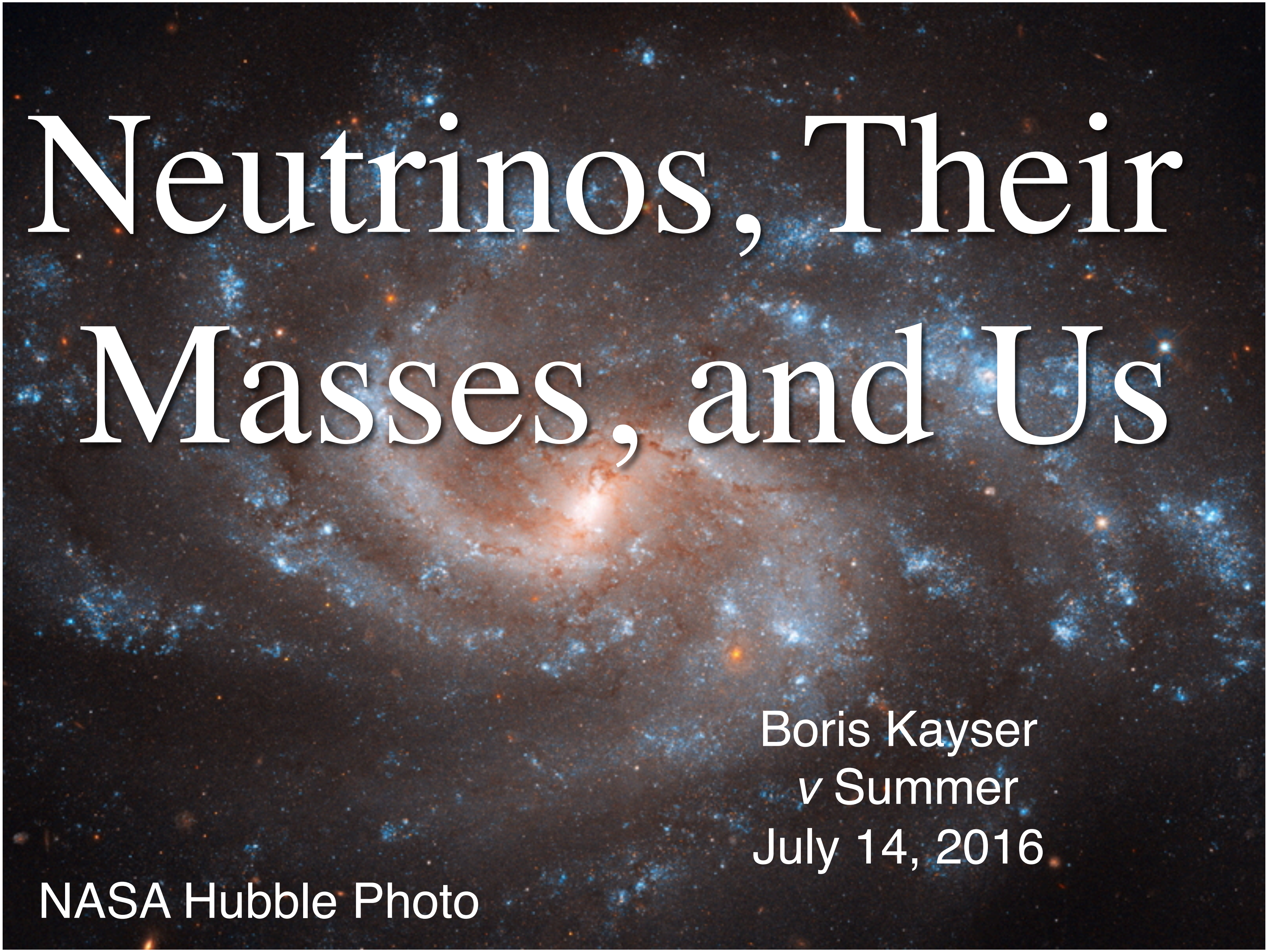
Neutrinos, Their Masses, and Us



Boris Kayser
ν Summer
July 14, 2016

NASA Hubble Photo

The Neutrino Revolution
(1998 – …)

Neutrinos have nonzero masses!

The 2015 Nobel Prize in Physics went to **Takaaki Kajita** and **Art McDonald** for the experiments that proved this.

Super-Kamiokande, Japan

Sudbury Neutrino Observatory, Canada

The 2016 Breakthrough Prize in Fundamental Physics went to these two experiments and four subsequent ones.

What Is The Origin of Neutrino Mass?

For that matter, what is the origin of the masses of all the other particles?

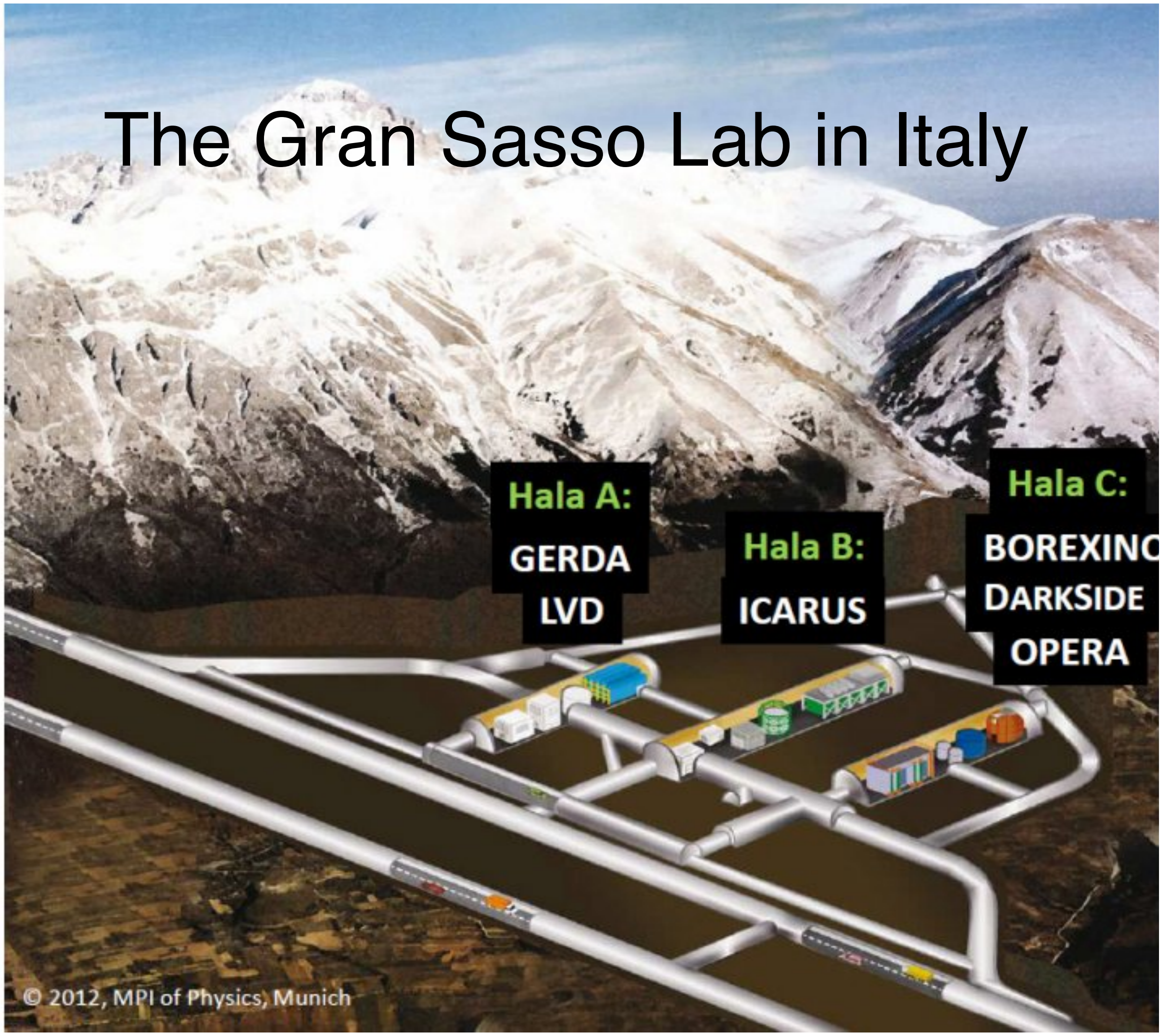
The fundamental constituents of matter are the ***quarks***, the ***charged leptons***, and the ***neutrinos***.

The discovery and study of the ***Higgs particle*** at CERN's Large Hadron Collider has provided strong evidence that the ***quarks*** and ***charged leptons*** derive their masses from an interaction with the ***Higgs field***, which is present throughout space.

Most theorists strongly suspect that the origin of the neutrino masses is different from the origin of the quark and charged lepton masses.

The Standard-Model ***Higgs field*** is probably still involved, but there is probably something more —
something way outside the Standard Model:

Majorana masses


The Gran Sasso Lab in Italy

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Is the Origin of Neutrino Mass Different?

