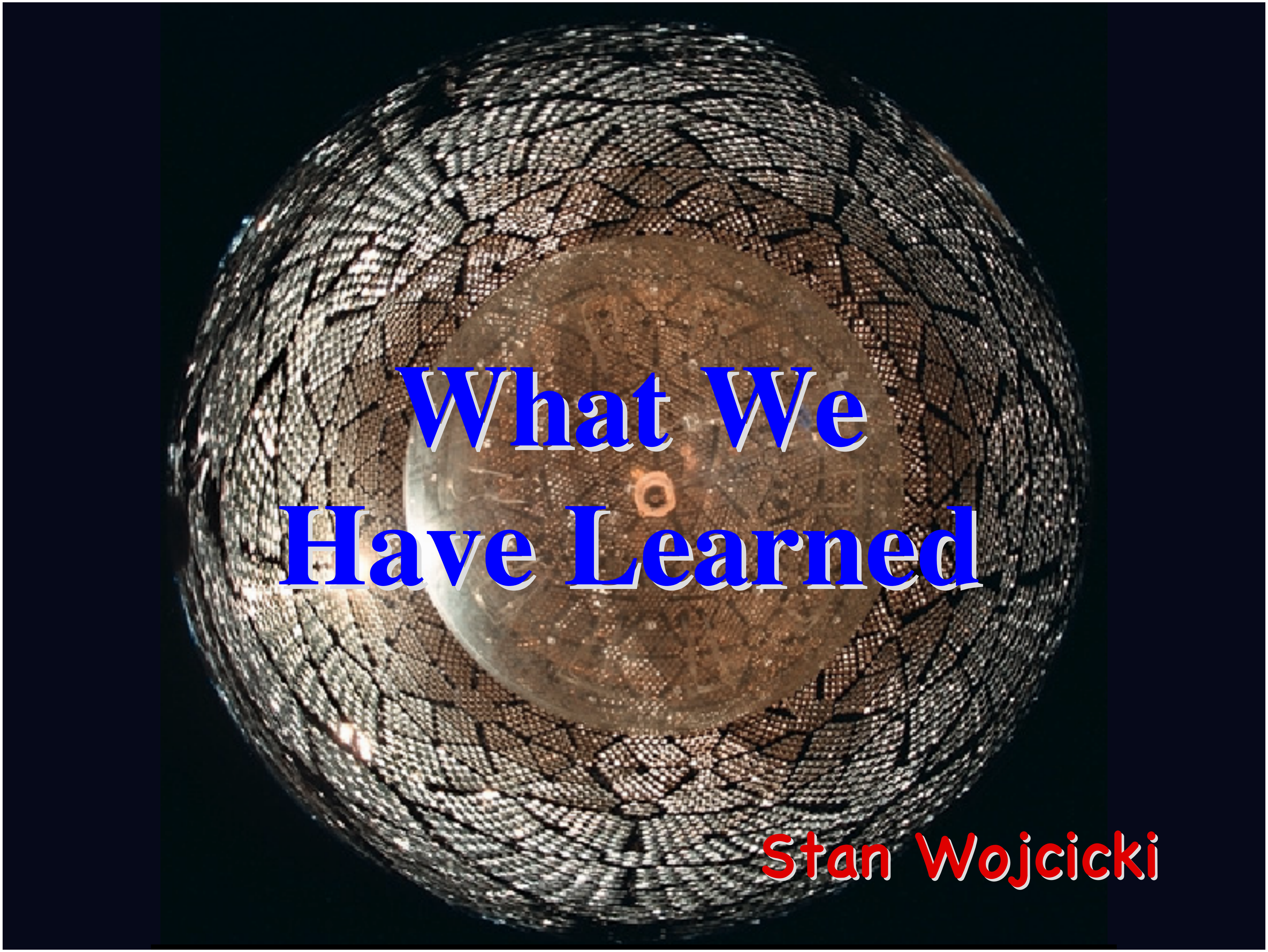
