

# Neutrinos (I – III)

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## Tentative Outline for The Lectures

1. Brief History of the Neutrino;
2. Neutrino Puzzles – The Discovery of Neutrino Masses;
3. Neutrino Oscillations;
4. What We Know We Don't Know;
5. Neutrino Masses As Physics Beyond the Standard Model;
6. Some Ideas for Tiny Neutrino Masses, and Some Consequences.

[note: Questions/Suggestions/Complaints are ALWAYS welcome]

### Some Neutrino references (WARNING: Biased Sample)

- “Are There Really Neutrinos? – An Evidential History,” Allan Franklin, Perseus Books, 2001. Good discussion of neutrino history.
- A. de Gouvêa, “TASI lectures on neutrino physics,” hep-ph/0411274;
- A. de Gouvêa, “Neutrinos have mass: So what?,” Mod. Phys. Lett. A **19**, 2799 (2004) [hep-ph/0503086];
- R. N. Mohapatra *et al.*, “Theory of neutrinos: A White paper,” Rept. Prog. Phys. **70**, 1757 (2007) [hep-ph/0510213];
- R. N. Mohapatra, A. Yu. Smirnov, “Neutrino Mass and New Physics,” Ann. Rev. Nucl. Part. Sci. **56**, 569 (2006) [hep-ph/0603118];
- M. C. Gonzalez-Garcia, M. Maltoni, “Phenomenology with Massive Neutrinos,” Phys. Rept. **460**, 1 (2008) [arXiv:0704.1800 [hep-ph]];
- A. Strumia, F. Vissani, “Neutrino masses and mixings,” hep-ph/0606054 (2010);
- “The Physics of Neutrinos,” V. Barger, D. Marfatia, K. Whisnant, Princeton University Press (2012);
- “J. Hewett *et al.*, “Fundamental Physics at the Intensity Frontier,” arXiv:1205.267;
- A. de Gouvêa *et al.*, “Working Group Report: Neutrinos,” arXiv:1310.4340.

## 1 - Brief History of the Neutrino

1. 1896: Henri Becquerel discovers natural radioactivity while studying phosphorescent properties of uranium salts.
  - $\alpha$  rays: easy to absorb, hard to bend, positive charge, mono-energetic;
  - $\beta$  rays: harder to absorb, easy to bend, negative charge, spectrum?;
  - $\gamma$  rays: no charge, very hard to absorb.
2. 1897: J.J. Thompson discovers the electron.
3. 1914: Chadwick presents definitive evidence for a continuous  $\beta$ -ray spectrum. Origin unknown. Different options include several different energy loss mechanisms.

It took 15+ years to decide that the “real”  $\beta$ -ray spectrum was really continuous. Reason for continuous spectrum was a total mystery:

- QM: Spectra are discrete;
- Energy-momentum conservation:  $N \rightarrow N' + e^-$  — electron energy and momentum well-defined.

**Nuclear Physics before 1930:**  $\text{nucleus} = n_p p + n_e e^-$ .

Example:  ${}^4\text{He} = 4p + 2e^-$ , works well. However:  ${}^{14}\text{N} = 14p + 7e^-$  is expected to be a fermion. However, it was experimentally known that  ${}^{14}\text{N}$  was a boson!

There was also a problem with the magnetic moment of nuclei:  $\mu_N, \mu_p \ll \mu_e$  ( $\mu = eh/4mc$ ). How can the nuclear magnetic moment be so much smaller than the electron one if the nucleus contains electrons?

**SOLUTION: Bound, nuclear electrons are very weird!**

This can also be used to solve the continuous  $\beta$ -ray spectrum: energy need not be conserved in nuclear processes! (N. Bohr)

“... This would mean that the idea of **energy and its conservation fails** in dealing with processes involving the emission and capture of **nuclear electrons**. This does not sound improbable if we remember all that has been said about **peculiar properties of electrons in the nucleus**.” (G. Gamow, Nuclear Physics Textbook, 1931).

## enter the neutrino...

1. 1930: Postulated by Pauli to (a) resolve the problem of continuous  $\beta$ -ray spectra, and (b) reconcile nuclear model with spin-statistics theorem.  $\Rightarrow$
2. 1932: Chadwick discovers the neutron.  
neutron  $\neq$  Pauli's neutron = neutrino (Fermi);

3. 1934: Fermi theory of Weak Interactions – current-current interaction

$$\mathcal{H} \sim G_F (\bar{p}\Gamma n) (\bar{e}\Gamma\nu_e), \quad \text{where } \Gamma = \{1, \gamma_5, \gamma_\mu, \gamma_\mu\gamma_5, \sigma_{\mu\nu}\}$$

Way to “see” neutrinos:  $\bar{\nu}_e + p \rightarrow e^+ + n$ . Prediction for the cross-section - too small to ever be observed...

4. 1935: (Yukawa postulates the existence of mesons (pions) as mediators of the nuclear (strong) force:  $m_\pi \sim 100$  MeV.)
5. 1936/37: (“Meson” discovered in cosmic rays. Another long, tortuous story. Turns out to be the muon...)
6. 1947: (Marshak, Bethe postulate the 2 meson hypothesis ( $\pi \rightarrow \mu$ ). Pion observed in cosmic rays.)

Dear Radioactive Ladies and Gentlemen,

I have come upon a desperate way out regarding the wrong statistics of the  $^{14}\text{N}$  and  $^6\text{Li}$  nuclei, as well as the continuous  $\beta$ -spectrum, in order to save the “alternation law” statistics and the energy law. To wit, the possibility that there could exist in the nucleus electrically neutral particles, which I shall call “neutrons,” and satisfy the exclusion principle... The mass of the neutrons should be of the same order of magnitude as the electron mass and in any case not larger than 0.01 times the proton mass. The continuous  $\beta$ -spectrum would then become understandable from the assumption that in  $\beta$ -decay a neutron is emitted along with the electron, in such a way that the sum of the energies of the neutron and the electron is constant... For the time being I dare not publish anything about this idea and address myself to you, dear radioactive ones, with the question how it would be with experimental proof of such a neutron, if it were to have the penetrating power equal to about ten times larger than a  $\gamma$ -ray.

I admit that my way out may not seem very probable *a priori* since one would probably have seen the neutrons a long time ago if they exist. But only the one who dares wins, and the seriousness of the situation concerning the continuous  $\beta$ -spectrum is illuminated by my honored predecessor, Mr Debye who recently said to me in Brussels: “Oh, it is best not to think about this at all, as with new taxes.” One must therefore discuss seriously every road to salvation. Thus, dear radioactive ones, examine and judge. Unfortunately, I cannot appear personally in Tübingen since a ball... in Zürich... makes my presence here indispensable... .

Your most humble servant, W. Pauli

*Adapted summary of an English Translation to Pauli's letter dated December 4, 1930, from Ref. 3.*

## observing the unobservable:

1. 1956: “Discovery” of the neutrino (Reines and Cowan) in the Savannah River Nuclear Reactor site.  $\Rightarrow$

$\bar{\nu}_e + p \rightarrow e^+ + n$ . Measure positron ( $e^+e^- \rightarrow \gamma s$ ) and neutron ( $nN \rightarrow N^* \rightarrow N + \gamma s$ ) in delayed coincidence in order to get rid of backgrounds.

2. 1958: Neutrino Helicity Measured (Goldhaber et al.). Neutrinos are purely **left-handed**. Interact only weakly (Parity violated maximally).

$e^- + {}^{152}\text{Eu}(J=0) \rightarrow {}^{152}\text{Sm}^*(J=1) + \nu \rightarrow {}^{152}\text{Sm}(J=1) + \nu + \gamma$

3. 1962: The second neutrino:  $\nu_\mu \neq \nu_e$  (Lederman, Steinberger, Schwarts at BNL). First neutrino beam.

$p + Z \rightarrow \pi^+ X \rightarrow \mu^+ \nu_\mu \Rightarrow$

$$\nu_\mu + Z \rightarrow \mu^- + Y \text{ (“always”)}$$

$$\nu_\mu + Z \rightarrow e^- + Y \text{ (“never”)}$$

4. 2001:  $\nu_\tau$  directly observed (DONUT experiment at FNAL). Same strategy:  $\nu_\tau + Z \rightarrow \tau^- + Y$ . ( $\tau$ -leptons discovered in the 1970’s).  $\Rightarrow$



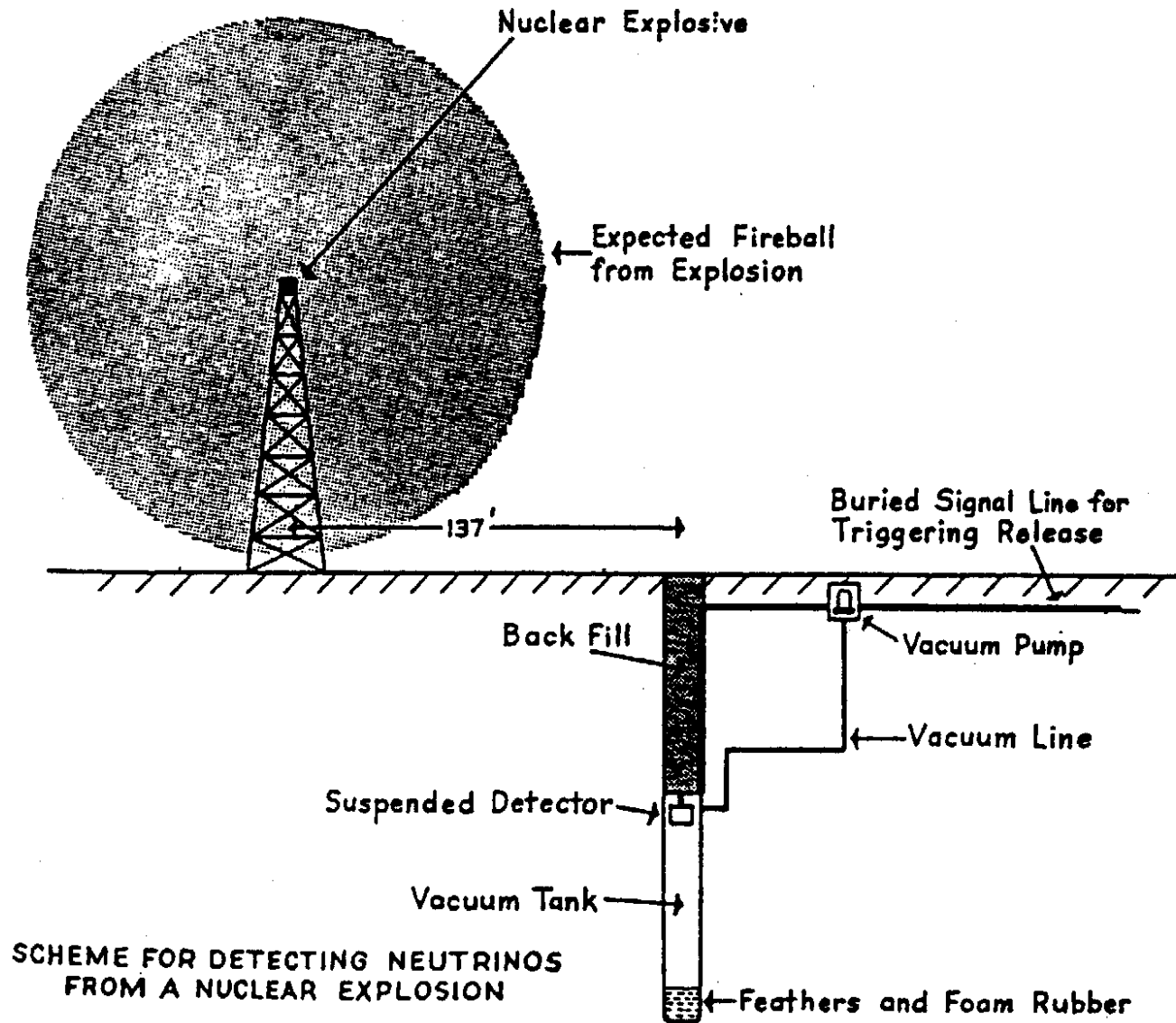


FIGURE 5.1 Scheme for detecting neutrinos from a nuclear explosion (Cowan, 1964).

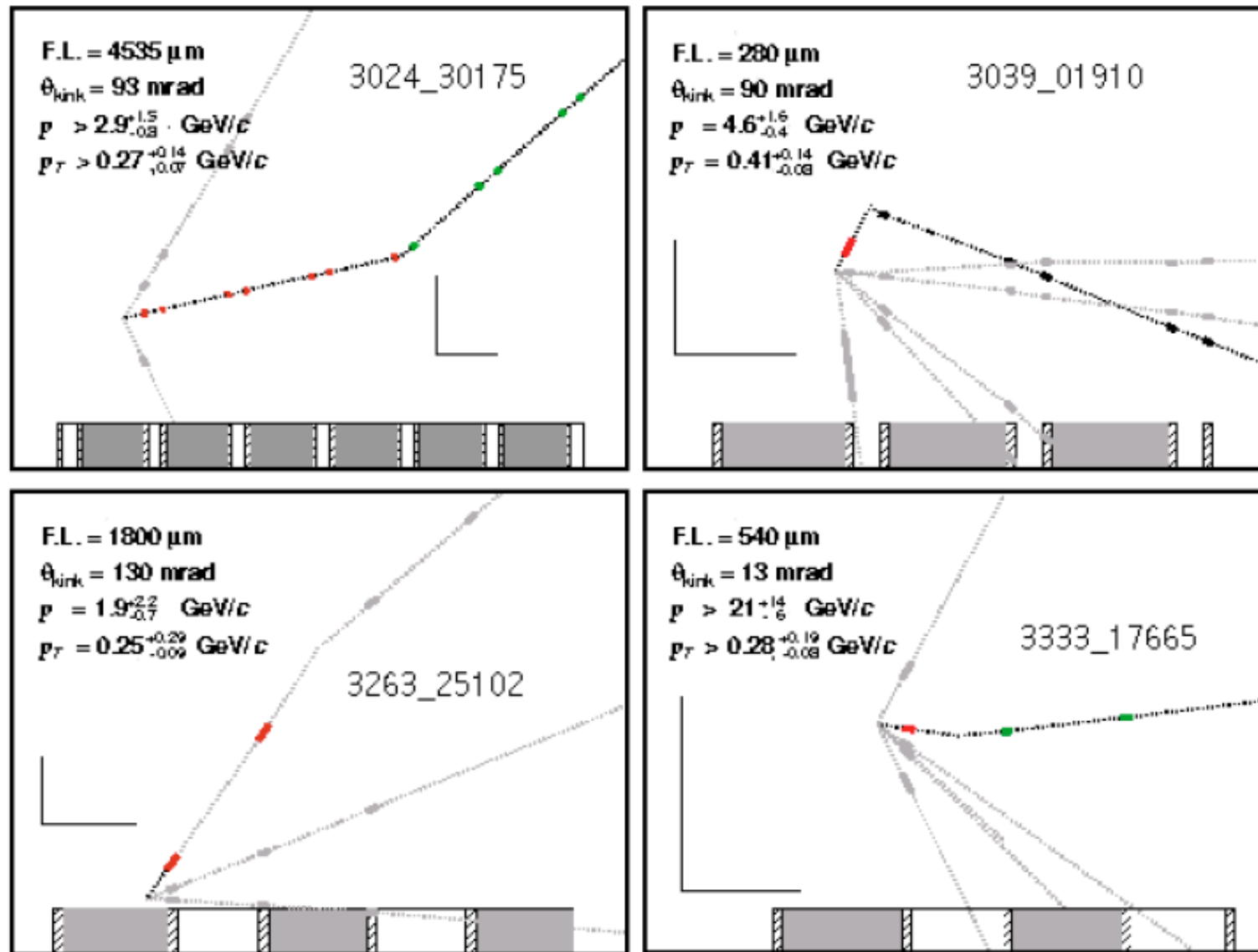


Figure 4-6: The four tau neutrino charged current events. The scale is given by the perpendicular lines (vertical: 0.1 mm, horizontal: 1 mm). The bar on the bottom shows the target material (solid: steel, hatched: emulsion, clear: plastic base).

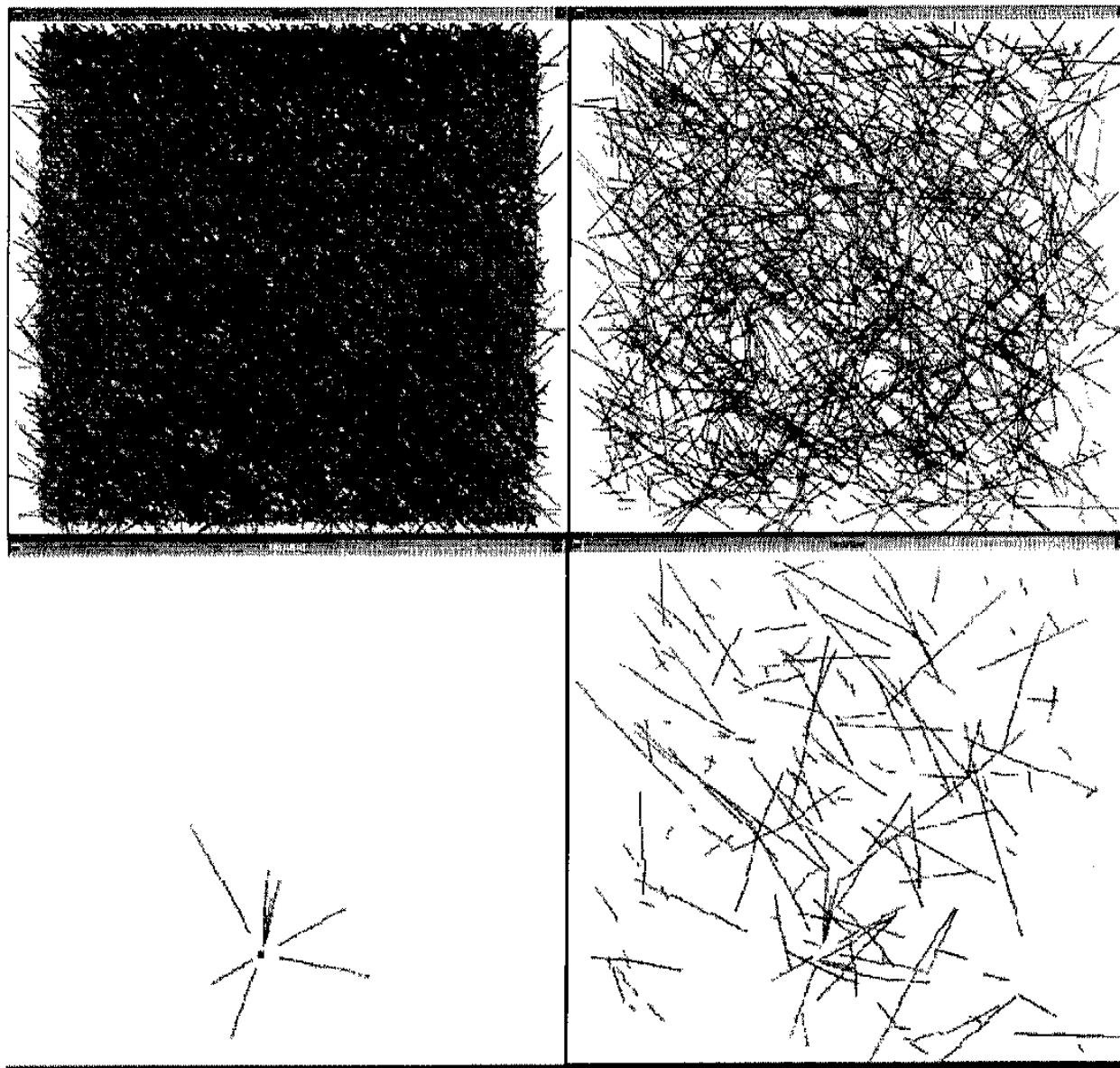
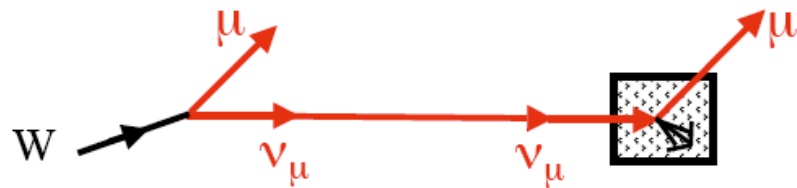
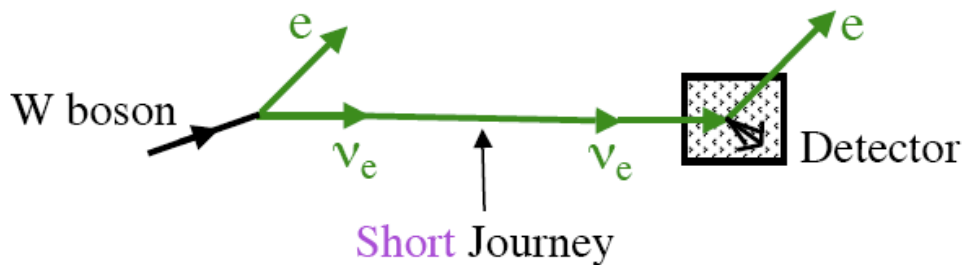


図 5.12: net scan 反応点探索の各段階 (左上から時計回り)。1) 読み込んだ全ての飛跡 ( $5 \times 5\text{mm}^2$ )、2) 測定領域を突き抜けている飛跡の排除、3) 低運動量の飛跡の排除、4) 一点 ( $4\mu\text{m}$  以内) 収束している飛跡

## What we Knew of Neutrinos: End of the 20th Century



- come in three flavors (see figure);
- interact only via weak interactions ( $W^\pm, Z^0$ );
- have ZERO mass – helicity good quantum number;
- $\nu_L$  field describes 2 degrees of freedom:
  - left-handed state  $\nu$ ,
  - right-handed state  $\bar{\nu}$  (CPT conjugate);
- neutrinos carry lepton number:
  - $L(\nu) = +1$ ,
  - $L(\bar{\nu}) = -1$ .

## 2– Neutrino Puzzles – 1960’s to 2000’s

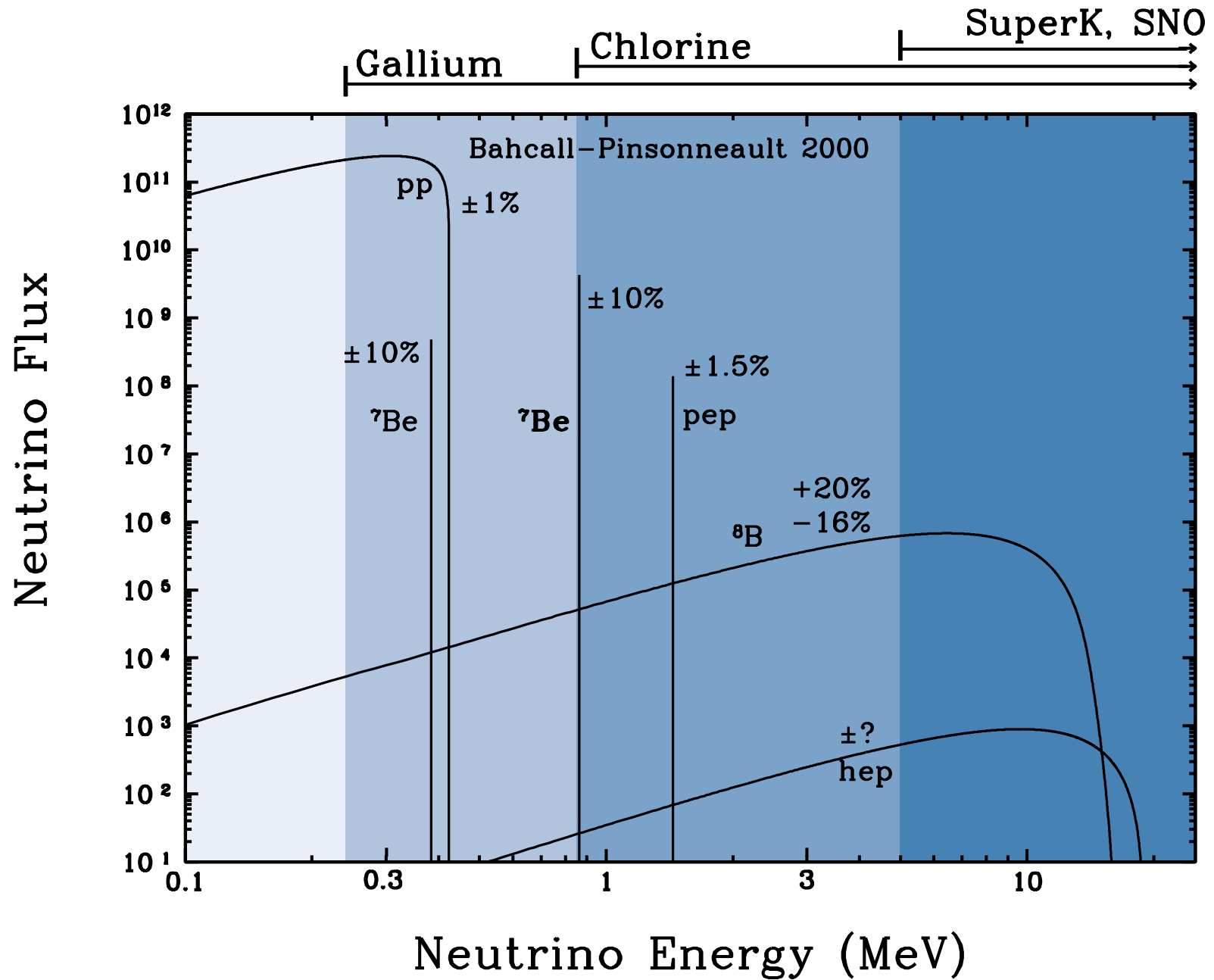
Long baseline neutrino experiments have revealed that **neutrinos change flavor** after propagating a finite distance, violating the definitions in the previous slide. The rate of change depends on the neutrino energy  $E_\nu$  and the baseline  $L$ .

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

Table 1. Nuclear reactions responsible for producing almost all of the Sun’s energy and the different “types” of solar neutrinos (nomenclature): *pp*-neutrinos, *pep*-neutrinos, *hep*-neutrinos,  ${}^7\text{Be}$ -neutrinos, and  ${}^8\text{B}$ -neutrinos. ‘Termination’ refers to the fraction of interacting protons that participate in the process.

