Present Status and Future of Neutrino Physics

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The big questions

- Are neutrinos Majorana?
- δ_{CP}
- Mass hierarchy
- $\theta_{23} = \pi/4$?
- Resolution of LSND and the other short-baseline anomalies
- New physics (on top of neutrino mass)?

Status quo

A common framework for all the neutrino data† is oscillation of three active neutrinos

- $\Delta m^2_{21} \sim 8 \cdot 10^{-5}\,\mathrm{eV}^2$ and $\theta_{12} \sim 1/2$
- $\Delta m^2_{31} \sim 2 \cdot 10^{-3}\,\mathrm{eV}^2$ and $\theta_{23} \sim \pi/4$
- $\theta_{13} \sim 0.16$

This implies a lower bound on the mass of the heaviest neutrino

$$\sqrt{2 \cdot 10^{-3}\,\mathrm{eV}^2} \sim 0.04\,\mathrm{eV}$$

† apart from short-baseline anomalies

Mixing matrices

Quarks

$$|U_{CKM}| = \begin{pmatrix} 1 & 0.2 & 0.005 \\ 0.2 & 1 & 0.04 \\ 0.005 & 0.04 & 1 \end{pmatrix}$$

Neutrinos

$$|U_\nu| = \begin{pmatrix} 0.8 & 0.5 & 0.15 \\ 0.4 & 0.6 & 0.7 \\ 0.4 & 0.6 & 0.7 \end{pmatrix}$$

Neutrinos are massive – so what?

Neutrinos in the Standard Model (SM) are strictly massless, therefore the discovery of neutrino oscillation, which implies non-zero neutrino masses requires the addition of new degrees of freedom.

The Nobel Prize in Physics 2015

Takaaki Kajita, Arthur B. McDonald

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The Nobel Prize in Physics 2015

Photo: A. Mahmoud

Takaaki Kajita

Prize share: 1/2

Photo: A. Mahmoud

Arthur B. McDonald

Prize share: 1/2

The Nobel Prize in Physics 2015 was awarded jointly to Takaaki Kajita and Arthur B. McDonald *"for the discovery of neutrino oscillations, which shows that neutrinos have mass"*

We always knew they are ...

The SM, likely, is an effective field theory, *i.e.* at some high scale Λ new degrees of freedom will appear

$$\mathcal{L}_{SM} + \frac{1}{\Lambda}\mathcal{L}_5 + \frac{1}{\Lambda^2}\mathcal{L}_6 + \ldots$$

The first operators sensitive to new physics have dimension 5. It turns out there is only one dimension 5 operator

$$\mathcal{L}_5 = \frac{1}{\Lambda}(LH)(LH) \to \frac{1}{\Lambda}(L\langle H\rangle)(L\langle H\rangle) = m_\nu \nu\nu$$

Weinberg

Effective theories

The problem in effective theories is, that there are *a priori* unknown pre-factors for each operator

$$\mathcal{L}_{SM} + \frac{\#}{\Lambda}\mathcal{L}_5 + \frac{\#}{\Lambda^2}\mathcal{L}_6 + \ldots$$

Typically, one has $\# = \mathcal{O}(1)$, but there may be reasons for this being wrong.

Therefore, we do not know the scale of new physics responsible for neutrino masses – anywhere from keV to the Planck scale is possible.

Neutrino masses are different

The crucial difference between neutrinos and other fermions is the possibility of a Majorana mass term

$$m_L \bar{\psi}_L \psi_R^C + m_R \bar{\psi}_R \psi_L^C$$

on top of the usual Dirac mass term

$$m_D \bar{\psi}_L \psi_R$$

Neutrino mass determination

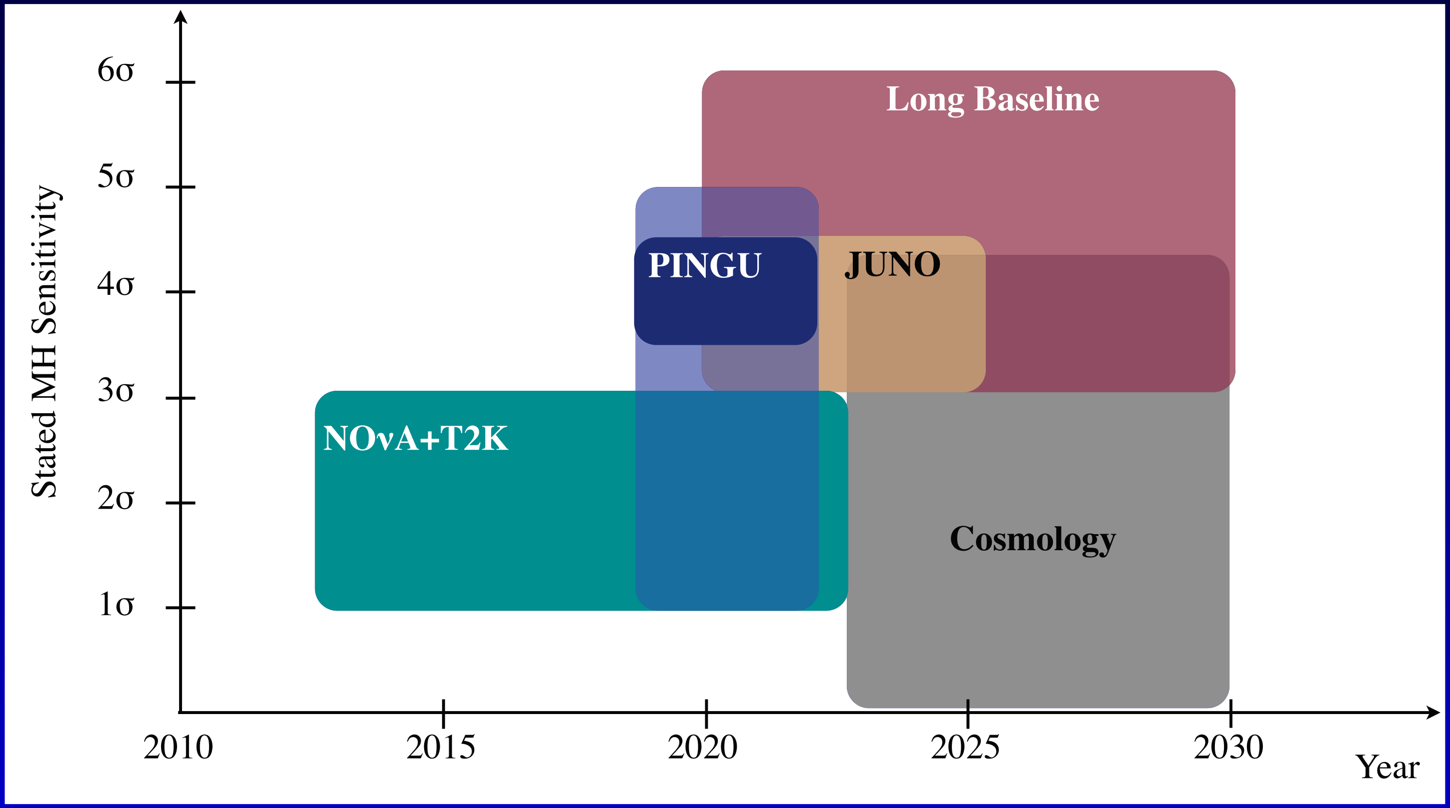
Finding the scale Λ of neutrino mass generation rests crucially on knowing

- Dirac vs Majorana mass
- Absolute size of mass

All direct experimental techniques for mass determination rely on ν_e, which is mostly made up of m_1 and m_2.

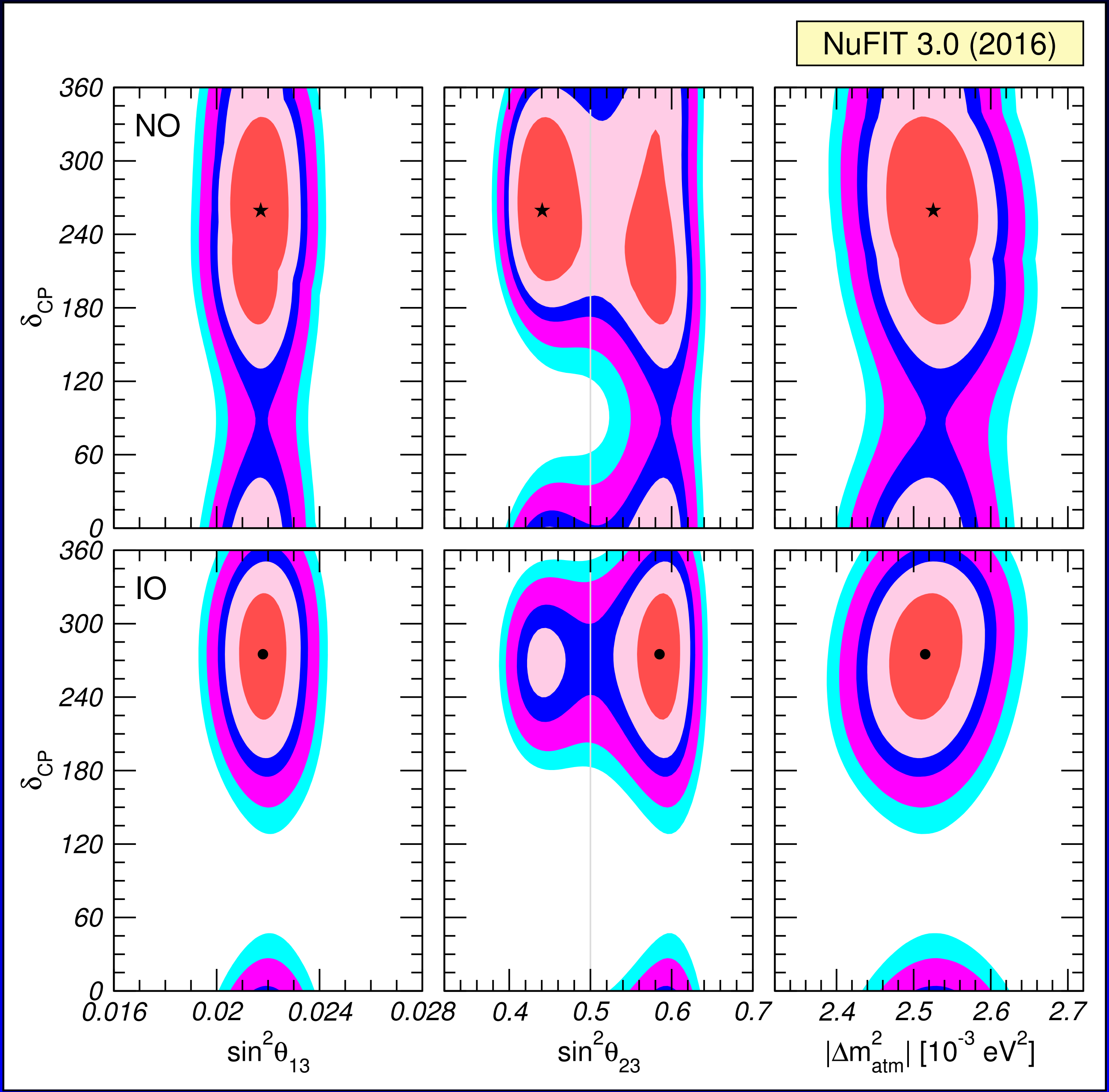
Mass hierarchy

Literature survey arXiv:1307.5487



Many experiments are expected to have a result at or above 3 σ within a decade from now.

