Light sterile neutrinos: fact or fiction?

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The IceCube Particle Astrophysics Symposium
May 8 – 10, 2017; Madison, WI

Evidence in favor

- LSND $\bar{\nu}_\mu \to \bar{\nu}_e$
- MiniBooNE $\bar{\nu}_\mu \to \bar{\nu}_e$ and $\nu_\mu \to \nu_e$
- T2K $\nu_e \to \nu_e$
- Gallium $\nu_e \to \nu_e$
- Reactors $\nu_e \to \nu_e$

Disappearance and appearance

$\nu_\mu \to \nu_e$ requires that the sterile neutrino mixes with both ν_e and ν_μ

$\Rightarrow$ there must be effects in *both* $\nu_e \to \nu_e$ and $\nu_\mu \to \nu_\mu$

Up to factors of 2, the energy averaged probabilities obey

$$P_{\mu e} \lesssim (1 - P_{\mu\mu})(1 - P_{ee})$$

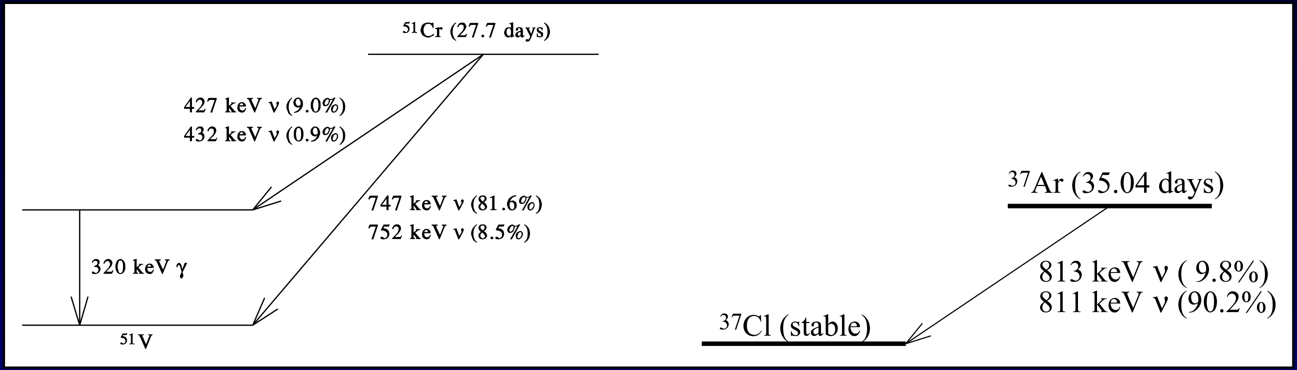
Gallium anomaly

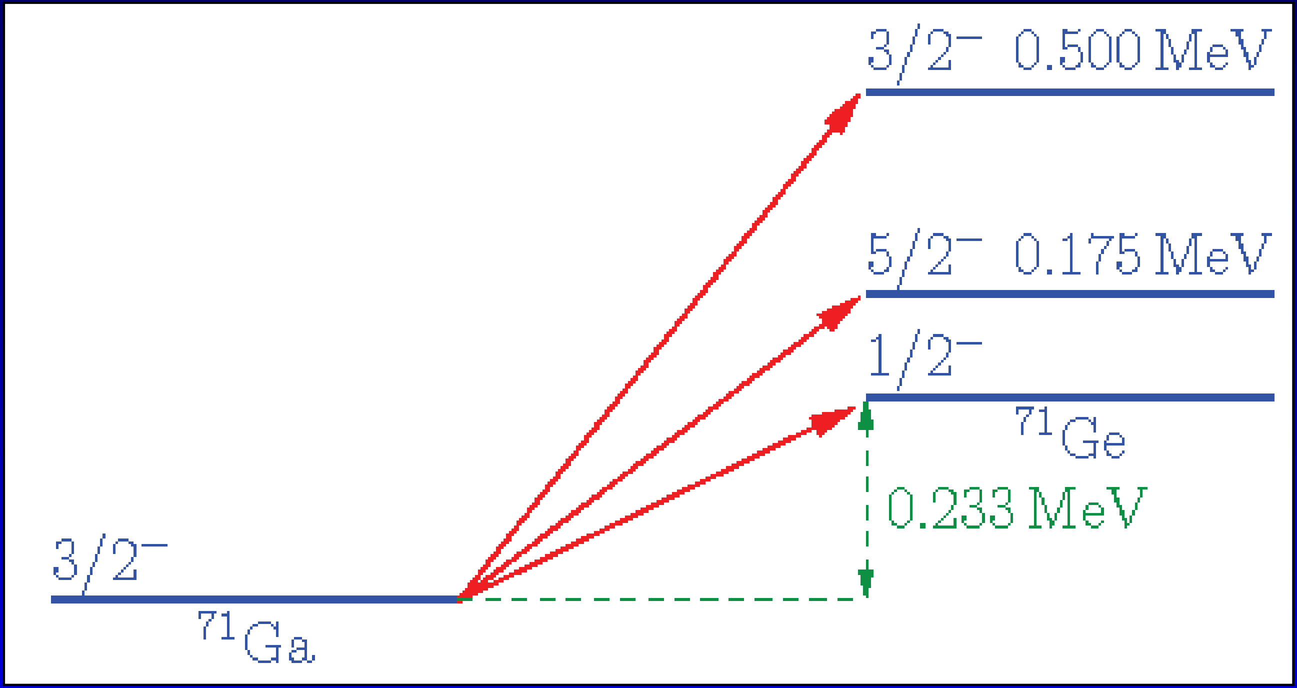
	GALLEX		SAGE	
k	G1	G2	S1	S2
source	^{51}Cr	^{51}Cr	^{51}Cr	^{37}Ar
R_B^k	0.953 ± 0.11	$0.812^{+0.10}_{-0.11}$	0.95 ± 0.12	$0.791 \pm ^{+0.084}_{-0.078}$
R_H^k	$0.84^{+0.13}_{-0.12}$	$0.71^{+0.12}_{-0.11}$	$0.84^{+0.14}_{-0.13}$	$0.70 \pm ^{+0.10}_{-0.09}$
radius [m]	1.9		0.7	
height [m]	5.0		1.47	
source height [m]	2.7	2.38	0.72	

