# What We Know, and What We Would Like To Find Out

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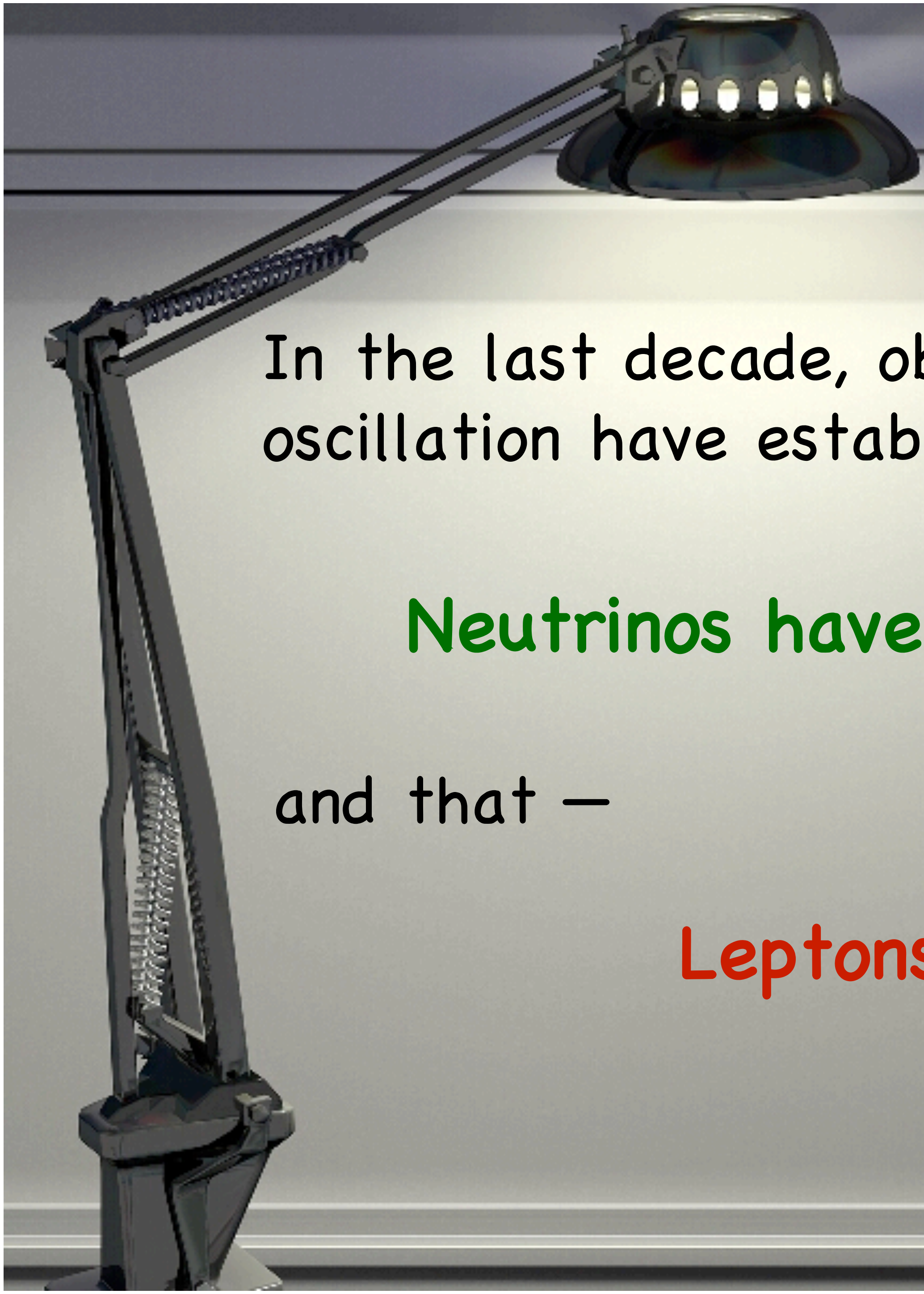
Minnesota
October 23, 2008



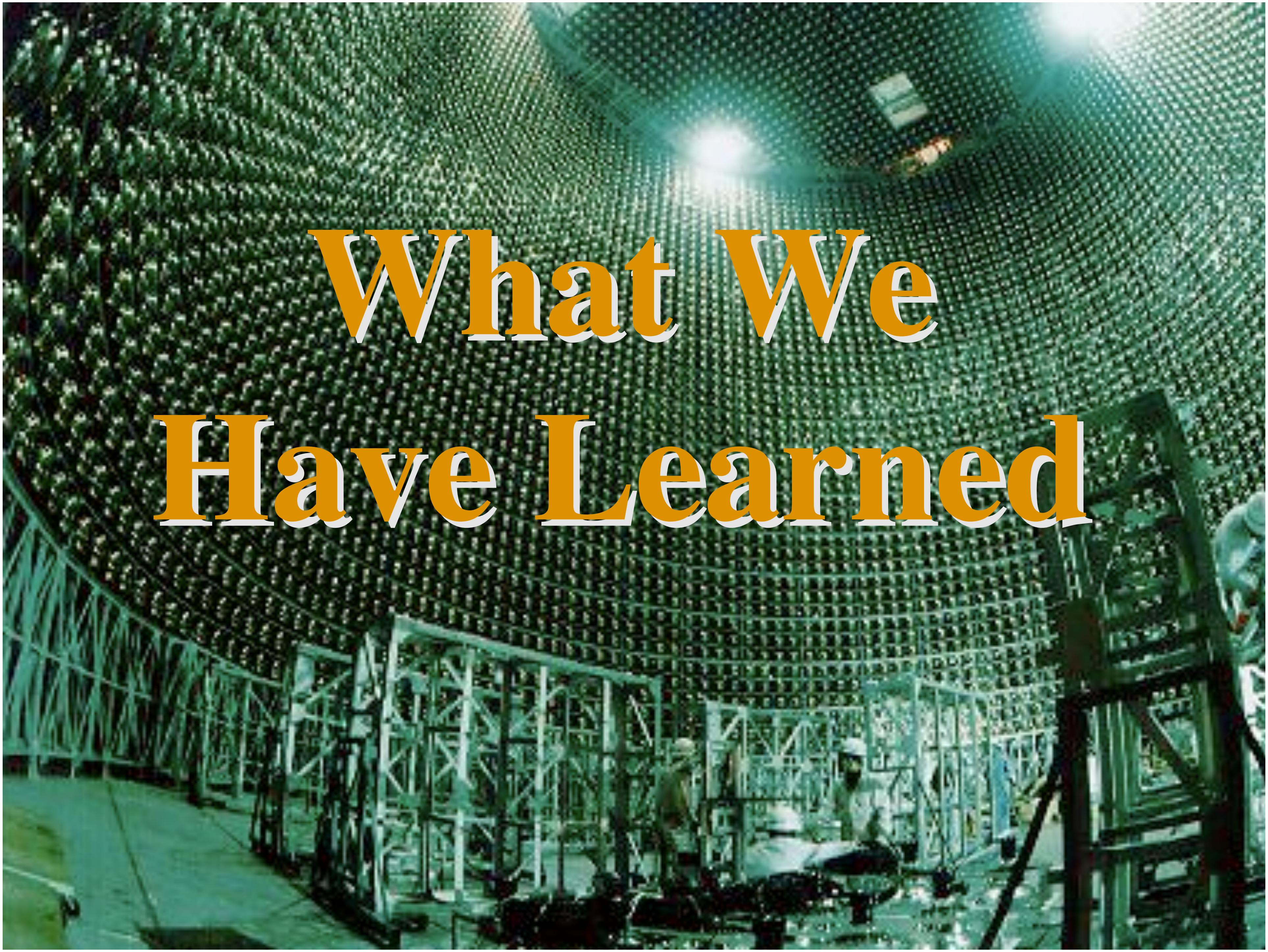
In the last decade, observations of neutrino oscillation have established that —

