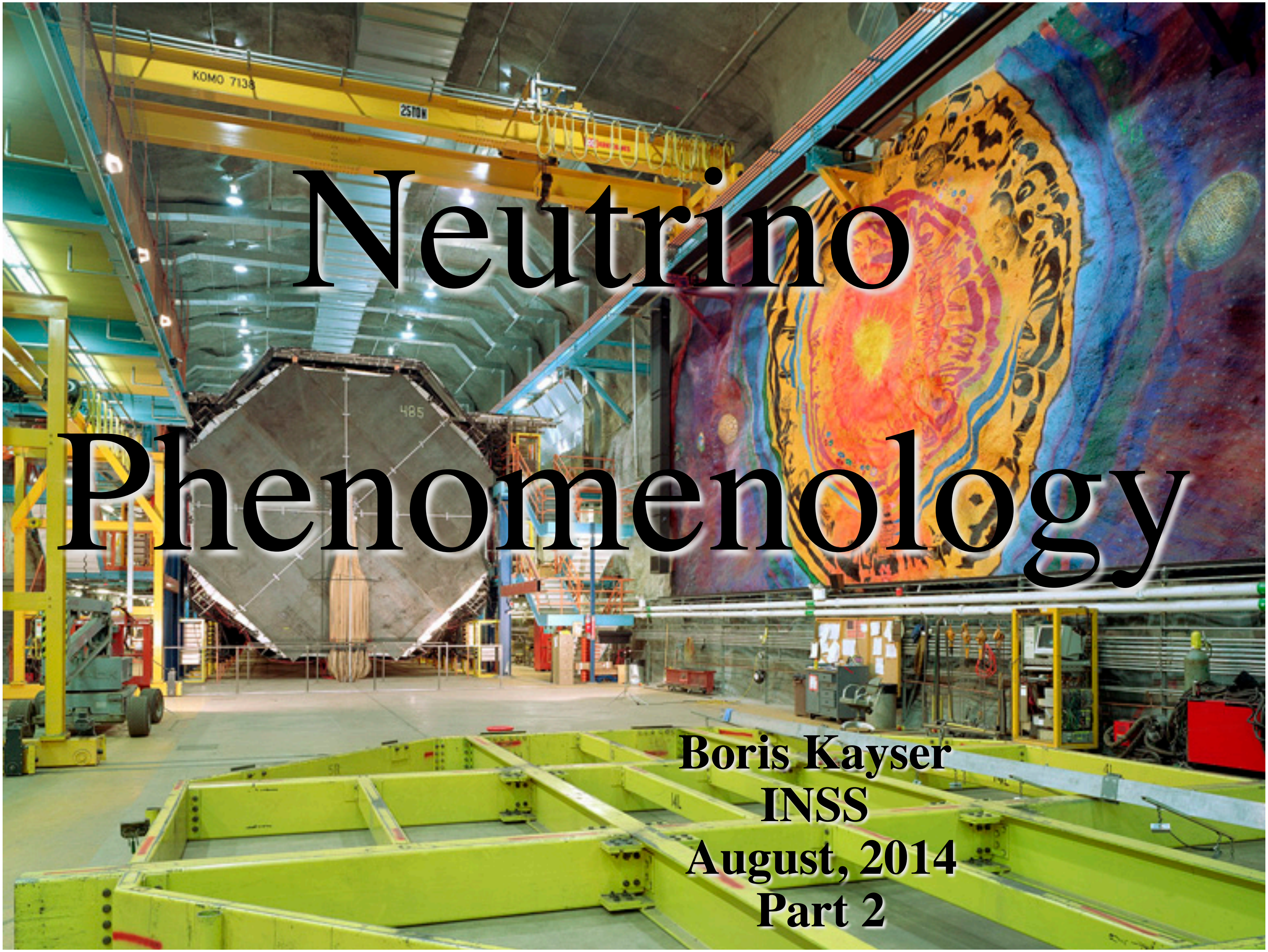

Neutrino Phenomenology

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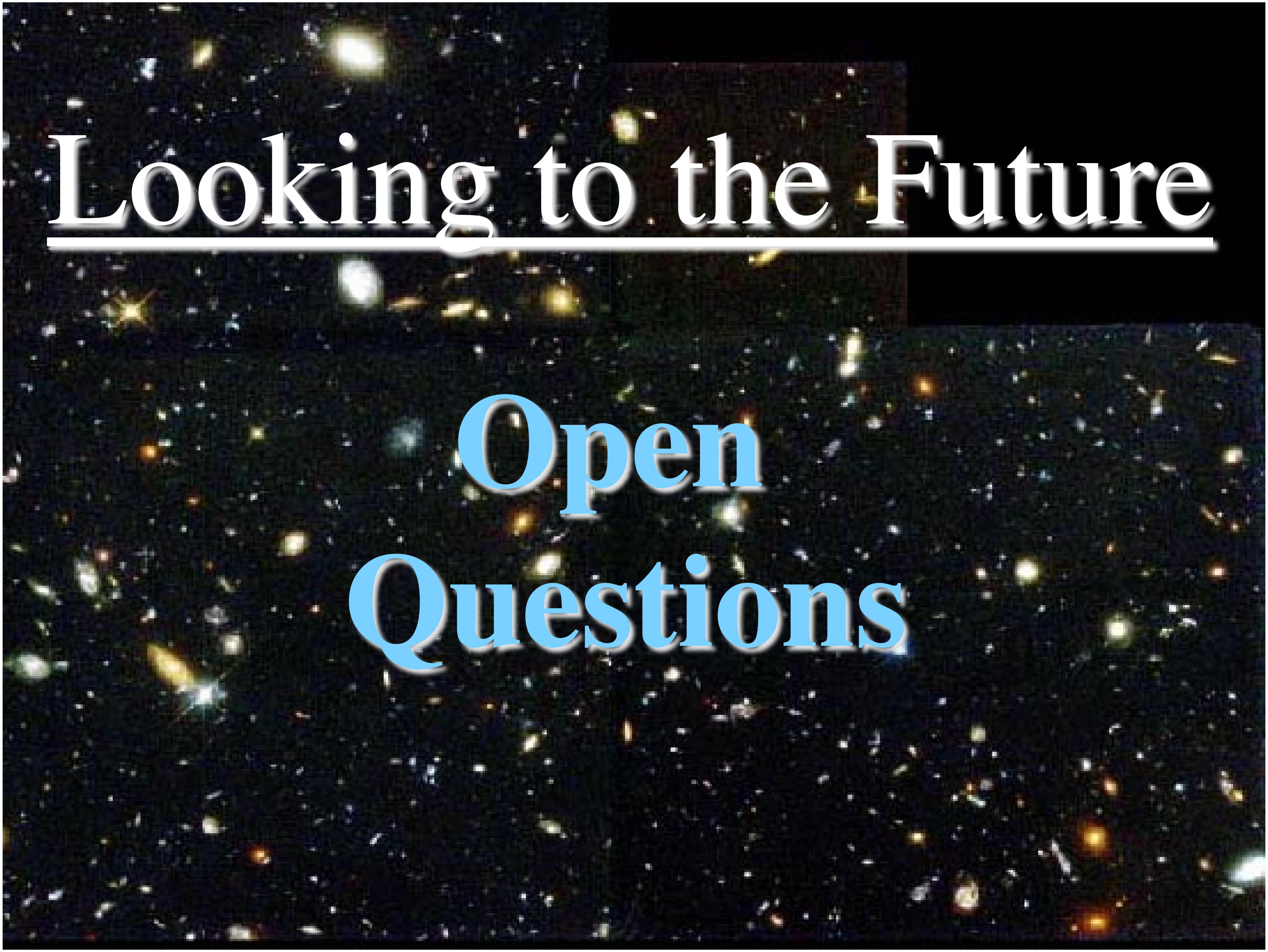
INSS
August, 2014
Part 2



Looking to the Future

Open Questions

- What is the absolute scale of neutrino mass?

