Recent Neutrino Results

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Outline

1. Where We Are – Non-controversial Stuff (Very Brief);
2. Some Recent Solar Neutrino Results;
3. Where We Are Going – Non-controversial Stuff;
4. On the Short-Baseline “Anomalies”;
5. What We Are Trying to Understand;
6. The OPERA Anomaly (Very, Very Brief).

Caution: I am not an experimentalist. Experimental results will be shown in an oversimplified manner that does not do justice to the experiments or all the scientists involved.

Very Quick Reminder: 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.

- $\nu_\mu \to \nu_\tau$ and $\bar{\nu}_\mu \to \bar{\nu}_\tau$ — atmospheric experiments [“indisputable”];
- $\nu_e \to \nu_{\mu,\tau}$ — solar experiments [“indisputable”];
- $\bar{\nu}_e \to \bar{\nu}_{\rm other}$ — reactor neutrinos [“indisputable”];
- $\nu_\mu \to \nu_{\rm other}$ from accelerator experiments [“indisputable”].

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

Phenomenological Understanding of Neutrino Masses & Mixing

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

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

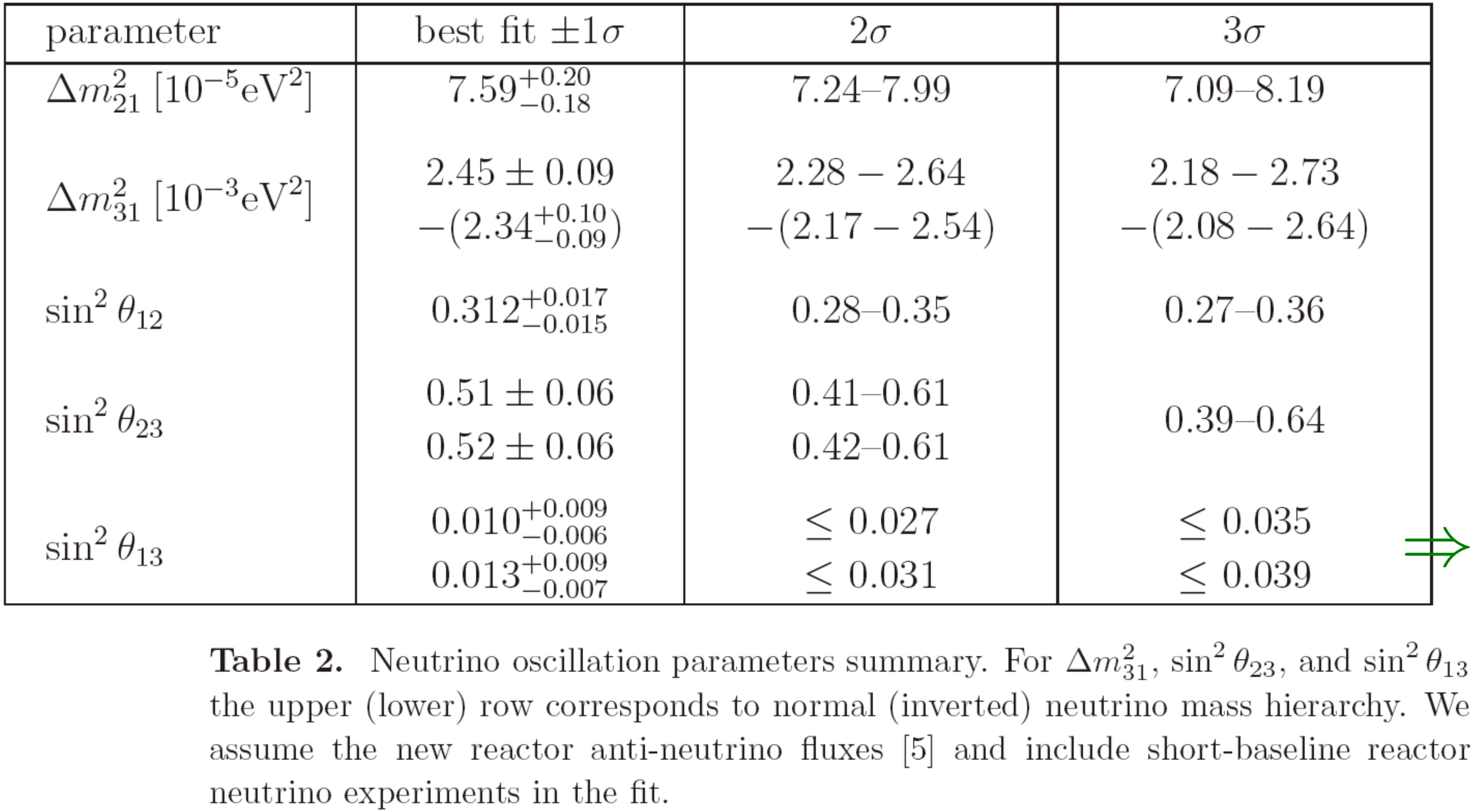
- $m_1^2 < m_2^2$ $\Delta m^2_{31} < 0$ – Inverted Mass Hierarchy
- $m_2^2 - m_1^2 \ll |m_3^2 - m_{1,2}^2|$ $\Delta m^2_{31} > 0$ – Normal Mass Hierarchy

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

[for a detailed discussion see AdG, Jenkins, arXiv:0804.3627]

Three Flavor Mixing Hypothesis Fits All* Data Really Well.

⇒ Good Measurements of Oscillation Observables



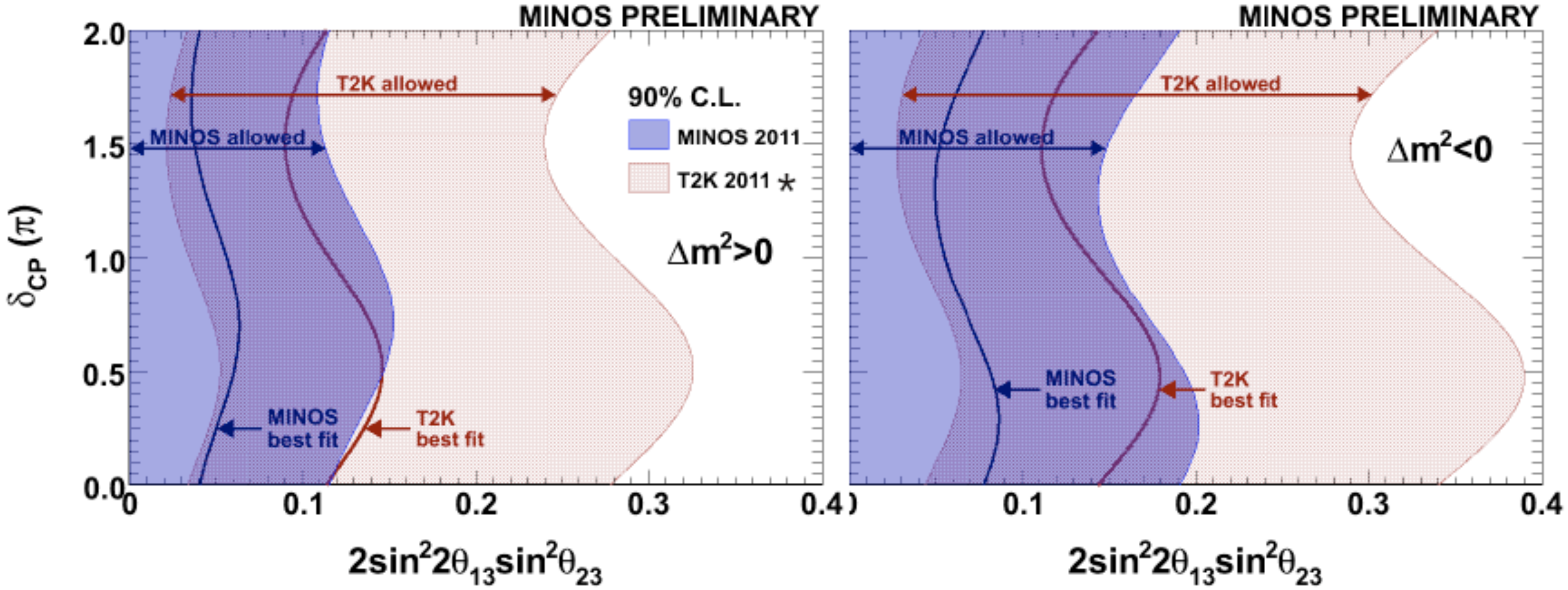
parameter	best fit $\pm 1\sigma$	2σ	3σ
Δm^2_{21} $[10^{-5}\mathrm{eV}^2]$	$7.59^{+0.20}_{-0.18}$	7.24–7.99	7.09–8.19
Δm^2_{31} $[10^{-3}\mathrm{eV}^2]$	2.45 ± 0.09 $-(2.34^{+0.10}_{-0.09})$	$2.28 - 2.64$ $-(2.17 - 2.54)$	$2.18 - 2.73$ $-(2.08 - 2.64)$
$\sin^2\theta_{12}$	$0.312^{+0.017}_{-0.015}$	0.28–0.35	0.27–0.36
$\sin^2\theta_{23}$	0.51 ± 0.06 0.52 ± 0.06	0.41–0.61 0.42–0.61	0.39–0.64
$\sin^2\theta_{13}$	$0.010^{+0.009}_{-0.006}$ $0.013^{+0.009}_{-0.007}$	≤ 0.027 ≤ 0.031	≤ 0.035 ≤ 0.039

⇒

Table 2. Neutrino oscillation parameters summary. For Δm^2_{31}, $\sin^2\theta_{23}$, and $\sin^2\theta_{13}$ the upper (lower) row corresponds to normal (inverted) neutrino mass hierarchy. We assume the new reactor anti-neutrino fluxes [5] and include short-baseline reactor neutrino experiments in the fit.

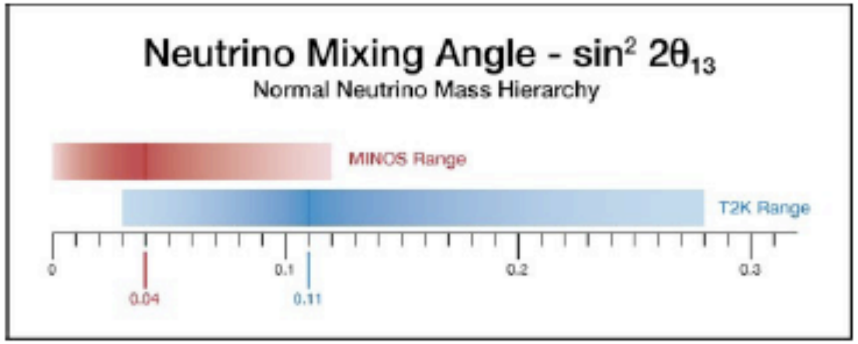
* Modulo short baseline anomalies.

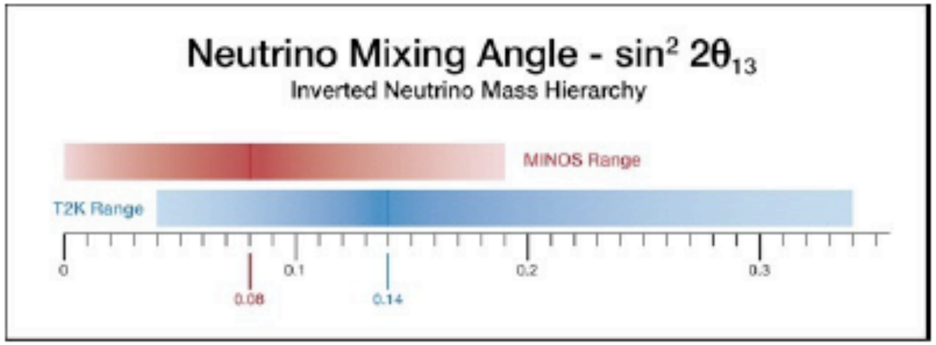
[Schwetz *et al*, 1103.0734]



* arXiv:1106.2822

Overlay of our allowed region with T2K's
(NOT a combined fit)





Hint For Nonzero U_{e3}(?) Not to be written in stone just yet. . .

. . . but next year may prove to be very exciting!

