Neutrino Physics

Boris Kayser
CERN

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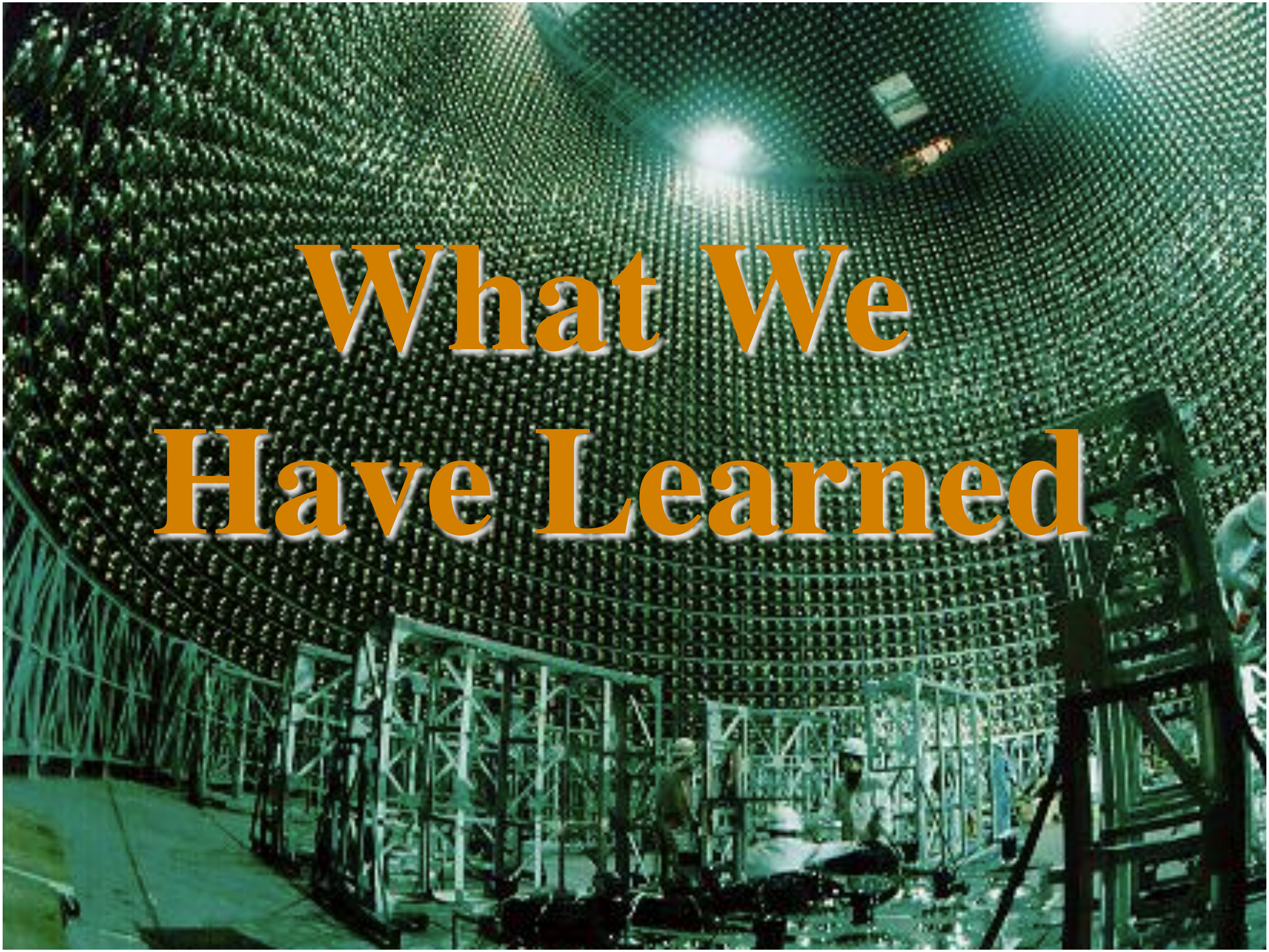
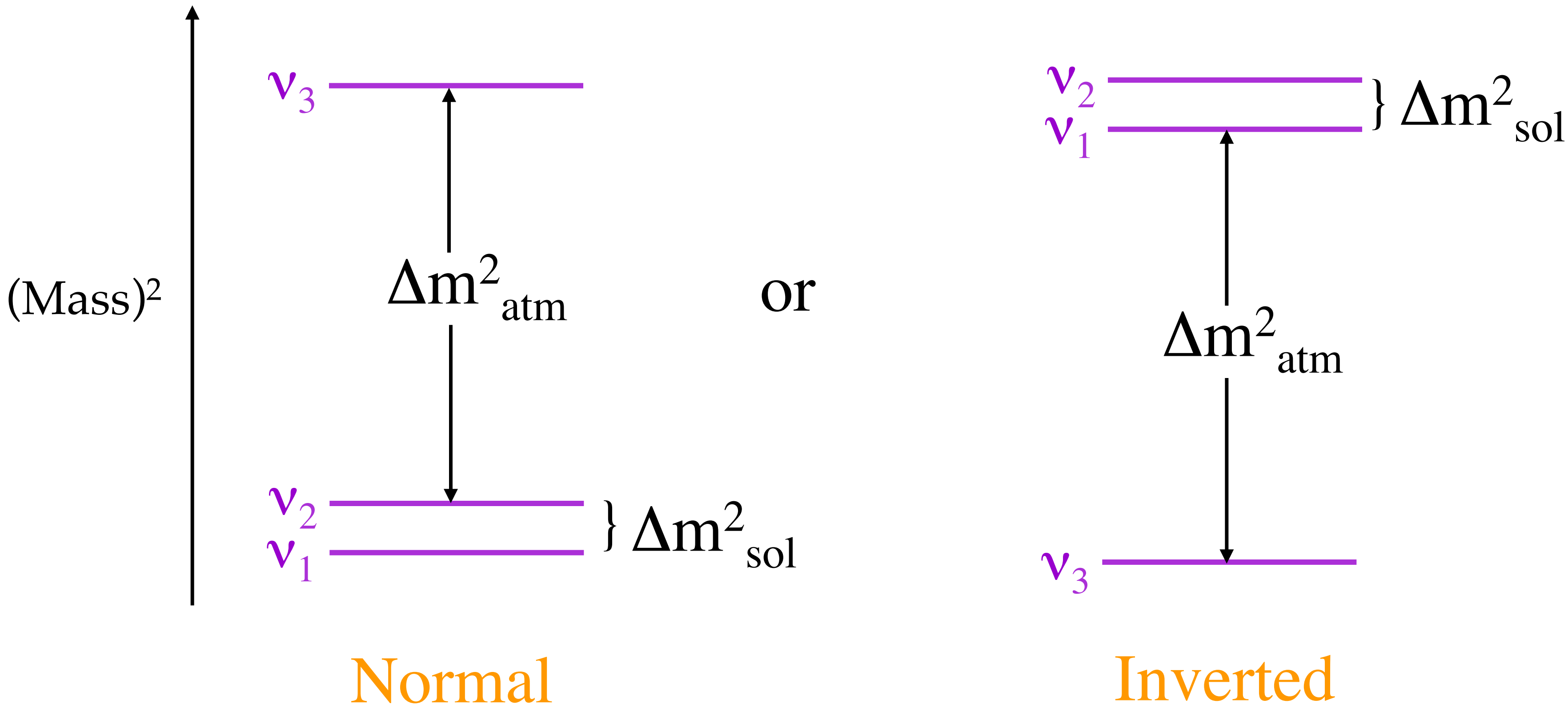
Part 2

NASA Hubble Photo

What We Have Learned



The $(\text{Mass})^2$ Spectrum



$|\Delta m^2_{sol}| \cong 7.5 \times 10^{-5}\ \text{eV}^2$, $\quad |\Delta m^2_{atm}| \cong 2.4 \times 10^{-3}\ \text{eV}^2$

The Lepton Mixing Matrix *U*

Atmospheric — Reactor (L ~ 1 km) — Solar

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

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

Does not affect oscillation

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

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

Note big mixing!

$\theta_{12} \approx 33°$, $\theta_{23} \approx 40\text{-}52°$, $\theta_{13} \approx 8\text{-}9°$ ← *Not very small!*

The phases violate CP. δ would lead to $P(\overline{\nu}_\alpha \to \overline{\nu}_\beta) \neq P(\nu_\alpha \to \nu_\beta)$.

