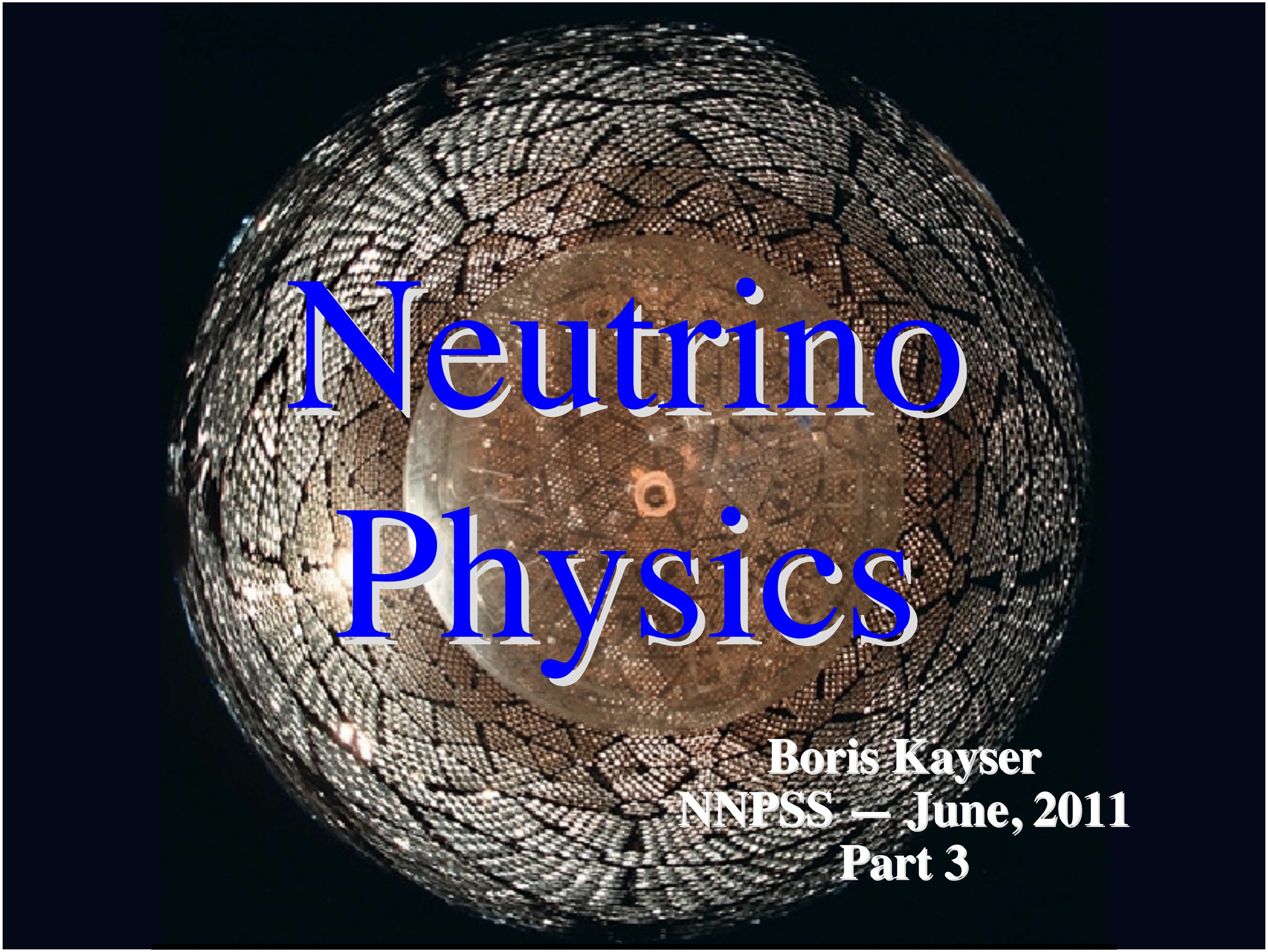

Neutrino
Physics
Boris Kayser
NNPSS — June, 2011
Part 3

Looking to the Future

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 θ_{13}?

How close to maximal is θ_{23}?

• Is the spectrum like  or  ?

• Do neutrino interactions violate CP?

