What have we learned from Neutrinos?

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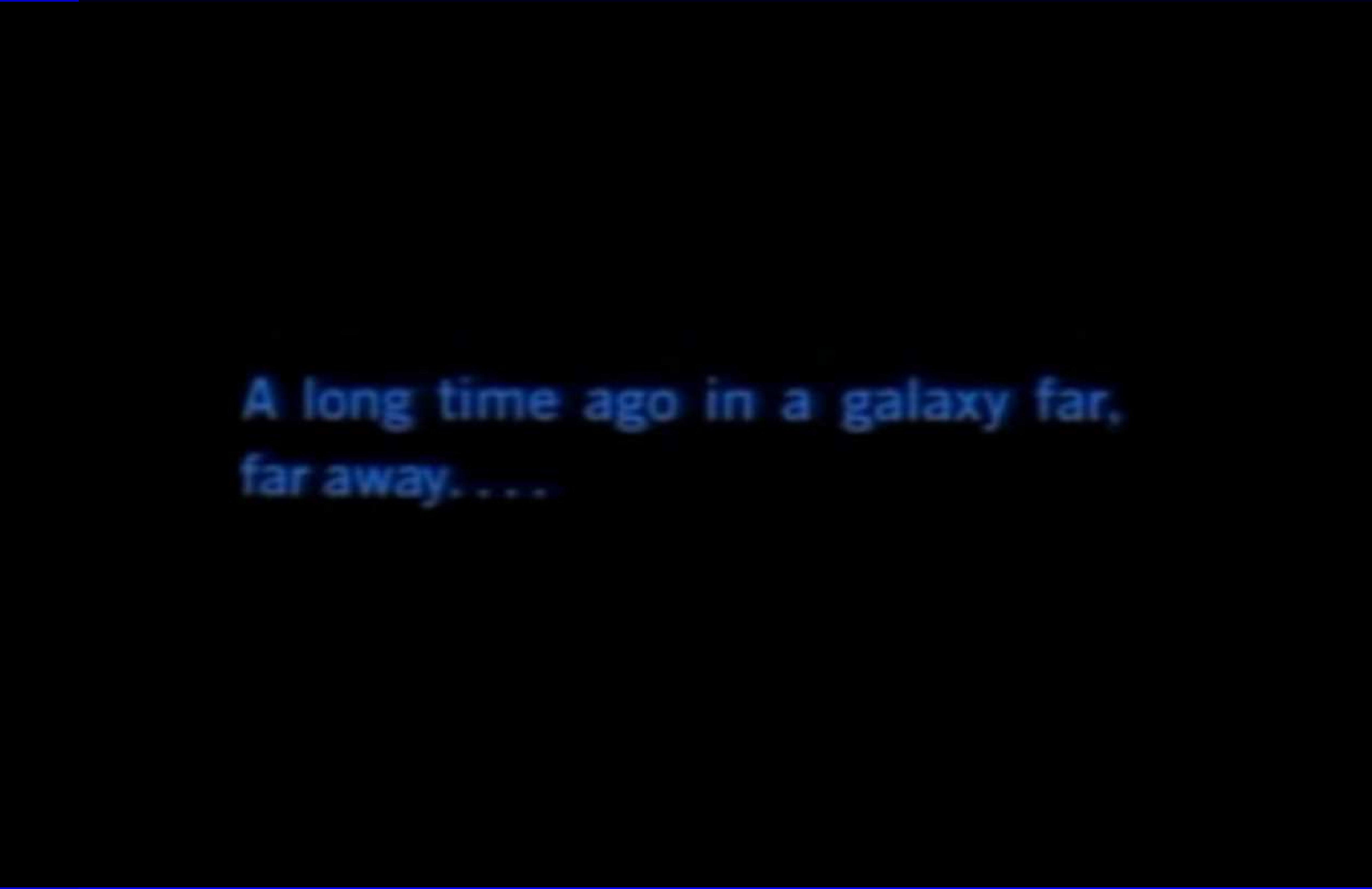


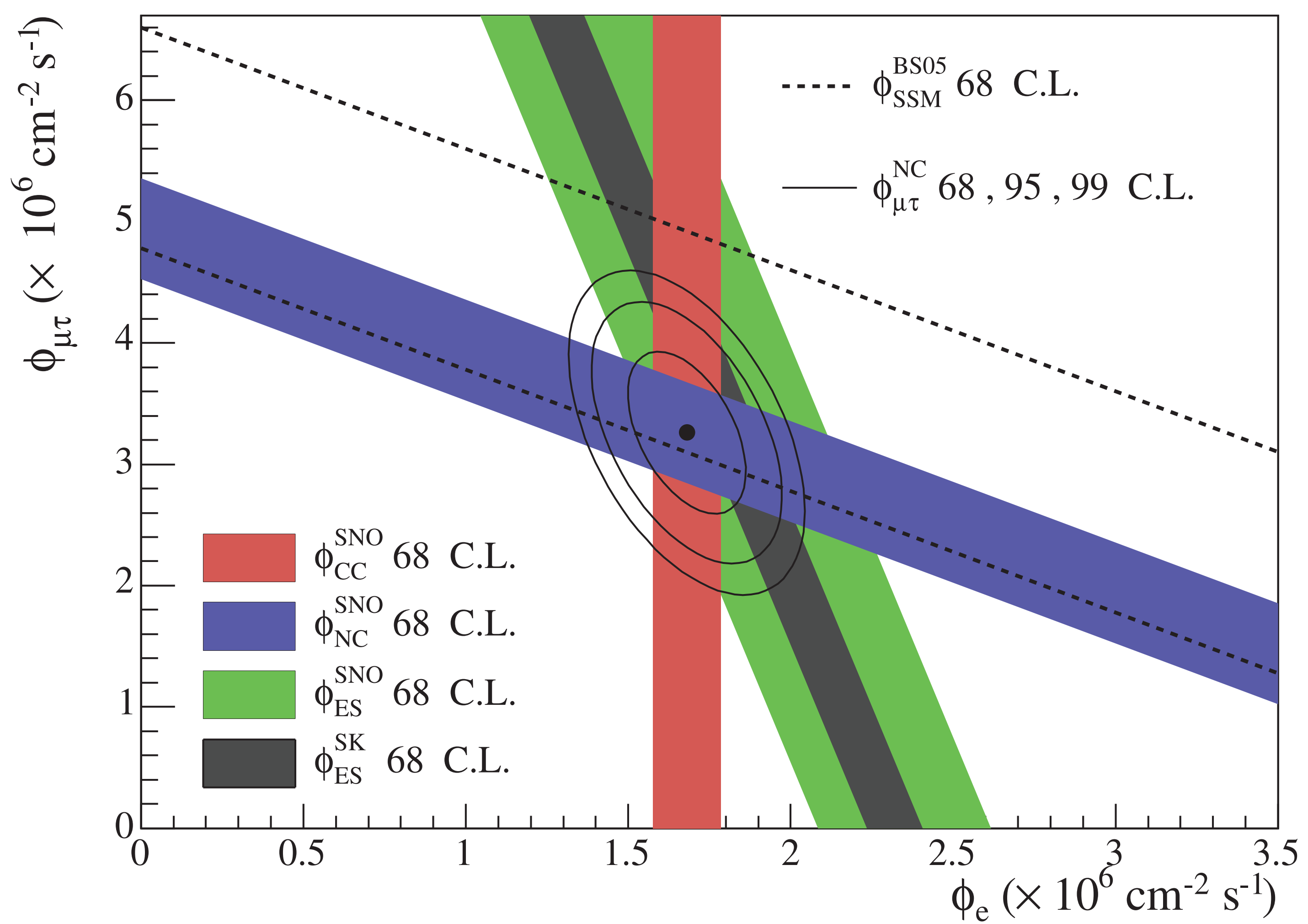
A long time ago in a galaxy far, far away. . . .

