Double Beta Decay:
A Very Special Experiment

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NASA Hubble Photo

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

Cannot occur in the Standard Model

Observation at any level would imply —

- Lepton number L is not conserved
- Neutrinos have *Majorana masses* — masses with a different origin than the quark and charged lepton masses
- Neutrinos are their own antiparticles

Observation of $0\nu\beta\beta$ would make more plausible —

- The See-Saw model of the origin of neutrino mass

- Leptogenesis, an outgrowth of the See-Saw, which may be the origin of the baryon-antibaryon asymmetry of the universe

What does all this mean?

Why is it interesting?

Nonconservation of Lepton Number L

The Lepton Number L is defined by —

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

This is the quantum number that distinguishes antileptons from leptons.

It is the leptonic analogue of the Baryon Number B, which distinguishes antibaryons from baryons.

$0\nu\beta\beta$

Clearly does not conserve L: $\Delta L = 2$.

Non-perturbative ***Sphaleron*** processes in the Standard Model (SM) do not conserve L.

But Sphaleron processes can only change L by a multiple of 3.

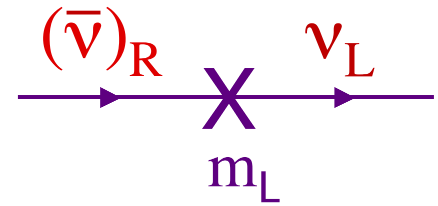
2 is not a multiple of 3.

The $\Delta L = 2$ of $0\nu\beta\beta$ is outside the SM.

Majorana Masses

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

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



Majorana masses mix ν and $\bar{\nu}$, so they do not conserve the Lepton Number L, changing it by $\Delta L = 2$, precisely what is needed for $0\nu\beta\beta$.

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.**

SM Higgs

Majorana ν masses cannot come from $H_{SM}\bar{\nu}_L\nu_R$, the ν analogue of the Higgs coupling that leads to the q and ℓ masses, and the progenitor of a *Dirac* ν mass term.

Possible progenitors of Majorana mass terms:

$$H_{SM} H_{SM} \overline{\nu_L^c} \nu_L , \quad H_{I_W=1} \overline{\nu_L^c} \nu_L , \quad m_R \overline{\nu_R^c} \nu_R$$

Not renormalizable

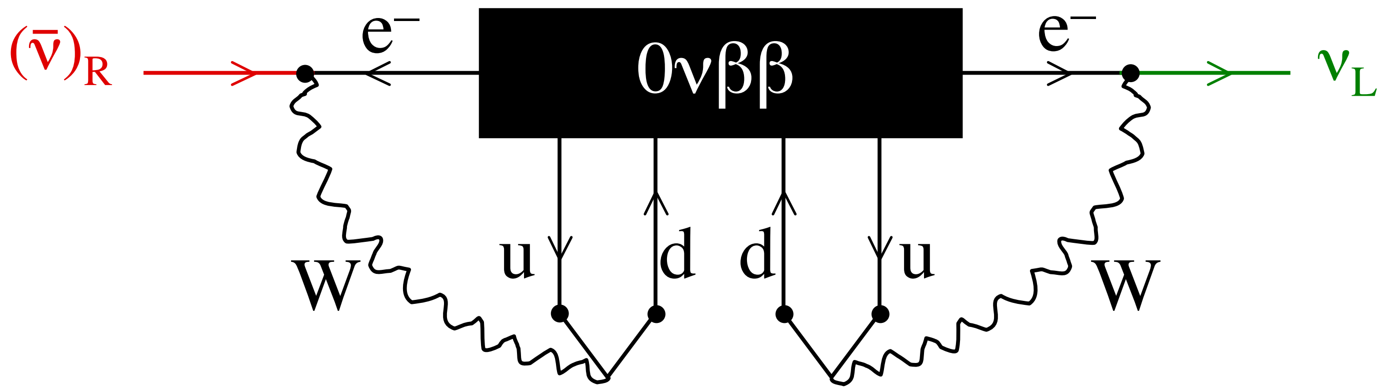
This Higgs not in SM

No Higgs

Majorana neutrino masses must have a different origin than the masses of quarks and charged leptons.

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

(Schechter and Valle)



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

Of course, ***this*** Majorana mass term is ***tiny***:

$< 10^{-23}$ eV.

(Duerr, Lindner, Merle; Rodejohann)

Neutrino oscillation data imply masses **$> 10^{-2}$ eV**.

$\therefore$ There must be other sources of neutrino mass.

But $0\nu\beta\beta$ ⟹ A Majorana mass term, however tiny.

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.

Right-Handed Majorana mass terms
are allowed by the SM symmetries.

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

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*.

Why Majorana Masses ⟹ Majorana Neutrinos

The objects ν_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 $\nu \leftrightarrow \bar{\nu}$ mixing.

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

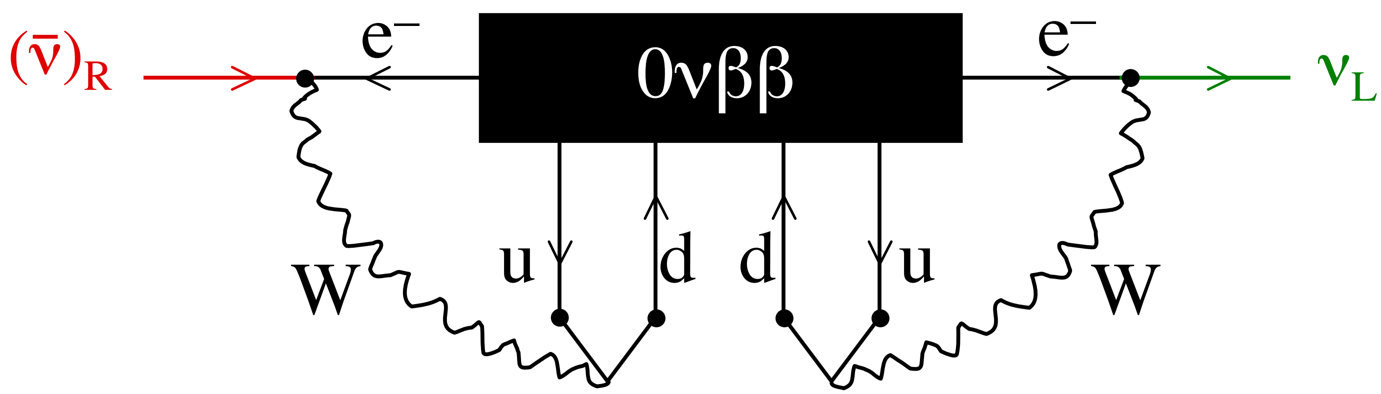
$$K_{S,L} \cong (K^0 \pm \overline{K^0})/\sqrt{2}\ . \qquad \overline{K_{S,L}} = K_{S,L}\ .$$