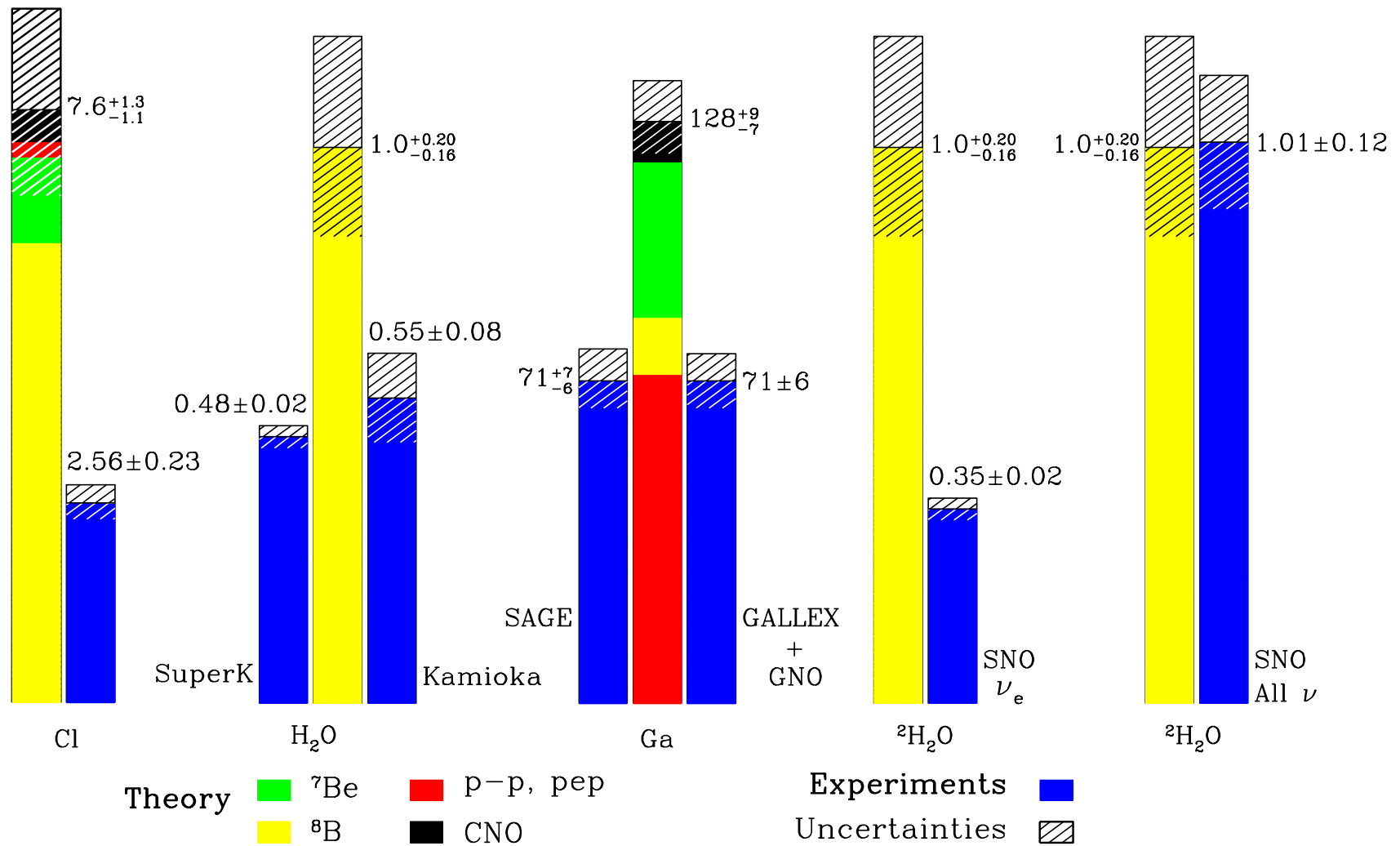
Reaction	Termination (%)	Neutrino Energy (MeV)	Nomenclature
$p + p \rightarrow {}^2\text{H} + e^+ + \nu_e$	99.96	$< 0.423$	<i>pp</i> -neutrinos
$p + e^- + p \rightarrow {}^2\text{H} + \nu_e$	0.044	1.445	<i>pep</i> -neutrinos
${}^2\text{H} + p \rightarrow {}^3\text{He} + \gamma$	100	–	–
${}^3\text{He} + {}^3\text{He} \rightarrow {}^4\text{He} + p + p$	85	–	–
${}^3\text{He} + {}^4\text{He} \rightarrow {}^7\text{Be} + \gamma$	15	–	–
${}^7\text{Be} + e^- \rightarrow {}^7\text{Li} + \nu_e$	15	0.863(90%) 0.386(10%)	${}^7\text{Be}$ -neutrinos
${}^7\text{Li} + p \rightarrow {}^4\text{He} + {}^4\text{He}$	–	–	–
${}^7\text{Be} + p \rightarrow {}^8\text{B} + \gamma$	0.02	–	–
${}^8\text{B} \rightarrow {}^8\text{Be}^* + e^+ + \nu_e$	–	$< 15$	${}^8\text{B}$ -neutrinos
${}^8\text{Be} \rightarrow {}^4\text{He} + {}^4\text{He}$	–	–	–
${}^3\text{He} + p \rightarrow {}^4\text{He} + e^+ + \nu_e$	0.00003	$< 18.8$	<i>hep</i> -neutrinos

Note: Adapted from Ref. 12. Please refer to Ref. 12 for a more detailed explanation.



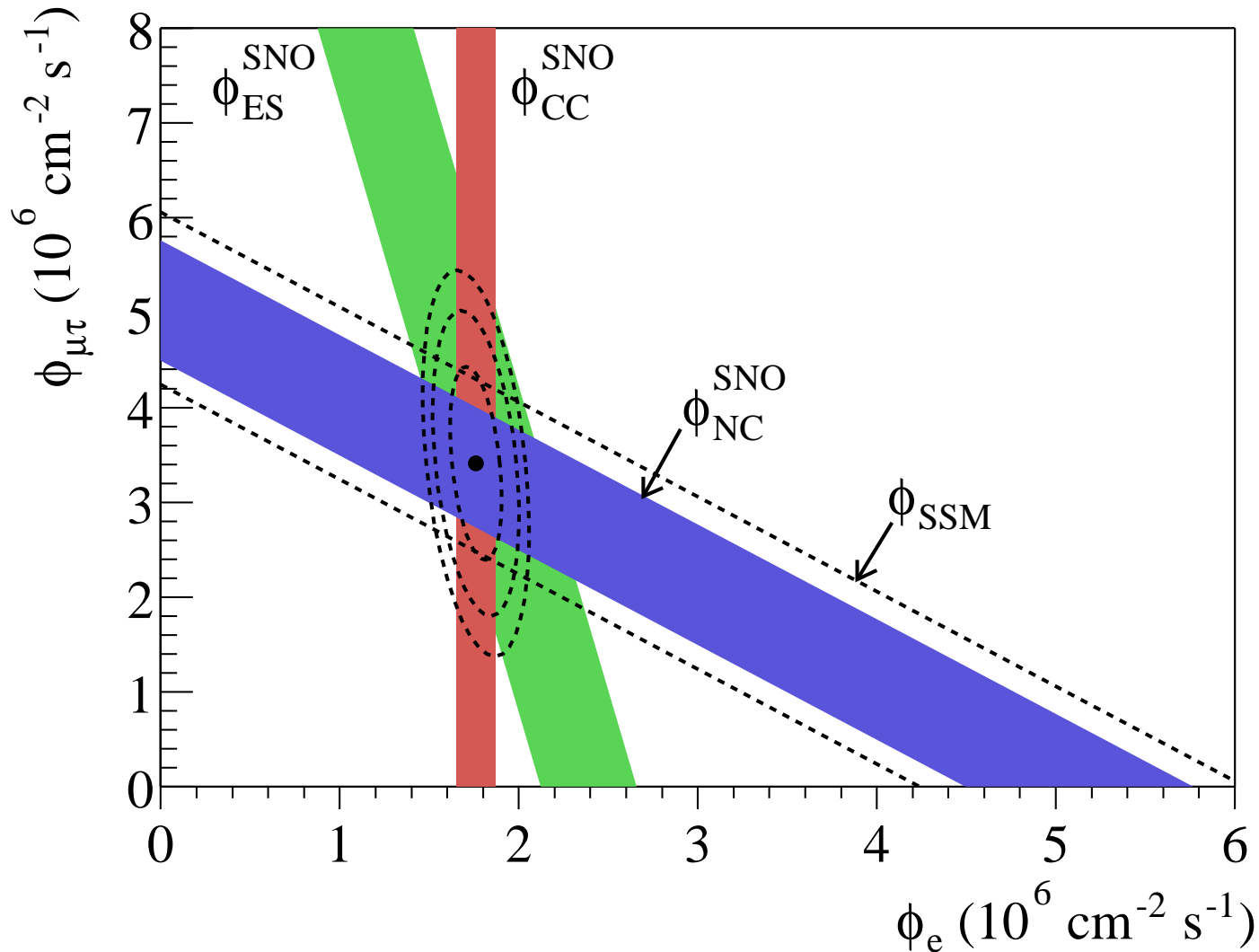
# Total Rates: Standard Model vs. Experiment

## Bahcall–Pinsonneault 2000

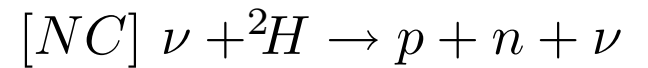
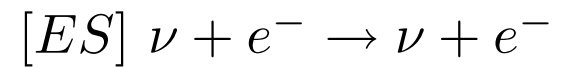
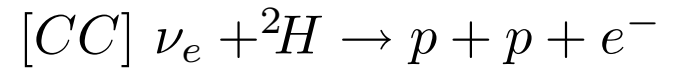




## The SNO Experiment: conclusive evidence for flavor change

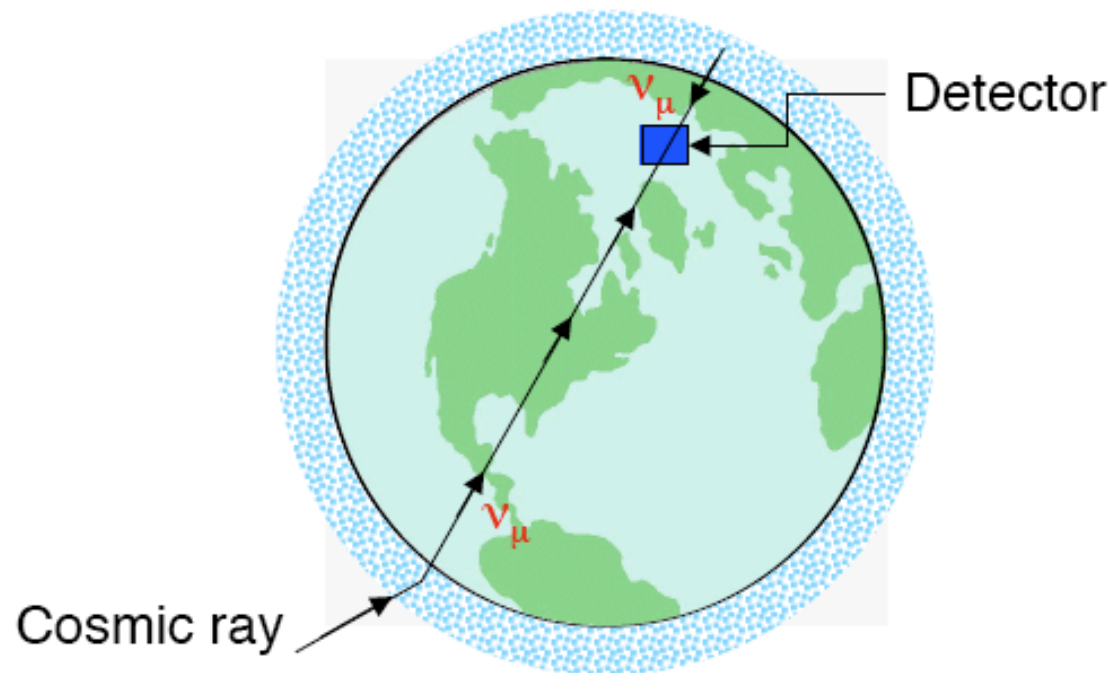


### SNO Measures:



different reactions  
sensitive to different  
neutrino flavors.

# Atmospheric Neutrinos



Isotropy of the  $\gtrsim 2$  GeV cosmic rays + Gauss' Law + No  $\nu_\mu$  disappearance

$$\Rightarrow \frac{\phi_{\nu_\mu}(\text{Up})}{\phi_{\nu_\mu}(\text{Down})} = 1 .$$

But Super-Kamiokande finds for  $E_\nu > 1.3$  GeV

$$\frac{\phi_{\nu_\mu}(\text{Up})}{\phi_{\nu_\mu}(\text{Down})} = 0.54 \pm 0.04 .$$

UP  $\neq$  DOWN – neutrinos can tell time!  $\rightarrow$  neutrinos have mass.

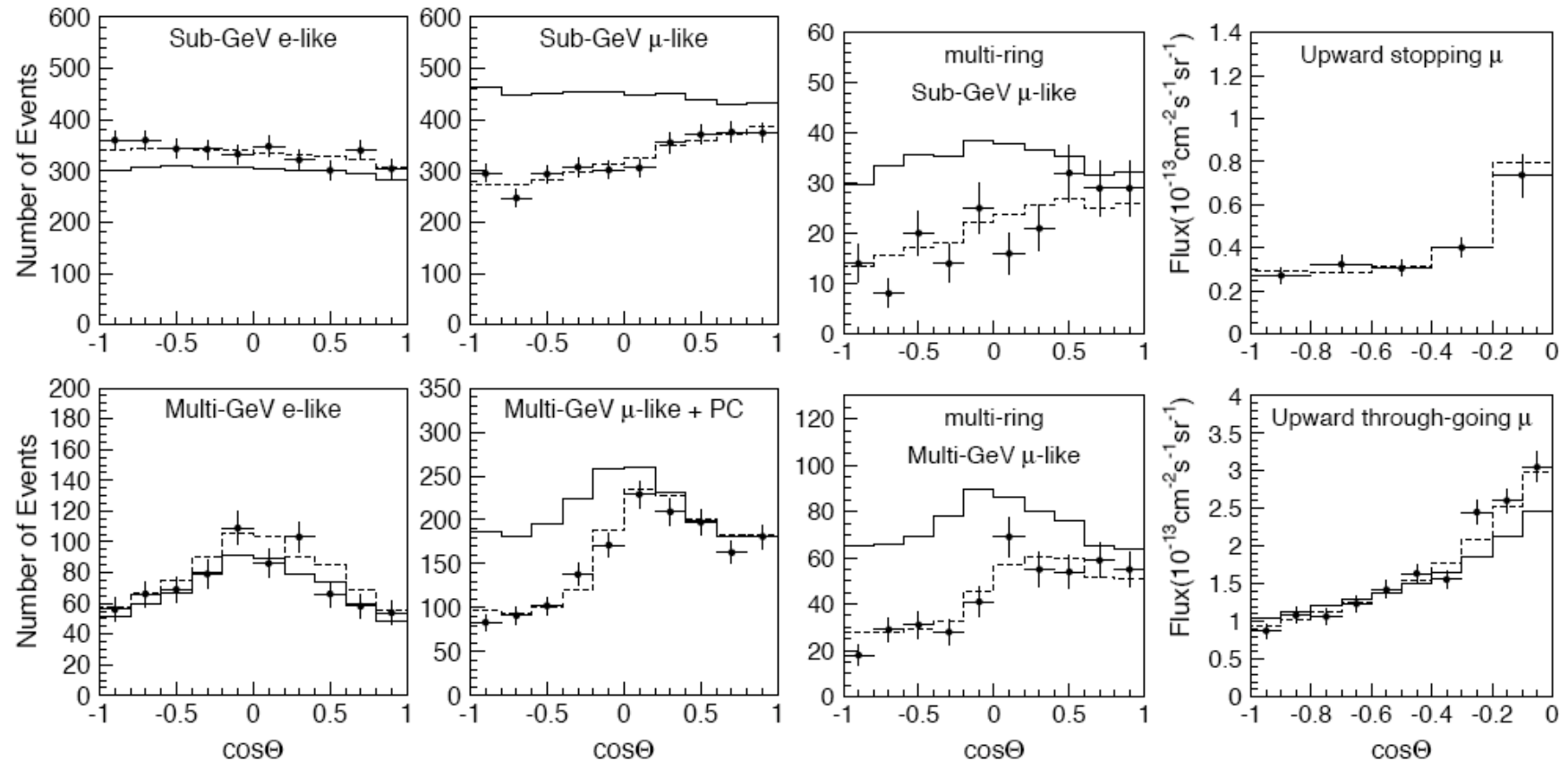


Figure 4. Zenith angle distribution for fully-contained single-ring  $e$ -like and  $\mu$ -like events, multi-ring  $\mu$ -like events, partially contained events and upward-going muons. The points show the data and the solid lines show the Monte Carlo events without neutrino oscillation. The dashed lines show the best-fit expectations for  $\nu_\mu \leftrightarrow \nu_\tau$  oscillations. From M. Ishitsuka [Super-Kamiokande Collaboration], hep-ex/0406076.

### 3 - Mass-Induced Neutrino Flavor Oscillations

Neutrino Flavor change can arise out of several different mechanisms. The simplest one is to appreciate that, once **neutrinos have mass, leptons can mix**. This turns out to be the correct mechanism (certainly the dominant one), and **only** explanation that successfully explains **all** long-baseline data consistently.

Neutrinos with a well defined mass:

$$\nu_1, \nu_2, \nu_3, \dots \quad \text{with masses } m_1, m_2, m_3, \dots$$

How do these states (neutrino mass eigenstates) relate to the neutrino flavor eigenstates ( $\nu_e, \nu_\mu, \nu_\tau$ )?

$$\nu_\alpha = U_{\alpha i} \nu_i \quad \alpha = e, \mu, \tau, \quad i = 1, 2, 3$$

$U$  is a unitary mixing matrix. I'll talk more about it later.

## The Propagation of Massive Neutrinos

Neutrino mass eigenstates are eigenstates of the free-particle Hamiltonian:

$$|\nu_i\rangle = e^{-iE_i t} |\nu_i\rangle, \quad E_i^2 - |\vec{p}_i|^2 = m_i^2$$

The neutrino flavor eigenstates are linear combinations of  $\nu_i$ 's, say:

$$|\nu_e\rangle = \cos\theta |\nu_1\rangle + \sin\theta |\nu_2\rangle.$$

$$|\nu_\mu\rangle = -\sin\theta |\nu_1\rangle + \cos\theta |\nu_2\rangle.$$

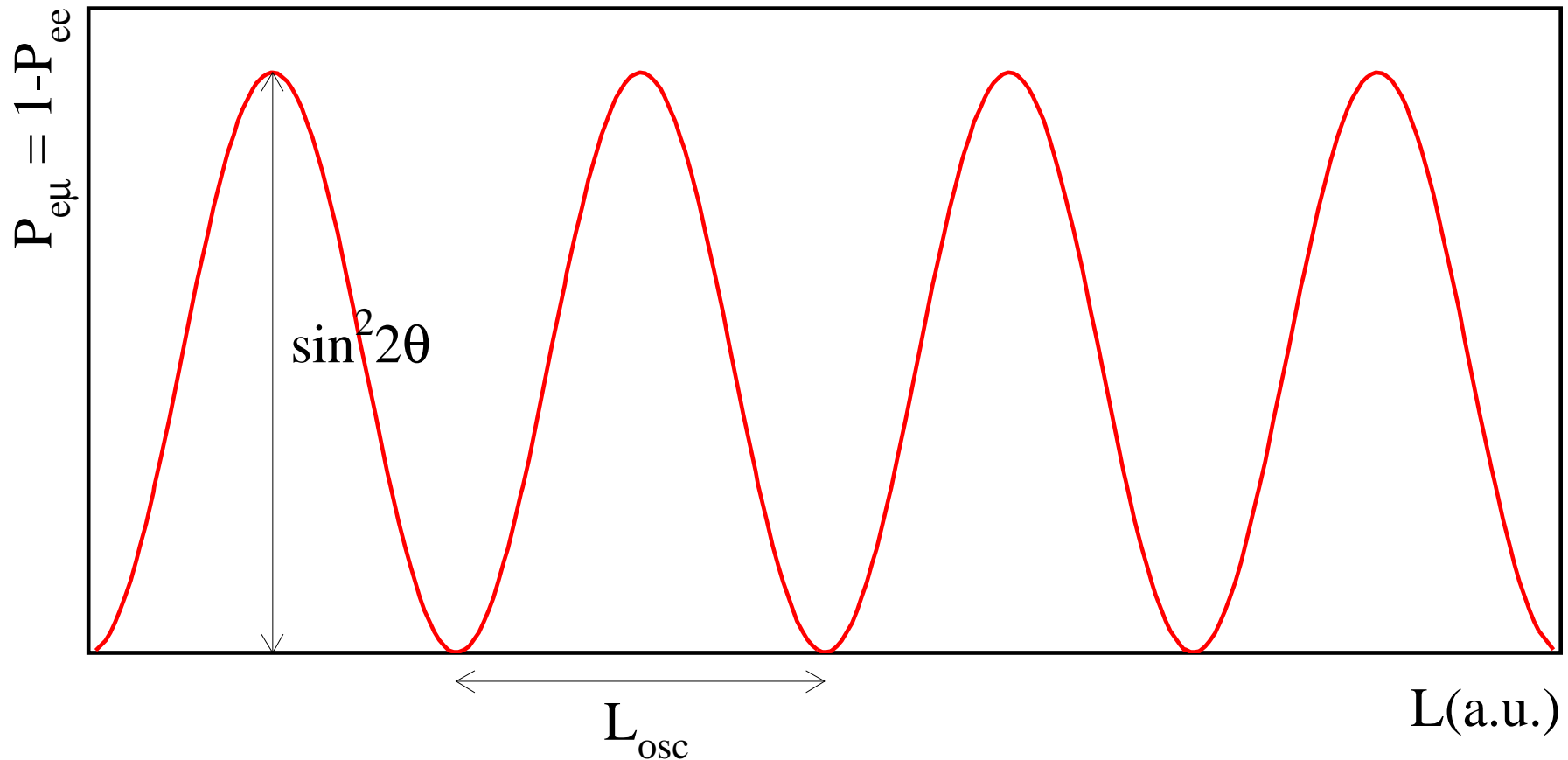
If this is the case, a state produced as a  $\nu_e$  evolves in vacuum into

$$|\nu(t, \vec{x})\rangle = \cos\theta e^{-ip_1 x} |\nu_1\rangle + \sin\theta e^{-ip_2 x} |\nu_2\rangle.$$

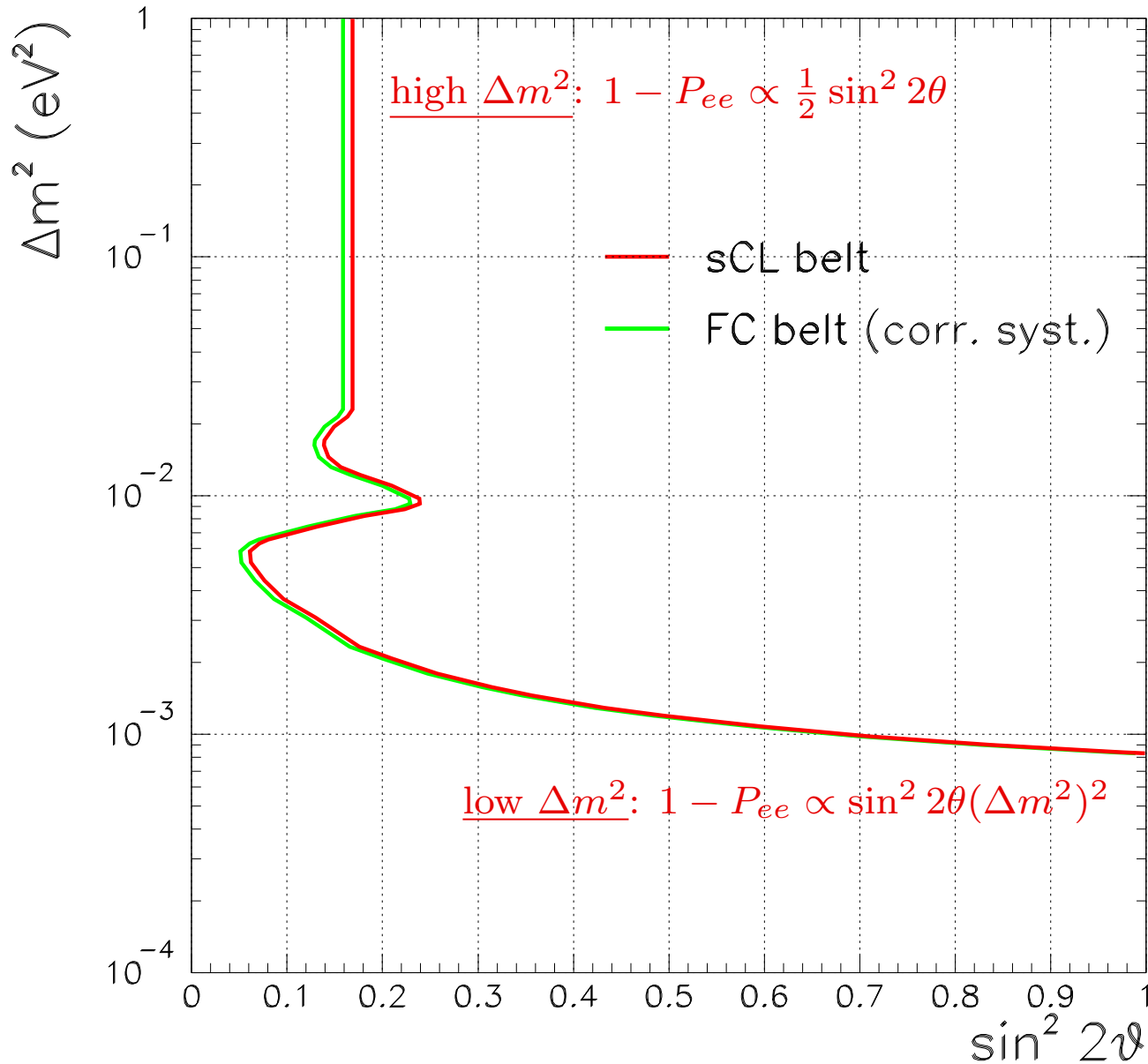
It is trivial to compute  $P_{e\mu}(L) \equiv |\langle \nu_\mu | \nu(t, z = L) \rangle|^2$ . It is just like a two-level system from basic undergraduate quantum mechanics! In the ultrarelativistic limit (always a good bet),  $t \simeq L$ ,  $E_i - p_{z,i} \simeq (m_i^2)/2E_i$ , and

$$P_{e\mu}(L) = \sin^2 2\theta \sin^2 \left( \frac{\Delta m^2 L}{4E_\nu} \right)$$

oscillation parameters:  $\left\{ \begin{array}{l} \pi \frac{L}{L_{\text{osc}}} \equiv \frac{\Delta m^2 L}{4E} = 1.267 \left( \frac{L}{\text{km}} \right) \left( \frac{\Delta m^2}{\text{eV}^2} \right) \left( \frac{\text{GeV}}{E} \right) \\ \text{amplitude } \sin^2 2\theta \end{array} \right.$



# CHOOZ experiment



$$P_{ee} = 1 - \sin^2 2\theta \sin^2 \left( \frac{\Delta m^2 L}{4E} \right)$$

result:  $1 - P_{ee} < 0.05$

There is a long (and oftentimes confused and confusing) history behind this derivation and several others. A comprehensive discussion can be found, for example, in

E.K. Akhmedov, A. Yu. Smirnov, 0905.1903 [hep-ph]

In a nutshell, neutrino oscillations as described above occur whenever

- Neutrino Production and Detection are Coherent  $\rightarrow$  cannot “tell”  $\nu_1$  from  $\nu_2$  from  $\nu_3$  but “see”  $\nu_e$  or  $\nu_\mu$  or  $\nu_\tau$ .
- Decoherence effects due to wave-packet separation are negligible  $\rightarrow$  baseline not too long that different “velocity” components of the neutrino wave-packet have time to physically separate.
- The energy released in production and detection is large compared to the neutrino mass  $\rightarrow$  so we can assign all of the effect to the neutrino propagation, independent from the production process. Also assures ultra-relativistic approximation good.