- 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 spectrum like  or  ?

- Do neutrino interactions violate CP?

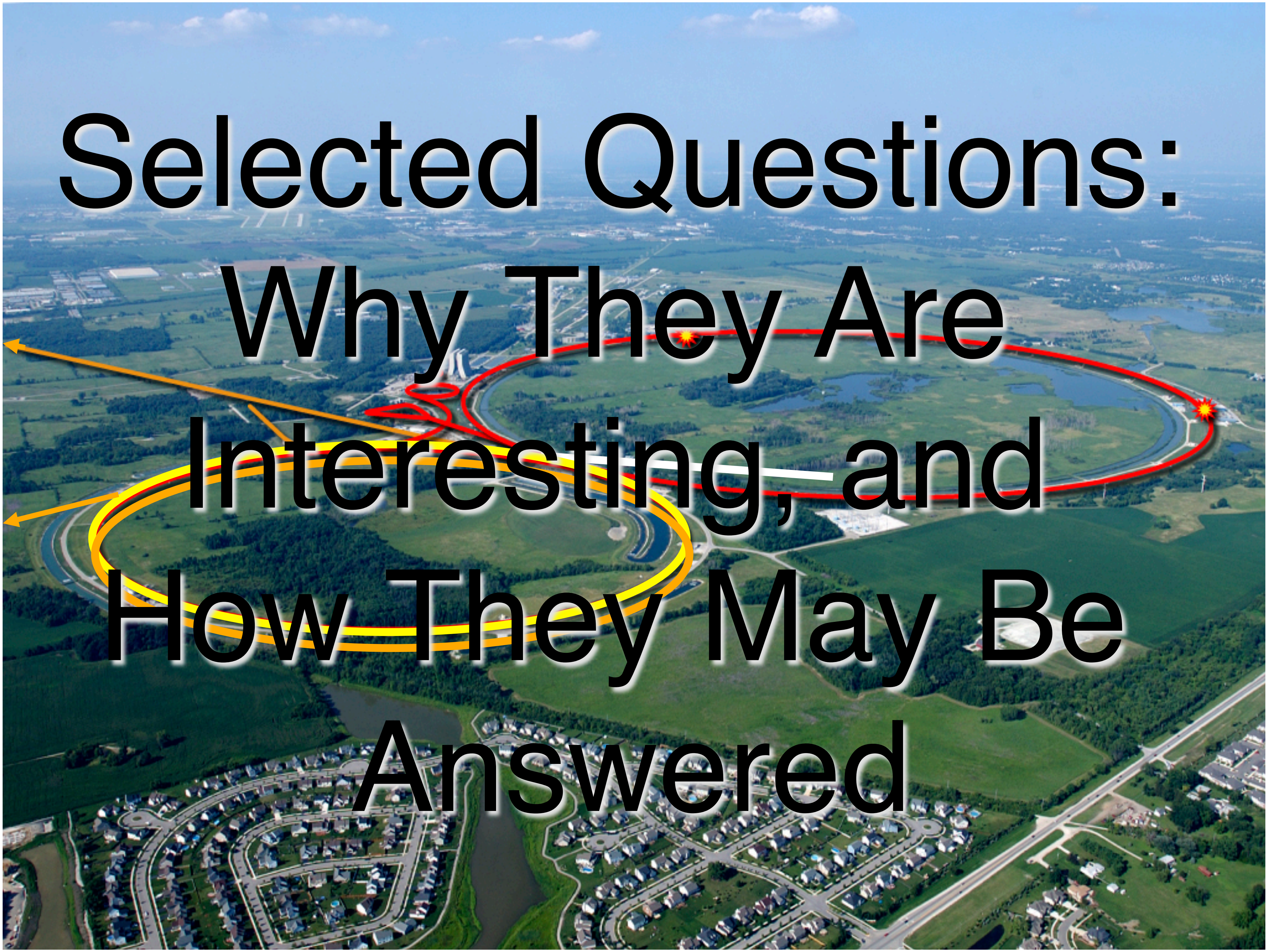
Is $P(\bar{\nu}_\alpha \rightarrow \bar{\nu}_\beta) \neq P(\nu_\alpha \rightarrow \nu_\beta)$?

