Neutrino Phenomenology

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Indian-Summer School
September, 2012
Part 2


Looking to the Future
The Open
Questions

- What is the absolute scale of neutrino mass?

- Do neutrinos have ***Majorana*** masses? Are neutrinos their own antiparticles?

- Are there ***more*** than 3 mass eigenstates?

  - Are there “sterile” neutrinos?

- What are the neutrino magnetic and electric dipole moments?

How close to maximal is θ_{23}?

•Is the spectrum like  or  ?

•Do neutrino interactions violate CP?

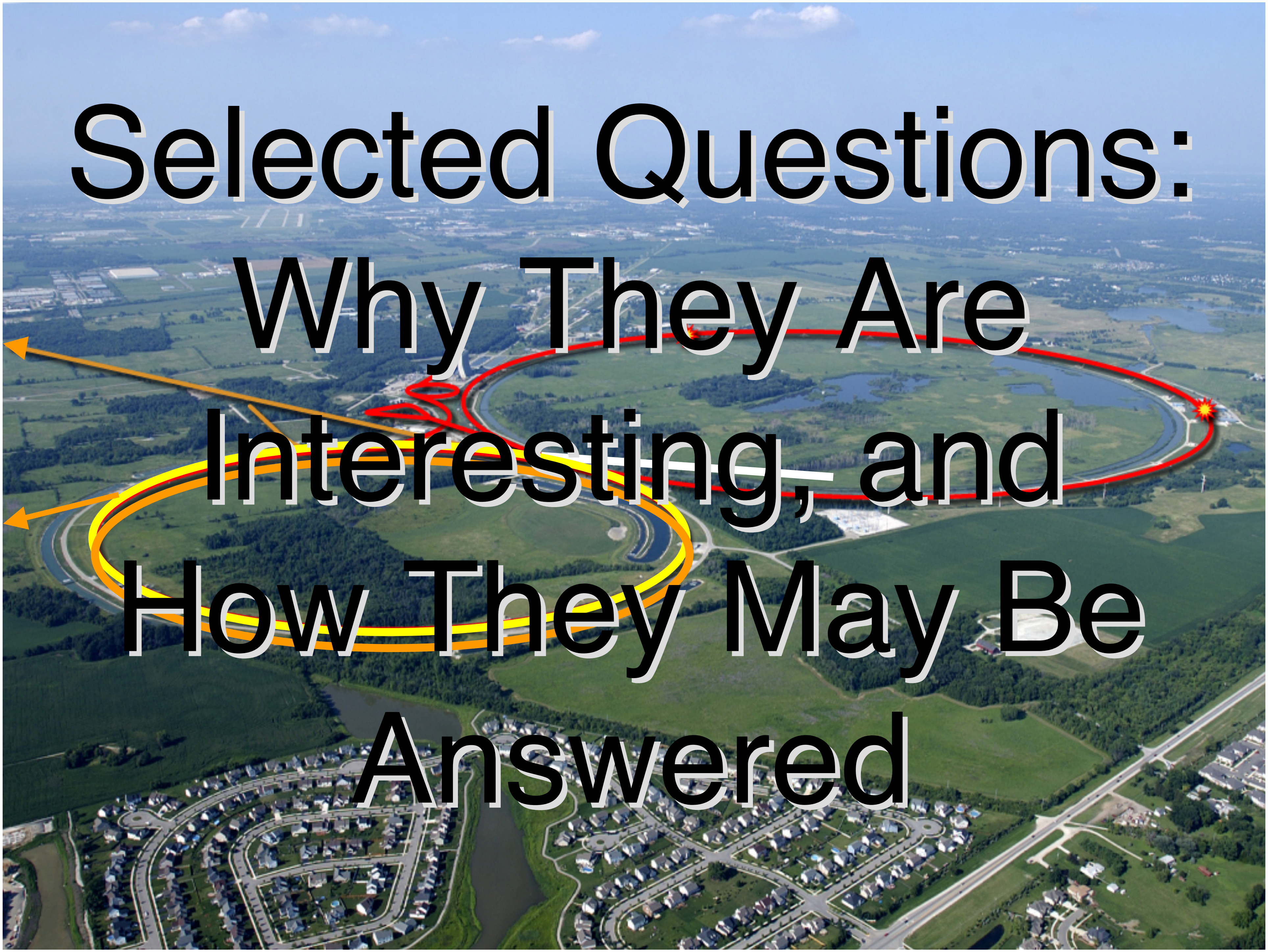
Is $P(\bar{\nu}_\alpha \rightarrow \bar{\nu}_\beta) \neq P(\nu_\alpha \rightarrow \nu_\beta)$?

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

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

- What physics is behind neutrino mass?

- What surprises are in store?


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

Do Neutrinos Have ***Majorana*** Masses?

What does this question mean?

Who cares about the answer?

There are two kinds of masses for fermions:
Dirac masses and ***Majorana*** masses.

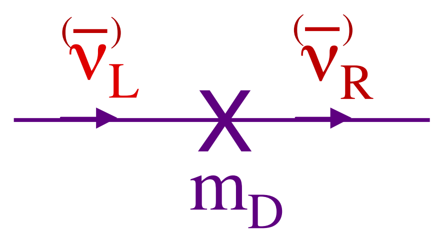
Dirac Masses

Dirac neutrino masses are the neutrino analogues of the SM quark and charged lepton masses.

