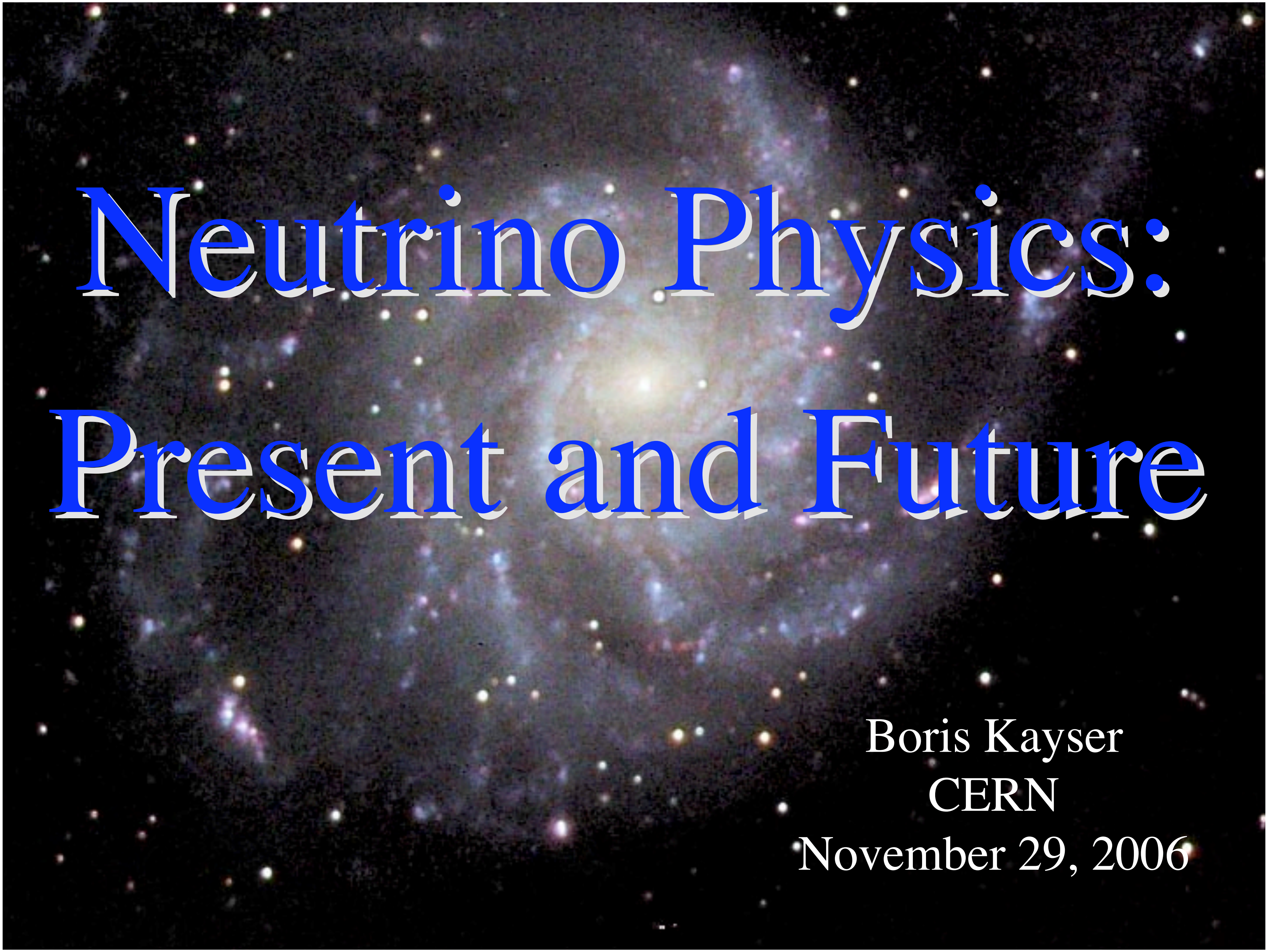

Neutrino Physics: Present and Future

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The Open
Questions

- What is the absolute scale of neutrino mass?

- Are neutrinos their own antiparticles?

- Are there “sterile” neutrinos?

We must be alert to surprises!

•What is the pattern of mixing among the different types of neutrinos?

What is θ_{13}? Is θ_{23} maximal?