$$P_{\mu\mu} = 1 - \sin^2 2\theta \sin^2 \left( \frac{\Delta m^2 L}{4E} \right) \quad \text{Works great for } \sin^2 2\theta \sim 1 \text{ and } \Delta m^2 \sim 10^{-3} \text{ eV}^2$$

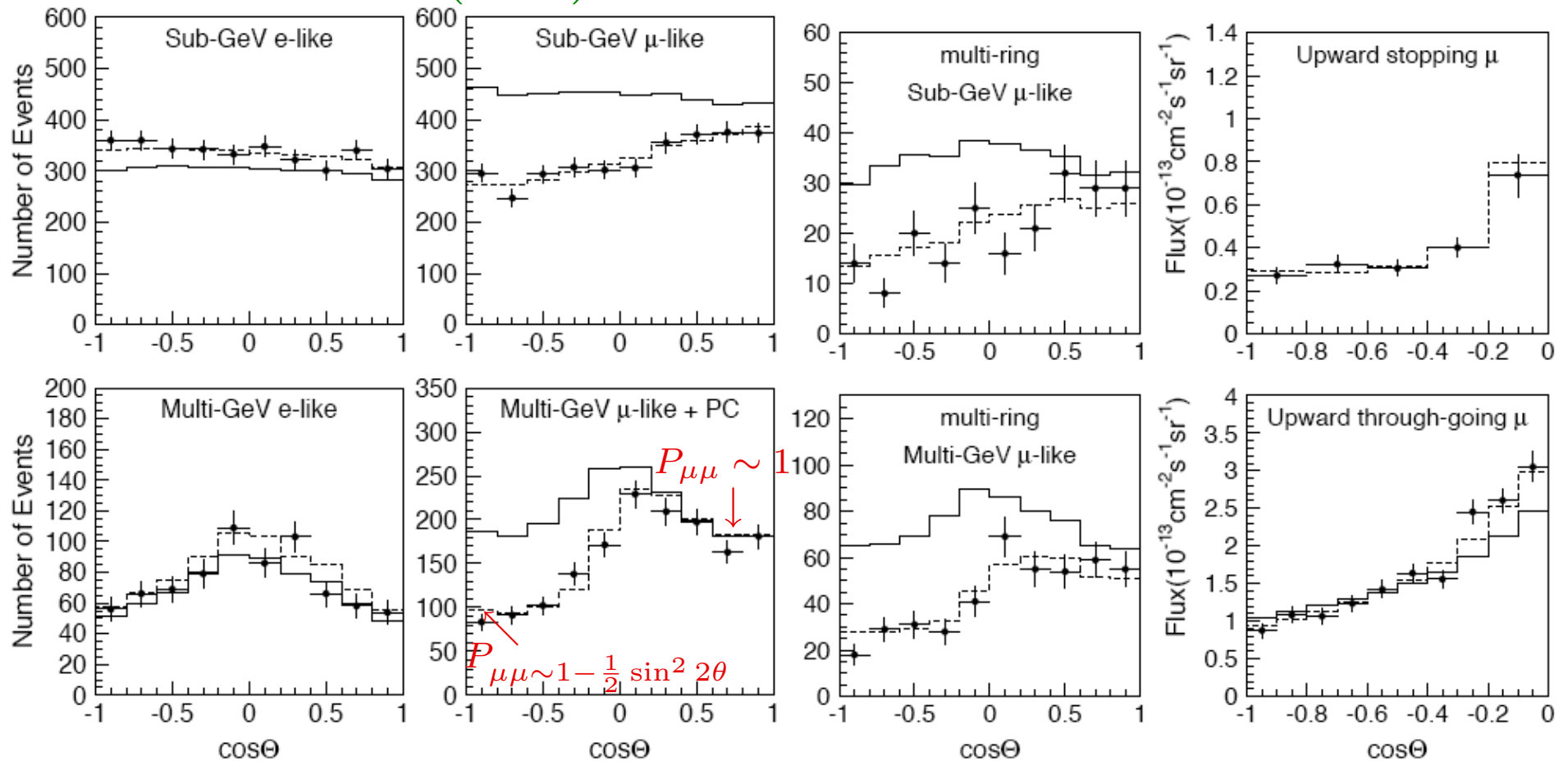
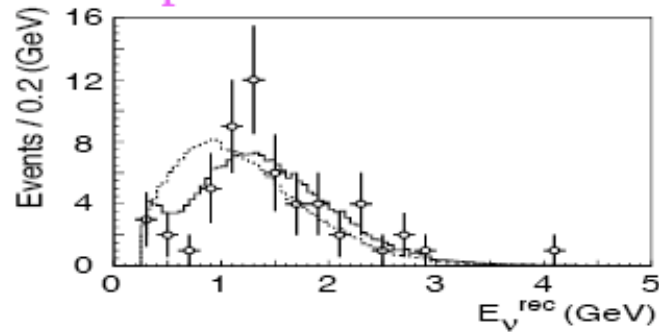


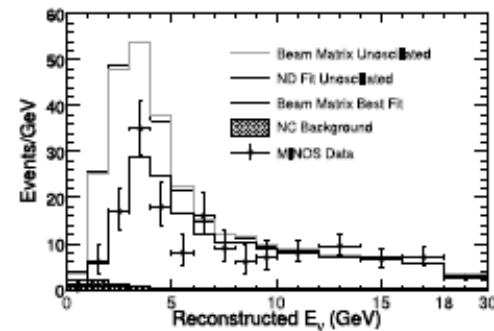
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K2K MINOS Opera/Icarus	$\nu_\mu$ at KEK $\nu_\mu$ at Fermilab $\nu_\mu$ at CERN	SK Soundan Gran Sasso	L=250 km L=735 km L=740 km
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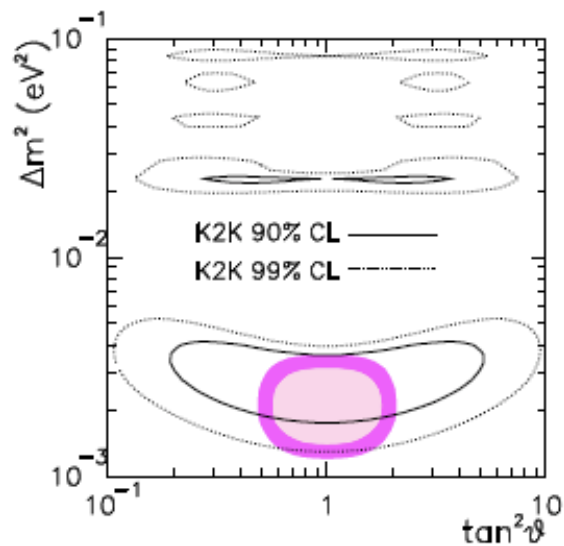
K2K 2004: spectral distortion



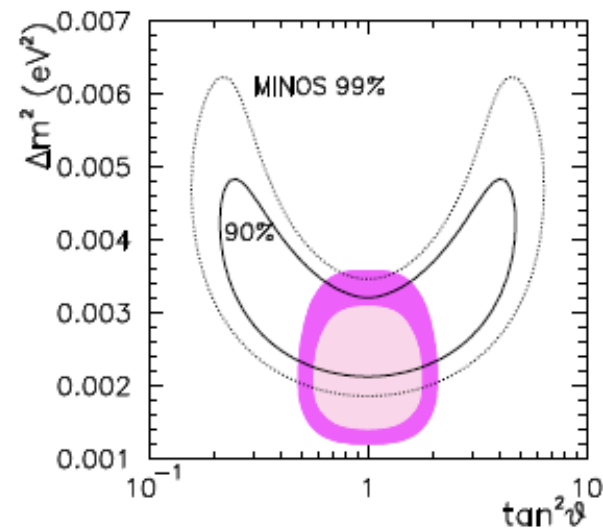
MINOS 2006: spectral distortion



Confirmation of ATM oscillations



Confirmation of ATM oscillations



[Gonzalez-Garcia, PASI 2006]

## Matter Effects

The neutrino propagation equation, in the ultra-relativistic approximation, can be re-expressed in the form of a Schrödinger-like equation. In the mass basis:

$$i \frac{d}{dL} |\nu_i\rangle = \frac{m_i^2}{2E} |\nu_i\rangle,$$

up to a term proportional to the identity. In the weak/flavor basis

$$i \frac{d}{dL} |\nu_\beta\rangle = U_{\beta i} \frac{m_i^2}{2E} U_{i\alpha}^\dagger |\nu_\alpha\rangle.$$

In the  $2 \times 2$  case,

$$i \frac{d}{dL} \begin{pmatrix} |\nu_e\rangle \\ |\nu_\mu\rangle \end{pmatrix} = \frac{\Delta m^2}{2E} \begin{pmatrix} \sin^2 \theta & \cos \theta \sin \theta \\ \cos \theta \sin \theta & \cos^2 \theta \end{pmatrix} \begin{pmatrix} |\nu_e\rangle \\ |\nu_\mu\rangle \end{pmatrix},$$

(again, up to additional terms proportional to the  $2 \times 2$  identity matrix).

Fermi Lagrangian, after a Fiertz rearrangement of the charged-current terms:

$$\mathcal{L} \supset \bar{\nu}_{eL} i \partial_\mu \gamma^\mu \nu_{eL} - 2\sqrt{2}G_F (\bar{\nu}_{eL} \gamma^\mu \nu_{eL}) (\bar{e}_L \gamma_\mu e_L) + \dots$$

Equation of motion for one electron neutrino state in the presence of a non-relativistic electron background, in the rest frame of the electrons:

$$\langle \bar{e}_L \gamma_\mu e_L \rangle = \delta_{\mu 0} \frac{N_e}{2}$$

where  $N_e \equiv e^\dagger e$  is the average electron number density (at rest, hence  $\delta_{\mu 0}$  term). Factor of 1/2 from the “left-handed” half.

Dirac equation for a one neutrino state inside a cold electron “gas” is (ignore neutrino mass)

$$(i\partial^\mu \gamma_\mu - \sqrt{2}G_F N_e \gamma_0) |\nu_e\rangle = 0.$$

In the ultrarelativistic limit, (plus  $\sqrt{2}G_F N_e \ll E$ ), dispersion relation is

$$E \simeq |\vec{p}| \pm \sqrt{2}G_F N_e, \quad + \text{ for } \nu, \quad - \text{ for } \bar{\nu}$$

$$i \frac{d}{dL} \begin{pmatrix} |\nu_e\rangle \\ |\nu_\mu\rangle \end{pmatrix} = \left[ \frac{\Delta m^2}{2E} \begin{pmatrix} \sin^2 \theta & \cos \theta \sin \theta \\ \cos \theta \sin \theta & \cos^2 \theta \end{pmatrix} + \begin{pmatrix} A & 0 \\ 0 & 0 \end{pmatrix} \right] \begin{pmatrix} |\nu_e\rangle \\ |\nu_\mu\rangle \end{pmatrix},$$

$A = \pm\sqrt{2}G_F N_e$  (+ for neutrinos, – for antineutrinos).

Note: Similar effect from neutral current interactions common to all (active) neutrino species  $\rightarrow$  proportional to the identity.

In general, this is hard to solve, as  $A$  is a function of  $L$ : two-level non-relativistic quantum mechanical system in the presence of time dependent potential.

In some cases, however, the solution is rather simple.

Constant  $A$ : good approximation for neutrinos propagating through matter inside the Earth [exception: neutrinos that see Earth's internal structure (the crust, the mantle, the outer core, the inner core)]

$$i \frac{d}{dL} \begin{pmatrix} |\nu_e\rangle \\ |\nu_\mu\rangle \end{pmatrix} = \begin{pmatrix} A & \Delta/2 \sin 2\theta \\ \Delta/2 \sin 2\theta & \Delta \cos 2\theta \end{pmatrix} \begin{pmatrix} |\nu_e\rangle \\ |\nu_\mu\rangle \end{pmatrix}, \quad \Delta \equiv \Delta m^2 / 2E.$$

$$P_{e\mu} = \sin^2 2\theta_M \sin^2 \left( \frac{\Delta_M L}{2} \right),$$

where

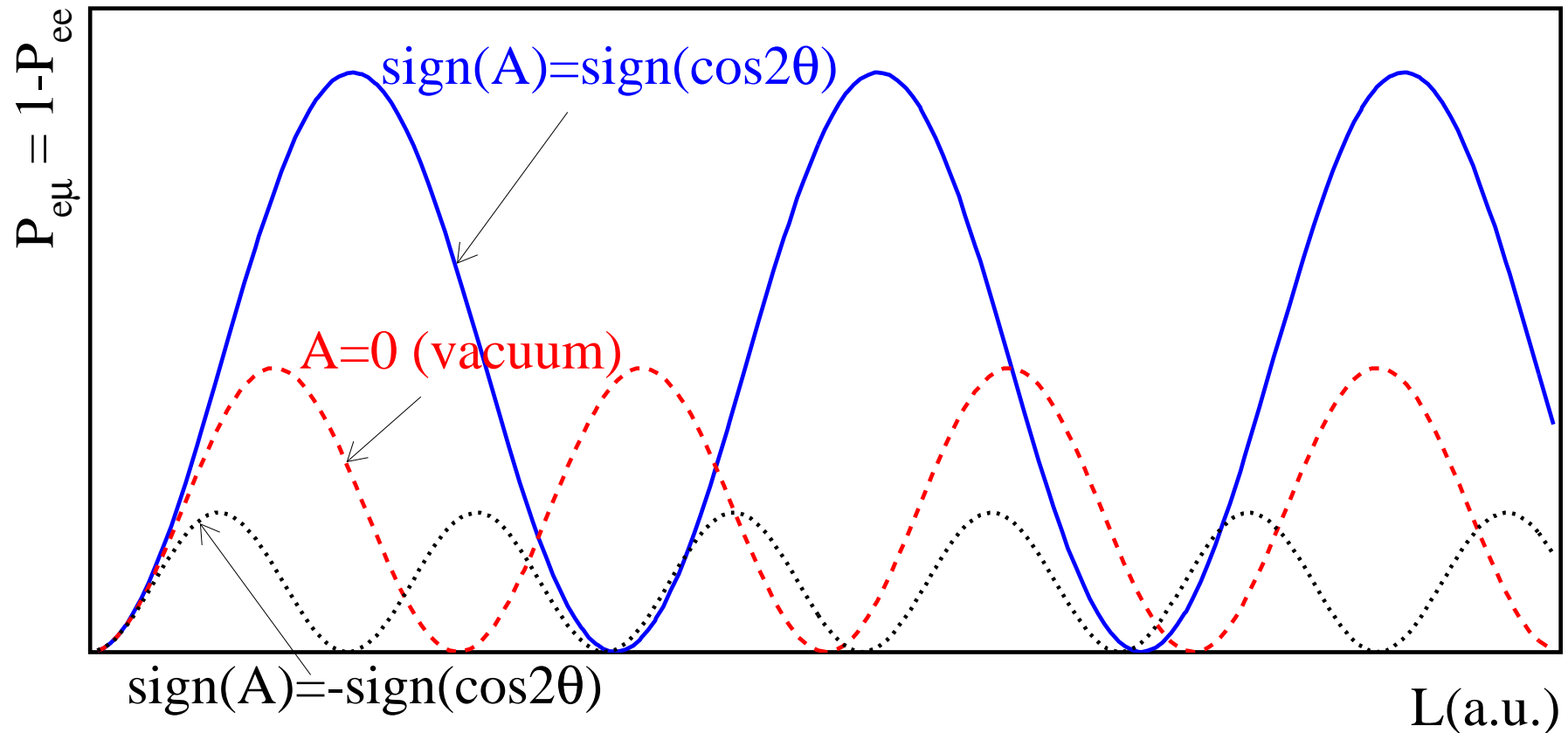
$$\begin{aligned} \Delta_M &= \sqrt{(A - \Delta \cos 2\theta)^2 + \Delta^2 \sin^2 2\theta}, \\ \Delta_M \sin 2\theta_M &= \Delta \sin 2\theta, \\ \Delta_M \cos 2\theta_M &= A - \Delta \cos 2\theta. \end{aligned}$$

The presence of matter affects neutrino and antineutrino oscillation differently.

Nothing wrong with this: CPT-theorem relates the propagation of neutrinos in an electron background to the propagation of antineutrinos in a positron background.

Enlarged parameter space in the presence of matter effects.

For example, can tell whether  $\cos 2\theta$  is positive or negative.



## The MSW Effect

Curiously enough, the oldest neutrino puzzle is the one that is most subtle to explain. This is because solar neutrinos traverse a strongly varying matter density on their way from the center of the Sun to the surface of the Earth.

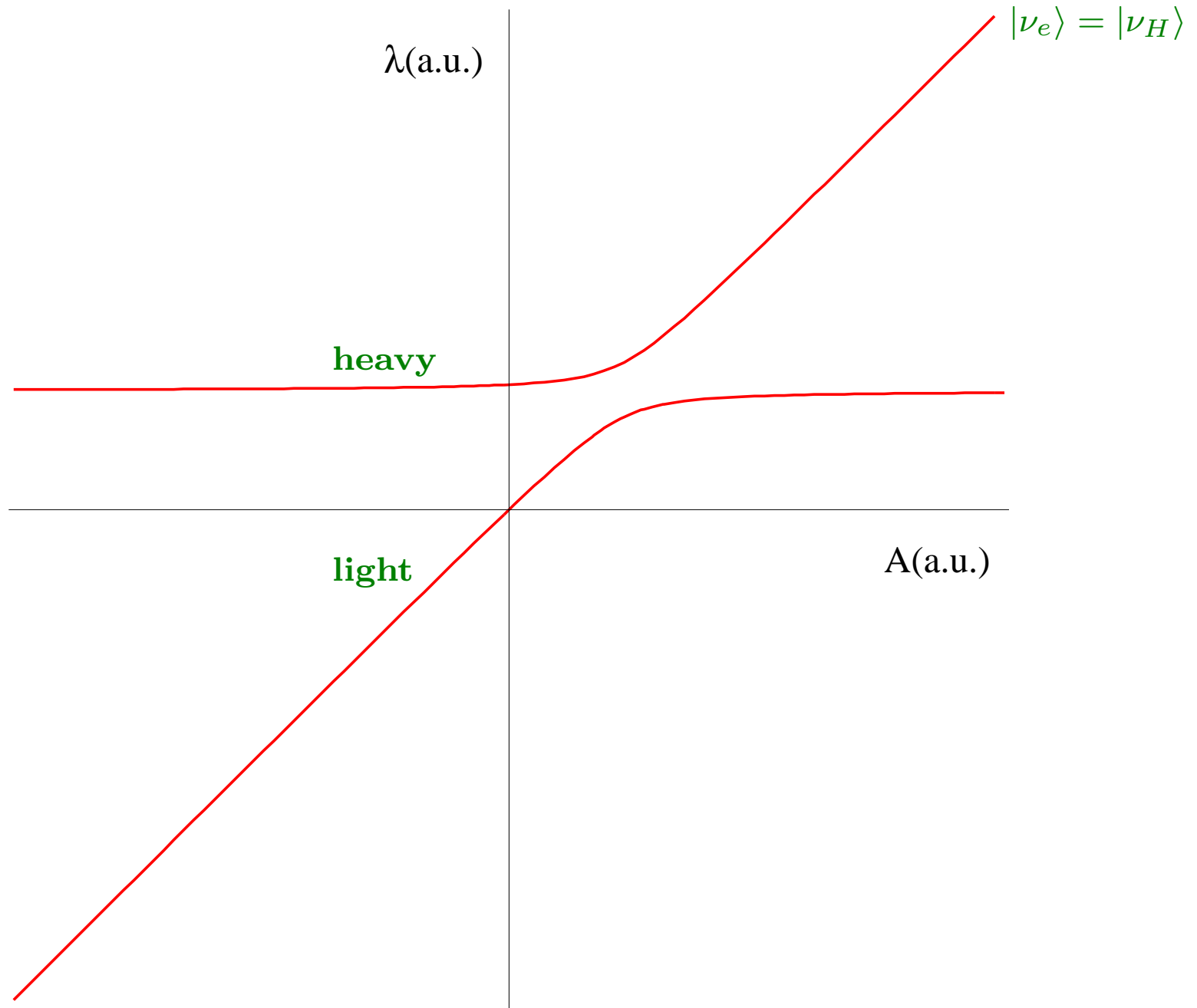
For the Hamiltonian

$$\left[ \Delta \begin{pmatrix} \sin^2 \theta & \cos \theta \sin \theta \\ \cos \theta \sin \theta & \cos^2 \theta \end{pmatrix} + A \begin{pmatrix} 1 & 0 \\ 0 & 0 \end{pmatrix} \right],$$

it is easy to compute the eigenvalues as a function of  $A$ :

(remember,  $\Delta = \Delta m^2 / 2E$ )





$A$  decreases “slowly” as a function of  $L \Rightarrow$  system evolves adiabatically.

$|\nu_e\rangle = |\nu_{2M}\rangle$  at the core  $\rightarrow |\nu_2\rangle$  in vacuum,

$$P_{ee}^{\text{Earth}} = |\langle \nu_e | \nu_2 \rangle|^2 = \sin^2 \theta.$$

Note that  $P_{ee} \simeq \sin^2 \theta$  applies in a **wide range of energies and baselines**, as long as the approximations mentioned above apply —**ideal to explain the energy independent suppression of the  $^8\text{B}$  solar neutrino flux!**

Furthermore, large average suppressions of the neutrino flux are allowed if  $\sin^2 \theta \ll 1$ . Compare with  $\bar{P}_{ee}^{\text{vac}} = 1 - 1/2 \sin^2 2\theta > 1/2$ .

One can expand on the result above by loosening some of the assumptions.  $|\nu_e\rangle$  state is produced in the Sun’s core as an *incoherent* mixture of  $|\nu_{1M}\rangle$  and  $|\nu_{2M}\rangle$ . Introduce adiabaticity parameter  $P_c$ , which measures the probability that a  $|\nu_{iM}\rangle$  matter Hamiltonian state will *not* exit the Sun as a  $|\nu_i\rangle$  mass-eigenstate.

$$\begin{aligned}
|\nu_e\rangle &\rightarrow |\nu_{1M}\rangle, \text{ with probability } \cos^2 \theta_M, \\
&\rightarrow |\nu_{2M}\rangle, \text{ with probability } \sin^2 \theta_M,
\end{aligned}$$

where  $\theta_M$  is the matter angle at the neutrino **production point**.

$$\begin{aligned}
|\nu_{1M}\rangle &\rightarrow |\nu_1\rangle, \text{ with probability } (1 - P_c), \\
&\rightarrow |\nu_2\rangle, \text{ with probability } P_c, \\
|\nu_{2M}\rangle &\rightarrow |\nu_1\rangle \text{ with probability } P_c, \\
&\rightarrow |\nu_2\rangle \text{ with probability } (1 - P_c).
\end{aligned}$$

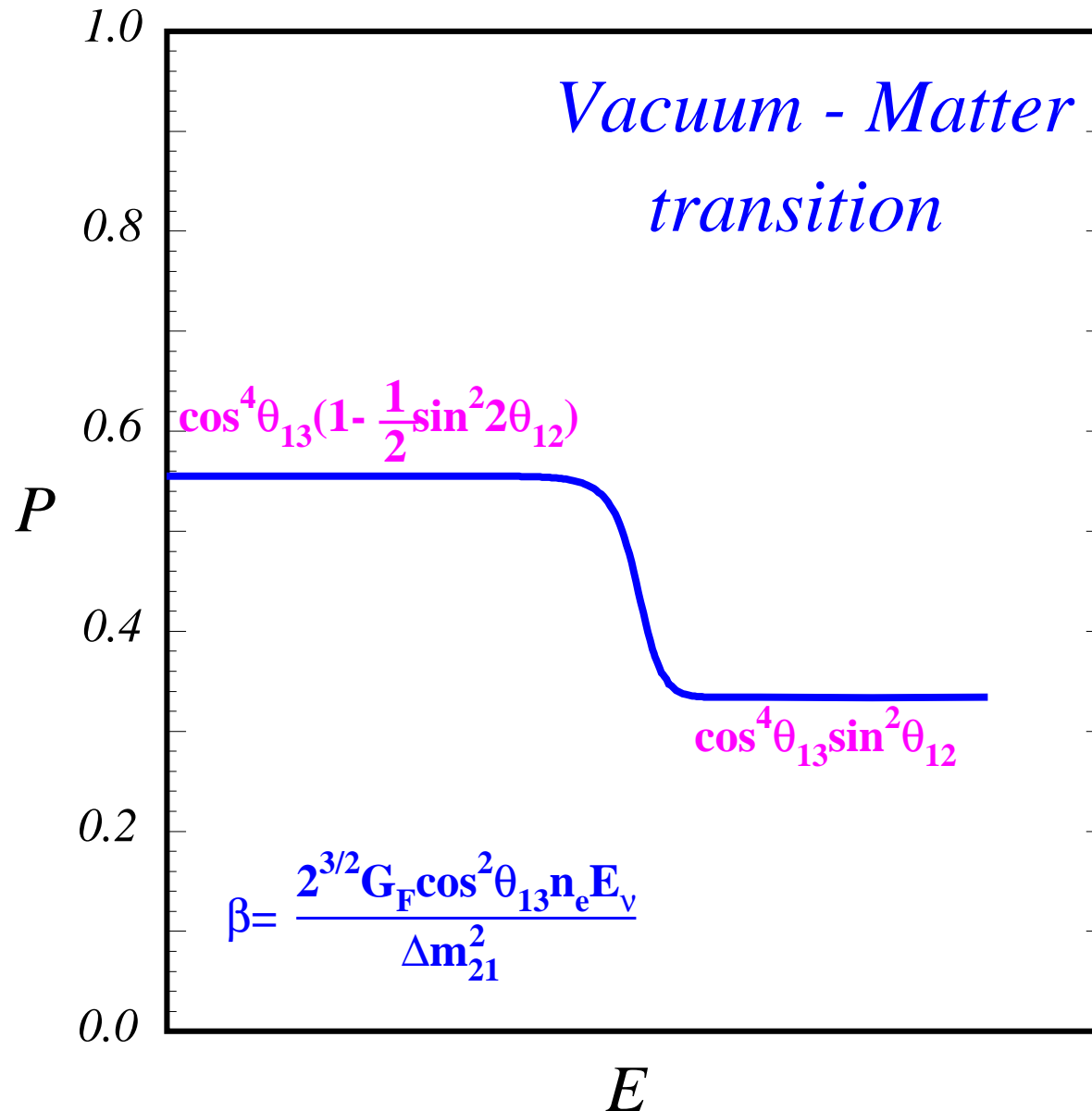
$P_{1e} = \cos^2 \theta$  and  $P_{2e} = \sin^2 \theta$  so

$$\begin{aligned}
P_{ee}^{\text{Sun}} = &\cos^2 \theta_M [(1 - P_c) \cos^2 \theta + P_c \sin^2 \theta] \\
&+ \sin^2 \theta_M [P_c \cos^2 \theta + (1 - P_c) \sin^2 \theta].
\end{aligned}$$

For  $N_e = N_{e0} e^{-L/r_0}$ ,  $P_c$ , (crossing probability), is exactly calculable

$$P_c = \frac{e^{-\gamma \sin^2 \theta} - e^{-\gamma}}{1 - e^{-\gamma}}, \quad \gamma = 2\pi r_0 \Delta. \tag{1}$$

Adiabatic condition:  $\gamma \gg 1$ , when  $P_c \rightarrow 0$ .