**Neutrinos have nonzero masses**

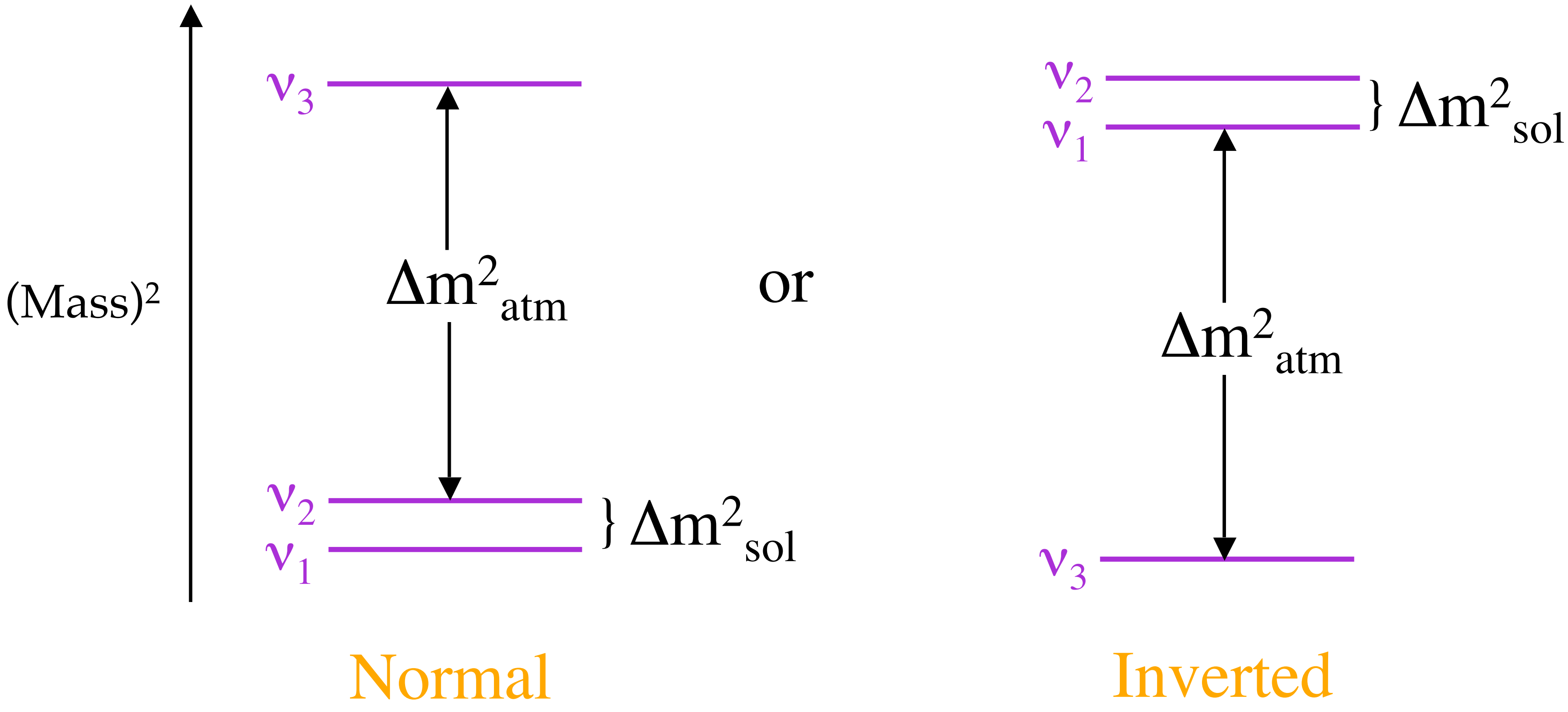
and that —

**Leptons mix.**

# What We Have Learned



# The $(\mathrm{Mass})^2$ Spectrum



$\Delta m^2_{\mathrm{sol}} \cong 7.6 \text{ x } 10^{-5}\ \mathrm{eV}^2$, $\Delta m^2_{\mathrm{atm}} \cong 2.4 \text{ x } 10^{-3}\ \mathrm{eV}^2$

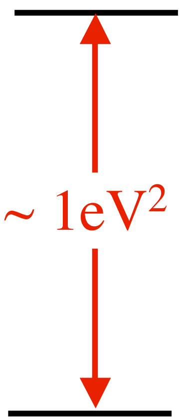
# Are There *More* Than 3 Mass Eigenstates?

When only two neutrinos count,

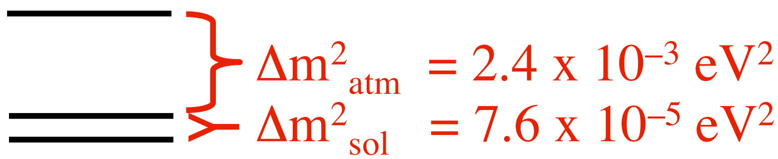
$$P\left(\nu_\alpha \to \nu_\beta\right) = \sin^2 2\theta \sin^2\left[1.27\Delta m^2\left(eV^2\right)\frac{L(km)}{E(GeV)}\right]$$

