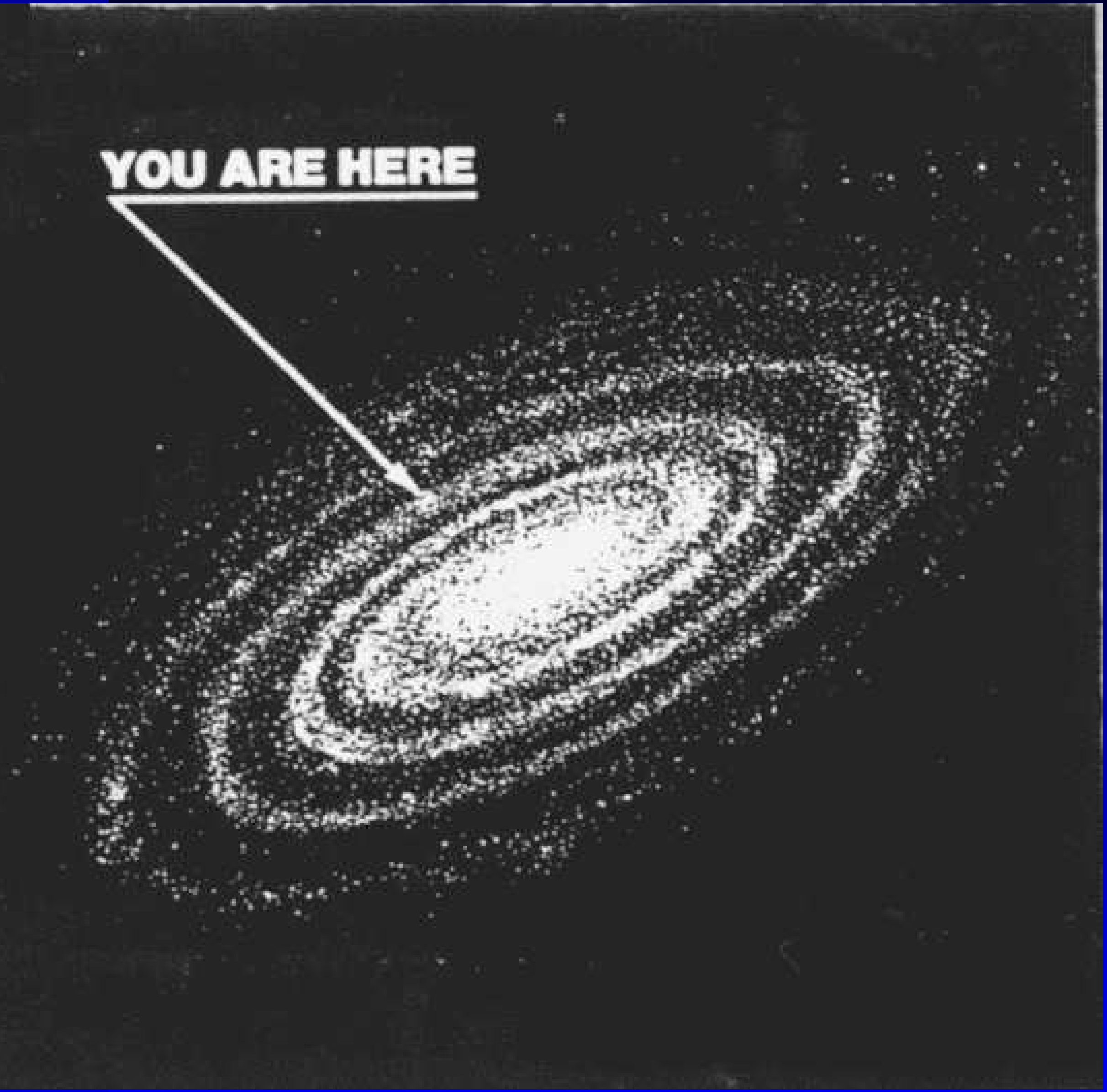

Patrick Huber

Center for Neutrino Physics
at Virginia Tech

NuFact 2016
International Workshop
on Neutrino Factories and
Super Beams
ICISE
Quy Nhon, Vietnam
August 22-27, 2016

Disclaimer

I have given a talk with the same title at the closing of NuFact 2012 in Williamsburg.

So here, I will focus on what has happened since then. . .

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"*

The big questions in 2012

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

And essentially, we still would like to see these questions answered in 2016.

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

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

but we currently do not know which neutrino is the heaviest.

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.

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

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

Thus studying neutrino masses is, in principle, the most sensitive probe for new physics at high scales

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

- lepton number may be conserved $\rightarrow$ no Majorana mass term
- lepton number may be approximately conserved $\rightarrow$ small pre-factor for $\mathcal{L}_5$

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

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

This allows for things like the seesaw mechanism (many versions) and implies that the neutrino flavor sector probes very different physics than the quark sector.