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

$$\nu_i = \nu + \bar{\nu}. \quad \overline{\nu_i} = \nu_i\ .$$

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

(Schechter and Valle)



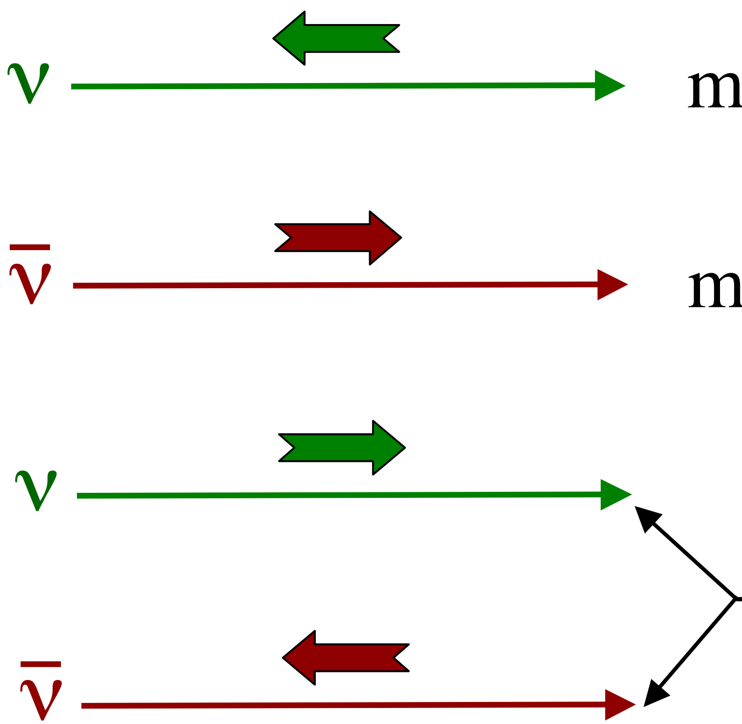
$(\bar{\nu})_R \rightarrow \nu_L$: A Majorana mass term

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

The Nature of Majorana Neutrinos

SM Interactions Of A Dirac Neutrino

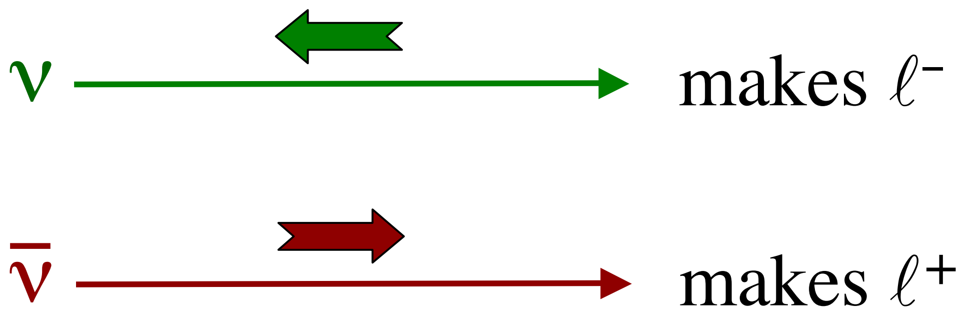
We have 4 mass-degenerate states:



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



The weak interactions violate *parity*.
(They can tell *Left* from *Right*.)

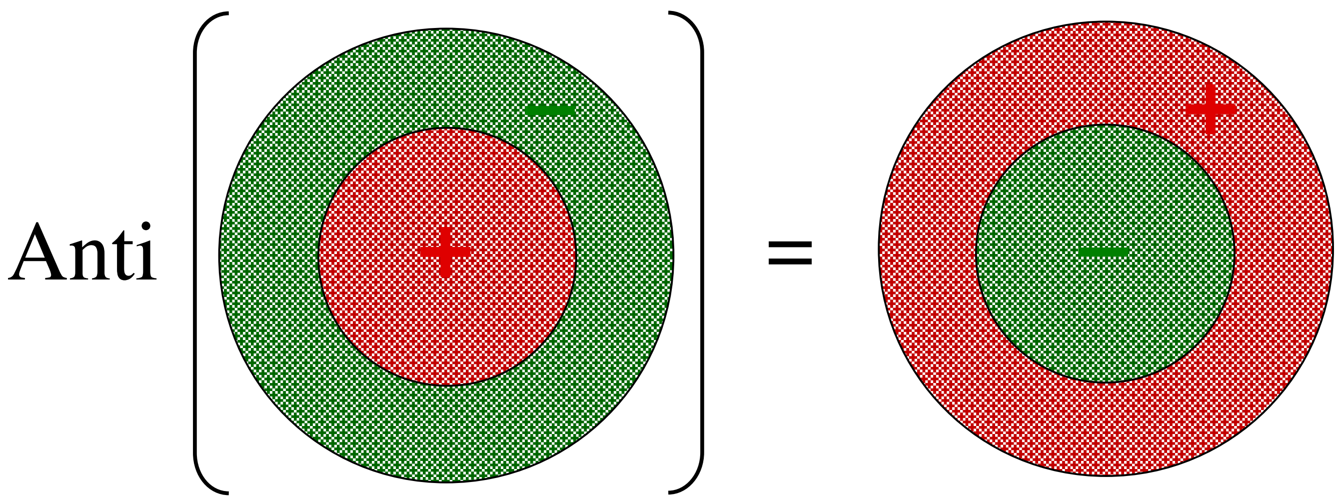
An incoming left-handed neutral lepton makes ℓ^-.

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

Electromagnetic Properties

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

No!

