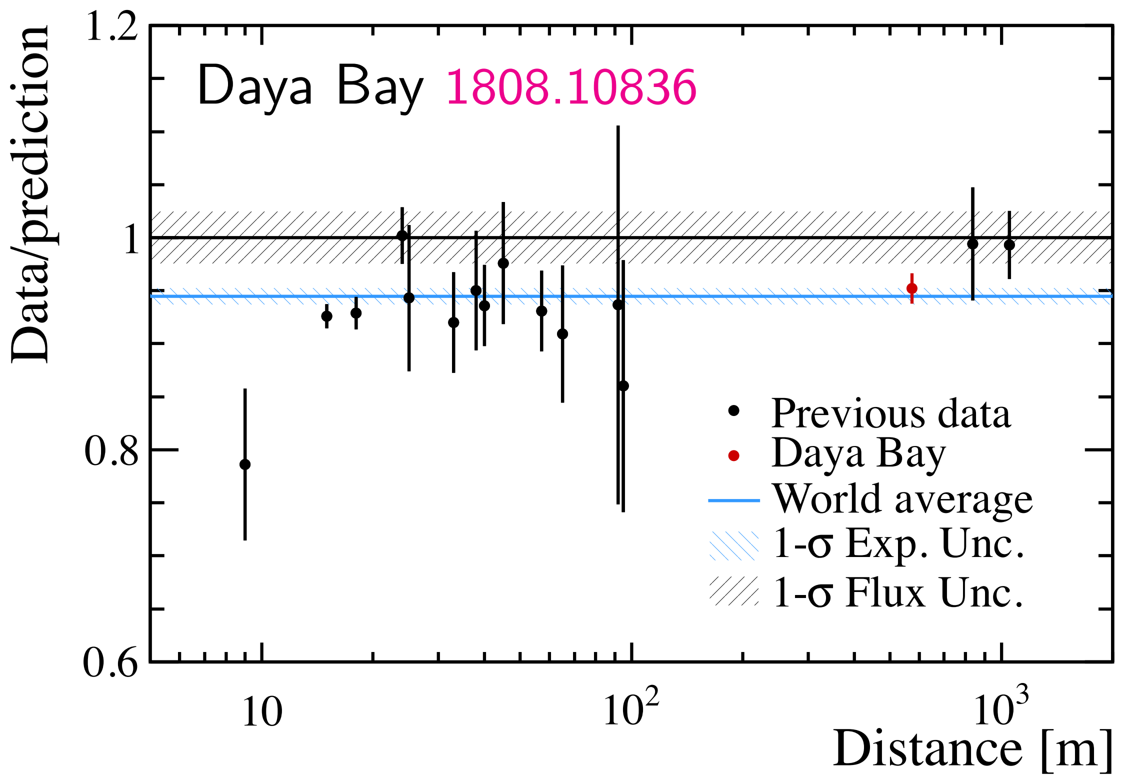
Planck 1807.06209



- need to invoke non-standard cosmology and/or additional exotic neutrino properties

Reactor anomaly

- calculation of neutrino flux from nuclear reactors predict too many neutrinos Mueller et al., 1101.2663, Huber, 1106.0687
- can be explained by ν_e disappearance at eV-scale Mention et al, 1101.2755

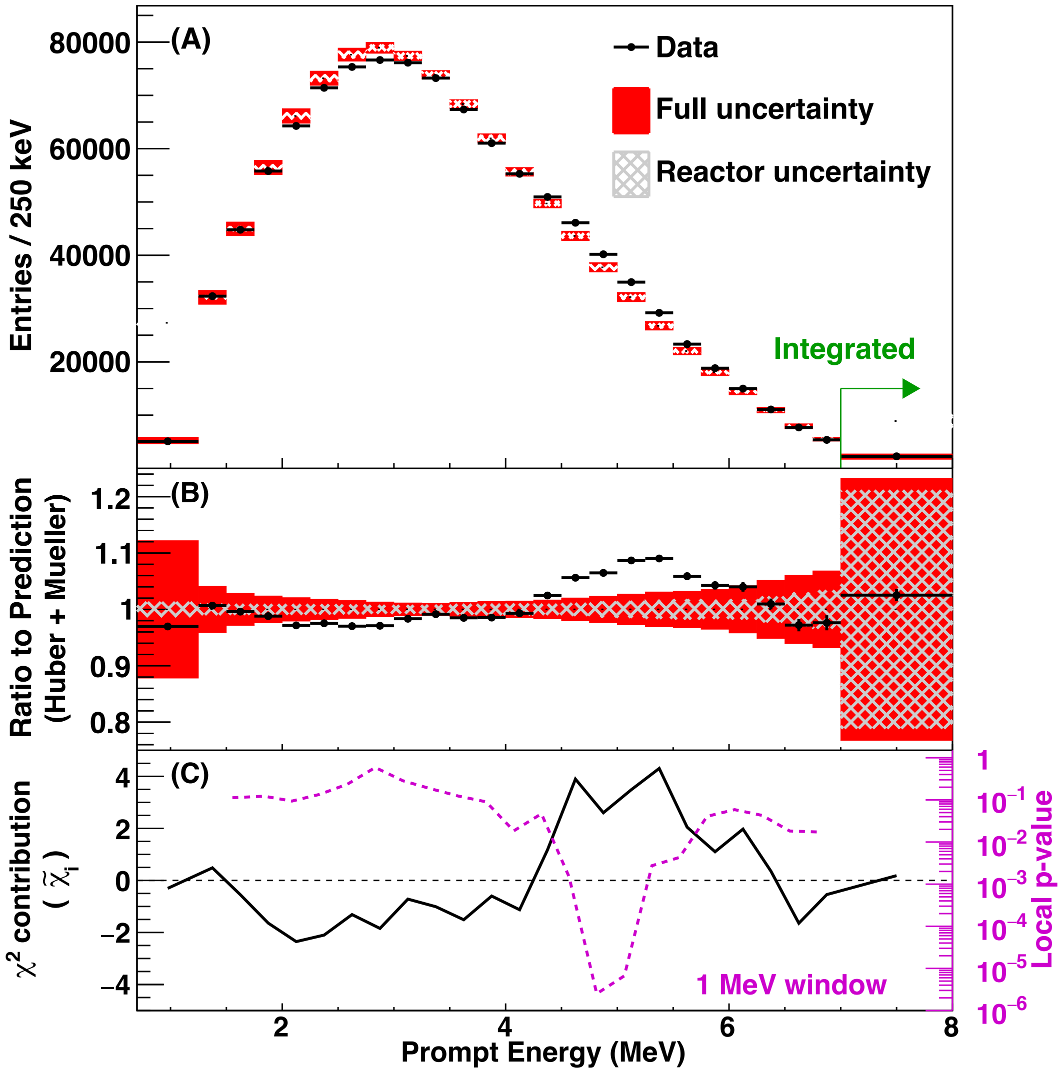


$$f = 0.952 \pm 0.014 \pm 0.023$$

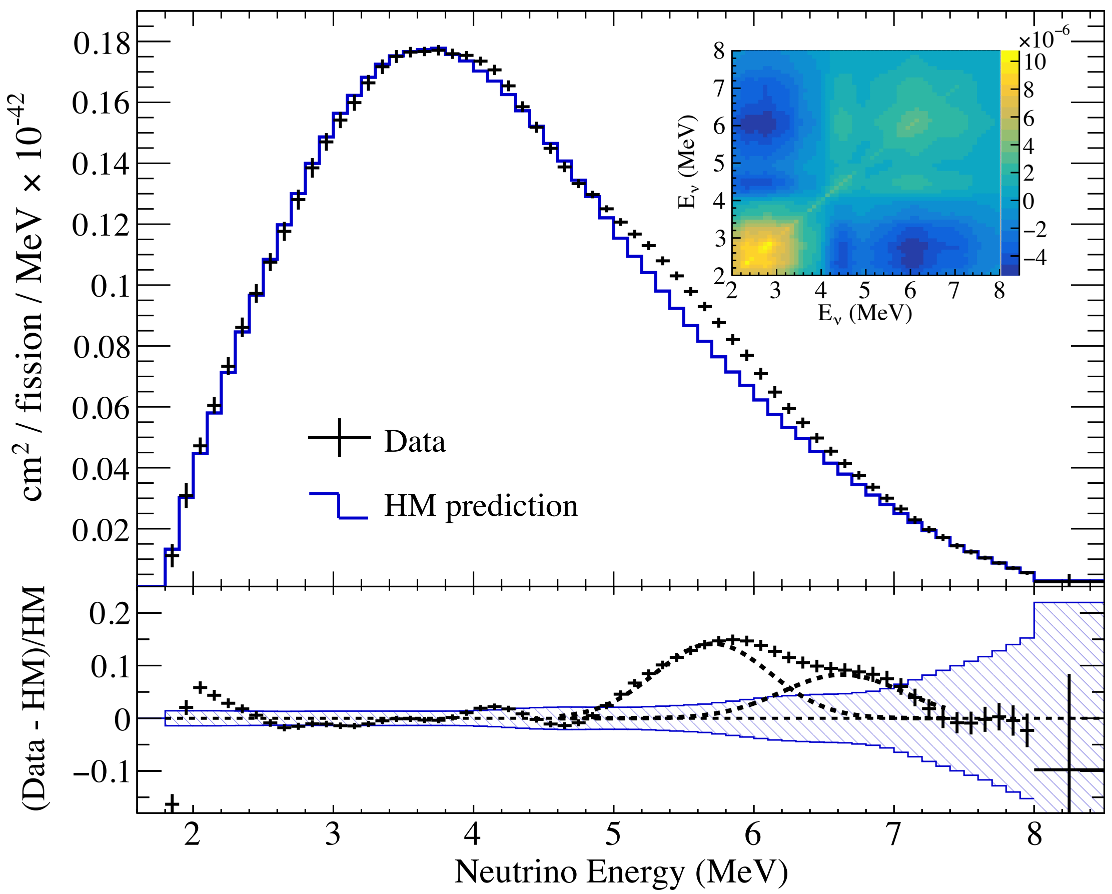
(relativ to Huber-Mueller pred.)

