Exploring the Neutrino Questions

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The Neutrino Revolution
(1998 – …)

Neutrinos have nonzero masses!

This discovery comes from
the observation of
neutrino flavor change
(***neutrino oscillation***).

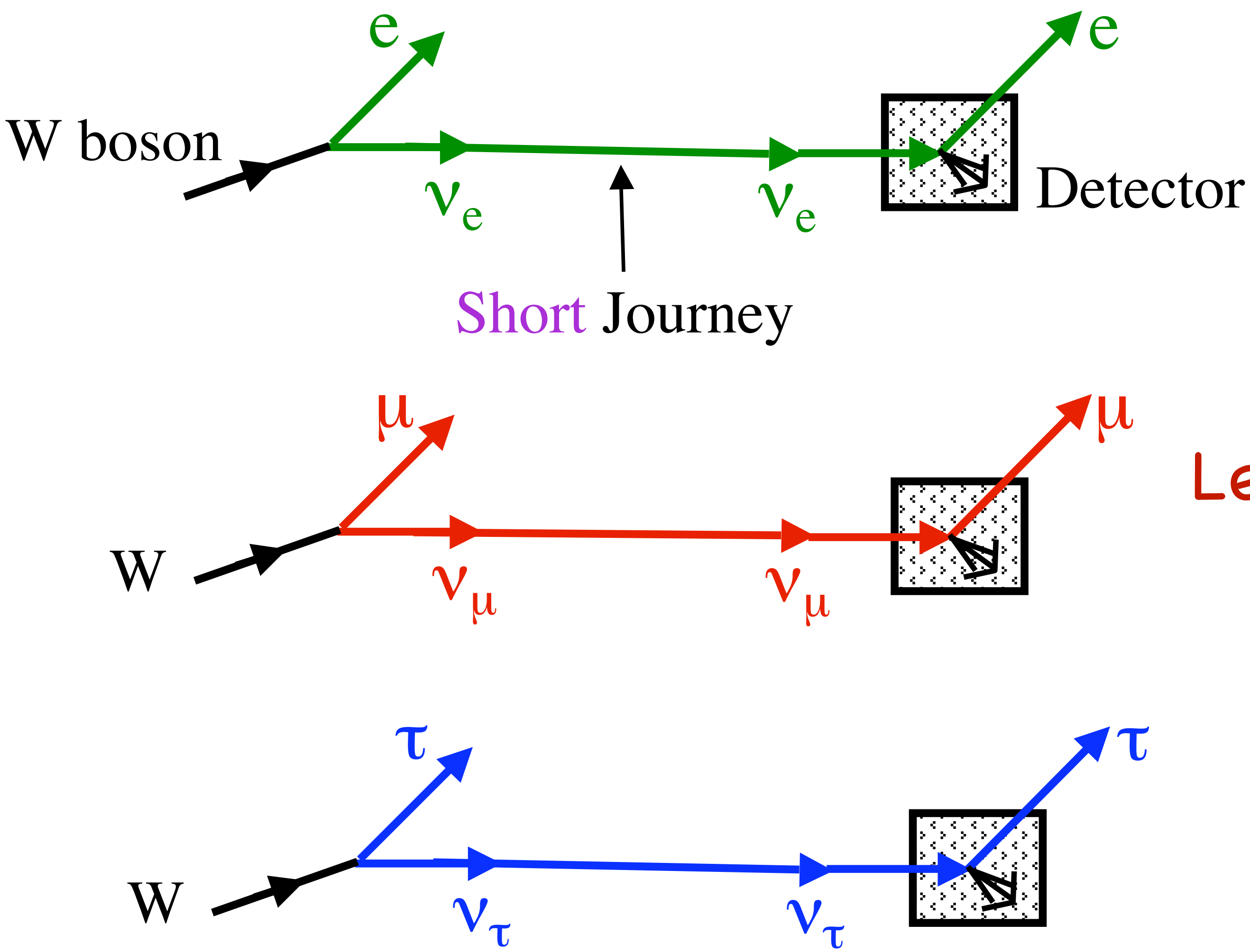
Neutrino Flavor Change

The known neutrino flavors:

Each of these is associated with the corresponding charged-lepton flavor:

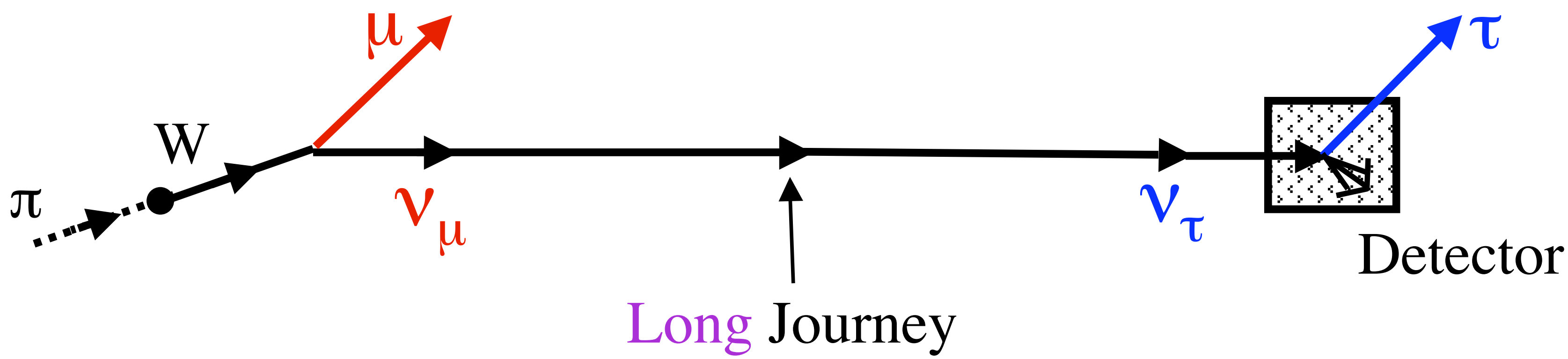
$$\begin{array}{ccccc} \nu_e & , & \nu_\mu & , & \nu_\tau \\ \updownarrow & & \updownarrow & & \updownarrow \\ e & , & \mu & , & \tau \end{array}$$

The Meaning of this Association



Lederman et al.

But if neutrinos have masses, we can have —



Give ν time to change character

$$\nu_\mu \longrightarrow \nu_\tau$$

The last eight years have brought us compelling evidence that such flavor changes actually occur.

Flavor Change Requires ***Leptonic Mixing***

The neutrinos $\nu_{e,\mu,\tau}$ of definite flavor

$(W \rightarrow e\nu_e$ or $\mu\nu_\mu$ or $\tau\nu_\tau)$

are superpositions of neutrinos of definite mass:

$$|\nu_\alpha> = \sum_i U^*_{\alpha i} \, |\nu_i> \quad .$$

Neutrino of flavor $\alpha = e, \mu,$ or τ

Unitary Leptonic Mixing Matrix

Neutrino of definite mass m_i

Inverting: $|\nu_i> = \sum_\alpha U_{\alpha i} \, |\nu_\alpha> .$

Flavor-α fraction of $\nu_i = |U_{\alpha i}|^2$.

