Overview of The Physics Of "Long-Baseline" Neutrino Detectors

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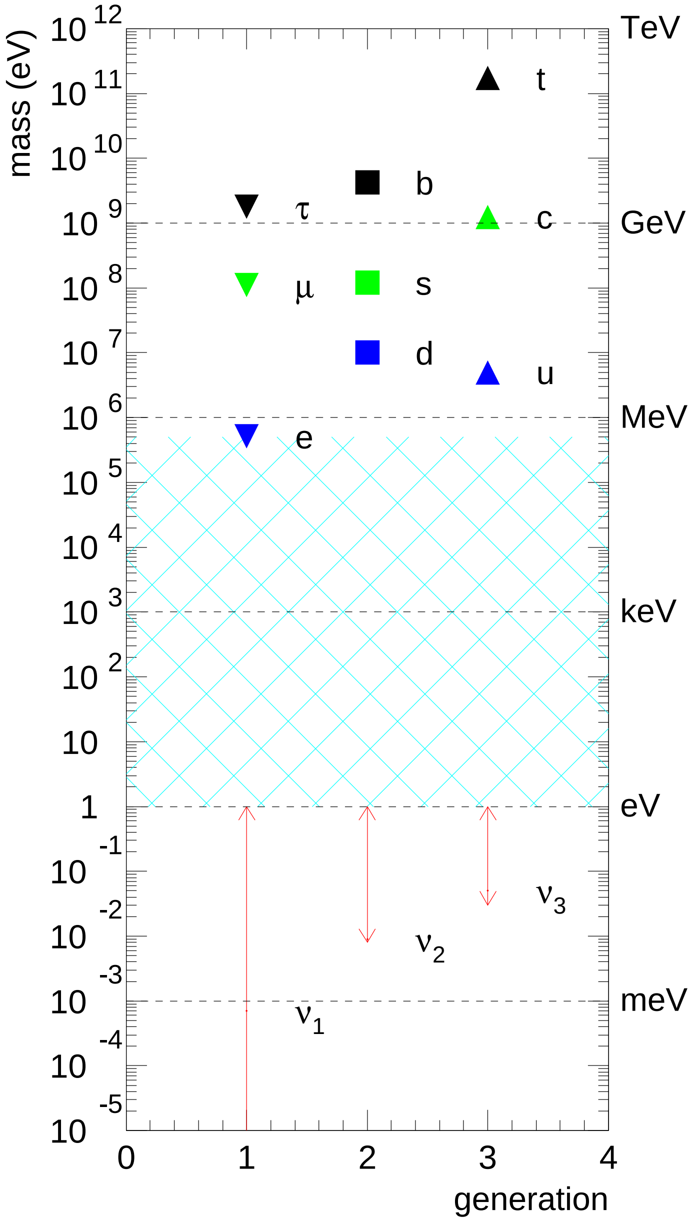
Outline

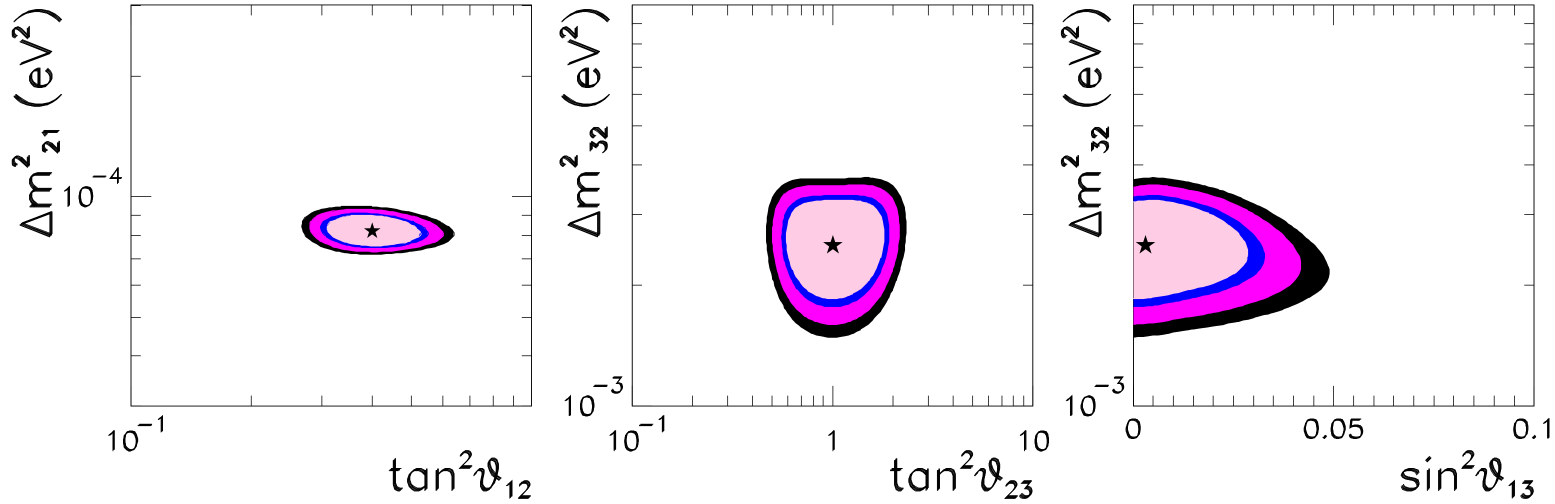
1. What we learned about neutrinos (very brief);
2. The Known Unknowns (very brief);
3. Oscillation Physics with Long-Baseline Experiments (very brief);
4. Atmospheric Neutrinos;
5. Solar Neutrinos;
6. Comments on Proton Decay;
7. Others;
8. Summary.



NEUTRINOS HAVE MASS

albeit very tiny ones...

Our Phenomenological Understanding of the Neutrino Sector:



(update Gonzalez-Garcia, Maltoni, hep-ph/0406056)

(update Gonzalez-Garcia, Peña-Garay, hep-ph/0306001)

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

$$m_1^2 < m_2^2$$

$$m_2^2 - m_1^2 \ll |m_3^2 - m_{1,2}^2|$$

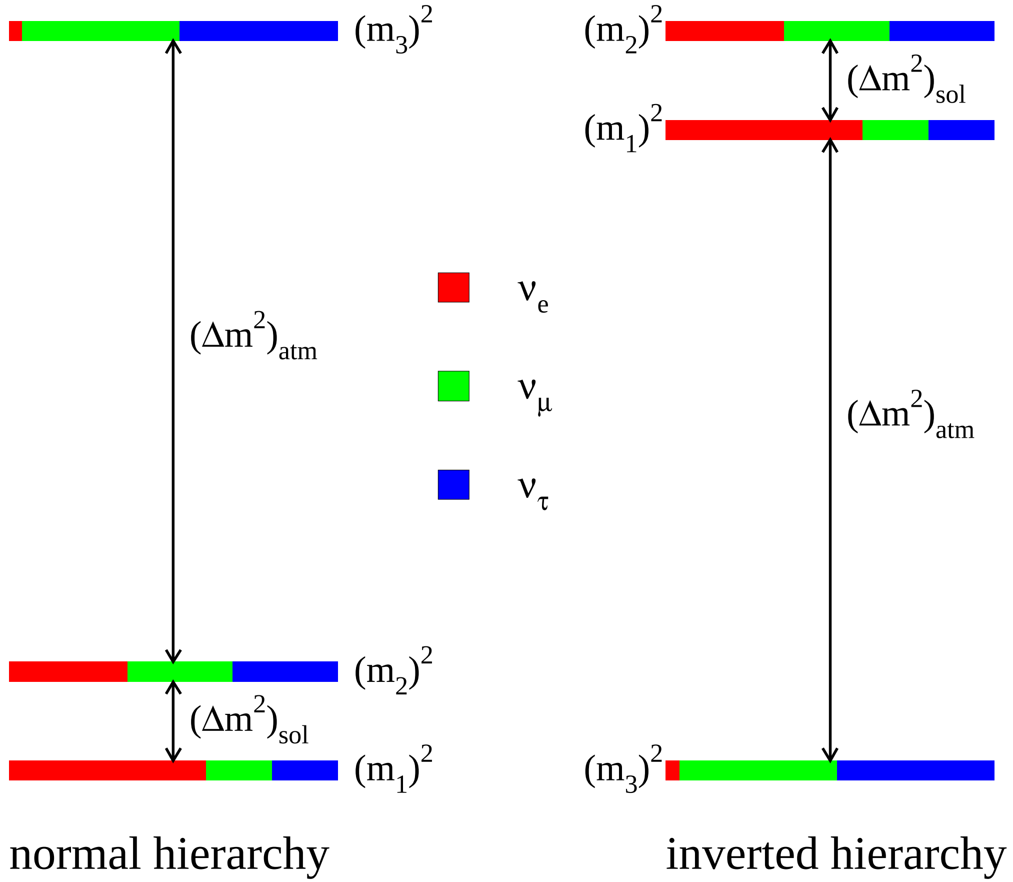
$\tan^2\theta_{12} \equiv \frac{|U_{e2}|^2}{|U_{e1}|^2}$; $\tan^2\theta_{23} \equiv \frac{|U_{\mu 3}|^2}{|U_{\tau 3}|^2}$;

$U_{e3} \equiv \sin\theta_{13} e^{-i\delta}$

$\Delta m_{13}^2 > 0$ – Normal Mass Hierarchy

$\Delta m_{13}^2 < 0$ – Inverted Mass Hierarchy

What We Know We Don't Know



- 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? ($\Delta m^2_{13} > 0$?)