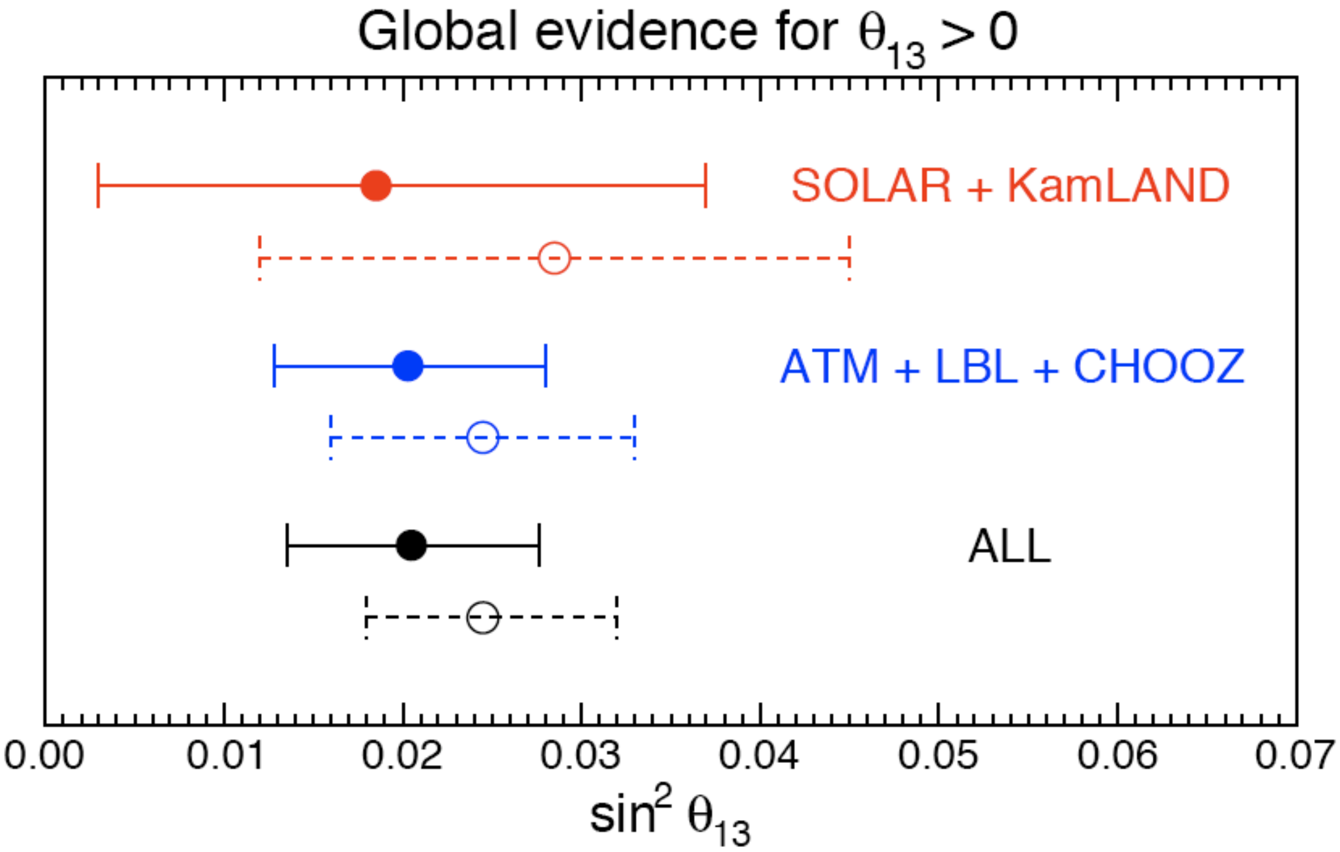
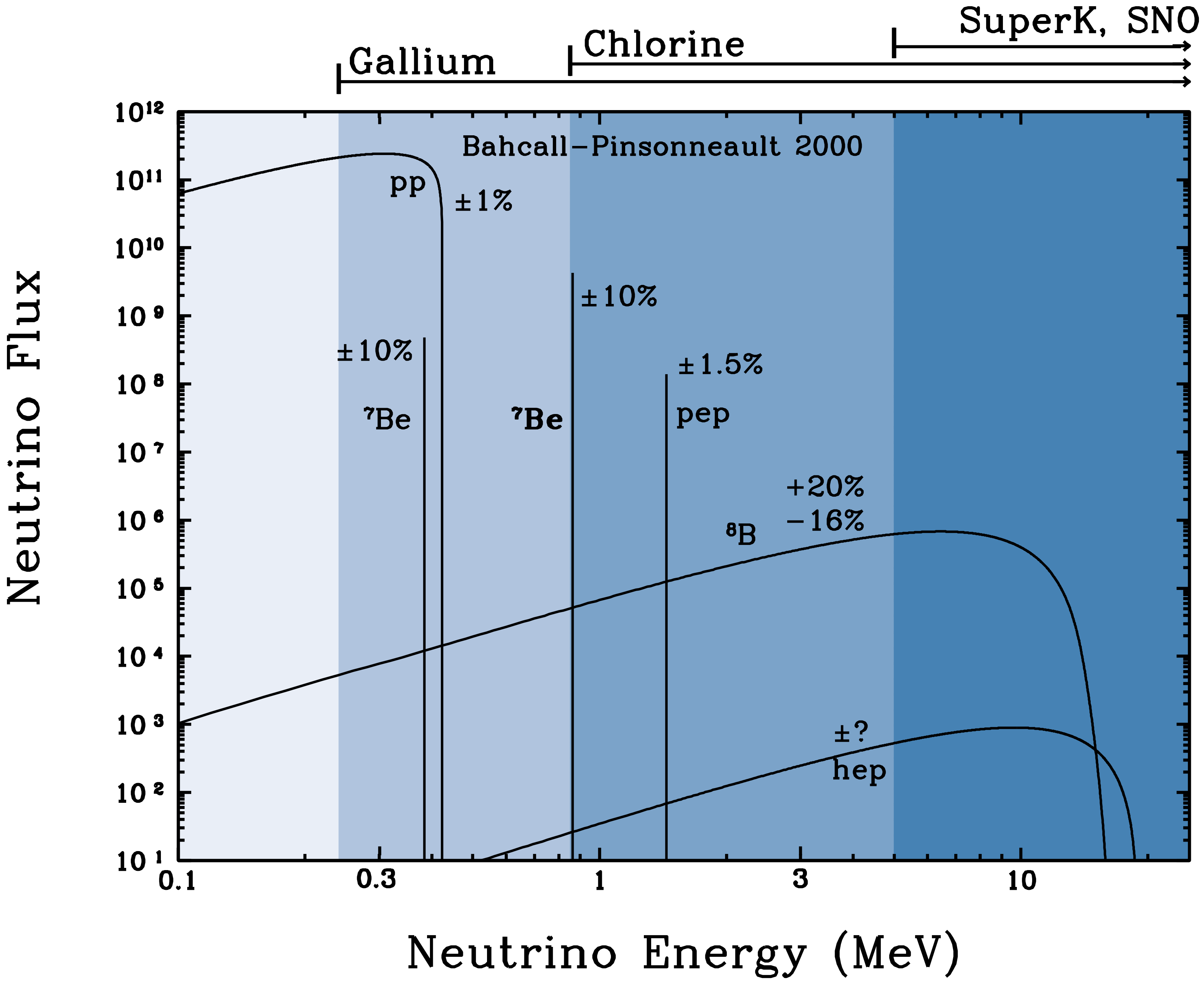
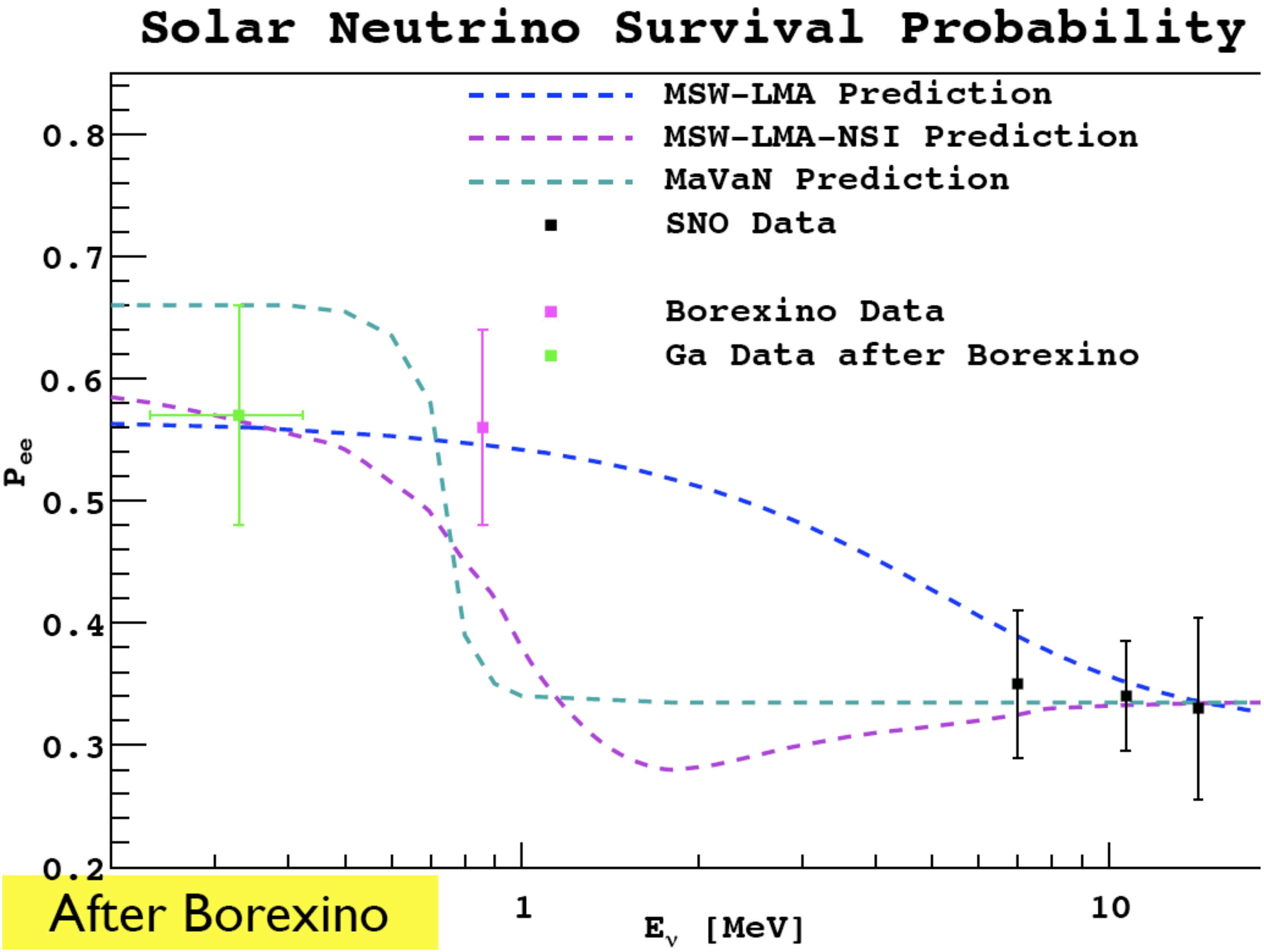


FIG. 3: Global 3ν analysis. Preferred ±1σ ranges for the mixing parameter $\sin^2\theta_{13}$ from partial and global data sets. Solid and dashed error bars refer to old and new reactor neutrino fluxes, respectively.

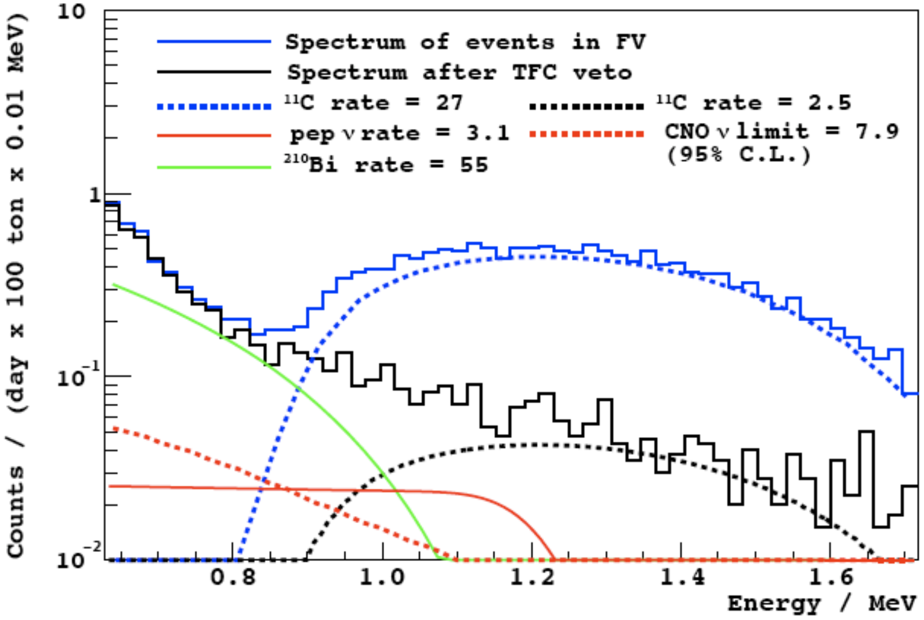
Fogli *et al.*, arXiv:1106.6028.

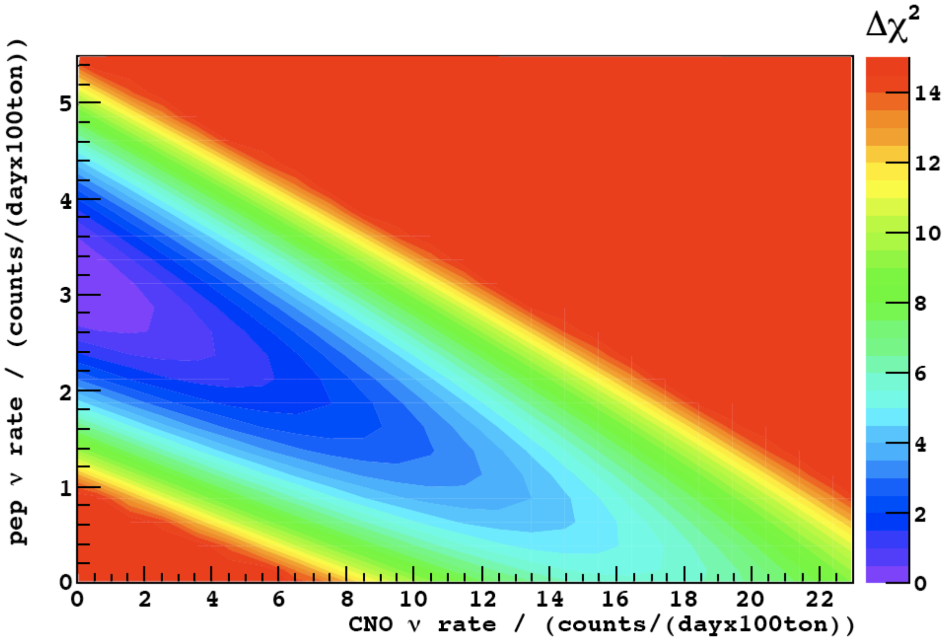

SuperK, SNO
Chlorine
Gallium
Bahcall−Pinsonneault 2000
pp
±1%
±10%
^{7}Be
^{7}Be
±10%
±1.5%
pep
+20%
−16%
^{8}B
±?
hep
10^{12}
10^{11}
10^{10}
10^9
10^8
10^7
10^6
10^5
10^4
10^3
10^2
10^1
0.1
0.3
1
3
10
Neutrino Flux
Neutrino Energy (MeV)

