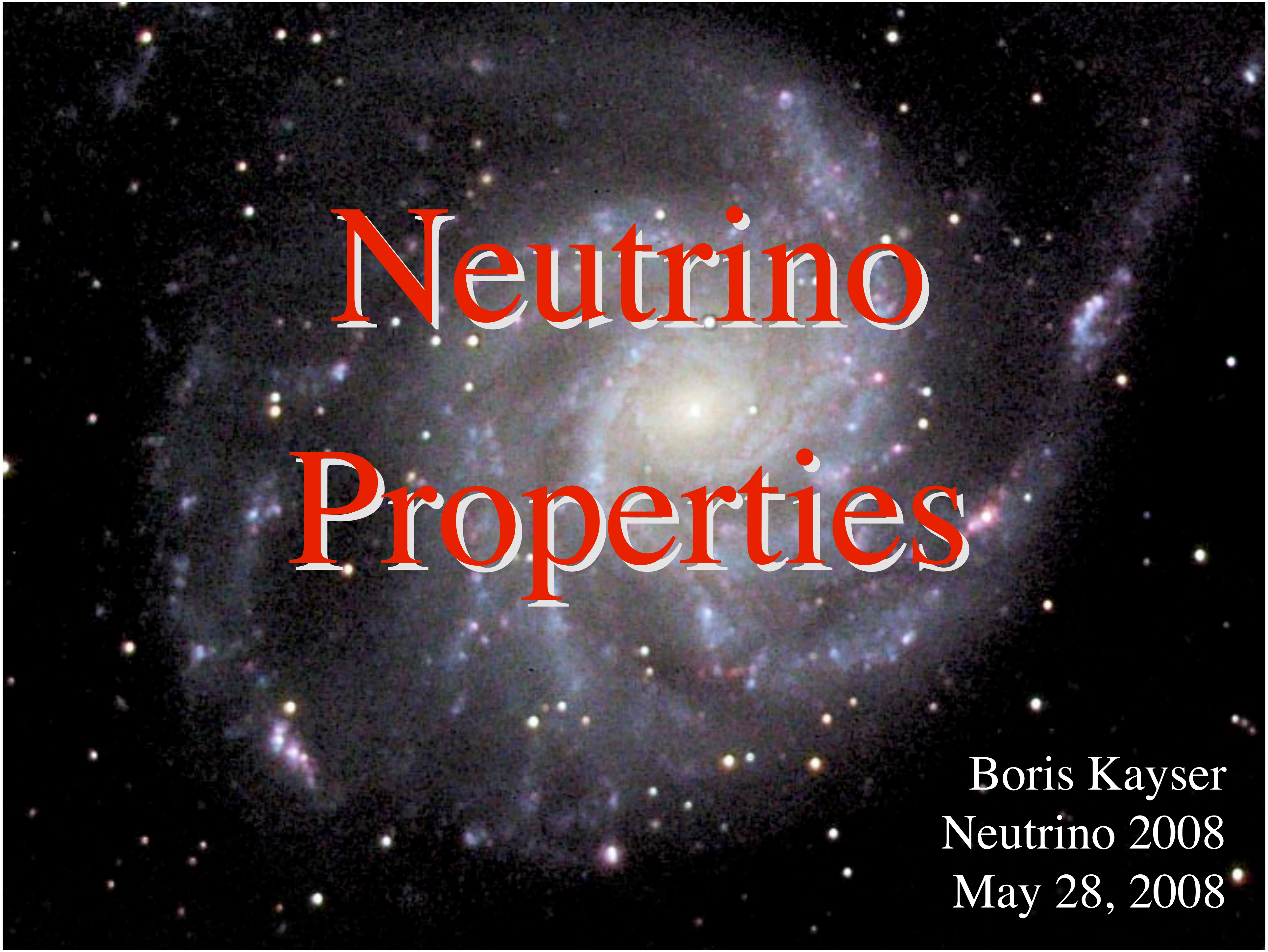
Neutrino Properties

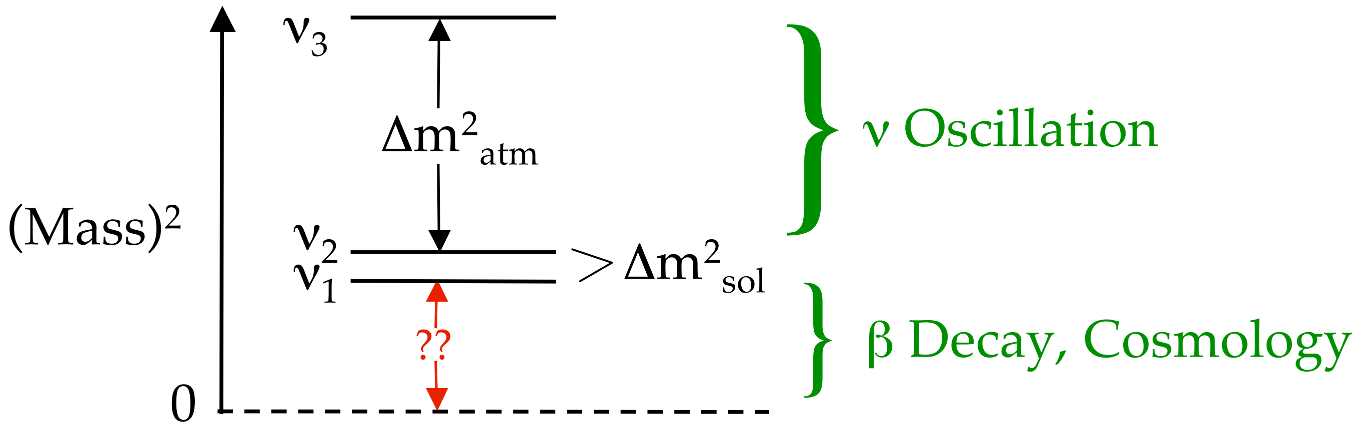


Boris Kayser

Neutrino 2008

May 28, 2008

What Is the Absolute Scale of Neutrino Mass?