Understanding Fermion Mixing

The other puzzling phenomenon uncovered by the neutrino data is the fact that Neutrino Mixing is Strange. What does this mean?

It means that lepton mixing is very different from quark mixing:

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

[$|(V_{MNS})_{e3}| < 0.2$]

WHY?

They certainly look VERY different, but which one would you label as "strange"?

[from reactor white paper]

Theoretical predictions:

$\Delta m^2_{13} > 0$ "typical" prediction of all* Type-I see-saw GUT models

inverted hierarchy requires* "more flavor structure"

Reference	$\sin\theta_{13}$	$\sin^2 2\theta_{13}$
SO(10)		
Goh, Mohapatra, Ng [40]	0.18	0.13
Orbifold SO(10)		
Asaka, Buchmüller, Covi [41]	0.1	0.04
SO(10) + flavor symmetry		
Babu, Pati, Wilczek [42]	$5.5 \cdot 10^{-4}$	$1.2 \cdot 10^{-6}$
Blazek, Raby, Tobe [43]	0.05	0.01
Kitano, Mimura [44]	0.22	0.18
Albright, Barr [45]	0.014	$7.8 \cdot 10^{-4}$
Maekawa [46]	0.22	0.18
Ross, Velasco-Sevilla [47]	0.07	0.02
Chen, Mahanthappa [48]	0.15	0.09
Raby [49]	0.1	0.04
SO(10) + texture		
Buchmüller, Wyler [50]	0.1	0.04
Bando, Obara [51]	0.01 .. 0.06	$4 \cdot 10^{-4}$ .. 0.01
Flavor symmetries		
Grimus, Lavoura [52, 53]	0	0
Grimus, Lavoura [52]	0.3	0.3
Babu, Ma, Valle [54]	0.14	0.08
Kuchimanchi, Mohapatra [55]	0.08 .. 0.4	0.03 .. 0.5
Ohlsson, Seidl [56]	0.07 .. 0.14	0.02 .. 0.08
King, Ross [57]	0.2	0.15
Textures		
Honda, Kaneko, Tanimoto [58]	0.08 .. 0.20	0.03 .. 0.15
Lebed, Martin [59]	0.1	0.04
Bando, Kaneko, Obara, Tanimoto [60]	0.01 .. 0.05	$4 \cdot 10^{-4}$ .. 0.01
Ibarra, Ross [61]	0.2	0.15
3 × 2 see-saw		
Appelquist, Piai, Shrock [62, 63]	0.05	0.01
Frampton, Glashow, Yanagida [64]	0.1	0.04
Mei, Xing [65] (normal hierarchy)	0.07	0.02
(inverted hierarchy)	> 0.006	$> 1.6 \cdot 10^{-4}$
Anarchy		
de Gouvêa, Murayama [66]	> 0.1	> 0.04
Renormalization group enhancement		
Mohapatra, Parida, Rajasekaran [67]	0.08 .. 0.1	0.03 .. 0.04

Table 1: Incomplete selection of predictions for θ_{13}. The numbers should be considered as order of magnitude statements.

* Albright, hep-ph/0407155

The literature on this subject is very large. The most exciting driving force (my opinion) is the fact that one can make *bona fide* predictions:

$\Rightarrow U_{e3}$, CP-violation, mass-hierarchy unknown!

Unfortunately, theorists have done too good a job, and people have successfully predicted everything...

More data needed to "sort things out."

generic predictions for subleading parameters. Note correlations between $|U_{e3}|$ and $\cos 2\theta_{23}$, plus dependency on mass-hierarchy.

Case	Texture	Hierarchy	$\lvert U_{e3}\rvert$	$\lvert\cos 2\theta_{23}\rvert$ (n.s.)	$\lvert\cos 2\theta_{23}\rvert$	Solar Angle
A	$\frac{\sqrt{\Delta m^2_{13}}}{2}\begin{pmatrix} 0 & 0 & 0 \\ 0 & 1 & 1 \\ 0 & 1 & 1 \end{pmatrix}$	Normal	$\sqrt{\frac{\Delta m^2_{12}}{\Delta m^2_{13}}}$	O(1)	$\sqrt{\frac{\Delta m^2_{12}}{\Delta m^2_{13}}}$	O(1)
B	$\sqrt{\Delta m^2_{13}}\begin{pmatrix} 1 & 0 & 0 \\ 0 & \frac{1}{2} & -\frac{1}{2} \\ 0 & -\frac{1}{2} & \frac{1}{2} \end{pmatrix}$	Inverted	$\frac{\Delta m^2_{12}}{\lvert\Delta m^2_{13}\rvert}$	–	$\frac{\Delta m^2_{12}}{\lvert\Delta m^2_{13}\rvert}$	O(1)
C	$\frac{\sqrt{\Delta m^2_{13}}}{\sqrt{2}}\begin{pmatrix} 0 & 1 & 1 \\ 1 & 0 & 0 \\ 1 & 0 & 0 \end{pmatrix}$	Inverted	$\frac{\Delta m^2_{12}}{\lvert\Delta m^2_{13}\rvert}$	O(1)	$\frac{\Delta m^2_{12}}{\lvert\Delta m^2_{13}\rvert}$	$\lvert\cos 2\theta_{12}\rvert \sim \frac{\Delta m^2_{12}}{\lvert\Delta m^2_{13}\rvert}$
Anarchy	$\sqrt{\Delta m^2_{13}}\begin{pmatrix} 1 & 1 & 1 \\ 1 & 1 & 1 \\ 1 & 1 & 1 \end{pmatrix}$	Normal[a]	> 0.1	O(1)	–	O(1)

[a] One may argue that the anarchical texture prefers but does not require a normal mass hierarchy.

[enlarged from AdG, PRD69, 093007 (2004)]

What About Maximal Atmospheric Mixing?

"Textures" are another way to parametrize neutrino mixing and to try and understand salient features: $|U_{e3}| \ll 1$, $\cos 2\theta_{23} \ll 1$, $\Delta m^2_{12} \ll \Delta m^2_{13}$, etc. Usually "quark independent."

Oscillations at Long-Baseline Experiments

MAIN GOAL: probe $\nu_\mu \to \nu_e$ oscillations governed by Δm^2_{13}

In vaccum

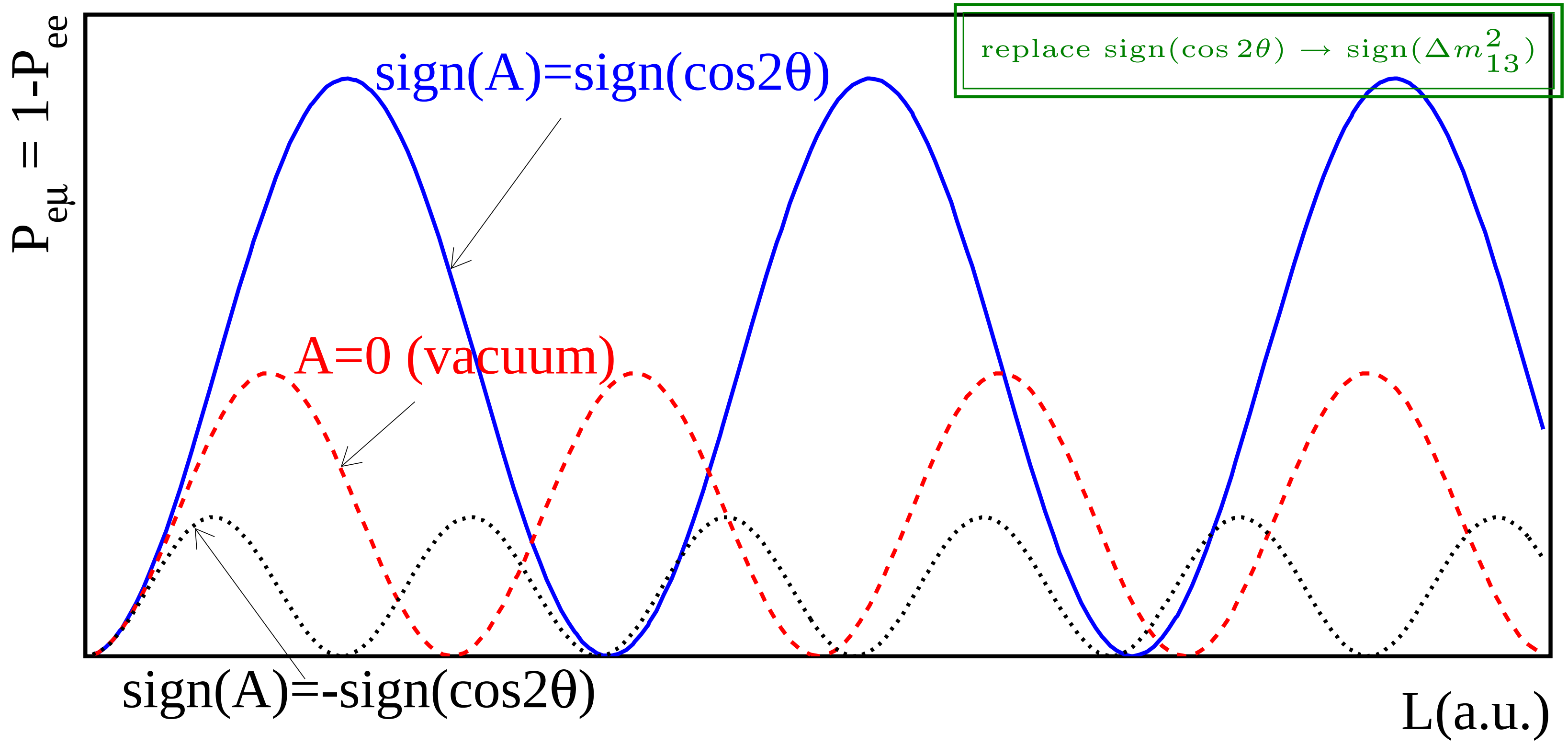
$$P_{\mu e} = \sin^2\theta_{23}\sin^2 2\theta_{13}\sin^2\left(\frac{\Delta m^2_{13}L}{4E}\right) + \text{ “subleading”}.$$

• Sensitivity to $\sin^2\theta_{13}$. More precisely, $\sin^2\theta_{23}\sin^2 2\theta_{13}$.