↑ ~~CP~~

But note the crucial role of $s_{13} \equiv \sin \theta_{13}$.

We know essentially nothing about the phases. Only hints.

There Is Nothing Special About θ_{13}

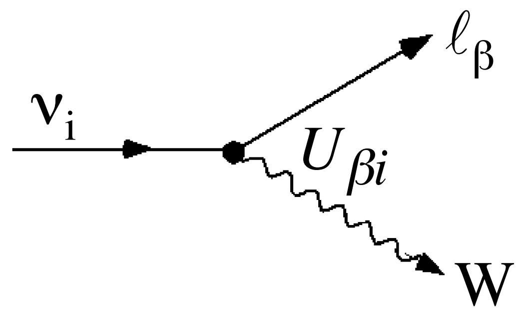
All mixing angles must be nonzero for ~~*CP*~~ in oscillation.

For example —

$$P\left(\bar{\nu}_\mu \to \bar{\nu}_e\right) - P\left(\nu_\mu \to \nu_e\right) = 2\cos\theta_{13}\sin 2\theta_{13}\sin 2\theta_{12}\sin 2\theta_{23}\sin\delta \times \sin\left(\Delta m^2{}_{31}\frac{L}{4E}\right)\sin\left(\Delta m^2{}_{32}\frac{L}{4E}\right)\sin\left(\Delta m^2{}_{21}\frac{L}{4E}\right)$$

In the factored form of U, one can put δ next to θ_{12} instead of θ_{13}.

The Meaning of the Mixing Matrix Elements

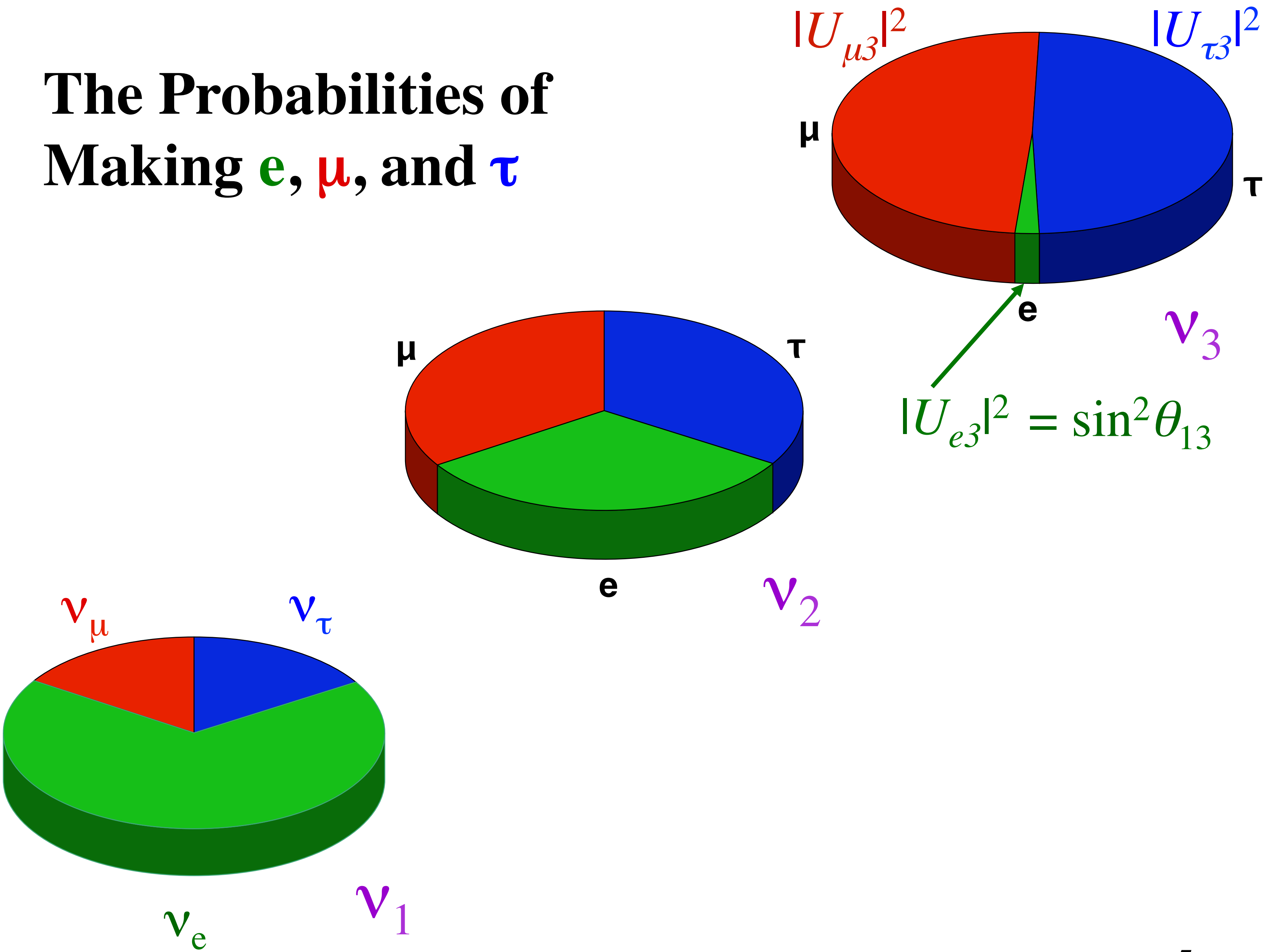


means that when a ν_i creates a charged lepton, the probability that this charged lepton will be, in particular, of flavor β is —