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

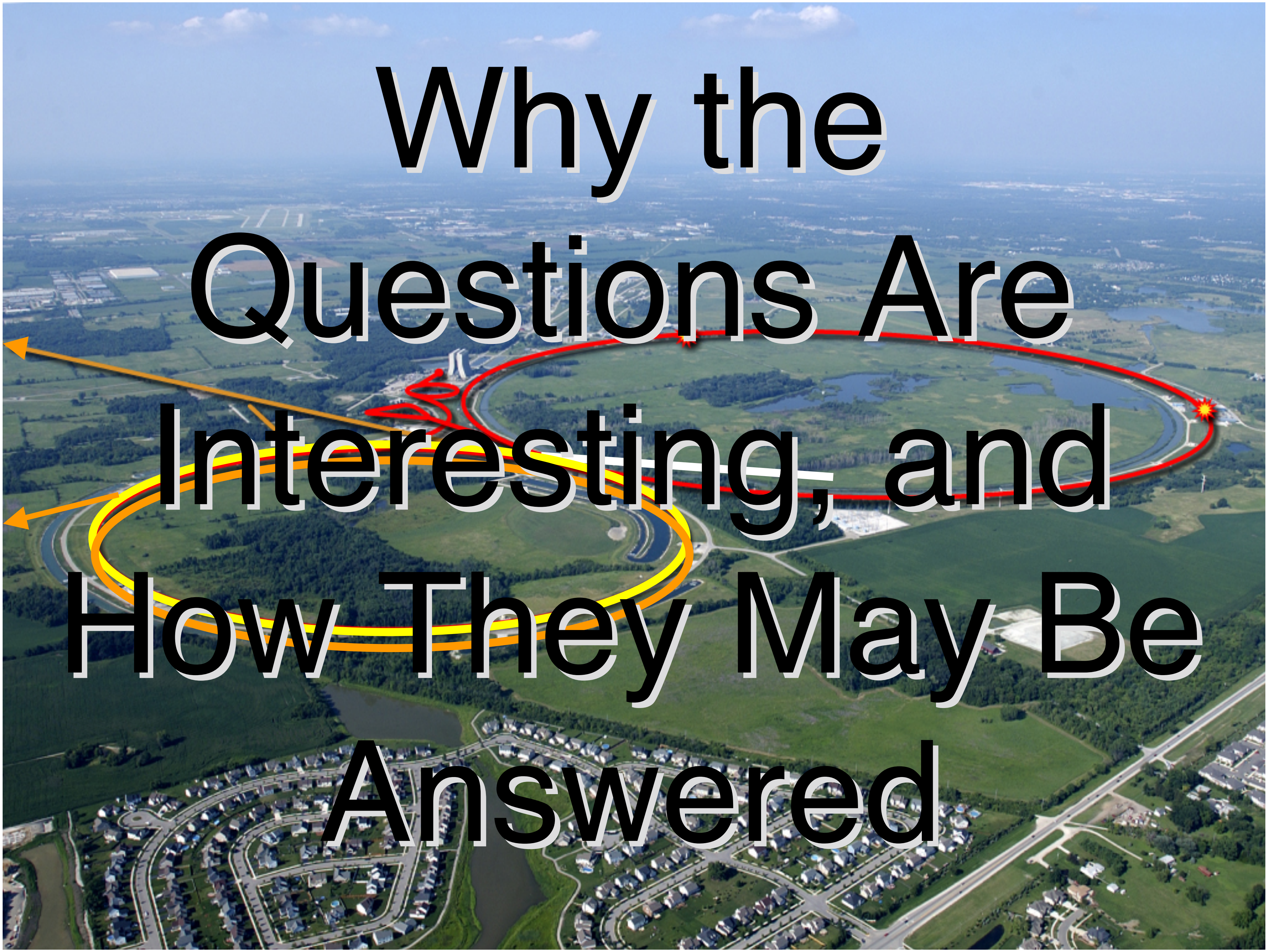
- What can neutrinos and the universe tell us about one another?

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

- What physics is behind neutrino mass?

- What surprises are in store?

Why the Questions Are Interesting, and How They May Be Answered



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

What Is the Question?

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

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

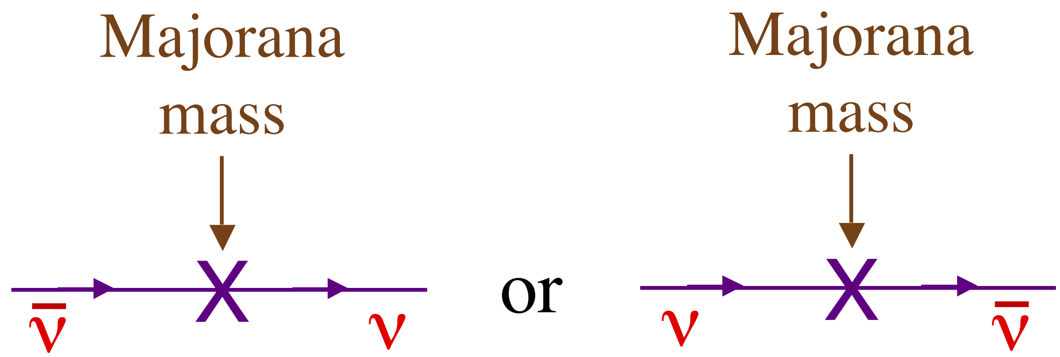
or

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

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

Majorana Masses

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

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

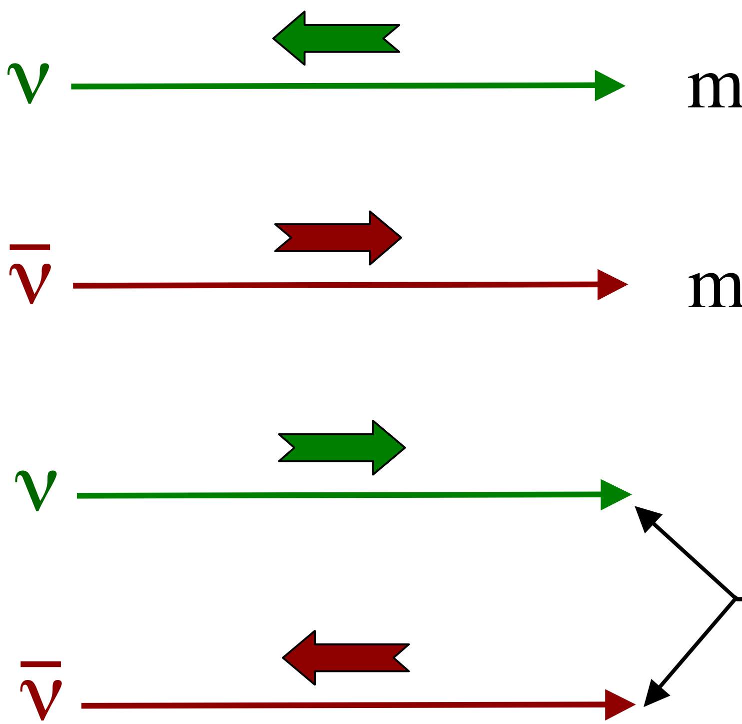
Majorana masses induce $\nu \longleftrightarrow \bar{\nu}$ mixing.

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

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

SM Interactions Of A Dirac Neutrino

We have 4 mass-degenerate states:



	Conserved L
ν makes ℓ^-	+1
$\bar{\nu}$ makes ℓ^+	–1

These states, when Ultra Rel., do not interact.