First hints for non-maximal θ_{23}



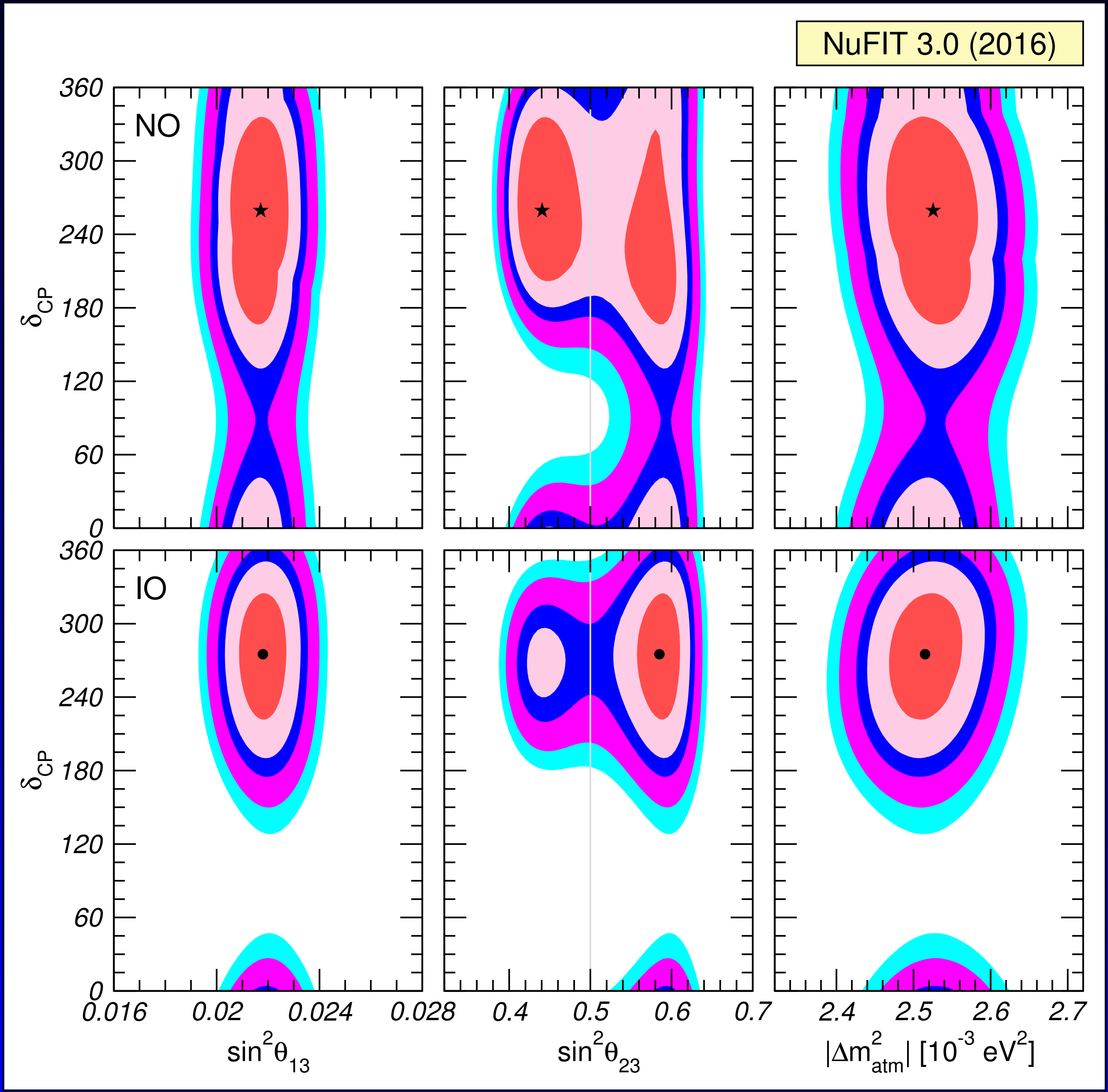
CP violation

There are only very few parameters in the νSM which can violate CP

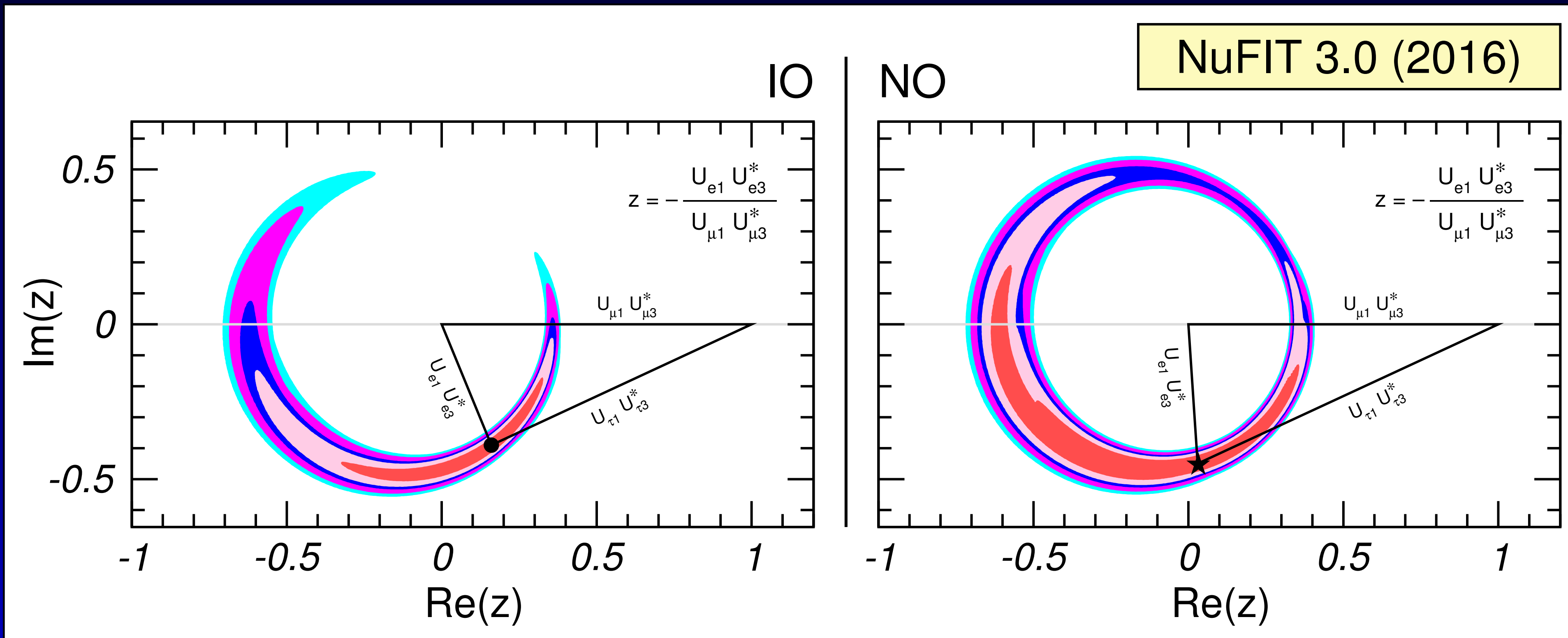
- CKM phase – measured to be $\gamma \simeq 70^\circ$
- θ of the QCD vacuum – measured to be $< 10^{-10}$
- Dirac phase of neutrino mixing
- Possibly: 2 Majorana phases of neutrinos

At the same time we know that the CKM phase is not responsible for the Baryon Asymmetry of the Universe…

First hints for CP violation?



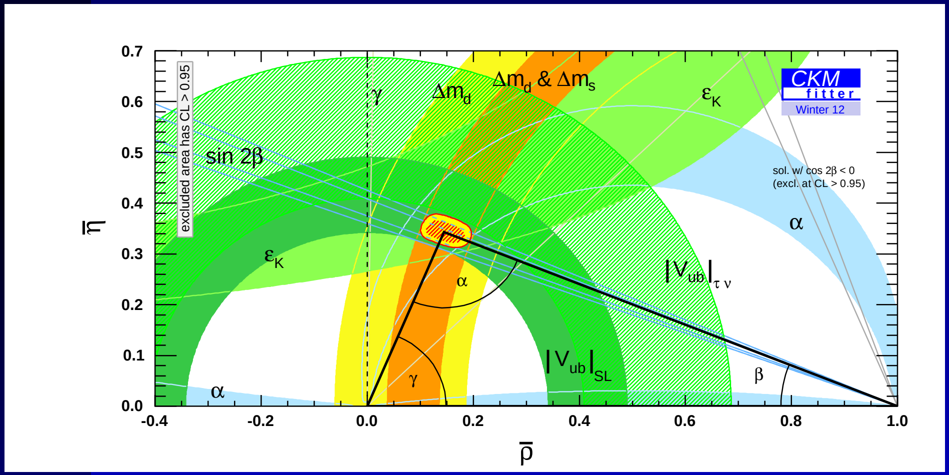
Unitarity triangles



We currently have no way to directly measure any of sides containing ν_τ.

What did we learn from that?

Our expectations where to find BSM physics are driven by models – but we should not confuse the number of models with the likelihood for discovery.



- CKM describes all flavor effects
- SM baryogenesis difficult
- New Physics at a TeV
  - does not exist or
  - has a special flavor structure

and a vast number of parameter and model space excluded.

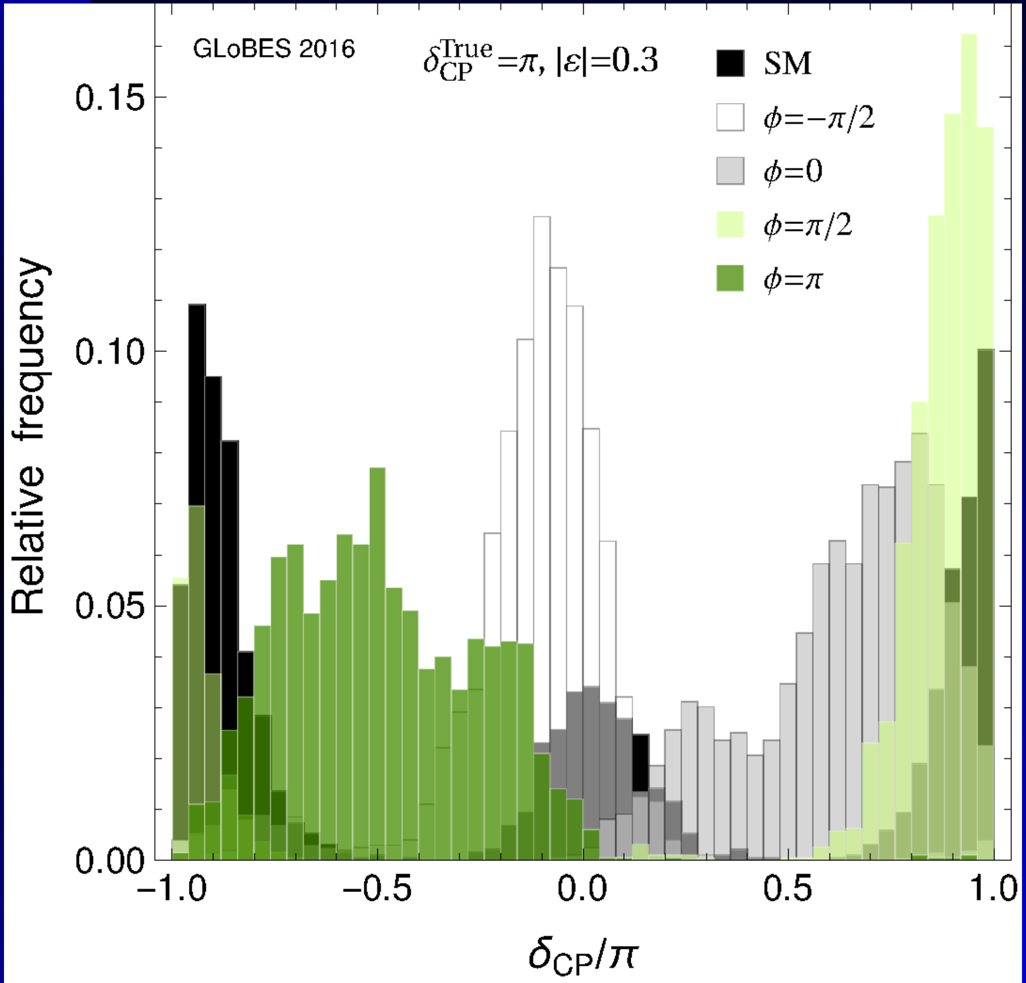
Non-standard interactions

NSI are the workhorse for BSM physics in the neutrino sector. They can be parameterized by terms like this

$$\mathcal{L}_{\mathrm{NSI}} = -2\sqrt{2} G_f \epsilon^{fP}_{\alpha\beta} (\bar{\nu}_\alpha \gamma^\rho \nu_\beta)(\bar{f} \gamma_\rho P f)\,,$$

where f can be any fermion and P is the projection onto right and left-handed components. Wolfenstein, 1978

Impact on three flavors



Three flavor analysis are not safe from these effects!

PH, D. Vanegas, 2016

In this example, CP conserving new physics fakes CP violation in oscillation!