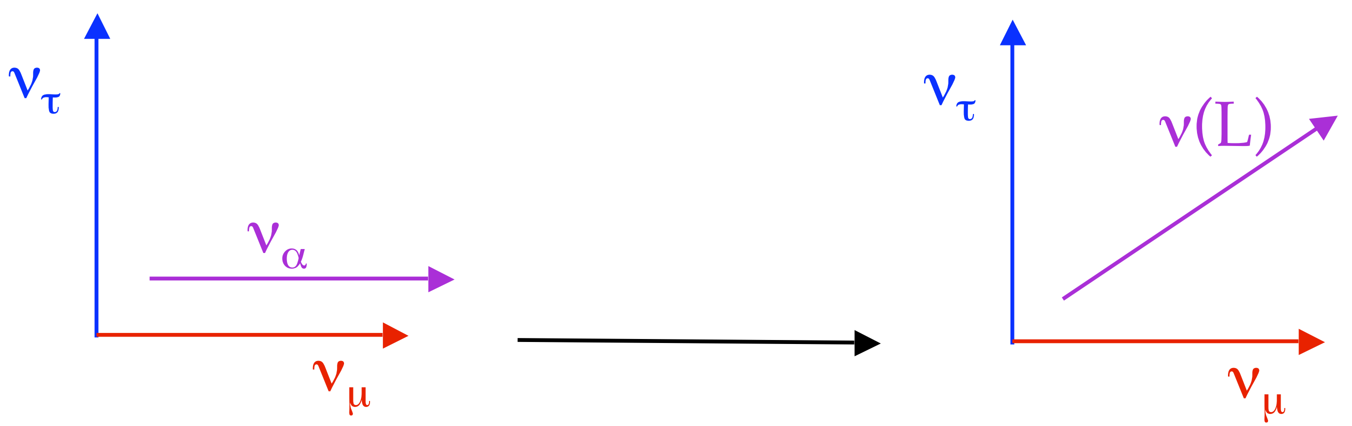
Neutrino Flavor Change ("Oscillation")

Suppose a neutrino is born with flavor α and energy E.

$$\nu_\alpha = \sum_i U^*_{\alpha i}\nu_i \xrightarrow[\text{Distance L}]{} \sum_i U^*_{\alpha i}\nu_i e^{ip_i(E)L/\hbar} \equiv \nu(L) \neq \nu_\alpha$$

$$\sqrt{E^2-(m_i c^2)^2}\,/\,c$$

The neutrino has evolved into a mixture of the flavors.



When Only Two Neutrinos Matter

Often, only 2 neutrinos need to be considered.

Then —

Mixing Angle

$$U = \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix}$$

Then—

$$P(\nu_\alpha \rightarrow \nu_{\beta\neq\alpha}) = \sin^2 2\theta \, \sin^2\left[1.27\, \Delta m^2(\mathrm{eV}^2)\, \frac{L(\mathrm{km})}{E(\mathrm{GeV})}\right]$$

Probability

$$\Delta m^2 \equiv m_2^{\,2} - m_1^{\,2}$$

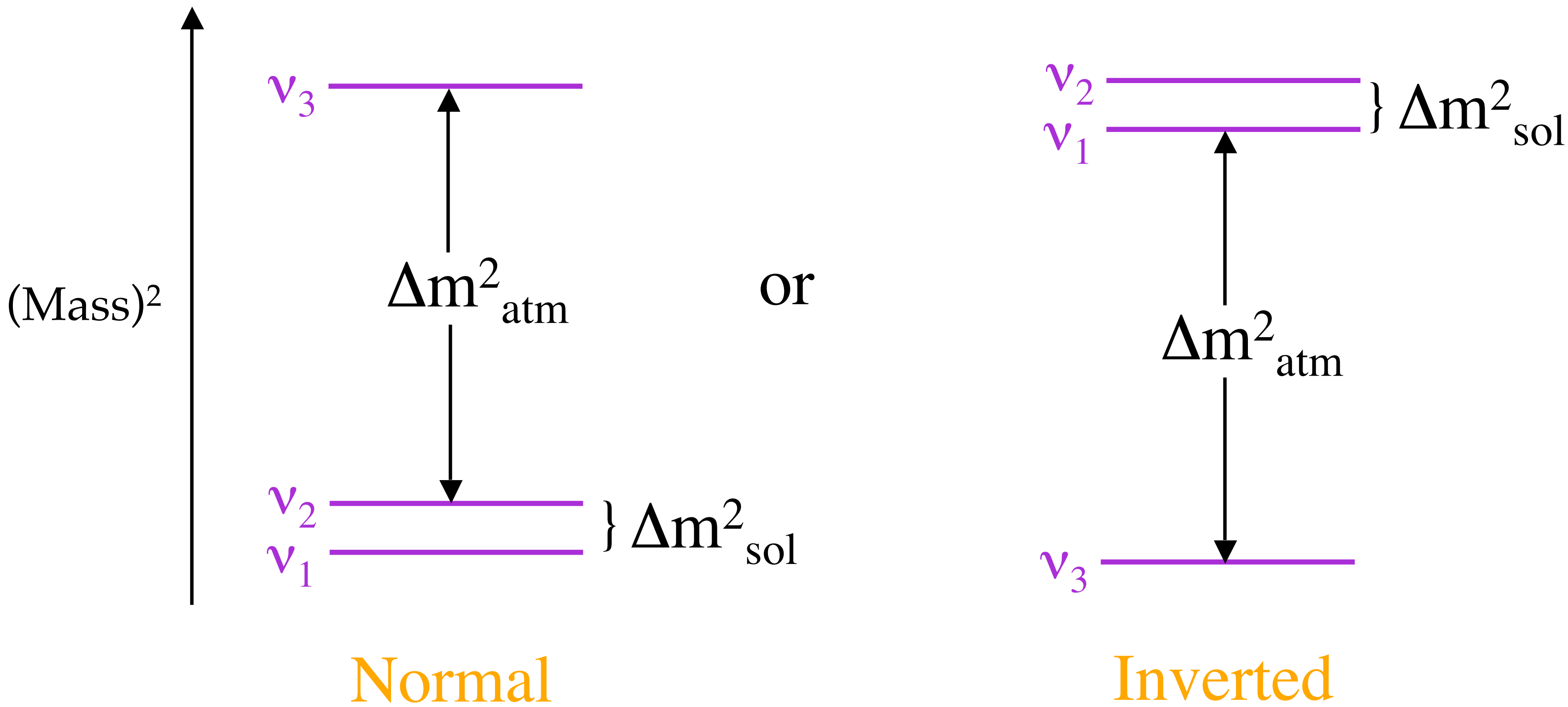
Neutrino oscillation ⇒ Neutrino mass & leptonic mixing

Evidence For Flavor Change

Neutrinos	Evidence of Flavor Change
Solar	Compelling
Reactor (L ~ 180 km)	Compelling
Atmospheric	Compelling
Accelerator (L = 250 and 735 km)	Compelling
Stopped μ^+ Decay $\begin{pmatrix}\text{LSND} \\ L \approx 30\text{ m}\end{pmatrix}$	Unconfirmed

What We Have Learned

The (Mass)^2 Spectrum



$\Delta m^2_{sol} \cong 8 \times 10^{-5}\ \mathrm{eV}^2$, $\Delta m^2_{atm} \cong 2.7 \times 10^{-3}\ \mathrm{eV}^2$

Are there *more* mass eigenstates, as LSND suggests?