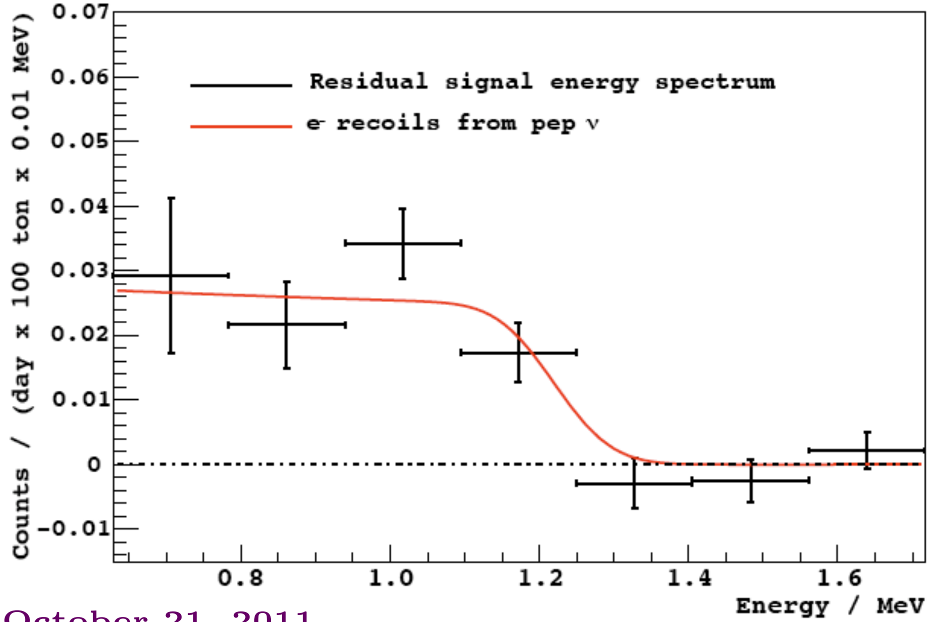


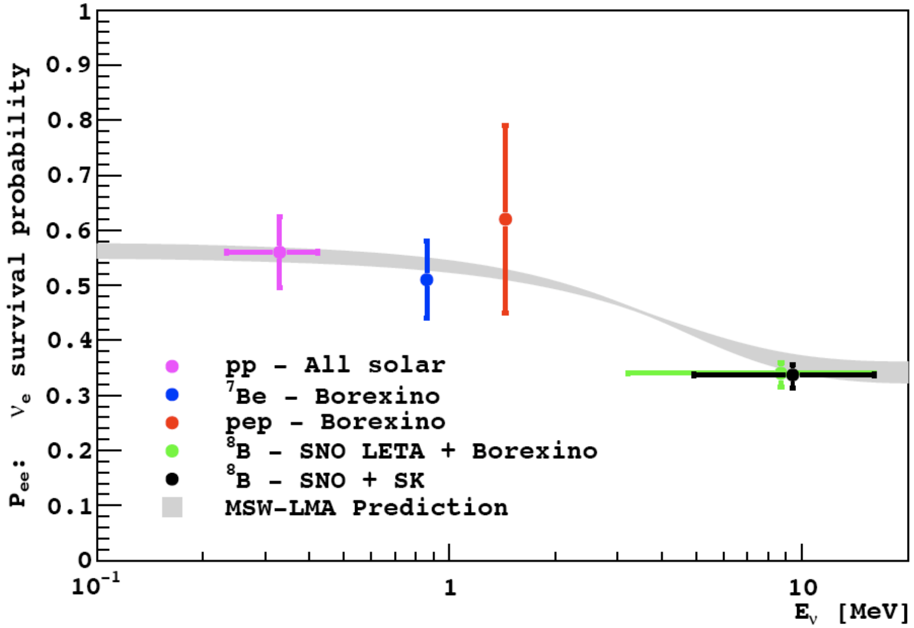
After Borexino

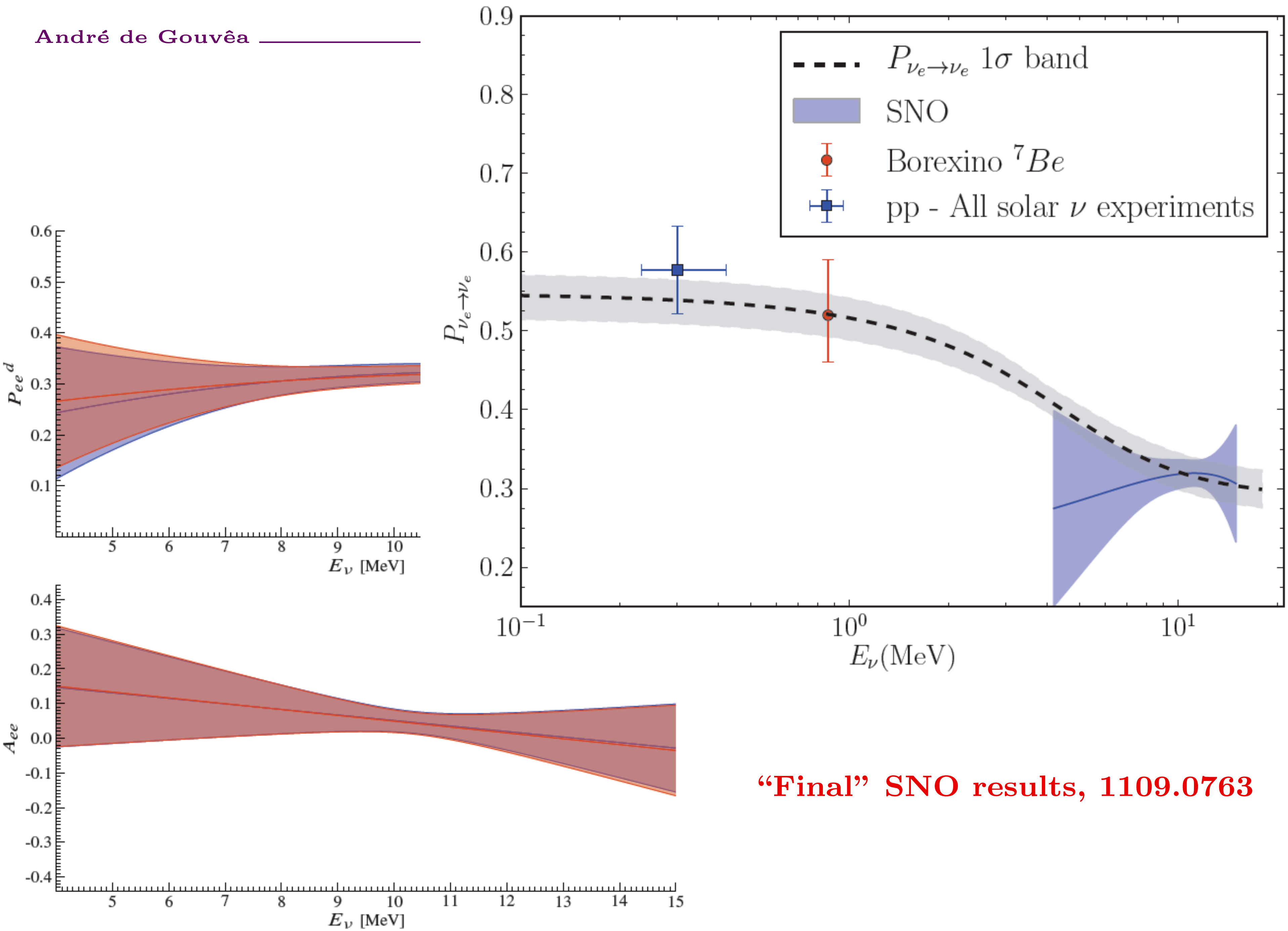
Borexino, 1110.3230





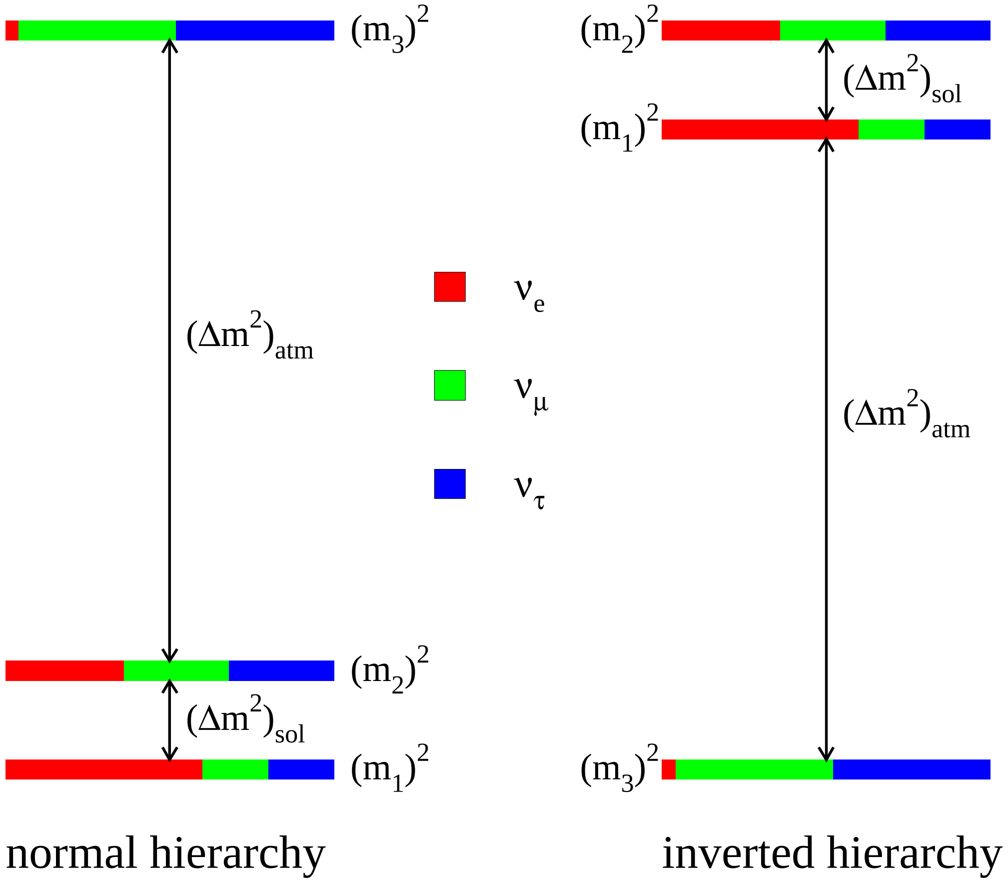






“Final” SNO results, 1109.0763

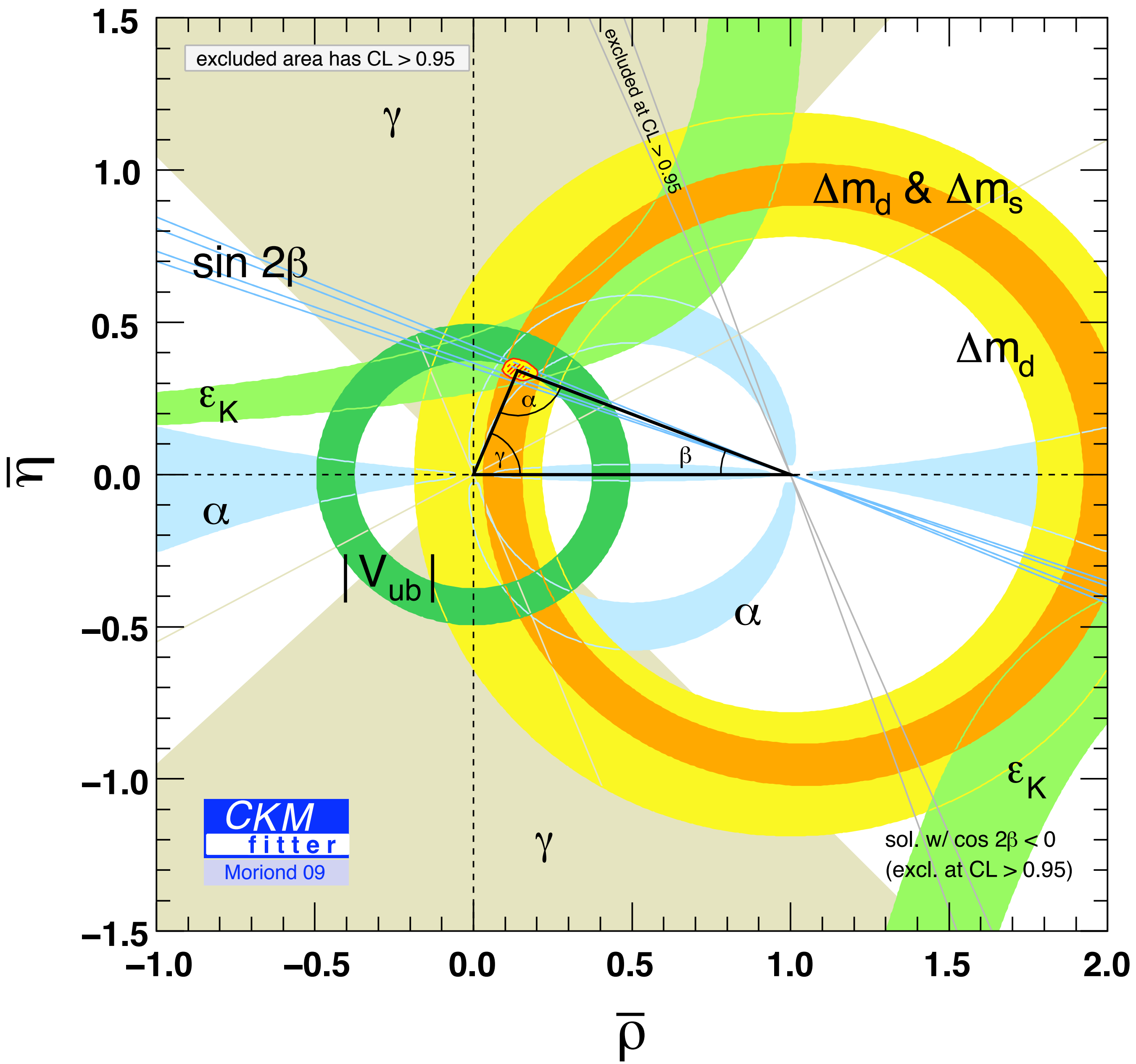
What We Know We Don't Know (1): Missing Oscillation Parameters



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

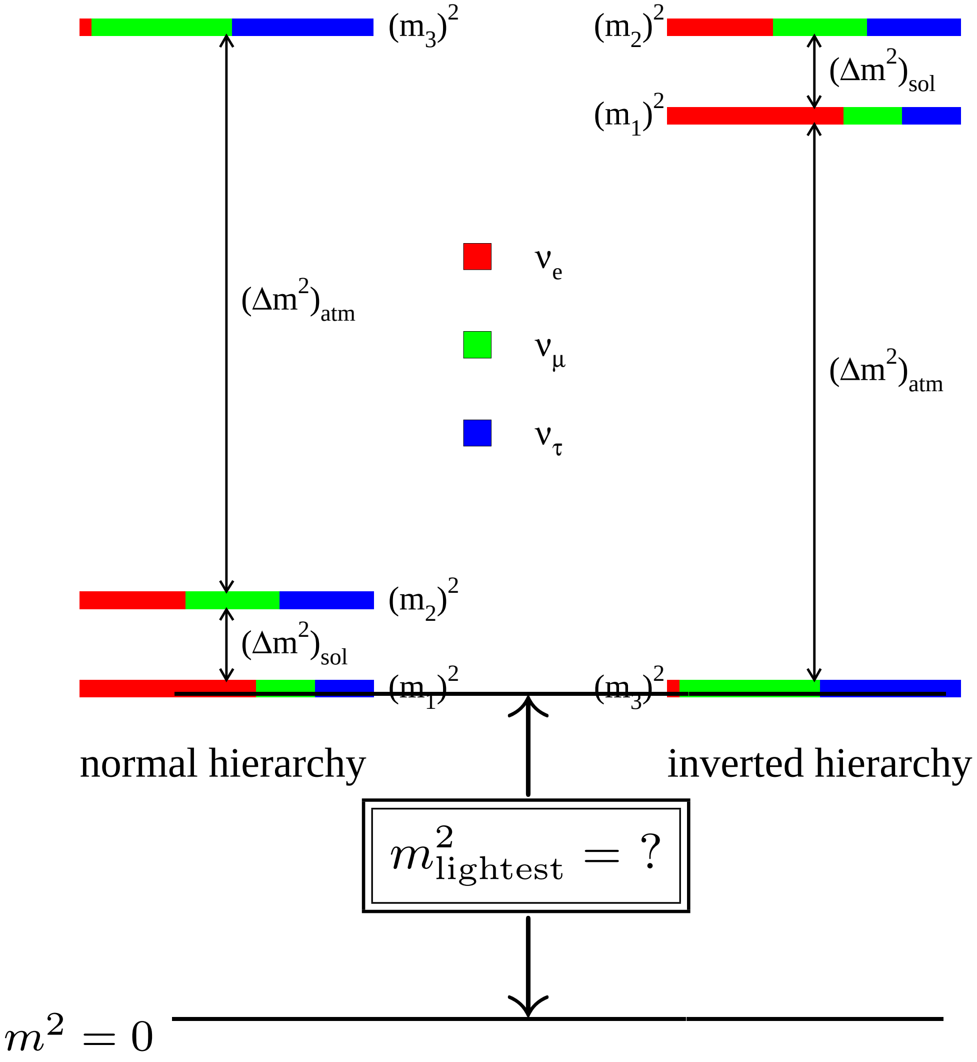
⇒ All of the above can "only" be addressed with new neutrino oscillation experiments

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



We need to do this in the lepton sector!