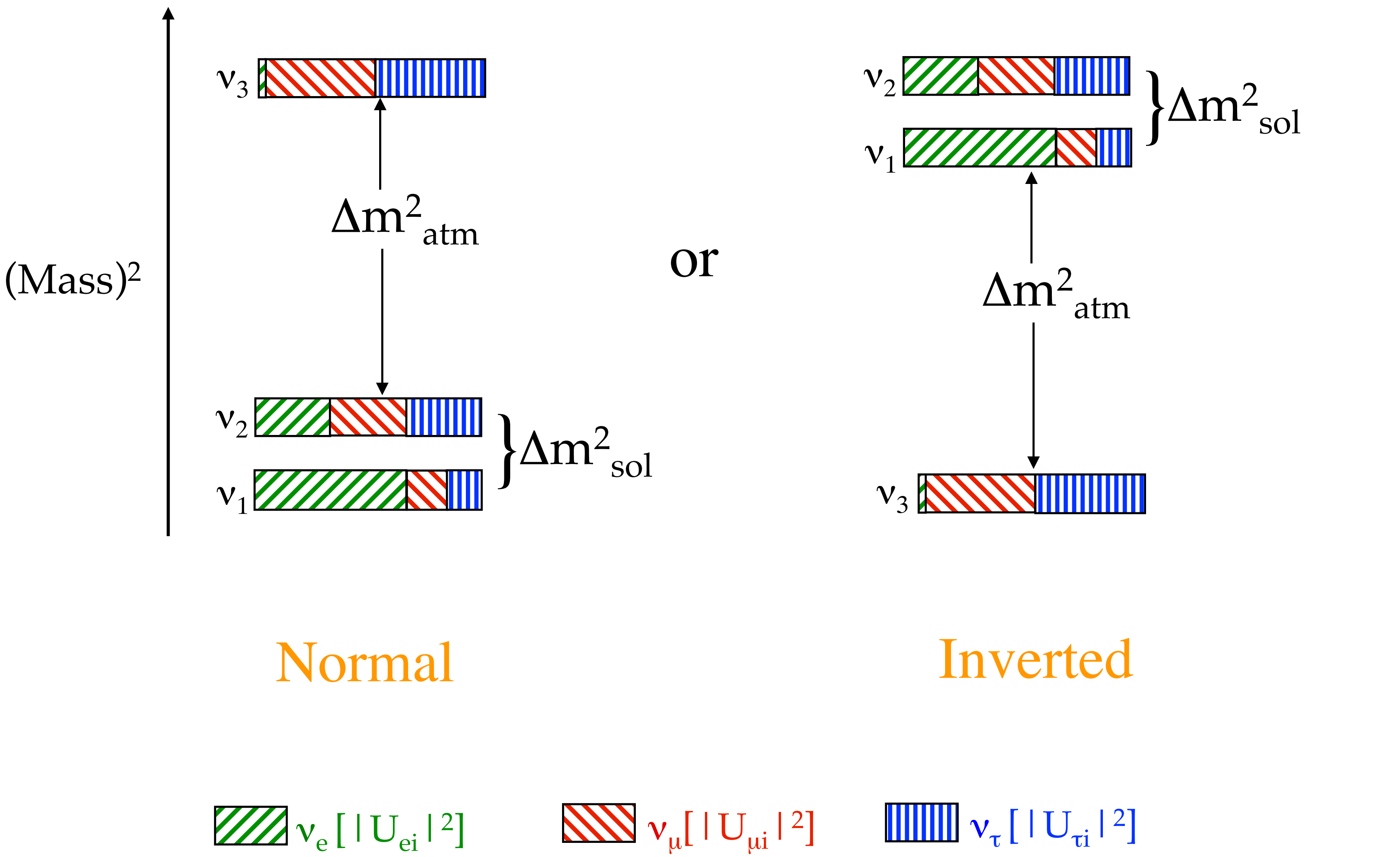
$$\left|U_{\beta i}\right|^2$$

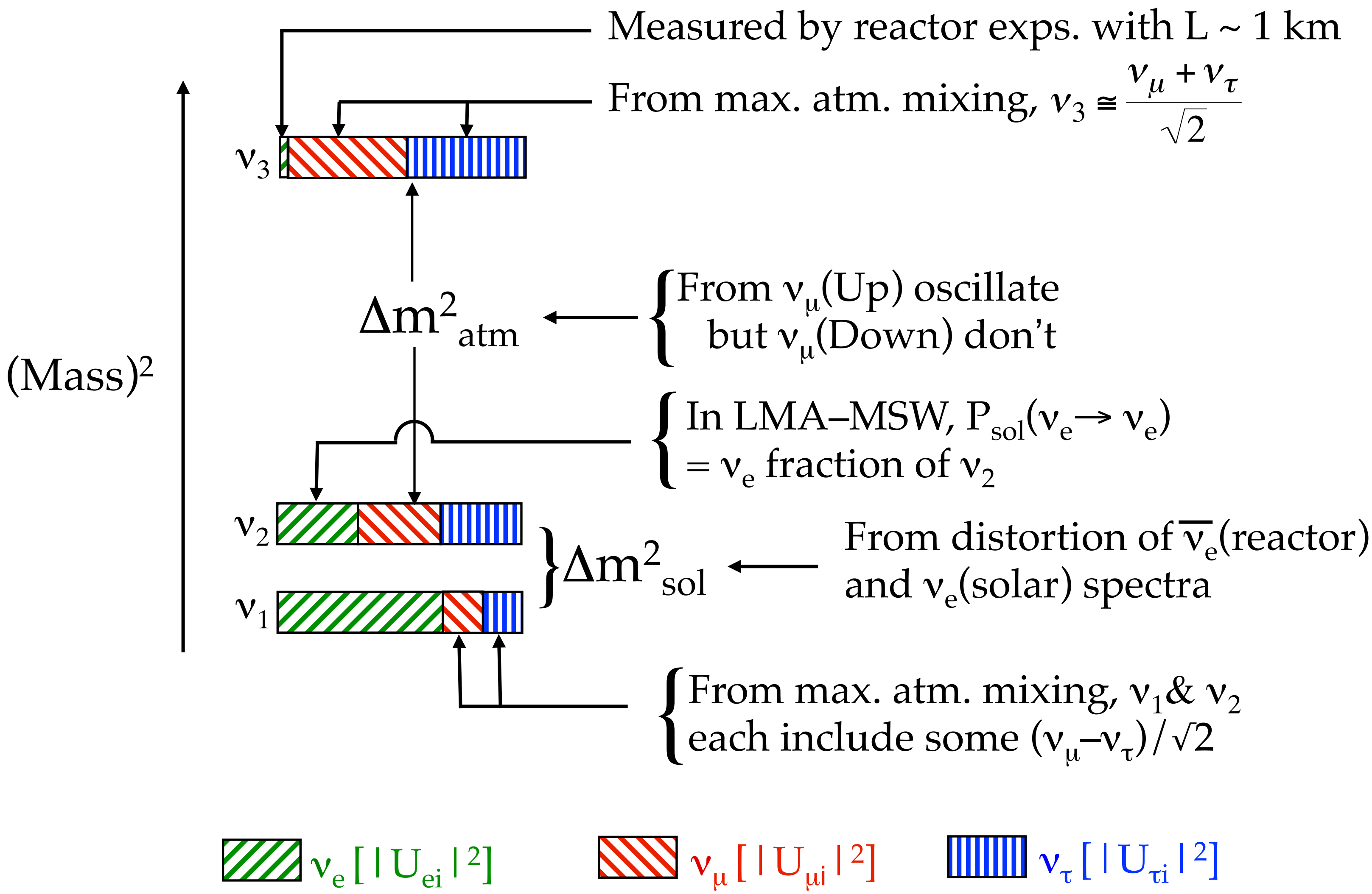
From the measured mixing angles —

The Probabilities of Making e, μ, and τ



A linear version of the same information is —




Measured by reactor exps. with L ~ 1 km
From max. atm. mixing, $\nu_3 \cong \frac{\nu_\mu + \nu_\tau}{\sqrt{2}}$
ν_3
Δm^2_{atm}
From ν_μ(Up) oscillate but ν_μ(Down) don't
(Mass)^2
In LMA–MSW, $P_{sol}(\nu_e \to \nu_e)$ = ν_e fraction of ν_2
ν_2
Δm^2_{sol}
From distortion of $\overline{\nu}_e$(reactor) and ν_e(solar) spectra
ν_1
From max. atm. mixing, ν_1 & ν_2 each include some $(\nu_\mu - \nu_\tau)/\sqrt{2}$
ν_e [$|U_{ei}|^2$]
ν_μ [$|U_{\mu i}|^2$]
ν_τ [$|U_{\tau i}|^2$]

Looking to the Future

The 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?

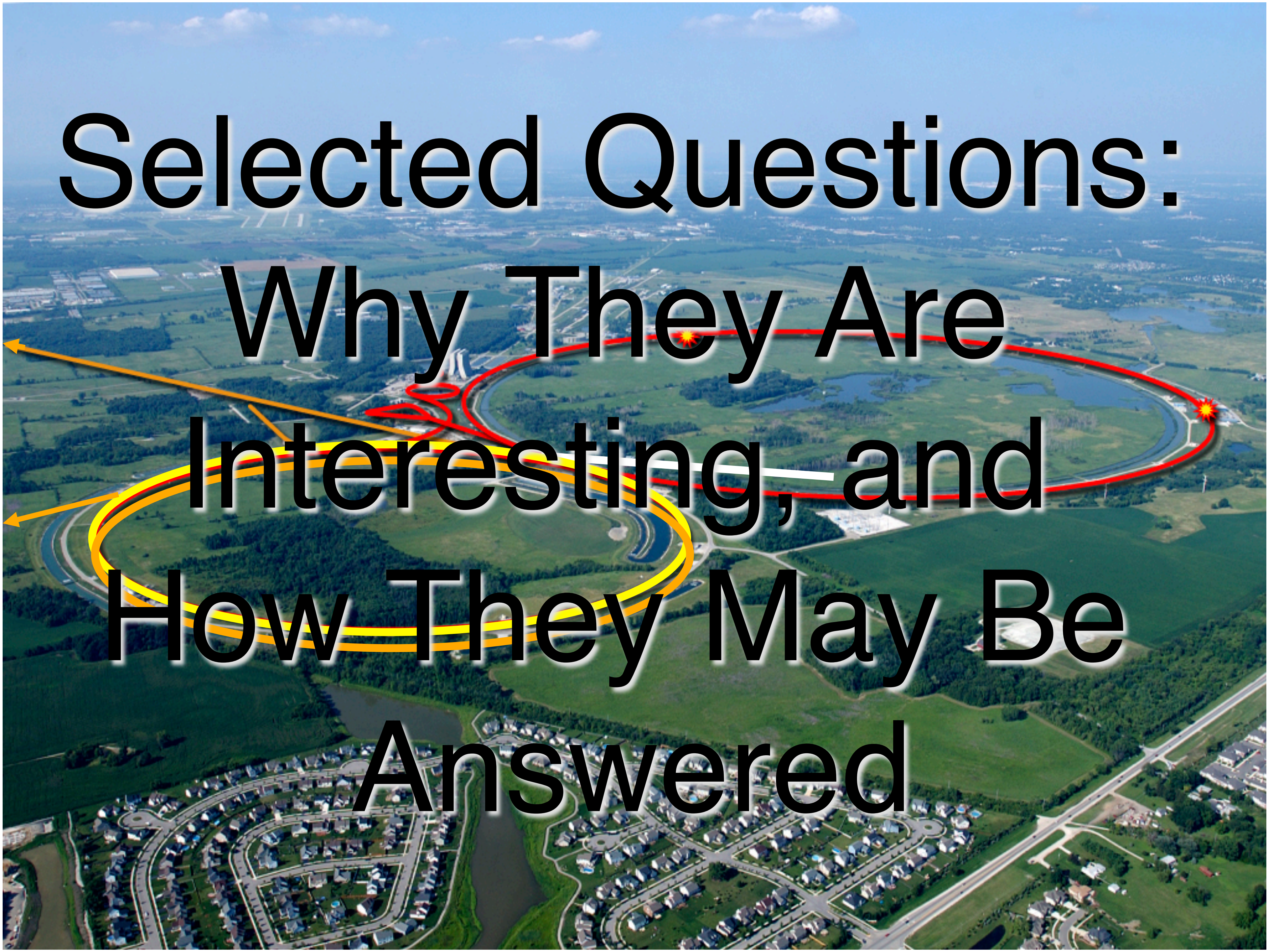
•Are we descended from heavy neutrinos?