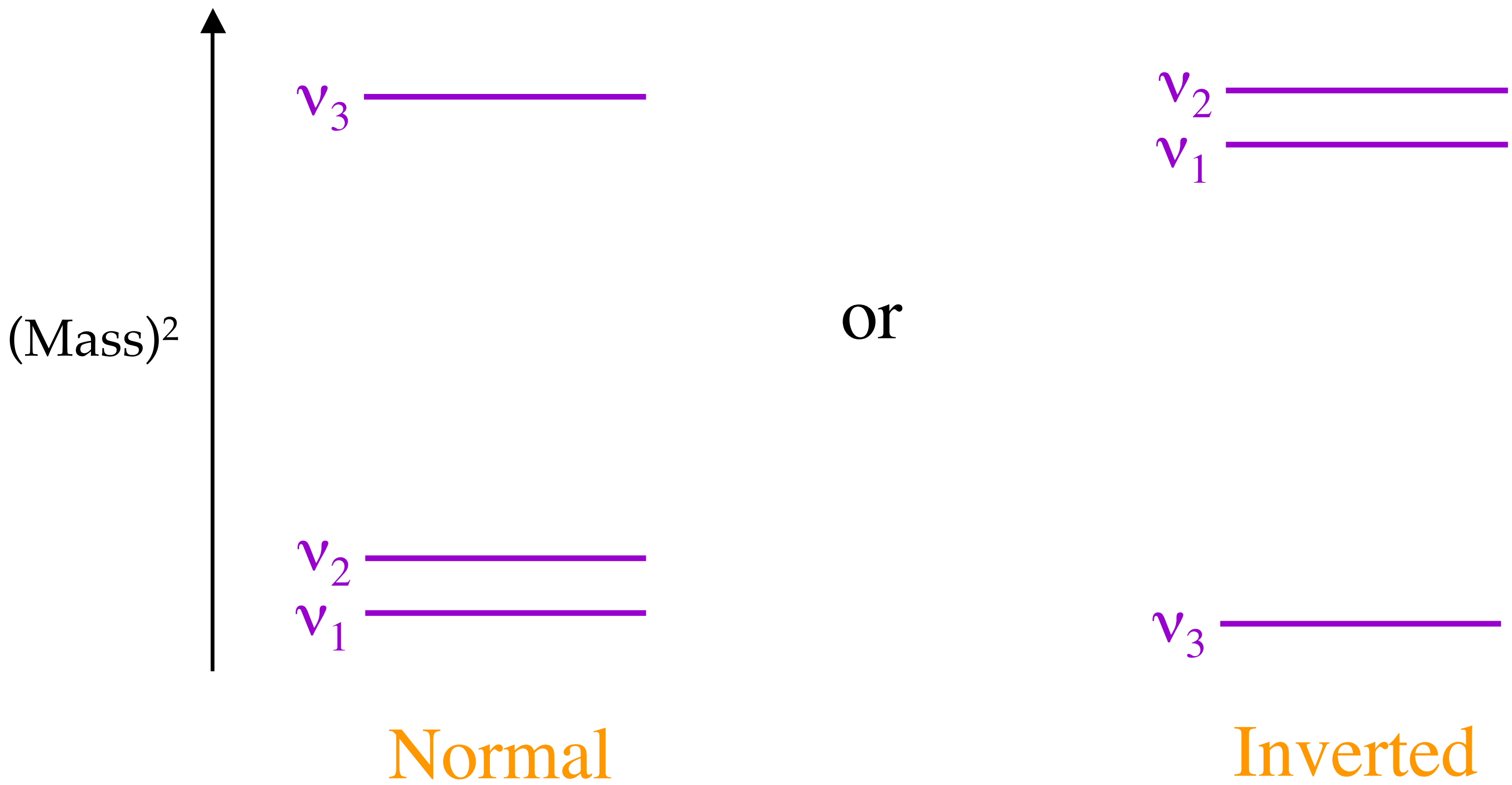
Open Neutrino Questions