We need:

- $P_{ee} \sim 0.3$  ( $^8\text{B}$  neutrinos)
- $P_{ee} \sim 0.6$  ( $^7\text{Be}$ ,  $pp$  neutrinos)

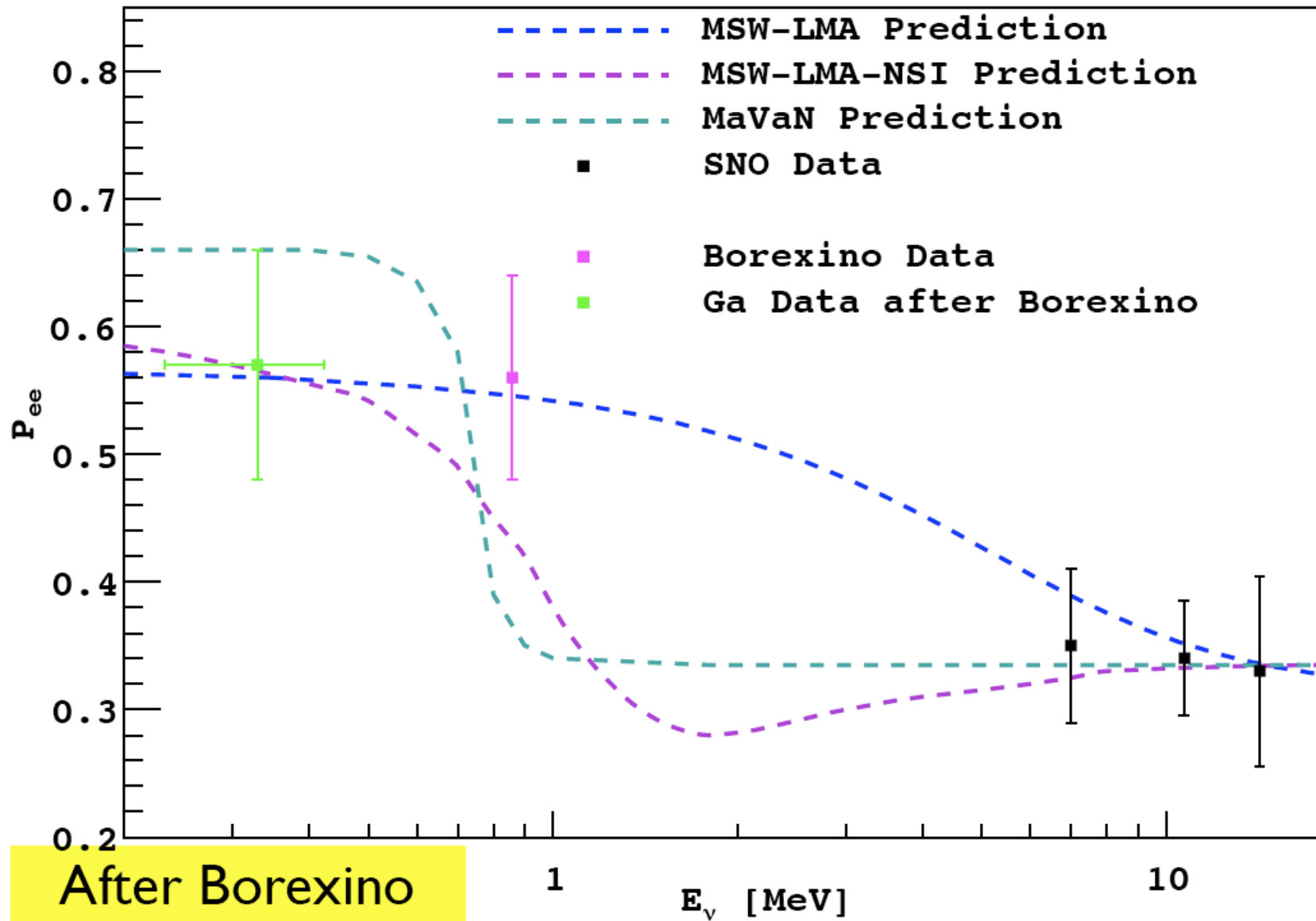
$$\Rightarrow \sin^2 \theta \sim 0.3$$

$$\Rightarrow \Delta m^2 \sim 10^{-(5 \text{ to } 4)} \text{ eV}^2$$

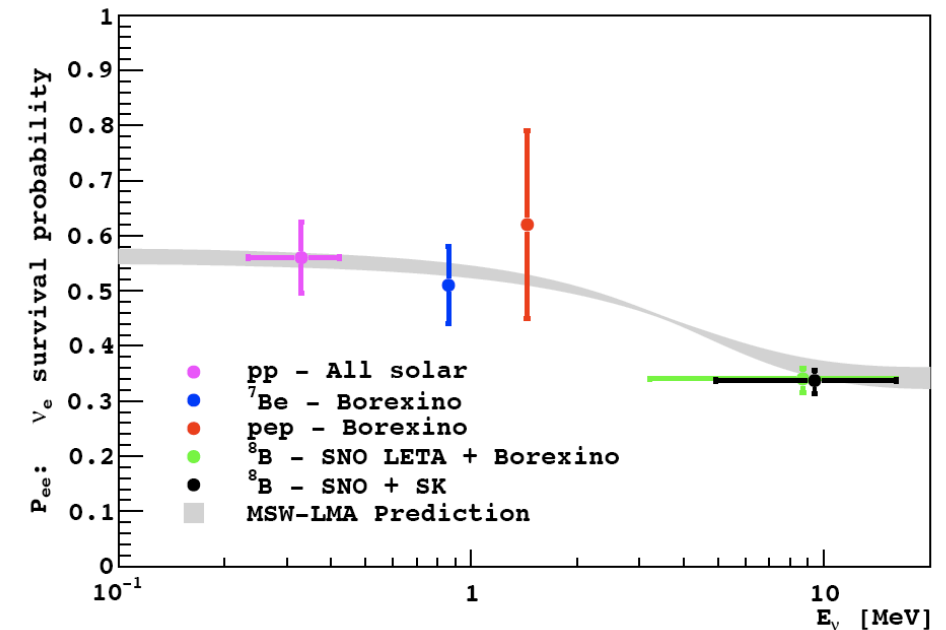
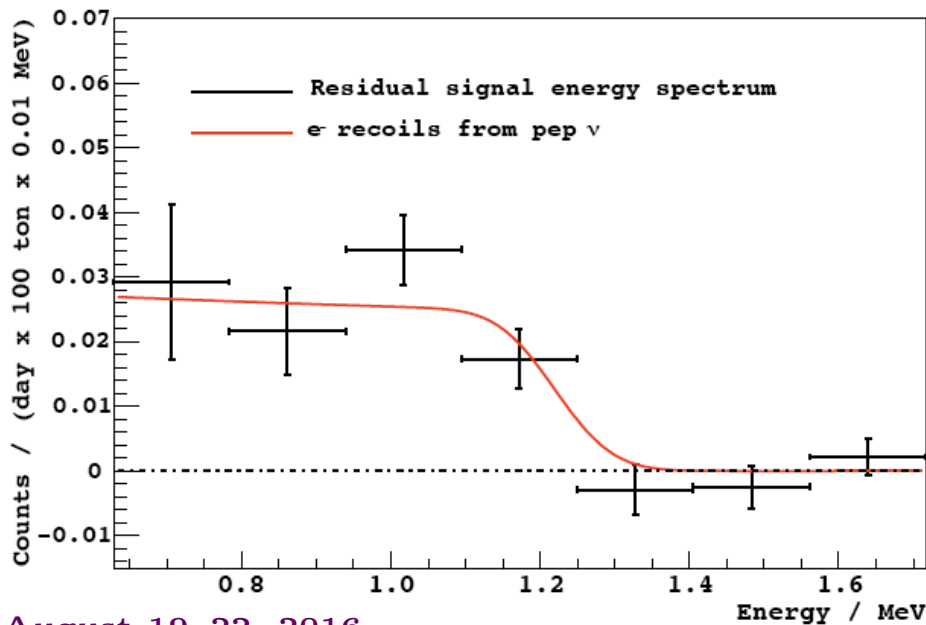
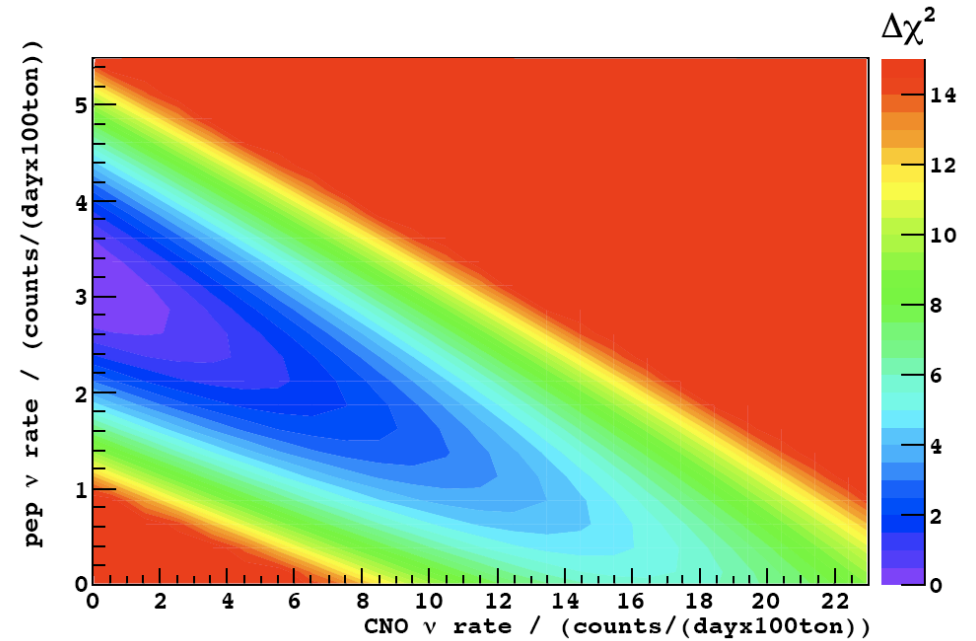
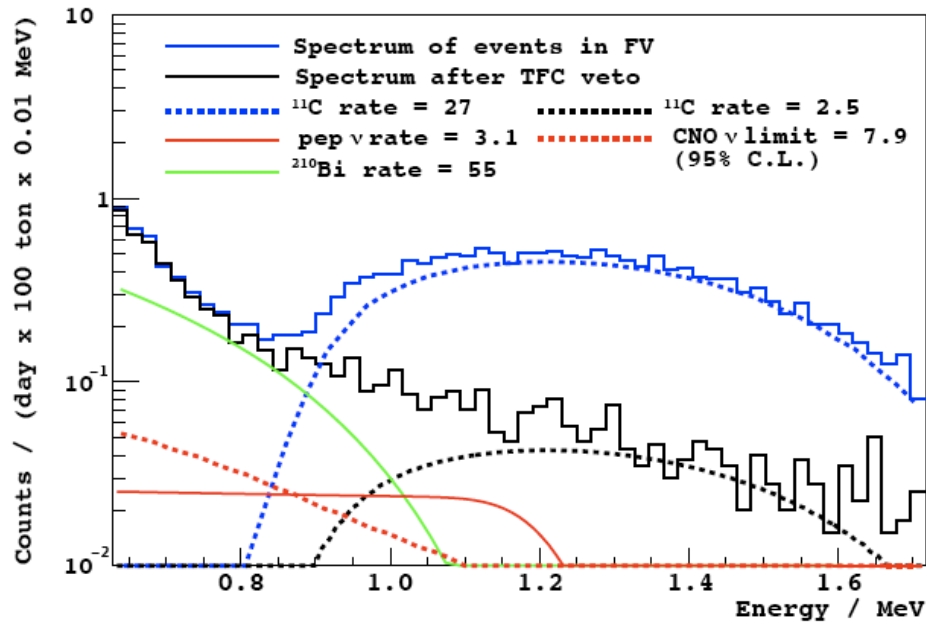
for a long time, there were many other options!

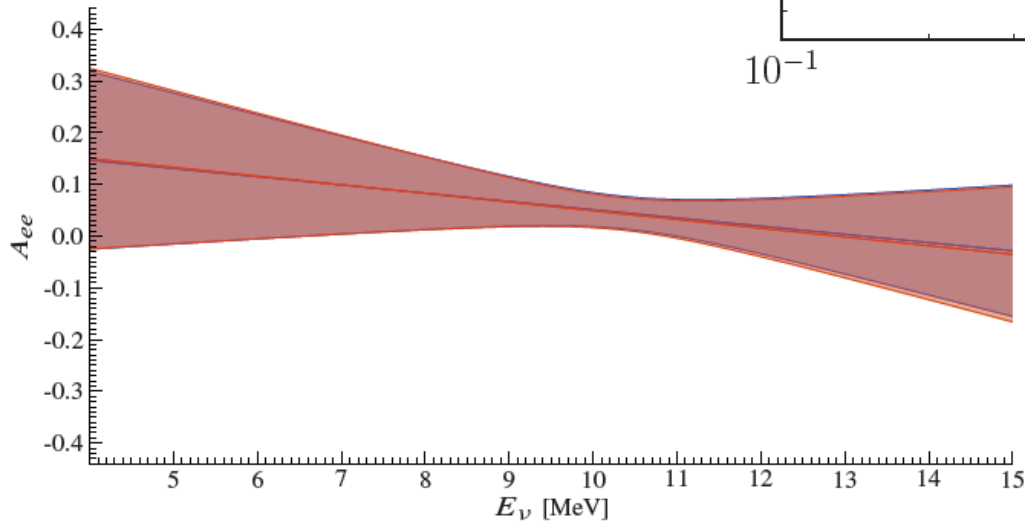
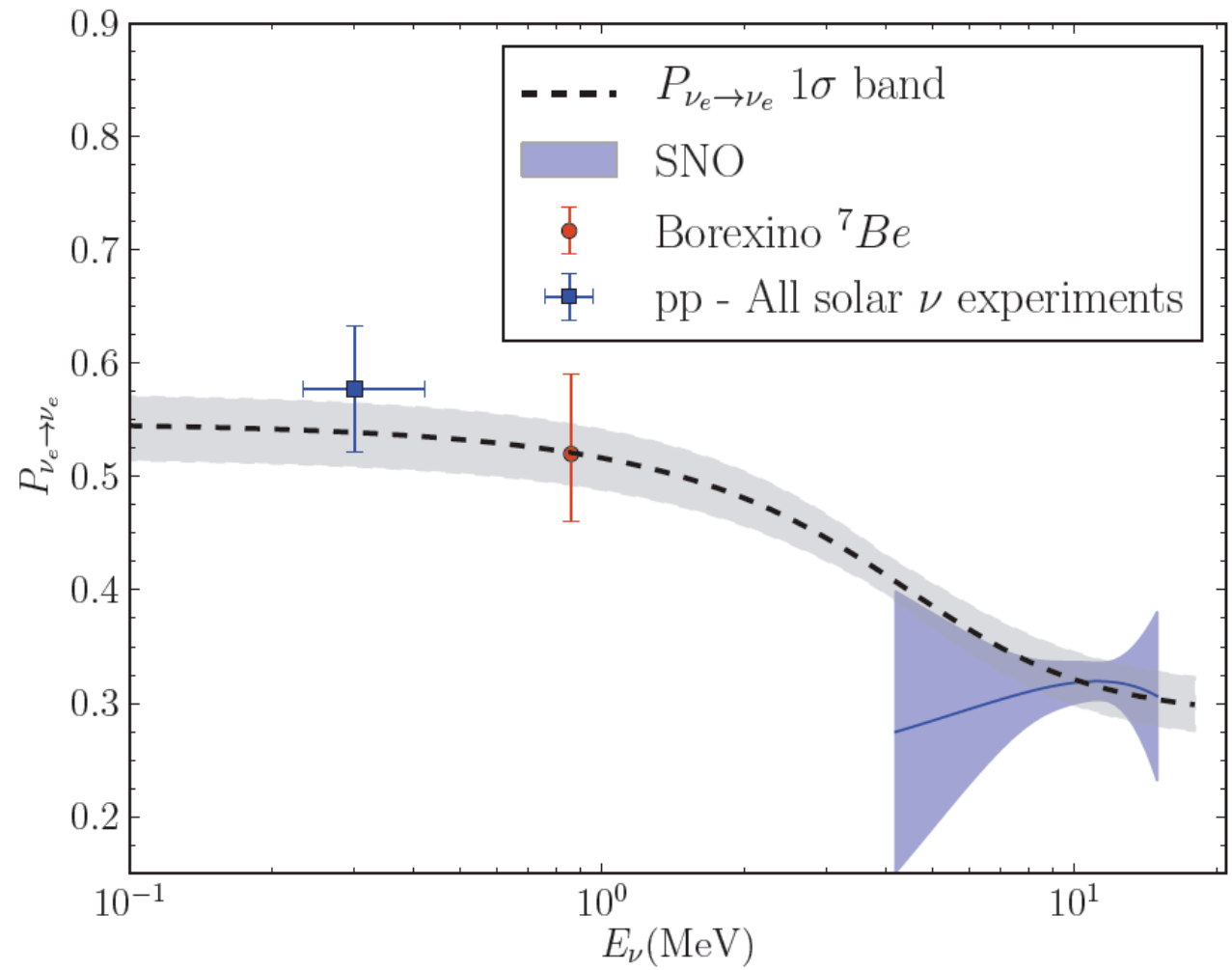
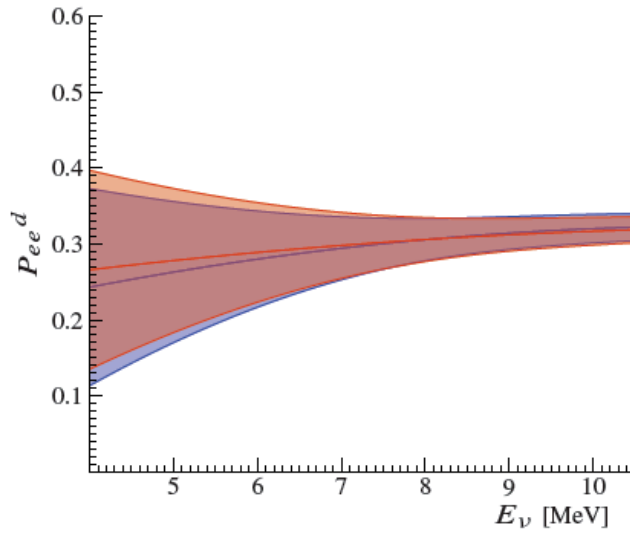
(LMA, LOW, SMA, VAC)

# Solar Neutrino Survival Probability



# Borexino, 1110.3230



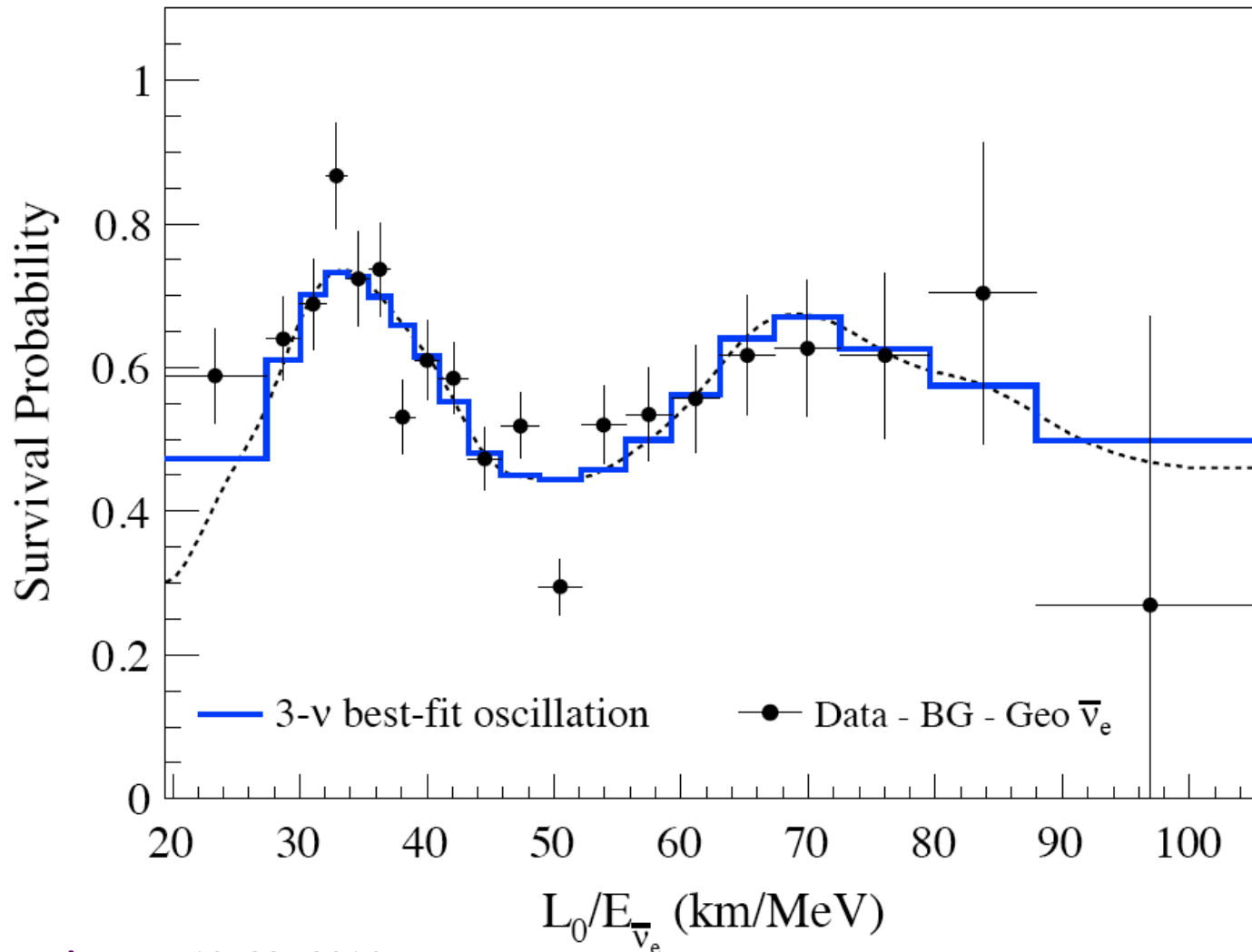


**“Final” SNO results, 1109.0763**

# Solar oscillations confirmed by Reactor experiment: KamLAND

[arXiv:1303.4667]

$$\text{phase} = 1.27 \left( \frac{\Delta m^2}{5 \times 10^{-5} \text{ eV}^2} \right) \left( \frac{5 \text{ MeV}}{E} \right) \left( \frac{L}{100 \text{ km}} \right)$$



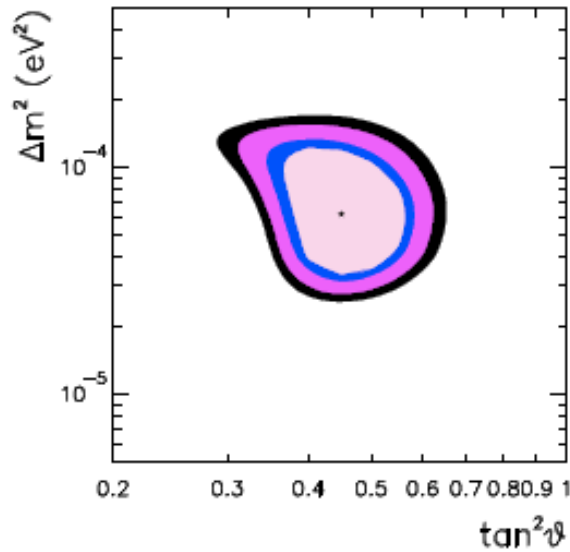
$$P_{ee} = 1 - \sin^2 2\theta \sin^2 \left( \frac{\Delta m^2 L}{4E} \right)$$

**oscillatory behavior!**



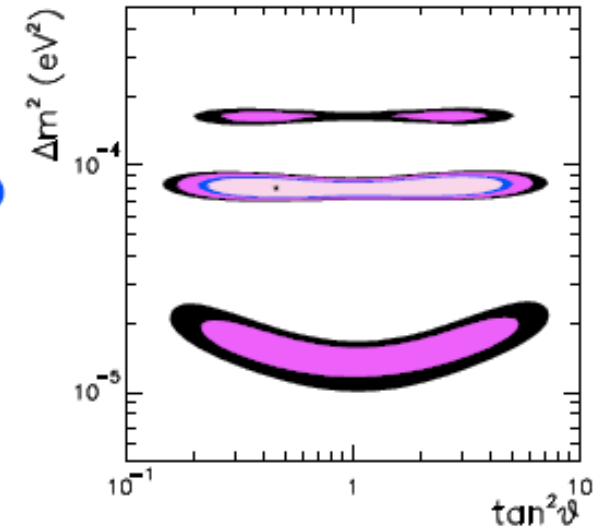
Solar

$\nu_e \rightarrow \nu_{\text{active}}$

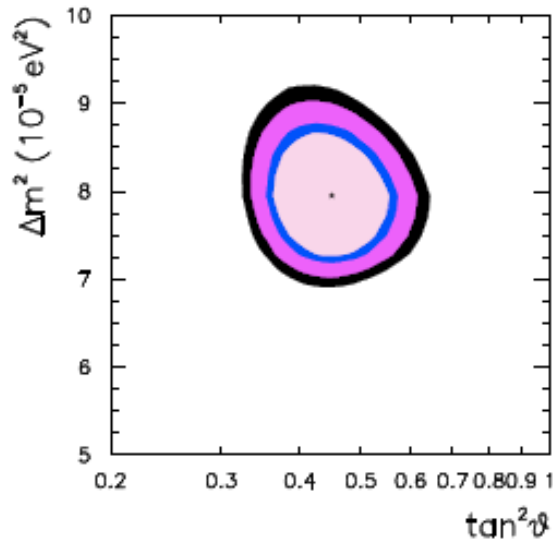


+ KamLAND

$\bar{\nu}_e \nrightarrow \bar{\nu}_e$



$\nu_e$  oscillation parameters compatible with  $\bar{\nu}_e$ : Sensible to assume CPT:  $P_{ee} = P_{\bar{e}\bar{e}}$



