Neutrino Anomalies

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Something Funny Happened on the Way to the 21st Century

ν Flavor Oscillations

Neutrino oscillation experiments have revealed that neutrinos change flavor after propagating a finite distance. The rate of change depends on the neutrino energy E_ν and the baseline L. The evidence is overwhelming.

- $\nu_\mu \to \nu_\tau$ and $\bar{\nu}_\mu \to \bar{\nu}_\tau$ — atmospheric and accelerator experiments;
- $\nu_e \to \nu_{\mu,\tau}$ — solar experiments;
- $\bar{\nu}_e \to \bar{\nu}_{\rm other}$ — reactor experiments;
- $\nu_\mu \to \nu_{\rm other}$ and $\bar{\nu}_\mu \to \bar{\nu}_{\rm other}$— atmospheric and accelerator expts;
- $\nu_\mu \to \nu_e$ — accelerator experiments.

The simplest and **only satisfactory** explanation of **all** this data is that neutrinos have distinct masses, and mix.

A Realistic, Reasonable, and Simple Paradigm:

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{e\tau 2} & U_{\tau 3} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

Definition of neutrino mass eigenstates (who are ν_1, ν_2, ν_3?):

- $m_1^2 < m_2^2$ $\Delta m_{13}^2 < 0$ – Inverted Mass Hierarchy
- $m_2^2 - m_1^2 \ll |m_3^2 - m_{1,2}^2|$ $\Delta m_{13}^2 > 0$ – Normal Mass Hierarchy

$$\tan^2\theta_{12} \equiv \frac{|U_{e2}|^2}{|U_{e1}|^2}; \quad \tan^2\theta_{23} \equiv \frac{|U_{\mu 3}|^2}{|U_{\tau 3}|^2}; \quad U_{e3} \equiv \sin\theta_{13} e^{-i\delta}$$

[For a detailed discussion see e.g. AdG, Jenkins, PRD78, 053003 (2008)]

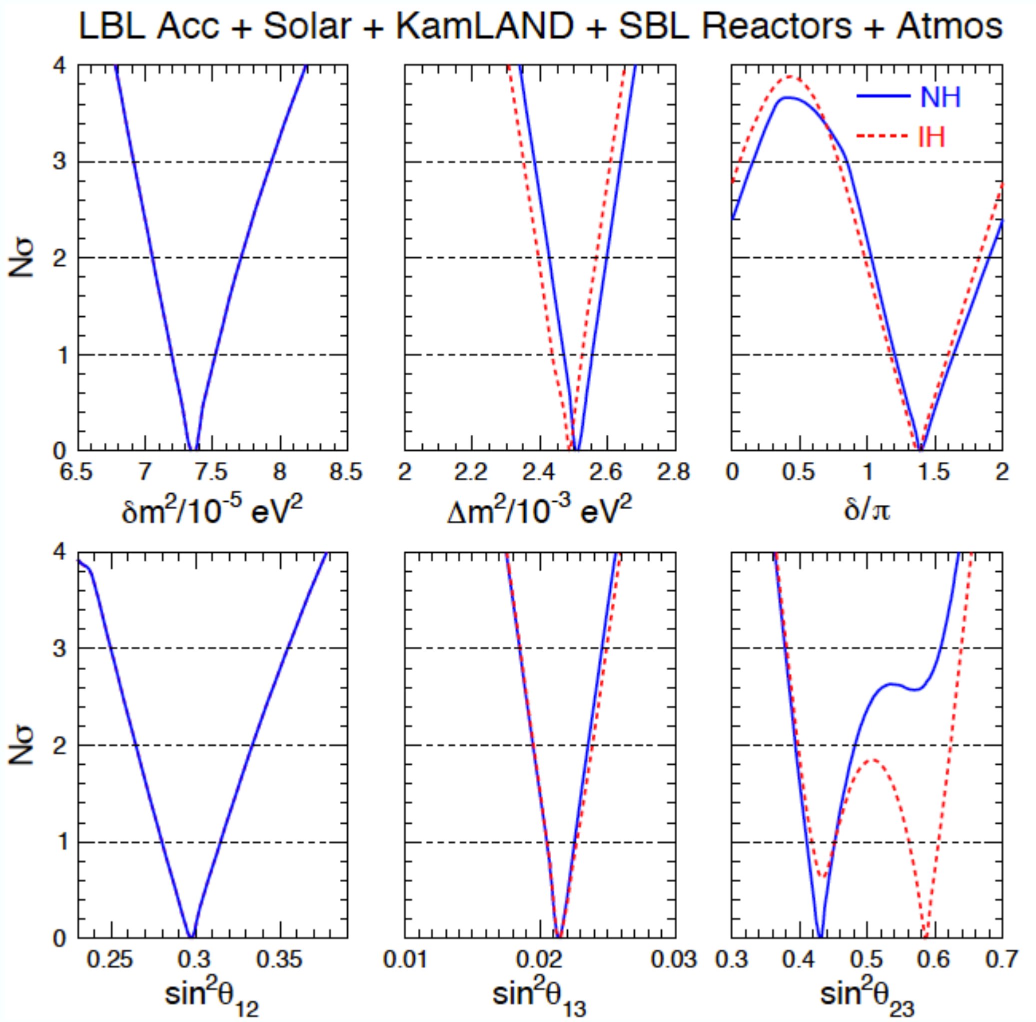
The Three-Flavor Paradigm Fits All* Data Really Well

[* modulo short-baseline anomalies – LATER]

Bounds on single oscillation parameters

(preliminary update)

[A. Marrone, Talk at Neutrino 2016]



CP phase trend:

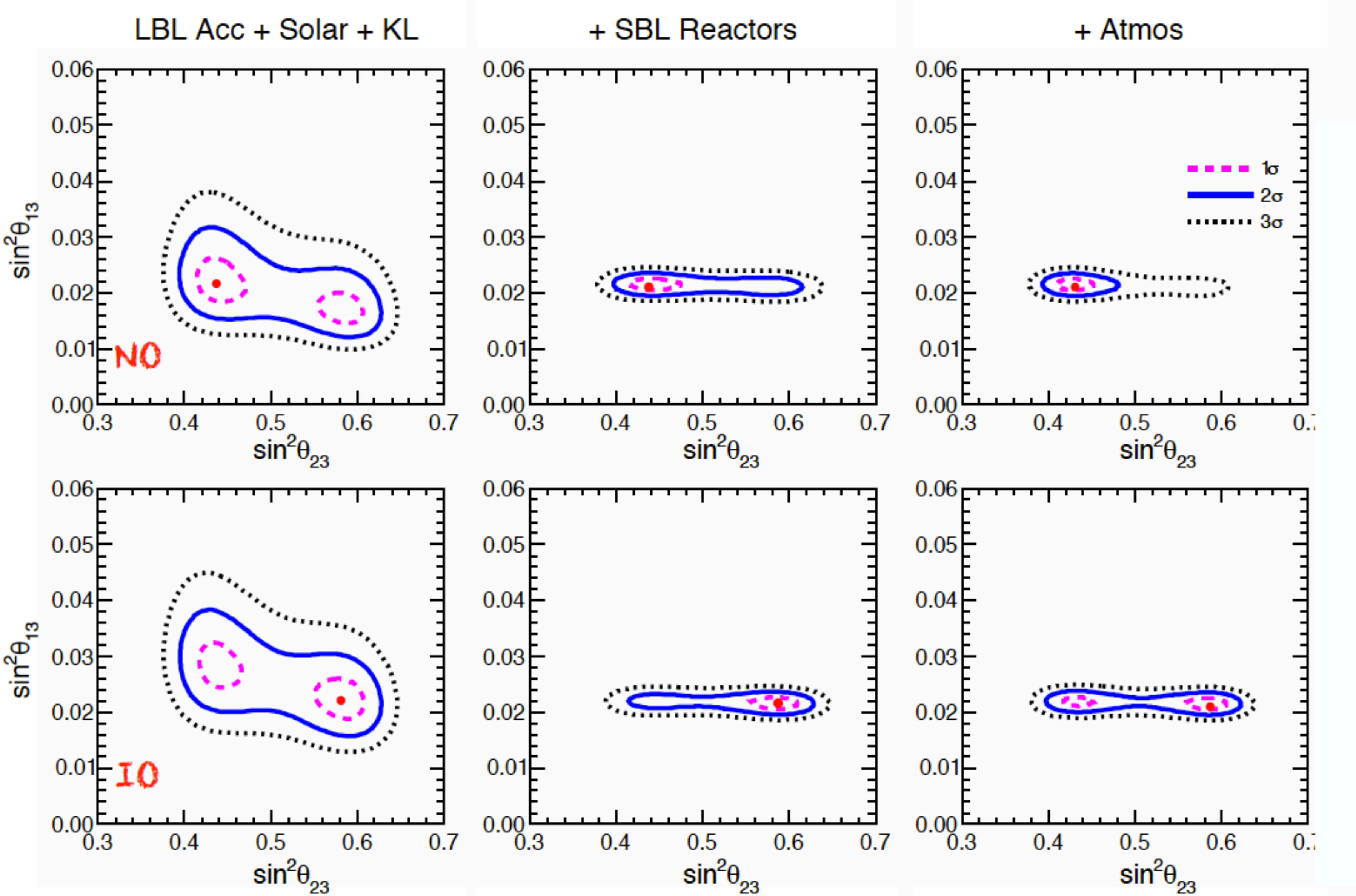
- $\delta \sim 1.4\,\pi$ at best fit
- CP-conserving cases ($\delta = 0, \pi$) disfavored at $\sim 2\sigma$ level or more
- Significant fraction of the $[0,\pi]$ range disfavored at $>3\sigma$

θ_{23} trend:

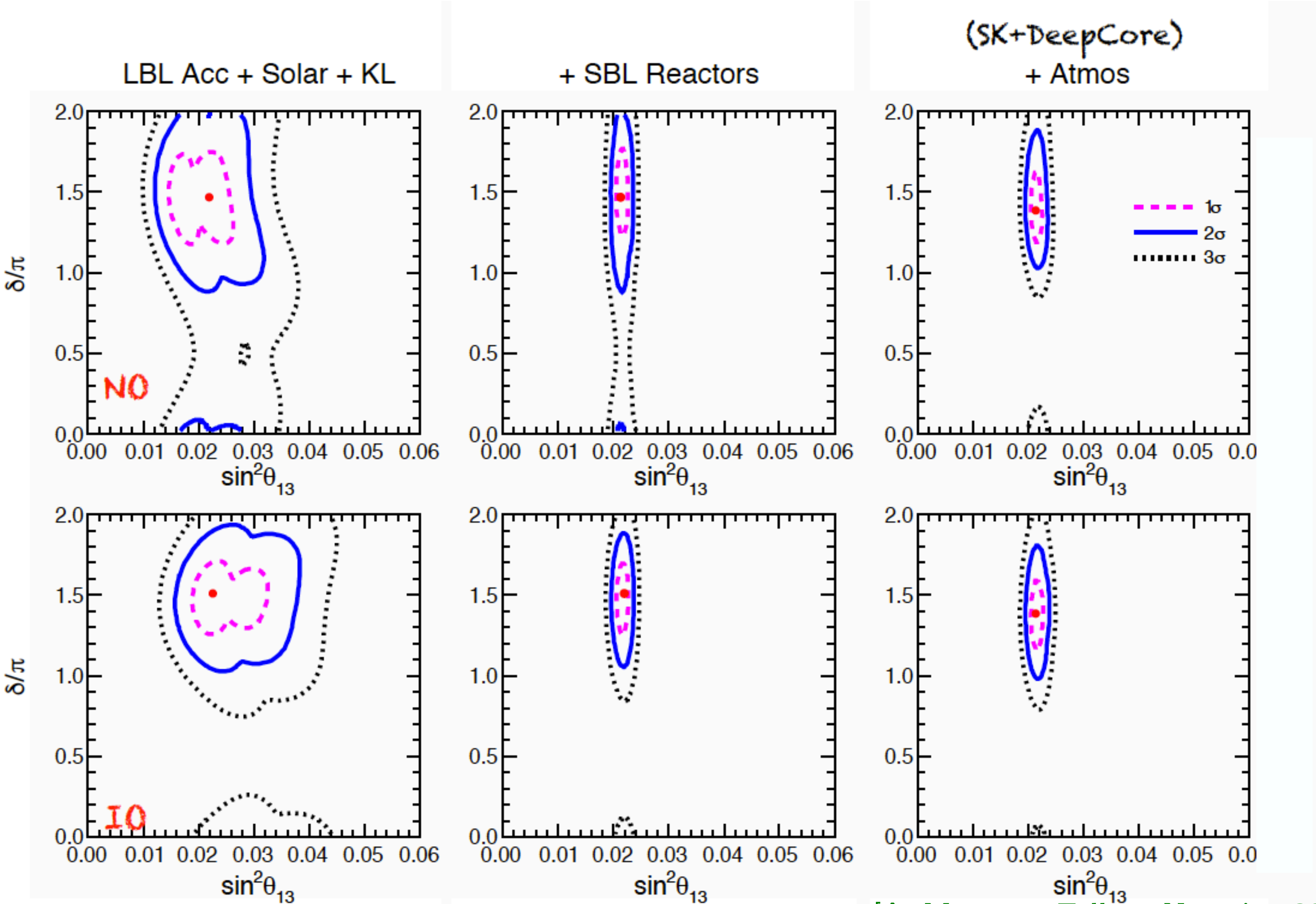
- maximal mixing disfavored at about $\sim 2\sigma$ level
- best-fit octant flips with mass ordering

$$\Delta\chi^2_{\rm IO-NO} = 3.1$$

inverted ordering slightly disfavored



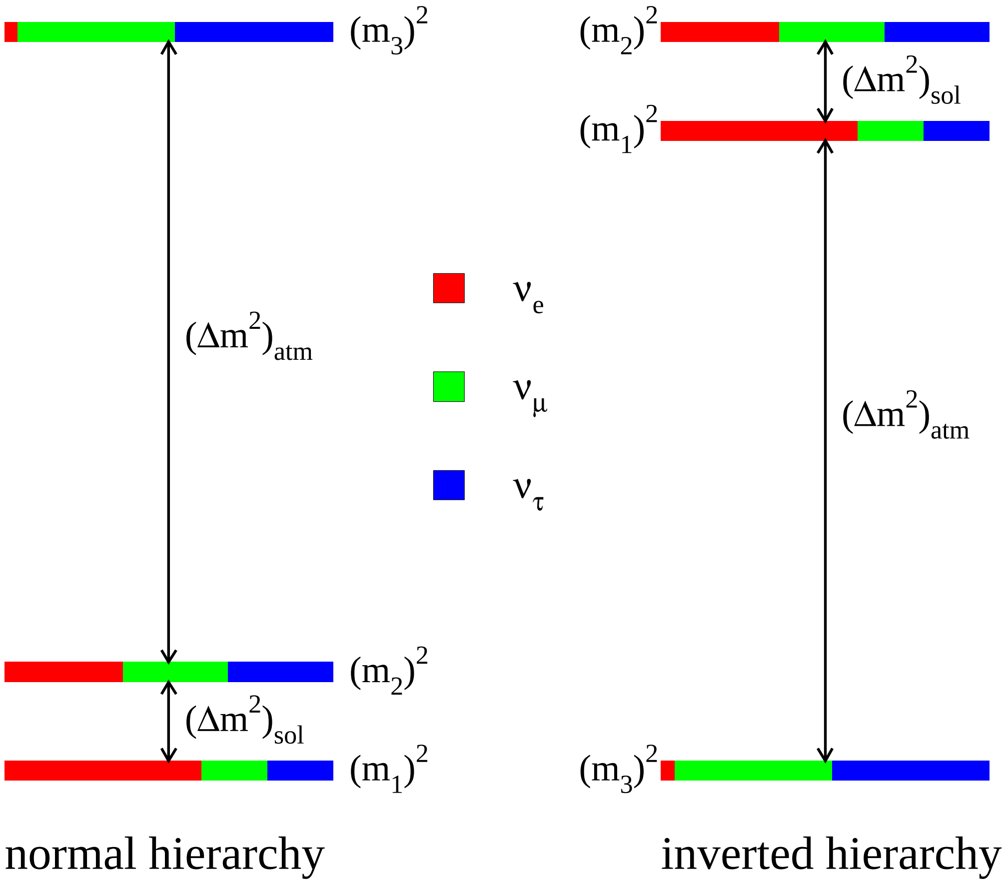
Atmospheric data do not spoil this trend but introduce some differences in the relative likelihood of the two octants in NO and IO. Octant degeneracy may show up in terms of "bumps" or "double bands" when marginalized away –> [A. Marrone, Talk at Neutrino 2016]



[A. Marrone, Talk at Neutrino 2016]

Results in the (δ, θ_{13}) plane corroborated by atmospheric data

Understanding Neutrino Oscillations: Are We There Yet? [NO!]

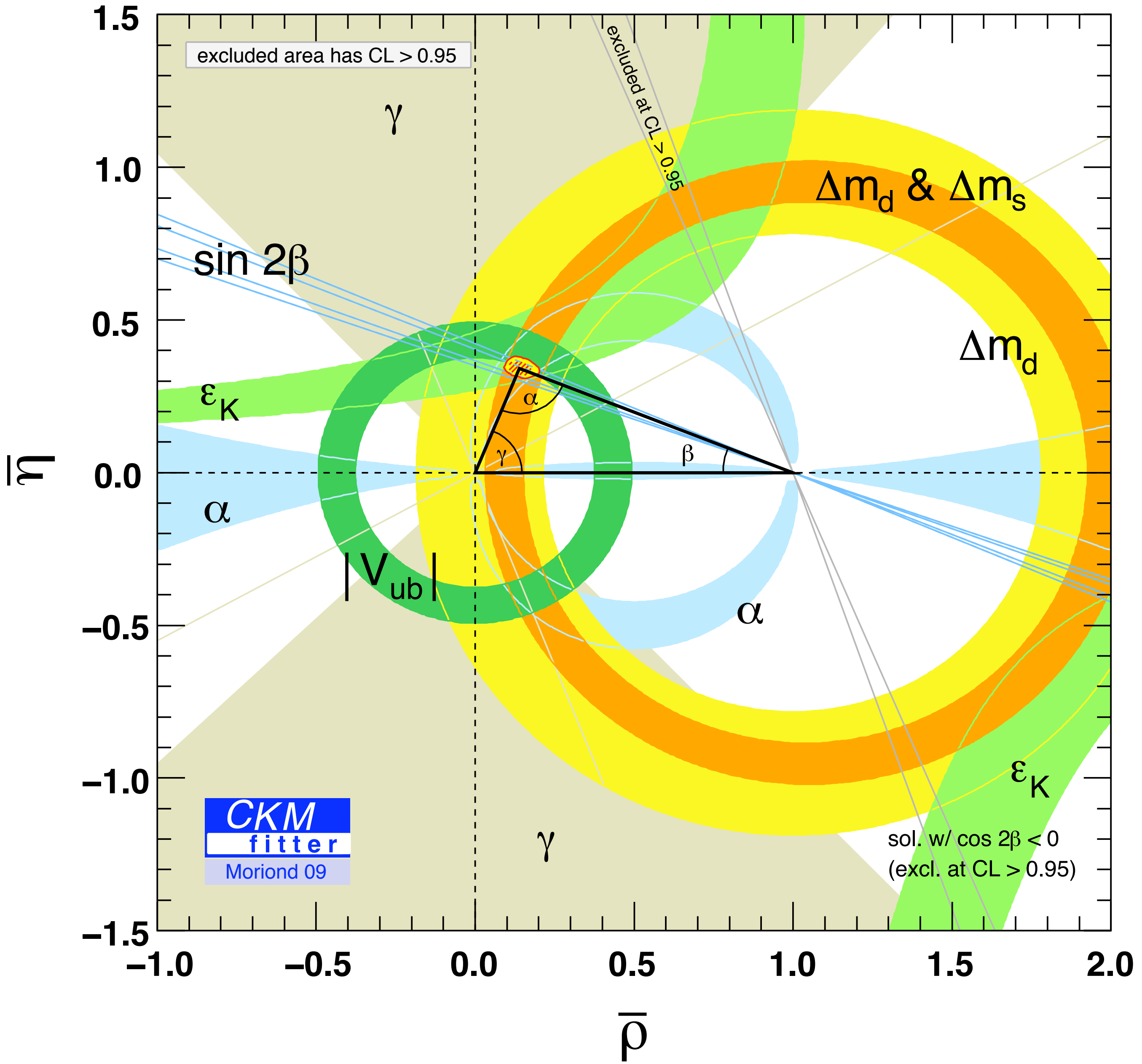


- ~~What is the ν_e component of ν_3?~~ ($\theta_{13} \neq 0$!)
- Is CP-invariance violated in neutrino oscillations? ($\delta \neq 0, \pi$?) ['yes' hint]
- Is ν_3 mostly ν_μ or ν_τ? [$\theta_{23} \neq \pi/4$ hint]
- What is the neutrino mass hierarchy? ($\Delta m^2_{13} > 0$?) [NH weak hint]

$\Rightarrow$ All of the above can "only" be addressed with new neutrino oscillation experiments

Ultimate Goal: Not Measure Parameters but Test the Formalism (Over-Constrain Parameter Space)

What we ultimately want to achieve:



We need to do this in the lepton sector!