e, μ, or τ

*Rapid* $\bar{\nu}_\mu \to \bar{\nu}_e$ oscillation reported by LSND —



in contrast to



At least **4** mass eigenstates → At least 1 $\nu_{Sterile}$

# Is the LSND Signal Genuine Neutrino Oscillation?

MiniBooNE results up to 9:00 am today *suggest* that the answer is —

*No.*

*While awaiting further news —*

*We will assume there are*
*only 3 neutrino mass eigenstates.*

# Leptonic Mixing

This has the consequence that —

Mass eigenstate

Flavor eigenstate

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

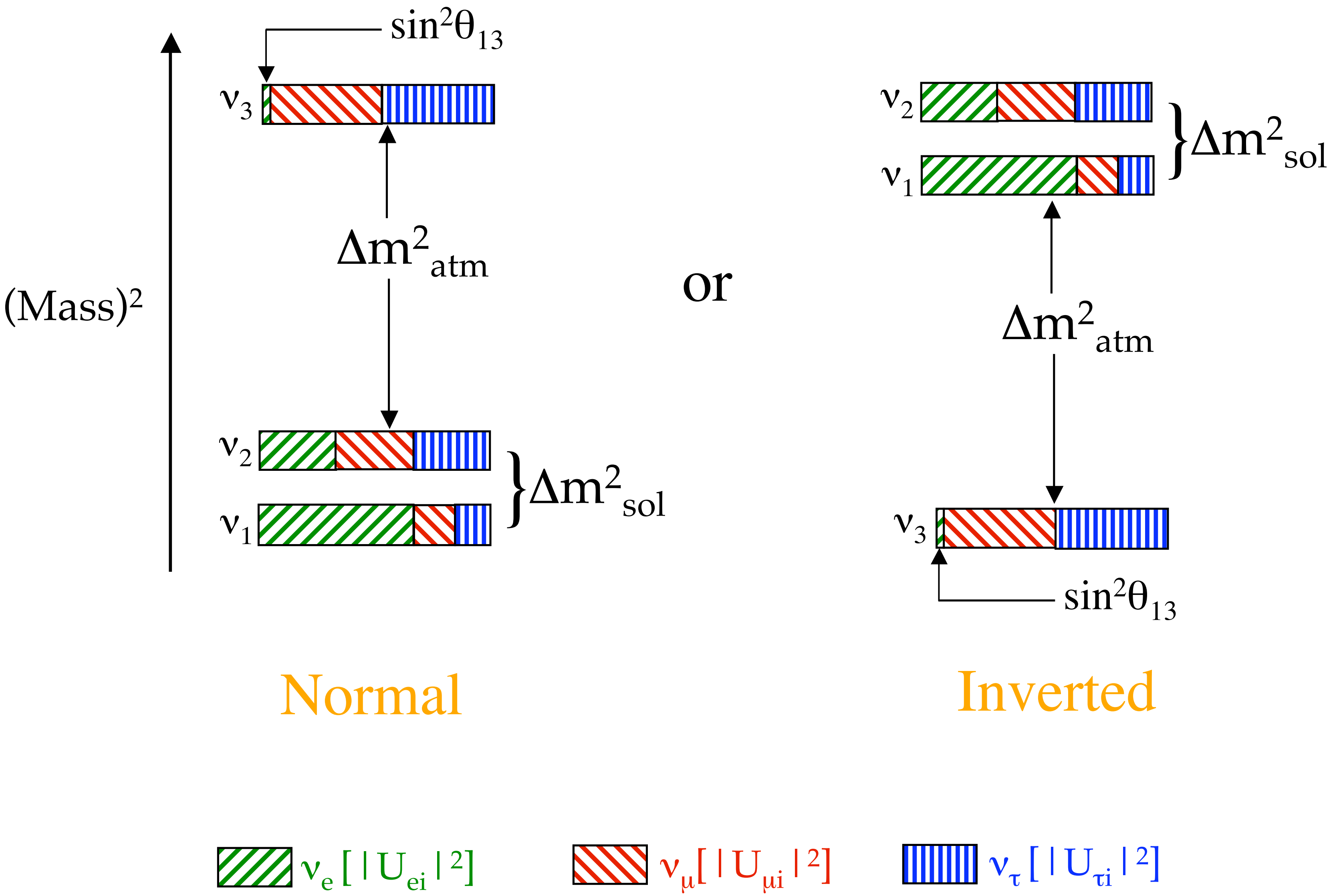
e, μ, or τ

PMNS Leptonic Mixing Matrix

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

When a $\nu_i$ interacts and produces a charged lepton, the probability that this charged lepton will be of flavor α is $|U_{\alpha i}|^2$ .

# The spectrum, showing its approximate flavor content, is



# The Mixing Matrix

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

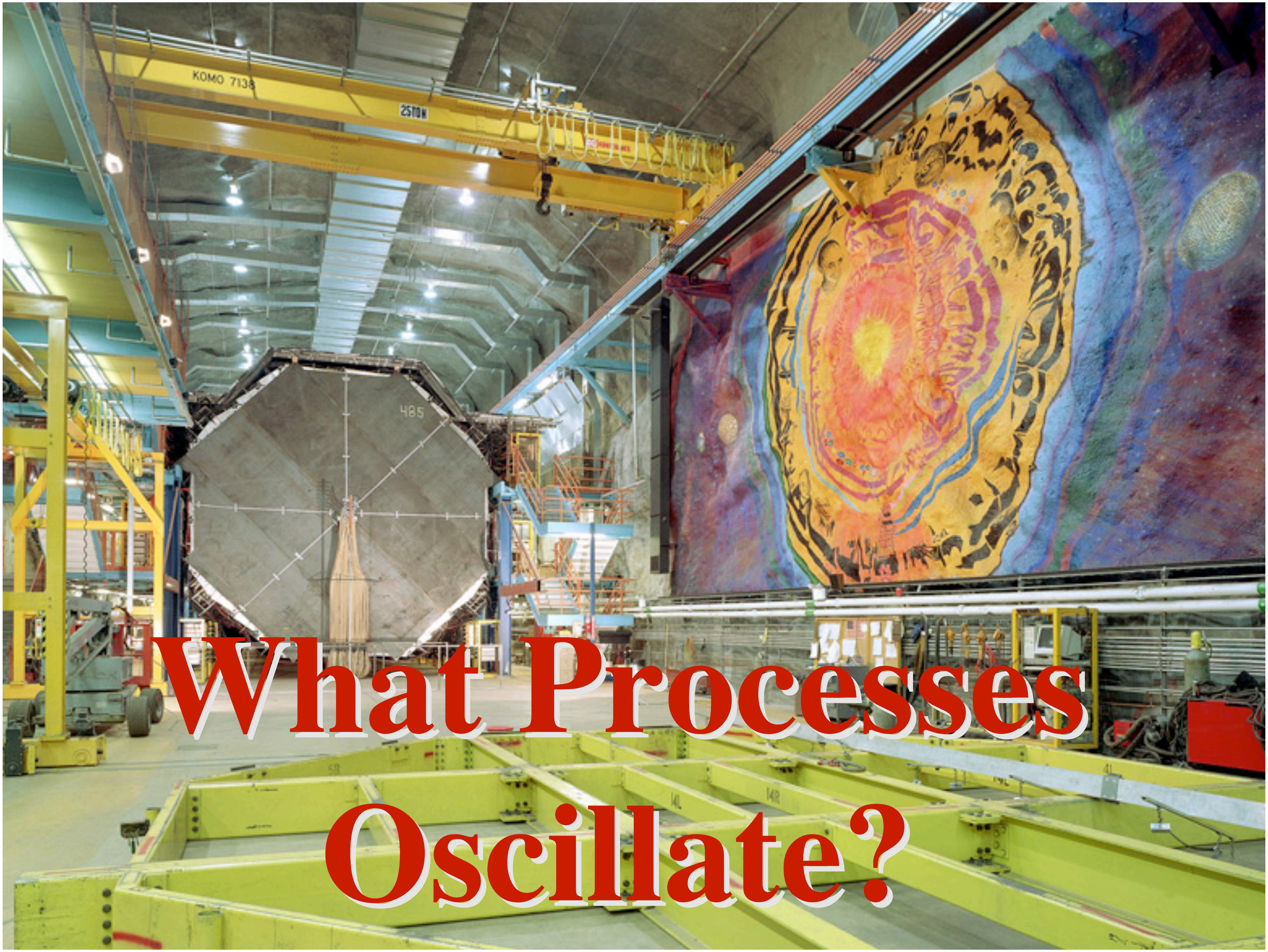
$$c_{ij} \equiv \cos\theta_{ij} \qquad \times \underset{\text{Majorana } \cancel{CP} \text{ phases}}{\begin{bmatrix} e^{i\alpha_1/2} & 0 & 0 \\ 0 & e^{i\alpha_2/2} & 0 \\ 0 & 0 & 1 \end{bmatrix}}$$
$$s_{ij} \equiv \sin\theta_{ij}$$

$\theta_{12} \approx \theta_{sol} \approx 34°$, $\theta_{23} \approx \theta_{atm} \approx 38\text{-}52°$, $\theta_{13} \lesssim 10°$