What We Know We Don’t Know (2): How Light is the Lightest Neutrino?



So far, we’ve only been able to measure neutrino mass-squared differences.

The lightest neutrino mass is only poorly constrained: $m^2_{\text{lightest}} < 1 \text{ eV}^2$

qualitatively different scenarios allowed:

- $m^2_{\text{lightest}} \equiv 0$;
- $m^2_{\text{lightest}} \ll \Delta m^2_{12,13}$;
- $m^2_{\text{lightest}} \gg \Delta m^2_{12,13}$.

Need information outside of neutrino oscillations.

kinematical effect of neutrino masses: precision measurement of β-decay

sensitive to an effective "electron neutrino mass": $m^2_{\nu_e} \equiv \sum_i |U_{ei}|^2 m_i^2$

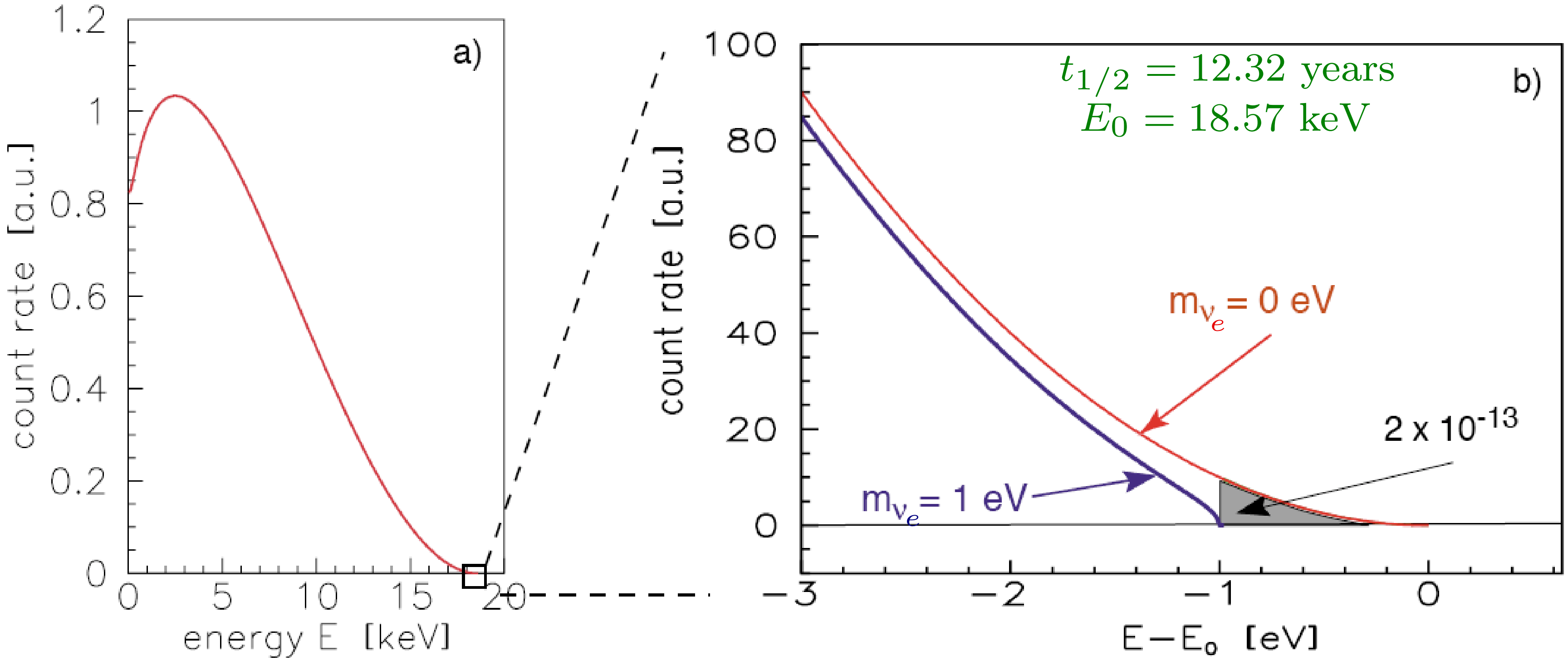


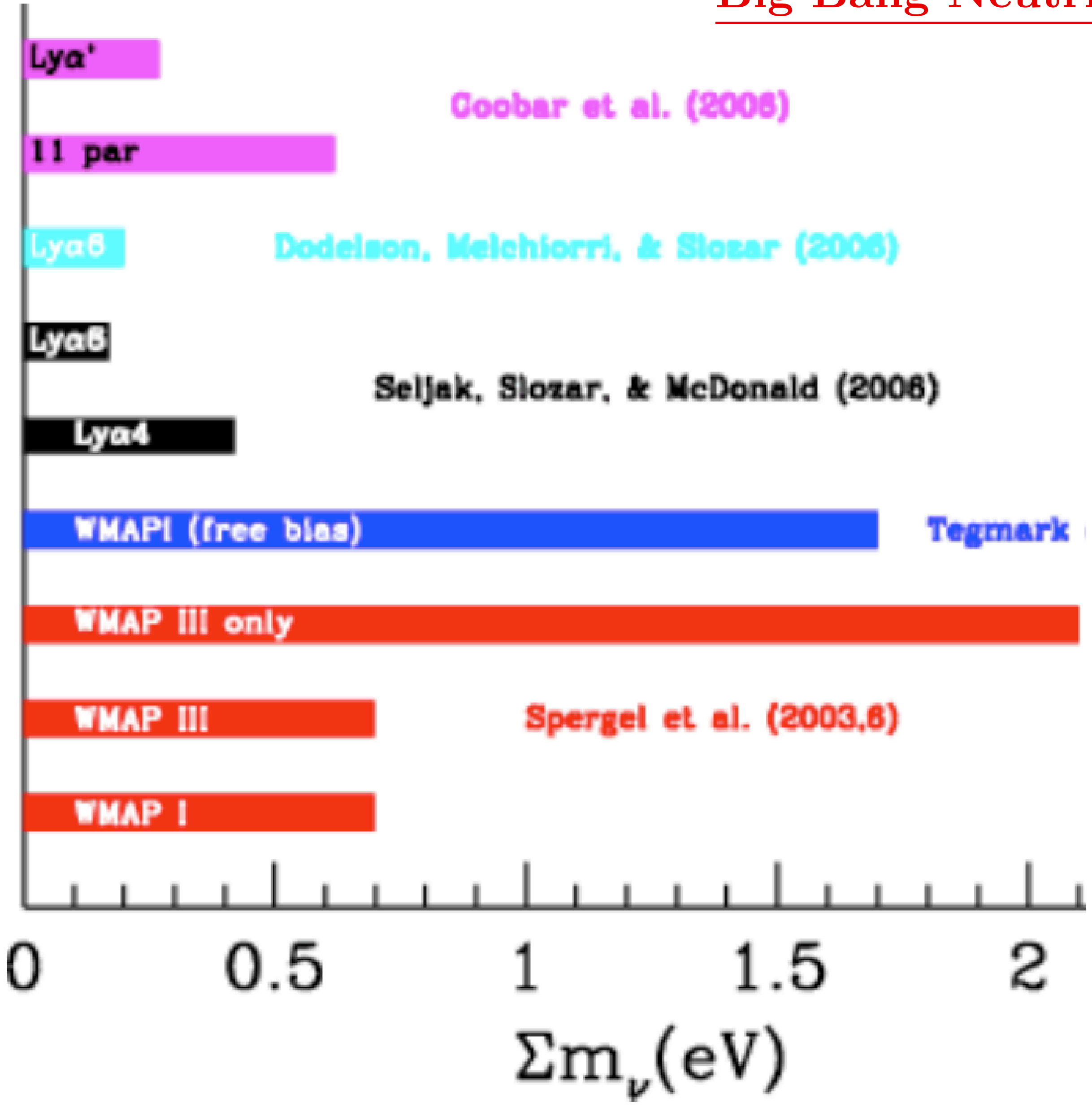
Figure 2: The electron energy spectrum of tritium β decay: (a) complete and (b) narrow region around endpoint E_0. The β spectrum is shown for neutrino masses of 0 and 1 eV.

NEXT GENERATION: The Karlsruhe Tritium Neutrino (KATRIN) Experiment:

(not your grandmother's table top experiment!)

$$\boxed{\text{sensitivity } m^2_{\nu_e} > (0.2\text{ eV})^2}$$

Big Bang Neutrinos are Warm Dark Matter

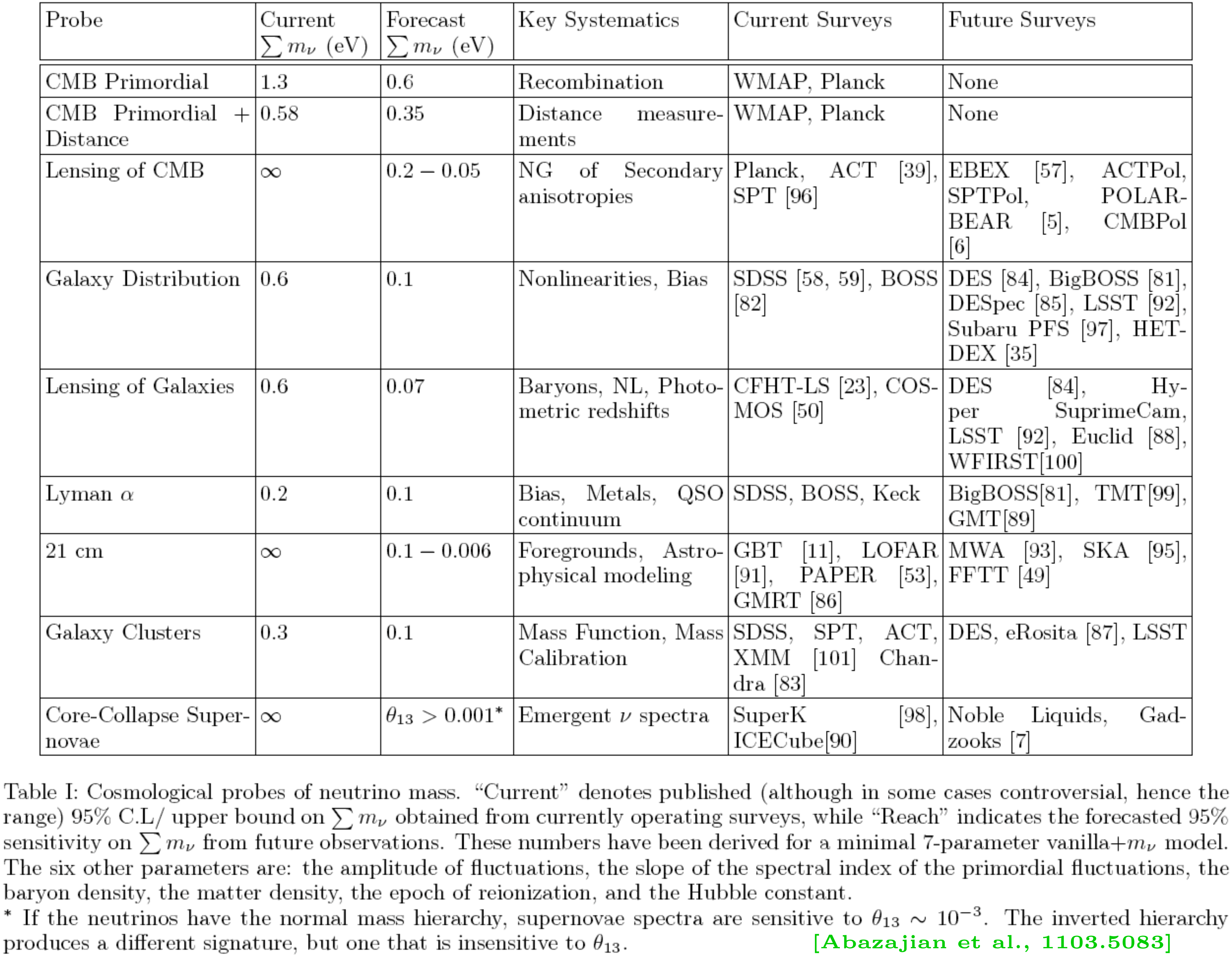


- Constrained by the Large Scale Structure of the Universe.

Constraints depend on

- Data set analysed;
- "Bias" on other parameters;
- . . .

Bounds can be evaded with non-standard cosmology. Will we learn about neutrinos from cosmology or about cosmology from neutrinos?



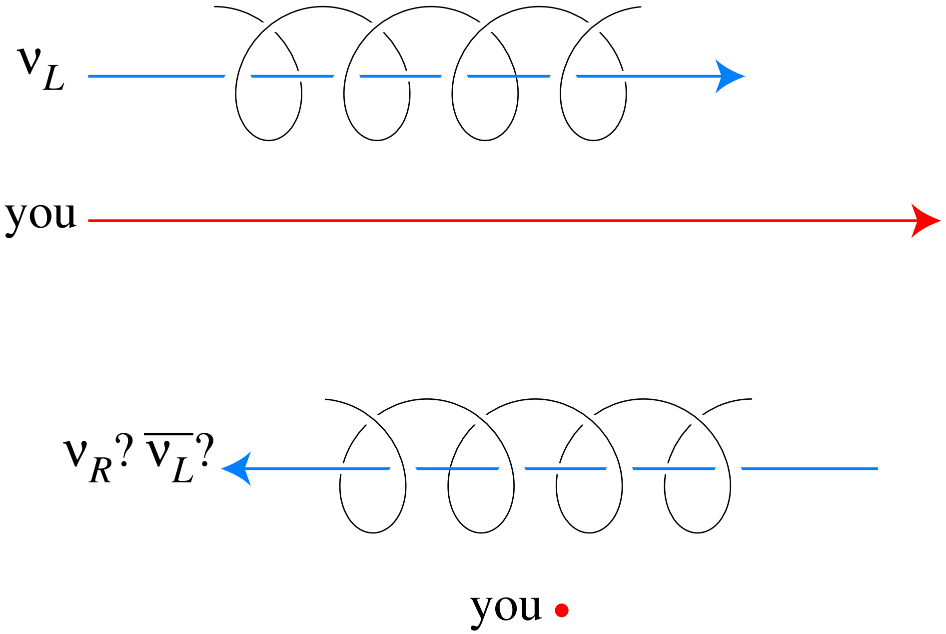
Probe	Current $\sum m_\nu$ (eV)	Forecast $\sum m_\nu$ (eV)	Key Systematics	Current Surveys	Future Surveys
CMB Primordial	1.3	0.6	Recombination	WMAP, Planck	None
CMB Primordial + Distance	0.58	0.35	Distance measurements	WMAP, Planck	None
Lensing of CMB	∞	$0.2 - 0.05$	NG of Secondary anisotropies	Planck, ACT [39], SPT [96]	EBEX [57], ACTPol, SPTPol, POLARBEAR [5], CMBPol [6]
Galaxy Distribution	0.6	0.1	Nonlinearities, Bias	SDSS [58, 59], BOSS [82]	DES [84], BigBOSS [81], DESpec [85], LSST [92], Subaru PFS [97], HETDEX [35]
Lensing of Galaxies	0.6	0.07	Baryons, NL, Photometric redshifts	CFHT-LS [23], COSMOS [50]	DES [84], Hyper SuprimeCam, LSST [92], Euclid [88], WFIRST[100]
Lyman α	0.2	0.1	Bias, Metals, QSO continuum	SDSS, BOSS, Keck	BigBOSS[81], TMT[99], GMT[89]
21 cm	∞	$0.1 - 0.006$	Foregrounds, Astrophysical modeling	GBT [11], LOFAR [91], PAPER [53], GMRT [86]	MWA [93], SKA [95], FFTT [49]
Galaxy Clusters	0.3	0.1	Mass Function, Mass Calibration	SDSS, SPT, ACT, XMM [101] Chandra [83]	DES, eRosita [87], LSST
Core-Collapse Supernovae	∞	$\theta_{13} > 0.001^*$	Emergent ν spectra	SuperK [98], ICECube[90]	Noble Liquids, Gadzooks [7]

Table I: Cosmological probes of neutrino mass. "Current" denotes published (although in some cases controversial, hence the range) 95% C.L/ upper bound on $\sum m_\nu$ obtained from currently operating surveys, while "Reach" indicates the forecasted 95% sensitivity on $\sum m_\nu$ from future observations. These numbers have been derived for a minimal 7-parameter vanilla+m_ν model. The six other parameters are: the amplitude of fluctuations, the slope of the spectral index of the primordial fluctuations, the baryon density, the matter density, the epoch of reionization, and the Hubble constant.