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

What we have **really measured** (very roughly):

- Two mass-squared differences, at several percent level – many probes;
- $|U_{e2}|^2$ – solar data;
- $|U_{\mu 2}|^2 + |U_{\tau 2}|^2$ – solar data;
- $|U_{e2}|^2|U_{e1}|^2$ – KamLAND;
- $|U_{\mu 3}|^2(1 - |U_{\mu 3}|^2)$ – atmospheric data, K2K, MINOS;
- $|U_{e3}|^2(1 - |U_{e3}|^2)$ – Double Chooz, Daya Bay, RENO;
- $|U_{e3}|^2|U_{\mu 3}|^2$ (upper bound $\rightarrow$ evidence) – MINOS, T2K.

We still have a ways to go!

What Could We run Into?

- New neutrino states. In this case, the 3×3 mixing matrix would not be unitary.
- New neutrino–matter interactions. These lead to, for example, new matter effects. If we don't take these into account, there is no reason for the three-flavor interpretations of oscillation data to "close."
- Weird stuff. CPT-violation. Decoherence effects (aka "violations of Quantum Mechanics.")
- etc.

I will come back to this.

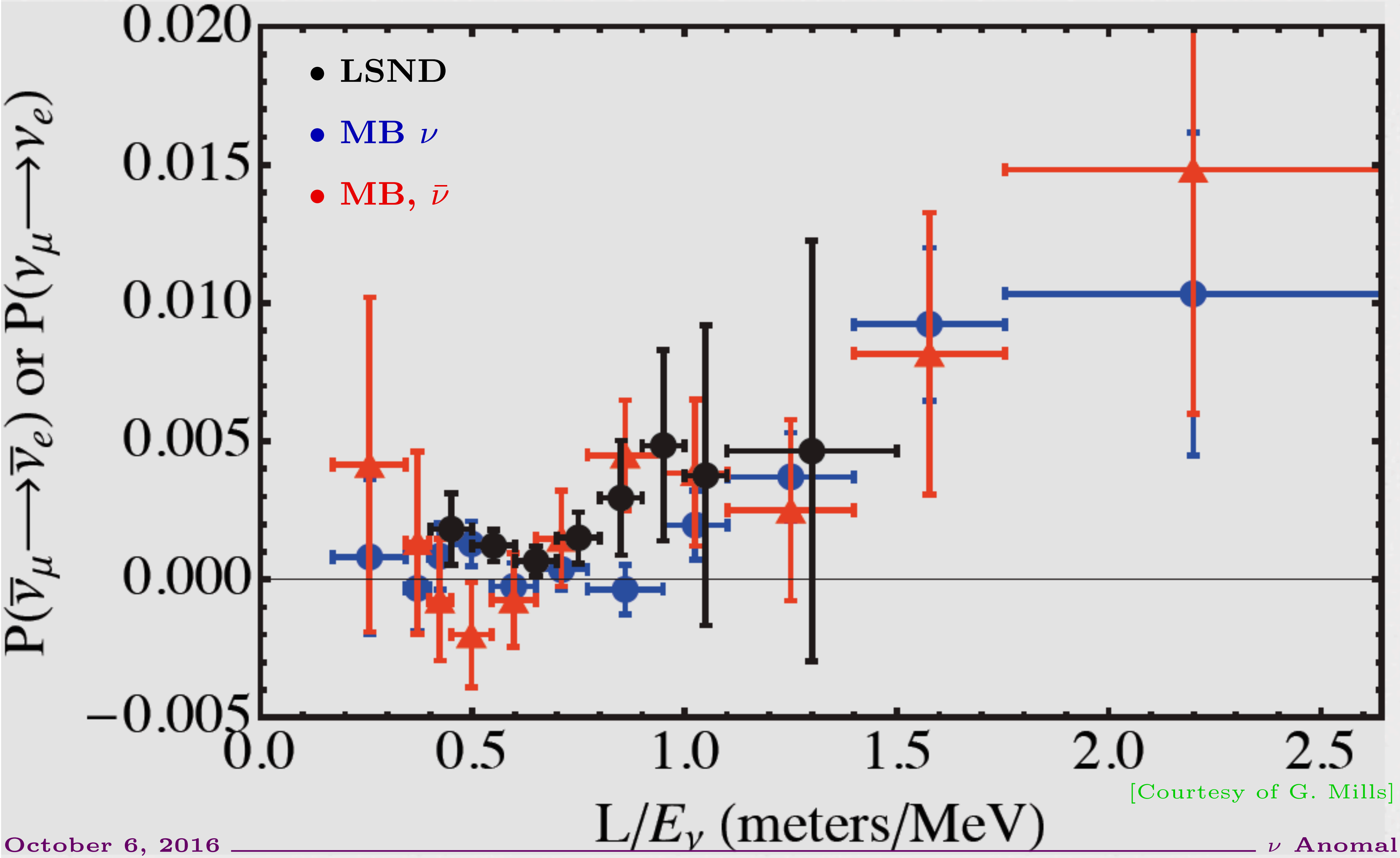
Not all is well: The Short Baseline Anomalies

Different data sets, sensitive to L/E values small enough that the known oscillation frequencies do not have "time" to operate, point to unexpected neutrino behavior. These include

- $\nu_\mu \to \nu_e$ appearance — LSND, MiniBooNE;
- $\nu_e \to \nu_{\rm other}$ disappearance — radioactive sources;
- $\bar{\nu}_e \to \bar{\nu}_{\rm other}$ disappearance — reactor experiments.

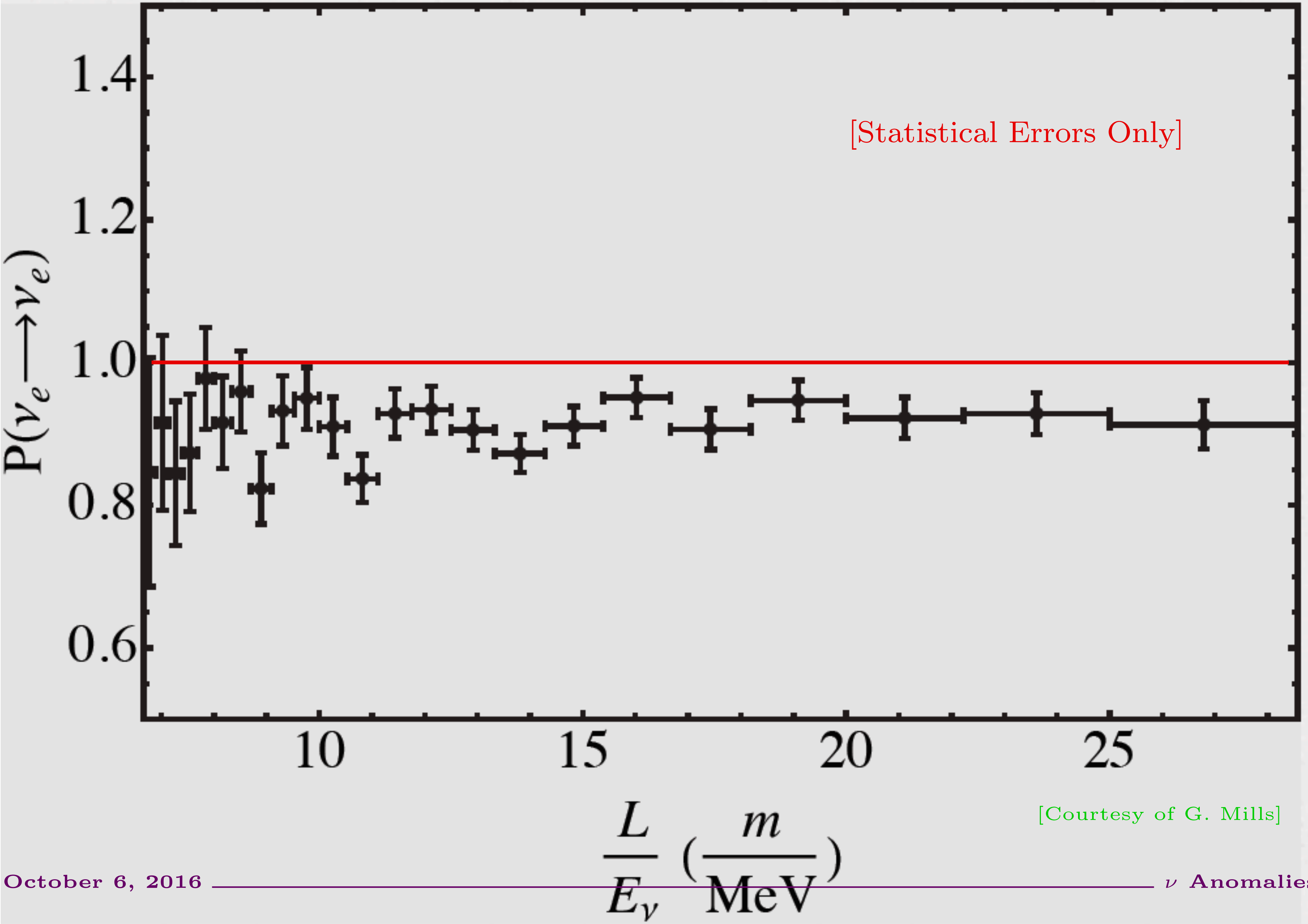
None are entirely convincing, either individually or combined. However, there may be something very very interesting going on here…

