



Sterile neutrino review (theory)

Thomas Schwetz



www.kit.edu

KIT – The Research University in the Helmholtz Association

In memory of

Samoil Bilenky 1923 — 2020

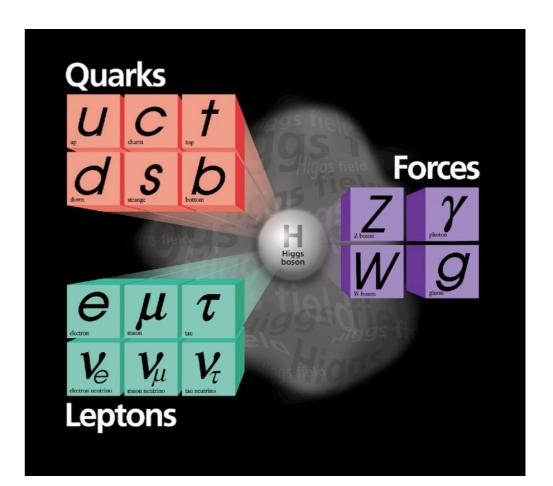




The Standard Model

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 \rightarrow "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 → 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:

$$\mathcal{L}_{\mathbf{Y}} = -y \overline{L}_L \widetilde{\phi} N_R + \text{h.c.}$$

bare Majorana mass term:

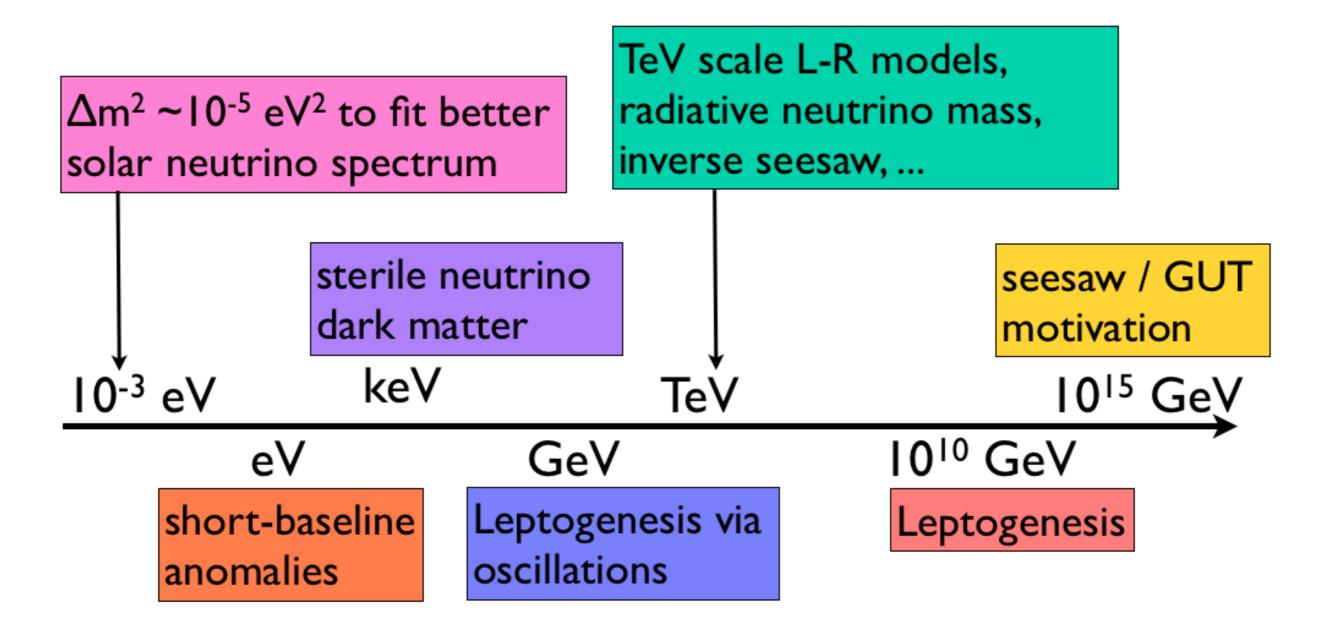
lepton number is no longeran accidental symmetry!

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

- 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)
 ⇒ new scale in the theory



Sterile neutrinos at which mass scale?





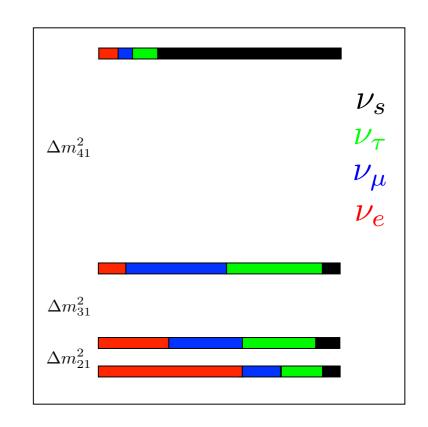
Sterile neutrinos at which mass scale?

- 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 ($\overline{\nu}_e$ disappearance)
 - predicted vs measured rate
 - distance dependent spectral distortions
- Gallium anomaly (ν_e disappearance)
- ▶ LSND ($\bar{\nu}_{\mu} \rightarrow \bar{\nu}_{e}$ appearance)
- MiniBooNE ($\nu_{\mu} \rightarrow \nu_{e}, \bar{\nu}_{\mu} \rightarrow \bar{\nu}_{e}$ 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;

 \rightarrow predict N_{eff} \approx 4

Shi, Schramm, Fields, 93; Enqvist, Kainulainen, Thomson, 92]

$$\label{eq:Neff} \begin{split} & \mbox{$$I$} \\ N_{\rm eff} = 2.9 \pm 0.5 \ , \ (95\% {\rm CL}, \ {\rm Helium} + {\rm Deuterium} + {\rm BBN}) \\ N_{\rm eff} = 2.92 \pm 0.37 \ , \ (95\% {\rm CL}, \ {\rm CMB} + \Lambda {\rm CDM}) \\ \end{split} \qquad \qquad \mbox{Böser et al., 1906.01739} \end{split}$$