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

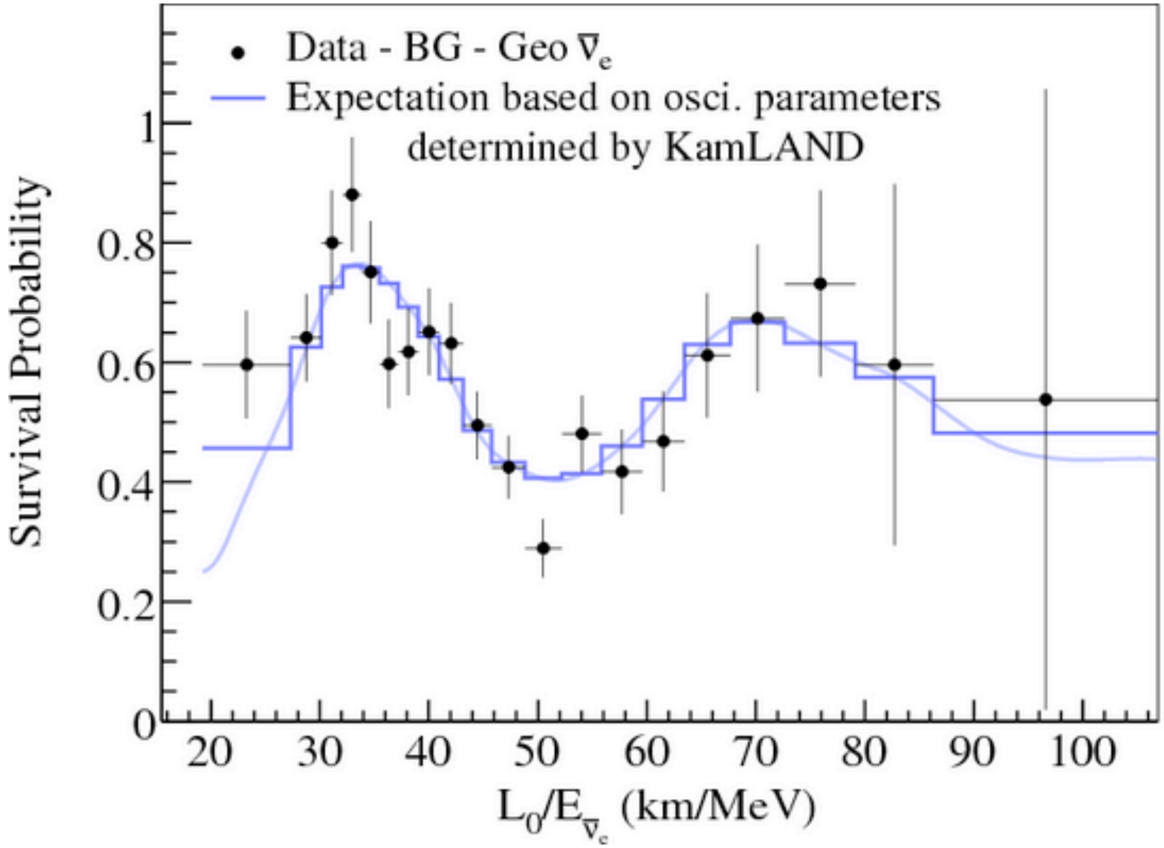
But note the crucial role of $s_{13} \equiv \sin\theta_{13}$.

# What Processes Oscillate?



# KamLAND Evidence for Oscillatory Behavior

**Survival probability $P(\bar{\nu}_e \rightarrow \bar{\nu}_e)$ of reactor $\bar{\nu}_e$**

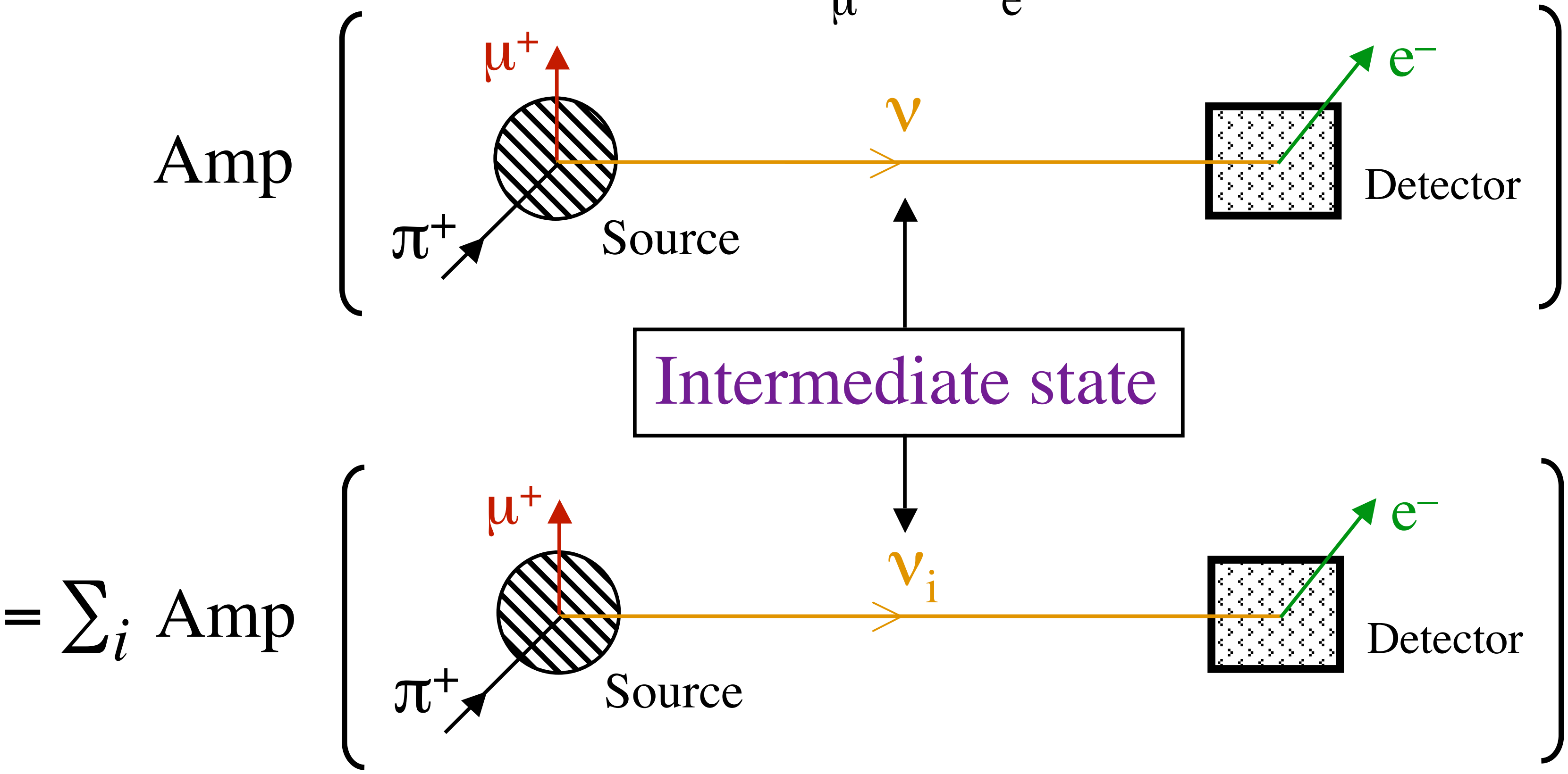


$L_0$ = 180 km is a flux-weighted average travel distance.

