Neutrino Physics: An Introduction To the Current Scene

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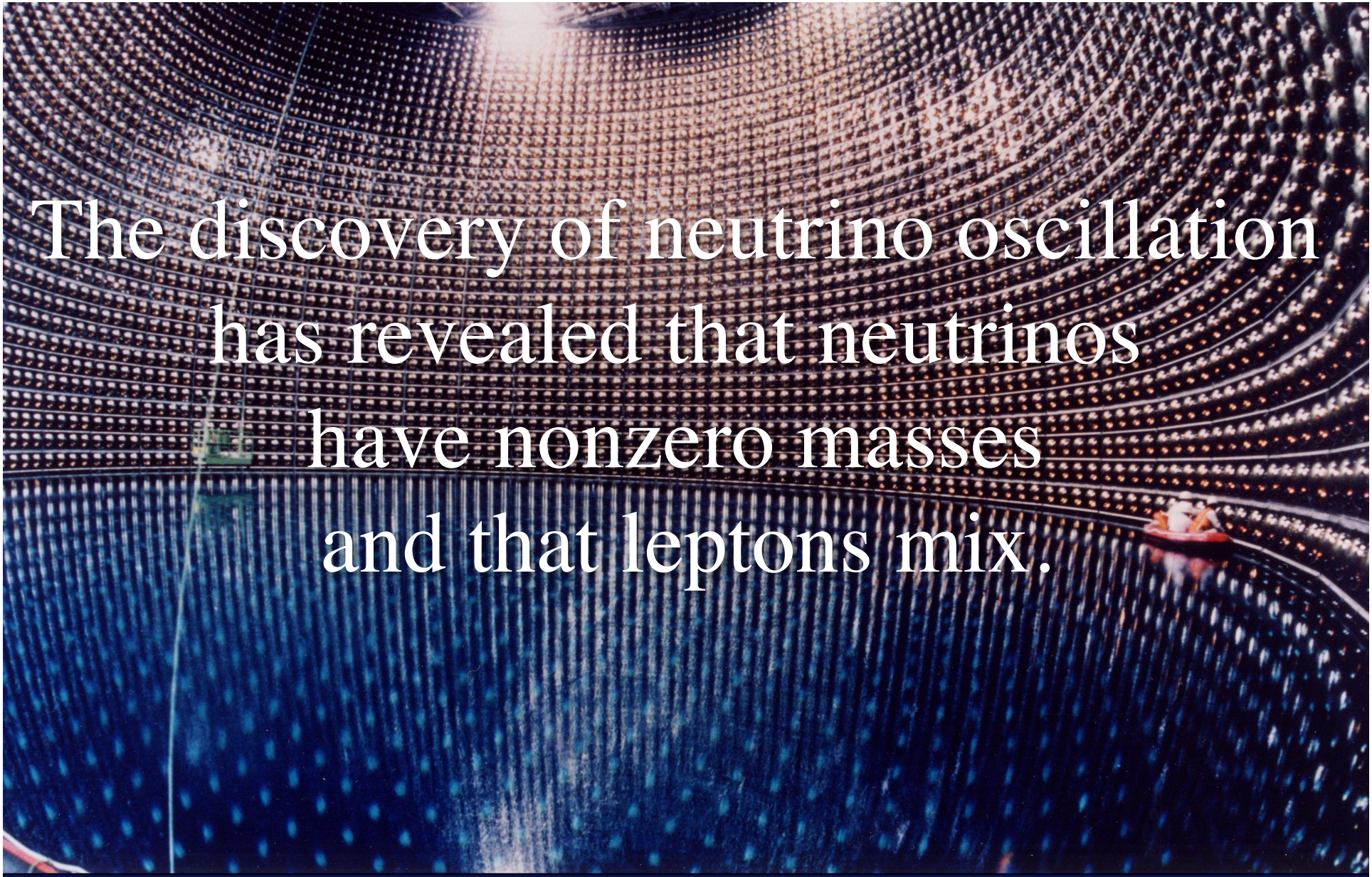
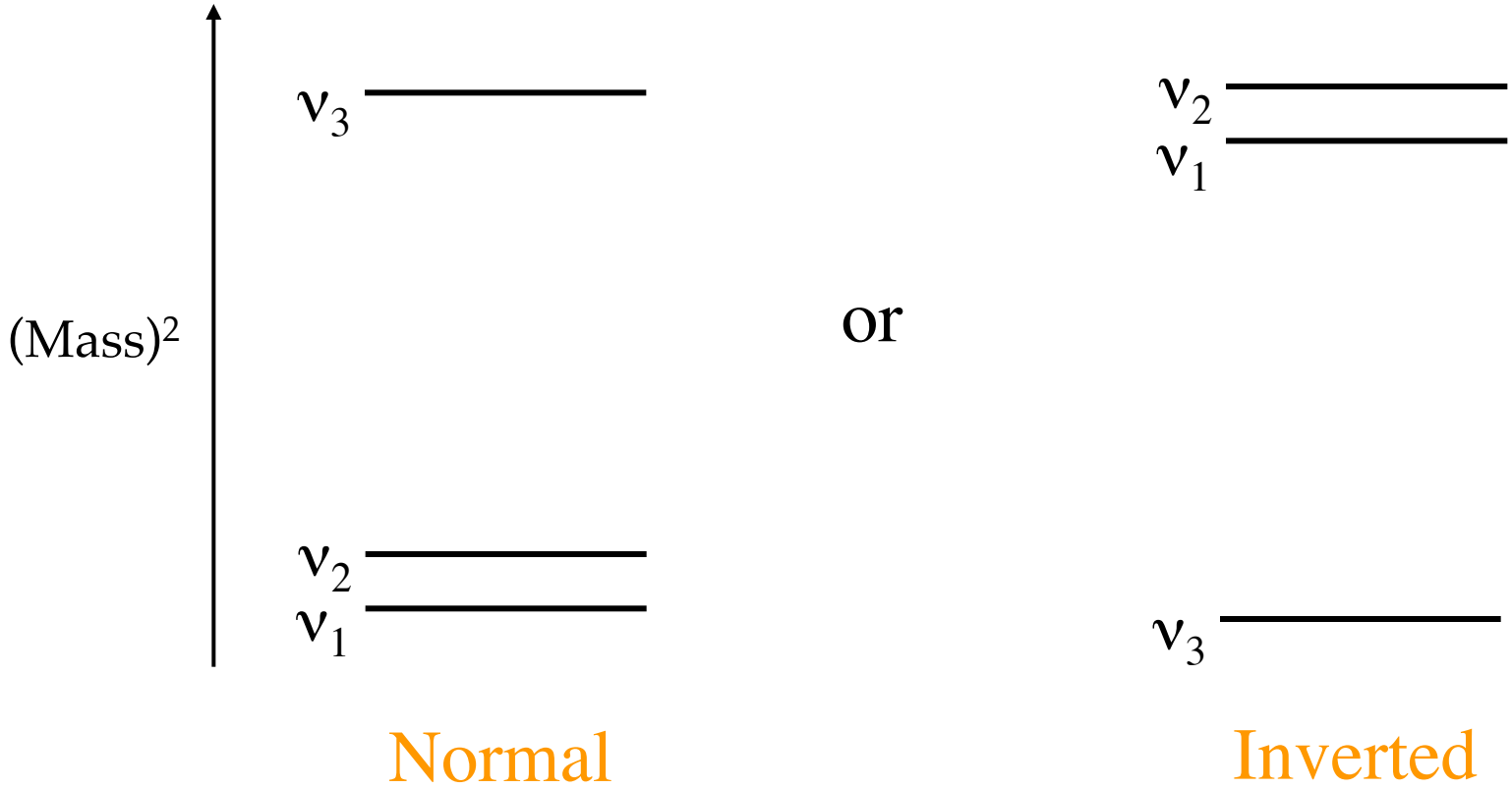
NASA Hubble Photo