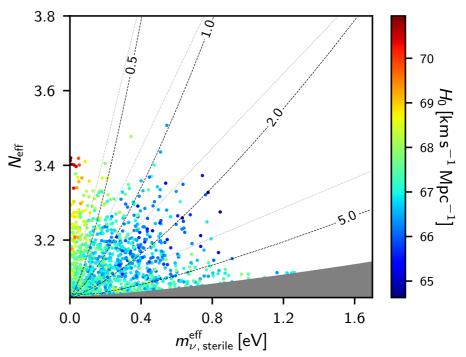
Tension with cosmology

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

> $\sum m_{
> u} <$ 0.24 eV (CMB) $\sum m_{
> u} <$ 0.12 eV (CMB+BAO)

limits at 95% CL

Planck 1807.06209



• need to invoke non-standard additional exotic neutrino properties additional exotic neutrino properties $\sum m_v - H_0$ plane, colour-coded by σ_8 . Solid black contours show the constraints from *Planck* TT,TE,EE+lowE+lensing, COSIFIC DEVICE TT,TE,EE+lowE+lensing+BAO, and the dashed green lines adthe region with $\sum m_v < 0.056 \text{ eV}$ ruled out by neutrino oscillation experiments. Mass splittings observed in neutrino oscilla-

tion experiments also imply that the region left of the dotted vertical line can only be a normal hierarchy (NH), while the region to the right could be either the normal hierarchy or at unverted hierarchy (IH).

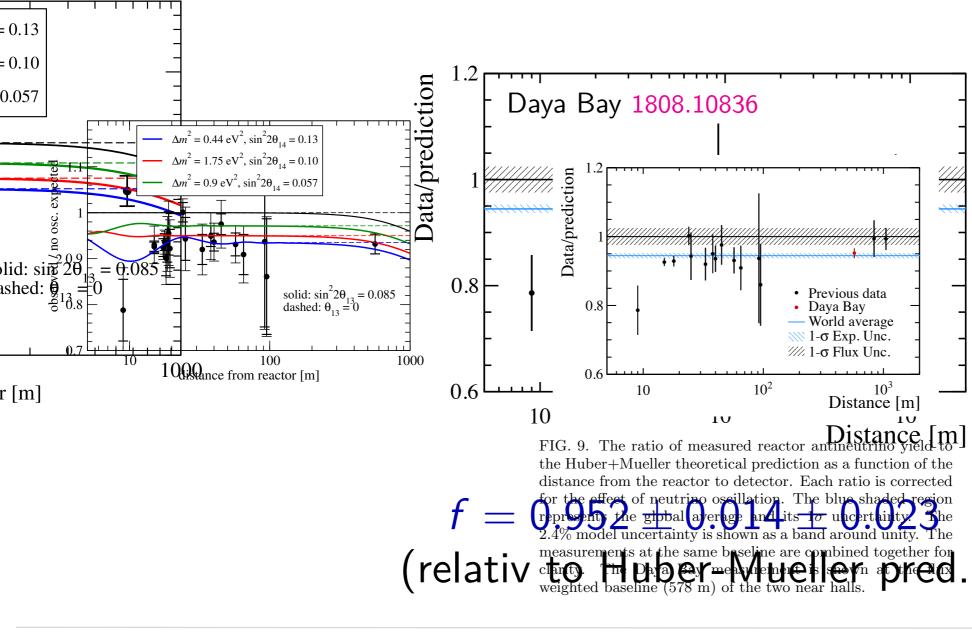
Th. Schwetz - GDR, 23 Nov 2020

Planck Collaboration:

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 v_e disappearance at eV-scale Mention et al, 1101.2755



Th. Schwetz - GDR, 23 Nov 2020

V. SUMMARY

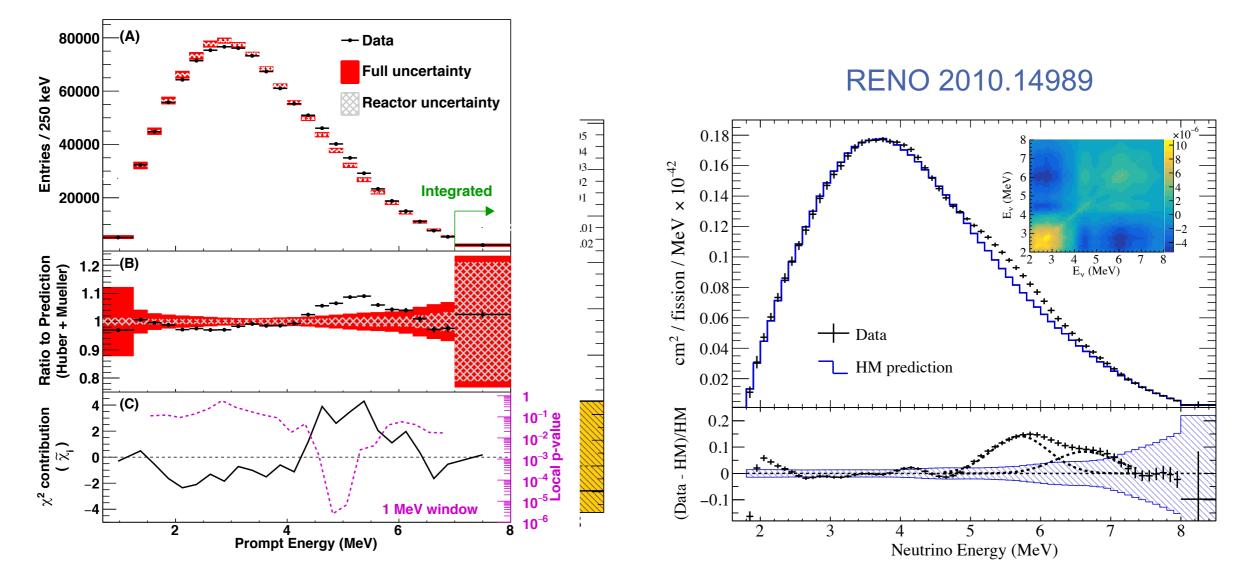
In summary, an improved antineutrino measurement is reported at Daya Bay with a 1230 data set. The precision of the measured mean yield is improved by 29% with a significantly improneutron detection efficiency estimation. The new rea antineutrino flux is $\sigma_f = (5.91\pm0.09)\times10^{-43}$ cm²/fiss The ratio with respect to predicted reactor antineut yield R is $0.952 \pm 0.014 \pm 0.023$ (Huber-Mueller) $1.001 \pm 0.015 \pm 0.027$ (ILL-Vogel), where the uncertainty is experimental and the second is to the reactor models. This yield measurement consistent with the world data, and further comfit the discrepancy between the world reactor antineut flux and the Huber-Mueller model.

