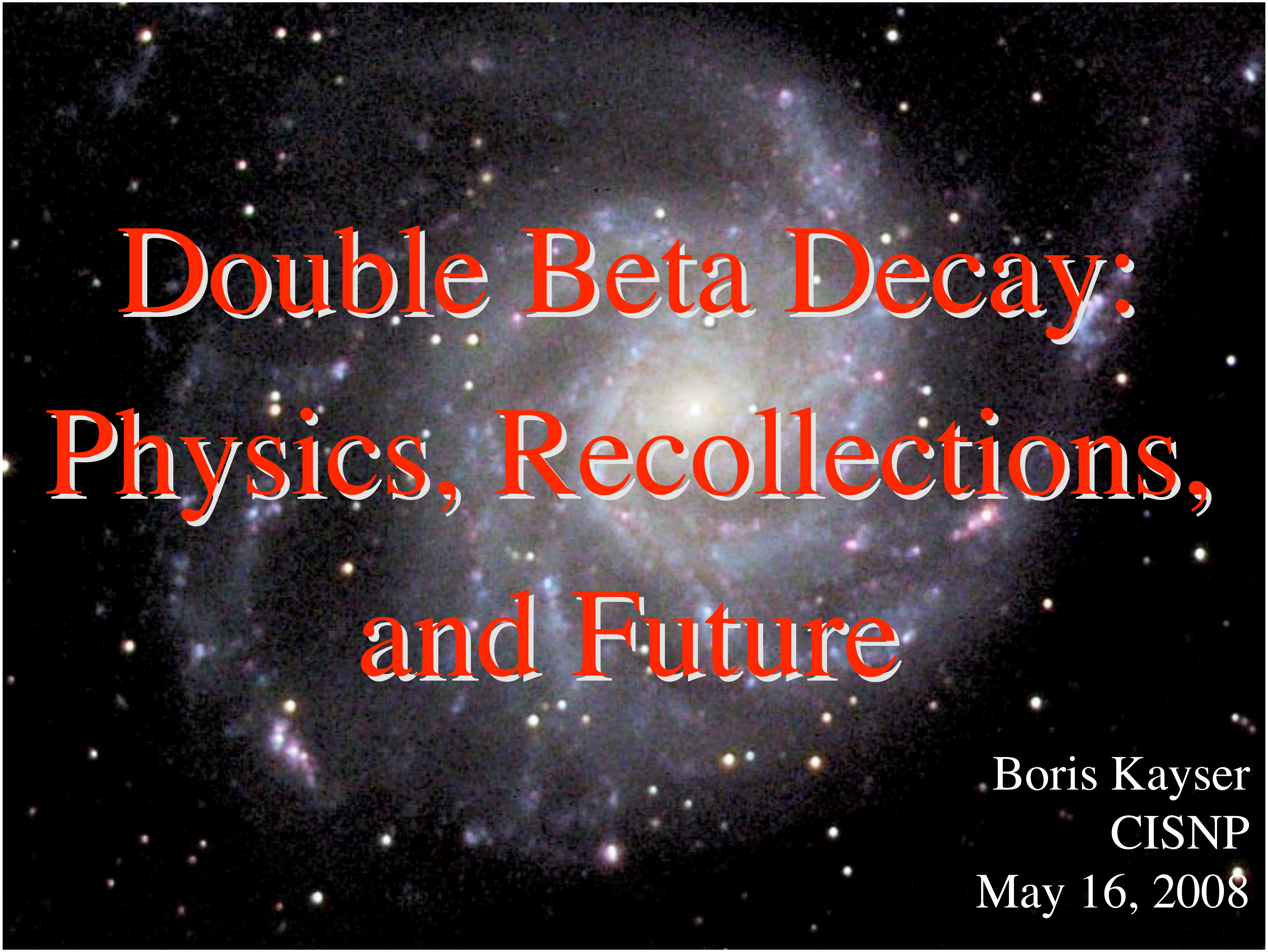

# Double Beta Decay: Physics, Recollections, and Future

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May 16, 2008

# Are Neutrinos Majorana Particles? (Does $\bar{\nu} = \nu$?)

# What Is the Question?

For each *mass eigenstate* $\nu_i$ , does —

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

or

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

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

We note that $\overline{\nu_i} = \nu_i$ means —

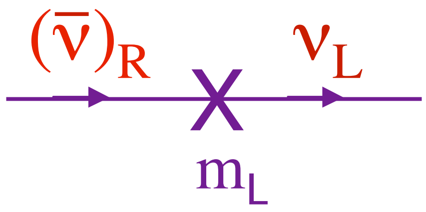
$$\overline{\nu_i}(h) = \nu_i(h)$$

helicity

# 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 —

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



Majorana masses do not conserve the Lepton Number L defined by —

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

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 ν masses cannot come from a “Yukawa”
coupling $\bar{\nu}_R \nu_L$ x (Standard-Model Higgs) like that
which leads to the quark and charged-lepton masses.

