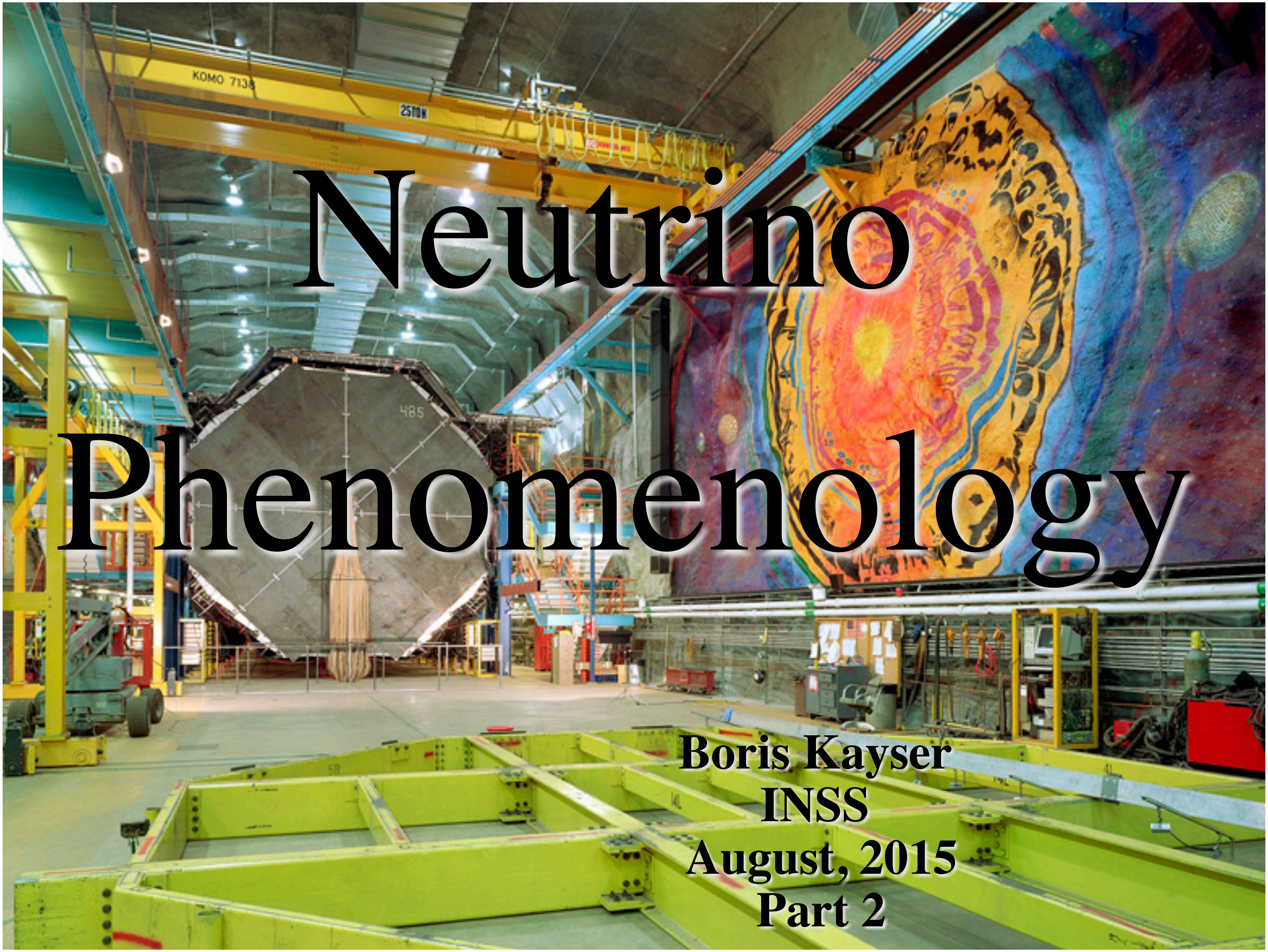

Neutrino Phenomenology

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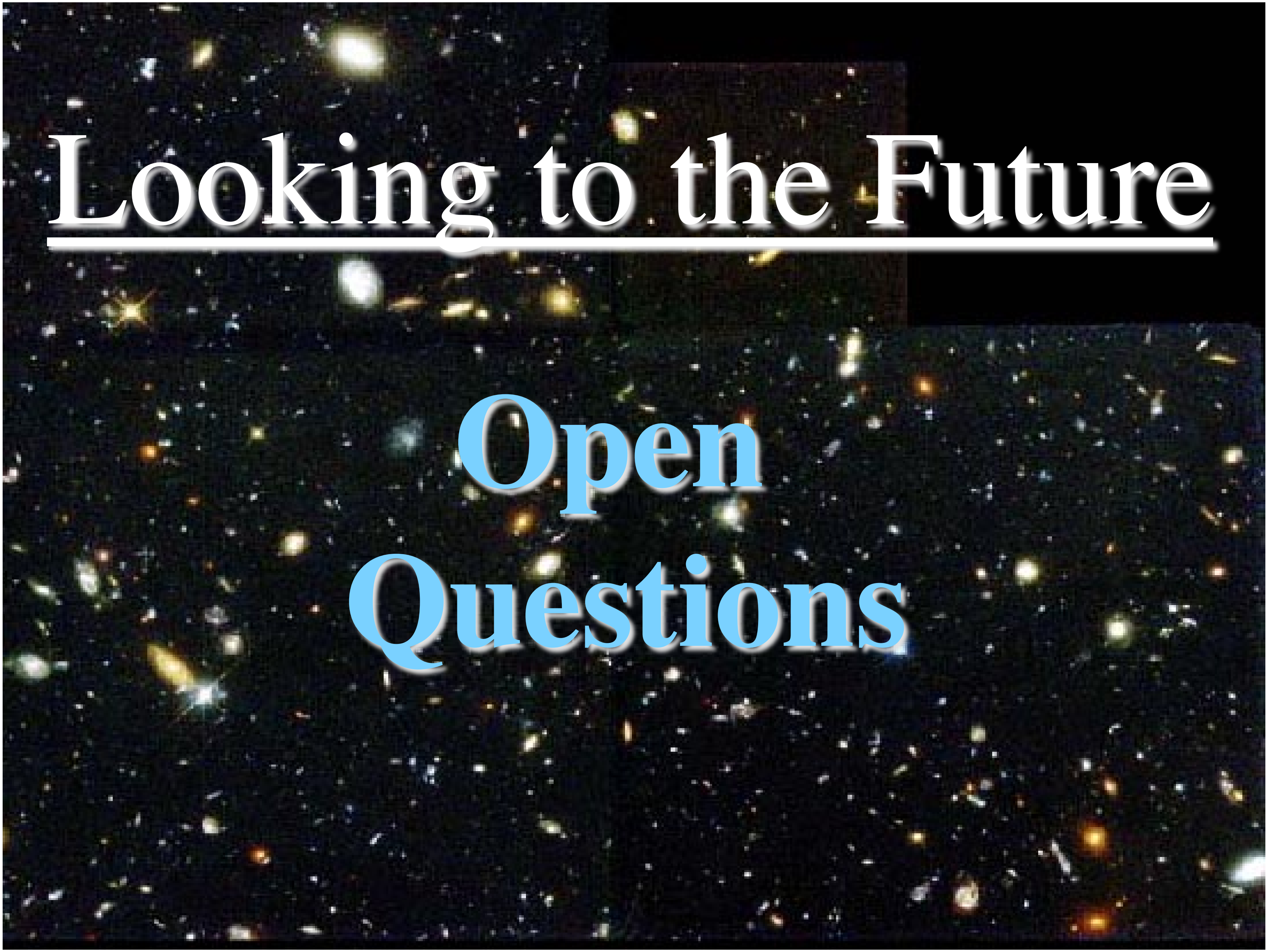
INSS
August, 2015
Part 2



Looking to the Future

Open Questions

- Is the physics behind the masses of neutrinos different from that behind the masses of all other known particles?
- Are neutrinos their own antiparticles?