ACKNOWLEDGMENTS

The Daya Bay Experiment is supported in part by Ministry of Science and Technology of China, the Department of Energy, the Chinese Academy of Scienthe CAS Center for Excellence in Particle Phy the National Natural Science Foundation of Ch the Guangdong provincial government of The municipal government, the China General Encloar Po-Crown, the Departs Council of the Honor K

5-MeV bump

Daya Bay 1607.05378





Reactor anomaly

 need to fit measured beta-spectra from ²³⁵U, ²³⁹Pu, ²⁴¹Pu [Schreckenbach et al., 80s]
 ²³⁸U [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



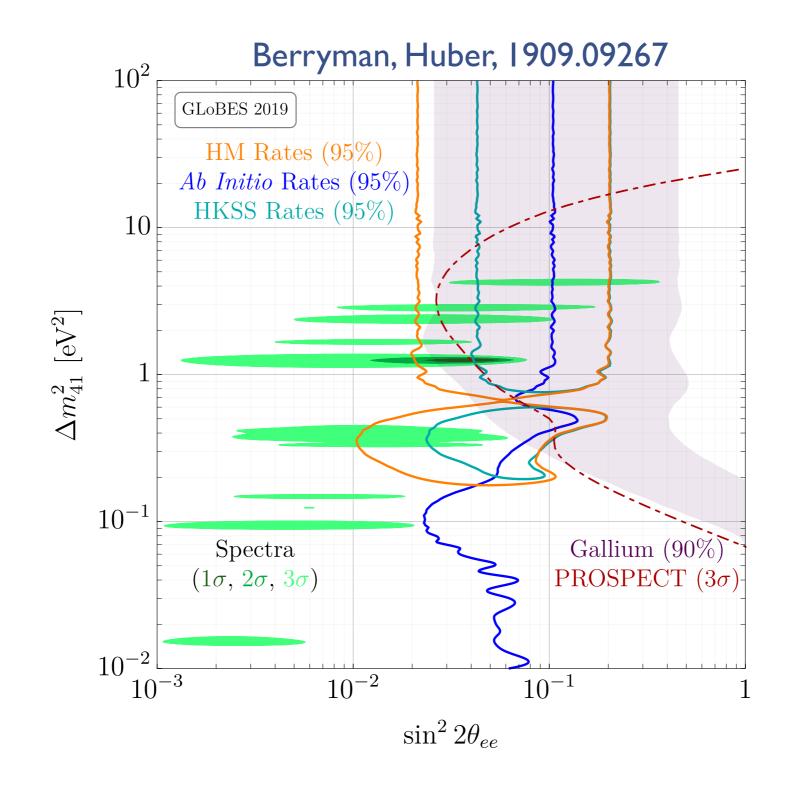
Reactor anomaly — recent updates

- new ab initio calculations [Estienne et al., 1904.09358] find decrease in ²³⁵U 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					\frown
	Analysis	$\chi^2_{3\nu}$	$\chi^2_{\rm min}$	$n_{\rm data}$	p	$n\sigma$
Huber, Muller, 2011	HM Rates	41.4	33.5	40	2.0×10^{-2}	2.3
Estienne et al., 1904.09358	Ab Initio Rates	39.2	37.0	40	0.34	0.95
Hayen et al., 1908.08302	→ 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
	$\left \text{DANSS} + \text{NEOS} \right $	98.9	84.7	84	8.1×10^{-4}	3.3