25% deficit of ν_e from radioactive sources at short distances

- effect depends on nuclear matrix element

Nuclear matrix elements – I





Nuclear matrix elements – II

Correction from excited states Haxton 1998

$$0.667\frac{GT(5/2^-)}{GT(gs)} + 0.218\frac{GT(3/2^-)}{GT(gs)}$$

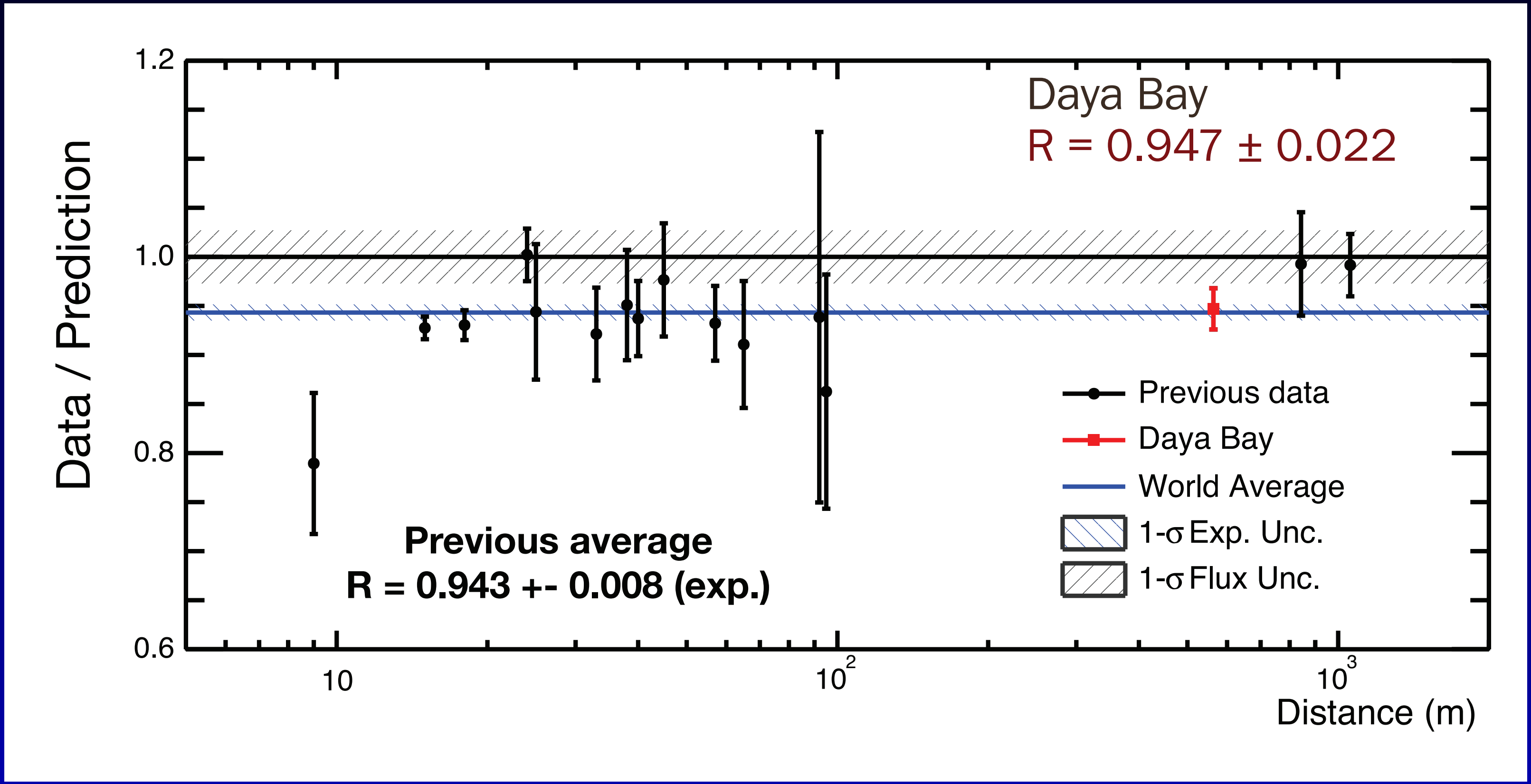
$GT(5/2^-)$ and $GT(3/2^-)$ are measured by exchange reactions

		$GT(5/2^-)$	$GT(3/2^-)$
Krofcheck et al. (2011)	71Ga(p;n)71Ge	< 0.005	0.011 ± 0.002
Frekers et al. (1985)	71Ga(3He;3H)71Ge	0.0034 ± 0.0026	0.0176 ± 0.0014

Combined: $\bar{R} = 0.84 \pm 0.05$ (that's nearly $3\,\sigma$)

Giunti et al., 2015

The reactor anomaly



Daya Bay, 2014

Mueller *et al.*, 2011, 2012 – where are all the neutrinos gone?