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

# 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 $\nu_L \leftrightarrow \nu_L{}^c$ 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 $\nu_L \leftrightarrow \nu_L{}^c$ 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) is defined by the fields it contains, its symmetries (notably gauge invariance), and its renormalizability.

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

*Majorana masses* are allowed by the SM symmetries.

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

# To Determine Whether Majorana Masses Occur in Nature

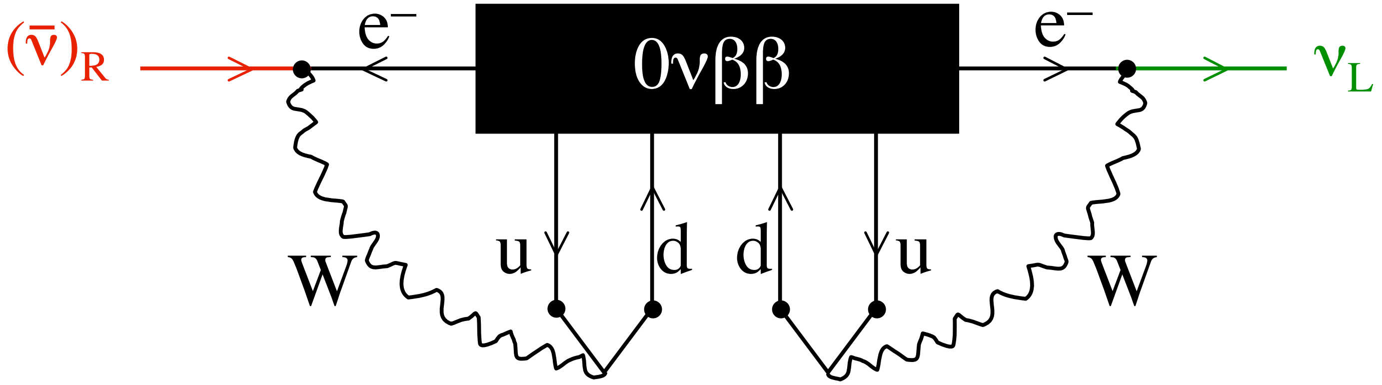
# The Promising Approach — Seek

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

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:

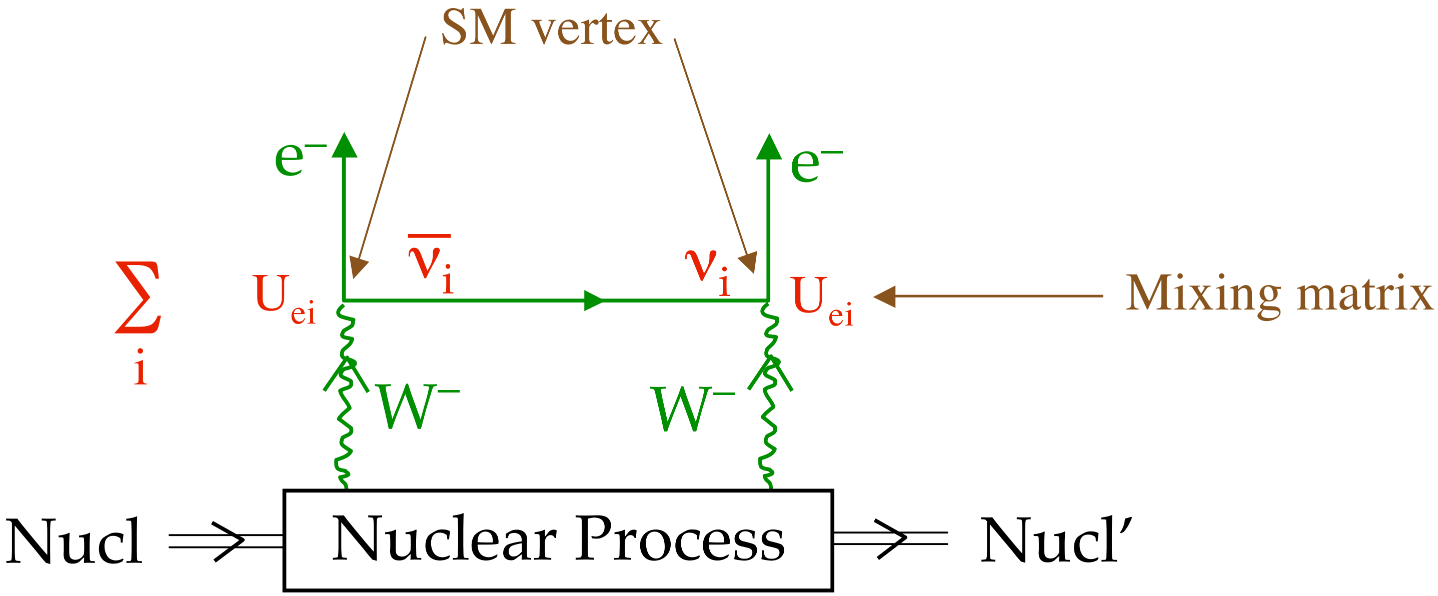
Schechter and Valle



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

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

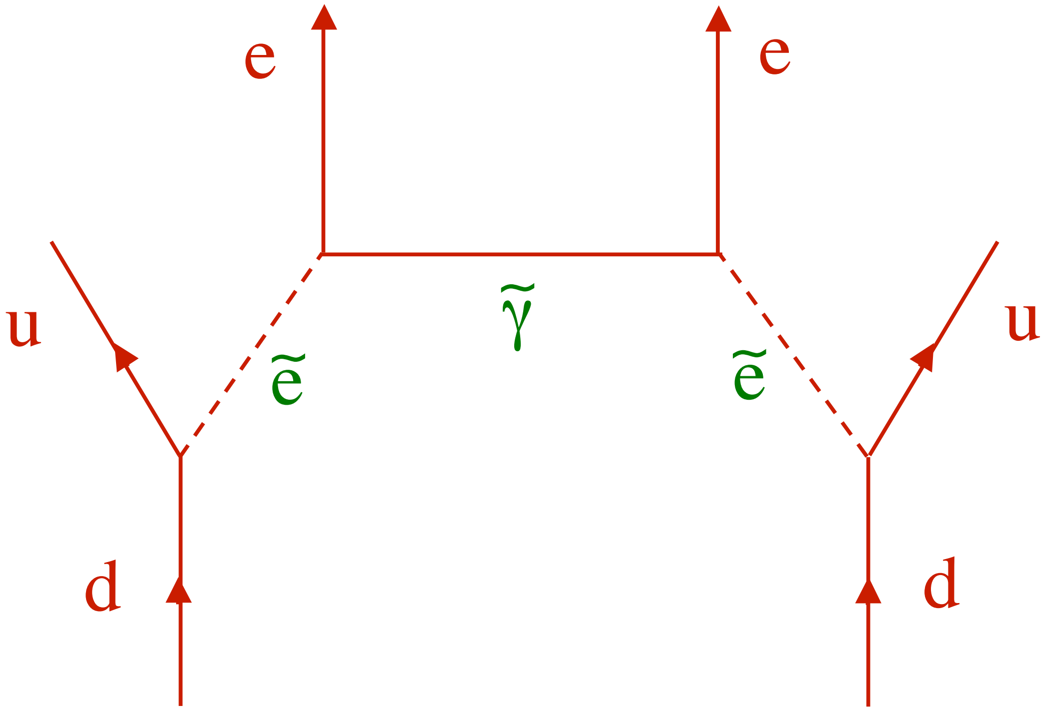
# We anticipate that 0νββ is dominated by a diagram with Standard Model vertices:



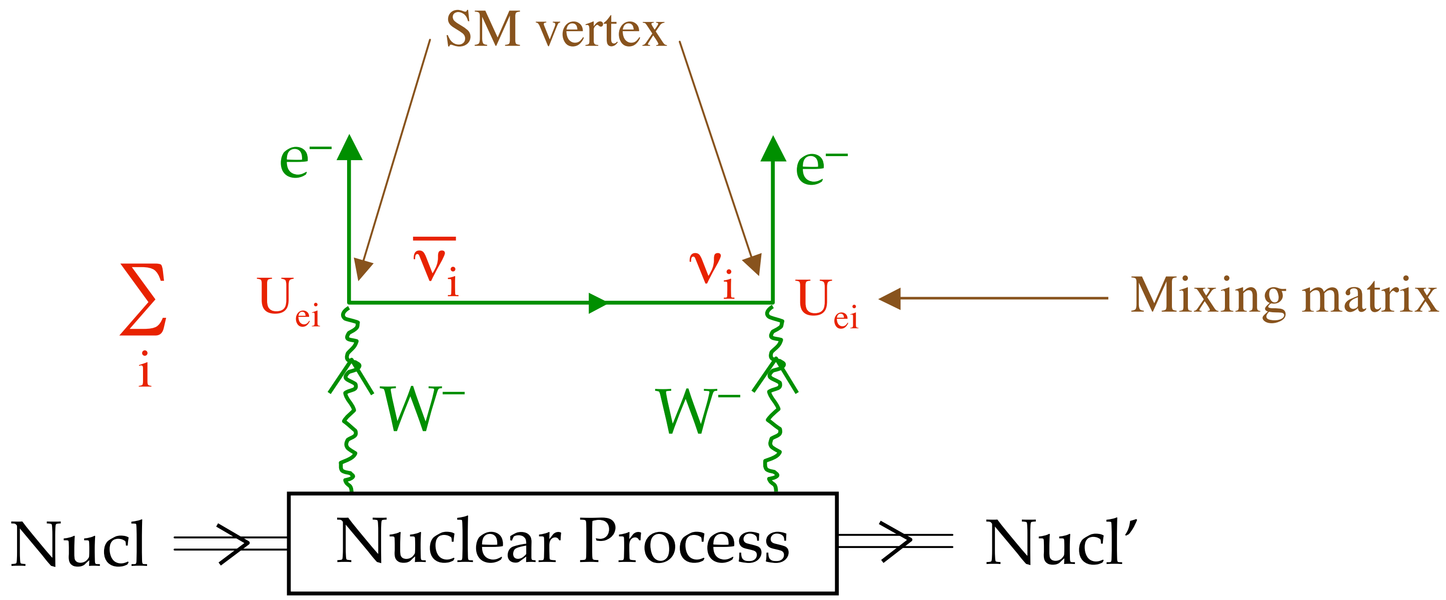
But there could be other contributions to 0νββ, which at the quark level is the process