- Is the $(\text{mass})^2$ spectrum like  or  ?

- What is the absolute scale of neutrino mass?

- Do neutrino interactions violate CP?

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

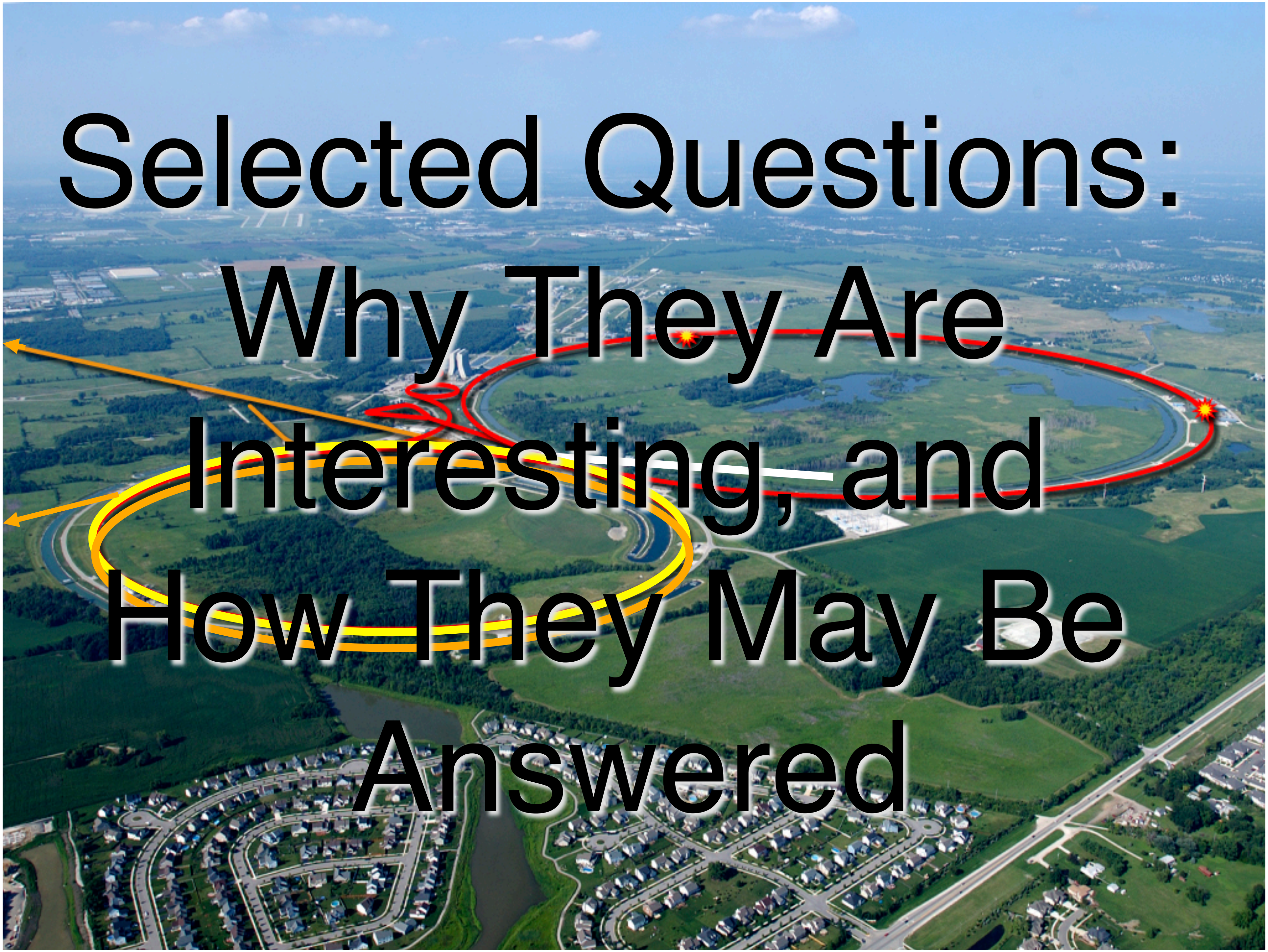
- Is CP violation involving neutrinos the key to understanding the matter – antimatter asymmetry of the universe?
- Are we descended from heavy neutrinos?

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

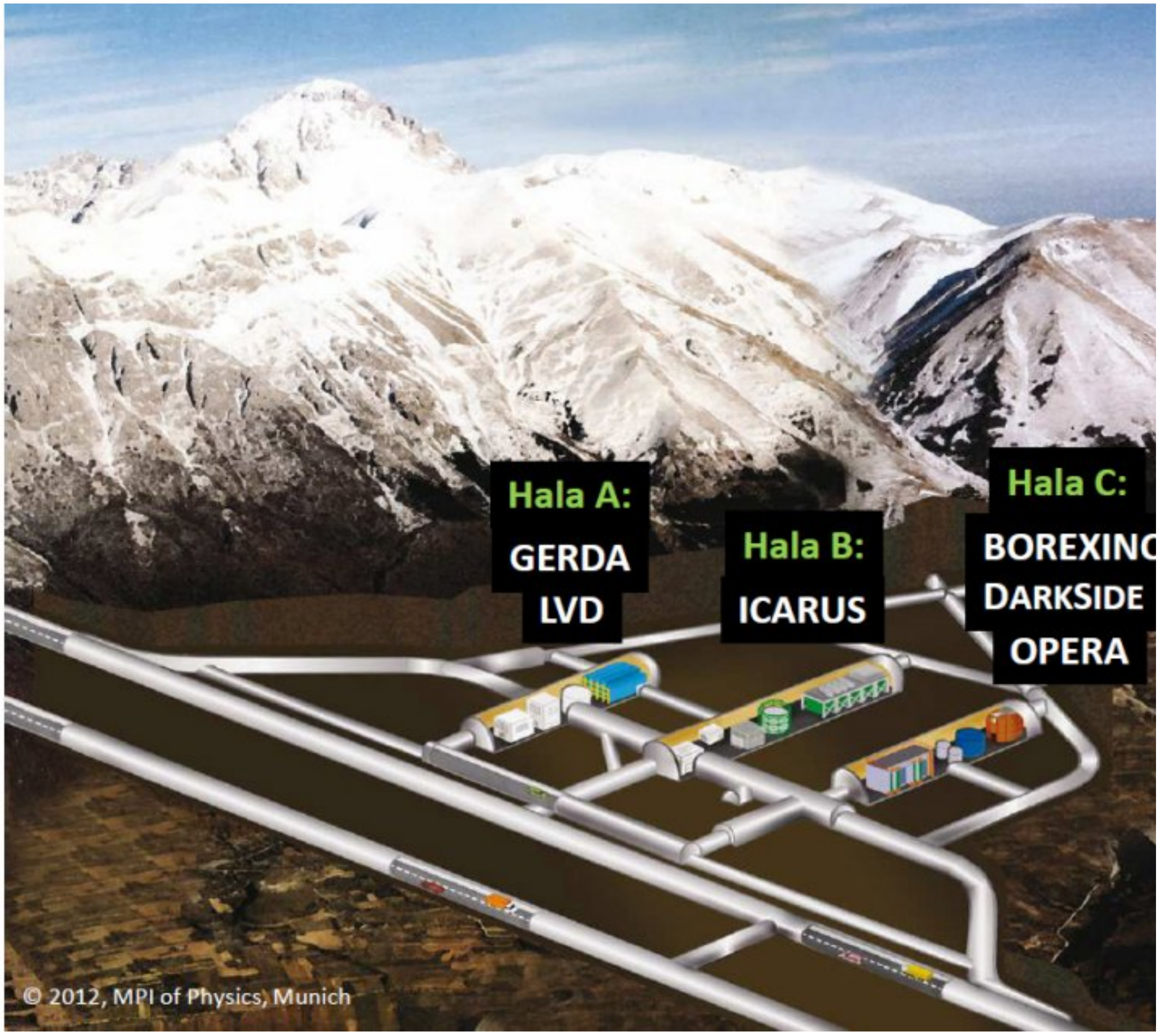
- Are there *more* than 3 mass eigenstates?
  - Are there non-weakly-interacting "sterile" neutrinos?

