Status of Light Sterile Neutrinos

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Beyond Standard Model Physics with Neutrino Driven Sources
MIT
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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 $\nu_e \to \nu_e$
- Cosmology

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

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

LSND and MiniBooNE

You know more about this than I do!

Fermilab SBN

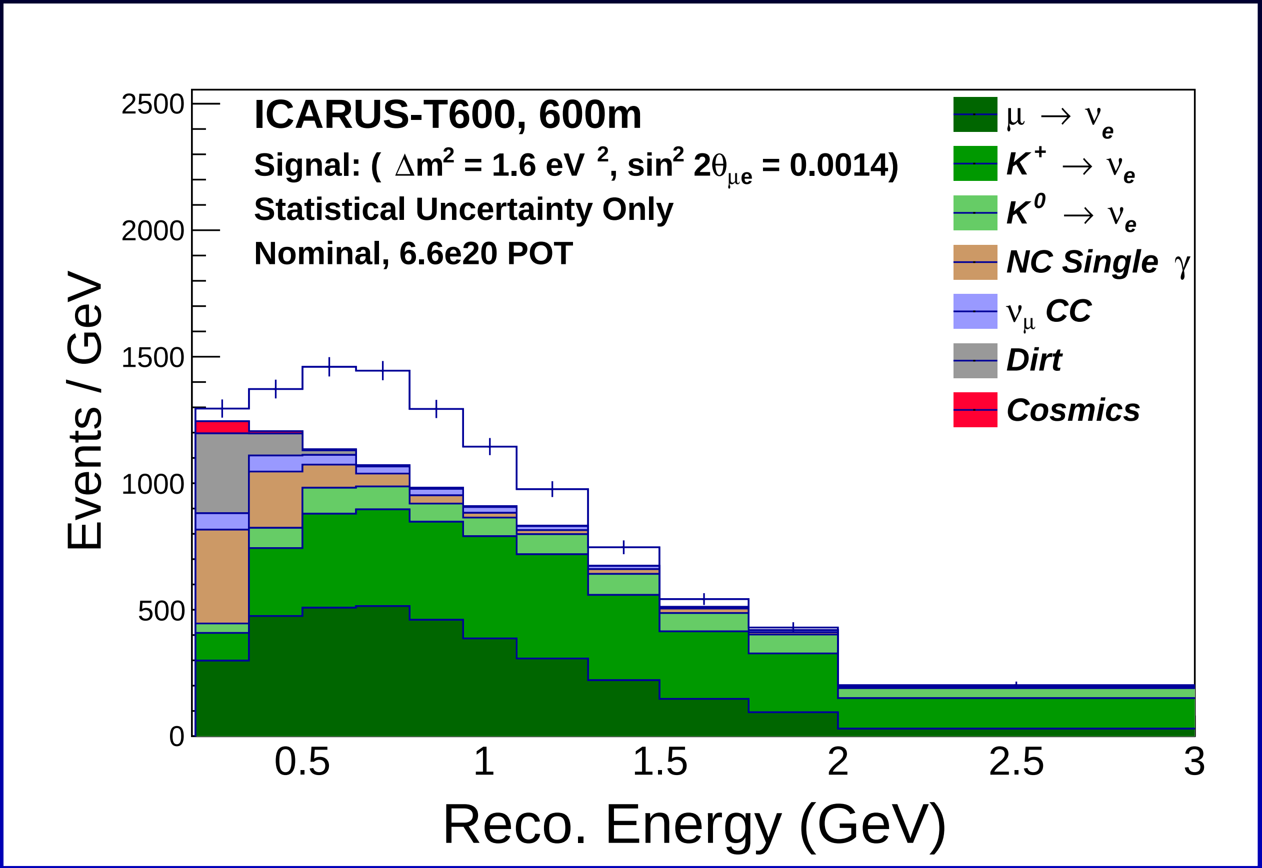
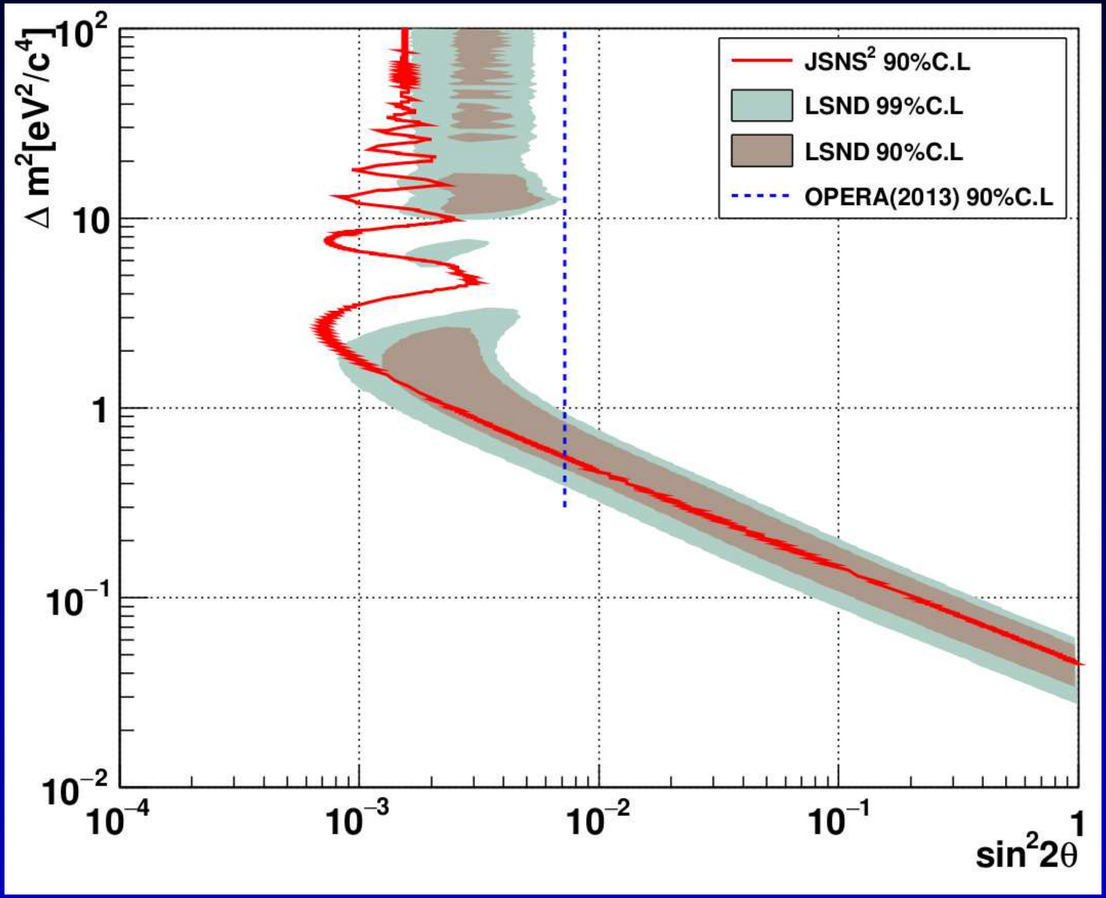


Figure courtesy D. Schmitz and C. Adams

Signal to noise not so different from LSND. . . will a near detector of completely different design help?

JSNS2



Pion decay at rest at JSNS, Gd-doped scintillator.

JSNS2, 2017

Direct test of the LSND result $\rightarrow$ should have beed done 20 years ago!