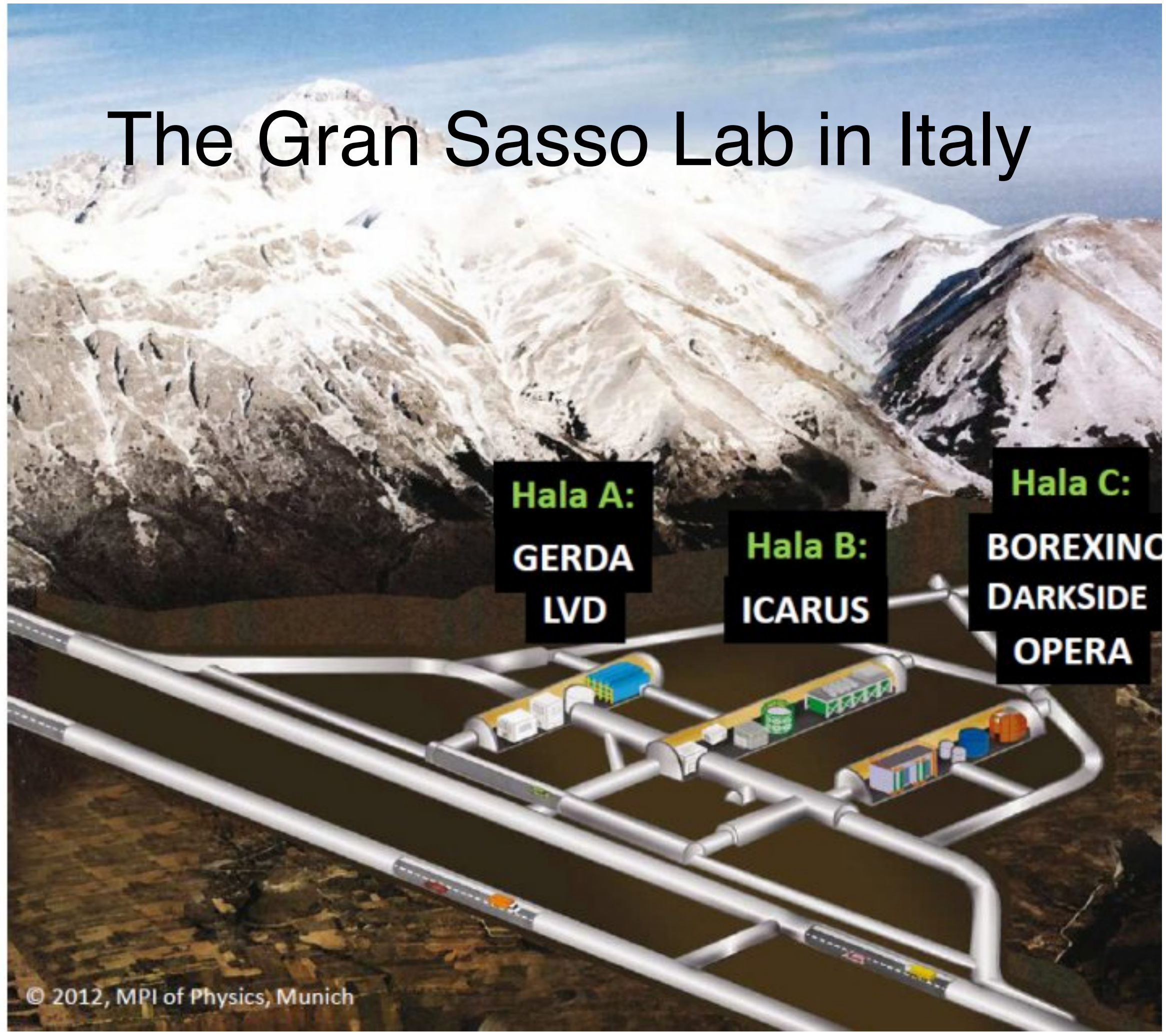
- What can neutrinos and the universe tell us about one another?

- 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 relativity?
  - Violation of CPT invariance?
  - Departures from quantum mechanics?


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



Is the Origin of Neutrino Mass Different?

Neutrino Masses Without Field Theory

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

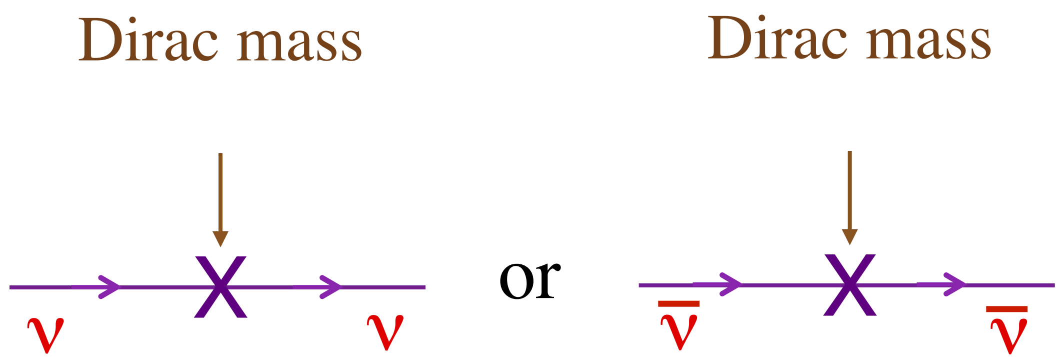
We start with underlying neutrino states ν and $\bar{\nu}$ that are distinct from each other, like other familiar fermions, and are not the mass eigenstates.