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

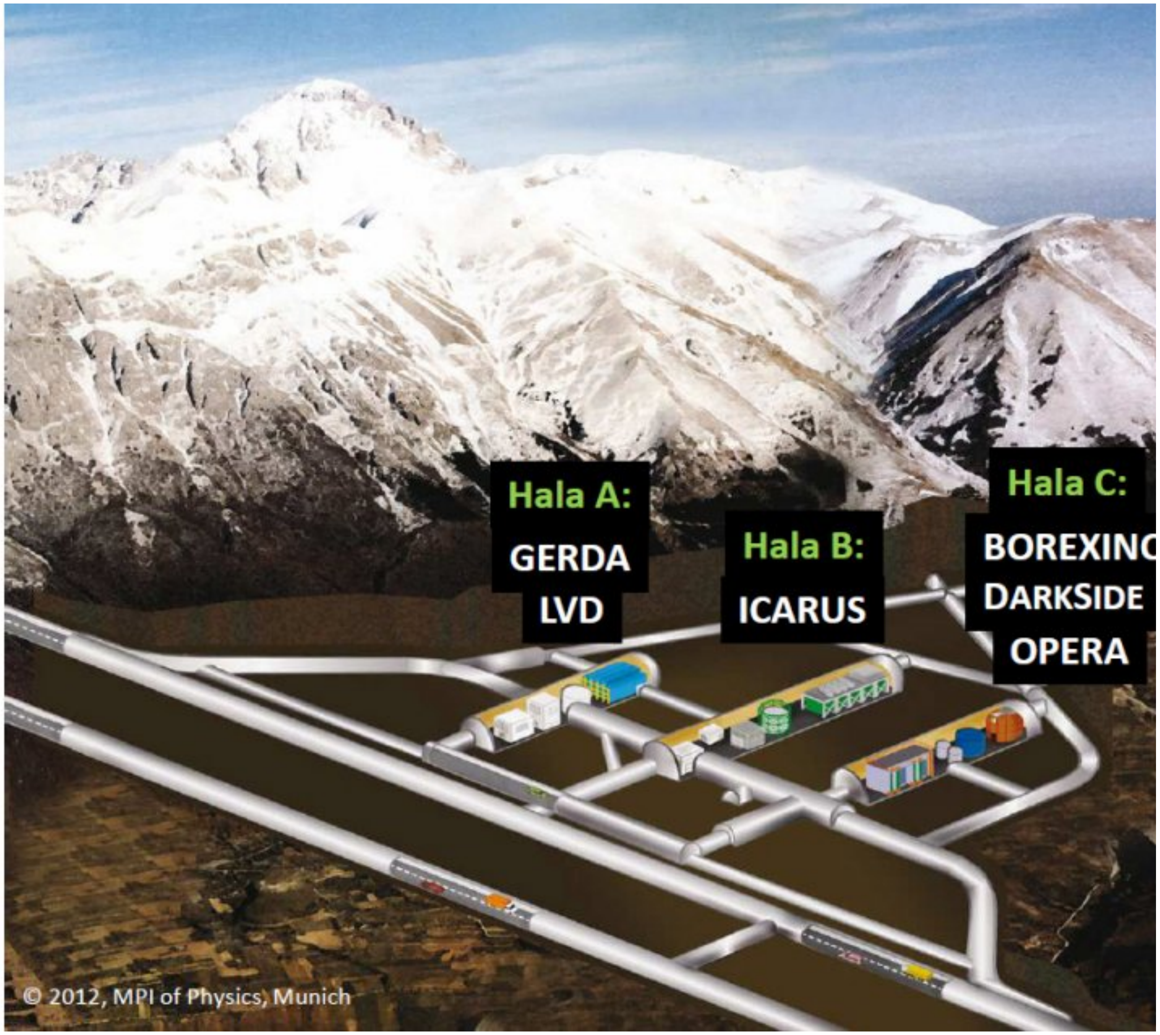
- What can neutrinos and the universe tell us about one another?

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

- Do neutrinos break the rules?
  - Non-Standard-Model interactions?
  - 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.

$$\mathcal{L}_{SM} = \overset{\text{Coupling constant}}{y}\,\underset{\text{SM Higgs field}}{\overline{H}^0}\,\bar{\nu}_L\overset{\text{Must add to the SM}}{\nu_R} \Rightarrow y\underbrace{\left\langle \overline{H}^0 \right\rangle_0}_{\text{Vacuum expectation value}}\bar{\nu}_L\nu_R \equiv m_\nu\bar{\nu}_L\nu_R \leftarrow \left\{\textbf{Dirac mass}\right.$$