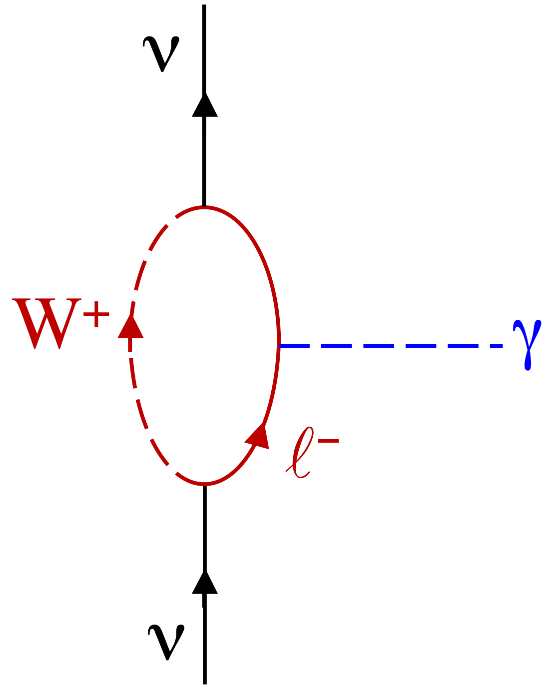


But for a Majorana neutrino —

Anti (ν) = ν

Dipole Moments

In the Standard Model, loop diagrams like —



produce, for a *Dirac* neutrino of mass m_ν, a magnetic dipole moment —

$$\mu_\nu = 3 \text{ x } 10^{-19} \, (m_\nu/1\text{eV}) \, \mu_B$$

(Marciano, Sanda; Lee, Shrock; Fujikawa, Shrock)

A *Majorana* neutrino cannot have a magnetic or electric dipole moment:

$$\vec{\mu}\left[\ \underset{e^{+}}{\Uparrow}\ \right] = -\,\vec{\mu}\left[\ \underset{e^{-}}{\Uparrow}\ \right]$$

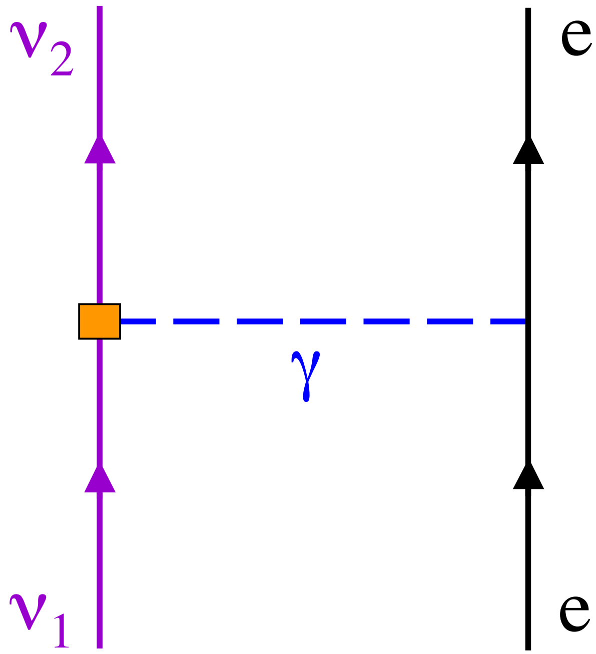
But for a Majorana neutrino,

$$\overline{\nu_i} = \nu_i$$

Therefore,

$$\vec{\mu}\,[\overline{\nu_i}] = \vec{\mu}\,[\nu_i] = 0$$

Both *Dirac* and *Majorana* neutrinos can have ***transition*** dipole moments, leading to —



One can look for the dipole moments this way.

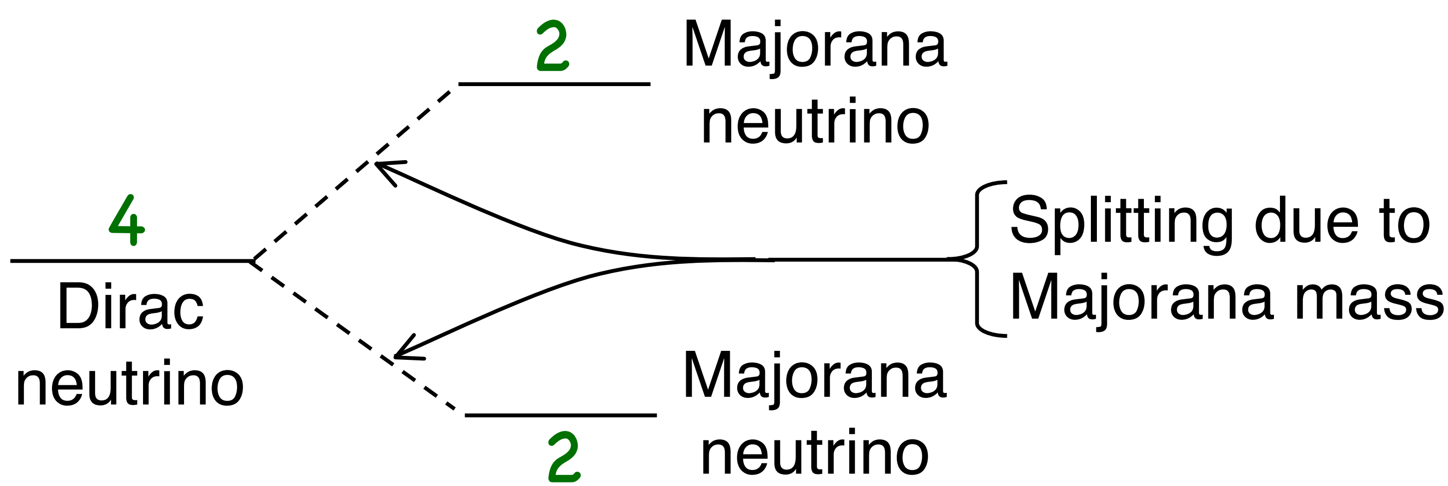
To be visible, they would have to *vastly* exceed Standard Model predictions.