Flavor models

Simplest un-model – anarchy Murayama, Naba, DeGouvea

$$dU = ds_{12}^2\, dc_{13}^4\, ds_{23}^2\, d\delta_{CP}\, d\chi_1\, d\chi_2$$

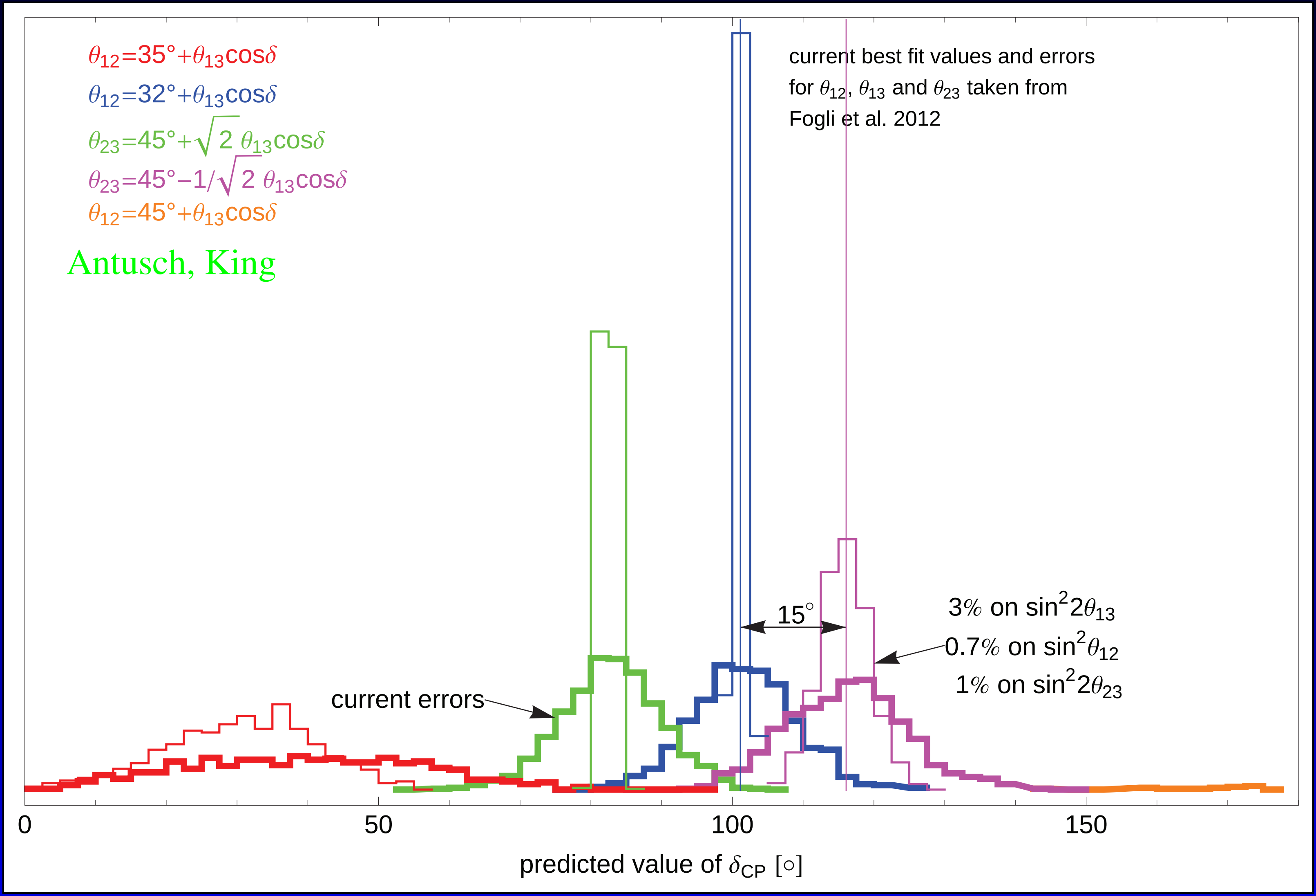
predicts flat distribution in δ_{CP}

Simplest model – Tri-bimaximal mixing Harrison, Perkins, Scott

$$\begin{pmatrix} \sqrt{\frac{1}{3}} & \frac{1}{\sqrt{3}} & 0 \\ -\frac{1}{\sqrt{6}} & \frac{1}{\sqrt{3}} & \frac{1}{\sqrt{2}} \\ \frac{1}{\sqrt{6}} & -\frac{1}{\sqrt{3}} & \frac{1}{\sqrt{2}} \end{pmatrix}$$

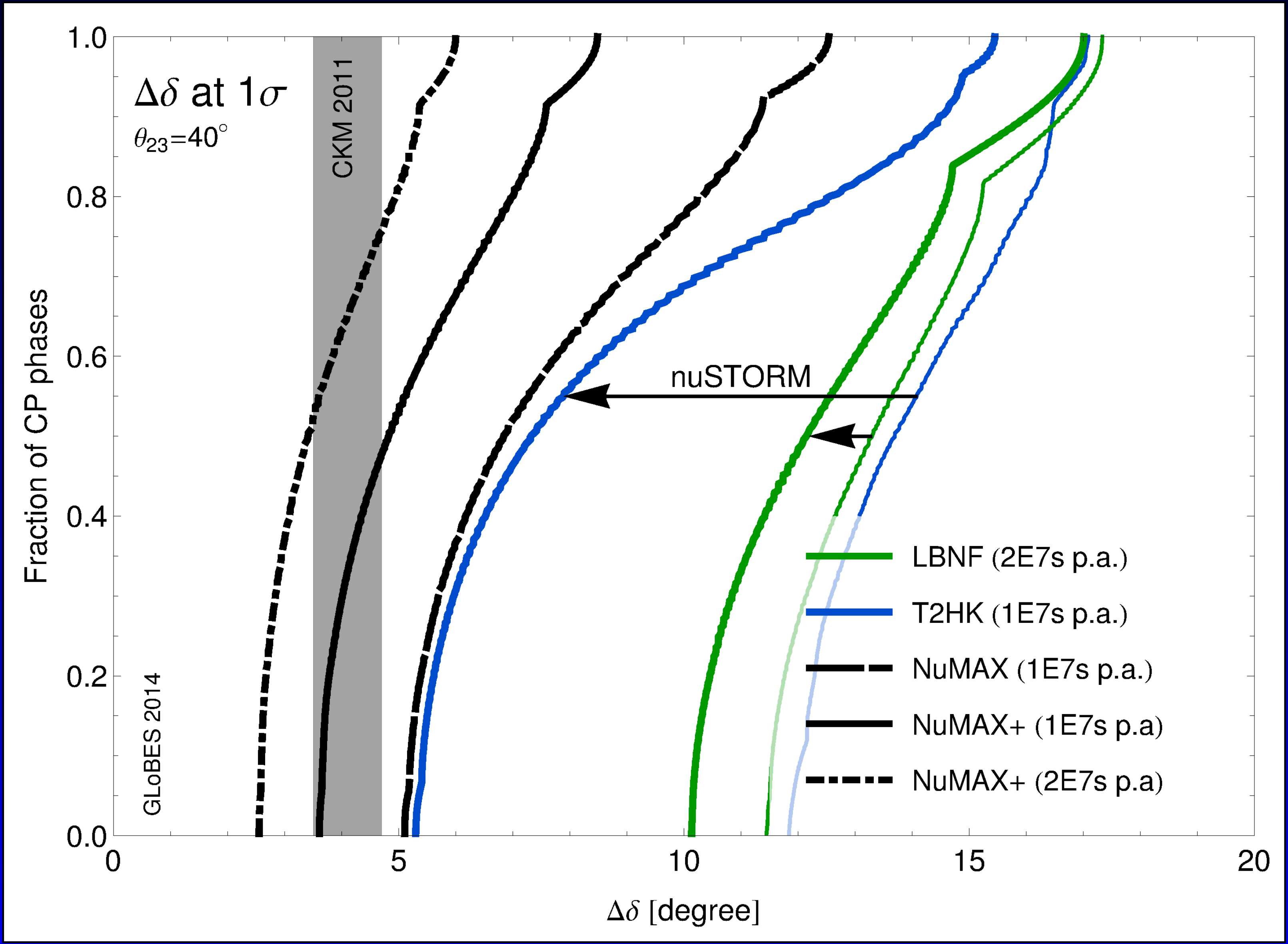
to still fit data, obviously corrections are needed – predictivity?

Sum rules



$3\,\sigma$ resolution of 15° distance requires 5° error. NB – smaller error on θ_{12} requires dedicated experiment like JUNO

How low can you go?



PH, Bross, Palmer, 2014.

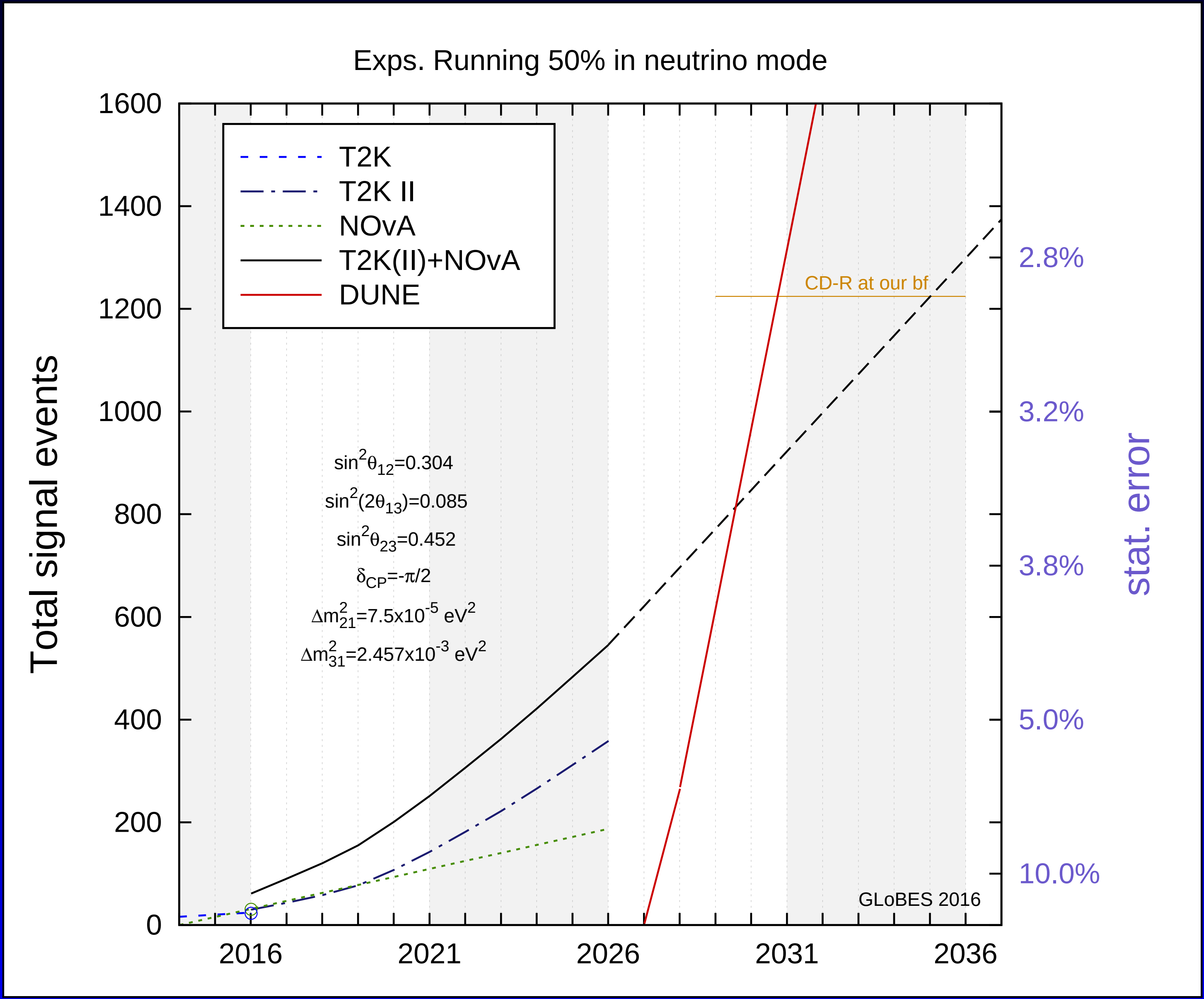
What can we learn from that?

– If we refute three flavor oscillation with significance, we have found new physics, but this requires great precision.