Well, actually more like 20 years ago on this planet, we “knew” that neutrinos

- are massless (and in particular not 17 keV in mass)
- if not, their mixings will be like in the quark sector, small
- something is wrong with Davis’ experiments (chemist!) and Bahcall’s (astrophysicist!) calculation

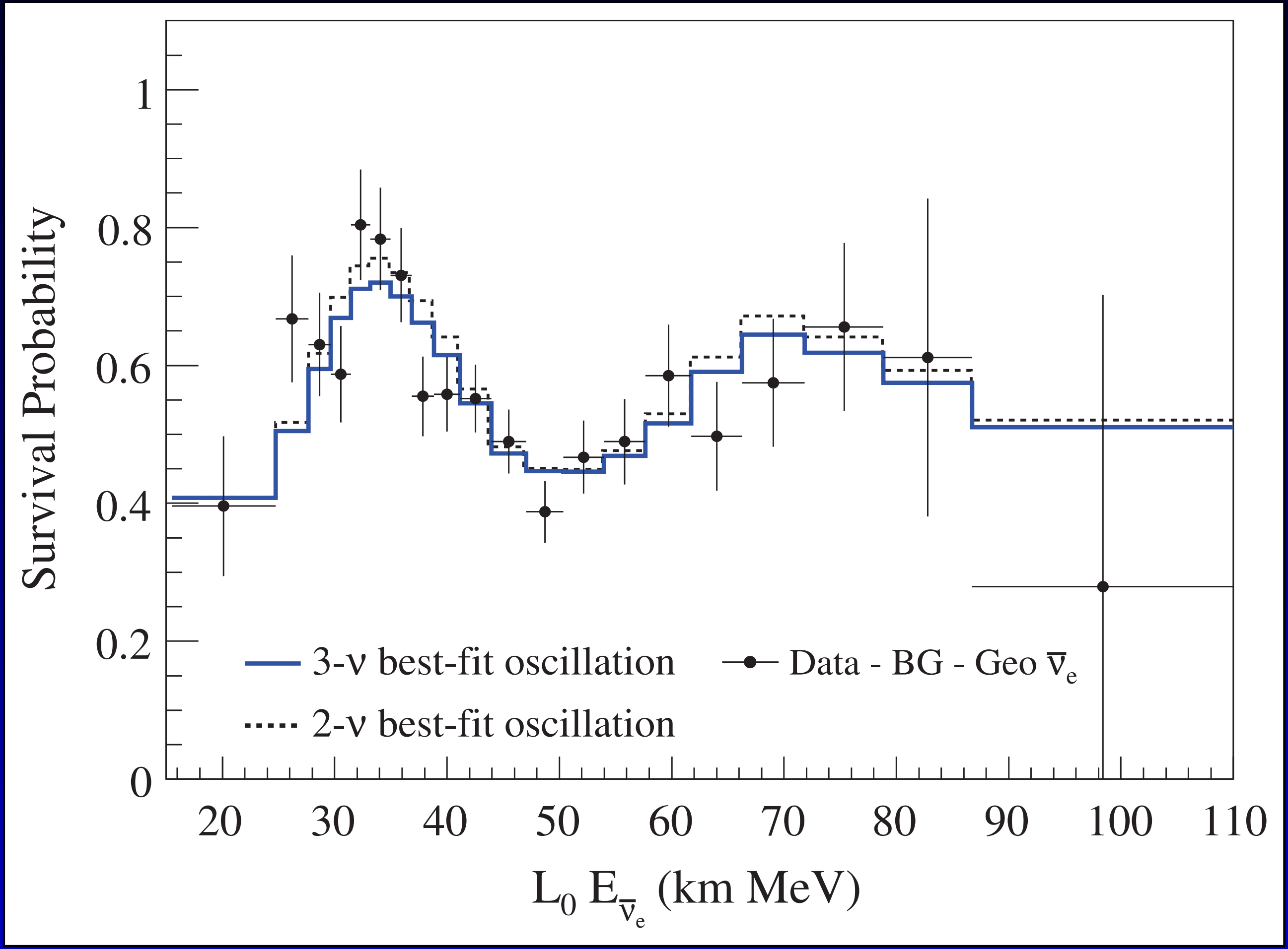
and then there we things like $m^2 < 0$, the atmospheric anomaly, $\ldots$

Solar neutrinos



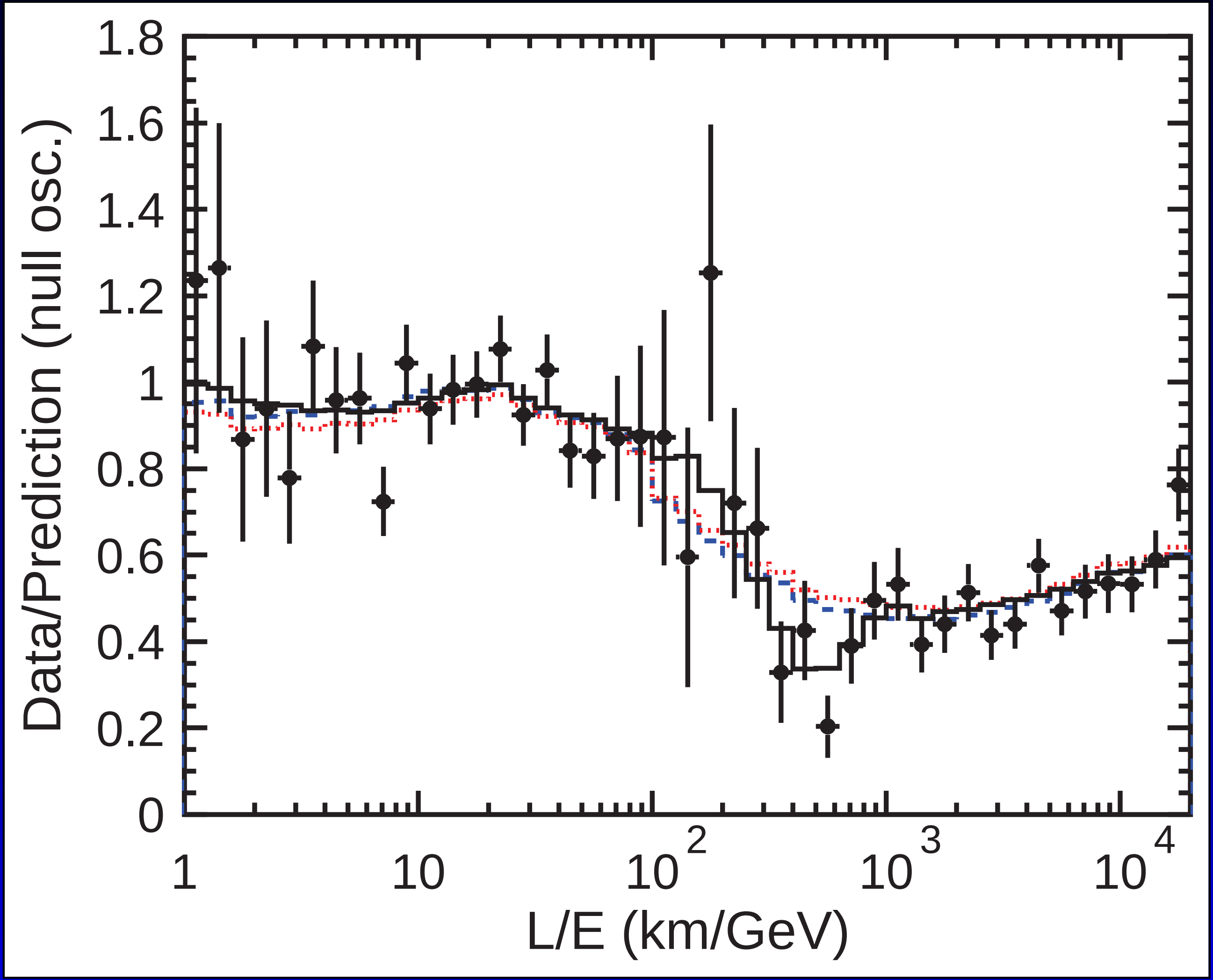
SNO proves conversion of ν_e to $\nu_{\mu,\tau}$ – Davis and Bahcall were right!