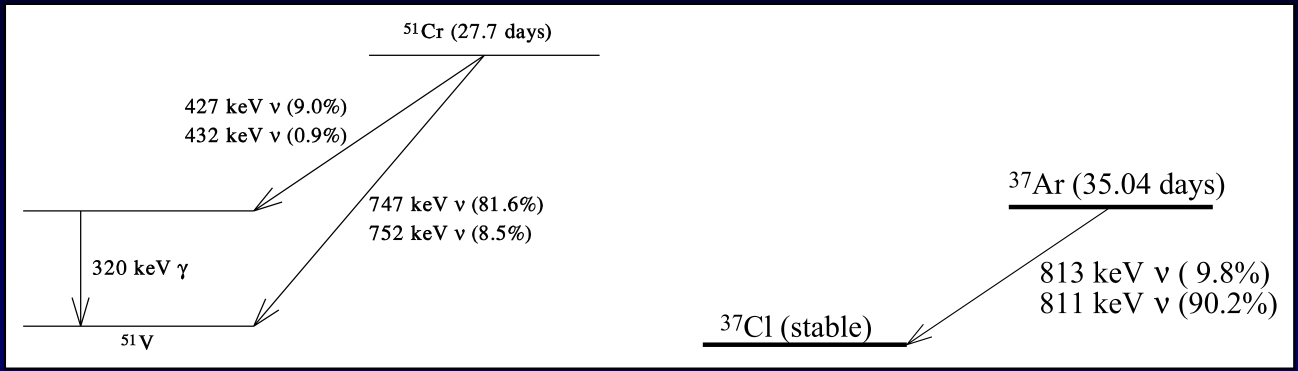
Gallium anomaly

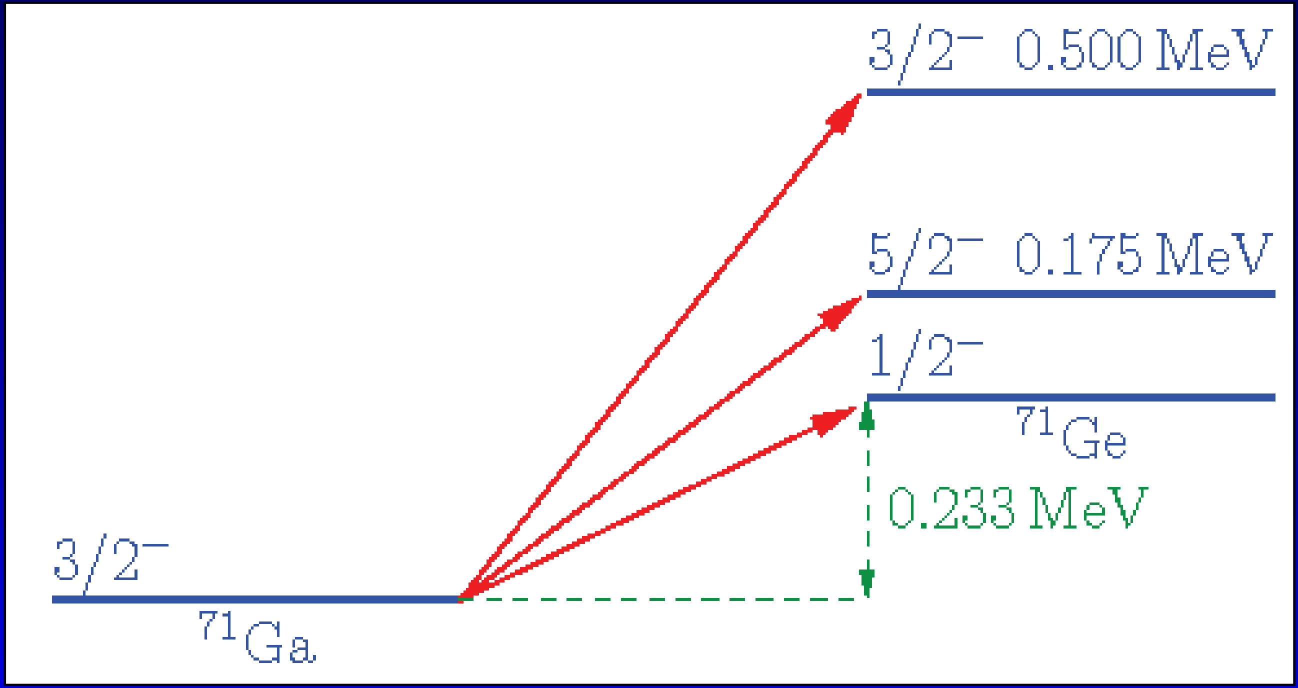
	GALLEX		SAGE	
k	G1	G2	S1	S2
source	^{51}Cr	^{51}Cr	^{51}Cr	^{37}Ar
R^k_{B}	0.953 ± 0.11	$0.812^{+0.10}_{-0.11}$	0.95 ± 0.12	$0.791 \pm {}^{+0.084}_{-0.078}$
R^k_{H}	$0.84^{+0.13}_{-0.12}$	$0.71^{+0.12}_{-0.11}$	$0.84^{+0.14}_{-0.13}$	$0.70 \pm {}^{+0.10}_{-0.09}$
radius [m]	1.9		0.7	
height [m]	5.0	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

25% deficit of ν_e from radioactive sources at short distances

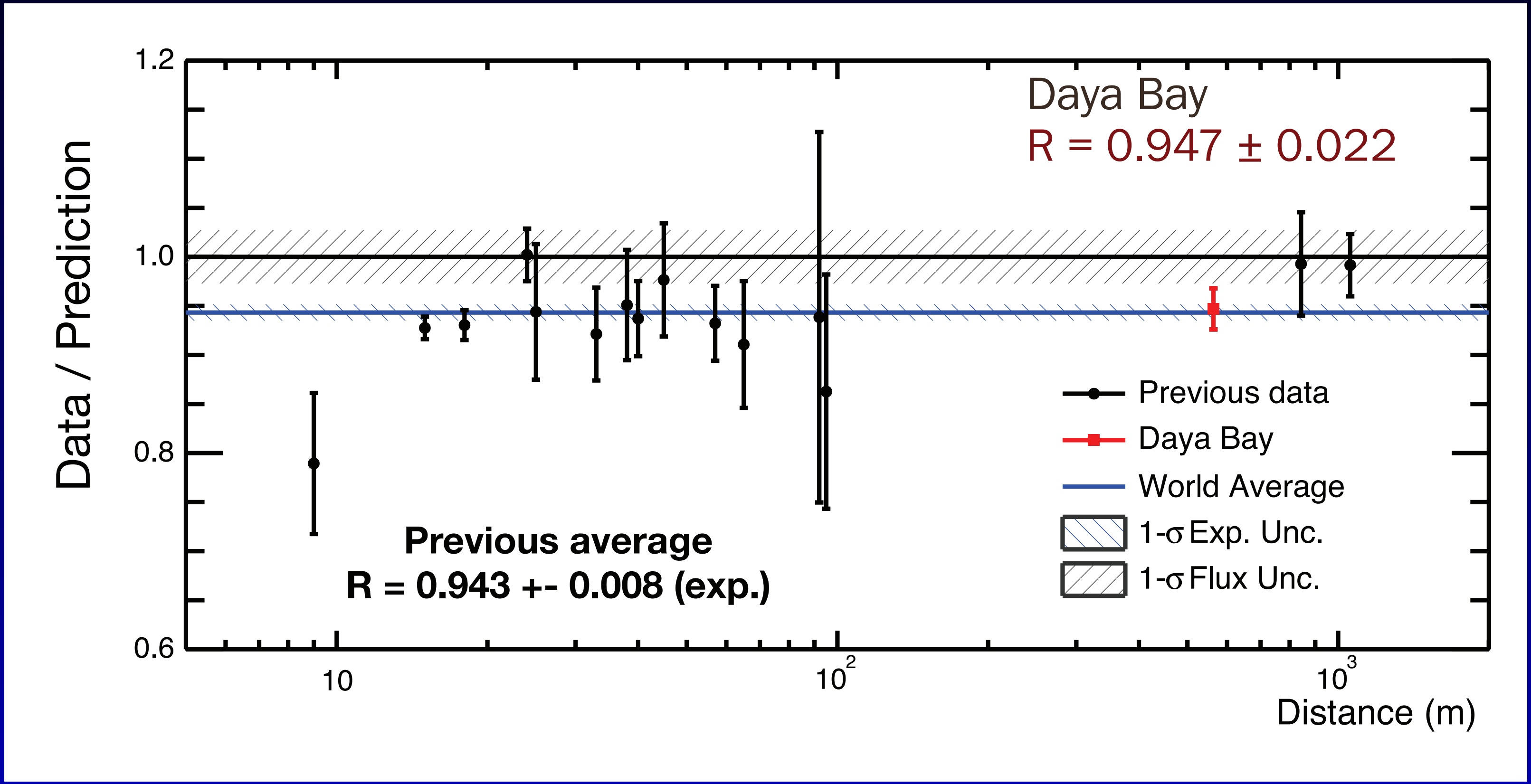
- Effect depends on nuclear matrix element
- R is a calibration constant