- Do neutrinos have Non-Standard-Model interactions?

- Do neutrinos break the rules?
  - Violation of Lorentz invariance?
  - Violation of CPT invariance?
  - Departures from quantum mechanics?



Selected Questions: Why They Are Interesting, and How They May Be Answered



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Is the Origin of Neutrino Mass Different?

Perhaps, neutrino masses have the same source as the quark and charged lepton masses:

The Standard Model (SM) Brout – Englert – Higgs mechanism for fermion masses.

Coupling constant

Must add to the SM

$$\mathcal{L}_{SM} = y\overline{H}^0\overline{\nu}_L\nu_R \Rightarrow y\underbrace{\left\langle \overline{H}^0 \right\rangle_0}_{\text{Vacuum expectation value}}\overline{\nu}_L\nu_R \equiv m_\nu\overline{\nu}_L\nu_R \leftarrow \left\{ \textbf{Dirac mass} \right.$$

SM Higgs field

$$\left\langle \overline{H}^0 \right\rangle_0 \equiv v = 174\text{ GeV}\,,\quad \text{so}\quad y = \frac{m_\nu}{v} \sim \frac{0.1\,\text{eV}}{174\text{ GeV}} \sim 10^{-12}$$

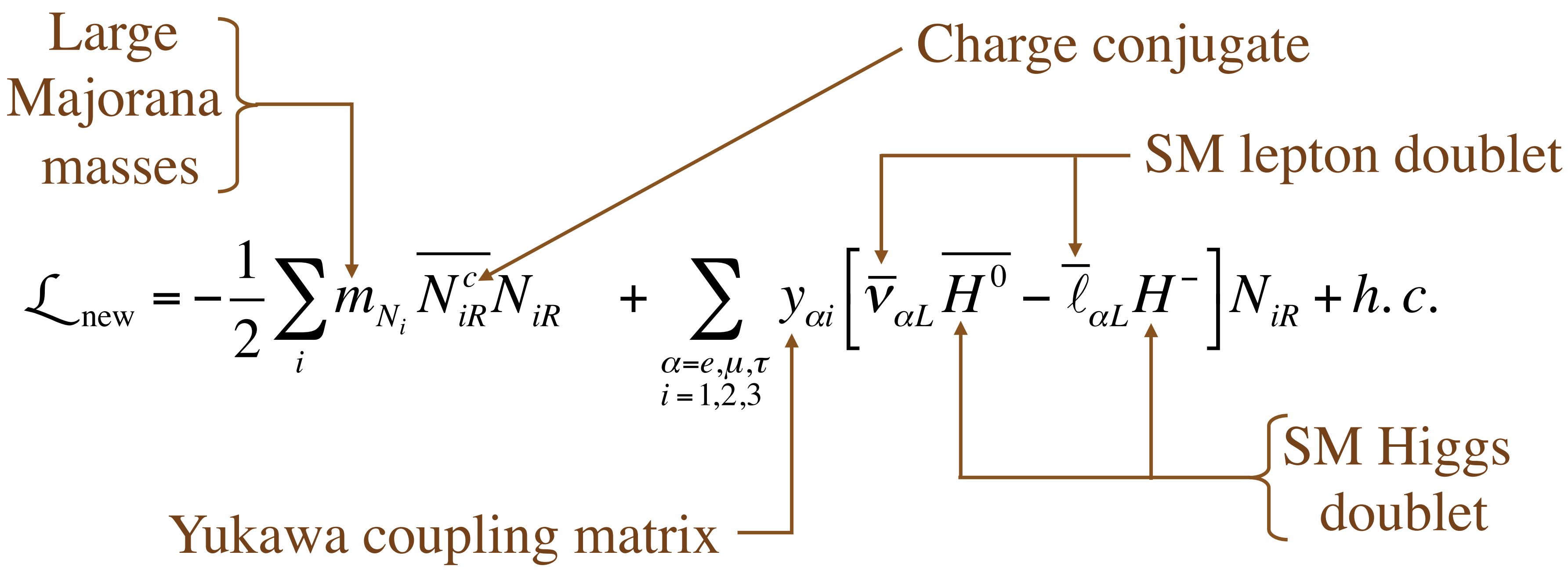
A coupling constant this much smaller than unity leaves many theorists skeptical.

— An alternative possibility —

Majorana masses and the **See-Saw** picture

The See-Saw model is the most popular theory of why neutrinos are so light.

The straightforward (type-I) See-Saw model adds to the SM 3 heavy neutrinos N_i, with —



Large Majorana masses

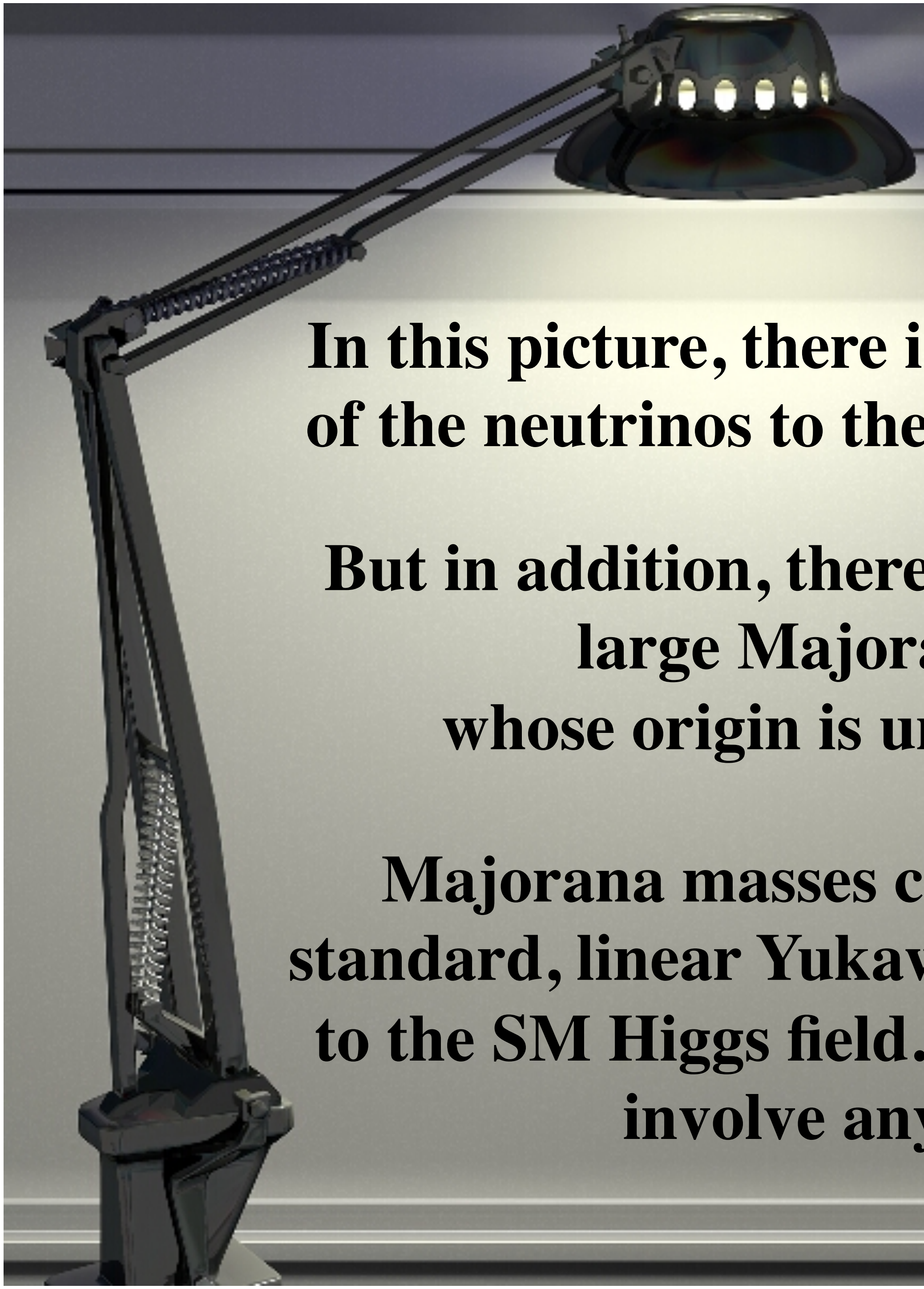
Charge conjugate

SM lepton doublet

$$\mathcal{L}_{\text{new}} = -\frac{1}{2}\sum_i m_{N_i}\overline{N^c_{iR}}N_{iR} + \sum_{\substack{\alpha=e,\mu,\tau\\ i=1,2,3}} y_{\alpha i}\left[\overline{\nu}_{\alpha L}\overline{H^0} - \overline{\ell}_{\alpha L}H^-\right]N_{iR} + h.c.$$