Reactor neutrinos



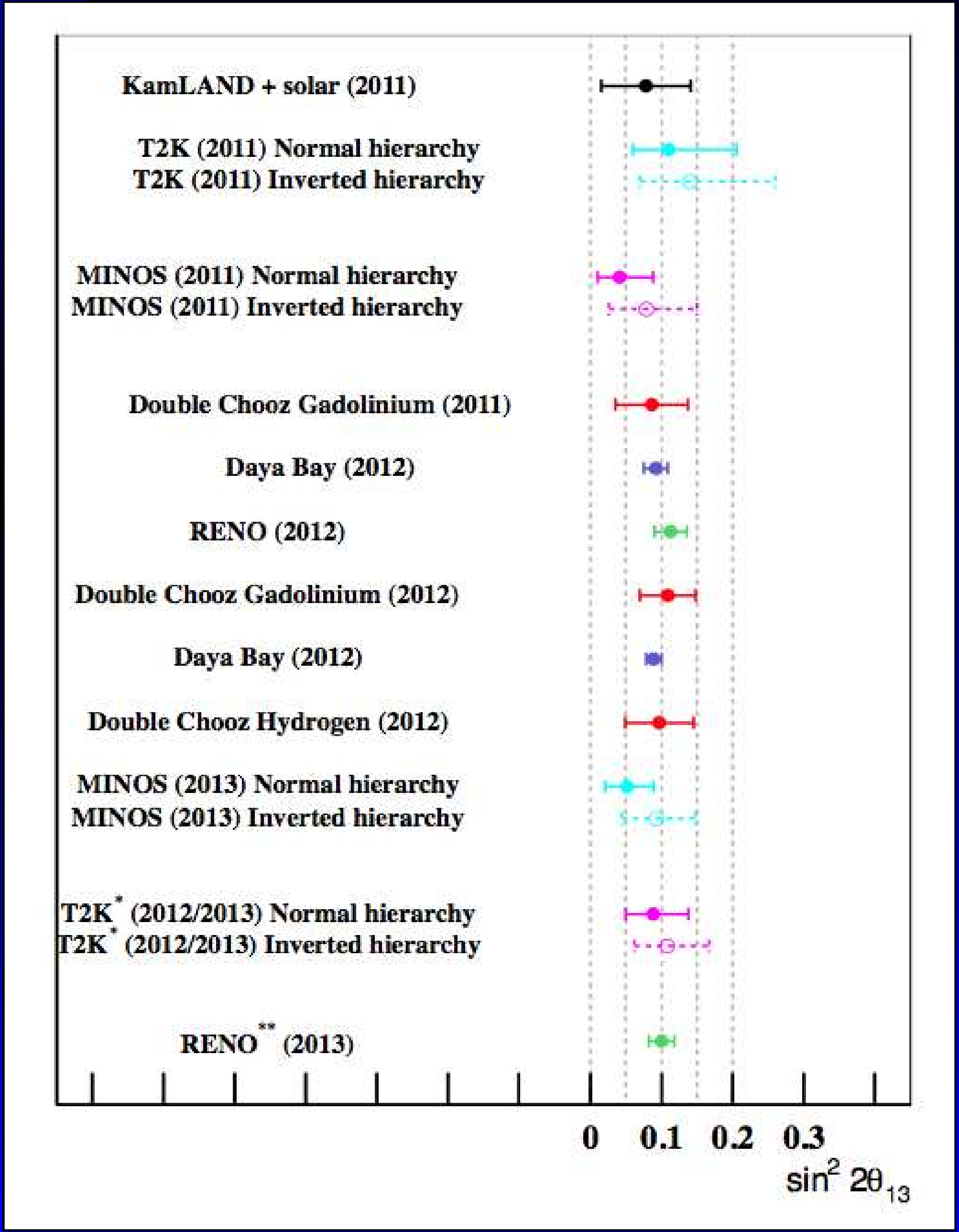
KamLAND confirms large mixing angle for solar oscillation and establishes oscillation.

Atmospheric neutrinos



Super-Kamiokande demonstrates $\nu_\mu \to \nu_\tau$ oscillation is responsible for atmospheric results – other explanations strongly disfavored

θ_{13} is large!



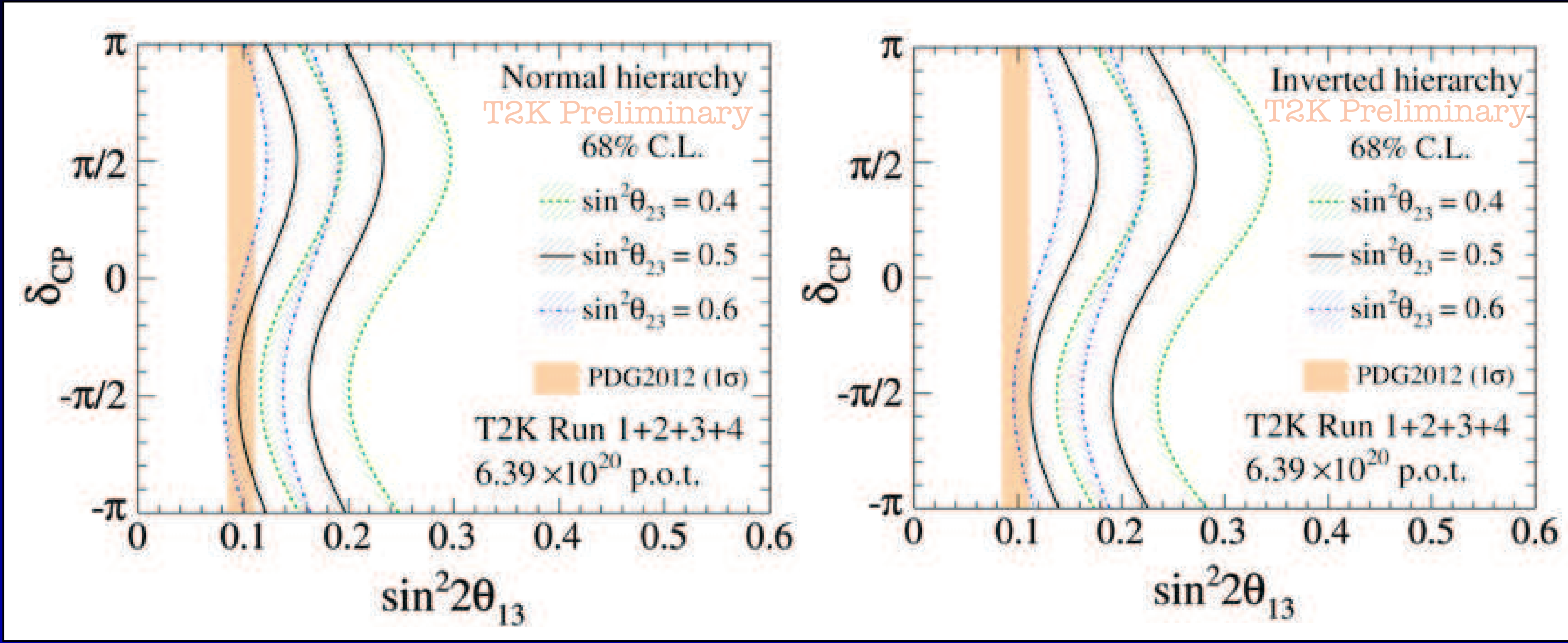
Many results from reactor and beam experiments

Some single results exceed 5 σ significance

All results agree well

NB – 2 years ago we had only 2 σ indications.