How far above zero
is the whole pattern?

Oscillation Data

$\Rightarrow$ Mass[Heaviest ν_i] $> \sqrt{\Delta m^2_{atm}} \cong 0.05$ eV

A Cosmic Connection

Cosmological Data + Cosmological Assumptions ➡

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

Mass(ν_i)

(Seljak, Slosar, McDonald
Pastor)

If there are only 3 neutrinos,

$0.05 \text{ eV} \lesssim \text{Mass[Heaviest } \nu_i] < (0.07 - 0.4) \text{ eV}$

$\sqrt{\Delta m^2_{atm}}$ Cosmology

The *cosmological assumptions* seem reasonable, but are not guaranteed. A *laboratory determination* of the absolute ν mass scale will be essential.

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

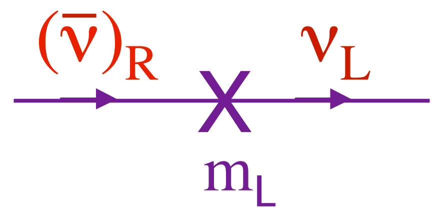
- $\overline{\nu_i}(h) \neq \nu_i(h)$ (Dirac neutrinos) ?

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

Majorana Masses

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 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 $\leftrightarrow$ $\bar{\text{f}}$.

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 $H_{SM}\bar{\nu}_R\nu_L$, the analogue of the q and ℓ mass terms.

Possible Majorana mass terms:

$$\underbrace{H_{SM} H_{SM} \overline{\nu_L^c} \nu_L}_{\text{Not renormalizable}}, \quad \underbrace{H_{I_W=1}}_{\text{This Higgs not in SM}} \overline{\nu_L^c} \nu_L, \quad \underbrace{m_R \overline{\nu_R^c} \nu_R}_{\text{No Higgs}}$$

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

Why Majorana Masses $\Longrightarrow$ 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 $\nu_L \leftrightarrow \nu_L{}^c$ 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 weak isospin invariance), and its renormalizability.

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

Since $I_W(\nu_R) = 0$, *Right-Handed Majorana mass terms* $m_R \overline{\nu_R^c} \nu_R$ are allowed by the SM symmetries.