MiniBooNE & LSND



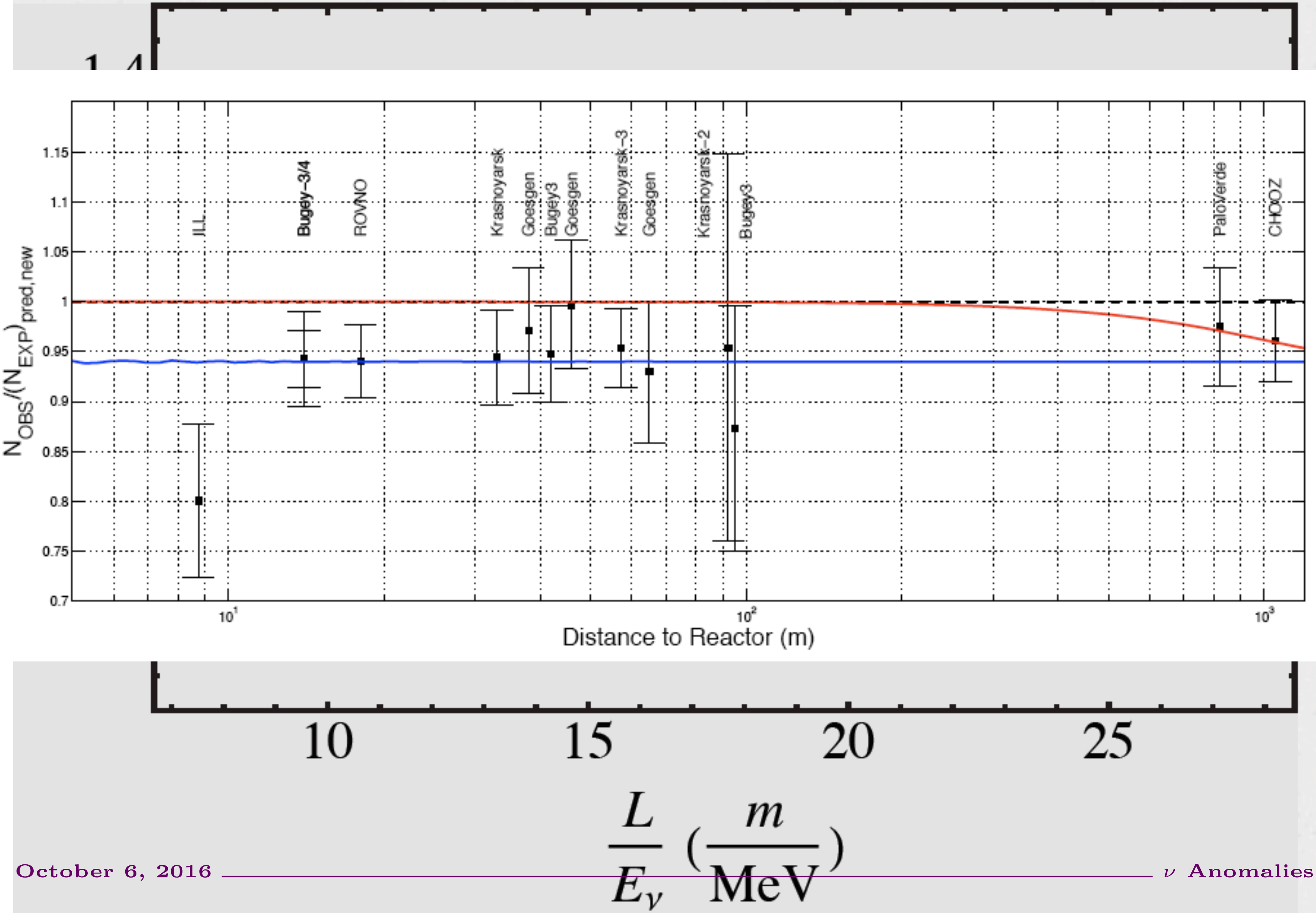
[Courtesy of G. Mills]

Bugey 40 m



[Courtesy of G. Mills]

Bugey 40 m



ILL
Bugey-3/4
ROVNO
Krasnoyarsk
Goesgen
Bugey3
Goesgen
Krasnoyarsk-3
Goesgen
Krasnoyarsk-2
Bugey3
PaloVerde
CHOOZ
$N_{OBS}/(N_{EXP})_{pred,new}$
1.15
1.1
1.05
1
0.95
0.9
0.85
0.8
0.75
0.7
10^1
10^2
10^3
Distance to Reactor (m)
10
15
20
25
$\frac{L}{E_\nu}$ $(\frac{m}{\mathrm{MeV}})$

What is Going on Here?

- Are these "anomalies" related?
- Is this neutrino oscillations, other new physics, or something else?
- Are these related to the origin of neutrino masses and lepton mixing?
- How do clear this up **definitively**?

Need new clever experiments, of the short-baseline type!

Observable wish list:

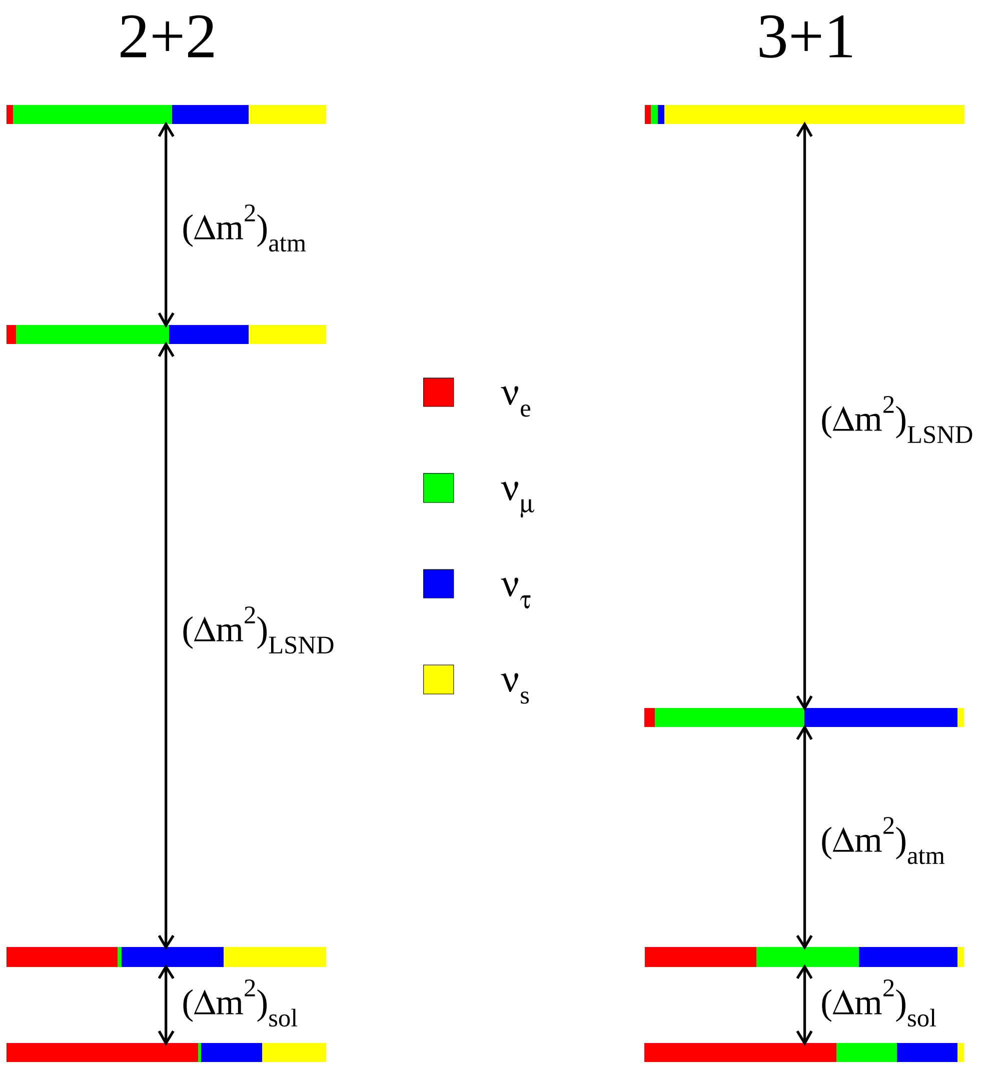
- ν_μ disappearance (and antineutrino);
- ν_e disappearance (and antineutrino);
- $\nu_\mu \leftrightarrow \nu_e$ appearance;
- $\nu_{\mu,e} \to \nu_\tau$ appearance.

A neutrino oscillation solution require new neutrino states ν_4, ν_5, etc with masses m_4, m_5, etc. Reason is simple: L/E too small (hence *Short Baseline Anomalies*).

$$\left(\begin{array}{c} \nu_e \\ \nu_\mu \\ \nu_\tau \\ \nu_{s_1} \\ \vdots \end{array}\right) = \left(\begin{array}{ccccc} U_{e1} & U_{e2} & U_{e3} & U_{e4} & \cdots \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} & U_{\mu 4} & \cdots \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} & U_{\tau 4} & \cdots \\ U_{s_1 1} & U_{s_1 2} & U_{s_1 3} & U_{s_1 4} & \cdots \\ \vdots & \vdots & \vdots & \vdots & \ddots \end{array}\right) \left(\begin{array}{c} \nu_1 \\ \nu_2 \\ \nu_3 \\ \nu_4 \\ \vdots \end{array}\right)$$

The probability that ν_4 is measured as a ν_e is U_{e4}, the probability that ν_5 is measured as a ν_μ is $U_{\mu 5}$, and so on.

[Parameterizing the matrix is interesting. See AdG, Jenkins, PRD78, 053003 (2008)]



$\Rightarrow$ 2+2 requires large sterile effects in either solar or atmospheric oscillations, not observed

Experiment	dof	channel	comments
Short-baseline reactors	76	$\bar{\nu}_e \to \bar{\nu}_e$	SBL
Long-baseline reactors	39	$\bar{\nu}_e \to \bar{\nu}_e$	LBL
KamLAND	17	$\bar{\nu}_e \to \bar{\nu}_e$	
Gallium	4	$\nu_e \to \nu_e$	SBL
Solar neutrinos	261	$\nu_e \to \nu_e$ + NC data	
LSND/KARMEN ^{12}C	32	$\nu_e \to \nu_e$	SBL
CDHS	15	$\nu_\mu \to \nu_\mu$	SBL
MiniBooNE ν	15	$\nu_\mu \to \nu_\mu$	SBL
MiniBooNE $\bar{\nu}$	42	$\bar{\nu}_\mu \to \bar{\nu}_\mu$	SBL
MINOS CC	20	$\nu_\mu \to \nu_\mu$	LBL
MINOS NC	20	$\nu_\mu \to \nu_s$	LBL
Atmospheric neutrinos	80	$\overset{(-)}{\nu}_\mu \to \overset{(-)}{\nu}_\mu$ + NC matter effect	
LSND	11	$\bar{\nu}_\mu \to \bar{\nu}_e$	SBL
KARMEN	9	$\bar{\nu}_\mu \to \bar{\nu}_e$	SBL
NOMAD	1	$\nu_\mu \to \nu_e$	SBL
MiniBooNE ν	11	$\nu_\mu \to \nu_e$	SBL
MiniBooNE $\bar{\nu}$	11	$\bar{\nu}_\mu \to \bar{\nu}_e$	SBL
E776	24	$\overset{(-)}{\nu}_\mu \to \overset{(-)}{\nu}_e$	SBL
ICARUS	1	$\nu_\mu \to \nu_e$	LBL
total	689		

Table 1. Summary of the data used in this work divided into $\overset{(-)}{\nu}_e$, $\overset{(-)}{\nu}_\mu$ disappearance, and appearance data. The column "dof" gives the number of data points used in our analysis minus the number of free nuisance parameters for each experiment.

J. Kopp *et al*, arXiv:1303.3011

Bottom line: Fits to *all data* are mediocre – no "feel good" solution! On the other hand, I think it is not correct to say the hypothesis is ruled out.