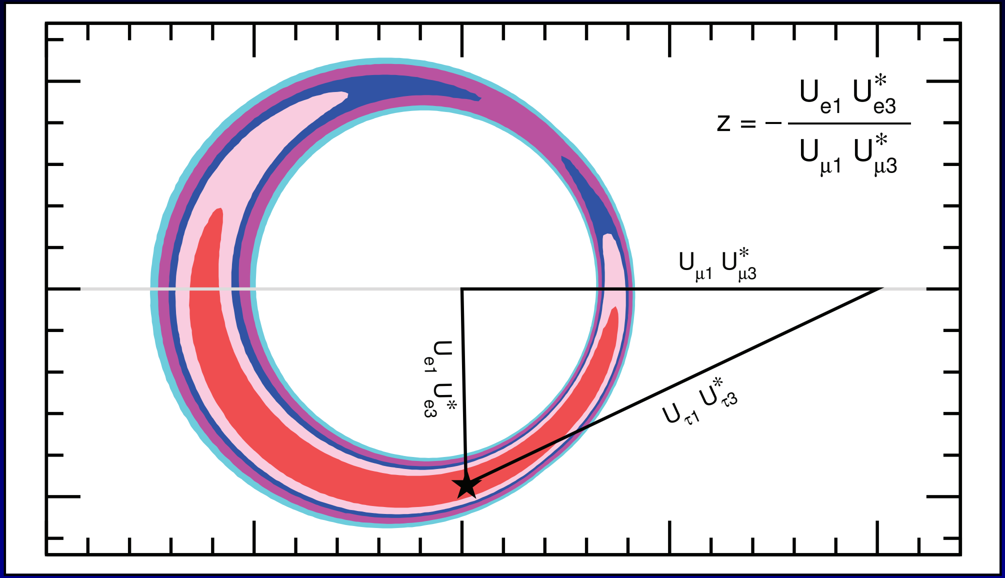
Neutrino mass determination

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

- Dirac vs Majorana mass
- Absolute size of mass

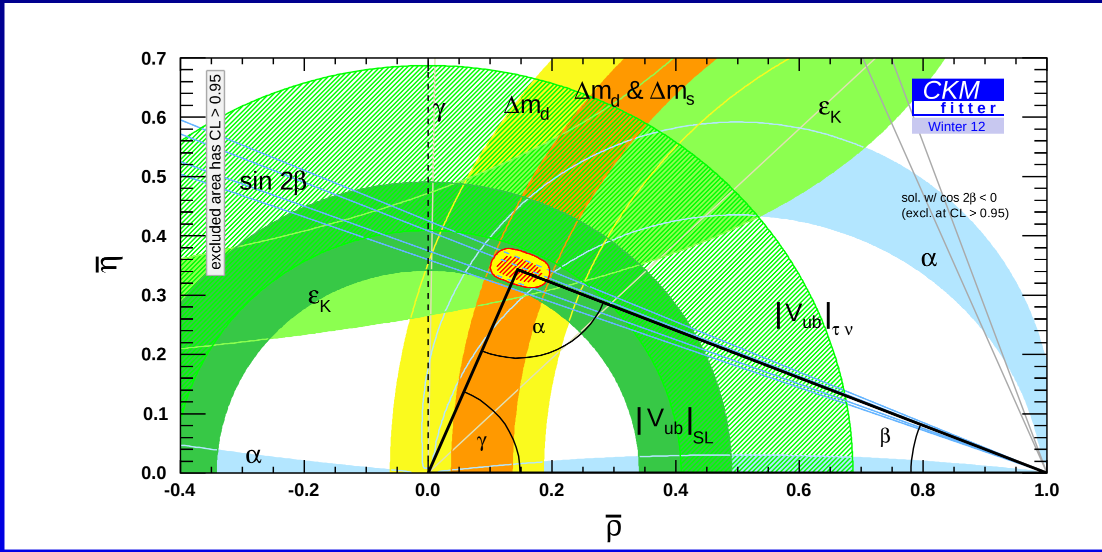
All direct experimental techniques for mass determination rely on ν_e, which is mostly made up of m_1 and m_2. Thus, the effective mass in both kinematic searches and $0\nu\beta\beta$ has a lower bound only if $m_1, m_2 > m_3$, which we call the inverted mass hierarchy.

Unitarity triangles



Neutrino sector

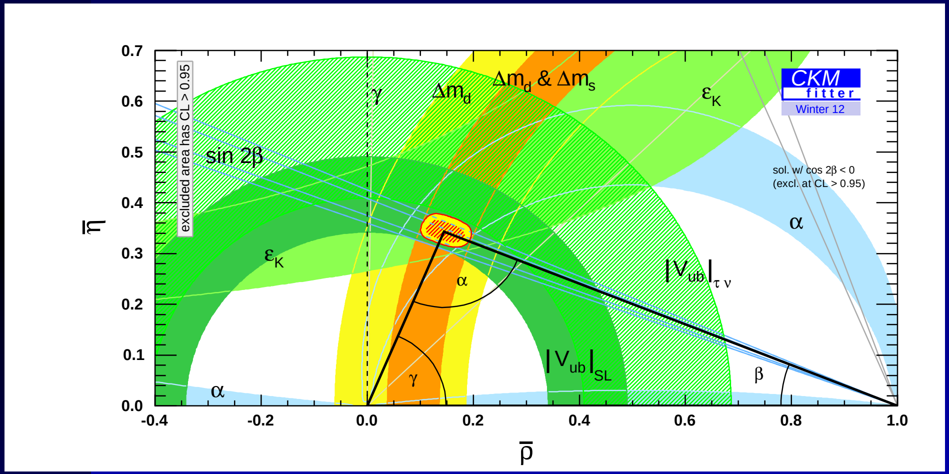
Gonzalez-Garcia, Maltoni, Schwetz, 2014



Quark sector

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.



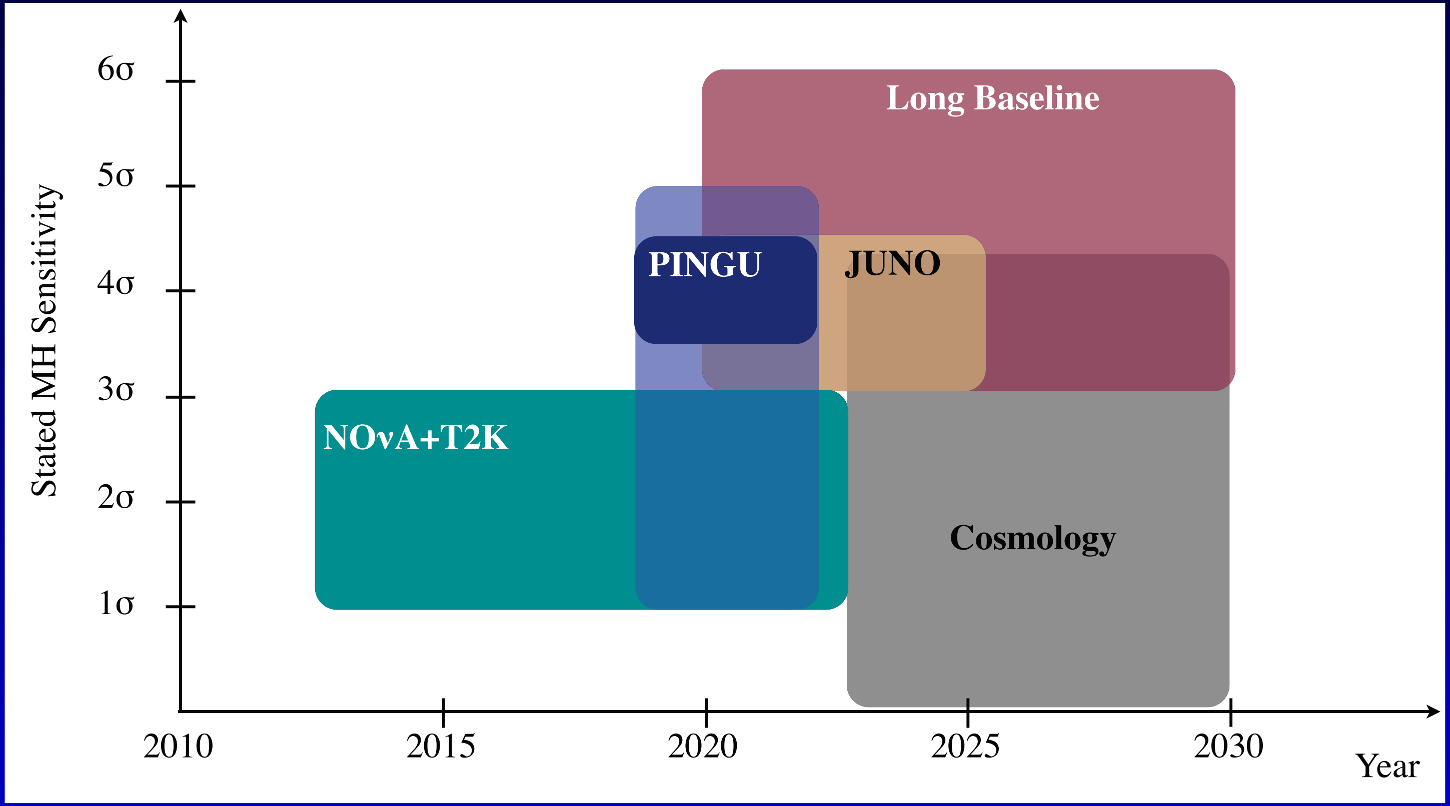
- CKM describes all flavor effects
- SM baryogenesis difficult
- New Physics at a TeV
  - does not exist or
  - has a special flavor structure

and a vast number of parameter and model space excluded.

Neutrinos are very different from quarks, therefore precision measurements will yield very different answers, relating to physics at scales inaccessible by any collider.