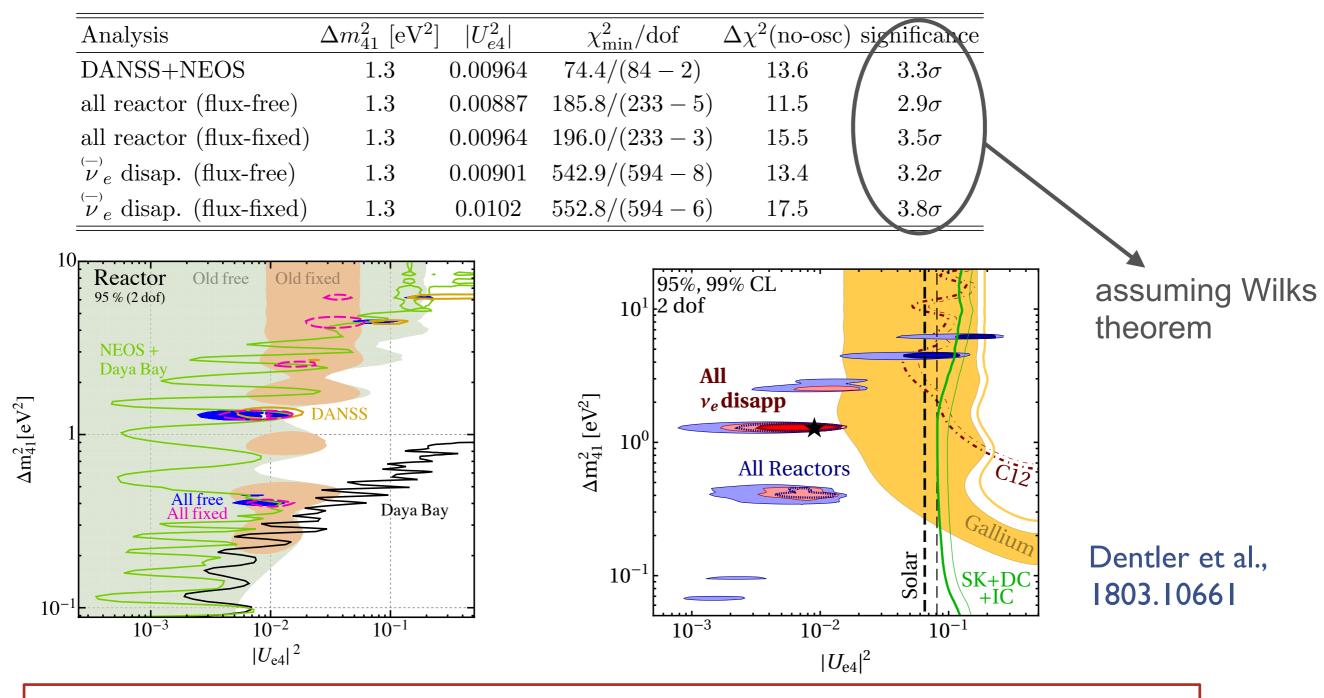


Reactor anomaly — recent updates





Hints from relative shape measurements — 2018 status



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

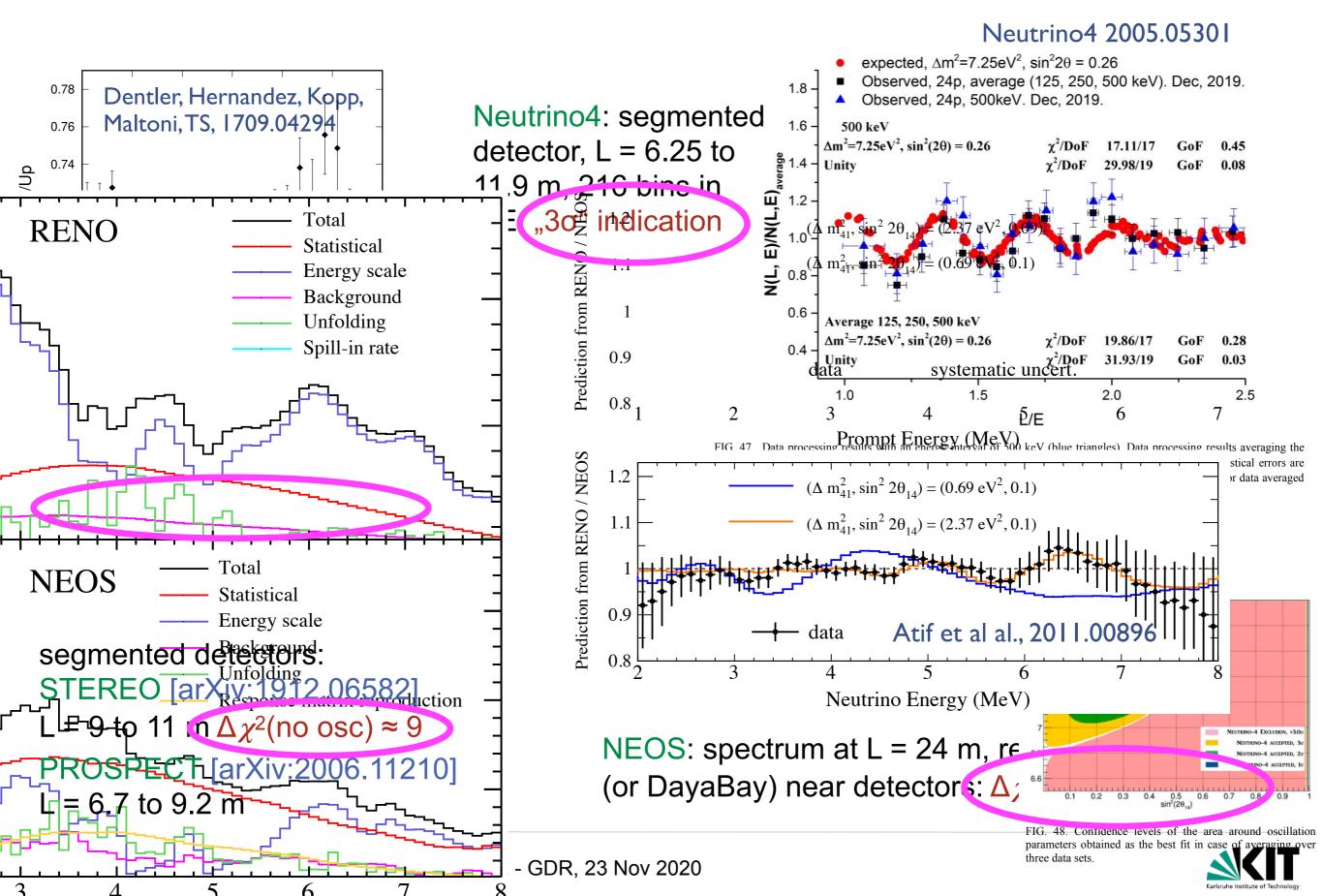


Recent relative spectral measurements

- 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

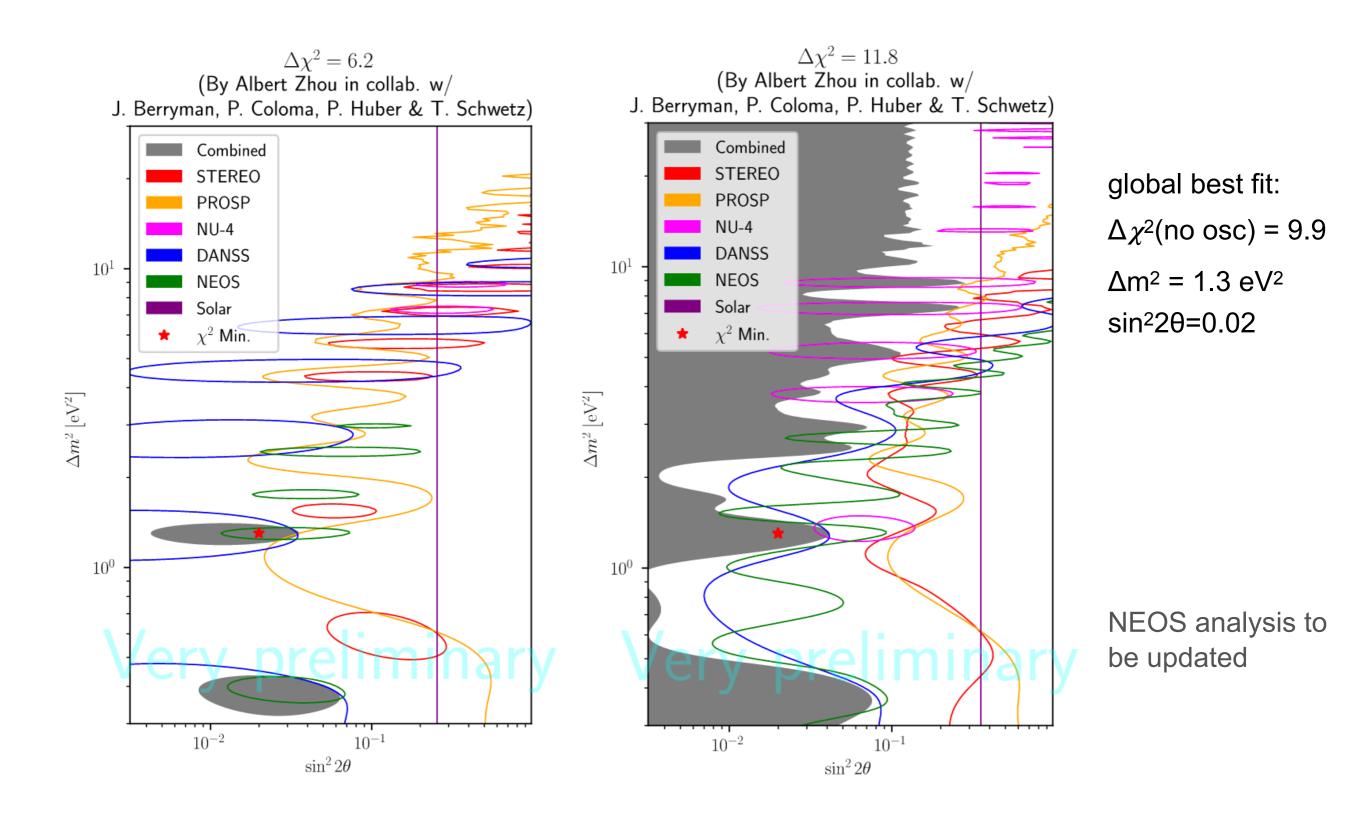


Recent relative spectral measurements

- 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





On the statistical significance of spectral distortions

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

Coloma, Huber, Schwetz, 2008.06083

Several reasons to expect Wilk's theorem to fail:

- physical boundary $\sin^2 2\theta \ge 0$
- Δm^2 becomes unphysical for sin²2 $\theta \rightarrow 0$ (and vice versa)
- oscillatory dependence on Δm^2

 \rightarrow 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

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

Coloma, Huber, Schwetz, 2008.06083

- 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:

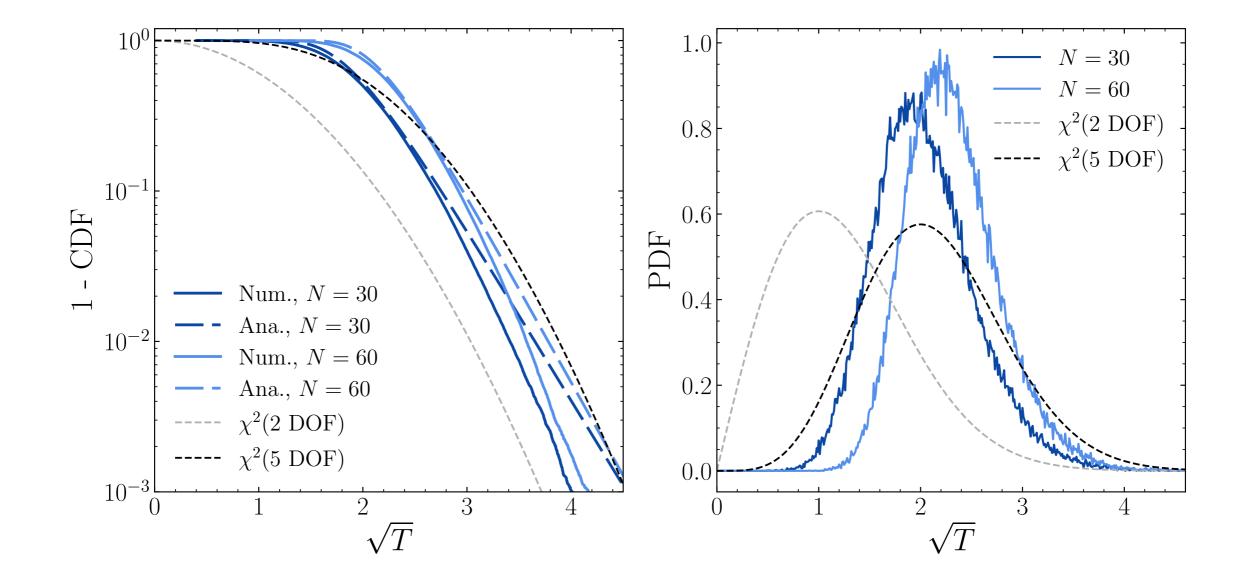
$$T = \chi^2(\text{no osc}) - \chi^2(\text{best fit}) = \chi^2(0,0) - \chi^2(\widehat{\sin^2 2\theta}, \widehat{\Delta m^2})$$

 distribution of sqrt(T) is the distribution of the maximum of N standardnormal variables, where N is of order # bins

$$\sqrt{T} = \max_{k} [a_k] \qquad a_k \dots N \text{ std normal vars}$$



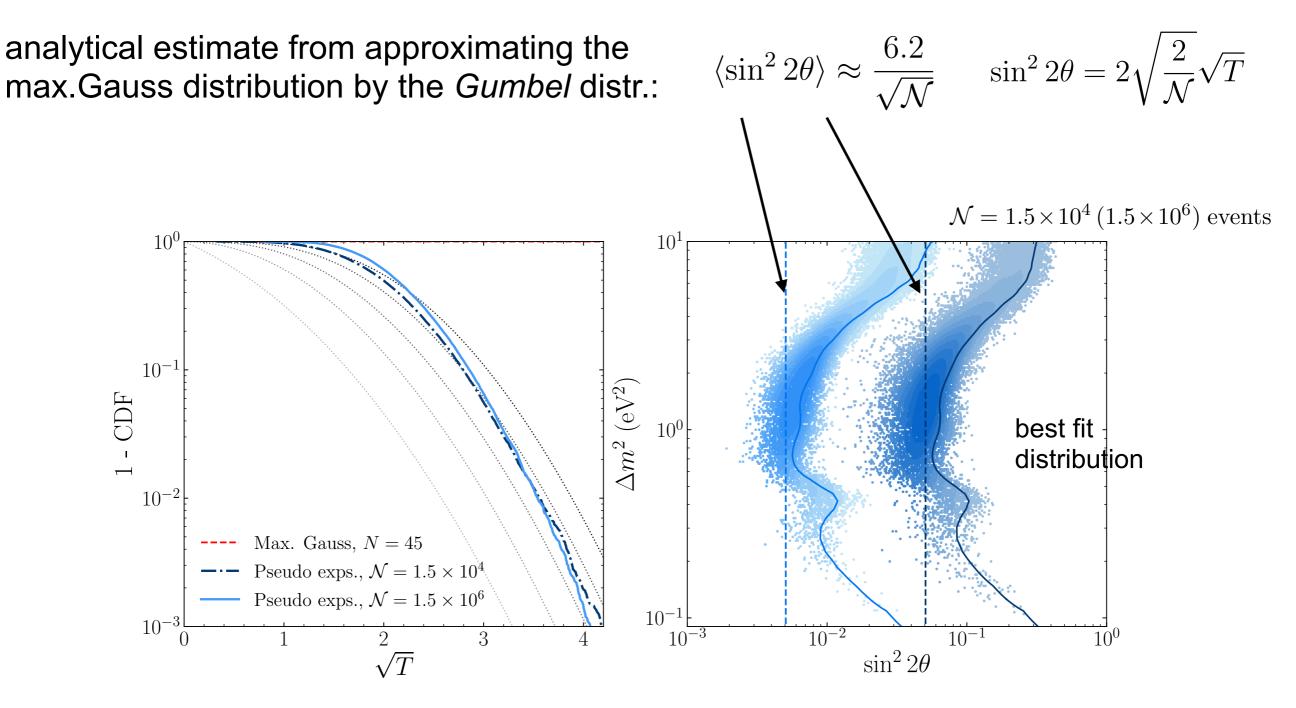
Max. Gaussian vs χ^2 distribution





Simulation of toy reactor experiment

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



best fit value is a *biased estimator* for $sin^22\theta$!