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

We can have two types of masses:

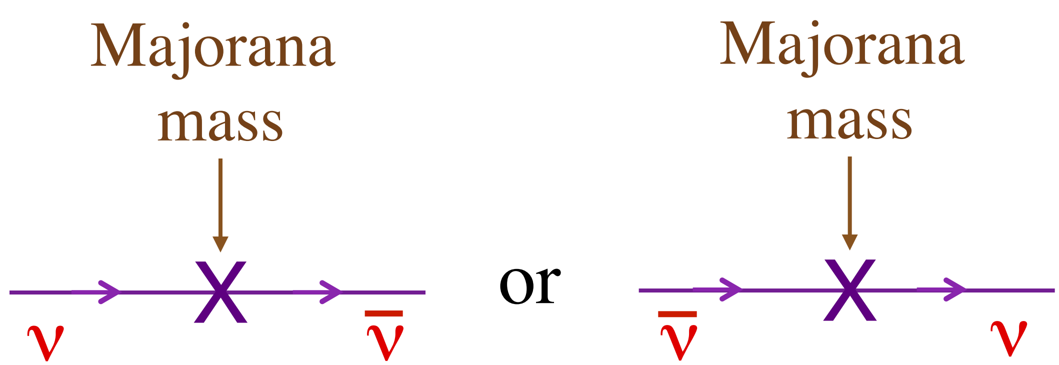
Dirac Mass

A Dirac mass
has the effect:



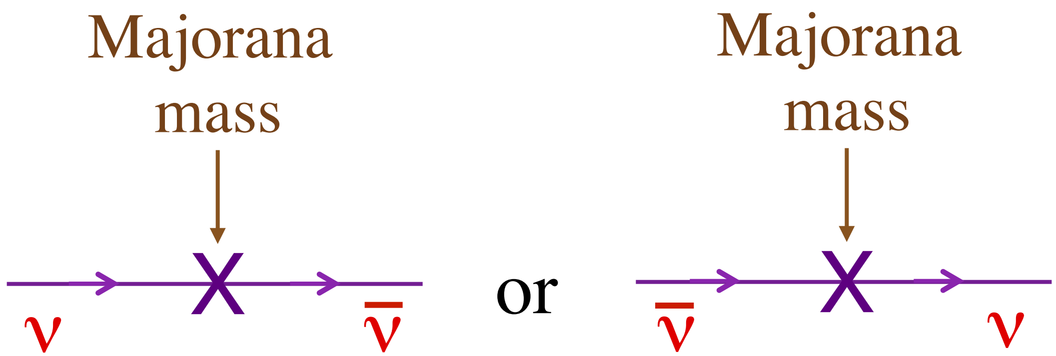
Majorana Mass

A Majorana mass
has the effect:



Majorana Mass

A Majorana mass has the effect:



Majorana masses mix ν and ν̄, 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,

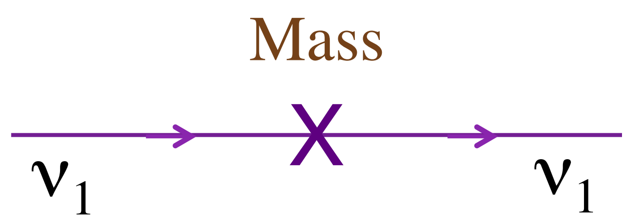
— or through interaction with a Higgs-like field
which is not in the Standard Model,
and carries a different value of the "weak isospin"
quantum number than the Standard Model Higgs,

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

The study of neutrino masses is part of the quest
to understand the origins of all mass.

The Mass Eigenstates When There Are Majorana Masses

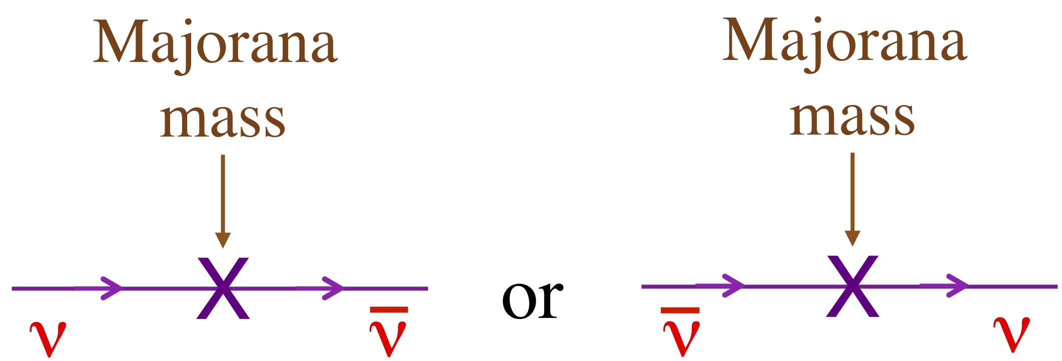
For any fermion mass eigenstate, e.g. ν_1, the action of its mass is —



The mass eigenstate is sent back into itself.

Recall that —

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



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)

"Majorana neutrinos"

The Terminology

Suppose ν_i is a ***mass eigenstate***, with ***given helicty*** $h \equiv \overrightarrow{\text{Spin}} \bullet \widehat{\text{Momentum}}$.

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

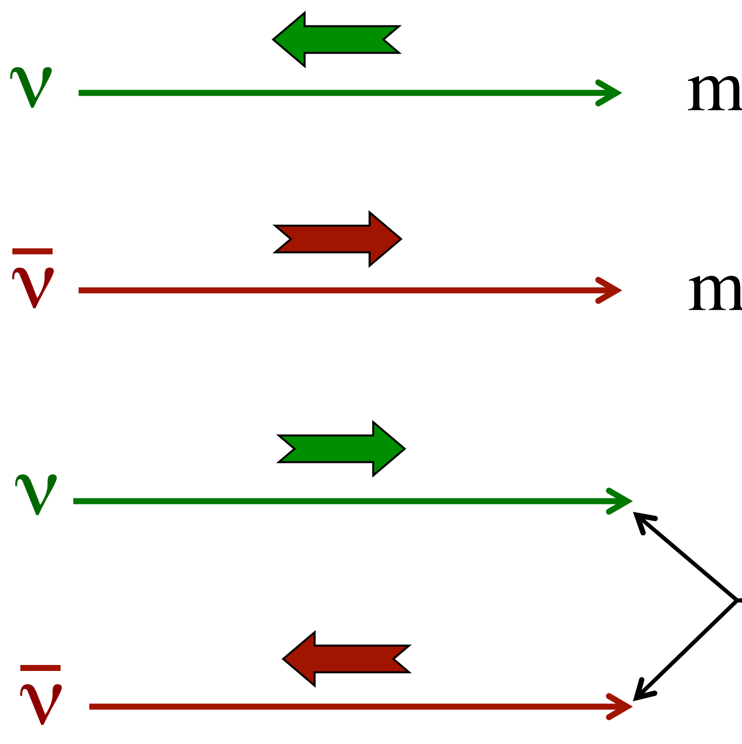
or

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

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

SM Interactions Of A Dirac Neutrino

We have 4 mass-degenerate states:

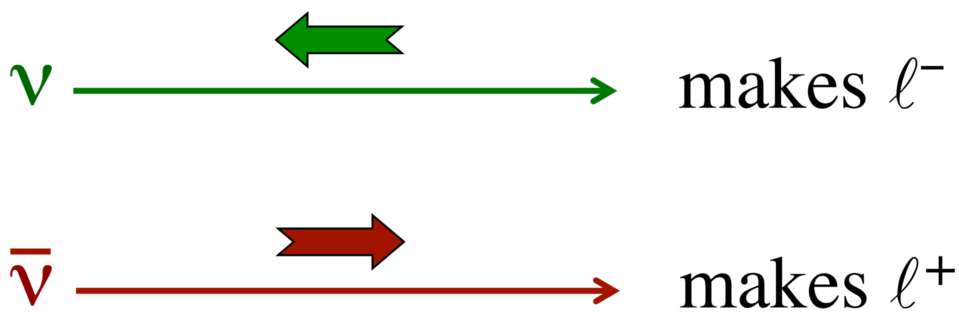


		Conserved L
ν	makes ℓ^-	+1
$\bar{\nu}$	makes ℓ^+	–1

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:



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^+.