* If the neutrinos have the normal mass hierarchy, supernovae spectra are sensitive to $\theta_{13} \sim 10^{-3}$. The inverted hierarchy produces a different signature, but one that is insensitive to θ_{13}.

[Abazajian et al., 1103.5083]

What We Know We Don't Know (3) – Are Neutrinos Majorana Fermions?



A massive charged fermion (s=1/2) is described by 4 degrees of freedom:

$$(e^-_L \leftarrow \text{CPT} \rightarrow e^+_R)$$
$$\updownarrow \text{“Lorentz”}$$
$$(e^-_R \leftarrow \text{CPT} \rightarrow e^+_L)$$

A massive neutral fermion (s=1/2) is described by 4 or 2 degrees of freedom:

$$(\nu_L \leftarrow \text{CPT} \rightarrow \bar{\nu}_R)$$
$$\updownarrow \text{“Lorentz”} \qquad \text{‘DIRAC’}$$
$$(\nu_R \leftarrow \text{CPT} \rightarrow \bar{\nu}_L)$$

$$(\nu_L \leftarrow \text{CPT} \rightarrow \bar{\nu}_R)$$
$$\text{‘MAJORANA’} \qquad \updownarrow \text{“Lorentz”}$$
$$(\bar{\nu}_R \leftarrow \text{CPT} \rightarrow \nu_L)$$

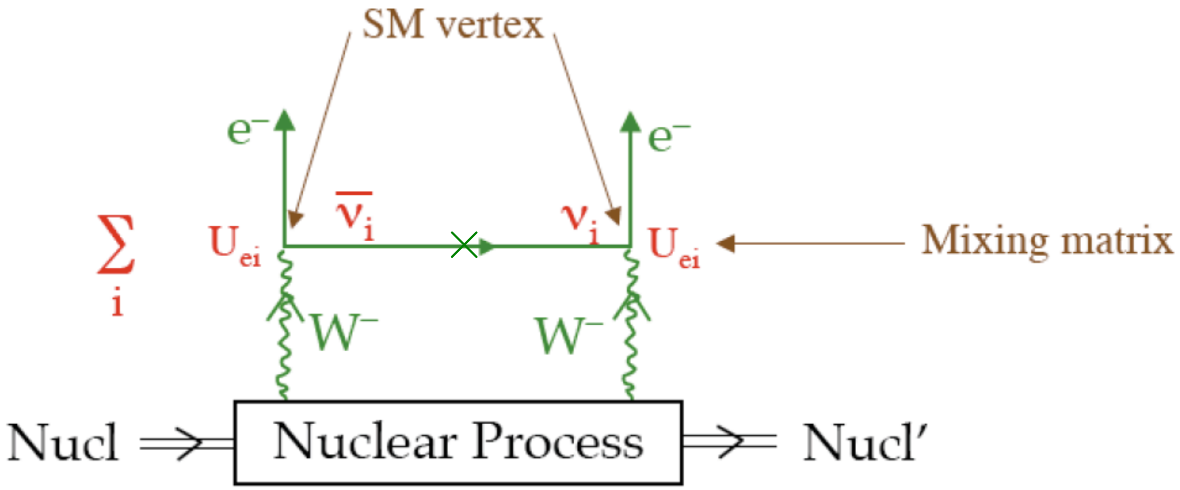
How many degrees of freedom are required to describe massive neutrinos?

Search for the Violation of Lepton Number (or $B-L$)

Best Bet: search for

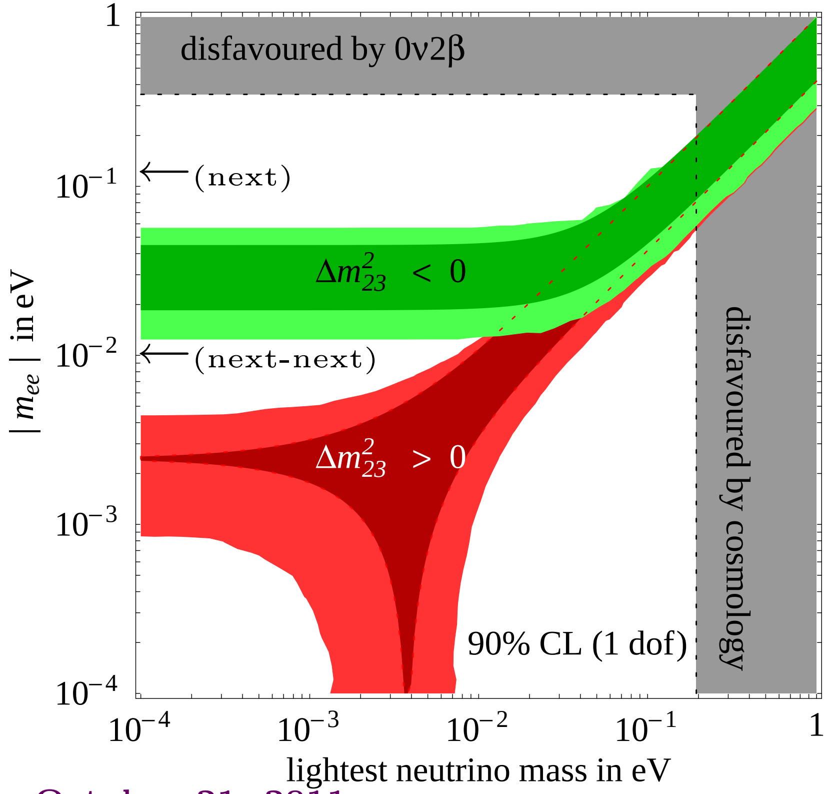
Neutrinoless Double-Beta

Decay: $\boxed{Z \rightarrow (Z+2)e^- e^-}$



Helicity Suppressed Amplitude $\propto \frac{m_{ee}}{E}$

Observable: $m_{ee} \equiv \sum_i U_{ei}^2 m_i$



⇐ **no longer lamp-post physics!**

Evidence(?) For Physics Beyond the Three–Massive–Neutrinos Paradigm

- LSND $\bar{\nu}_\mu \to \bar{\nu}_e$;
- MiniBooNE $\nu_\mu \to \nu_e$;
- MiniBooNE $\bar{\nu}_\mu \to \bar{\nu}_e$;
- Reactor Anomaly;
- ~~MINOS ν_μ versus $\bar{\nu}_\mu$ oscillations;~~
- Ga Anomaly;
- ?

Plus

- Where is the “up-turn” in P_{ee} for low-energy solar neutrinos?

Antineutrinos

$$\left|\Delta\overline{m}^2_{\rm atm}\right| = 2.62^{+0.31}_{-0.28} \times 10^{-3}{\rm eV}^2$$

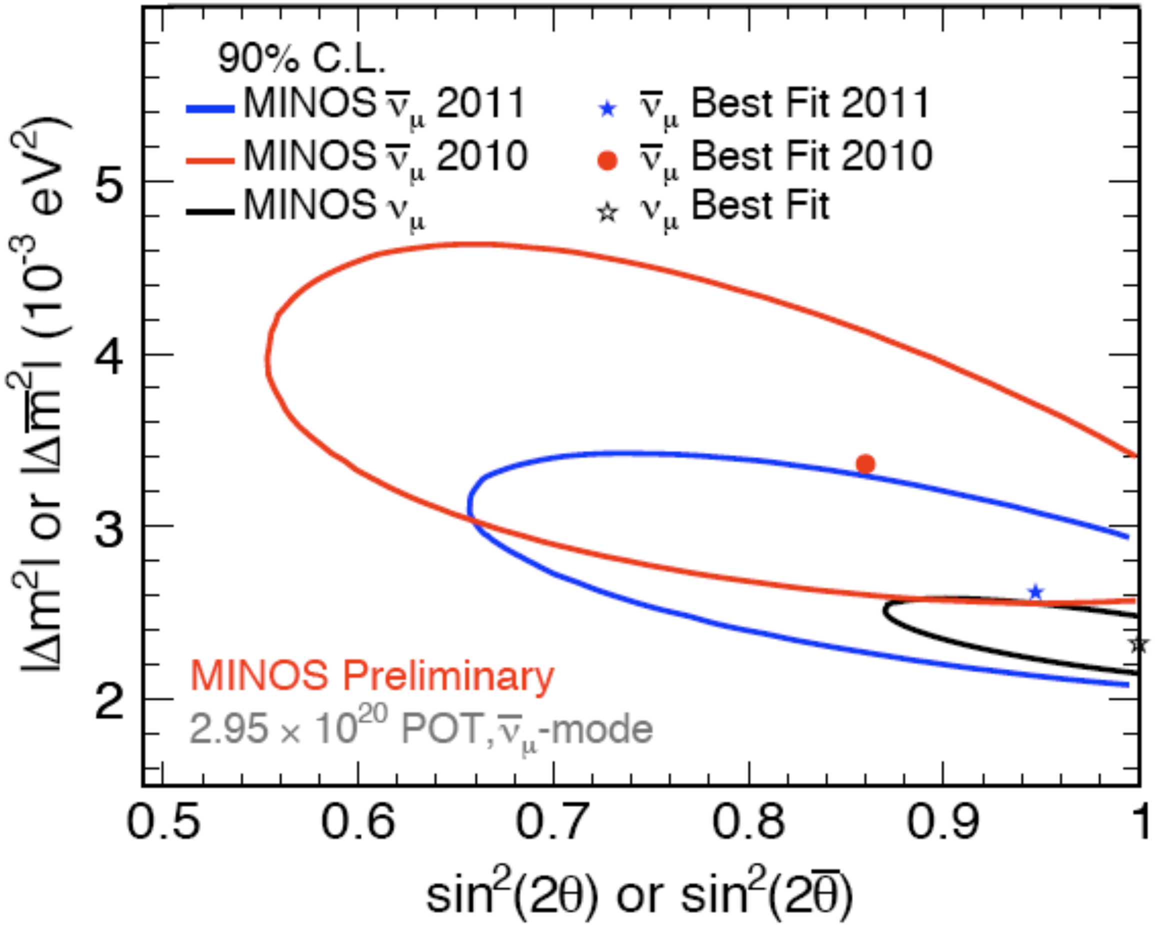
$$\sin^2(2\bar{\theta}_{23}) > 0.75 \ (90\% \ {\rm C.L.})$$

Neutrinos

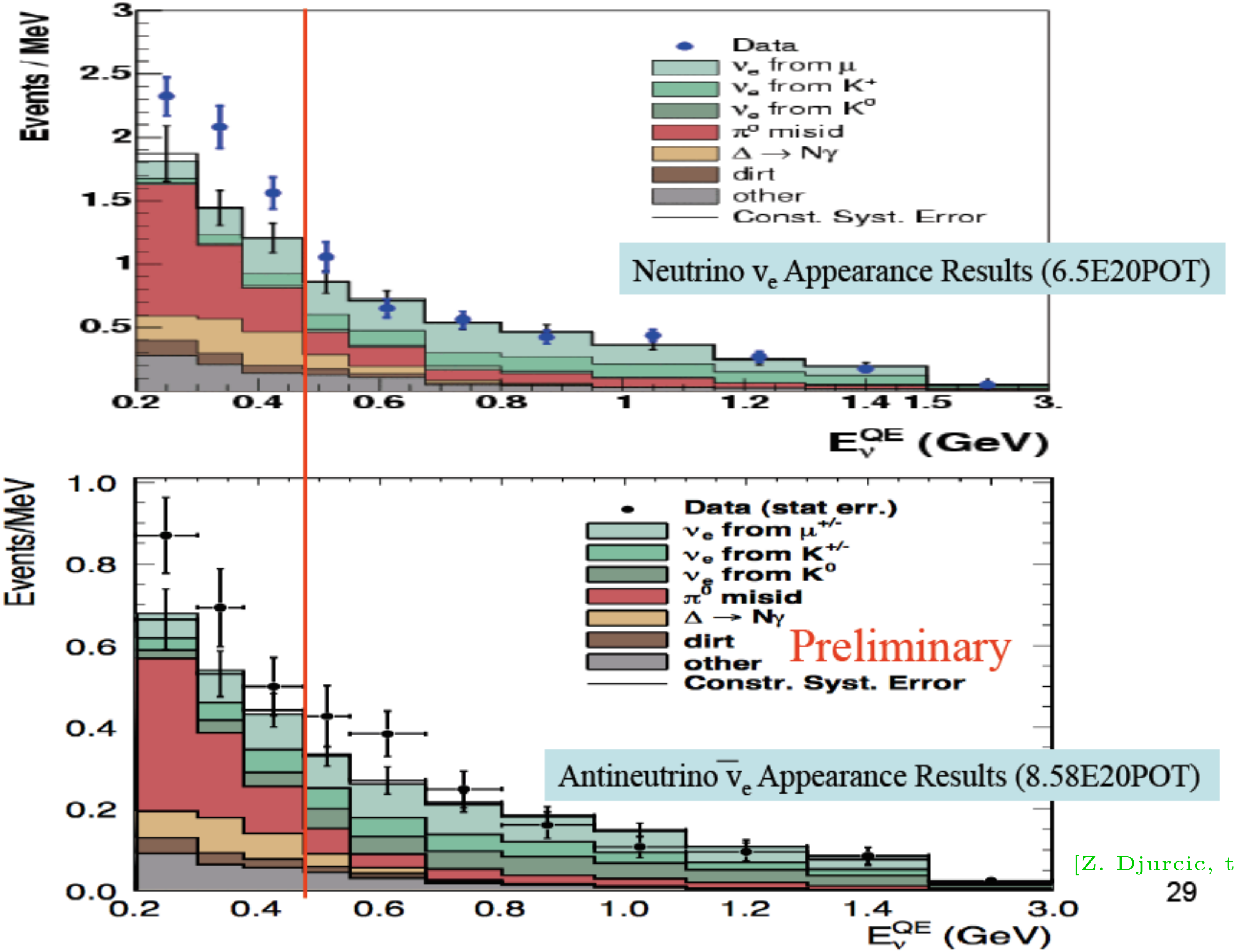
$$\left|\Delta m^2_{\rm atm}\right| = 2.32^{+0.12}_{-0.08} \times 10^{-3}{\rm eV}^2$$

$$\sin^2(2\theta_{23}) > 0.90 \ (90\% \ {\rm C.L.})$$

- Comparison with MINOS 90% C.L. contour for Run IV antineutrino data
- Comparison with MINOS 90% C.L. contour for neutrino mode