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

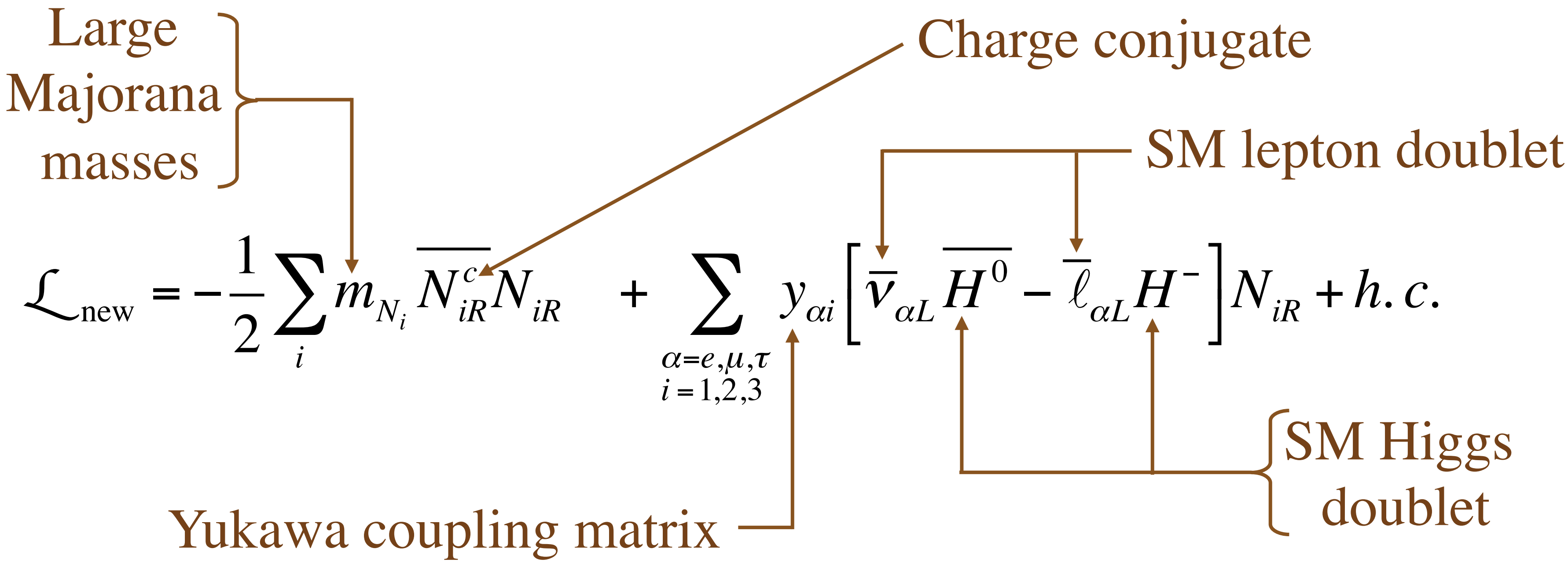
A coupling constant this much smaller than unity leaves many theorists skeptical.