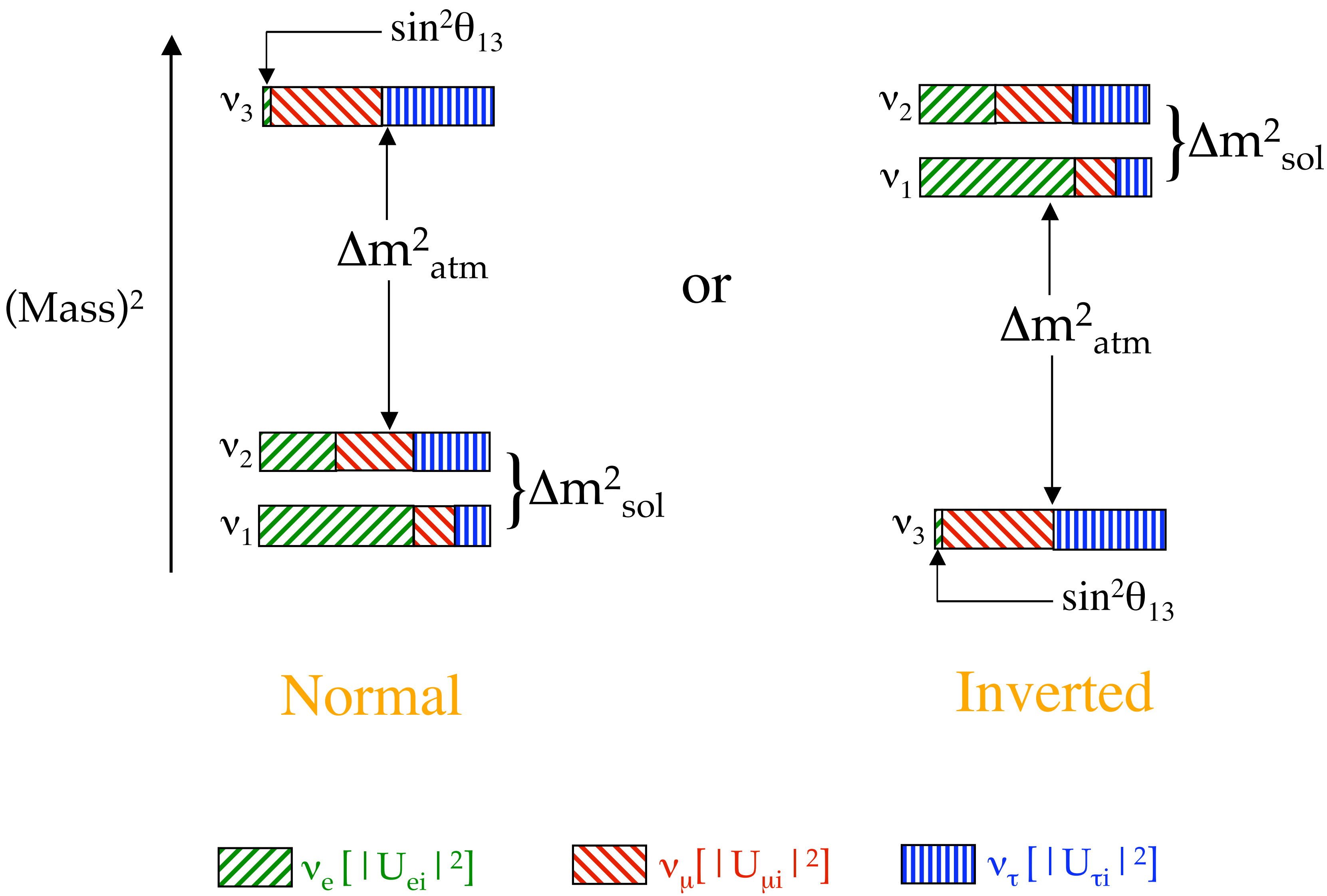
Leptonic Mixing

This has the consequence that —

$$|\nu_i> = \sum_\alpha U_{\alpha i}\, |\nu_\alpha> .$$

Flavor-α fraction of $\nu_i = |U_{\alpha i}|^2$.

The spectrum, showing its approximate flavor content, is



The Mixing Matrix

$$U = \begin{array}{ccc} \text{Atmospheric} & \text{Cross-Mixing} & \text{Solar} \\ \begin{bmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{bmatrix} \times & \begin{bmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{bmatrix} \times & \begin{bmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{bmatrix} \end{array}$$

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

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

Majorana $\cancel{CP}$ phases

$\theta_{12} \approx \theta_{sol} \approx 34°,\ \theta_{23} \approx \theta_{atm} \approx 37\text{-}53°,\ \theta_{13} \lesssim 10°$

δ would lead to $P(\bar{\nu}_\alpha \rightarrow \bar{\nu}_\beta) \neq P(\nu_\alpha \rightarrow \nu_\beta)$. $\cancel{CP}$

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

The Open Questions

• What is the absolute scale of neutrino mass?

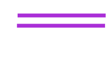
•Are neutrinos their own antiparticles?

•Are there “sterile” neutrinos?

We must be alert to surprises!

•What is the pattern of mixing among the different types of neutrinos?

What is θ_{13}? Is θ_{23} maximal?

•Is the spectrum like  or  ?

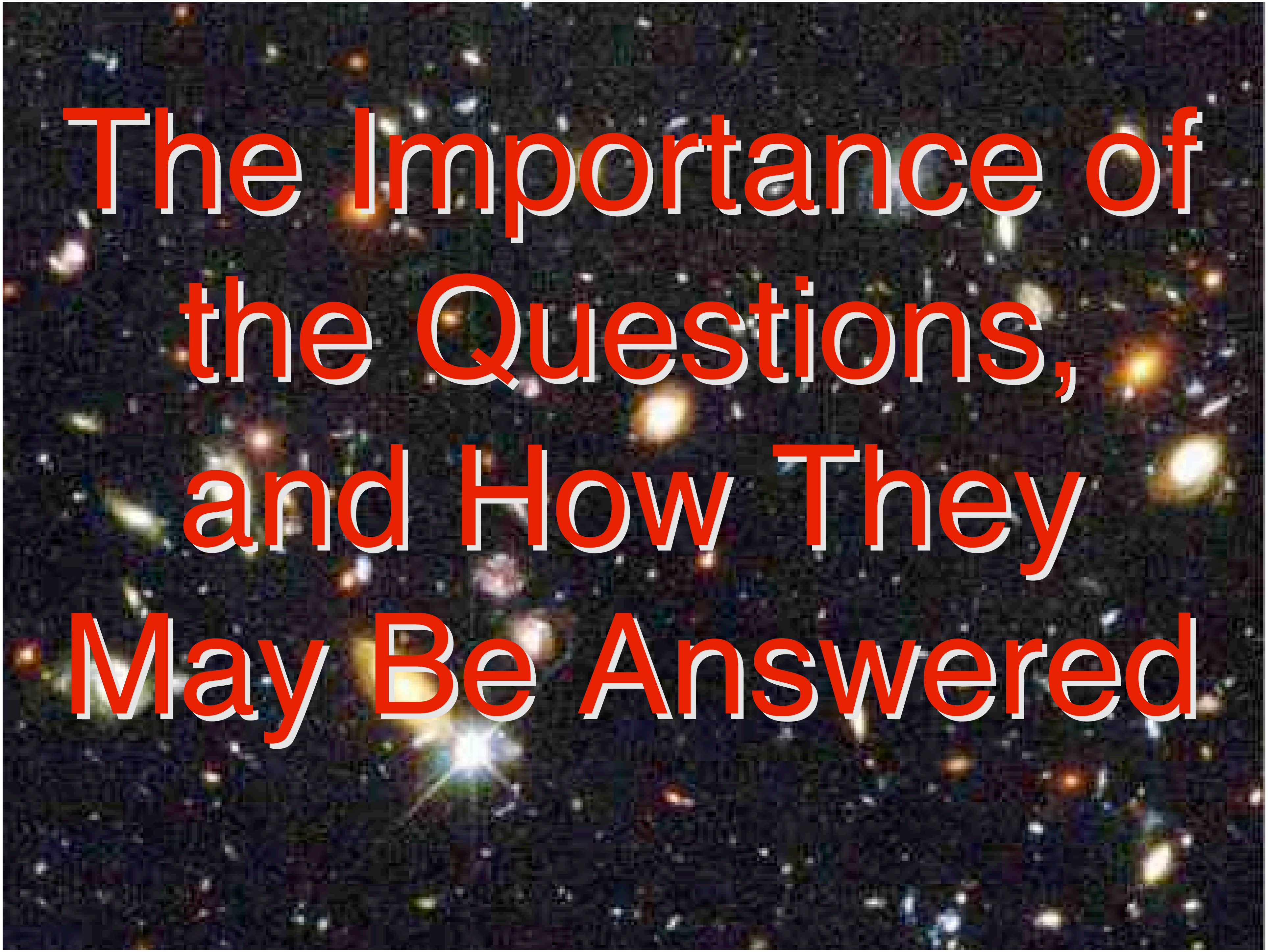
•Do neutrinos violate the symmetry CP?

Is $P(\bar{\nu}_\alpha \rightarrow \bar{\nu}_\beta) \neq P(\nu_\alpha \rightarrow \nu_\beta)$?

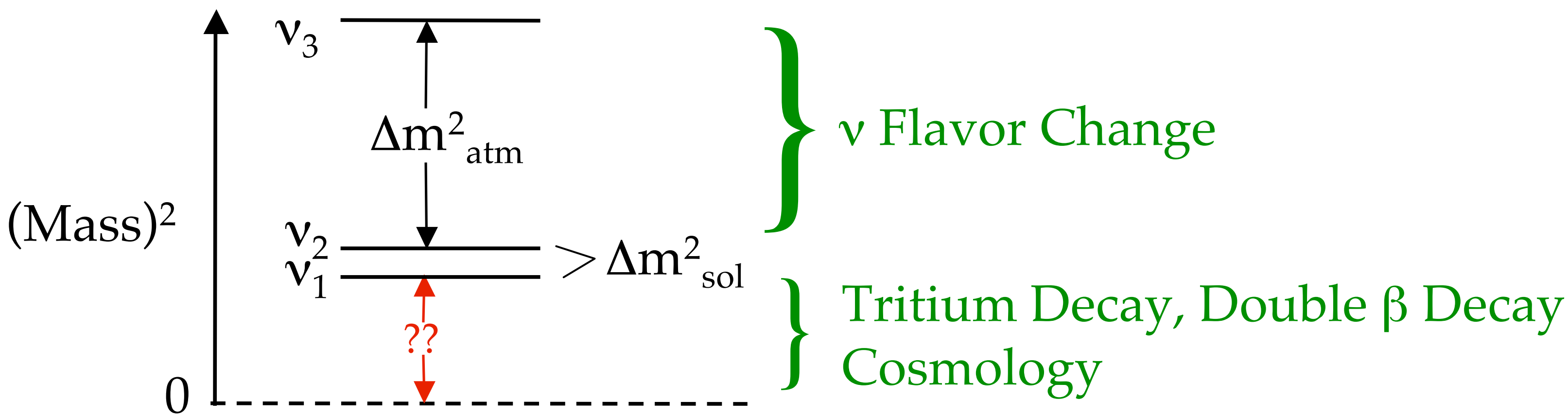
- What can neutrinos and the universe tell us about one another?