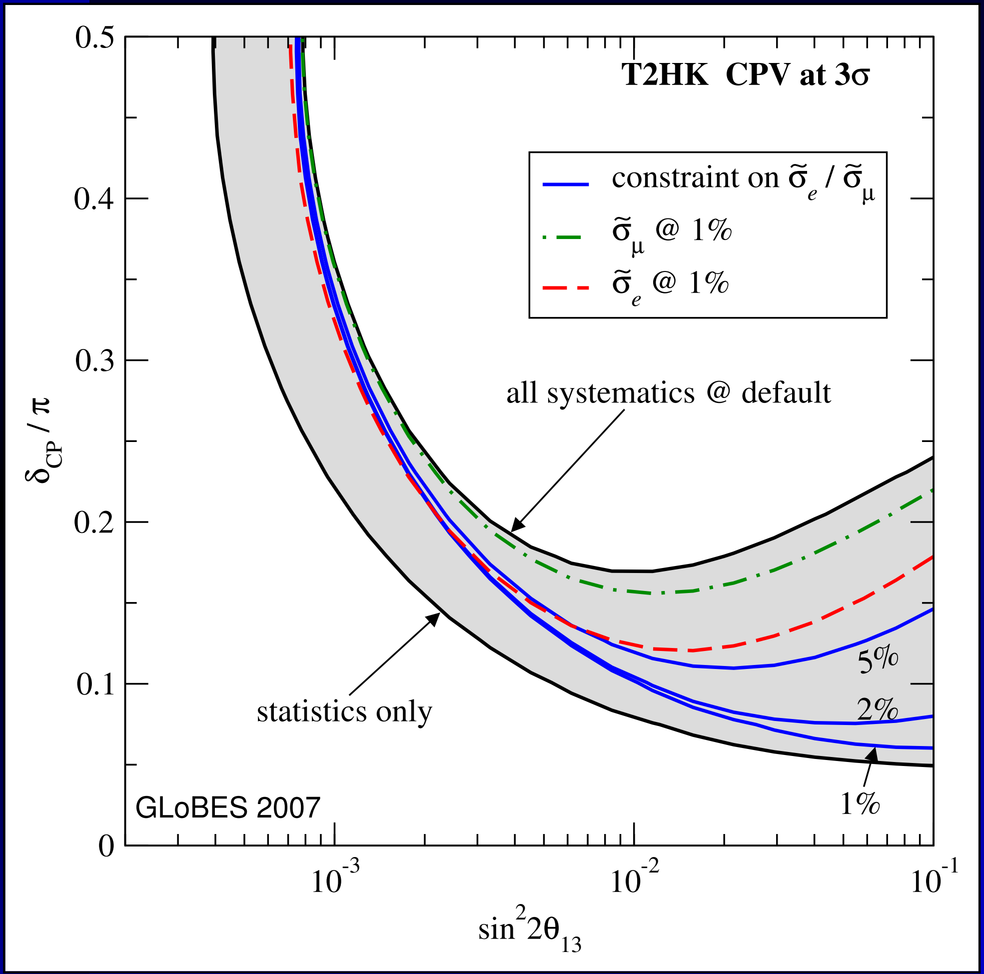
– If we confirm three flavor oscillation with great precision, we need the context of specific models to learn anything about BSM physics.

Corollary: Only if we do this precisely we really will learn something!

The way forward



Neutrino cross sections

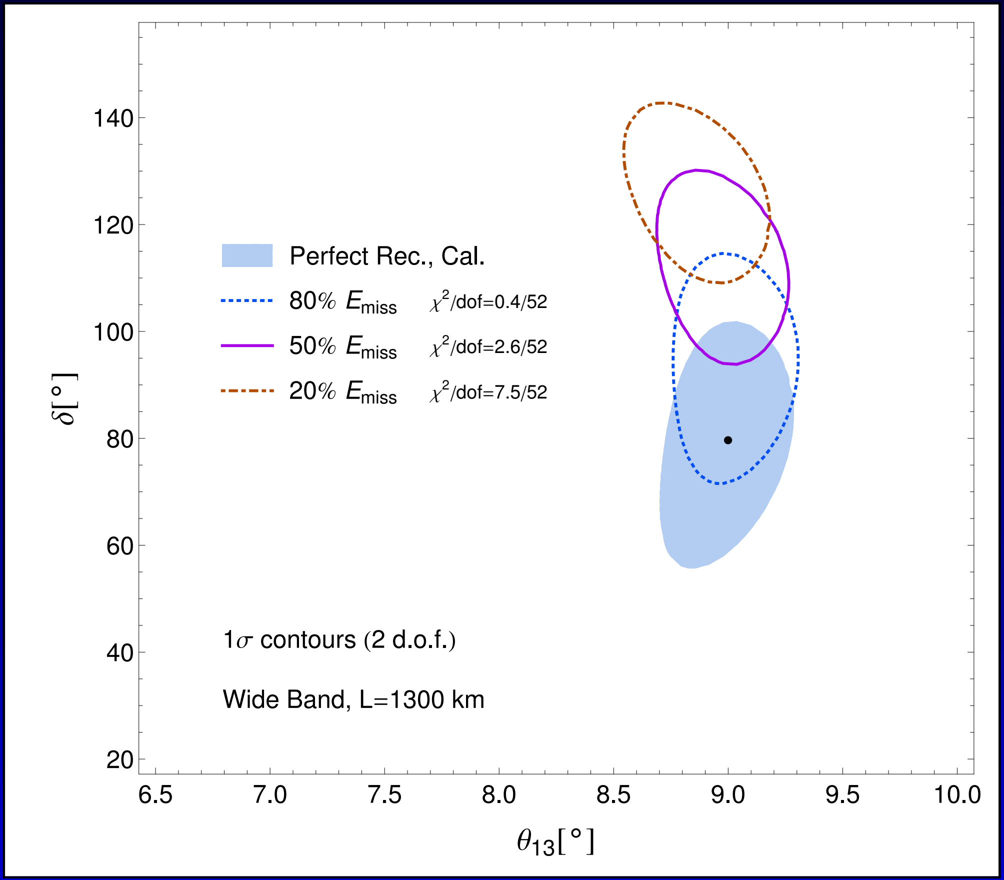


PH, Mezzetto, Schwetz, 2007

Using current cross section uncertainties and a perfect near detector.

Differences between ν_e and ν_μ are significant below 1 GeV, see e.g. Day, McFarland, 2012

Nuclear effects – example



Ankowski *et al.*, 2015

In elastic scattering a certain number of neutrons is made

Neutrons will be largely invisible even in a liquid argon TPC

$\Rightarrow$ missing energy

Theory and cross sections

Theory is cheap, but multi-nucleon systems and their dynamic response are a hard problem and there is not a huge number of people working on this. . .

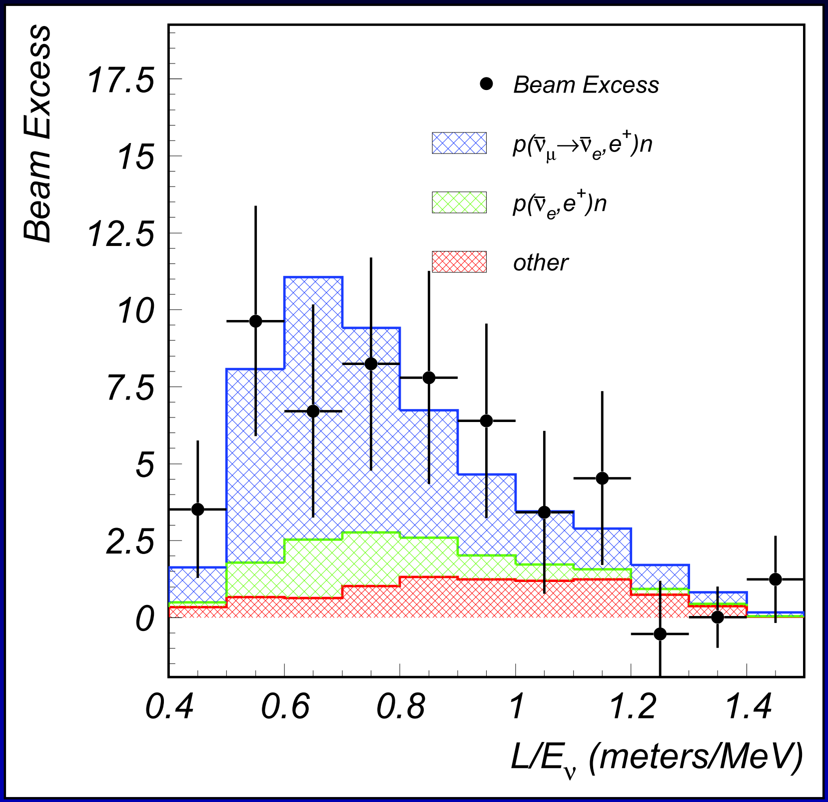
Any result will be based on assumptions and not on controlled approximation.

