What We Have Learned

and

The Open Questions

Boris Kayser
SLAC Summer Institute
August 3-4, 2004

What Have We Learned ?

We do not know how many neutrino mass eigenstates there are.

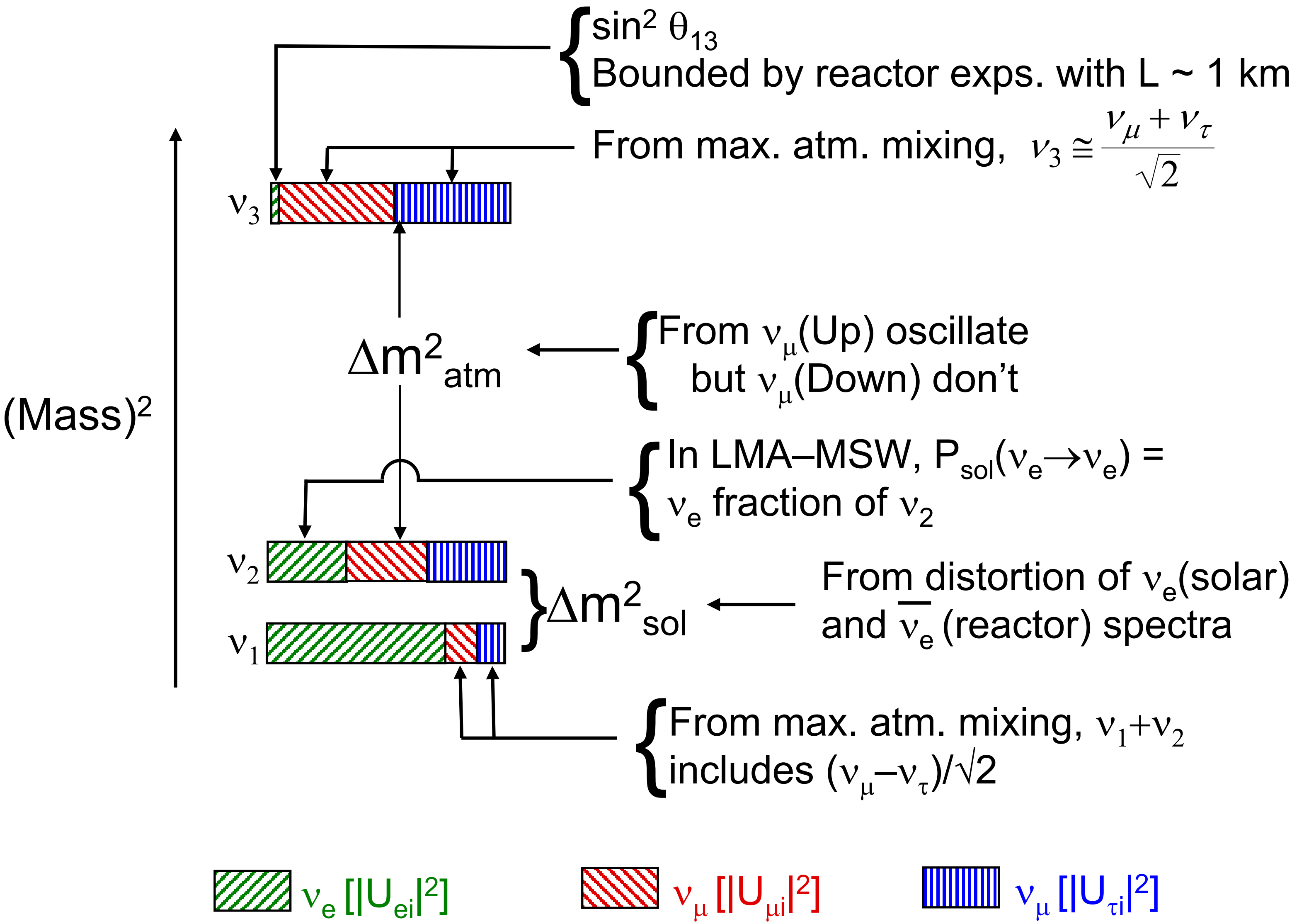
There are at least 3.

If LSND is confirmed, there are more than 3.