Neutrino Masses Without Field Theory

We will describe what the quantum field theory does, but without equations.

We start with underlying neutrino states ν and $\bar{\nu}$ that are distinct from each other, like other familiar fermions, and are not the mass eigenstates.

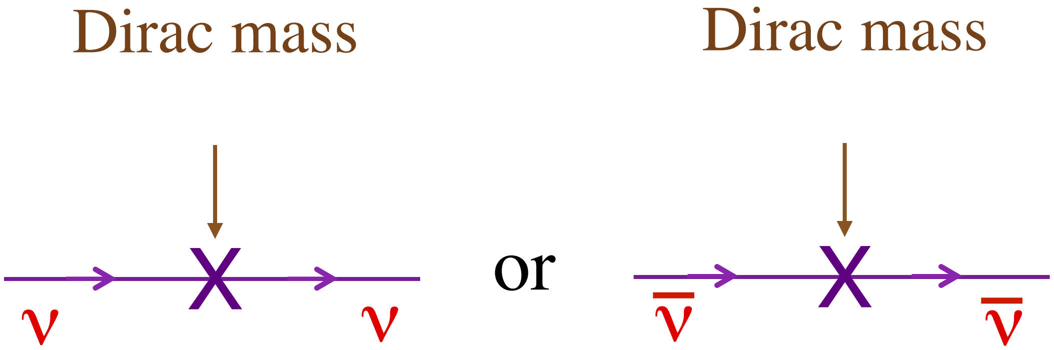
If ν_1 is a mass eigenstate, $H|\nu_1\rangle = (\text{Mass of } \nu_1)|\nu_1\rangle$.

We will have to see what the mass eigenstates are later.

We can have two types of masses:

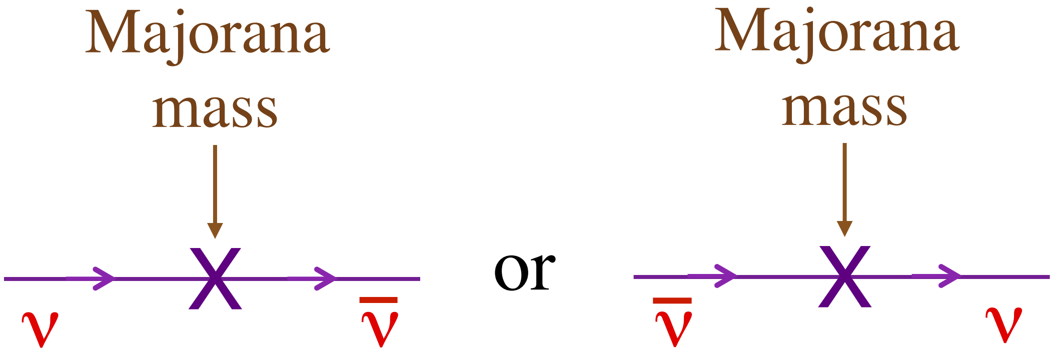
Dirac Mass

A Dirac mass
has the effect:



Majorana Mass

A Majorana mass
has the effect:



Majorana Mass

A Majorana mass
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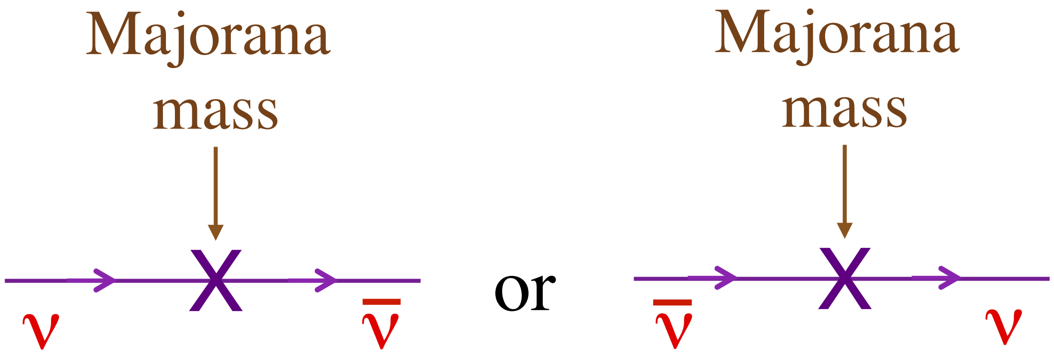


Majorana masses mix ν and $\bar{\nu}$, so they do not conserve the Lepton Number L that distinguishes leptons from antileptons:

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

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

Quark and ***charged-lepton*** Majorana masses
are **forbidden** by electric charge conservation.

But ***neutrinos*** are electrically neutral,
so they **can** have Majorana masses.

Neutrino Majorana masses would make
the neutrinos *very* distinctive, because —

Majorana neutrino masses have a different origin
than the quark and charged-lepton masses.

The Possible Origins of Majorana Masses

According to the Standard Model —

Quark and charged lepton masses arise from an interaction with the Higgs field.

Dirac neutrino masses would arise in the same way.

But ***Majorana*** neutrino masses cannot arise as the quark and charged lepton masses do.

Majorana neutrino masses are from physics way outside the Standard Model.

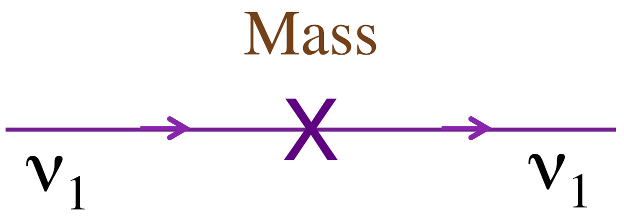
A ***Majorana*** neutrino mass can arise
without interaction with any Higgs field,

— or through interaction with a Higgs-like field
which is not in the Standard Model,
and carries a different value of the "weak isospin"
quantum number than the Standard Model Higgs,

— or through interaction with the Standard Model Higgs,
but not the same kind of interaction
as would generate the quark masses.

The Mass Eigenstates When There Are Majorana Masses

For any fermion mass eigenstate, e.g. ν_1, the action of its mass is —



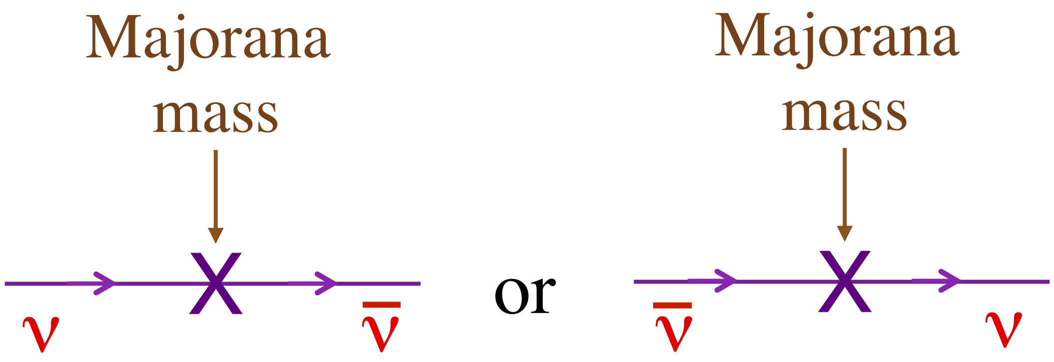
Mass

ν_1 ν_1

The mass eigenstate is sent back into itself.

Recall that —

A ***Majorana*** mass has the effect:



Majorana mass

ν $\bar{\nu}$

or

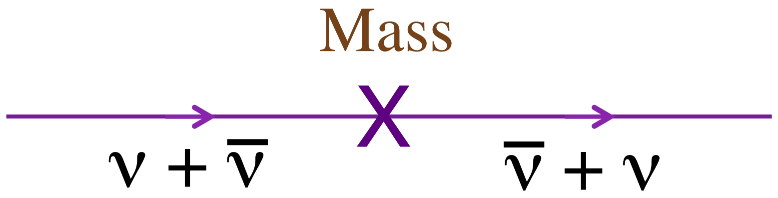
Majorana mass

$\bar{\nu}$ ν

Then the mass eigenstate neutrino ν_1 must be —

$$\nu_1 = \nu + \bar{\nu} \; ,$$

since the Majorana mass term sends this neutrino back into itself, as required for any mass eigenstate particle:



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

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

For given helicity $h \equiv \overrightarrow{\text{Spin}} \bullet \widehat{\text{Momentum}}$

"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*

We have just shown that if neutrinos have *Majorana masses*, then the mass eigenstates are *Majorana neutrinos*.

Production and Subsequent Interaction of a Neutrino

— *The Dirac View*

$\pi^+ \longrightarrow \mu^+ + \nu$ followed by $\nu + \overset{(p,\, n)}{d} \longrightarrow \mu^- + p + p$

But —

$\pi^- \longrightarrow \mu^- + \bar{\nu}$ followed by $\bar{\nu} + d \longrightarrow \mu^+ + n + n$

The lepton number defined by —

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

is conserved.