The See-Saw

The Most Popular Explanation Of Why Neutrinos Are So Light

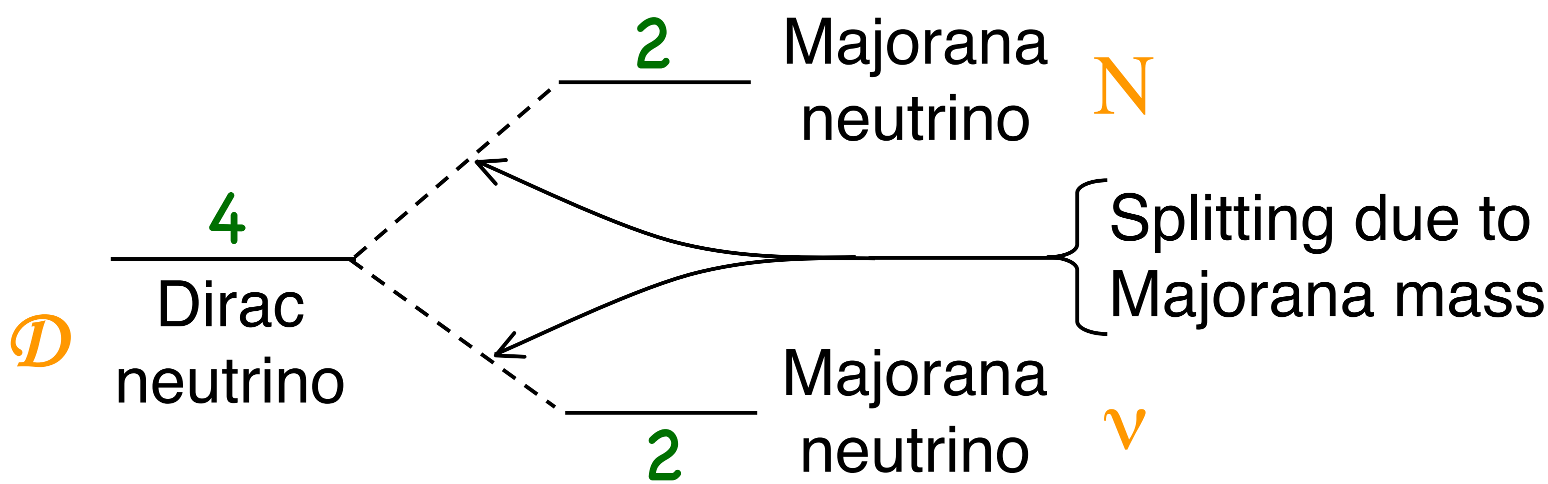
Majorana Masses Split Dirac Neutrinos

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



What Happens In the See-Saw

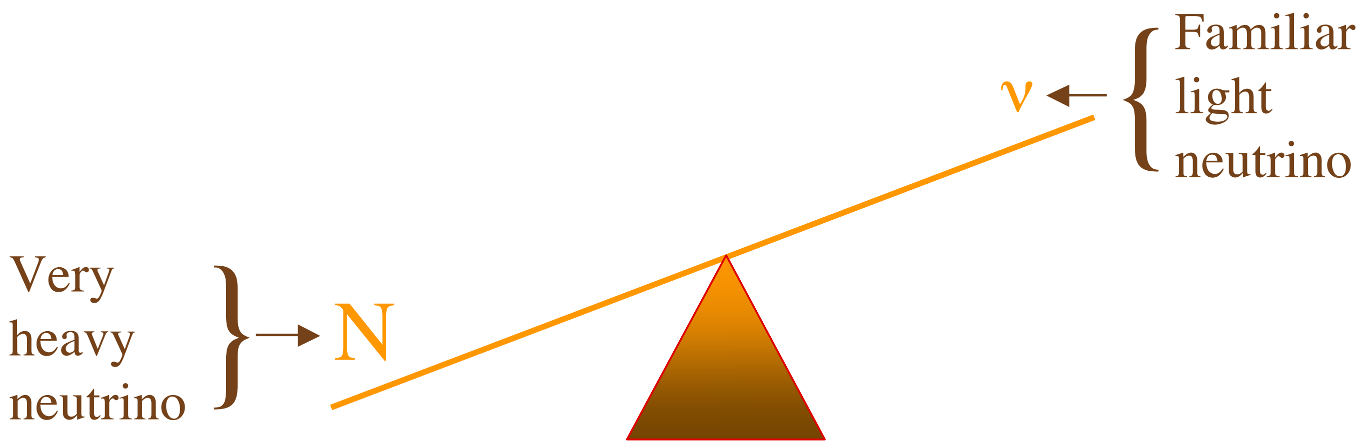
A ***BIG*** Majorana mass term splits a Dirac neutrino into two ***widely-spaced*** Majorana neutrinos.



$$m_\nu m_N \approx m_{\mathcal{D}}^2$$ ***The See-Saw Relation***

If $m_{\mathcal{D}}$ *is a typical fermion mass,* m_N *will be very large.*

The See-Saw Picture



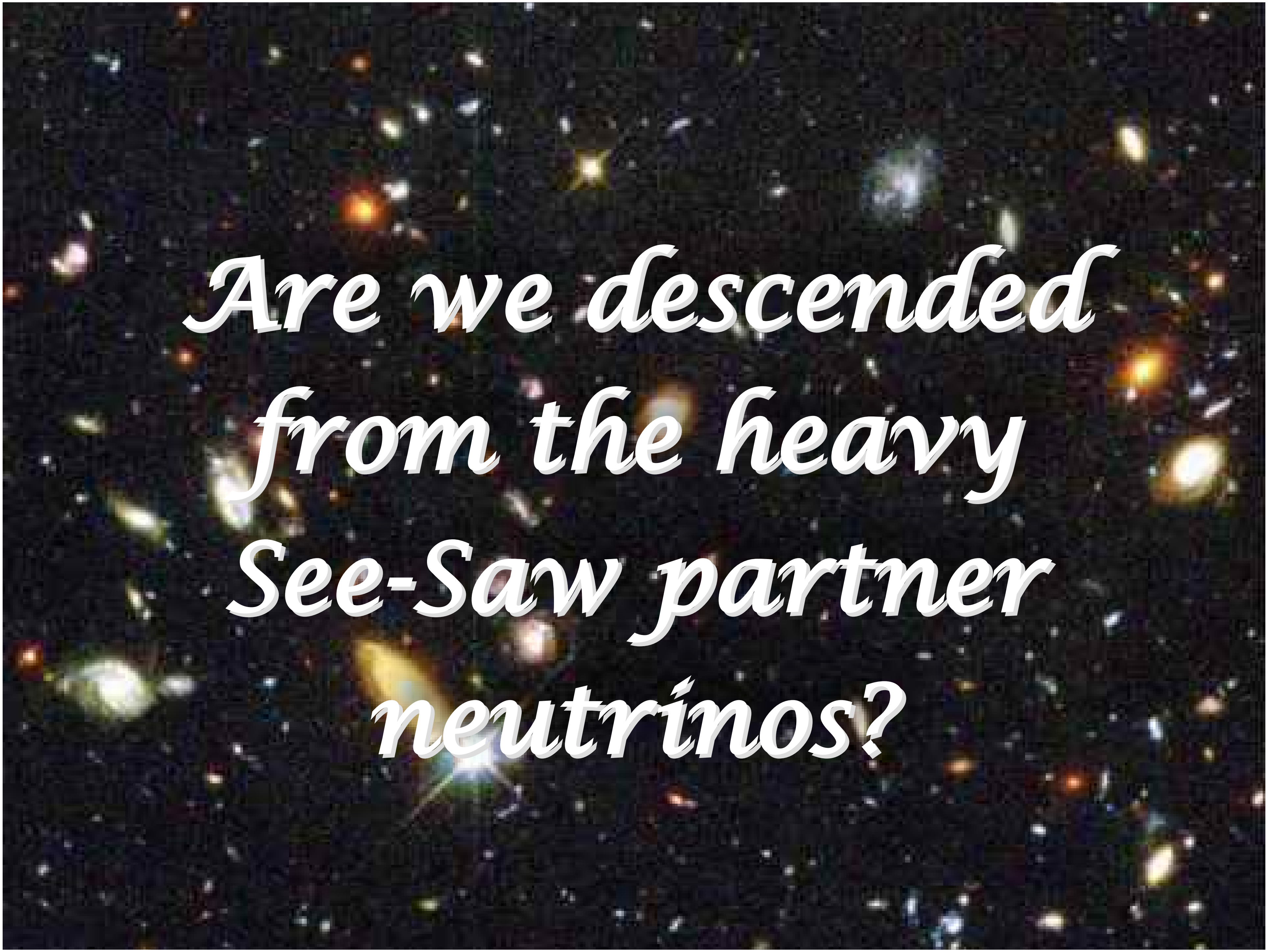
Yanagida;
Gell-Mann, Ramond, Slansky;
Mohapatra, Senjanovic;
Minkowski