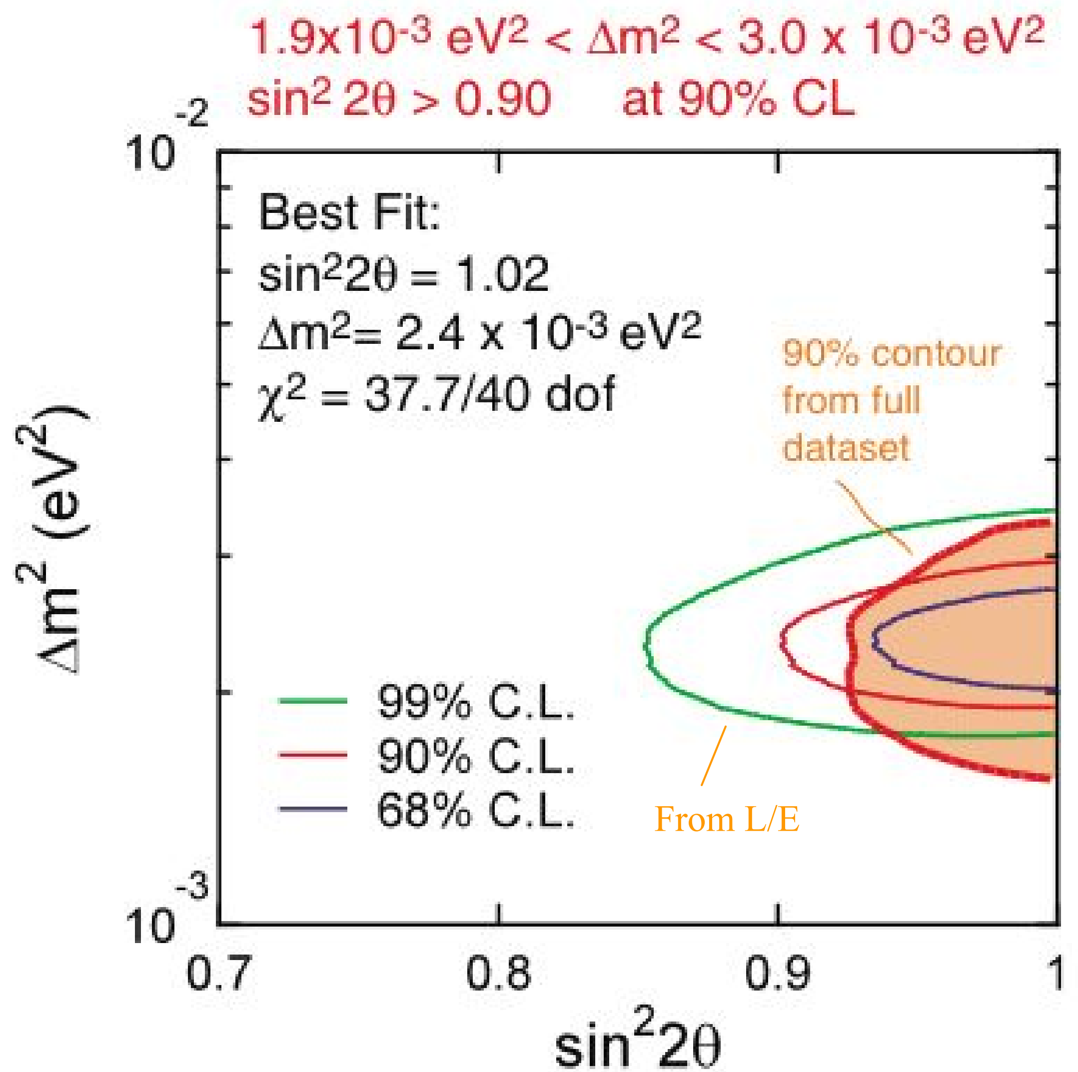
4?   6? ∞?

If LSND is not confirmed, nature may contain only 3 neutrinos.