Comparison of ν_e and $\bar{\nu}_e$ Appearance Results

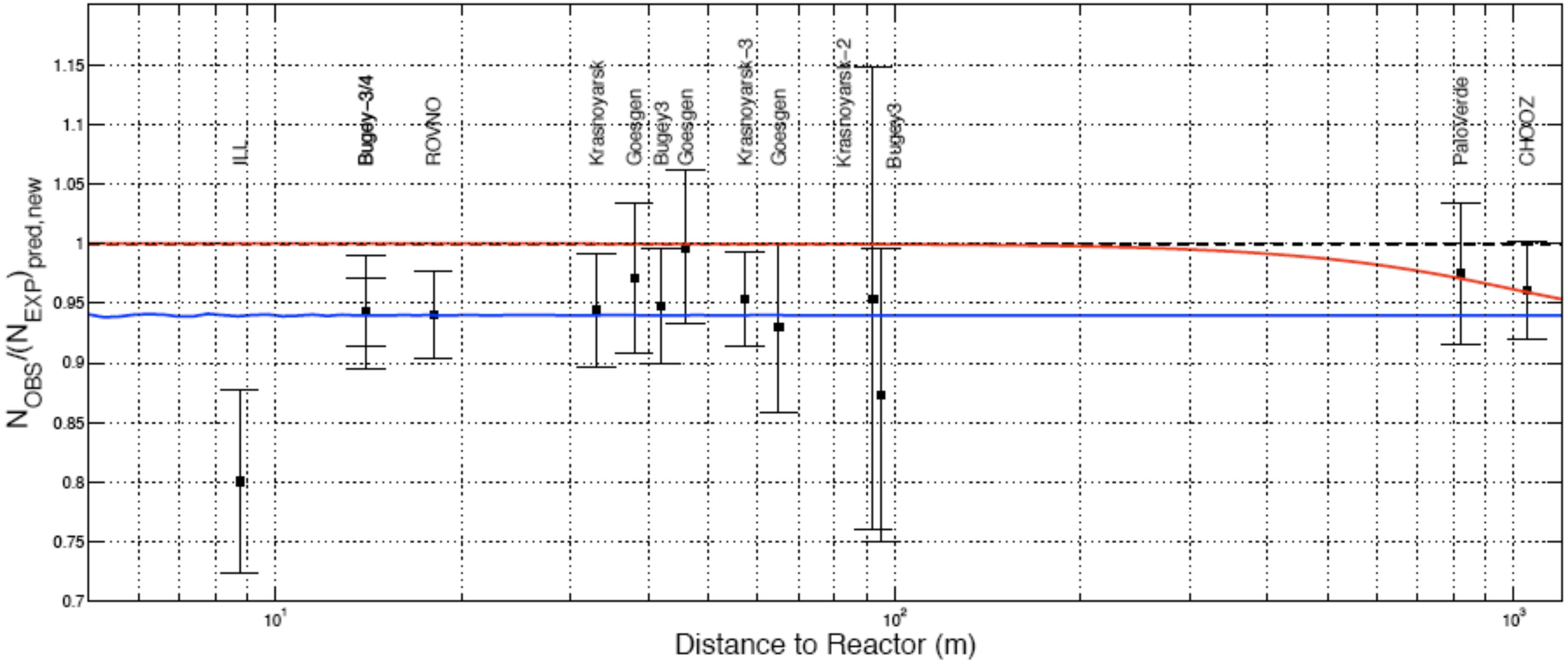


Neutrino ν_e Appearance Results (6.5E20POT)

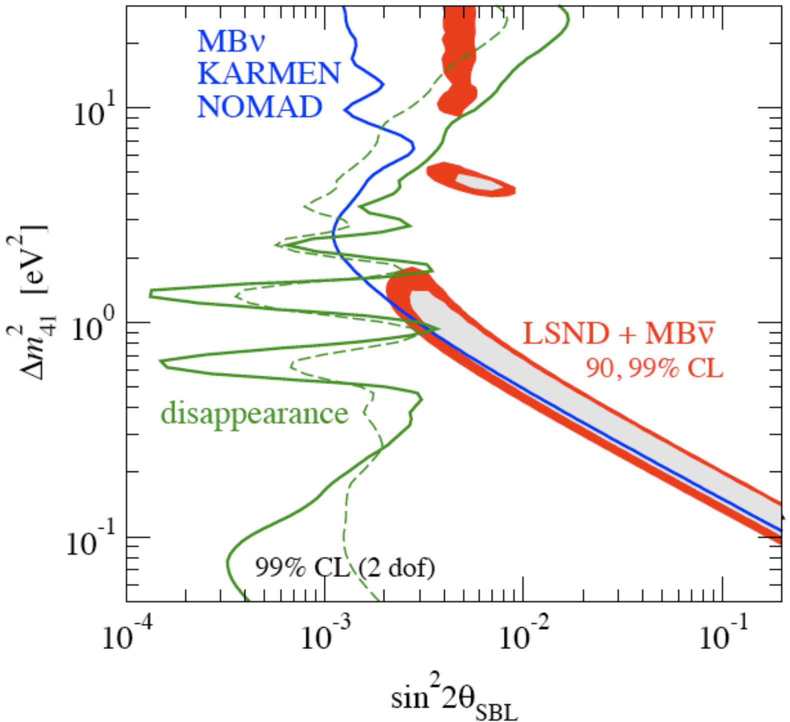
Preliminary

Antineutrino $\bar{\nu}_e$ Appearance Results (8.58E20POT)

[Z. Djurcic, talk at NuFact11]

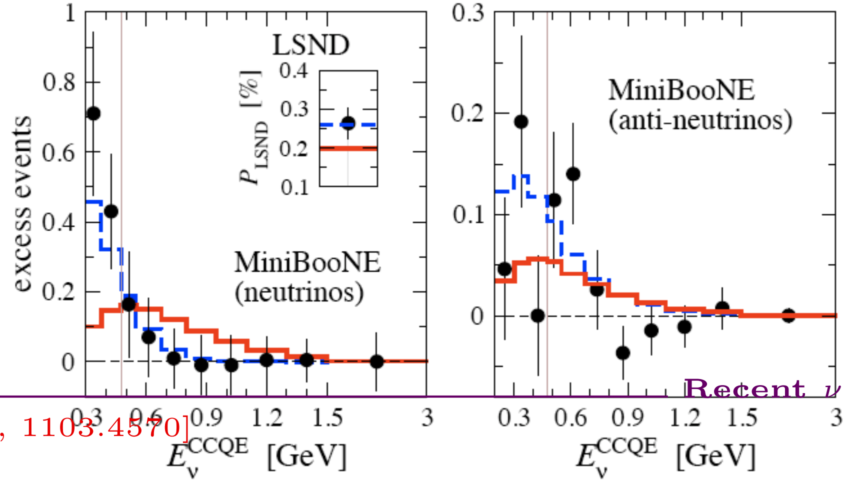


More Room For New Neutrinos?



	Δm^2_{41}	$\lvert U_{e4}\rvert$	$\lvert U_{\mu 4}\rvert$	Δm^2_{51}	$\lvert U_{e5}\rvert$	$\lvert U_{\mu 5}\rvert$	δ/π	χ^2/dof
3+2	0.47	0.128	0.165	0.87	0.138	0.148	1.64	110.1/130
1+3+1	0.47	0.129	0.154	0.87	0.142	0.163	0.35	106.1/130

Table II: Parameter values and χ^2 at the global best fit points for 3+2 and 1+3+1 oscillations (Δm^2's in eV^2).



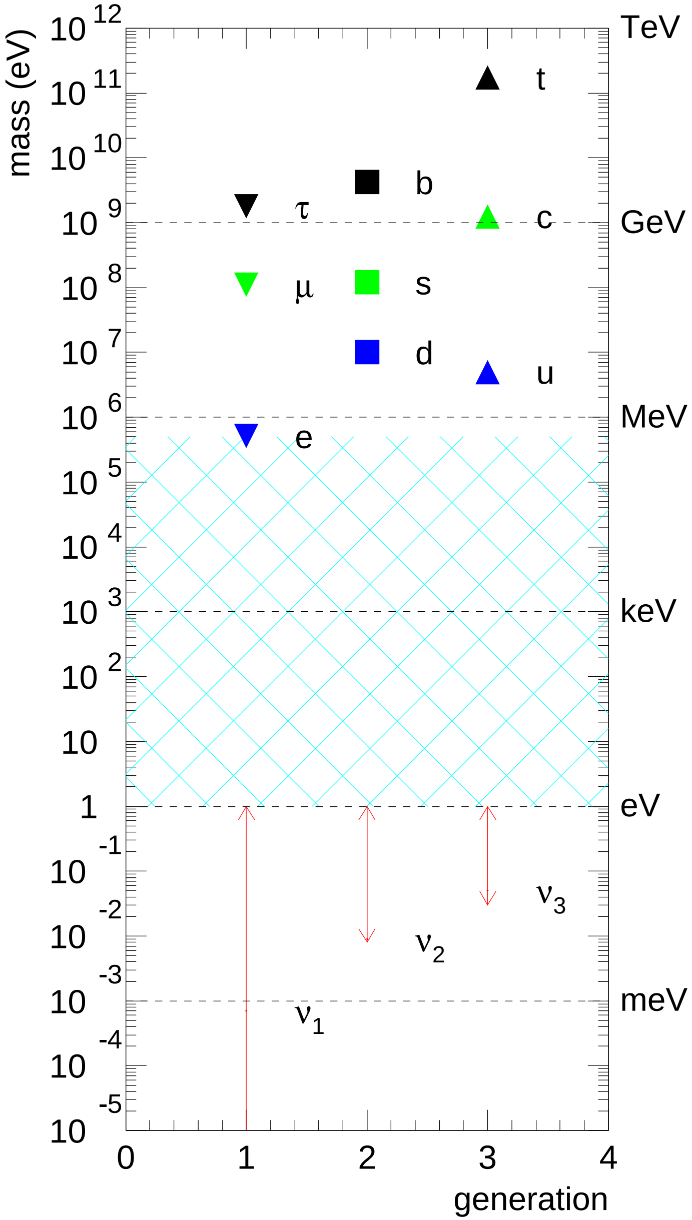
[Kopp,Maltoni,Schwetz, 1103.4570]

igure 3: Global constraints on sterile neutrinos in the 3+1
odel. We show the allowed regions at 90% and 99% CL from

(Some) Phenomenological Explanations

More important: assuming these fit all current data, how do we tell which one, if any, is correct?

• Sterile Neutrinos (light, stable variety);	Short Baseline Osc.
• New Neutrino Interactions;	Neutrino Oscillations, Charged-Leptons (?)
• Lorentz Invariance/CPT-Violation;	Neutrino Oscillations, Directional Effects
• Sterile Neutrinos (heavy, unstable variety).	Mesons, Muons



What We Are Trying To Understand:

⇐ NEUTRINOS HAVE TINY MASSES

⇓ LEPTON MIXING IS “WEIRD” ⇓

$$V_{MNS} \sim \begin{pmatrix} 0.8 & 0.5 & \mathbf{0.2} \\ 0.4 & 0.6 & 0.7 \\ 0.4 & 0.6 & 0.7 \end{pmatrix} \qquad V_{CKM} \sim \begin{pmatrix} 1 & 0.2 & 0.001 \\ 0.2 & 1 & 0.01 \\ 0.001 & 0.01 & 1 \end{pmatrix}$$

What Does It Mean?

Who Cares About Neutrino Masses: Only* "Palpable" Evidence of Physics Beyond the Standard Model

The SM we all learned in school predicts that neutrinos are strictly massless. Massive neutrinos imply that the the SM is incomplete and needs to be replaced/modified.

Furthermore, the SM has to be replaced by something qualitatively different.

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* There is only a handful of questions our model for fundamental physics cannot explain properly. These are, in order of "palpability" (my opinion):

- What is the physics behind electroweak symmetry breaking? (Higgs <u>or</u> not in SM).
- What is the dark matter? (not in SM).
- Why does the Universe appear to be accelerating? Why does it appear that the Universe underwent rapid acceleration in the past? (not in SM – is this "particle physics?").

What is the New Standard Model? [νSM]

The short answer is – WE DON’T KNOW. Not enough available info!

$$\Updownarrow$$

Equivalently, there are several completely different ways of addressing neutrino masses. The key issue is to understand what else the νSM candidates can do. [are they falsifiable?, are they “simple”?, do they address other outstanding problems in physics?, etc]

We need more experimental input.

The Seesaw Lagrangian

A simple[a], renormalizable Lagrangian that allows for neutrino masses is

$$\mathcal{L}_\nu = \mathcal{L}_{\rm old} - \lambda_{\alpha i} L^\alpha H N^i - \sum_{i=1}^{3} \frac{M_i}{2} N^i N^i + H.c.,$$

where N_i ($i = 1, 2, 3$, for concreteness) are SM gauge singlet fermions.

$\mathcal{L}_\nu$ is the most general, renormalizable Lagrangian consistent with the SM gauge group and particle content, plus the addition of the N_i fields.

After electroweak symmetry breaking, $\mathcal{L}_\nu$ describes, besides all other SM degrees of freedom, six Majorana fermions: **six neutrinos.**

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[a] Only requires the introduction of three fermionic degrees of freedom, no new interactions or symmetries.

What We Know About M:

- $M=0$: the six neutrinos “fuse” into three Dirac states. Neutrino mass matrix given by $\mu_{\alpha i}\equiv\lambda_{\alpha i}v$.

  The symmetry of $\mathcal{L}_\nu$ is enhanced: $U(1)_{B-L}$ is an exact global symmetry of the Lagrangian if all M_i vanish. Small M_i values are ’tHooft natural.