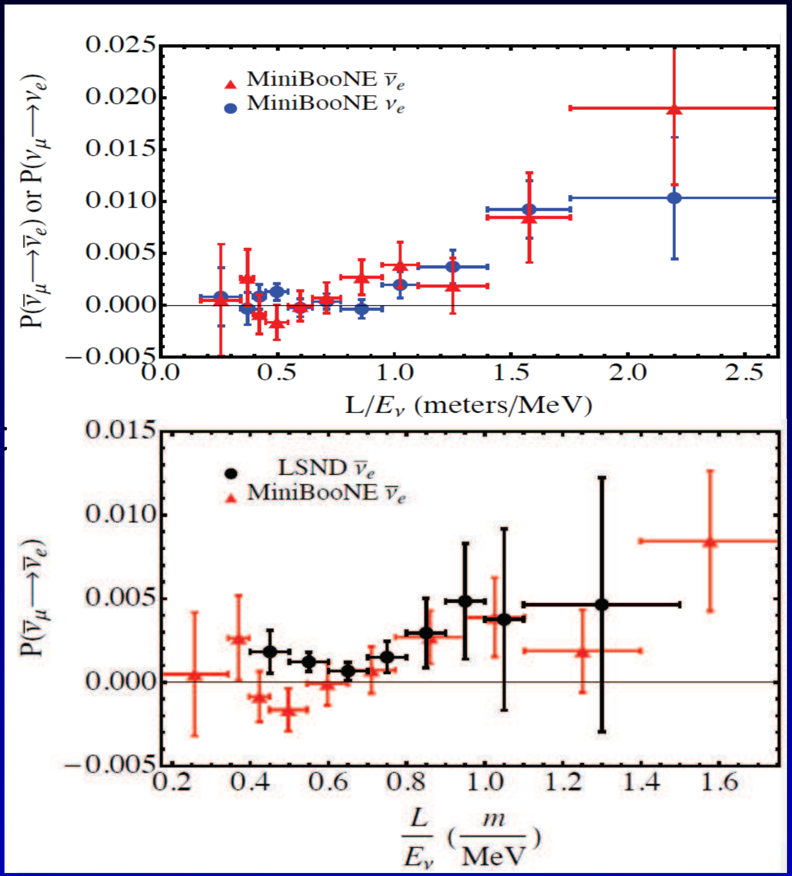
Light sterile neutrinos

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 $\nu_e \to \nu_e$

LSND and MiniBooNE





$$P(\bar{\nu}_\mu \to \bar{\nu}_e) \simeq 0.003$$

Fermilab SBN

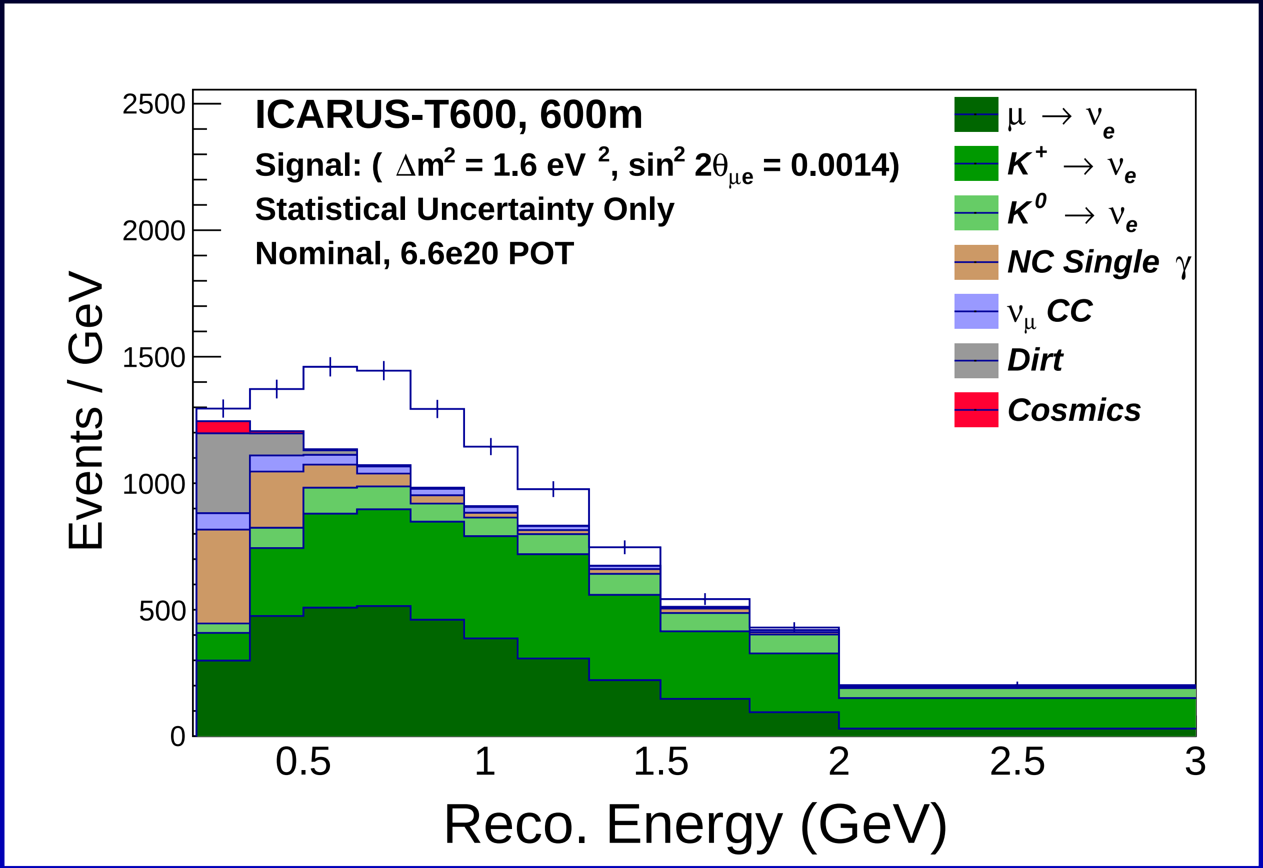


Figure courtesy D. Schmitz and C. Adams

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

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

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

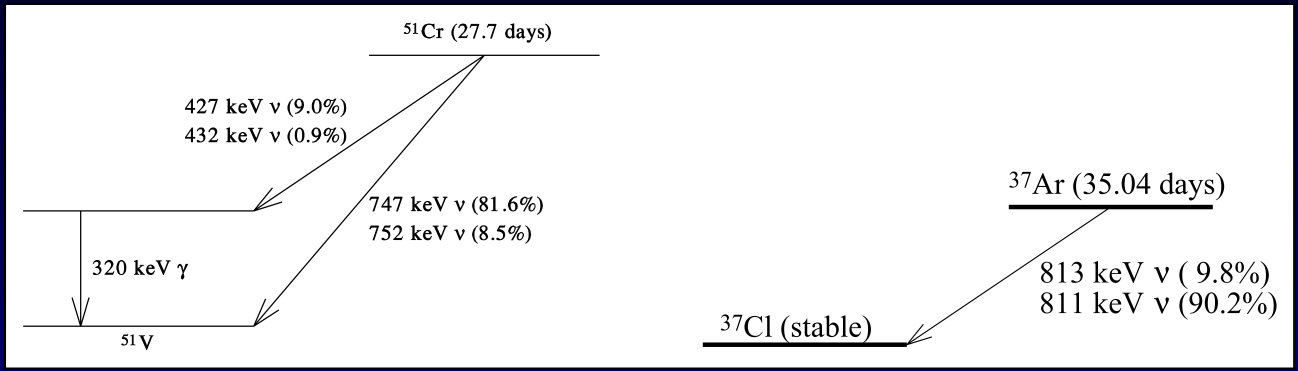
Gallium anomaly

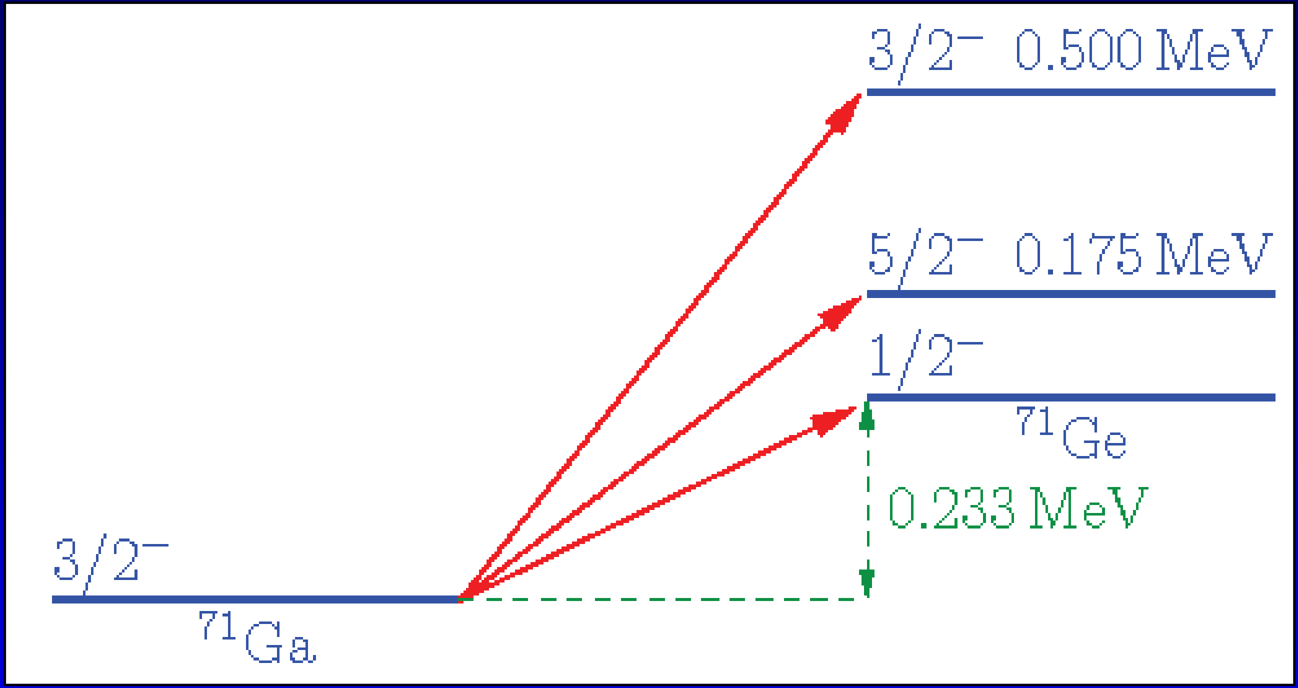
	GALLEX		SAGE	
k	G1	G2	S1	S2
source	^{51}Cr	^{51}Cr	^{51}Cr	^{37}Ar
$R^k_{\rm B}$	0.953 ± 0.11	$0.812^{+0.10}_{-0.11}$	0.95 ± 0.12	$0.791 \pm {}^{+0.084}_{-0.078}$
$R^k_{\rm H}$	$0.84^{+0.13}_{-0.12}$	$0.71^{+0.12}_{-0.11}$	$0.84^{+0.14}_{-0.13}$	$0.70 \pm {}^{+0.10}_{-0.09}$
radius [m]	1.9		0.7	
height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

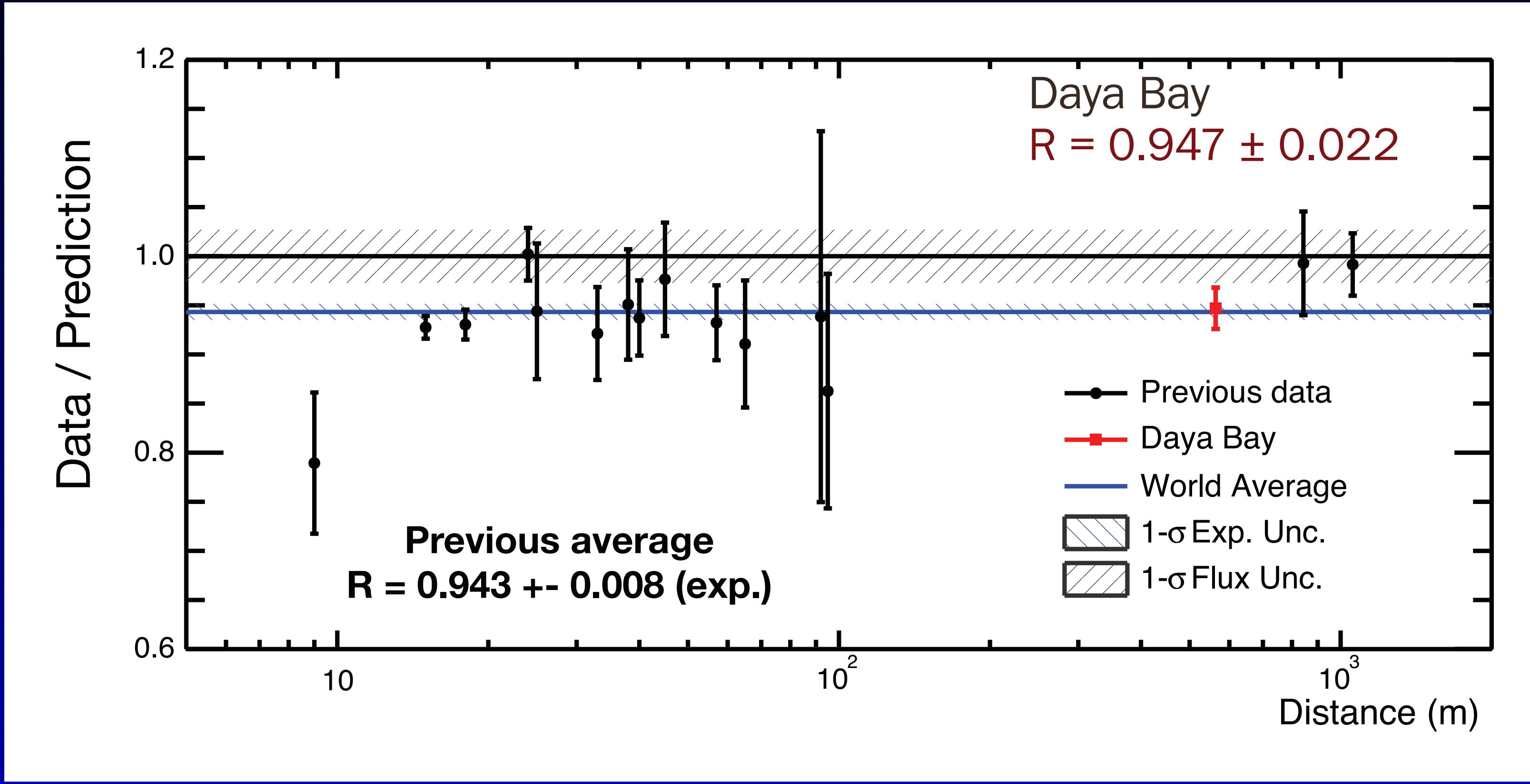
- effect depends on nuclear matrix element
- calibration measurment

Nuclear matrix elements





The reactor anomaly



Daya Bay, 2014

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

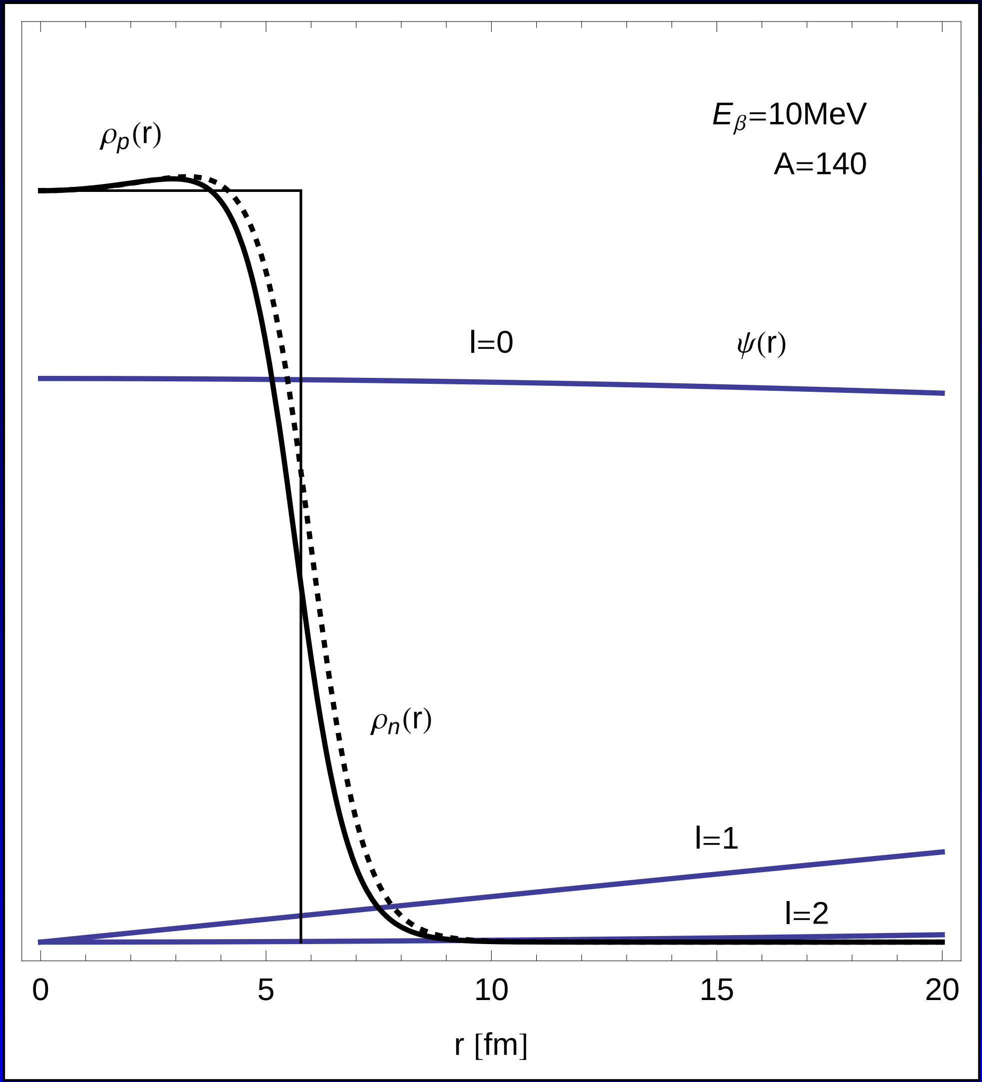
Contributors to the anomaly

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

- 3% increase in reactor neutrino fluxes
- decrease in neutron lifetime (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.