Then, from the existing data, the neutrino spectrum looks like —

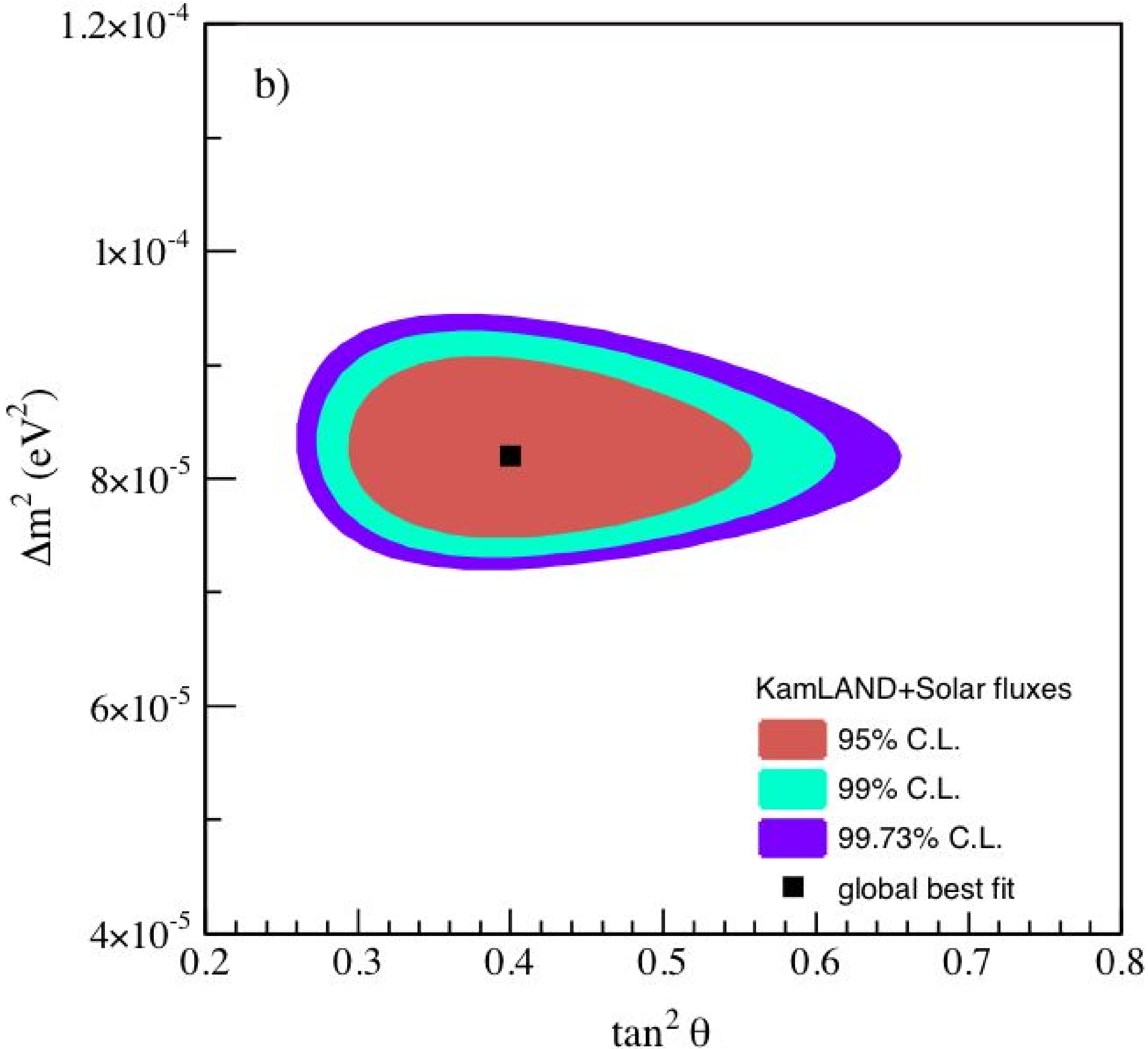


$\sin^2 \theta_{13}$
Bounded by reactor exps. with L ~ 1 km
From max. atm. mixing, $\nu_3 \cong \frac{\nu_\mu + \nu_\tau}{\sqrt{2}}$
ν_3
Δm^2_{atm}
From ν_μ(Up) oscillate
but ν_μ(Down) don't
(Mass)^2
In LMA–MSW, $P_{sol}(\nu_e \to \nu_e)$ =
ν_e fraction of ν_2
ν_2
Δm^2_{sol}
From distortion of ν_e(solar)
and $\bar{\nu}_e$ (reactor) spectra
ν_1
From max. atm. mixing, $\nu_1 + \nu_2$
includes $(\nu_\mu - \nu_\tau)/\sqrt{2}$
ν_e $[|U_{ei}|^2]$
ν_μ $[|U_{\mu i}|^2]$
ν_μ $[|U_{\tau i}|^2]$



From Ed Kearns

Atmospheric Δm^2 and mixing angle from SuperKamiokande L/E analysis and full data set



From hep-ex/0406035

Solar Δm^2 and mixing angle from KamLAND analysis of KamLAND and solar neutrino data

The Mixing Matrix

The flavor content picture shows the $|U_{\alpha i}|^2$, but not the signs or phases of the $U_{\alpha i}$.

Atmospheric / Cross-Mixing / Solar

$$U = \begin{bmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{bmatrix} \times \begin{bmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{bmatrix} \times \begin{bmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

$$\times \begin{bmatrix} e^{i\alpha_1/2} & 0 & 0 \\ 0 & e^{i\alpha_2/2} & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

$c_{ij} \equiv \cos\theta_{ij}$
$s_{ij} \equiv \sin\theta_{ij}$

Majorana ~~CP~~ phases

$\theta_{12} \approx \theta_{sol} \approx 32°$, $\theta_{23} \approx \theta_{atm} \approx 35\text{-}55°$, $\theta_{13} \lesssim 15°$

δ would lead to $P(\overline{\nu}_\alpha \to \overline{\nu}_\beta) \neq P(\nu_\alpha \to \nu_\beta)$. ~~CP~~

But note the crucial role of $s_{13} \equiv \sin\theta_{13}$.

How Does the Large Mixing Angle MSW Effect Work?

The solar matter effect is important for the high-energy ^{8}B neutrinos, not the low-energy pp neutrinos.

Since ν_3 couples at most feebly to electrons ($\sin^2\theta_{13} < 0.06$), and solar neutrinos are born ν_e, the solar neutrinos are mixtures of just ν_1 and ν_2.

Solar neutrino flavor change is $\nu_e \rightarrow \nu_x$, where ν_x is some combination of ν_μ and ν_τ.

This is a 2-neutrino system.

In the sun,

$\{_e$ $\{_x$

$$H = \frac{\Delta m^2_{sol}}{4E}\begin{bmatrix} -\cos 2\theta_{sol} & \sin 2\theta_{sol} \\ \sin 2\theta_{sol} & \cos 2\theta_{sol} \end{bmatrix} + \sqrt{2}G_F N_e \begin{bmatrix} 1 & 0 \\ 0 & 0 \end{bmatrix} \begin{matrix} \{_e \\ \{_x \end{matrix}$$

At the center of the sun,

$\sqrt{2}G_F N_e \approx 0.75 \times 10^{-5}\ \mathrm{eV}^2 / \mathrm{MeV}$.