To Determine Whether Majorana Masses Occur in Nature

The Promising Approach — Seek

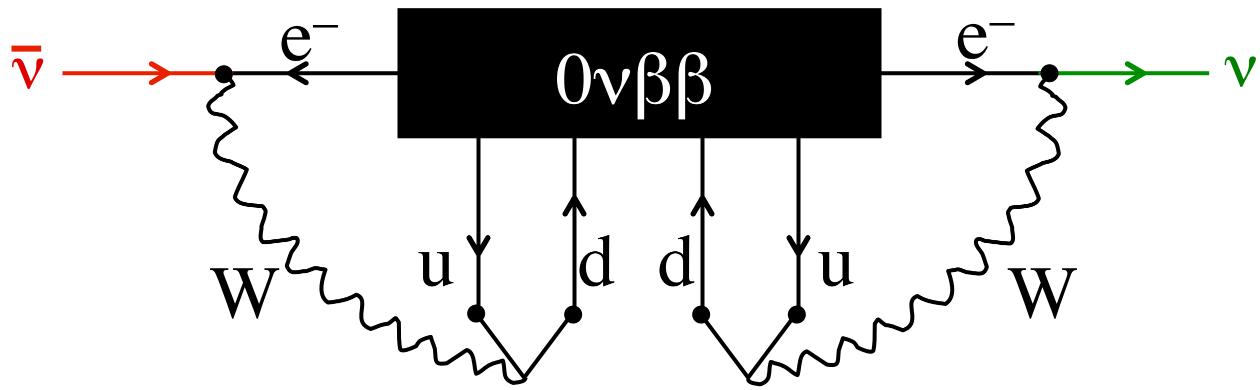
Neutrinoless Double Beta Decay [$0\nu\beta\beta$]

We are looking for a ***small*** Majorana neutrino mass. Thus, we will need ***a lot*** of parent nuclei (say, one ton of them).

Note that 0νββ violates conservation of lepton number L by ΔL = 2.

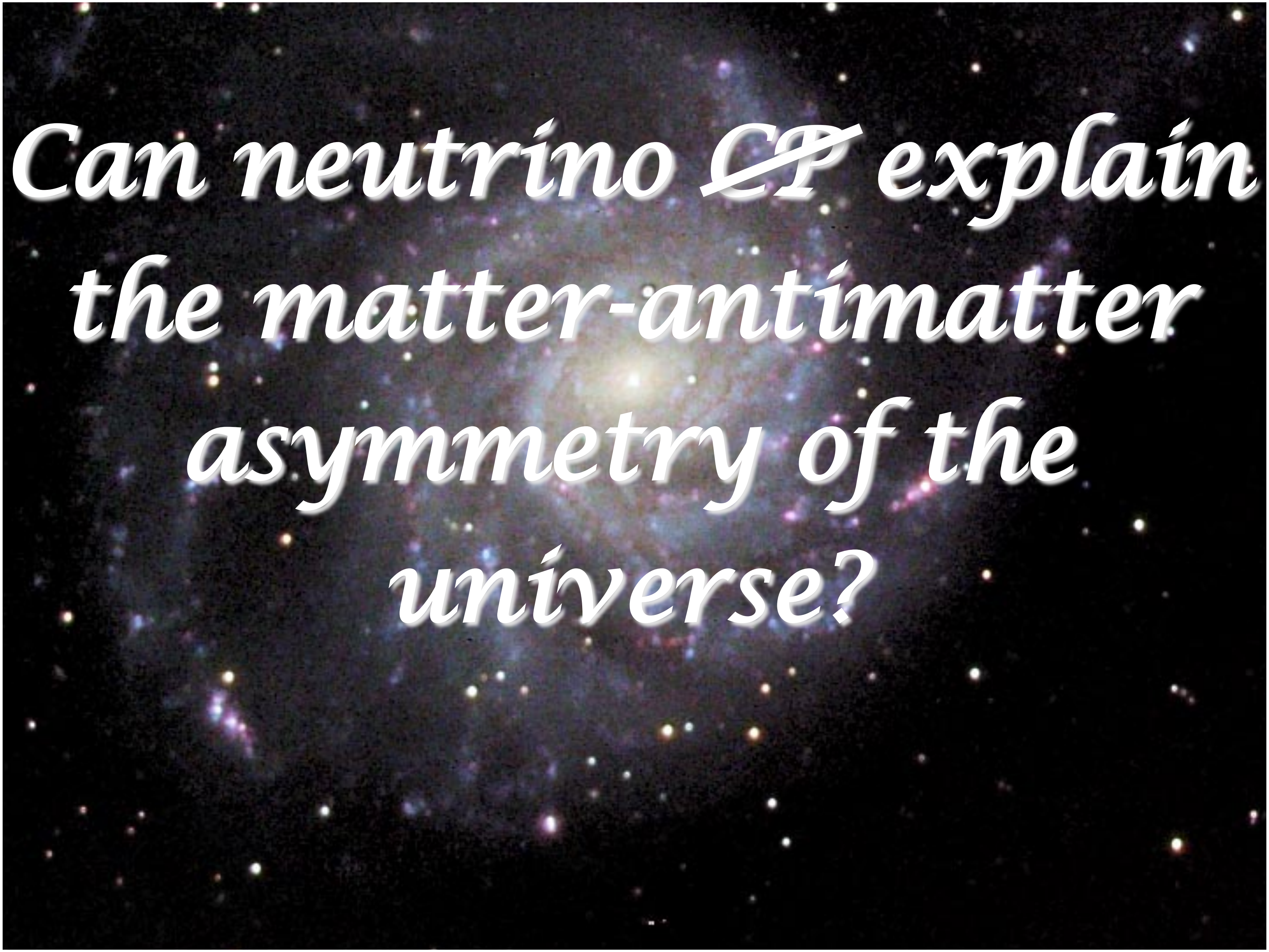
Whatever physics causes $0\nu\beta\beta$, its observation would imply the existence of a Majorana mass term:

(Schechter and Valle)



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

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


Can neutrino ~~CP~~ explain
the matter-antimatter
asymmetry of the
universe?

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***.

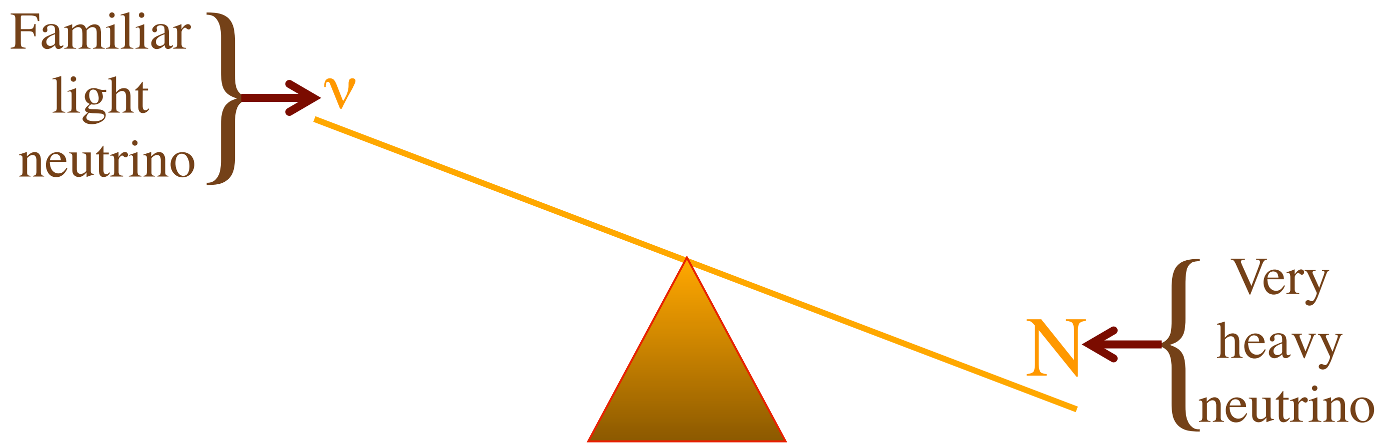
This change requires that ***matter*** and ***antimatter*** behave differently. Thus, we must have ~~CP~~.
Can we find a CP-violating scenario to explain the change?

An appealing candidate: *Leptogenesis*.

(Fukugita, Yanagida)

Leptogenesis

Leptogenesis is an outgrowth of the ***See-Saw Mechanism*** for generating very small neutrino masses.