Latest results



First observation of ν_e appearance

First step towards leptonic CP violation – long journey…

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

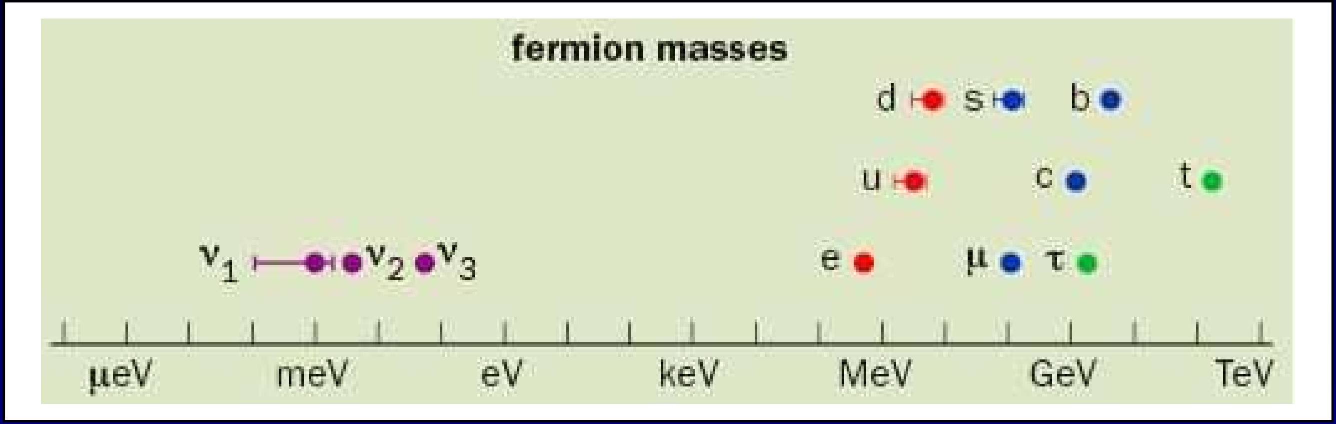
$$|U_{CKM}| = \begin{pmatrix} 1 & 0.2 & 0.005 \\ 0.2 & 1 & 0.04 \\ 0.005 & 0.04 & 1 \end{pmatrix}$$

Neutrinos

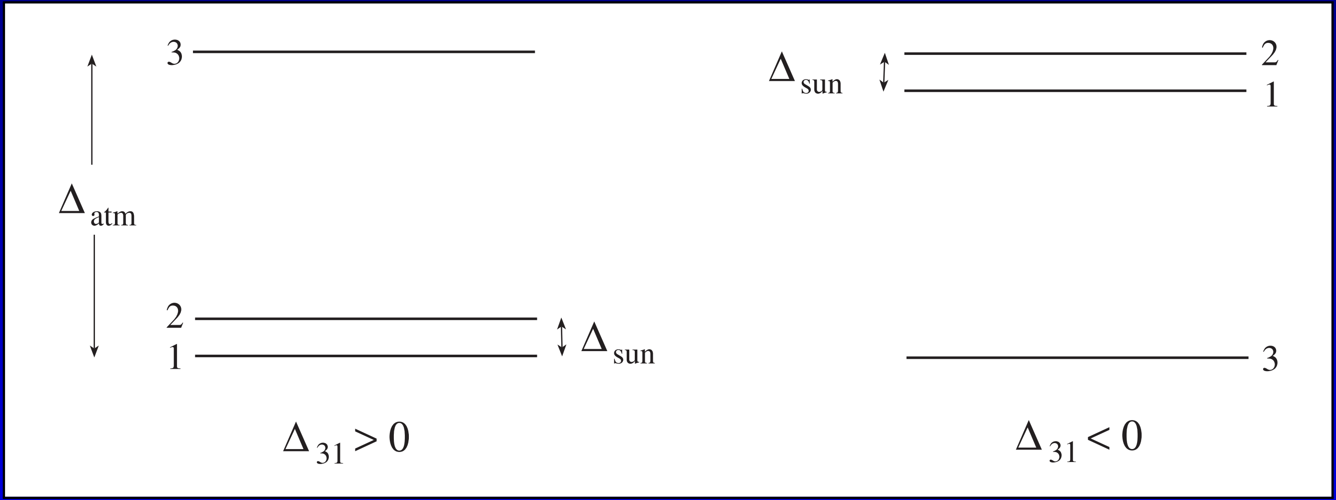
$$|U_\nu| = \begin{pmatrix} 0.8 & 0.5 & 0.15 \\ 0.4 & 0.6 & 0.7 \\ 0.4 & 0.6 & 0.7 \end{pmatrix}$$

Fermion masses

Scale



Ordering – mass hierarchy



Low energy observables

The most sensitive low energy observables are

- Which one is the heaviest neutrino? –$0\nu\beta\beta$, β-decay endpoint, Oscillation
- Absolute m_ν – β-decay endpoint, Cosmology
- Majorana vs Dirac mass – $0\nu\beta\beta$
- Is θ_{23} maximal? – Oscillation
- Is there leptonic CP violation? – Oscillation
- Are there only 3 light neutrinos? – Oscillation

Up to this point, this has been a review of two decades of stunning experimental results – neutrino physics is a data driven field and it seems that theory has a hard time catching up. . .

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 → no Majorana mass term
- lepton number may be approximately conserved → 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

$$-\frac{1}{2}m_L(\bar{\psi}_L\psi_R^C + \bar{\psi}_R\psi_L^C) - \frac{1}{2}m_R(\bar{\psi}_R\psi_L^C + \bar{\psi}_L\psi_R^C)$$

on top of the usual Dirac mass term

$$m_D(\bar{\psi}_L\psi_R + \bar{\psi}_R\psi_L)$$

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.