The discovery of neutrino oscillation
has revealed that neutrinos
have nonzero masses
and that leptons mix.

What We Have Learned

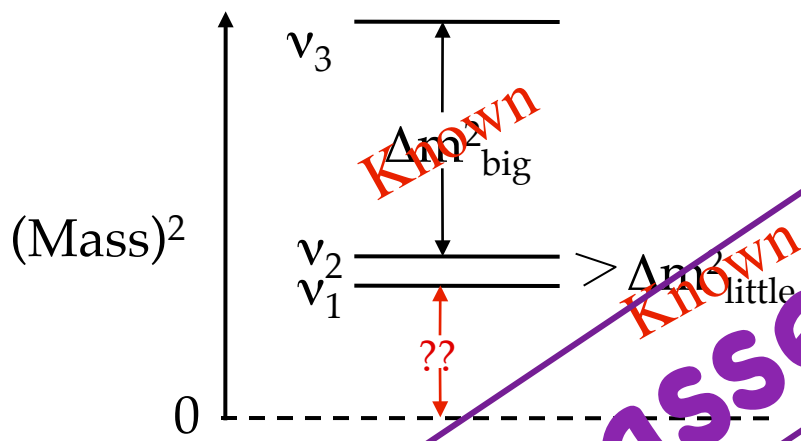
The Three – Neutrino $(\text{Mass})^2$ Spectrum



$$\Delta m^2_{21} \equiv m^2_2 - m^2_1 \cong 7.5 \times 10^{-5}\ \text{eV}^2, \qquad \Delta m^2_{32} \cong 2.4 \times 10^{-3}\ \text{eV}^2$$

There might be more mass eigenstates.

Constraints On the Absolute Scale of Neutrino Mass



How far above zero is the whole pattern?