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 $l > 1$

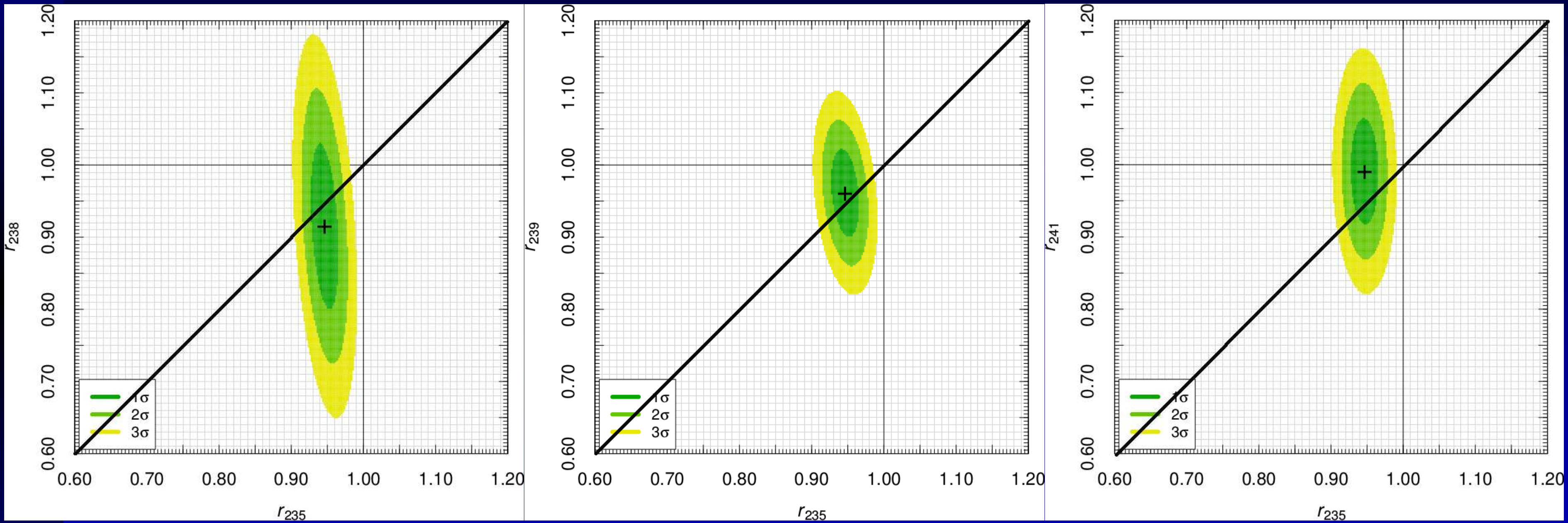
Significant dependence on nuclear structure in forbidden decays→ large uncertainties!

Look at past data

a	Experiment	f_{235}^a	f_{238}^a	f_{239}^a	f_{241}^a	$R_{a,\mathrm{SH}}^{\mathrm{exp}}$	σ_a^{exp} [%]	σ_a^{cor} [%]	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

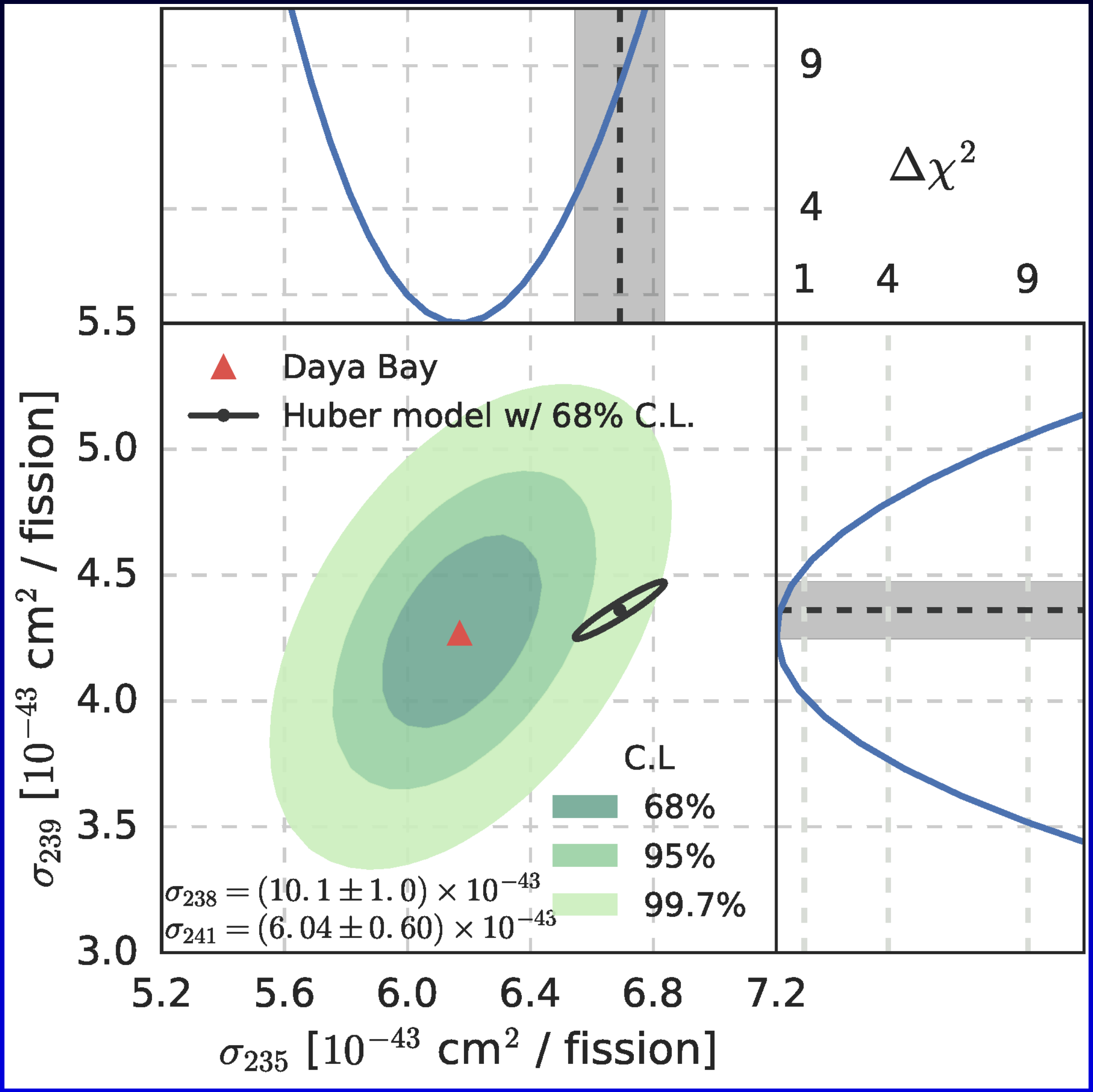
What does this tell us?