For $\otimes m^2_{sol} \approx 8 \times 10^{-5}\ \mathrm{eV}^2$ and typical ^8B neutrino energy of ~8 MeV,

$\otimes m^2_{sol} / 4E \approx 0.25 \times 10^{-5}\ \mathrm{eV}^2 / \mathrm{MeV}$.

The interaction term in H dominates, and $\{_e$ is approximately an eigenstate of H.

The ^{8}B solar neutrino propagates outward adiabatically.

It remains the slowly - changing heavier eigenstate of the slowly - changing H.

It emerges from the sun as the heavier eigenstate of H_{Vac}, ν_2.

It stays ν_2 until it reaches the earth. Nothing “oscillates”!

Since $\nu_2 = \nu_e \sin\theta_{sol} + \nu_x \cos\theta_{sol}$, (See U matrix)

Prob[See ν_e at earth] = $\sin^2\theta_{sol}$.

What Would We Like To Find Out?

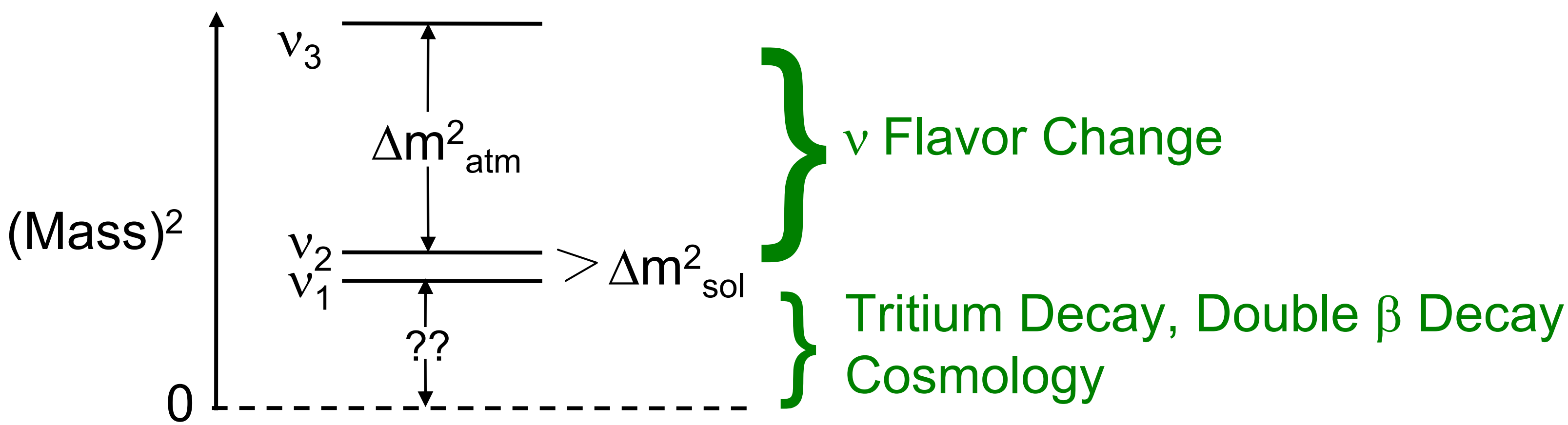
— The Future —

Some of the Open Questions

- How many neutrino species are there? Are there sterile neutrinos?

MiniBooNE will confirm or refute LSND.

- What are the masses of the mass eigenstates ν_i?