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

To Determine Whether Majorana Masses Occur in Nature

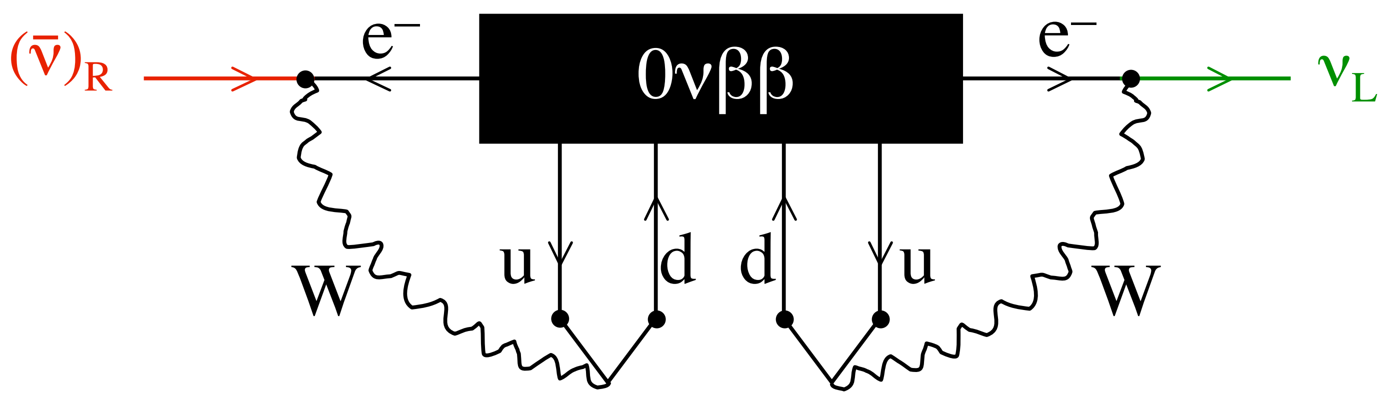
The Promising Approach — Seek

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

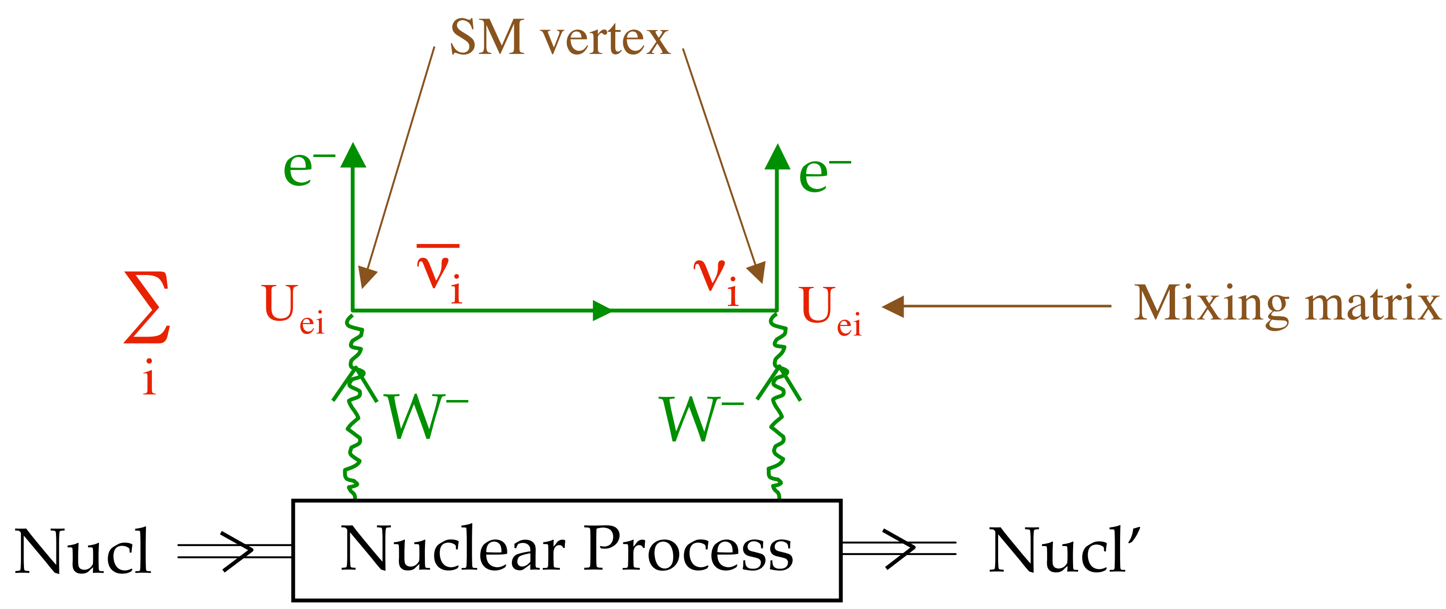
(Schechter and Valle)



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

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

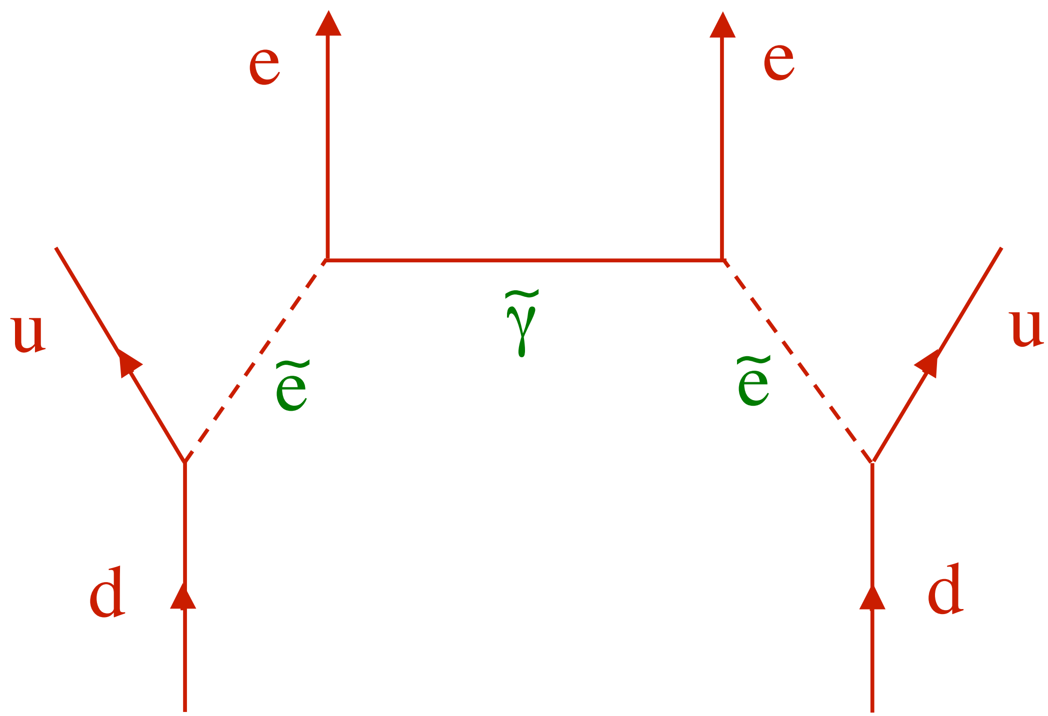
We anticipate that 0νββ is dominated by a diagram with Standard Model vertices:



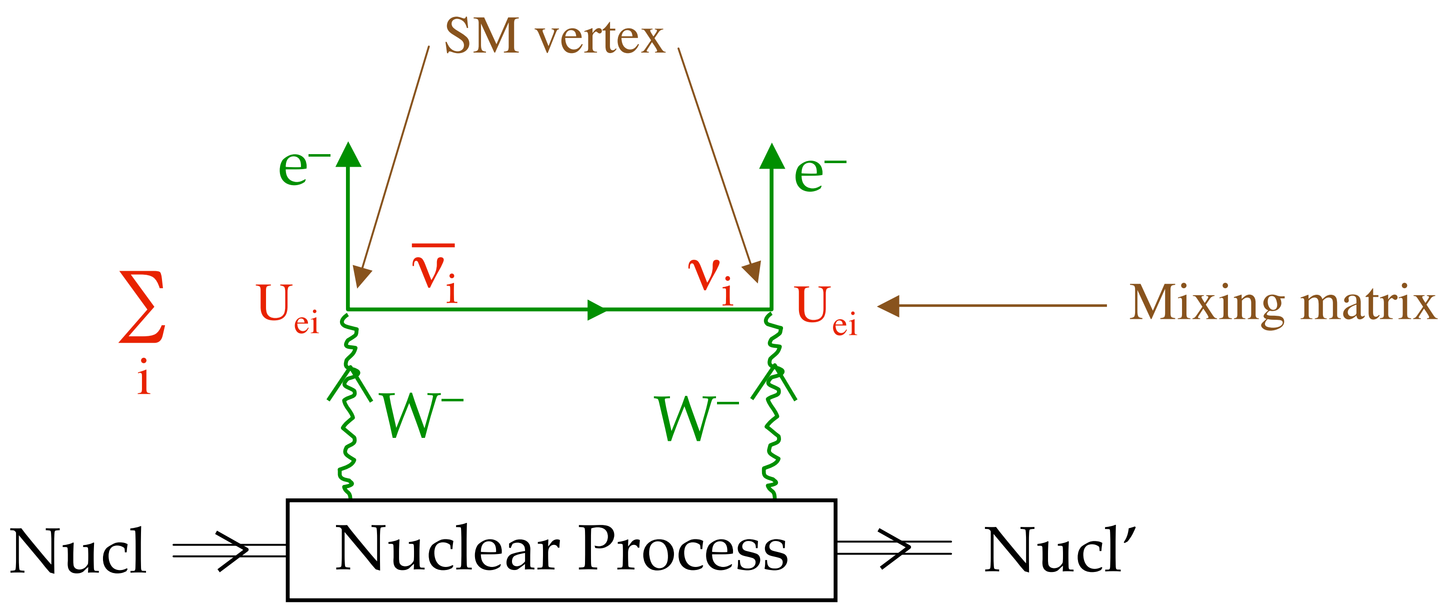
But there could be other contributions to $0\nu\beta\beta$, which at the quark level is the process

$dd \rightarrow uuee$.

An example from Supersymmetry:



If the dominant mechanism is —



then —

Mass (ν_i)

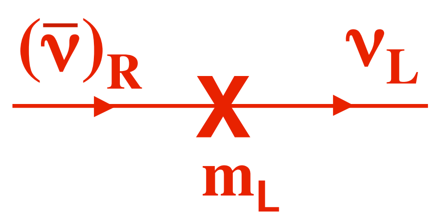
$$\mathrm{Amp}[0\nu\beta\beta] \propto \left| \sum_i m_i U_{ei}^{\,2} \right| \equiv m_{\beta\beta}$$

Why Amp[$0\nu\beta\beta$] Is $\propto$ Neutrino Mass

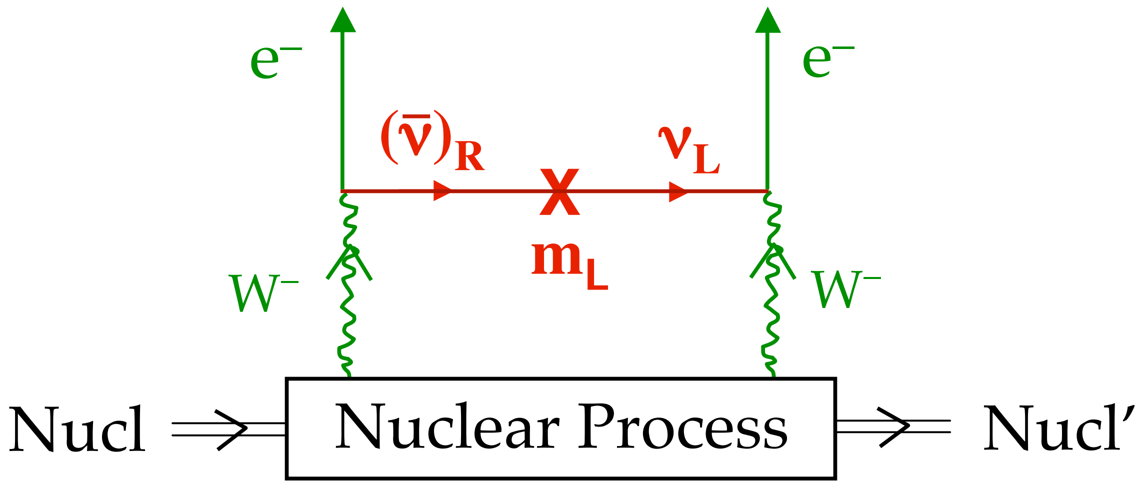
— manifestly does not conserve L.

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 —

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



Treating the neutrino masses perturbatively,
we have —



A Left-Handed Majorana mass term is just what is needed to —

1) Violate L

2) Flip handedness

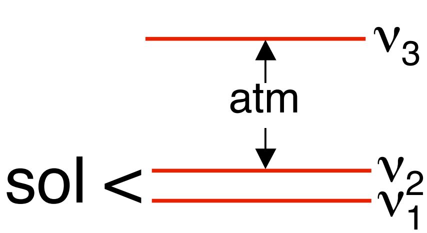
— and allow the decay to occur.