	$\chi^2_{\rm min}/{\rm dof}$	GOF	$\chi^2_{\rm PG}/{\rm dof}$	PG	$\chi^2_{\rm app,glob}$	$\Delta\chi^2_{\rm app}$	$\chi^2_{\rm dis,glob}$	$\Delta\chi^2_{\rm dis}$
3+1	712/(689 − 9)	19%	18.0/2	1.2×10^{-4}	95.8/68	7.9	616/621	10.1
3+2	701/(689 − 14)	23%	25.8/4	3.4×10^{-5}	92.4/68	19.7	609/621	6.1
1+3+1	694/(689 − 14)	30%	16.8/4	2.1×10^{-3}	82.4/68	7.8	611/621	9.0

Table 7. Global χ^2 minima, GOF values, and parameter goodness-of-fit (PG) test [125] for the consistency of appearance versus disappearance experiments in the 3+1, 3+2, and 1+3+1 schemes. The corresponding parameter values at the global best fit points are given in Tab. 8. The last four columns give the contributions of appearance and disappearance data to $\chi^2_{\rm PG}$, see Eq. (6.2).

New in 2016 – Data on ν_μ disappearance from MINOS and Ice Cube, combined with data on $\bar{\nu}_e$ from Daya Bay did not make matters better.

J. Kopp *et al*, arXiv:1303.3011

$$[\sin^2 2\theta_{\alpha\alpha} = 4|U_{\alpha 4}|^2(1-|U_{\alpha 4}|^2) \quad \sin^2 2\theta_{e\mu} = 4|U_{e4}|^2|U_{\mu 4}|^2]$$

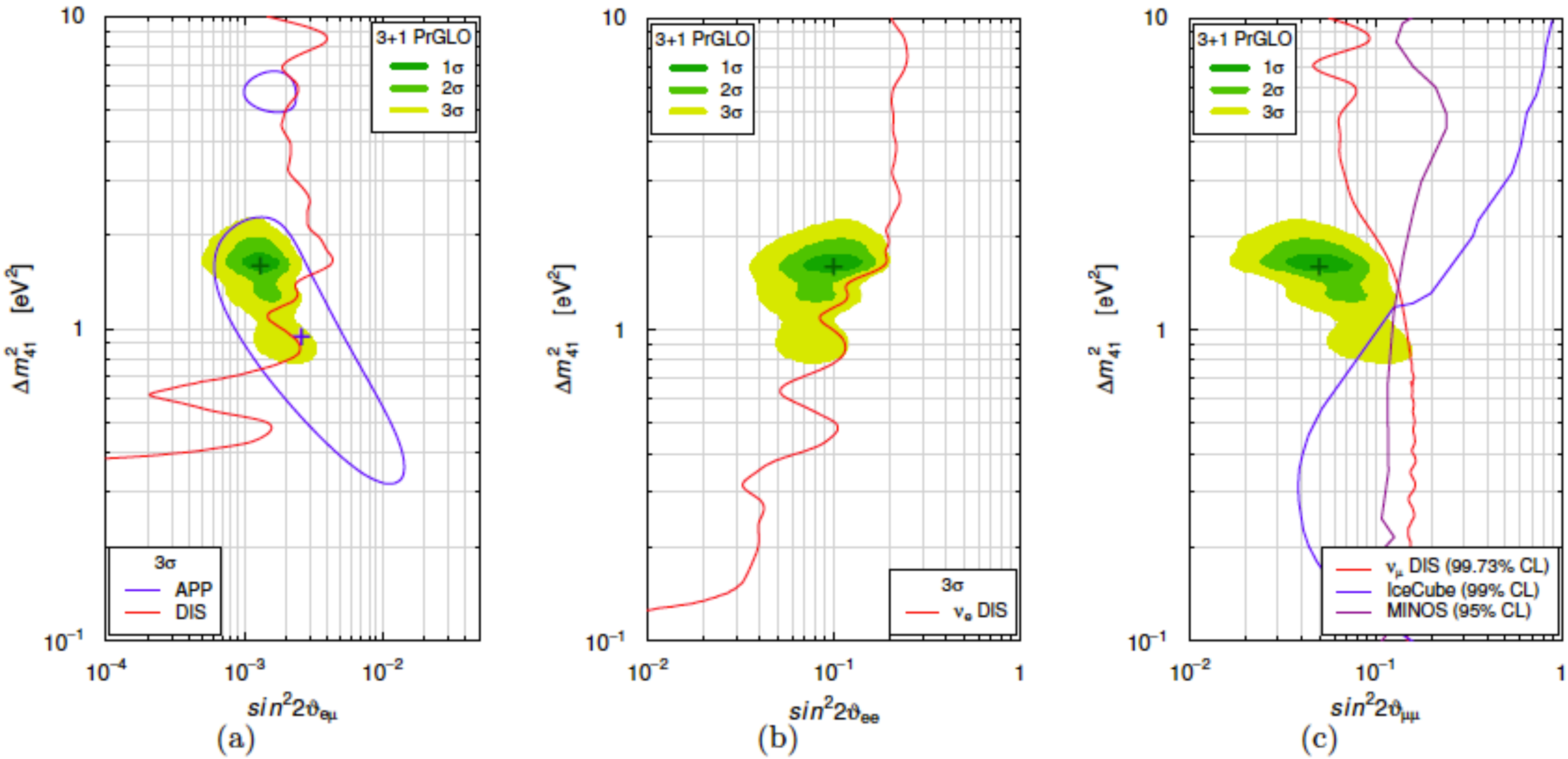
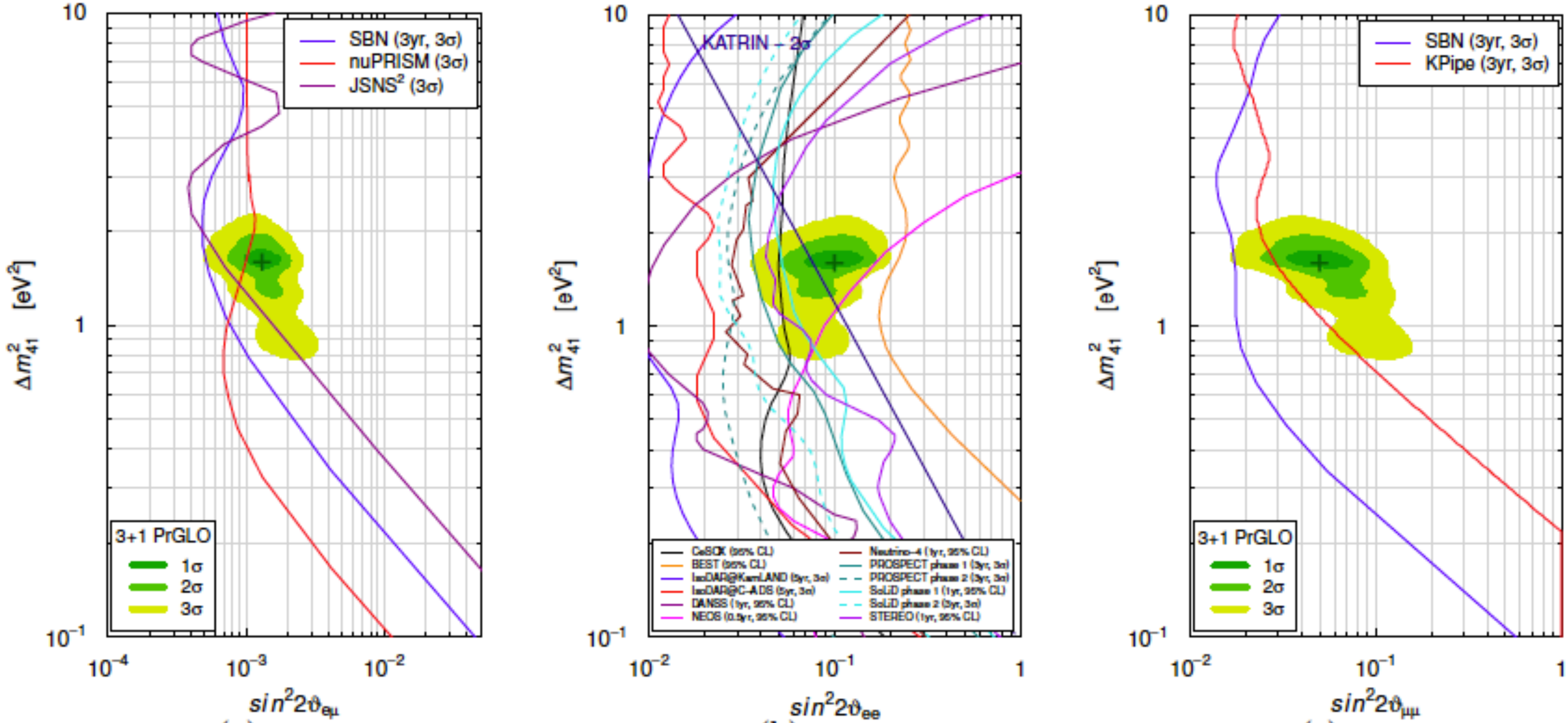


Figure 3. Allowed regions in the $\sin^2 2\vartheta_{e\mu}$–Δm^2_{41} (a), $\sin^2 2\vartheta_{ee}$–Δm^2_{41} (b), and $\sin^2 2\vartheta_{\mu\mu}$–$\Delta m^2_{41}$ (c) planes obtained in the pragmatic 3+1 global fit PrGLO of short-baseline neutrino oscillation data compared with the 3σ allowed regions obtained from $\overset{(-)}{\nu}_\mu \to \overset{(-)}{\nu}_e$ short-baseline appearance data (APP) and the 3σ constraints obtained from $\overset{(-)}{\nu}_e$ short-baseline disappearance data (ν_e DIS), $\overset{(-)}{\nu}_\mu$ short-baseline disappearance data (ν_μ DIS) and the combined short-baseline disappearance data (DIS). The best-fit points of the global (PrGLO) and APP fits are indicated by crosses.

[Giunti, arXiv:1609.04688]

Near Future Expectations – Lots of Activity



(a) (b) (c)

Figure 4. Sensitivities of future experiments compared with the PrGLO allowed regions of Fig. 3.