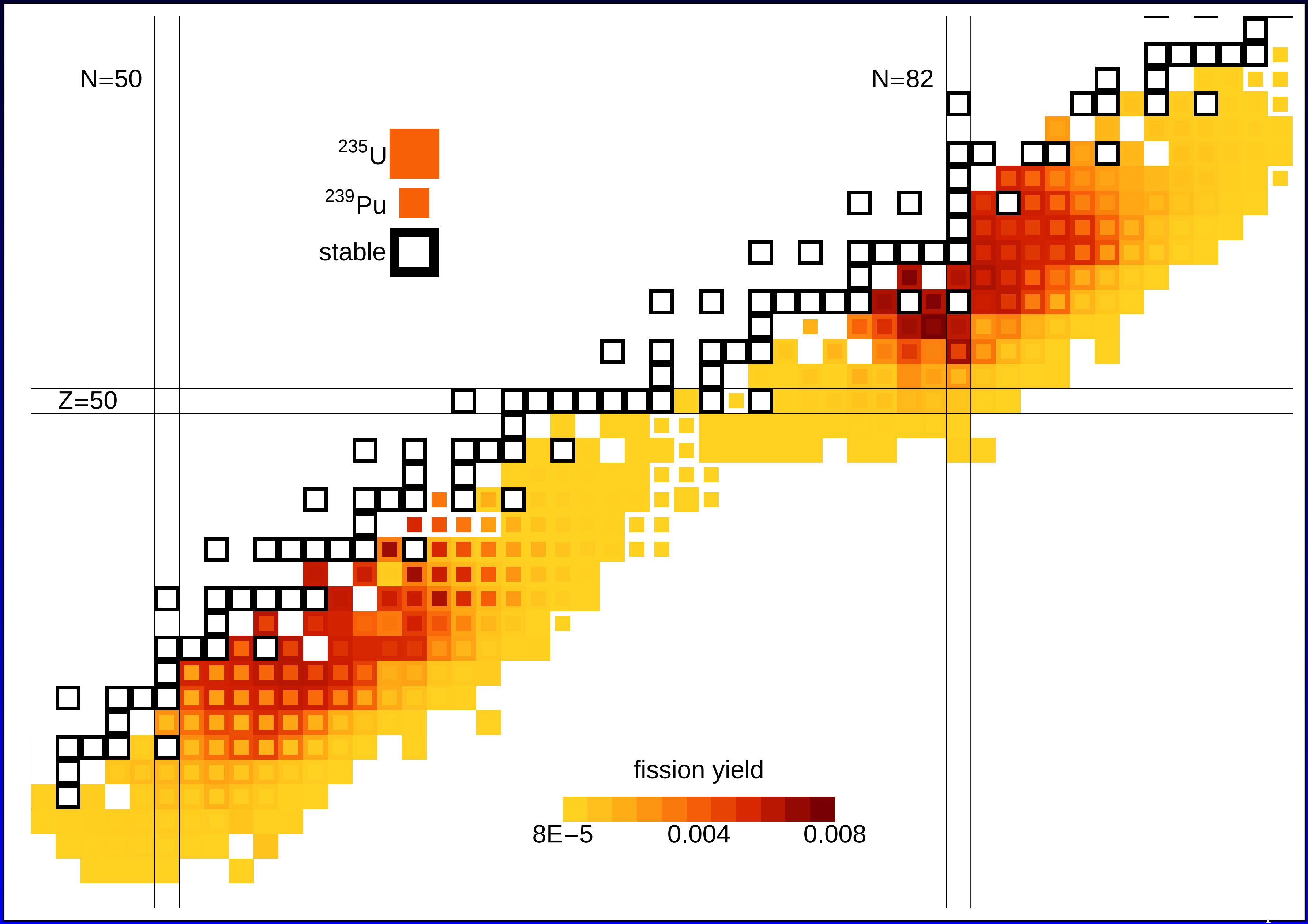
Contributors to the anomaly

6% deficit of $\bar{\nu}_e$ from nuclear reactors at short distances

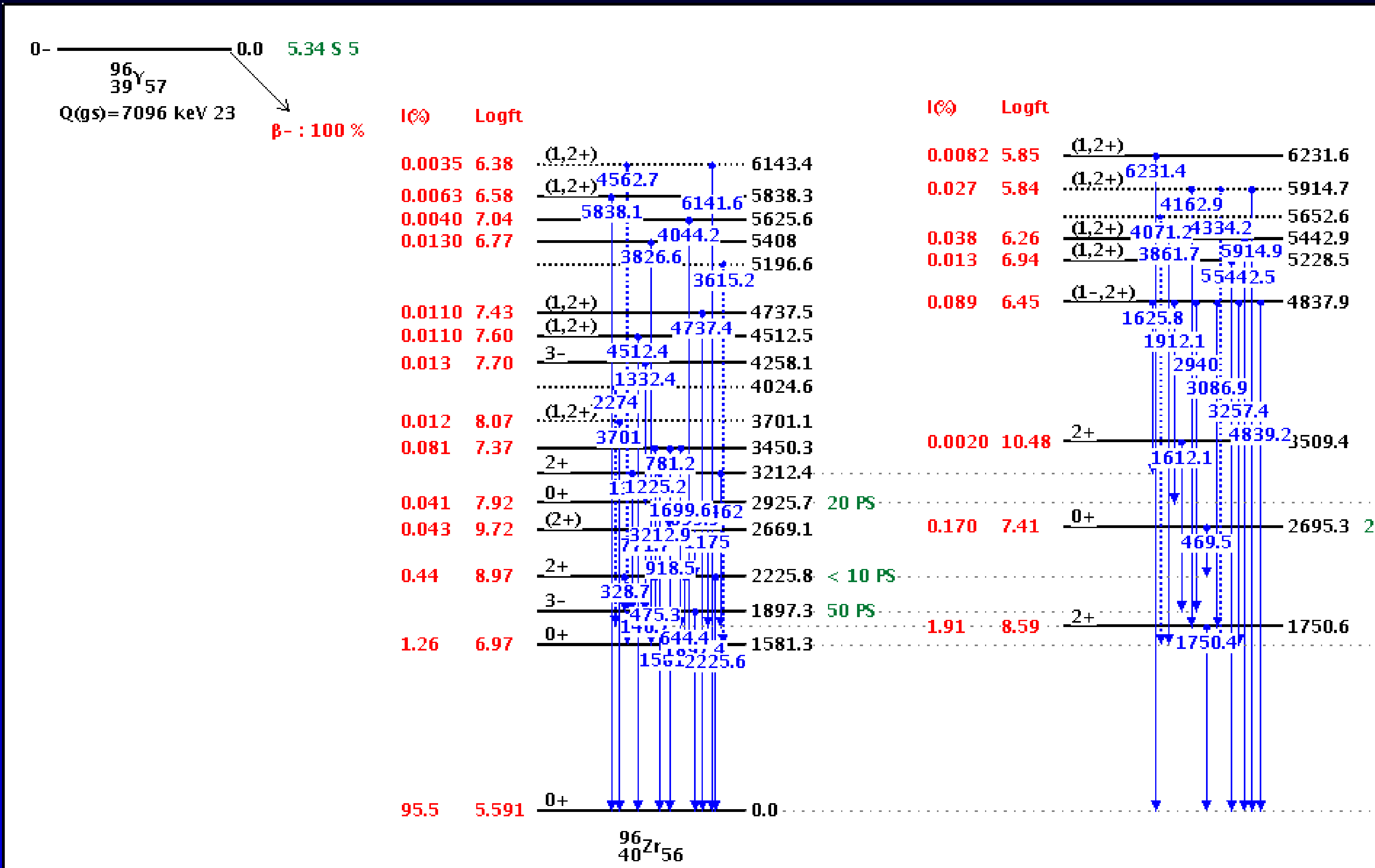
- 3% increase in reactor neutrino fluxes
- decrease in neutron lifetime (see submitted position paper)
- inclusion of long-lived isotopes (non-equilibrium correction)

The effects is therefore only partially due to the fluxes, but the error budget is clearly dominated by the fluxes.

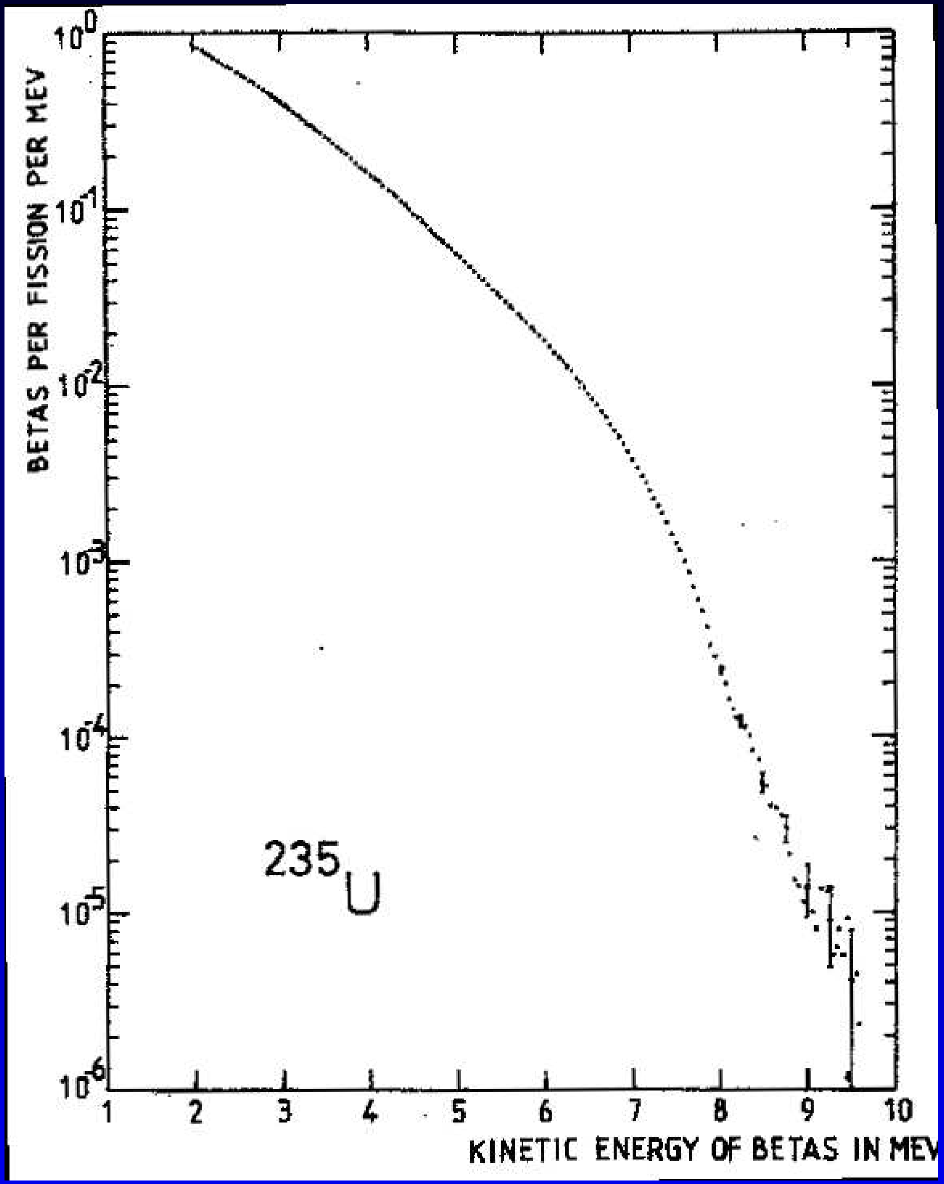
Neutrinos from fission



β-branches



β-spectrum from fission



Schreckenbach, *et al.* 1985.

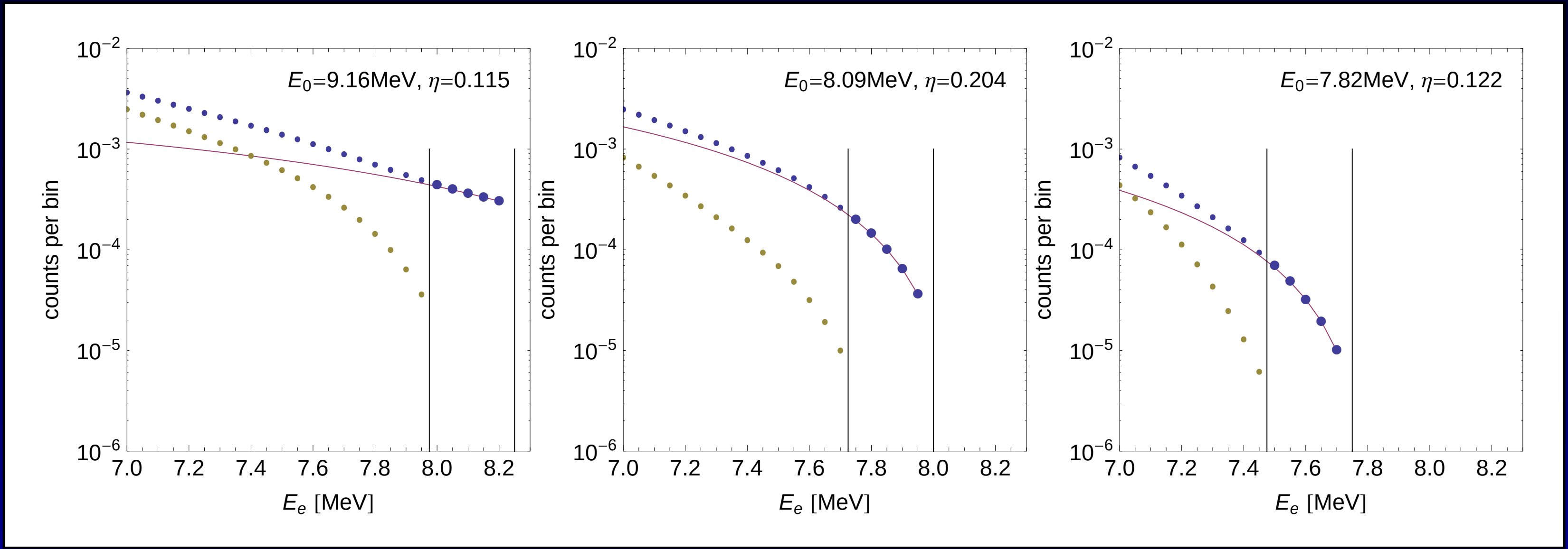
^{235}U foil inside the High Flux Reactor at ILL