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

How sensitive need an experiment be?

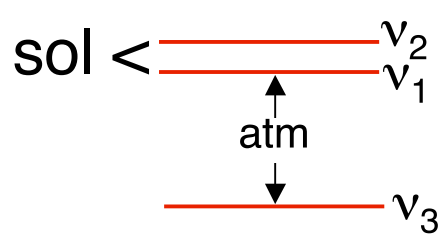
Suppose there are only 3 neutrino mass eigenstates. (More might help.)

Then the spectrum looks like —



Normal hierarchy

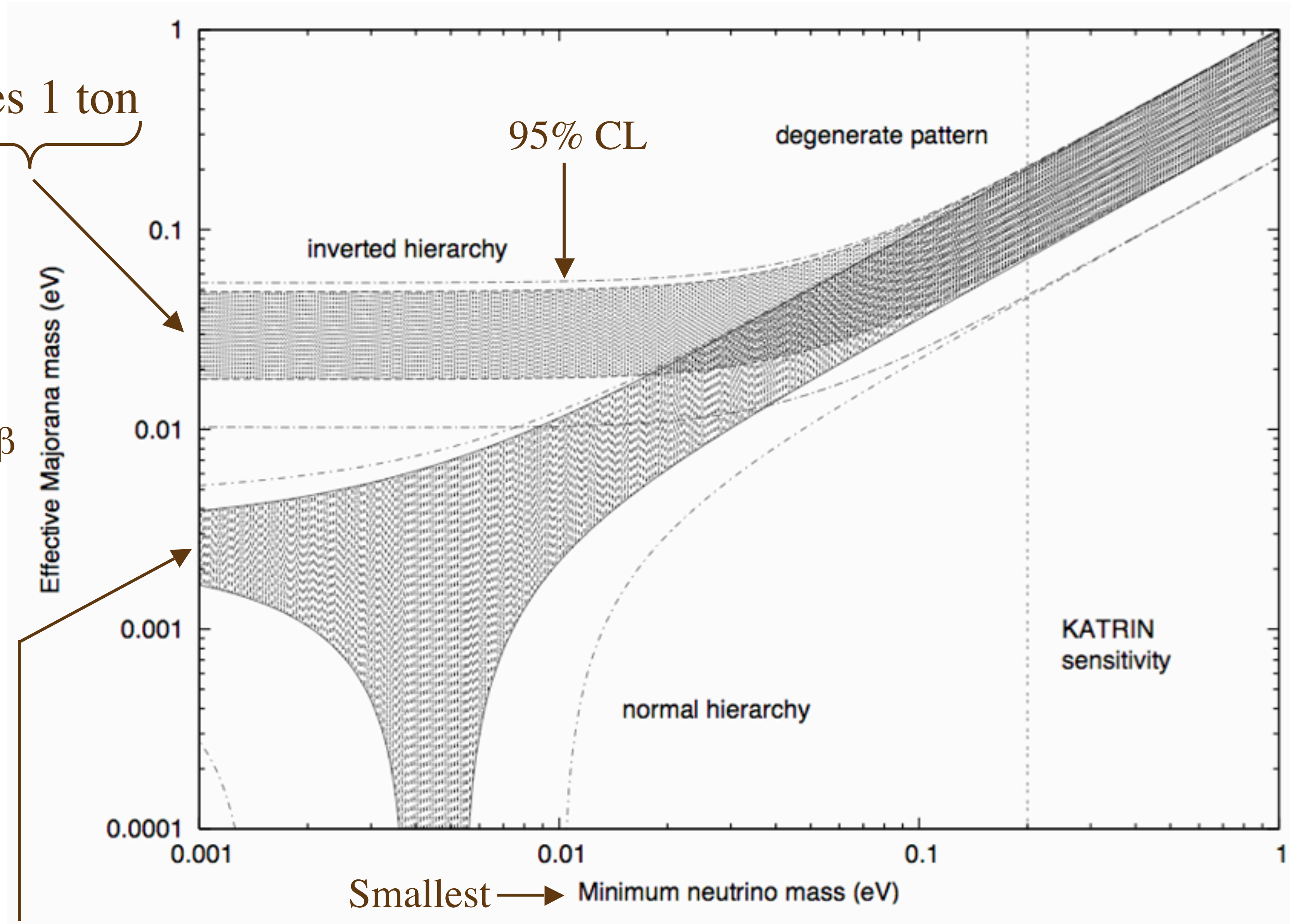
or



Inverted hierarchy

Takes 1 ton

$m_{\beta\beta}$



Takes
100 tons

$m_{\beta\beta}$ 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 a good target for the next generation of experiments.

Determining $m_{\beta\beta}$

The most important goal of $0\nu\beta\beta$ searches
is to **observe** the process.

Observation at any non-zero level
would establish that —

- Neutrinos have Majorana masses
- Neutrinos are Majorana particles
- Lepton number is not conserved

What We Would Learn From Information On $m_{\beta\beta}$

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

Suppose $0\nu\beta\beta$ searches are negative, but establish convincingly that $m_{\beta\beta} < 0.01$ eV. Then, barring unlikely cancellations from exotic mechanisms, we can say that **neutrinos are Dirac particles**: $\bar{\nu} \neq \nu$.