SM Higgs doublet

Yukawa coupling matrix

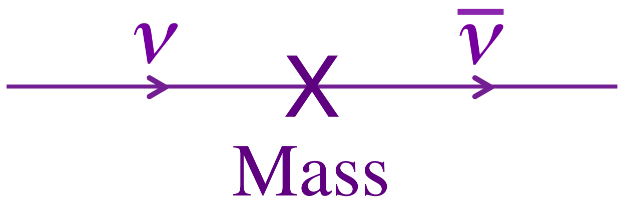


In this picture, there is still a coupling
of the neutrinos to the SM Higgs field.

But in addition, there is a new ingredient:
large Majorana masses,
whose origin is unknown physics.

Majorana masses cannot come from the standard, linear Yukawa coupling of neutrinos to the SM Higgs field. These masses need not involve any scalar field.

Majorana mass terms have the effect —



(Or the reverse)

Because they mix neutrino and antineutrino,
they do not conserve $L \equiv \#(\text{Leptons}) - \#(\text{Antileptons})$.

There is then no conserved quantum number
to distinguish antineutrinos from neutrinos.

Consequence: The neutrino mass eigenstates ν_1, ν_2, ν_3 are their own antiparticles.

$$\bar{\nu}_i = \nu_i$$ (for given helicity)

Majorana neutrinos

The Terminology

Suppose ν_i is a ***mass eigenstate,***

with given helicty h.

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

or

- $\overline{\nu}_i(h) \neq \nu_i(h)$ *Dirac neutrino*

If neutrinos have *Majorana masses*, then the mass eigenstates are *Majorana neutrinos*.

Neutrinos are *Special*

A Majorana mass for any fermion f causes $f \longleftrightarrow \bar{f}$.

Therefore, *quark* and *charged-lepton* Majorana masses are forbidden by electric charge conservation.

Among the fermionic constituents of matter, only the neutrinos can have Majorana masses.

Neutrino masses can have a different origin than the masses of all other particles.

Lepton Number *L*

The lepton number *L* (not lepton *flavor*) is defined by —

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

$$\text{or} \quad L \equiv \#(\text{Leptons}) - \#(\text{Antileptons}).$$

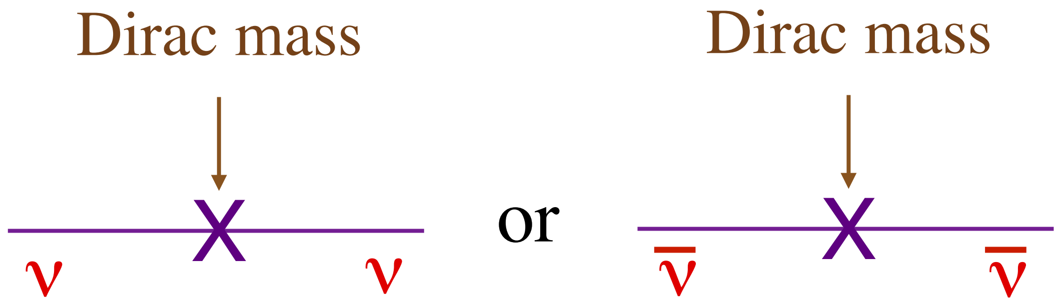
The SM weak interactions conserve *L*:

$$\mathcal{L}_{SM} = -\frac{g}{\sqrt{2}} \sum_{\substack{\alpha = e,\mu,\tau \\ i=1,2,3}} \left(\overline{\ell}_{L\alpha} \gamma^\lambda U_{\alpha i} \nu_{Li} W_\lambda^- + \overline{\nu}_{Li} \gamma^\lambda U_{\alpha i}^* \ell_{L\alpha} W_\lambda^+ \right)$$

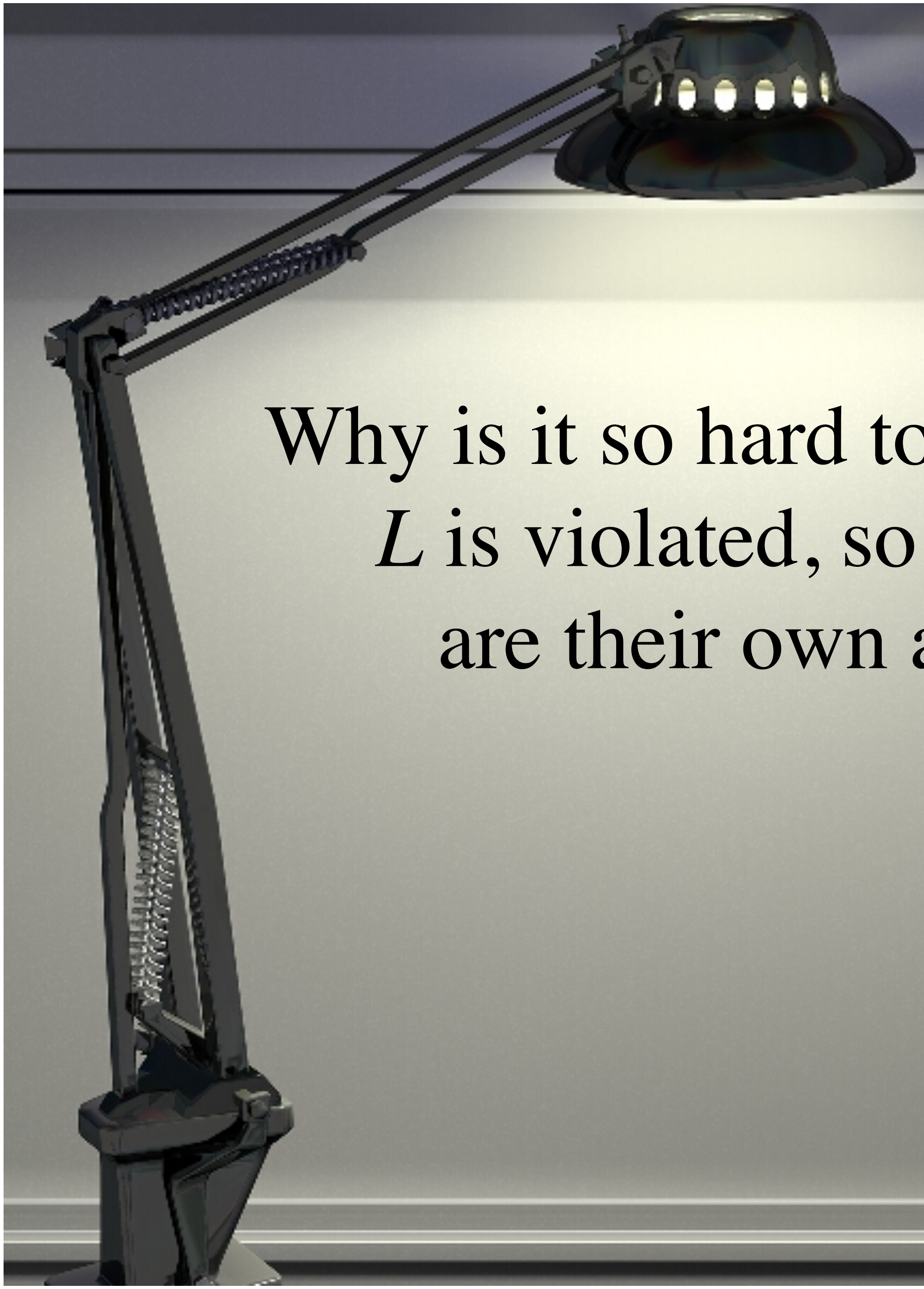
$$\nu \longrightarrow \ell \qquad\qquad \overline{\nu} \longrightarrow \overline{\ell}$$

So do ***Dirac*** masses.