Giunti, 2016

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

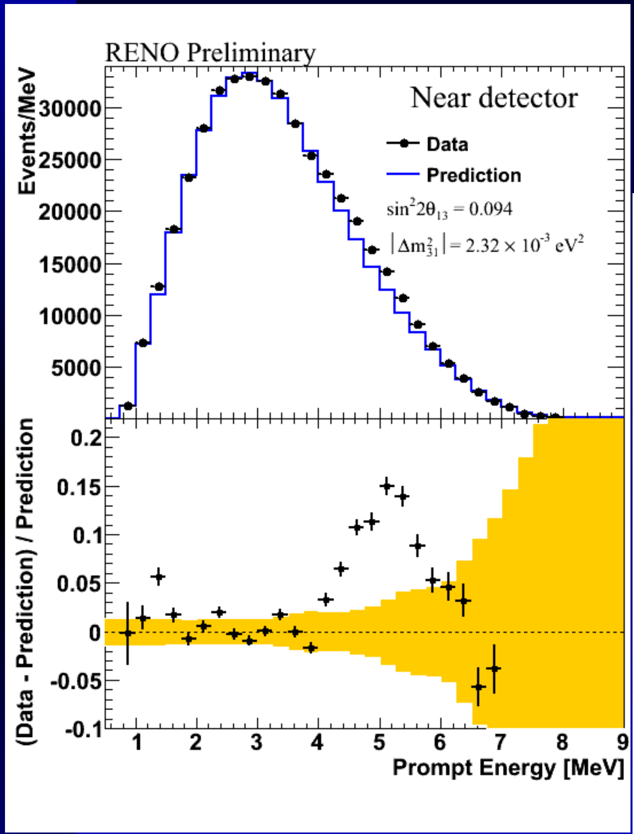
Latest result of Daya Bay

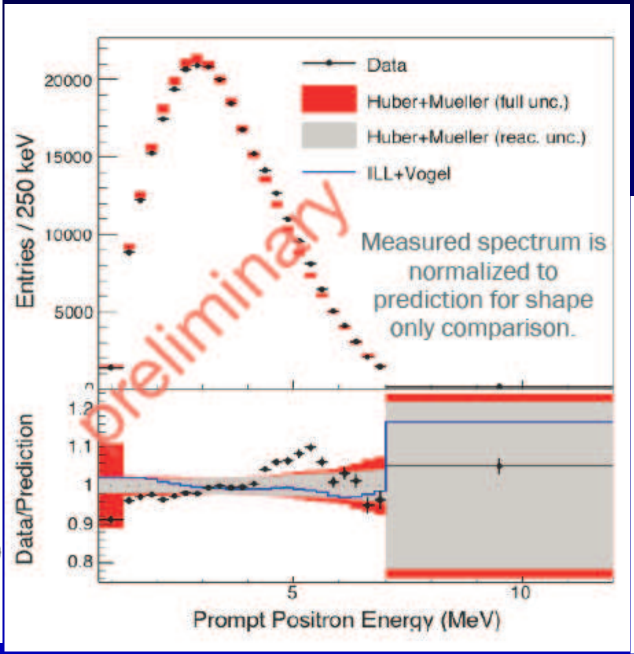


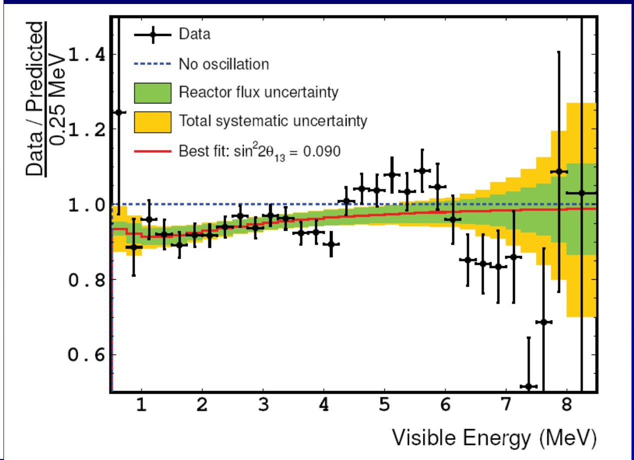
Daya Bay, 2017

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

The 5 MeV bump





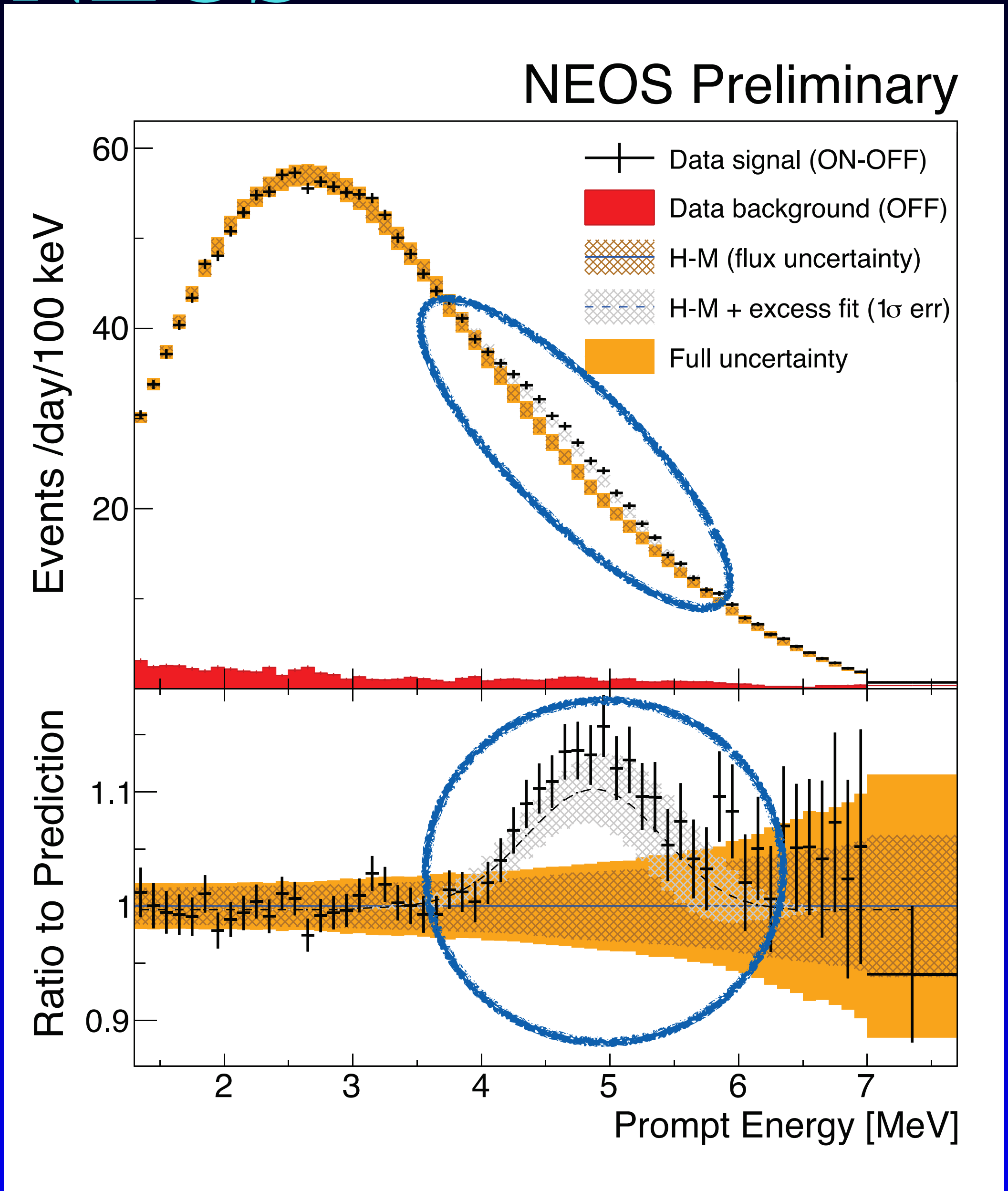


Seen by all three reactor experiments

Tracks reactor power

Seems independent of burn-up

NEOS

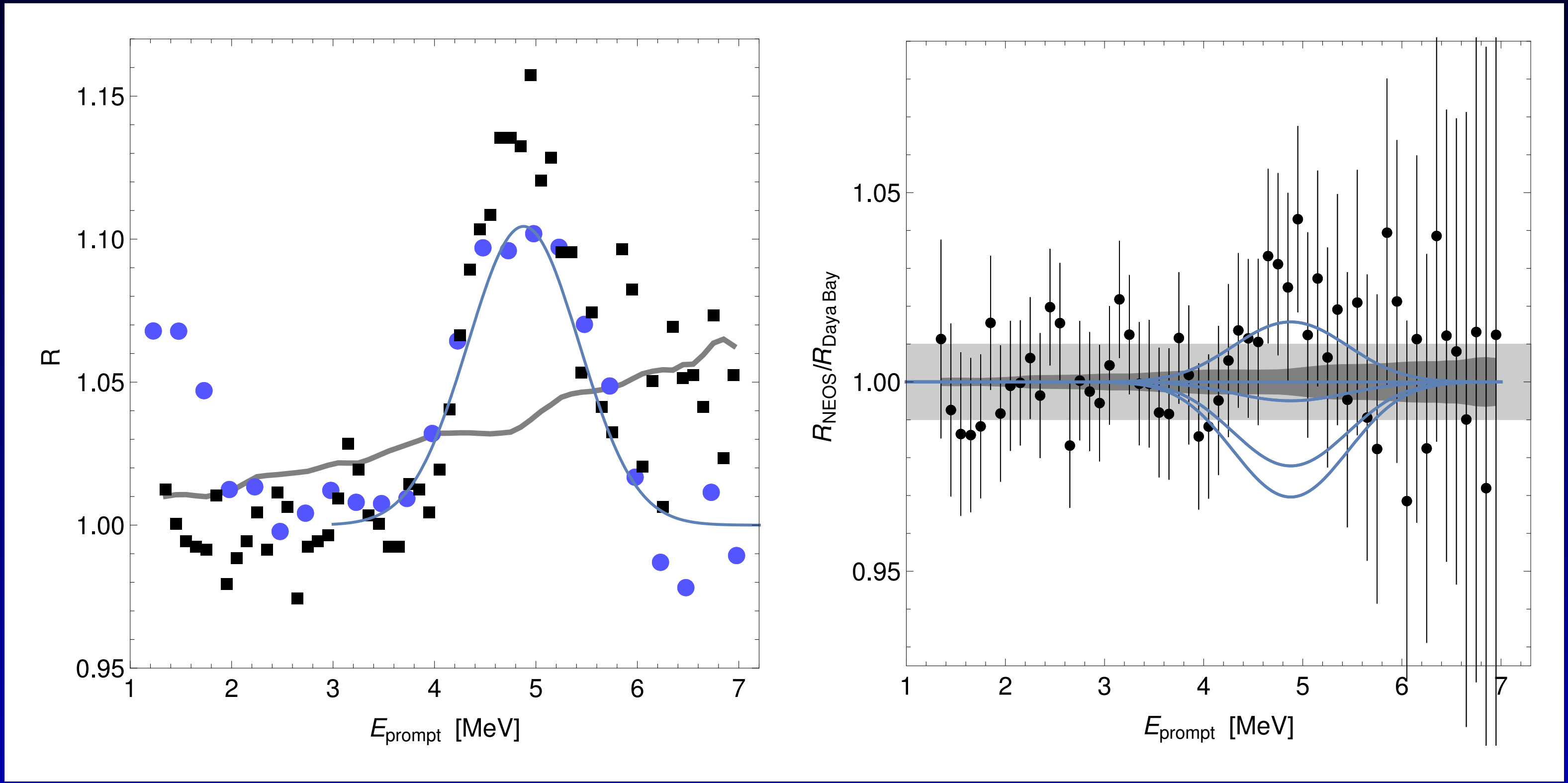


Y. Oh, ICHEP 2016

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

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

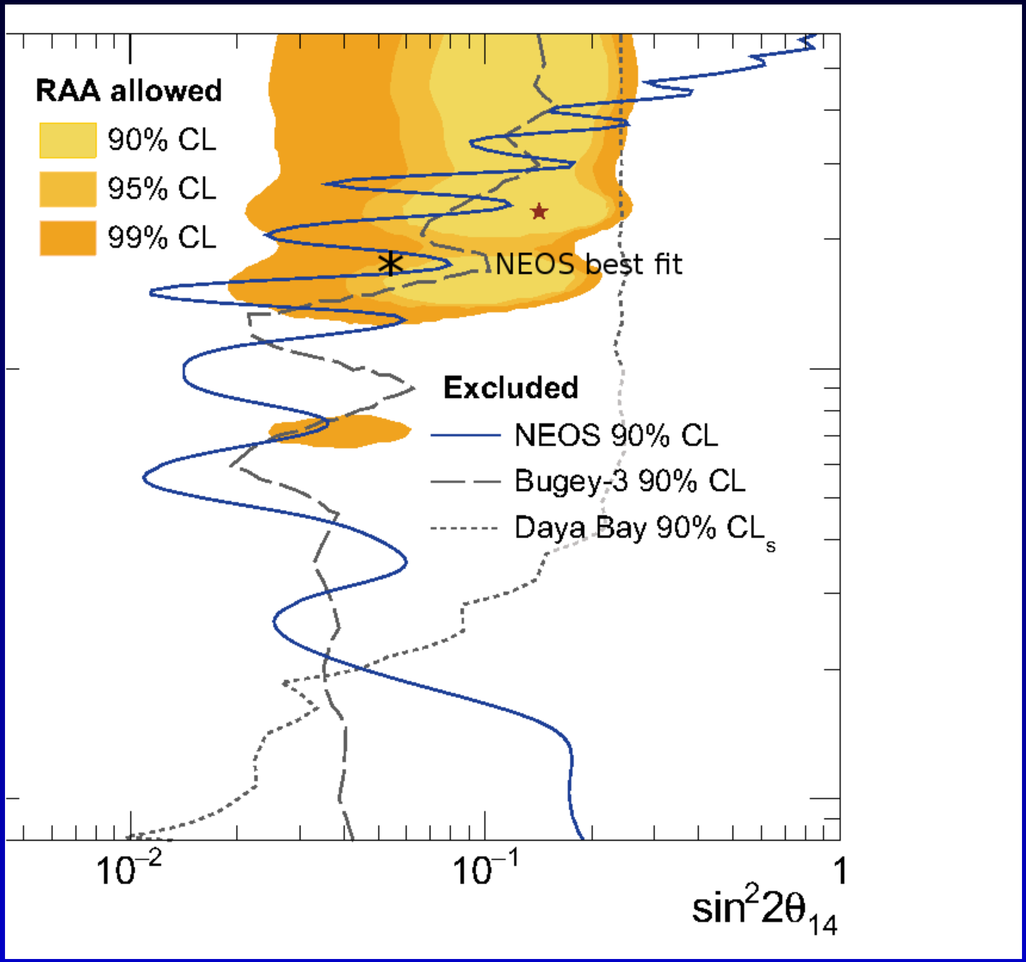
NEOS vs Daya Bay



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

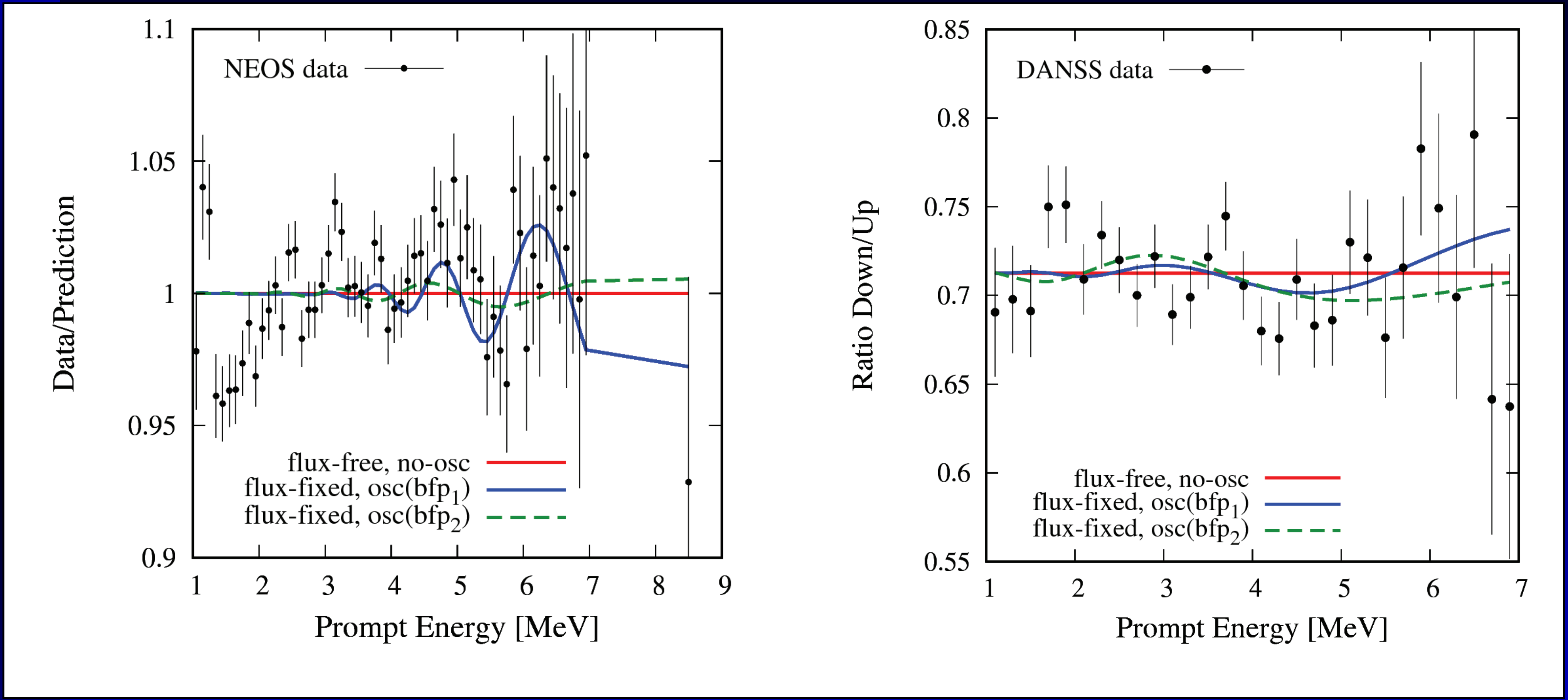


adapted from NEOS, 2016

DANSS has a similar result.