Electron spectroscopy with a magnetic spectrometer

Same method used for ^{239}Pu and ^{241}Pu

For ^{238}U recent measurement by Haag *et al.*, 2013

Virtual branches



1 – fit an allowed β-spectrum with free normalization η and endpoint energy E_0 the last s data points

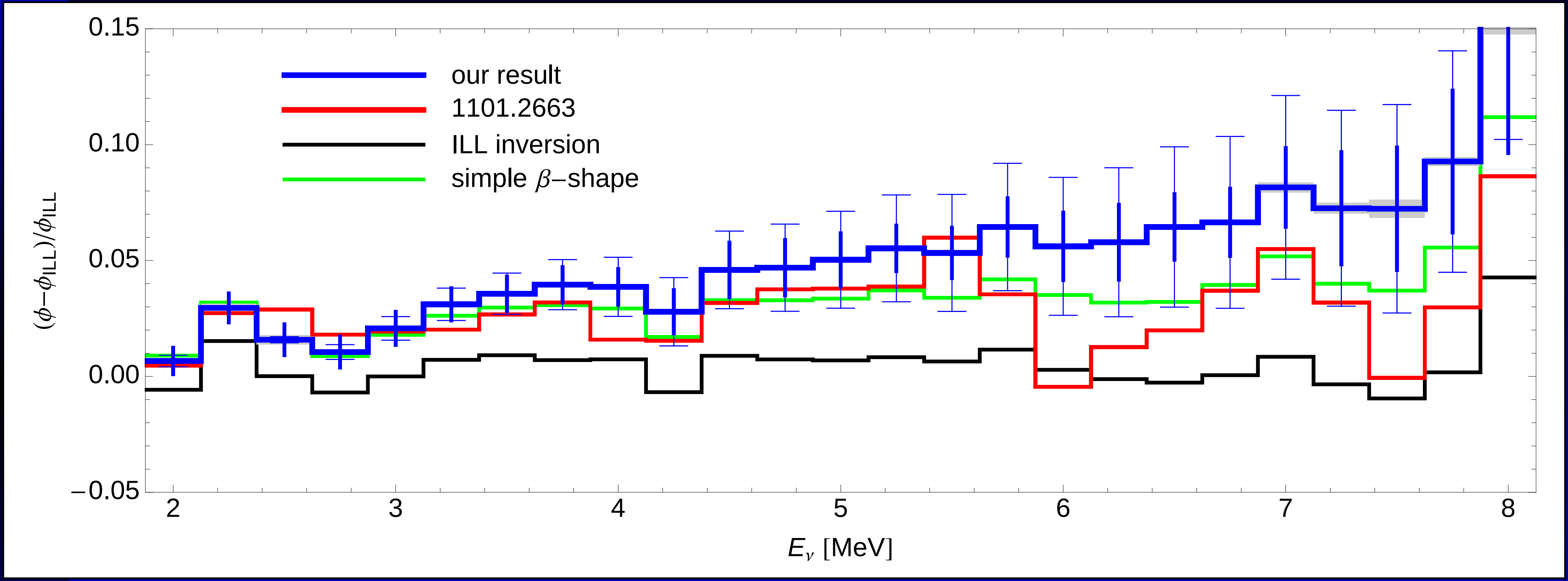
2 – delete the last s data points

3 – subtract the fitted spectrum from the data

4 – goto 1

Invert each virtual branch using energy conservation into a neutrino spectrum and add them all. *e.g.* Vogel, 2007