A ***Dirac*** mass has the effect:



If there are no visibly large non-SM interactions that violate lepton number L, any violation of L that we might discover would have to come from Majorana neutrino masses.

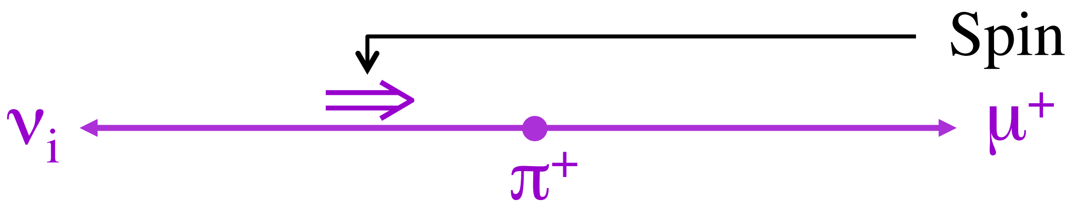


Why is it so hard to find out whether *L* is violated, so that neutrinos are their own antiparticles?

We assume neutrino ***interactions*** are correctly described by the SM. Then the ***interactions*** conserve L ($\nu \rightarrow \ell^-$; $\bar{\nu} \rightarrow \ell^+$).

An Idea that Does Not Work
[and illustrates why most ideas do not work]

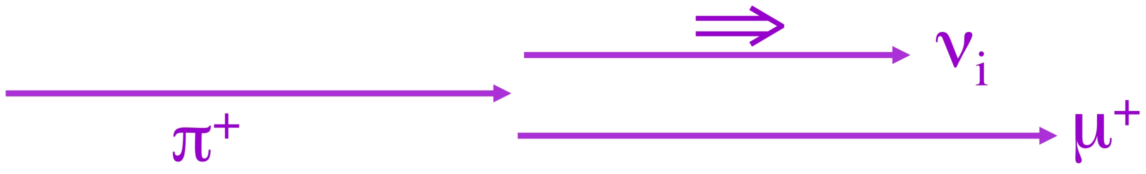
Produce a ν_i via—



Pion Rest Frame

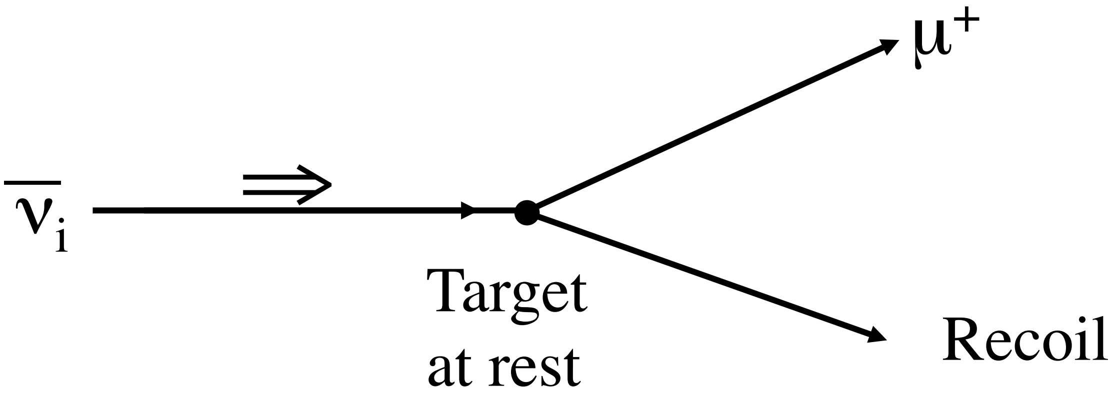
Give the neutrino a Boost:

$\beta_\pi(\text{Lab}) > \beta_\nu(\pi \text{ Rest Frame})$



Lab. Frame

The SM weak interaction causes—



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

helicity

If $\nu_i \xrightarrow{\Rightarrow} = \bar{\nu}_i \xrightarrow{\Rightarrow}$,

our $\nu_i \xrightarrow{\Rightarrow}$ will make μ^+ too.

Minor Technical Difficulties

$$\beta_\pi(\text{Lab}) \;>\; \beta_\nu(\pi \text{ Rest Frame})$$

$$\Rightarrow \frac{E_\pi(\text{Lab})}{m_\pi} > \frac{E_\nu(\pi \text{ Rest Frame})}{m_{\nu_i}}$$

$$\Rightarrow E_\pi(\text{Lab}) \gtrsim 10^5 \text{ TeV if } m_{\nu_i} \sim 0.05 \text{ eV}$$

Fraction of all π – decay ν_i that get helicity flipped

$$\approx \left(\frac{m_{\nu_i}}{E_\nu(\pi \text{ Rest Frame})}\right)^2 \sim 10^{-18} \text{ if } m_{\nu_i} \sim 0.05 \text{ eV}$$

Since *L*-violation comes only from Majorana neutrino ***masses***, any attempt to observe it will be at the mercy of the tiny neutrino masses.

(B.K. & Stodolsky)

So what approach ***does*** work?

- **Presence of Majorana masses**
- **Non-conservation of *L***
- **Self-conjugacy of neutrinos ($\bar{\nu} = \nu$)**

— are all signature predictions of the See-Saw picture.

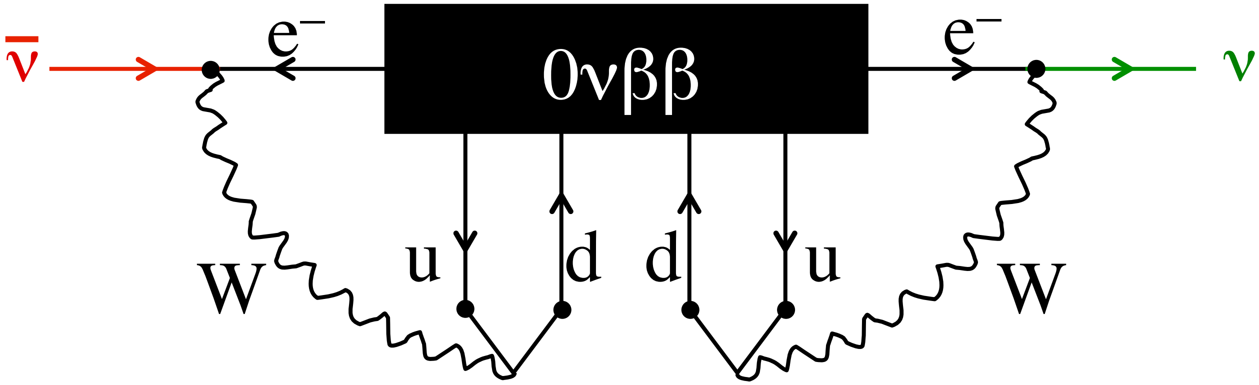
All three predictions would be confirmed by the observation of neutrinoless double beta decay (0νββ)

$\Delta L = 2$

does not conserve L.