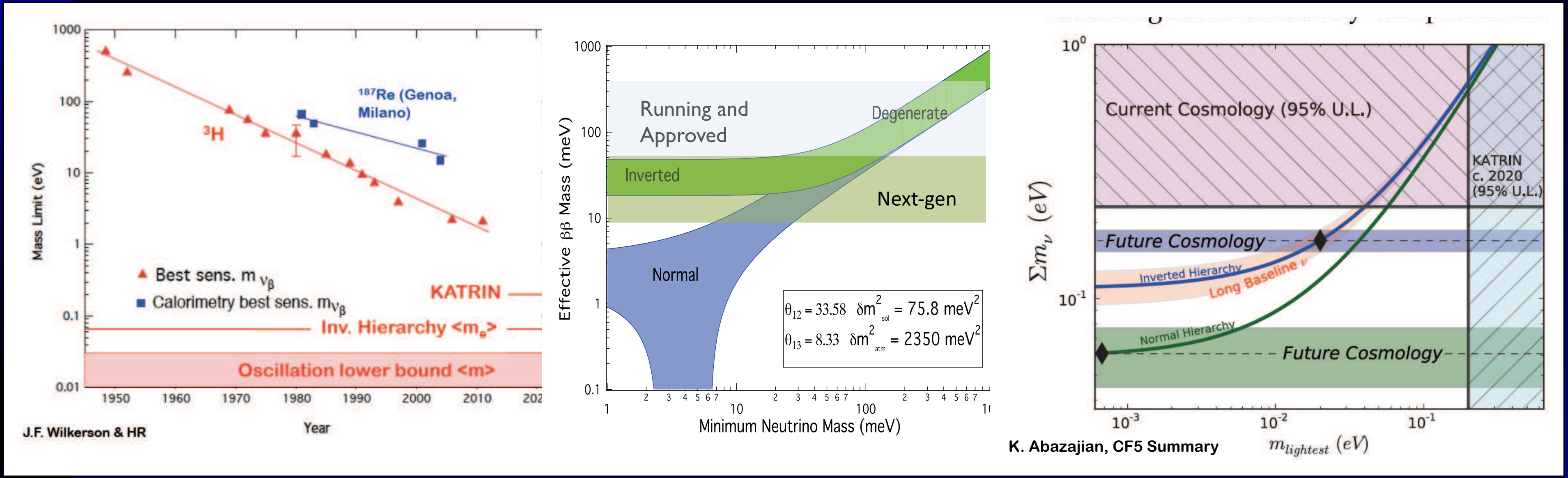
Neutrino mass determination

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 hierachy.

Mass measurements



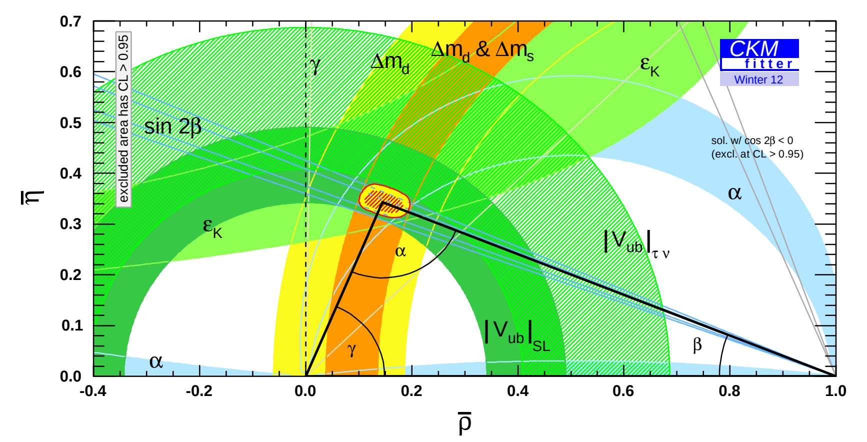
J.F. Wilkerson & HR

K. Abazajian, CF5 Summary

Three methods – direct kinematic mass searches, neutrinoless $\beta\beta$-decay, cosmology – really measure very different things and the latter two have strong model dependencies in their interpretation.

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.

Non-standard interactions

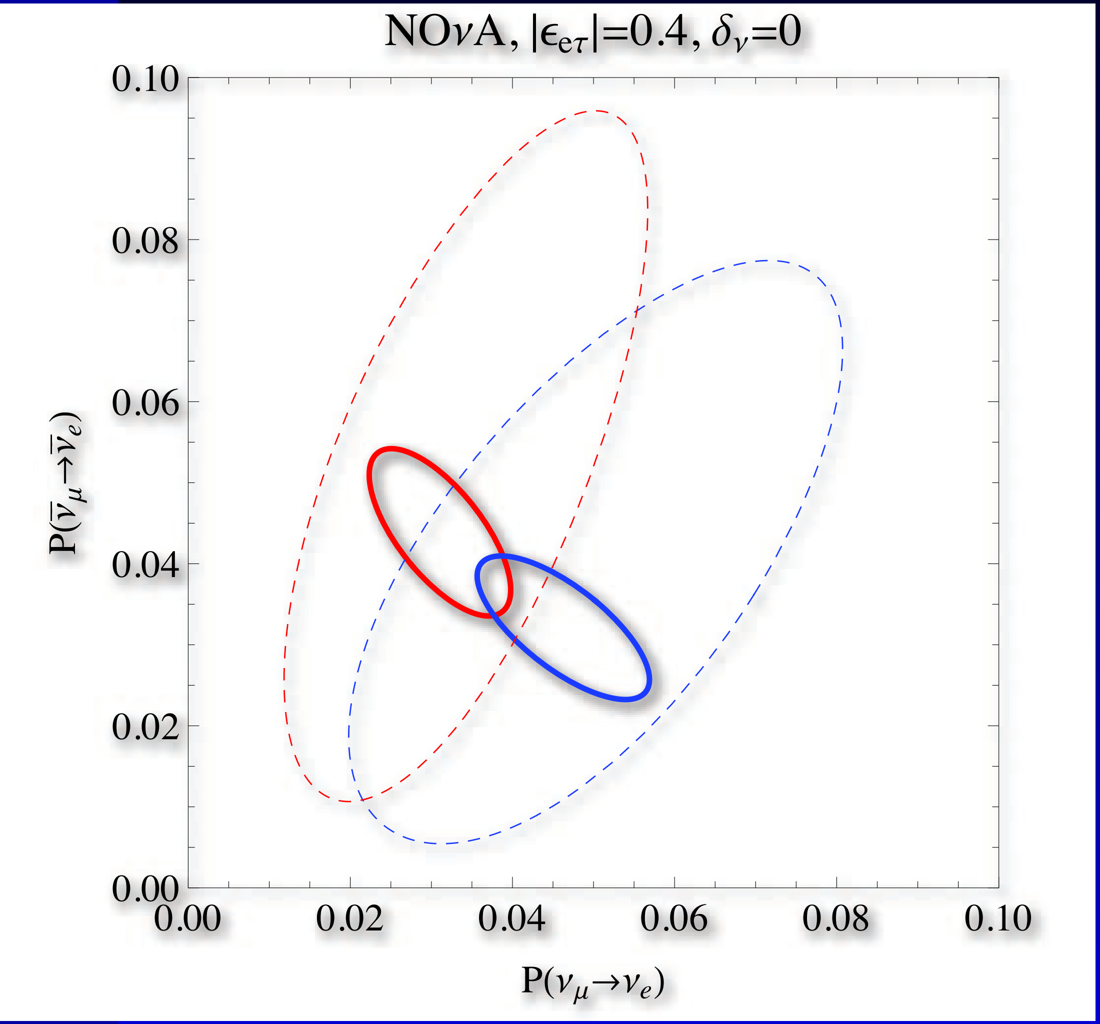
NSI are the workhorse for BSM physics in the neutrino sector. They can be parameterized by terms like this

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

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

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



Friedland, 2012

Three flavor analysis are not safe from these effects!

Especially, global fits for the phase and mass hierarchy need to be aware of NSI.