Nuclear matrix elements





The reactor anomaly



Daya Bay, 2014

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

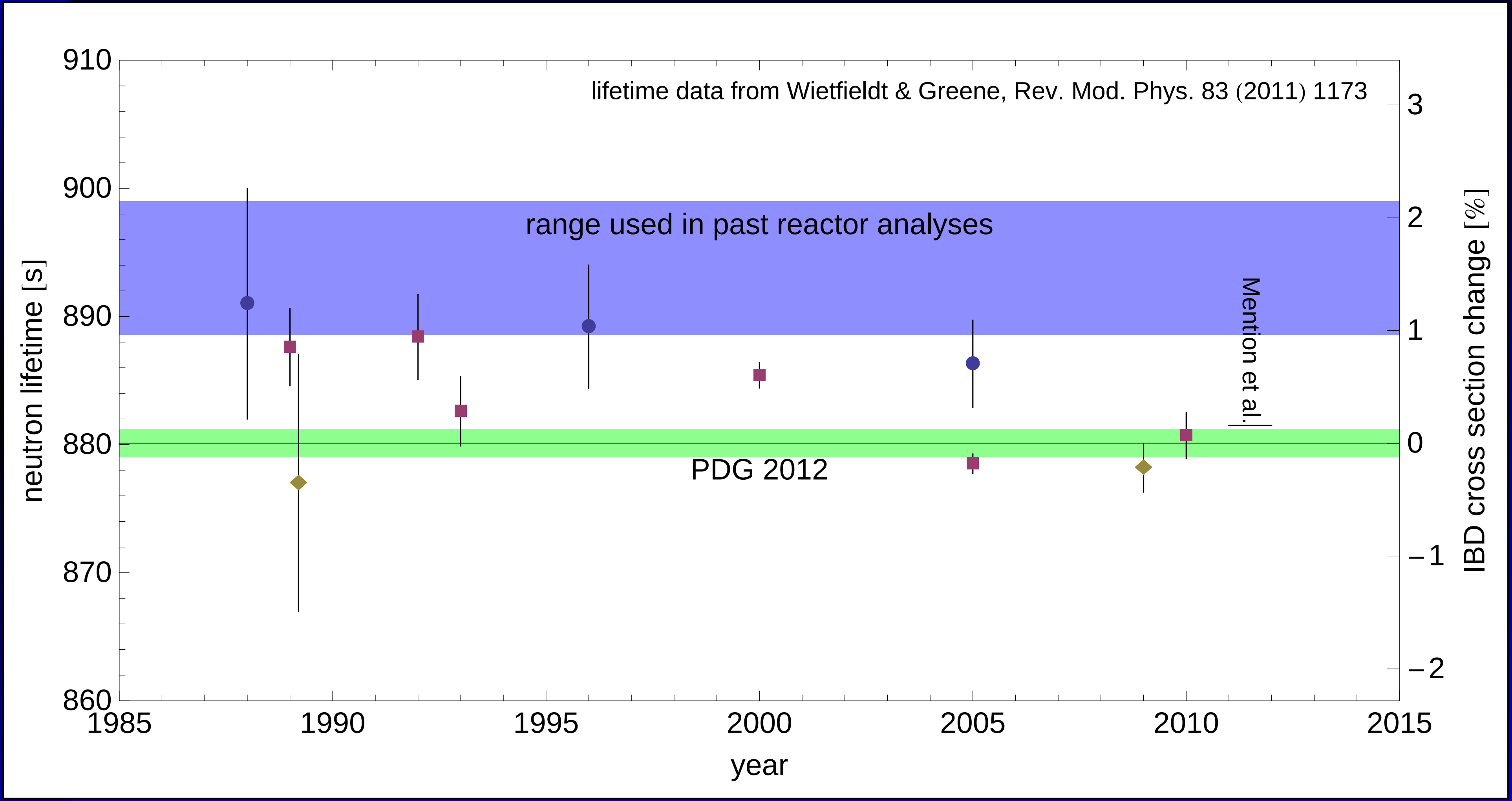
Contributors to the anomaly

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

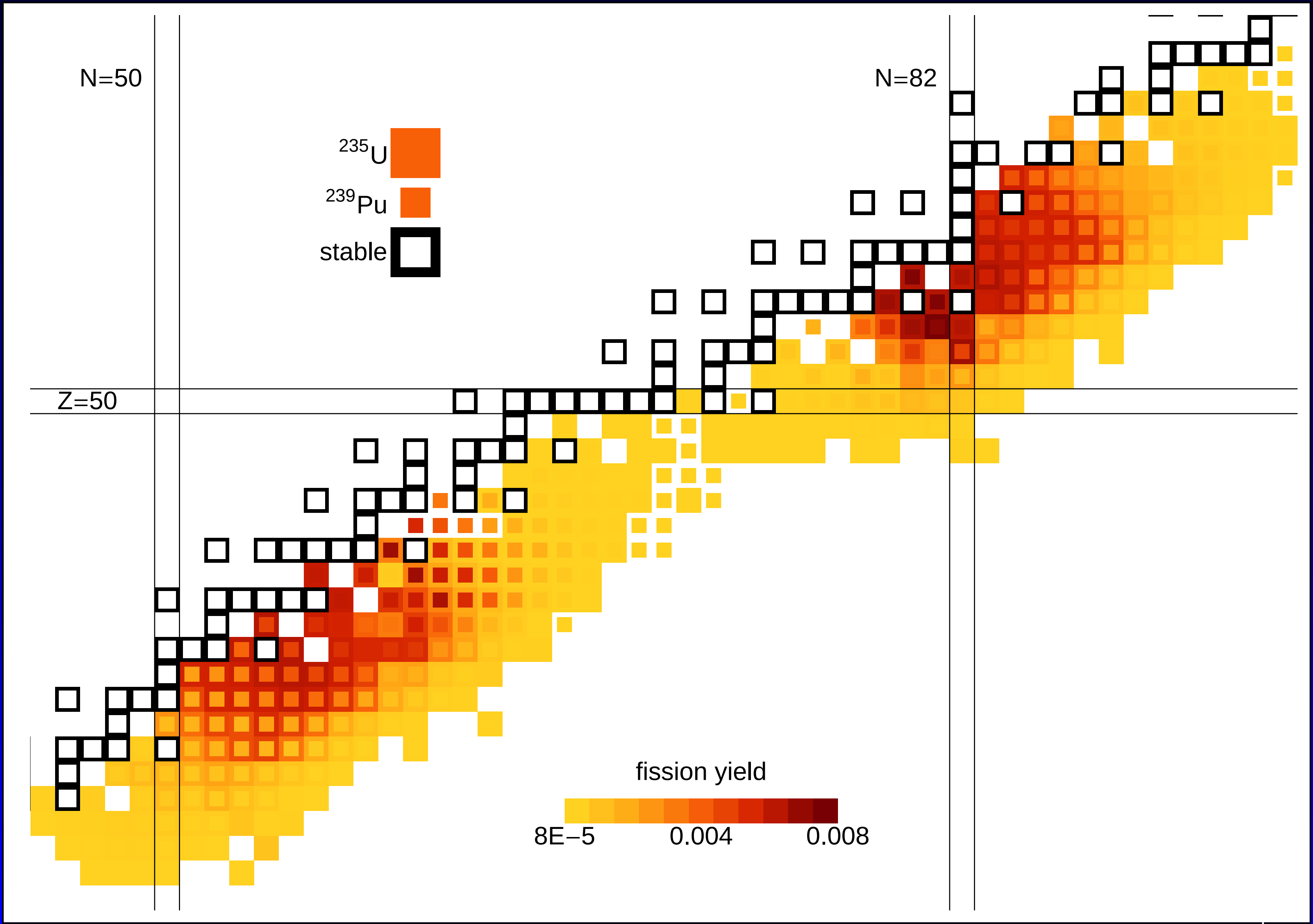
- 3% increase in reactor neutrino fluxes
- decrease in neutron lifetime
- inclusion of long-lived isotopes (non-equilibrium correction)