- $M\gg\mu$: the six neutrinos split up into three mostly active, light ones, and three, mostly sterile, heavy ones. The light neutrino mass matrix is given by $m_{\alpha\beta}=\sum_i\mu_{\alpha i}M_i^{-1}\mu_{\beta i}$ $[m\propto 1/\Lambda\ \Rightarrow\ \Lambda=M/\mu^2]$.

  This the **seesaw mechanism.** Neutrinos are Majorana fermions. Lepton number is not a good symmetry of $\mathcal{L}_\nu$, even though L-violating effects are hard to come by.

- $M\sim\mu$: six states have similar masses. Active–sterile mixing is very large. This scenario is (generically) ruled out by active neutrino data (atmospheric, solar, KamLAND, K2K, etc).

- $M\ll\mu$: Neutrinos are Pseudo-Dirac fermions. Strong constraints from solar neutrino data for $M>10^{-9}$ eV. [AdG, Huang, Jenkins, arXiv:0906.1611]

Why are Neutrino Masses Small in the $M \neq 0$ Case?

If $\mu \ll M$, below the mass scale M,

$$\mathcal{L}_5 = \frac{LHLH}{\Lambda}.$$

Neutrino masses are small if $\Lambda \gg \langle H \rangle$. Data require $\Lambda \sim 10^{14}$ GeV.

In the case of the seesaw,

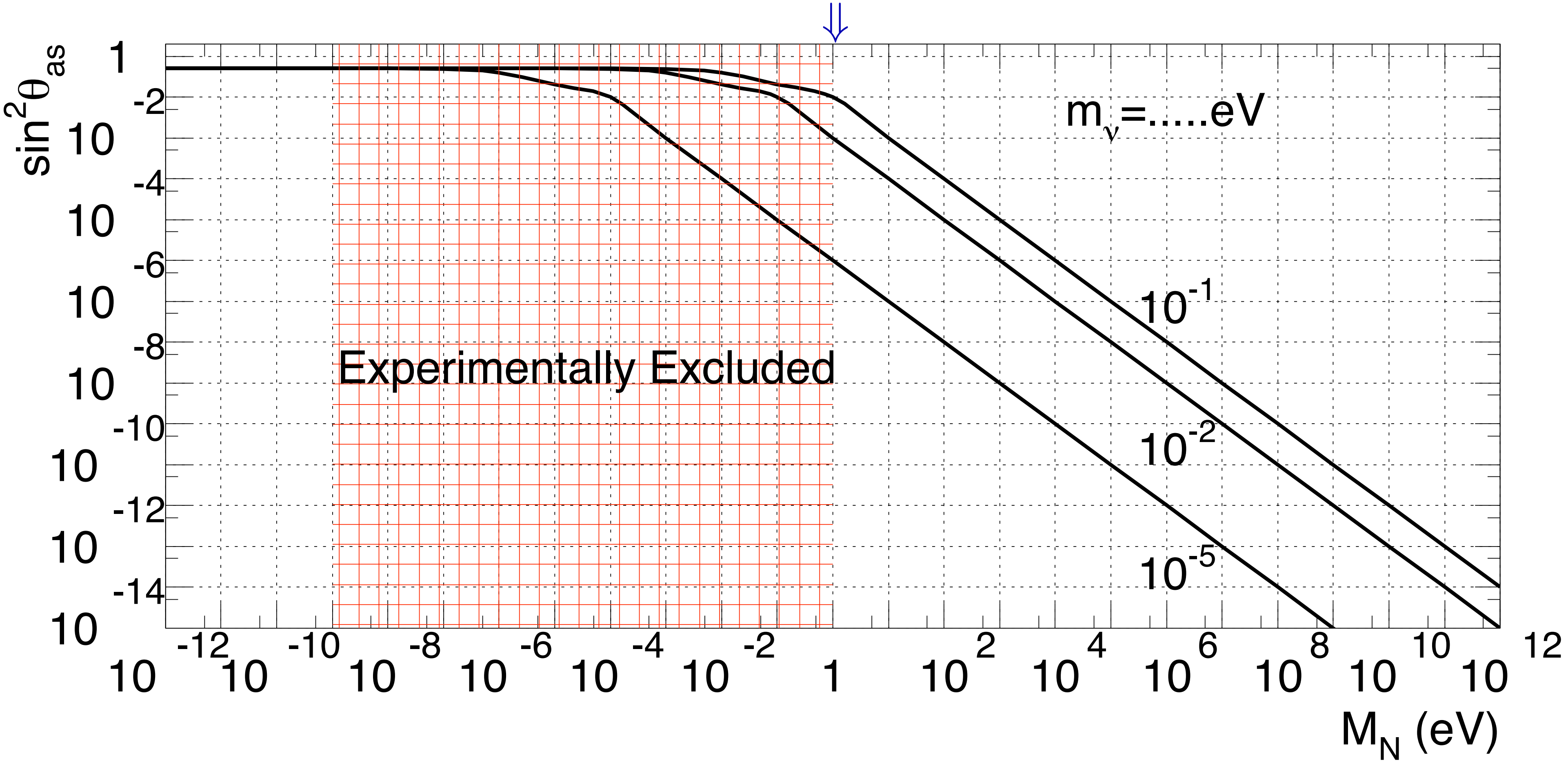
$$\Lambda \sim \frac{M}{\lambda^2},$$

so neutrino masses are small if either

- they are generated by physics at a very high energy scale $M \gg v$ (high-energy seesaw); or
- they arise out of a very weak coupling between the SM and a new, hidden sector (low-energy seesaw); or
- cancellations among different contributions render neutrino masses accidentally small ("fine-tuning").

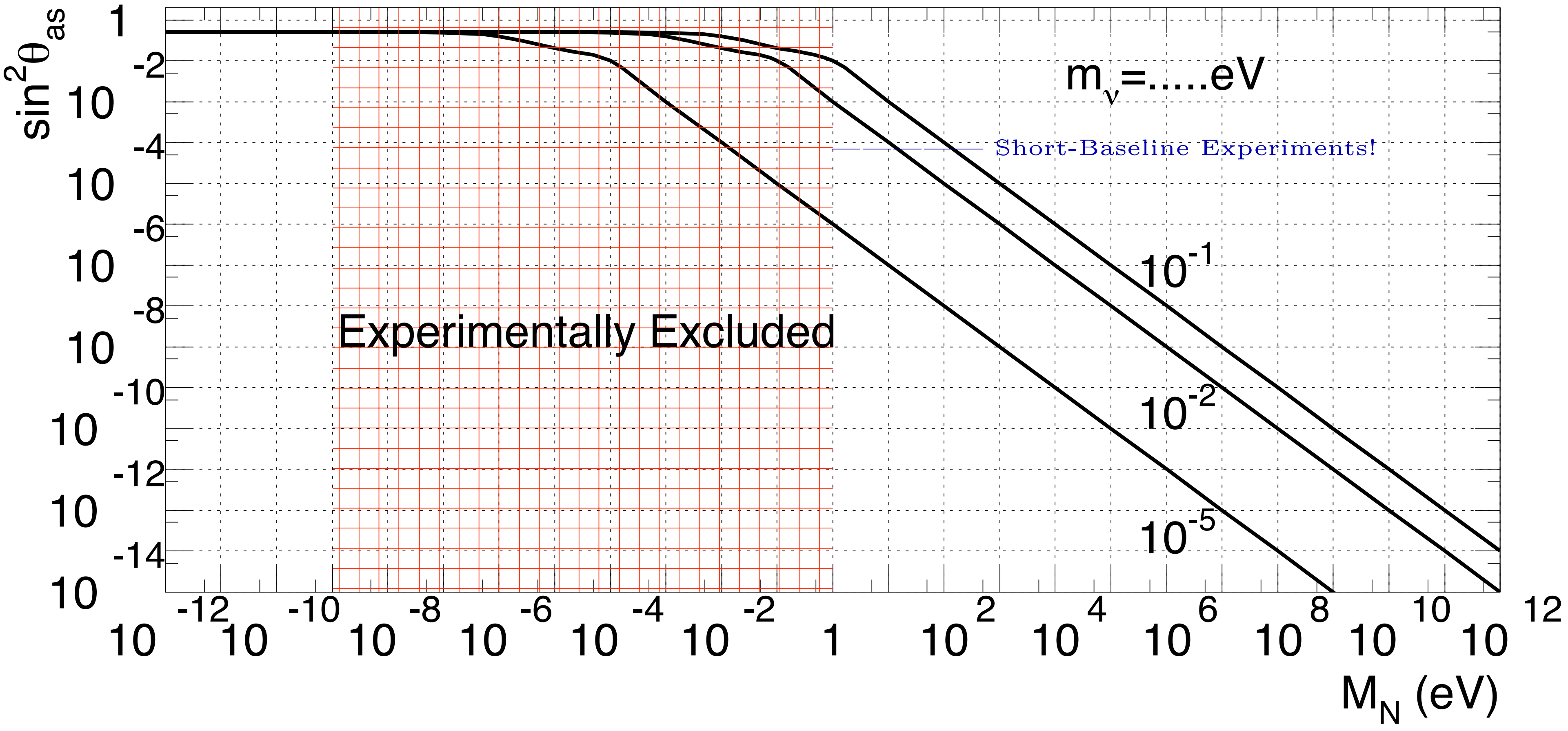
Constraining the Seesaw Lagrangian

[rough upper bound, see Donini et al, arXiv:1106.0064]



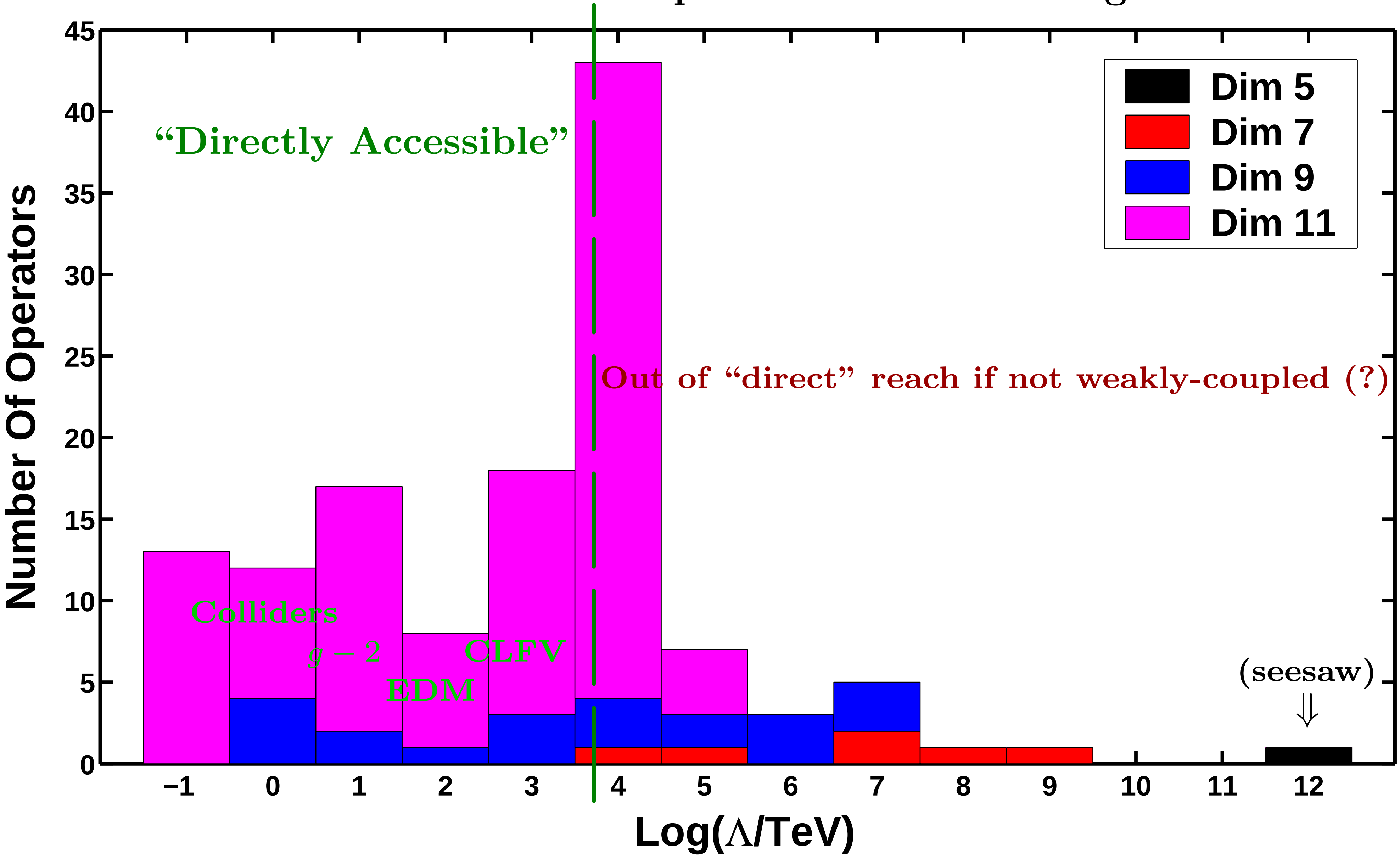
[AdG, Huang, Jenkins, arXiv:0906.1611]

Can we improve our sensitivity?

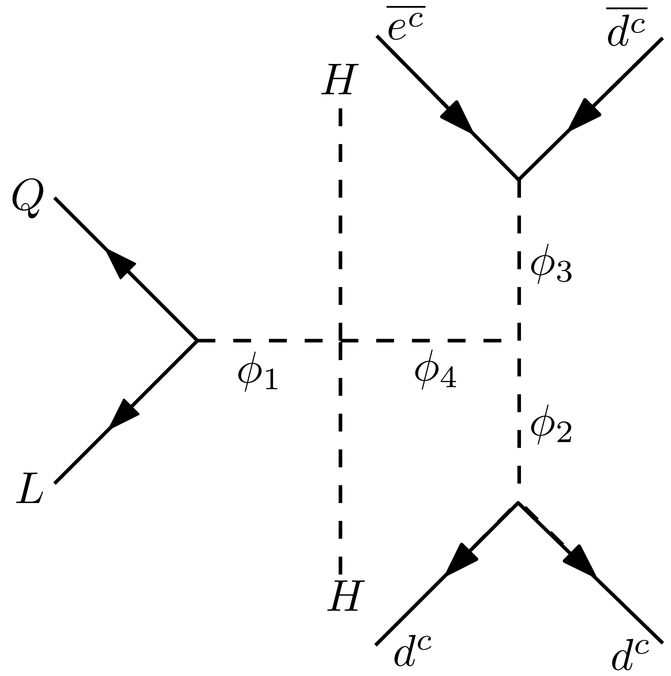


[AdG, Huang, 1110.xxxx]

This is Just the Tip of the Model Iceberg . . .