[C. Giunti, arXiv:1609.04688]

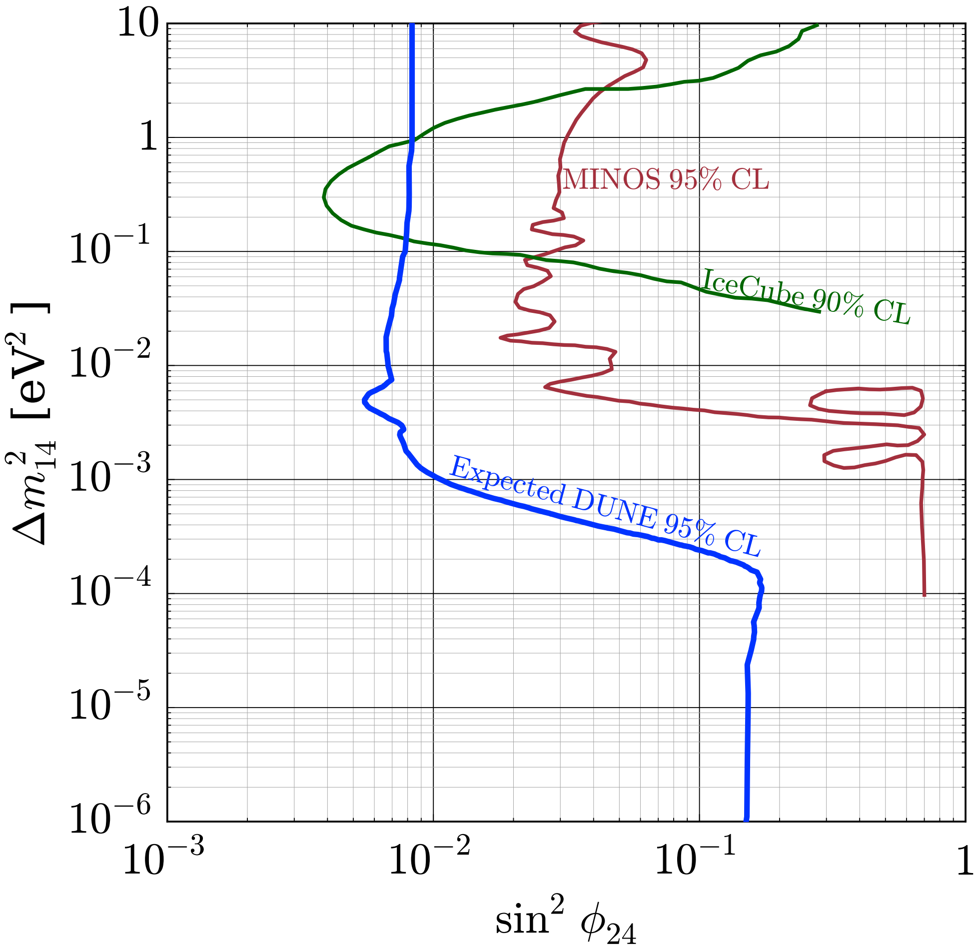
If the oscillation interpretation of the short-baseline anomalies turns out to be correct ...

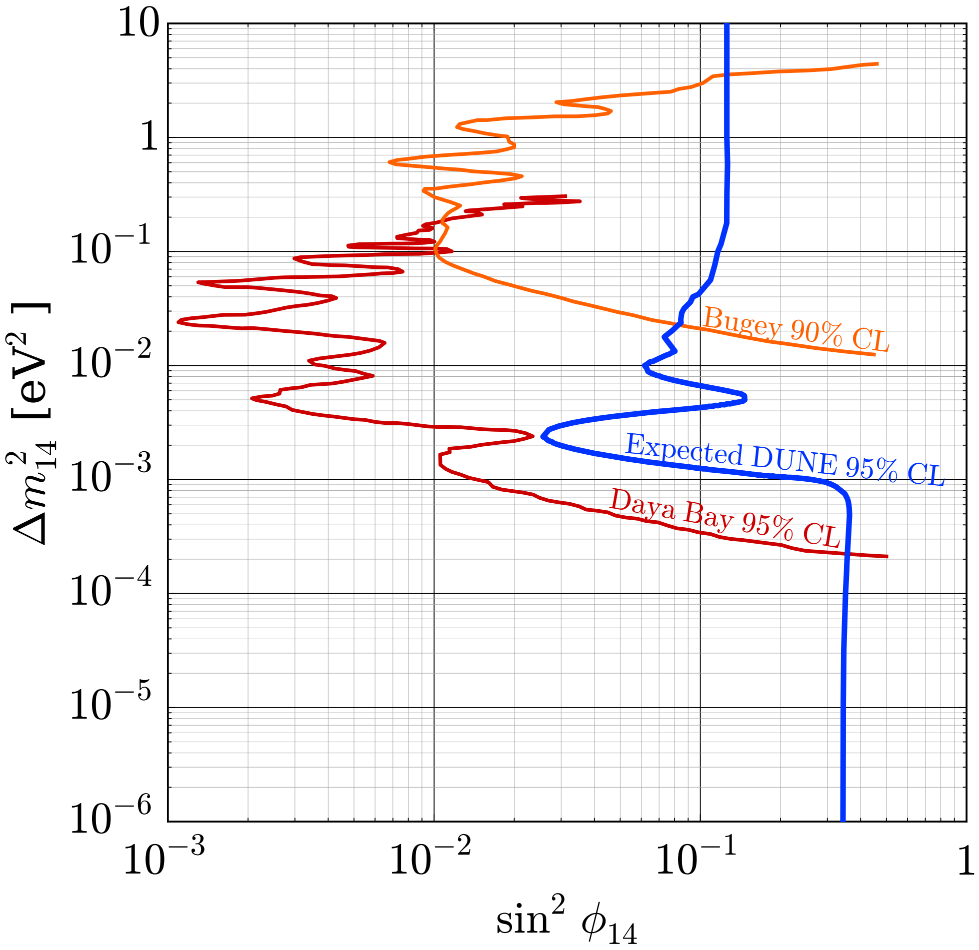
- We would have found new particle(s)!!!!!! [cannot overemphasize this!]
- Lots of Questions! What is it? Who ordered that? Is it related to the origin of neutrino masses? Is it related to dark matter?
- Lots of Work to do! Discovery, beyond reasonable doubt, will be followed by a panacea of new oscillation experiments. If, for example, there were one extra neutrino state the 4×4 mixing matrix would require three more mixing angles and three more CP-odd phases. Incredibly challenging. For example, two of the three CP-odd parameters, to zeroth order, can only be "seen" in tau-appearance.

For example, if the new neutrino states are the "right-handed neutrinos" from the standard seesaw, independent from the short-baseline anomalies (for an inverted mass hierarchy, $m_4 = 1$ eV$(\ll m_5)$) ...

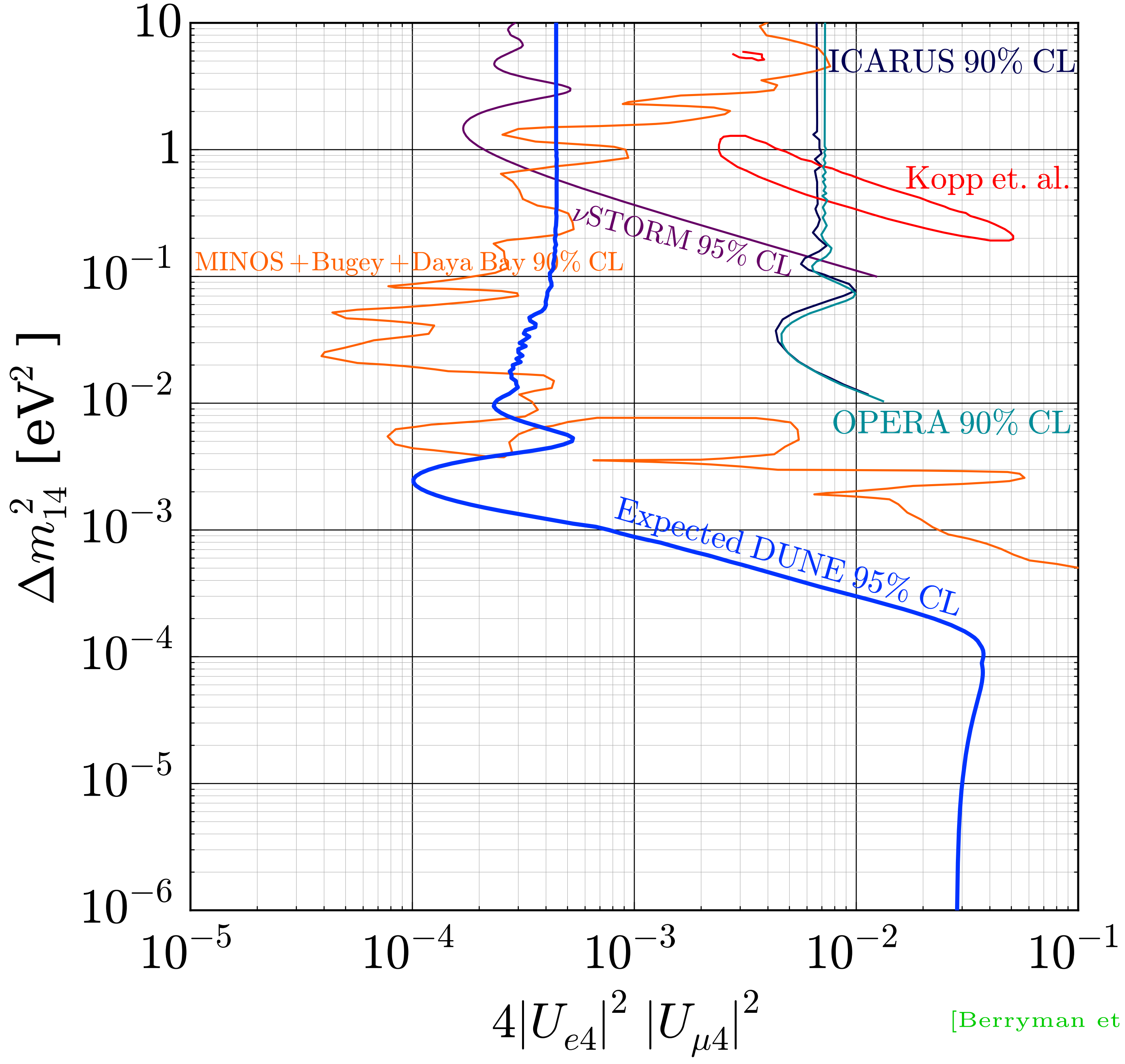
[AdG, Huang, 1110.6122]

- ν_e disappearance with an associated effective mixing angle $\sin^2 2\vartheta_{ee} > 0.02$. An interesting new proposal to closely expose the Daya Bay detectors to a strong β-emitting source would be sensitive to $\sin^2 2\vartheta_{ee} > 0.04$;
- ν_μ disappearance with an associated effective mixing angle $\sin^2 2\vartheta_{\mu\mu} > 0.07$, very close to the most recent MINOS lower bound;
- $\nu_\mu \leftrightarrow \nu_e$ transitions with an associated effective mixing angle $\sin^2 \vartheta_{e\mu} > 0.0004$;
- $\nu_\mu \leftrightarrow \nu_\tau$ transitions with an associated effective mixing angle $\sin^2 \vartheta_{\mu\tau} > 0.001$. A $\nu_\mu \to \nu_\tau$ appearance search sensitive to probabilities larger than 0.1% for a mass-squared difference of 1 eV^2 would definitively rule out $m_4 = 1$ eV if the neutrino mass hierarchy is inverted.