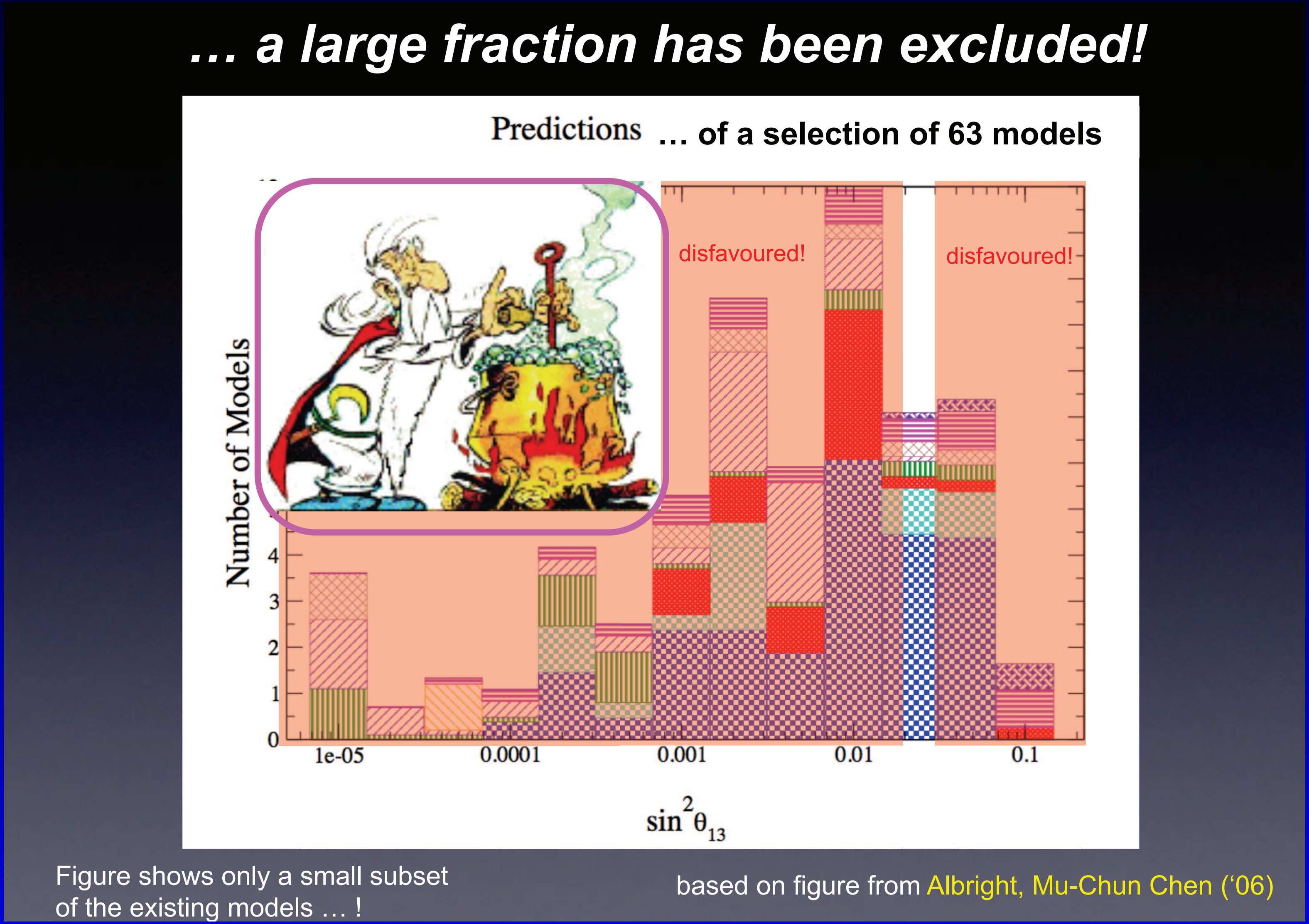
CP violation

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…

Model selection



… a large fraction has been excluded!

Predictions **… of a selection of 63 models**

Figure shows only a small subset of the existing models … !

based on figure from Albright, Mu-Chun Chen ('06)