Production and Subsequent Interaction of a Neutrino

— The Majorana View

$\pi^+ \rightarrow \mu^+ + \nu(\mathrm{LH})$ followed by $\nu(\mathrm{LH}) + \overset{(p,\, n)}{d} \rightarrow \mu^- + p + p$

But —

$\pi^- \rightarrow \mu^- + \nu(\mathrm{RH})$ followed by $\nu(\mathrm{RH}) + d \rightarrow \mu^+ + n + n$

The weak interactions of Left-Handed and Right-Handed fermions are different.

To Determine Whether Majorana Masses Occur in Nature

The Promising Approach — Seek

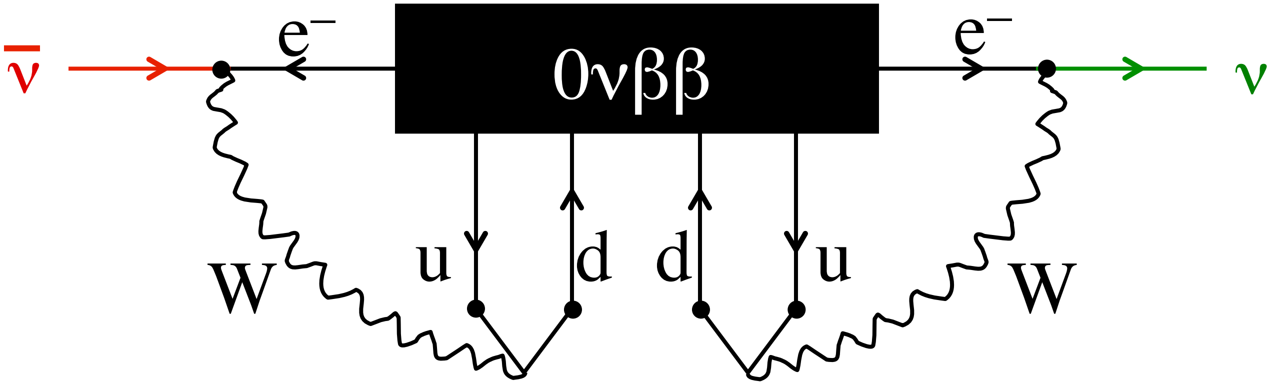
Neutrinoless Double Beta Decay [0νββ]

Observation at any non-zero level would imply —

- ➢Lepton number L is not conserved ($\Delta L = 2$)
- ➢Neutrinos have Majorana masses
- ➢Neutrinos are Majorana particles ($\bar{\nu} = \nu$)

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

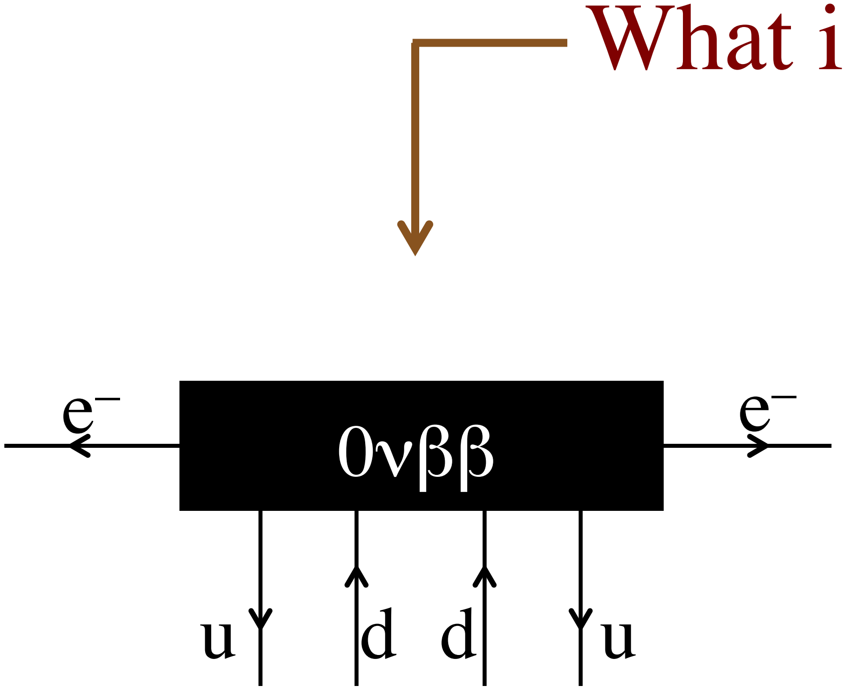
(Schechter and Valle)



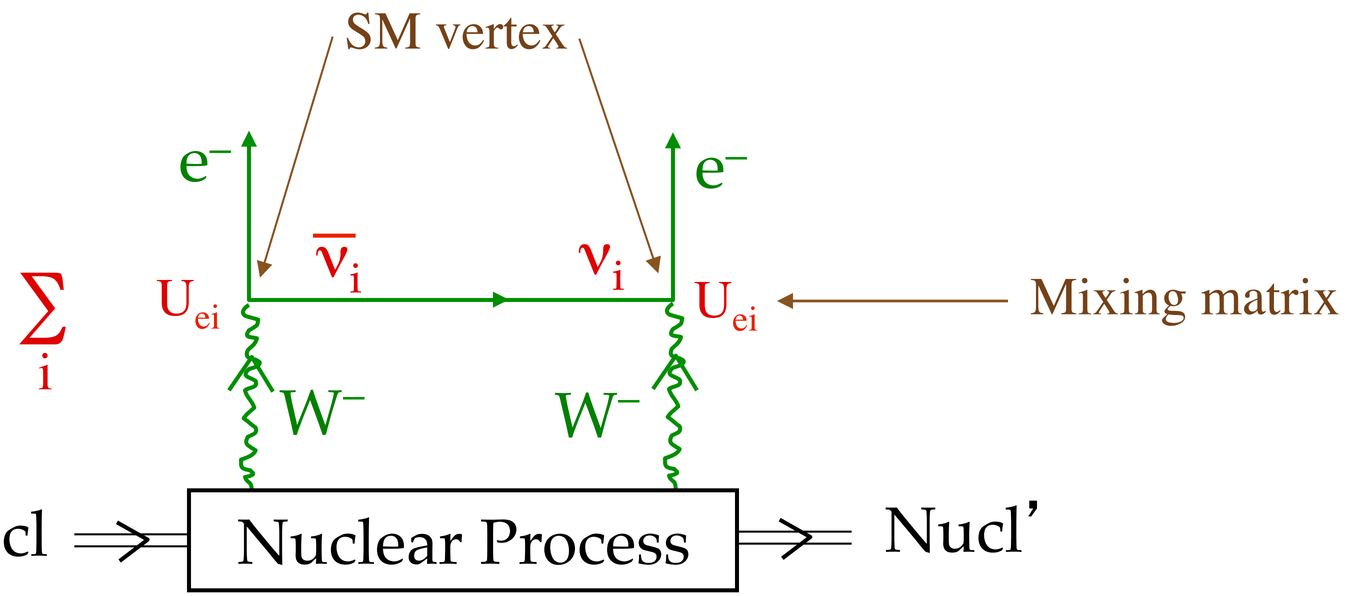
$\bar{\nu} \rightarrow \nu$: A (tiny) Majorana mass

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

What is inside?