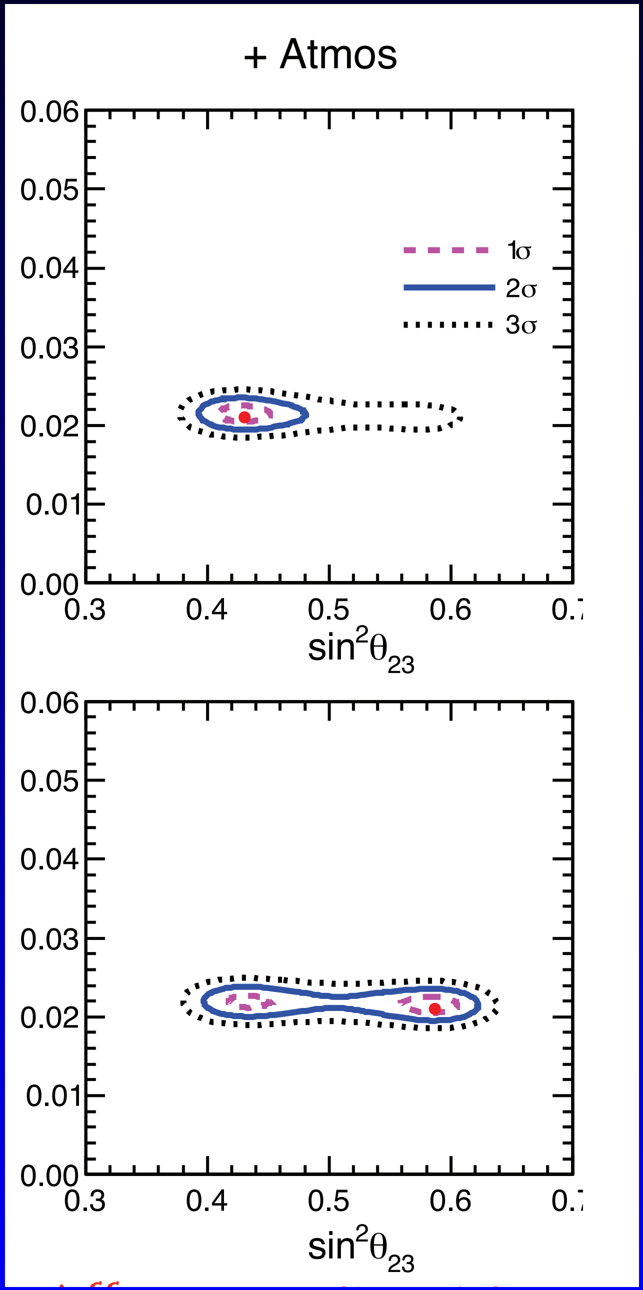
Mass hierarchy

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}



Marrone, Neutrino 2016

In normal hierarchy, maximal mixing is disfavored at $2\,\sigma$

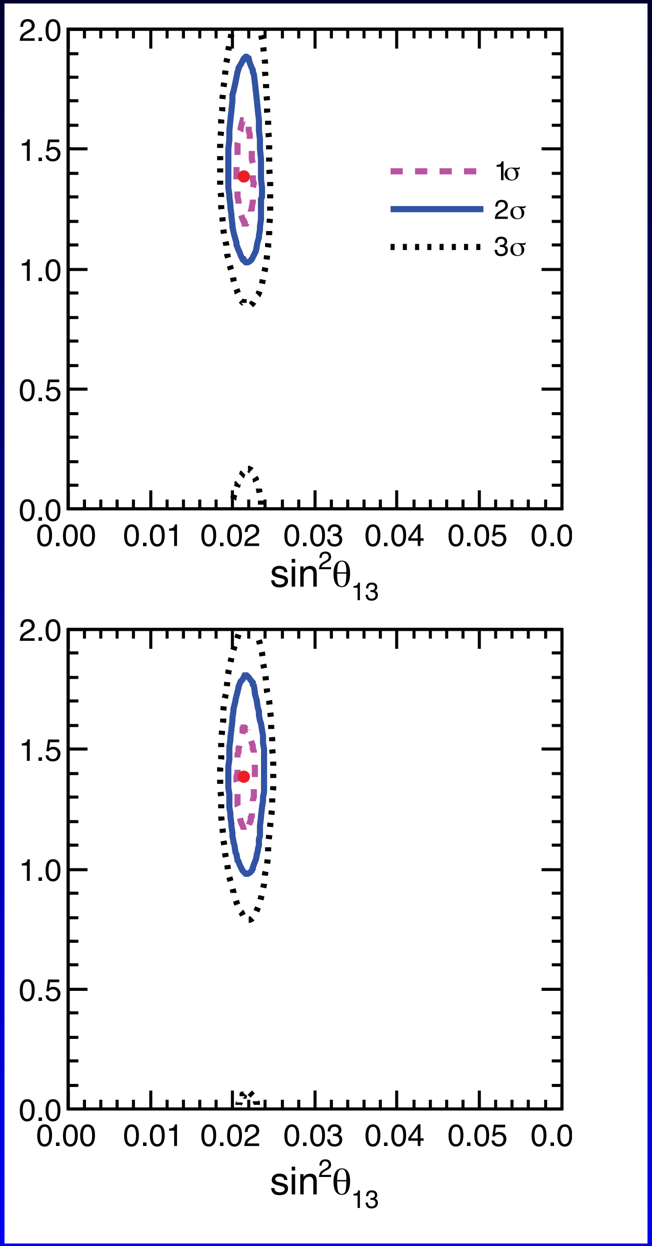
CP violation

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?



Marrone, Neutrino 2016

Latest T2K & NOvA combined with θ_{13} constraint from Daya Bay

Hint for $\delta = -\pi/2$?

Non-standard interactions

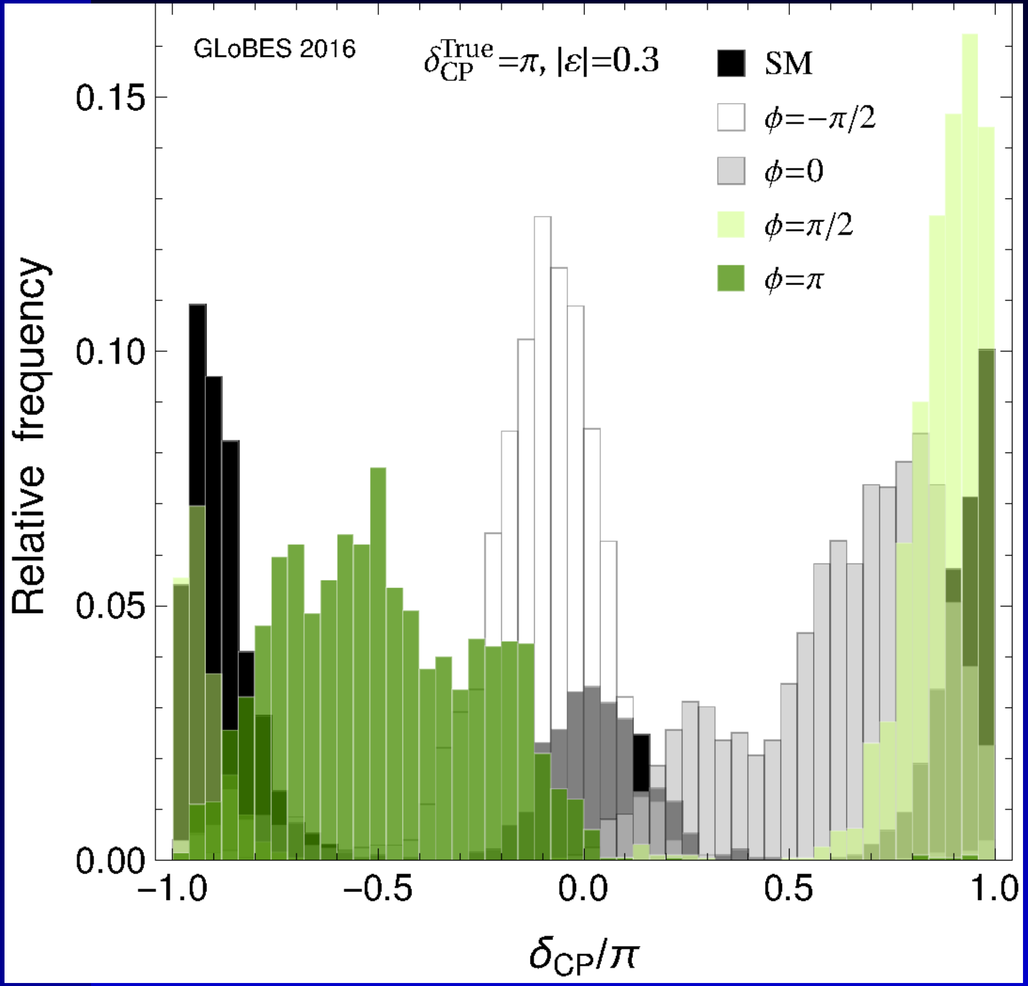
NSI are the workhorse for BSM physics in the neutrino sector. They can be parameterized by terms like this

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

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

At higher energy, this contact term has to be replaced with a propagating exchange particle. This scale typically is closely related to scale of neutrino mass generation and sizable effects occur if the scale $\ll m_{GUT}$.