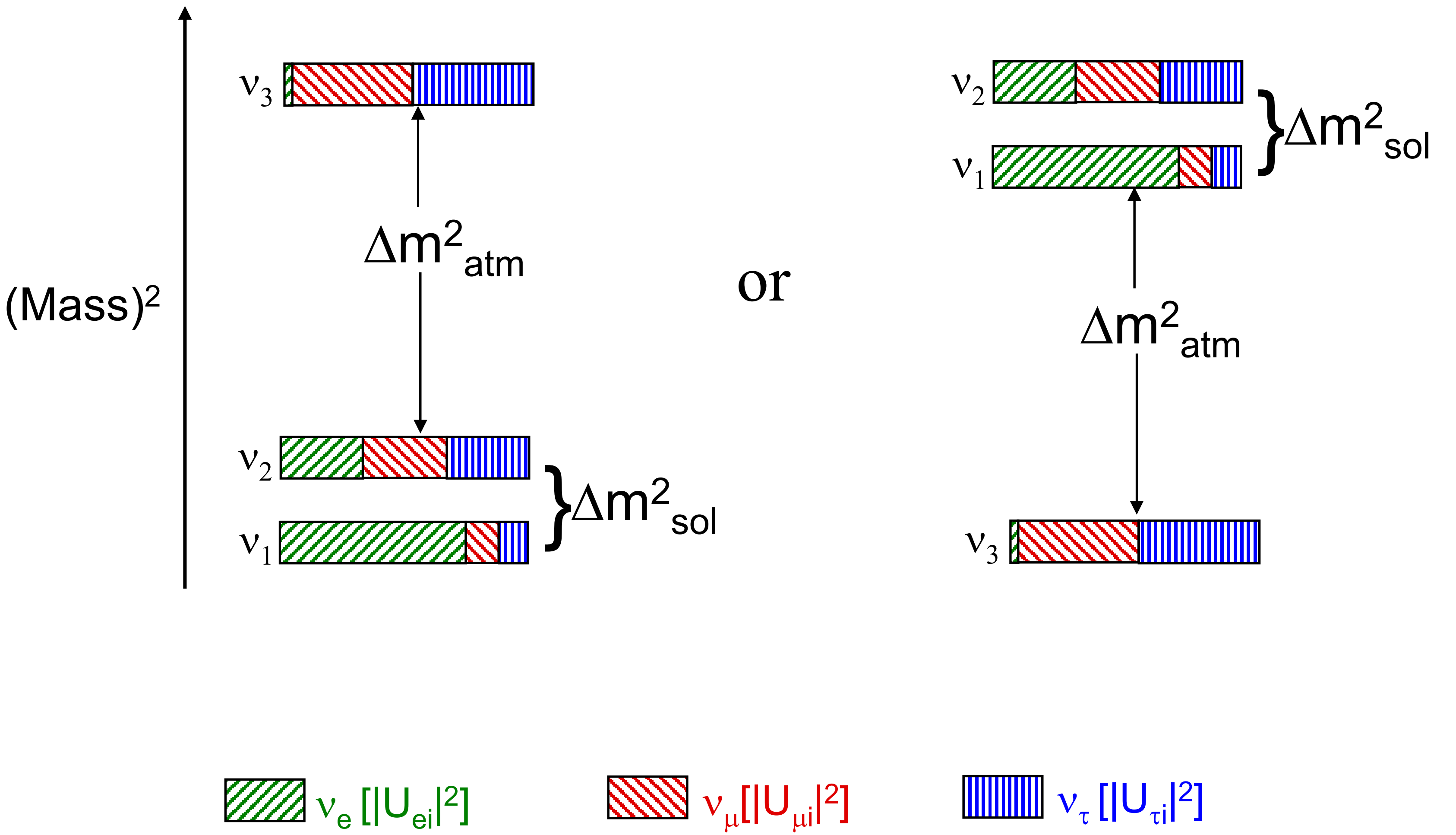


Is the spectral pattern  or  ?

$\overset{(-)}{\nu}$ behavior in earth matter can distinguish.

How far above zero is the whole pattern??

Is the spectrum —



Generically, SO(10) grand unified models predict  .

 is un-quark-like, and would probably involve a lepton symmetry with no quark analogue.

The symmetry might be something like $L_e - L_\mu - L_\tau$ conservation.

To determine whether the spectrum is normal or inverted, study the earth matter effect on $\overset{(-)}{\nu}_\mu \rightarrow \overset{(-)}{\nu}_e$.

These oscillations are proportional to $\sin^2 2\theta_{13}$.

Sign depends on character of spectrum

$$\sin^2 2\overset{(-)}{\theta}_M = \sin^2 2\theta_{13} / [\sin^2 2\theta_{13} + (\cos 2\theta_{13} \underset{(+)}{-} x)^2]$$

At superbeam energies,

$$\sin^2 2\overset{(-)}{\theta}_M \cong \sin^2 2\theta_{13} \left[1 \underset{(-)}{+} S \frac{E}{6\text{ GeV}} \right] .$$

Sign[m^2(—) - m^2(═)]

At oscillation maximum,

$$\frac{P(\nu_\mu \to \nu_e)}{P(\bar{\nu}_\mu \to \bar{\nu}_e)} \begin{cases} >1 \;; & \begin{matrix} \text{—} \\ \text{═} \end{matrix} \\ <1 \;; & \begin{matrix} \text{═} \\ \text{—} \end{matrix} \end{cases}$$

The effect is $\begin{cases} 30\% \;;\; E = 2\text{ GeV (NO}\nu\text{A)} \\ 10\% \;;\; E = 0.7\text{ GeV (T2K)} \end{cases}$

A Cosmic Connection

Cosmological Data + Cosmological Assumptions $\Rightarrow$

$$\Sigma\, m_i < 0.71 \text{ eV} .$$

Mass(ν_i)

(95% CL
Spergel et al.)

If there are only 3 neutrinos,

$$0.04 \text{ eV} < \text{Mass[Heaviest } \nu_i] < 0.23 \text{ eV}$$

$\sqrt{\Delta m^2_{atm}}$ Cosmology

✠ Does —

- $\bar{\nu}_i = \nu_i$ (Majorana neutrinos)

or

- $\bar{\nu}_i \neq \nu_i$ (Dirac neutrinos) ?

$e^+ \neq e^-$ since Charge(e^+) = – Charge(e^-).

But neutrinos may not carry any conserved charge-like quantum number.