- Is CP violation by neutrinos the key to understanding the matter – antimatter asymmetry of the universe?

- What physics is behind neutrino mass?


The Importance of
the Questions,
and How They
May Be Answered

What Is the Absolute Scale of Neutrino Mass?



How far above zero
is the whole pattern?

A Cosmic Connection

Oscillation Data $\Rightarrow \sqrt{\Delta m^2_{atm}} <$ Mass[Heaviest ν_i]

Cosmological Data + Cosmological Assumptions $\Rightarrow$

$$\Sigma\, m_i < (0.17 - 1.0)\ \text{eV}\ .$$

Mass(ν_i)

(Seljak, Slosar, McDonald
Pastor)

If there are only 3 neutrinos,

$$0.04\ \text{eV} \lesssim \text{Mass[Heaviest } \nu_i] < (0.07 - 0.4)\ \text{eV}$$

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

Are Neutrinos Their Own Antiparticles?

For each *mass eigenstate* ν_i, does —

- $\overline{\nu_i} = \nu_i$ (Majorana neutrinos)

or

- $\overline{\nu_i} \neq \nu_i$ (Dirac neutrinos) ?

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

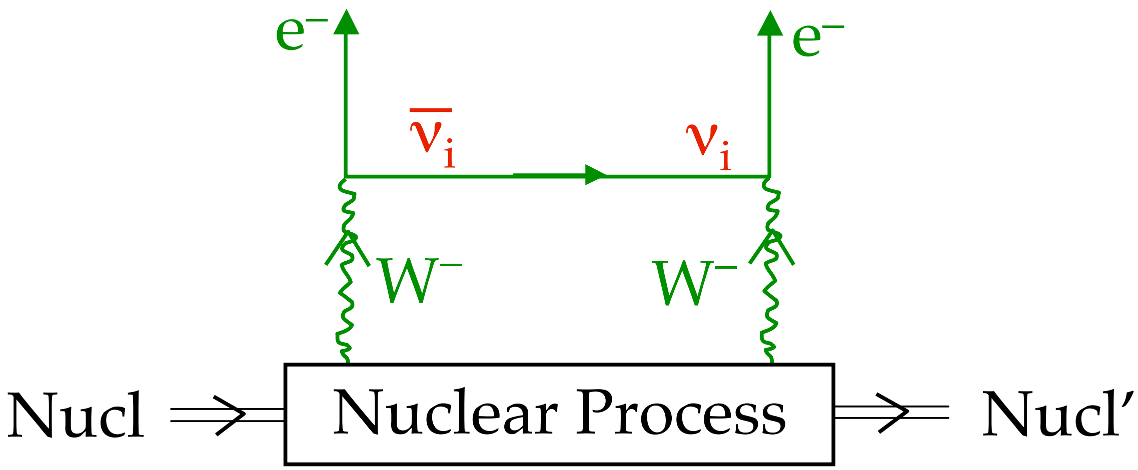
But neutrinos may not carry any conserved charge-like quantum number.

A conserved Lepton Number L defined by—
$L(\nu) = L(\ell^-) = -L(\overline{\nu}) = -L(\ell^+) = 1$ may not exist.

If it does not, then nothing distinguishes $\overline{\nu_i}$ from ν_i .

To look for L nonconservation, seek —

Neutrinoless Double Beta Decay



Observation would establish that —

- L is not conserved
- $\bar{\nu}_i = \nu_i$ (Neutrinos are Majorana particles)
- Neutrinos have distinctive *Majorana masses* not shared by charged leptons or quarks

Are There Sterile Neutrinos?

Rapid neutrino oscillation reported by LSND —

$\sim 1\text{eV}^2$

in contrast to

$\Delta m^2_{atm} = 2.7 \times 10^{-3}\ \text{eV}^2$

$\Delta m^2_{sol} = 8 \times 10^{-5}\ \text{eV}^2$

At least **4** mass eigenstates, hence at least **4** flavors.

Measured $\Gamma(Z \to \nu\bar{\nu})$ only **3** different *active* neutrinos.

At least **1** *sterile* neutrino.

Is the so-far unconfirmed oscillation reported by LSND genuine?

MiniBooNE aims to definitively answer this question.

The Mass Spectrum:  or  ?

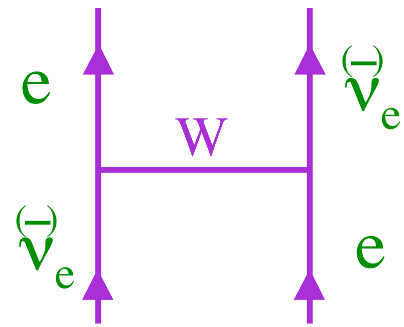
Generically, grand unified models (GUTS) favor —

GUTS relate the Leptons to the Quarks.

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

How To Determine If The Spectrum Is Normal Or Inverted

Exploit the fact that, in matter,



raises the effective mass of ν_e, and lowers that of $\bar{\nu}_e$.

This changes both the spectrum and the mixing angles.
Thus, it changes oscillation probabilities.
In particular, it makes P($\bar{\nu}$ oscillation) ≠ P(ν oscillation).

The matter effect grows with energy E.

At E ~ 1 GeV, at oscillation maximum, the matter effect results in —

Sign[m^2(—) - m^2(═)]

$$\frac{P\left(\nu_\mu \to \nu_e\right)}{P\left(\bar{\nu}_\mu \to \bar{\nu}_e\right)} \cong \frac{1 + S\left(E/6\,GeV\right)}{1 - S\left(E/6\,GeV\right)}$$

$$\begin{cases} > 1\ ; \\ < 1\ ; \end{cases}$$

(NOνA and Later Experiments)

Note the $\nu - \bar{\nu}$ asymmetry that is not from CP violation.

When the matter effect may be neglected —

$$P(\nu_\alpha \to \nu_\beta) \propto \sin^2[1.27\Delta m^2(\mathrm{eV}^2)L(\mathrm{km})/E(\mathrm{GeV})]$$

Distance traveled

Energy

The matter effect grows with energy.

At fixed L/E but two different energies —

$$\frac{P_{\mathrm{Hi\ E}}(\nu_\mu \to \nu_e)}{P_{\mathrm{Lo\ E}}(\nu_\mu \to \nu_e)} \begin{cases} >1 \ ; \\ <1 \ ; \end{cases}$$

(Mena, Nunokawa, Parke)

Do Neutrino Interactions Violate CP?

Are neutrinos the reason we exist?

The universe is presently

MATTER-Antimatter asymmetric:

It contains **MATTER** (of which we are made), but essentially no Antimatter (which would annihilate us).

Any initial asymmetry would have been washed out.

The present preponderance of **MATTER** over Antimatter could not have developed unless the two behave differently ($\cancel{CP}$).