• Insensitive to the sign of Δm^2_{13} at leading order. However, in this case, matter effects may come to the rescue.

As is well-known, neutrino oscillations get modified when these propagate in the presence of matter. Matter effects are sensitive to the neutrino mass ordering (in a way that I will describe shortly) and different for neutrinos and antineutrinos.

• Subleading terms dependent on solar parameters and are sensitive to the CP-odd phase δ. They are also the origin of all the degeneracies you must have heard too much about.



Requirements:

- $\sin^2 2\theta_{13}$ large enough – otherwise there is nothing to see!
- $|\Delta_{13}| \sim |A|$ – matter potential must be significant but not overwhelming.
- $\Delta_{13}^{\rm eff} L$ large enough – matter effects are absent near the origin.

On measuring $\sin^2\theta_{23}$ (the atmospheric mixing angle)

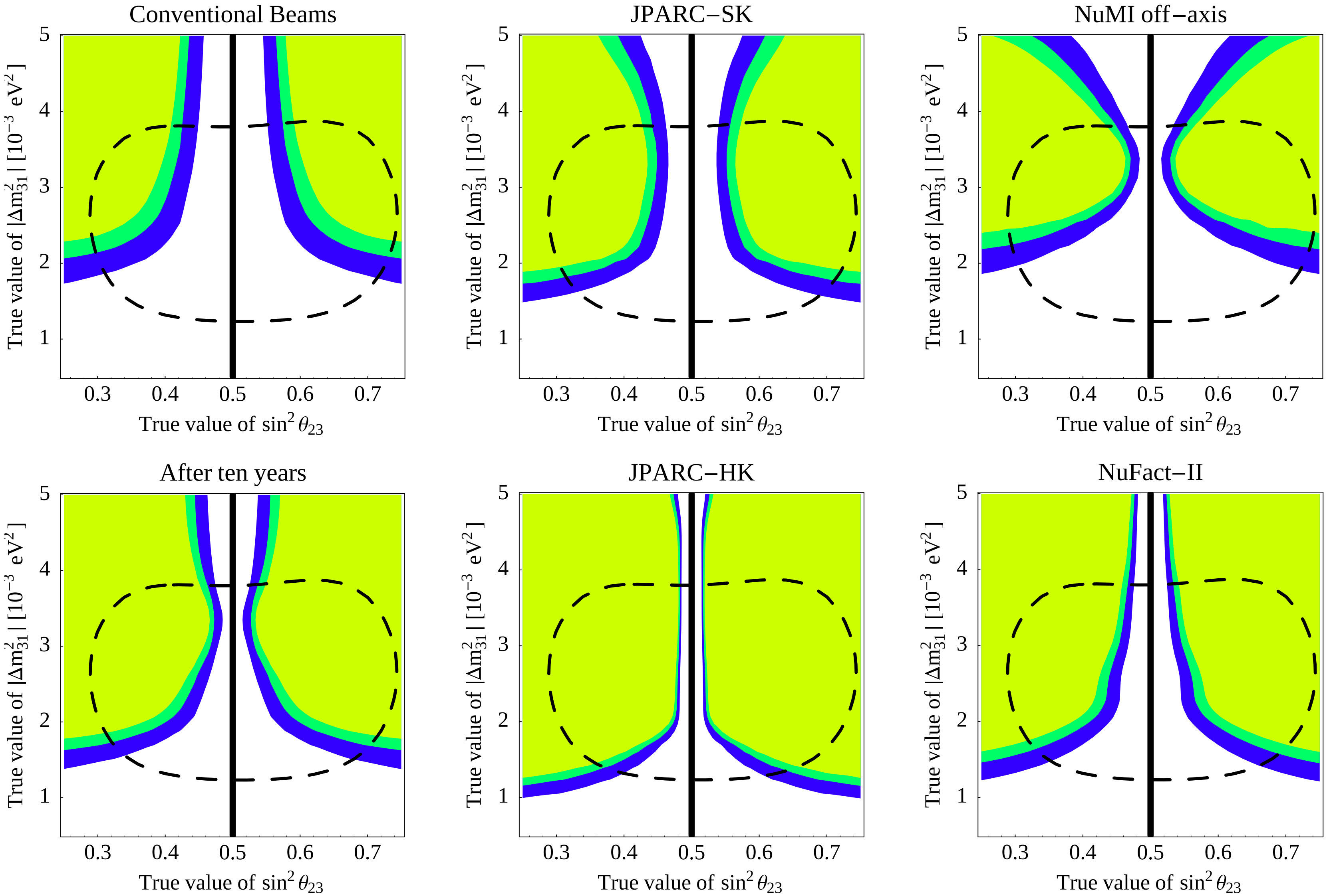
More specifically, we would like to ask whether it is possible to determine:

1. Is it maximal ($\sin^2\theta_{23} = 1/2$)?
2. Is $\sin^2\theta_{23} > 1/2$ or $\sin^2\theta_{23} < 1/2$?

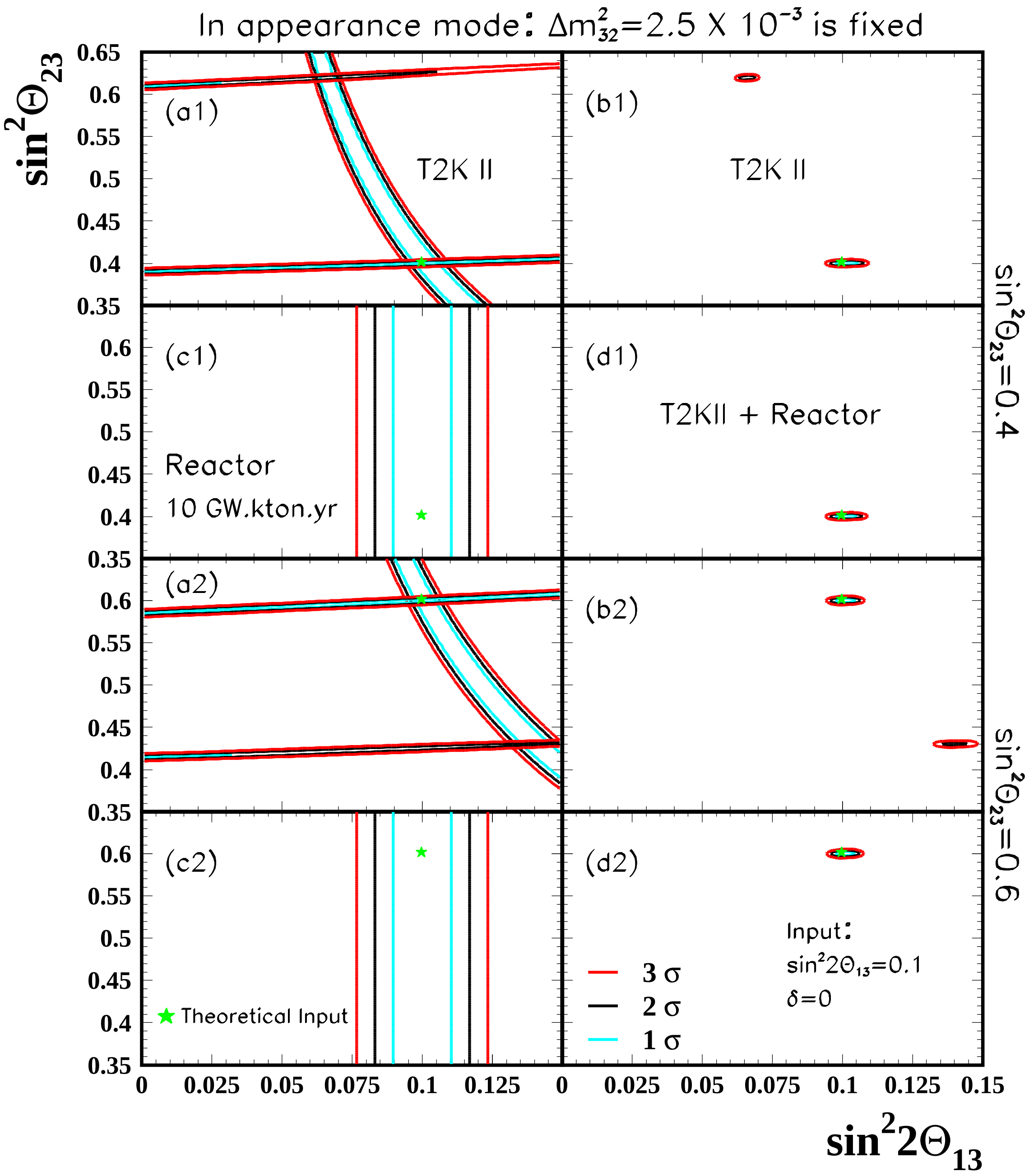
Limited information regarding (2) from disappearance channel. — $P_{\mu\mu} \propto \sin^2 2\theta_{23}$. Adding $P_{\mu e} \propto \sin^2\theta_{23}\sin^2 2\theta_{13}$ does not help!