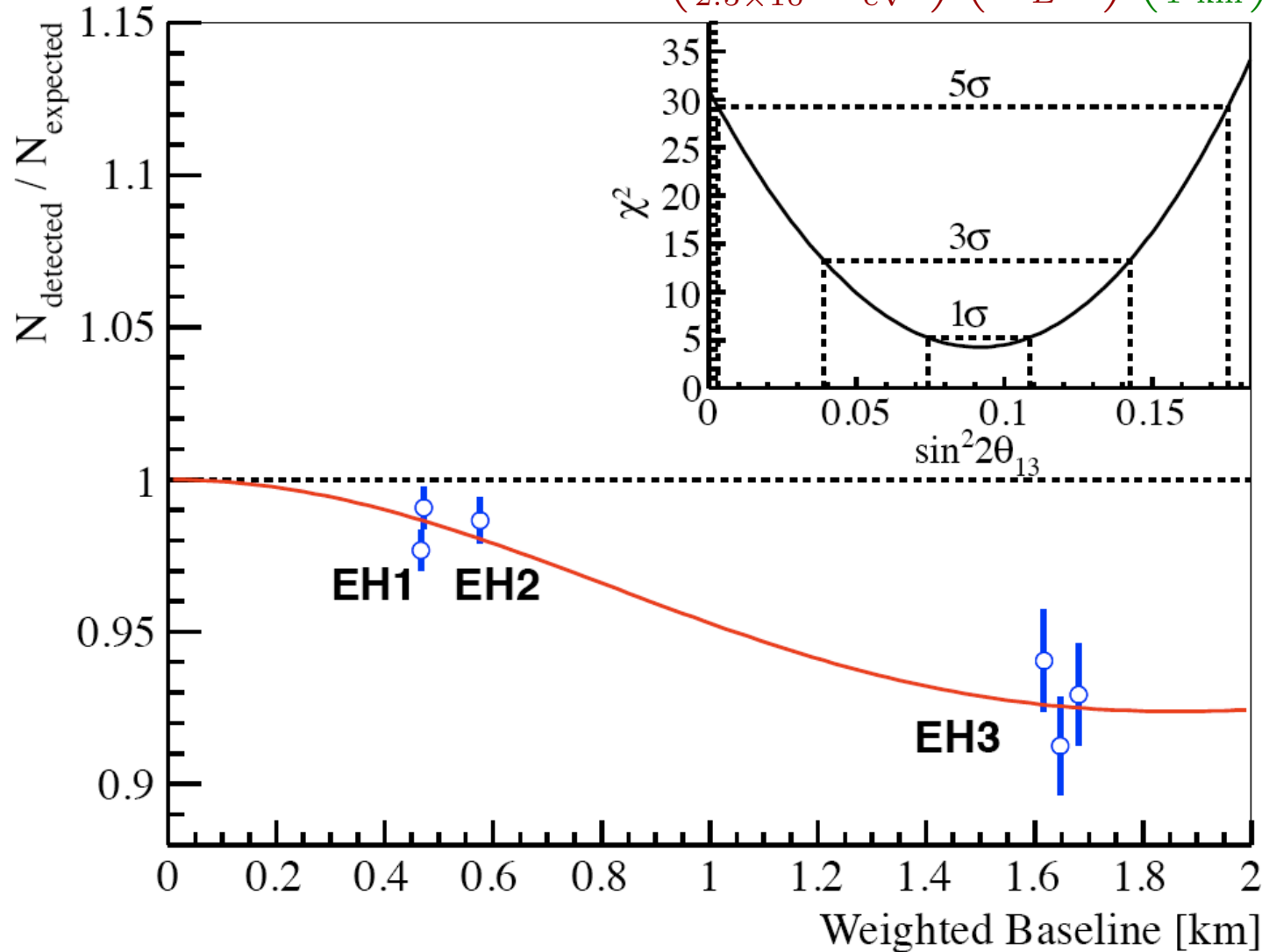
$$\Delta m_{\odot}^2 = (8_{-0.5}^{+0.4}) \times 10^{-5} \text{ eV}^2 \quad (1\sigma)$$

$$\tan^2 \theta_{\odot} = 0.45_{-0.05}^{+0.05}$$

[Gonzalez-Garcia, PASI 2006]

### Atmospheric Oscillations in the Electron Sector: Daya Bay, RENO, Double Chooz

$$\text{phase} = 0.64 \left( \frac{\Delta m^2}{2.5 \times 10^{-3} \text{ eV}^2} \right) \left( \frac{5 \text{ MeV}}{E} \right) \left( \frac{L}{1 \text{ km}} \right)$$



$$P_{ee} = 1 - \sin^2 2\theta \sin^2 \left( \frac{\Delta m^2 L}{4E} \right)$$

## Summarizing:

Both the solar and atmospheric puzzles can be properly explained in terms of **two-flavor** neutrino oscillations:

- **solar:**  $\nu_e \leftrightarrow \nu_a$  (linear combination of  $\nu_\mu$  and  $\nu_\tau$ ):  $\Delta m^2 \sim 10^{-4} \text{ eV}^2$ ,  $\sin^2 \theta \sim 0.3$ .
- **atmospheric:**  $\nu_\mu \leftrightarrow \nu_\tau$ :  $\Delta m^2 \sim 10^{-3} \text{ eV}^2$ ,  $\sin^2 \theta \sim 0.5$  (“maximal mixing”).
- **short-baseline reactors:**  $\nu_e \leftrightarrow \nu_a$  (linear combination of  $\nu_\mu$  and  $\nu_\tau$ ):  $\Delta m^2 \sim 10^{-3} \text{ eV}^2$ ,  $\sin^2 \theta \sim 0.02$ .

## Putting it all together – 3 flavor mixing:

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu1} & U_{\mu2} & U_{\mu3} \\ U_{\tau1} & U_{e\tau2} & U_{\tau3} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

Definition of neutrino mass eigenstates (who are  $\nu_1, \nu_2, \nu_3$ ):

- $m_1^2 < m_2^2$   $\Delta m_{13}^2 < 0$  – 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

$$\tan^2 \theta_{12} \equiv \frac{|U_{e2}|^2}{|U_{e1}|^2}; \quad \tan^2 \theta_{23} \equiv \frac{|U_{\mu3}|^2}{|U_{\tau3}|^2}; \quad U_{e3} \equiv \sin \theta_{13} e^{-i\delta}$$

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

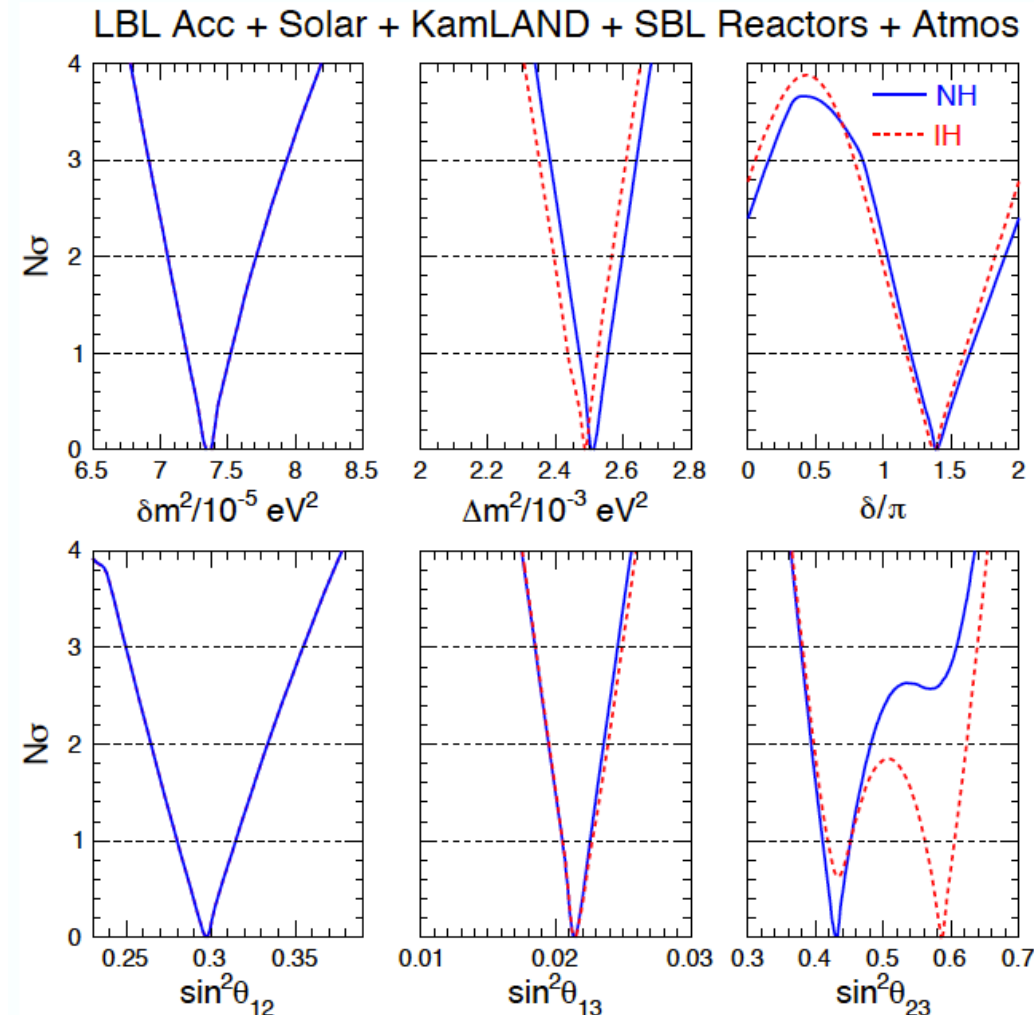
# The Three-Flavor Paradigm Fits All\* Data Really Well

[\* modulo short-baseline anomalies]

## Bounds on single oscillation parameters

(preliminary update)

[A. Marrone, Talk at Neutrino 2016]



### CP phase trend:

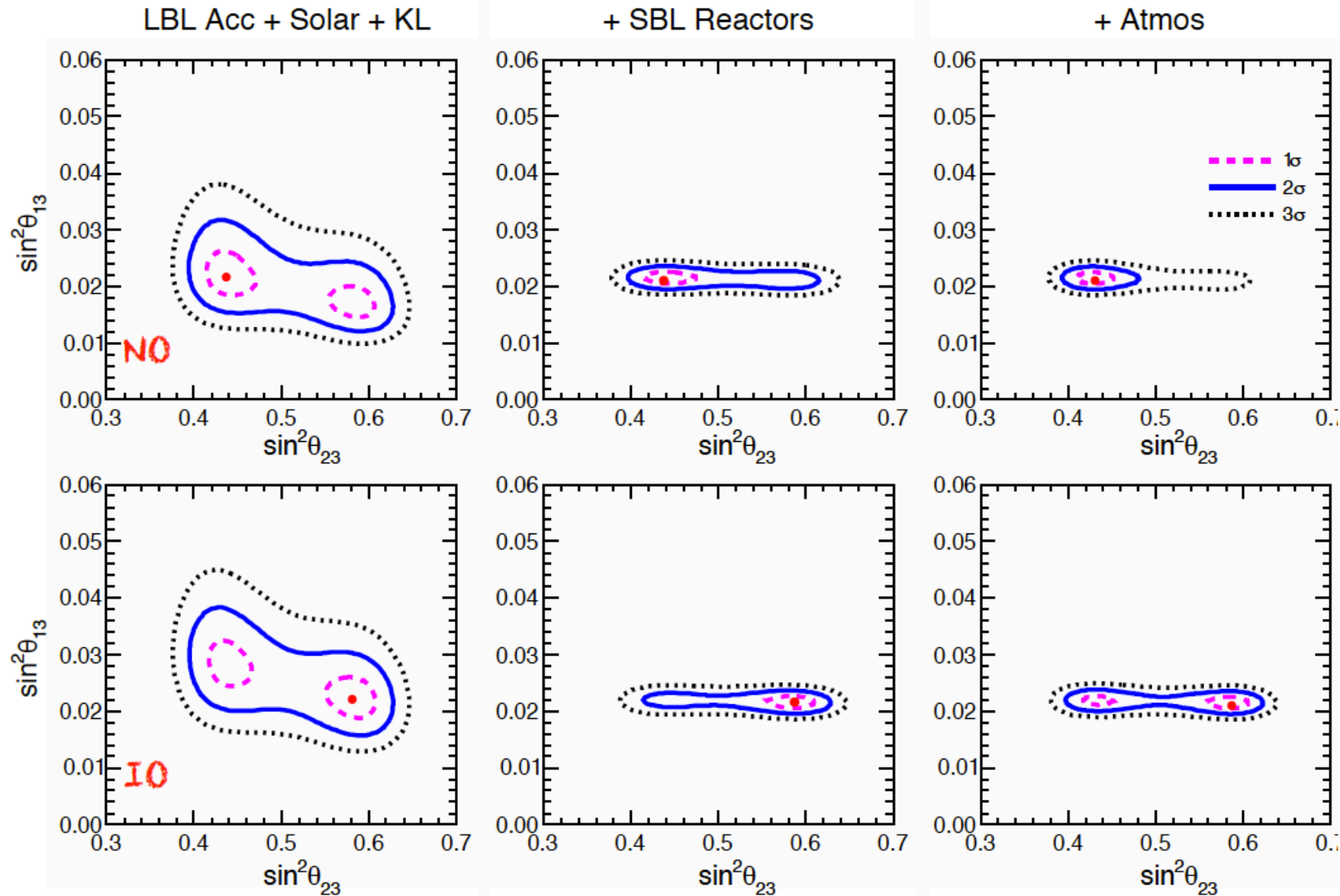
- $\delta \sim 1.4\pi$  at best fit
- CP-conserving cases ( $\delta = 0, \pi$ ) disfavored at  $\sim 2\sigma$  level or more
- Significant fraction of the  $[0, \pi]$  range disfavored at  $>3\sigma$

### $\theta_{23}$ trend:

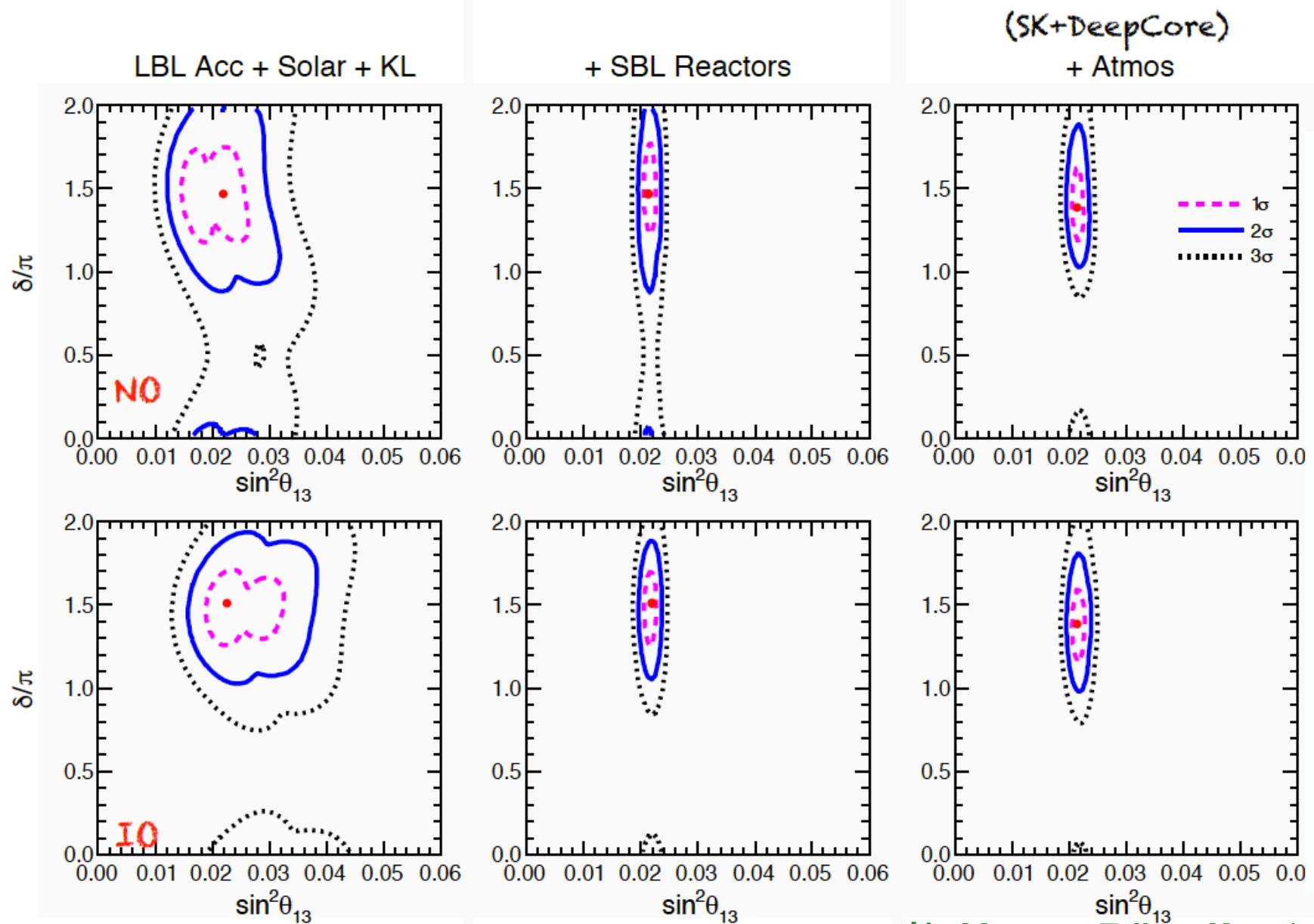
- maximal mixing disfavored at about  $\sim 2\sigma$  level
- best-fit octant flips with mass ordering

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

inverted ordering slightly disfavored



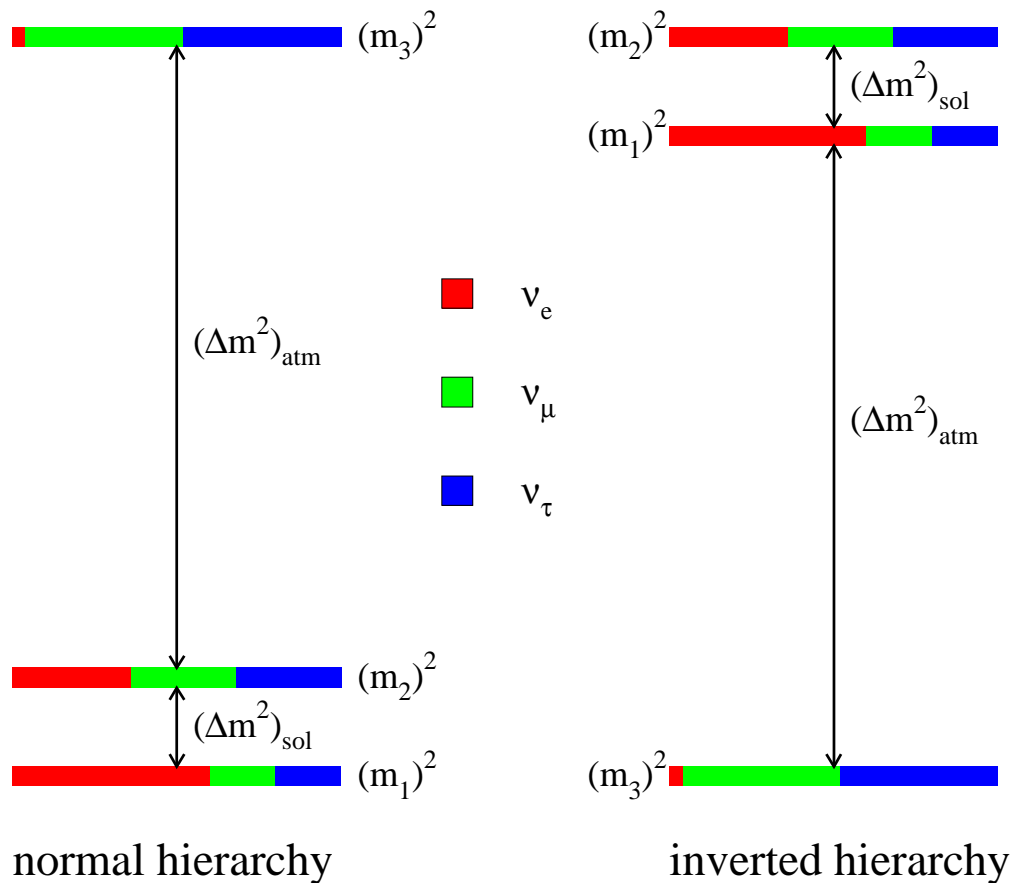
Atmospheric data do not spoil this trend but introduce some differences in the relative likelihood of the two octants in NO and IO. Octant degeneracy may show up in terms of "bumps" or "double bands" when marginalized away → [A. Marrone, Talk at Neutrino 2016]



[A. Marrone, Talk at Neutrino 2016]

Results in the  $(\delta, \theta_{13})$  plane corroborated by atmospheric data

## 4 - Understanding Neutrino Oscillations: What is Left to Do?

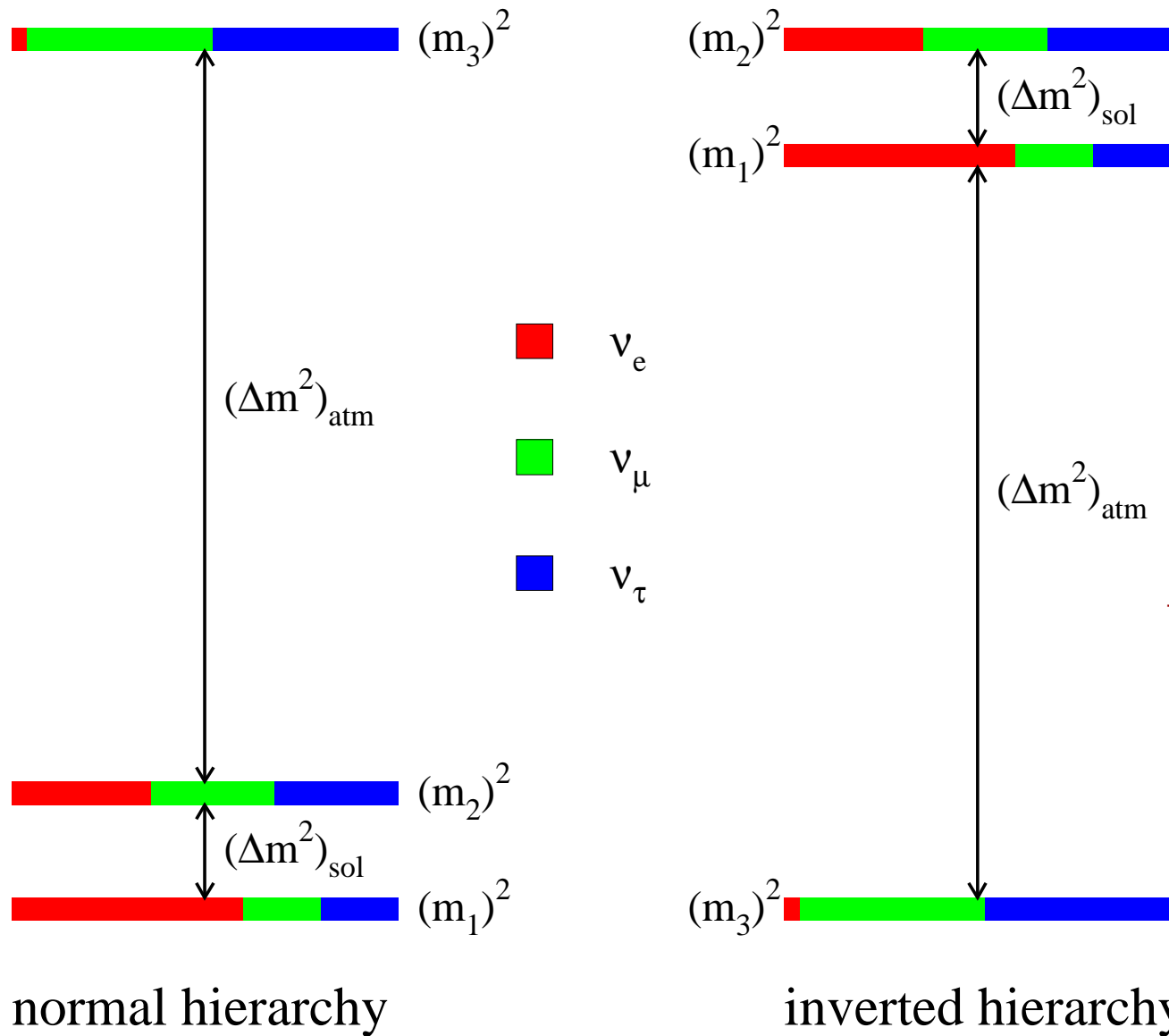


- What is the  $\nu_e$  component of  $\nu_3$ ? ( $\theta_{13} \neq 0!$ )
- Is CP-invariance violated in neutrino oscillations? ( $\delta \neq 0, \pi?$ ) [‘yes’ hint]
- Is  $\nu_3$  mostly  $\nu_\mu$  or  $\nu_\tau$ ? [ $\theta_{23} \neq \pi/4$  hint]
- What is the neutrino mass hierarchy? ( $\Delta m_{13}^2 > 0?$ ) [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)





## The Neutrino Mass Hierarchy

which is the right picture?

## Why Don't We Know the Neutrino Mass Hierarchy?

Most of the information we have regarding  $\theta_{23}$  and  $\Delta m_{13}^2$  comes from atmospheric neutrino experiments (SuperK). Roughly speaking, they measure

$$P_{\mu\mu} = 1 - \sin^2 2\theta_{23} \sin^2 \left( \frac{\Delta m_{13}^2 L}{4E} \right) + \text{subleading.}$$

It is easy to see from the expression above that the leading term is simply not sensitive to the sign of  $\Delta m_{13}^2$ .

On the other hand, because  $|U_{e3}|^2 \sim 0.02$  and  $\frac{\Delta m_{12}^2}{\Delta m_{13}^2} \sim 0.03$  are both small, we are **yet to observe the subleading effects**.

## Determining the Mass Hierarchy via Oscillations – the large $U_{e3}$ route

Again, necessary to probe  $\nu_\mu \rightarrow \nu_e$  oscillations (or vice-versa) governed by  $\Delta m_{13}^2$ . This is the oscillation channel that (almost) all next-generation, accelerator-based experiments are concentrating on, including the ongoing experiments T2K and NO $\nu$ A.

In vacuum

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

so that, again, this is insensitive to the sign of  $\Delta m_{13}^2$  at leading order. However, in this case, matter effects may come to the rescue.

As I discussed already, 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.