Neutrino masses are tiny

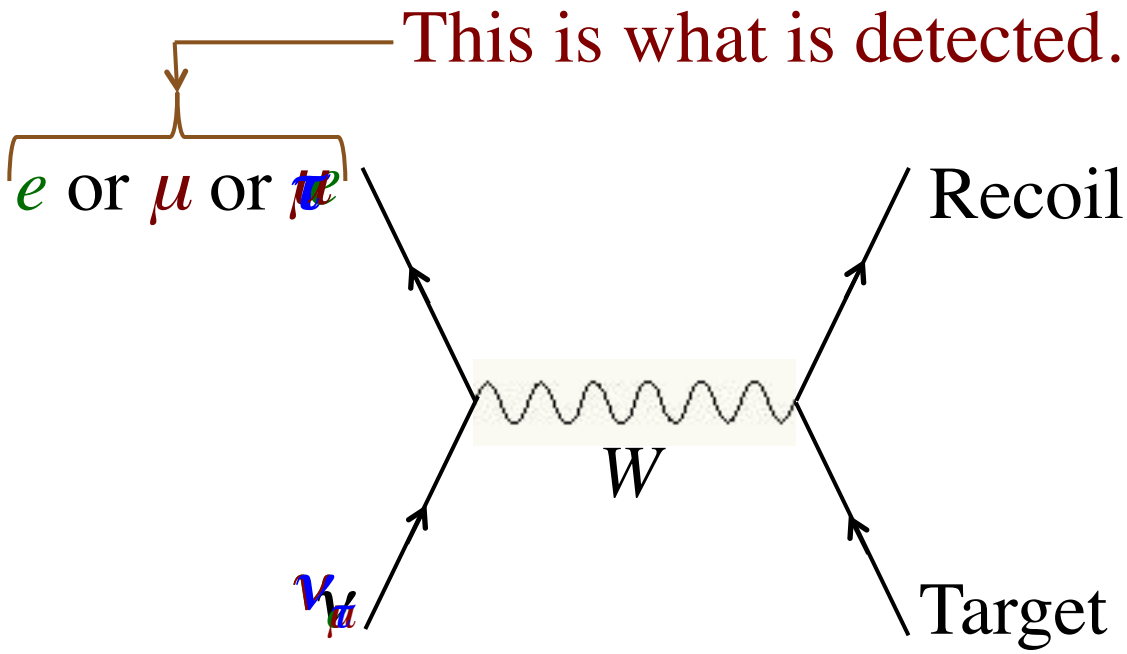
Cosmology, *under certain assumptions* → $\sum_{\text{All } i} m(\nu_i) < 0.23$ eV

Tritium beta decay → $\sqrt{0.69m^2(\nu_1) + 0.29m^2(\nu_2) + 0.02m^2(\nu_3)} < 2$ eV

Oscillation → Mass[Heaviest ν_i] $> \sqrt{\Delta m^2_{big}} > 0.04$ eV

Leptonic Mixing

A neutrino is often detected indirectly via —



So, we speak of neutrino "flavor" states ν_e ,ν_μ , and ν_τ that couple, respectively, to e, μ, and τ.

As far as we know, each neutrino flavor state couples only to the charged lepton mass eigenstate of the same flavor.

ν_e ,ν_μ , and ν_τ ***are not the neutrino mass eigenstates*** but ***superpositions*** of the mass eigenstates:

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

Neutrino of flavor α = e, μ, or τ

Unitary Leptonic Mixing Matrix

Neutrino of definite mass m_i

The leptonic mixing matrix

$$U = \begin{array}{c} \\ \nu_e \\ \nu_\mu \\ \nu_\tau \end{array} \begin{array}{c} \begin{array}{ccc} \nu_1 & \nu_2 & \nu_3 \end{array} \\ \begin{bmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{bmatrix} \end{array}$$

Leptonic mixing matrix

$$U = \begin{array}{c} \\ e \\ \mu \\ \tau \end{array} \begin{array}{c} \begin{array}{ccc} \nu_1 & \nu_2 & \nu_3 \end{array} \\ \begin{bmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{bmatrix} \end{array}$$

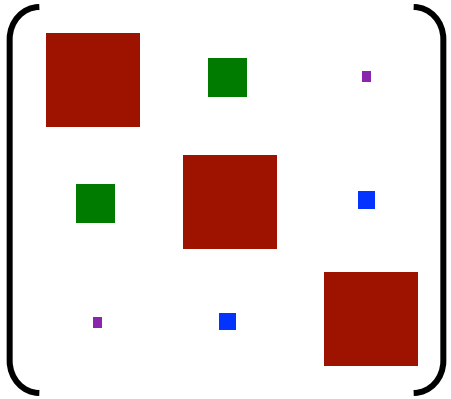
Quark mixing matrix

$$V = \begin{array}{c} \\ u \\ c \\ t \end{array} \begin{array}{c} \begin{array}{ccc} d & s & b \end{array} \\ \begin{bmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{bmatrix} \end{array}$$

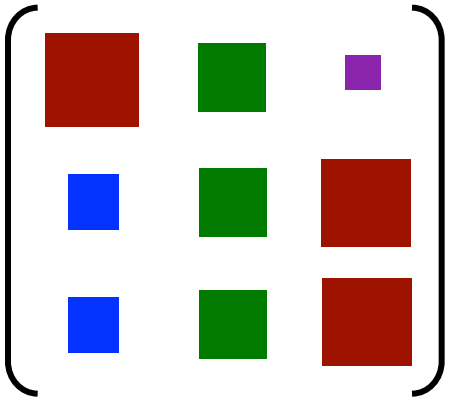
They play exactly the same role.