Significances have to evaluated by simulations

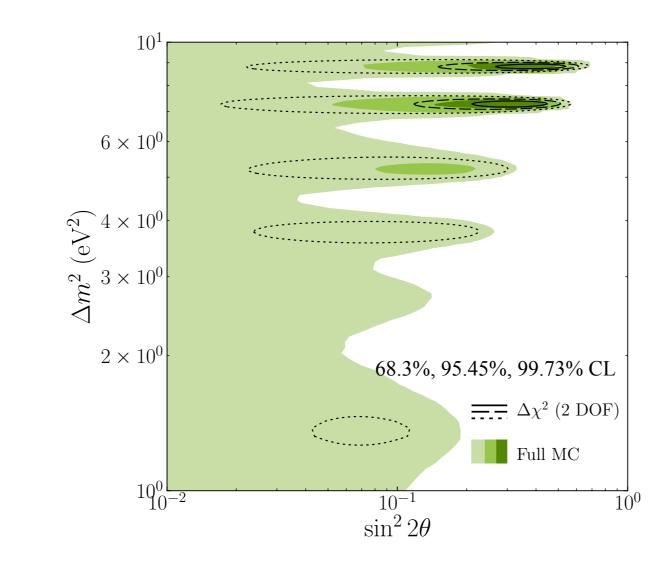
- cannot use Wilk's theorem to convert $\Delta \chi^2$ values into significances
- significances typically reduced by 0.5 to 1 σ

	CL [%]		<i>p</i> -va	lue [%]	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





significance for signal is reduced from 3.2σ (*p*=0.0016) to 2.6σ (*p*=0.0091) (based on stat. errors only)

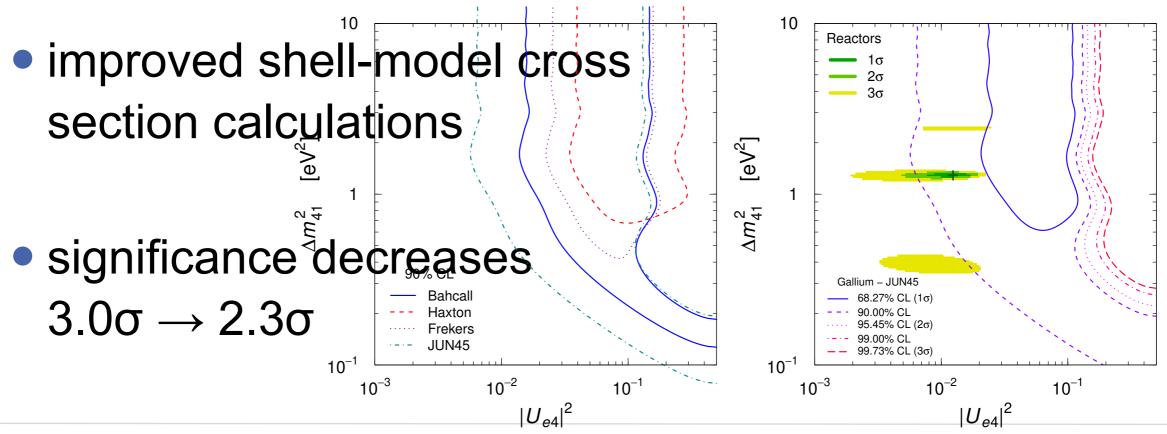


Update on Gallium anomaly

Kostensalo, Suhonen, Giunti, Srivastava, 1906.10980

Table 7: Ratios of measured and expected ⁷¹Ge 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
F	R _{Bahcall}	0.95 ± 0.11	0.81 ± 0.11	0.95 ± 0.12	0.79 ± 0.08	0.85 ± 0.06	2.6σ
F	R _{Haxton}	0.86 ± 0.13	0.74 ± 0.12	0.86 ± 0.14	0.72 ± 0.10	0.76 ± 0.10	2.5σ
F	$R_{\rm Frekers}$	0.93 ± 0.11	0.79 ± 0.11	0.93 ± 0.12	0.77 ± 0.08	0.84 ± 0.05	3.0σ
F	$R_{\rm JUN45}$	0.97 ± 0.11	0.83 ± 0.11	0.97 ± 0.12	0.81 ± 0.08	0.88 ± 0.05	2.3σ





	$\nu_e \& \bar{\nu}_e \text{ from } \mu^{\pm} \text{ Decay}$	425.3 ± 100.2	91.4 ± 27.6]
	$\nu_e \& \bar{\nu}_e \text{ from } K^{\pm} \text{ Decay}$	192.2 ± 41.9	51.2 ± 11.0	(
	$\nu_e \clubsuit \bar{\nu}_e$ from K_L^0 Decay	54.5 ± 20.5	51.4 ± 18.0	(
Hints	$\begin{array}{c} \nu_e & \nu_e & \text{from } K_L & \text{Decay} \\ \hline & \text{Other } \nu_e & \bar{\nu}_e \\ \hline & \text{Unconstrained Bkgd} \end{array}$	6.0 ± 32	672 6.0	
	Unconstrained Bkgd.	1590.5	398.2	
	Constrained Bkgd.	1577.8 ± 85.2	398.7 ± 28.6]
	Total Data	1959	478	
	Excess 2	0381.2 ± 85.2	79.3 ± 28.6	
	0.26% (LSND) $\nu_{\mu} \rightarrow \nu_{e}$	463.1	100.0	

FIG. 1: The MiniBooNE neutrino mode E_{ν}^{QE} distributions, corresponding to the total 12.84×10^{20} POT data, for ν_e CCQE data (points with statistical errors) and background thistogram with systematic errors). The dashed curve shows the best fit to the neutrino-mode data assuming standard two-neutrino oscillations.