dd → uuee.

An example from Supersymmetry:



In —



Mass ($\nu_i$)

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

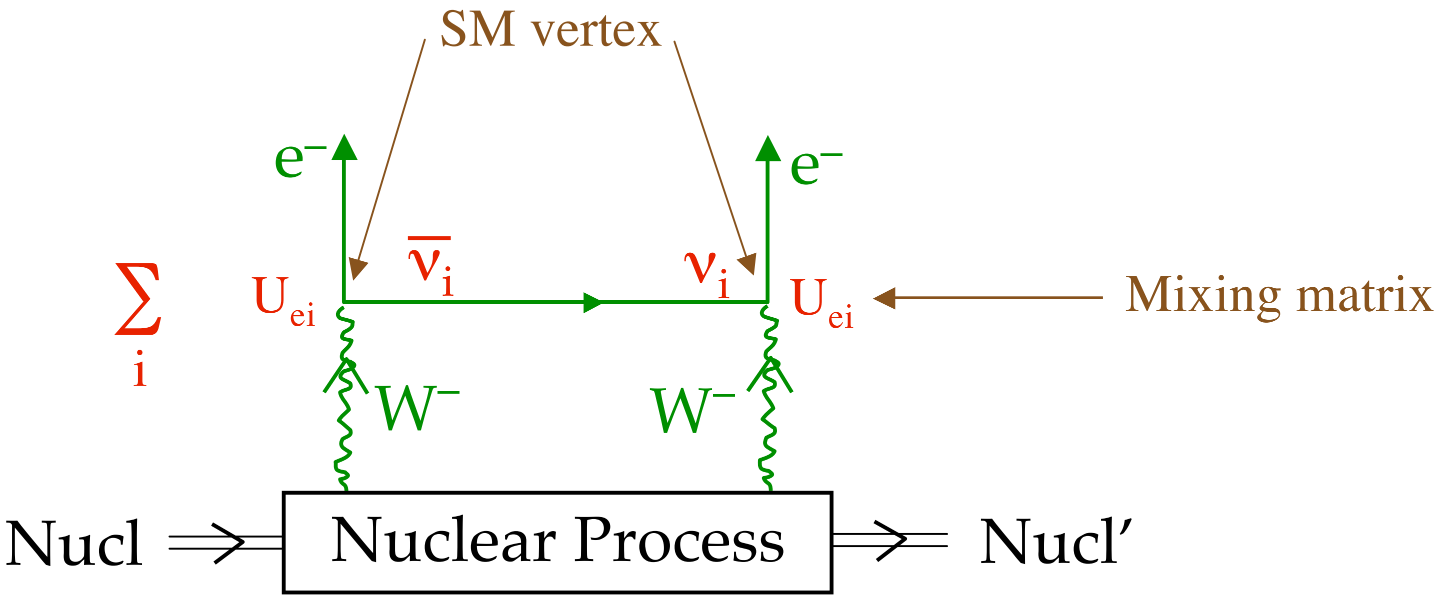
Thus, Amp [$\nu_i$ contribution] ∝ $m_i$

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

# Neutrinoless Double Beta Decay and Neutrino Mass — A Point of Principle

# — Down the Garden Path —

In —



Mass ($\nu_i$)

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

Thus, Amp [$\nu_i$ contribution] ∝ $m_i$

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

# The Trap

This makes it look as if $0\nu\beta\beta$ needs $\nu$ mass only because of a helicity mismatch, which a RH current could fix.

Suppose we had a parity-conserving world, that treats right-handed and left-handed particles in the same way.

Couldn't we then have $0\nu\beta\beta$ without any $\nu$ mass?