•Is the spectrum like  or  ?

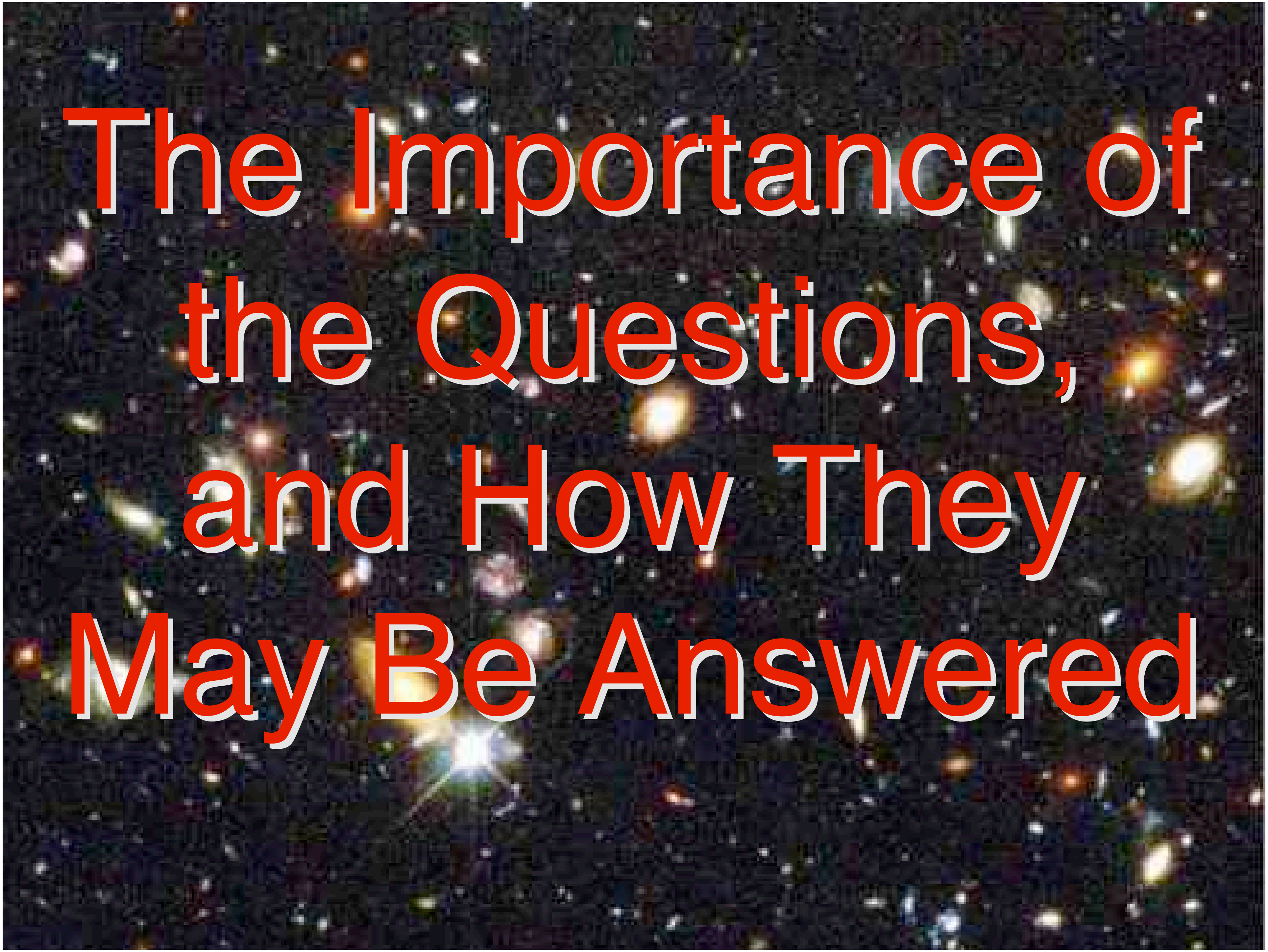
•Do neutrinos violate the symmetry CP?