5-MeV bump

Daya Bay 1607.05378



RENO 2010.14989



Reactor anomaly

- 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
- conversion method using „virtual beta branches“
- ab initio calculations using nuclear data tables
  problem of „forbidden“-decays

Reactor anomaly — recent updates

- 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

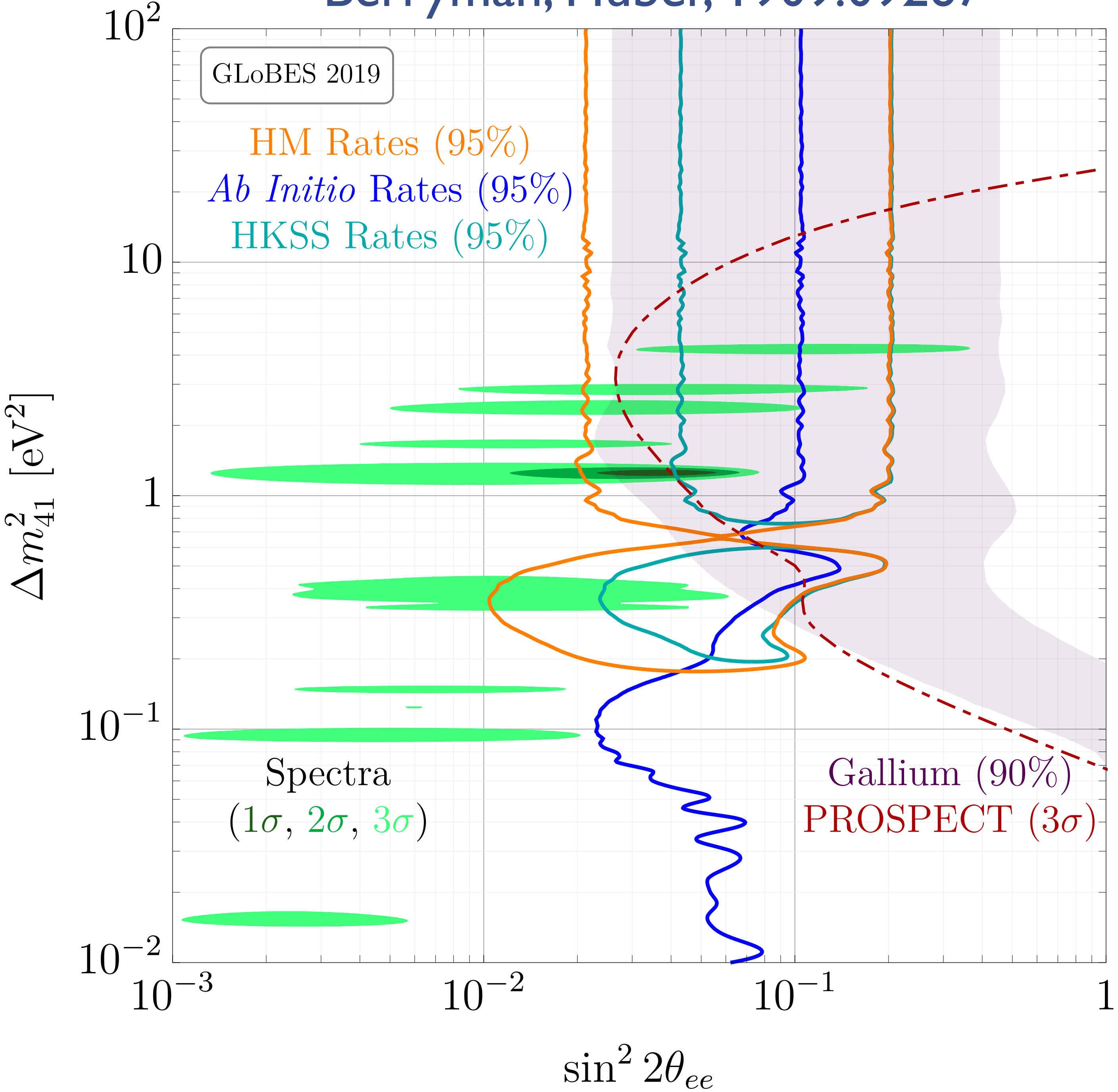
Estienne et al., 1904.09358 → *Ab Initio* Rates

Hayen et al., 1908.08302 → HKSS Rates

Analysis	$\chi^2_{3\nu}$	$\chi^2_{\min}$	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

Reactor anomaly — recent updates

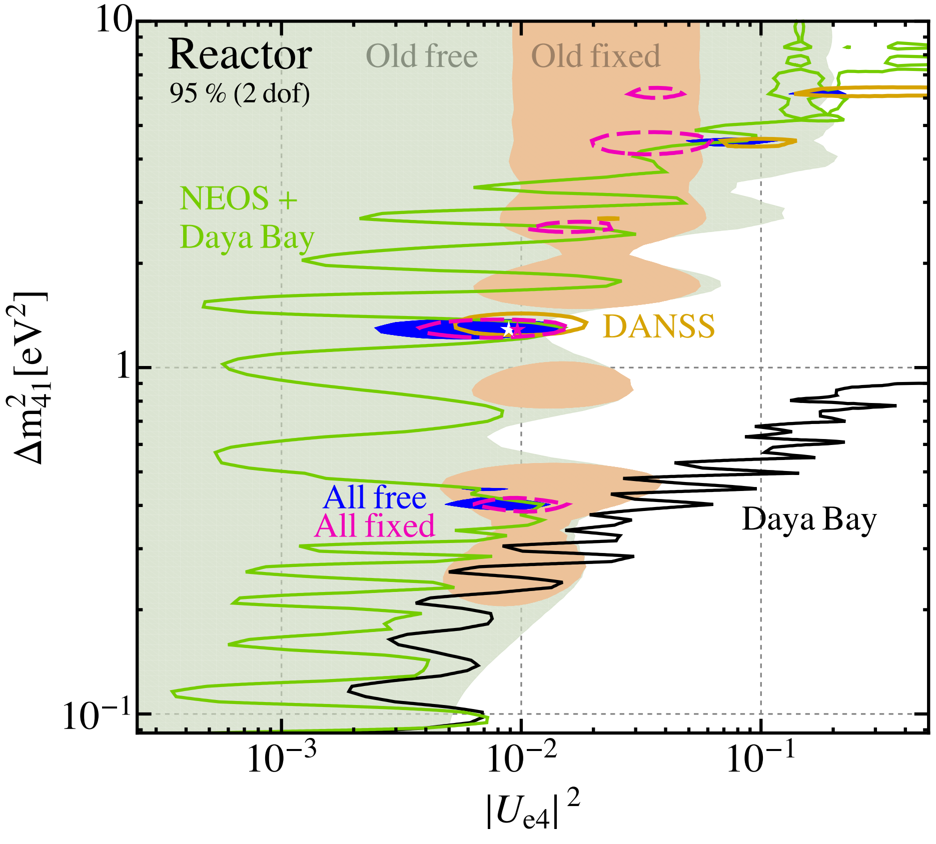
Berryman, Huber, 1909.09267

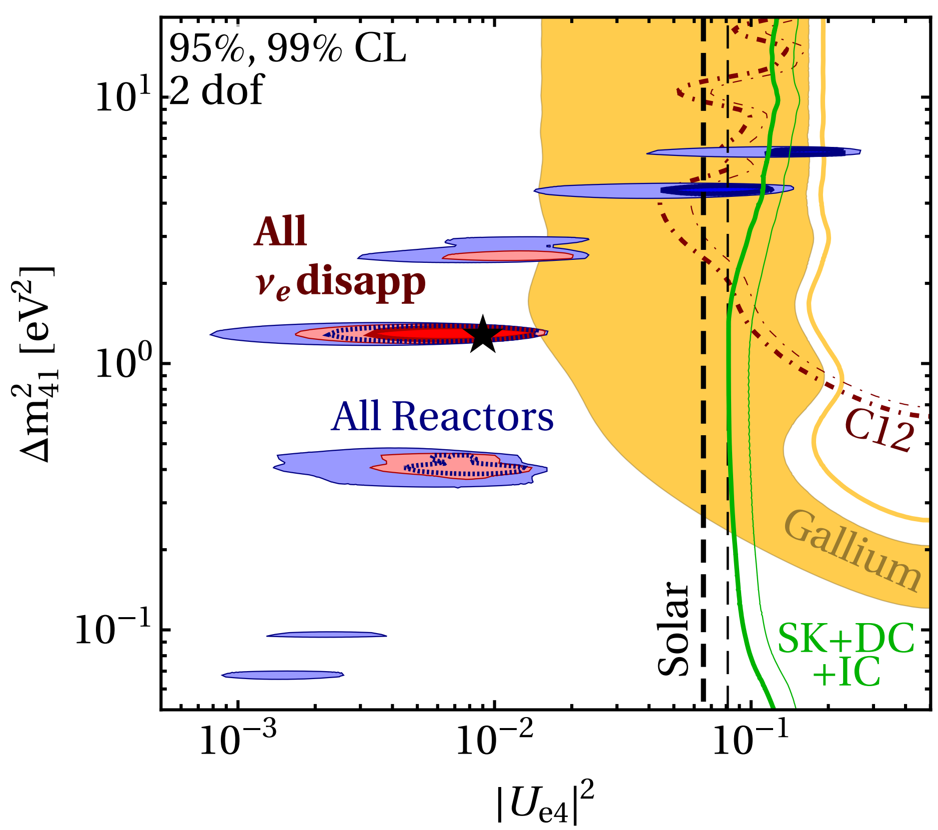


Hints from relative shape measurements — 2018 status

Analysis	Δm^2_{41} [eV^2]	$\lvert U^2_{e4}\rvert$	$\chi^2_{\min}$/dof	$\Delta\chi^2$(no-osc)	significance
DANSS+NEOS	1.3	0.00964	74.4/(84 – 2)	13.6	3.3σ
all reactor (flux-free)	1.3	0.00887	185.8/(233 – 5)	11.5	2.9σ
all reactor (flux-fixed)	1.3	0.00964	196.0/(233 – 3)	15.5	3.5σ
$\overset{(-)}{\nu}_e$ disap. (flux-free)	1.3	0.00901	542.9/(594 – 8)	13.4	3.2σ
$\overset{(-)}{\nu}_e$ disap. (flux-fixed)	1.3	0.0102	552.8/(594 – 6)	17.5	3.8σ

assuming Wilks theorem





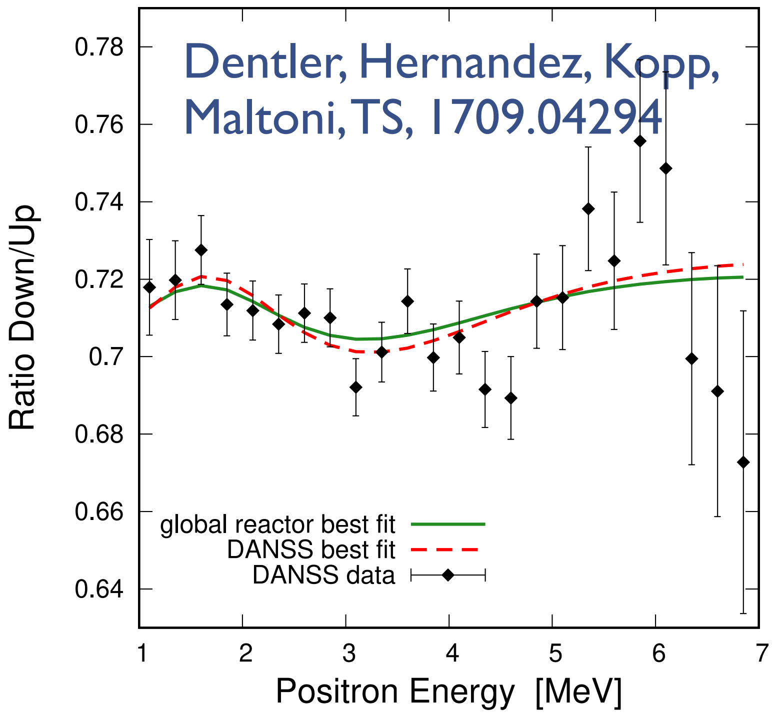
Dentler et al., 1803.10661

hint for sterile neutrino oscillations, independent of reactor flux calculations!