The Quark and Lepton Mixing Matrices

Quark mixing matrix =



Lepton mixing matrix =



The Extra Leptonic ~~CP~~ Phases

Assuming that $\boldsymbol{V}_{\mathbf{quark}}$ and $\boldsymbol{U}_{\mathbf{lepton}}$ are 3 x 3 and unitary, $\boldsymbol{V}_{\mathbf{quark}}$ can contain only **1** CP-violating phase factor, but $\boldsymbol{U}_{\mathbf{lepton}}$ may possibly contain **3**.

The extra leptonic phases are physical only if ***neutrinos are their own antiparticles***.

The quarks are definitely ***not*** their own antiparticles, so there are no extra phases in quark mixing.

The Lepton Mixing Matrix *U*

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

$$\times \underbrace{\begin{bmatrix} e^{i\alpha_1/2} & 0 & 0 \\ 0 & e^{i\alpha_2/2} & 0 \\ 0 & 0 & 1 \end{bmatrix}}_{\text{Does not affect oscillation}}$$

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

Note big mixing!

$\theta_{12} \approx 33°$, $\theta_{23} \approx 40\text{-}52°$, $\theta_{13} \approx 8\text{-}9°$ ← *Not very small!*

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

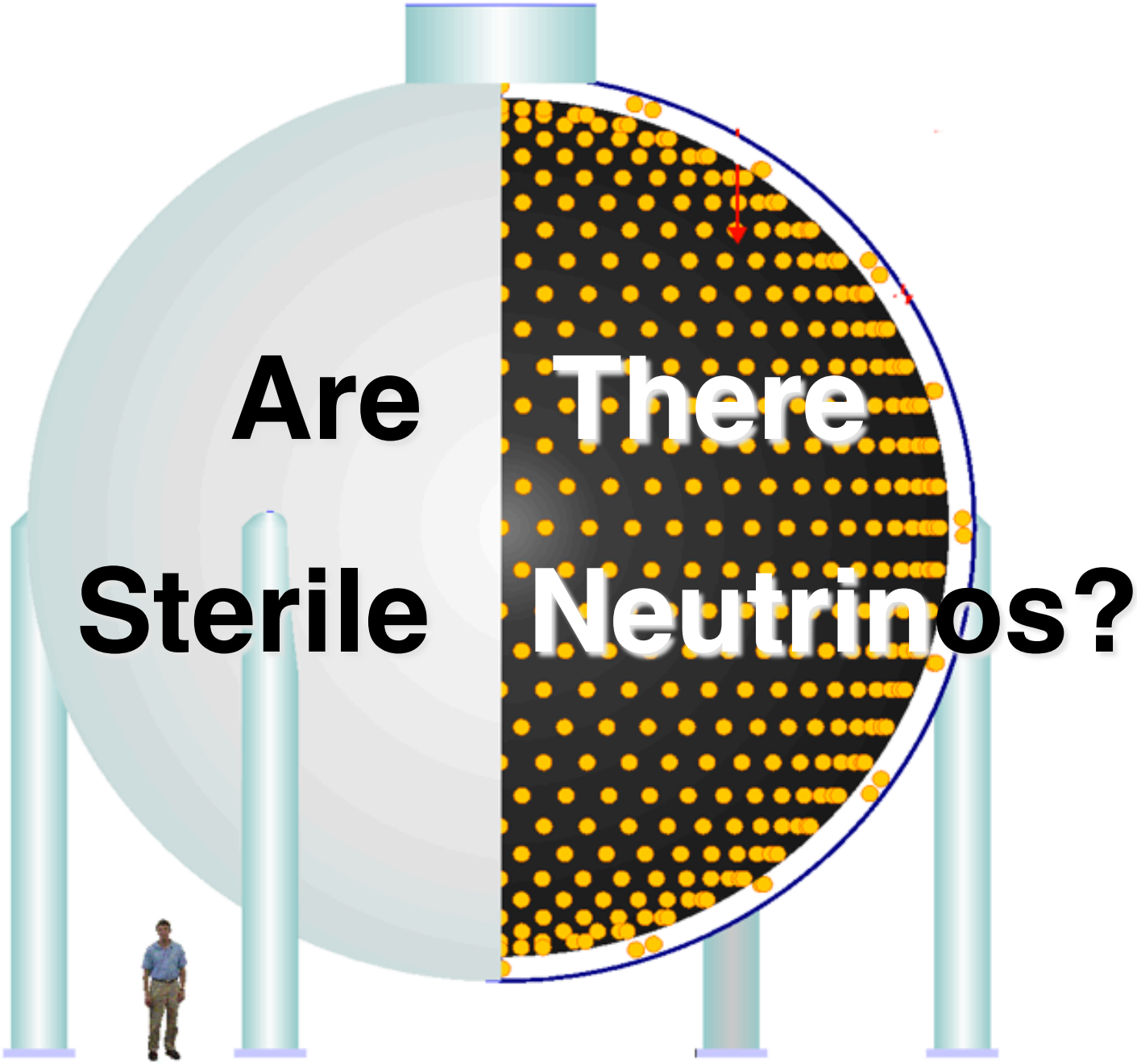
↑ ~~CP~~

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

We know essentially nothing about the phases. Only hints.

Important Notice

To determine oscillation probabilities
from measured event rates,
one must know the un-oscillated fluxes
and the interaction cross sections.


Are There
Sterile Neutrinos?