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

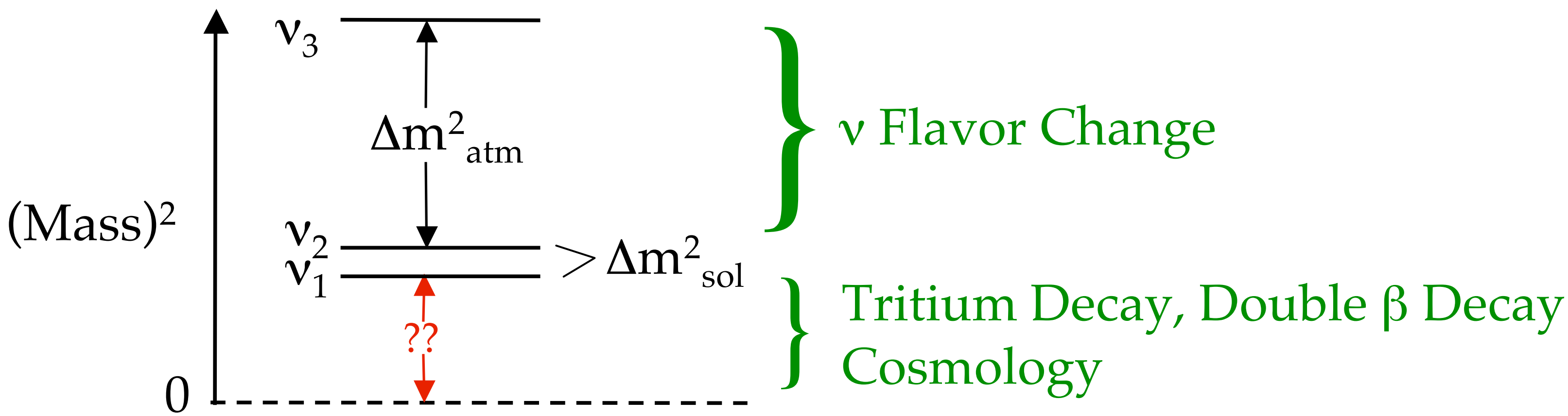
- What can neutrinos and the universe tell us about one another?

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

- What physics is behind neutrino mass?


The Importance of
the Questions,
and How They
May Be Answered

What Is the Absolute Scale of Neutrino Mass?



How far above zero
is the whole pattern?

A Cosmic Connection

Oscillation Data ⇒ $\sqrt{\Delta m^2_{atm}}$ < Mass[Heaviest ν_i]

Cosmological Data + Cosmological Assumptions ⇒

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

Mass(ν_i) ↑

(Seljak, Slosar, McDonald
Pastor)

If there are only 3 neutrinos,

$$0.04\ \text{eV} \lesssim \text{Mass[Heaviest } \nu_i] < (0.07 - 0.4)\ \text{eV}$$

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

Are Neutrinos Their Own Antiparticles?

What Is the Question?

For each *mass eigenstate* ν_i , does —

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

or

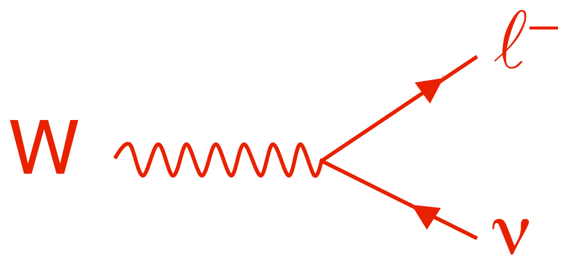
- $\overline{\nu}_i \neq \nu_i$ (Dirac neutrinos) ?

Equivalently, is the Lepton Number L defined by—
$L(\nu) = L(\ell^-) = -L(\overline{\nu}) = -L(\ell^+) = 1$ conserved?

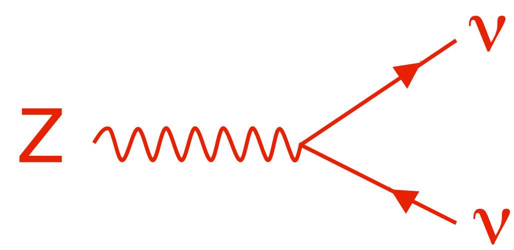
If not, then nothing distinguishes $\overline{\nu}_i$ from ν_i . We then have Majorana neutrinos.

How Can the Standard Model be Modified to Include Neutrino Masses?