Recent relative spectral measurements

- several new measurements using movable or segmented detectors:
  NEOS, DANSS, STEREO, PROSPECT, Neutrino-4
- provide 2-dim information in L and E
- look for relative spectral distortions as a function of L
- independent of theoretical flux predictions

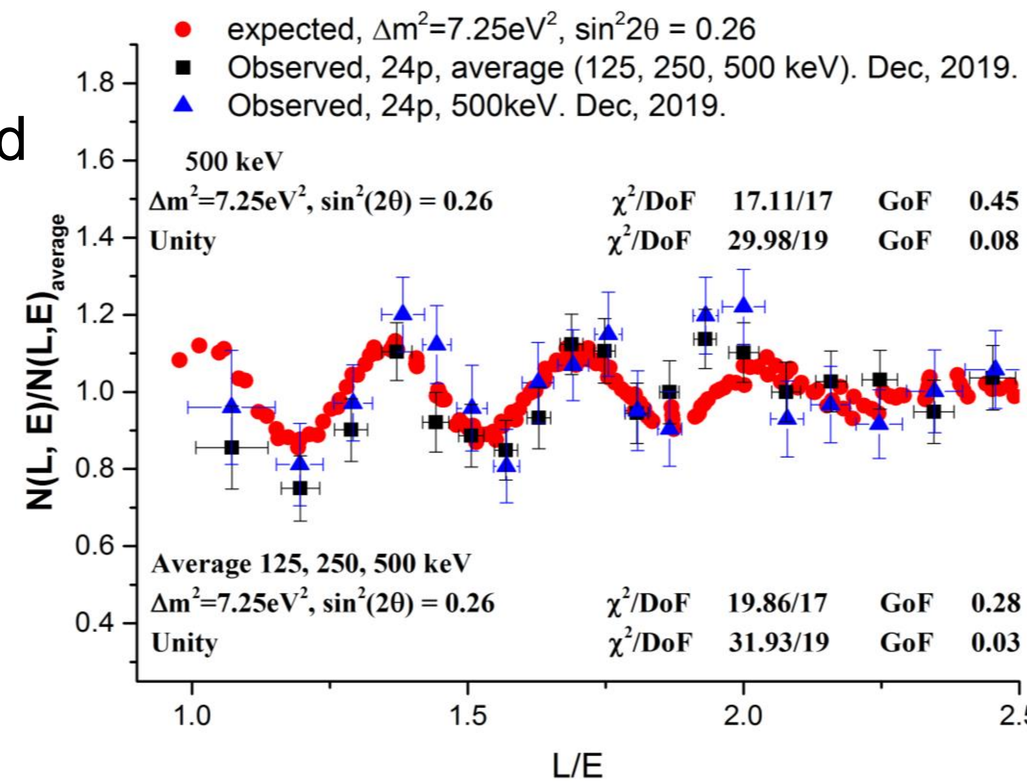
Recent relative spectral measurements



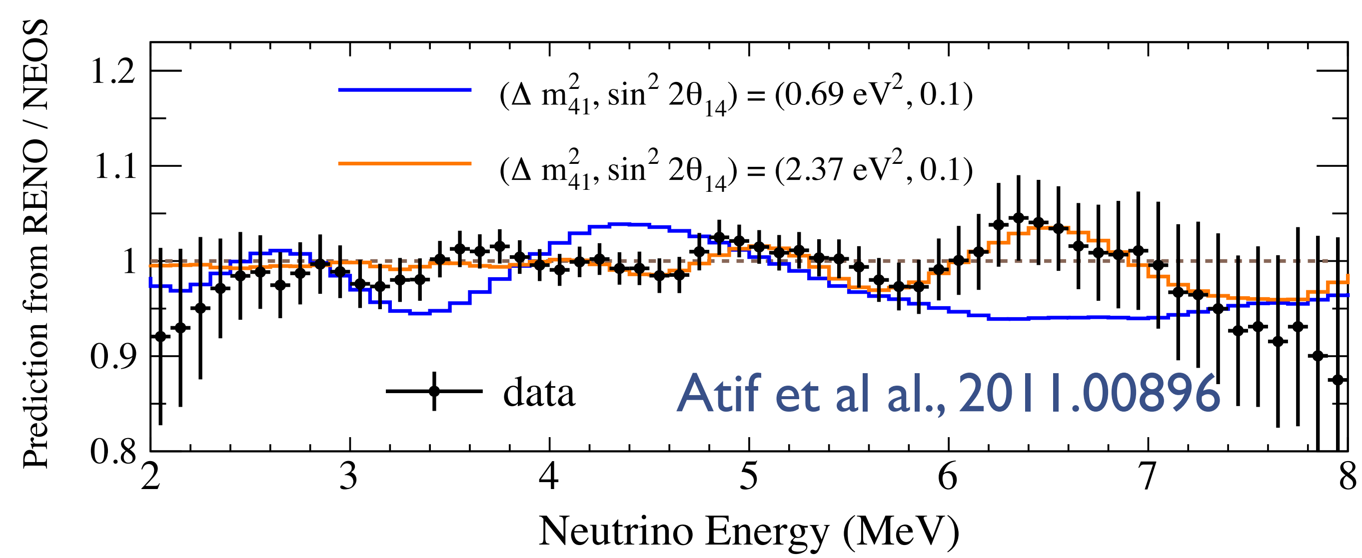
DANSS: relative spectra @ L = 10.7 and 12.7 m
prev. ~ 2σ hint decr. ~1.5σ
DANSS talk @ ICHEP20