Sterile Neutrino

One that does not couple to the SM W or Z boson

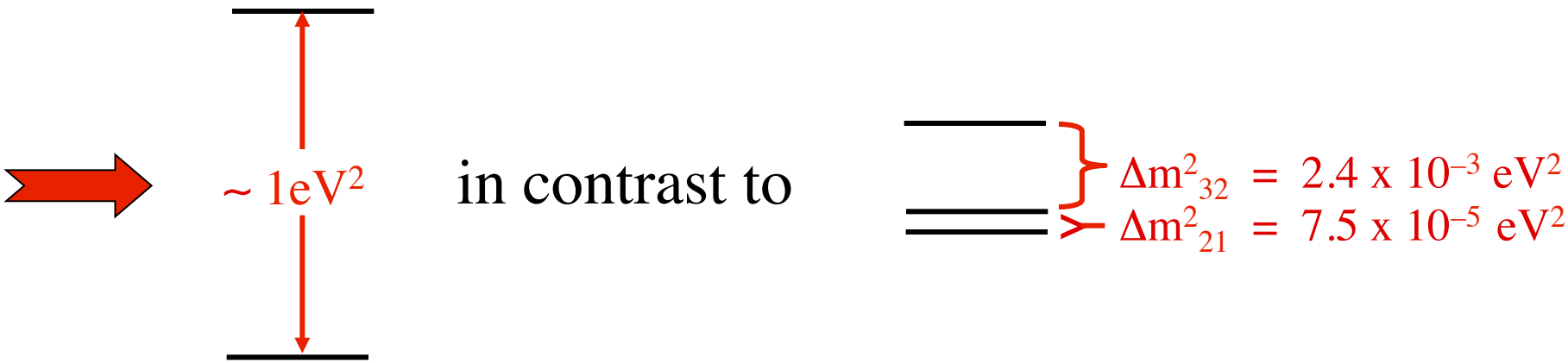
A "sterile" neutrino may well couple to some non-SM particles. These particles could perhaps be found at LHC or elsewhere.

Some Hints — First LSND

The LSND experiment at Los Alamos reported a ***rapid*** $\bar{\nu}_\mu \to \bar{\nu}_e$ oscillation at $L(km)/E(GeV) \sim 1$.

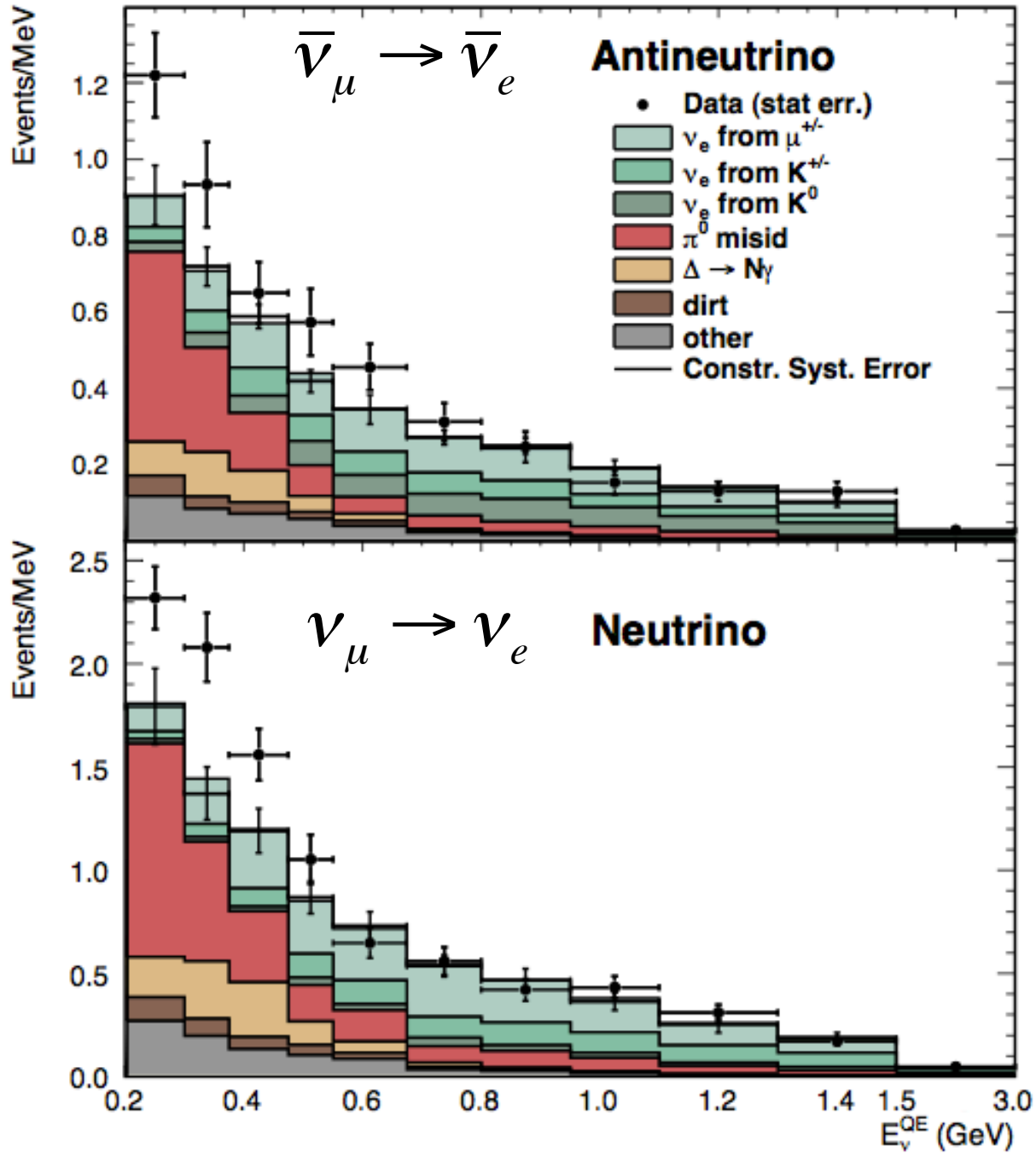
$$P\left(\overline{\nu_\mu} \to \overline{\nu_e}\right) = \sin^2 2\theta \sin^2\left[1.27\Delta m^2\left(eV^2\right)\frac{L(km)}{E(GeV)}\right] \sim 0.26\%$$