*$P(\bar{\nu}_e \rightarrow \bar{\nu}_e)$ actually oscillates!*

# Oscillation Comes From the *Coherence* of *Intermediate* ν States

$\nu_\mu \rightarrow \nu_e$



# Neutrinos In *Final* States Are *Incoherent*

In Electron-Capture decays —

$$\Gamma\left(\mathrm{Ion}_1 \to \mathrm{Ion}_2 + \nu; t\right) = \sum_i \Gamma\left(\mathrm{Ion}_1 \to \mathrm{Ion}_2 + \nu_i; t\right)$$

or —

$$\Gamma\left(\mathrm{Atom}_1 \to \mathrm{Atom}_2 + \nu; t\right) = \sum_i \Gamma\left(\mathrm{Atom}_1 \to \mathrm{Atom}_2 + \nu_i; t\right)$$

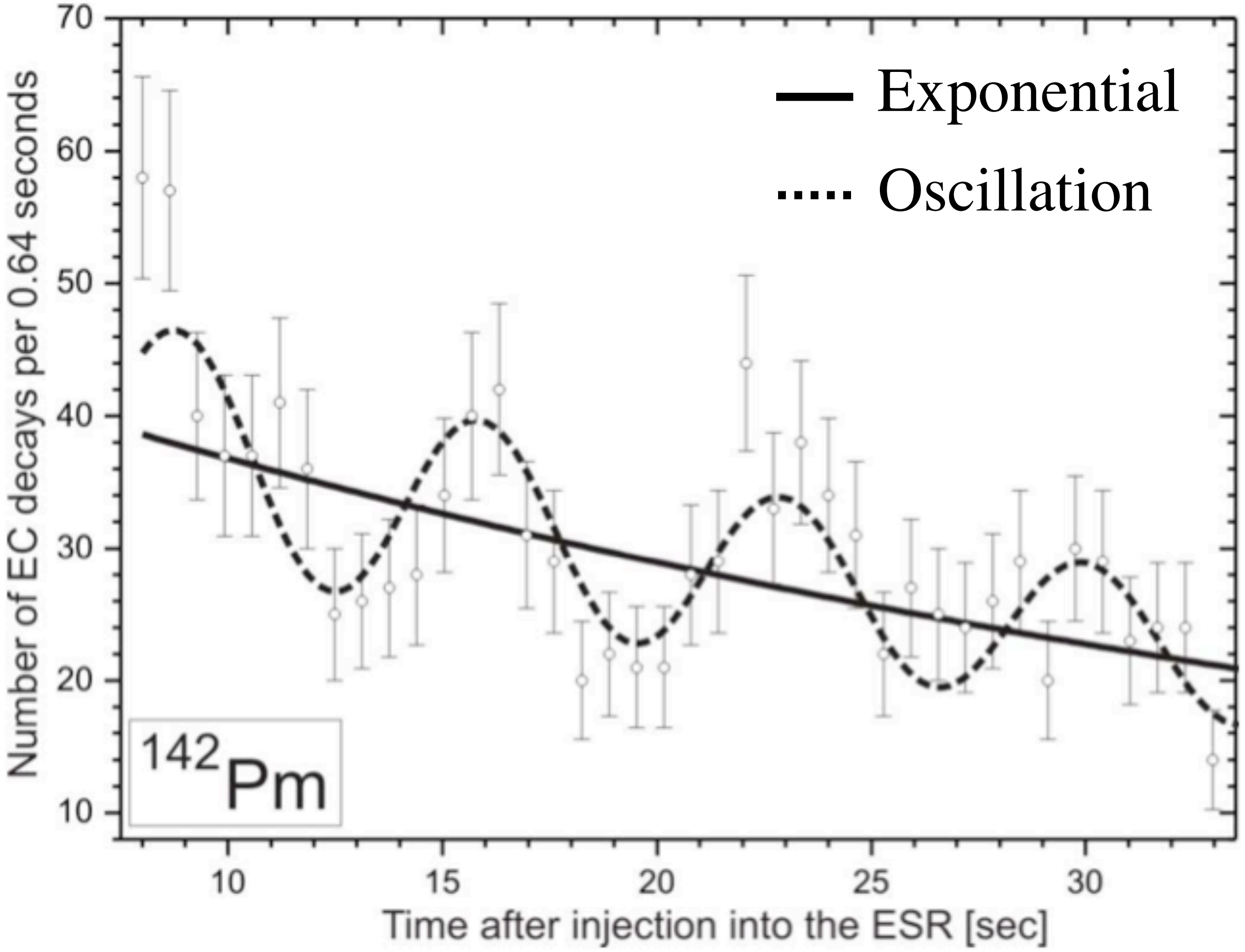
The different mass eigenstates $\nu_i$ contribute ***incoherently*** to the decay rate.

***The total decay rate should not oscillate.***

***(Unless the rate for decay to each $\nu_i$ does.)***

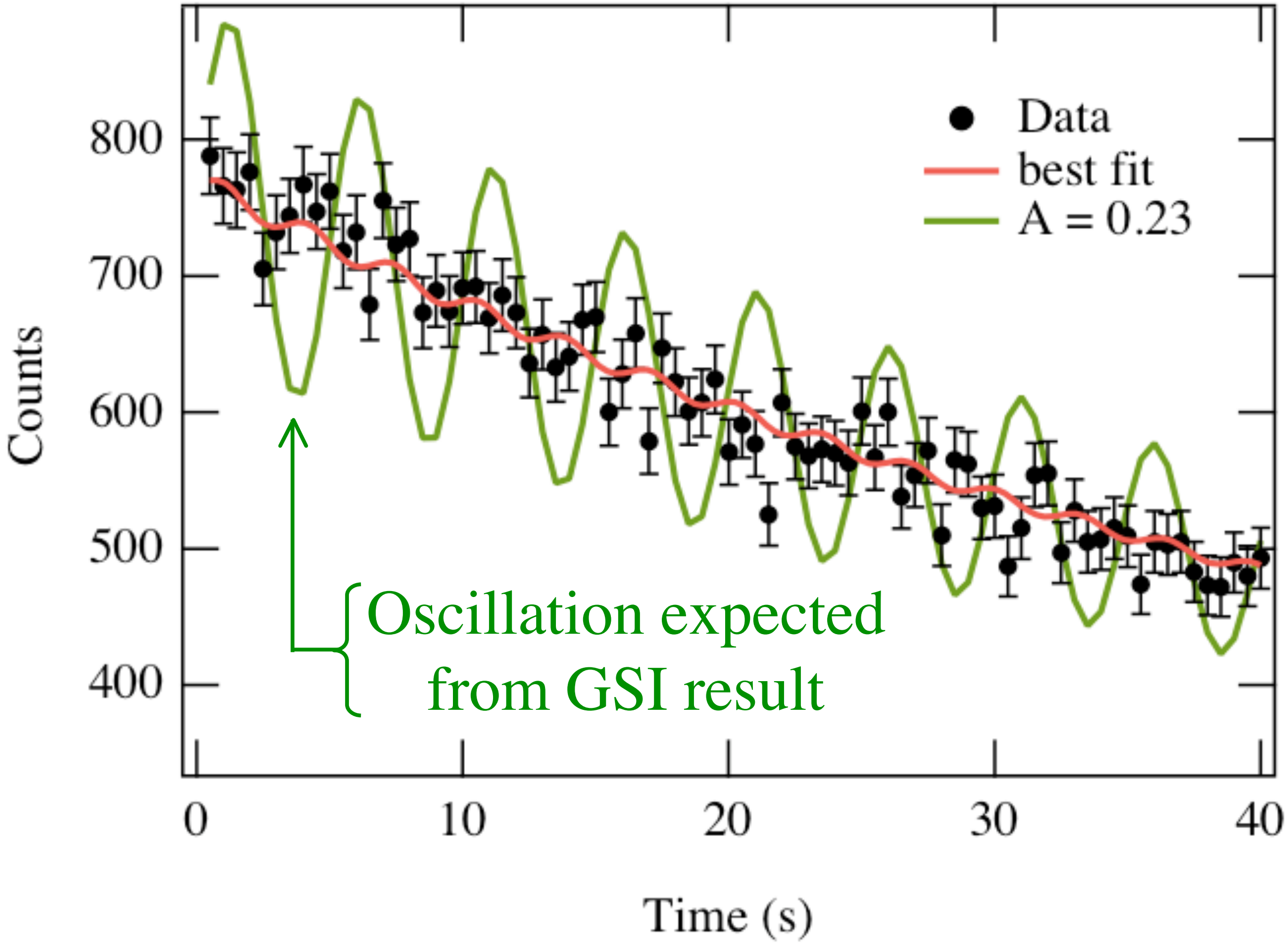
# Litvinov *et al.* —

EC decays of H-like $^{140}$Pr and $^{142}$Pm ions in a storage ring at GSI oscillate.