In order to resolve this issue, need more information form reactors, atmospheric neutrinos, $P_{e\tau} \propto \cos^2\theta_{23}$ (which required τ appearance and is beyond the reach of "standard" next-generation LBL experiments – usually requires Neutrino Factory).

Deciding that θ_{23} is not maximal with LBL experiments



Antusch *et al.*, PRD70, 097302 (2004).



⇐ Appearance + Disappearance not Enough

⇐ Reactors Can Resolve Degeneracy

Hiraide *et al.*, hep-ph/0601258

Atmospheric Neutrinos

Large, underground detectors serve as excellent atmospheric neutrino detectors (like SuperK!).

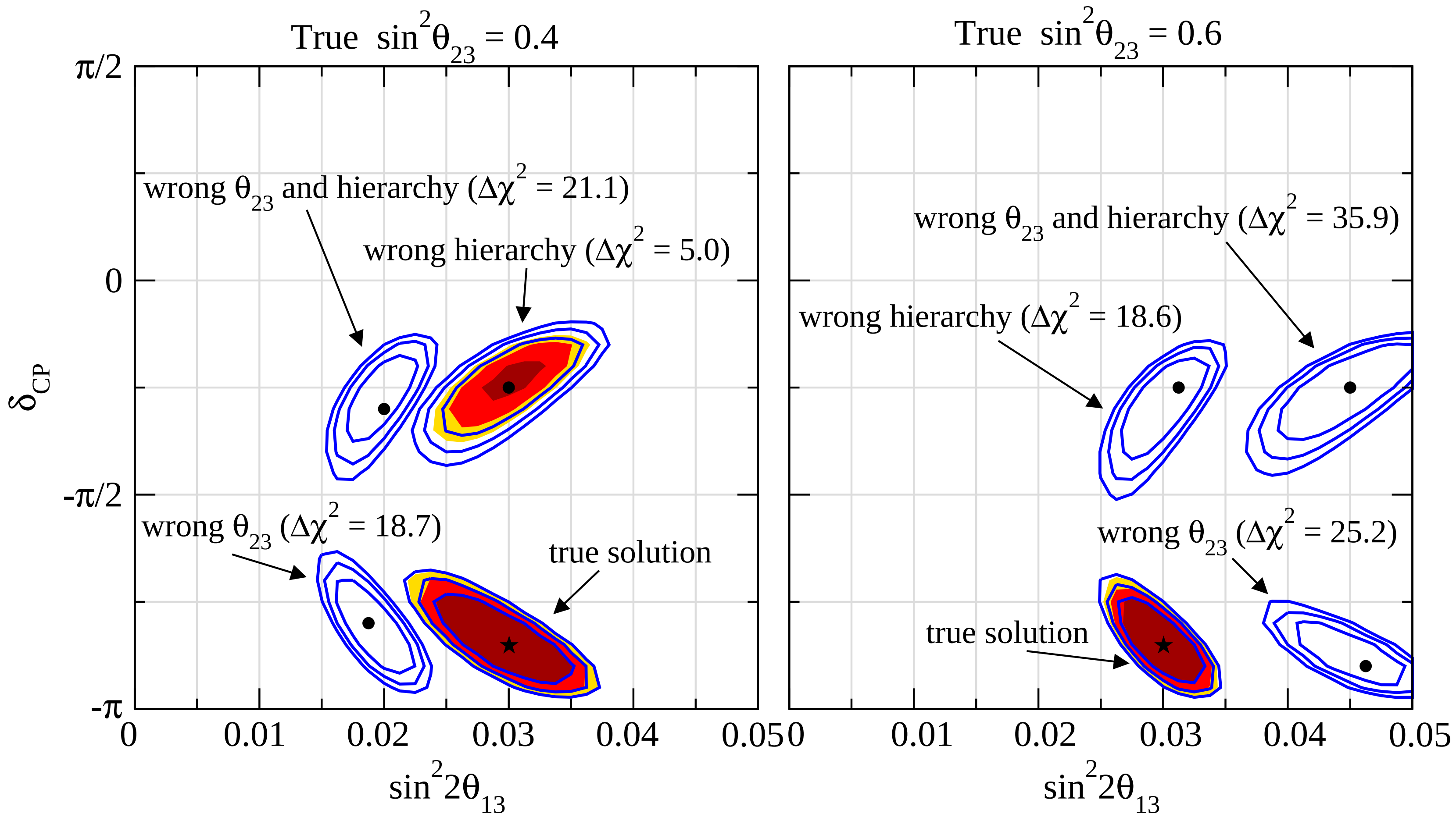
While the beam for atmospheric neutrinos is not very well known (large normalization uncertainly) but

- Broad energy spectrum (10^2 MeV to 10^2 GeV),
- Access to Several Baselines (10^1 km to 10^4 km).

Very Long baselines allow access to true three flavor oscillation effects, which help resolve degeneracies if the atmospheric data is combined with the LBL data.

Atmospheric neutrinos are also much more sensitive to matter effects: *e.g.* access to Earth's core, higher neutrino energies.

Combining LBL With Atmospheric Neutrinos – Same Detector



CLs: 2σ, 99%, and 3σ (2dof) [Huber *et al.*, PRD71, 053006 (2005)].

(T2K Phase II, 4MW on 1 Mton HyperK. ν and $\bar{\nu}$ running, 2+6 years)

— PAUSE —

(Some of) What We Don't Know We Don't Know

Given that neutrinos have mass and we are in position to probe whether neutrino are endowed with other "unexpected" properties, including,

- an electric/magnetic dipole moment;
- a finite lifetime.

We are also able to search for

- New neutrino contact interactions;
- New neutrino degrees of freedom (sterile neutrinos).

Finally, we can ask whether the leptonic sector respects a variety of fundamental symmetries, including

- Lorentz invariance;
- CPT invariance.

Example: New Neutrino–Matter Interactions

These are parameterized by effective four-fermion interactions, of the type:

$$L^{NSI} = -2\sqrt{2}G_F\left(\bar{\nu}_\alpha\gamma_\mu\nu_\beta\right)\left(\epsilon^{f\tilde{f}L}_{\alpha\beta}\bar{f}_L\gamma^\mu\tilde{f}_L + \epsilon^{f\tilde{f}R}_{\alpha\beta}\bar{f}_R\gamma^\mu\tilde{f}_R\right) + h.c.$$

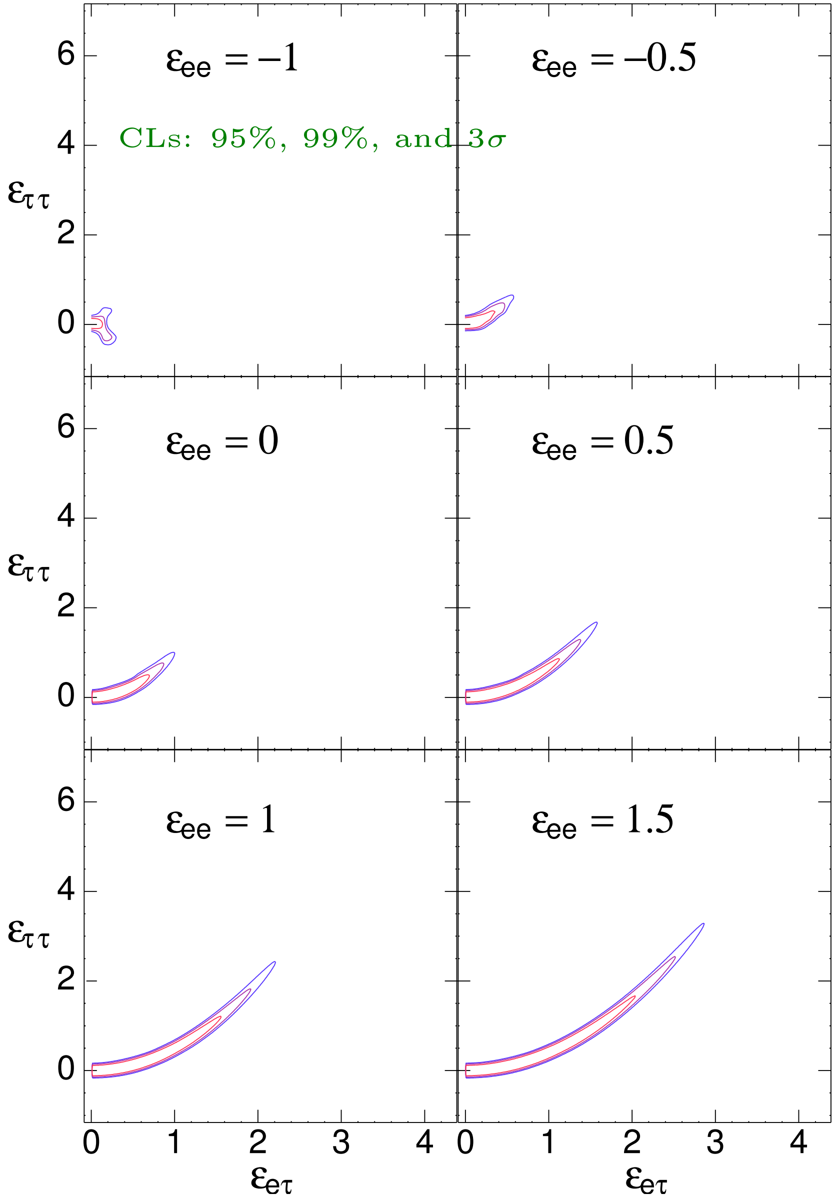
where $f, \tilde{f} = u, d, \ldots$ and $\epsilon^{f\tilde{f}}_{\alpha\beta}$ are dimensionless couplings that measure the strength of the four-fermion interaction relative to the weak interactions.