MiniBooNE 2020

1.8Ē ЛeV Data (stat err.) ν_{ρ} from μ^+ 7 v_{a} from K^{+/·} from K⁰ π⁰ misid 6 $\Delta \rightarrow N\gamma$ dirt 5 other Constr. Syst. Error Best Fit 3 arXiv:2006.16883 2 8.2 1.2 0.4 0.6 0.8 1 1.4 3.0 E_v^{QE} (GeV)

systematic uncertainties.) The dashed curves show the best fits to the neutrino-mode and antineutrino-mode data assuming standard two-neutrino oscillations.

combined neutrino+antineutrino

excess: 638.0±132.8 events (4.8 σ) curs at $\Delta m^2 = 0.040 \text{ eV}^2$ and $\sin^2 2\theta = 0.894$ with a $\chi^2/ndf = 35.2/28$, corresponding to a probability of 16.4%. This best fit agrees with the MiniBooNE only best fit described below. The MiniBooNE excess of events in both oscillation probability and L/E spectrum is, therefore, consistent with the LSND excess of events of the two experiments have completed with the two events in the two events in the two events in the two events in the two events have completed with the two events in the two events in the two events have completed with the two events in the two events have completed with the two events in the two events have completed with the two events have events in the two events have the two events have events have events have two events have two events have events have two events have two events have two events have events in the two events have events have two events ha

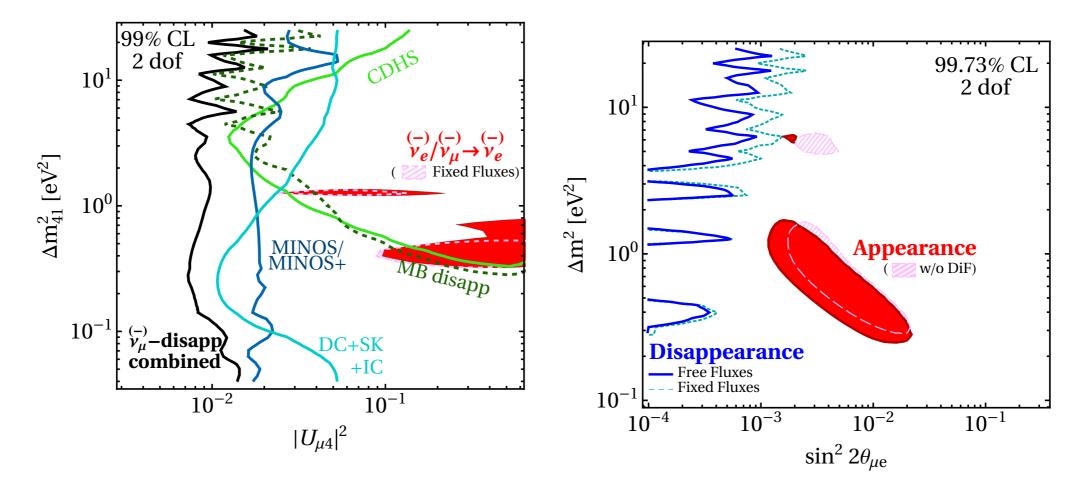
Beam Excess

energy range for the total 12.84×10^{20} POT data. Each 17.5 in of reconstructed • Egean Excess sponds to a distribution of "true" generated neutrino energies, which can overlap 15 adjacent bins. In neutrino mode, a total of 1959 date 12.5 ents pass the $\nu_e^{\otimes \mathbb{C}} \mathbb{C} \mathbb{C} \mathbb{C} \mathbb{E}^{t_e}$ event selection requirements with $200 \leq E_{\nu}^{QE} \approx 1250$ MeV, compared to a back-10 found expectation of $1577.8 \pm 39.7(stat.) \pm 75.4(syst.)$ The excess is then 381.2 ± 85.2 events or ϵ events. 7.5.5 σ effect. Note that the 162.0 event excess in the first 6.46 10^{20} POT data is approximately 1σ lower than the average excess, while the 219.2 event excess ir 2.5 he second 6.38 $\times 10^{20}$ POT data is approximately 10 higher than the average excess Combining the Mini-BooNE neutrino and antineutrino data, there are a total of 2437 events in the 200 $\triangleleft E_{\mu}^{QE} \triangleleft 1250$ MeV en-Q: dy region, conspared to a backgrouth expectation of 1976.5±44.5(stat.)±84L8 Esy(statever(MeV) his correspondent to a total ν_e plus $\bar{\nu}_e$ CCQE excess of 460.5 ± 95.8 events with respect to expectation or a 4.8σ excess. The significance of the combined LSND (3.8 σ) [1] and MiniBooNE Sig(1.3) Excession $\overline{6.1}\sigma \mathcal{V}_{Fig}$ ig ransw ions tal event ex-**3** coses as a function of E_{ν}^{QE} in both neutrino mode and antineutrino mode. The dashed curves show the best fits to standard two-neutrino oscillations.

Fig. 3 compares the L/E_{ν}^{QE} distributions for the Mini-BooNE data excesses in neutrino mode and antineutrino mode to the L/E distribution from LSND [1]. The error bars show statisticaThuSchweitzieGDRy23Alov12020 in the figure, there is agreement among all three data

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 $p\mbox{-value} < 10^{-6}$

Dentler et al, 1803.10661



Strong tension btw appearance and disappearance

\rightarrow sterile neutrino oscillation explanation of LSND/MB excluded

... robust result wrt to individual experiments

Analysis	$\chi^2_{ m min,global}$	$\chi^2_{ m min,app}$	$\Delta \chi^2_{ m app}$	$\chi^2_{ m min,disapp}$	$\Delta \chi^2_{\rm disapp}$	$\chi^2_{\rm PG}/{\rm dof}$	PG
Global	1120.9	79.1	11.9	1012.2	17.7	29.6/2	3.71×10^{-7}
Removing anomalous	s data sets						
w/o LSND	1099.2	86.8	12.8	1012.2	0.1	12.9/2	$1.6 imes 10^{-3}$
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 constraint	S						
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}
m w/o~MB~disapp	1054.9	79.1	14.7	947.2	13.9	28.7/2	$6.0 imes 10^{-7}$
w/o CDHS	1104.8	79.1	11.9	997.5	16.3	28.2/2	$7.5 imes 10^{-7}$
Removing classes of data							
$\stackrel{(-)}{\nu}_{e}$ dis vs app	628.6	79.1	0.8	542.9	5.8	6.6/2	$3.6 imes 10^{-2}$
$\stackrel{(-)}{\nu}_{\mu}$ dis vs app	564.7	79.1	12.0	468.9	4.7	16.7/2	$2.3 imes 10^{-4}$
$\stackrel{(-)}{\nu}_{\mu}^{\prime}$ dis + solar vs app	884.4	79.1	13.9	781.7	9.7	23.6/2	3.4×10^{-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

- de many of them invoke sterile neutrinos of some kind many of them are actually excluded by some data mares-Riuz, Pascoli, TS 05; Gninenko 09, 10; machado, Zukanovich, 18; Ballett, Pascoli, Ross-Lonergan, 18 Be

mant 05

- 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 31

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, ...