Impact on three flavors

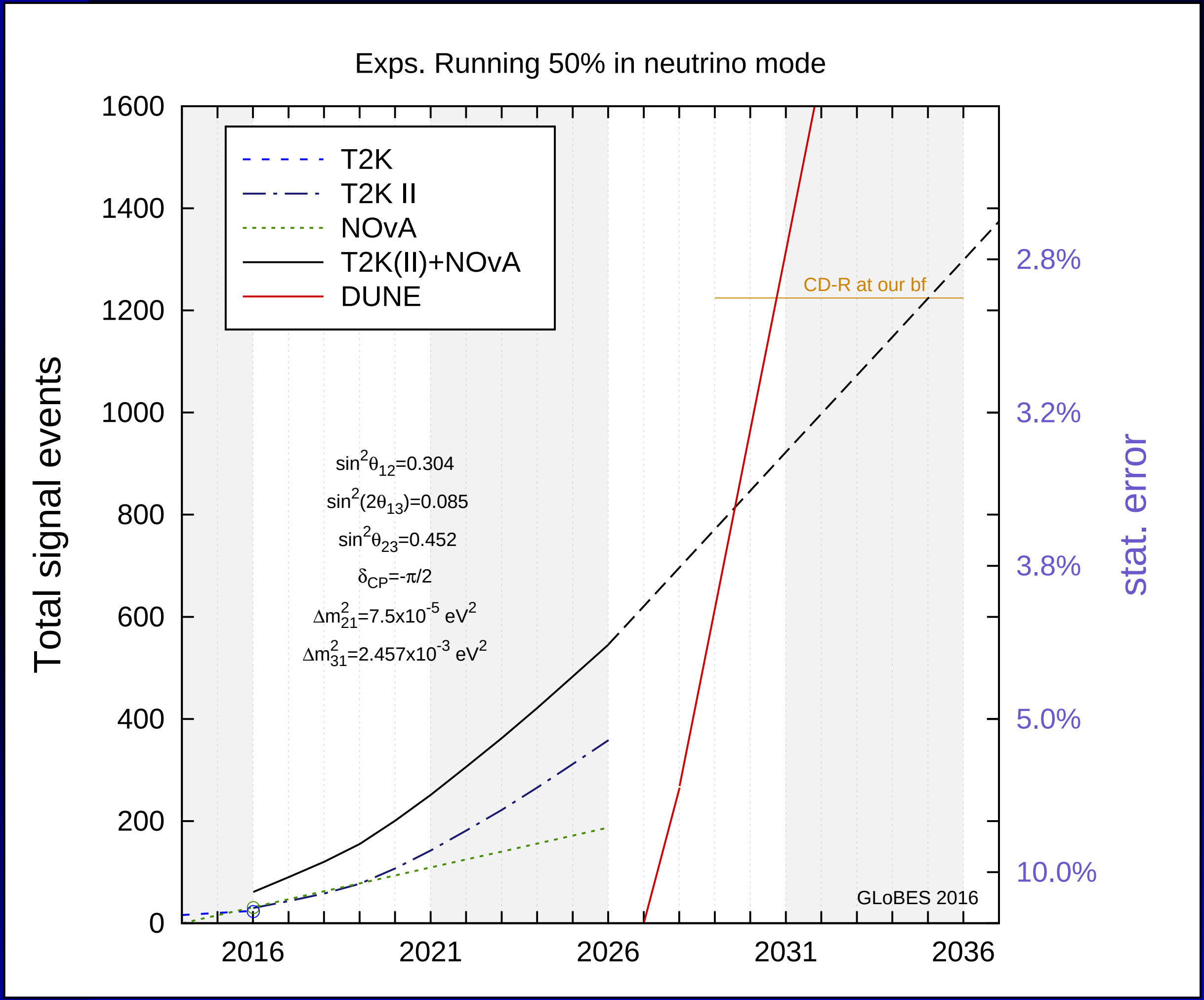


Three flavor analysis are not safe from these effects!