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

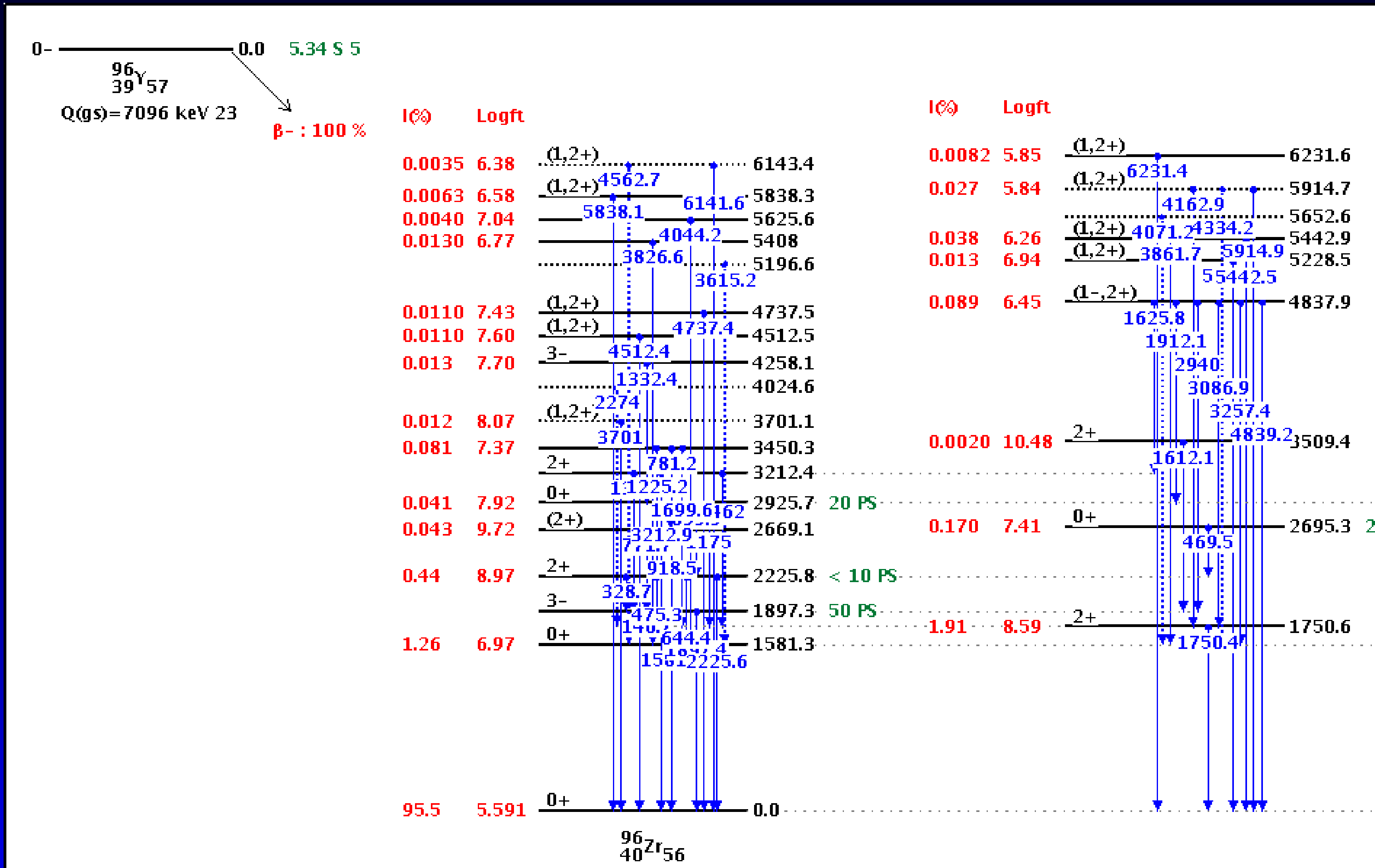
Neutron lifetime



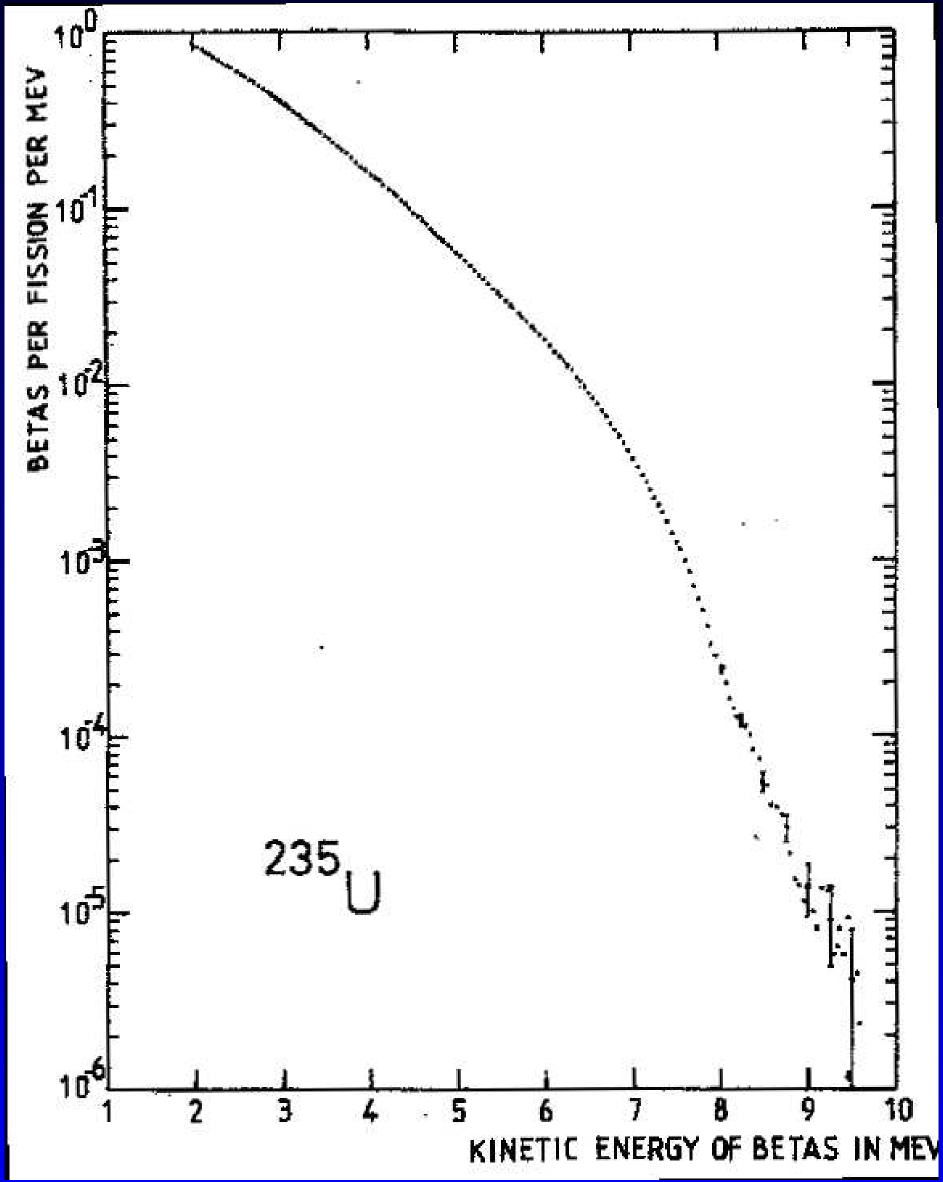
Neutrinos from fission



β-branches



β-spectrum from fission



Schreckenbach, *et al.* 1985.

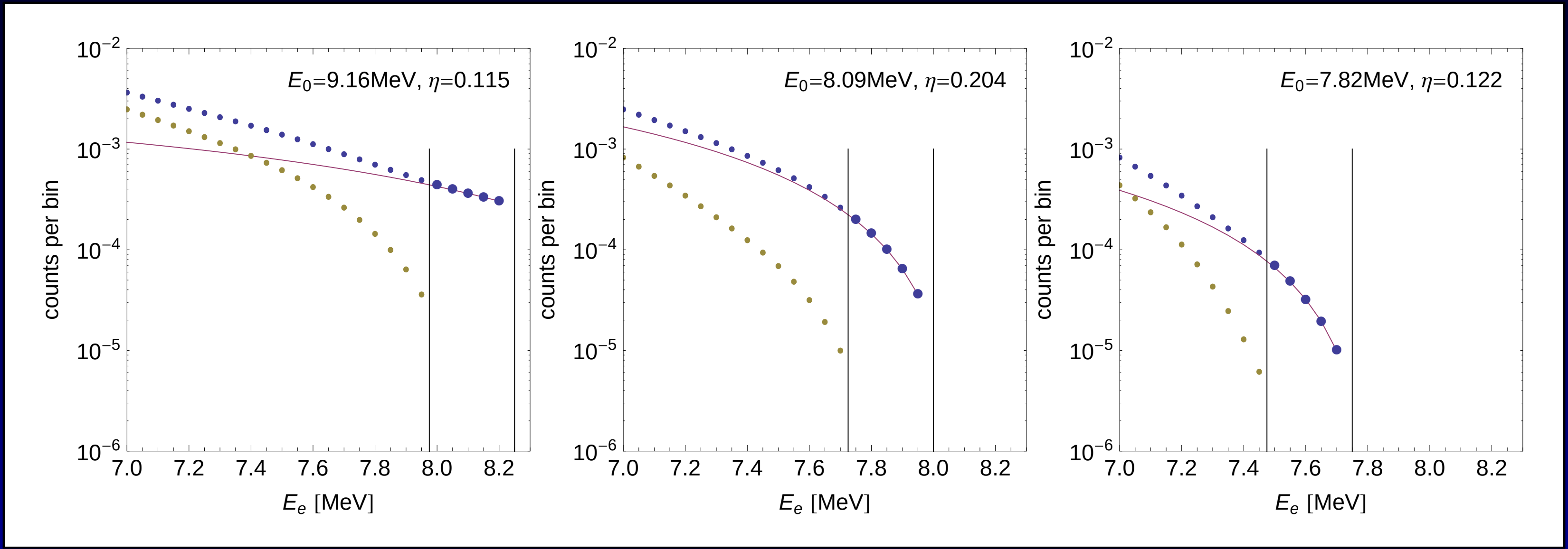
^{235}U foil inside the High Flux Reactor at ILL