Whatever diagrams cause 0νββ, its observation would imply the existence of a Majorana mass term:

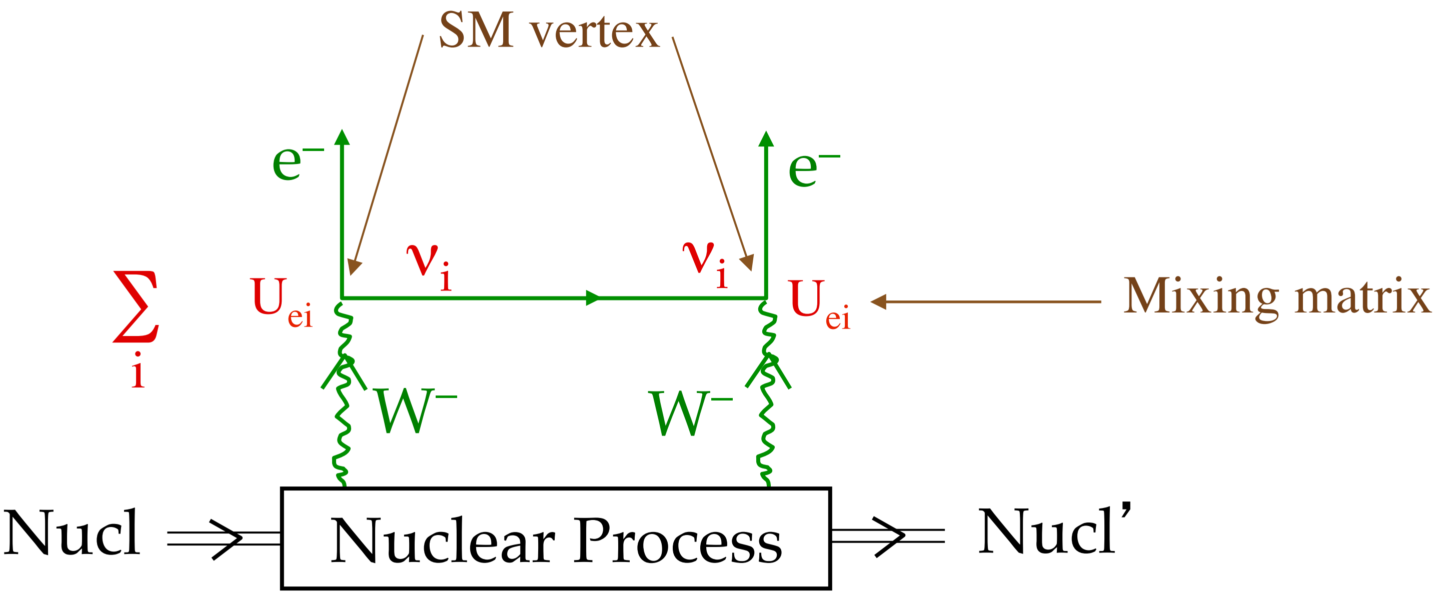
(Schechter and Valle)



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

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

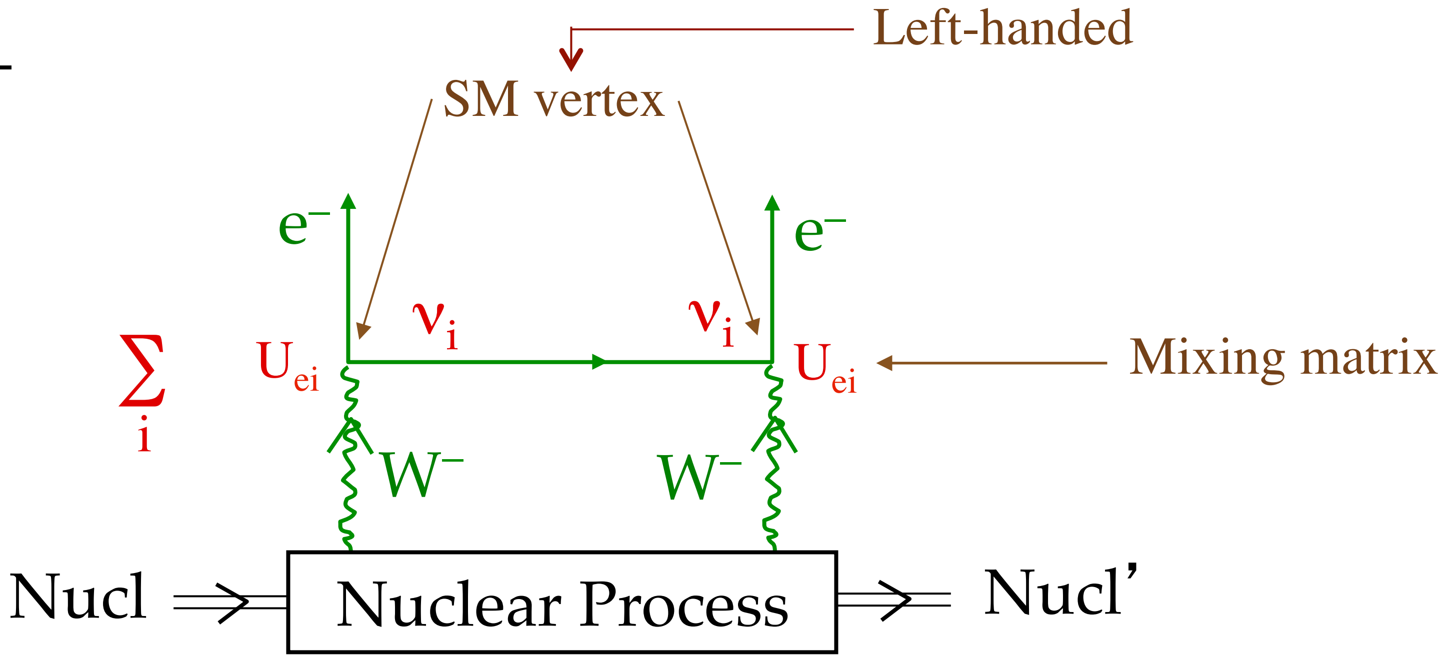
We anticipate that 0νββ is dominated by a diagram with light neutrino exchange and Standard Model vertices:



“The Standard Mechanism”

Amplitude for the Standard Mechanism

In —



Left-handed

SM vertex

Mixing matrix

Mass (ν_i)

the ν_i is emitted [RH + O{m_i/E}LH].

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

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

Origin Of the Proportionality To Mass

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

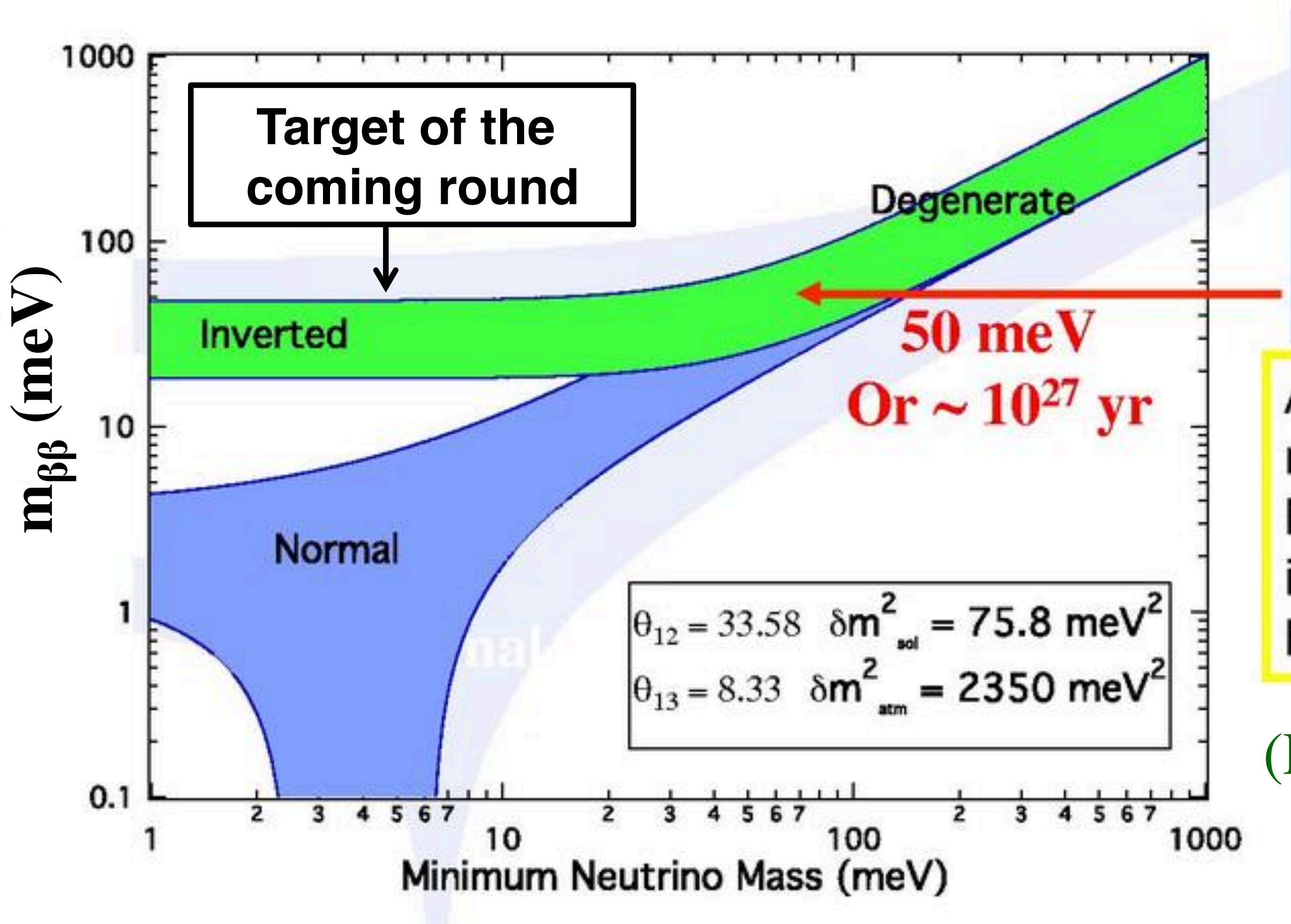
But the Standard Model (SM) weak interactions ***do*** conserve L.