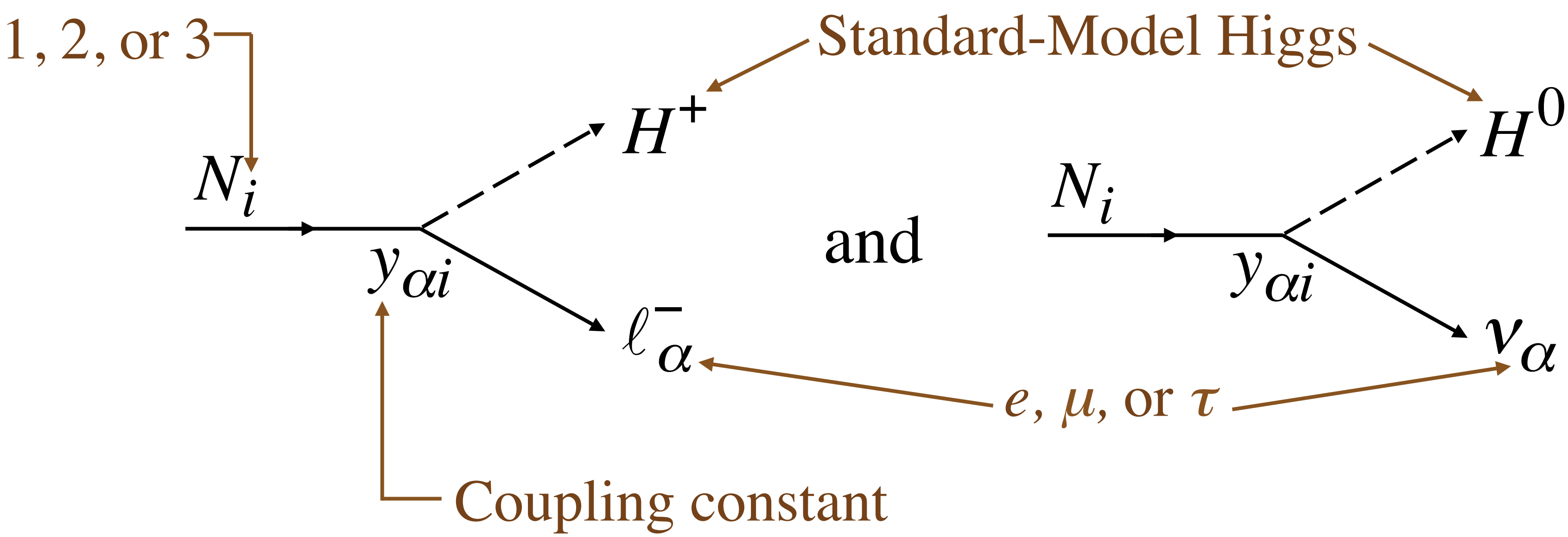
Yanagida; Gell-Mann, Ramond, Slansky; Mohapatra, Senjanovic; Minkowski

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

We assume that, just as there are 3 light neutrinos ν_1, ν_2, ν_3, there are 3 heavy neutrinos N_1, N_2, N_3.

$M_N \sim 10^{(9-14)}$ GeV, so we cannot produce the heavy neutrinos with any existing accelerator, but they would have been made in the ***hot*** Big Bang.

The N decays modes are —



Including the possibility of CP-mirror-image decays (every particle replaced by its antiparticle), the *N* decays modes are —

Standard-Model Higgs

$$N \to \ell^- + H^+ \quad , \quad N \to \ell^+ + H^-$$

CP mirror image modes

$$N \to \nu + H^0 \quad , \quad N \to \bar{\nu} + \overline{H^0}$$

Standard-Model Higgs

The See-Saw picture depends on Majorana masses.

In the See-Saw picture, $\bar{N} = N$.

And today $\bar{\nu} = \nu$. *Try to confirm by observing* $0\nu\beta\beta$.

CP violation in the N decays, ***coming from phases among the $y_{\alpha i}$***, will lead to —

$$\Gamma\left(N \to \ell^- + H^+\right) \neq \Gamma\left(N \to \ell^+ + H^-\right)$$

and

$$\Gamma\left(N \to \nu + H^0\right) \neq \Gamma\left(N \to \bar{\nu} + \overline{H^0}\right)$$

This will produce a universe with unequal numbers of leptons (ℓ^- and ν) and antileptons (ℓ^+ and $\bar{\nu}$).

In this universe the lepton number L, defined by $L\left(\ell^-\right) = L(\nu) = -L\left(\ell^+\right) = -L(\bar{\nu}) = 1$, is not zero.

This is Leptogenesis — Step 1

Leptogenesis — Step 2

The Standard-Model ***Sphaleron*** process acts.
This process does not conserve the Lepton Number L,
or its Baryonic equivalent, the Baryon Number B, defined by

$$B(\text{nucleon}) = -B(\text{antinucleon}) = 3B(\text{quark}) = -3B(\text{antiquark}) = 1$$

$$B_i = 0$$
$$L_i \neq 0$$

Initial state from N decays

Sphaleron Process

$$B_f \cong -\frac{1}{3} L_i$$
$$L_f \cong \frac{2}{3} L_i \cong -2B_f$$

Final state

***There is now a nonzero** Baryon Number.*

Eventually, there will be nucleons,
but ~ no antinucleons.

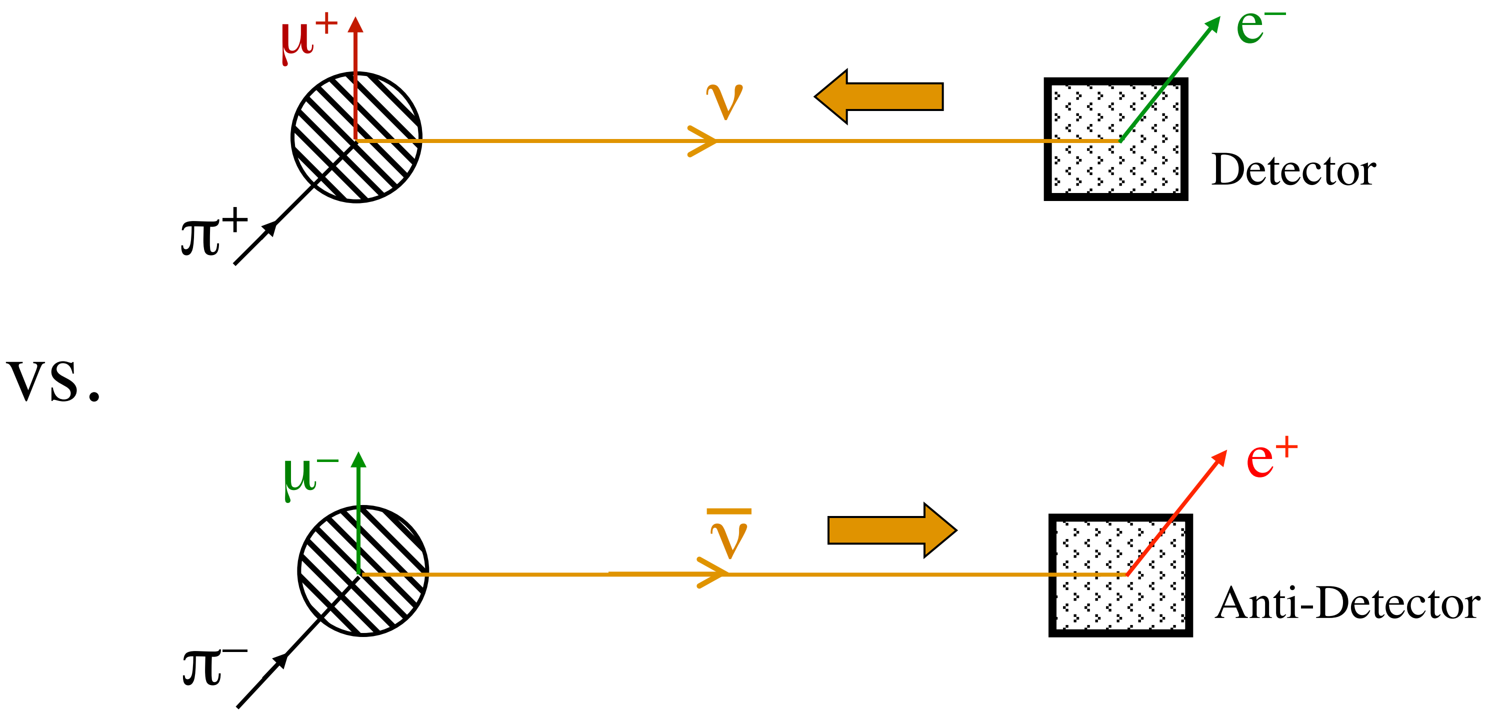
Reasonable parameters give
the observed $n_{\mathcal{N}uc} / n_\gamma$ ***.***

Generically, leptogenesis and light-neutrino $\not{CP}$ imply each other.

Seeking $\not{CP}$ in neutrino oscillation is now a worldwide goal.