Signature Predictions of the See-Saw

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

So look for 0νββ!

- The light neutrinos have heavy partners N_i


Are we descended
from the heavy
See-Saw partner
neutrinos?

The Challenge —
A Cosmic Broken Symmetry

The universe contains baryons,
but essentially no antibaryons.

The Baryon Number of the universe,

$$B \equiv n_B - n_{\overline{B}} = 3\left(n_q - n_{\overline{q}}\right)$$

is nonzero.

Standard cosmology: Any initial nonzero Baryon Number would have been erased.

How did $B = 0$ ➡ $B \neq 0$?

Sakharov: $B = 0$ $\Longrightarrow$ $B \neq 0$ requires $\not{CP}$.

The $\not{CP}$ in the quark mixing matrix,
seen in B and K decays, leads to
much too small a Baryon Number.

If ***quark*** $\not{CP}$ cannot generate
the observed Baryon Number,
can some scenario involving ***leptons*** do it?

The candidate scenario: *Leptogenesis*,
an outgrowth of the *See-Saw* ***picture***.

(Fukugita, Yanagida)

Leptogenesis — Step 1

The 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 ℓ^- or ℓ^+. $\not{CP}$ is expected in these decays.

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

$$N \to \ell^- + H^+ \quad \text{and} \quad N \to \ell^+ + H^-$$

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.

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

Initial state from N decays

→ **Sphaleron Process** →

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

Final state

There is now a nonzero *Baryon Number*.

There are baryons, but ~ no antibaryons.

Reasonable parameters give the observed n_B / n_γ .

What About the *Lepton Number*?

Big-Bang cosmology:

The leptons in the universe include electrons and ***many*** neutrinos.

$$\#(\text{electrons}) = \#(\text{protons}) < \#(\text{protons} + \text{neutrons}) = 6 \times 10^{-10}\,\#(\text{photons})$$

#(neutrinos) ≈ #(photons) >> #(electrons)

If $0\nu\beta\beta \neq 0$:

L is not conserved and $\bar{\nu} = \nu$,
so the relic neutrino background
does not have a well-defined *L*.

As long as the neutrinos were ultra-relativistic, their helicities functioned like lepton number. But today many (perhaps all) of them are non-relativistic.

Consequently, we will focus on the *Baryon Number* of the universe.

The See-Saw, Leptogenesis, and $0\nu\beta\beta$

By confirming the existence of Majorana masses and the Majorana character of neutrinos—

— the observation of **$0\nu\beta\beta$** would make the *See-Saw* picture more plausible.

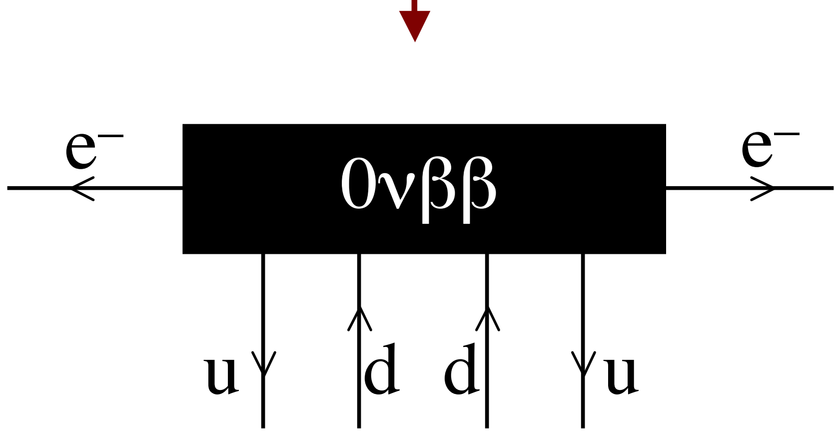
— hence, it would make *Leptogenesis*, an outgrowth of the *See-Saw*, more plausible.

Other evidence making *Leptogenesis* more plausible would be the observation of $\not{CP}$ in neutrino oscillation or **$0\nu\beta\beta$**.