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

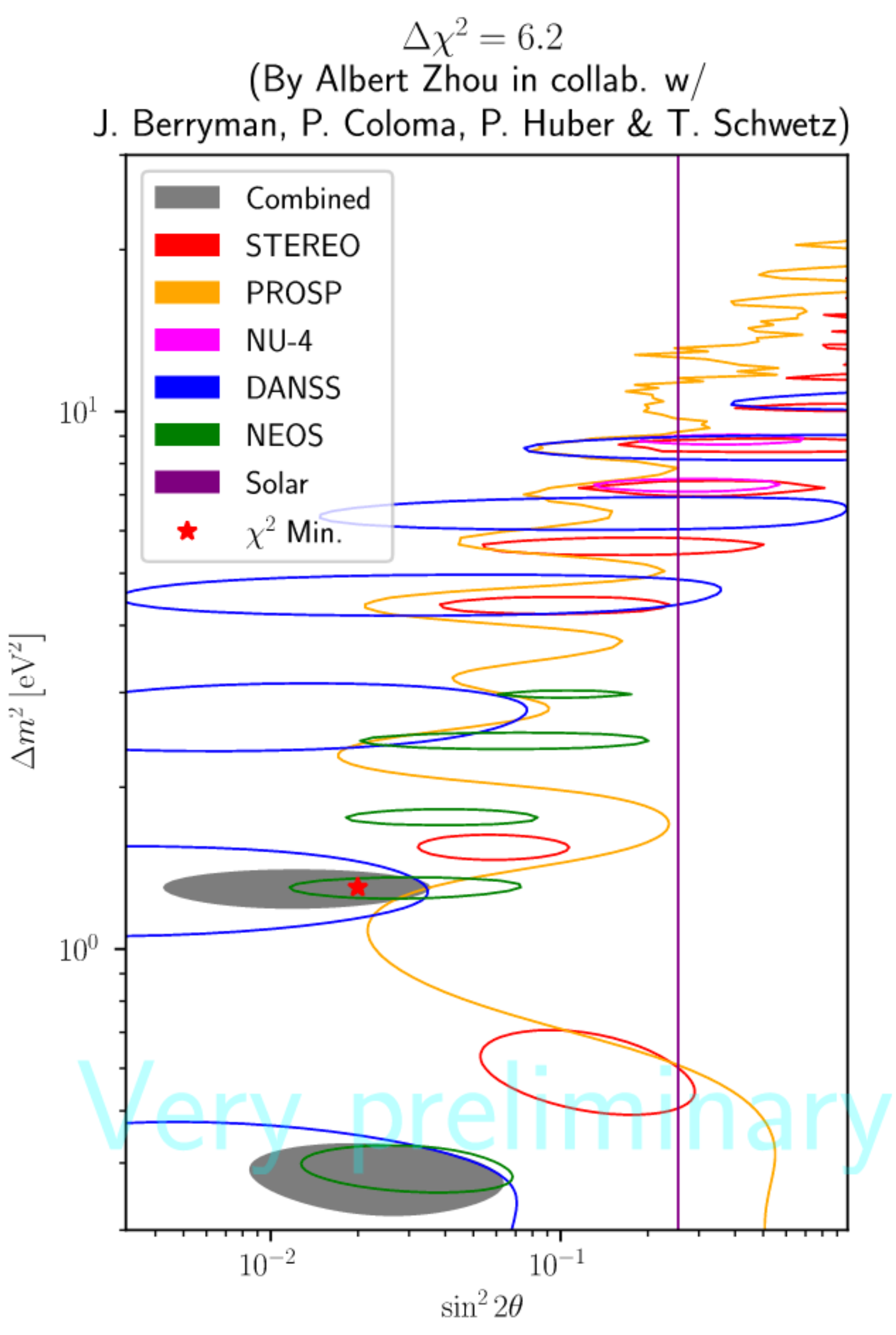


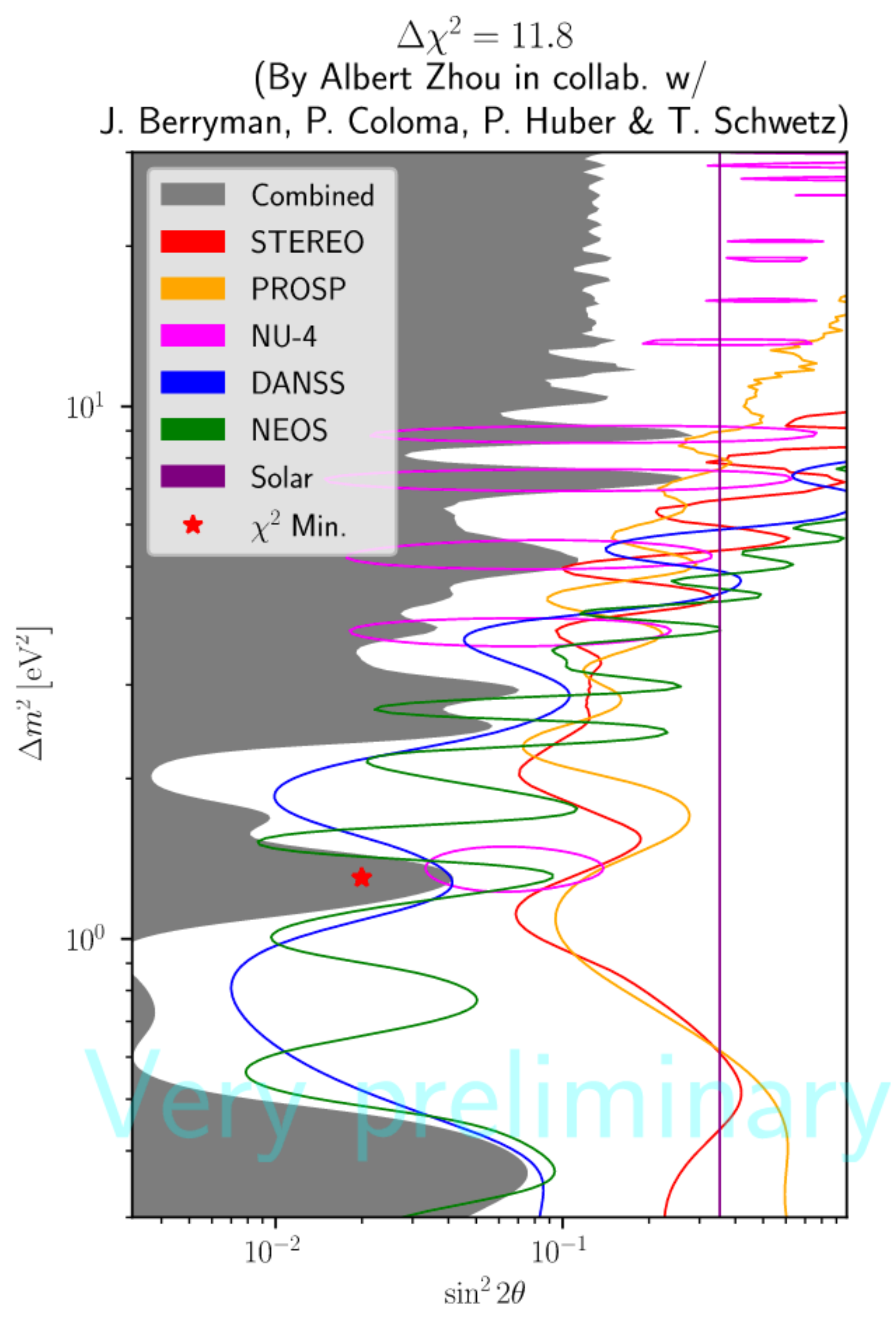
NEOS: spectrum at L = 24 m, relative to RENO (or DayaBay) near detectors: $\Delta\chi^2$(no osc) = 11.7

Recent relative spectral measurements

- several new measurements using movable or segmented detectors: NEOS, DANSS, STEREO, PROSPECT, Neutrino-4
- several „hints“ for spectral distortions
- questions:
  - how likely is it to get such a result from fluctuations?
  - is a consistent explanation for all of them in terms of sterile oscillations emerging?

Spectral shape measurements — combined analysis





global best fit:

$\Delta\chi^2$(no osc) = 9.9

$\Delta m^2 = 1.3$ eV^2

$\sin^2 2\theta = 0.02$

NEOS analysis to be updated

On the statistical significance of spectral distortions

$$P^{\mathrm{osc}} = 1 - \frac{1}{2}\sin^2 2\theta \left(1 - \cos\frac{\Delta m^2 L}{2E}\right)$$

Coloma, Huber, Schwetz, 2008.06083

Several reasons to expect Wilk's theorem to fail:

- physical boundary $\sin^2 2\theta \geq 0$
- Δm^2 becomes unphysical for $\sin^2 2\theta \to 0$ (and vice versa)
- oscillatory dependence on Δm^2

→ expect large deviations of usual test-statistic from a χ^2 distribution

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

On the statistical significance of spectral distortions

Coloma, Huber, Schwetz, 2008.06083

$$\chi^2(s,\kappa) = \sum_{i=1}^{N} [n_i - s\cos\varphi_{\kappa i}]^2$$

- sterile osc. search is similar to fitting white noise with cosine of arbitrary amplitude and frequency

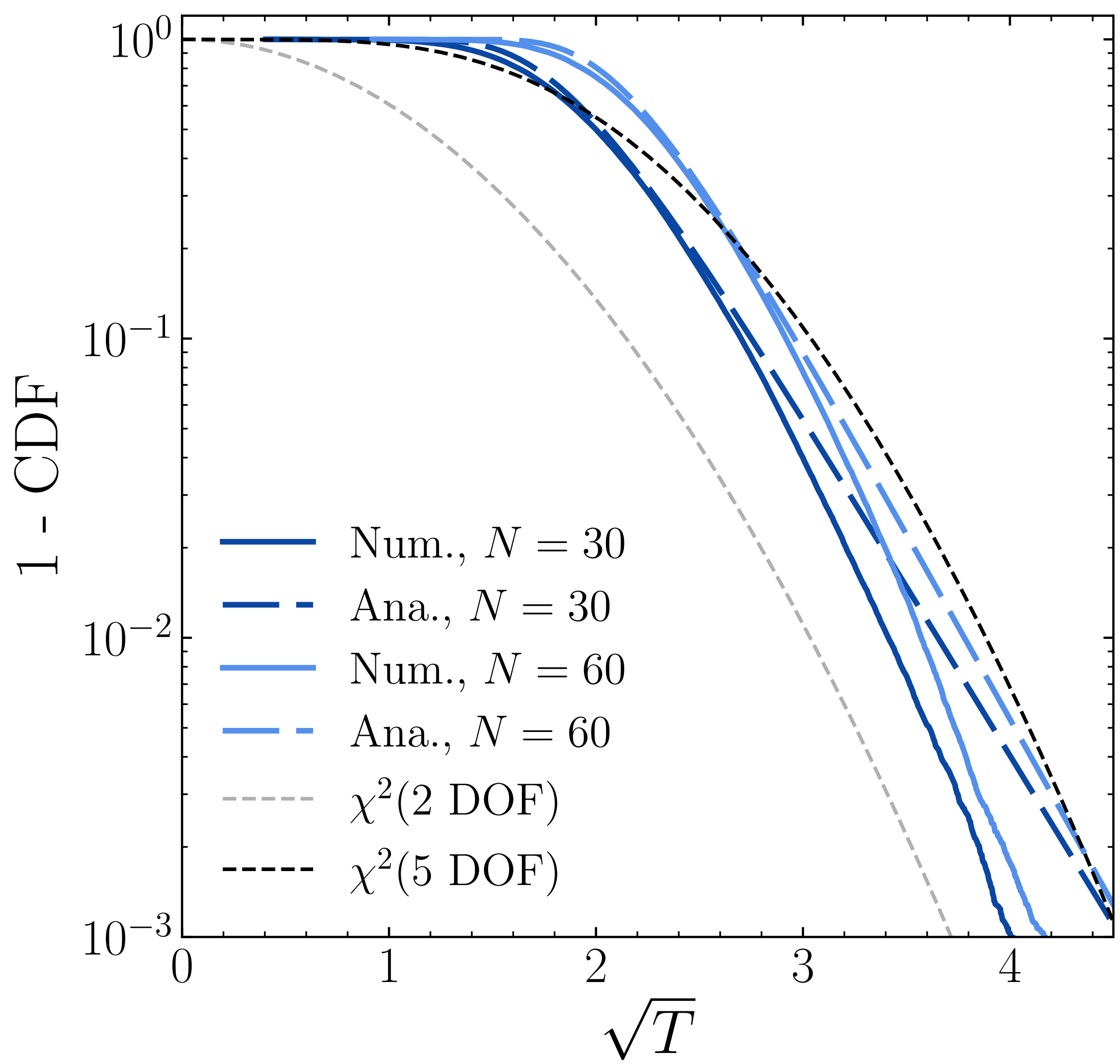
- consider usual test statistic to test for the presence of a signal:

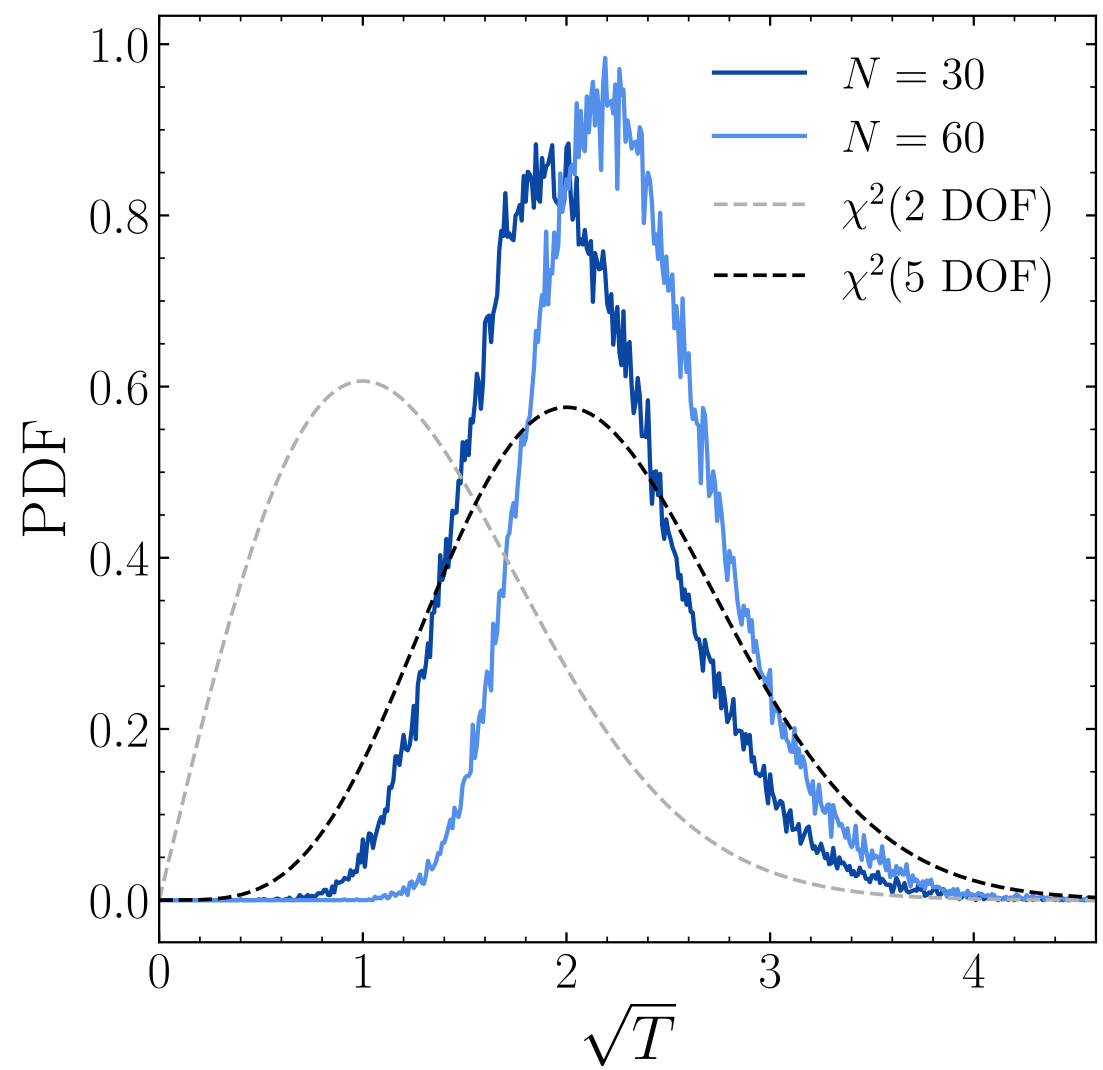
$$T = \chi^2(\text{no osc}) - \chi^2(\text{best fit}) = \chi^2(0,0) - \chi^2(\widehat{\sin^2 2\theta}, \widehat{\Delta m^2})$$

- distribution of sqrt(*T*) is the distribution of the maximum of *N* standard-normal variables, where *N* is of order # bins

$$\sqrt{T} = \max_k [a_k] \qquad a_k \ldots N \text{ std normal vars}$$

Max. Gaussian vs χ^2 distribution



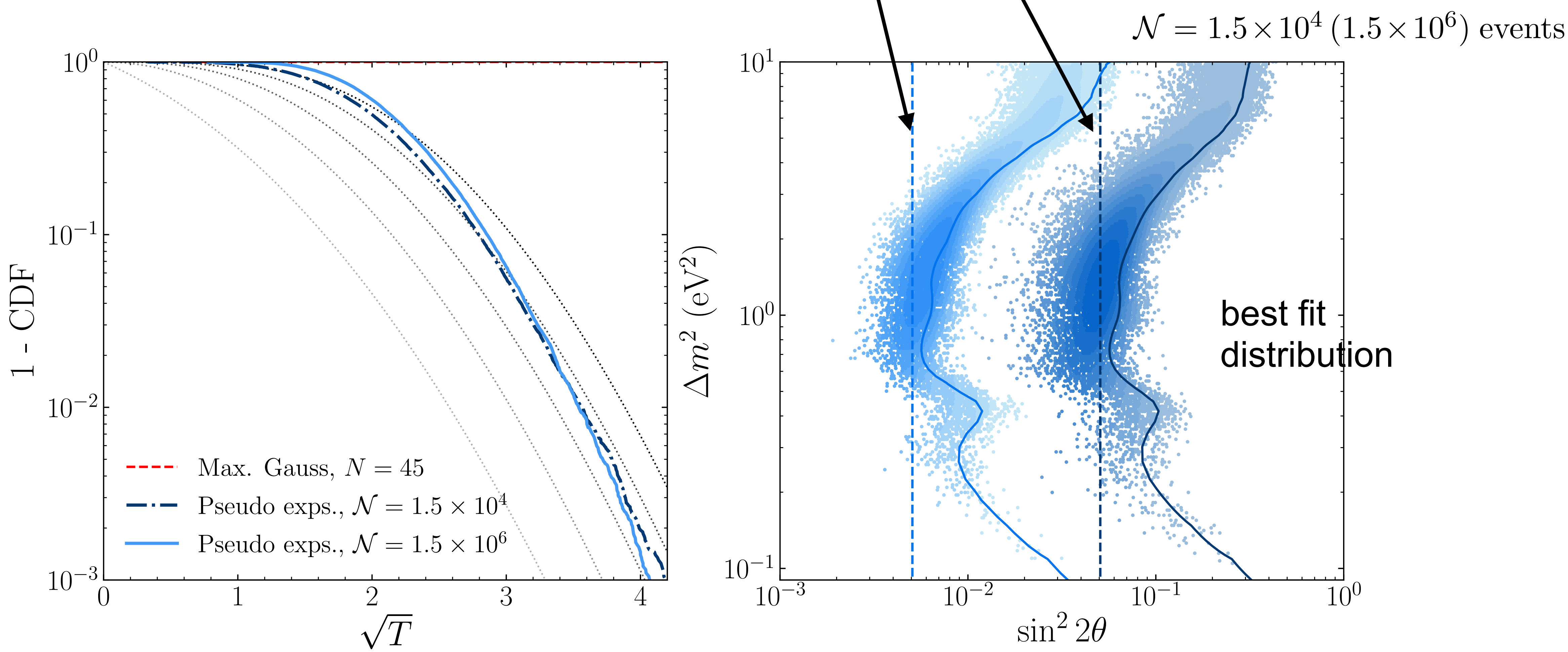


Simulation of toy reactor experiment

- it is very likely to find *some* frequency which fits random fluctuations

analytical estimate from approximating the max.Gauss distribution by the *Gumbel* distr.:

$$\langle \sin^2 2\theta \rangle \approx \frac{6.2}{\sqrt{\mathcal{N}}} \qquad \sin^2 2\theta = 2\sqrt{\frac{2}{\mathcal{N}}}\sqrt{T}$$



best fit value is a *biased estimator* for $\sin^2 2\theta$!

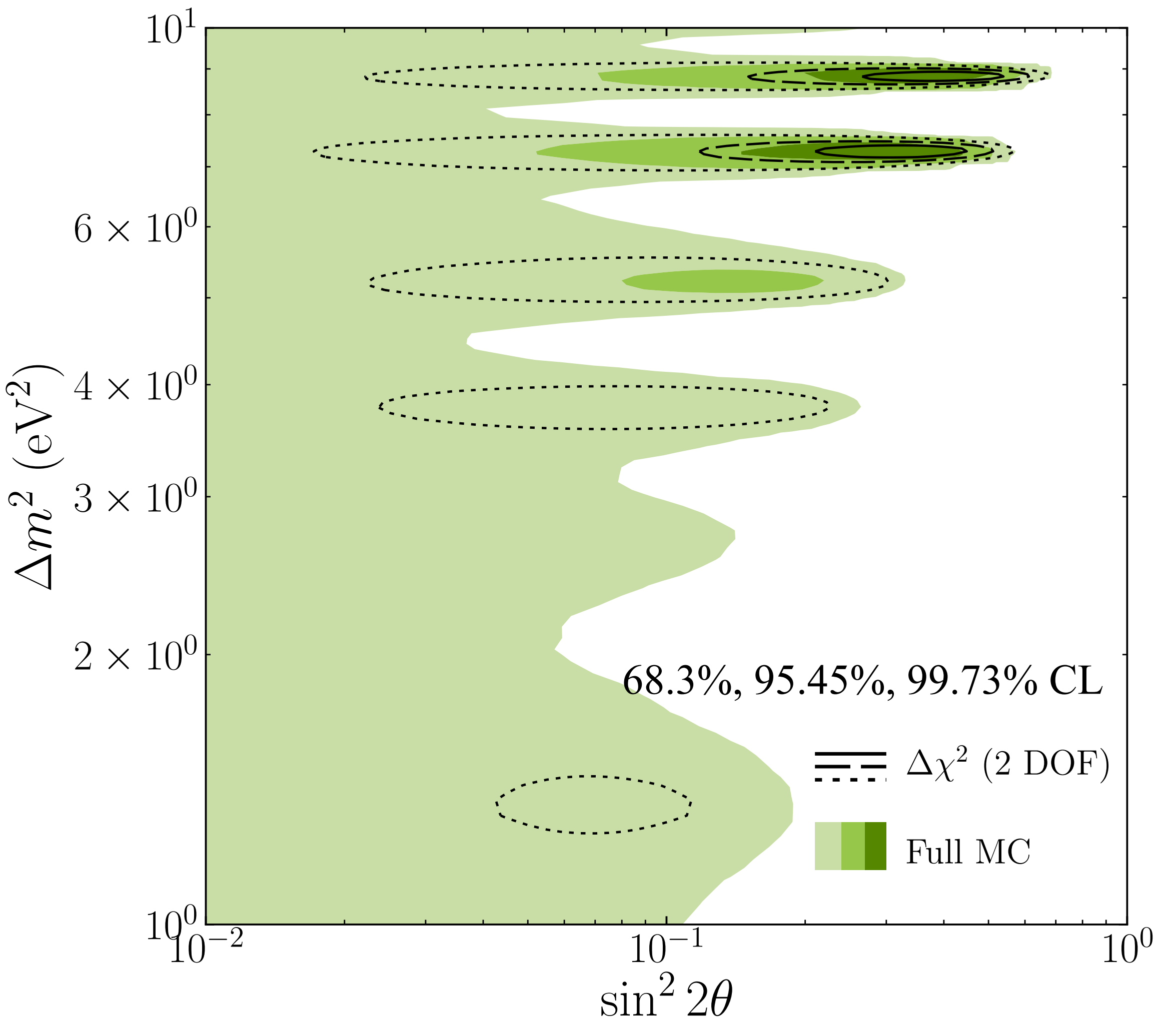
Significances have to evaluated by simulations