To build a Dirac mass for the neutrino ν, we require not only the left-handed field ν_L in the Standard Model, but also a right-handed neutrino field ν_R.

The Dirac neutrino mass term is —

$$m_D \overline{\nu_R} \nu_L$$

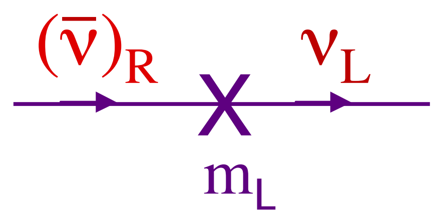


Dirac neutrino masses do not mix neutrinos and antineutrinos.

Majorana Masses

Out of, say, a left-handed neutrino field, ν_L, and its charge-conjugate, $\nu_L{}^c$, we can build a Left-Handed Majorana mass term —

$$m_L \overline{\nu_L}\, \nu_L{}^c$$



Majorana masses do mix ν and $\bar{\nu}$, so they do not conserve the Lepton Number L defined by —

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

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

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

Neutrino **Majorana masses would make the neutrinos** ***very*** **distinctive.**

SM Higgs

Majorana ν masses cannot come from $\underset{\text{SM Higgs}}{H_{SM}}\bar{\nu}_R \nu_L$, the progenitor of the Dirac mass term, and the ν analogue of the Higgs coupling that leads to the q and ℓ masses.

Possible (Weak-Isospin-Conserving) progenitors of Majorana mass terms:

$$\underbrace{H_{SM} H_{SM} \overline{\nu_L^c} \nu_L}_{\text{Not renormalizable}}, \quad \underbrace{H_{I_W=1}}_{\text{This Higgs not in SM}} \overline{\nu_L^c} \nu_L, \quad \underbrace{m_R \overline{\nu_R^c} \nu_R}_{\text{No Higgs}}$$

Majorana neutrino masses must have a different origin than the masses of quarks and charged leptons.

Why Most Theorists Expect Majorana Masses

The Standard Model (SM) is defined by the fields it contains, its symmetries (notably weak isospin invariance), and its renormalizability.

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

Majorana mass terms
are allowed by the SM symmetries.

Then quite likely *Majorana masses* occur in nature too.

Majorana Neutrino Masses $\Rightarrow \bar{\nu} = \nu$

That is, for each ***mass eigenstate*** ν_i ,
and ***given helicty*** h, —

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

rather than

- $\bar{\nu}_i(h) \neq \nu_i(h)$ (Dirac neutrinos)

Why Majorana Masses $\Longrightarrow$ Majorana Neutrinos

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

$m_L \overline{\nu_L}\, \nu_L{}^c$ induces $\nu_L \leftrightarrow \nu_L{}^c$ mixing.

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

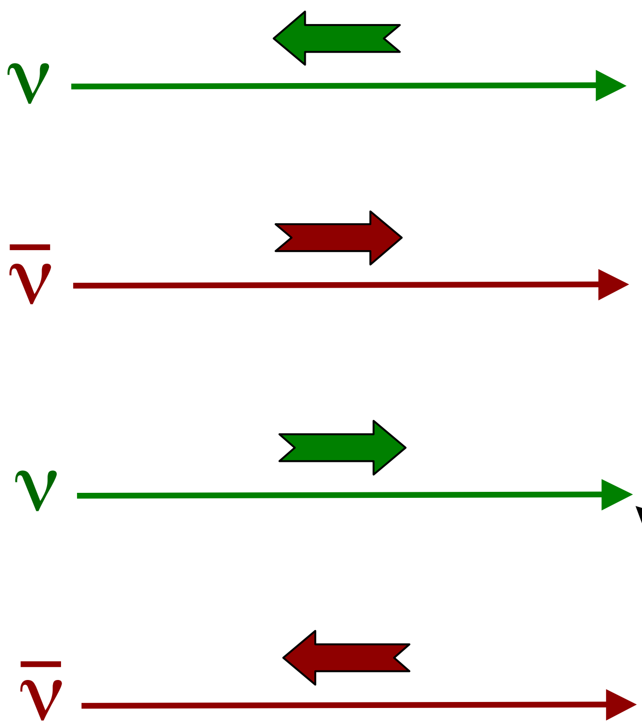
$$K_{S,L} \cong (K^0 \pm \overline{K^0})/\sqrt{2}\ . \qquad \overline{K_{S,L}} = K_{S,L}\ .$$

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

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

SM Interactions Of A Dirac Neutrino

We have 4 mass-degenerate states:



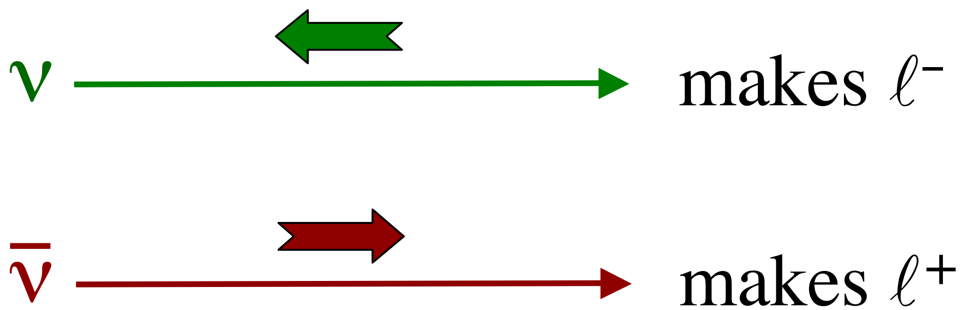
	Conserved L
makes ℓ^-	+1
makes ℓ^+	–1

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:



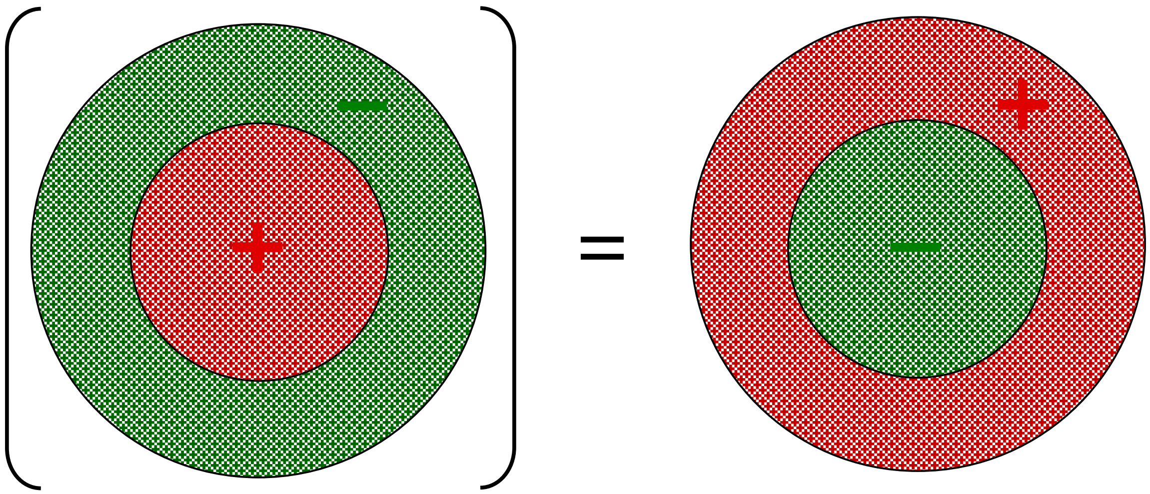
The weak interactions violate *parity*.
(They can tell *Left* from *Right*.)

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

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

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

No!