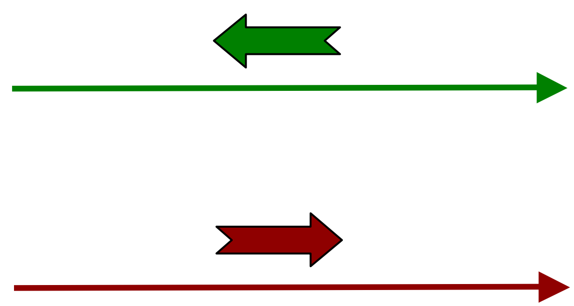
(The weak interaction is Left Handed.)

SM Interactions Of A Majorana Neutrino

We have only 2 mass-degenerate states:

ν makes ℓ^-

$\bar{\nu}$ makes ℓ^+



The weak interactions violate *parity*.

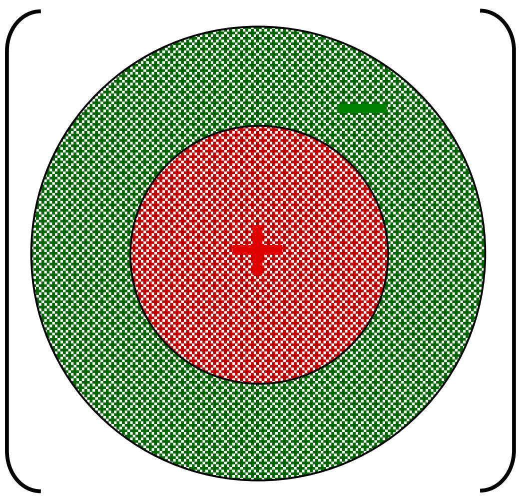
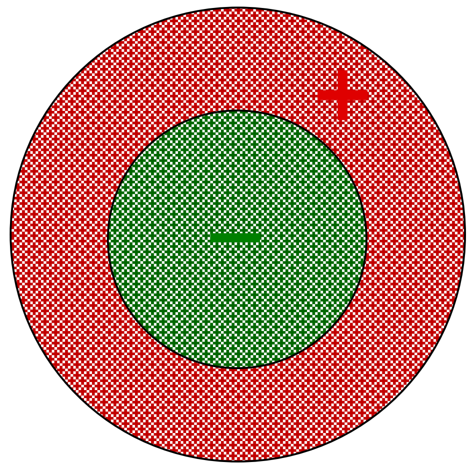
(They can tell *Left* from *Right*.)

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

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

Can a Majorana Neutrino Have an Electric Charge *Distribution*?

No!

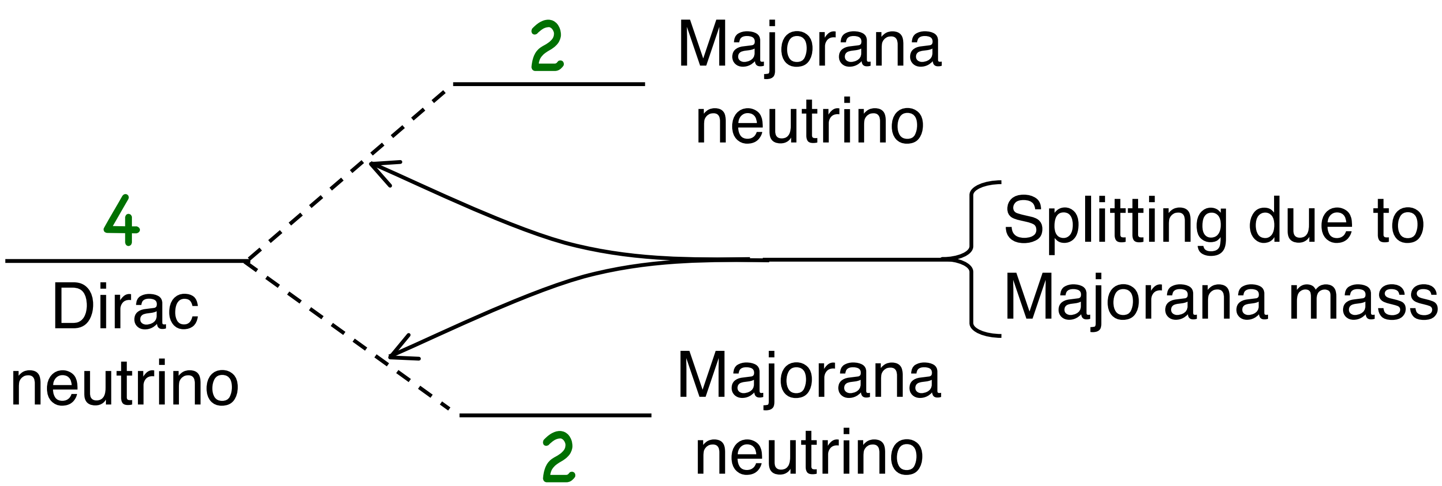
Anti  = 

But for a Majorana neutrino —

Anti (ν) = ν

Majorana Masses Split Dirac Neutrinos

A Majorana mass term splits a Dirac neutrino into two Majorana neutrinos.



Why Most Theorists Expect Majorana Masses

The Standard Model (SM) is defined by the fields it contains, its symmetries (notably weak isospin invariance), and its renormalizability.

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

Majorana mass terms
are allowed by the SM symmetries.