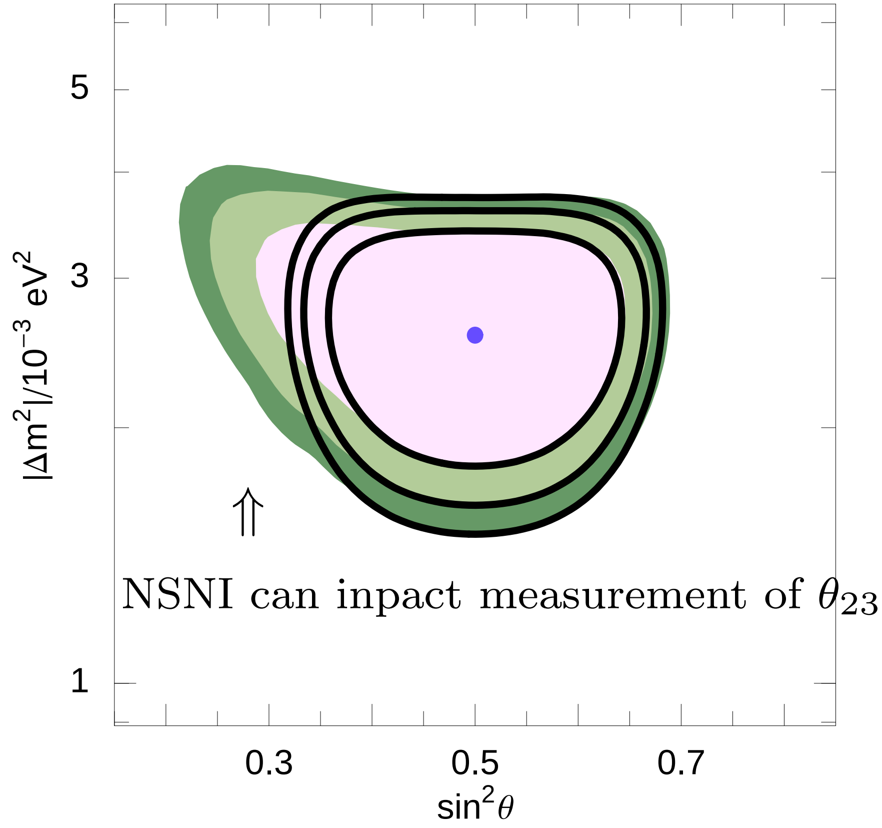
While some of the ϵs are well constrained (especially those involving muons), some are only very poorly known. These are best searched for in neutrino oscillation experiments, where they mediate anomalous matter effects:

$$H_{\rm mat} = \sqrt{2}G_F n_e \begin{pmatrix} 1+\epsilon_{ee} & \epsilon^*_{e\mu} & \epsilon^*_{e\tau} \\ \epsilon_{e\mu} & \epsilon_{\mu\mu} & \epsilon^*_{\mu\tau} \\ \epsilon_{e\tau} & \epsilon_{\mu\tau} & \epsilon_{\tau\tau} \end{pmatrix}, \qquad \epsilon_{\alpha\beta} = \sum_{f=u,d,e} \epsilon^{ff}_{\alpha\beta}\frac{n_f}{n_e}$$

—— END PAUSE ——

Atmospheric Neutrinos and Non-Standard Interactions





⇐ current constraint on such subleading effects.

More stringent bounds expected from MINOS.

Improved sensitivity from new ATM and LBL.

[Friedland and Lunardini, PRD72, 053009 (2005)].

Solar Neutrinos

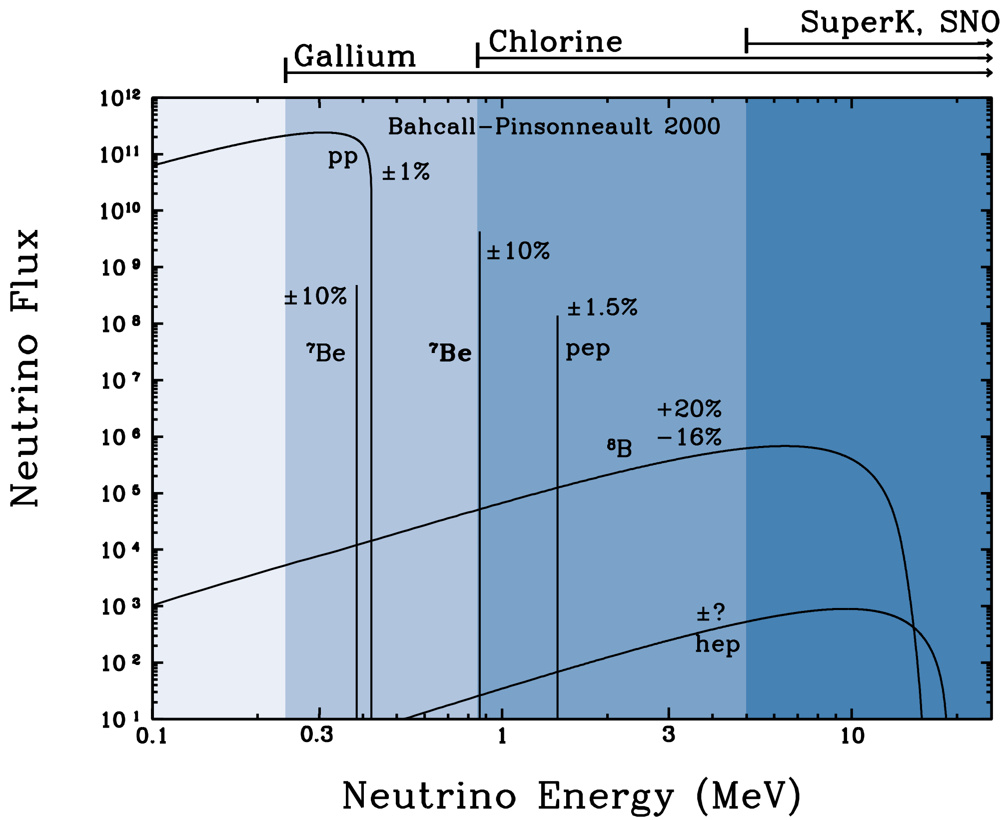
SuperK and SNO have measured, with great precision, "high energy" solar neutrinos, $E_\nu > 5$ MeV. The next natural step is to measure low energy ($E_\nu < 1$ MeV) "solar neutrinos".

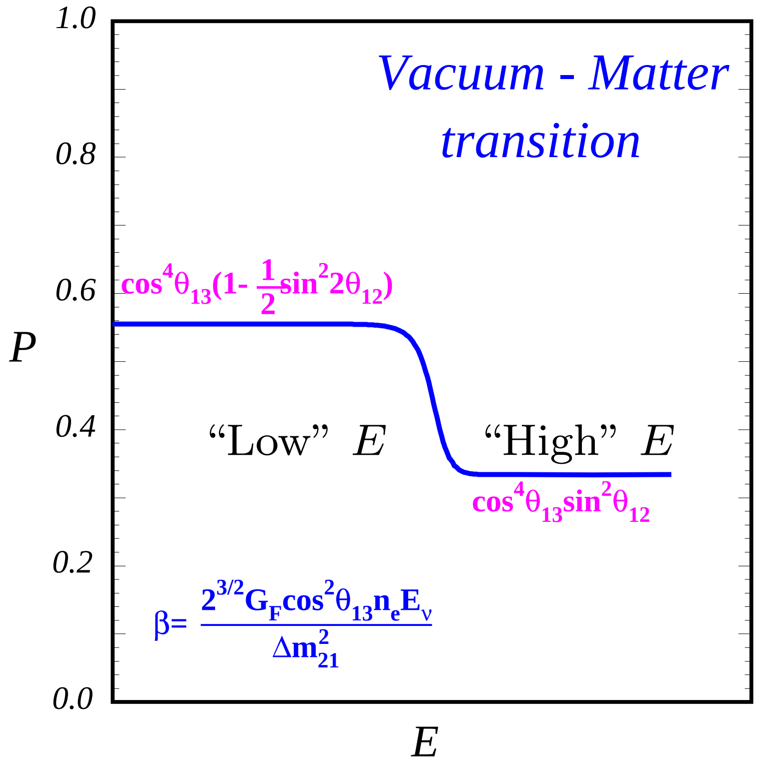
In order to do this, we need deep underground detectors. These are **not** your typical LBL detector. Different techniques have been proposed in order to obtain sensitivity to sub-MeV neutrinos and reduce radioactive backgrounds.

We don't expect significant improvements as far as solar parameters are concerned, but solar neutrinos could play a big role in the case of new new physics (and I won't talk about astrophysics at all).

Important ingredients: strong magnetic fields (time dependency?), large, smoothly varying matter density, effect, very low neutrino energies.