Reactor antineutrino fluxes

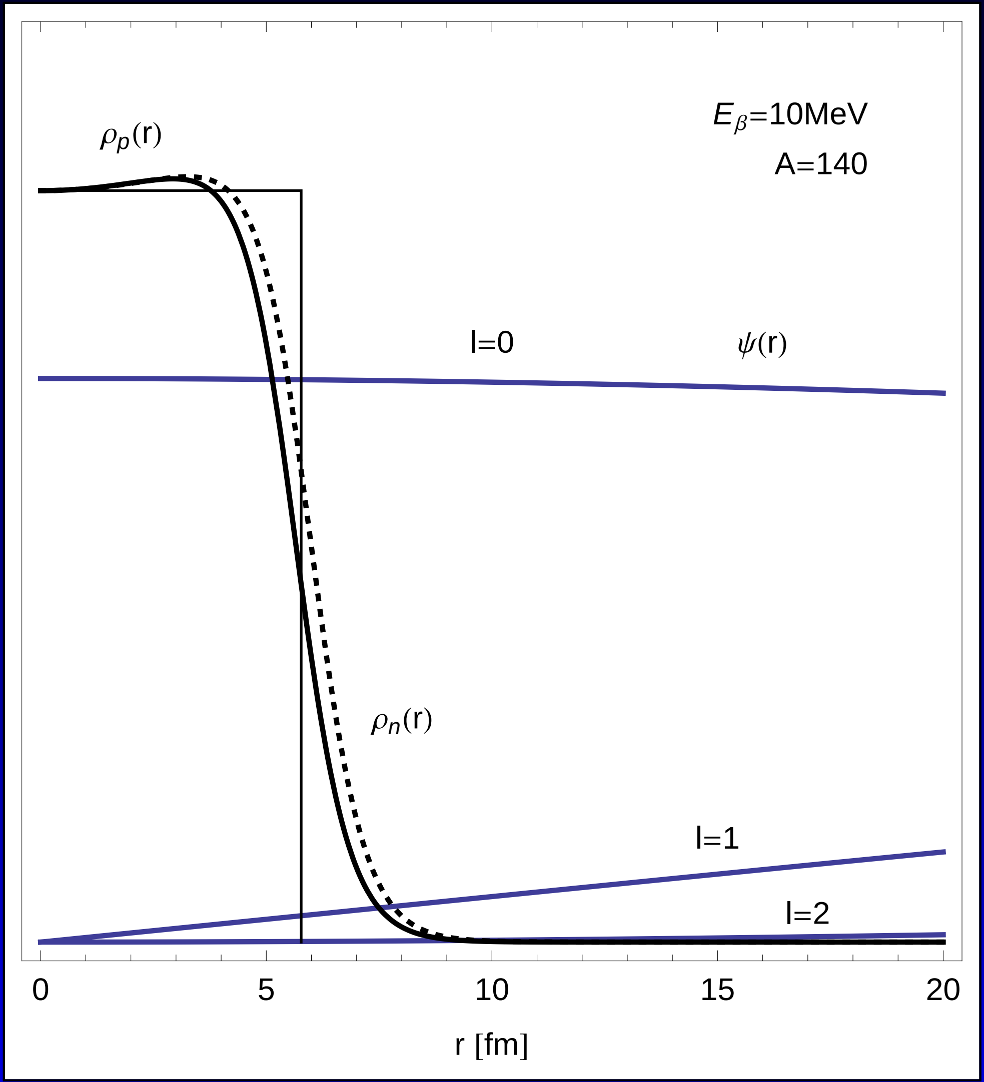


Shift with respect to ILL results, due to

a) different effective nuclear charge distribution

b) branch-by-branch application of shape corrections

Forbidden decays



$e,\bar{\nu}$ final state can form a singlet or triplet spin state J=0 or J=1

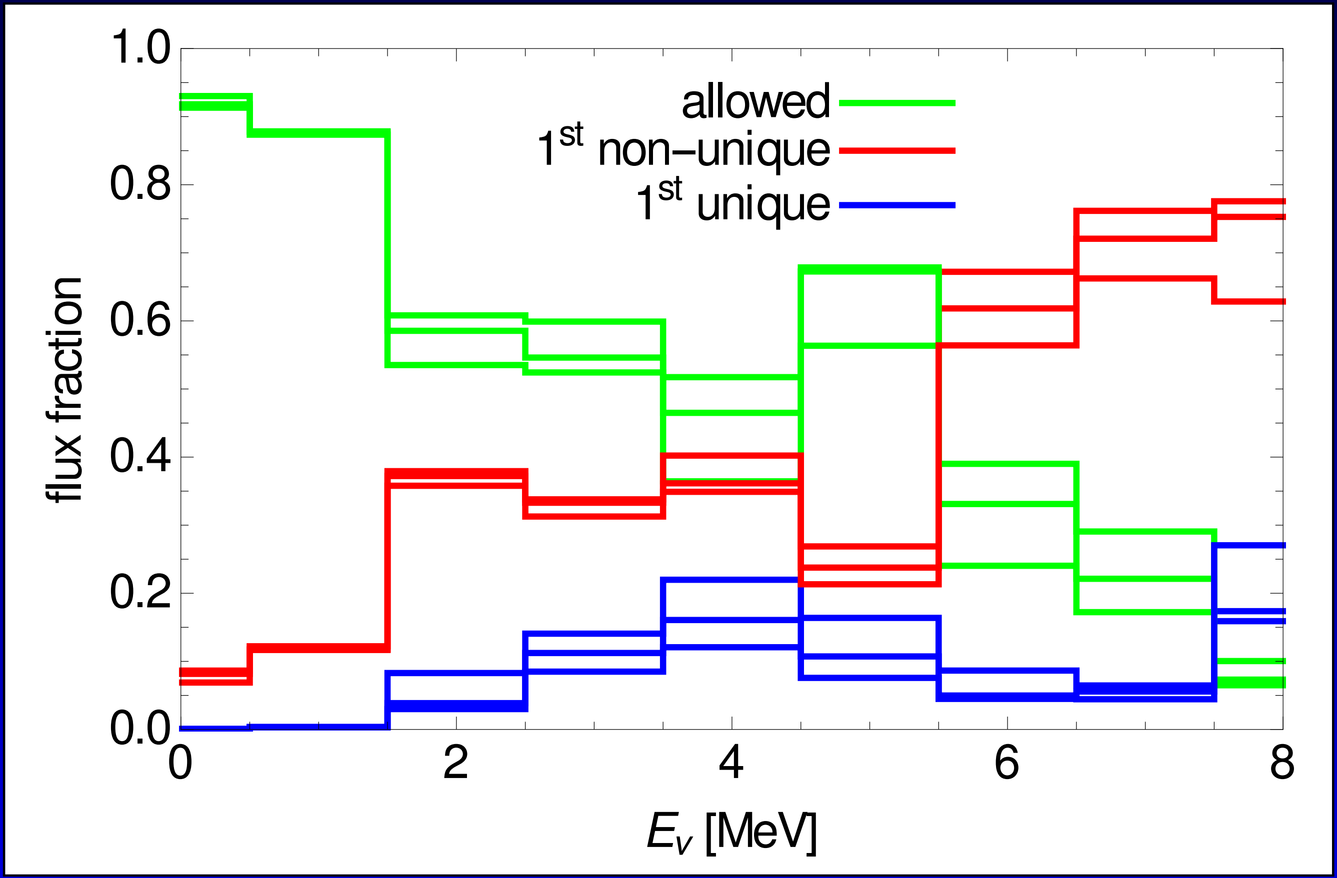
Allowed:
s-wave emission ($l = 0$)

Forbidden:
p-wave emission ($l = 1$) or $l > 1$

Significant dependence on nuclear structure in forbidden decays$\rightarrow$ large uncertainties!

Same for all

Based on JEFF fission yields and using ENSDF spin-parity assignments

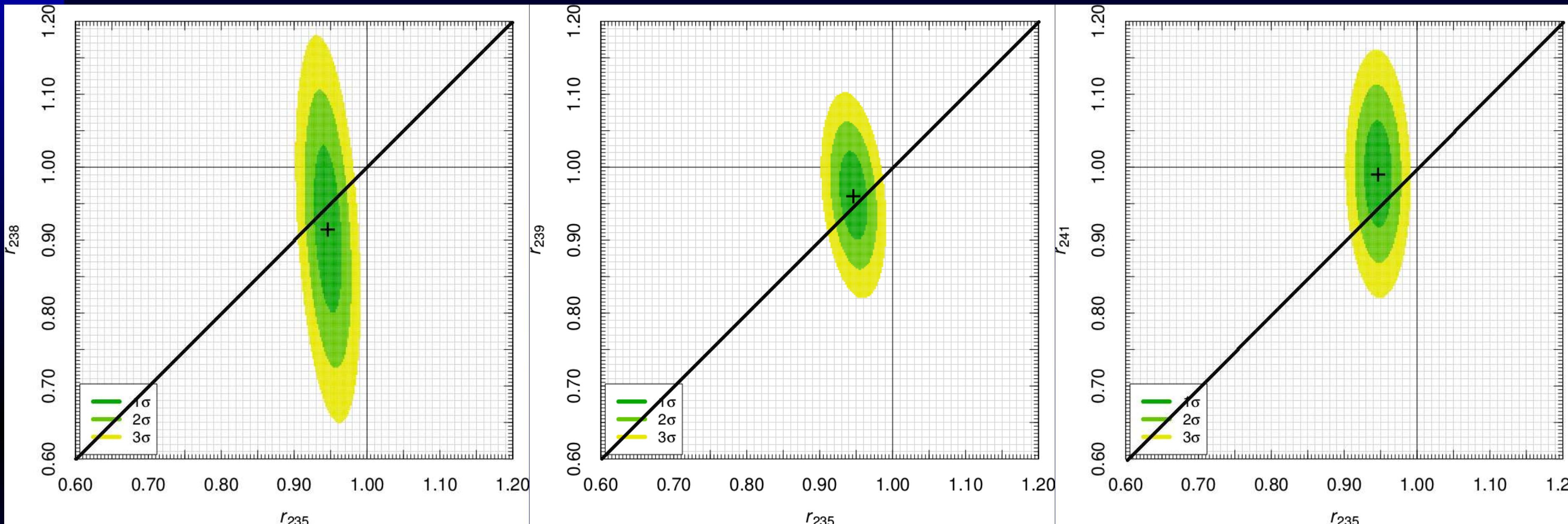


Look at past data

a	Experiment	f^a_{235}	f^a_{238}	f^a_{239}	f^a_{241}	$R^{\text{exp}}_{a,\text{SH}}$	σ^{exp}_a [%]	σ^{cor}_a [%]	L_a [m]
1	Bugey-4	0.538	0.078	0.328	0.056	0.932	1.4	1.4	15
2	Rovno91	0.606	0.074	0.277	0.043	0.930	2.8	1.8	18
3	Rovno88-1I	0.607	0.074	0.277	0.042	0.907	6.4	3.8	18
4	Rovno88-2I	0.603	0.076	0.276	0.045	0.938	6.4	3.8	18
5	Rovno88-1S	0.606	0.074	0.277	0.043	0.962	7.3	3.8	18
6	Rovno88-2S	0.557	0.076	0.313	0.054	0.949	7.3	3.8	25
7	Rovno88-3S	0.606	0.074	0.274	0.046	0.928	6.8	3.8	18
8	Bugey-3-15	0.538	0.078	0.328	0.056	0.936	4.2	4.1	15
9	Bugey-3-40	0.538	0.078	0.328	0.056	0.942	4.3	4.1	40
10	Bugey-3-95	0.538	0.078	0.328	0.056	0.867	15.2	4.1	95
11	Gosgen-38	0.619	0.067	0.272	0.042	0.955	5.4	3.8	37.9
12	Gosgen-46	0.584	0.068	0.298	0.050	0.981	5.4	3.8	45.9
13	Gosgen-65	0.543	0.070	0.329	0.058	0.915	6.7	3.8	64.7
14	ILL	1	0	0	0	0.792	9.1	8.0	8.76
15	Krasnoyarsk87-33	1	0	0	0	0.925	5.0	4.8	32.8
16	Krasnoyarsk87-92	1	0	0	0	0.942	20.4	4.8	92.3
17	Krasnoyarsk94-57	1	0	0	0	0.936	4.2	2.5	57
18	Krasnoyarsk99-34	1	0	0	0	0.946	3.0	2.5	34
19	SRP-18	1	0	0	0	0.941	2.8	0.0	18.2
20	SRP-24	1	0	0	0	1.006	2.9	0.0	23.8
21	Nucifer	0.926	0.061	0.008	0.005	1.014	10.7	0.0	7.2
22	Chooz	0.496	0.087	0.351	0.066	0.996	3.2	0.0	≈ 1000
23	Palo Verde	0.600	0.070	0.270	0.060	0.997	5.4	0.0	≈ 800
24	Daya Bay	0.561	0.076	0.307	0.056	0.946	2.0	0.0	≈ 550
25	RENO	0.569	0.073	0.301	0.056	0.946	2.1	0.0	≈ 410
26	Double Chooz	0.511	0.087	0.340	0.062	0.935	1.4	0.0	≈ 415