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

To Determine Whether Majorana Masses Occur in Nature

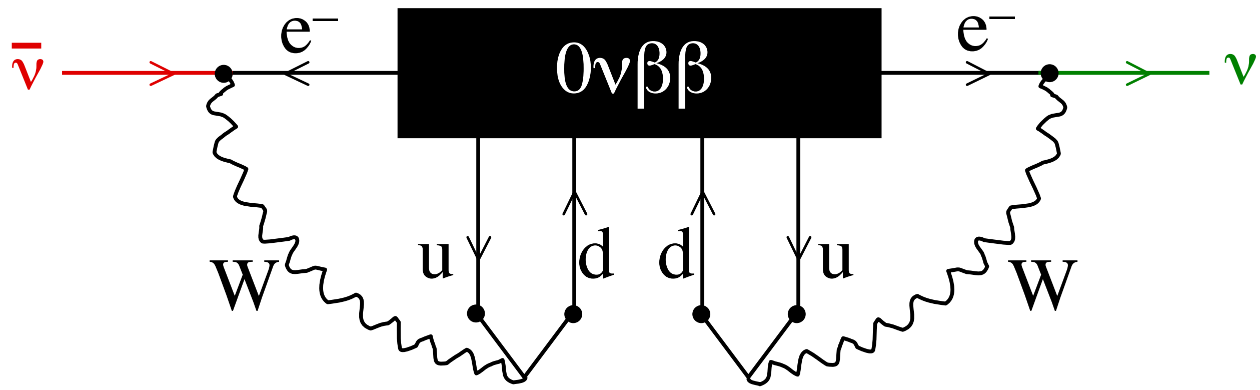
The Promising Approach — Seek

Neutrinoless Double Beta Decay [0νββ]

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

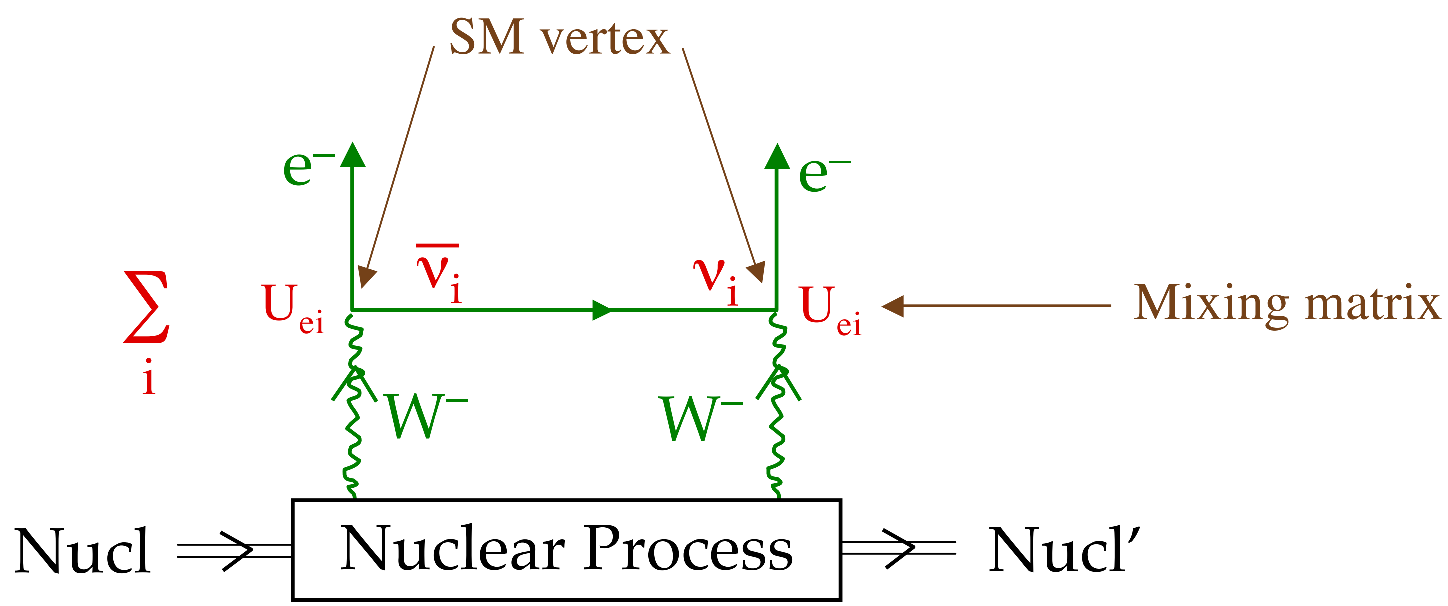
(Schechter and Valle)



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

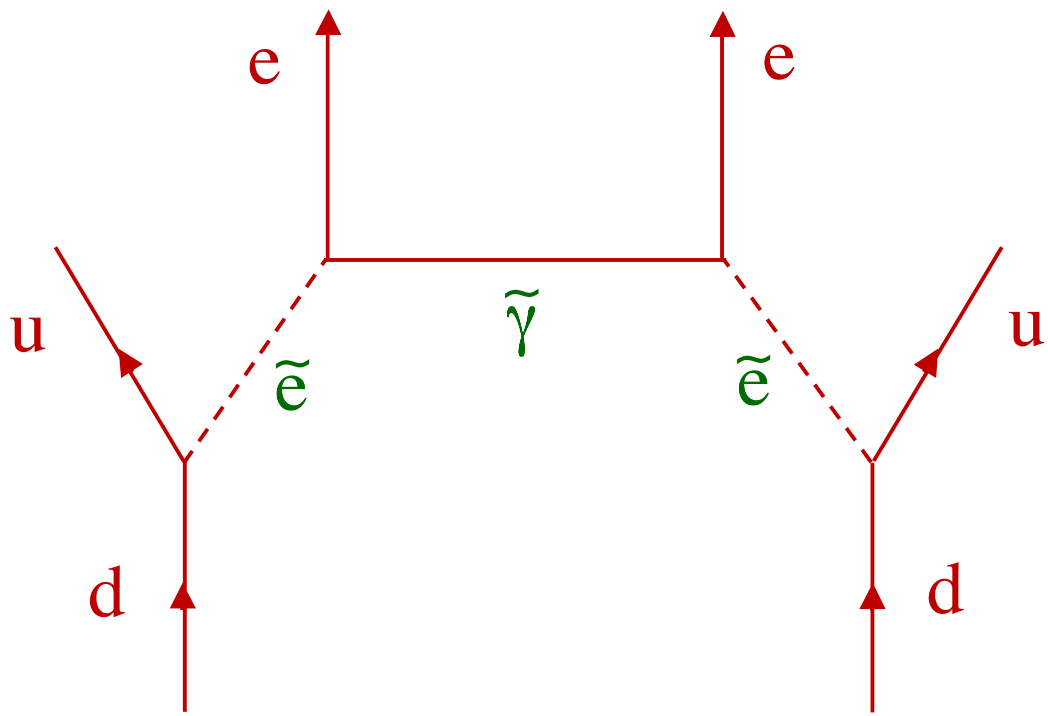
$\therefore\ 0\nu\beta\beta \Rightarrow \bar{\nu}_i = \nu_i$