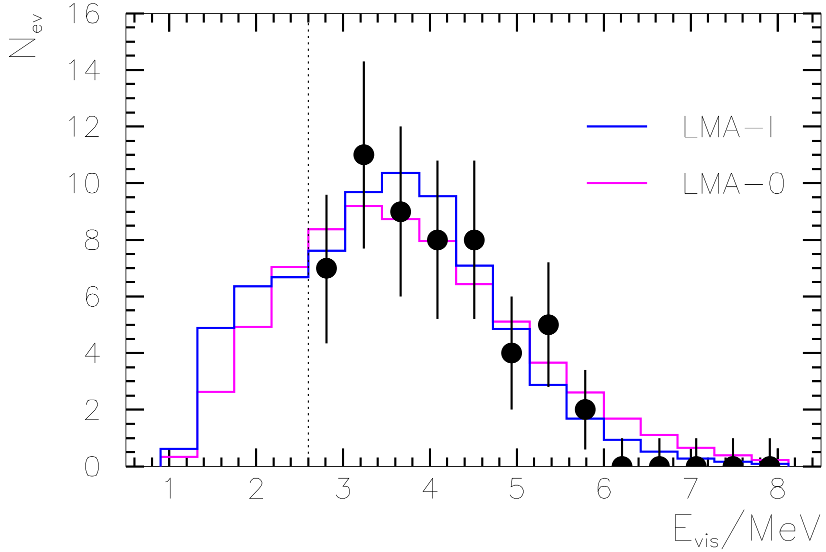
We Have Only Precisely Studied a Tiny Fraction of the Solar νs!

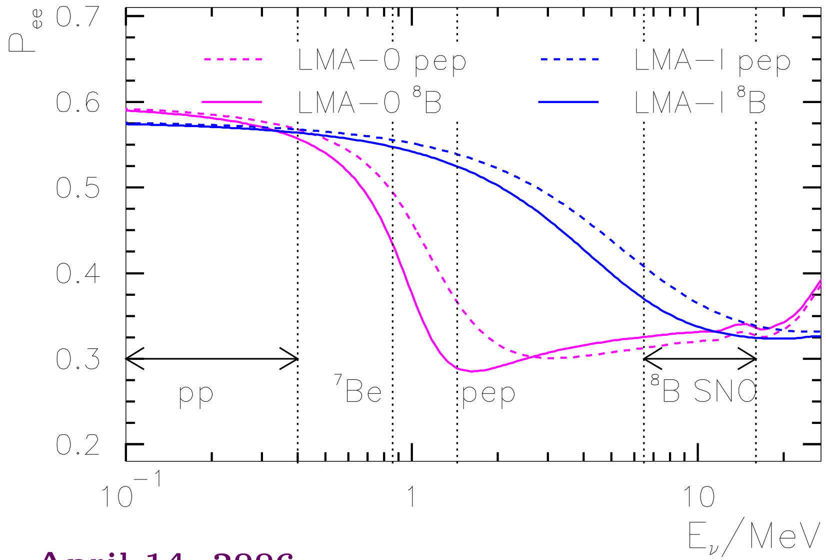




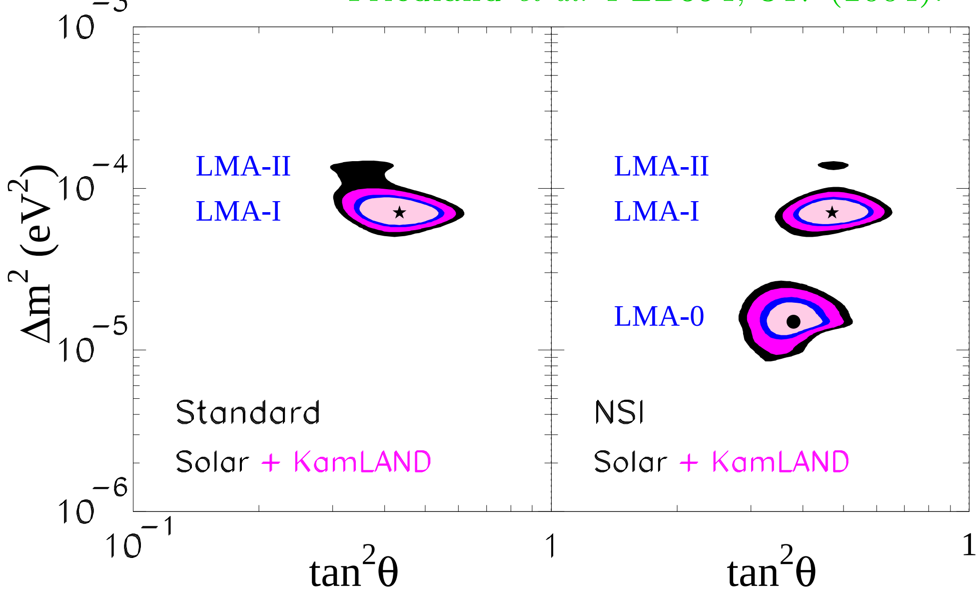
. . . and we have only looked at the "boring side" of the LMA solution!

Non-Standard ν Interactions and Low-Energy Solar νs





Friedland *et al.* PLB594, 347 (2004).

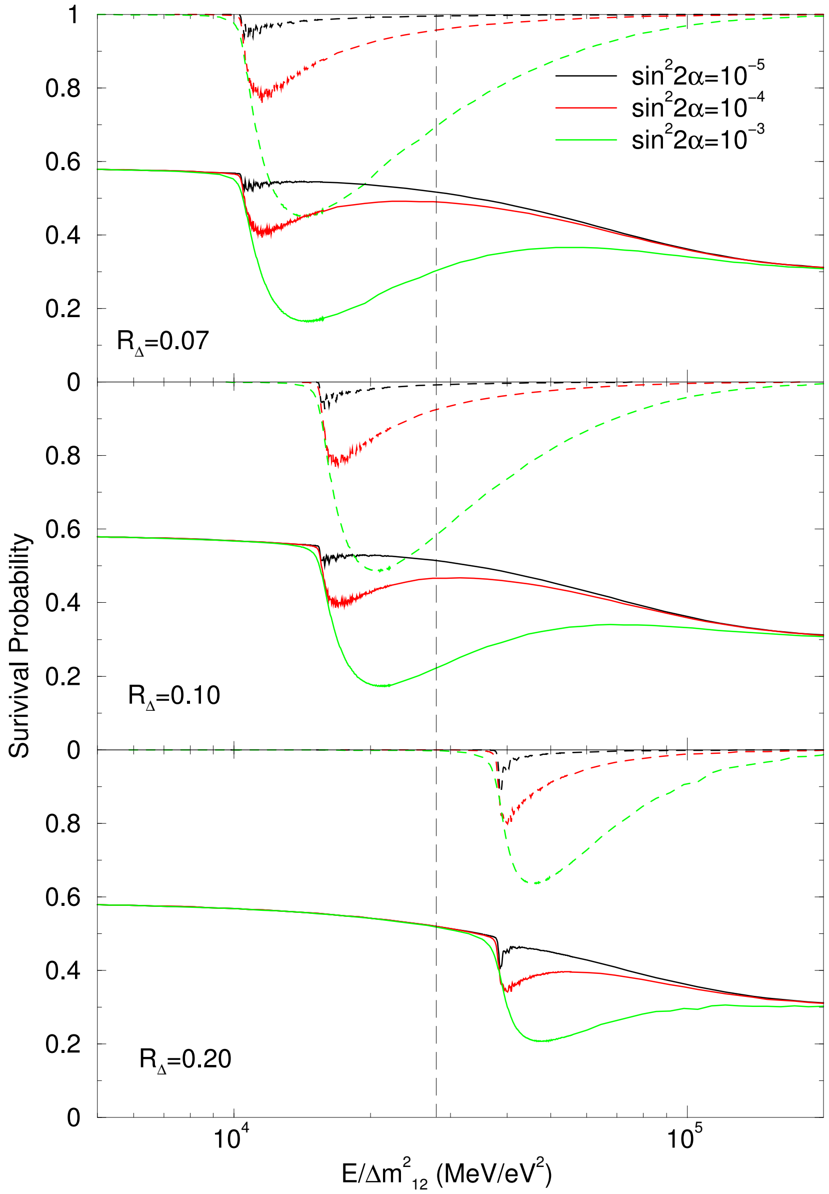


$$\text{LMA 0} \Rightarrow \epsilon_{ee} - \epsilon_{\tau\tau}\sin^2\theta_{23} = -0.065$$

$$2\epsilon_{e\tau}\sin\theta_{23} = 0.15$$

[WARNING: This is "old" KamLAND data]

Sterile Solar νs – Why is Chlorine Data Low?



de Holanda, Smirnov, PRD69, 113002 (2004).