Boris Kayser, Blois, 19 July 2010


What We
Have Learned
Stan Wojcicki

The (Mass)^2 Spectrum



$$\Delta m^2_{21} \cong 7.6 \times 10^{-5}\ \mathrm{eV}^2, \quad \Delta m^2_{32} \cong 2.4 \times 10^{-3}\ \mathrm{eV}^2$$

Are there *more* mass eigenstates, as LSND suggests, and MiniBooNE recently hints?

Absolute Mass Scale

Tritium β decay: $\langle m_i \rangle < 2\text{eV}$

Mass(ν_i)

Cosmology: $\Sigma\, m_i < (0.17 - 1.0)$ eV

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 the neutrinos of definite mass:

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

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

Neutrino of definite mass m_i

Unitary (?) Leptonic Mixing Matrix

The Mixing Matrix

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

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

Doesn't affect oscillation

Hints??

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

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

$\theta_{12} \approx 34°$, $\theta_{23} \approx 39\text{-}51°$, $\theta_{13} \lesssim 11°$

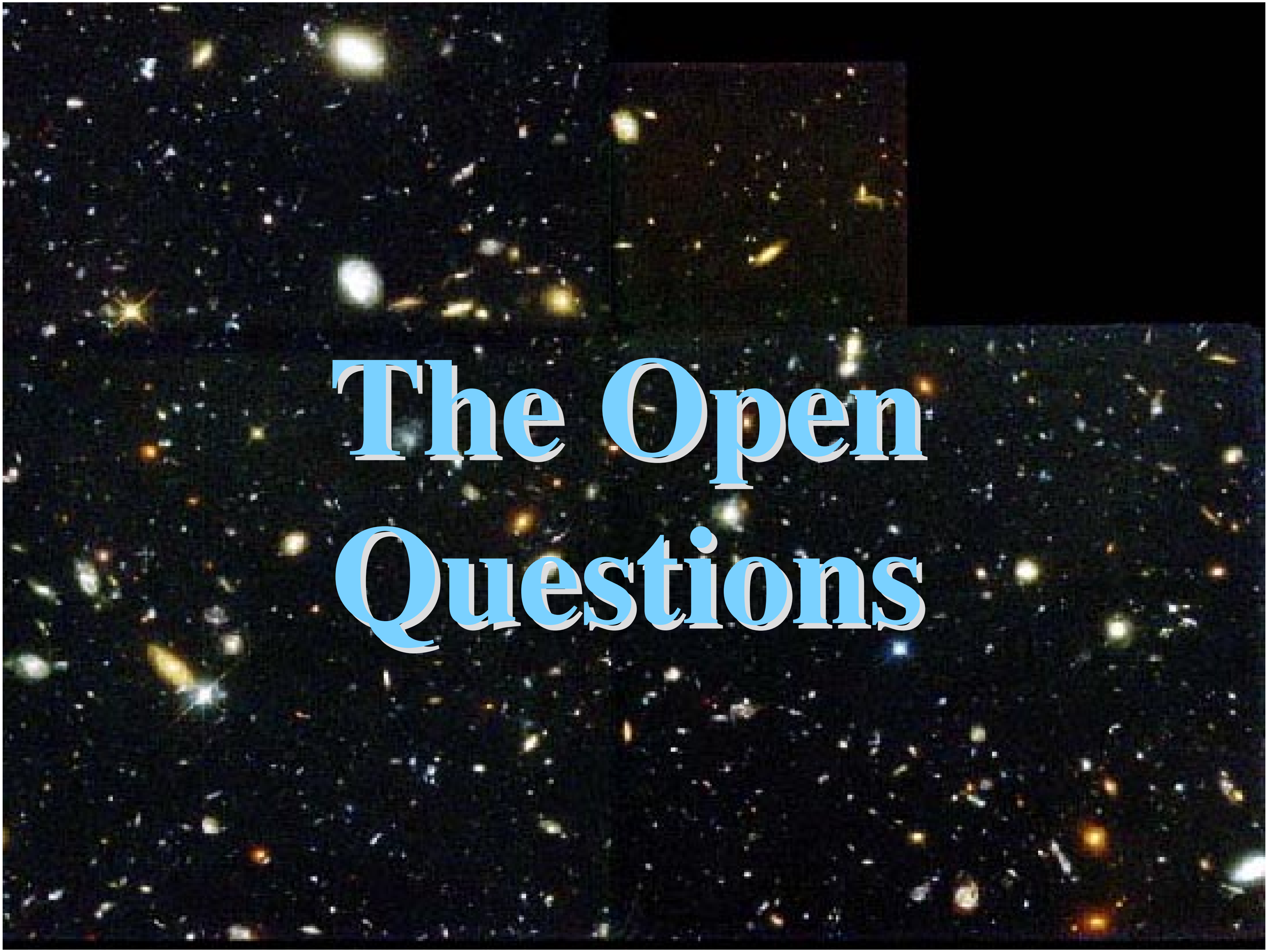
δ would lead to $P(\bar{\nu}_\alpha \rightarrow \bar{\nu}_\beta) \neq P(\nu_\alpha \rightarrow \nu_\beta)$. ~~CP~~

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

Multiplied out, the mixing matrix is close to the simple Tri-Bi-Maximal mixing:

$$U_{TBM} = \begin{pmatrix} \sqrt{\frac{2}{3}} & \sqrt{\frac{1}{3}} & 0 \\ -\sqrt{\frac{1}{6}} & \sqrt{\frac{1}{3}} & \sqrt{\frac{1}{2}} \\ \sqrt{\frac{1}{6}} & -\sqrt{\frac{1}{3}} & \sqrt{\frac{1}{2}} \end{pmatrix}$$

Is there a deep underlying reason, such as a symmetry, for this pattern?


The Open
Questions

- What is the absolute scale of neutrino mass?

- Are neutrinos their own antiparticles?

- Are there ***more*** than 3 mass eigenstates?

- Are there "sterile" neutrinos?

- What are the neutrino magnetic and electric dipole moments?

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

What is θ_{13}?

•Is the spectrum like  or  ?

•Do neutrino – matter interactions violate CP?