A conserved Lepton Number L defined by—

$L(\nu) = L(l^-) = -L(\bar{\nu}) = -L(l^+) = 1$ may not exist.

If it does not, then nothing distinguishes $\bar{\nu}_i$ from ν_i . We then have Majorana neutrinos.

Why Many Theorists Think L Is Not Conserved

The Standard Model (SM) is defined by the fields it contains, its symmetries (notably Electroweak Isospin Invariance), and its renormalizability.

Anything allowed by the symmetries occurs.

The SM contains no ν_R field, only ν_L, and no ν mass.

But now we know the neutrino has mass.

If we try to conserve L, we accommodate this mass by adding a Dirac, L - conserving, mass term: $m_D \overline{\nu_L} \nu_R$.

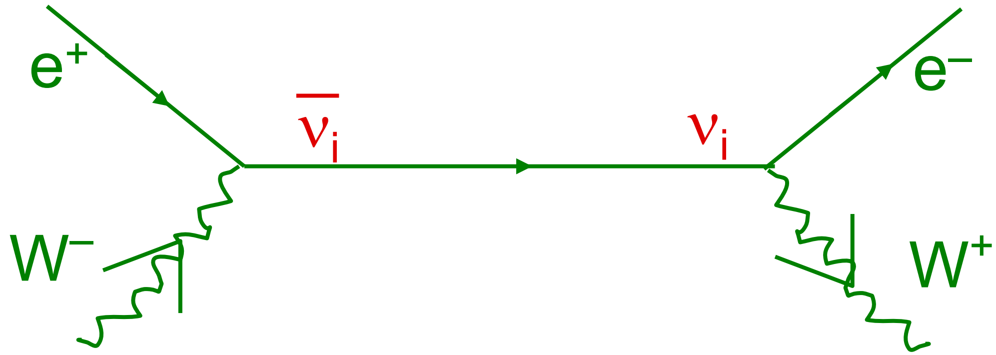
To do that, we had to add ν_R to the SM.

Unlike ν_L , ν_R carries no Electroweak Isospin.

Thus, no SM symmetry prevents the occurrence of the Majorana mass term $m_M \overline{\nu_R^{\,c}}\, \nu_R$.

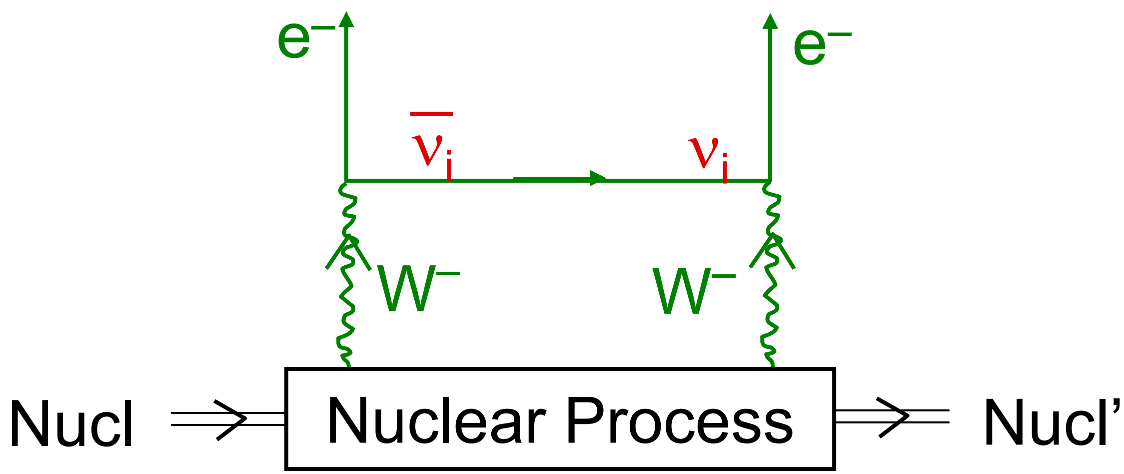
This mass term causes $\nu \rightarrow \bar{\nu}$. It does not conserve L.

If L is not conserved, and neutrinos are their own antiparticles, then we can have —