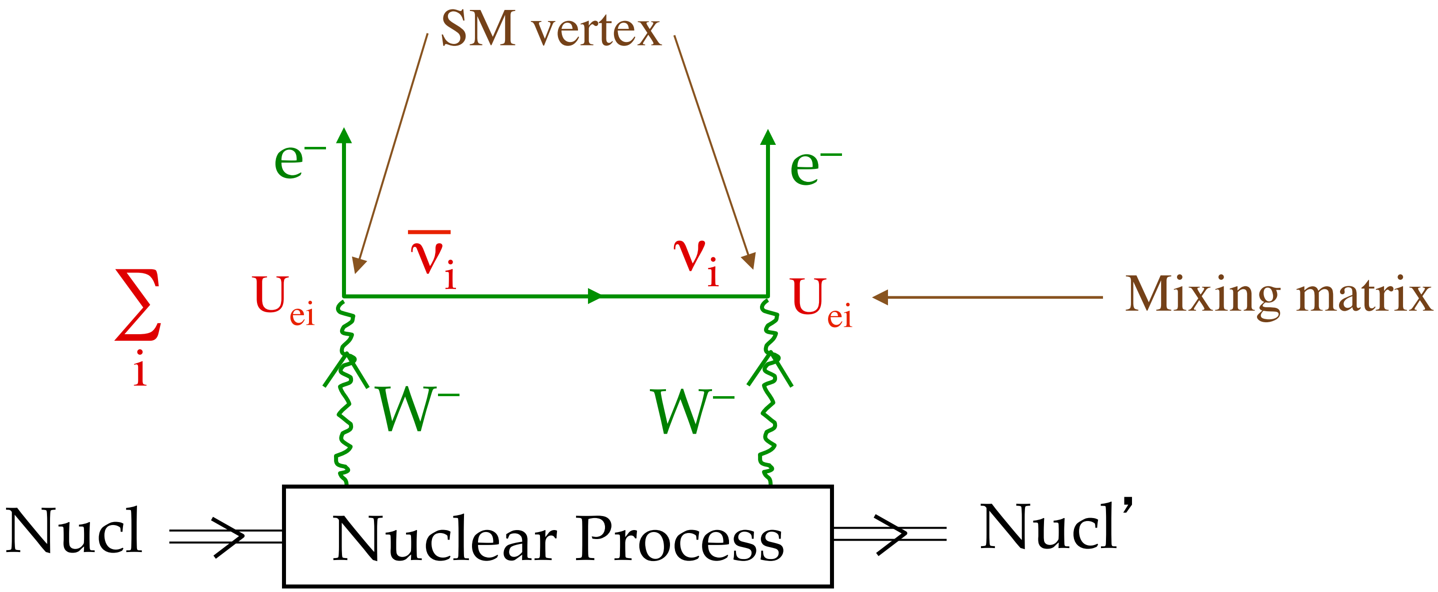


We anticipate that 0νββ is dominated by a diagram with light neutrino exchange and Standard Model vertices:



“The Standard Mechanism”

If the dominant mechanism is —


SM vertex

e^- e^-

$\sum_i$ U_{ei} $\overline{\nu}_i$ ν_i U_{ei}

Mixing matrix

W^- W^-

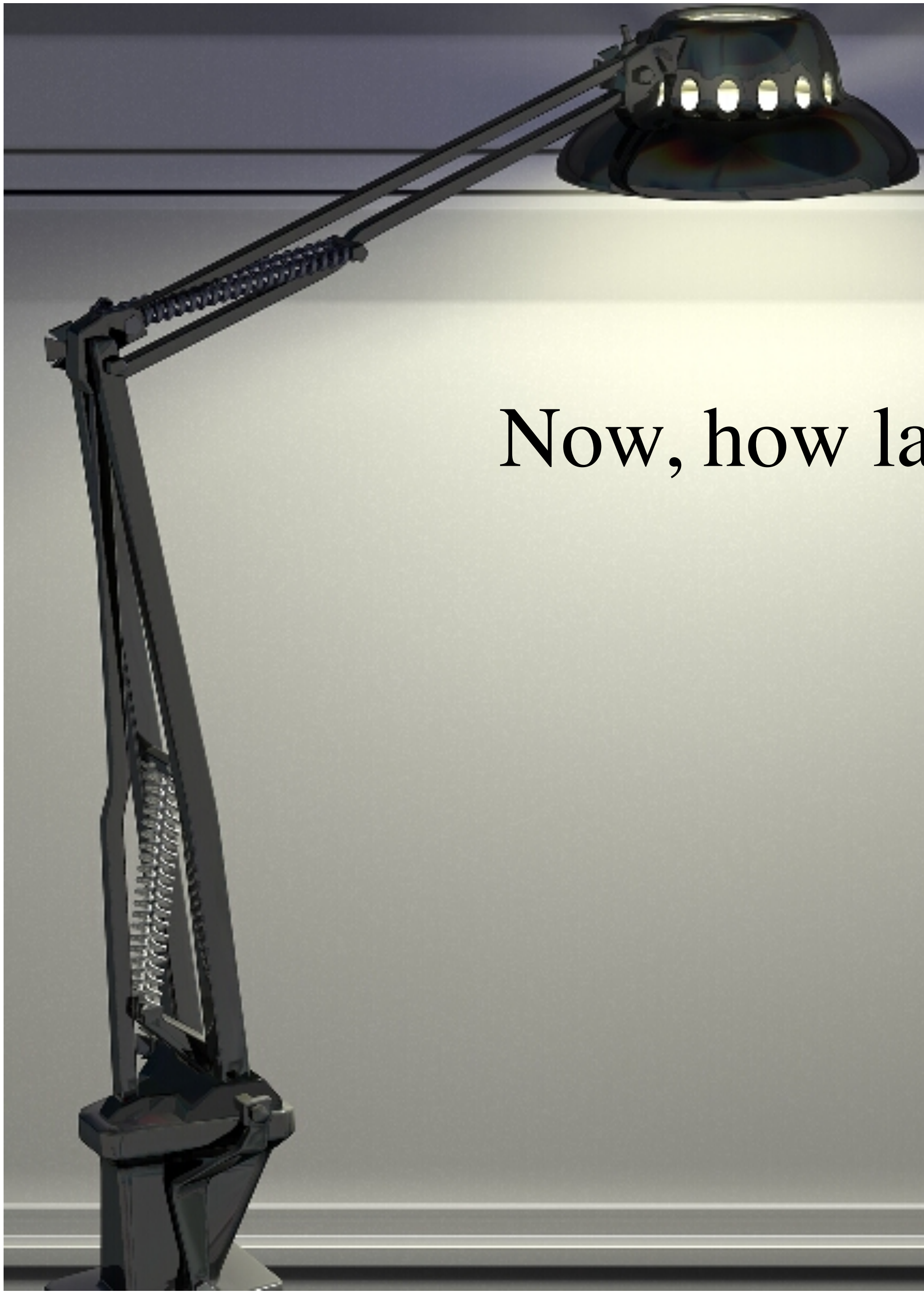
Nucl Nuclear Process Nucl’

Then —

Mass (ν_i)

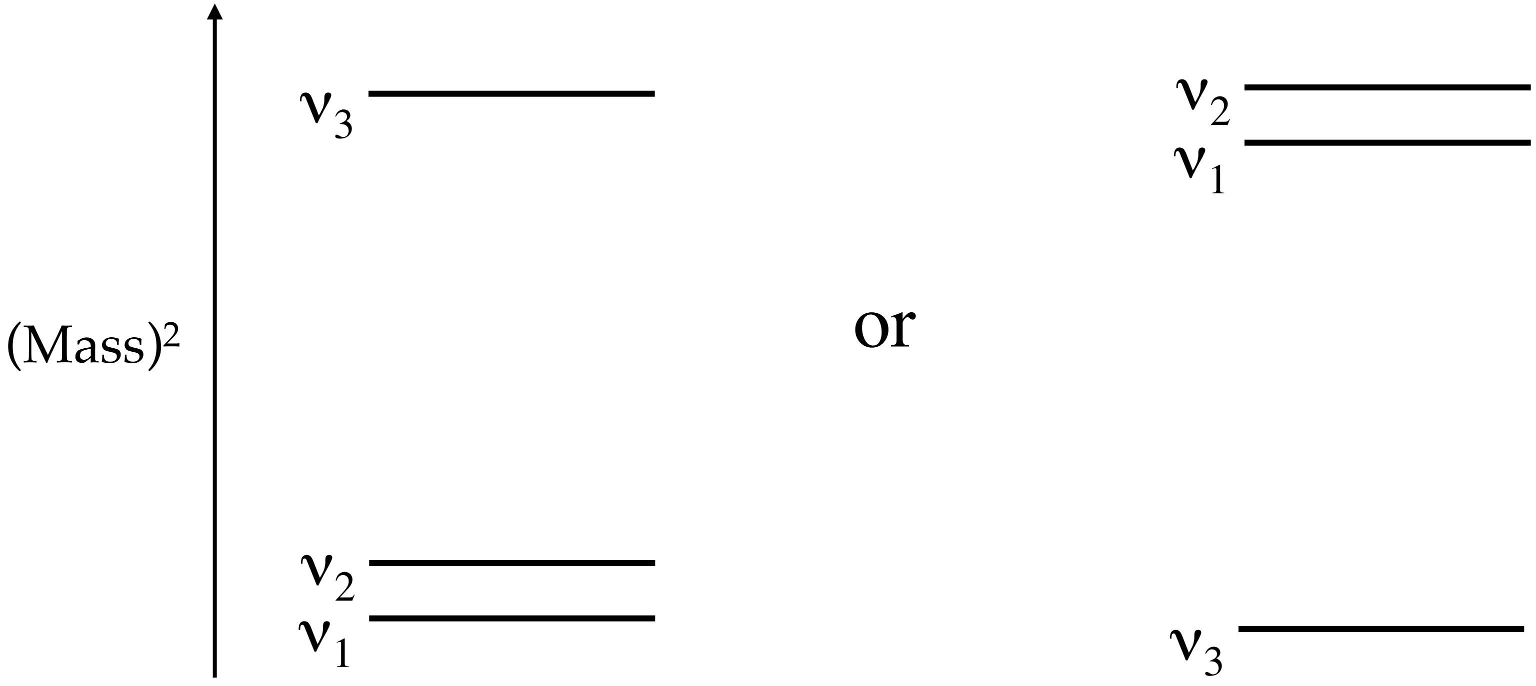
$$\mathrm{Amp}[0\nu\beta\beta] \propto \left| \sum m_i U_{ei}^2 \right| \equiv m_{\beta\beta}$$

The mass is the source of
the lepton number violation.