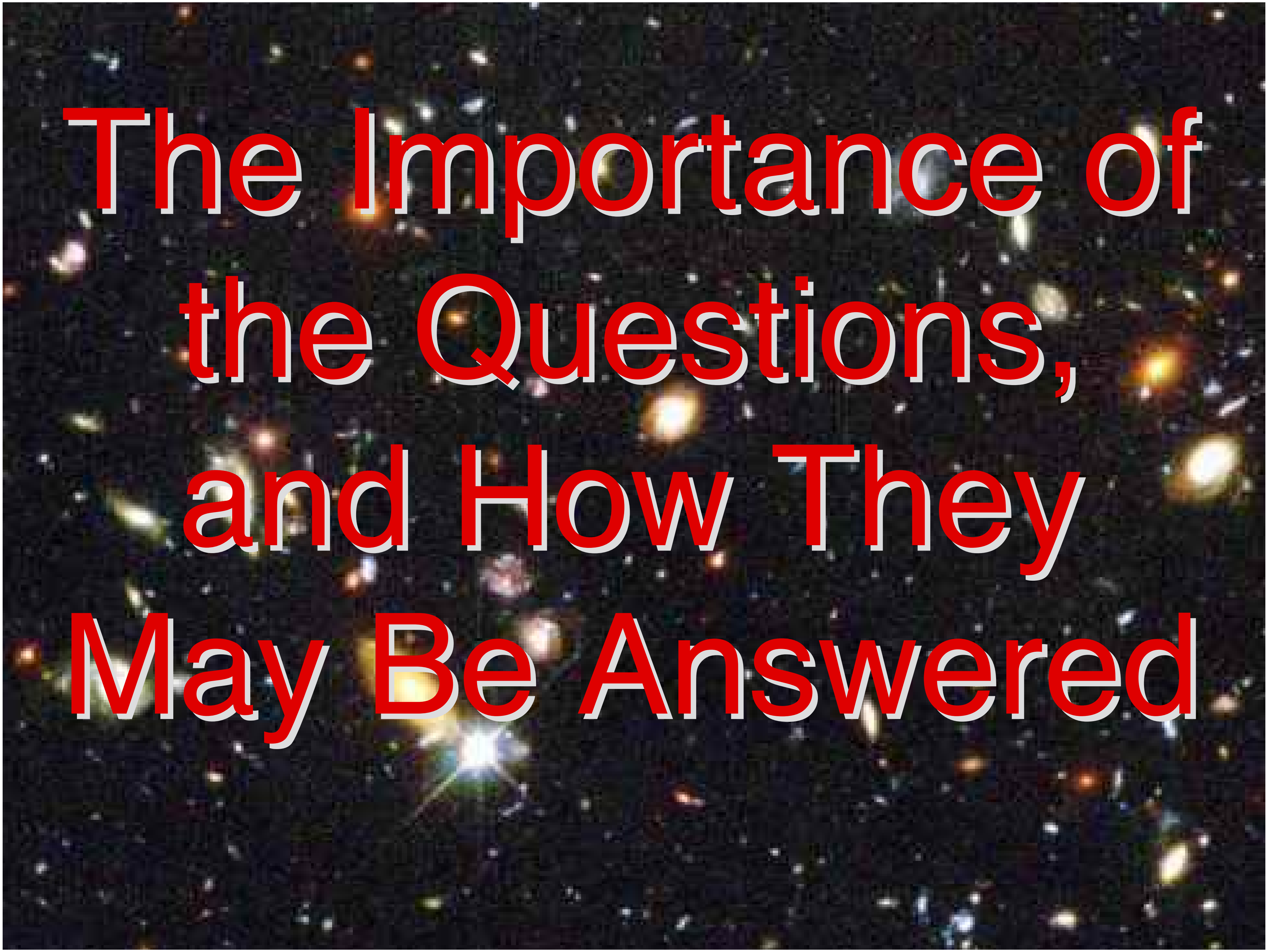
Is $P(\bar{\nu}_\alpha \rightarrow \bar{\nu}_\beta) \neq P(\nu_\alpha \rightarrow \nu_\beta)$?

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

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

- What physics is behind neutrino mass?

- What surprises are in store?


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

Are Neutrinos Their Own Antiparticles?

For each ***mass eigenstate*** ν_i , and ***given helicty*** h, does —

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

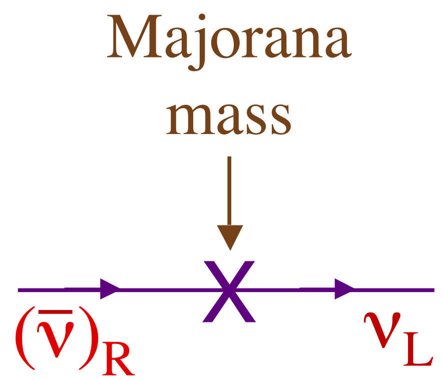
or

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

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

Majorana Masses

An example of their effect:



Majorana masses mix ν and $\bar{\nu}$, so they do not conserve the Lepton Number L that distinguishes leptons from antileptons:

$$L(\nu) = L(\ell^-) = -L(\bar{\nu}) = -L(\ell^+) = 1$$

A Majorana mass for any fermion f causes $f \leftrightarrow \bar{f}$.

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

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

Majorana neutrino masses have a different origin than the quark and charged-lepton masses.