— 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

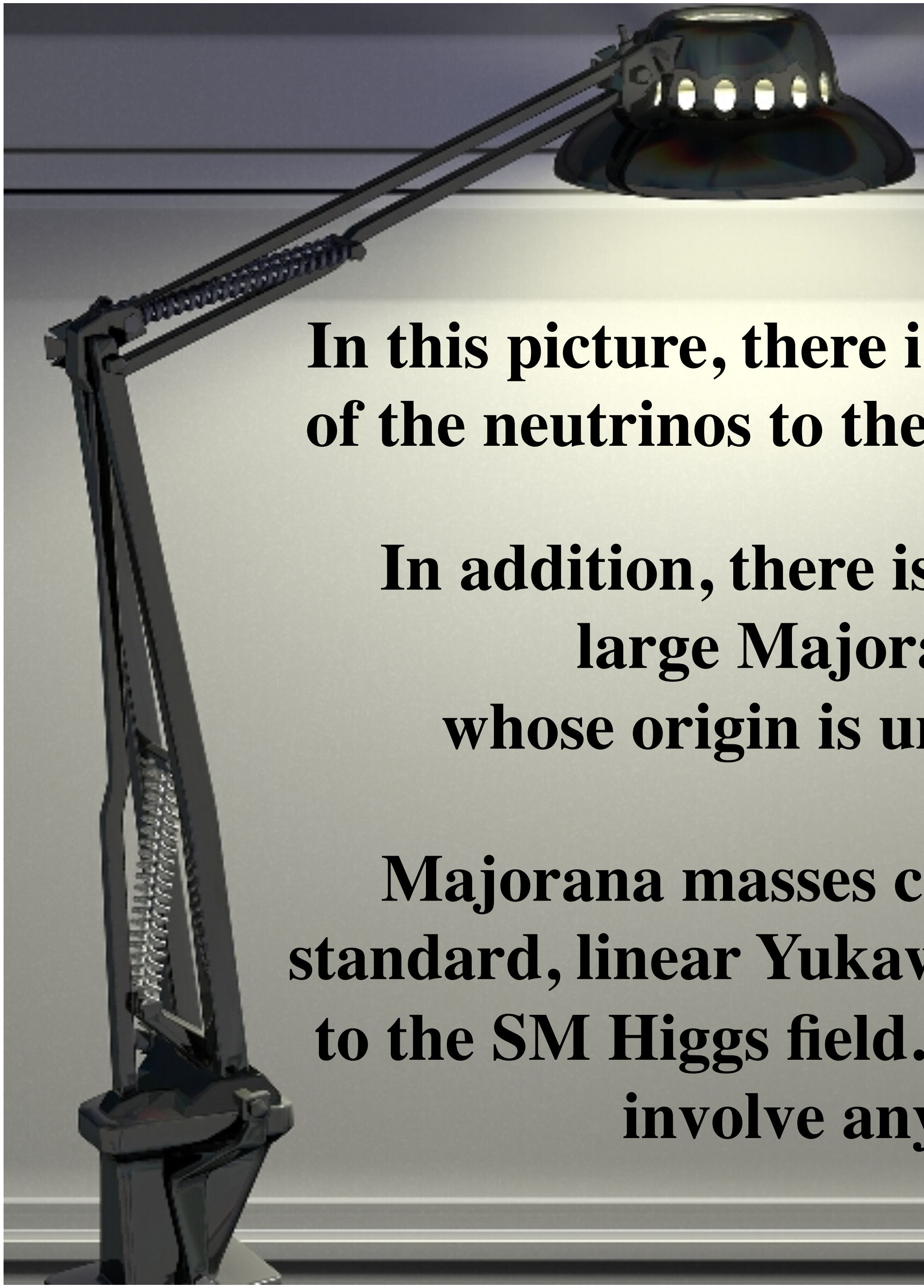
Charge conjugate

SM lepton doublet

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

SM Higgs doublet

Yukawa coupling matrix



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

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 $L \equiv$ #(Leptons) – #(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

Another Way To See That Majorana Masses $\Longrightarrow \bar{\nu}_i = \nu_i$

As a result of $K^0 \longleftrightarrow \overline{K^0}$ 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 $\nu \longleftrightarrow \bar{\nu}$ mixing, the neutrino mass eigenstate ν_i is —

$$\nu_i = \nu + \bar{\nu}. \qquad \bar{\nu}_i = \nu_i\ .$$

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*.

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.

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

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

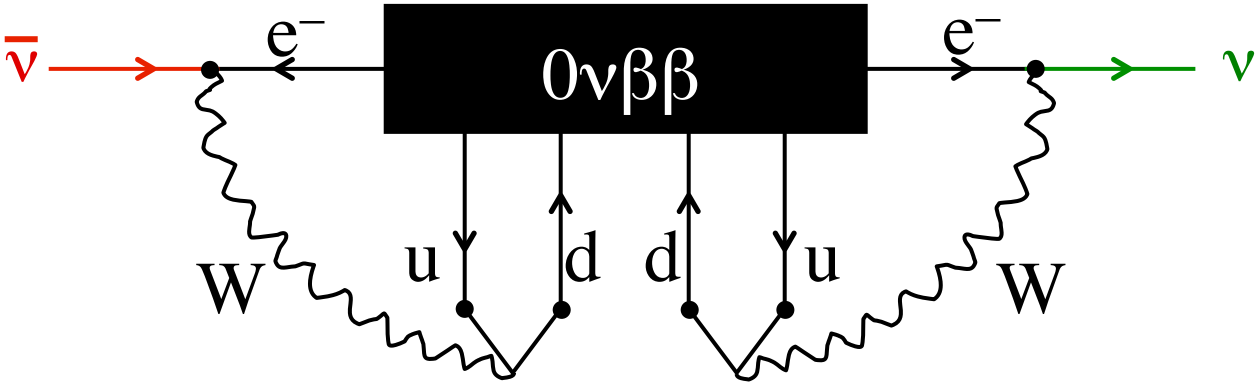
All three predictions would be confirmed by the observation of neutrinoless double beta decay (0νββ)

$\Delta L = 2$

does not conserve L.

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

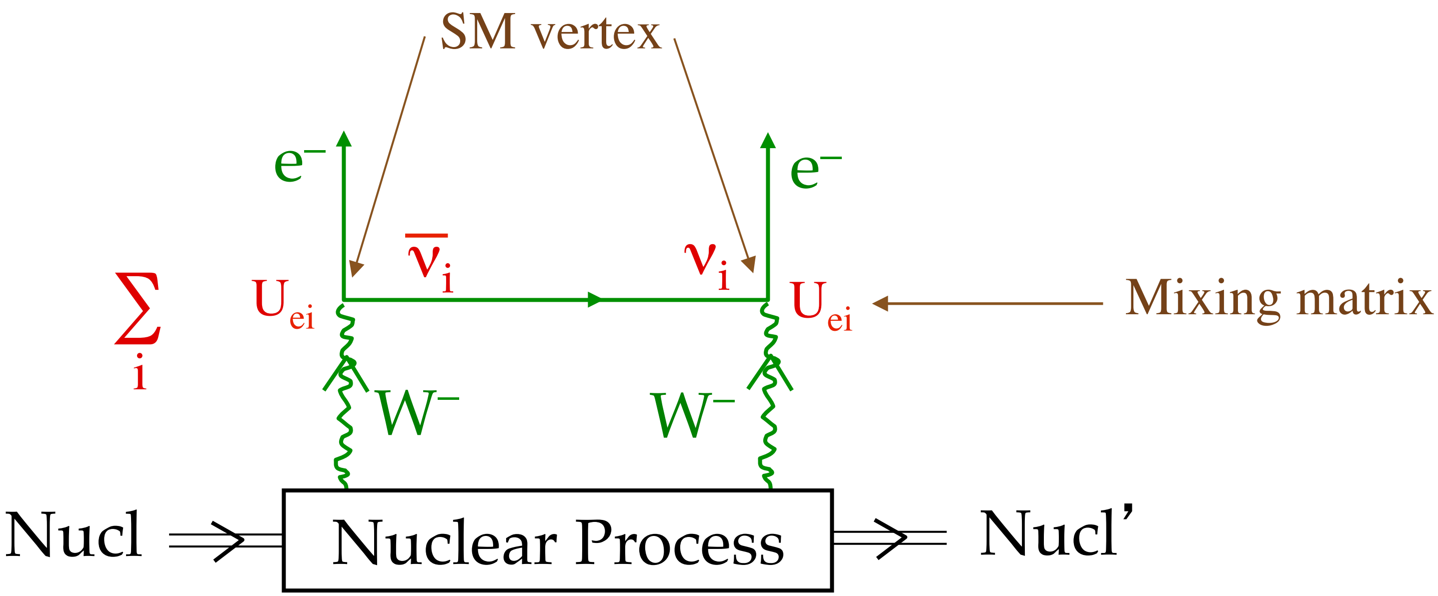
(Schechter and Valle)