**No!**

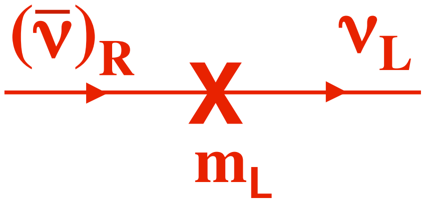
**$\nu$ mass is still required.**

# Why?

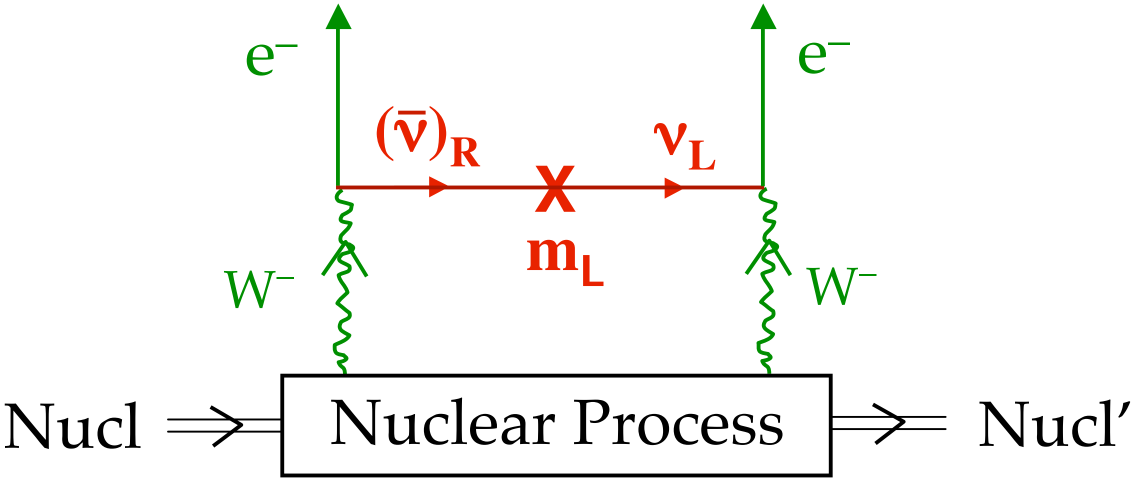
— manifestly does not conserve L.

But the Standard Model (SM) weak interactions *do* conserve L. Absent any non-SM L-violating interactions, the $\Delta L = 2$ of $0\nu\beta\beta$ can only come from *Majorana neutrino masses*, such as —

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



# Assuming Standard Model vertices, 0νββ is —



The Majorana neutrino mass term plays two roles:

1) Violate L

2) Flip handedness

It will be needed for (1) even when not needed for (2).

# A Parity-Conserving Toy-Model Illustration

Suppose there is only one generation.

Suppose the W couples to the electron and neutrino via a parity-conserving vector current:

$$-L_W = \frac{g}{\sqrt{2}} W_\lambda^- \overline{e} \gamma^\lambda \nu + \text{h.c.} = \frac{g}{\sqrt{2}} W_\lambda^- \left( \overline{e_L} \gamma^\lambda \nu_L + \overline{e_R} \gamma^\lambda \nu_R \right) + \text{h.c.}$$

Suppose the neutrino mass term is also
L ⇔ R invariant:

$$-L_M = \frac{1}{2} m_M \left( \overline{\nu_L^c} \nu_L + \overline{\nu_R^c} \nu_R \right) + m_D \overline{\nu_R} \nu_L + \text{h.c.}$$

We take $m_{M,D}$ real, $m_M > m_D$, and neglect the electron mass.

The neutrino mass eigenstates are the two Majorana particles —

$$\nu_2 = \frac{1}{\sqrt{2}}\left[(\nu_L + \nu_R) + (\nu_L + \nu_R)^c\right], \text{ with mass } m_2 = m_M + m_D ,$$

and

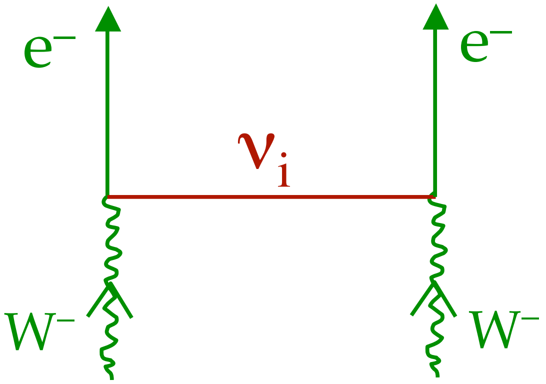
$$\nu_1 = \frac{1}{\sqrt{2}}\left[(\nu_L - \nu_R) + (\nu_L - \nu_R)^c\right], \text{ with mass } m_1 = m_M - m_D .$$

In terms of them —

$$-L_W = \frac{g}{\sqrt{2}} W_\lambda^- \left[\overline{e_L}\gamma^\lambda \frac{1}{\sqrt{2}}(\nu_{2L} + \nu_{1L}) + \overline{e_R}\gamma^\lambda \frac{1}{\sqrt{2}}(\nu_{2R} - \nu_{1R})\right] + \text{h.c.}$$

Consider now the particle-physics part of $0\nu\beta\beta$ —

$$\sum_{i=1,2}$$



If the electrons both emerge Left-Handed (LH), only the LH leptonic currents contribute.