The S(tandard) M(odel)



and

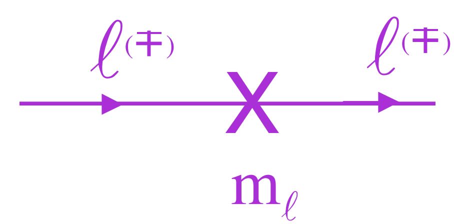


couplings conserve the Lepton Number L
defined by —

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

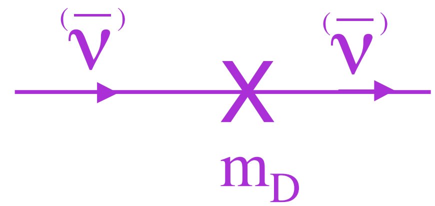
So do the Dirac charged-lepton mass terms

$$m_\ell \overline{\ell_L} \ell_R$$



- Original SM: $m_\nu = 0$.
- Why not add a Dirac mass term,

$$m_D \bar{\nu}_L \nu_R$$



Then everything conserves L, so for each mass eigenstate ν_i,

$$\bar{\nu}_i \neq \nu_i \qquad \text{(Dirac neutrinos)}$$

$$[L(\bar{\nu}_i) = - L(\nu_i)]$$

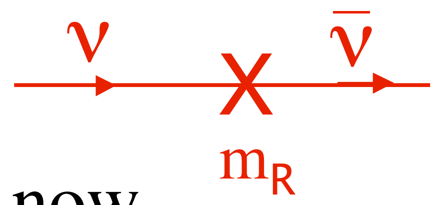
- The SM contains no ν_R field, only ν_L.

To add the Dirac mass term, we had to add ν_R to the SM.

Unlike ν_L, ν_R carries no Electroweak Isospin.

Thus, no SM principle prevents the occurrence of the Majorana mass term

$$m_R \overline{\nu_R{}^c}\, \nu_R$$



But this does not conserve L, so now

$$\bar{\nu}_i = \nu_i \qquad \text{(Majorana neutrinos)}$$

[No conserved L to distinguish $\bar{\nu}_i$ from ν_i]

We note that $\bar{\nu}_i = \nu_i$ means —

$$\bar{\nu}_i(h) = \nu_i(h)$$

helicity

The objects ν_R and $\nu_R{}^c$ in $m_R \overline{\nu_R{}^c} \nu_R$ are not the mass eigenstates, but just the neutrinos in terms of which the model is constructed.

$m_R \overline{\nu_R{}^c} \nu_R$ induces $\nu_R \leftrightarrow \nu_R{}^c$ mixing.

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

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

As a result of $\nu_R \leftrightarrow \nu_R{}^c$ mixing, the neutrino mass eigenstate is —

$$\nu_i = \nu_R + \nu_R{}^c = \text{“} \, \nu + \overline{\nu} \, \text{”} \, .$$

Many Theorists Expect Majorana Masses

The Standard Model (SM) is defined by the fields it contains, its symmetries (notably Electroweak Isospin Invariance), and its renormalizability.

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

If this is also true for neutrino masses, then neutrinos have Majorana masses.

- The presence of Majorana masses
- $\overline{\nu_i} = \nu_i$ (Majorana neutrinos)
- L not conserved

— are all equivalent

Any one implies the other two.

(Recent work: Hirsch, Kovalenko, Schmidt)