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

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

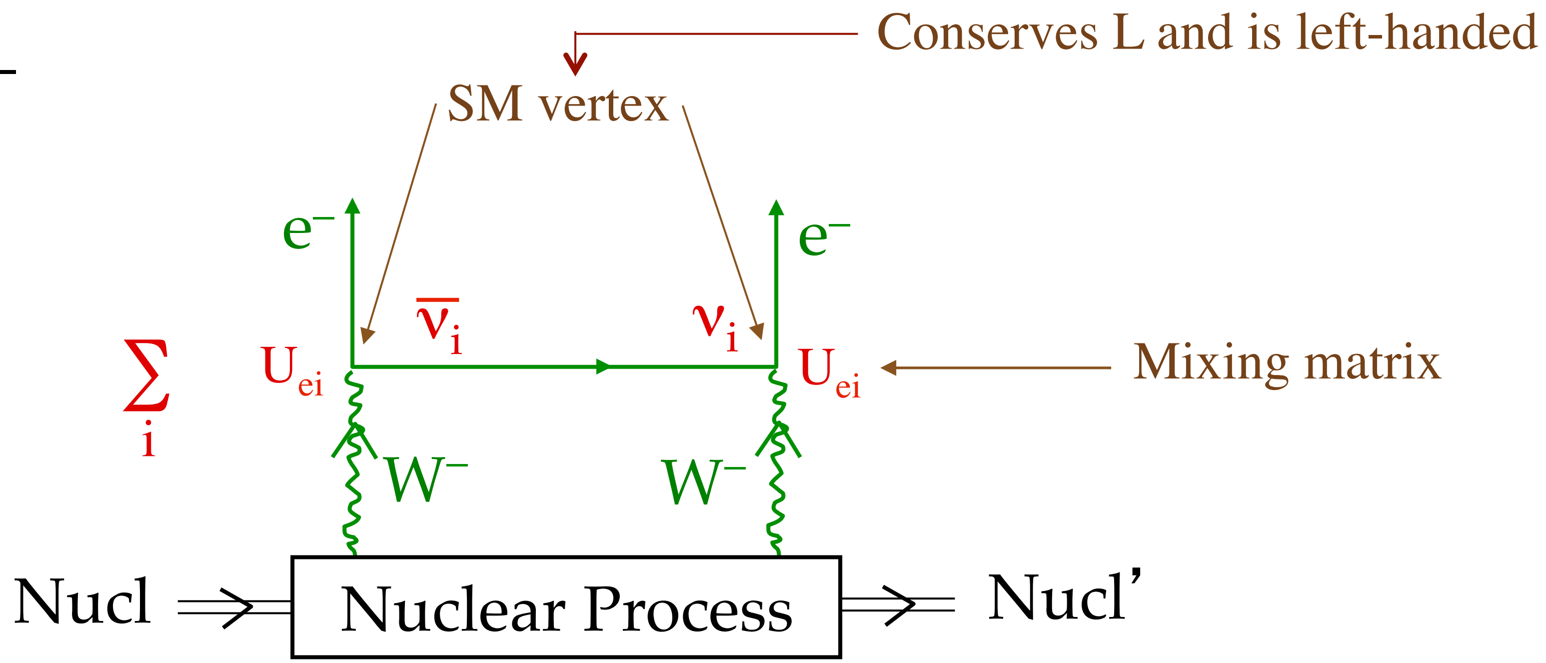
We anticipate that 0νββ is dominated by a diagram with light neutrino exchange and Standard Model vertices:



“The Standard Mechanism”

— Down the Garden Path —

In —



Conserves L and is left-handed

SM vertex

Mixing matrix

Mass (ν_i)

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

Thus, Amp [ν_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 ν mass only because of a helicity mismatch, which a RH current could fix.

If we had a RH current at one vertex, couldn't we then have $0\nu\beta\beta$ without any ν mass?

No!

ν mass is still required.

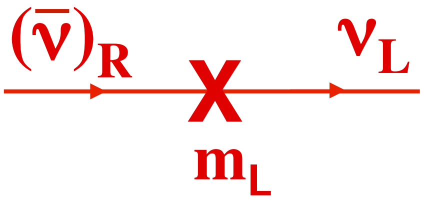
Why?

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

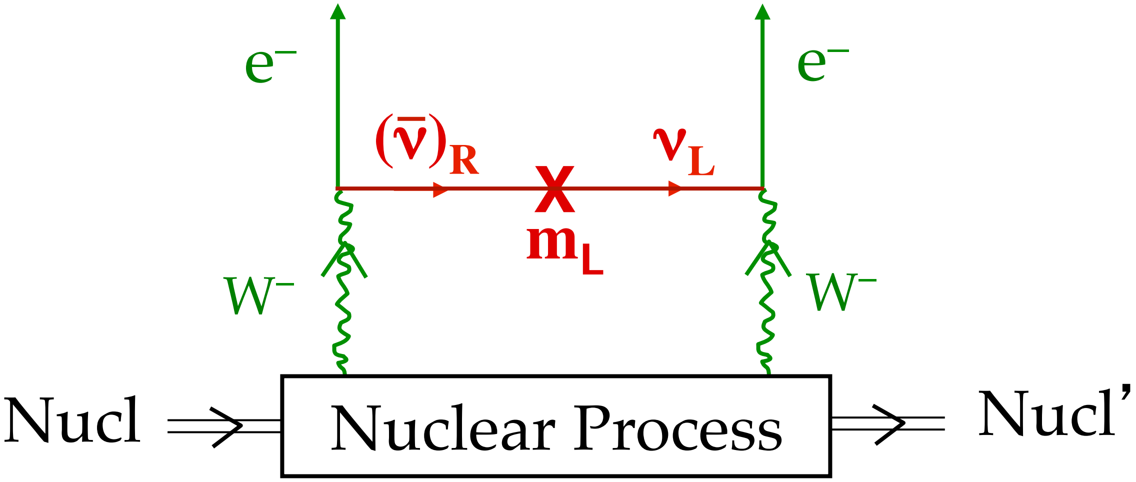
But the Standard Model (SM) weak interactions ***do*** conserve L. And simply reversing the handedness at one vertex would not change that.