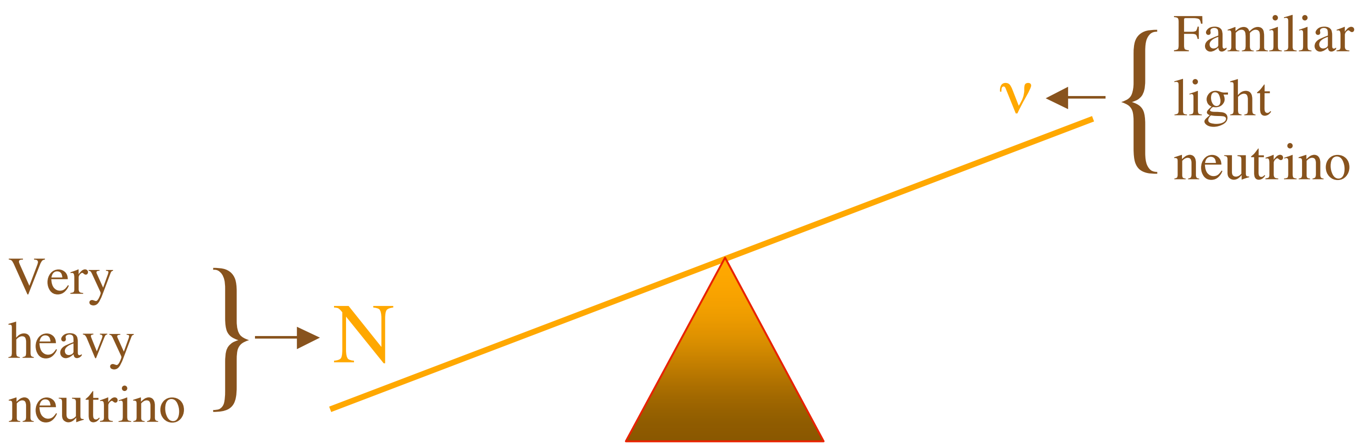
The observed difference between **QUARK** and Antiquark behavior, as described by the Standard Model, is inadequate.

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.

If* MATTER *and* Antimatter *interact differently with the light neutrinos* ν*, then quite likely they also interact differently with the heavy neutrinos* N*.

(In the See-Saw model, all these interactions have a common origin.)

Then in the early universe, we would have had —

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

This phenomenon (*Leptogenesis*) would have led to a universe containing unequal amounts of **MATTER** and Antimatter.

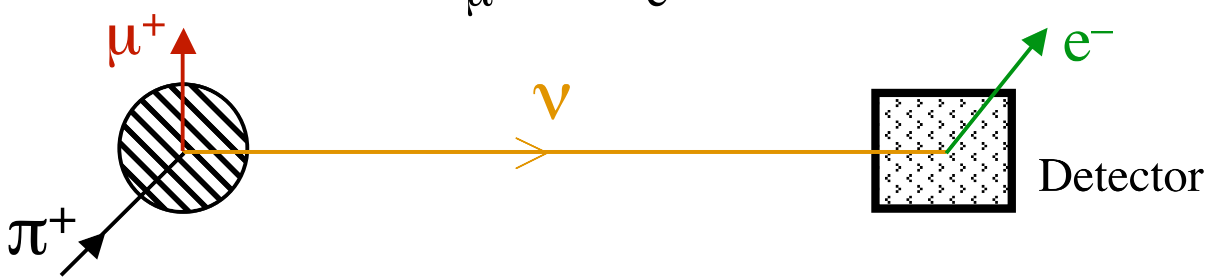
Perhaps this was the original source of the present preponderance of **MATTER** over Antimatter in the universe.

If N decays led to the present preponderance of **MATTER** over Antimatter, then we are all descendants of heavy neutrinos.

Do Matter and Antimatter Interact Differently With Light Neutrinos?

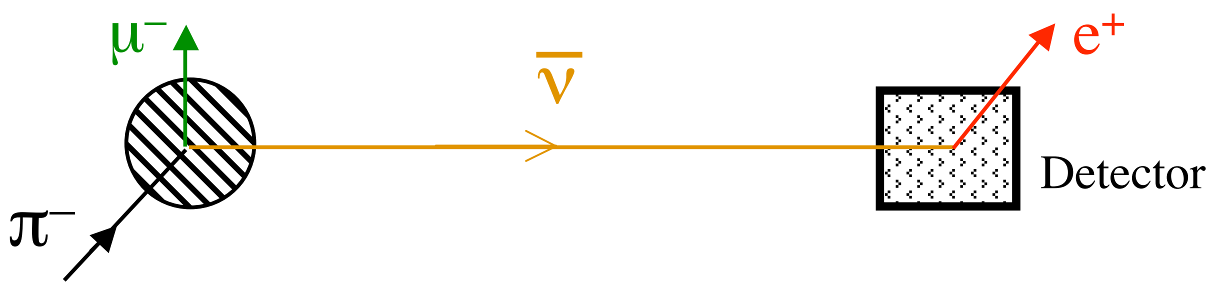
$$\nu_\mu \rightarrow \nu_e$$

Compare



$$\bar{\nu}_\mu \rightarrow \bar{\nu}_e$$

with



Is $P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e) \neq P(\nu_\mu \rightarrow \nu_e)$? $\cancel{CP}$

Separating $\not{CP}$ From the Matter Effect

Genuine $\not{CP}$ and the matter effect both lead to a difference between ν and $\bar{\nu}$ oscillation.

But genuine $\not{CP}$ and the matter effect depend quite differently from each other on L and E.

To disentangle them, one must make oscillation measurements at different L and/or E.