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

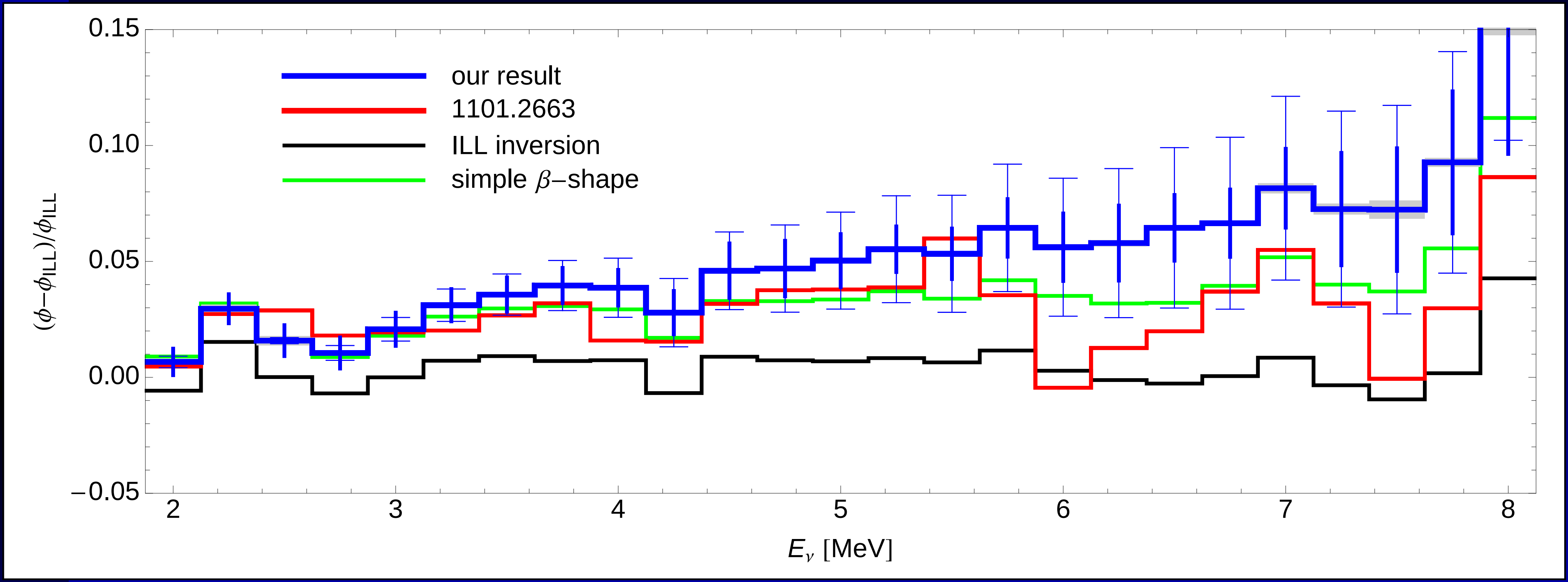
2 – delete the last s data points

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

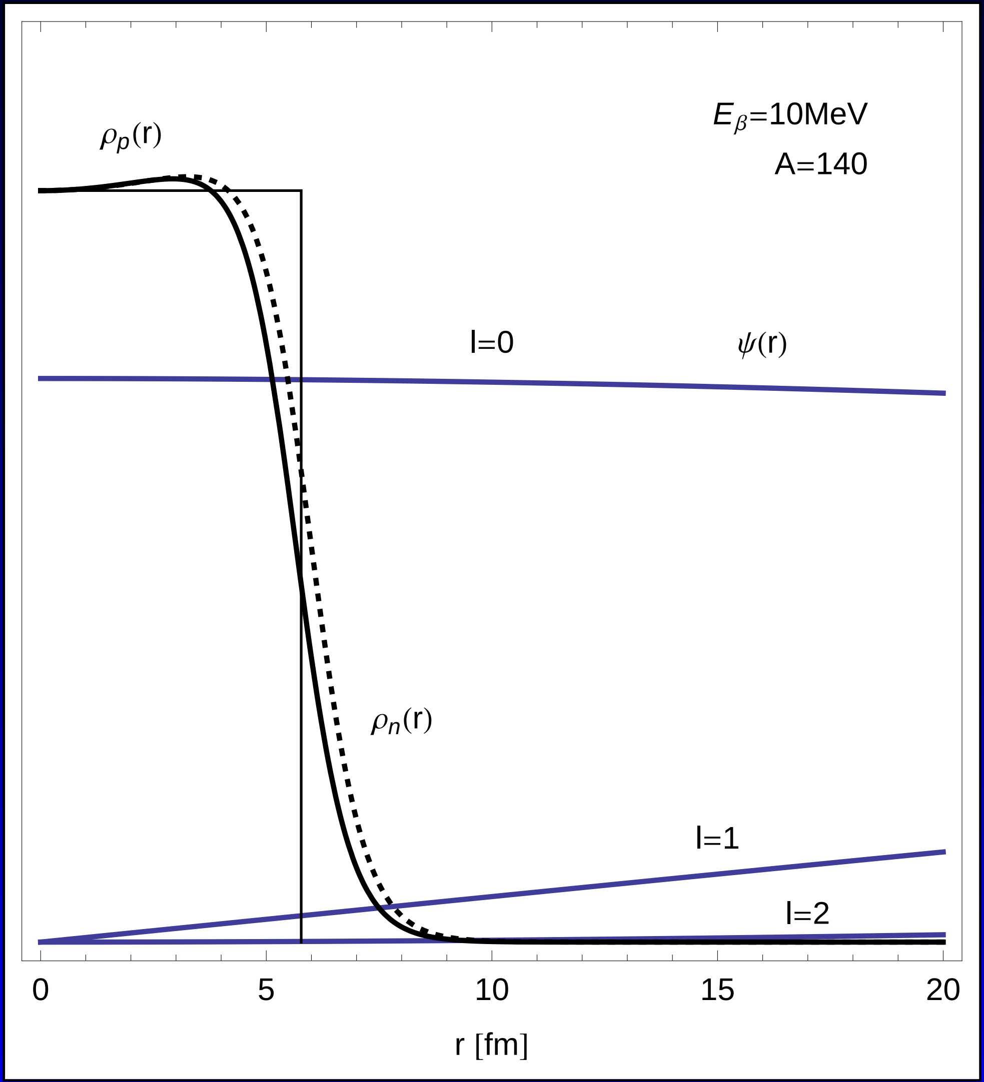


Shift with respect to ILL results, due to

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

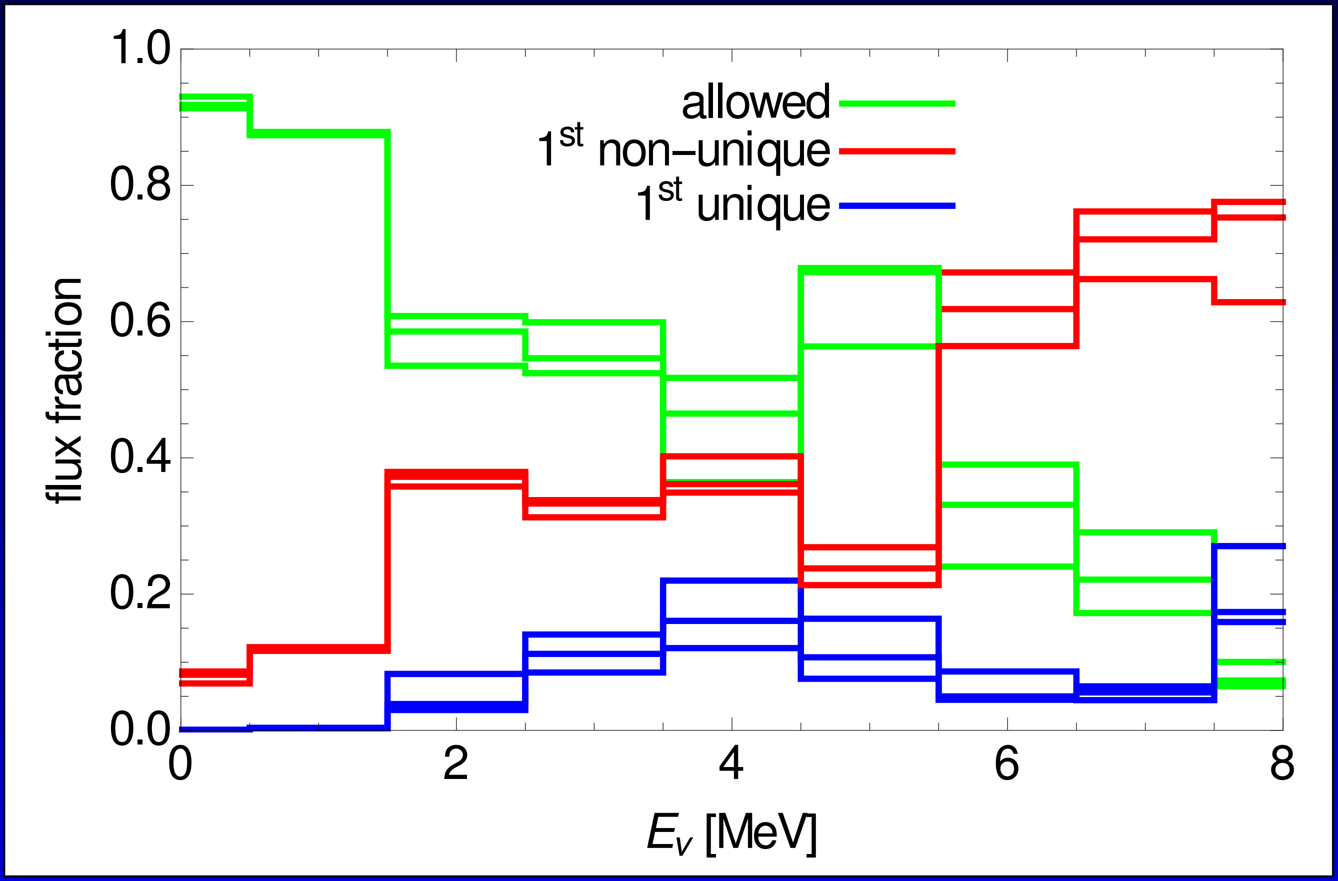
Allowed:
s-wave emission ($l = 0$)