Thus, 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).

Once Upon a Time

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

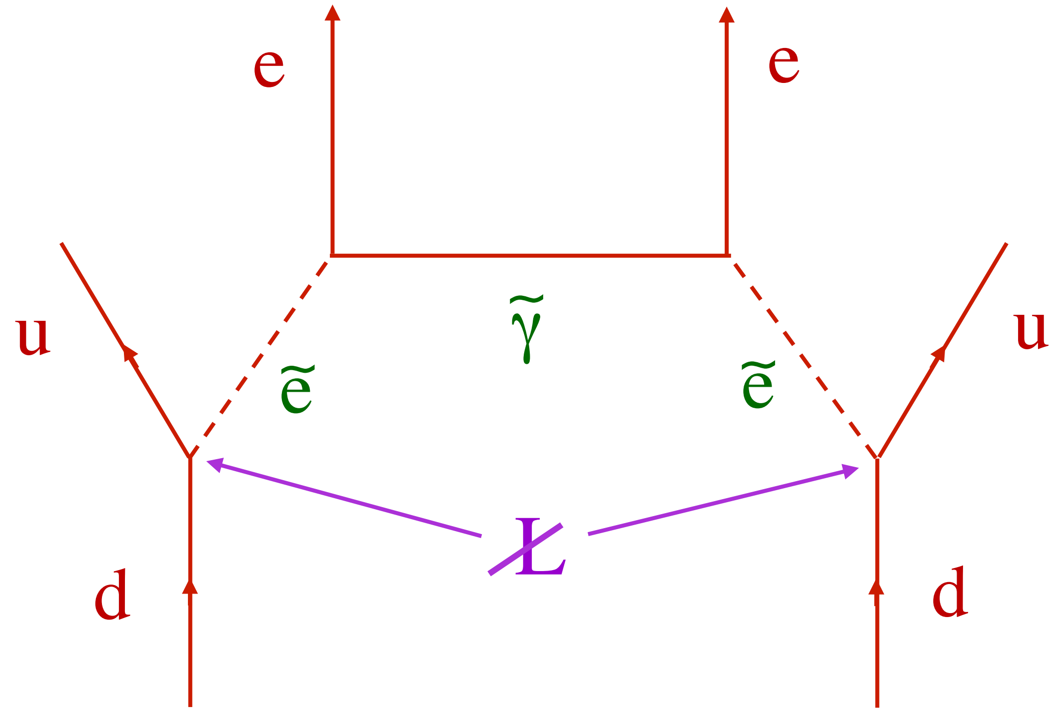
Now

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.

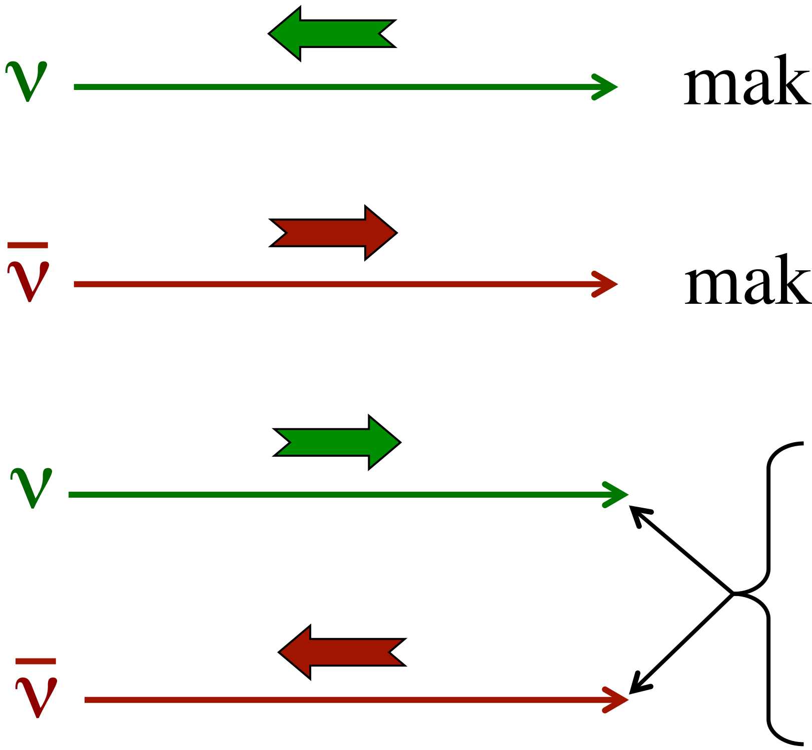
(B.K., Petcov, Rosen; Enqvist, Maalampi, Mursula; B.K.)