Vetter *et al.* —

EC decays of neutral $^{142}$Pm atoms at LBNL ***do not*** oscillate.



Oscillation expected
from GSI result

Faestermann *et al.*: EC decays of neutral $^{180}$Re atoms
in Munich ***do not*** oscillate either.

# Theoretical Opinion

Neutrino mixing can make decay rates oscillate:

Faber, Ivanov, Kienle, Kleinert, Lipkin, Reda

No it cannot:

Giunti, Kienert, Kopp, Lindner, Merle, Peshkin

**Lipkin**: Putting the mother ion in a magnetic field, which is done only in the GSI experiment, makes a difference.

To be continued …….

# 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 $\theta_{13}$?

- Is the spectrum like  or  ?

- Do neutrino – matter interactions violate CP?

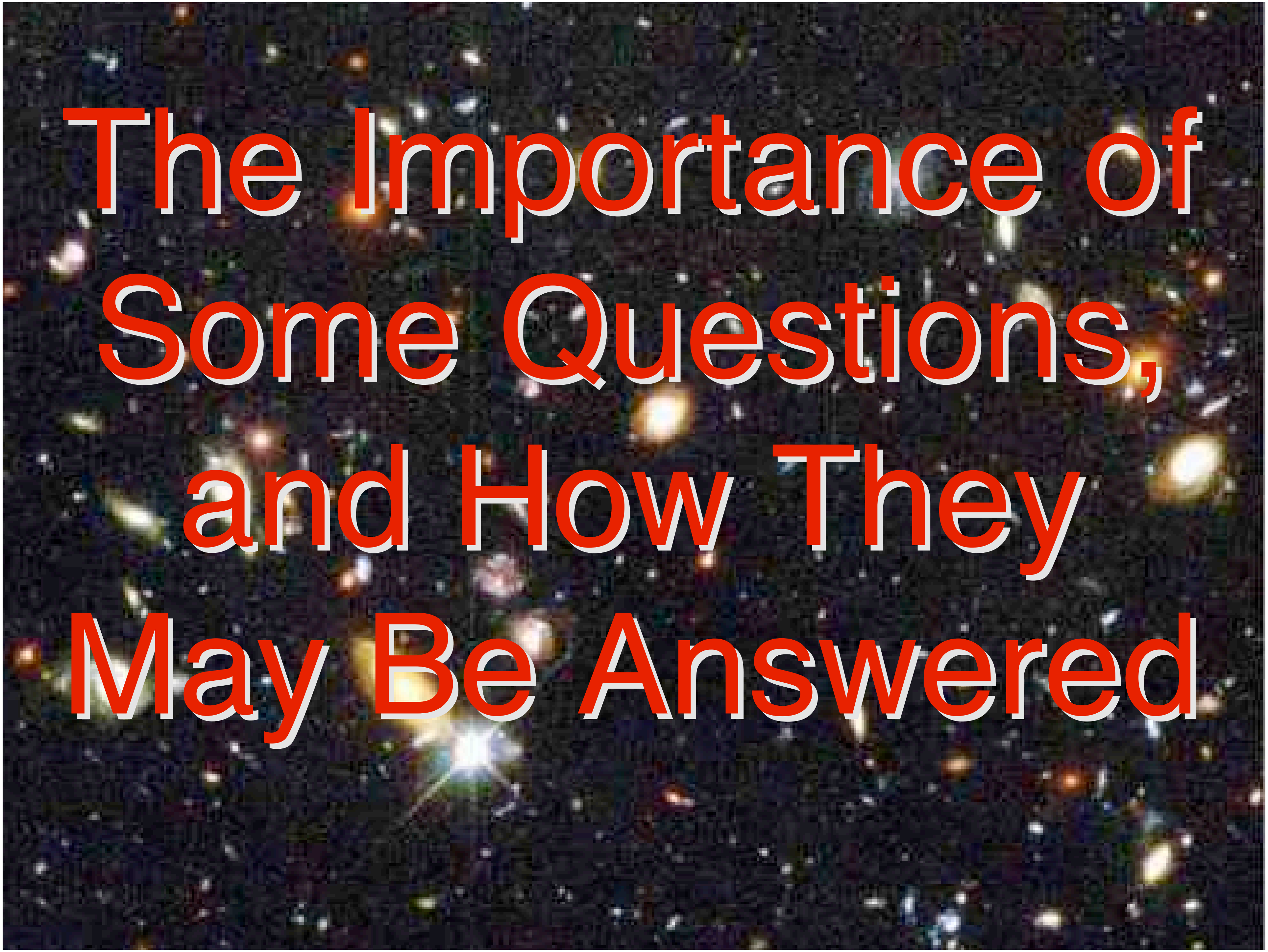
Is $P(\bar{\nu}_\alpha \to \bar{\nu}_\beta) \neq P(\nu_\alpha \to \nu_\beta)$ ?

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

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

- What physics is behind neutrino mass?

# The Importance of Some Questions, and How They May Be Answered



# Does $\bar{\nu} = \nu$?

# What Is the Question?

For each ***mass eigenstate*** $\nu_i$ , and ***given helicty*** h, does —

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

or

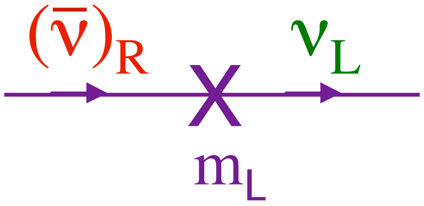
- $\overline{\nu_i}(h) \neq \nu_i(h)$ (Dirac neutrinos) ?

Equivalently, do neutrinos have *Majorana masses*? If they do, then the mass eigenstates are *Majorana neutrinos*.

# Majorana Masses

Out of, say, a left-handed neutrino field, $\nu_L$, and its charge-conjugate, $\nu_L{}^c$, we can build a Majorana mass term —

$$m_L \overline{\nu_L}\, \nu_L{}^c$$



*Quark* and *charged-lepton* Majorana masses are forbidden by electric charge conservation.

*Neutrino* Majorana masses would make the neutrinos very distinctive.

# Why Majorana Masses ⇒ Majorana Neutrinos

The objects $\nu_L$ and $\nu_L{}^c$ in $m_L \overline{\nu_L}\, \nu_L{}^c$ are not the mass eigenstates, but just the neutrinos in terms of which the model is constructed.

$m_L \overline{\nu_L}\, \nu_L{}^c$ induces $\nu_L \longleftrightarrow \nu_L{}^c$ mixing.

As a result of $K^0 \longleftrightarrow \overline{K^0}$ mixing, the neutral K mass eigenstates are —

$$K_{S,L} \cong (K^0 \pm \overline{K^0})/\sqrt{2}\ . \qquad \overline{K_{S,L}} = K_{S,L}\ .$$

As a result of $\nu_L \longleftrightarrow \nu_L{}^c$ mixing, the neutrino mass eigenstate is —

$$\nu_i = \nu_L + \nu_L{}^c = \text{“}\ \nu + \overline{\nu}\ \text{”}. \quad \overline{\nu_i} = \nu_i\ .$$

# Why Most Theorists Expect Majorana Masses

The Standard Model (SM) may be defined by its $SU(2)_L \times U(1)_Y$ gauge symmetry and its renormalizability, and by its field content.

Leaving neutrino masses aside, anything allowed by the SM principles occurs in nature.

*Majorana mass terms*
are allowed by the SM principles.

Then quite likely *Majorana masses*
occur in nature too.