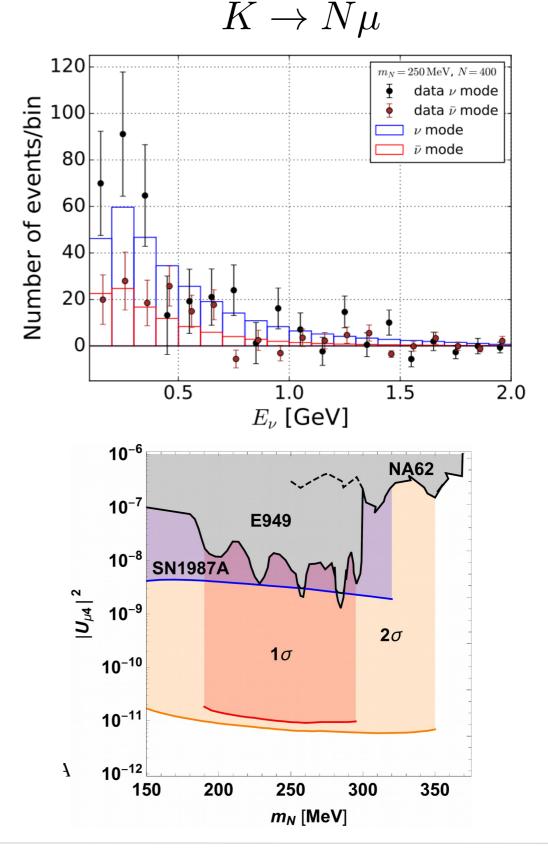
- sterile neutrino N with $m_N \sim keV$ to ~500 MeV
- produce N either by mixing or by up-scattering
- decay:
 - \bullet N $\rightarrow \Phi$ v_e with standard neutrino interact in detector
 - electromagn. decay inside MB detector N $\rightarrow v\gamma$ / ve[±] (no LSND explanation)



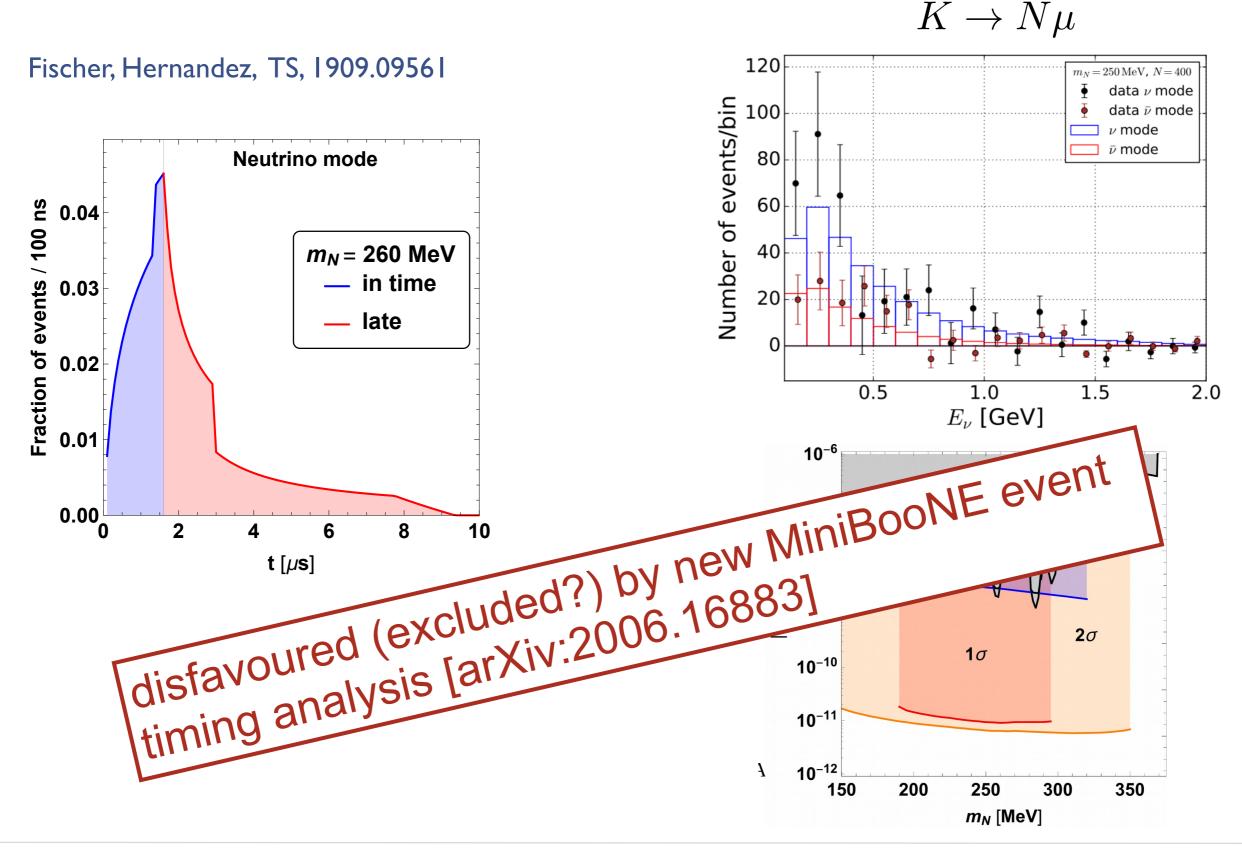
MiniBooNE and a decaying sterile neutrino — example:

Fischer, Hernandez, TS, 1909.09561

- sterile neutrino N with
 m_N ~ 250 MeV (m_π < m_N < m_K)
- produce N in kaon decays via mixing K → N µ/e
- decay inside MB detector N $\rightarrow v\gamma$ via $\mathcal{O}_{N\rightarrow\gamma\nu} = \frac{1}{\Lambda} \bar{N} \sigma^{\alpha\beta} \nu F_{\alpha\beta}$



MiniBooNE and a decaying sterile neutrino — example:





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 $3.0\sigma \to 2.3\sigma$ 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!