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

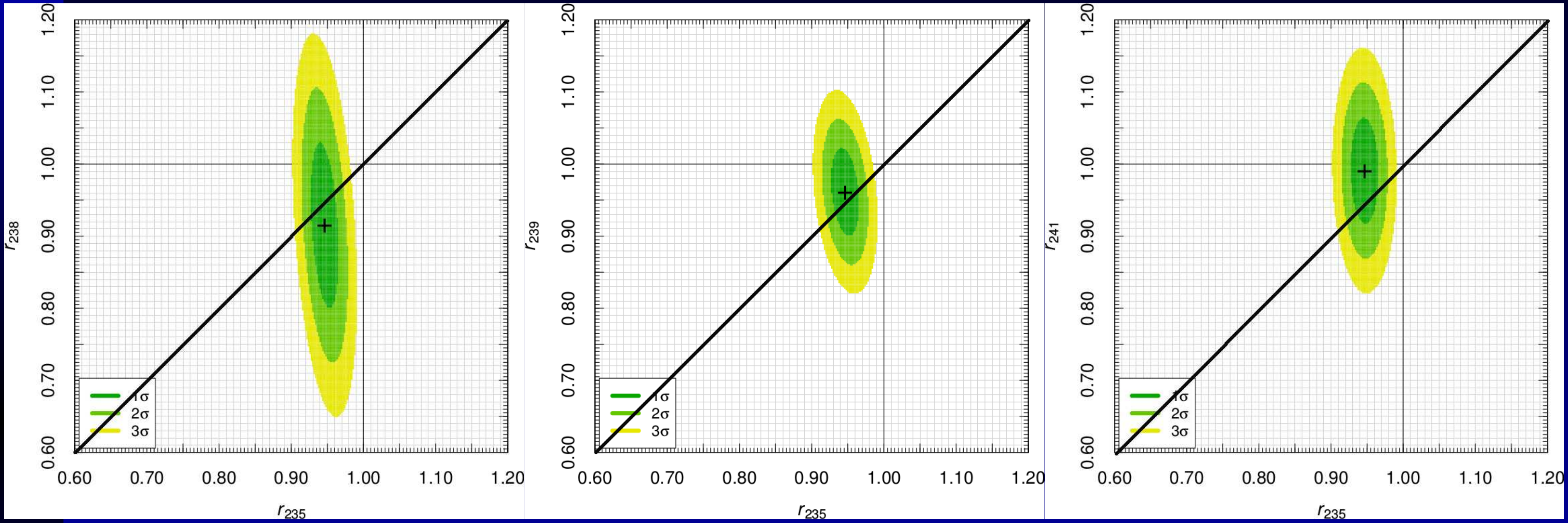


Look at past data

a	Experiment	f^a_{235}	f^a_{238}	f^a_{239}	f^a_{241}	$R^{\rm exp}_{a,\rm SH}$	$\sigma^{\rm exp}_a$ [%]	$\sigma^{\rm cor}_a$ [%]	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

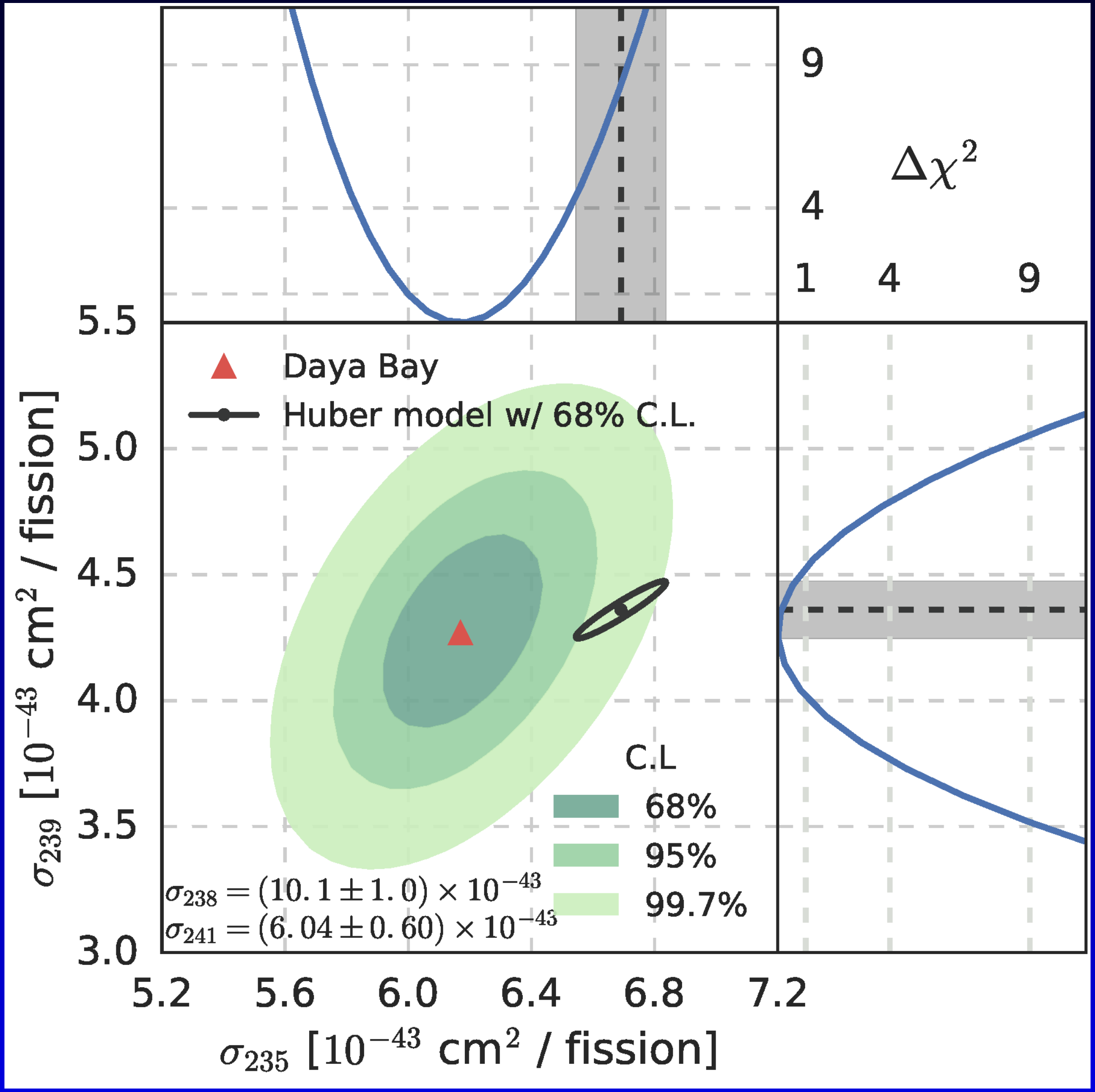
What does this tell us?



Giunti, 2016

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

Latest result of Daya Bay

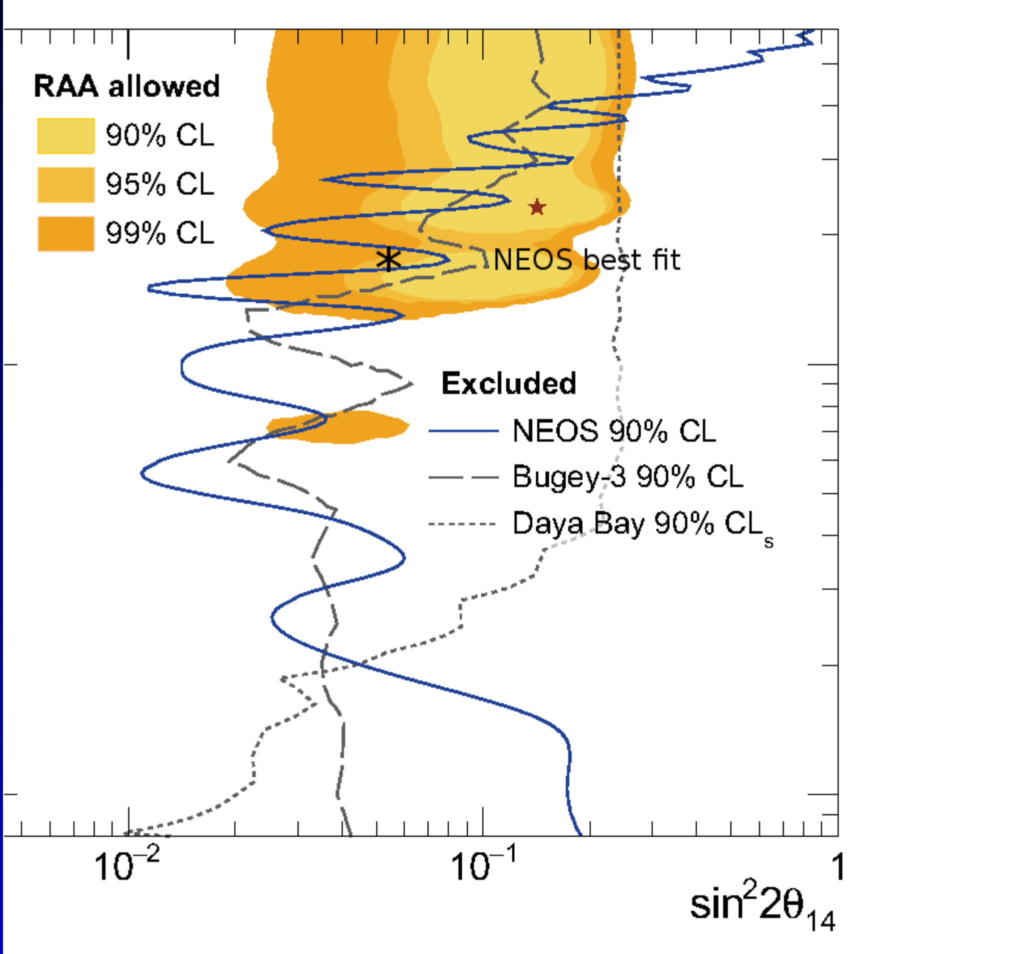


Daya Bay, 2017

Only an issue if the prediction of Pu239 in the Huber+Mueller model is correct.
Hayes *et al.*, 2017

Or there are some other neglected time depedent flux components
PH, in preparation.