Giunti, 2016

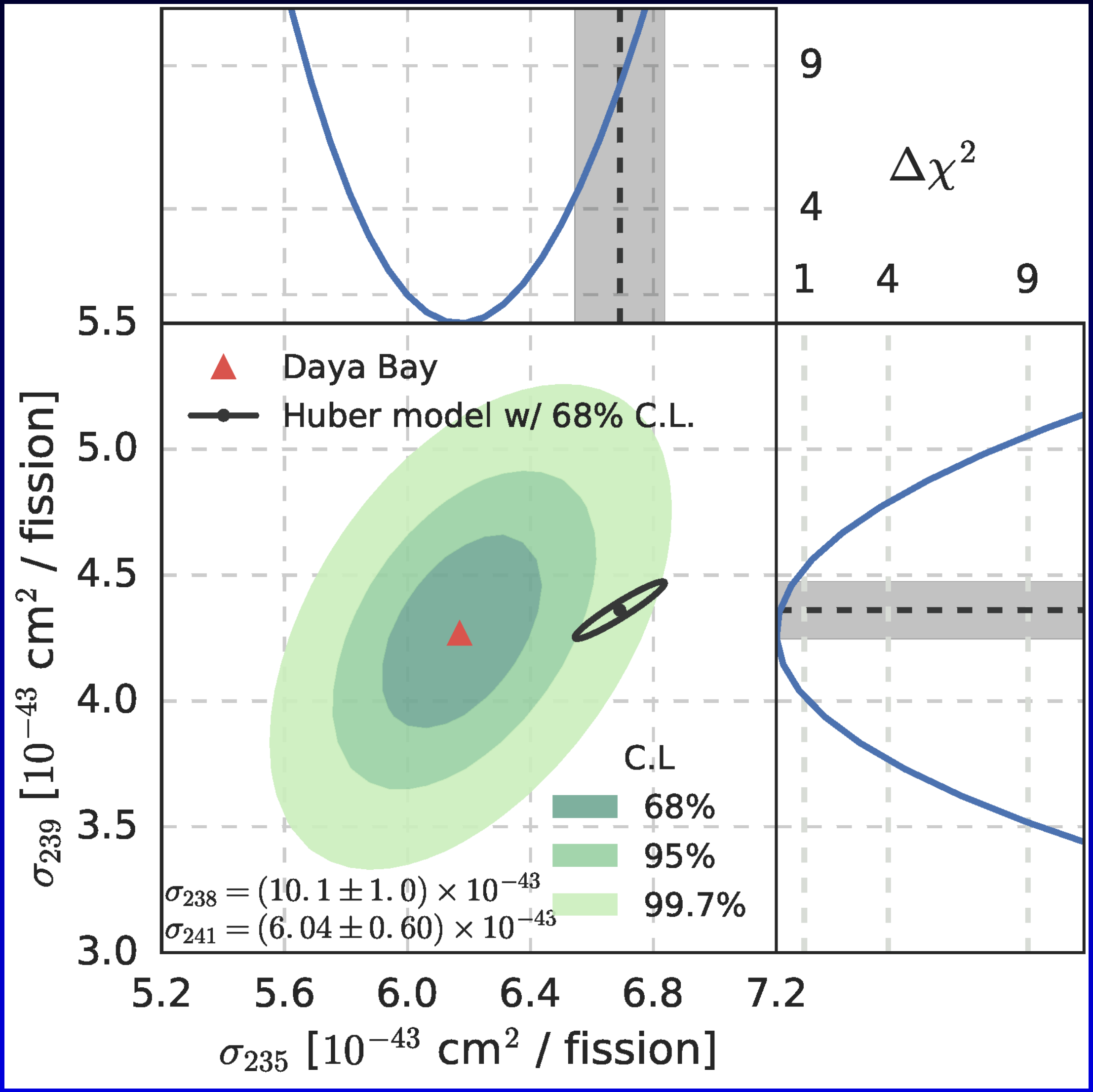
What does this tell us?



Giunti, 2016

Is U235 odd?
Are the error bars for U235 just smaller?

Latest result of Daya Bay

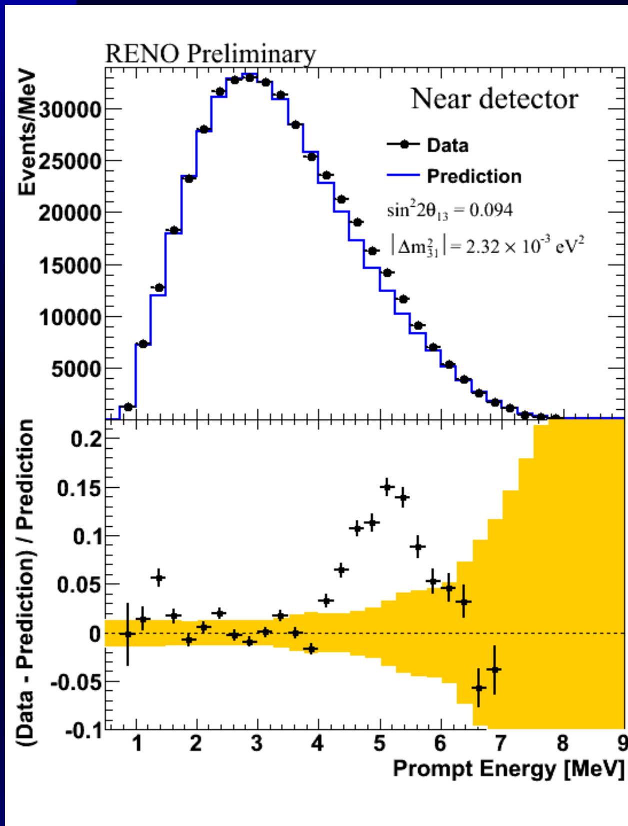


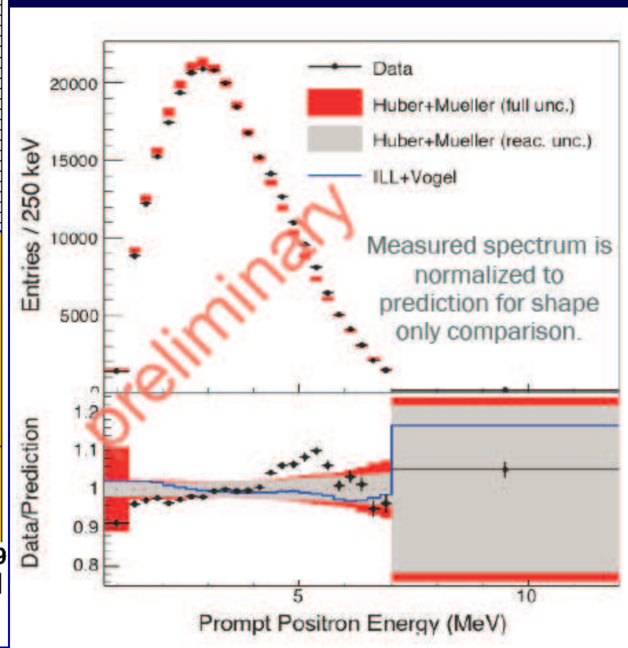
Daya Bay, 2017, see also talks by B. Littlejohn and K. Heeger

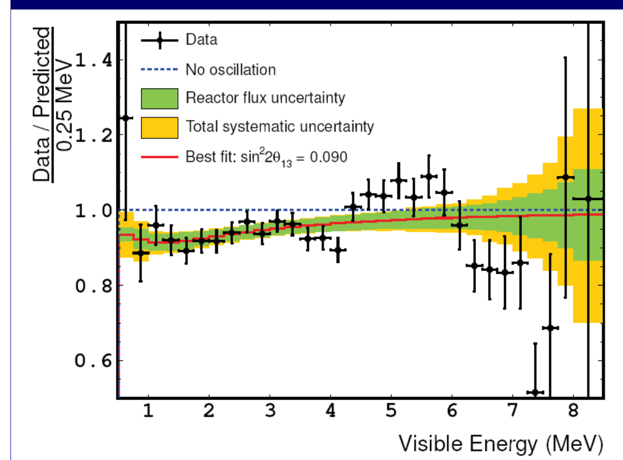
More neutrino measurements

- In Daya Bay, RENO and Double Chooz, the distance is such that all sterile oscillations are averaged away – no confusion between nuclear physics and new physics
- The statistics in the Daya Bay near detectors is around 1 million events
- In combination, this should provide a good test of our ability to compute reactor fluxes