Why Majorana Masses ⟹ Majorana Neutrinos

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

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

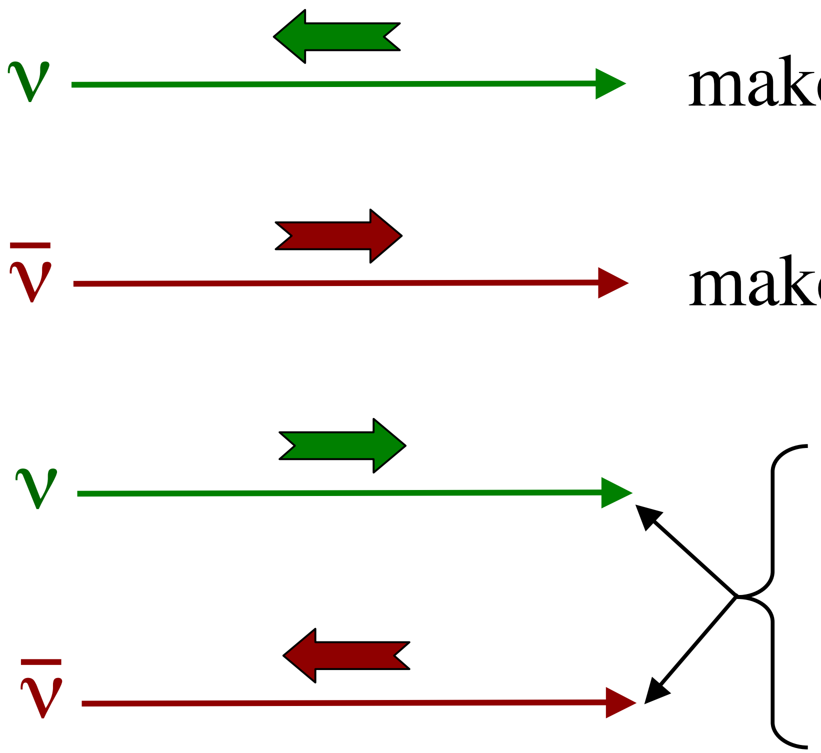
Majorana masses induce $\nu \leftrightarrow \bar{\nu}$ mixing.

As a result of $\nu \leftrightarrow \bar{\nu}$ mixing, the neutrino mass eigenstate is —

$$\nu_i = \nu + \bar{\nu}\ . \qquad \bar{\nu}_i = \nu_i\ .$$

A Dirac Neutrino

We have 4 mass-degenerate states:



makes ℓ^-

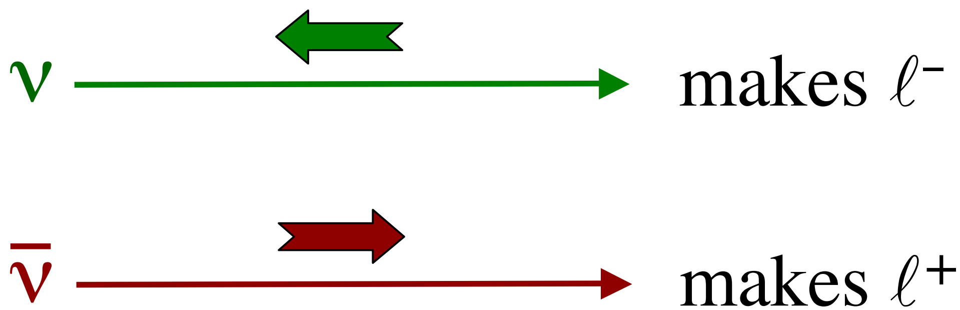
makes ℓ^+

These states do not interact.

(The weak interaction is Left Handed.)

A Majorana Neutrino

We have only 2 mass-degenerate states:



The weak interactions violate *parity*.

An incoming left-handed neutral lepton makes ℓ^-.

An incoming right-handed neutral lepton makes ℓ^+.

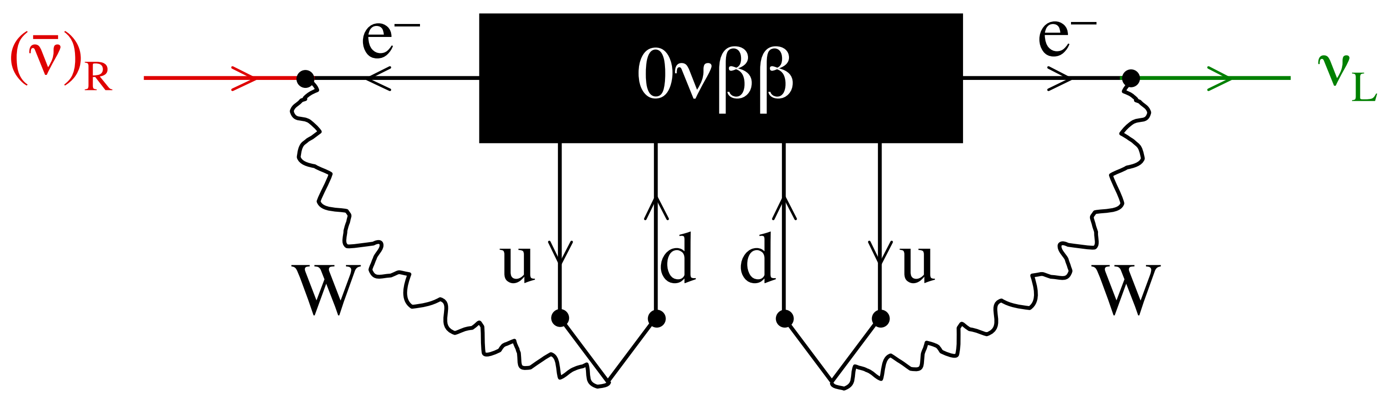
To Determine Whether Majorana Masses Occur in Nature