From μ^+ decay at rest; E ~ 30 MeV



At least **4** mass eigenstates

{from measured $\Gamma(Z \to \nu\bar{\nu})$} At least **1** sterile neutrino

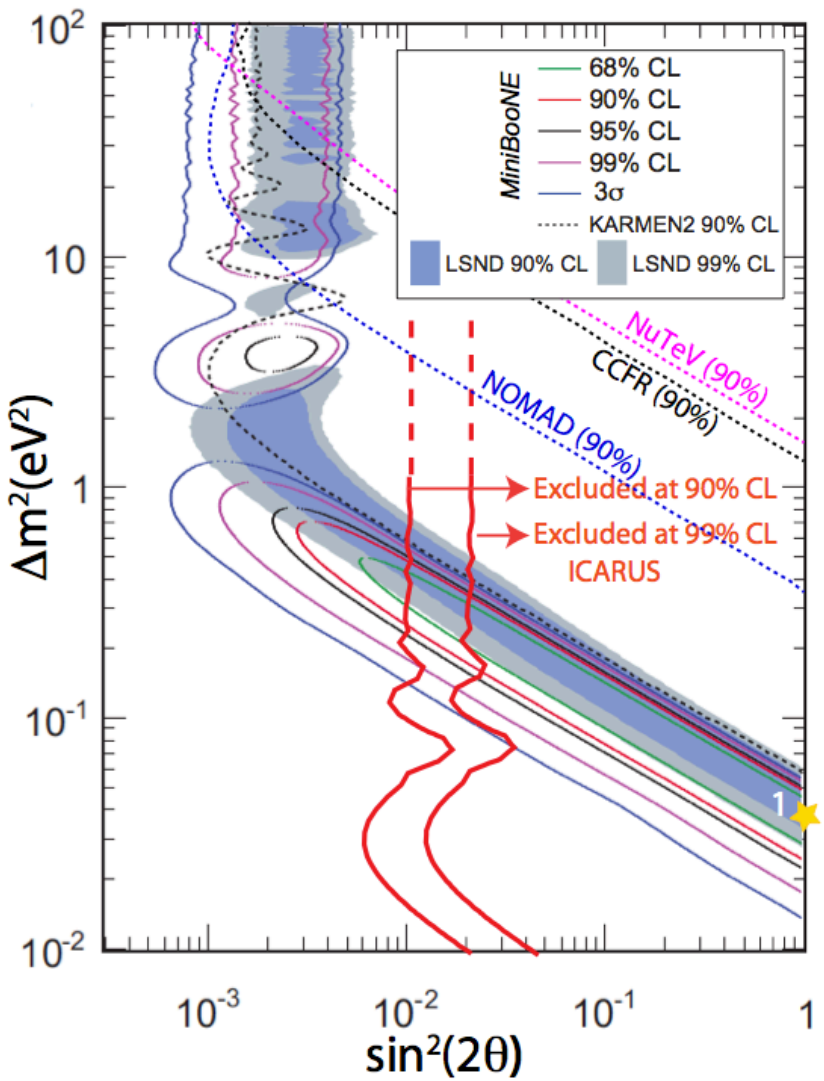


The Hint From MiniBooNE

78.4 ± 28.5
excess events

162.0 ± 47.8
excess events

ICARUS and OPERA, at $L/E \approx 35$ km/GeV, have not seen $\nu_\mu \rightarrow \nu_e$. This disfavors somewhat a $\nu_\mu \rightarrow \nu_e$ interpretation of the low-energy MiniBooNE ν_e excess.



ICARUS exclusion

Looking to the Future

Open Questions

•What is the absolute scale of neutrino mass?

•Is the physics behind the masses of neutrinos different from that behind the masses of all other known particles?

•Are neutrinos their own antiparticles?

•Is the spectrum like  or  ?

•Do neutrino interactions violate CP?