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

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

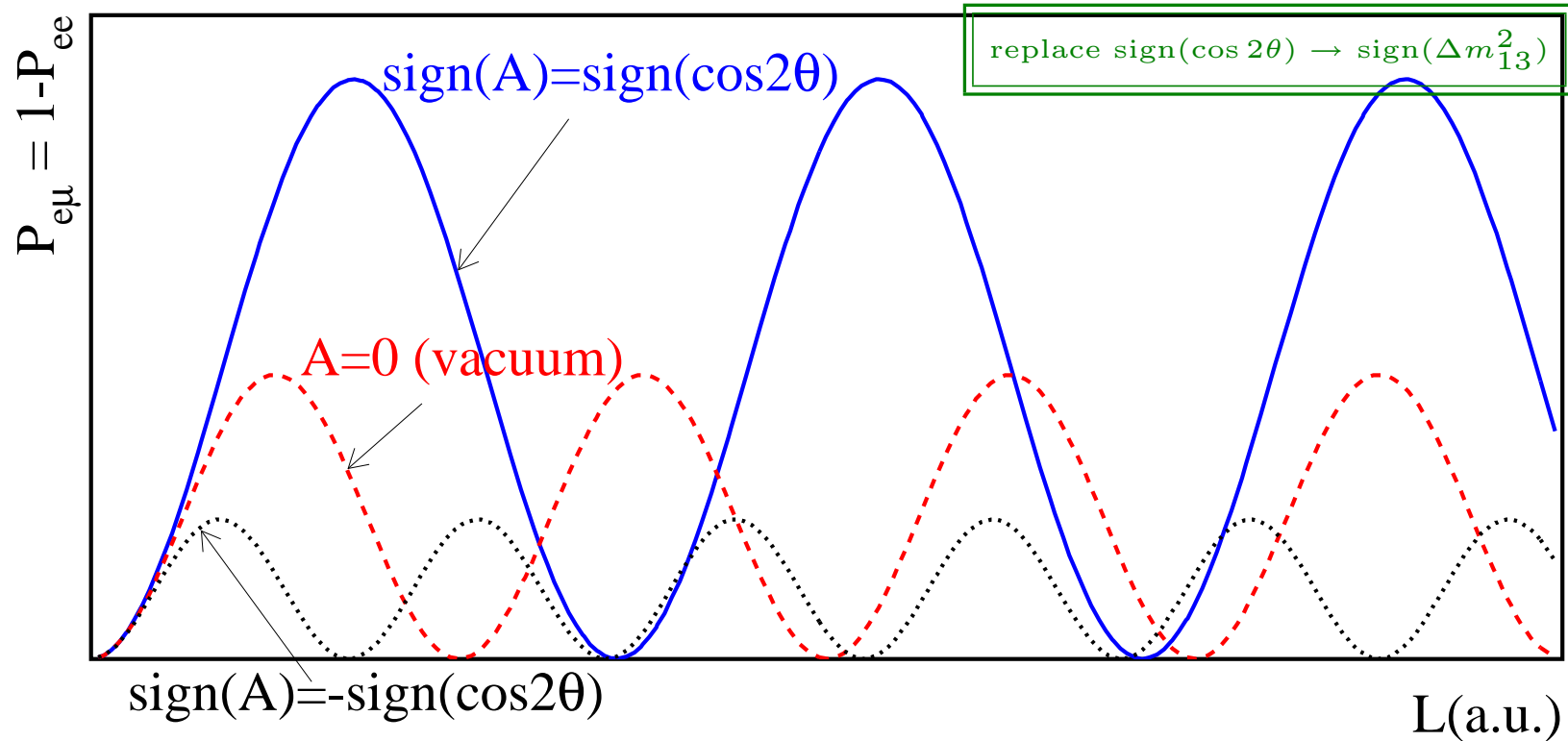
$$\sin^2 2\theta_{13}^{\text{eff}} = \frac{\Delta_{13}^2 \sin^2 2\theta_{13}}{(\Delta_{13}^{\text{eff}})^2},$$

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

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

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

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



### 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.
- $\Delta_{13}^{\text{eff}} L$  large enough – matter effects are absent near the origin.

## The “Holy Grail” of Neutrino Oscillations – CP Violation

In the old Standard Model, there is only one<sup>a</sup> source of CP-invariance violation:

⇒ The complex phase in  $V_{CKM}$ , the quark mixing matrix.

Indeed, as far as we have been able to test, all CP-invariance violating phenomena agree with the CKM paradigm:

- $\epsilon_K$ ;
- $\epsilon'_K$ ;
- $\sin 2\beta$ ;
- etc.

Recent experimental developments, however, provide strong reason to believe that this is not the case: neutrinos have mass, and leptons mix!

---

<sup>a</sup>modulo the QCD  $\theta$ -parameter, which will be “willed away” henceforth.

## Golden Opportunity to Understand Matter versus Antimatter?

The SM with massive Majorana neutrinos accommodates **five** irreducible CP-invariance violating phases.

- One is the phase in the CKM phase. We have measured it, it is large, and we don't understand its value. At all.
- One is  $\theta_{QCD}$  term ( $\theta G\tilde{G}$ ). We don't know its value but it is only constrained to be very small. We don't know why (there are some good ideas, however).
- Three are in the neutrino sector. One can be measured via neutrino oscillations. 50% increase on the amount of information.

We don't know much about CP-invariance violation. Is it really fair to presume that CP-invariance is generically violated in the neutrino sector solely based on the fact that it is violated in the quark sector? Why?

Cautionary tale: “Mixing angles are small”

## CP-invariance Violation in Neutrino Oscillations

The most promising approach to studying CP-violation in the leptonic sector seems to be to compare  $P(\nu_\mu \rightarrow \nu_e)$  versus  $P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e)$ .

The amplitude for  $\nu_\mu \rightarrow \nu_e$  transitions can be written as

$$A_{\mu e} = U_{e2}^* U_{\mu 2} (e^{i\Delta_{12}} - 1) + U_{e3}^* U_{\mu 3} (e^{i\Delta_{13}} - 1)$$

where  $\Delta_{1i} = \frac{\Delta m_{1i}^2 L}{2E}$ ,  $i = 2, 3$ .

The amplitude for the CP-conjugate process can be written as

$$\bar{A}_{\mu e} = U_{e2} U_{\mu 2}^* (e^{i\Delta_{12}} - 1) + U_{e3} U_{\mu 3}^* (e^{i\Delta_{13}} - 1).$$

[remember: according to unitarity,  $U_{e1} U_{\mu 1}^* = -U_{e2} U_{\mu 2}^* - U_{e3} U_{\mu 3}^*$ ]



In general,  $|A|^2 \neq |\bar{A}|^2$  (CP-invariance violated) as long as:

- Nontrivial “Weak” Phases:  $\arg(U_{ei}^* U_{\mu i}) \rightarrow \delta \neq 0, \pi$ ;
- Nontrivial “Strong” Phases:  $\Delta_{12}, \Delta_{13} \rightarrow L \neq 0$ ;
- Because of Unitarity, we need all  $|U_{\alpha i}| \neq 0 \rightarrow$  three generations.

All of these can be satisfied, with a little luck: given that two of the three mixing angles are known to be large, **we need**  $|U_{e3}| \neq 0$ . (✓)

The goal of next-generation neutrino experiments is to determine the magnitude of  $|U_{e3}|$ . We need to know this in order to understand how to study CP-invariance violation in neutrino oscillations!

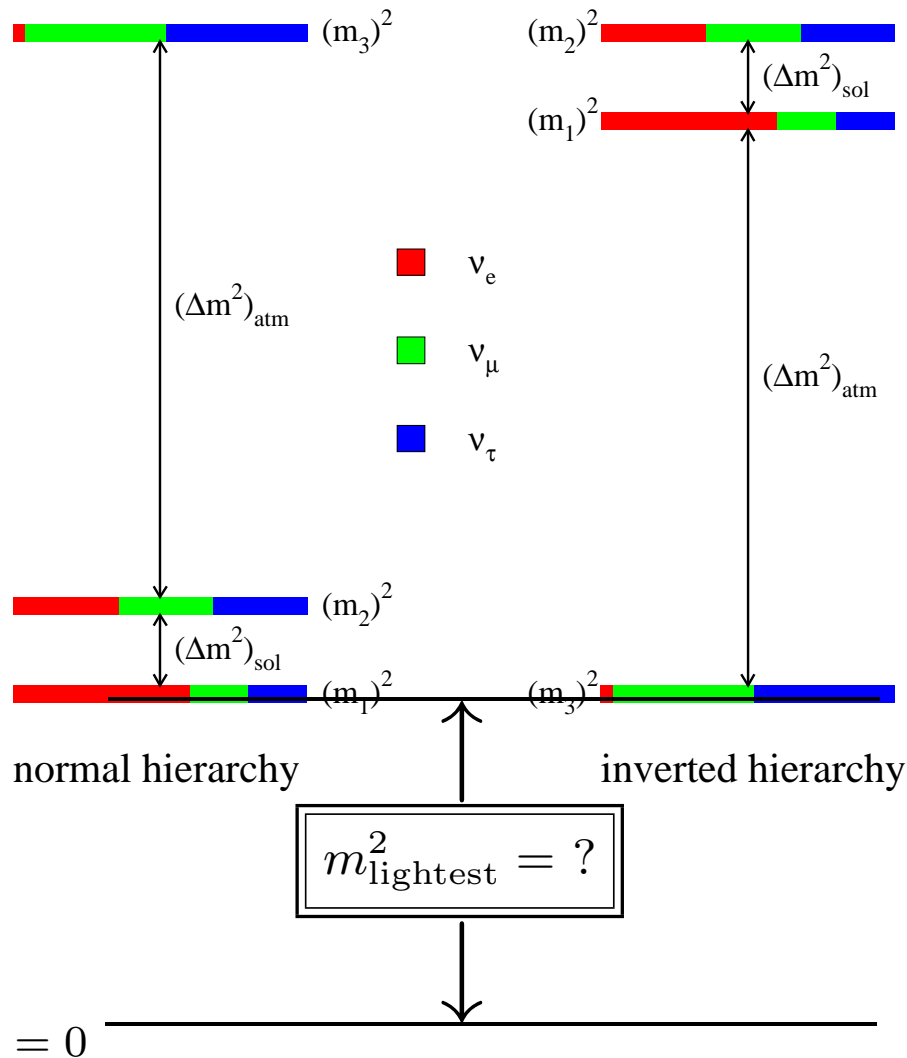
In the real world, life is much more complicated. The lack of knowledge concerning the mass hierarchy,  $\theta_{13}$ ,  $\theta_{23}$  leads to several degeneracies.

Note that, in order to see CP-invariance violation, we **need** the “subleading” terms!

In order to ultimately measure a new source of CP-invariance violation, we will need to combine different measurements:

- oscillation of muon neutrinos and antineutrinos,
- oscillations at accelerator and reactor experiments,
- experiments with different baselines,
- etc.

## 4– What We Know We Don't Know (ii): 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.

## The most direct probe of the lightest neutrino mass – precision measurements of $\beta$ -decay

Observation of the effect of non-zero neutrino masses **kinematically**.

When a neutrino is produced, some of the energy exchanged in the process should be spent by the non-zero neutrino mass.

Typical effects are very, very small – we've never seen them! The most sensitive observable is the electron energy spectrum from tritium decay.



Why tritium? Small  $Q$  value, reasonable abundances. Required sensitivity proportional to  $m^2/Q^2$ .

In practice, this decay is sensitive to an effective “electron neutrino mass”:

$$m_{\nu_e}^2 \equiv \sum_i |U_{ei}|^2 m_i^2$$

Experiments measure the **shape** of the end-point of the spectrum, not the value of the end point. This is done by counting events as a function of a low-energy cut-off. note: LOTS of Statistics Needed!

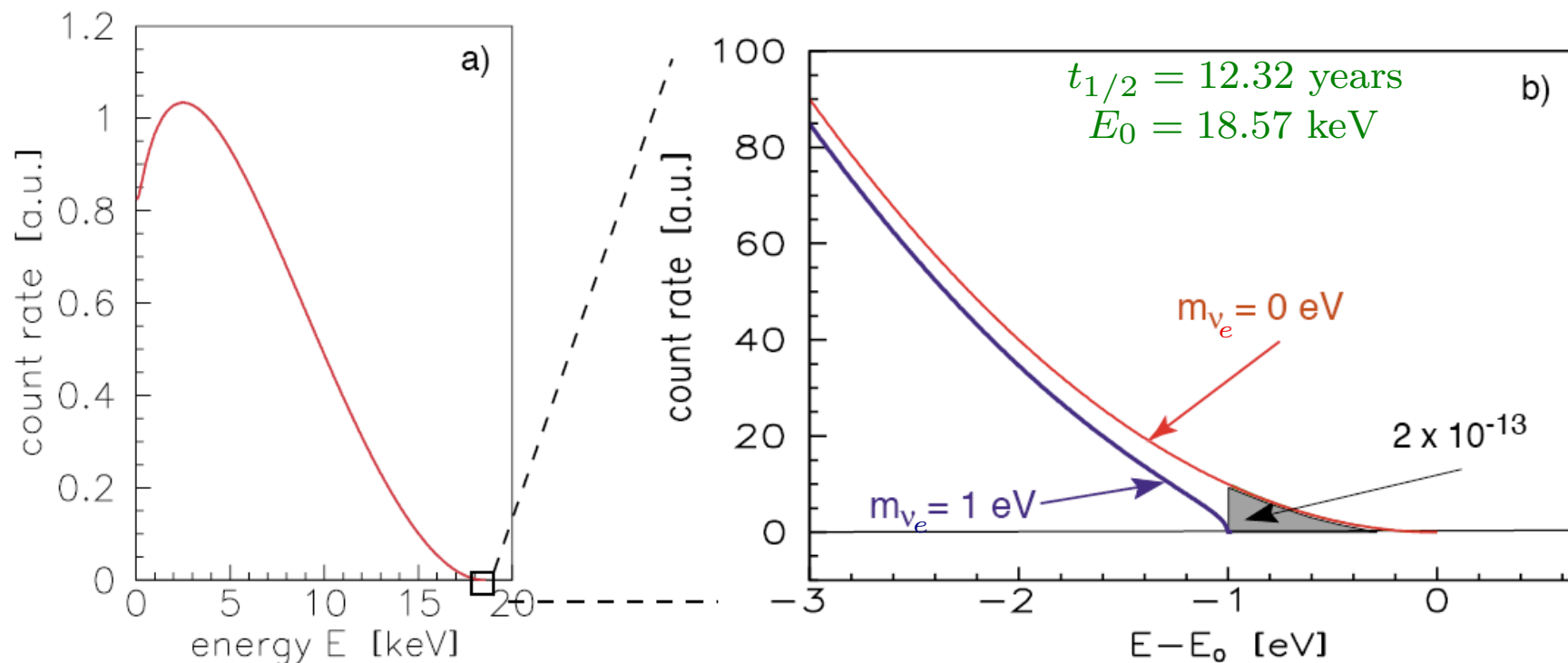


Figure 2: The electron energy spectrum of tritium  $\beta$  decay: (a) complete and (b) narrow region around endpoint  $E_0$ . The  $\beta$  spectrum is shown for neutrino masses of 0 and 1 eV.

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

(not your grandmother's table top experiment!)



## Big Bang Neutrinos are Warm Dark Matter

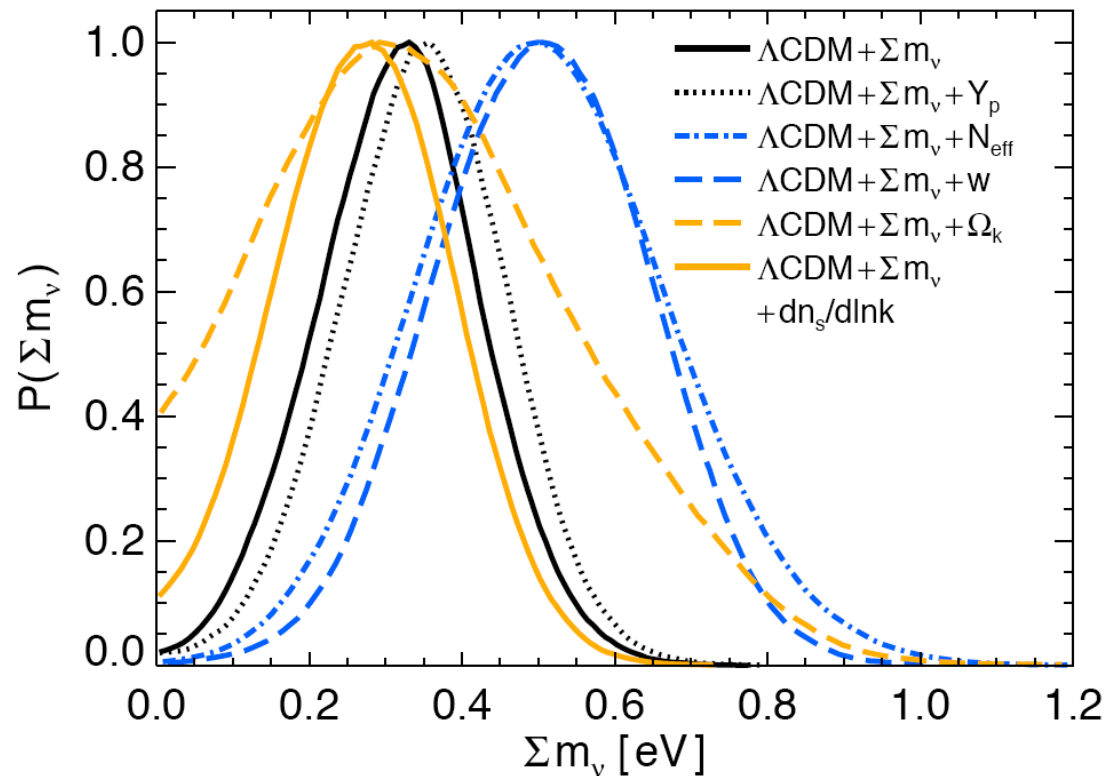


FIG. 10.— This figure illustrates the robustness of the neutrino mass detection to other parameter extensions. The marginalized one-dimensional posteriors for  $\sum m_\nu$  are shown for two-parameter extensions to  $\Lambda$ CDM for the combined CMB+BAO+ $H_0$ +SPT<sub>CL</sub> data sets (for  $w$ , SNe are used instead of  $H_0$ ). Allowing significant curvature or running can significantly reduce the preference for nonzero neutrino masses (to  $1.7$  and  $2.4\sigma$  respectively). Other extensions increase the preference for positive neutrino masses.

[Z. Hou *et al.* arXiv:1212.6267]

- Constrained by the Large Scale Structure of the Universe.

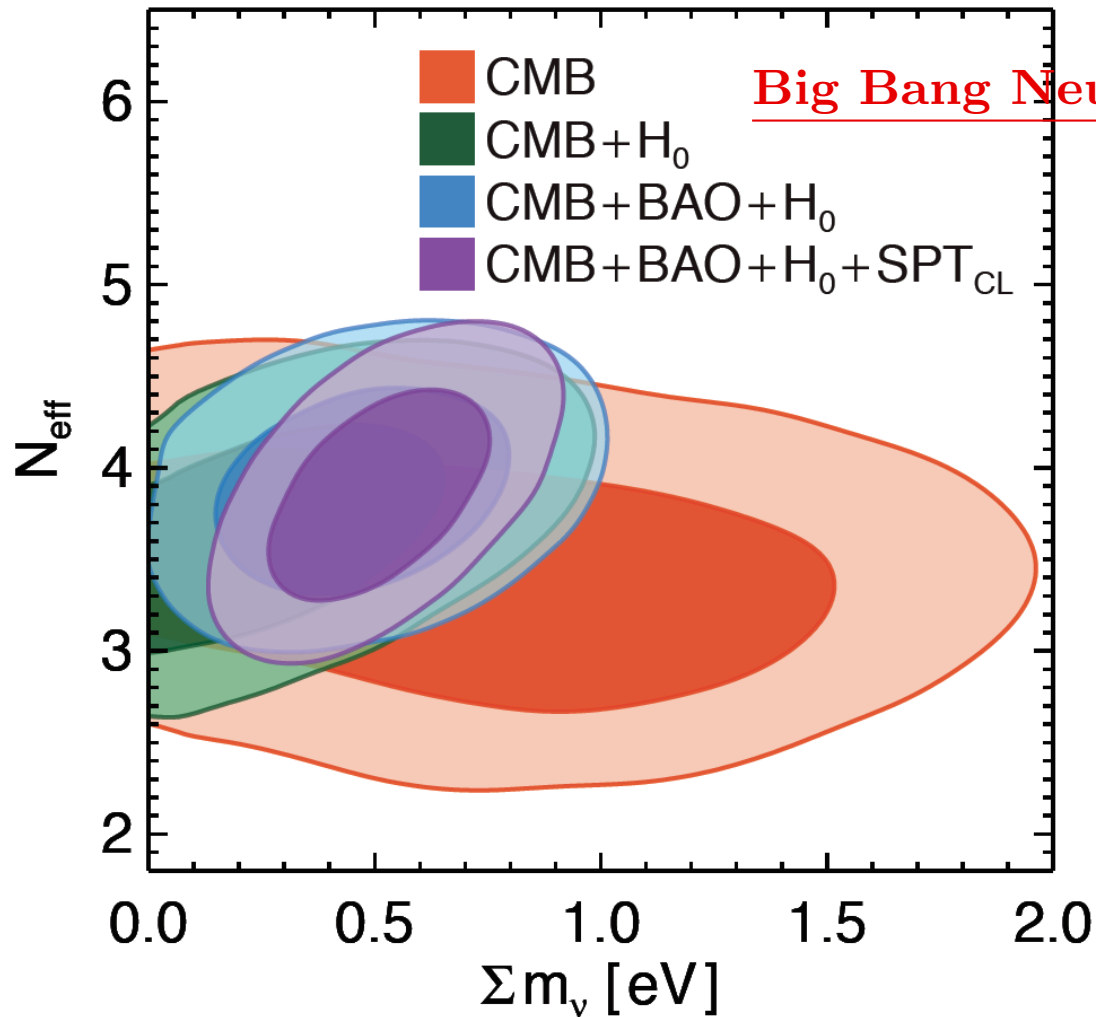
Constraints depend on

- 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**?



## Big Bang Neutrinos are Warm Dark Matter



- Constrained by the Large Scale Structure of the Universe.

Constraints depend on

- Data set analysed;
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- ...

Bounds can be evaded with non-standard cosmology. Will we learn about [neutrinos from cosmology](#) or about [cosmology from neutrinos](#)?

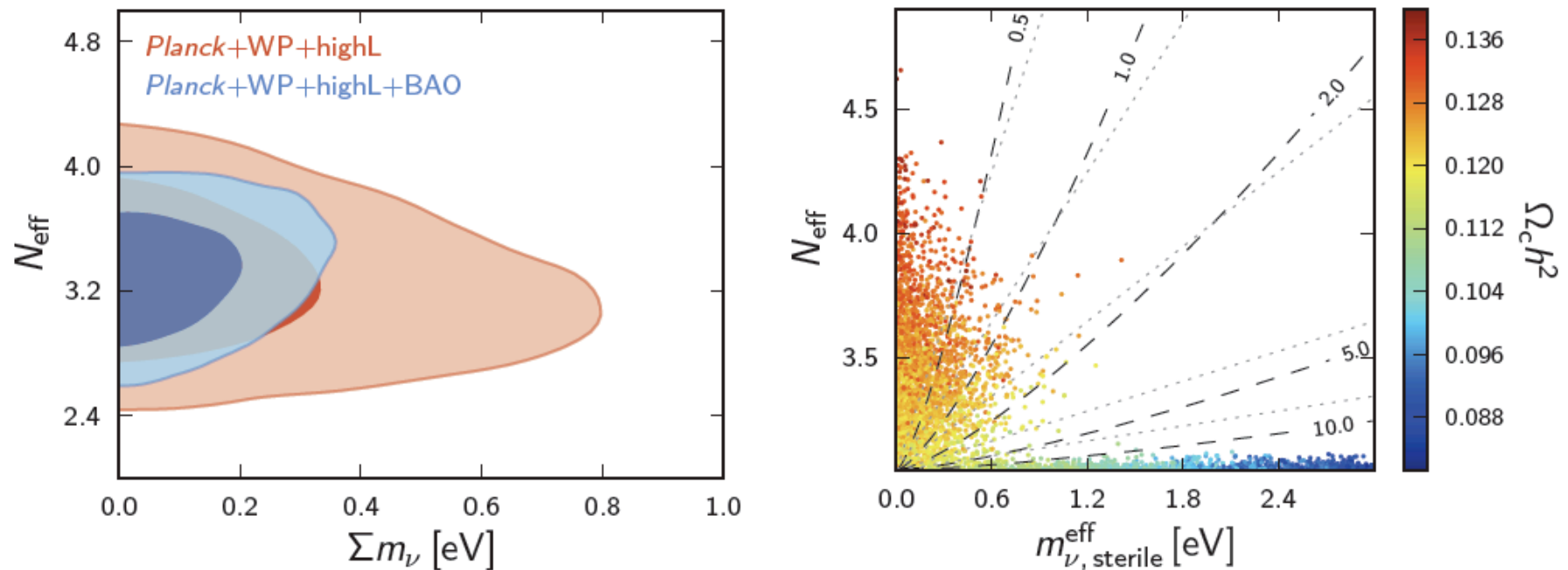
FIG. 18.— This figure demonstrates the impact of each combination of datasets on the constraints on  $\sum m_\nu$  and  $N_{\text{eff}}$ . The shaded contours are the 68% and 95% confidence intervals for the following data combinations: SPT+*WMAP*7 (CMB; red), CMB+ $H_0$  (green), CMB+ $H_0$ +BAO (blue), CMB+ $H_0$ +BAO+SPT<sub>CL</sub> (purple). The combined data are in  $>2\sigma$  tension with the  $\Lambda$ CDM assumption of three massless neutrino species.

[Z. Hou *et al.* arXiv:1212.6267]



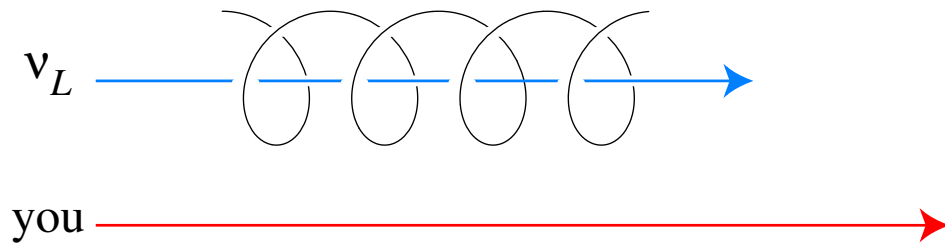
## Big Bang Neutrinos are Warm Dark Matter

Planck Collaboration: Cosmological parameters



**Fig. 28.** *Left:* 2D joint posterior distribution between  $N_{\text{eff}}$  and  $\sum m_\nu$  (the summed mass of the three active neutrinos) in models with extra massless neutrino-like species. *Right:* Samples in the  $N_{\text{eff}}-m_{\nu, \text{sterile}}^{\text{eff}}$  plane, colour-coded by  $\Omega_c h^2$ , in models with one massive sterile neutrino family, with effective mass  $m_{\nu, \text{sterile}}^{\text{eff}}$ , and the three active neutrinos as in the base  $\Lambda$ CDM model. The physical mass of the sterile neutrino in the thermal scenario,  $m_{\text{sterile}}^{\text{thermal}}$ , is constant along the grey dashed lines, with the indicated mass in eV. The physical mass in the Dodelson-Widrow scenario,  $m_{\text{sterile}}^{\text{DW}}$ , is constant along the dotted lines (with the value indicated on the adjacent dashed lines).

# 4- What We Know We Don't Know (iii) – Are Neutrinos Majorana Fermions?



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

$$(e_L^- \leftarrow \text{CPT} \rightarrow e_R^+)$$

$\updownarrow$  Lorentz

$$(e_R^- \leftarrow \text{CPT} \rightarrow e_L^+)$$

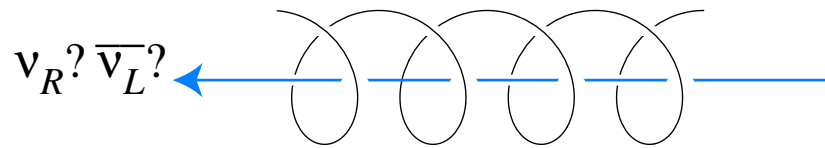
A massive neutral fermion ( $s=1/2$ ) is described by 4 or 2 degrees of freedom:

$$(\nu_L \leftarrow \text{CPT} \rightarrow \bar{\nu}_R)$$

$\updownarrow$  Lorentz

“DIRAC”

$$(\nu_R \leftarrow \text{CPT} \rightarrow \bar{\nu}_L)$$



you •

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

“MAJORANA”

$\updownarrow$  Lorentz

$$(\nu_L \leftarrow \text{CPT} \rightarrow \bar{\nu}_R)$$

$$(\bar{\nu}_R \leftarrow \text{CPT} \rightarrow \nu_L)$$

## Why Don't We Know the Answer (Yet)?

If neutrino masses were indeed zero, this is a nonquestion: there is no distinction between a massless Dirac and Majorana fermion.