Antusch, 2012

Flavor models

Simplest un-model – anarchy Murayama, Naba, DeGouvea

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

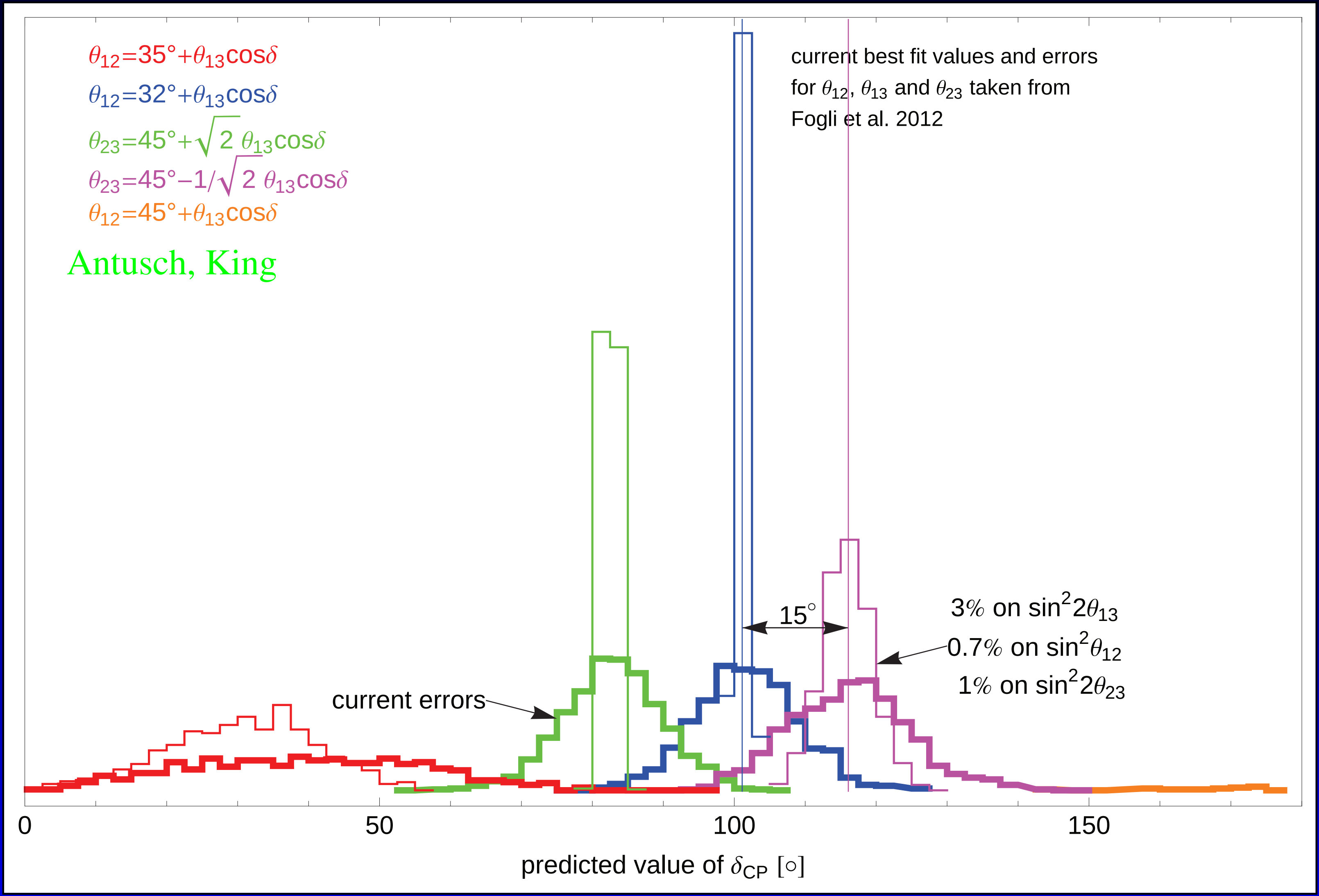
predicts flat distribution in δ_{CP}

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

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

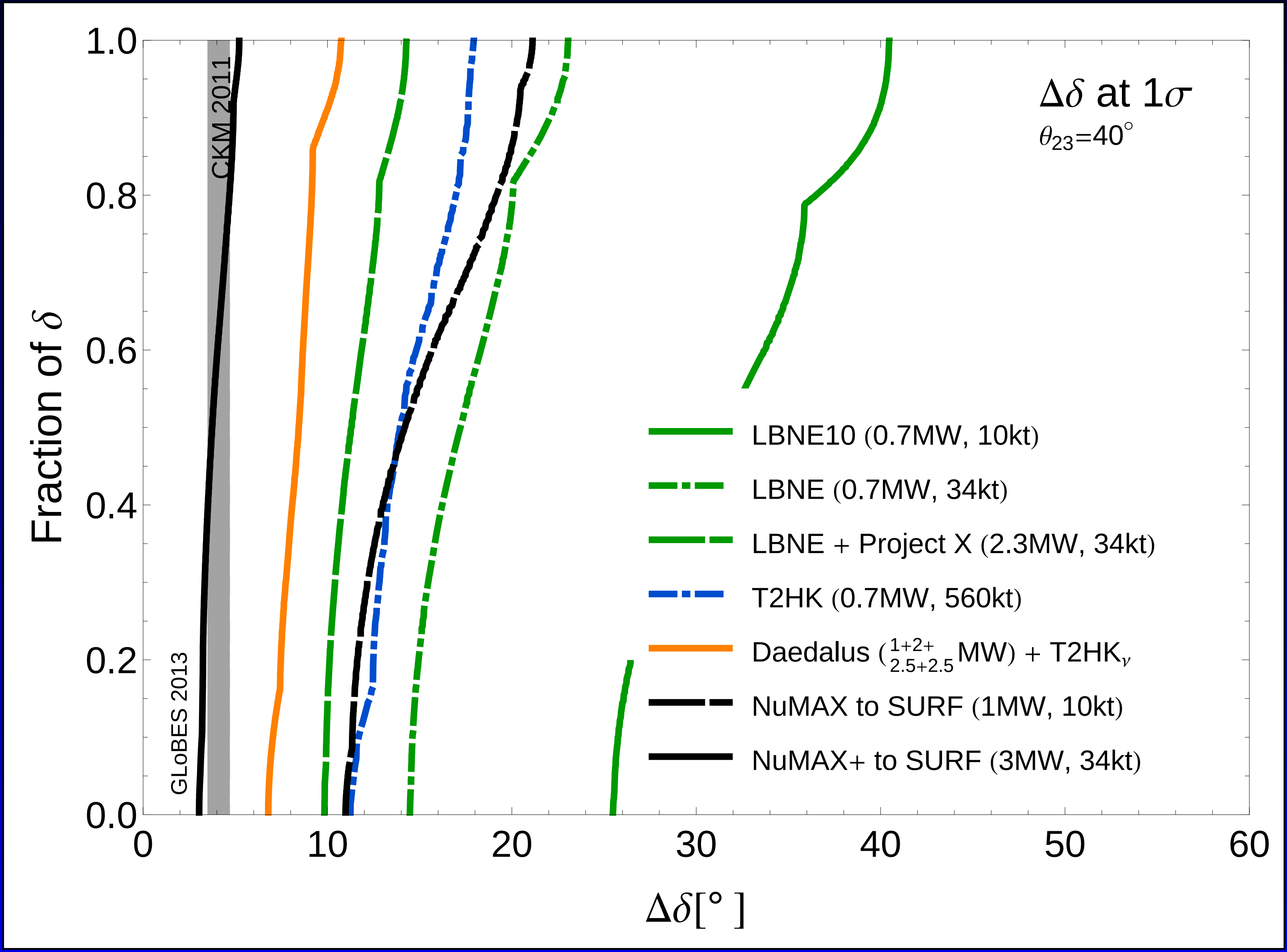
to still fit data, obviously corrections are needed – predictivity?

Sum rules

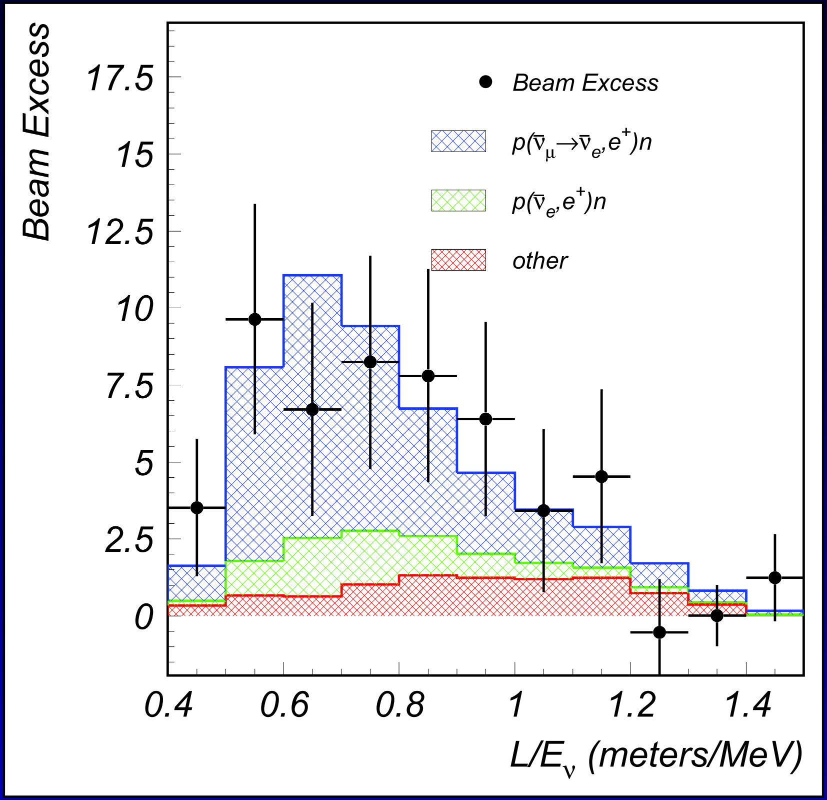


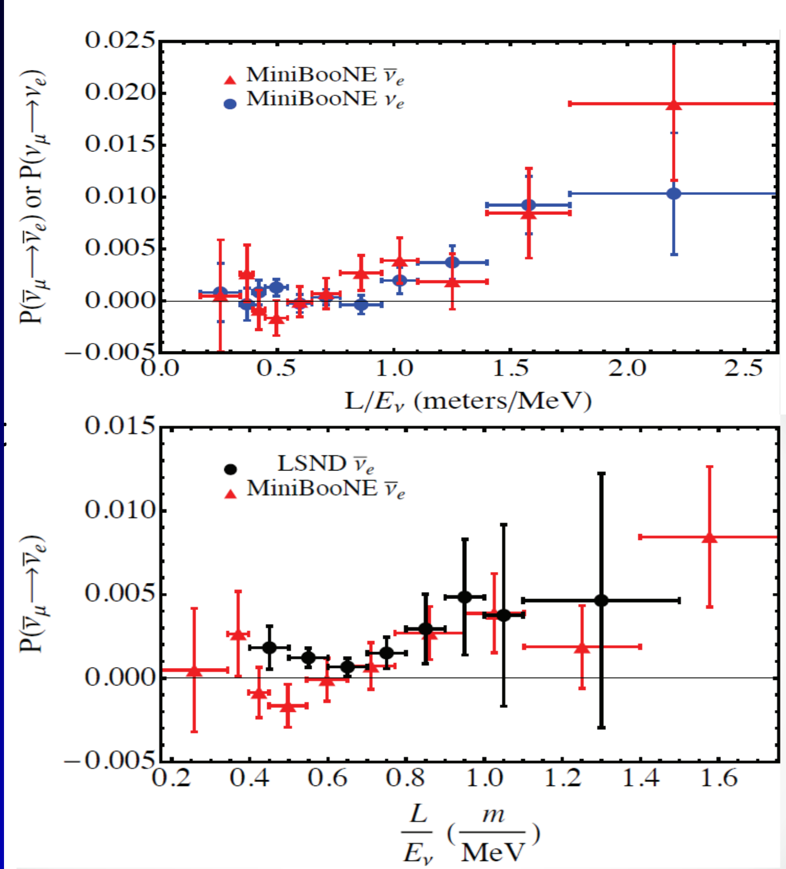
3 σ resolution of 15° distance requires 5° error. NB – smaller error on θ_{12} requires dedicated experiment like JUNO

Is 5° feasible?