- cannot use Wilk's theorem to convert $\Delta\chi^2$ values into significances
- significances typically reduced by 0.5 to 1 σ

	CL [%]		p-value [%]		Number of σ	
T	$\chi^2(2)$	max. G.	$\chi^2(2)$	max. G.	$\chi^2(2)$	max. G.
4.61	90.00	48.55	10.0	51.4	1.64	0.65
6.18	95.45	74.73	4.55	25.3	2.00	1.14
9.21	99.00	94.72	1.00	5.27	2.58	1.94
9.49	99.13	95.45	0.87	4.55	2.62	2.00
11.83	99.73	98.69	0.27	1.31	3.00	2.48
14.78	99.938	99.73	0.062	0.27	3.42	3.00

estimates from the max. Gauss distribution for N = 45 (some weak dependence on #bins)

Case study: Neutrino-4



Coloma, Huber, Schwetz, 2008.06083

significance for signal is reduced from

3.2σ (*p*=0.0016) to 2.6σ (*p*=0.0091) (based on stat. errors only)

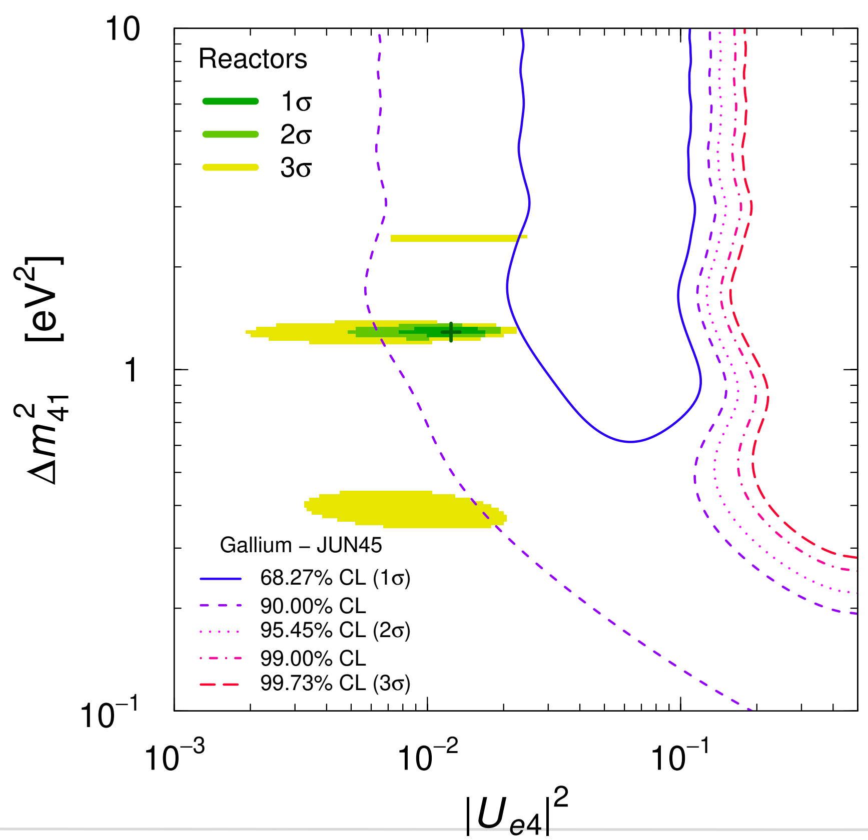
Update on Gallium anomaly

Kostensalo, Suhonen, Giunti, Srivastava, 1906.10980

Table 7: Ratios of measured and expected ^{71}Ge event rates in the four radioactive source experiments, their correlated average, and the statistical significance of the gallium anomaly obtained with the cross sections in Table 5.

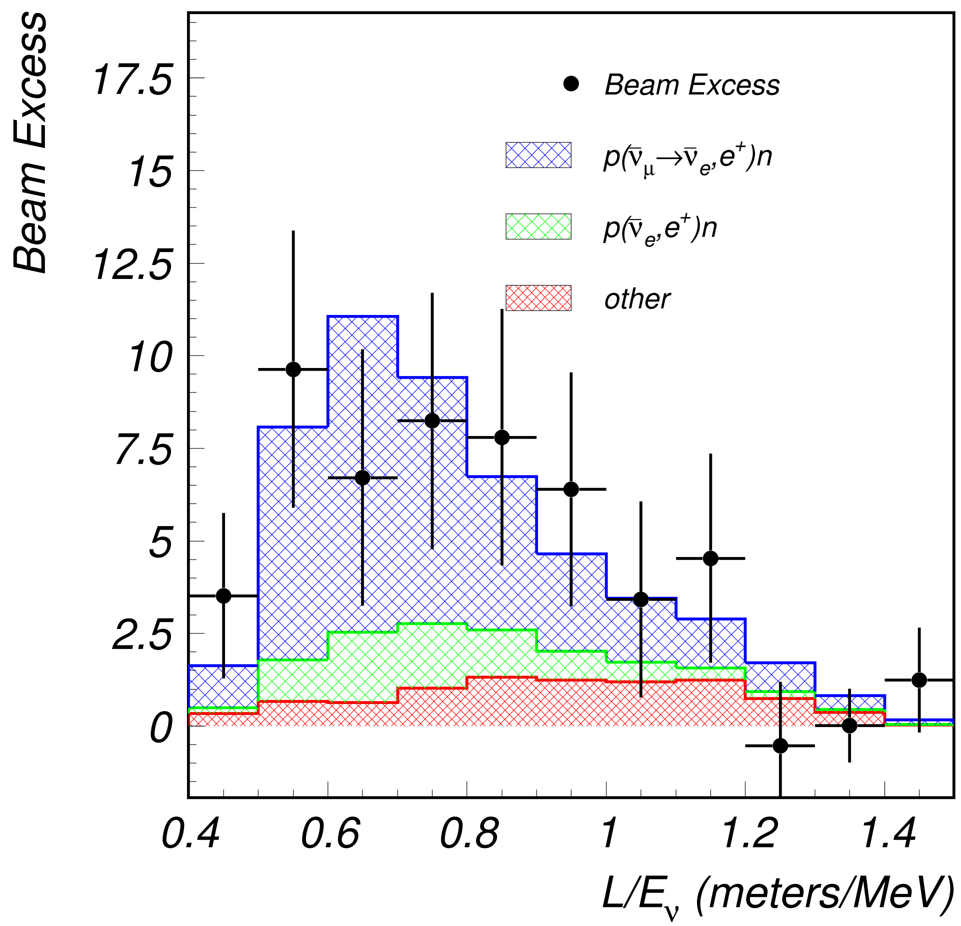
	GALLEX-1	GALLEX-2	SAGE-1	SAGE-2	Average	Anomaly
R_{Bahcall}	0.95 ± 0.11	0.81 ± 0.11	0.95 ± 0.12	0.79 ± 0.08	0.85 ± 0.06	2.6σ
R_{Haxton}	0.86 ± 0.13	0.74 ± 0.12	0.86 ± 0.14	0.72 ± 0.10	0.76 ± 0.10	2.5σ
R_{Frekers}	0.93 ± 0.11	0.79 ± 0.11	0.93 ± 0.12	0.77 ± 0.08	0.84 ± 0.05	3.0σ
R_{JUN45}	0.97 ± 0.11	0.83 ± 0.11	0.97 ± 0.12	0.81 ± 0.08	0.88 ± 0.05	2.3σ

- improved shell-model cross section calculations
- significance decreases $3.0\sigma \to 2.3\sigma$