We anticipate that $0\nu\beta\beta$ is dominated by a diagram with Standard Model vertices:

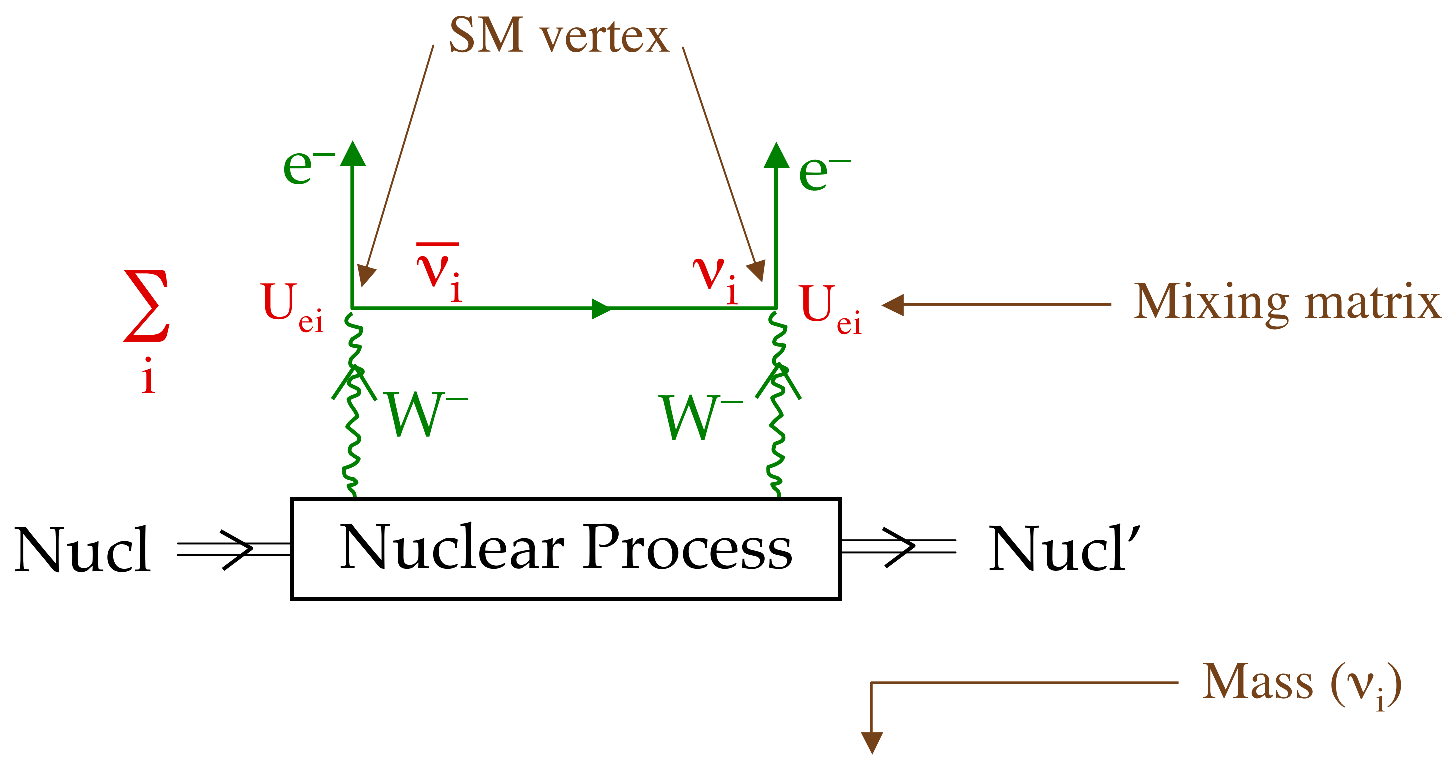


But there could be other contributions to $0\nu\beta\beta$, which at the quark level is the process $dd \rightarrow uuee$.

An example from Supersymmetry:



Assume the dominant mechanism is —



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

Thus, Amp [ν_i contribution] $\propto m_i$

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

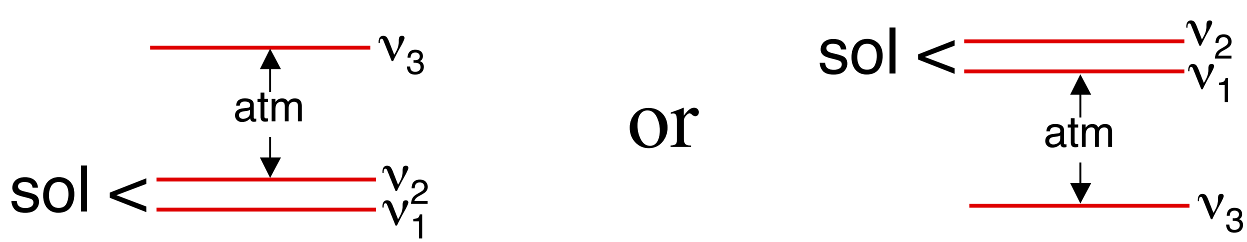
How Large is $m_{\beta\beta}$?

How sensitive need an experiment be?