To Determine If Neutrinos Are Majorana Particles

The Promising Approach —

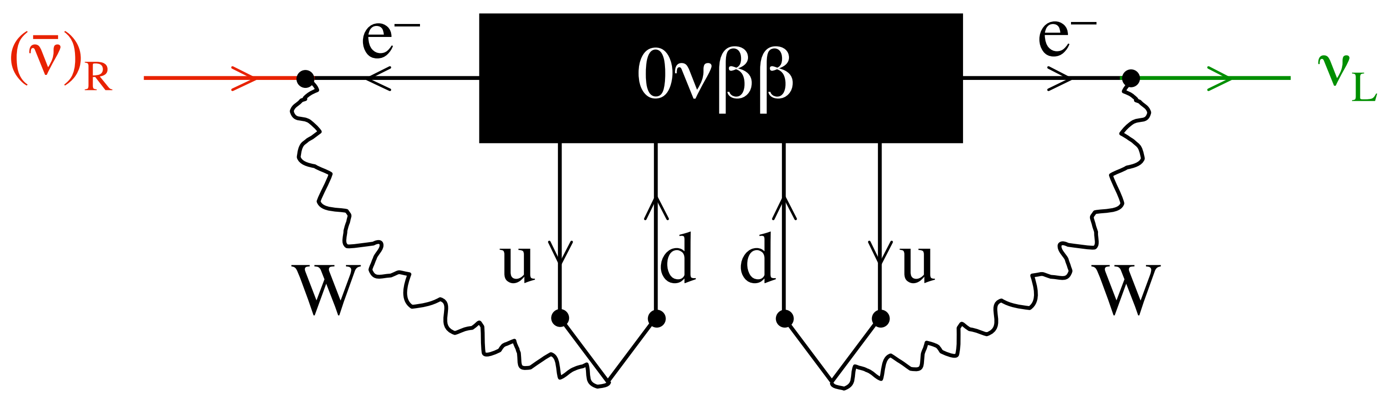
Neutrinoless Double Beta Decay [$0\nu\beta\beta$]

If we start with ***a lot*** of parent nuclei (say, one ton of them), we can cope with the smallness of $\not{L}$.

Observation would imply $\not{L}$ and $\bar{\nu}_i = \nu_i$.

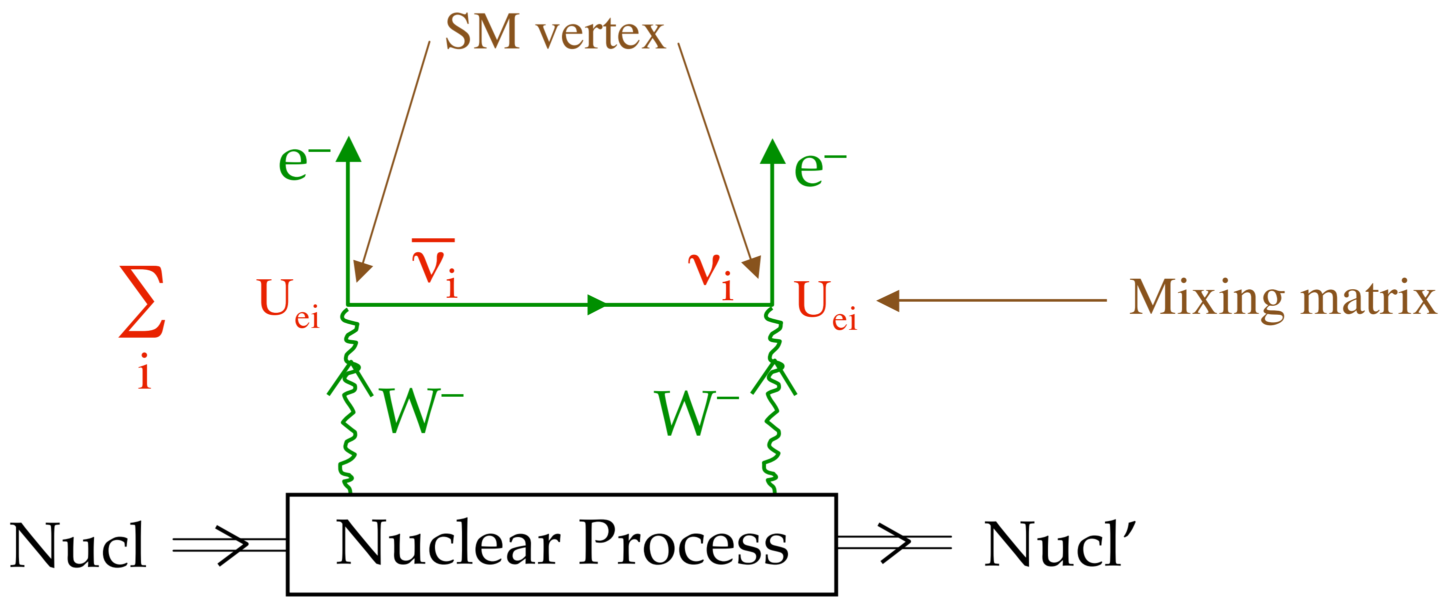
Whatever diagrams cause $0\nu\beta\beta$, its observation would imply the existence of a Majorana mass term:

Schechter and Valle

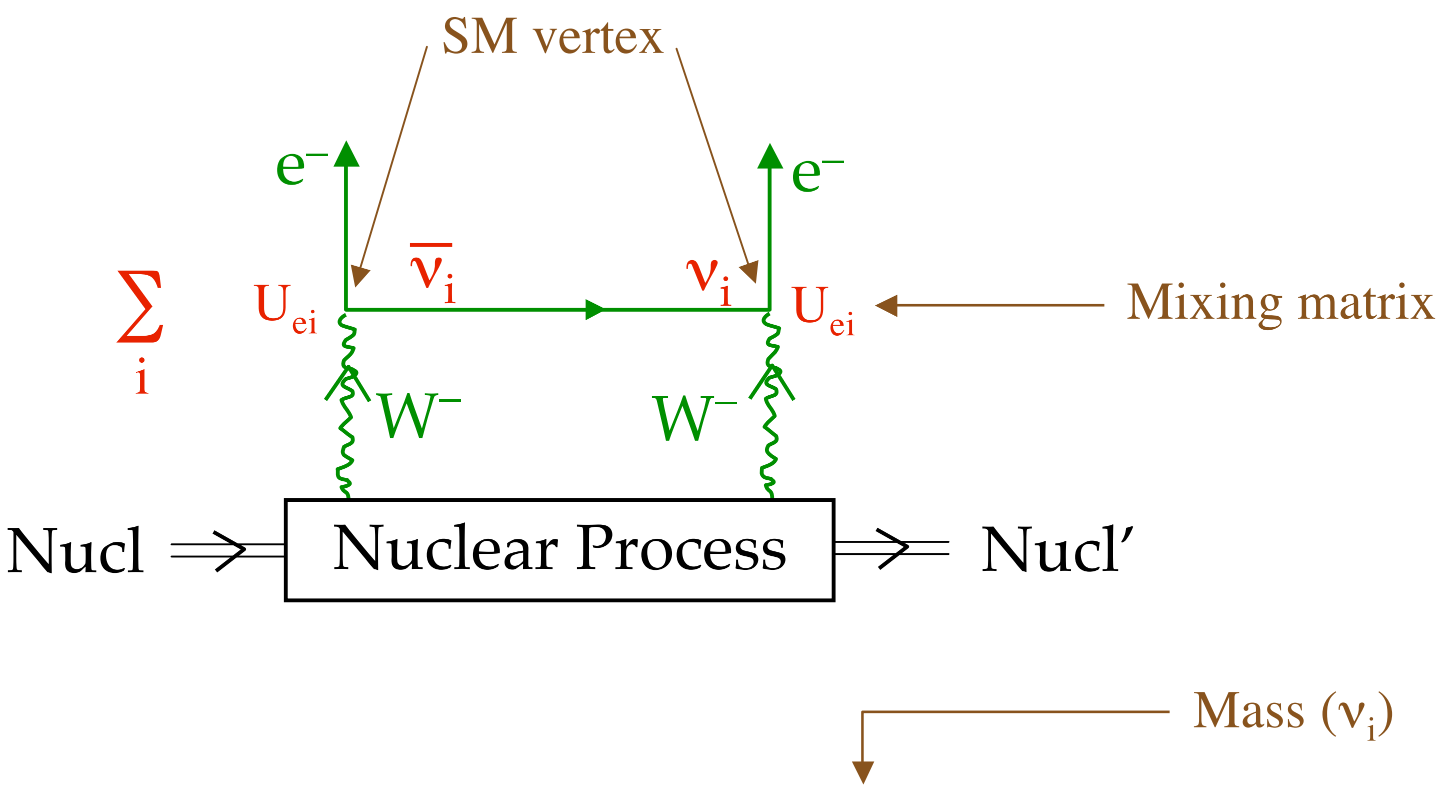


$(\bar{\nu})_R \rightarrow \nu_L$: A Majorana mass term

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



In —



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

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

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

The proportionality of $0\nu\beta\beta$ to mass is no surprise.

$0\nu\beta\beta$ violates L. But the SM interactions conserve L.

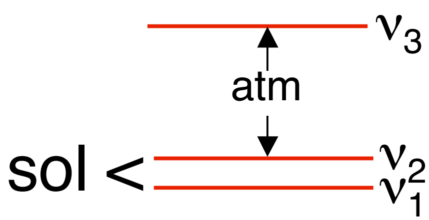
The L – violation in $0\nu\beta\beta$ comes from underlying **Majorana mass terms**.