Now, how large is $m_{\beta\beta}$?

The Three – Neutrino (Mass)^2 Spectrum



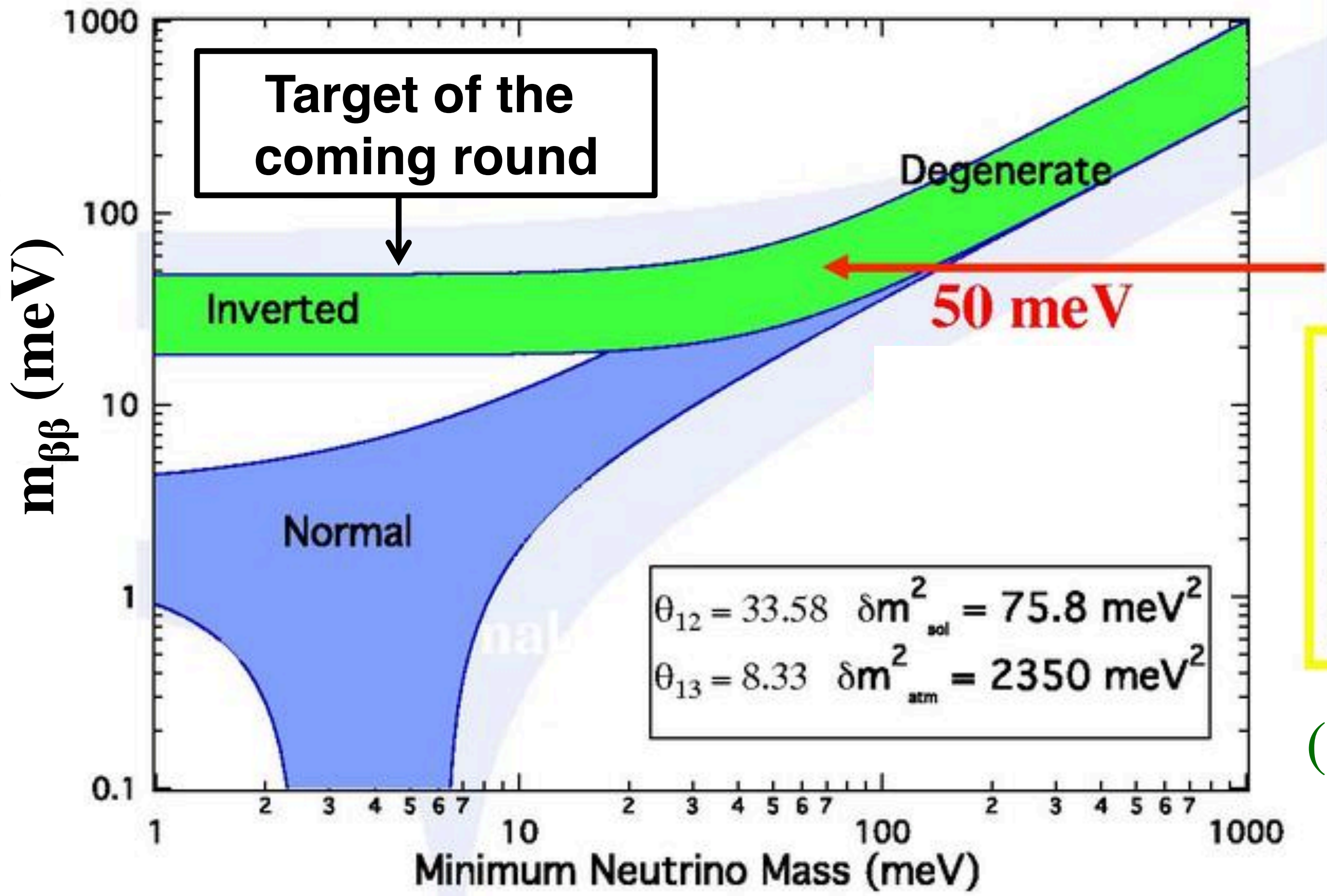
Normal

Inverted

$$\Delta m^2_{21} \equiv m^2_2 - m^2_1 \cong 7.5 \text{ x } 10^{-5} \text{ eV}^2, \qquad \Delta m^2_{32} \cong 2.4 \text{ x } 10^{-3} \text{ eV}^2$$

ββ Sensitivity

(mixing parameters from arXiv:1106.6028)



Target of the coming round

50 meV

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: $m_{\beta\beta} < (61 – 165)$ meV. KamLAND-Zen

The See-Saw Mechanism

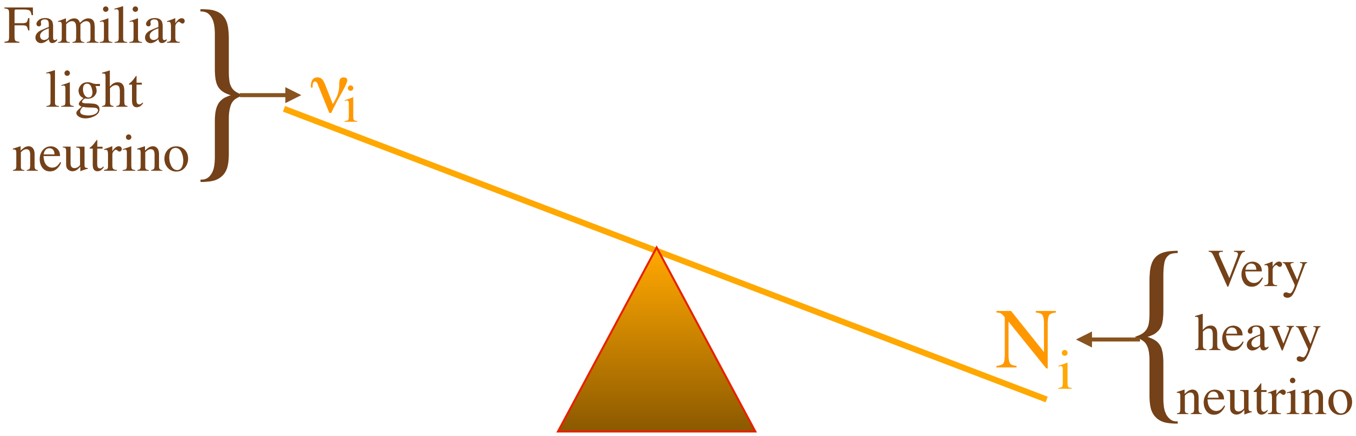
This is the most-studied class of models constructed to explain how neutrino masses can be so tiny.

The straightforward see-saw models do not contain any tiny input parameters.

Instead, these models hypothesize that, in addition to the 3 light neutrinos ν_1, ν_2, ν_3, there are also 3 ***heavy*** neutrinos N_1, N_2, N_3.

These models include not only Dirac masses (which involve the SM Higgs field), but also Majorana masses, so they do not conserve lepton number.

The arithmetic of these models has the effect that —



Familiar
light
neutrino

ν_i

N_i

Very
heavy
neutrino

$$M_\nu \propto 1/M_N$$

Yanagida;
Gell-Mann, Ramond, Slansky;
Mohapatra, Senjanovic;
Minkowski

Consequences of the See-Saw Picture

Since the neutrinos have Majorana masses,
they are Majorana neutrinos ($\overline{\nu}_i = \nu_i$).

Neutrinoless double beta decay does occur at some level.

The heavy neutrinos N_i would have been produced
in the ***hot*** Big Bang that started the universe,
leading to the possibility of *Leptogenesis*.

A Cosmic Challenge:
The Matter-Antimatter Asymmetry

Cosmologists: Just after the Big Bang, the universe contained equal amounts of ***matter*** and ***antimatter***.

Today: The universe contains ***matter*** but essentially no ***antimatter***.

We would not exist if there were still equal amounts of the two!

Leptogenesis is an appealing possible explanation of the genesis of the ***matter*** – ***antimatter*** asymmetry.