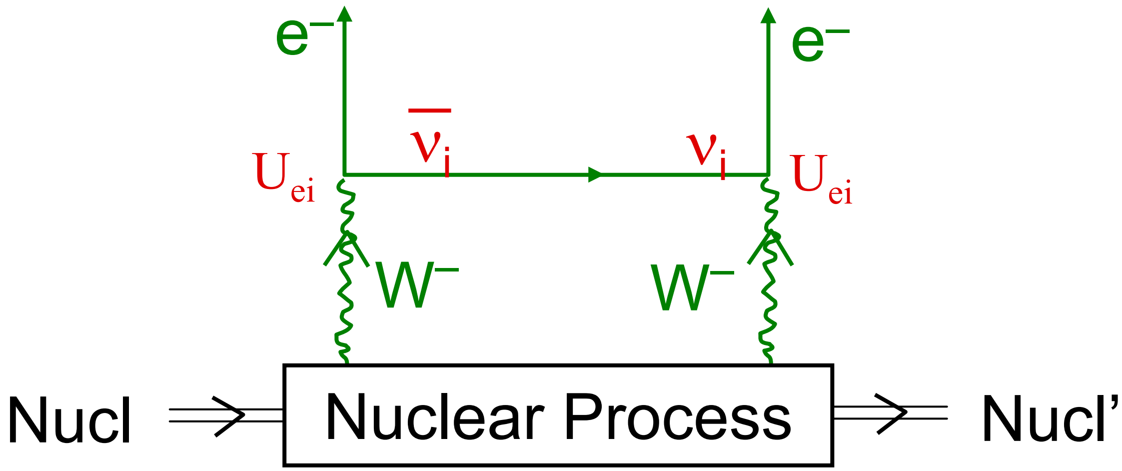
It is more practical to seek —

Neutrinoless Double Beta Decay [$0\nu\beta\beta$]



Observation would imply $\bar{\nu}_i = \nu_i$, making the neutrinos very different from the charged leptons and quarks.

In —



the $\bar{\nu}_i$ is emitted [RH + O{m_i/E}LH].

Thus, Amp [ν_i contribution] α m_i

$$\text{Amp}[0\nu\beta\beta] \propto \left|\sum_i m_i U_{ei}^2\right| \equiv m_{\beta\beta}$$

The proportionality of $0\nu\beta\beta$ to mass is no surprise.

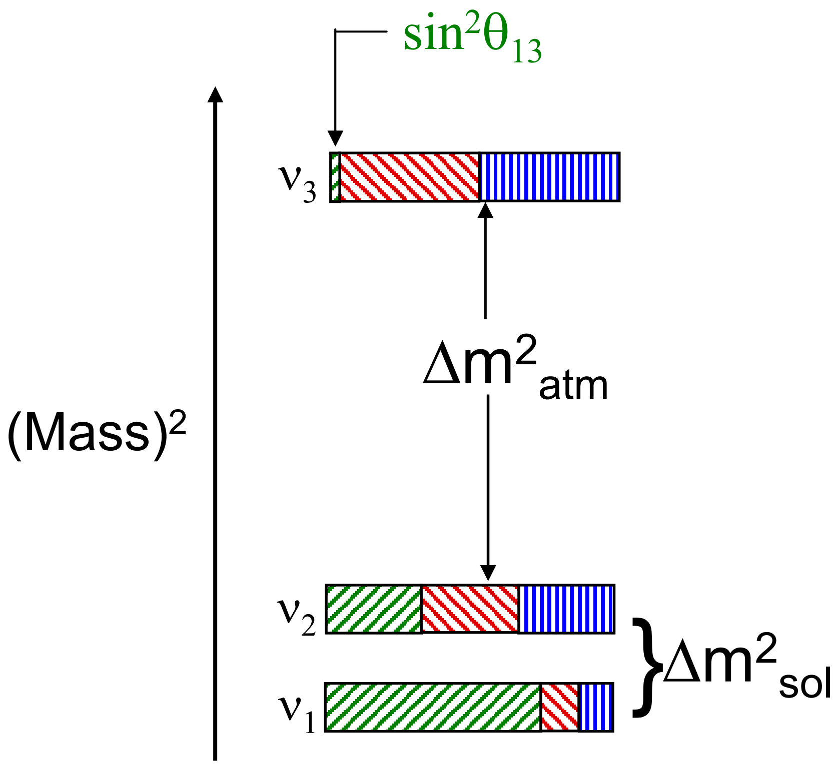
$0\nu\beta\beta$ violates L. But the SM interactions conserve L.

The L - violation in $0\nu\beta\beta$ comes from underlying Majorana mass terms.

In Pursuit of θ_{13}

Both CP violation and our ability to tell whether the spectrum is normal or inverted depend on θ_{13}.

How may θ_{13} be measured?



$\sin^2\theta_{13} = |U_{e3}|^2$ is the small ν_e piece of ν_3.

ν_3 is at one end of Δm^2_{atm}.

∴ We need an experiment with L/E sensitive to Δm^2_{atm}, and involving ν_e.

Possibilities

Reactor $\bar{\nu}_e$ disappearance while traveling L ~ 1.5 km. L/E ~ 500 km/GeV.

Accelerator $\nu_\mu \rightarrow \nu_e$ while traveling L > Several hundred km. L/E ~ 400 km/GeV.

✠ Do neutrino interactions violate CP?

Do the leptonic interactions, like the quark interactions, violate the fundamental symmetry of CP?

Is leptonic $\not{CP}$ responsible for the

MATTER antimatter

asymmetry of the universe?

✠ Is neutrino $\not{CP}$ the reason we exist?

The universe contains **MATTER**, but essentially no antimatter.

Good thing for us:

This preponderance of **MATTER** over antimatter could not have developed unless the two behave differently.