The Promising Approach — Seek

Neutrinoless Double Beta Decay [0νββ]

Whatever diagrams cause $0\nu\beta\beta$, its observation would imply the existence of a Majorana mass term:

(Schechter and Valle)



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

$\therefore\ 0\nu\beta\beta \Rightarrow \bar{\nu}_i = \nu_i$

Mixing,
Mass Ordering,
and ~~CP~~

The Questions For Oscillation Experiments

The theory of neutrino oscillations remains solid.

For a neutrino beam of energy E, the usual expression for the wavelength λ of the oscillation caused by a splitting Δm^2 is —

$$\lambda \equiv \text{Source to Detector distance for one oscillation} = \frac{4\pi E}{\Delta m^2} .$$

Recently, it was argued that this expression can be wrong by 27% to 57%!

The Δm^2 extracted from data using this expression would then be similarly wrong.

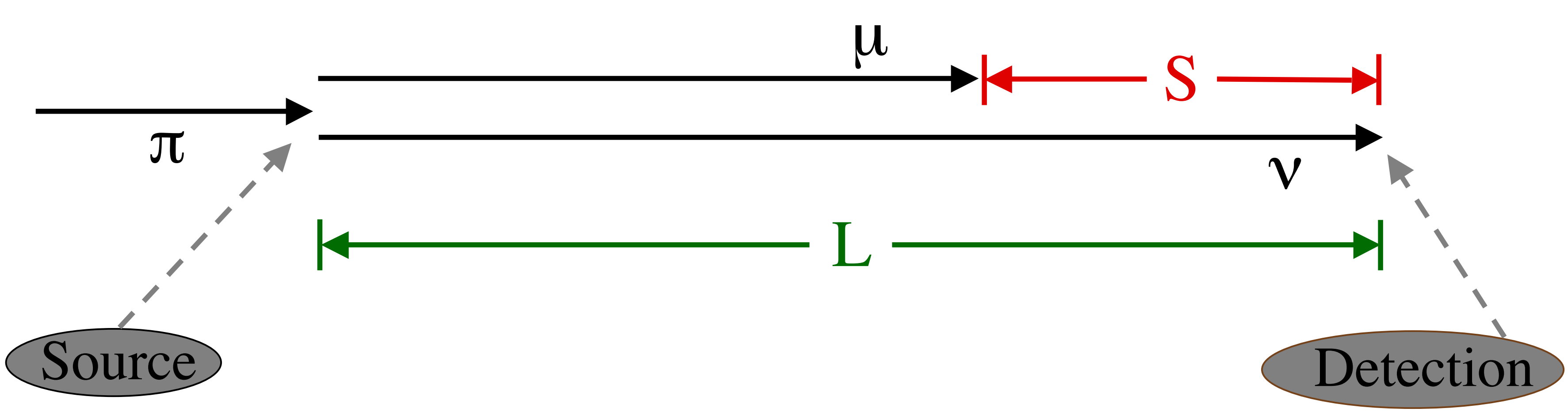
R. G. H. Robertson

Should one worry?

No!

The recent approach involves ***entanglement*** between the neutrino and its associated recoil — the muon in $\pi \to \mu\nu$.

The wavelength λ_S derived by this approach is in reality for oscillation as a function of the lab-frame $\nu - \mu$ separation S at the time in the π rest frame when the neutrino is detected:



One finds that —

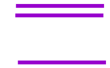
$$\frac{\lambda_S}{\lambda_{Usual}} = \frac{S}{L}$$

That is, the "new" wavelength λ_S is physically equivalent to the usual one.

It just refers to a different distance variable.

B. K., Kopp, Robertson, and Vogel

No need to worry!

The Mass Spectrum:  or  ?

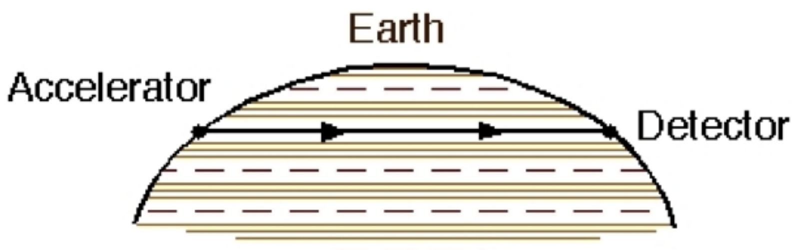
Generically, grand unified models (GUTS) favor —

GUTS relate the Leptons to the Quarks.