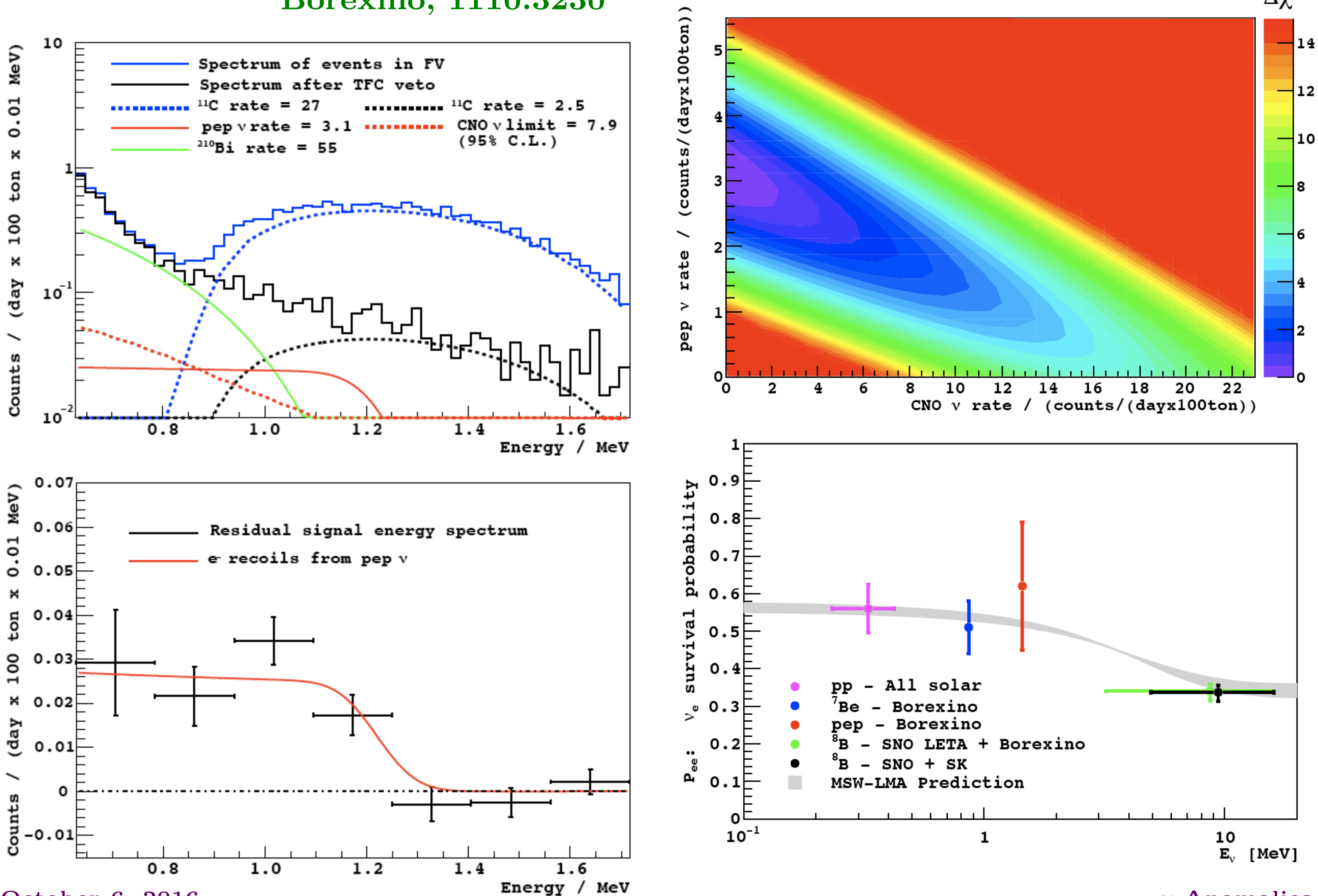


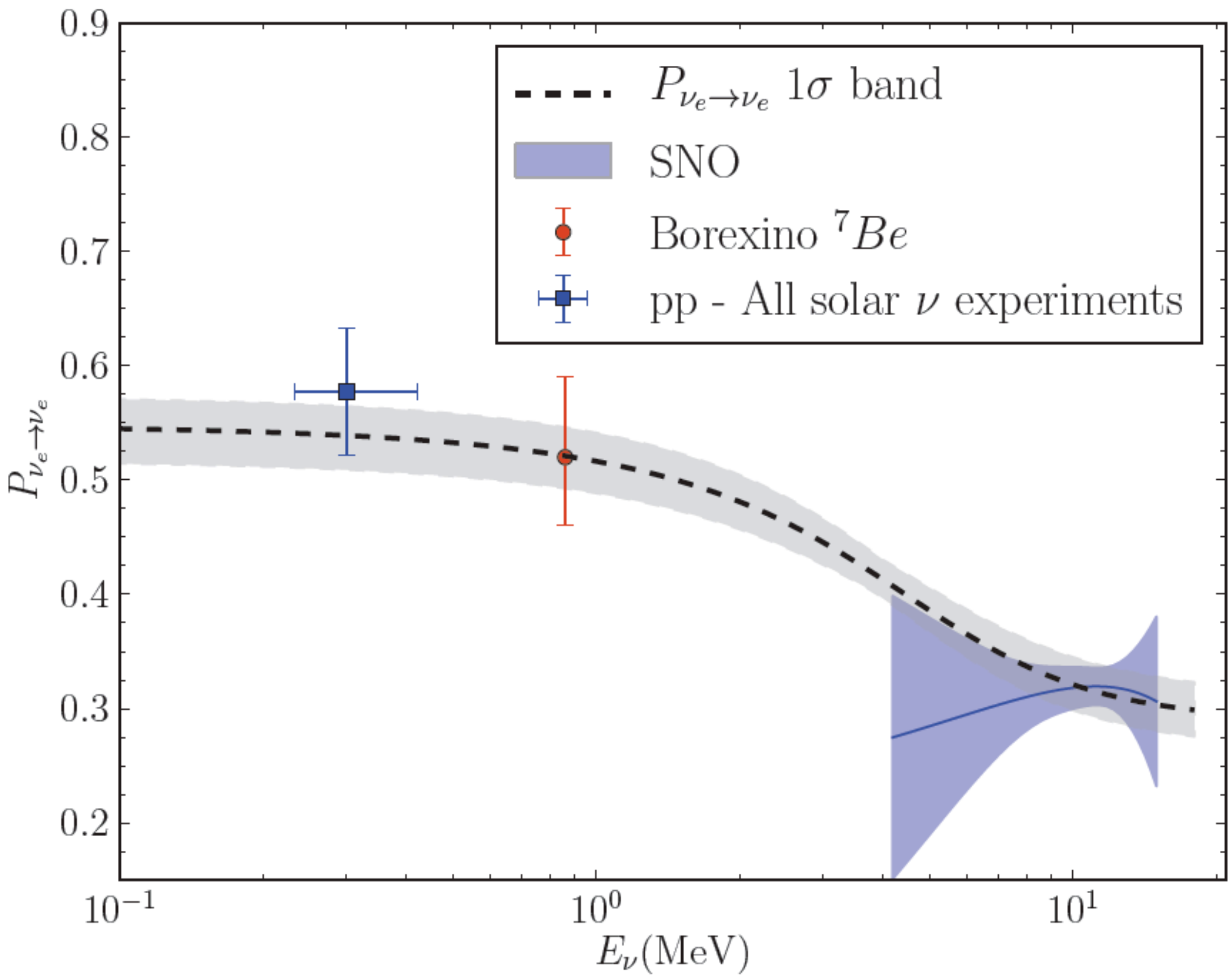
[Berryman et al, arXiv:1507.03986]

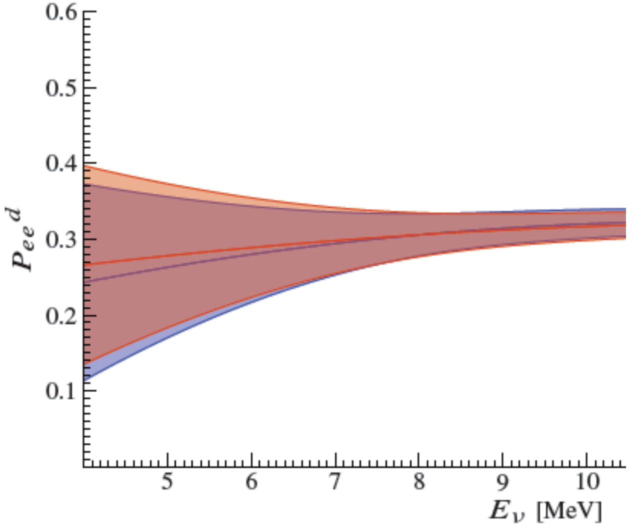


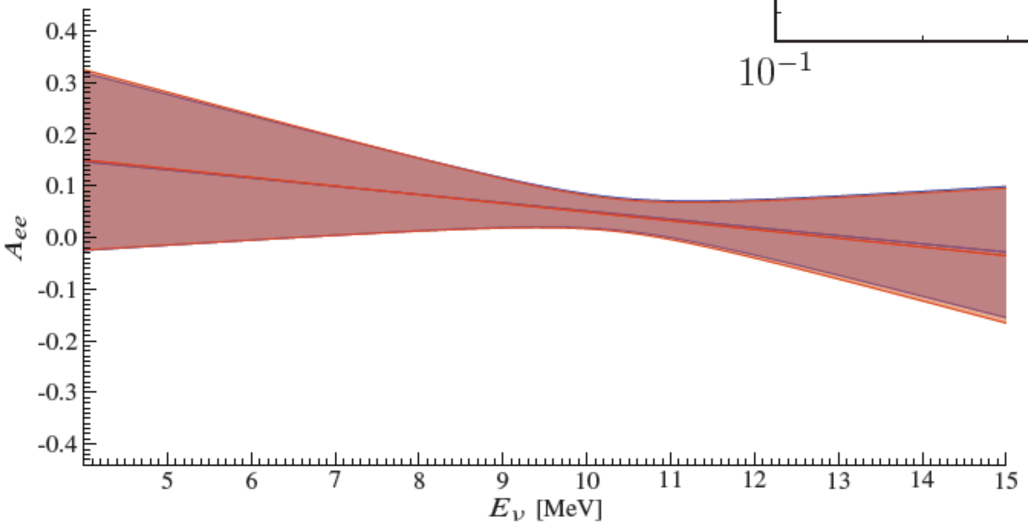
[Berryman et al, arXiv:1507.03986]