The 5 MeV bump





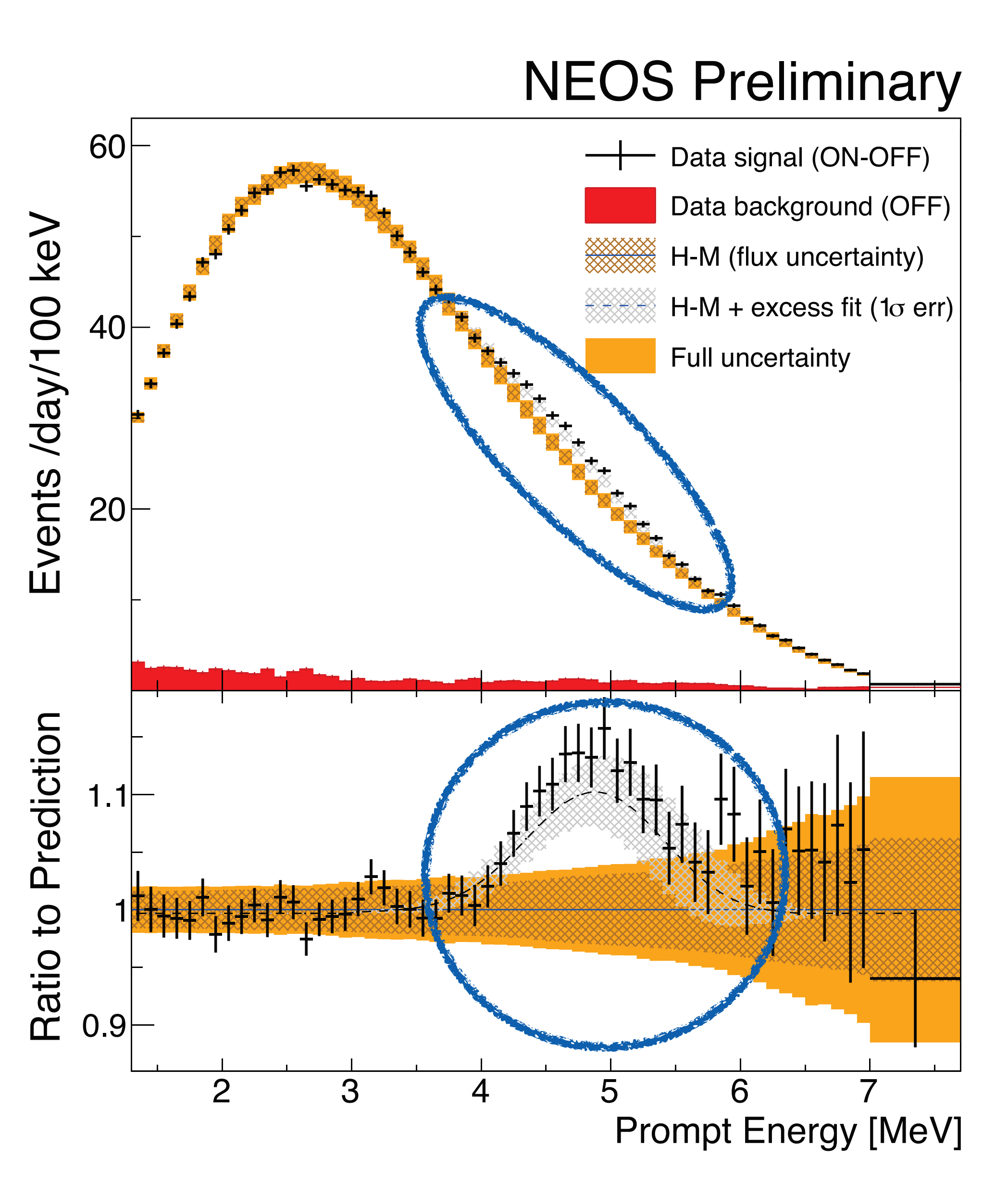


Seen by all three reactor experiments

Tracks reactor power

Seems independent of burn-up

NEOS

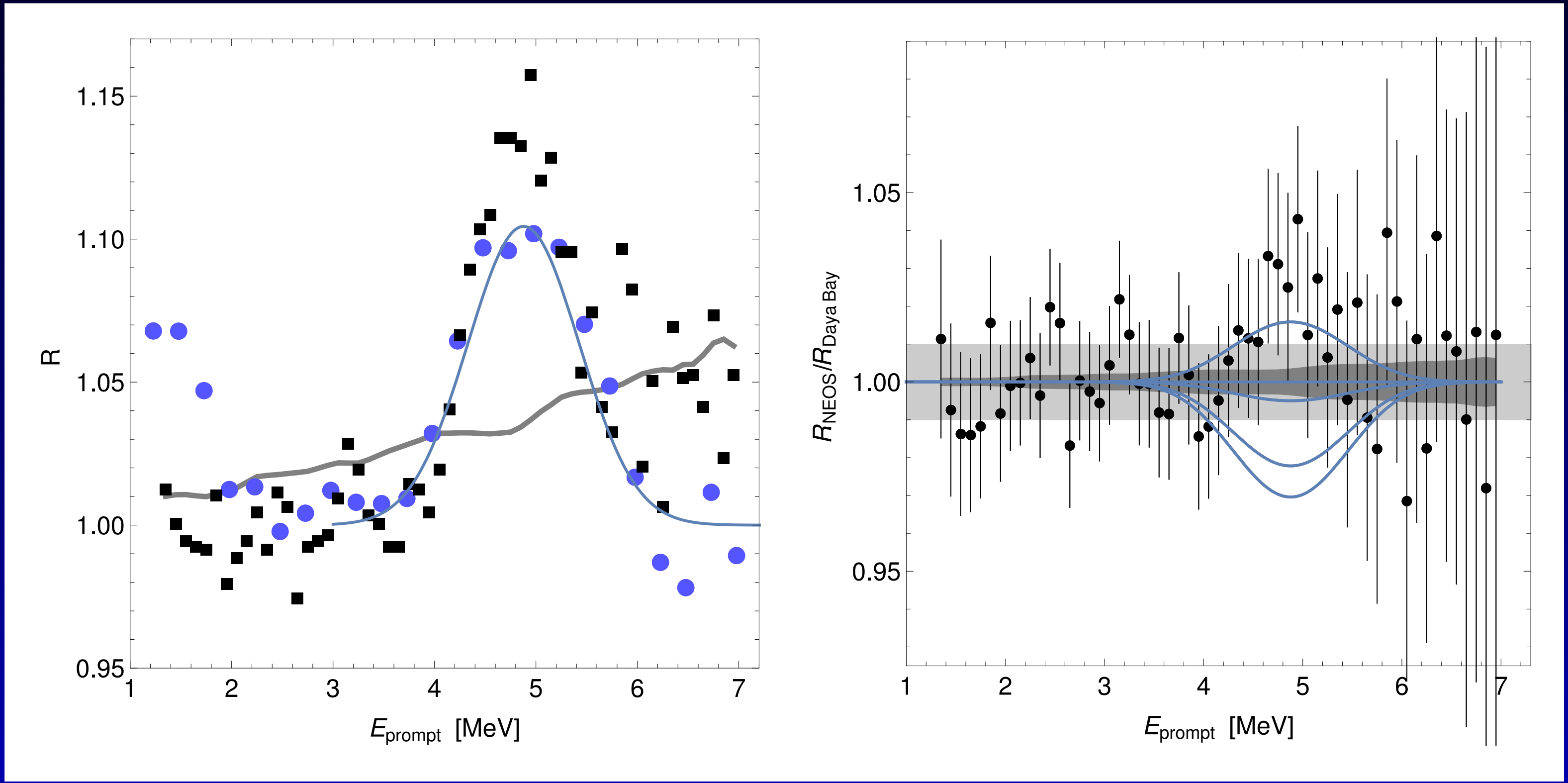


Y. Oh, ICHEP 2016

24m from a large core (power reactor), confirms bump, but unclear what it says about steriles…