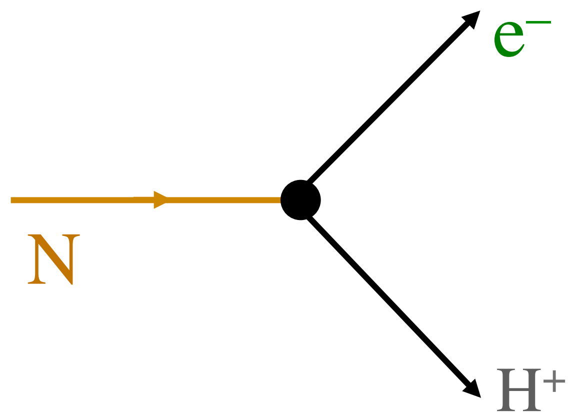
The search will use long-baseline accelerator neutrino beams to study $\nu_\mu \rightarrow \nu_e$ and $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$, or their inverses.

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

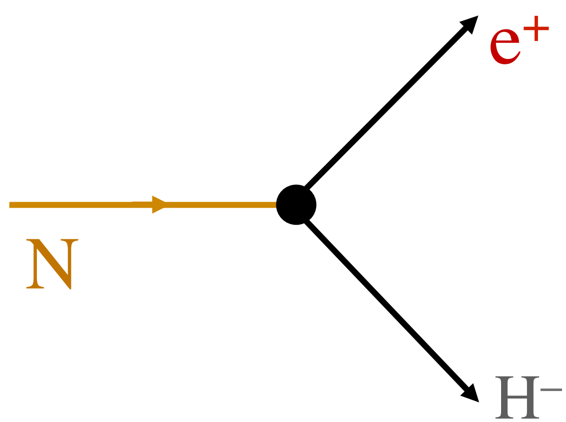


<u>Do these two CP-mirror-image processes have different rates?</u>

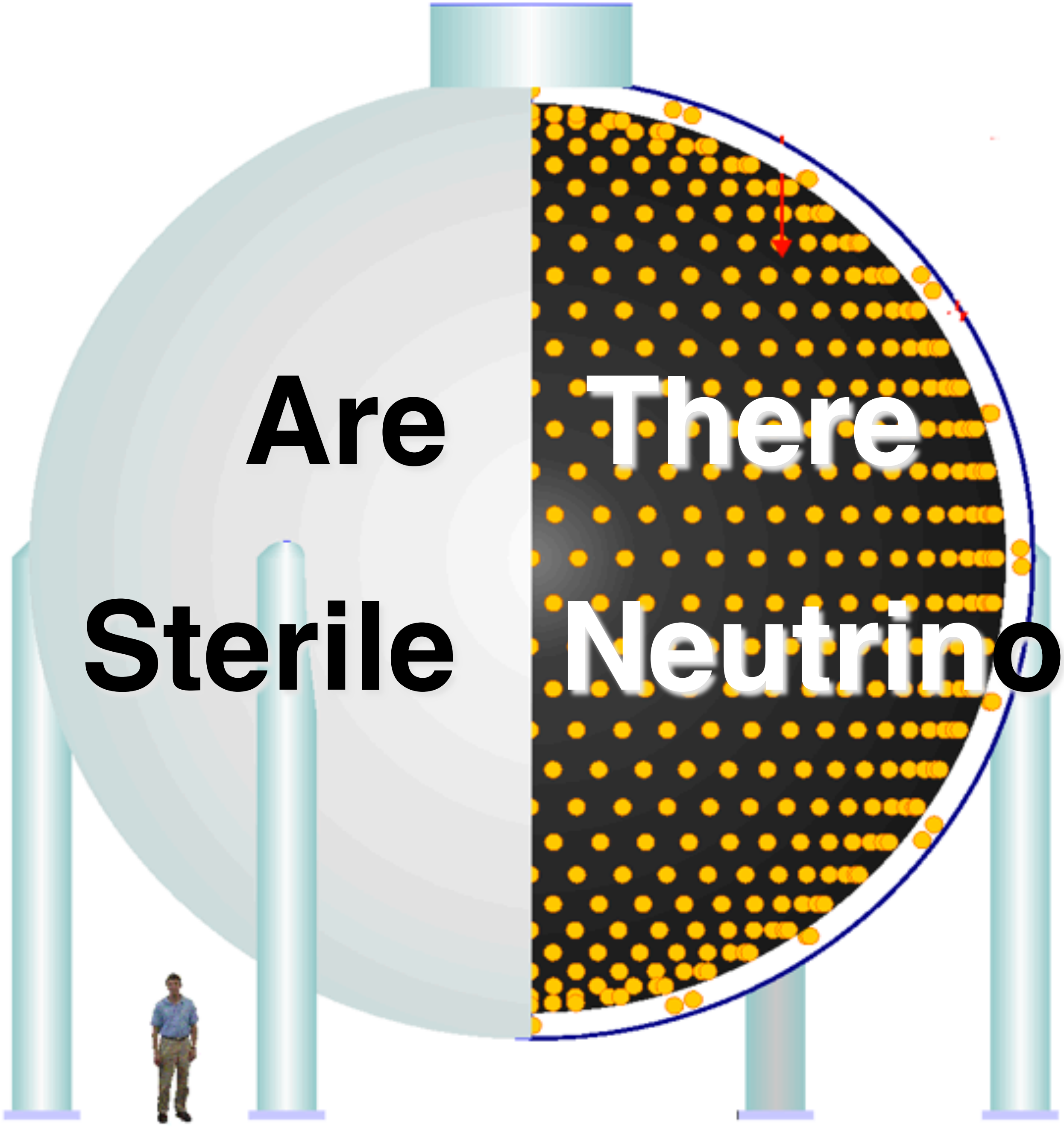
This is today's version of comparing —



with —



Are There Sterile Neutrinos?



Sterile Neutrino

One that does not couple to the SM *W* or *Z* boson

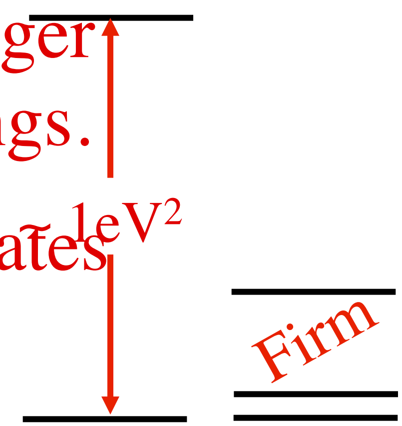
A "sterile" neutrino may well couple to some non-SM particles. These particles could perhaps be found at LHC or elsewhere.

The Hints of eV-Mass Sterile Neutrinos

$$\text{Probability}(\text{Oscillation}) \propto \sin^2\left[1.27\Delta m^2\left(\text{eV}^2\right)\frac{L(\text{m})}{E(\text{MeV})}\right]$$

There are several hints of oscillation with L(m)/E(MeV) ~ 1:

These ⇒ a $\Delta m^2 \sim 1\ \text{eV}^2$, bigger than the two established splittings.



⇒ At least **4** mass eigenstates

⇒ At least **4** flavors

Then $$\frac{\Gamma\left(Z \to \nu\bar{\nu}\right)\big|_{\text{Exp}}}{\Gamma\left(Z \to \text{One } \nu\bar{\nu} \text{ Flavor}\right)\big|_{\text{SM}}} = 2.984 \pm 0.009$$

⇒ At least **1** sterile neutrino

The Hints of eV^2-Scale Δm^2

Experiment	Possible Oscillation	Comment
LSND	$\bar{\nu}_\mu \to \bar{\nu}_e$	Interesting
MiniBooNE	$\nu_\mu \to \nu_e$	Somewhat disfavored by ICARUS & OPERA
MiniBooNE	$\bar{\nu}_\mu \to \bar{\nu}_e$	NOT constrained by ICARUS & OPERA
Reactor Exps.	$\bar{\nu}_e \to \text{Not } \bar{\nu}_e$	Flux uncertainty ~ 6% size of effect
^{51}Cr and ^{37}Ar Source Exps.	$\nu_e \to \text{Not } \nu_e$	Detection efficiency?

Q: So, are there eV-scale sterile neutrinos?

A: Some interesting experiments are planned or suggested.

Good luck!