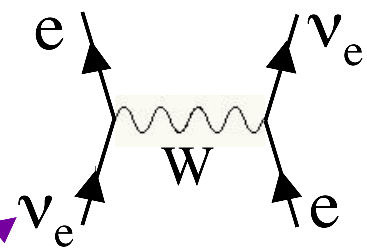
However, ***Majorana masses***, with no quark analogues, could turn  into  .

How To Determine If The Spectrum Is Normal Or Inverted

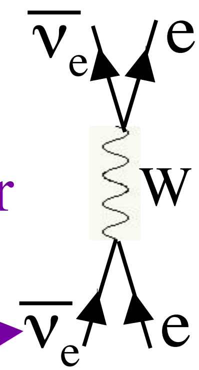
Exploit the ***matter effect***.



involves



or



Oppositely polarized

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

This leads to —

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


Do Neutrino Interactions
Violate CP?
Are we descended
from heavy neutrinos?

The Challenge — A Cosmic Broken Symmetry

The universe contains baryons,
but essentially no antibaryons.

Standard cosmology: Any initial baryon – antibaryon asymmetry would have been erased.

How did $n_B = n_{\overline{B}}$ ➡ $n_B >> n_{\overline{B}}$?

Sakharov: $n_B = n_{\overline{B}}$ $\Rightarrow$ $n_B >> n_{\overline{B}}$ requires $\not{C}\!\not{P}$.

The $\not{C}\!\not{P}$ in the quark mixing matrix,
seen in B and K decays, leads to
much too small a B–$\overline{B}$ asymmetry.

If ***quark*** $\not{C}\!\not{P}$ cannot generate
the observed B–$\overline{B}$ asymmetry,
can some scenario involving ***leptons*** do it?

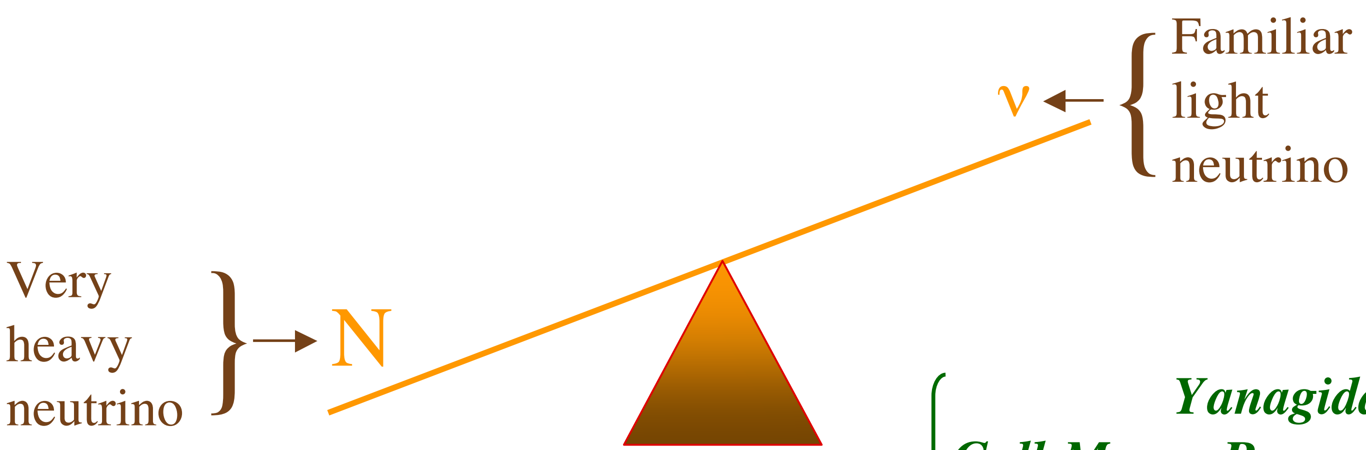
The candidate scenario: *Leptogenesis*.

(Fukugita, Yanagida)

Leptogenesis – The General Idea

Leptogenesis is an outgrowth of the most popular theory of why neutrinos are so light —

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.

Leptogenesis — Step 1

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

If ν 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, y.

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

$$N \rightarrow e^- + H^+ \quad \text{and} \quad N \rightarrow e^+ + H^-$$

Standard-Model Higgs

This produces a universe with unequal numbers of leptons and antileptons.

Leptogenesis — Step 2

The Standard-Model ***Sphaleron*** process,
which does not conserve Baryon Number B,
or Lepton Number L, but does conserve $B - L$, acts.

$$B_i = 0$$
$$L_i \neq 0$$

→ Sphaleron Process →

$$B_f \cong -\frac{1}{3} L_i$$
$$L_f \cong \frac{2}{3} L_i \cong -2B_f$$

Initial state from N decays

Final state

There is now a Baryon Asymmetry.