- $R_\Delta = \frac{\Delta m^2_{01}}{\Delta m^2_{12}}$ → very light, mostly sterile state
- solid line: P_{ee}
- dashed line: $1 - P_{es}$

^{7}Be neutrinos at 1.1×10^4 MeV/eV^2

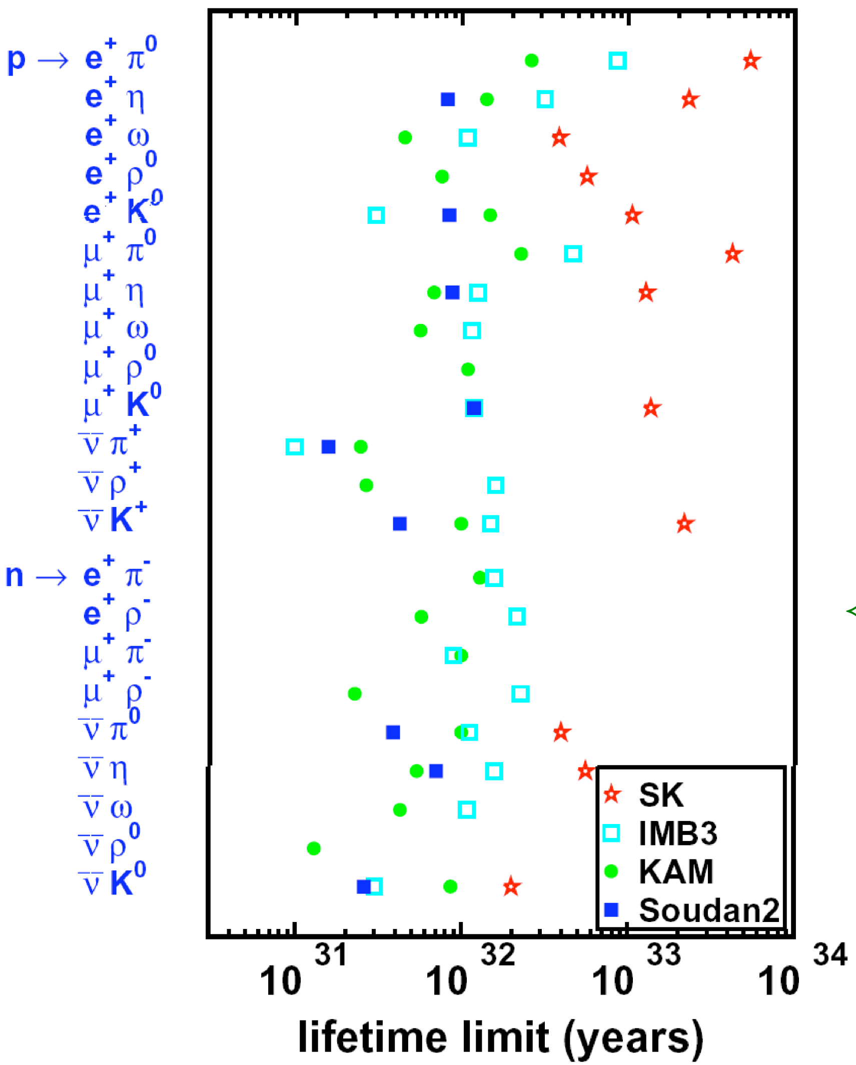
Low Energy ^{8}B neutrinos at 6.3×10^4 MeV/eV^2

Brief Digression on Nucleon Decay

Along with lepton number, baryon number is a fundamental global symmetry (at the classical level) of the Standard Model.

- The most visible consequence of baryon number is that the lightest baryon **must** be stable: this happens to be the proton (not an unfortunate coincidence, as far as we are concerned…).
- Curiously, $U(1)_B \times U(1)_L$ is not a symmetry at the quantum level (anomalies).[1] On the other hand, $U(1)_{B-L}$ (or $B-L$) is predicted to be preserved in the old SM (which predicts that neutrinos are massless).
- It is important to appreciate that $U(1)_{B-L}$ is, nonetheless, an **accidental symmetry** of the old SM. Generic Extensions of the SM violate $B-L$!

[1] The prediction for the proton lifetime mediated by quantum effects is beyond our wildestest experimental speculations.



Some extensions of the SM violate $U(1)_B$ at the classical level, but do not violate $B-L$.

The standard examples are grand unified theories, still the driving force behind nucleon decay searches.

$\Leftarrow$ All decay modes in this table conserve $B-L$

2003, M. Shiozawa
28th International
Cosmic Ray Conference

Neutrinos as evidence for physics at a very high energy scale – non-renormalizable operators

$$\mathcal{L}_{\nu\mathrm{SM}} \supset -\lambda_{ij}\frac{L^i H L^j H}{2M} + \mathcal{O}\left(\frac{1}{M^2}\right) + H.c.$$

There is only one dimension five operator [Weinberg, 1979]. If $M \gg 1$ TeV, it leads to only one observable consequence...

$$\text{after EWSB } \mathcal{L}_{\nu\mathrm{SM}} \supset \frac{m_{ij}}{2}\nu^i\nu^j; \quad m_{ij} = \lambda_{ij}\frac{v^2}{M}.$$

- Neutrino masses are small: $M \gg v \to m_\nu \ll m_f$ ($f = e, \mu, u, d$, etc)
- Neutrinos are Majorana fermions – Lepton number is violated!
- νSM effective theory – not valid for energies above M
- What is M? Data require $M < 10^{15}$ GeV.
- If this picture is correct, the $\mathcal{O}\left(\frac{1}{M^2}\right)$ terms lead to nucleon decay!

Nucleon Decay – Bottom Line

- If there is physics beyond the old SM, there is no reason for the proton to be stable. And we know there is physics beyond the SM (neutrinos, dark matter)

- On the other hand, we have very few handles on the proton lifetime, and on the decay modes. Different theoretical speculations lead to different predictions. None of them are known to be correct (and several have been proved wrong in the past, mostly by proton decay searches! – Chung Kee Jung may have more to say about this)

- It is **crucial** to pursue all decay modes and processes:
  - $B-L$ conserving: $p\to e^+\pi^0$, $p\to\bar{\nu}K^+$, $p\to e^+e^-e^+$ etc
  - $B-L$ violating: $p\to e^+\bar{\nu}\bar{\nu}$, $n\to e^+e^-\nu$, $\tau^-\to n\pi^-$, etc
  - $\Delta(B)=2$: $n\leftrightarrow\bar{n}$ oscillations, $nn\to\nu\bar{\nu}$, etc

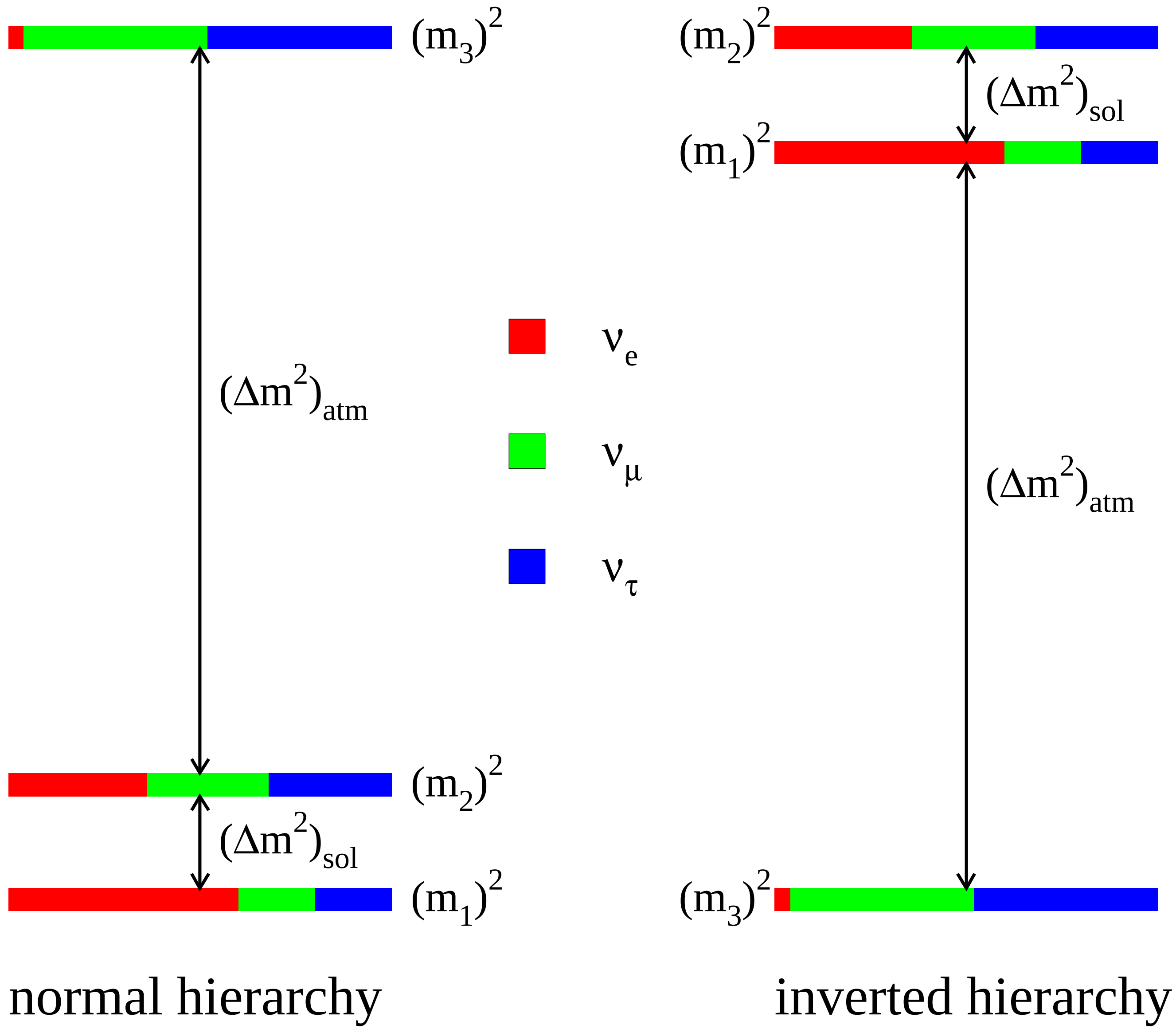
- Requirements: big detectors, deep underground. Furthermore, different detector technologies are more/less sensitive to different decay modes!