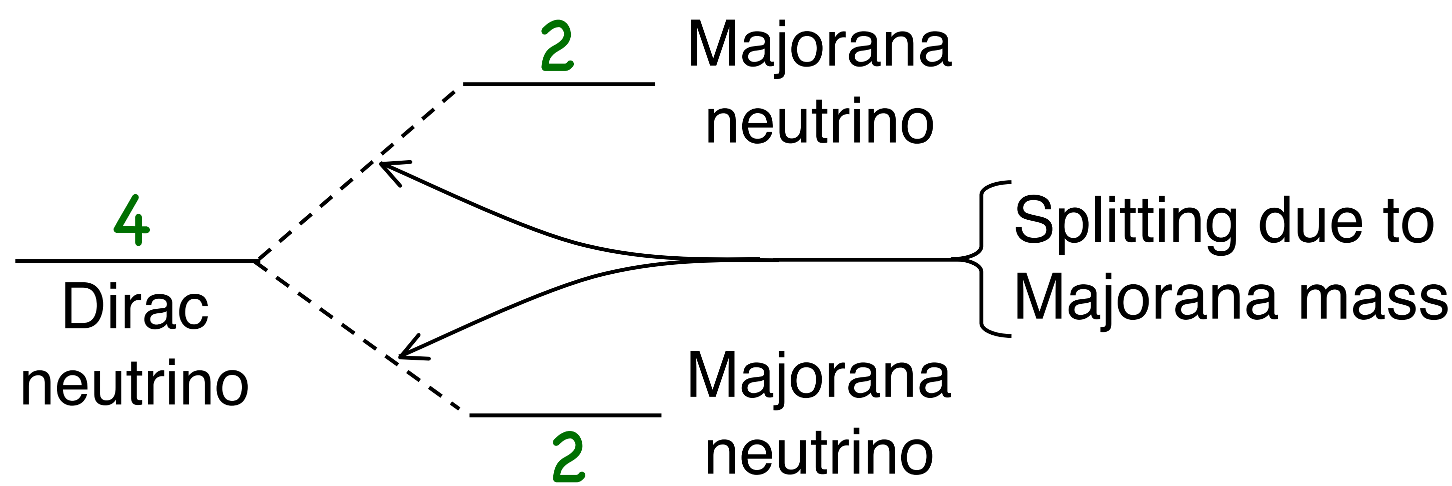
Anti 

But for a Majorana neutrino —

Anti (ν) = ν

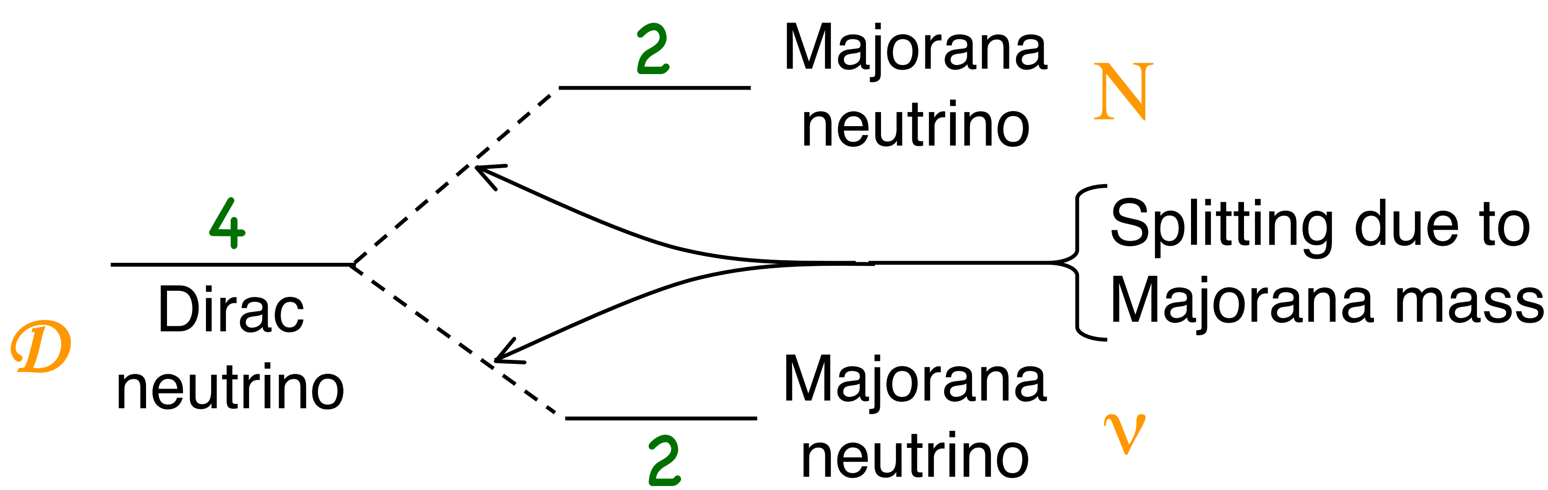
Majorana Masses Split Dirac Neutrinos

A Majorana mass term splits a Dirac neutrino into two Majorana neutrinos.



What Happens In the See-Saw

A ***BIG*** Majorana mass term splits a Dirac neutrino into two ***widely-spaced*** Majorana neutrinos.



$$m_\nu m_N \approx m_{\mathcal{D}}^2$$ ***The See-Saw Relation***

If $m_{\mathcal{D}}$ *is a typical fermion mass,* m_N *will be very large.*

Signature Predictions of the See-Saw

- The light neutrinos have heavy partners N_i

- Both light and heavy neutrinos are their own antiparticles (Majorana neutrinos)

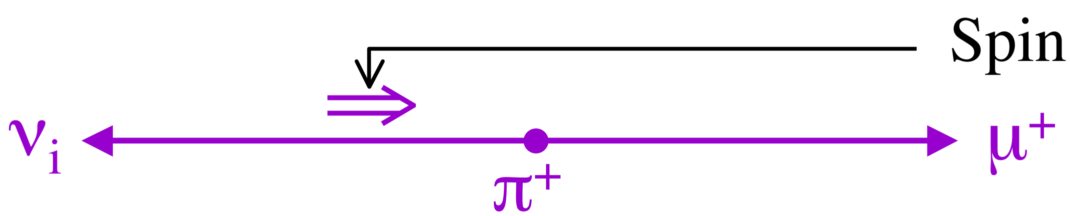
How Can We Determine Whether Majorana Masses Occur in Nature, So That $\bar{\nu} = \nu$?

Why don’t we already know whether 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]

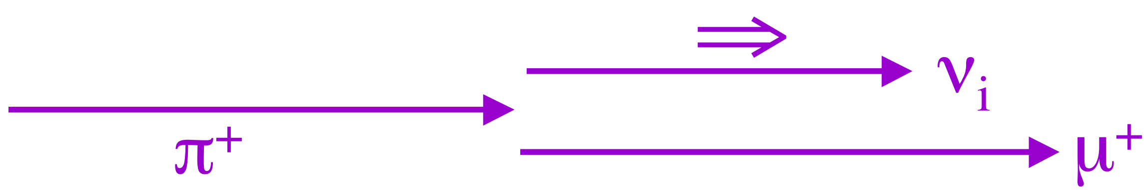
Produce a ν_i via—



Pion Rest Frame

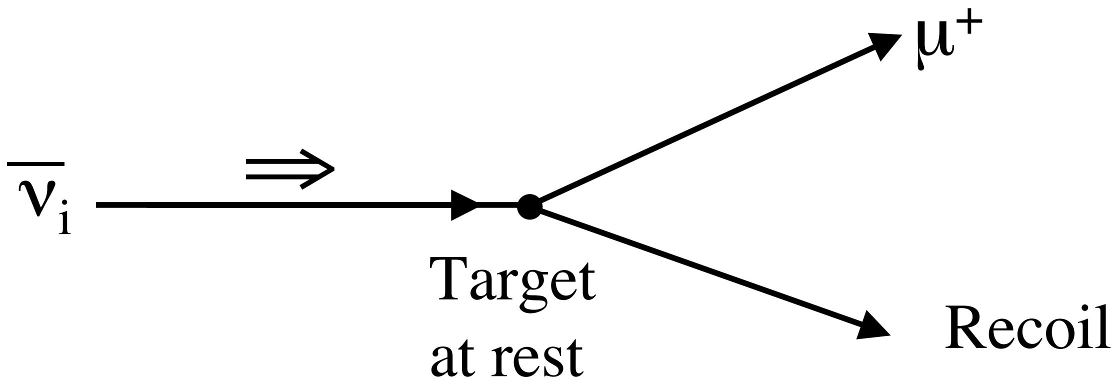
Give the neutrino a Boost:

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



Lab. Frame

The SM weak interaction causes—



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

helicity

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

our $\nu_i \xrightarrow{\quad\Rightarrow\quad}$ 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 neutrino masses.

(B.K. & Stodolsky)

The Promising Approach — Seek

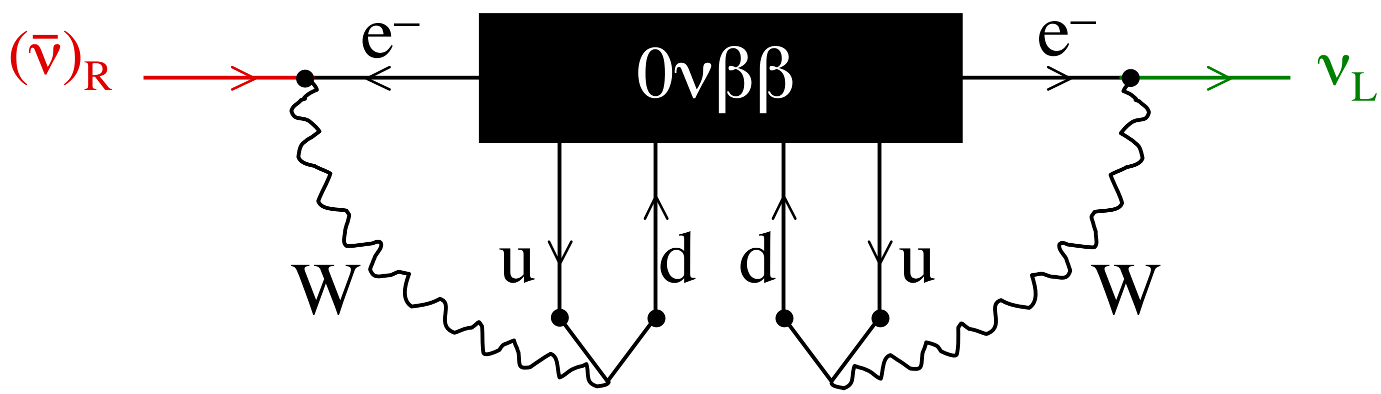
Neutrinoless Double Beta Decay [$0\nu\beta\beta$]

(Petr Vogel)

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

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 (tiny) Majorana mass term

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


Do Neutrino Interactions
Violate CP?
Are we descended
from heavy neutrinos?

The Challenge —
A Cosmic Broken Symmetry

Today: $B \equiv$ #(Baryons) – #(Antibaryons) $\neq 0$.

$$\frac{n_B}{n_\gamma} = 6 \times 10^{-10} \quad ; \quad \frac{n_{\overline{B}}}{n_B} \sim 0 \; (< 10^{-6})$$

Standard cosmology: Right after the Big Bang, $B = 0$.

How did $B = 0 \Rightarrow B \neq 0$?

Sakharov: $B = 0 \Longrightarrow B \neq 0$ requires $\cancel{CP}$.

The $\cancel{CP}$ in the quark mixing matrix,
seen in B and K decays, leads to
much too small a Baryon Number B.

Leptogenesis can explain the observed Baryon Number through CP-violating heavy neutrino decays.

(Fukugita, Yanagida)

A major motivation to look for $\cancel{CP}$ in neutrino oscillation:

Its observation would make it more plausible that —

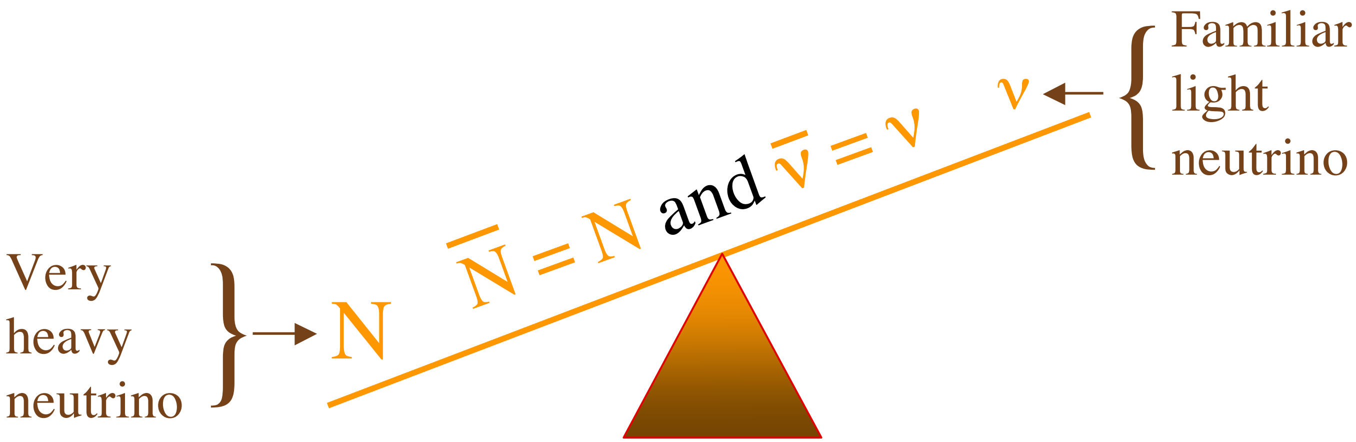
— the baryon-antibaryon asymmetry of the universe —

— did arise, at least in part, through **Leptogenesis**.