NEOS and sterile neutrinos

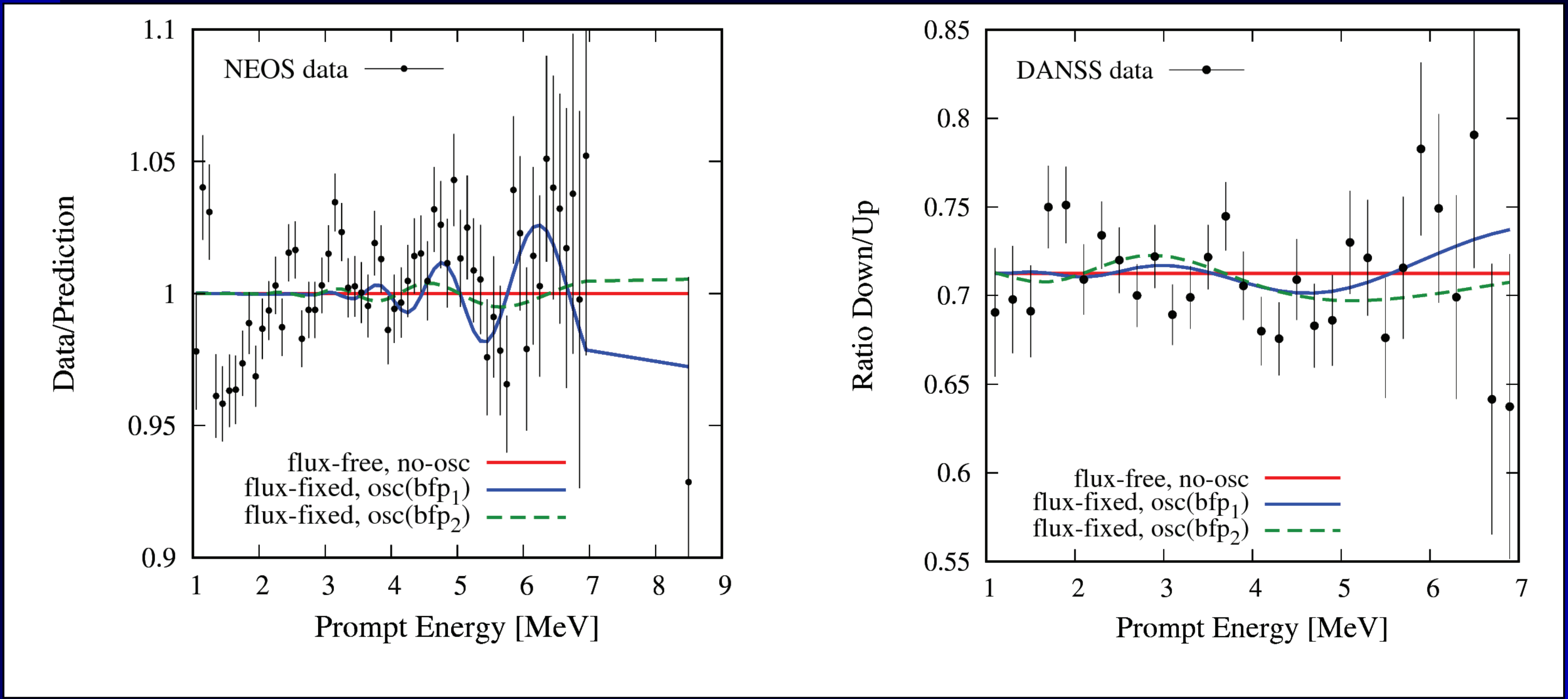


adapted from NEOS, 2016

DANSS has a similar result.

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.

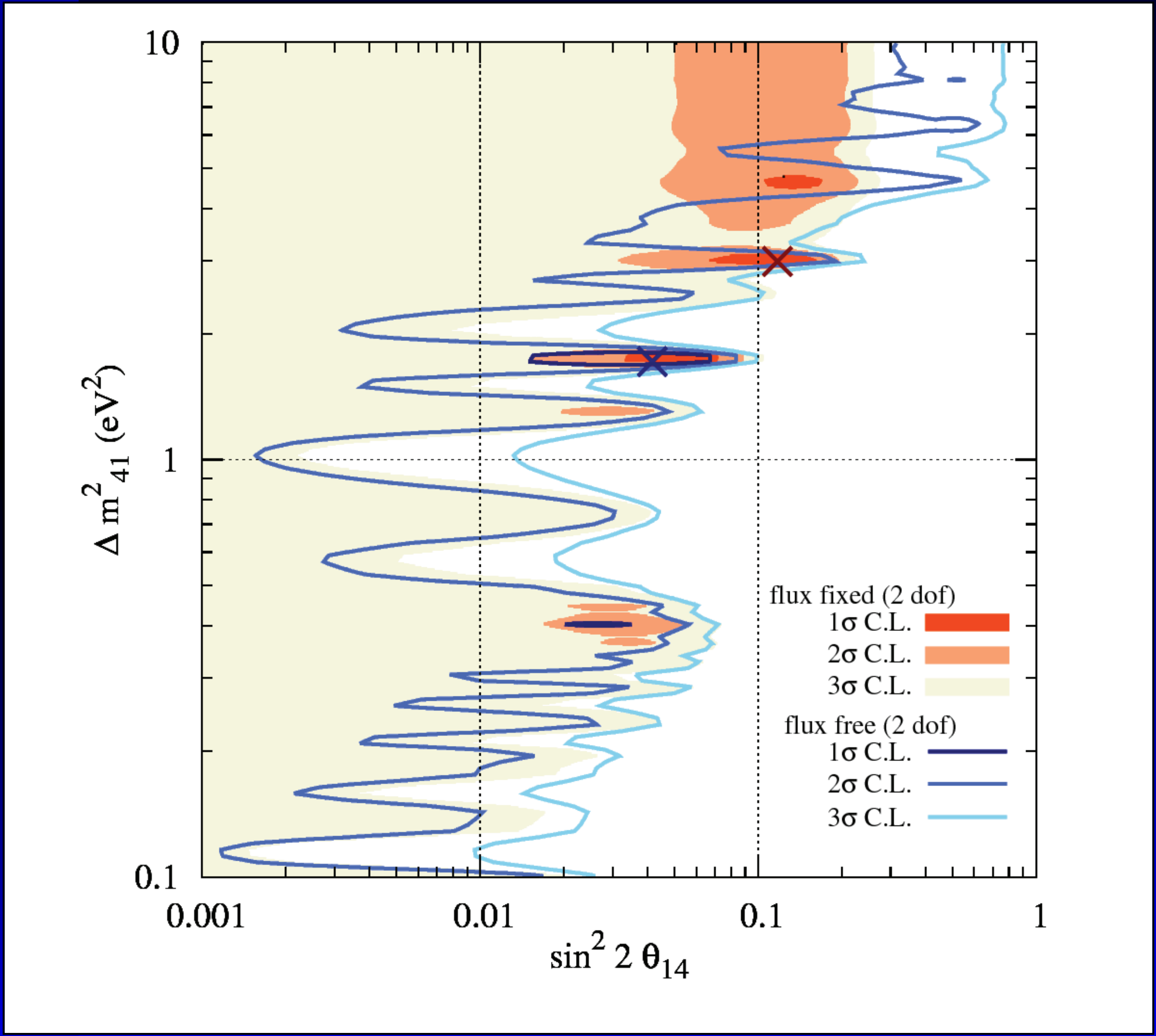
DANSS and NEOS



Dentler et al. 2017

This is a spectral effect independent of rate and shape predictions!