# To Determine Whether Majorana Masses Occur in Nature

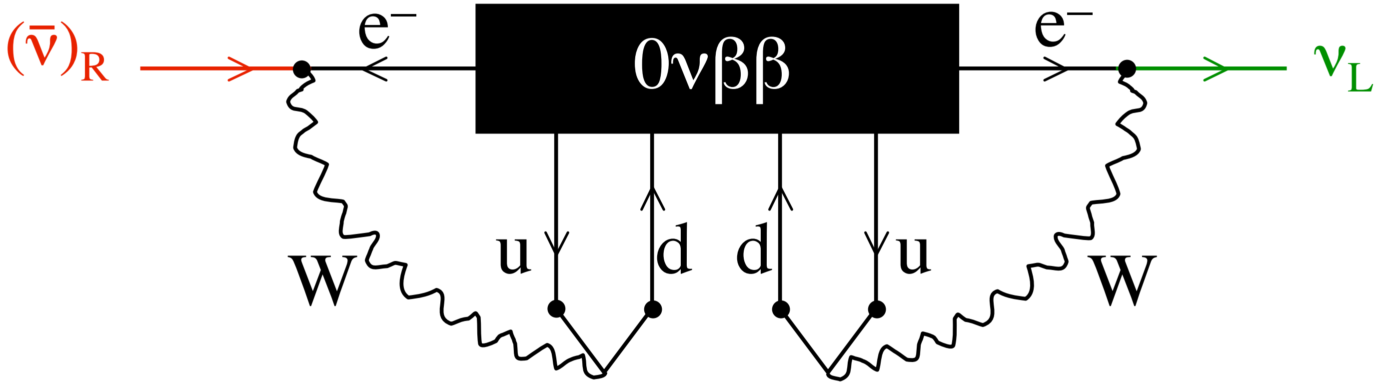
# The Promising Approach — Seek

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

We are looking for a ***small*** Majorana neutrino mass. Thus, we will need ***a lot*** of parent nuclei (say, one ton of them).

Whatever diagrams cause 0νββ, its observation would imply the existence of a Majorana mass term:

(Schechter and Valle)



$(\bar{\nu})_R \rightarrow \nu_L$ : A Majorana mass term

$\therefore$ 0νββ $\Longrightarrow$ $\bar{\nu}_i = \nu_i$

# Mixing,
# Mass Ordering,
# and ~~CP~~

# The Central Role of $\theta_{13}$

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

If $\sin^2 2\theta_{13} > 10^{-(2\text{-}3)}$, we can study both
of these issues with intense but conventional
accelerator $\nu$ and $\bar{\nu}$ beams, produced via
$\pi^+ \rightarrow \mu^+ + \nu_\mu$ and $\pi^- \rightarrow \mu^- + \bar{\nu}_\mu$ .

Determining $\theta_{13}$ is
an important step.

# Reactor Experiments To Determine $\theta_{13}$

Looking for disappearance of reactor $\bar{\nu}_e$, which have E ~ 3 MeV, while they travel L ~ 1.5 km is the cleanest way to determine $\theta_{13}$ .

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

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

# Accelerator Experiments

Accelerator neutrino experiments can also probe $\theta_{13}$ .
Now it is entwined with other parameters.

In addition, accelerator experiments can probe
*whether the mass spectrum is normal or inverted*,
and look for *CP violation*.

All of this is done by studying $\nu_\mu \rightarrow \nu_e$ and $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$
while the beams travel hundreds of kilometers.

# The Mass Spectrum:  or  ?

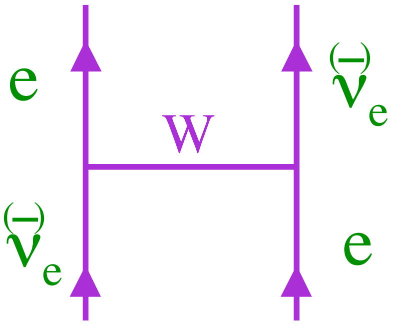
Generically, grand unified models (GUTS) favor —

GUTS relate the Leptons to the Quarks.

However, ***Majorana masses***, with no quark analogues, could turn  into  .

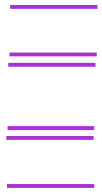
# How To Determine If The Spectrum Is Normal Or Inverted

Exploit the fact that, in matter,



affects $\nu$ and $\bar{\nu}$ oscillation ***(differently)***, and leads to —

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

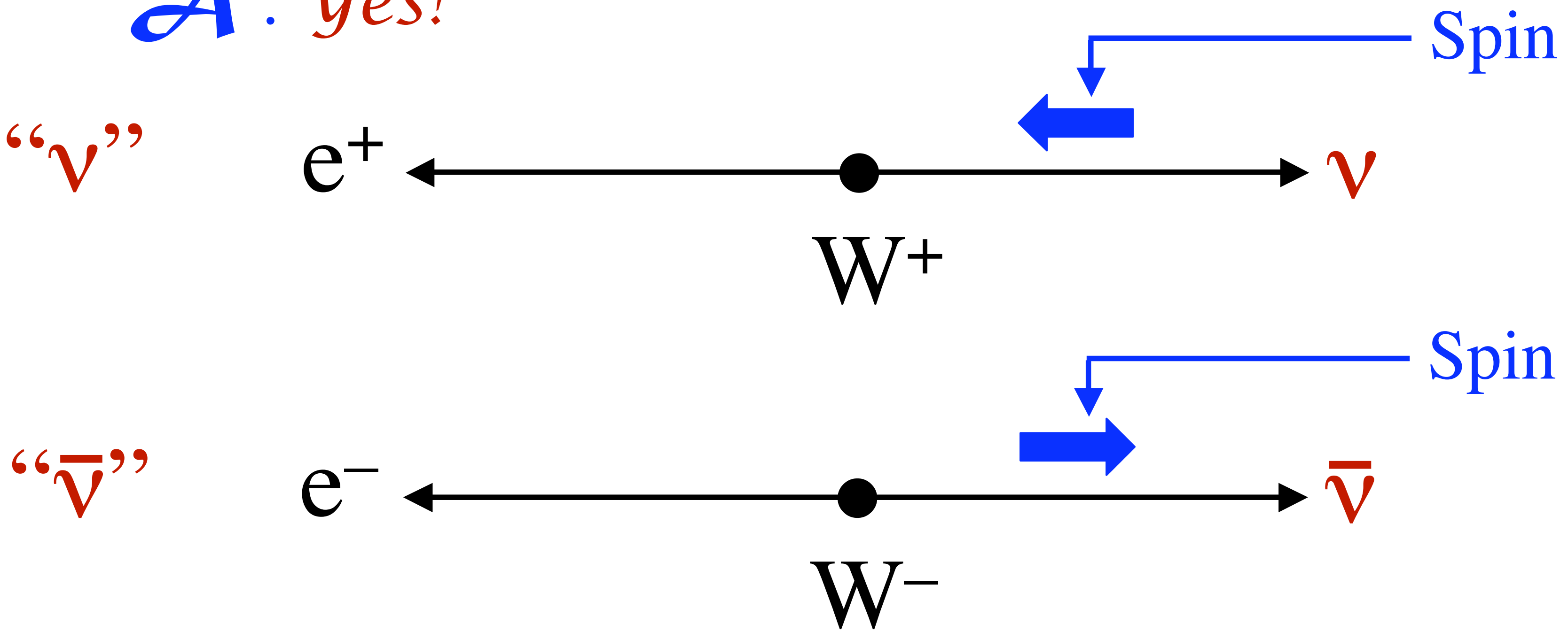


*Note fake ~~CP~~*

*Note dependence on the mass ordering*

**Q** : *Does matter still affect $\nu$ and $\bar{\nu}$ differently when $\bar{\nu} = \nu$?*

**A** : *Yes!*



Spin

“$\nu$” $e^+$ $\nu$

$W^+$

Spin

“$\bar{\nu}$” $e^-$ $\bar{\nu}$

$W^-$

The weak interactions violate ***parity***. Neutrino – matter interactions depend on the neutrino ***polarization***.