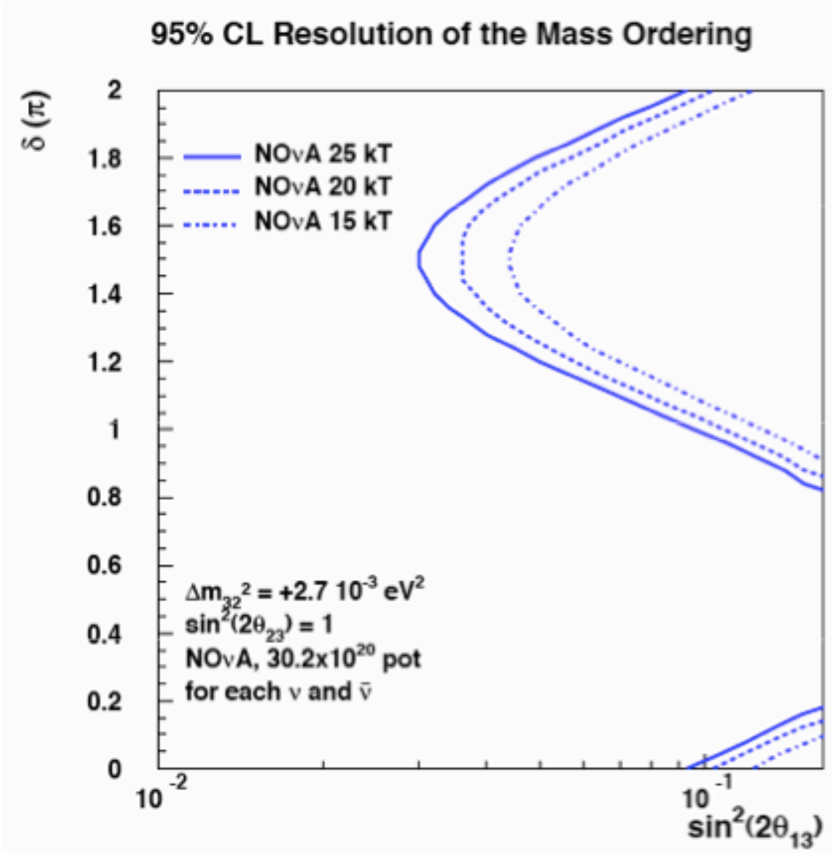
The Post-NOνA-Phase-1 Era

Accelerator neutrino experiments studying —

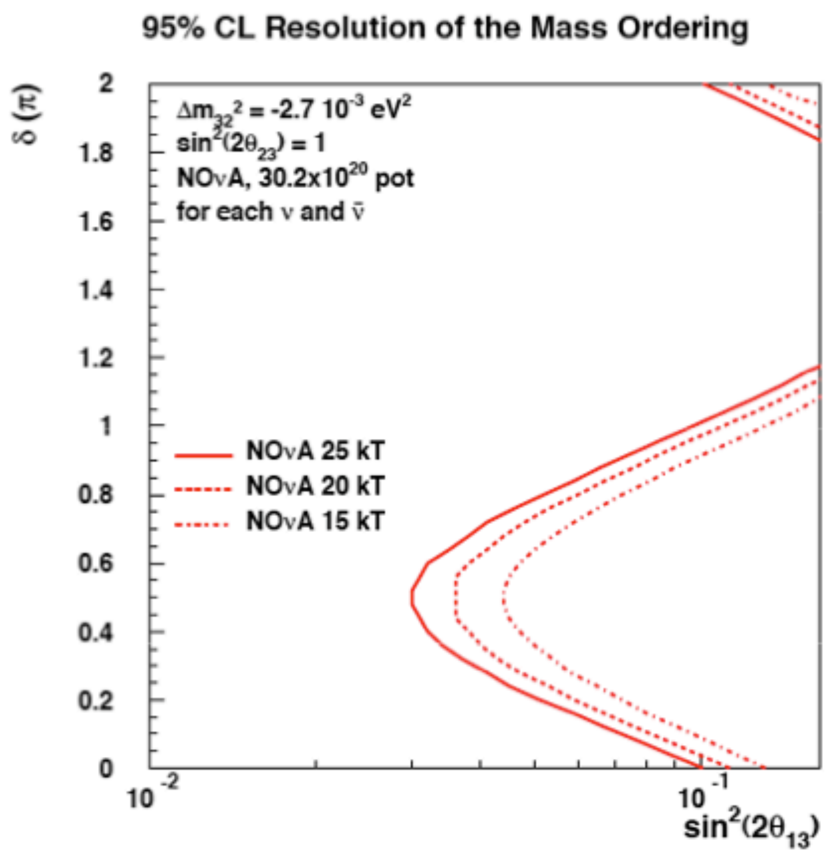
$$\nu_\mu \leftrightarrow \nu_e \quad \text{and} \quad \bar{\nu}_\mu \leftrightarrow \bar{\nu}_e$$

can probe ***the mass hierarchy***, ***CP violation***, and (as can reactor experiments) θ_{13}.

The sensitivity needed will depend on θ_{13}.



Normal



Inverted

NOνA Phase 1 Reach in Determining the Hierarchy

The US Long Baseline Study

A Brookhaven- and Fermilab-sponsored study is examining two options for the next phase:

- Additional detector mass at some location in the existing NuMI beamline
- A new, broad-band beam pointed at a detector in a new Deep Underground Science and Engineeing Laboratory (DUSEL)

Results, and feedback from the Neutrino Scientific Assessment Group (NuSAG), coming soon.

Neutrino Factories and β Beams

The ultimate in sensitivity. Crucial if $\sin^2 2\theta_{13} \lesssim 0.01$.
Have intense, flavor-pure beams.

Neutrino Factory: A muon storage ring, producing neutrinos via —

Doesn't make μ^-

$$\mu^+ \rightarrow e^+ + \nu_e + \bar{\nu}_\mu$$

β Beam: A boosted-radioactive-ion storage ring, producing neutrinos via, e.g., —

$$^{18}\mathrm{Ne} \rightarrow {}^{18}\mathrm{F} + e^+ + \nu_e$$

Monoenergetic ν_e from e^- capture

Then look for $\nu_e \rightarrow \nu_\mu$

Summary

We have learned a lot about the neutrinos in the last decade.

What we have learned raises some very interesting questions.

Exciting times lie ahead.

Backup Slides

The Physics of Neutrino Oscillation

Why Does Neutrino Flavor Change Imply Neutrino Mass?

The neutrinos we study pass through matter between their source and our detector.

Can't their ***interactions*** with the matter change their flavor?

In practice, **no**.

We have confirmed that the interactions between neutrinos and matter are very well described by the Standard Model of elementary particle physics.

Standard Model neutrino interactions do not change neutrino flavor.

Therefore, neutrinos must be changing their flavor *on their own*.

We confirm that they do this *over time*, and it is the *right* time — *proper* time:

When a particle of mass m travels a distance L with momentum p and energy E, the *proper time* τ that elapses in the particle's rest frame is given by —

$$\tau = m\frac{L}{p} \cong m\frac{L}{E}$$

For a relativistic neutrino

The probabilities of some flavor changes are indeed found to be functions of L/E.

The observed neutrino flavor changes are very successfully described, *in detail*, by the hypothesis that they arise from ***neutrino mass and leptonic mixing***.

Neutrino Flavor Change ("Oscillation") In Vacuo

Suppose a neutrino is born with flavor α and energy E.

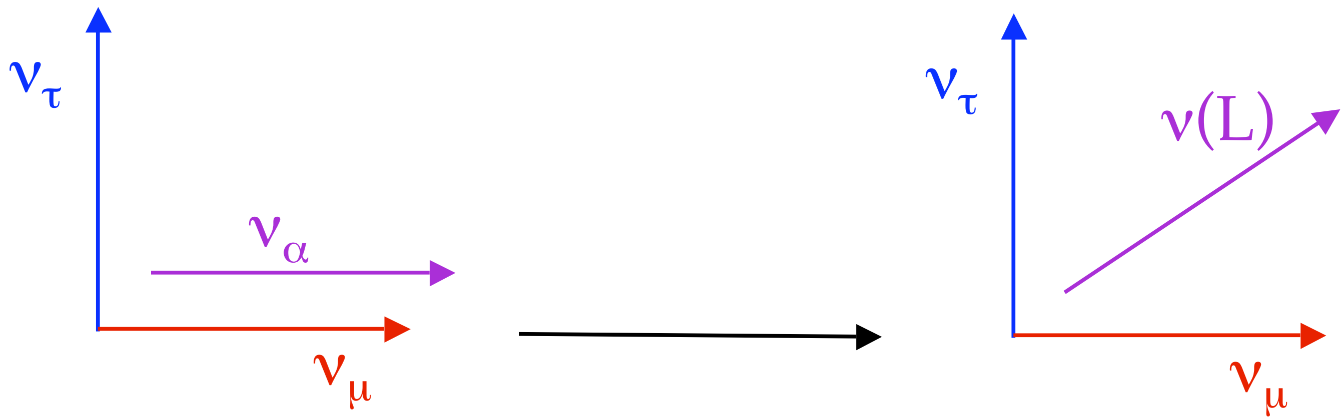
$$\nu_\alpha = \sum_i U^*_{\alpha i}\nu_i \xrightarrow{\text{Distance } L} \sum_i U^*_{\alpha i}\nu_i e^{ip_i(E)L} = \sum_i U^*_{\alpha i} e^{i\left(E - \frac{m_i^2}{2E}\right)L} \sum_\beta U_{\beta i}\nu_\beta$$

$$\sum_\beta U_{\beta i}\nu_\beta$$

$$\sqrt{E^2 - m_i^2} \cong E - \frac{m_i^2}{2E}$$

$$= e^{iEL}\sum_\beta \nu_\beta \left[\sum_i U^*_{\alpha i} e^{-im_i^2 \frac{L}{2E}} U_{\beta i}\right] \equiv \nu(L)$$