PH, D. Vanegas, 2016

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

The way forward

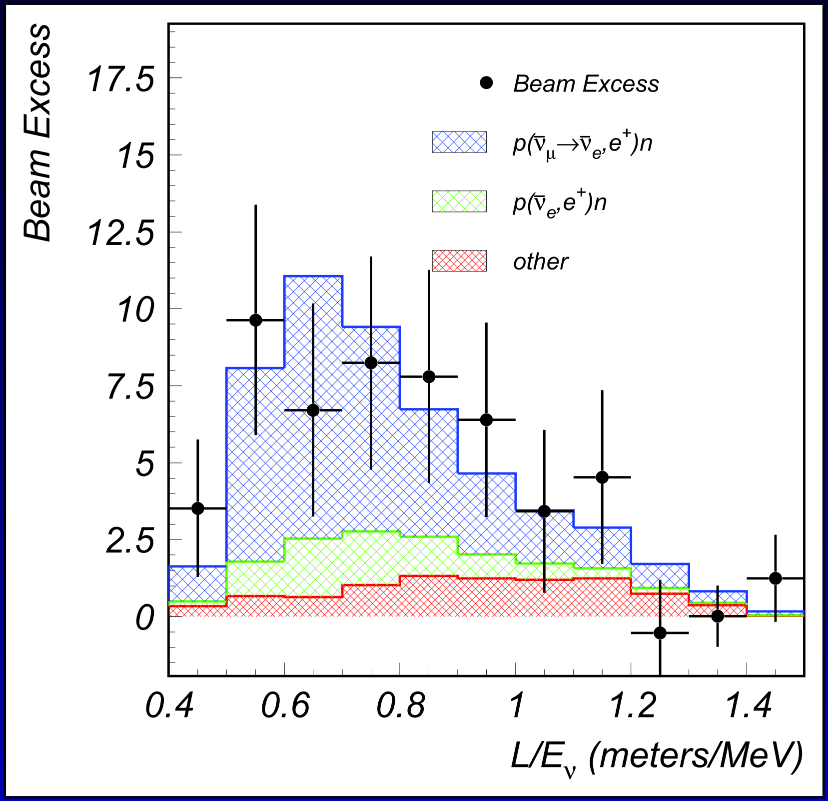


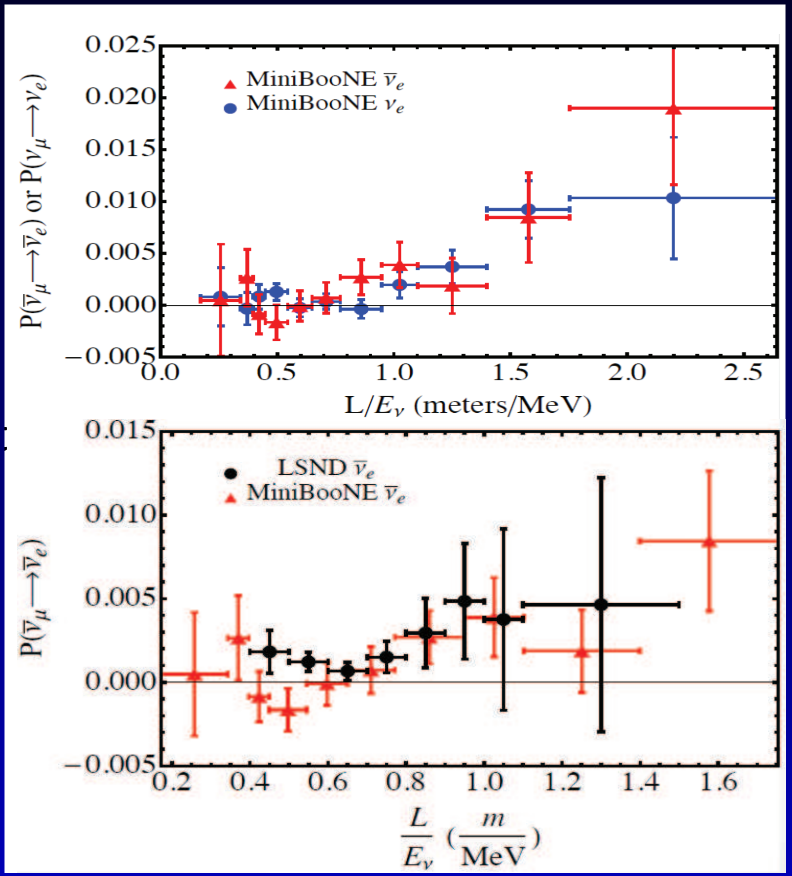
Clearly, we are on the (slow) road towards 3% measurements of the event rates

Translating this into a 3% measurements of the oscillation probability is very difficult

Not clear that DUNE is easier (or better) in that respect than existing experiments, this would require new technologies $\rightarrow$ nuPIL, nuSTORM

LSND and MiniBooNE





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

Fermilab SBN

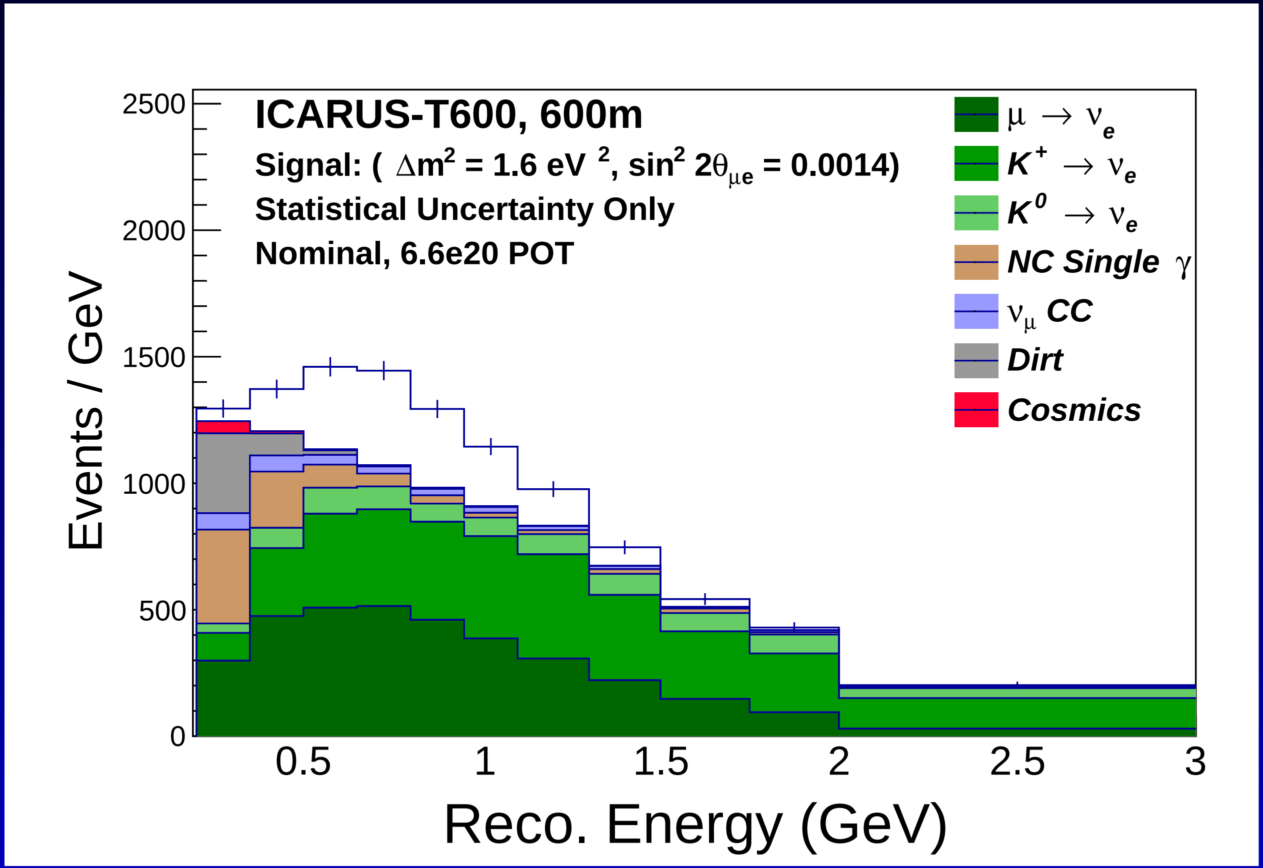


Figure courtesy D. Schmitz and C. Adams

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

Gallium anomaly

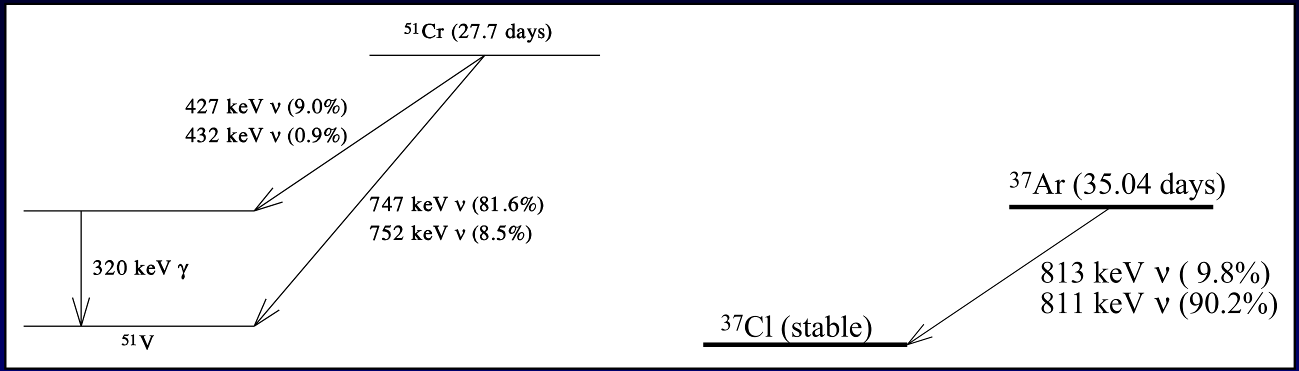
	GALLEX		SAGE	
k	G1	G2	S1	S2
source	^{51}Cr	^{51}Cr	^{51}Cr	^{37}Ar
R^k_{B}	0.953 ± 0.11	$0.812^{+0.10}_{-0.11}$	0.95 ± 0.12	$0.791 \pm ^{+0.084}_{-0.078}$
R^k_{H}	$0.84^{+0.13}_{-0.12}$	$0.71^{+0.12}_{-0.11}$	$0.84^{+0.14}_{-0.13}$	$0.70 \pm ^{+0.10}_{-0.09}$
radius [m]	1.9		0.7	
height [m]	5.0		1.47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