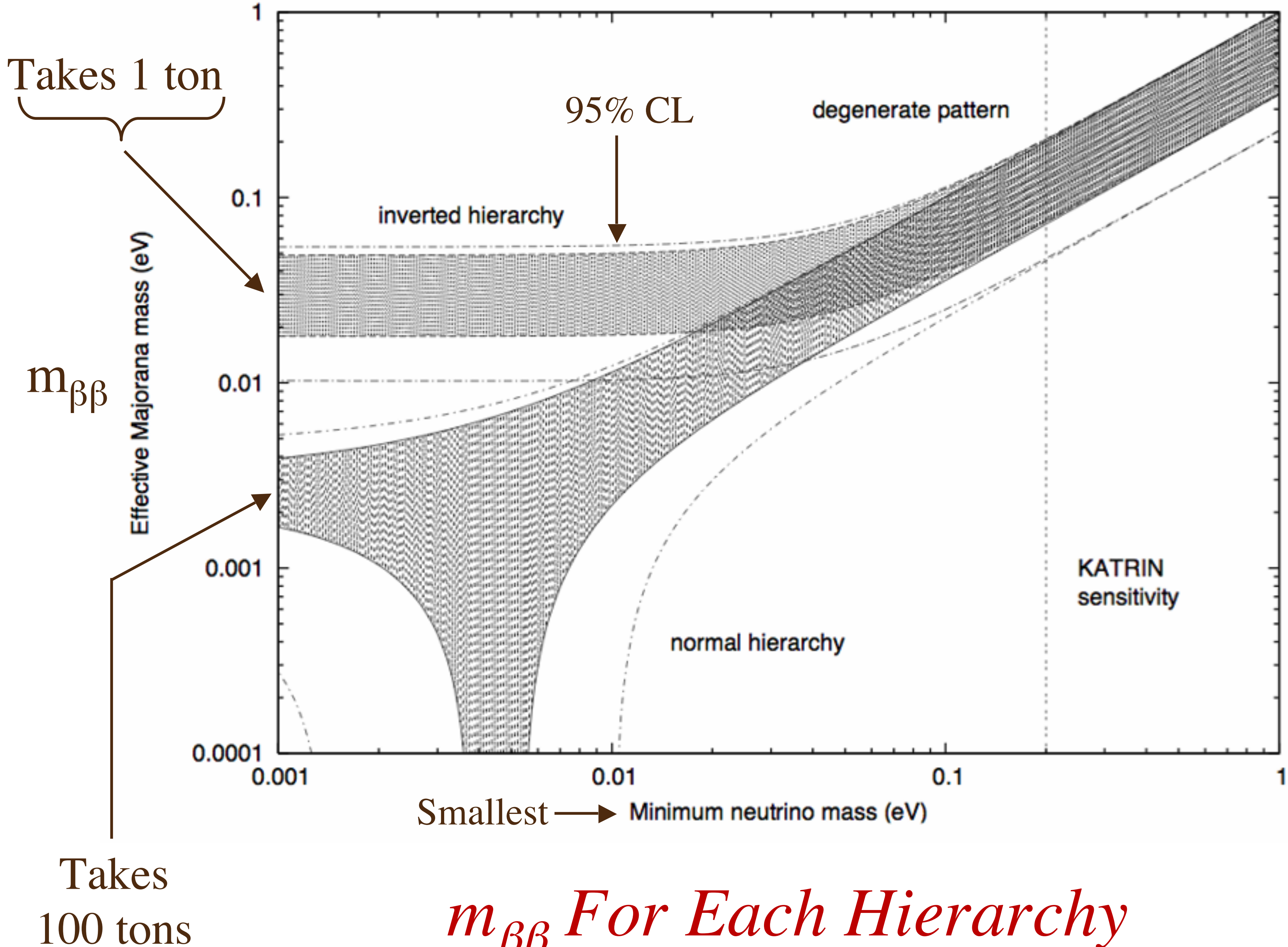
Note: $\Gamma = m_{\beta\beta}^2 |\text{Nuclear M.E.}|^2$ Phase Space

Suppose there are only 3 neutrino mass eigenstates. (More might help.)

Then the spectrum looks like —



Normal hierarchy   Inverted hierarchy



$m_{\beta\beta}$ For Each Hierarchy

There is no clear theoretical preference for either hierarchy.

If the hierarchy is **inverted**—

then $0\nu\beta\beta$ searches with sensitivity to $m_{\beta\beta} = 0.01$ eV have a very good chance to see a signal.

Sensitivity in this range is the target for the next generation of experiments.

We Must Be Alert To Surprises!

Are There

More Than 3

Mass Eigenstates?

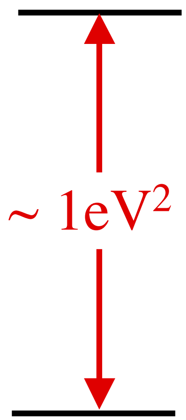
Are There

Sterile Neutrinos?