For this final state, one finds that the amplitude, $A_{LL}$, obeys —

$$A_{LL} \propto \frac{m_2}{q^2 - m_2^2} + \frac{m_1}{q^2 - m_1^2} \cong \frac{m_2 + m_1}{q^2} = \frac{2m_M}{q^2}$$

*The amplitude is proportional to the Majorana $\nu$ mass $m_M$.*

Similarly, if both electrons emerge right-handed, the amplitude, $A_{RR}$, obeys —

$$A_{RR} \propto \frac{m_2}{q^2 - m_2^2} + \frac{m_1}{q^2 - m_1^2} \cong \frac{m_2 + m_1}{q^2} = \frac{2m_M}{q^2}$$

Higher-order (in ν mass) terms:

Every term in $A_{LL}$ or $A_{RR}$ must flip both L and the chirality, so it must be proportional to —

$$m_M^{Odd} m_D^{Even}$$

*Expanding the denominators confirms that every term does have this character.*

If the electrons emerge with opposite handedness, both the LH and RH currents are involved, and one finds that the amplitude, $A_{LR}$, obeys —

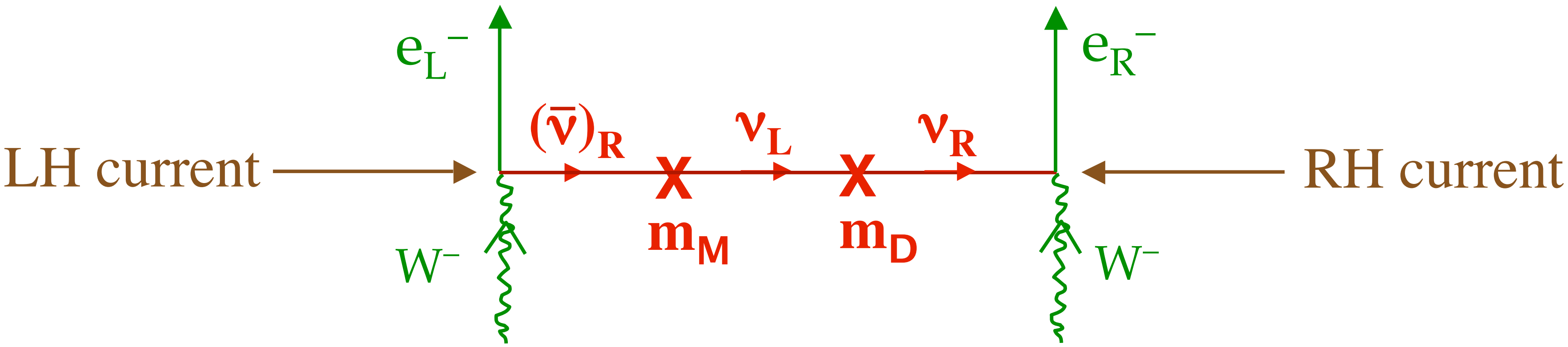
$$A_{LR} \propto i\not{q}\left(\frac{1}{q^2 - m_2^2} - \frac{1}{q^2 - m_1^2}\right) \cong i\not{q}\left(\frac{m_2^2 - m_1^2}{\left(q^2\right)^2}\right) = \frac{i\not{q}}{\left(q^2\right)^2} 4 m_M m_D$$

*The amplitude is proportional to the Majorana ν mass* $m_M$*.*

# Why $A_{LR}$ is also proportional to the Dirac mass $m_D$:

BK, Petcov, and Rosen;
Enqvist, Maalampi, and Mursula

The process is —



*Two flips of handedness are needed.*

Higher-order (in ν mass) terms:

Every term in $A_{LR}$ must flip L but not chirality, so it must be proportional to —

$$m_M^{Odd} \, m_D^{Odd}$$

*Expanding the denominators ($q^2 - m_i^2$) confirms that every term does have this character.*

*Including the electron mass doesn't make any difference.*

# Summary of this Point of Principle

Absent L-nonconserving interactions from beyond the Standard Model, 0νββ requires Majorana neutrino mass.

This mass is needed to introduce L-nonconservation, even if it is not needed for any other reason.