Leptogenesis – A Two-Step Process

Leptogenesis is an outgrowth of the most popular theory of why neutrinos are so light —

The See-Saw Mechanism



$$m_\nu \propto \frac{1}{m_N}$$

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

In standard leptogenesis, to account for the observed cosmic baryon – antibaryon asymmetry, ***and*** to explain the tiny light neutrino masses, we must have —

$$m_N \sim 10^{(9-10)}\ \mathrm{GeV} \quad .$$

Thus, the heavy neutrinos N represent New Physics far beyond the range of the Standard Model and the LHC.

But these heavy neutrinos would have been made in the ***hot*** Big Bang.

In a straightforward see-saw model, there are 3 heavy neutrinos N_i, to match the 3 light lepton families (ν_α, ℓ_α).

The heavy neutrinos are coupled to the rest of the world only through the "Yukawa" interaction —

$$\mathcal{L}_{\text{new}} = \sum_{\substack{\alpha=e,\mu,\tau\\ i=1,2,3}} y_{\alpha i}\left[\overline{\nu_{L\alpha}}\,\overline{H^0} - \overline{\ell_{L\alpha}}\,H^-\right] N_{Ri} + h.c.$$

RH component

Yukawa coupling matrix

SM Higgs anti-doublet

This "new" interaction simply gives leptons the same Yukawa interaction as the quarks have in the SM.

Each N_i couples to ν_α and ℓ_α with equal strength because of SM weak isospin invariance.

The Yukawa interaction —

$$\mathcal{L}_{\text{new}} = \sum_{\substack{\alpha=e,\mu,\tau \\ i=1,2,3}} y_{\alpha i} \left[\overline{\nu_{L\alpha}}\, \overline{H^0} - \overline{\ell_{L\alpha}} H^- \right] N_{Ri} + h.c.$$

causes the decays —

$$N \to \ell^{\mp} + H^{\pm} \quad \text{and} \quad N \to \overset{(-)}{\nu} + \overset{(-)}{H^0}$$

SM Higgs particle

$\cancel{CP}$ phases in the matrix y will lead to —

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

and

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

How Do Such $\cancel{CP}$ Inequalities Come About?

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

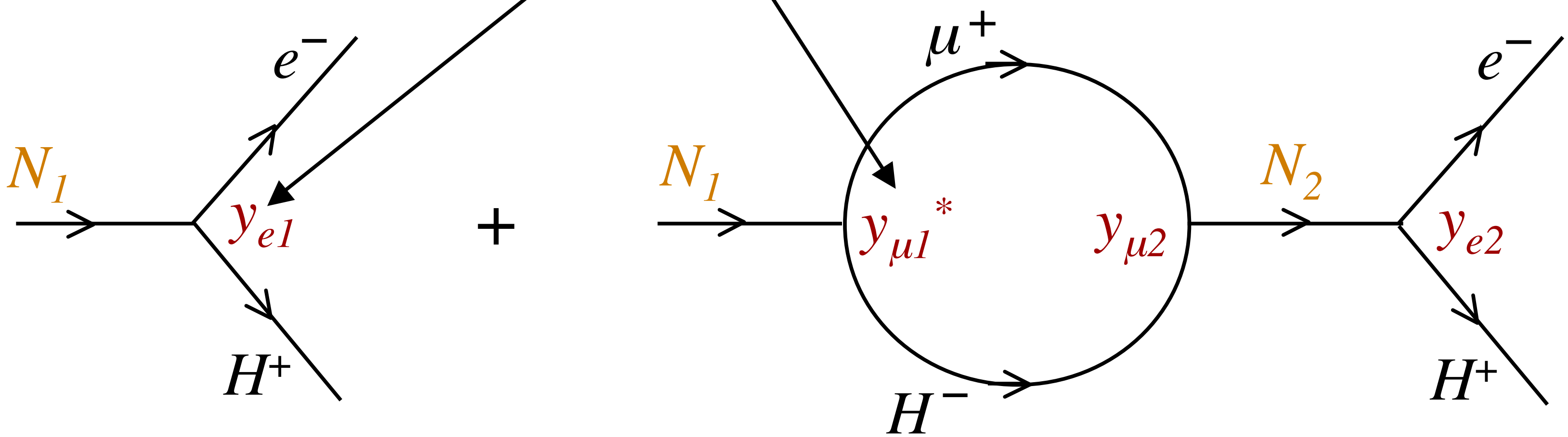
Phases never matter except in *interferences* between coherent amplitudes.

$\therefore$ These decays must involve interfering amplitudes.