Suppose accelerator experiments have **not** determined the hierarchy, but $0\nu\beta\beta$ searches have found a convincing signal with $m_{\beta\beta} < 0.01$ eV. Then, barring exotic mechanisms, the hierarchy must be **normal**.

Bahcall, Murayama, Pena-Garay; de Gouvêa, Jenkins

According to the Standard Model, the leptonic mixing matrix U is unitary.

Then, if $m_{Heaviest}$ is the mass of the heaviest neutrino mass eigenstate,

$$m_{\beta\beta} \equiv \left| \sum_i m_i U_{ei}^2 \right| \leq m_{Heaviest} \sum_i \left| U_{ei} \right|^2 = m_{Heaviest}$$

A measured value of $m_{\beta\beta}$ would be a lower bound on the mass of the heaviest neutrino.

Majorana CP-Violating Phases

Although the Cabibbo-Kobayashi-Maskawa **quark** mixing matrix can have only **one** ~~CP~~ phase, the Pontecorvo-Maki-Nakagawa-Sakata **leptonic** mixing matrix U can have **three**:

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

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

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

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

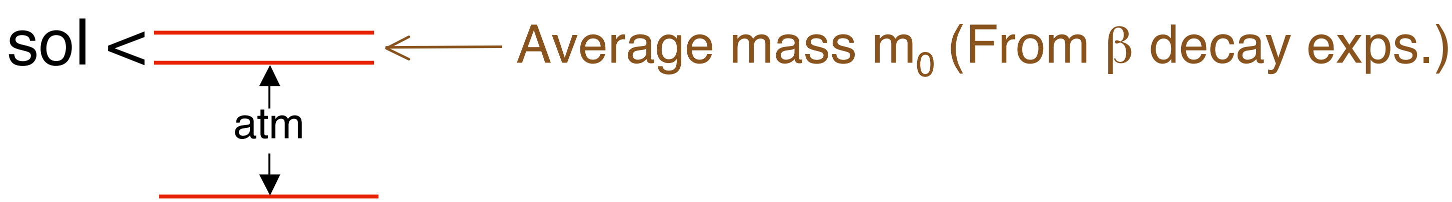
Analogue of the quark ~~CP~~ phase

Majorana ~~CP~~ phases

The Majorana ~~CP~~ phases are physical only if neutrinos are Majorana particles.

They only affect processes involving violation of lepton number L, such as $0\nu\beta\beta$.

Consider $0\nu\beta\beta$ when the neutrino mass spectrum is **inverted**:



For an inverted spectrum,

Majorana ~~CP~~ phases

$$m_{\beta\beta} \cong m_0[1 - \sin^2 2\theta_{12} \sin^2(\frac{\alpha_2-\alpha_1}{2})]^{½} \ .$$

Solar mixing angle

$$m_0 \cos 2\theta_{12} \le m_{\beta\beta} \le m_0$$

$$0.4\ m_0 \le m_{\beta\beta} \le m_0$$

From SNO

CP is violated if $\alpha_2 - \alpha_1 \neq 0, \pi$.

To establish CP, we must determine *$m_{\beta\beta}$ to within a factor of ~ 2.*

Pascoli, Petcov, Rodejohann; Barger, Glashow, Langacker, Marfatia

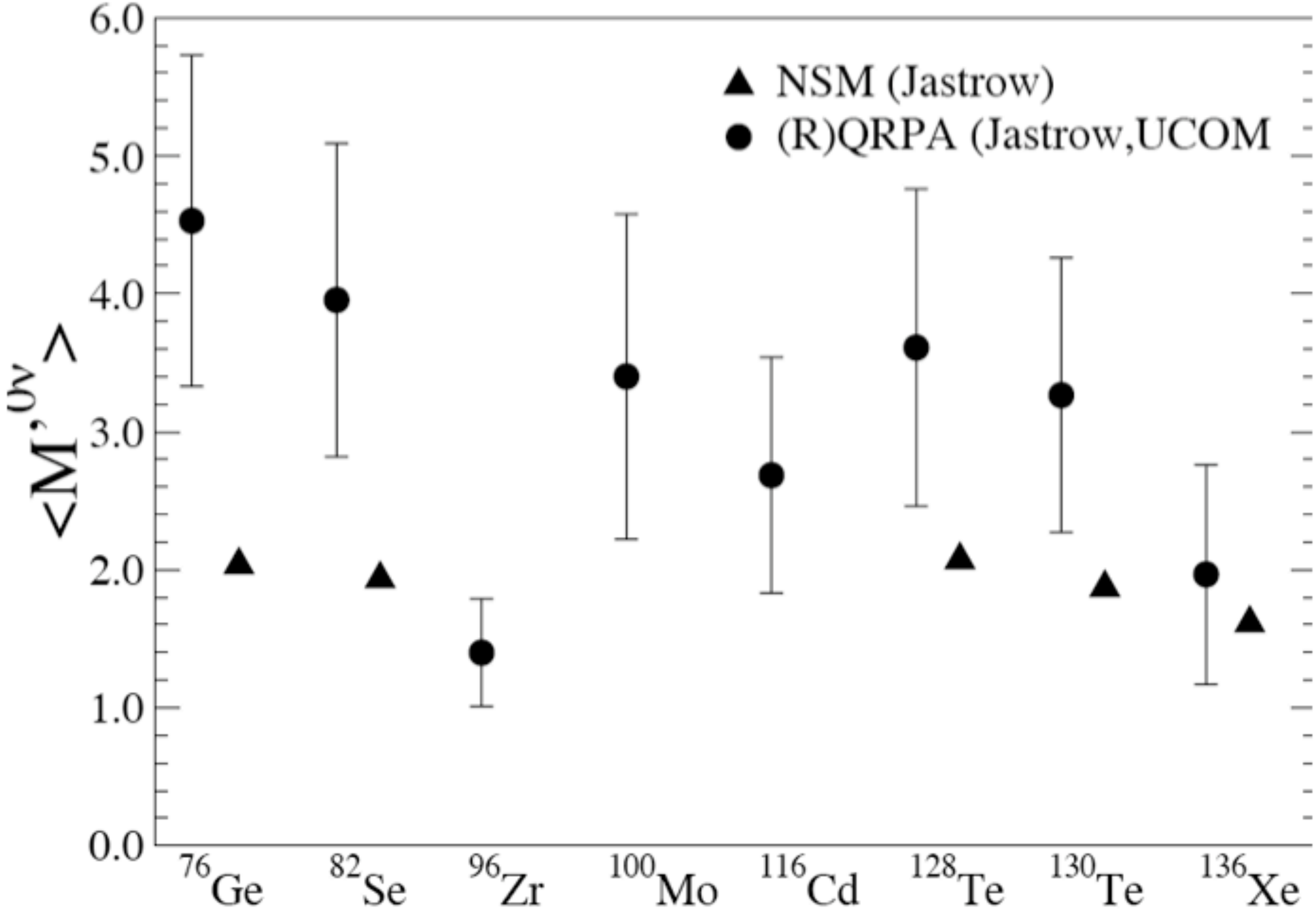
Nuclear Matrix Elements for $0\nu\beta\beta$