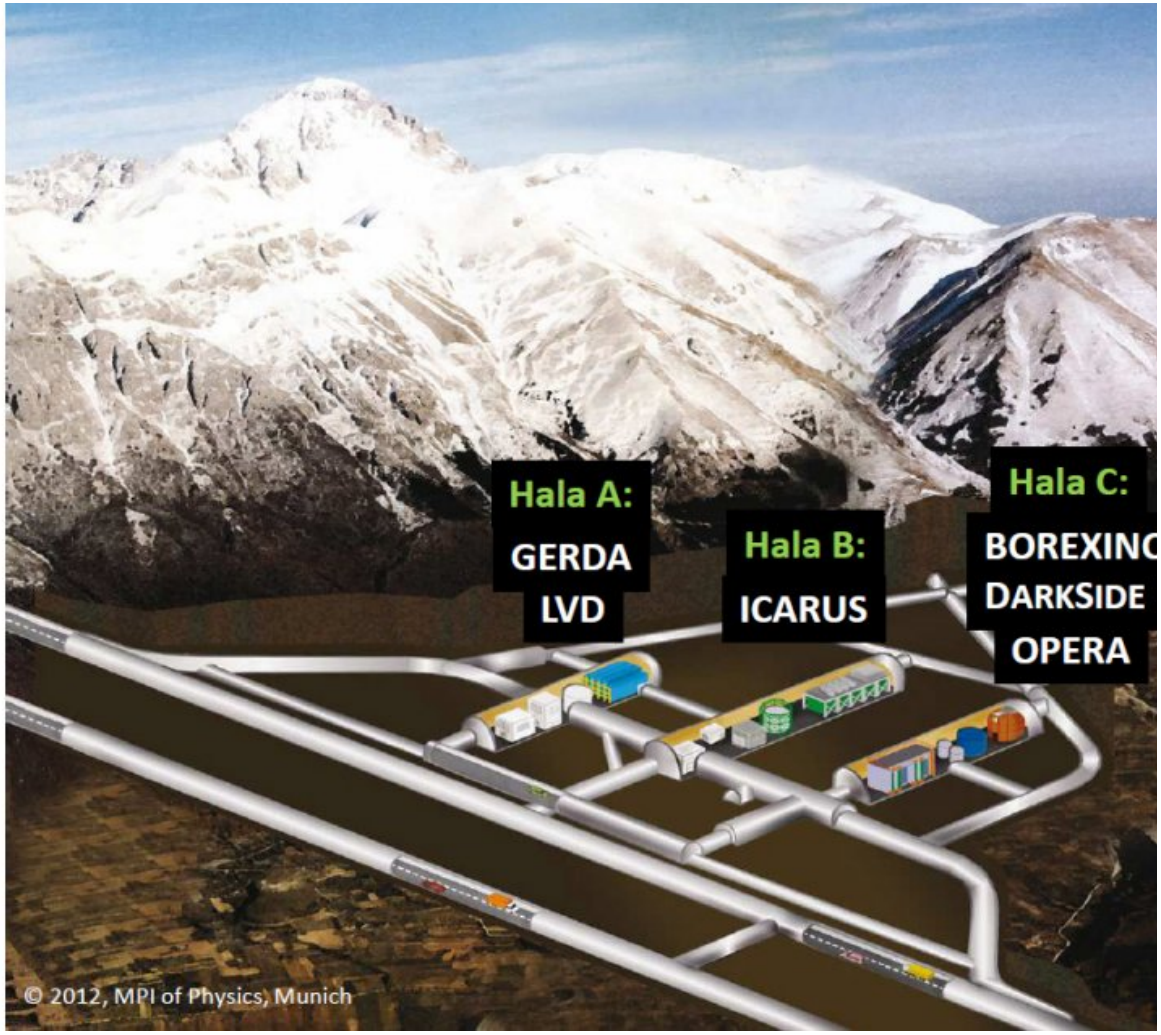
Is $P(\bar{\nu}_\alpha \rightarrow \bar{\nu}_\beta) \neq P(\nu_\alpha \rightarrow \nu_\beta)$?

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

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

- Are there ***more*** than 3 mass eigenstates?
  - Are there non-weakly-interacting "sterile" neutrinos?

- Do neutrinos break the rules?
  - Non-Standard-Model interactions?
  - Violation of Lorentz invariance?
  - Violation of CPT invariance?
  - Departures from quantum mechanics?



Are Neutrino Masses Different?

Perhaps, neutrino masses have the same source as the quark and charged lepton masses:

The Standard Model (SM) Brout – Englert – Higgs mechanism for fermion masses.

Coupling constant

Must add to the SM

$$\mathcal{L}_{SM} = y\overline{H}^0\overline{\nu}_L\nu_R \Rightarrow y\underbrace{\left\langle \overline{H}^0 \right\rangle_0}\overline{\nu}_L\nu_R \equiv m_\nu\overline{\nu}_L\nu_R$$

SM Higgs field

Vacuum expectation value

$$\left\langle \overline{H}^0 \right\rangle_0 \equiv v = 174\ \text{GeV}\ , \quad \text{so} \quad y = \frac{m_\nu}{v} \sim \frac{0.1\ \text{eV}}{174\ \text{GeV}} \sim 10^{-12}$$

A coupling constant this much smaller than unity leaves many theorists skeptical.