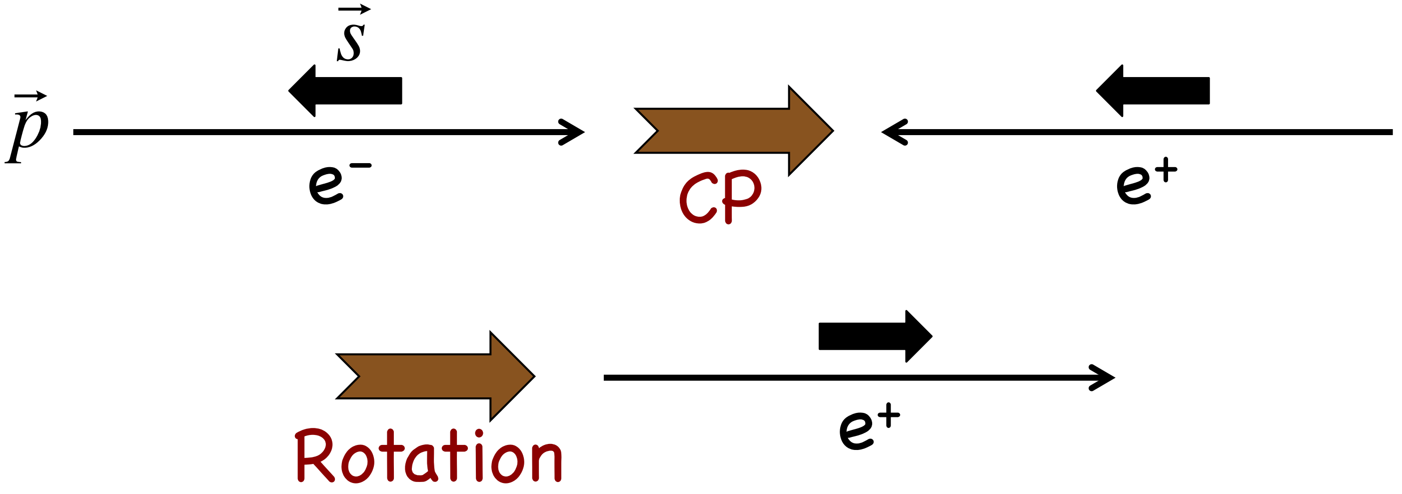
(Fukugita, Yanagida)

For the initial ***matter*** **–** ***antimatter*** ***symmetry*** to have turned into today's ***matter*** **–** ***antimatter*** ***asymmetry*** requires that matter and antimatter can behave differently.

A difference in their behaviors would be a ***violation of CP invariance***.

So what is that?

$$CP \equiv \underbrace{\text{Charge conjugation}}_{\substack{\text{Turns a particle}\\ \text{into its antiparticle}}} \times \underbrace{\text{Parity}}_{\substack{\text{Reverses}\\ \text{momentum}}}$$



For us, the helicity reversal does not matter.

Can think of CP as simply replacing every particle in some process by its antiparticle.

Violation of CP invariance ($\cancel{CP}$) means that this replacement changes the rate of the process.

Thus, *antimatter* and *matter* behave differently.

How It Works

$\cancel{CP}$ ***always*** comes from ***phases***.

Therefore, $\cancel{CP}$ always requires an ***interference*** between (at least) two amplitudes.

For example, an interference between the amplitudes for two Feynman diagrams.

Let us consider how a CP-violating rate difference between two CP-mirror-image processes, such as $B^+ \to D^0 K^+$ and $B^- \to \overline{D}^0 K^-$, arises.

Suppose some process P has the amplitude —

$$A = M_1 e^{i\theta_1} e^{i\delta_1} + M_2 e^{i\theta_2} e^{i\delta_2}$$

CP-invariant magnitude

CP-odd phase

CP-even phase

Then the CP-mirror-image process $\overline{\text{P}}$
has the amplitude —

$$\overline{A} = M_1 e^{i\theta_1} e^{-i\delta_1} + M_2 e^{i\theta_2} e^{-i\delta_2}$$

Then the rates for $\overline{\text{P}}$ and P differ by —

$$\overline{\Gamma} - \Gamma = \left|\overline{A}\right|^2 - \left|A\right|^2 = 4 M_1 M_2 \sin(\theta_1 - \theta_2) \sin(\delta_1 - \delta_2)$$

$$\overline{\Gamma} - \Gamma = \left|\overline{A}\right|^2 - \left|A\right|^2 = 4 M_1 M_2 \sin\left(\theta_1 - \theta_2\right) \sin\left(\delta_1 - \delta_2\right)$$

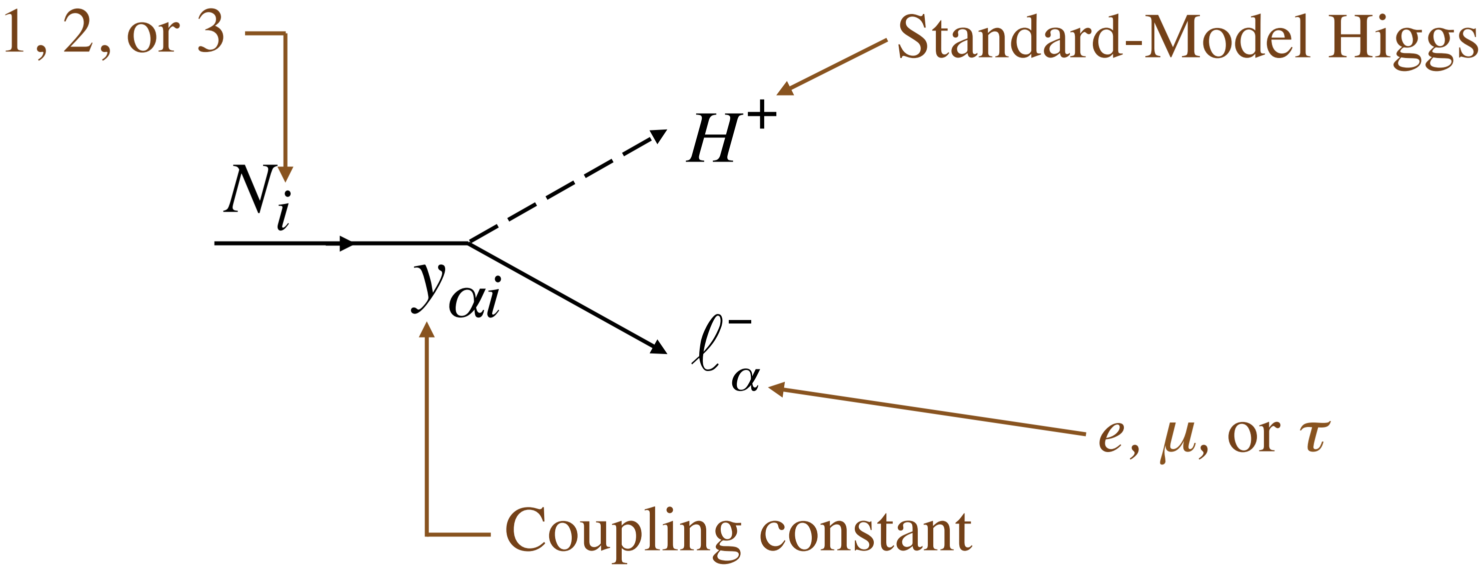
A CP-violating rate difference requires 3 ingredients:

- Two interfering amplitudes
- These two amplitudes must have different CP-even phases
- These two amplitudes must have different CP-odd phases

How ~~*CP*~~ Inequalities Between *N* Decay Rates Come About

Let us look at an example.