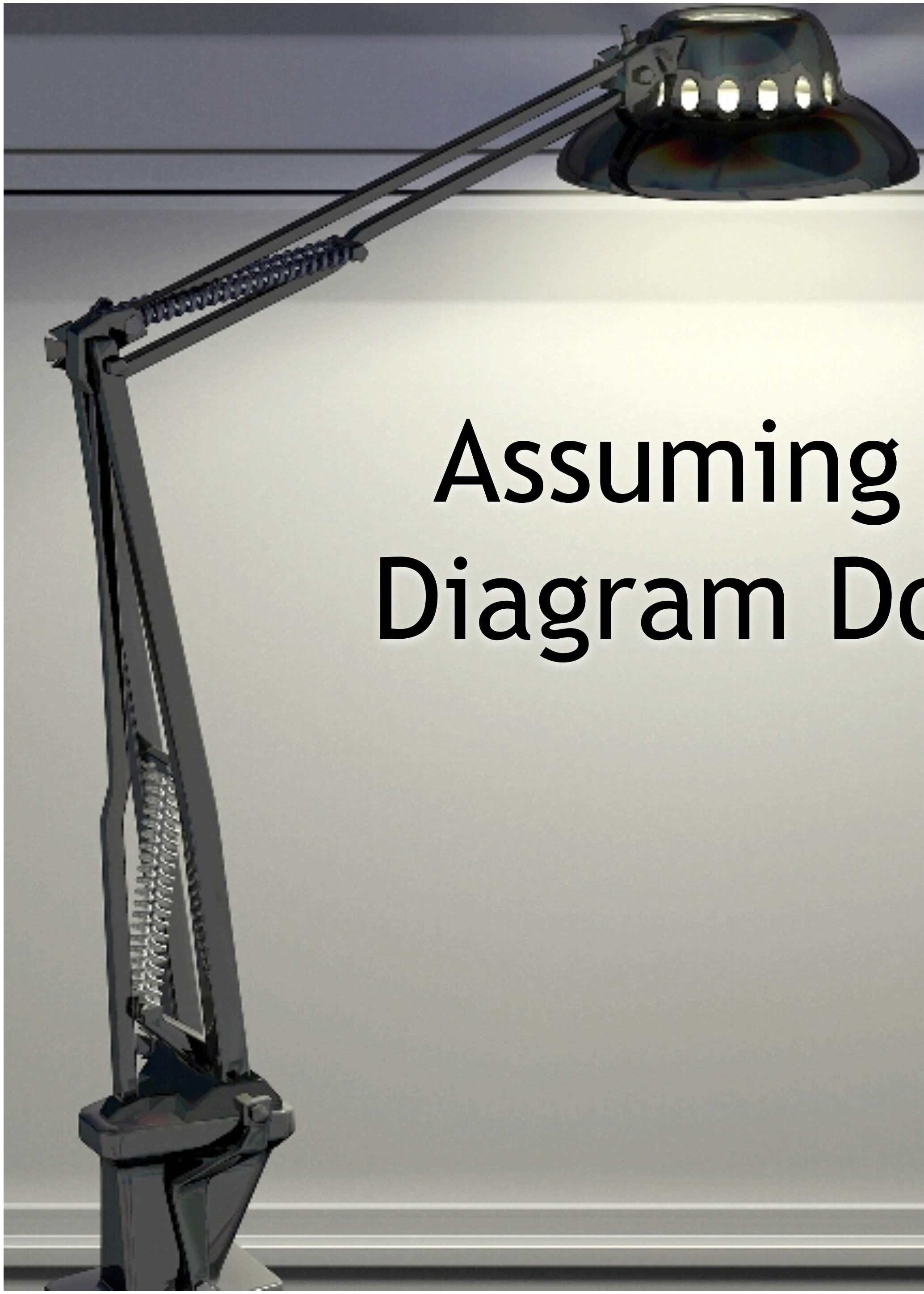
# A Recollection —
# Primakoff and Rosen

*Primakoff and Rosen were pioneers of the whole field of double beta decay.*

*A half-century ago, they contemplated $0\nu\beta\beta$ arising from non-SM, L-nonconserving interactions.*

*Then Majorana neutrino mass is not needed.*

*We have not yet seen any evidence for such interactions, but we do expect Majorana neutrino masses.*



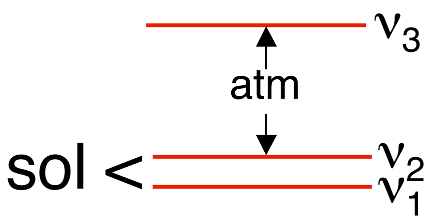
# Assuming the Usual Diagram Dominates —

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

How sensitive need an experiment be?

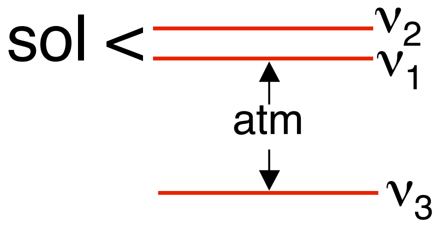
Suppose there are only 3 neutrino mass eigenstates. (More might help.)