An example:

From $y_{e1}\overline{\ell_{Le}}H^{-}N_{R1}$

From $y^{*}_{\mu 1}\overline{N_{R1}}H^{+}\ell_{L\mu}$



Tree

Loop

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

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, $N_1 \to e^+ + H^-$, all the coupling constants get complex conjugated, but the kinematical factors do not change.

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

Then —

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

The Three Ingredients For CP Violation

1. At least 2 interfering amplitudes
   (Here, one Tree and one Loop amplitude)

2. Factors with different CP-odd phases
   (Here, the Yukawa coupling constants y)

3. Factors with different CP-even phases
   (Here, the kinematical factors K)

The $\cancel{CP}$ inequalities —

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

and

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

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,
which does not conserve Baryon Number B,
or Lepton Number L, but does conserve $B - L$, acts.

$B_i = 0$

$L_i \neq 0$

→ Sphaleron Process →

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

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

Initial state from N decays

Final state

There is now a nonzero Baryon Number.

There are baryons, but ~ no antibaryons.

Reasonable parameters give the observed n_B / n_γ **.**

Leptogenesis and $\cancel{CP}$ In Light ν Oscillation

The Detailed See-Saw Relation In a Convenient Basis

Leptonic mixing matrix

Heavy N mass eigenvalues

$$UM_\nu U^T = -v^2\left(y\, M_N^{-1}\, y^T\right)$$

Light ν mass eigenvalues

The Higgs vev, a real number

$$\left(\underbrace{UM_\nu U^T}_{\text{Outputs}} = -v^2\underbrace{\left(y\, M_N^{-1}\, y^T\right)}_{\text{Inputs, in } \mathcal{L}}\right)$$

Through $\boldsymbol{U}$, the phases in $\boldsymbol{y}$ lead to $\not{C}\not{P}$ in light neutrino oscillation.

$$P(\overset{(-)}{\nu}_\alpha \rightarrow \overset{(-)}{\nu}_\beta) =$$

e, μ, or τ

Distance

$$= \delta_{\alpha\beta} - 4 \sum_{i>j} \Re(U^*_{\alpha i} U_{\beta i} U_{\alpha j} U^*_{\beta j}) \sin^2(\Delta m^2_{ij} \frac{L}{4E})$$

$$\underset{(-)}{+} 2 \sum_{i>j} \Im(U^*_{\alpha i} U_{\beta i} U_{\alpha j} U^*_{\beta j}) \sin(\Delta m^2_{ij} \frac{L}{2E})$$

Neutrino (Mass)^2 splitting

Energy

Generically, leptogenesis and light-neutrino ~~CP~~ imply each other.

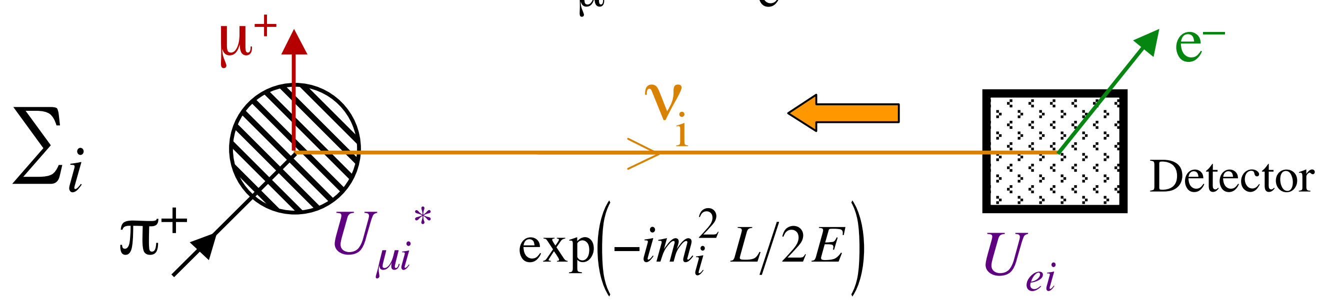
Seeking CP violation in neutrino oscillation is now a worldwide goal.

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.

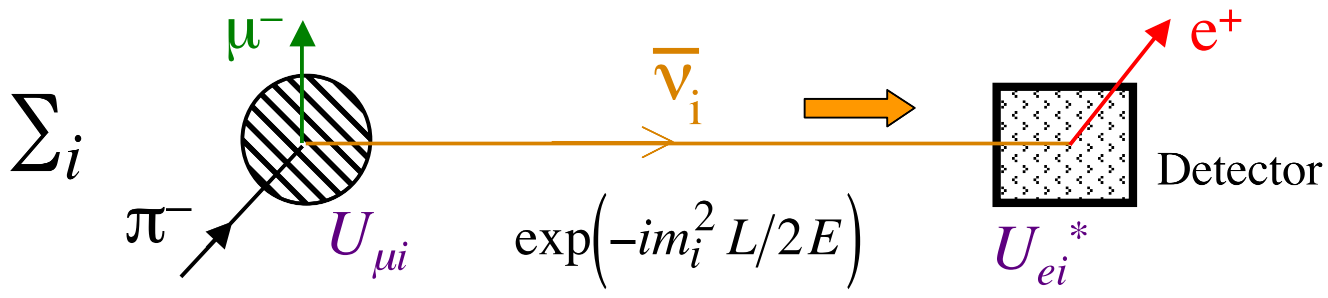
$\mathcal{Q}$: *Can CP violation still lead to*
$\mathcal{P}(\overline{\nu}_\mu \to \overline{\nu}_e) \neq \mathcal{P}(\nu_\mu \to \nu_e)$ *when* $\bar{\nu} = \nu$*?*

$\mathcal{A}$: *Certainly!*

Compare $\quad \nu_\mu \to \nu_e$



with $\quad$ "$\overline{\nu}_\mu \to \overline{\nu}_e$"



What Is the Mass Ordering?