Summary

- Large neutrino detectors are required in order to address what we know we don't know about neutrinos: θ_{13}, $\theta_{23}=\pi/4$, sign(Δm^2_{13}), and whether CP-invariance is violated in the lepton sector.
- Long baseline experiments (*i.e.*, neutrino beams aimed at these large detectors) provide all necessary ingredients to address the questions above (in the "long run") **if** $\sin^2\theta_{13}$ is large enough and bf if the baseline is long enough. The main "workhorse" for all analyses is $\nu_{\mu}\to\nu_e$ oscillations.
- The **same** detectors can study atmospheric neutrinos, as long as they are deep underground. The study of atmospheric neutrinos can be of create importance when it comes to addressing the known unknowns.
- Atmospheric neutrinos can also teach us about **unknown unknowns**. I gave an example of how atmospheric neutrino data constrains non-standard neutrino–matter interactions. Improved sensitivity can be obtained in next-generation set-up.

- The **same** detector may be able to extend our sensitivity to nucleon decay, if it is located deep underground. The "type" of sensitivity depends on the detector techology (say, water Cherenkov detector versus large liquid argon TPC).
- Deep underground neutrino detectors are also useful for studying solar neutrinos. The "next step" in solar neutrino studies is to precisely study low energy solar neutrinos (say, ^{7}Be and *pp* neutrinos). The detectors capable of doing this are, in general, not directly related to LBL-associated detectors. There may be synergy with other types of physics (*e.g.* dark matter searches).
- Low energy solar neutrino experiments are sensitive to unknown unknowns. I gave examples of their impact for probing non-standard neutrino interactions, and a "hint" for a very light sterile neutrino. Other examples include sensitivity to neutrino electromagnetic dipole moments.

EXTRA SLIDES



just like the quarks:

neutrino **flavor** eigenstates ν_e, ν_μ, ν_τ need not agree with neutrino **mass** eigenstates ν_1, ν_2, ν_3

two bases related by unitary transformation

$$\nu_\alpha = U_{\alpha i}\nu_i$$

How Did We Find Out?

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

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

If $\Delta_{12} \equiv \frac{\Delta m^2_{12}}{2E}$ terms are ignored, the $\nu_\mu \to \nu_e$ oscillation probability is described, in constant matter density, by

$$P_{\mu e} \simeq P_{e\mu} \simeq \sin^2\theta_{23}\sin^2 2\theta_{13}^{\rm eff}\sin^2\left(\frac{\Delta_{13}^{\rm eff}L}{2}\right),$$

$$\sin^2 2\theta_{13}^{\rm eff} = \frac{\Delta_{13}^2\sin^2 2\theta_{13}}{(\Delta_{13}^{\rm eff})^2},$$

$$\Delta_{13}^{\rm eff} = \sqrt{(\Delta_{13}\cos 2\theta_{13} - A)^2 + \Delta_{13}^2\sin^2 2\theta_{13}},$$

$$\Delta_{13} = \frac{\Delta m^2_{13}}{2E},$$

$A \equiv \pm\sqrt{2}G_F N_e$ is the matter potential. It is positive for neutrinos and negative for antineutrinos.

$P_{\mu e}$ depends on the relative sign between Δ_{13} and A. It is different for the two different mass hierarchies, and different for neutrinos and antineutrinos.

Bound on CPT-violating "solar" observables:

$$\Delta(\Delta m^2) < 1.1 \times 10^{-4}\ \text{eV}^2\ (3\ \sigma)$$

From solar data!

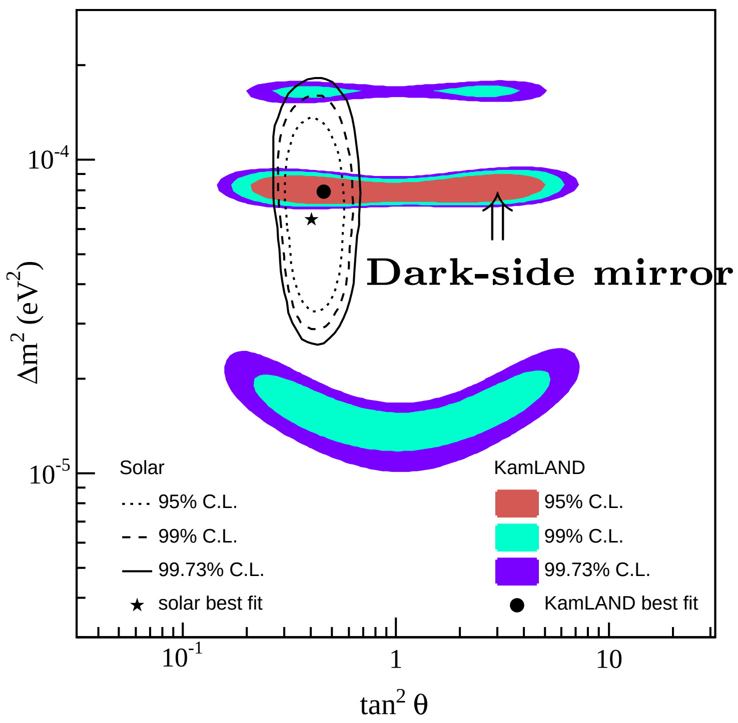
$$\Delta(\sin^2\theta) < 0.7$$

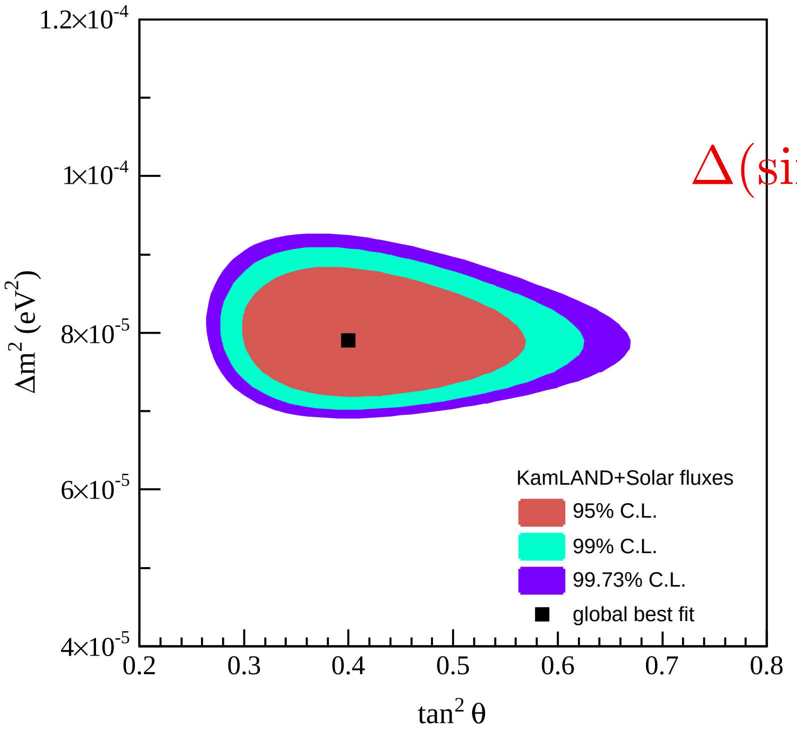
will not improve much – matter efffects do not matter!

$\Downarrow$

$$\Delta(\sin^2\theta) = |\cos 2\theta|?$$

$$(\theta + \bar{\theta} = \pi/2?)$$





AdG, Peña-Garay, PRD71, 093002 (2005)

In order to address whether CPT-invariance is "maximally violated" in the solar mixing we need:

- Antineutrinos
- Matter effects

Possible experiments include

- Supernova neutrinos $\Rightarrow P_{\bar{\nu}_e} \simeq \cos^2\theta$; can it really be done?
- Very long baseline $\bar{\nu}_e \leftrightarrow \bar{\nu}_{\mu,e}$ searches with frequency $\Delta\bar{m}^2_{\rm Kam}$
- **?**

NEUTRINO MAGNETIC MOMENTS

Now that neutrinos have mass, they are "allowed" to have a nonzero magnetic moment μ_ν.

The nature of μ_ν will depend on whether the neutrino is its own antiparticle:

$$\mathcal{L}_{m.m.} = \mu_\nu^{ij}(\nu_i \sigma_{\mu\nu} \nu_j F^{\mu\nu}) + H.c.,$$

$$\mu_\nu^{ij} = -\mu_\nu^{ji}, \quad i,j = 1,2,3 \ \rightarrow \ \text{Majorana Magnetic Moment}$$

or

$$\mathcal{L}_{m.m.} = \mu_\nu^{ij}(\bar{\nu}_i \sigma_{\mu\nu} N F^{\mu\nu}) + H.c.,$$

$$i,j = 1,2,3 \ \rightarrow \ \text{Dirac Magnetic Moment}$$

In either version of the new SM, μ is really small:

$$\mu \leq \frac{3eG_F}{8\sqrt{2}\pi^2}m_\nu = 3\times 10^{-20}\mu_B\left(\frac{m_\nu}{10^{-1}\text{ eV}}\right); \qquad \mu_B = \frac{e}{2m_e}$$

Bounds come from a variety of sources and constrain different linear combination of elements of μ.

- $\bar{\nu}_e e^- \to \nu_\beta\ (\bar{\nu}_\beta)\ e^-$, $\forall\beta\ (\beta = e,\mu,\tau)$ TEXONO, MUNU reactor expt's, SuperK solar
- searches for electron antineutrinos from the Sun ($\nu_e \stackrel{(m.m.)}{\longrightarrow} \bar{\nu}_\beta \stackrel{(osc)}{\longrightarrow} \bar{\nu}_e$) $\vec{B}$ in the Sun?, how well oscillation parameters are known? (KamLAND!)
- astrophysics red giants, SN1987A, …

$$\Rightarrow \boxed{\mu_\nu < 1.5\times 10^{-10}\mu_B} \quad \text{(PDG accepted bound);}$$

also $O(10^{-[12\div 11]})$ bounds from astrophysics and solar neutrinos.