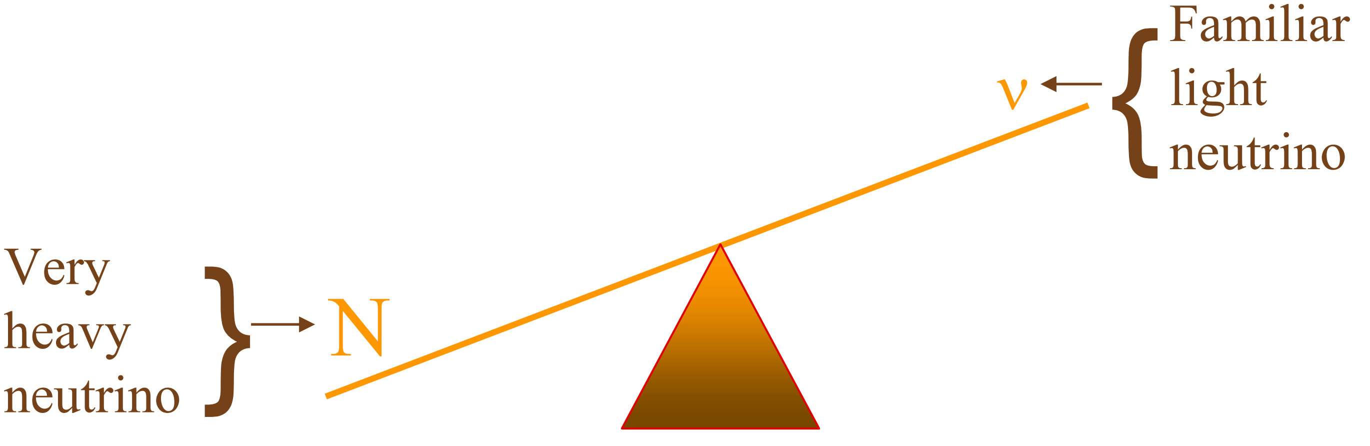
The observed difference between **QUARK** and antiquark behavior, as described by the Standard Model, is inadequate.

Could the interactions of **MATTER** and antimatter with neutrinos provide the crucial difference?

There is a natural way in which they could.

The most popular theory of why neutrinos are so light is the —

See-Saw Mechanism



The heavy neutrinos N would have been made in the hot Big Bang.

The heavy neutrinos N, like the light ones ν, are Majorana particles. Thus, an N can decay into e^- or e^+.

But if, in violation of CP, Matter and antimatter couple differently to these heavy neutrinos N, then we can have —

$$\text{Probability} [N \rightarrow e^- + \ldots] \neq \text{Probability} [N \rightarrow e^+ + \ldots]$$

(e^-: Matter; e^+: antimatter)

in the early universe.

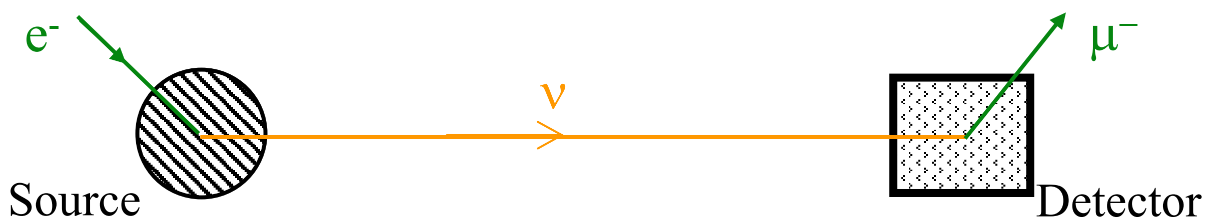
This phenomenon (leptogenesis) would have led to a universe containing unequal amounts of leptonic Matter and antimatter.

SM sphaleron processes would then have converted some of the leptonic asymmetry into a baryon asymmetry.

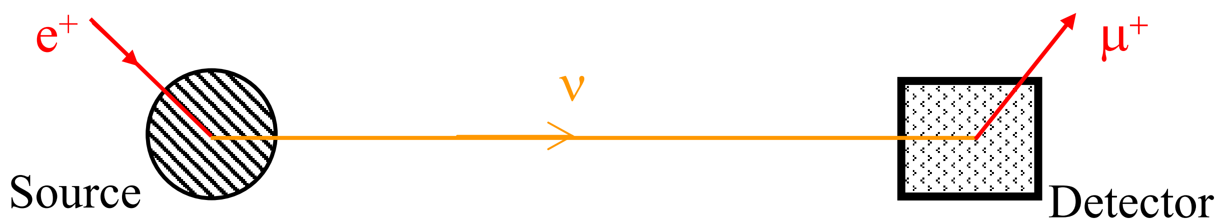
We cannot repeat the early universe.

But we can lend credibility to the hypothesis of leptogenesis by showing that Matter and antimatter couple differently to the light neutrinos ν.

A neutrino flavor change involving Matter:



A neutrino flavor change involving antimatter:



If these two flavor changes have different probabilities, then quite likely so do —

$N \rightarrow e^- + \ldots$ and $N \rightarrow e^+ + \ldots$

If N decays led to the present preponderance of Matter over antimatter, then we are all descendants of heavy neutrinos.

Conclusion

Wonderful experiments, involving the beautiful physics of flavor change, have led to the discovery of neutrino mass.

This discovery has raised very interesting questions that we must now try to answer.