# Do Neutrino Interactions Violate CP?

The observed $\cancel{CP}$ in the weak interactions of ***quarks*** cannot explain the *Baryon Asymmetry* of the universe.

Is ***leptonic*** $\cancel{CP}$, through *Leptogenesis*, the origin of the *Baryon Asymmetry* of the universe?

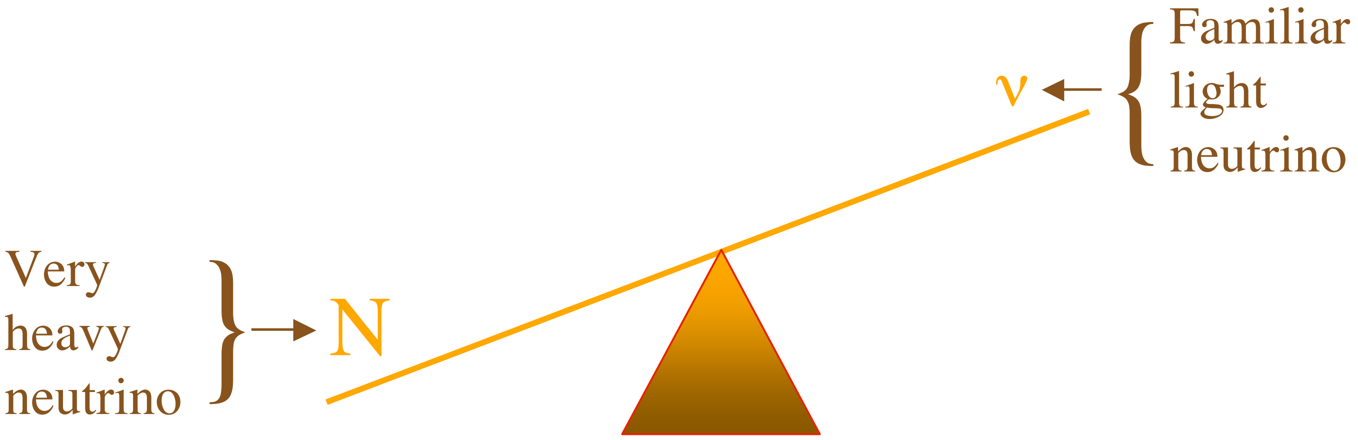
(Fukugita, Yanagida)

# *Leptogenesis In Brief*

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

See-Saw Mechanism

(Yanagida; Gell-Mann, Ramond, Slansky; Mohapatra, Senjanovic; Minkowski)



The ***very*** 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 $\ell^-$ or $\ell^+$.

***If neutrino oscillation violates CP, then quite likely so does N decay. In the See-Saw, these two CP violations have a common origin: One Yukawa coupling matrix.***

Then, in the early universe, we would have had different rates for the CP-mirror-image decays –

$$N \rightarrow \ell^- + \varphi^+ \qquad \text{and} \qquad N \rightarrow \ell^+ + \varphi^-$$

Standard-Model Higgs

This would have led to unequal numbers of leptons and antileptons (*Leptogenesis*).

Then, Standard-Model ***Sphaleron*** processes would have turned ~ 1/3 of this leptonic asymmetry into a *Baryon Asymmetry*.

# Electromagnetic Leptogenesis

(Bell, B.K., Law)

A new, alternative leptogenesis scenario in which the leptonic asymmetry arises from —

$$\Gamma(N \rightarrow \ell^- + \varphi^0 + W^+) \neq \Gamma(N \rightarrow \ell^+ + \overline{\varphi^0} + W^-)$$

Heavy EW singlet neutrino

This too can produce the observed *Baryon Asymmetry* of the universe.

Has the link between $\cancel{CP}$ in neutrino oscillation and the *Baryon Asymmetry* been broken?

# — No —

***These new couplings lead to neutrino masses.***

***If leptogenesis is driven by these couplings, then the neutrino masses probably are too.***

***CP-violating couplings will lead to CP-violating mass matrices, which in turn will lead to CP violation in oscillation.***

***As in standard leptogenesis, $\cancel{CP}$ in neutrino oscillation and $\cancel{CP}$ in the early universe are linked.***

# How To Search for $\cancel{CP}$ In Neutrino Oscillation

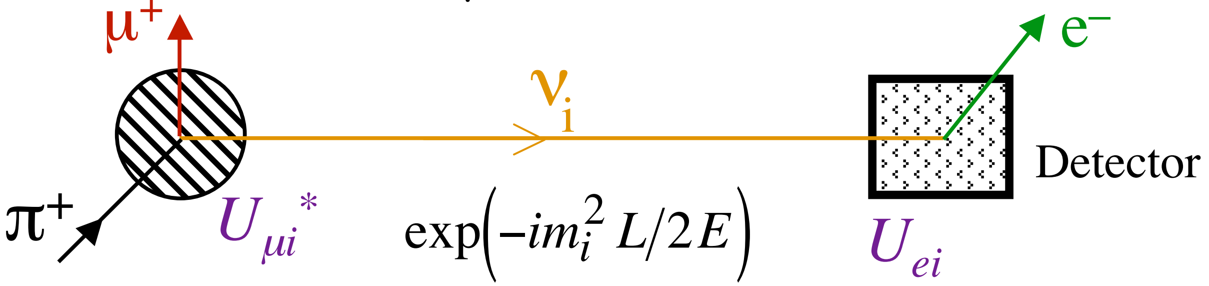
Look for $P(\bar{\nu}_\alpha \rightarrow \bar{\nu}_\beta) \neq P(\nu_\alpha \rightarrow \nu_\beta)$

***Q*** : *Can CP violation still lead to $\mathcal{P}(\bar{\nu}_\mu \to \bar{\nu}_e) \neq \mathcal{P}(\nu_\mu \to \nu_e)$ when $\bar{\nu} = \nu$?*

***A*** : *Certainly!*

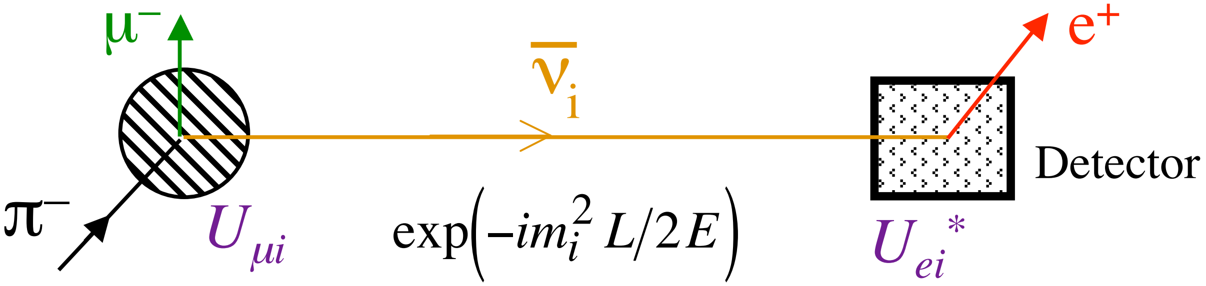
Compare $\nu_\mu \to \nu_e$

$\sum_i$



with "$\bar{\nu}_\mu \to \bar{\nu}_e$"

$\sum_i$



# Summary

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

What we have learned raises some very interesting questions.

We look forward to answering them.