If $0\nu\beta\beta$ is dominated by light neutrino exchange, then —

$$\Gamma(0\nu\beta\beta) = (m_{\beta\beta})^2 \text{ x } (\text{Nuclear m. e.})^2 \text{ x } (\text{Phase space})$$

The nuclear m. e. $\mathcal{M}^{0\nu}$ is calculated by the Quasi Particle Random Phase Approximation (QRPA) or the Nuclear Shell Model (NSM).

Full estimated range of $M^{0\nu}$ within QRPA framework and comparison with NSM
(higher order currents now included in NSM)



Vogel

Sources of Uncertainty in the QRPA Calculations

$0\nu\beta\beta$ is nn → pp + ee. If the two neutrons are separated by > 2 – 3 fm, there is *near cancellation* between the J(nn) = 0 and the J(nn) ≠ 0 contributions.

As a result, there is great sensitivity to short-distance features, such as which separation distances dominate, nucleon structure, and short-range repulsion.

There is also sensitivity to the strength g_{pp} of the particle-particle neutron-proton interaction. This parameter is fixed by reference to $2\nu\beta\beta$ decay.

The Bottom Line

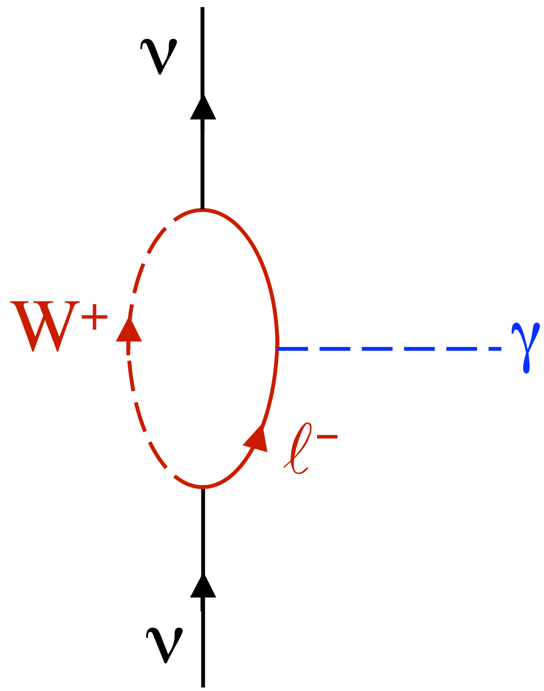
For the commonly-considered $0\nu\beta\beta$ candidates, such as ^{76}Ge, the nuclear m. e. is uncertain by a factor of 2, and perhaps a factor of 3.

Hopefully, this will improve, to permit cleaner interpretation of $0\nu\beta\beta$ results.

Special thanks to Petr Vogel for nuclear-physics wisdom.

What Are the Neutrino Dipole Moments?