appears to disfavor $\Delta m^2 < 1\,\mathrm{eV}^2$

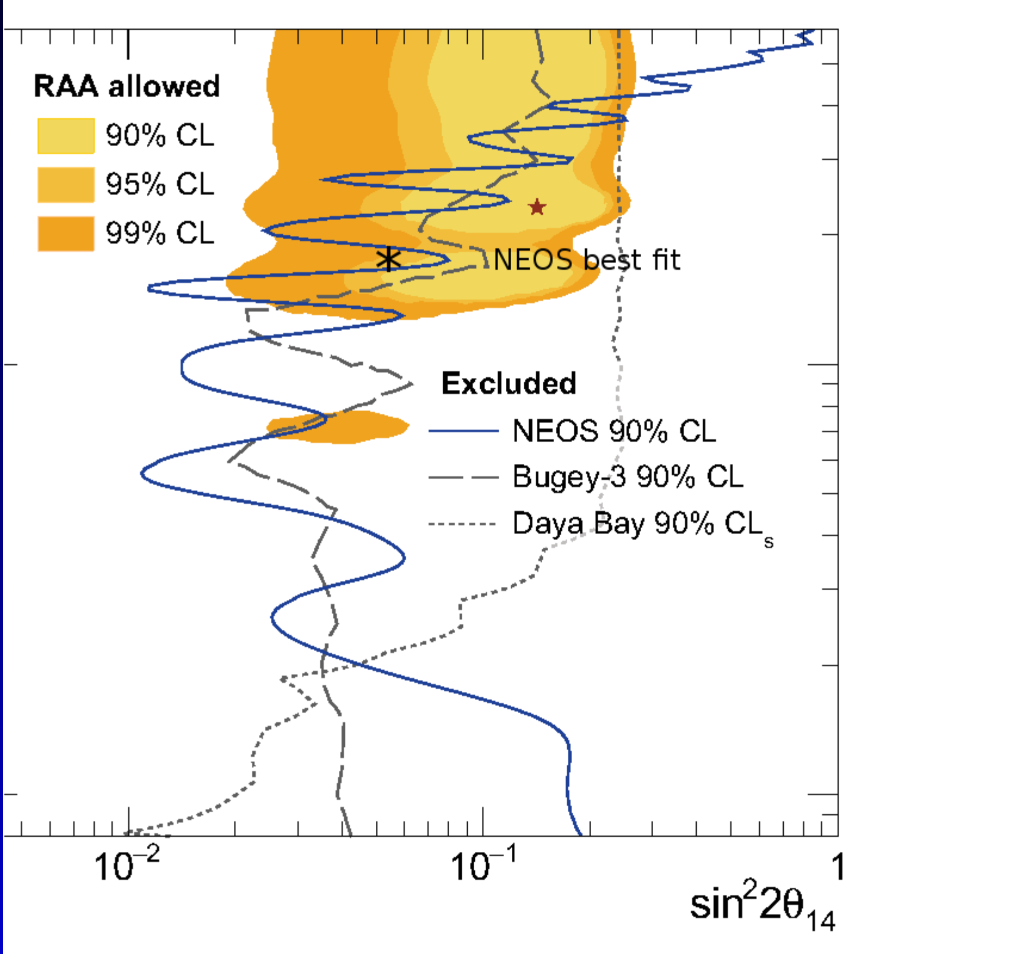
NEOS vs Daya Bay



Huber, 2017

There is more U235 in NEOS, since core is fresh $\Rightarrow$ $3 - 4\,\sigma$ evidence against Pu as sole source of bump, but equal bump size is still allowed at better than $2\,\sigma$.

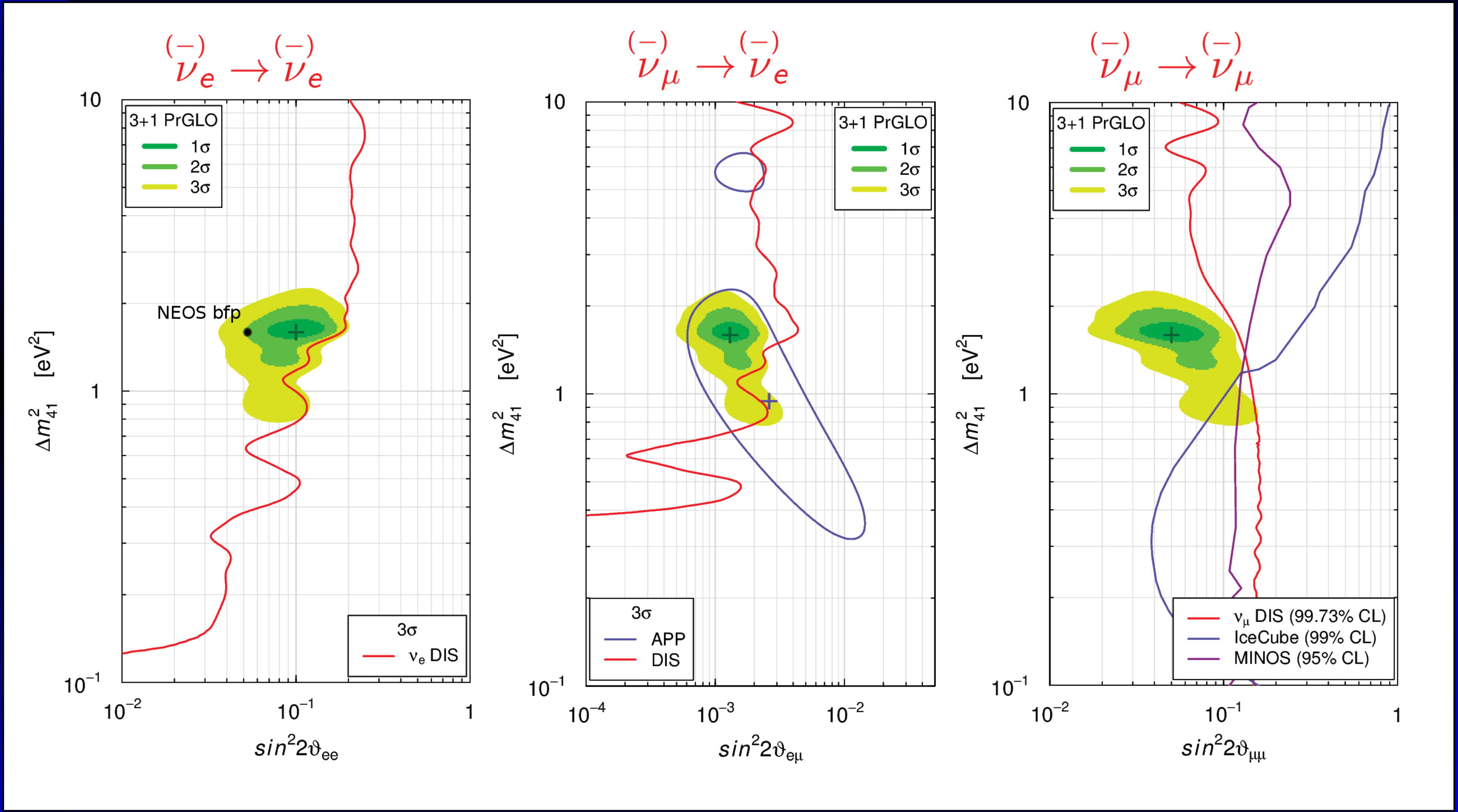
NEOS and sterile neutrinos



adapted from NEOS, 2016

NEOS reports a limit, but their best fit occurs at $\sin^2 2\theta = 0.05$ and $\Delta m^2 = 1.73\,\mathrm{eV}^2$ with a χ^2 value 6.5 below the no-oscillation hypothesis.

Global picture



adapted from Giunti, Neutrino 2016, see also talk by J. Conrad

No tension in $\nu_e \to \nu_e$ or $\nu_\mu \to \nu_\mu$.

Score card

	data	theory	no direct tension
LSND	0	+	-
MiniBooNE	+	- -	- -
T2K	+	- -	++
Gallium	+	++	++
Reactors	++	0	+

++ strong, + adequate, 0 undecided, - likely issue, - - clearly a problem

A eV-scale sterile neutrino is a simple explanation for all the observations.

The gallium result is very hard to explain away. Reactors are coming under pressure from their own precision.

Questions?