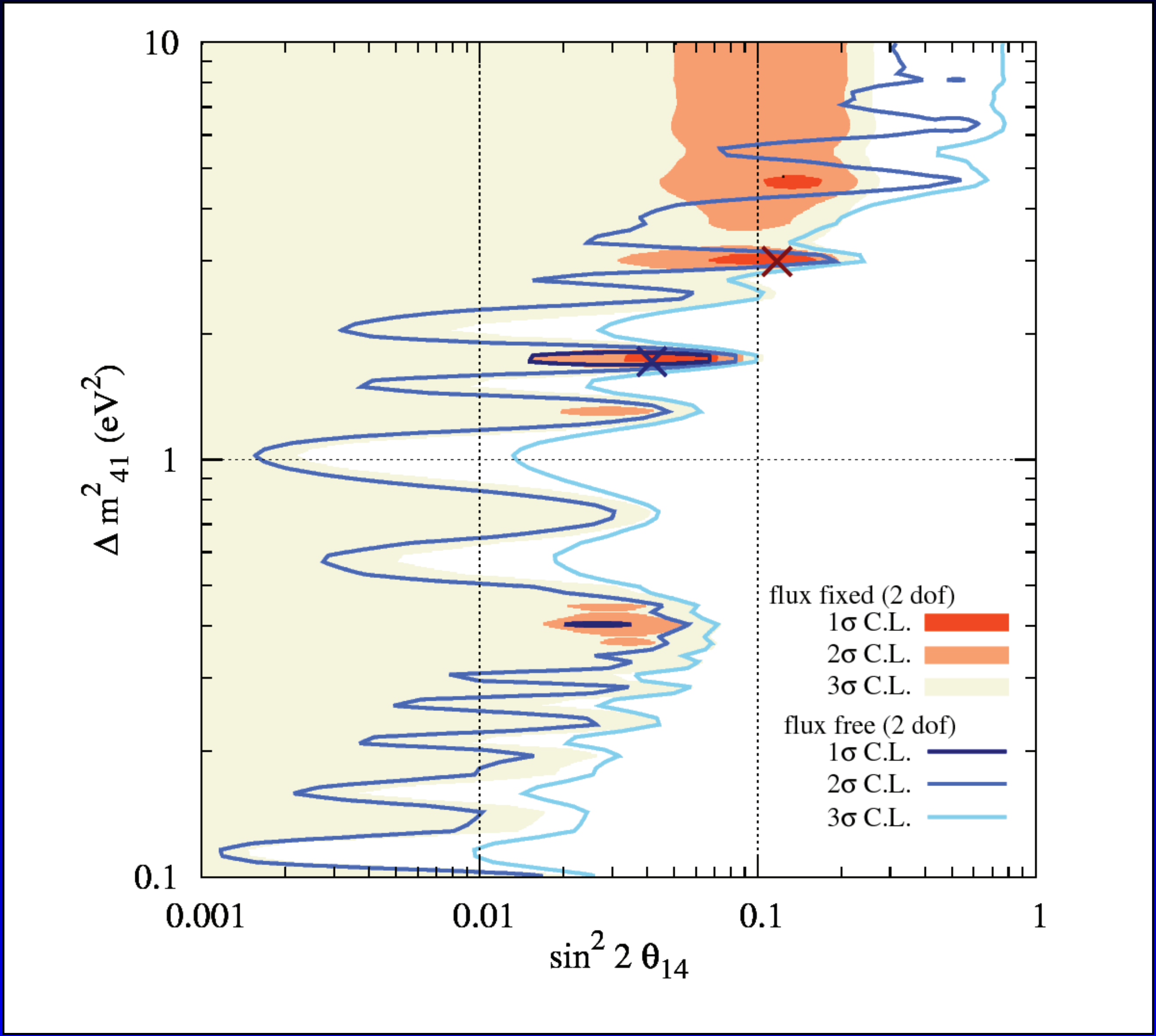
NEOS reports a limit, but their best fit occurs at $\sin^2 2\theta = 0.05$ and $\Delta m^2 = 1.73\,\mathrm{eV}^2$ with a χ^2 value 6.5 below the no-oscillation hypothesis.

DANSS and NEOS



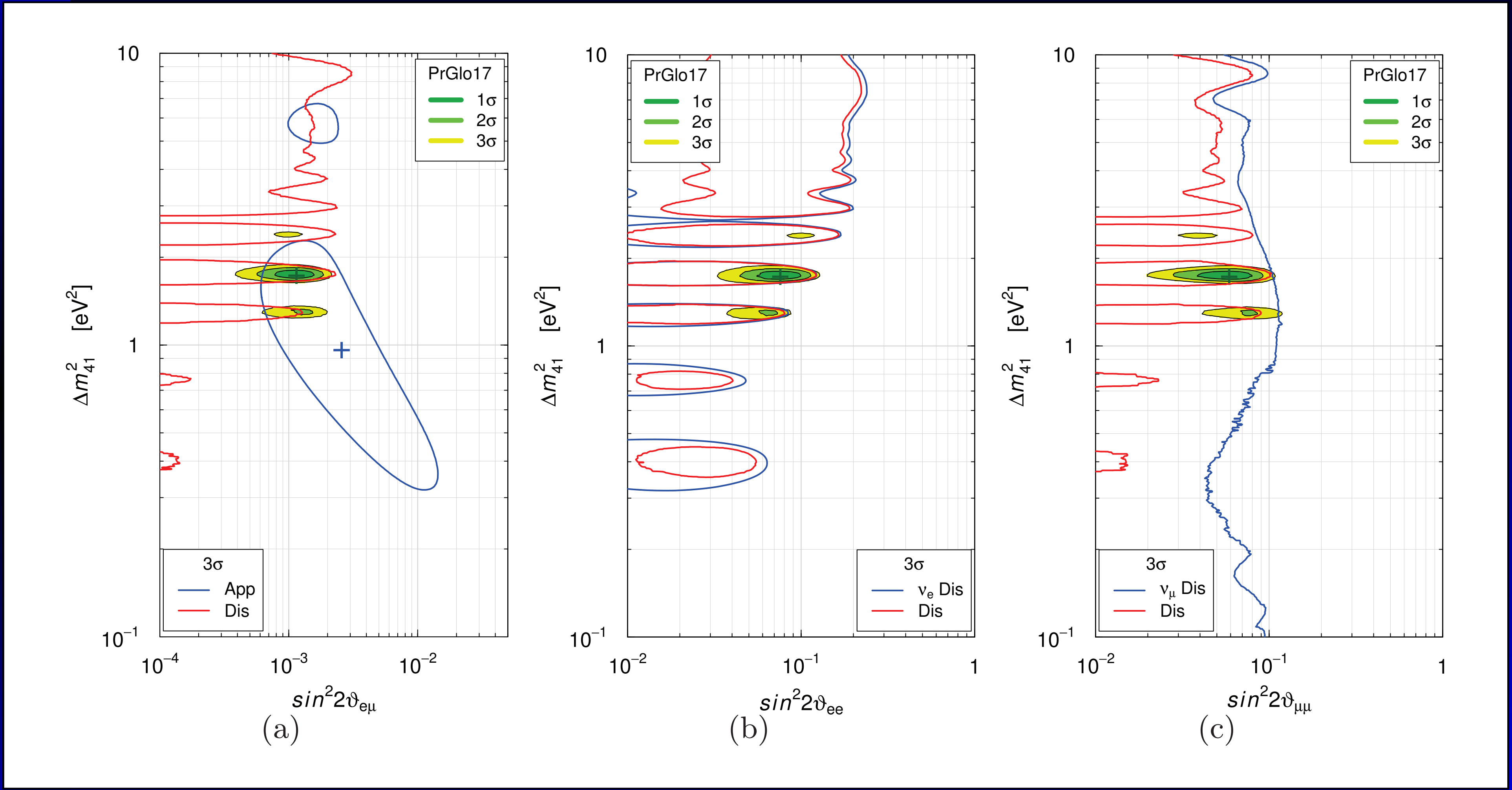
Dentler et al. 2017

Reactor fit



Dentler et al. 2017

Global fit



Gariazzo *et al.*, 2017

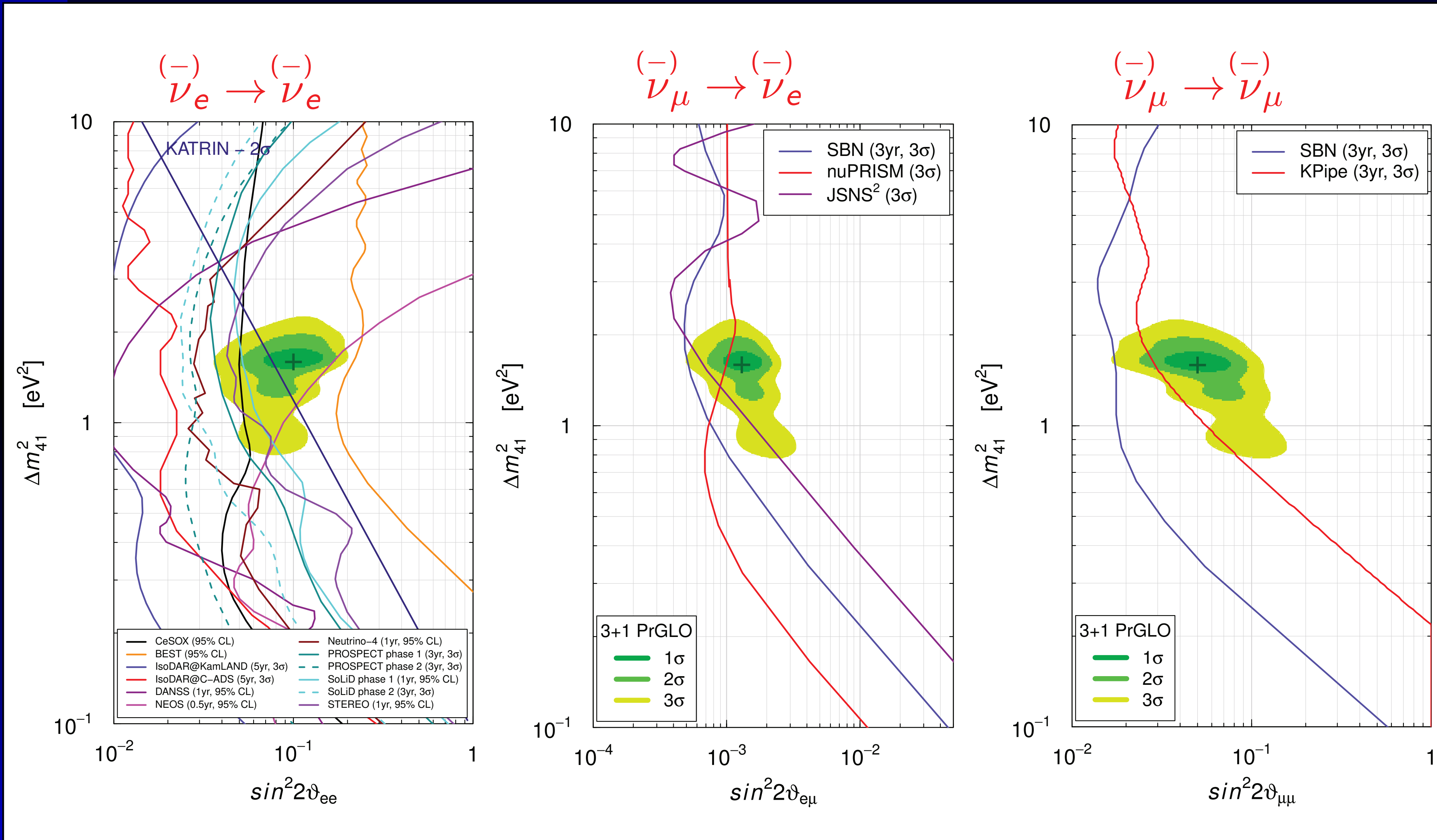
Finding a sterile neutrino

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.

MiniBooNE reloaded?



Giunti, Neutrino 2016

. . . and that assumes all is going according to plan!

Summary

Neutrino oscillation is solid evidence for new physics

- Current data allows large corrections to three flavor. framework
- Precision measurements have the best potential to uncover even "newer" physics – either by finding discrepancies or correlations among results.
- Can existing neutrino production techniques provide sufficiently low systematics?

Summary

Sterile neutrinos - aka anomalies

Tension in global fits

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

Still, one of the best evidence we currently have for New Physics, anywhere!

NuFact 2018

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

The Department of Physics at Virginia Tech invites applications for a tenure-track faculty position in Particle Physics Phenomenology with a focus on neutrinos and dark matter.

Email: pheno_search@phys.vt.edu
Phone: +1 (540) 231 8727
URL: http://listings.jobs.vt.edu/postings/79786