— An alternative possibility —

Majorana masses and the **See-Saw** picture

The See-Saw model is the most popular theory of why neutrinos are so light.

The straightforward (type-I) See-Saw model adds to the SM 3 heavy neutrinos N_i, with —

Large Majorana masses

SM lepton doublet

$$\mathcal{L}_{\text{new}} = -\frac{1}{2}\sum_i m_{N_i} N_{iR}^2 + \sum_{\substack{\alpha=e,\mu,\tau \\ i=1,2,3}} y_{\alpha i}\left[\bar{\nu}_{\alpha L}\overline{H^0} - \bar{\ell}_{\alpha L} H^-\right] N_{iR} + h.c.$$

Yukawa coupling matrix

SM Higgs doublet

In this picture, there is still a coupling of the neutrinos to the SM Higgs field.

In addition, there is a new ingredient: large Majorana masses, whose origin is unknown physics.

Majorana masses cannot come from the standard, linear Yukawa coupling of neutrinos to the SM Higgs field.

Majorana mass terms have the effect —

(Or the reverse)

Because they mix neutrino and antineutrino,
they do not conserve $L \equiv$ #(Leptons) – #(Antileptons).

There is then no conserved quantum number
to distinguish antineutrinos from neutrinos.

Consequence: The neutrino mass eigenstates ν_1, ν_2, ν_3 are their own antiparticles.

$$\bar{\nu}_i = \nu_i$$

Majorana neutrinos

- **Presence of Majorana masses**
- **Non-conservation of *L***
- **Self-conjugacy of neutrinos ($\bar{\nu} = \nu$)**

— are all signature predictions of the See-Saw picture.

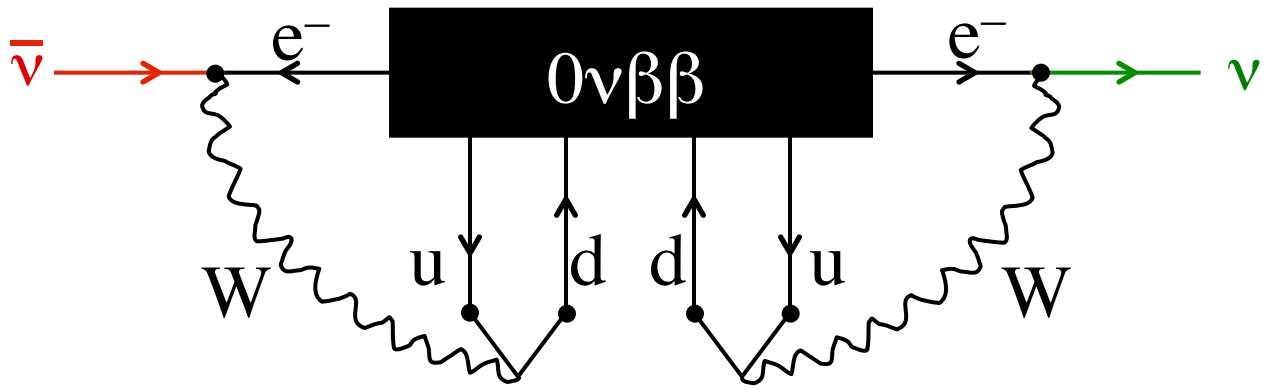
All three predictions would be confirmed by the observation of neutrinoless double beta decay (0νββ)

$\Delta L = 2$

does not conserve L.

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

(Schechter and Valle)

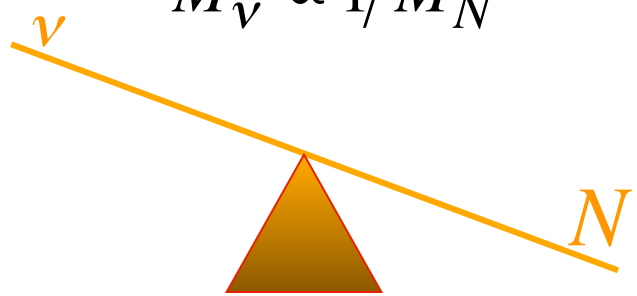


$\bar{\nu} \rightarrow \nu$: A (tiny) Majorana mass term

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

The See-Saw picture leads to —

$$M_\nu \propto 1/M_N$$



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

What Is the Mass Ordering?

The Mass Spectrum: $\overline{\underline{\underline{\ }}}$ or $\underline{\overline{\overline{\ }}}$?

Generically, grand unified models (GUTS) favor —

$$\overline{\underline{\underline{\ }}}$$

GUTS relate the Leptons to the Quarks.

However, ***Majorana masses***, with no quark analogues, could turn $\overline{\underline{\underline{\ }}}$ into $\underline{\overline{\overline{\ }}}$.

The mass ordering is a prime neutrino-mass model discriminator. (Winter at Neutrino 2014)

If the mass spectrum is inverted, and neutrinos have Majorana masses, there is a lower bound on the rate for neutrinoless double beta decay.

Summary

Neutrino oscillation has proved that neutrinos have nonzero masses, and that leptons mix.

The ν masses may have a quite different origin than the quark and charged lepton masses.

Leptonic mixing is like quark mixing, but with interesting differences.

Surprises may well be coming.