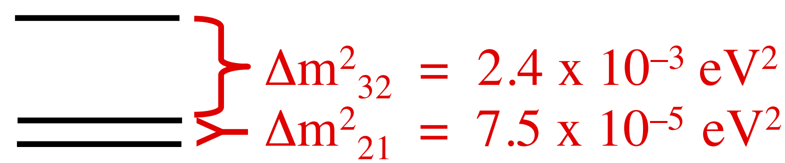
The Hint From LSND

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

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



in contrast to



At least **4** mass eigenstates

(From the **Z** width) At least **1** sterile neutrino

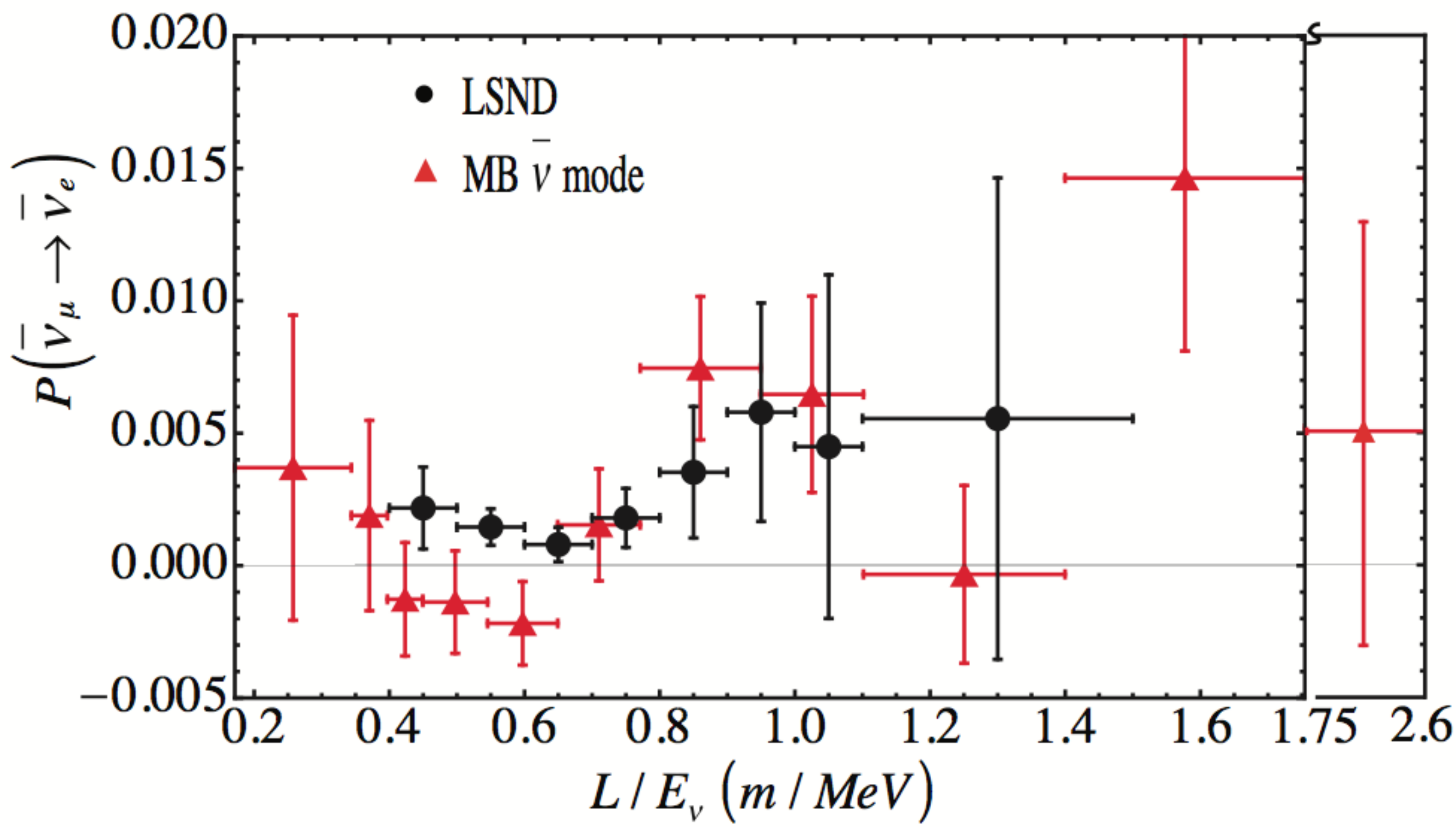
Is the LSND Signal Genuine Neutrino Oscillation?

The MiniBooNE experiment is trying to confirm or refute LSND.

In MiniBooNE, both L and E are ~ 17 times larger than they were in LSND, and L/E is comparable.

MiniBooNE has recently reported its $\bar{\nu}_\mu \to \bar{\nu}_e$ results.

Direct MiniBooNE-LSND Comparison of $\bar{\nu}$ Data



(Phys.Rev.Lett.105:181801, 2010)

Do LSND and MiniBooNE see the same thing???

The Reactor $\overline{\nu}_e$ Flux Surprise

The prediction for the un-oscillated $\overline{\nu}_e$ flux from reactors has increased by about 3%.

(Mueller et al.)

Measurements of the $\overline{\nu}_e$ flux at (10 – 100)m from reactor cores now show a ~ 6% disappearance.

(Mention et al.)

Disappearance at L(m)/E(MeV) ~ 1 suggests oscillation with Δm^2 ~ 1 eV^2, like LSND and MiniBooNE.

Fits to all data with 2 extra neutrinos are improved.

(Kopp et al.)

Clearly, more information is needed.

While awaiting further news —

We will assume there are
only 3 neutrino mass eigenstates,
and no sterile neutrinos.


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.

$$\frac{n_B}{n_\gamma} = 6 \times 10^{-10} \quad ; \quad \frac{n_{\overline{B}}}{n_B} \sim 0\ (< 10^{-6})$$

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

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

Sakharov: $n_{\overline{B}} = n_B$ $\Rightarrow$ $n_{\overline{B}} << n_B$ requires ~~CP~~.

The ~~CP~~ in the quark mixing matrix, seen in B and K decays, leads to much too small a $B-\overline{B}$ asymmetry.

If ***quark*** ~~CP~~ cannot generate the observed $B-\overline{B}$ asymmetry, can some scenario involving ***leptons*** do it?

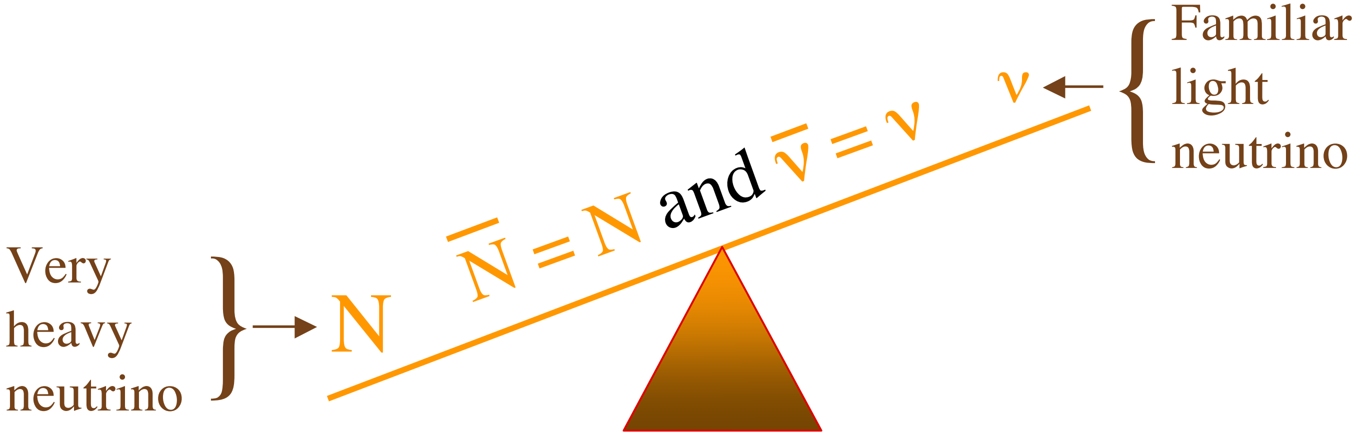
The candidate scenario: *Leptogenesis*.