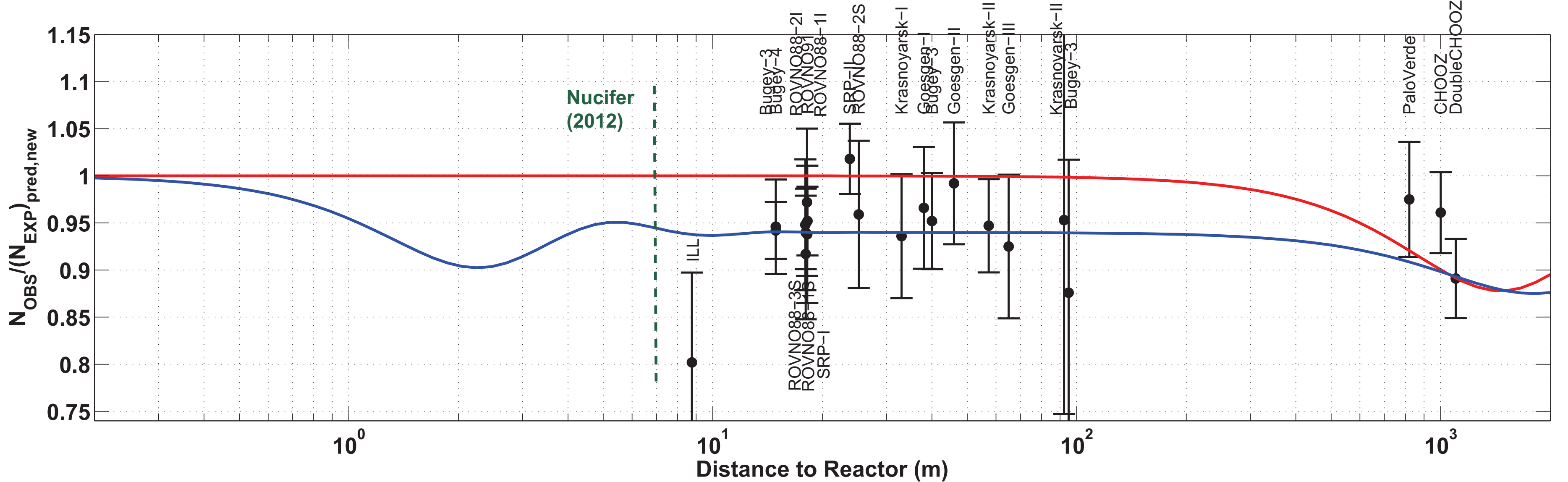
LSND and MiniBooNE





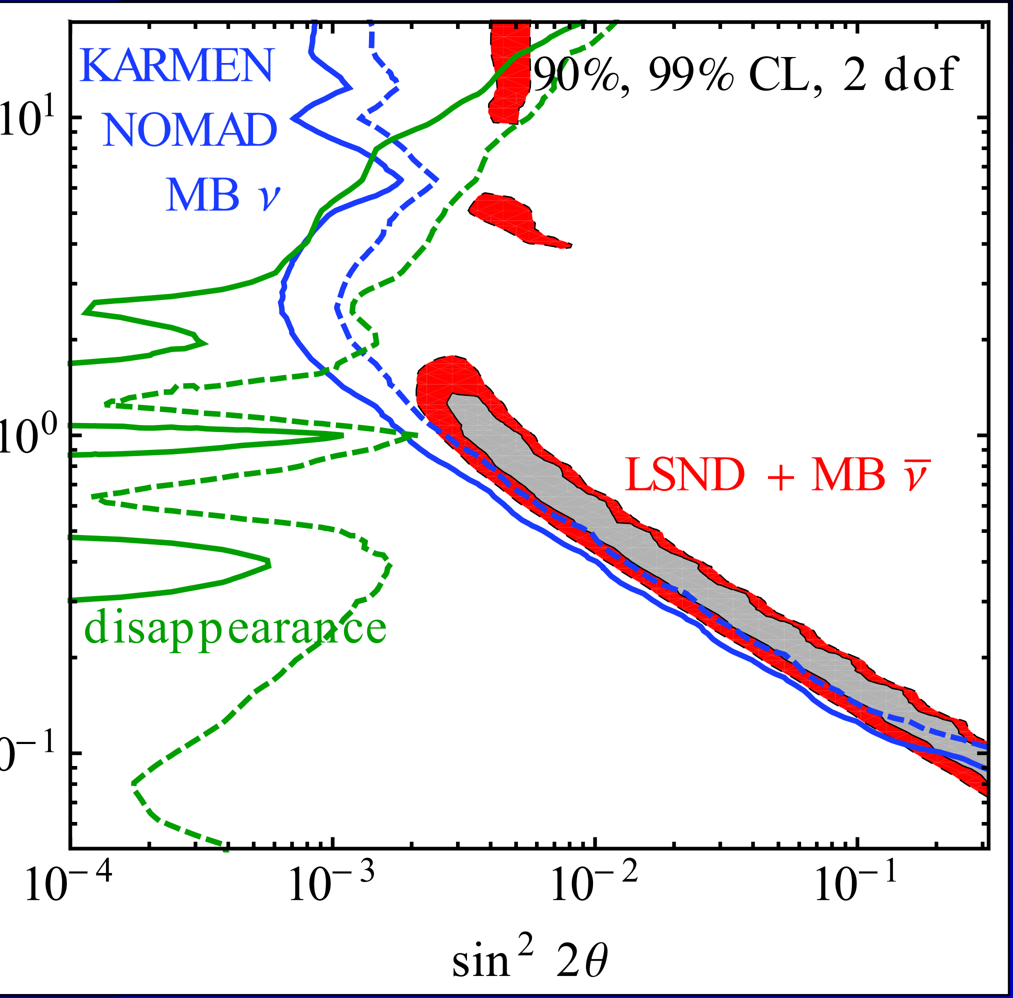
$$P(\bar{\nu}_\mu \to \bar{\nu}_e) \simeq 0.003$$

Reactor and Gallium anomalies



	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	

Disappearance constraints



Absence of effects in

- atmospheric
- Bugey
- CDHS
- MINOS
- …

data creates considerable tension in 3+N sterile neutrino models

More details can be found in the sterile neutrino white paper, arXiv:1204.5379.

Sterile oscillation

In general, in a 3+N sterile neutrino oscillation model one finds that the energy averaged probabilities obey the following inequality

$$P(\nu_\mu \to \nu_e) \leq 4[P(\nu_e \to \nu_e) - 1][P(\nu_\mu \to \nu_\mu) - 1]$$

independent of CP transformations. Therefore, a stringent test of the model is to measure

- $P(\nu_\mu \to \nu_e)$ – appearance
- $P(\bar{\nu}_\mu \to \bar{\nu}_e)$ – appearance
- $P(\nu_\mu \to \nu_\mu)$ or $P(\bar{\nu}_\mu \to \bar{\nu}_\mu)$ – disappearance
- $P(\nu_e \to \nu_e)$ or $P(\bar{\nu}_e \to \bar{\nu}_e)$ – disappearance

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

- Neutrino oscillation is solid evidence for new physics
- Current data allows $\mathcal{O}(1)$ corrections to three flavor framework
- Precision measurements have the best potential to uncover even “newer” physics
- Sterile neutrinos?

Neutrinos have provided us with many surprises and neutrinos are still largely unexplored !