Thus, the $\Delta L = 2$ of $0\nu\beta\beta$ can only come from *Majorana neutrino masses*.

In the standard mechanism, the amplitude for $0\nu\beta\beta$ must vanish when the neutrino masses do.

ββ Sensitivity

(mixing parameters from arXiv:1106.6028)



Target of the coming round

50 meV
Or ~ 10^{27} yr

Even a null result will constrain the possible mass spectrum possibilities!

A $m_{\beta\beta}$ limit of ~15 meV would disfavor Majorana neutrinos in an inverted hierarchy.

(From Steve Elliott)

Present bound: $T_{1/2}^{0\nu\beta\beta}\left({}^{76}\text{Ge}\right) > 3.0 \times 10^{25}\,\text{yr}\;(90\%\ \text{CL})$ (GERDA +)

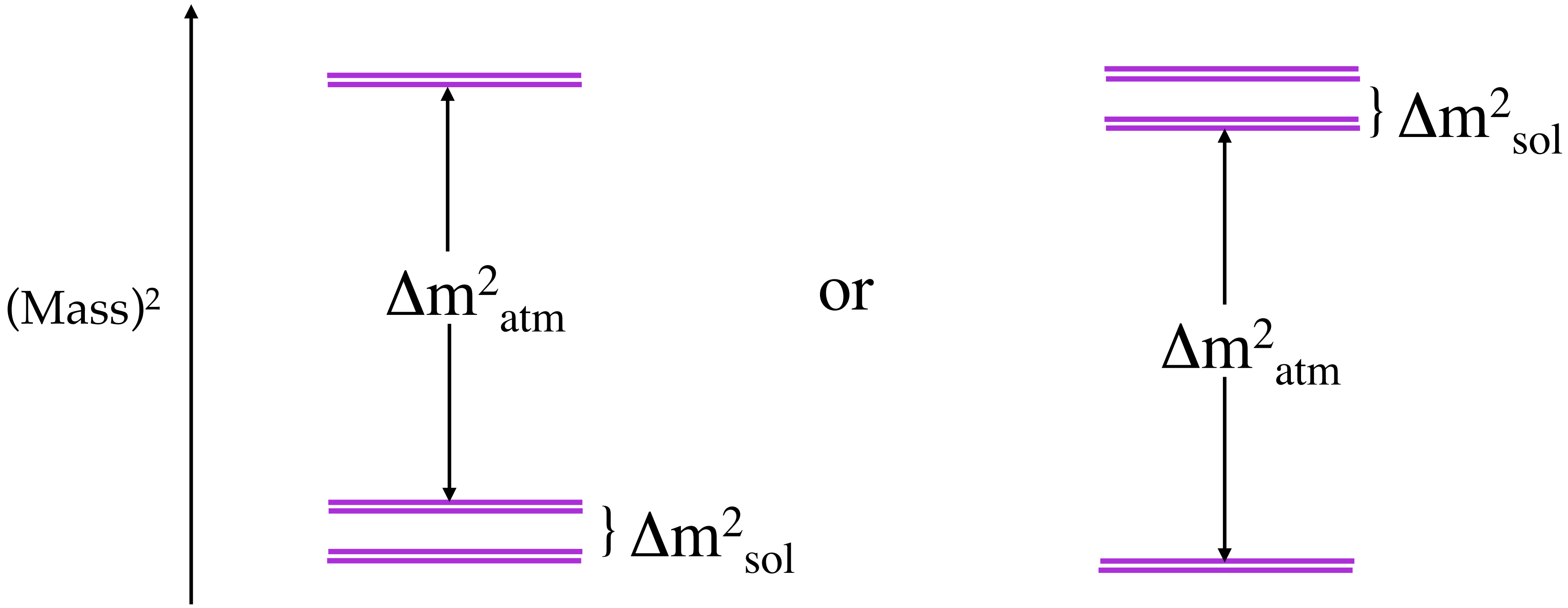
Observation of **$0\nu\beta\beta$** at any non-zero level would imply —

- Lepton number L is not conserved ($\Delta L = 2$)
- Neutrinos have Majorana masses
- Neutrinos are Majorana particles (self-conjugate)

But 

Knowing the mass spectrum is  , and establishing a $T_{1/2}^{0\nu\beta\beta}$ bound larger than what corresponds to $m_{\beta\beta} = 15$ meV, would ***not prove*** that neutrinos are Dirac particles.