In the Standard Model, loop diagrams like —



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

$$\mu_\nu = 3 \times 10^{-19}\ (m_\nu/1\mathrm{eV})\ \mu_B$$

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

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

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

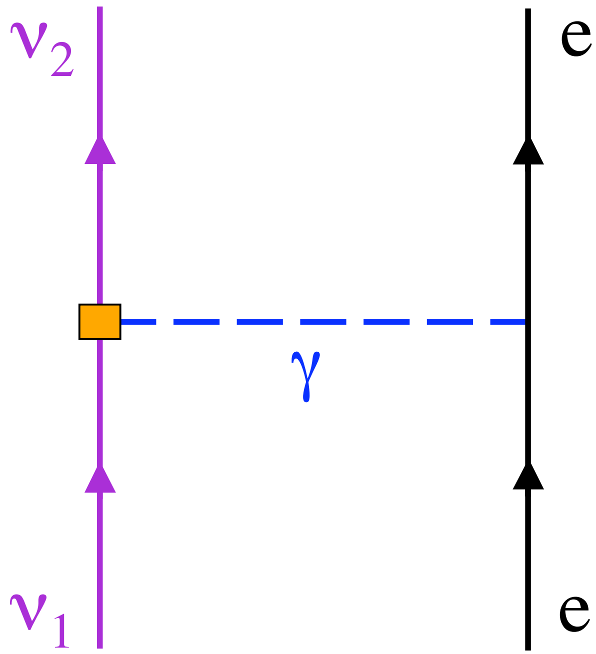
But for a Majorana neutrino,

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

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.

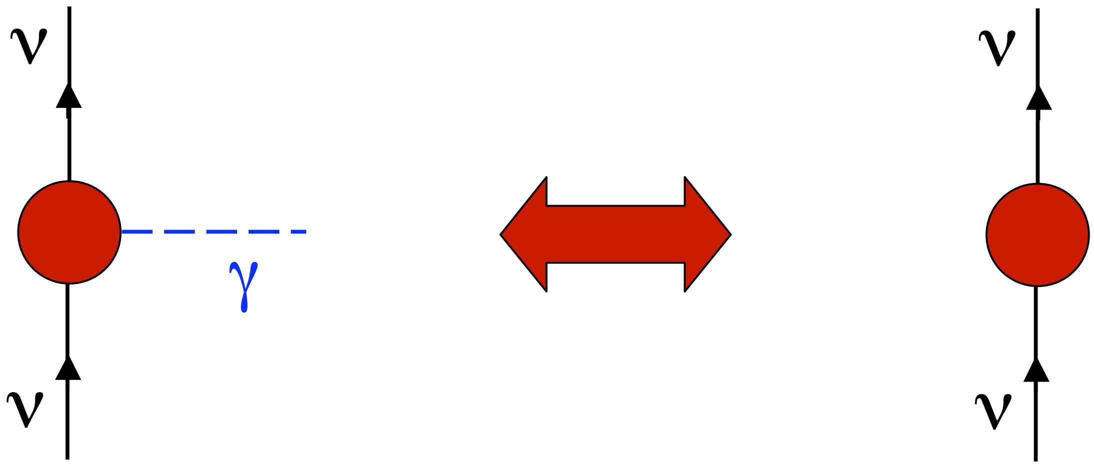
Present Bounds On Dipole Moments

$$
\text{Upper bound} = \begin{cases} 7 \text{ x } 10^{-11}\, \mu_B & ;\ \text{Wong et al. (Reactor)} \\ 5.4 \text{ x } 10^{-11}\, \mu_B & ;\ \text{Borexino (Solar)} \\ 3 \text{ x } 10^{-12}\, \mu_B & ;\ \text{Raffelt (Stellar E loss)} \end{cases}
$$

New Physics can produce larger dipole moments than the $\sim 10^{-20}\mu_B$ SM ones.

But the dipole moments cannot be arbitrarily large.

The Dipole Moment – Mass Connection



Dipole Moment

Mass Term

$$\mu_\nu \sim \frac{eX}{\Lambda}$$

Scale of New Physics

$$m_\nu \sim X\Lambda$$

$$m_\nu \sim \frac{\Lambda^2}{2m_e}\frac{\mu_\nu}{\mu_B} \sim \left(\frac{\mu_\nu}{10^{-18}\mu_B}\right)\left(\frac{\Lambda}{1\mathrm{TeV}}\right)^2 \mathrm{eV}$$

(Bell *et al.*)

Any dipole moment leads to a contribution to the neutrino mass that grows with the scale Λ of the new physics behind the dipole moment.

The dipole moment must not be so large as to lead to a violation of the upper bound on neutrino masses.

The constraint —

$$m_\nu \sim \frac{\Lambda^2}{2m_e}\frac{\mu_\nu}{\mu_B} \sim \left(\frac{\mu_\nu}{10^{-18}\mu_B}\right)\left(\frac{\Lambda}{1\,\mathrm{TeV}}\right)^2 \mathrm{eV}$$

can be evaded by some new physics.

But the evasion can only go so far.

In the *Majorana* case, a *symmetry* suppresses the contribution of the dipole moment to the neutrino mass. So a bigger dipole moment is permissible. One finds —

For *Dirac* neutrinos, $\mu < 10^{-15}\,\mu_B$ for $\Lambda > 1$ TeV

For *Majorana* neutrinos, $\mu <$ ***Present Bound***

(Bell, Cirigliano, Davidson, Gorbahn, Gorchtein, Ramsey-Musolf, Santamaria, Vogel, Wise, Wang)

An observed μ below the present bound but well above $10^{-15}\ \mu_B$ would imply that neutrinos are Majorana particles.

A dipole moment that large requires L-violating new physics $\lesssim$ 1000 TeV.

Neutrinoless double beta decay at the planned level of sensitivity only requires this new physics at $\sim 10^{15}$ GeV, near the Grand Unification scale.

Searching for $0\nu\beta\beta$ is the more conservative way to probe whether $\bar{\nu} = \nu$.

Conclusion

Some very highly motivated experiments lie ahead.

We look forward to the results.