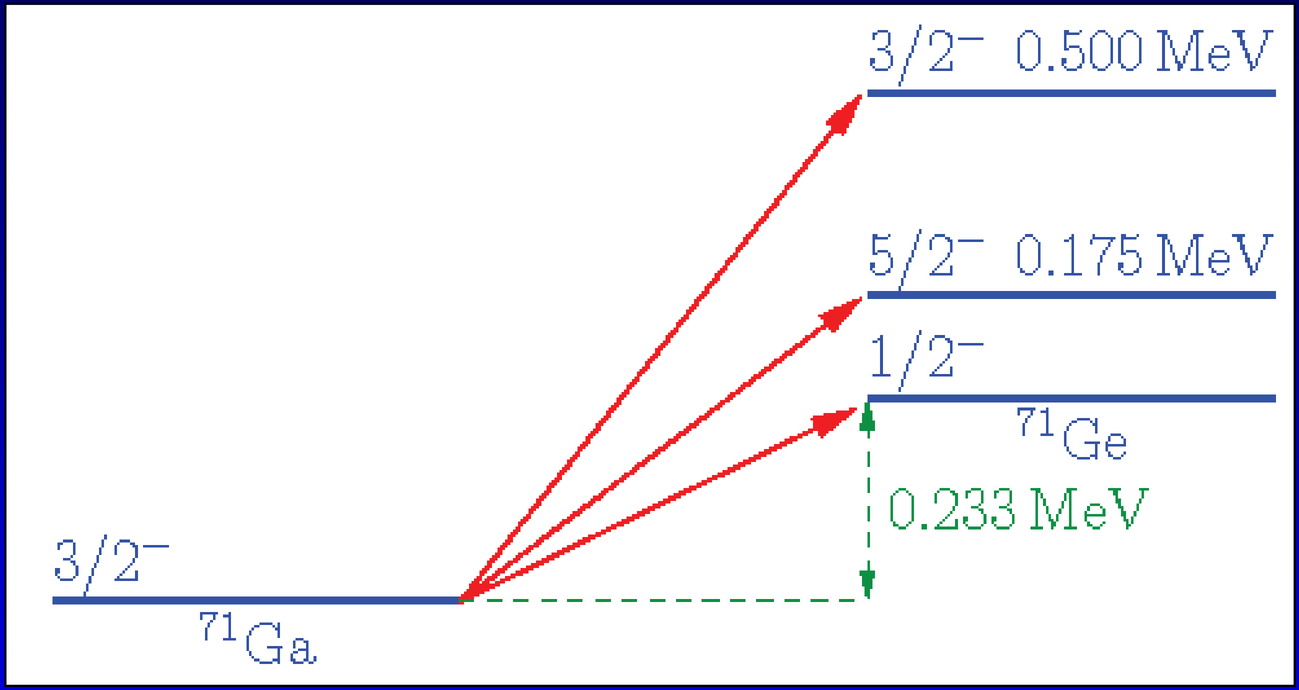
25% deficit of ν_e from radioactive sources at short distances

Effect depends on nuclear matrix elements

This measurement was intended as a calibration – is R a physics measurement or a calibration constant?

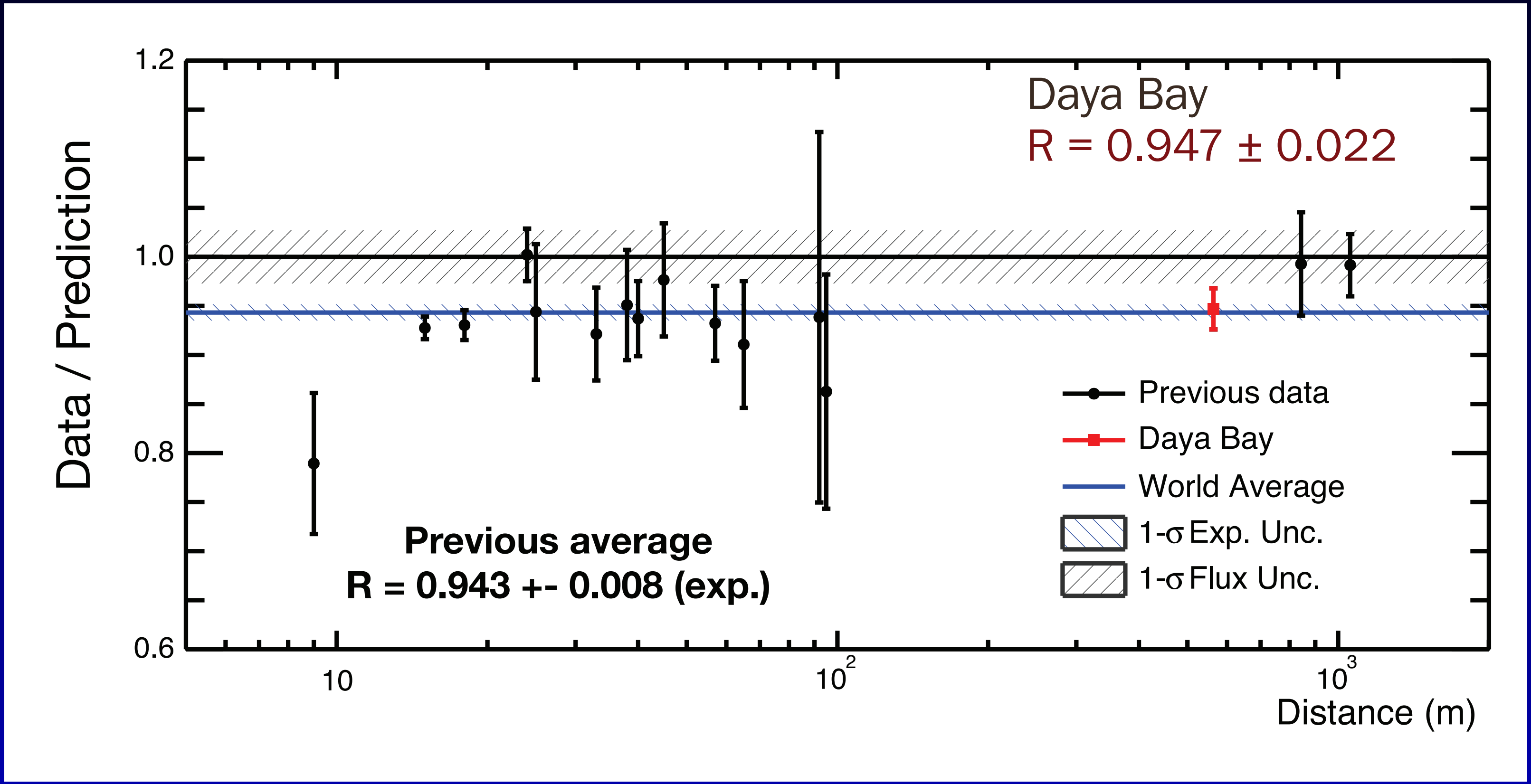
Nuclear matrix elements





Recent measurements of $Ga^{71}(He^3,H^3)Ge^{71}$ seem to support the Gallium anomaly Frekers *et al.*, 2011

The reactor anomaly



Daya Bay, preliminary, 2014

The increase in predicted neutrino fluxes, triggered a re-analysis of existing reactor data

And this was found by Mueller *et al.*, 2011, 2012 – where are all the neutrinos gone?