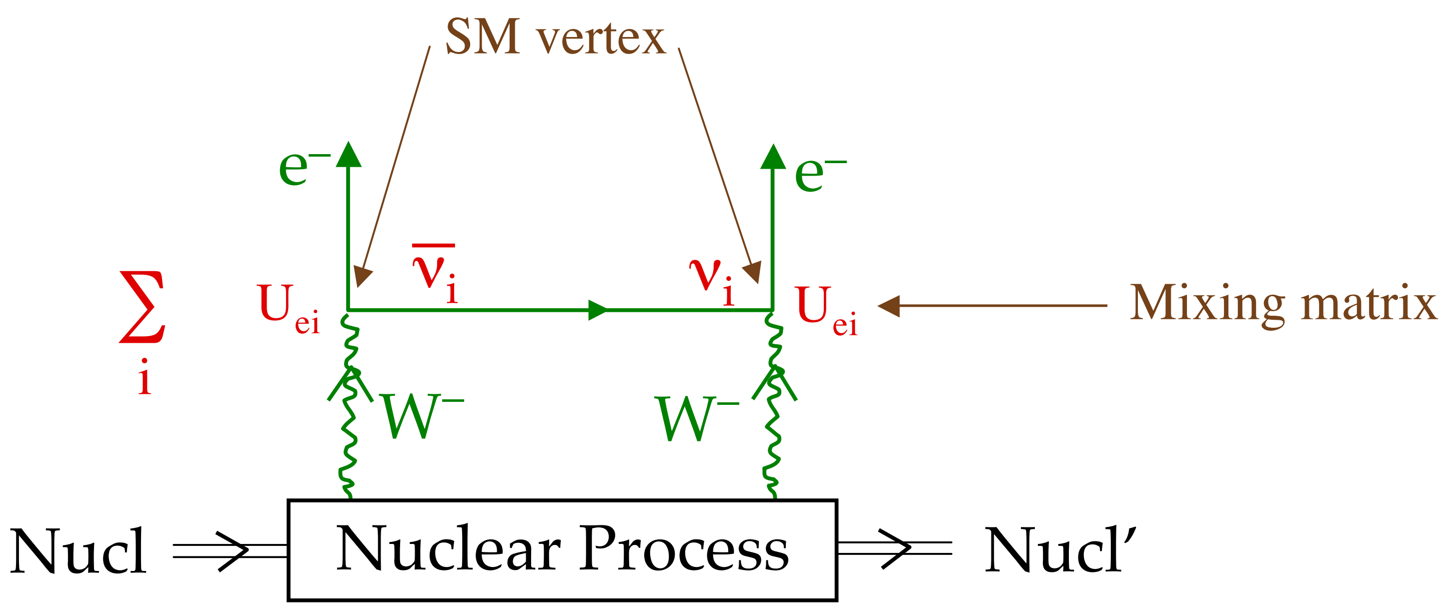
— 0νββ —

A Closer Look

What is inside?



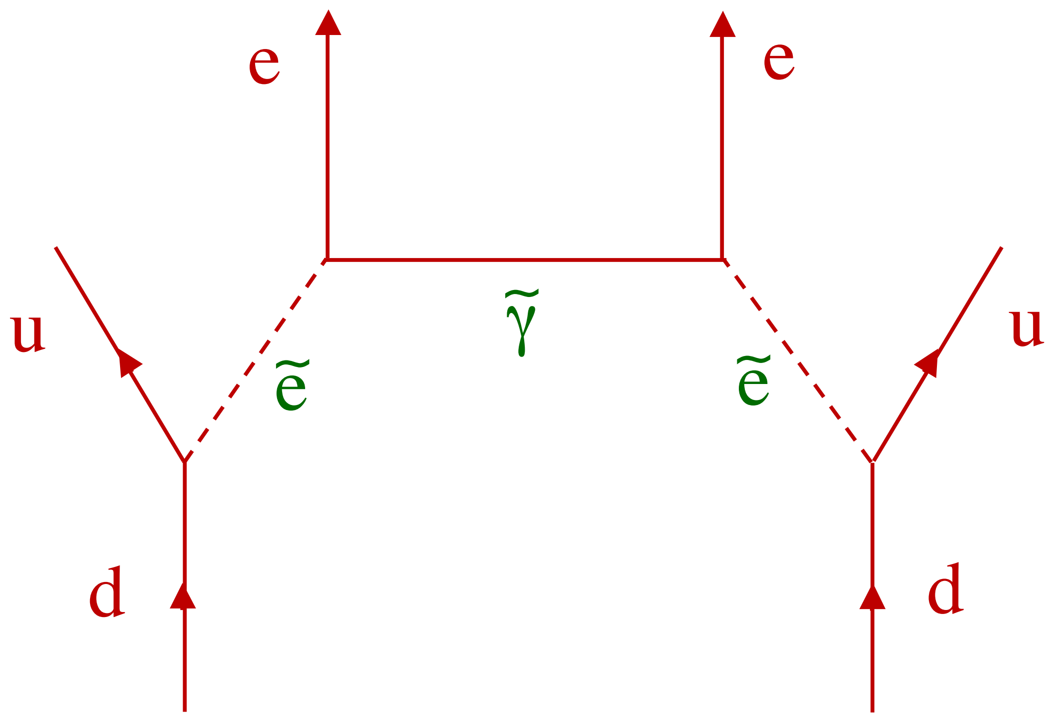
We anticipate that 0νββ is dominated by a diagram with light neutrino exchange and Standard Model vertices:



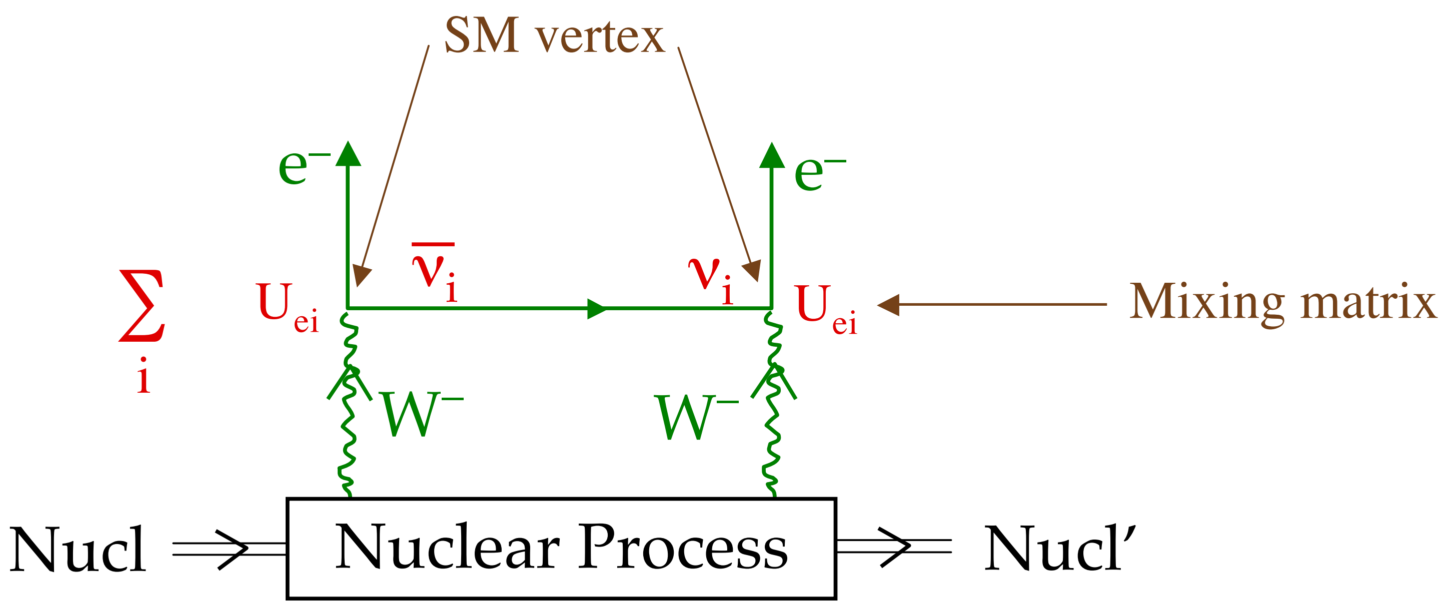
"The Standard Mechanism"