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

How sensitive need an experiment be?

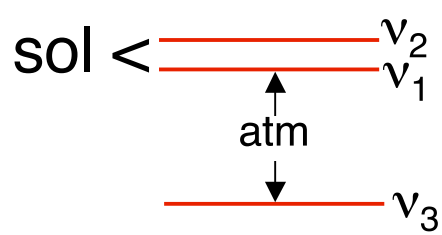
Suppose there are only 3 neutrino mass eigenstates. (More might help.)

Then the spectrum looks like —

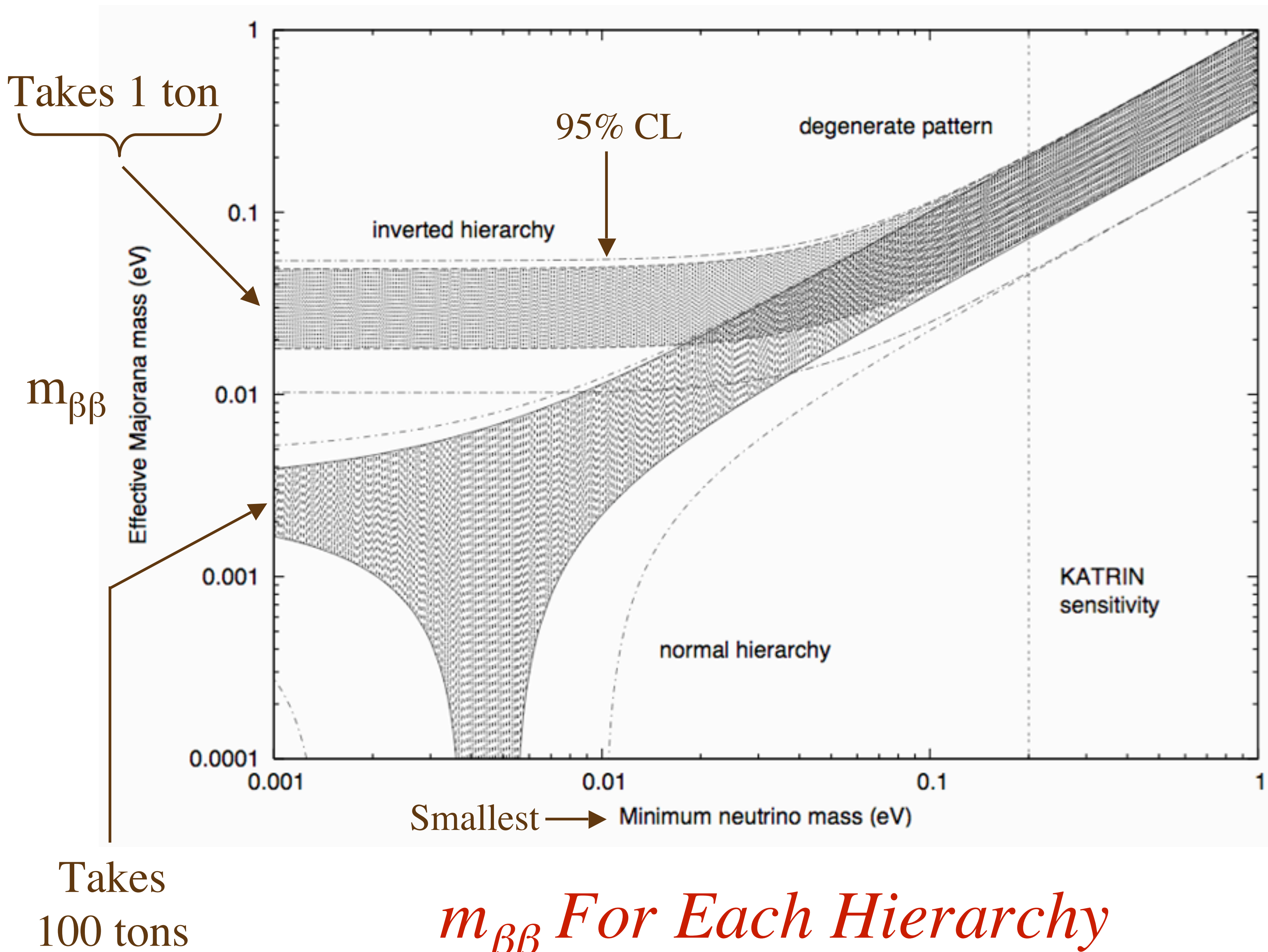


Normal hierarchy

or



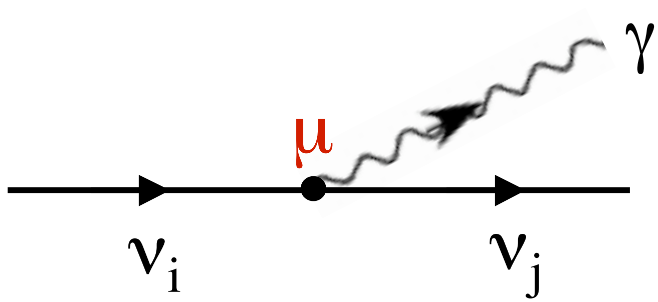
Inverted hierarchy



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

Possible Information From Neutrino Magnetic Moments

Both Majorana and Dirac neutrinos can have *transition* magnetic dipole moments μ:



For *Dirac* neutrinos, $\mu < 10^{-15}\ \mu_{Bohr}$

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

$$\text{Present bound} = \begin{cases} 7 \times 10^{-11}\ \mu_{Bohr} & ; \text{Wong et al. (Reactor)} \\ 3 \times 10^{-12}\ \mu_{Bohr} & ; \text{Raffelt (Stellar E loss)} \end{cases}$$