[arXiv:0708.1344 [hep-ph]]



Order-One Coupled, Weak Scale Physics Can Also Explain Naturally Small Majorana Neutrino Masses:

Multi-loop neutrino masses from lepton number violating new physics.

$$-\mathcal{L}_{\nu\rm SM} \supset \sum_{i=1}^{4} M_i\phi_i\bar{\phi}_i + iy_1QL\phi_1 + y_2d^cd^c\phi_2 + y_3e^cd^c\phi_3 + \lambda_{14}\bar{\phi}_1\phi_4HH + \lambda_{234}M\phi_2\bar{\phi}_3\phi_4 + h.c.$$

$m_\nu \propto (y_1y_2y_3\lambda_{234})\lambda_{14}/(16\pi)^4$ → neutrino masses at 4 loops, requires $M_i \sim 100$ GeV!

WARNING: For illustrative purposes only. Details still to be worked out. Scenario most likely ruled out by charged-lepton flavor-violation, LEP, Tevatron, and HERA.

How Do We Learn More?

In order to learn more, we need more information. Any new data and/or idea is welcome, including

- searches for charged lepton flavor violation;

  ($\mu \rightarrow e\gamma$, $\mu \rightarrow e$-conversion in nuclei, etc)

- searches for lepton number violation;

  (neutrinoless double beta decay, etc)

- neutrino oscillation experiments;

  (Daya Bay, NOνA, etc)

- searches for fermion electric/magnetic dipole moments

  (electron edm, muon $g-2$, etc);

- precision studies of neutrino – matter interactions;

  (Minerνa, NuSOnG, etc)

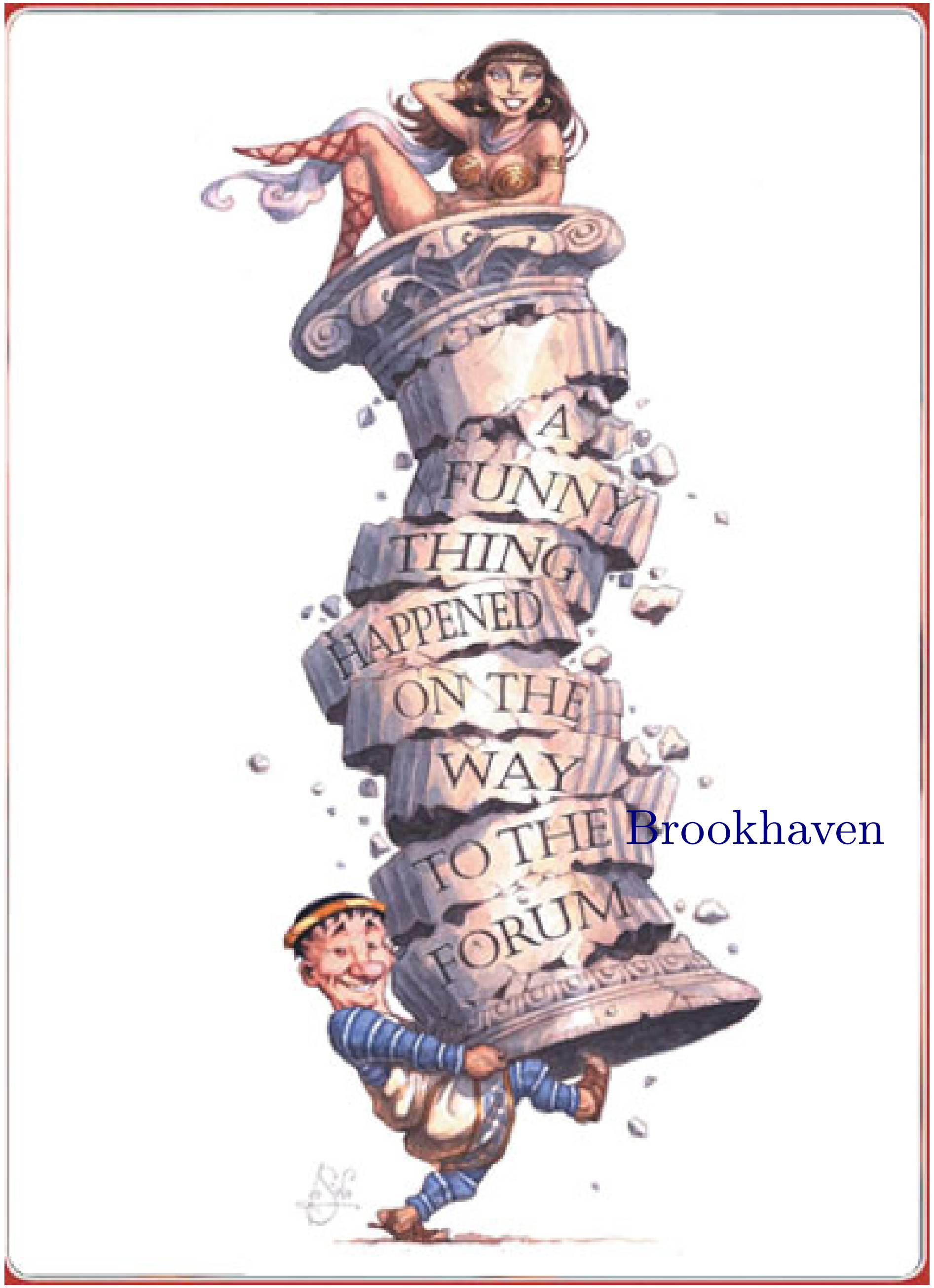
- collider experiments:

  (LHC, etc)

  - *Can* we "see" the physics responsible for neutrino masses at the LHC? – YES!

    Must we see it? – NO, but we won't find out until we try!
  - we need to understand the physics at the TeV scale before we can really understand the physics behind neutrino masses (is there low-energy SUSY?, etc).

And Now For Something Completely Different. . .



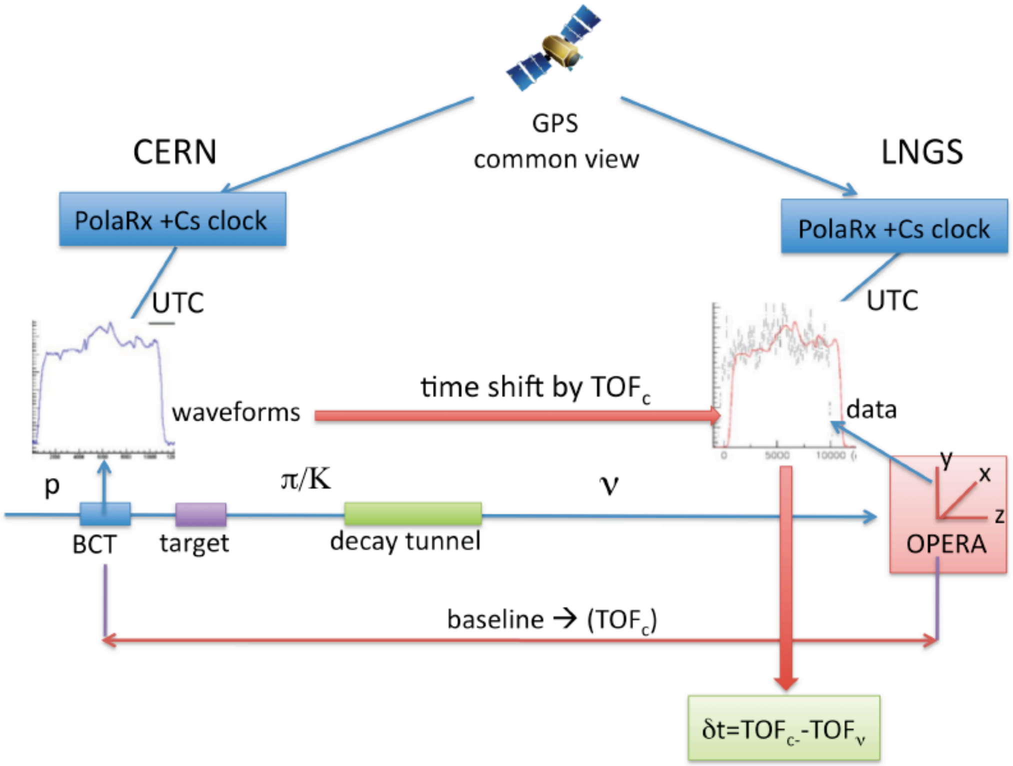


Fig. 5: Schematic of the time of flight measurement.

$$\frac{(v-c)}{c} = (2.48 \pm 0.28 \pm 0.30) \times 10^{-5}$$

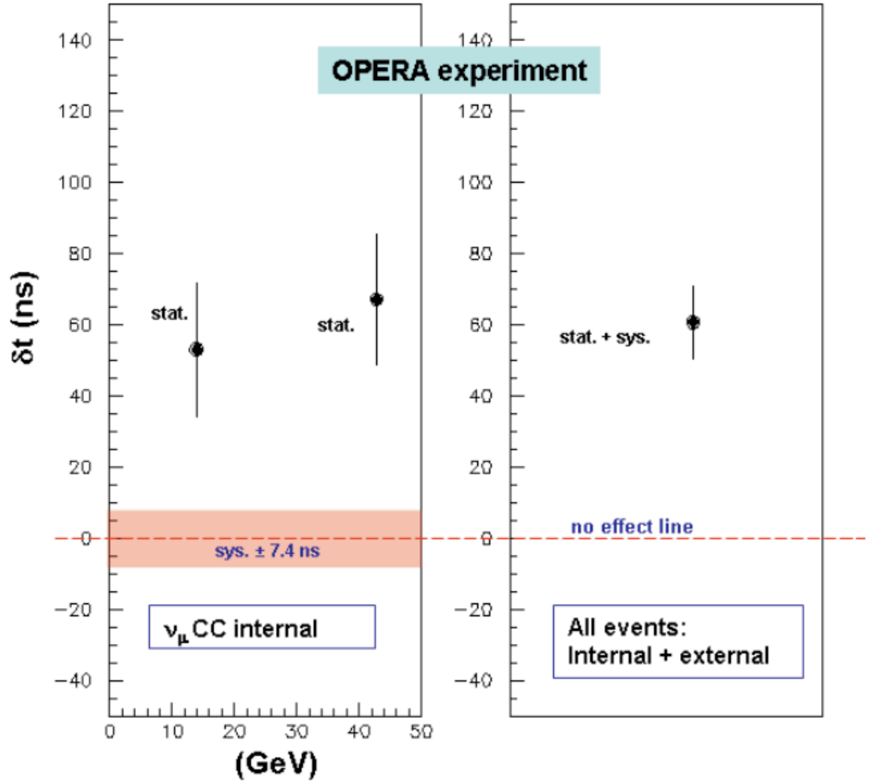


Fig. 13: Summary of the results for the measurement of δt. The left plot shows δt as a function of the ener
ν_μ CC internal events. The errors attributed to the two points are just statistical in order to make their r
comparison easier since the systematic error (represented by a band around the no-effect line) cancels out. Th
plot shows the global result of the analysis including both internal and external events (for the latter the
cannot be measured). The error bar includes statistical and systematic uncertainties added in quadrature.

[OPERA Coll. arXiv:1109.4897]

Neutrinos travelling faster than the speed of light!? How can that be?

- This would be an amazing discovery! Still needs to be confirmed by at least one more experiment. Ideally, it would have to be confirmed using a different method.

- Contradiction with other experimental data? In particular neutrinos SN1987A neutrinos arrive at the expected time (compared to the light signal)…

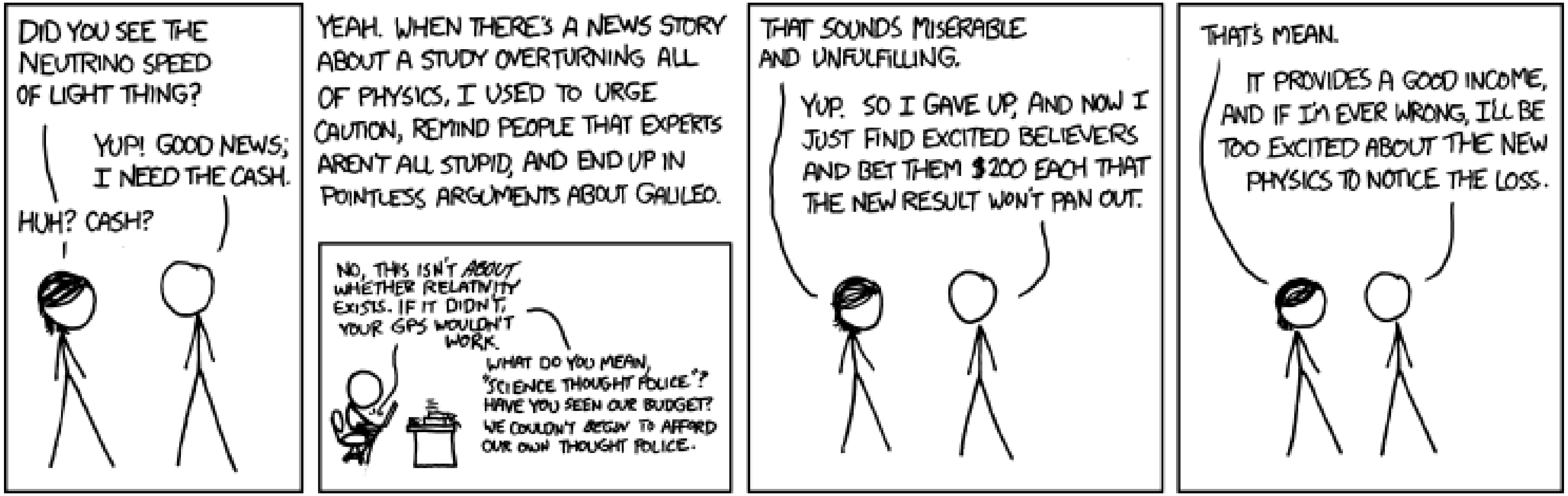
- Easy way out (not so easy – $\nu \to \nu e^+ e^-$, [Cohen, Glashow, arXiv:1109.6562]): modify the neutrino dispersion relation → Lorentz Invariance Violation

$$E^2 - |\vec{p}|^2 = m^2 \quad \to \quad E^2 - |\vec{p}|^2 = m^2(E)$$

The community is frantically at work!

98 Citations According to INSPIRE as of 12:16, today.

[Note: the OPERA preprint is dated September 22, 2011]



[http://xkcd.com]

"Nothing travels faster than light." — NA-H (BF11 Public Lecture)

Slightly More Scientific Thoughts…

- This will be tested in the near future (a couple of years?) by MINOS and T2K.
- This is probably the most precise measurement of a fundamental particle's velocity other than the photon and the electron.
- Great example (even if, most likely, it is proven that neutrino propagation is not superluminal) of the many opportunities we allow ourselves by constructing precision neutrino oscillation experiments!

CONCLUSIONS

1. we have a very successful parametrization of the neutrino sector, but we still don't understand where neutrino masses come from;
2. neutrino masses are very small – we don't know why, but we think it means something important;
3. we need a minimal νSM Lagrangian. In order to decide which one is "correct" we must uncover the faith of lepton number.
4. We still know very little about the new physics uncovered by neutrino oscillations.
5. We need more experimental data in order to decide what is really going on!
6. There is plenty of room for surprises. Neutrinos are very narrow but deep probes of all sorts of phenomena. Remember: neutrino oscillation experiments are "quantum interference devices".