Processes that are proportional to the Majorana nature of the neutrino vanish in the limit  $m_\nu \rightarrow 0$ . Since neutrino masses are very small, the probability for these to happen is very, very small:  $A \propto m_\nu/E$ .

The “smoking gun” signature is the observation of LEPTON NUMBER violation. This is easy to understand: Majorana neutrinos are their own antiparticles and, therefore, cannot carry any quantum numbers — including lepton number.

The deepest probes are searches for Neutrinoless Double-Beta Decay.

Weak Interactions are Purely Left-Handed (Chirality):

For example, in the scattering process  $e^- + X \rightarrow \nu_e + X$ , the electron neutrino is, in a reference frame where  $m \ll E$ ,

$$|\nu_e\rangle \sim |L\rangle + \left(\frac{m}{E}\right) |R\rangle.$$

If the neutrino is a Majorana fermion,  $|R\rangle$  behaves mostly like a “ $\bar{\nu}_e$ ,” (and  $|L\rangle$  mostly like a “ $\nu_e$ ,”) such that the following process could happen:

$$e^- + X \rightarrow \nu_e + X, \text{ followed by } \nu_e + X \rightarrow e^+ + X, \quad P \simeq \left(\frac{m}{E}\right)^2$$

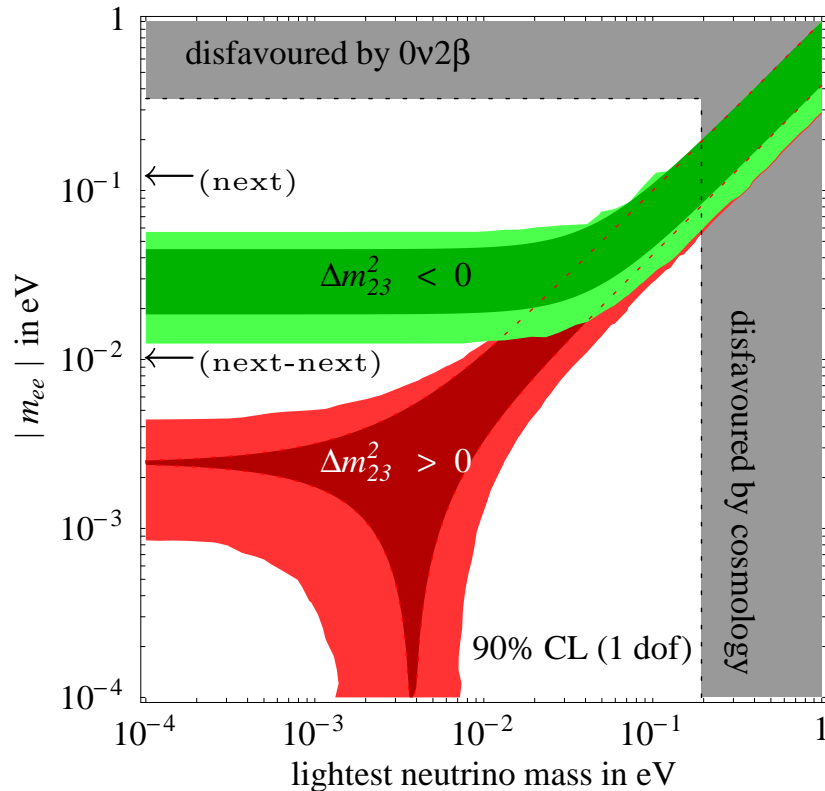
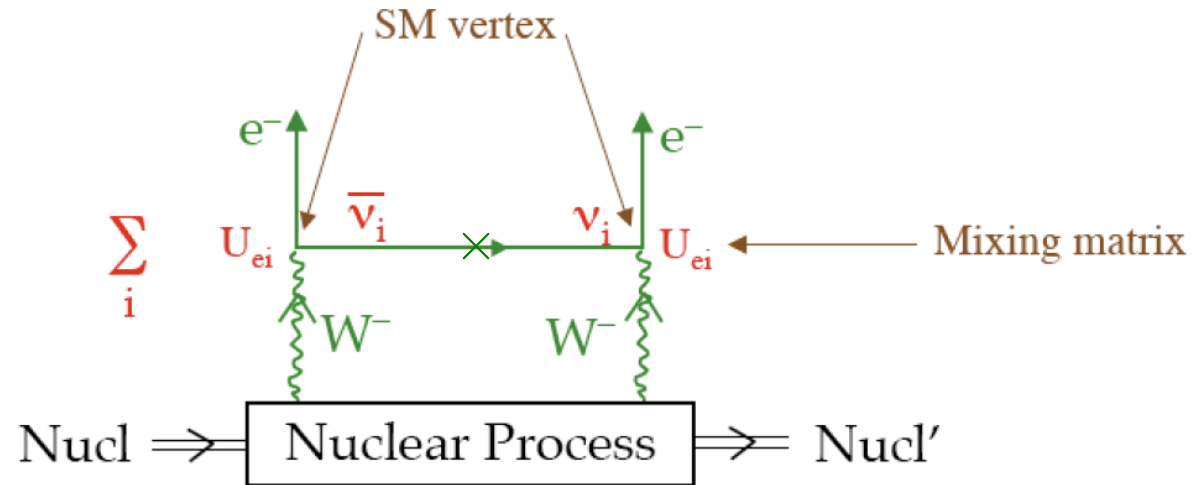
Lepton number can be violated by 2 units with small probability. Typical numbers:  $P \simeq (0.1 \text{ eV}/100 \text{ MeV})^2 = 10^{-18}$ . VERY Challenging!

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

**Best Bet:** search for

Neutrinoless Double-Beta

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



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

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

**no longer lamp-post physics!**

## How many new CP-violating parameters in the neutrino sector?

If the neutrinos are Majorana fermions, there are more physical observables in the leptonic mixing matrix.

Remember the parameter counting in the quark sector:

9 (3 × 3 unitary matrix)

−5 (relative phase rotation among six quark fields)

4 (3 mixing angles and 1 CP-odd phase).

If the neutrinos are Majorana fermions, the parameter counting is quite different: there are no right-handed neutrino fields to “absorb” CP-odd phases:

9 (3 × 3 unitary matrix)

−3 (three right-handed charged lepton fields)

6 (3 mixing angles and 3 CP-odd phases).

There is CP-invariance violating parameters even in the 2 family case:

$4 - 2 = 2$ , one mixing angle, one CP-odd phase.

$$\mathcal{L} \supset \bar{e}_L U W^\mu \gamma_\mu \nu_L - \bar{e}_L (M_e) e_R - \bar{\nu}_L^c (M_\nu) \nu_L + H.c.$$

Write  $U = E^{-i\xi/2} U' E^{i\alpha/2}$ , where  $E^{i\beta/2} \equiv \text{diag}(e^{i\beta_1/2}, e^{i\beta_2/2}, e^{i\beta_3/2})$ ,  
 $\beta = \alpha, \xi$

$$\mathcal{L} \supset \bar{e}_L U' W^\mu \gamma_\mu \nu_L - \bar{e}_L E^{i\xi/2} (M_e) e_R - \bar{\nu}_L^c (M_\nu) E^{-i\alpha} \nu_L + H.c.$$

$\xi$  phases can be “absorbed” by  $e_R$ ,

$\alpha$  phases cannot go away!

on the other hand

Dirac Case:

$$\mathcal{L} \supset \bar{e}_L U W^\mu \gamma_\mu \nu_L - \bar{e}_L (M_e) e_R - \bar{\nu}_R (M_\nu) \nu_L + H.c.$$

$$\mathcal{L} \supset \bar{e}_L U' W^\mu \gamma_\mu \nu_L - \bar{e}_L E^{i\xi/2} (M_e) e_R - \bar{\nu}_R (M_\nu) E^{-i\alpha/2} \nu_L + H.c.$$

$\xi$  phases can be “absorbed” by  $e_R$ ,  $\alpha$  phases can be “absorbed” by  $\nu_R$ ,

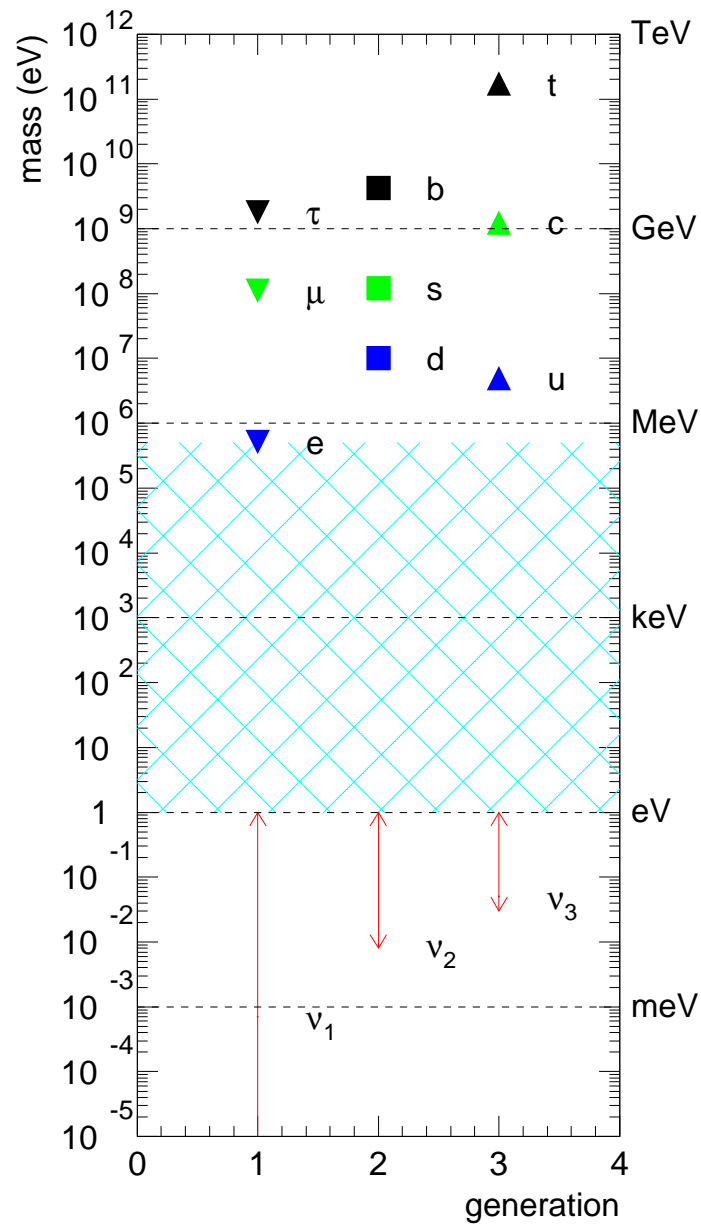


$$V_{MNS} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu1} & U_{\mu2} & U_{\mu3} \\ U_{\tau1} & U_{e\tau2} & U_{\tau3} \end{pmatrix}' \begin{pmatrix} e^{i\alpha_1/2} & 0 & 0 \\ 0 & e^{i\alpha_2/2} & 0 \\ 0 & 0 & e^{i\alpha_3/2} \end{pmatrix}.$$

It is easy to see that the Majorana phases never show up in neutrino oscillations ( $A \propto U_{\alpha i} U_{\beta i}^*$ ).

Furthermore, they only manifest themselves in phenomena that vanish in the limit  $m_i \rightarrow 0$  – after all they are only physical if we “know” that lepton number is broken.

$$A(\alpha_i) \propto m_i/E \rightarrow \text{tiny!}$$



# NEUTRINOS HAVE MASS

albeit very tiny ones...

SO WHAT?

## 5 - Only\* “Palpable” Evidence of Physics Beyond the Standard Model

The SM we all learned in school predicts that neutrinos are strictly massless. Hence, 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 (these are personal. Feel free to complain).

- What is the physics behind electroweak symmetry breaking? (Higgs ✓).
- What is the dark matter? (not in SM).
- Why is there more matter than antimatter? (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).

## Standard Model in One Slide, No Equations

The SM is a **quantum field theory** with the following defining characteristics:

- Gauge Group ( $SU(3)_c \times SU(2)_L \times U(1)_Y$ );
- Particle Content (fermions:  $Q, u, d, L, e$ , scalars:  $H$ ).

Once this is specified, the SM is **unambiguously determined**:

- Most General Renormalizable Lagrangian;
- Measure All Free Parameters, and You Are Done! (after several decades of hard experimental work...)

If you follow these rules, neutrinos have no mass. Something has to give.

## What is the New Standard Model? [ $\nu$ SM]

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



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

We need more experimental input, and it looks like it may be coming in the near/intermediate future!

## Neutrino Masses, EWSB, and a New Mass Scale of Nature

The LHC has revealed that the minimum SM prescription for electroweak symmetry breaking — the one Higgs double model — is at least approximately correct. What does that have to do with neutrinos?

The tiny neutrino masses point to three different possibilities.

1. Neutrinos talk to the Higgs boson very, very **weakly** (Dirac neutrinos);
2. Neutrinos talk to a **different Higgs** boson – there is a new source of electroweak symmetry breaking! (Majorana neutrinos);
3. Neutrino masses are small because there is **another source of mass** out there — a new energy scale indirectly responsible for the tiny neutrino masses, a la the seesaw mechanism (Majorana neutrinos).

Searches for  $0\nu\beta\beta$  help tell (1) from (2) and (3), the LHC, charged-lepton flavor violation, *et al* may provide more information.

## 6 - $\nu$ SM – One Path

SM as an effective field theory – non-renormalizable operators

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

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

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

- Neutrino masses are small:  $\Lambda \gg v \rightarrow m_\nu \ll m_f$  ( $f = e, \mu, u, d$ , etc)
- Neutrinos are Majorana fermions – Lepton number is violated!
- $\nu$ SM effective theory – not valid for energies above at most  $\Lambda$ .
- What is  $\Lambda$ ? First naive guess is that  $\Lambda$  is the Planck scale – does not work.  
Data require  $\Lambda \sim 10^{14}$  GeV (related to GUT scale?) [note  $y^{\text{max}} \equiv 1$ ]

What else is this “good for”? Depends on the ultraviolet completion!

Note that this VERY similar to the “discovery” weak interactions.

Imagine the following scenario:

$$U(1)_{E\&M} + e(q = -1), \mu(q = -1), \nu_e(q = 0), \nu_\mu(q = 0).$$

The most general renormalizable Lagrangian explains *all* QED phenomena once all couplings are known  $(\alpha, m_f)$ .

New physics: the muon decays!  $\mu^- \rightarrow e^- \bar{\nu}_e \nu_\mu$ . This can be interpreted as evidence of effective four fermion theory (nonrenormalizable operators):

$$-\frac{4G_F}{\sqrt{2}} \sum_{\gamma} g_{\gamma} (\bar{e}\Gamma^{\gamma}\nu) (\bar{\nu}_e\Gamma_{\gamma}\mu), \quad \Gamma_{\gamma} = 1, \gamma_5, \gamma_{\mu}, \dots$$

Prediction: will discover new physics at an energy scale **below**  $\sqrt{1/G_F} \simeq 250$  GeV. We know how this turned out  $\Rightarrow W^{\pm}, Z^0$  discovered slightly below 100 GeV!



Full disclosure:

All higher dimensional operators are completely negligible, **except** those that mediate **proton decay**, like:

$$\frac{\lambda_B}{M^2} QQQQL$$

The fact that the proton does not decay forces  $M/\lambda_B$  to be much larger than the energy scale required to explain neutrino masses.

Why is that? **We don't know...**

## Example: the (Type I) Seesaw Mechanism

A simple<sup>a</sup>, renormalizable Lagrangian that allows for neutrino masses is

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

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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<sup>a</sup>Only requires the introduction of three fermionic degrees of freedom, no new interactions or symmetries.

## What We Really Know About $M$ and $\lambda$ :

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

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 quasi-Dirac fermions. Active–sterile mixing is maximal, but new oscillation lengths are very long.

## Accommodating Small Neutrino Masses

If  $\mu = \lambda v \ll M$ , 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.

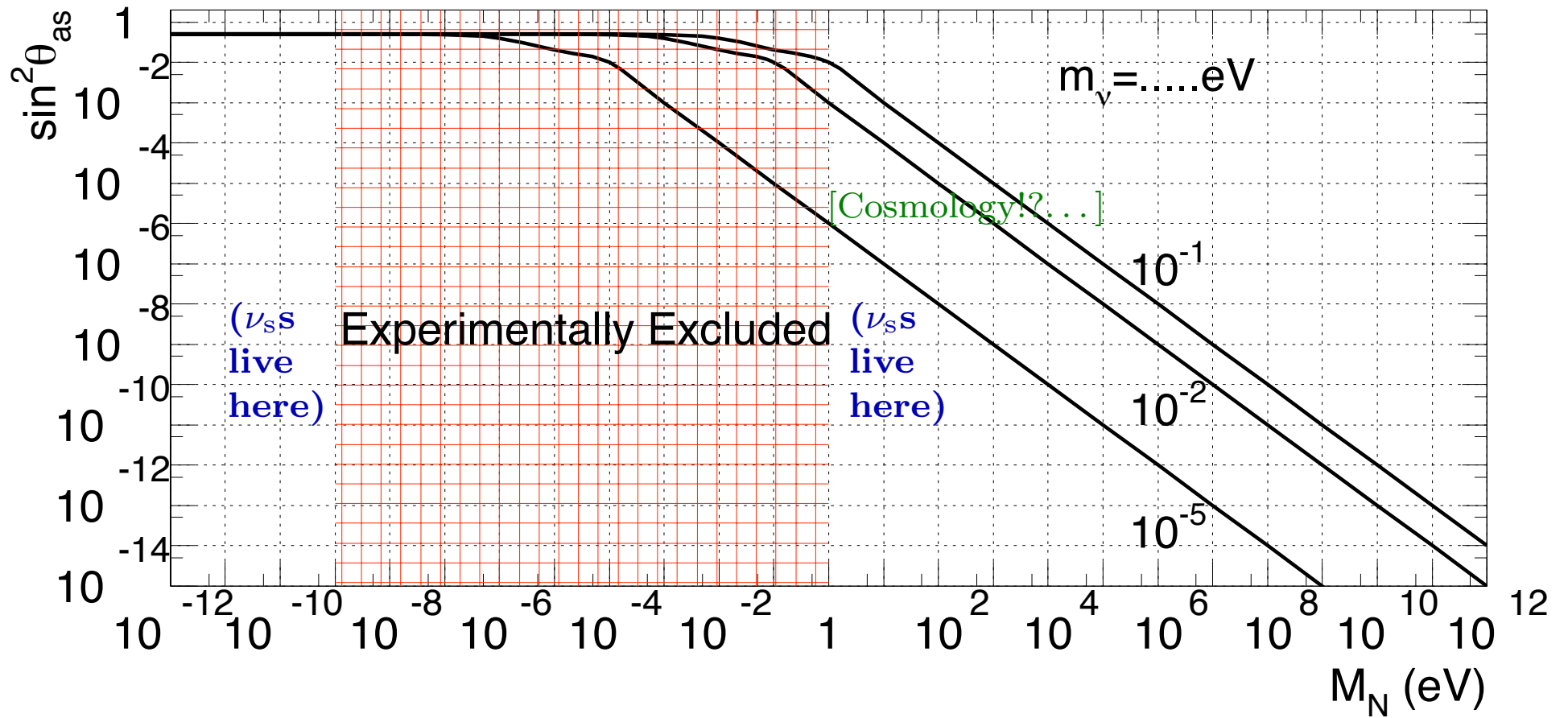
In the case of the seesaw,

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

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



[AdG, Huang, Jenkins, arXiv:0906.1611]

## High-Energy Seesaw: Brief Comments

- This is everyone's favorite scenario.
- Upper bound for  $M$  (e.g. Maltoni, Niczyporuk, Willenbrock, hep-ph/0006358):

$$M < 7.6 \times 10^{15} \text{ GeV} \times \left( \frac{0.1 \text{ eV}}{m_\nu} \right).$$

- Hierarchy problem hint (e.g., Casas et al, hep-ph/0410298; Farina et al, ; 1303.7244; AdG et al, 1402.2658):  $M < 10^7 \text{ GeV}$ .
- Leptogenesis! “Vanilla” Leptogenesis requires, very roughly, smallest  $M > 10^9 \text{ GeV}$ .
- Stability of the Higgs potential (e.g., Elias-Miró et al, 1112.3022):  $M < 10^{13} \text{ GeV}$ .
- Physics “too” heavy! No observable consequence other than leptogenesis. Will we ever convince ourselves that this is correct? (Buckley et al, hep-ph/0606088)

## “Higher Order” Neutrino Masses from $\Delta L = 2$ Physics

Imagine that there is **new physics that breaks lepton number by 2 units** at some energy scale  $\Lambda$ , but that it does not, in general, lead to neutrino masses **at the tree level**.

We know that neutrinos will get a mass at some order in perturbation theory – which order is model dependent!

**For example:**

- SUSY with trilinear R-parity violation – neutrino masses at one-loop;
- Zee models – neutrino masses at one-loop;
- Babu and Ma – neutrino masses at two loops;
- Chen et al, 0706.1964 – neutrino masses at two loops;
- Angel et al, 1308.0463 – neutrino masses at two loops;
- etc.

André de Gouvêa  
AdG, Jenkins,  
0708.1344 [hep-ph]

## Effective Operator Approach

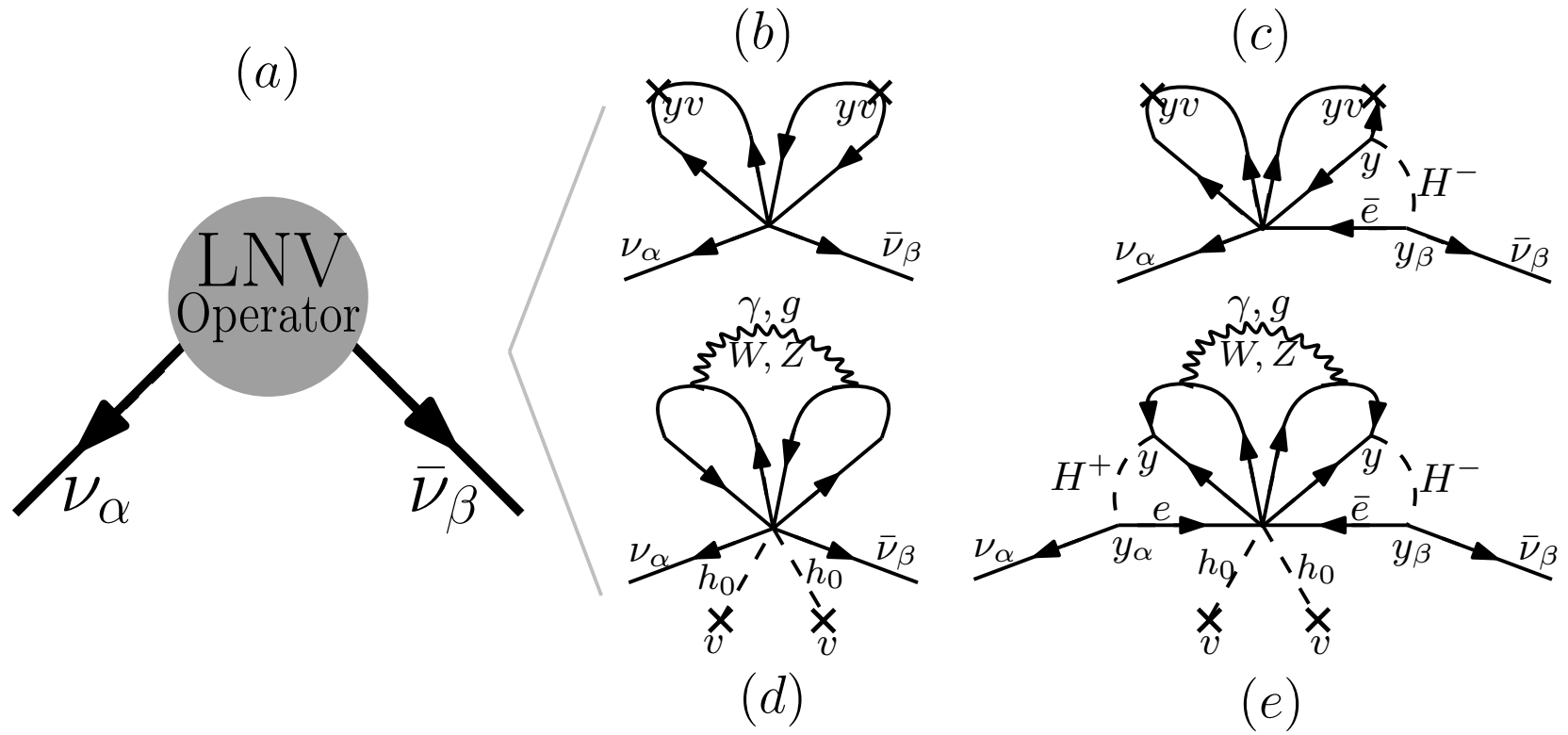
(there are 129  
of them if you  
discount different  
Lorentz structures!)