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:



If the dominant mechanism is –



Then –

Mass (ν_i)

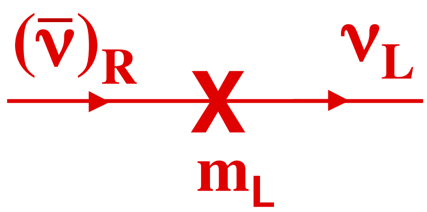
$$\text{Amp}[0\nu\beta\beta] \propto \left| \sum m_i U_{ei}^2 \right| \equiv m_{\beta\beta}$$

Why Amp[0νββ] Is ∝ Neutrino Mass When SM Vertices Are Assumed

— manifestly does not conserve L: $\Delta L = 2$.

But the Standard Model (SM) weak interactions ***do*** conserve L. Thus, the $\Delta L = 2$ of 0νββ can only come from *Majorana neutrino masses*, such as —

$$m_L(\overline{\nu_L{}^c}\,\nu_L + \overline{\nu_L}\,\nu_L{}^c)$$



Once Upon a Time

"Replacing one of the SM vertices by a right-handed current will eliminate the need for neutrino mass."

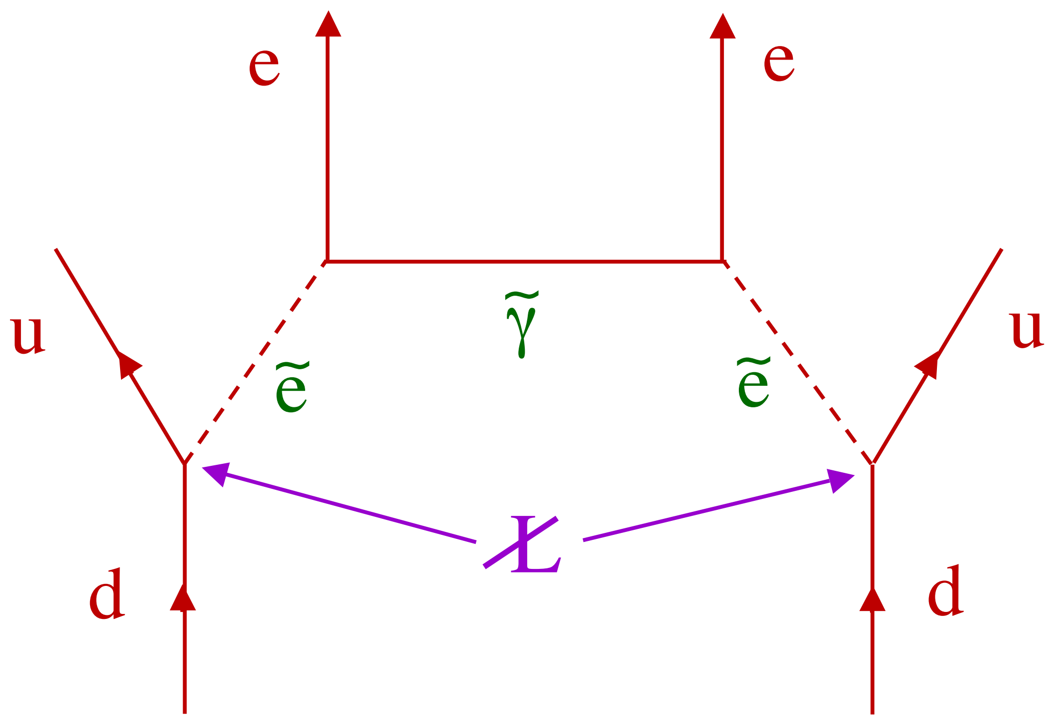
Now

Not true: Majorana neutrino mass is still needed to violate lepton number.

In fact, with one SM LH vertex and one non-SM RH vertex, the amplitude is quadratic in neutrino mass.

(B.K., Petcov, Rosen; Enqvist, Maalampi, Mursula; B.K.)

To have 0νββ without any input neutrino mass requires a ***lepton-number-violating*** interaction, such as —

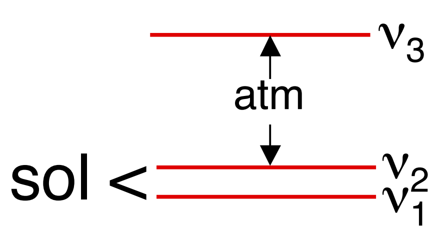


In the Standard Mechanism, How Large is $m_{\beta\beta}$?

How sensitive need an experiment be?

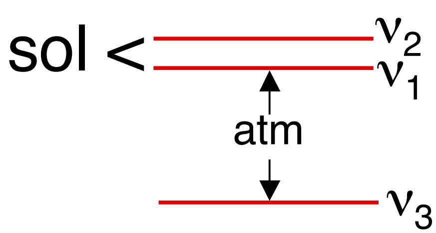
Assume there are only 3 neutrino mass eigenstates.