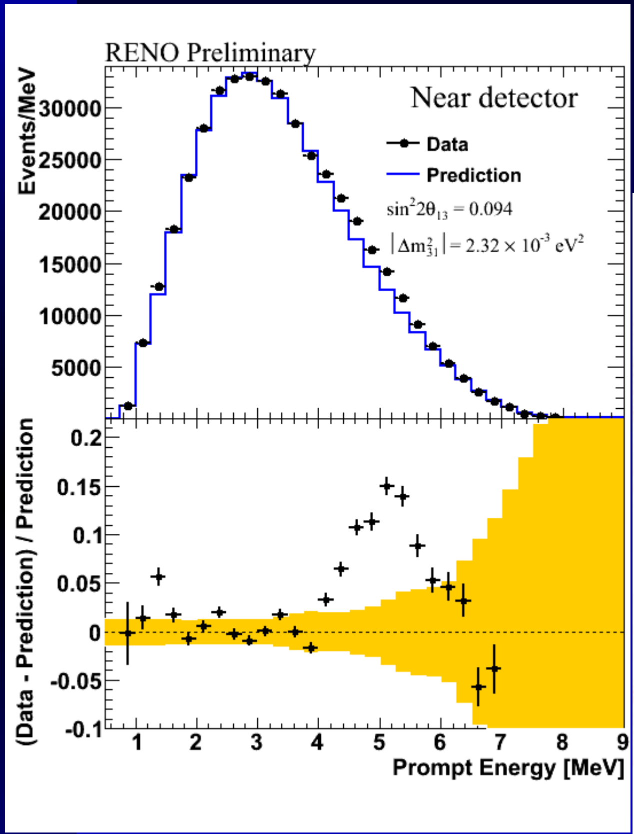
Contributors to the anomaly

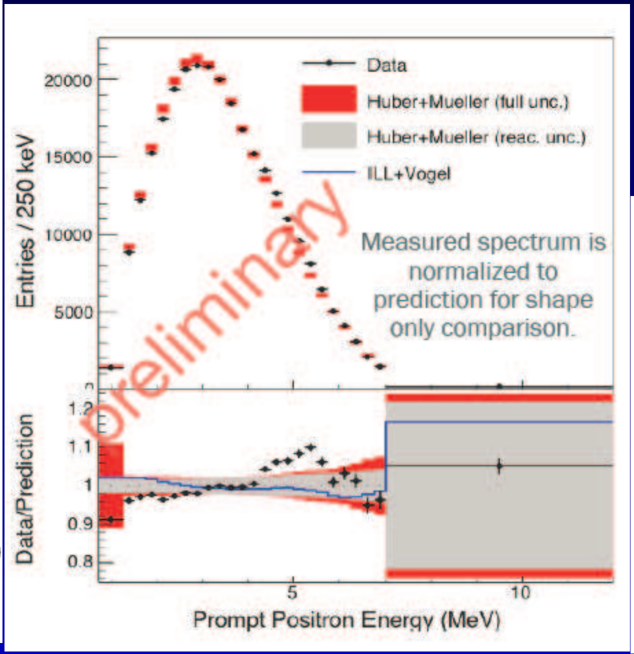
6% deficit of $\bar{\nu}_e$ from nuclear reactors at short distances

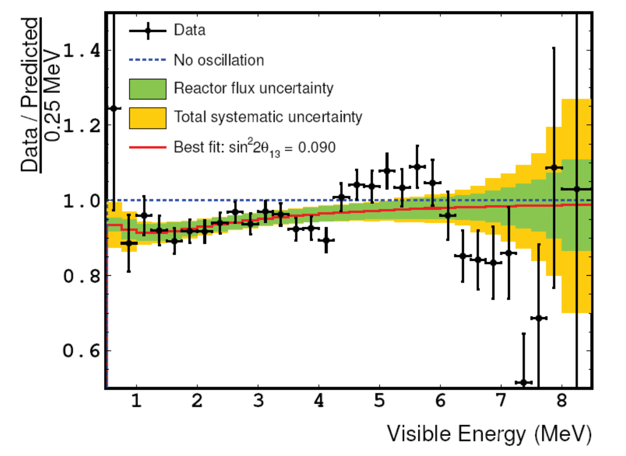
- 3% increase in reactor neutrino fluxes
- decrease in neutron lifetime
- inclusion of long-lived isotopes (non-equilibrium correction)