One Loophole: A Doubled Spectrum

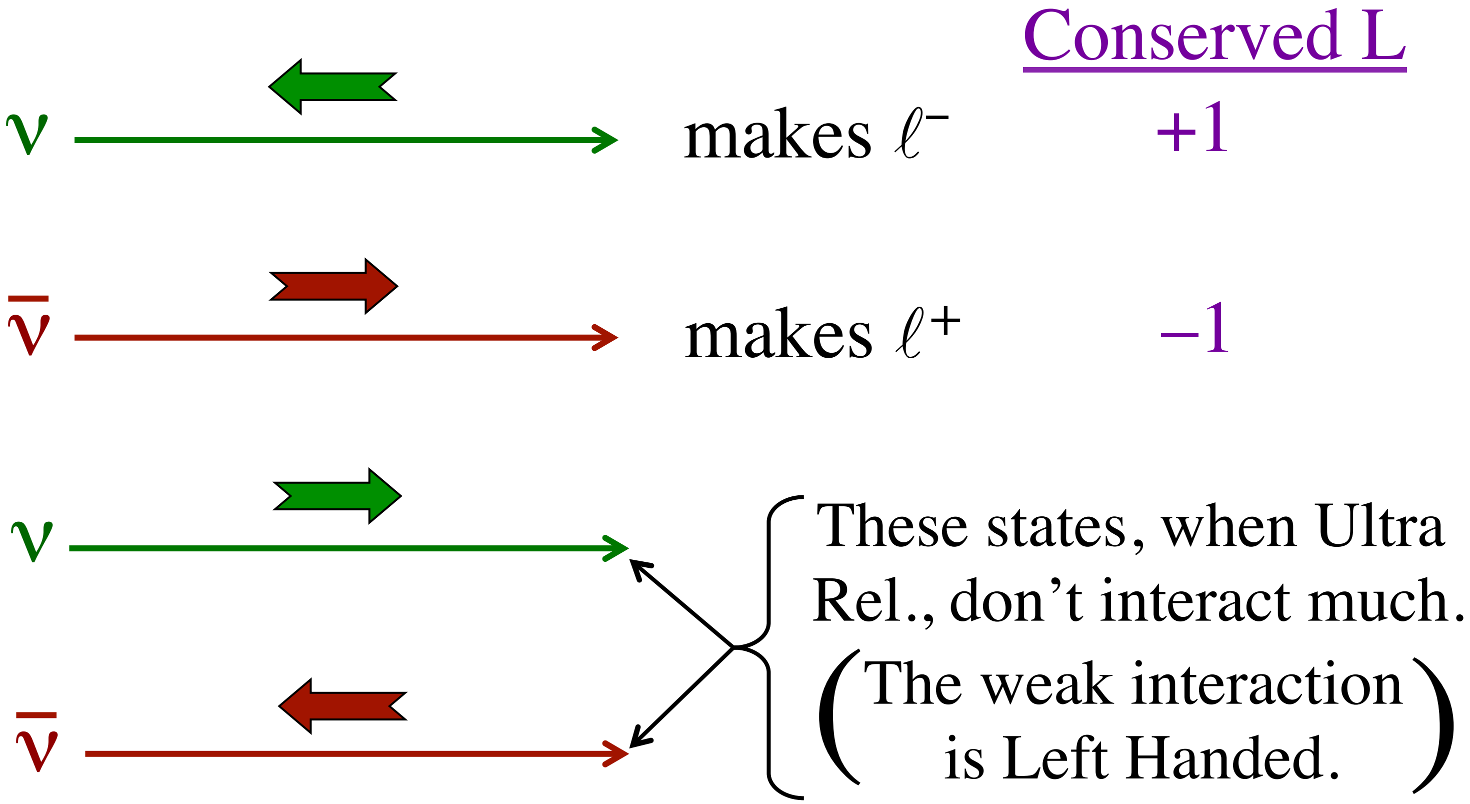


The small spacings can be too small to have been detected in neutrino oscillation.

Each pair is split by a tiny Majorana mass, and its contributions to $\Sigma\, m_i U_{ei}^2$ almost cancel.

SM Interactions Of A Dirac Neutrino

We have 4 mass-degenerate states:

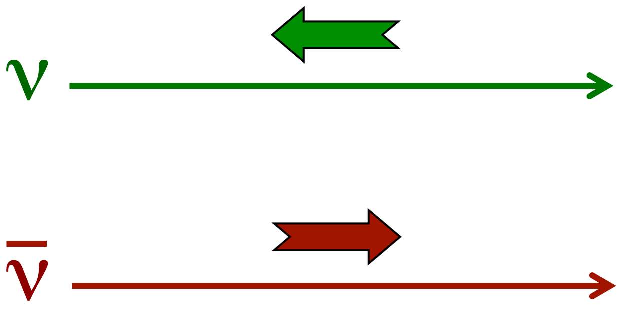


		Conserved L
ν	makes ℓ^-	+1
$\bar{\nu}$	makes ℓ^+	–1
ν		
$\bar{\nu}$		

These states, when Ultra Rel., don’t interact much.
(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 *Left-Handed* weak interactions violate *parity*.

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

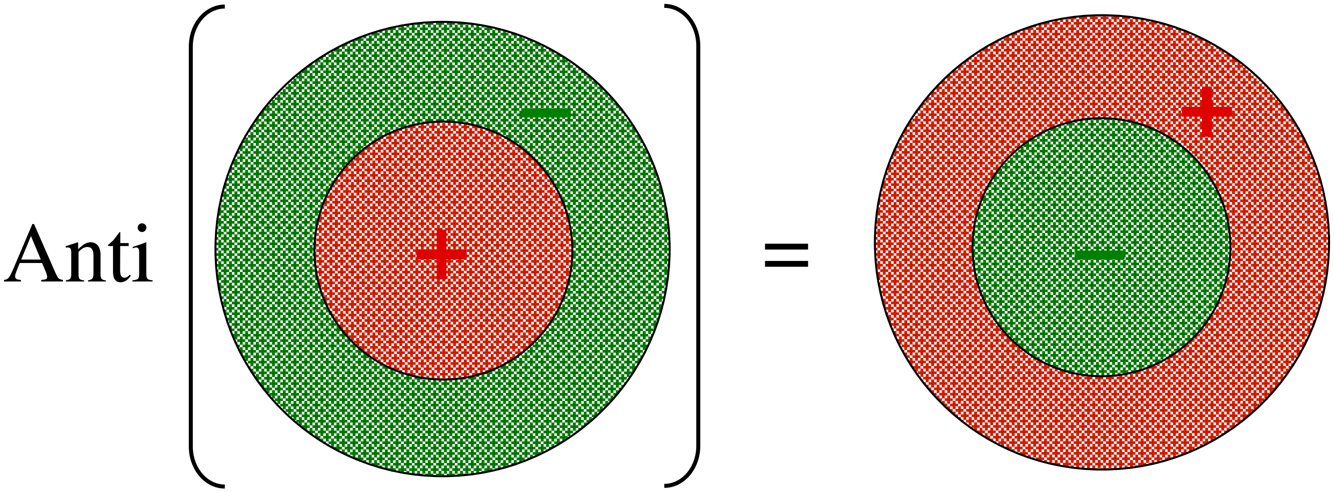
An incoming left-handed neutral lepton makes ℓ^-.

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

Some Electromagnetic Properties of Neutrinos

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

No!

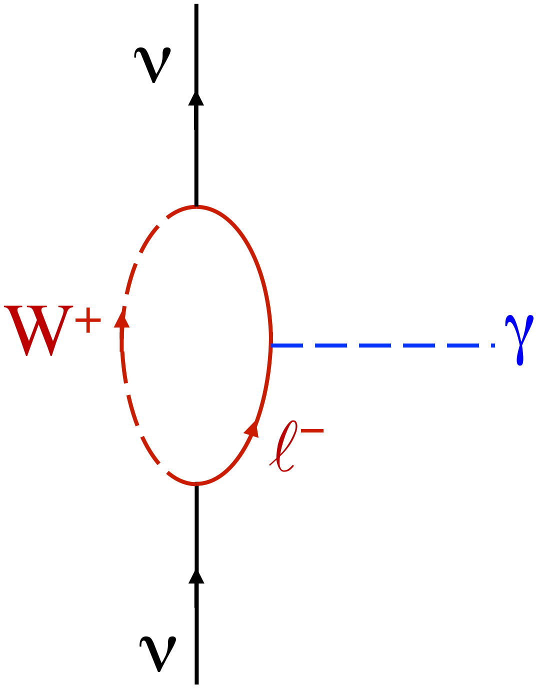


But for a Majorana neutrino —

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 —

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

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

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

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

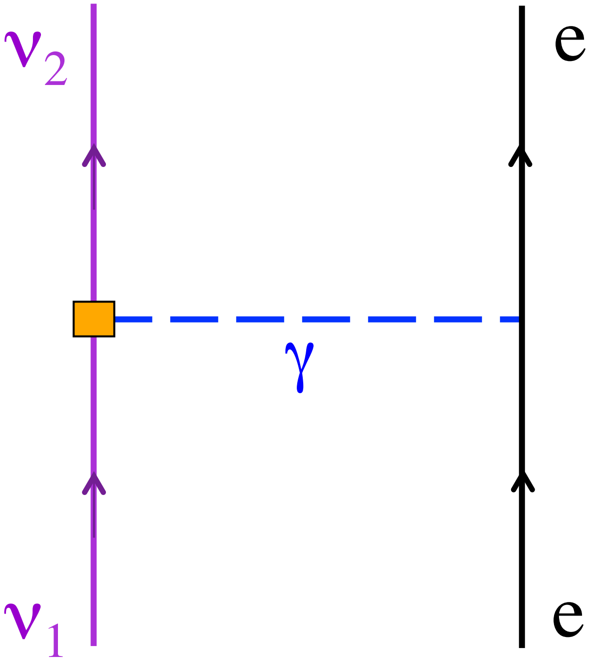
But for a Majorana neutrino,

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

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.