Borexino, 1110.3230









"Final" SNO results, 1109.0763

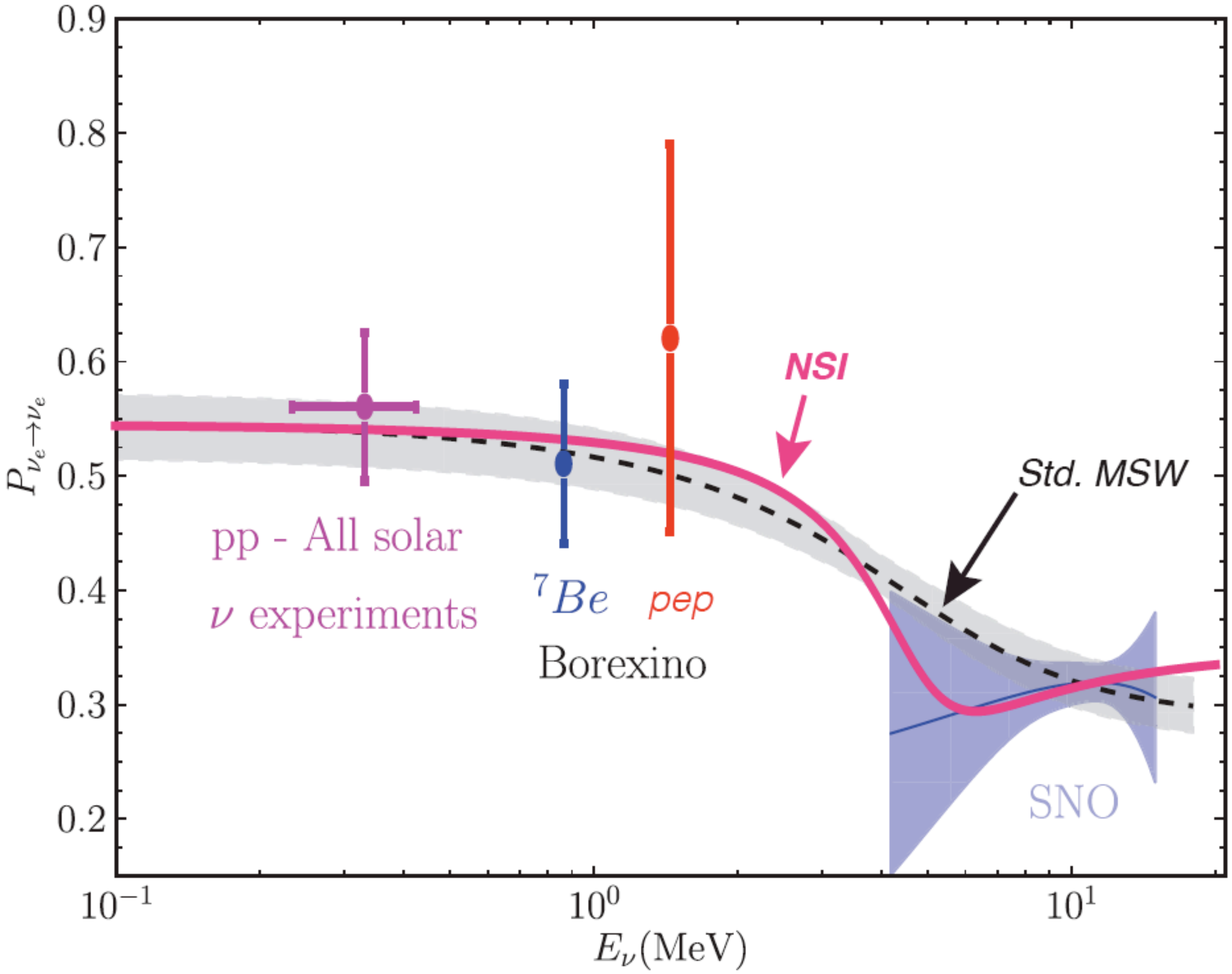


FIG. 1: Recent SNO solar neutrino data [18] on $P(\nu_e \to \nu_e)$ (blue line with 1 σ band). The LMA MSW solution (dashed black curve with gray 1 σ band) appears divergent around a few MeV, whereas for NSI with $\varepsilon_{e\tau} = 0.4$ (thick magenta), the electron neutrino probability appears to fit the data better. The data points come from the recent Borexino paper [19].

Solar Neutrinos

We are not done yet!

- see "vaccum-matter" transition
- probe for new physics: NSI, pseudo-Dirac, . . .
- probe of the solar interior! "solar abundance problem" (see e.g. 1104.1639)

'CNO neutrinos may provide information on planet formation!'

[Friedland, Shoemaker 1207.6642]

Non-Standard Neutrino Interactions (NSI)

Effective Lagrangian:

$$\mathcal{L}^{\rm NSI} = -2\sqrt{2}G_F(\bar{\nu}_\alpha\gamma_\rho\nu_\beta)\sum_{f=e,u,d}(\epsilon_{\alpha\beta}^{fL}\overline{f}_L\gamma^\rho f_L + \epsilon_{\alpha\beta}^{fR}\overline{f}_R\gamma^\rho f_R) + h.c.,$$

For oscillations,

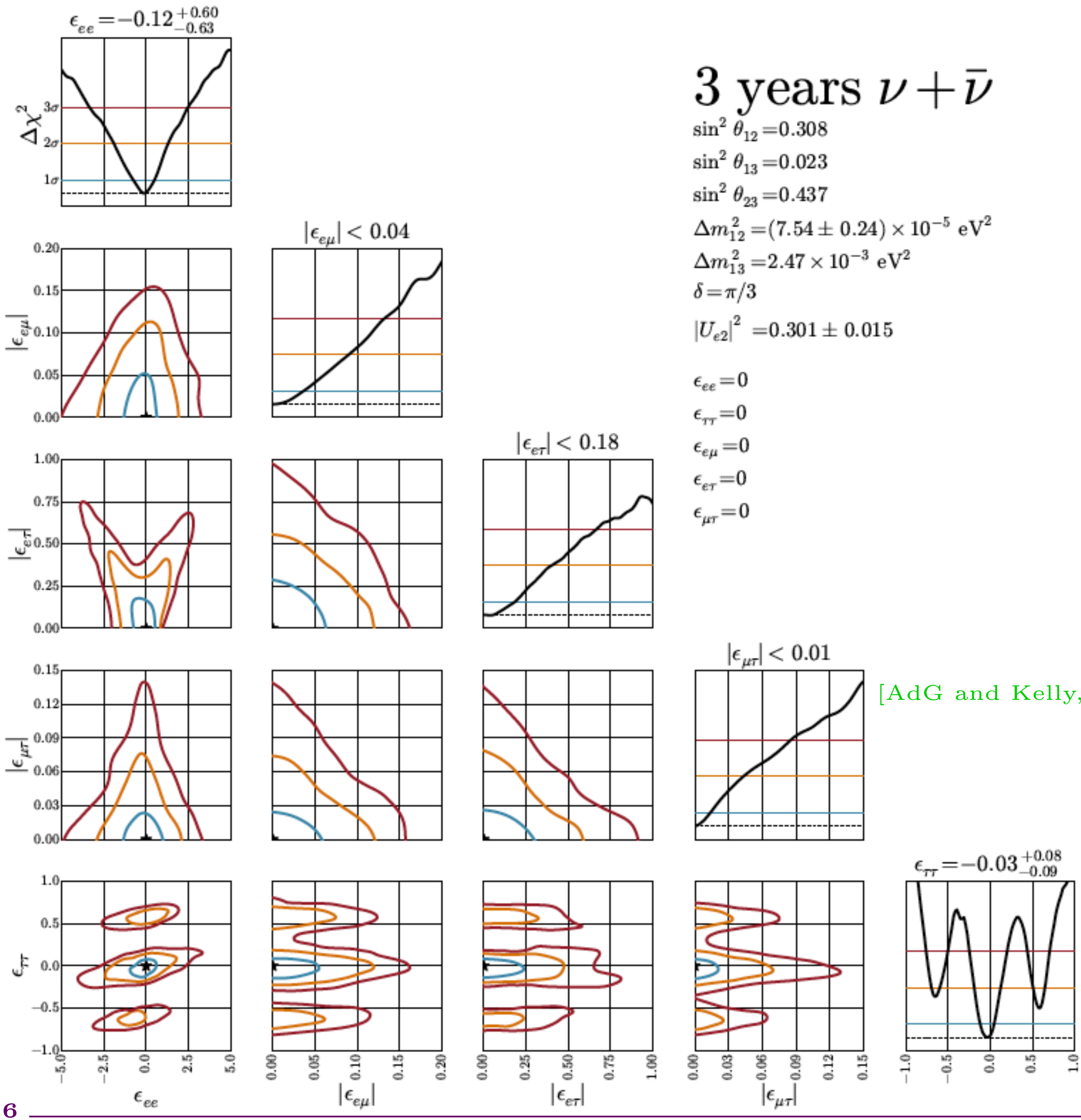
$$H_{ij} = \frac{1}{2E_\nu}{\rm diag}\left\{0, \Delta m^2_{12}, \Delta m^2_{13}\right\} + V_{ij},$$

where

$$V_{ij} = U^\dagger_{i\alpha}V_{\alpha\beta}U_{\beta j},$$

$$V_{\alpha\beta} = A\begin{pmatrix} 1+\epsilon_{ee} & \epsilon_{e\mu} & \epsilon_{e\tau} \\ \epsilon^*_{e\mu} & \epsilon_{\mu\mu} & \epsilon_{\mu\tau} \\ \epsilon^*_{e\tau} & \epsilon^*_{\mu\tau} & \epsilon_{\tau\tau}\end{pmatrix},$$

$A=\sqrt{2}G_F n_e$. $\epsilon_{\alpha\beta}$ are linear combinations of the $\epsilon_{\alpha\beta}^{fL,R}$. Important: Propagation effects only. We don't include NSI effects in production or detection.



[AdG and Kelly, arXiv:1511.05562]

FIG. 4: Expected exclusion limits at 68.3% (red), 95% (orange), and 99% (blue) CL at DUNE assuming data consistent with

Parting Words

The venerable Standard Model sprung a leak in the end of the last century: neutrinos are not massless! [and we are still trying to patch it. . .]

1. We still **know very little** about the new physics uncovered by neutrino oscillations. In particular, the new physics (broadly defined) can live almost anywhere between sub-eV scales and the GUT scale.

2. **Neutrino masses are very small** – we don't know why, but we think it means something important.

3. **Neutrino mixing is "weird"** – we don't know why, but we think it means something important.

4. What is going on with the **short-baseline anomalies?**

5. There is plenty of **room for surprises**, as neutrinos are very deep probes of all sorts of physical phenomena. Neutrino oscillations are "quantum interference devices," potentially sensitive to whatever else might be out there (keep in mind, neutrino masses might be physics at $\Lambda \simeq 10^{14}$ GeV).