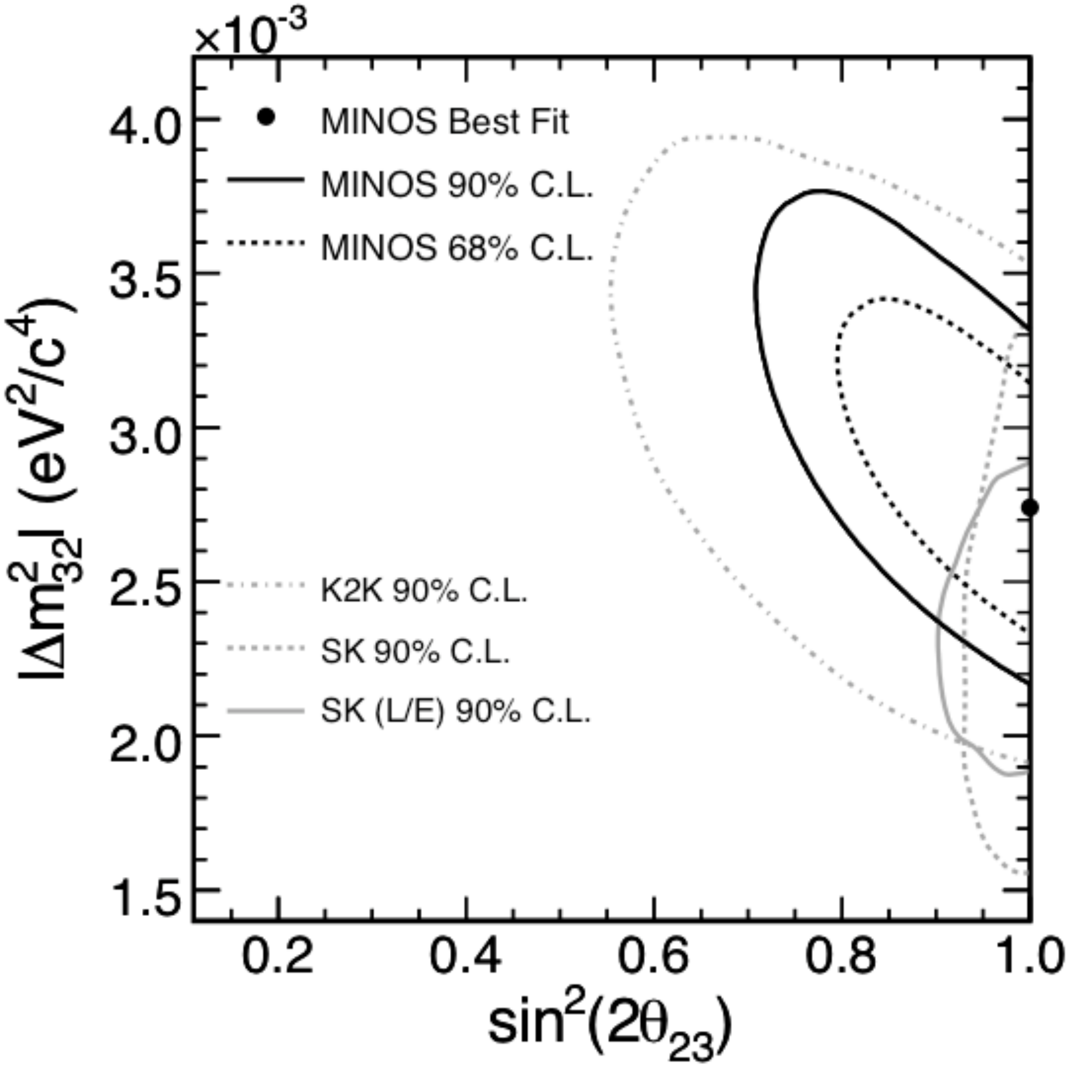
The neutrino has evolved into a mixture of the flavors.



$$\nu(L) = e^{iEL}\sum_{\beta} \nu_{\beta} \left[\sum_{i} U^{*}_{\alpha i}\, e^{-im_i^2 \frac{L}{2E}} U_{\beta i}\right]$$

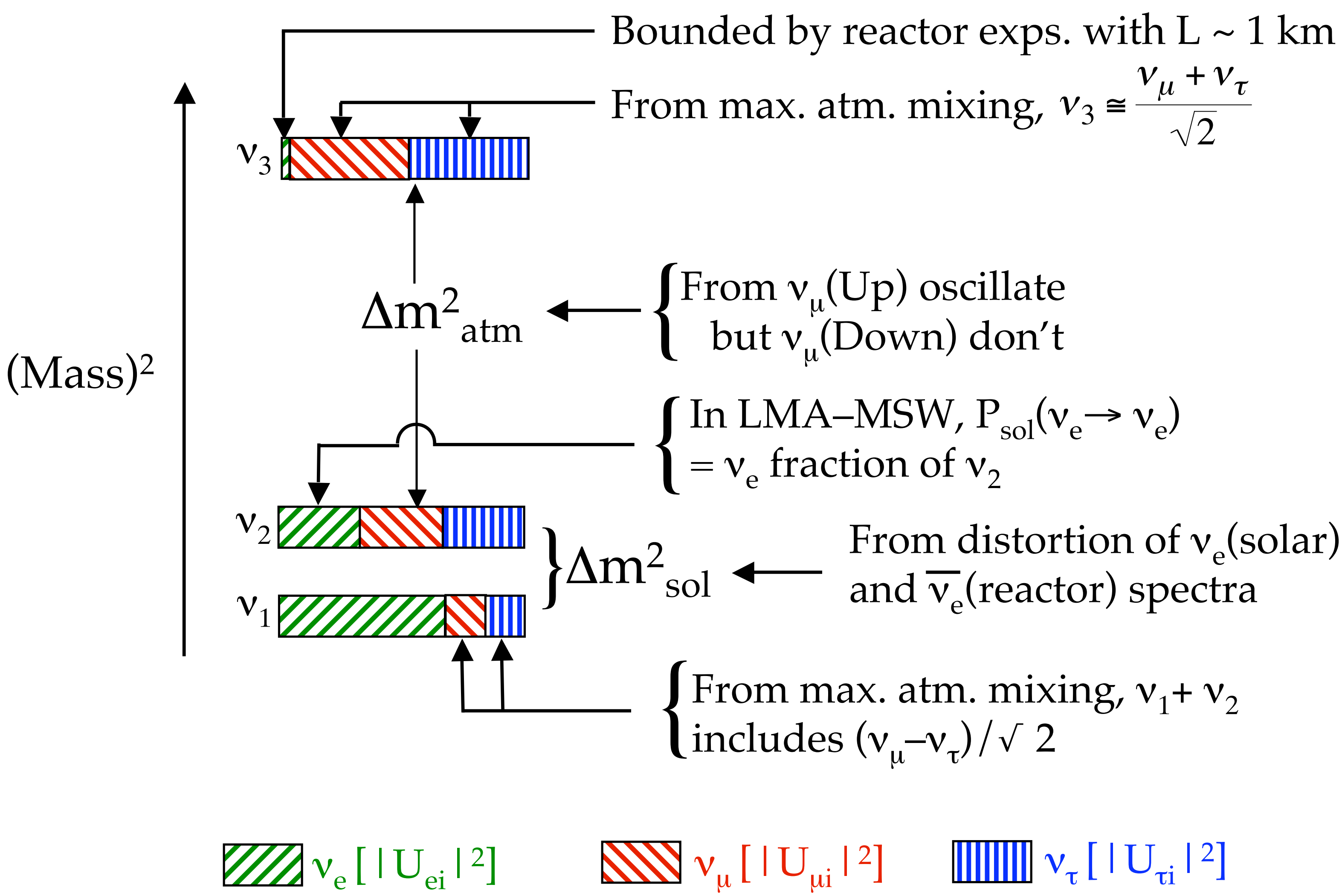
$$\mathrm{Prob}\left(\nu_{\alpha} \to \nu_{\beta}\right) = \left|\sum_{i} U^{*}_{\alpha i}\, e^{-im_i^2 \frac{L}{2E}} U_{\beta i}\right|^{2}$$

Latest Results From MINOS



From hep-ex/ 0607088

The Atmospheric Δm^2 and Mixing Angle



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 $\overline{\nu}_e$(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_τ [$|U_{\tau i}|^2$]

Good Luck

Because $(\Delta m^2_{sol} / \Delta m^2_{atm}) << 1$ and $\theta_{13} << 1$, all confirmed flavor change processes seen so far are effectively two-neutrino processes.

Because $\theta_{13} << 1$, $\theta_{atm} \approx \theta_{23}$ and $\theta_{sol} \approx \theta_{12}$.

This has greatly simplified the analysis of what is happening.

The Majorana $\cancel{CP}$ Phases

The phase α_i is associated with neutrino mass eigenstate ν_i:

$$U_{\alpha i} = U^0_{\alpha i} \exp(i\alpha_i/2) \text{ for all flavors } \alpha.$$

$$\mathrm{Amp}(\nu_\alpha \rightarrow \nu_\beta) = \sum_i U_{\alpha i}^* \exp(-\, i m_i^2 L/2E)\, U_{\beta i}$$

is insensitive to the Majorana phases α_i.

Only the phase δ can cause CP violation in neutrino oscillation.

There Is Nothing Special About θ_{13}

All mixing angles must be nonzero for ~~CP~~.