In the see-saw model, the N_i decays modes are —



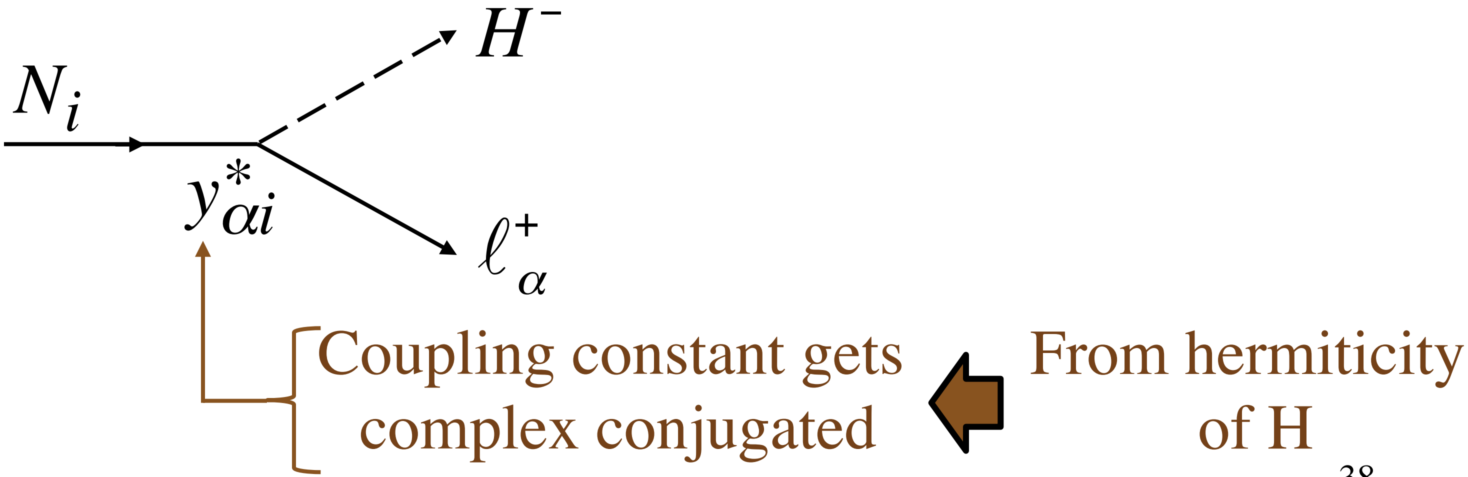
1, 2, or 3

Standard-Model Higgs

e, μ, or τ

Coupling constant

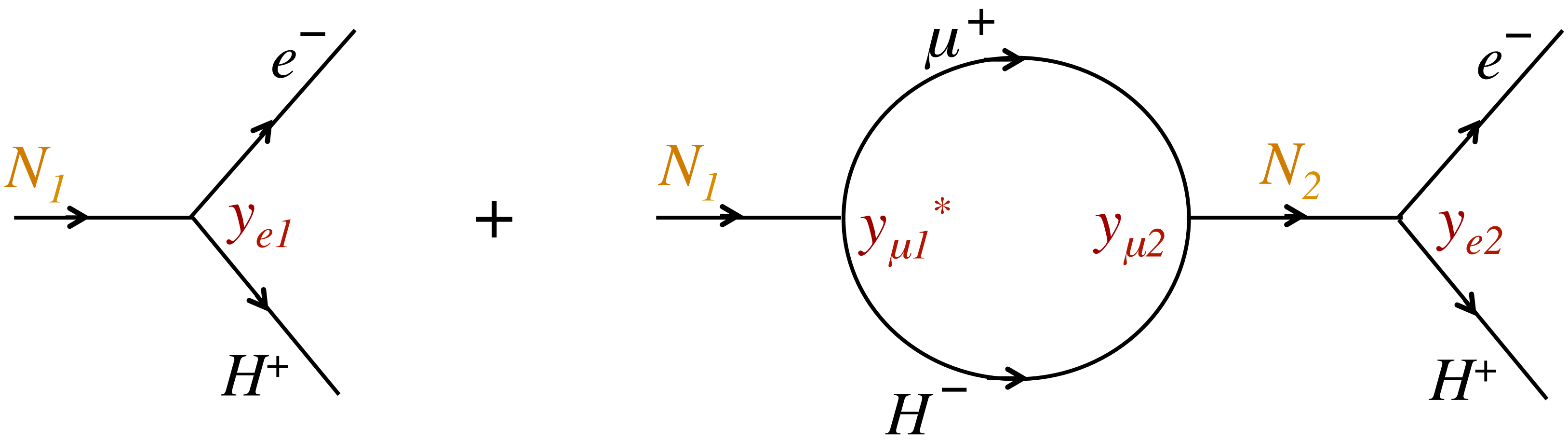
The CP-mirror-image decays are (recall $\overline{N}_i = N_i$) —



Coupling constant gets complex conjugated

From hermiticity of H

The amplitude for $N_1 \rightarrow e^- + H^+$ includes —



Tree

Loop

$$\Gamma\left(N_1 \rightarrow e^- + H^+\right) = \left| \underset{\uparrow}{y_{e1}} K_{\text{Tree}} + \underset{\uparrow}{y_{\mu 1}^* y_{\mu 2} y_{e2}} K_{\text{Loop}} \right|^2$$

Kinematical factors

$$\Gamma\left(N_1 \to e^- + H^+\right) = \left| y_{e1} K_{\text{Tree}} + y_{\mu 1}^* y_{\mu 2} y_{e2} K_{\text{Loop}} \right|^2$$

When we go to the CP-mirror-image decay, $N_1 \rightarrow e^+ + H^-$, all the coupling constants get complex conjugated, but the kinematical factors do not change.

$$\Gamma\left(N_1 \to e^+ + H^-\right) = \left| y_{e1}^* K_{\text{Tree}} + y_{\mu 1} y_{\mu 2}^* y_{e2}^* K_{\text{Loop}} \right|^2$$

All three ingredients needed for $\cancel{CP}$ are present.

$$\boxed{\begin{aligned} &\Gamma\left(N_1 \to e^- + H^+\right) - \Gamma\left(N_1 \to e^+ + H^-\right) \\ &= 4\,\text{Im}\left(y_{e1}^* y_{\mu 1}^* y_{e2} y_{\mu 2}\right) \text{Im}\left(K_{\text{Tree}} K_{\text{Loop}}^*\right) \end{aligned}}$$

If $\Gamma\left(N_1 \rightarrow e^- + H^+\right) \neq \Gamma\left(N_1 \rightarrow e^+ + H^-\right)$, then starting with a universe with equal numbers of ***electrons*** and ***positrons***, these N_1 decays would leave behind a universe with unequal numbers of the two.

More generally, if $\Gamma\left(N_i \rightarrow \ell_\alpha^- + H^+\right) \neq \Gamma\left(N_i \rightarrow \ell_\alpha^+ + H^-\right)$, then starting with a universe with equal numbers of ***leptons*** and ***antileptons***, the N_i decays would leave behind a universe with unequal numbers of the two.

Then the SM ***Sphaleron*** process will convert part of this ***lepton*** – ***antilepton*** asymmetry into a ***quark*** – ***antiquark*** asymmetry, which eventually will turn into a ***nucleon*** – ***antinucleon*** asymmetry.

This is how *Leptogenesis* of the ***matter*** **–** ***antimatter***
asymmetry of the universe works.

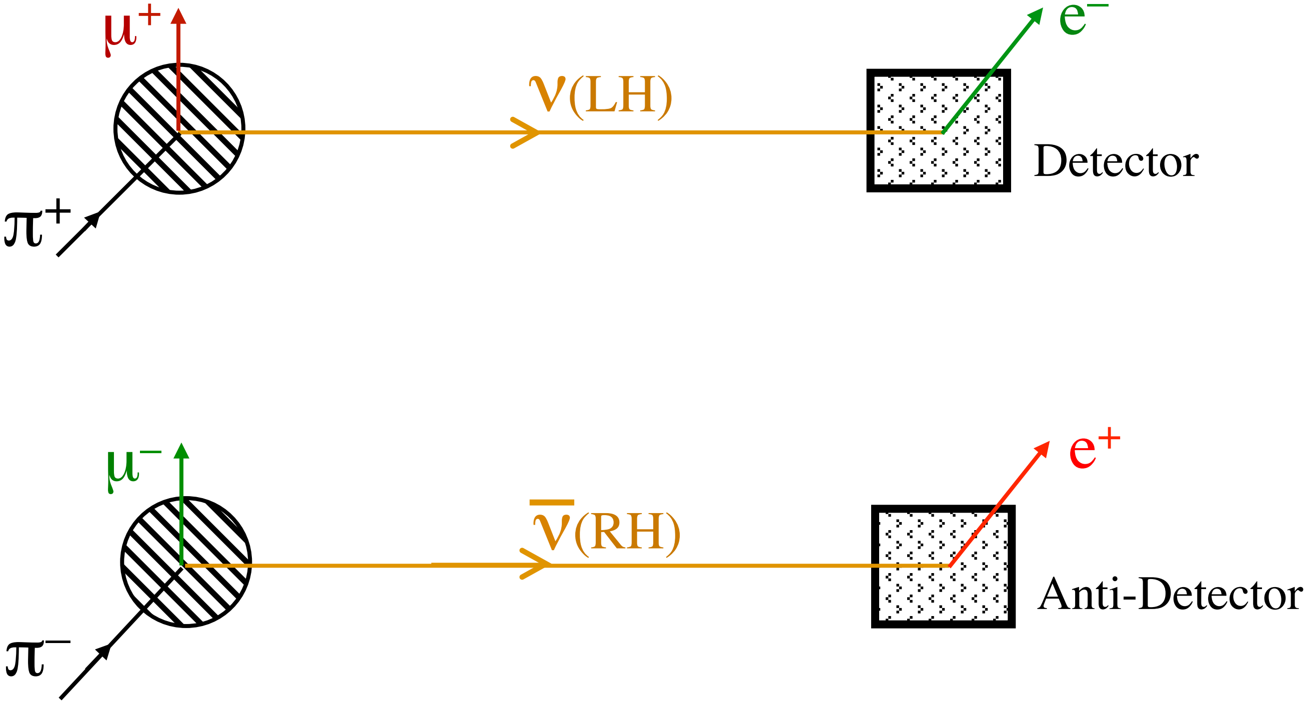
Note that it requires CP violation ***among the leptons***.

So far, we have seen CP violation only ***among the quarks***,
and we know that this quark CP violation cannot explain
the ***matter*** **–** ***antimatter*** asymmetry of the universe.

To play their role in *Leptogenesis*,
the heavy neutrinos N must have masses of $10^{(9-14)}$ GeV.