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

The 5 MeV bump





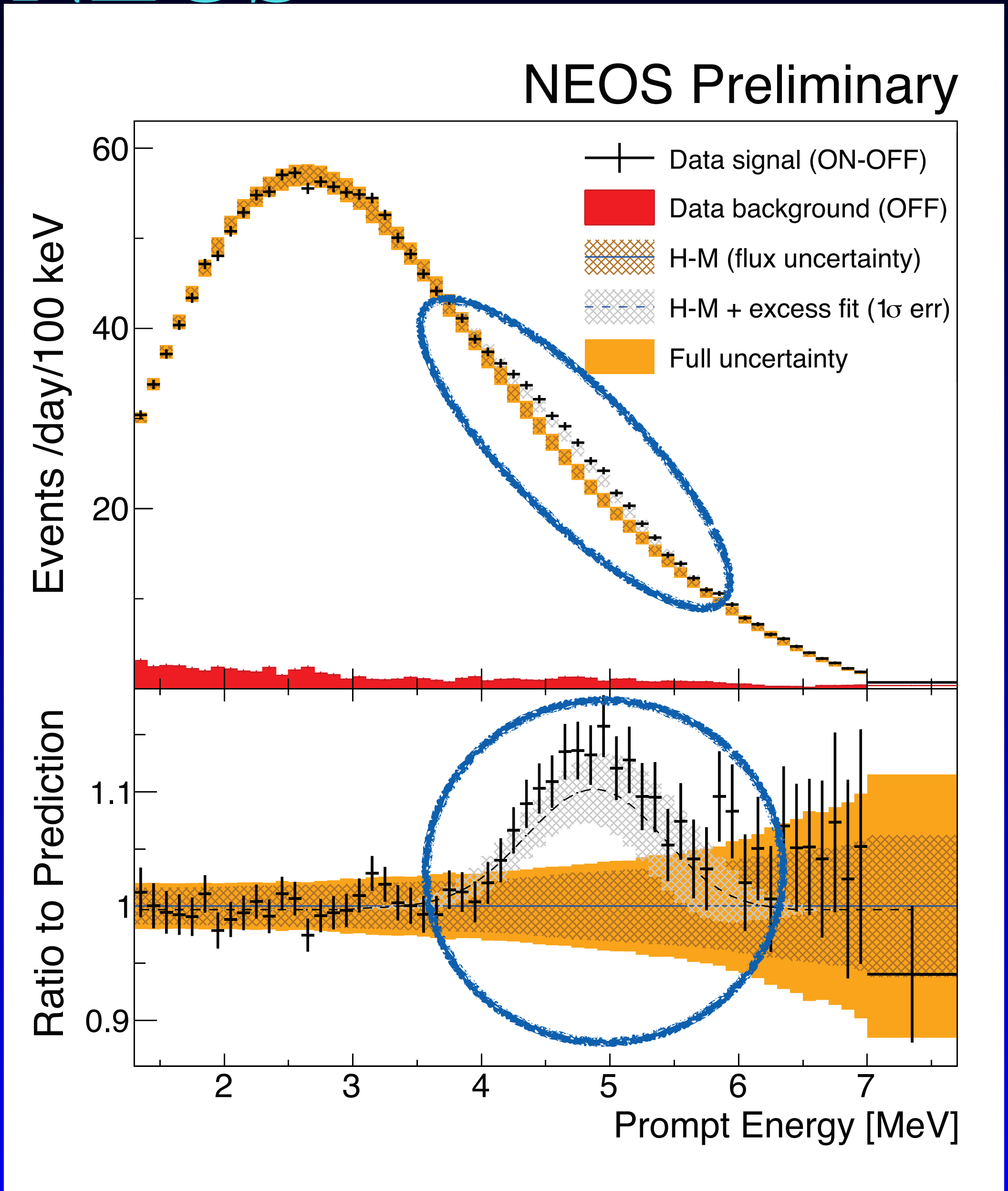


Seen by all three reactor experiments

Tracks reactor power

Seems independent of burn-up

NEOS

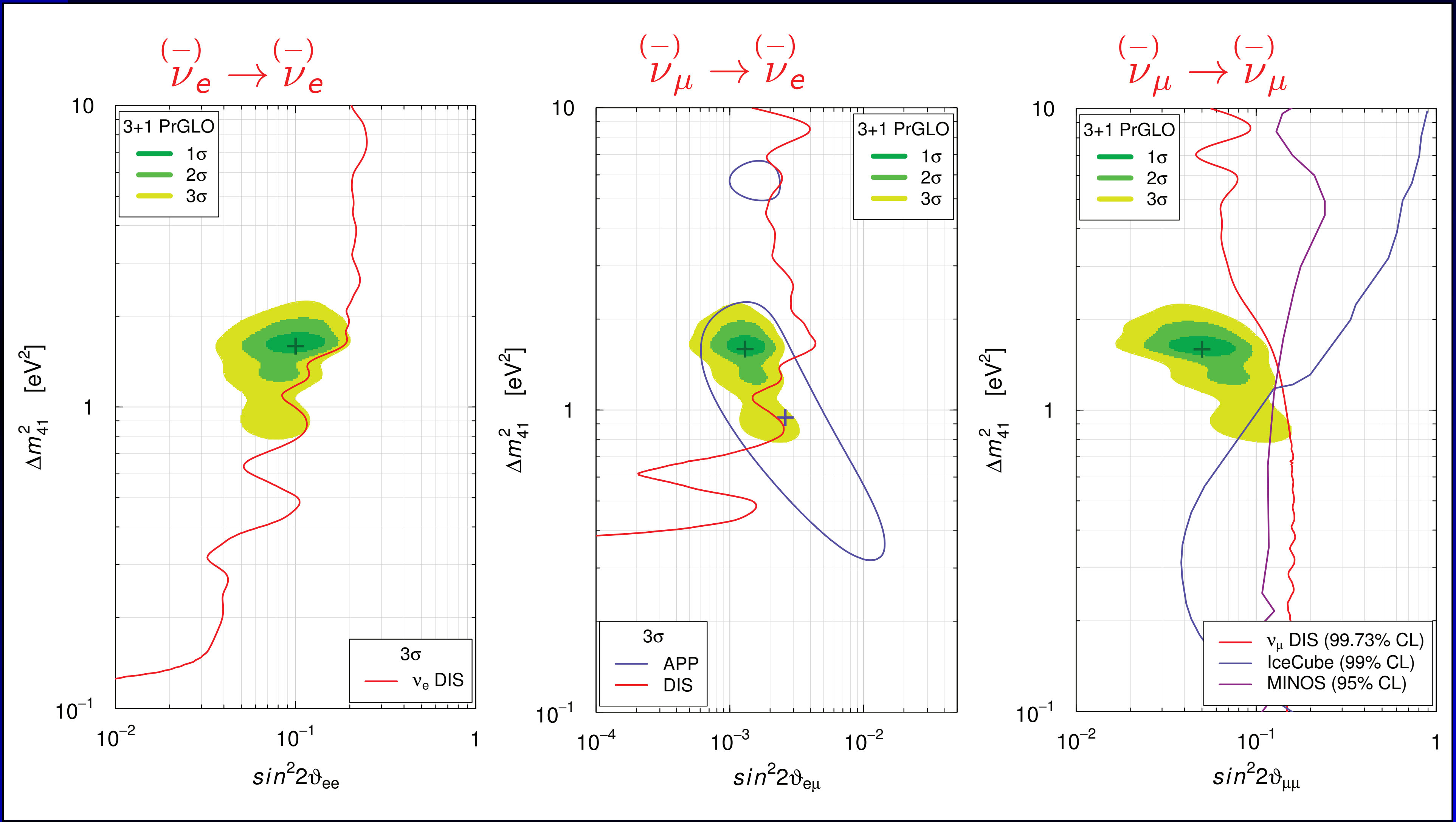


Y. Oh, ICHEP 2016

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

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

Disappearance constraints



Giunti, Neutrino 2016

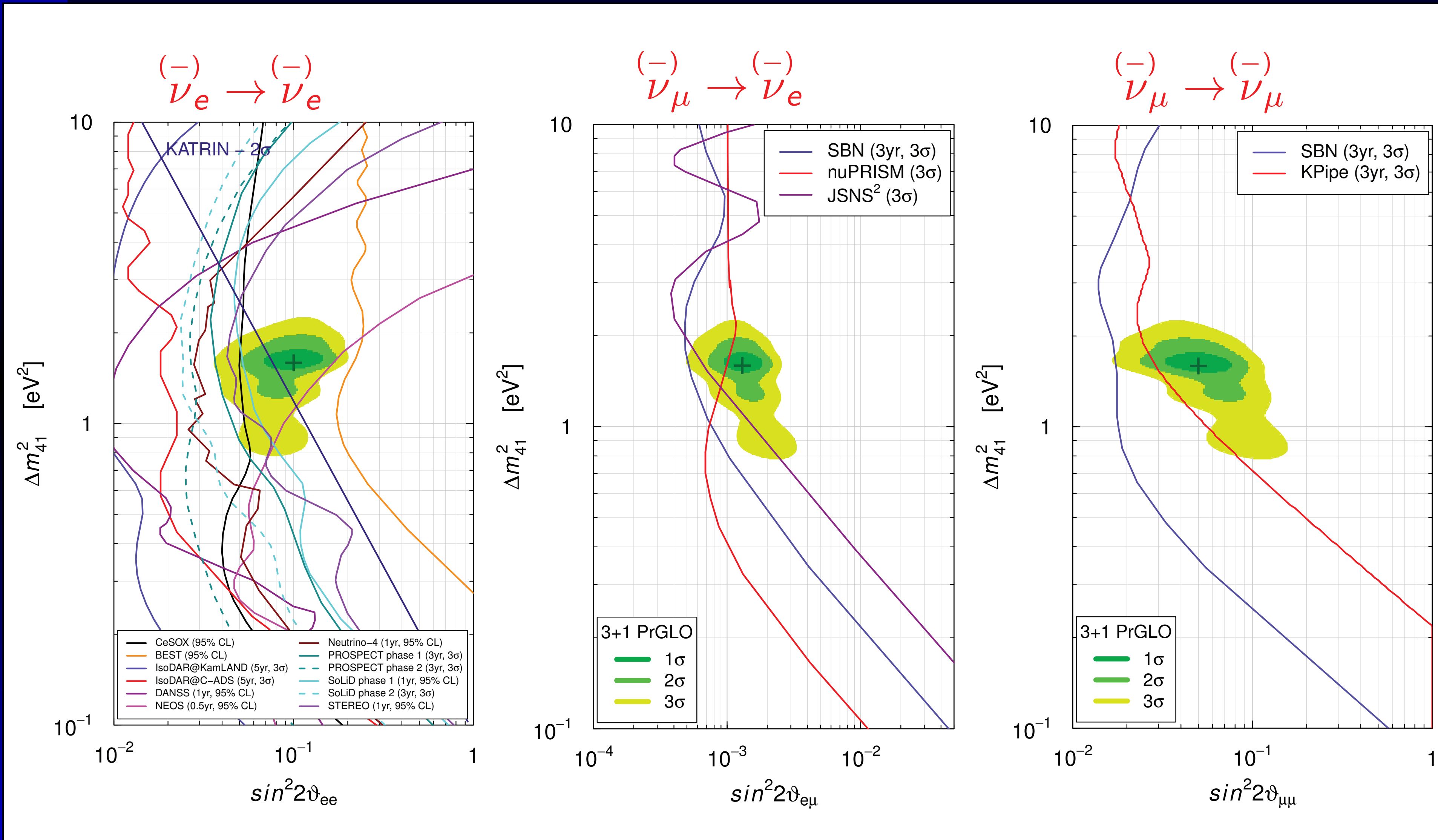
Finding a sterile neutrino

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

- DUNE is a factor 2 in statistics for the global program
- Can existing neutrino production techniques provide systematics to make use of better statistics?
- Current data allows large corrections to three flavor framework
- Precision measurements have the best potential to uncover even “newer” physics

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, best evidence we currently have for more New Physics, anywhere!

but we seem to be unable to mount a coherent program to address those anomalies