For example —

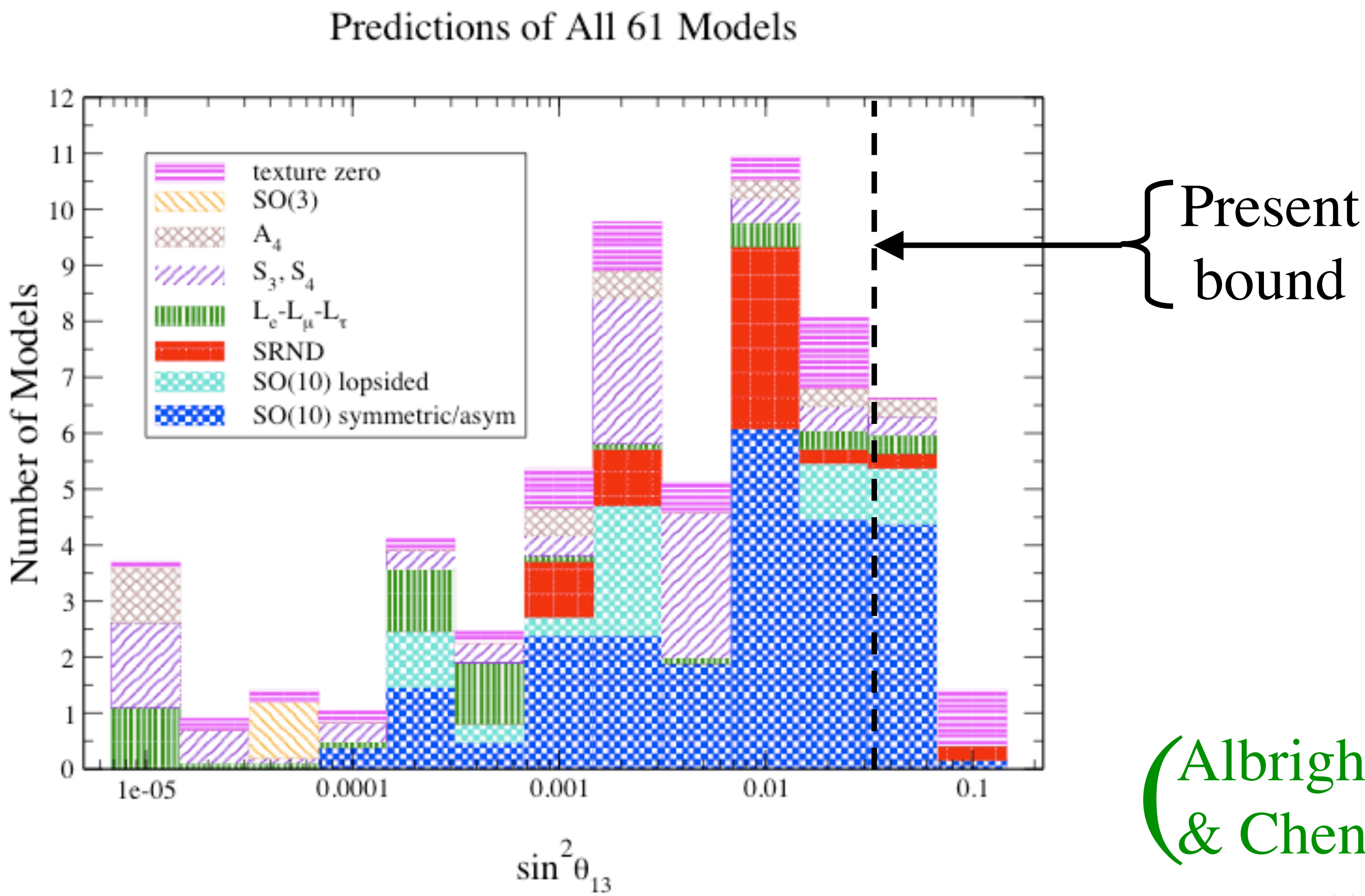
$$P(\bar{\nu}_\mu \to \bar{\nu}_e) - P(\nu_\mu \to \nu_e) = 2\cos\theta_{13}\sin 2\theta_{13}\sin 2\theta_{12}\sin 2\theta_{23}\sin\delta$$
$$\times \sin\left(\Delta m^2{}_{31}\frac{L}{4E}\right)\sin\left(\Delta m^2{}_{32}\frac{L}{4E}\right)\sin\left(\Delta m^2{}_{21}\frac{L}{4E}\right)$$

In the factored form of U, one can put δ next to θ_{12} instead of θ_{13}.

How Large Is θ_{13}?

We know only that $\sin^2\theta_{13} < 0.032$ (at 2σ).

The theoretical prediction of θ_{13} is not sharp:



(Albright & Chen)

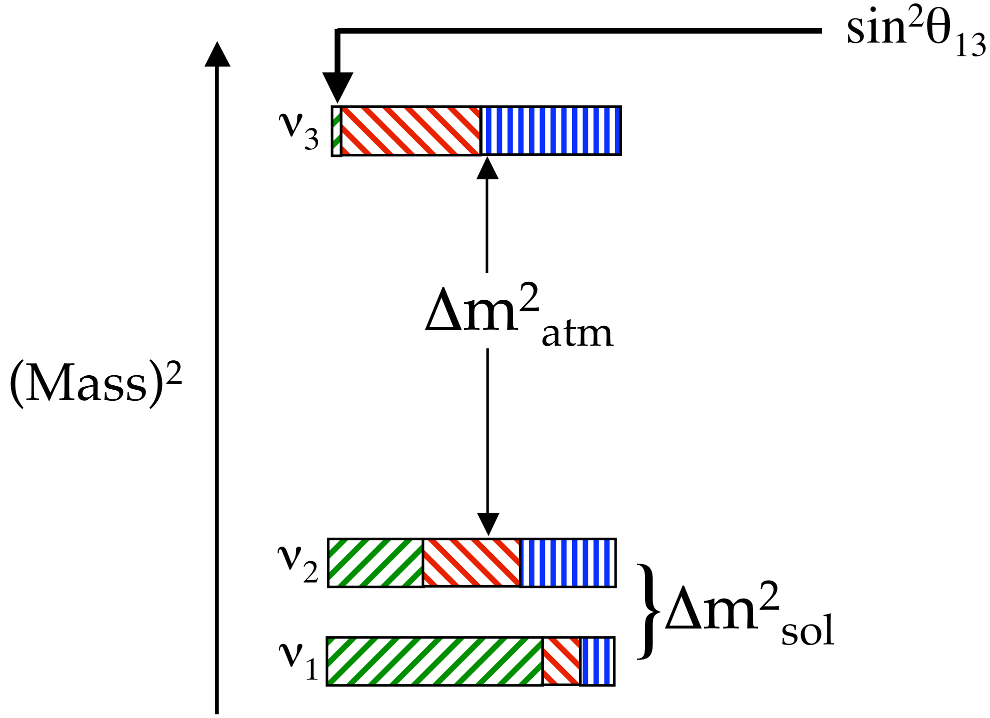
The Central Role of θ_{13}

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

If $\sin^2\theta_{13} > (0.0025 - 0.0050)$, we can study both of these issues with intense but conventional ν and $\bar{\nu}$ beams.

Determining θ_{13} is an important stepping-stone.

How θ_{13} May 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}.

$\therefore$ We need an experiment with L/E sensitive to Δm^2_{atm} (L/E ~ 500 km/GeV) , and involving ν_e.

Complementary Approaches

Reactor Experiments

Reactor $\bar{\nu}_e$ disappearance while traveling L ~ 1.5 km. This process depends on θ_{13} alone:

$$P(\bar{\nu}_e \text{ Disappearance}) =$$

$$= \sin^2 2\theta_{13} \sin^2[1.27\Delta m^2_{atm}(eV^2)L(km)/E(GeV)]$$

(Double CHOOZ and Daya Bay)

Accelerator Experiments

Accelerator $\nu_\mu \rightarrow \nu_e$ while traveling L > Several hundred km. This process depends on θ_{13}, θ_{23}, on whether the spectrum is normal or inverted, and on whether CP is violated through the phase δ.

(NOνA, T2K, and Their Successors)

Neglecting matter effects (to keep the formula from getting too complicated):

The accelerator long-baseline $\overset{(-)}{\nu}_e$ appearance experiment measures —

$$P[\overset{(-)}{\nu}_\mu \to \overset{(-)}{\nu}_e] \cong \sin^2 2\theta_{13} \sin^2 \theta_{23} \sin^2 \Delta_{31}$$
$$+ \sin 2\theta_{13} \cos\theta_{13} \sin 2\theta_{23} \sin 2\theta_{12} \sin\Delta_{31} \sin\Delta_{21} \cos(\Delta_{32} \pm \delta)$$
$$+ \sin^2 2\theta_{12} \cos^2 \theta_{23} \cos^2 \theta_{13} \sin^2 \Delta_{21}$$

$$\Delta_{ij} \equiv \Delta m_{ij}^2 L/4E$$

The plus (minus) sign is for neutrinos (antineutrinos).