Then the spectrum looks like —

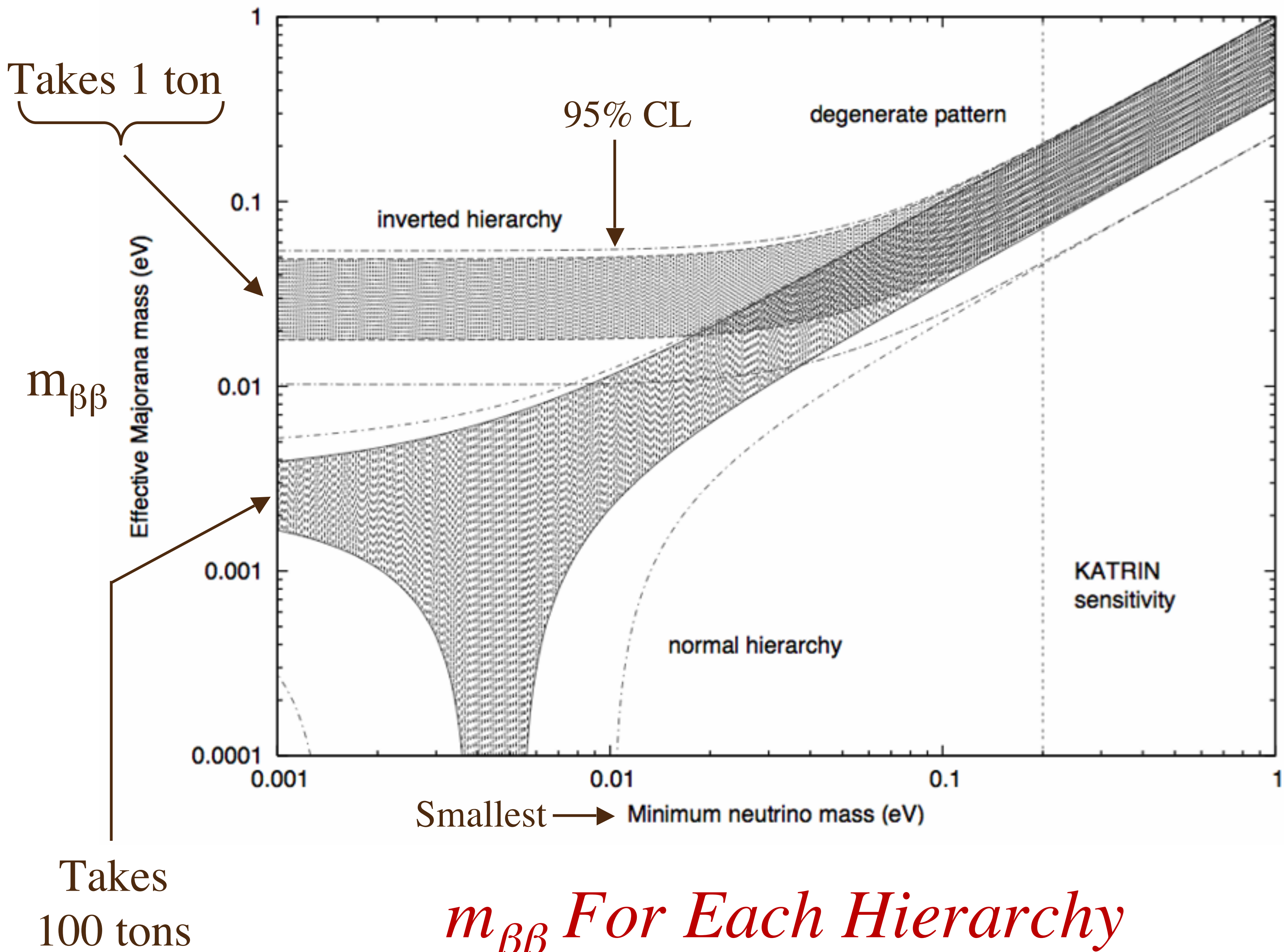


Normal hierarchy

or



Inverted hierarchy



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

There is no clear theoretical preference for either hierarchy.

If the hierarchy is **inverted**—

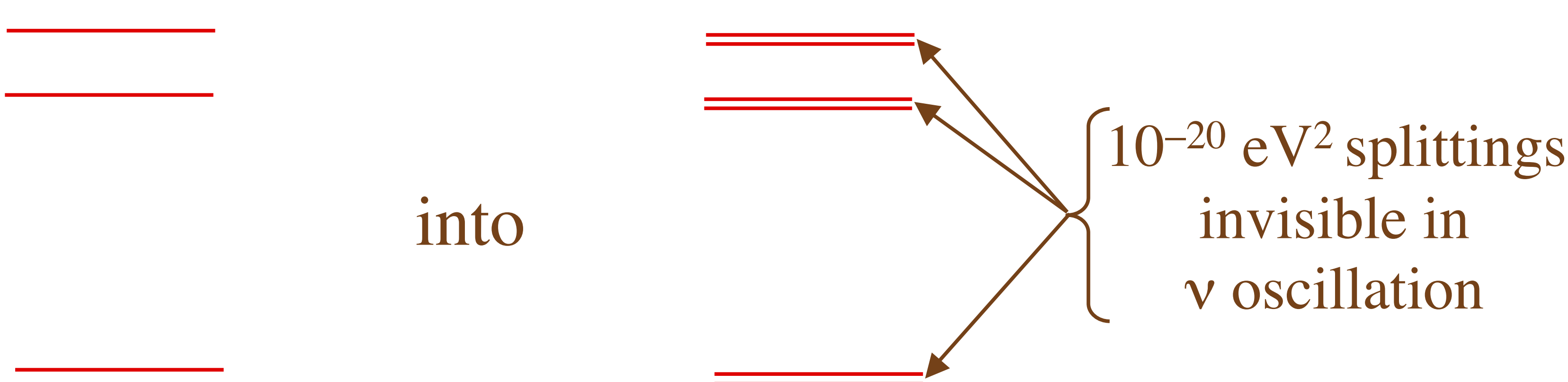
then $0\nu\beta\beta$ searches with sensitivity to $m_{\beta\beta} = 0.01$ eV have a very good chance to see a signal.

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

Suppose accelerator experiments have determined the hierarchy to be ***inverted***.

Suppose $0\nu\beta\beta$ searches are negative, and establish convincingly that $m_{\beta\beta} < 0.01$ eV. ***This would suggest, but not prove, that neutrinos are Dirac particles.***

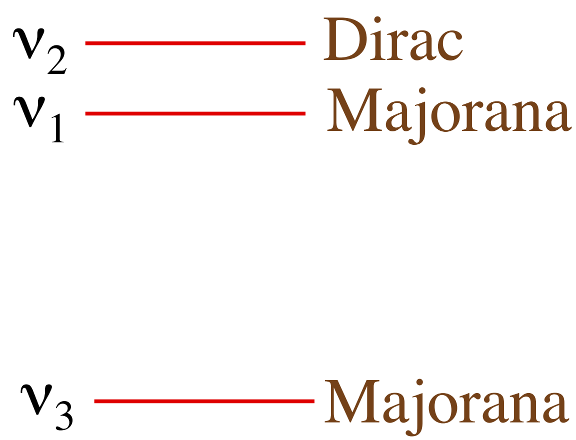
Tiny Majorana masses could turn —



6 Majorana neutrinos, making 3 pseudo (almost) Dirac neutrinos.

Schizophrenia (Split Personality)

(Allahverdi, Dutta, Mohapatra)



In this scenario, the lower bound on $m_{\beta\beta}$ when the hierarchy is inverted is ~ doubled, to ~ 0.02 eV.

Summary

A non-zero signal for $0\nu\beta\beta$ would be a tremendously important discovery.

Good luck in finding it!