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



SM Interactions Of A Dirac Neutrino

We have 4 mass-degenerate states:



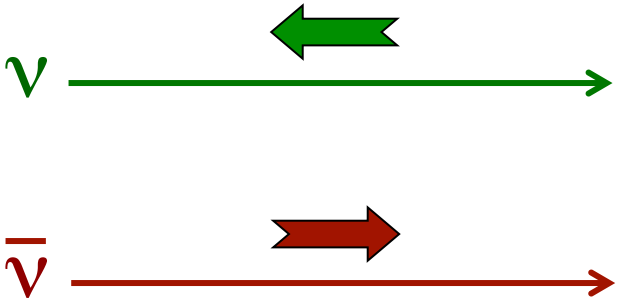
		Conserved L
ν	makes ℓ^-	$+1$
$\bar{\nu}$	makes ℓ^+	-1

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:



ν makes ℓ^-

$\bar{\nu}$ makes ℓ^+

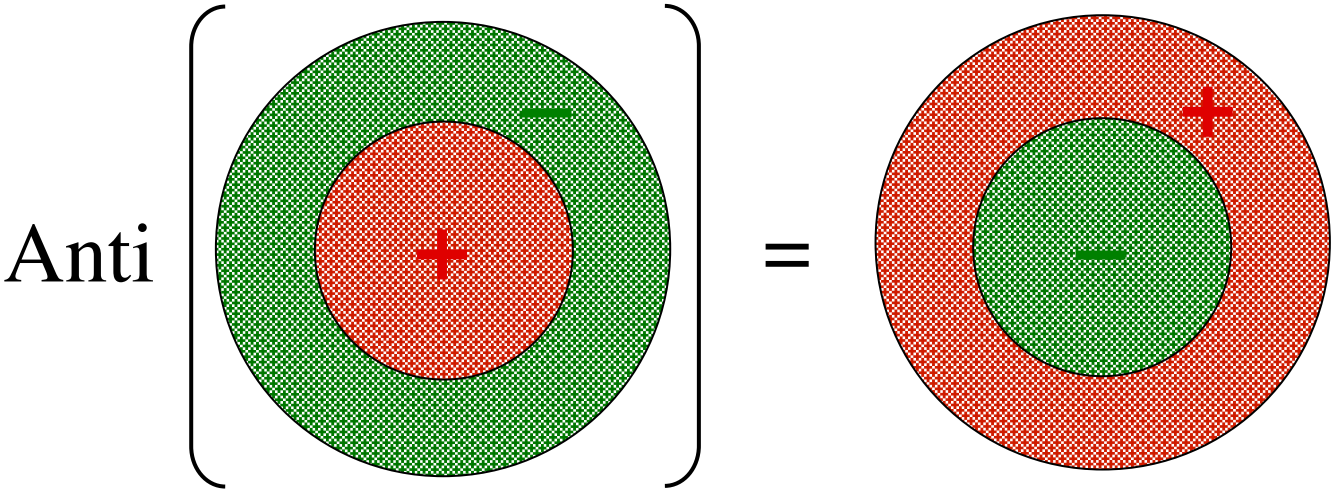
The weak interactions violate *parity*.
(They can tell *Left* from *Right*.)

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

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

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

No!

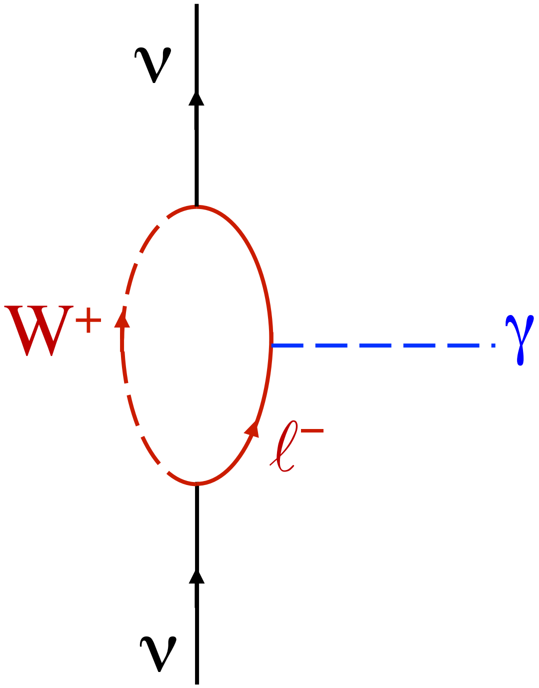


But for a Majorana neutrino —

$$\text{Anti}\ (\nu) = \nu$$

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:

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

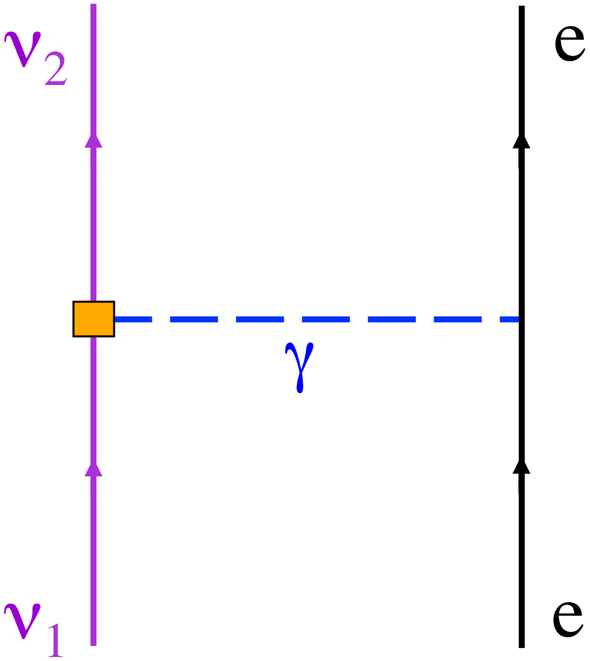
But for a Majorana neutrino,

$$\overline{\nu}_i = \nu_i$$

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.