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

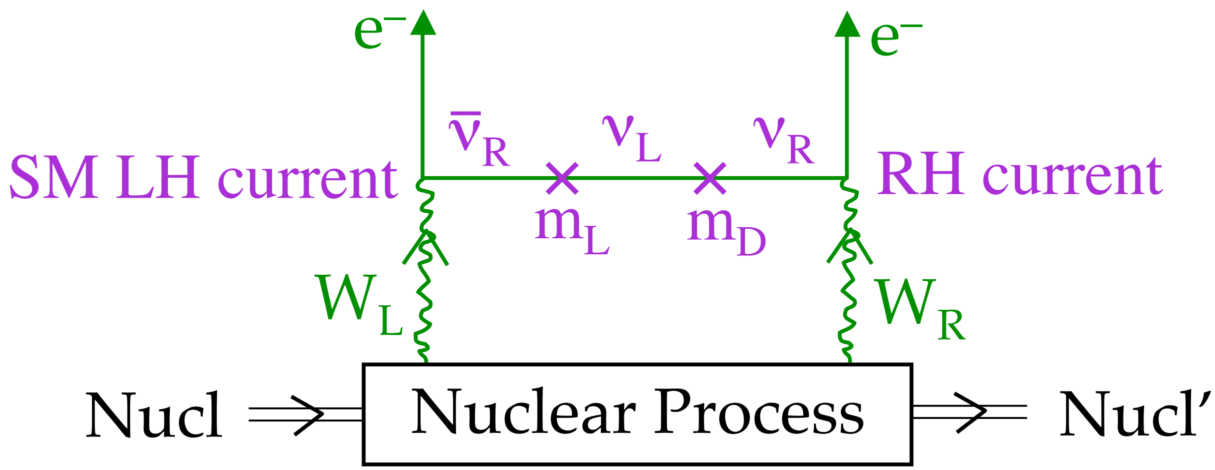
However, a dipole moment that large requires L-violating new physics below 100 TeV.

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

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

Backup Slides

Wouldn't the dependence on neutrino mass be eliminated by a Right-Handed Current?



The SM LH current does not violate L.

An identical current, but of opposite handedness, wouldn't violate L either.

We still need the L-violating Majorana neutrino mass to make this process occur.

With a RH current at one vertex,

$$\text{Amp}[0\nu\beta\beta] \propto (\nu\ \text{mass})^2\ .$$

Contributions with a RH current at one vertex
are not likely to be significant.

$$\left\{\begin{matrix}\text{BK, Petcov, Rosen} \\ \text{Enqvist, Maalampi, Mursula}\end{matrix}\right\}$$