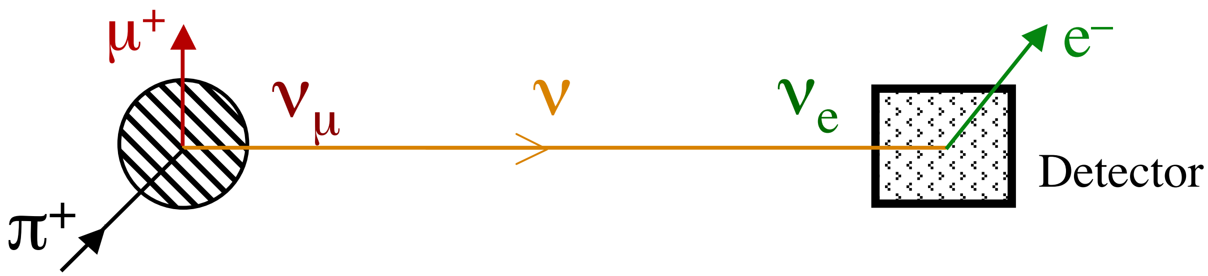
Evidence for the See-Saw and for Leptogenesis

The observation of **$0\nu\beta\beta$** would be evidence in favor of the ***See-Saw***.

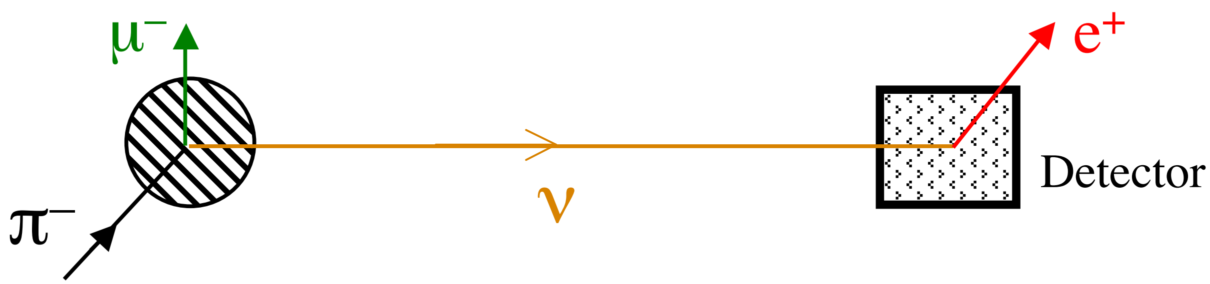
The observation of **~~CP~~** in neutrino oscillation would be evidence in favor of ***Leptogenesis***.

Does Neutrino Oscillation Violate CP?

Compare

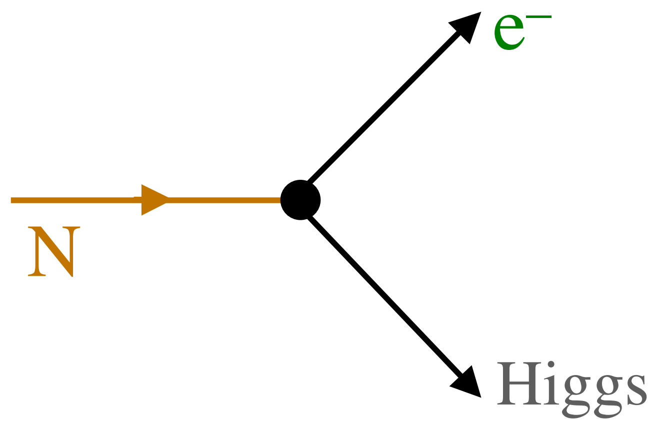


with

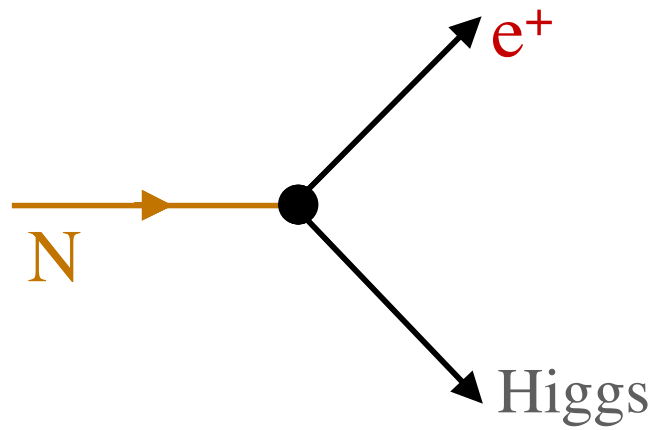


*Do these two processes have **different** rates? (~~CP~~)*

This is today's version of comparing —



with —



Physicists in Europe, Japan, and the U.S. are working hard to design an experimental facility that can make this comparison, or a related one.

Young-Kee Kim

Summary

There are some very interesting questions to answer.

Exciting times lie ahead.