(Fukugita, Yanagida)

Leptogenesis – A Two-Step Process

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

In standard leptogenesis, to account for the observed cosmic baryon – antibaryon asymmetry, ***and*** to explain the tiny light neutrino masses, we must have —

$$m_N \sim 10^{(9-10)}\ \text{GeV} \quad .$$

This puts the heavy neutrinos N far beyond LHC range.

But these heavy neutrinos would have been made in the ***hot*** Big Bang.

In the see-saw picture —

$$N \to \ell^{\mp} + H^{\pm} \quad \text{and} \quad N \to \overset{(-)}{\nu} + \overset{(-)}{H^0}$$

SM Higgs particle

Assume 3 heavy neutrinos N_i to match the number (3) of light lepton (ℓ_α, ν_α) families.

By SM weak-isospin symmetry —

$$\Gamma\left(N_i \to \ell_\alpha^- + H^+\right) = \Gamma\left(N_i \to \nu_\alpha + H^0\right)$$

There are 3 × 3 = 9 independent "coupling constants" (lowest order decay amplitudes) $y_{\alpha i}$, forming a matrix y.

$\not{CP}$ phases in the matrix y will lead to —

$$\Gamma\left(N \to \ell^- + H^+\right) \neq \Gamma\left(N \to \ell^+ + H^-\right)$$

and

$$\Gamma\left(N \to \nu + H^0\right) \neq \Gamma\left(N \to \bar{\nu} + \overline{H^0}\right)$$

This produces a universe with unequal numbers of leptons (ℓ^- and ν) and antileptons (ℓ^+ and $\bar{\nu}$).

In this universe the lepton number L, defined by $L\left(\ell^-\right) = L(\nu) = -L\left(\ell^+\right) = -L(\bar{\nu}) = 1$, is not zero.

This is Leptogenesis — Step 1

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.

Initial state from N decays

Final state

There is now a nonzero Baryon Number.

There are baryons, but ~ no antibaryons.

Reasonable parameters give the observed n_B / n_γ .

Leptogenesis and $\not{C}\not{P}$ In Light ν Oscillation

In a convenient basis, the coupling matrix
y is the only source of CP violation among the leptons.

The see-saw relation is —

$$M_\nu = -v^2 U^T \left(y^* M_N^{-1} y^\dagger \right) U$$

Heavy N mass eigenvalues → M_N^{-1}

Light ν mass eigenvalues → M_ν

Real number → v^2

Leptonic mixing matrix → U

Through ***U***, the phases in ***y*** lead to
~~CP~~ in light neutrino oscillation.

$$P(\overset{(-)}{\nu}_\alpha \rightarrow \overset{(-)}{\nu}_\beta) =$$

e, μ, or τ

Distance

$$= \delta_{\alpha\beta} - 4\sum_{i>j} \Re(U^*_{\alpha i}U_{\beta i}U_{\alpha j}U^*_{\beta j})\sin^2(\Delta m^2_{ij}\frac{L}{4E})$$

$$\underset{(-)}{+}2\sum_{i>j} \Im(U^*_{\alpha i}U_{\beta i}U_{\alpha j}U^*_{\beta j})\sin(\Delta m^2_{ij}\frac{L}{2E})$$

Neutrino (Mass)^2 splitting

Energy

The observation of CP violation in neutrino oscillation would make it more plausible that ***leptogenesis*** *occurred in the early universe.*

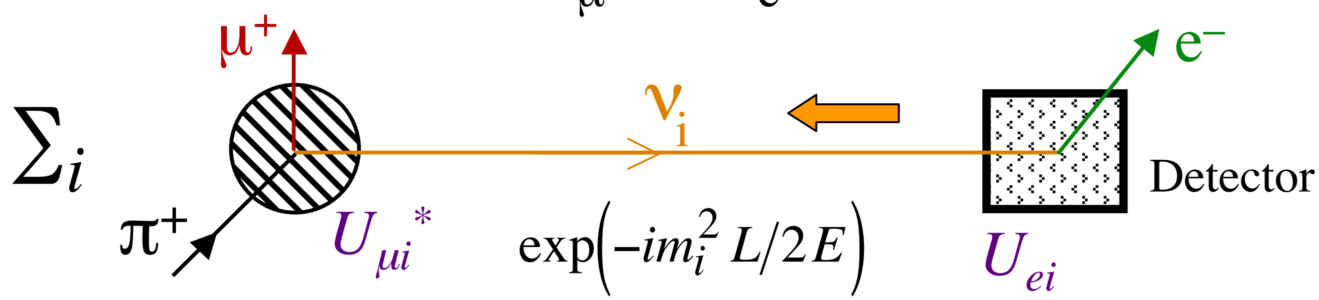
Seeking CP violation in neutrino oscillation is now a worldwide goal.

The search will use long-baseline accelerator neutrino beams to study $\nu_\mu \to \nu_e$ ***and*** $\bar{\nu}_\mu \to \bar{\nu}_e$ ***, or their inverses.***

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

A : *Certainly!*

Compare $\nu_\mu \to \nu_e$



with “$\overline{\nu}_\mu \to \overline{\nu}_e$”