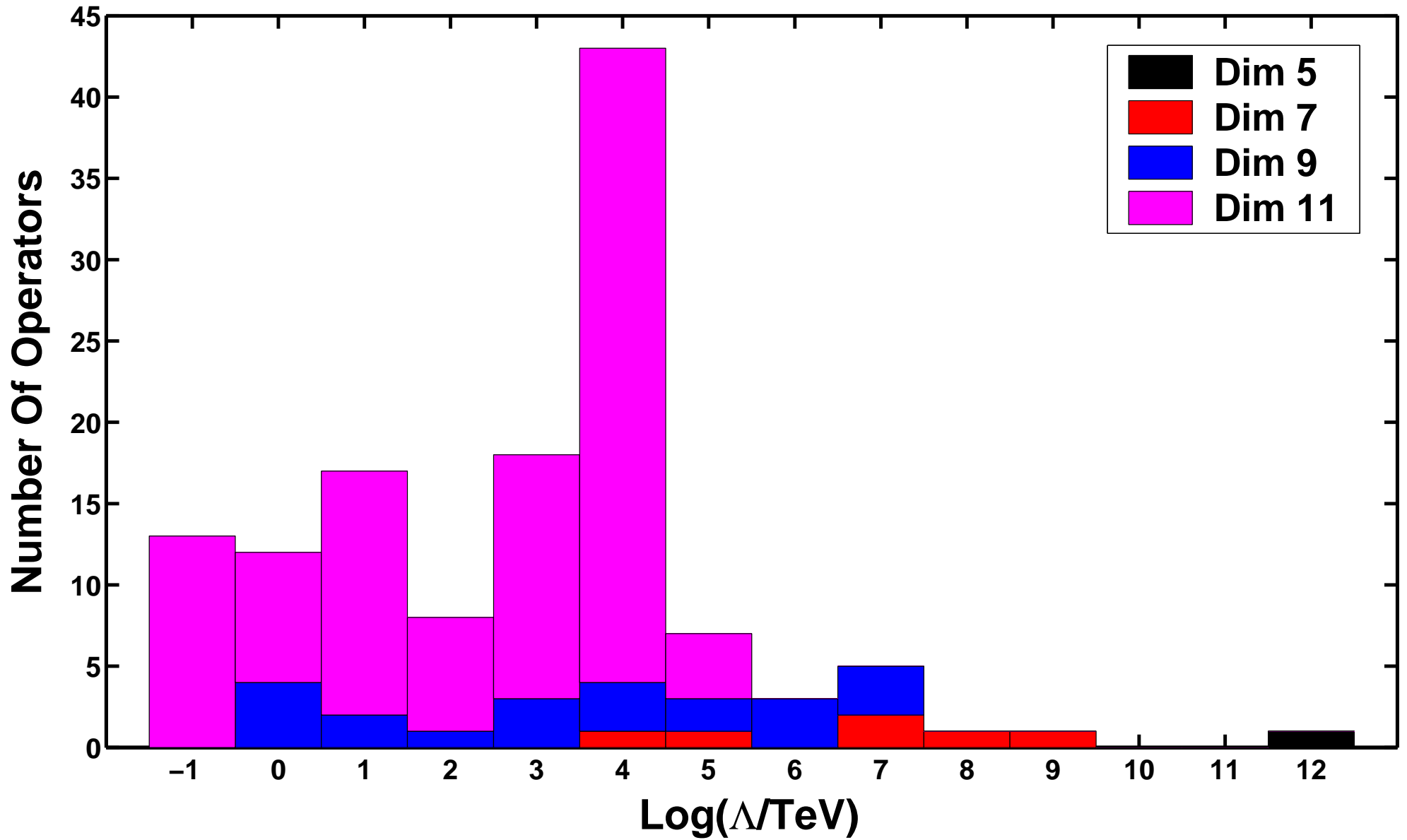
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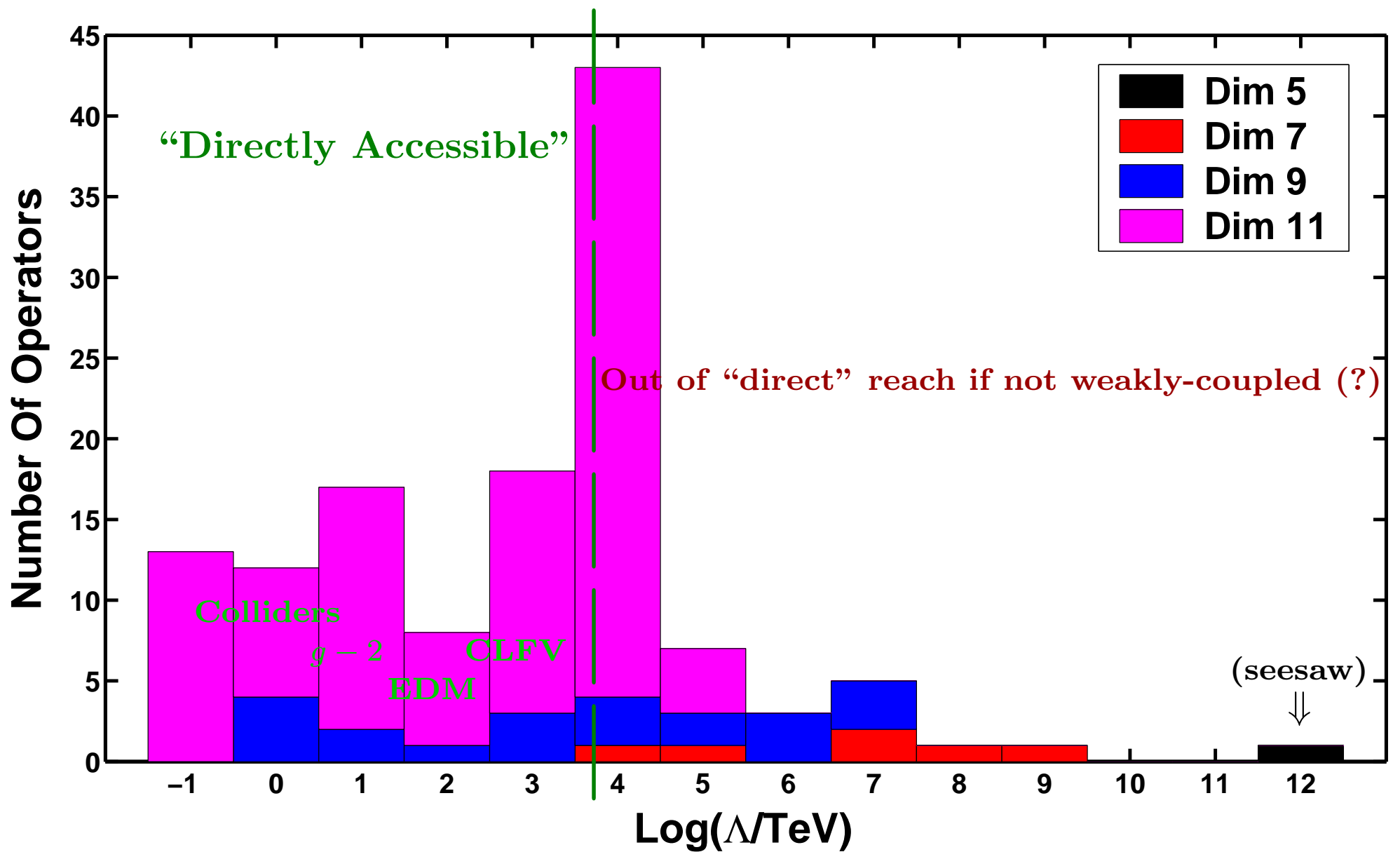
August 19–22, 2016

4 <sub>a</sub>	$L^i L^j \bar{Q}_i \bar{u}^c H^k \epsilon_{j k}$	$\frac{y_u}{16\pi^2} \frac{v^2}{\Lambda}$	$4 \times 10^9$	$\beta\beta\nu$
4 <sub>b</sub>	$L^i L^j \bar{Q}_k \bar{u}^c H^k \epsilon_{i j}$	$\frac{y_u g^2}{(16\pi^2)^2} \frac{v^2}{\Lambda}$	$6 \times 10^6$	Northwestern $\beta\beta\nu$
5	$L^i L^j Q^k d^c H^l H^m \bar{H}_i \epsilon_{j l} \epsilon_{k m}$	$\frac{y_d}{(16\pi^2)^2} \frac{v^2}{\Lambda}$	$6 \times 10^5$	$\beta\beta\nu$
6	$L^i L^j \bar{Q}_k \bar{u}^c H^l H^k \bar{H}_i \epsilon_{j l}$	$\frac{y_u}{(16\pi^2)^2} \frac{v^2}{\Lambda}$	$2 \times 10^7$	$\beta\beta\nu$
7	$L^i Q^j \bar{e}^c \bar{Q}_k H^k H^l H^m \epsilon_{i l} \epsilon_{j m}$	$y_{\ell\beta} \frac{g^2}{(16\pi^2)^2} \frac{v^2}{\Lambda} \left( \frac{1}{16\pi^2} + \frac{v^2}{\Lambda^2} \right)$	$4 \times 10^2$	mix
8	$L^i \bar{e}^c \bar{u}^c d^c H^j \epsilon_{i j}$	$y_{\ell\beta} \frac{y_d y_u}{(16\pi^2)^2} \frac{v^2}{\Lambda}$	$6 \times 10^3$	mix
9	$L^i L^j L^k e^c L^l e^c \epsilon_{i j} \epsilon_{k l}$	$\frac{y_\ell^2}{(16\pi^2)^2} \frac{v^2}{\Lambda}$	$3 \times 10^3$	$\beta\beta\nu$
10	$L^i L^j L^k e^c Q^l d^c \epsilon_{i j} \epsilon_{k l}$	$\frac{y_\ell y_d}{(16\pi^2)^2} \frac{v^2}{\Lambda}$	$6 \times 10^3$	$\beta\beta\nu$
11 <sub>a</sub>	$L^i L^j Q^k d^c Q^l d^c \epsilon_{i j} \epsilon_{k l}$	$\frac{y_d^2 g^2}{(16\pi^2)^3} \frac{v^2}{\Lambda}$	30	$\beta\beta\nu$
11 <sub>b</sub>	$L^i L^j Q^k d^c Q^l d^c \epsilon_{i k} \epsilon_{j l}$	$\frac{y_d^2}{(16\pi^2)^2} \frac{v^2}{\Lambda}$	$2 \times 10^4$	$\beta\beta\nu$
12 <sub>a</sub>	$L^i L^j \bar{Q}_i \bar{u}^c \bar{Q}_j \bar{u}^c$	$\frac{y_u^2}{(16\pi^2)^2} \frac{v^2}{\Lambda}$	$2 \times 10^7$	$\beta\beta\nu$
12 <sub>b</sub>	$L^i L^j \bar{Q}_k \bar{u}^c \bar{Q}_l \bar{u}^c \epsilon_{i j} \epsilon^{k l}$	$\frac{y_u^2 g^2}{(16\pi^2)^3} \frac{v^2}{\Lambda}$	$4 \times 10^4$	$\beta\beta\nu$
13	$L^i L^j \bar{Q}_i \bar{u}^c L^l e^c \epsilon_{j l}$	$\frac{y_\ell y_u}{(16\pi^2)^2} \frac{v^2}{\Lambda}$	$2 \times 10^5$	$\beta\beta\nu$
14 <sub>a</sub>	$L^i L^j \bar{Q}_k \bar{u}^c Q^k d^c \epsilon_{i j}$	$\frac{y_d y_u g^2}{(16\pi^2)^3} \frac{v^2}{\Lambda}$	$1 \times 10^3$	$\beta\beta\nu$
14 <sub>b</sub>	$L^i L^j \bar{Q}_i \bar{u}^c Q^l d^c \epsilon_{j l}$	$\frac{y_d y_u}{(16\pi^2)^2} \frac{v^2}{\Lambda}$	$6 \times 10^5$	$\beta\beta\nu$
15	$L^i L^j L^k d^c \bar{L}_i \bar{u}^c \epsilon_{j k}$	$\frac{y_d y_u g^2}{(16\pi^2)^3} \frac{v^2}{\Lambda}$	$1 \times 10^3$	$\beta\beta\nu$
16	$L^i L^j e^c d^c \bar{e}^c \bar{u}^c \epsilon_{i j}$	$\frac{y_d y_u g^4}{(16\pi^2)^4} \frac{v^2}{\Lambda}$	2	$\beta\beta\nu$ , LHC
17	$L^i L^j d^c d^c \bar{d}^c \bar{u}^c \epsilon_{i j}$	$\frac{y_d y_u g^4}{(16\pi^2)^4} \frac{v^2}{\Lambda}$	2	$\beta\beta\nu$ , LHC
18	$L^i L^j d^c u^c \bar{u}^c \bar{u}^c \epsilon_{i j}$	$\frac{y_d y_u g^4}{(16\pi^2)^4} \frac{v^2}{\Lambda}$	2	$\beta\beta\nu$ , LHC
19	$L^i Q^j d^c d^c \bar{e}^c \bar{u}^c \epsilon_{i j}$	$y_{\ell\beta} \frac{y_d^2 y_u}{(16\pi^2)^3} \frac{v^2}{\Lambda}$	1	$\beta\beta\nu$ , HELv, LHC, mix
20	$L^i d^c \bar{Q}_i \bar{u}^c \bar{e}^c \bar{u}^c$	$y_{\ell\beta} \frac{y_d y_u^2}{(16\pi^2)^3} \frac{v^2}{\Lambda}$	40	$\beta\beta\nu$ , mix
21 <sub>a</sub>	$L^i L^j L^k e^c Q^l u^c H^m H^n \epsilon_{i j} \epsilon_{k m} \epsilon_{l n}$	$\frac{y_\ell y_u}{(16\pi^2)^2} \frac{v^2}{\Lambda} \left( \frac{1}{16\pi^2} + \frac{v^2}{\Lambda^2} \right)$	$2 \times 10^3$	$\beta\beta\nu$
21 <sub>b</sub>	$L^i L^j L^k e^c Q^l u^c H^m H^n \epsilon_{i l} \epsilon_{j m} \epsilon_{k n}$	$\frac{y_\ell y_u}{(16\pi^2)^2} \frac{v^2}{\Lambda} \left( \frac{1}{16\pi^2} + \frac{v^2}{\Lambda^2} \right)$	$2 \times 10^3$	$\beta\beta\nu$
22	$L^i L^j L^k e^c \bar{L}_k \bar{e}^c H^l H^m \epsilon_{i l} \epsilon_{j m}$	$\frac{g^2}{(16\pi^2)^3} \frac{v^2}{\Lambda}$	$4 \times 10^4$	$\beta\beta\nu$
23	$L^i L^j L^k e^c \bar{Q}_k \bar{d}^c H^l H^m \epsilon_{i l} \epsilon_{j m}$	$\frac{y_\ell y_d}{(16\pi^2)^2} \frac{v^2}{\Lambda} \left( \frac{1}{16\pi^2} + \frac{v^2}{\Lambda^2} \right)$	40	$\beta\beta\nu$
24 <sub>a</sub>	$L^i L^j Q^k d^c Q^l d^c H^m \bar{H}_i \epsilon_{j k} \epsilon_{l m}$	$\frac{y_d^2}{(16\pi^2)^3} \frac{v^2}{\Lambda}$	$1 \times 10^2$	$\beta\beta\nu$
24 <sub>b</sub>	$L^i L^j Q^k d^c Q^l d^c H^m \bar{H}_i \epsilon_{j m} \epsilon_{k l}$	$\frac{y_d^2}{(16\pi^2)^3} \frac{v^2}{\Lambda}$	$1 \times 10^2$	Neutrinos $\beta\beta\nu$
25	$L^i L^j Q^k d^c Q^l u^c H^m H^n \epsilon_{i m} \epsilon_{j n} \epsilon_{k l}$	$\frac{y_d y_u}{(16\pi^2)^2} \frac{v^2}{\Lambda} \left( \frac{1}{16\pi^2} + \frac{v^2}{\Lambda^2} \right)$	$4 \times 10^3$	$\beta\beta\nu$









## Dirac Neutrinos – Enhanced Symmetry!(Symmetries?)

Back to

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

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

## Dirac Neutrinos – Enhanced Symmetry!(Symmetries?)

If all  $M_i \equiv 0$ , the neutrinos are Dirac fermions.

$$\mathcal{L}_\nu = \mathcal{L}_{\text{old}} - \lambda_{\alpha i} L^\alpha H N^i + H.c.,$$

where  $N_i$  ( $i = 1, 2, 3$ , for concreteness) are SM gauge singlet fermions. In this case, the  $\nu$ SM global symmetry structure is enhanced. For example,  $U(1)_{B-L}$  is an exactly conserved, global symmetry. This is new!

**Downside:** The neutrino Yukawa couplings  $\lambda$  are tiny, less than  $10^{-12}$ .

What is wrong with that? We don't like tiny numbers, but Nature seems to not care very much about what we like...

More to the point, the failure here is that it turns out that the neutrino masses are not, trivially, qualitatively different. This seems to be a “missed opportunity.”

There are lots of ideas that lead to very small Dirac neutrino masses.

Maybe right-handed neutrinos exist, but neutrino Yukawa couplings are forbidden – hence neutrino masses are tiny.

One possibility is that the  $N$  fields are charged under some new symmetry (gauged or global) that is spontaneously broken.

$$\lambda_{\alpha i} L^\alpha H N^i \rightarrow \frac{\kappa_{\alpha i}}{\Lambda} (L^\alpha H)(N^i \Phi),$$

where  $\Phi$  (spontaneously) breaks the new symmetry at some energy scale  $v_\Phi$ . Hence,  $\lambda = \kappa v_\Phi / \Lambda$ . How do we test this?

E.g., [AdG and D. Hernández, arXiv:1507.00916](#)

Gauged chiral new symmetry for the right-handed neutrinos, no Majorana masses allowed, plus a heavy messenger sector. Predictions: new stable massive states (mass around  $v_\Phi$ ) which look like (i) dark matter, (ii) (Dirac) sterile neutrinos are required. Furthermore, there is a new heavy  $Z'$ -like gauge boson.

⇒ Natural Connections to Dark Matter, Sterile Neutrinos, Dark Photons!

## Understanding Fermion Mixing

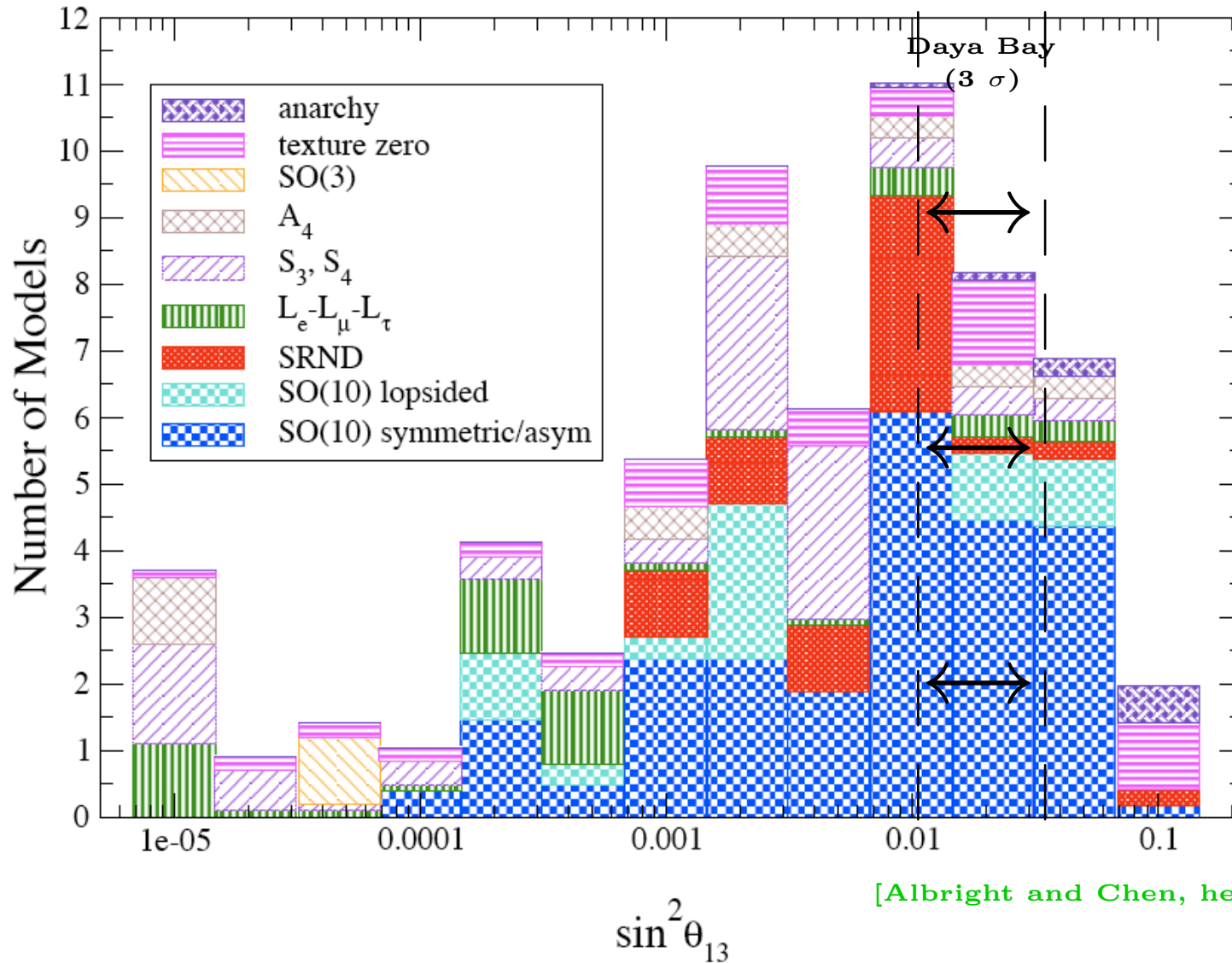
The other puzzling phenomenon uncovered by the neutrino data is the fact that **Neutrino Mixing is Strange**. What does this mean?

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

$$V_{MNS} \sim \begin{pmatrix} 0.8 & 0.5 & 0.2 \\ 0.4 & 0.6 & 0.7 \\ 0.4 & 0.6 & 0.7 \end{pmatrix} \quad V_{CKM} \sim \begin{pmatrix} 1 & 0.2 & 0.001 \\ 0.2 & 1 & 0.01 \\ 0.001 & 0.01 & 1 \end{pmatrix} \quad \boxed{\text{WHY?}}$$

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

They certainly look **VERY** different, but which one would you label as “strange”?



“Left-Over” Predictions:  $\delta$ , mass-hierarchy,  $\cos 2\theta_{23}$



10 anarchical mixing matrices, plus the “real” one

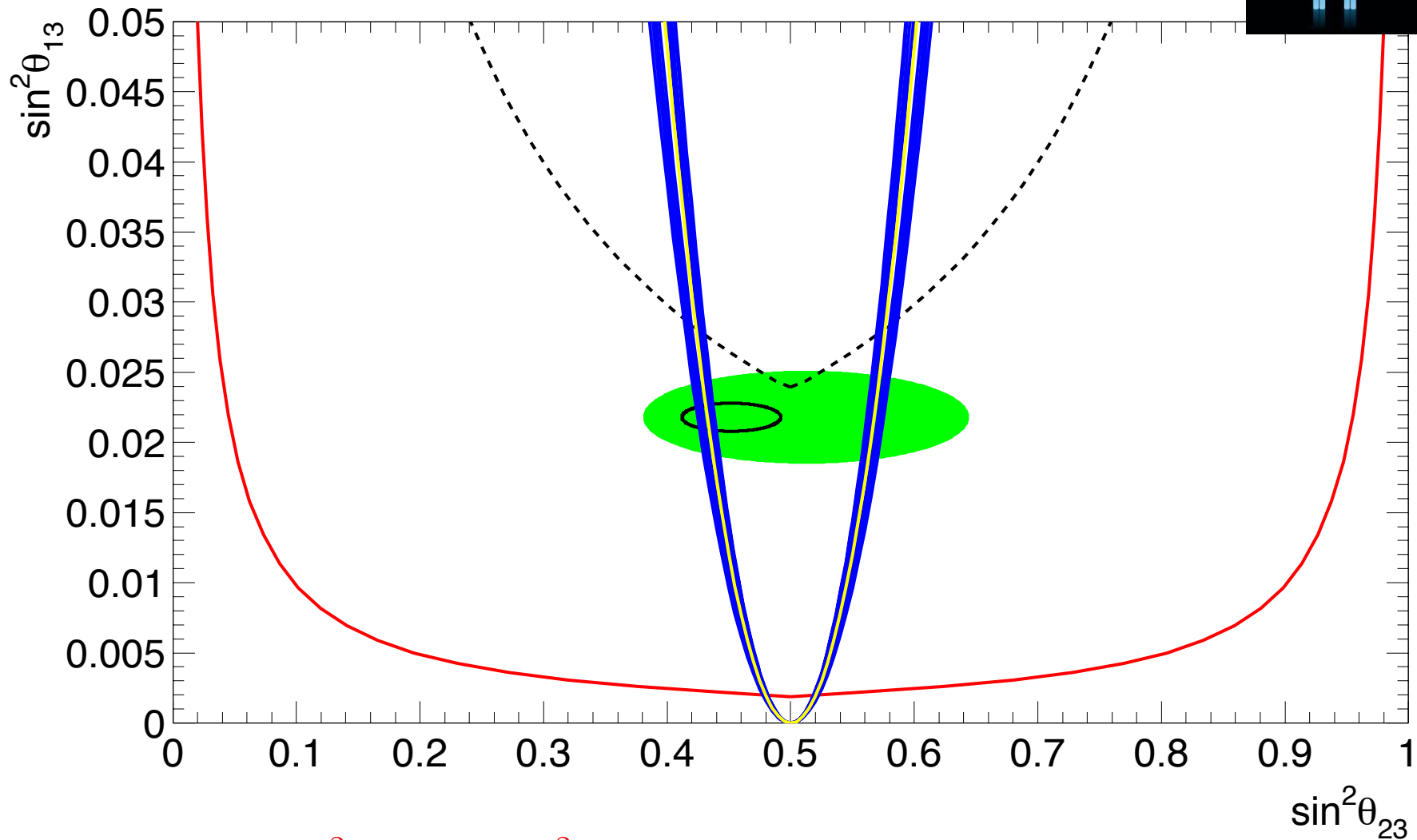
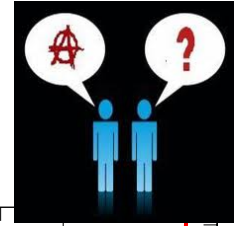
$$\begin{pmatrix} |U_{e1}|^2 & |U_{e2}|^2 & |U_{e3}|^2 \\ \cdots & \cdots & |U_{\mu 3}|^2 \\ \cdots & \cdots & |U_{\tau 3}|^2 \end{pmatrix} = \begin{pmatrix} 0.69 & 0.29 & 0.02 \\ \cdots & \cdots & 0.40 \\ \cdots & \cdots & 0.58 \end{pmatrix}, \quad \begin{pmatrix} 0.36 & 0.35 & 0.29 \\ \cdots & \cdots & 0.68 \\ \cdots & \cdots & 0.03 \end{pmatrix},$$

$$\begin{pmatrix} 0.83 & 0.11 & 0.06 \\ \cdots & \cdots & 0.87 \\ \cdots & \cdots & 0.07 \end{pmatrix}, \quad \begin{pmatrix} 0.71 & 0.13 & 0.16 \\ \cdots & \cdots & 0.20 \\ \cdots & \cdots & 0.64 \end{pmatrix}, \quad \begin{pmatrix} 0.24 & 0.47 & 0.29 \\ \cdots & \cdots & 0.58 \\ \cdots & \cdots & 0.13 \end{pmatrix},$$

$$\begin{pmatrix} 0.16 & 0.35 & 0.49 \\ \cdots & \cdots & 0.13 \\ \cdots & \cdots & 0.38 \end{pmatrix}, \quad \begin{pmatrix} 0.63 & 0.24 & 0.13 \\ \cdots & \cdots & 0.73 \\ \cdots & \cdots & 0.14 \end{pmatrix}, \quad \begin{pmatrix} 0.12 & 0.35 & 0.53 \\ \cdots & \cdots & 0.12 \\ \cdots & \cdots & 0.35 \end{pmatrix},$$

$$\begin{pmatrix} 0.22 & 0.55 & 0.23 \\ \cdots & \cdots & 0.12 \\ \cdots & \cdots & 0.65 \end{pmatrix}, \quad \begin{pmatrix} 0.21 & 0.37 & 0.42 \\ \cdots & \cdots & 0.08 \\ \cdots & \cdots & 0.50 \end{pmatrix}, \quad \begin{pmatrix} 0.54 & 0.44 & 0.02 \\ \cdots & \cdots & 0.54 \\ \cdots & \cdots & 0.44 \end{pmatrix}.$$

**Anarchy vs. Order** — more precision required!



Order:  $\sin^2 \theta_{13} = C \cos^2 2\theta_{23}$ ,  $C \in [0.8, 1.2]$

[AdG, Murayama, 1204.1249]

## Piecing the Neutrino Mass Puzzle

Understanding the origin of neutrino masses and exploring the new physics in the lepton sector will require unique **theoretical** and **experimental** efforts, including ...

- understanding the fate of lepton-number. Neutrinoless double beta decay!
- a comprehensive long baseline neutrino program, towards precision oscillation physics.
- other probes of neutrino properties, including neutrino scattering.
- precision studies of charged-lepton properties ( $g - 2$ , edm), and searches for rare processes ( $\mu \rightarrow e$ -conversion the best bet at the moment).
- collider experiments. The LHC and beyond may end up revealing the new physics behind small neutrino masses.
- cosmic surveys. Neutrino properties affect, in a significant way, the history of the universe. Will we learn about neutrinos from cosmology, or about cosmology from neutrinos?
- searches for baryon-number violating processes.

## Concluding Remarks

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).