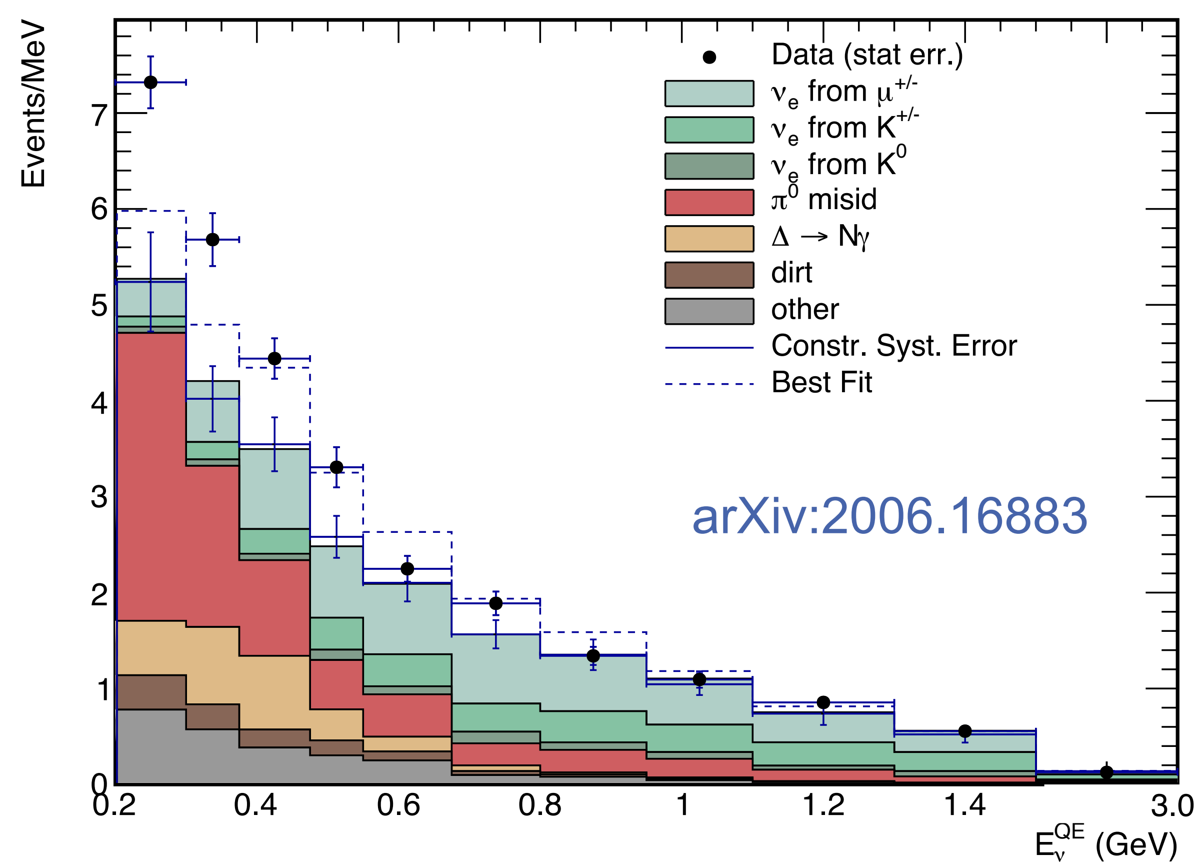


Hints for $\nu_\mu \to \nu_e$ appearance

LSND, 2001



MiniBooNE 2020

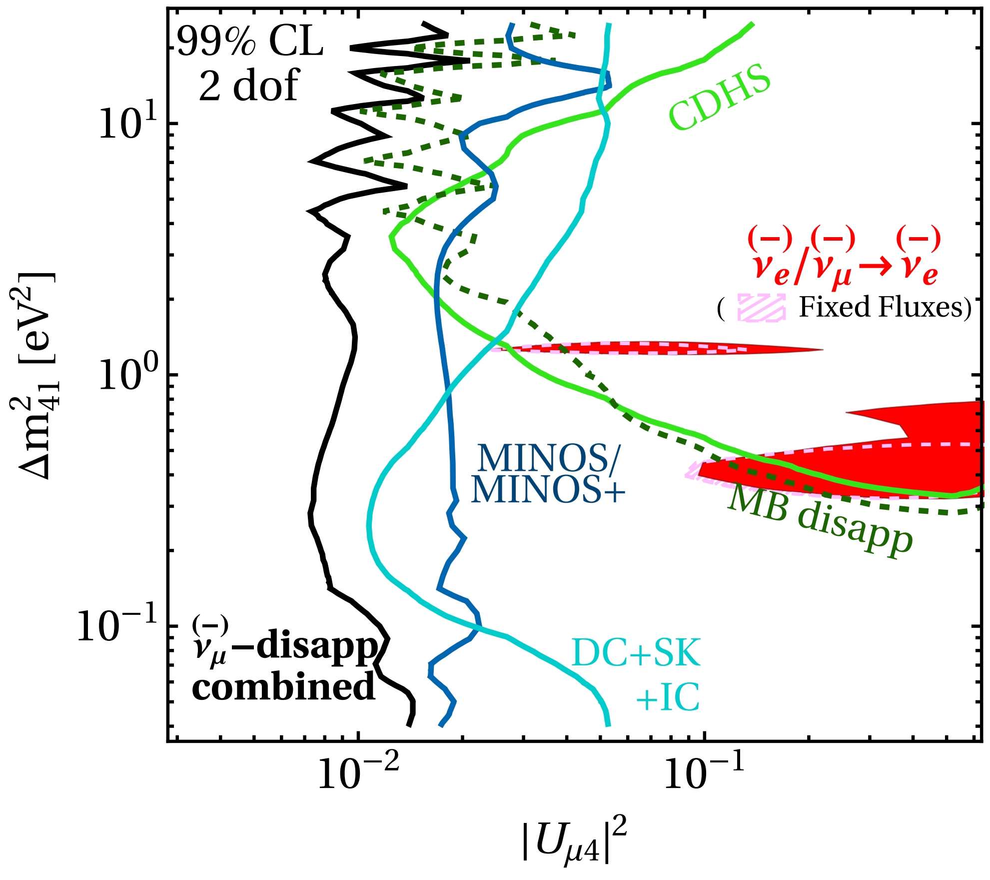


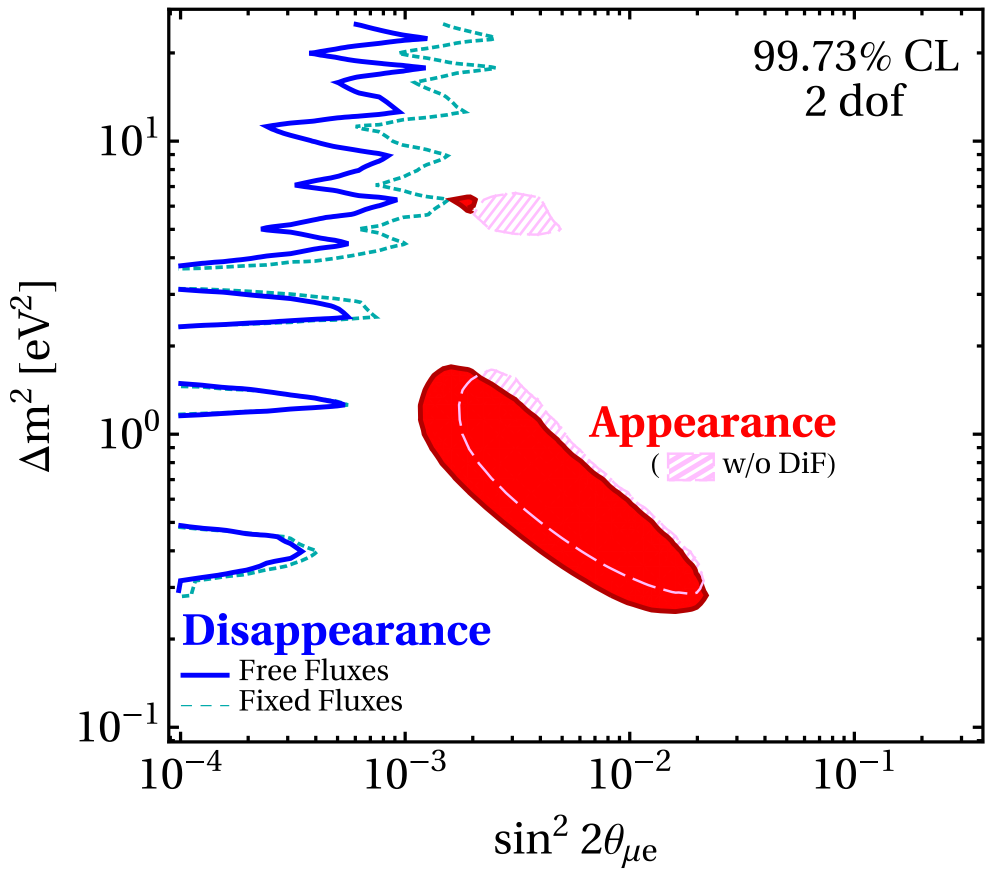
- signal for $\bar{\nu}_\mu \to \bar{\nu}_e$ transitions (3.8σ)

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

Strong tension btw appearance and disappearance

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





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

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

Dentler et al, 1803.10661

Strong tension btw appearance and disappearance

→ sterile neutrino oscillation explanation of LSND/MB excluded

… robust result wrt to individual experiments

Analysis	$\chi^2_{\text{min,global}}$	$\chi^2_{\text{min,app}}$	$\Delta\chi^2_{\text{app}}$	$\chi^2_{\text{min,disapp}}$	$\Delta\chi^2_{\text{disapp}}$	χ^2_{PG}/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}

reactor flux-free analysis

Dentler et al, 1803.10661

results for 2018 MiniB very similar (tension gets slightly worse)

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
- mass varying ν Kaplan,Nelson,Wei ... snant 05
- shortcuts of sterile ... Paes ... g, Weiler, 18
- de ... omares-Riuz, Pascoli, TS 05; Gninenko 09, 10; Be ... Machado, Zukanovich, 18; Ballett, Pascoli, Ross-Lonergan, 18
- 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 dep. mass or mixing TS 07
- sterile ν with nonstandard interactions Akhmedov, TS 10; Conrad, Karagiorgi, Shaevitz, 12; Liao, Marfatia, Whisnant 18

many of them invoke sterile neutrinos of some kind
many of them are actually excluded by some data

MiniBooNE and a decaying sterile neutrino

Palomares, Pascoli, Schwetz, 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, Schwetz, 1909.09561;
Dentler, Esteban, Kopp, Machado, 1911.01427; deGouvea, Peres, Prakash, Stenico, 1911.01447;
Brdar, Fischer, Smirnov, 2007.14411, …

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

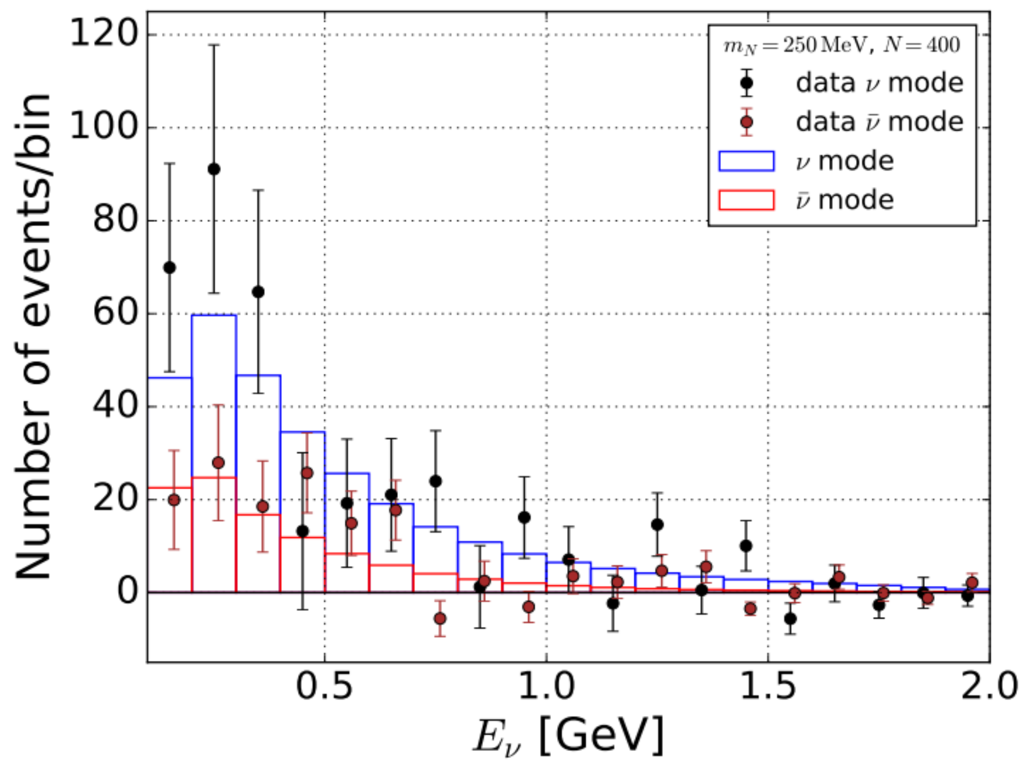
MiniBooNE and a decaying sterile neutrino — example:

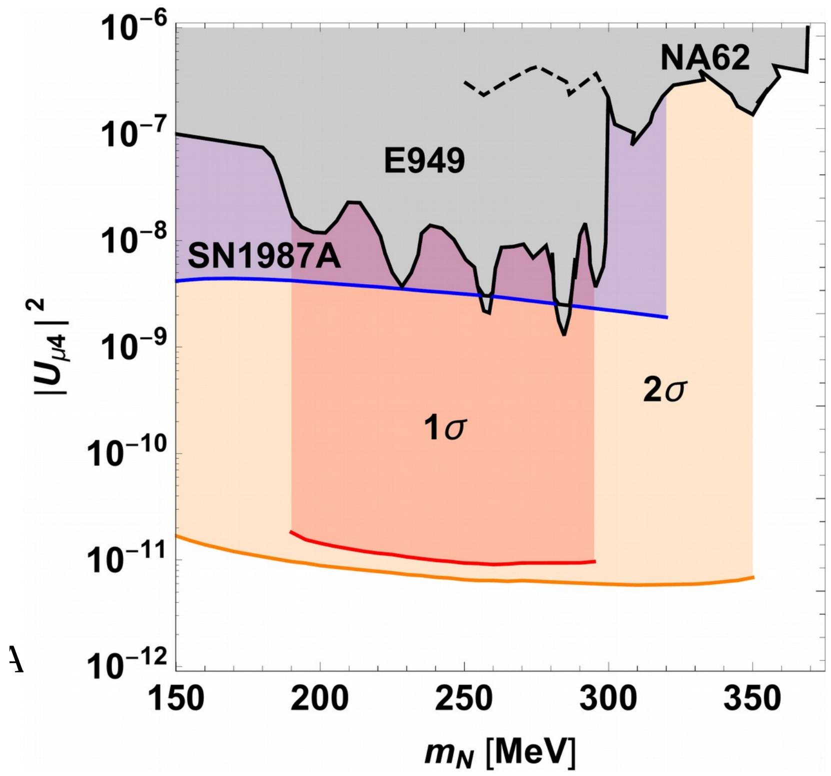
Fischer, Hernandez, TS, 1909.09561

- 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

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

$K \to N\mu$

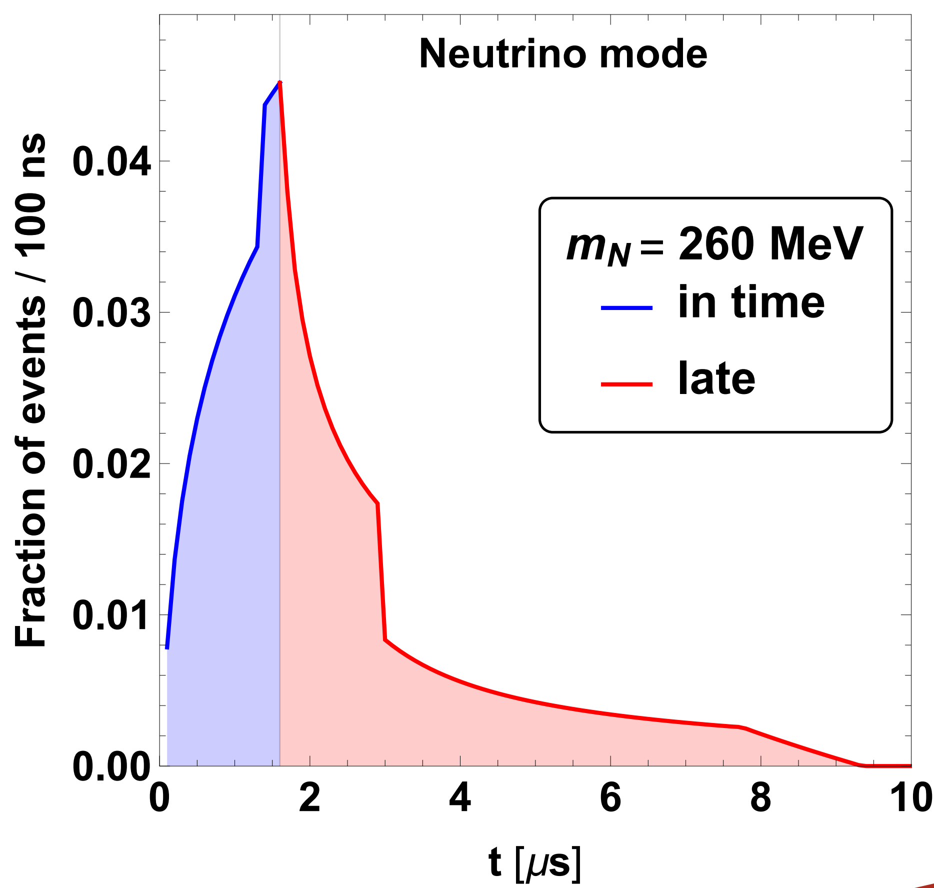


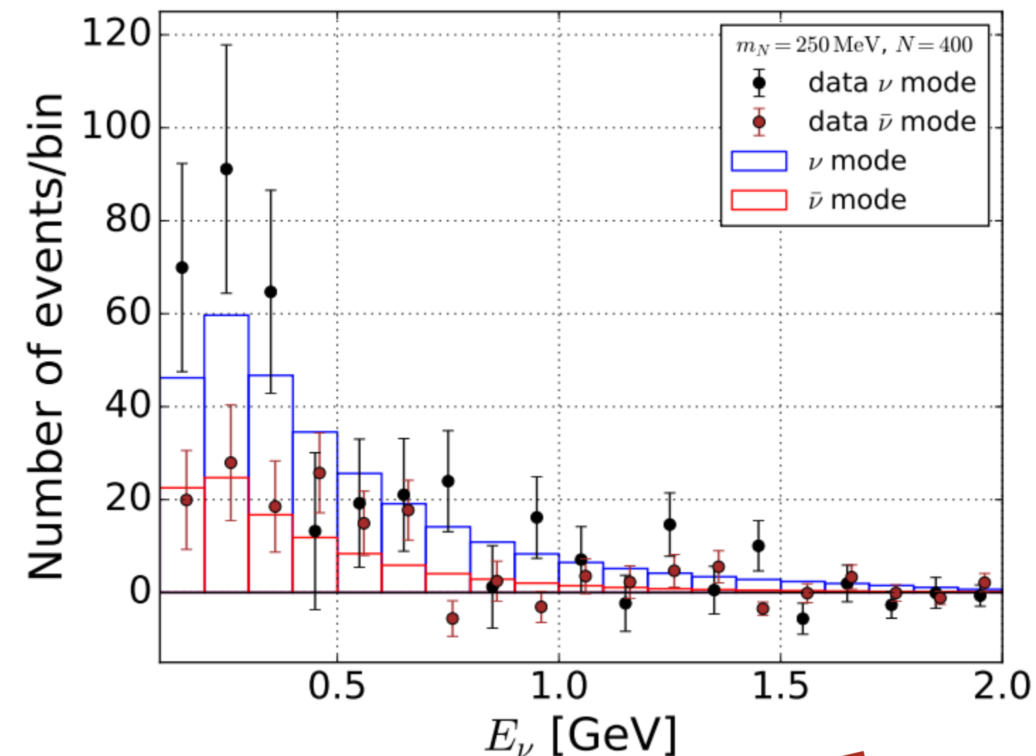


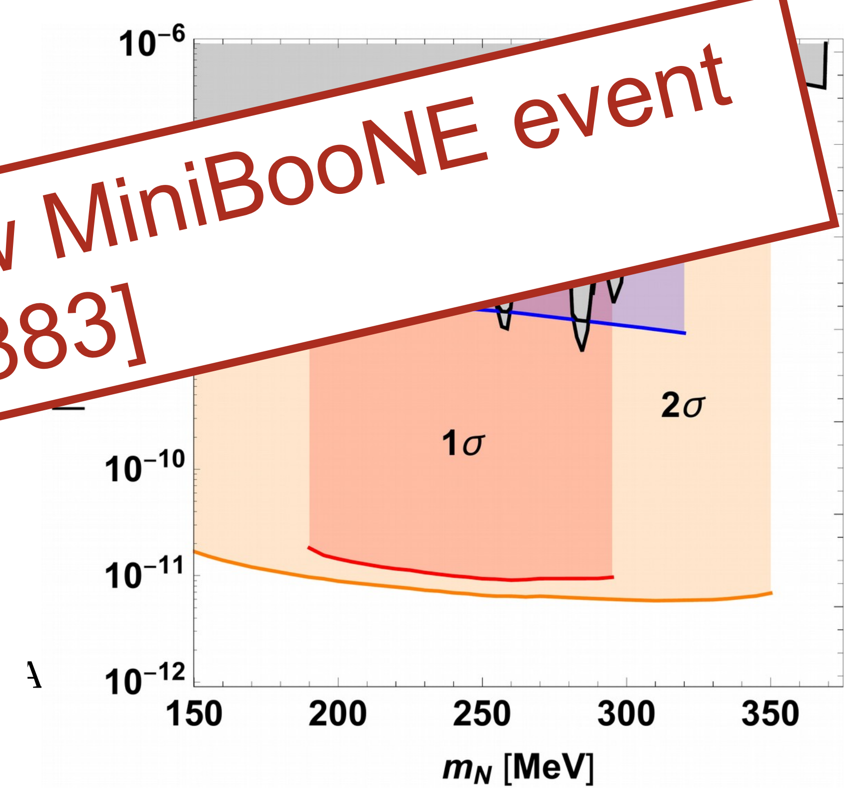
MiniBooNE and a decaying sterile neutrino — example:

$$K \to N\mu$$

Fischer, Hernandez, TS, 1909.09561







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

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;
Fischer, Hernandez, TS, 1909.09561; Dentler, Esteban, Kopp, Machado, 1911.01427;
deGouvea, Peres, Prakash, Stenico, 1911.01447; …

- exciting new physics
- rich phenomenology:
  timing / angular event distributions / photon vs electron signal
- most cannot explain LSND / reactor anomalies
- predict signatures in existing (near detectors) and/or upcoming experiments (Fermilab SBN)

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

Summary

- eV sterile @ reactors:
  - reactor flux predictions: situation unclear, probably dominated by theory uncertainties
  - spectral distortions at reactors: a number of 2-3σ hints, no clear best fit emerging, statistical interpretation: deviations from Wilk's theorem expected
- Gallium anomaly: significance decreases from 3.0σ → 2.3σ due to new shell-model cross section calculations
- LSND and MiniBooNE
  - sterile neutrino oscillation interpretation strongly disfavoured
  - no clear hints for more exotic explanations (but generically testable predictions)

Thank you for your attention!