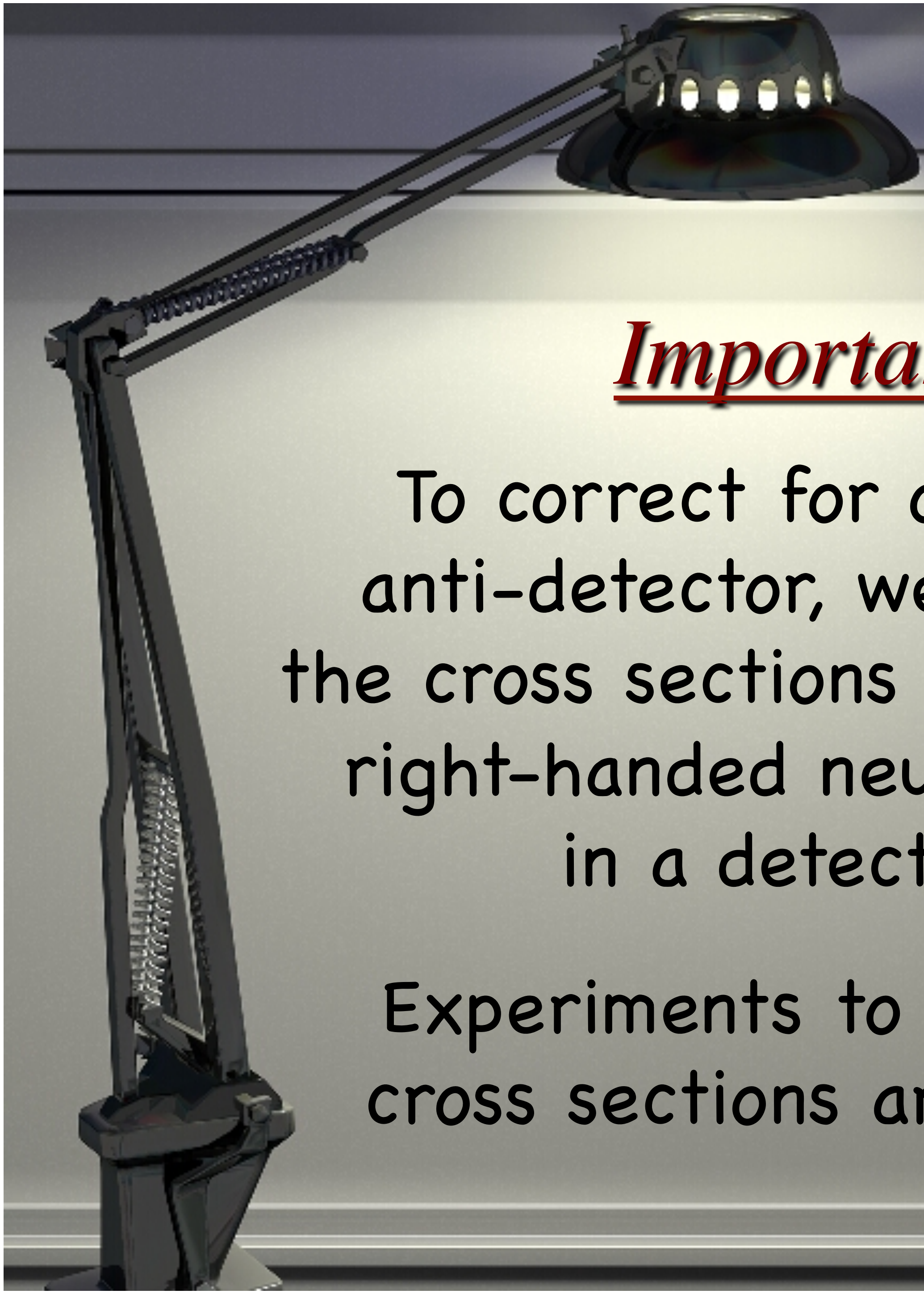
We cannot produce them at a collider and look
for CP violation in their decays. But —

To confirm leptonic CP violation, compare two CP-mirror-image neutrino oscillations.



vs.

Do these two CP-mirror-image processes have different rates?

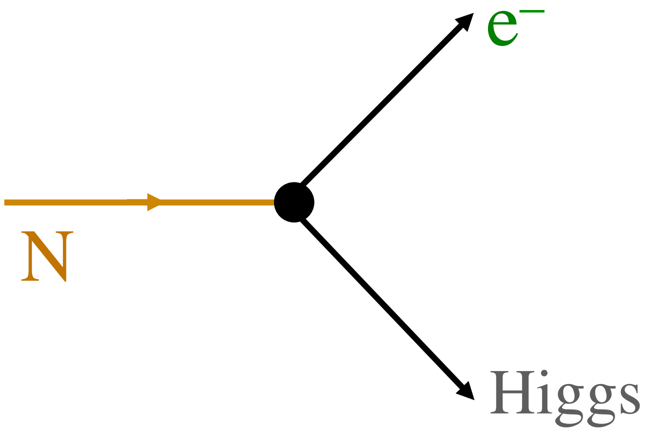


Important Notice

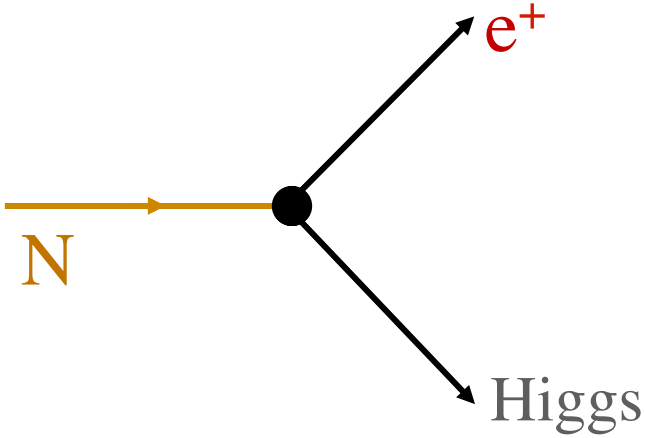
To correct for our not using an anti-detector, we must know how the cross sections for left-handed and right-handed neutrinos to interact in a detector compare.

Experiments to determine these cross sections are very important.

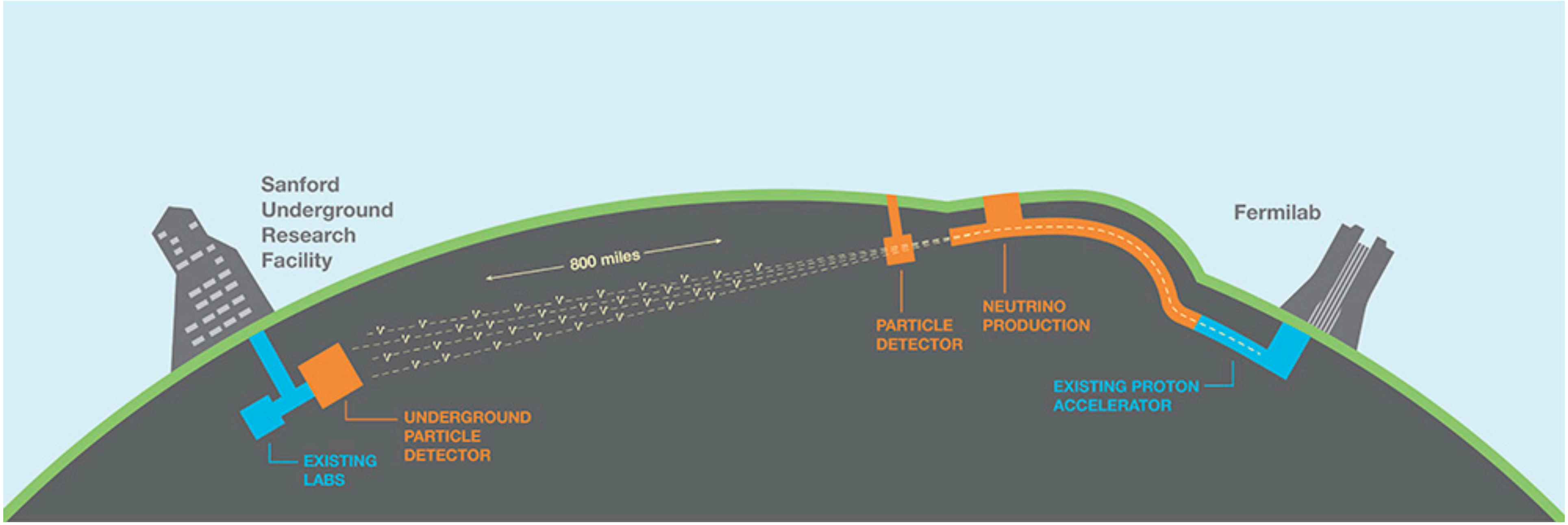
The coming ~~CP~~ experiments are today's version of comparing —



with —



The Deep Underground Neutrino Experiment (DUNE)



One of DUNE's major goals will be to seek and measure CP violation in neutrino oscillation.

A complementary program may be developed in Japan.

Summary

We have learned that neutrinos have nonzero masses.

These masses may have a quite different origin than the quark and charged lepton masses.

That origin may involve very heavy neutrinos from which we, and all matter, are descended.