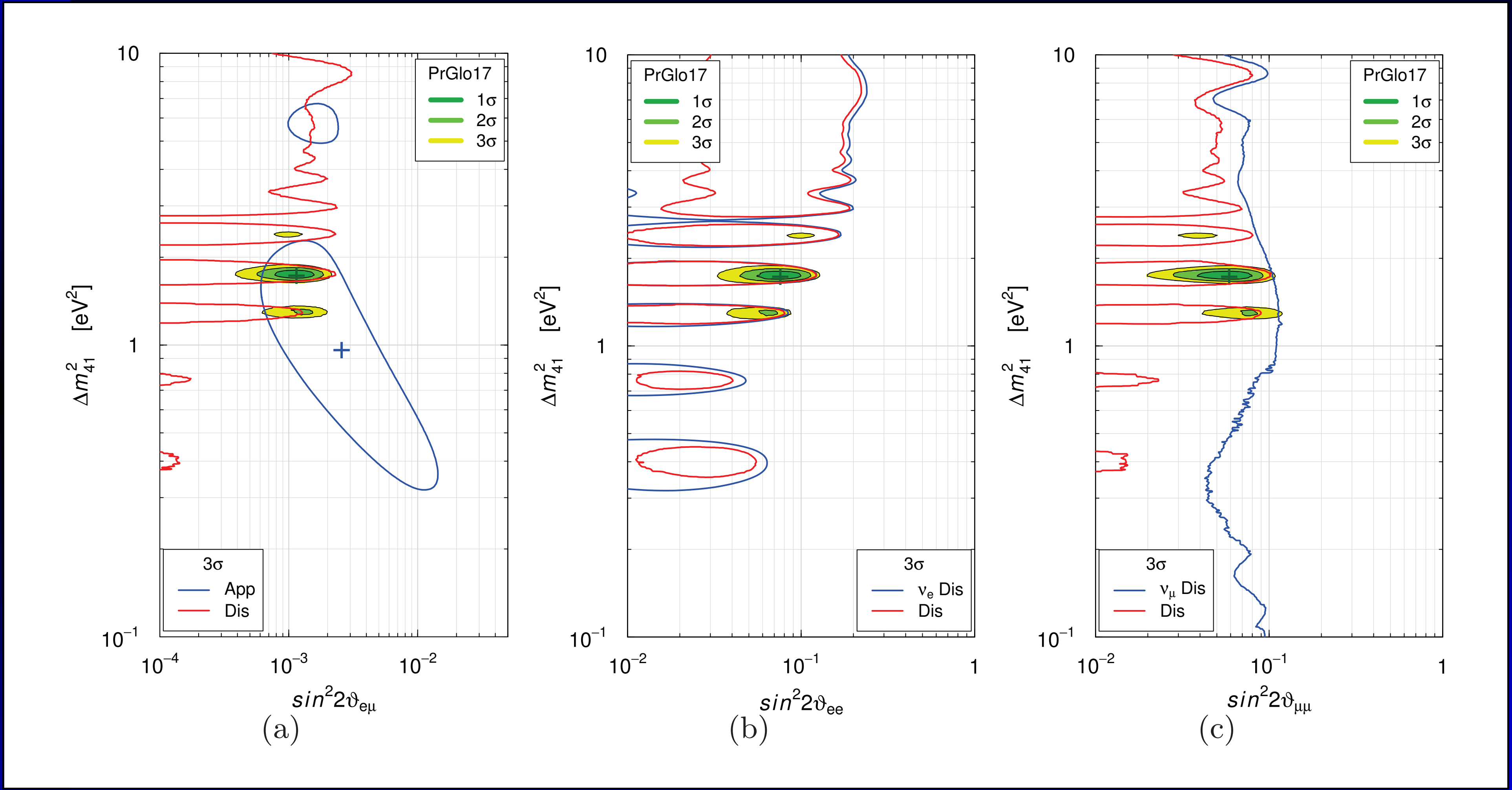
Reactor fit



Closed 2 σ contours even without using a flux prediction.

Dentler et al. 2017

Global fit



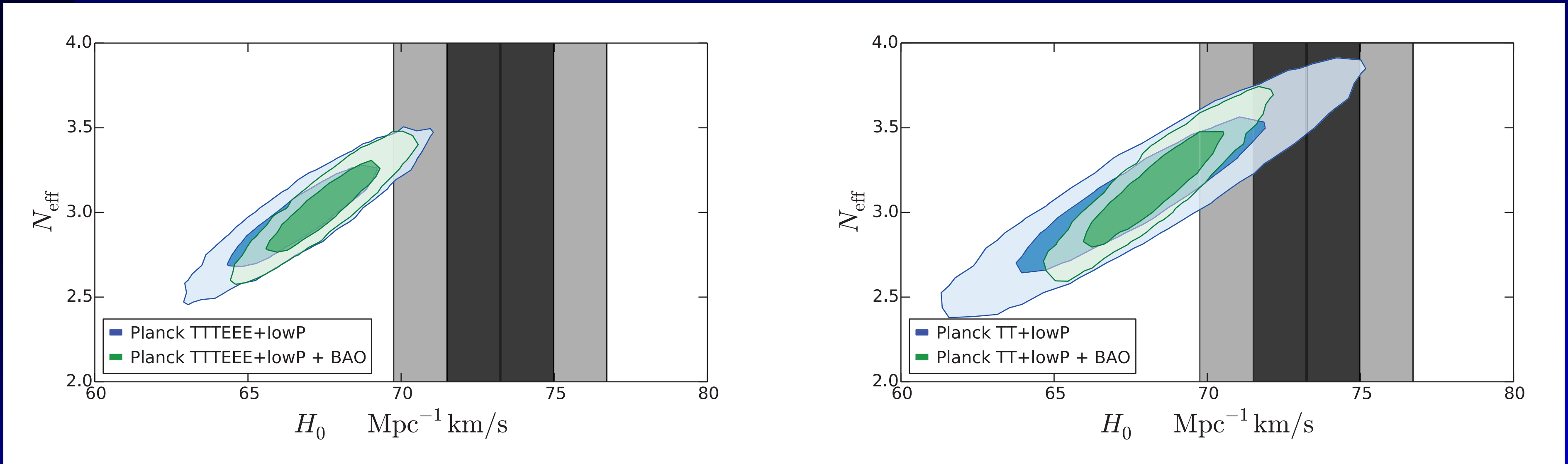
Gariazzo *et al.*, 2017

Cosmology 2016

Planck 2016

$$N_{\rm eff} = 3.15 \pm 0.23$$

leaving not much room for a forth neutrino.

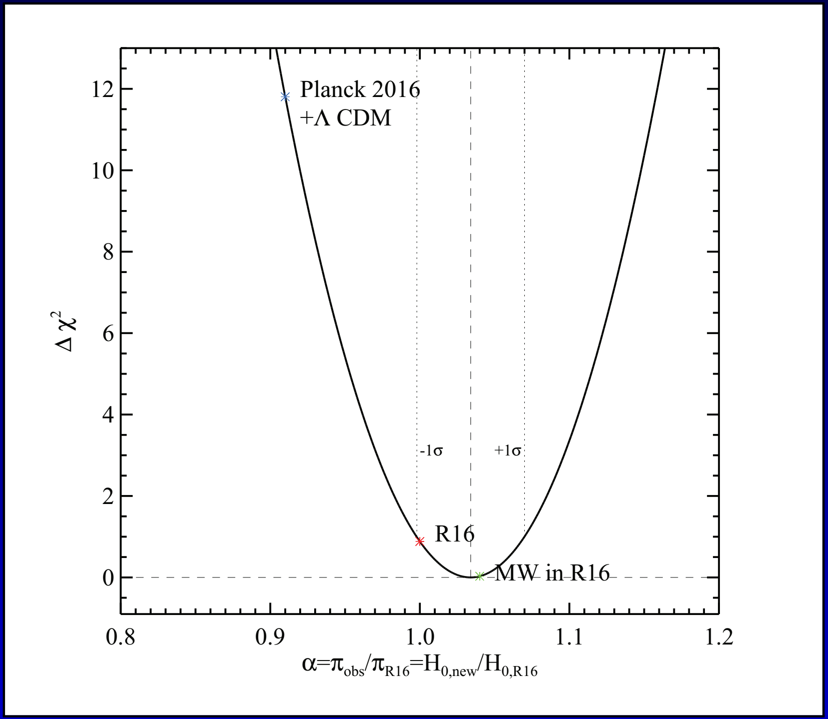


Bernal, Verde, Riess, 2016

H_0 and $N_{\rm eff}$ are fully correlated in Planck data.

Cosmlogy 2018

New measurement of local (=late) H_0 by fixing parallaxes to Cepheids yields:



Riess, *et al.* 2018

Which in turn makes $N_{\mathrm{eff}} \simeq 4$ compatible with data.

Finding a sterile neutrino

All pieces of evidence have in common that they are less than 5 σ effects and they may be all due to the extraordinary difficulty of performing neutrino experiments, if not:

- N sterile neutrinos are the simplest explanation
- Tension with null results in disappearance remains

Due to their special nature as SM gauge singlets sterile neutrinos are strong candidates for being a portal to a hidden sector – significant experimental activity.

Summary

Tension in global fits

- Maybe more complicated than sterile neutrino
- And/or not all data is right
- Lots of nuclear physics uncertainties

With NEOS and DANSS we have a positive indication from reactors independent of flux predictions.

In combination, light sterile neutrinos are one of the best cases for New Physics, anywhere!

Questions?

NuFact 2018

We invite you to NuFact 2018, August 12–18, at Virginia Tech, Blacksburg, VA.