Then the spectrum looks like —



Normal hierarchy

or

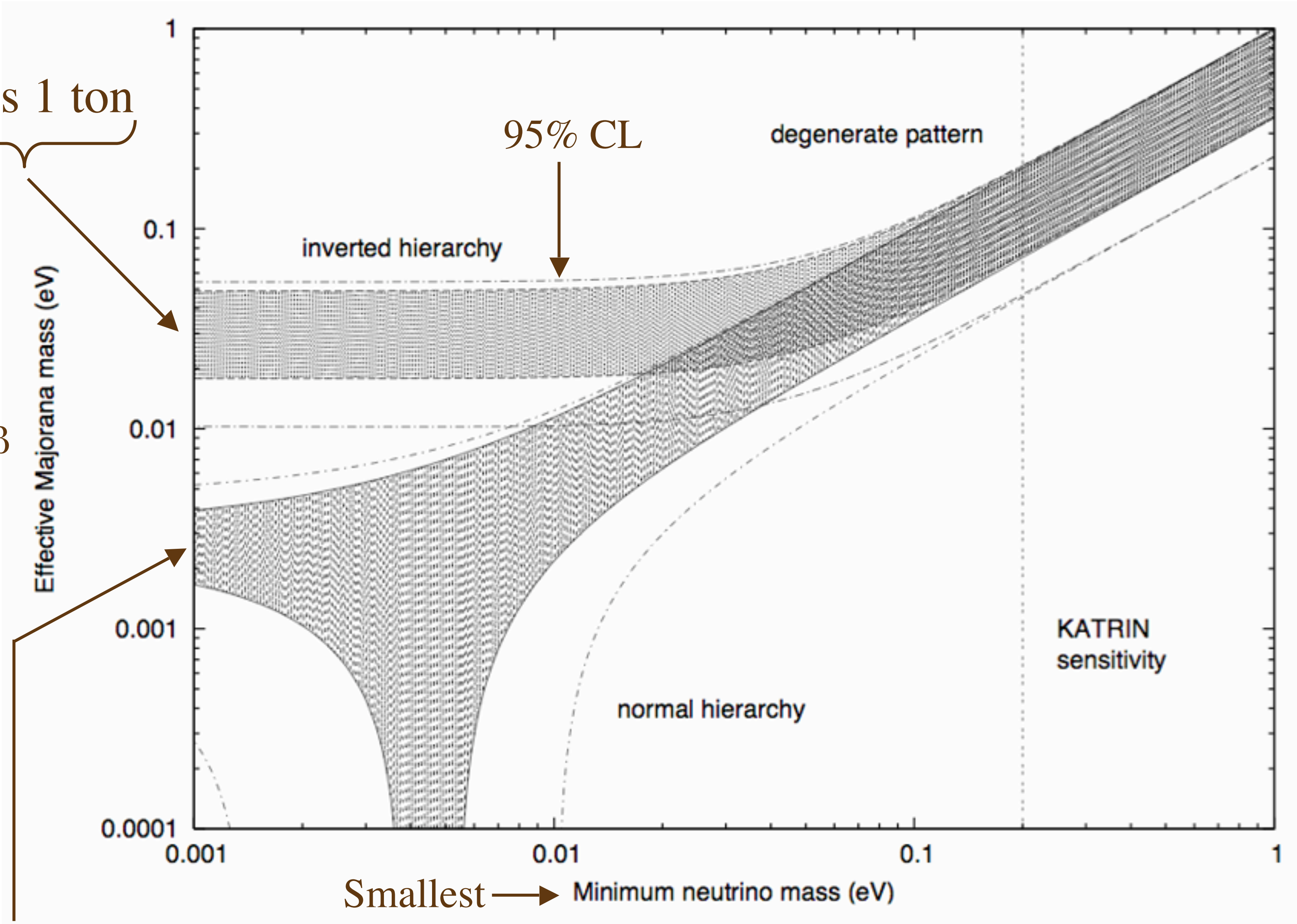


Inverted hierarchy

Takes 1 ton

95% CL

$m_{\beta\beta}$



Smallest ⟶

Takes
100 tons

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

There is no clear theoretical preference
for either hierarchy.

Suppose the hierarchy is found, via accelerator
neutrino experiments, to be **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.

If these $0\nu\beta\beta$ searches establish that $m_{\beta\beta} < 0.01$ eV,
then, barring unlikely cancellations from
exotic mechanisms, we can say that
neutrinos are Dirac particles: $\overline{\nu} \neq \nu$ .

Heartiest congratulations and thanks to
*Frank Avignone* and *Ettore Fiorini*
for leading the way to the present very exciting point
in the quest to find neutrinoless double beta decay.

Thanks, with fond memories, to *Peter Rosen*
for pioneering contributions to this field,
and for encouraging this very important quest.

*We eagerly await the results of the $0\nu\beta\beta$ searches*
*with sensitivity at the (0.01 – 0.05) eV scale.*