The Mass Spectrum: or ?

Generically, grand unified models (GUTS) favor —

GUTS relate the Leptons to the Quarks.

However, ***Majorana masses***, with no quark analogues, could turn into .

How To Determine If The Spectrum Is Normal Or Inverted

Exploit the ***matter effect*** on accelerator neutrinos.

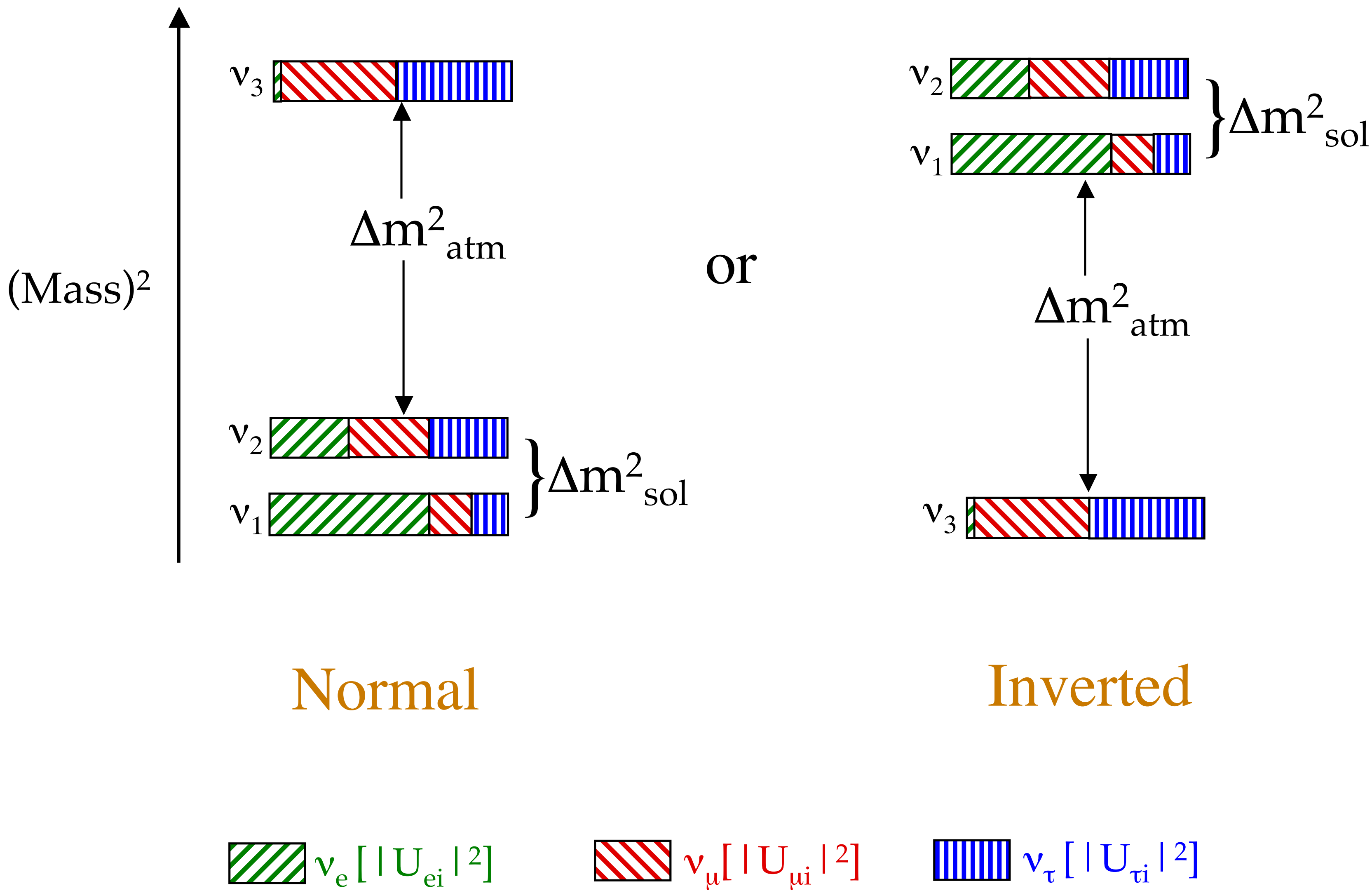
Recall that the matter effect ***raises*** the effective mass of ν_e, but ***lowers*** that of $\bar{\nu}_e$. Thus, it affects ν and $\bar{\nu}$ oscillation ***differently***, leading to:

$$\frac{P(\nu_\mu \to \nu_e)}{P(\bar{\nu}_\mu \to \bar{\nu}_e)} \begin{cases} > 1\ ; \\ < 1\ ; \end{cases}$$

Note fake ~~CP~~

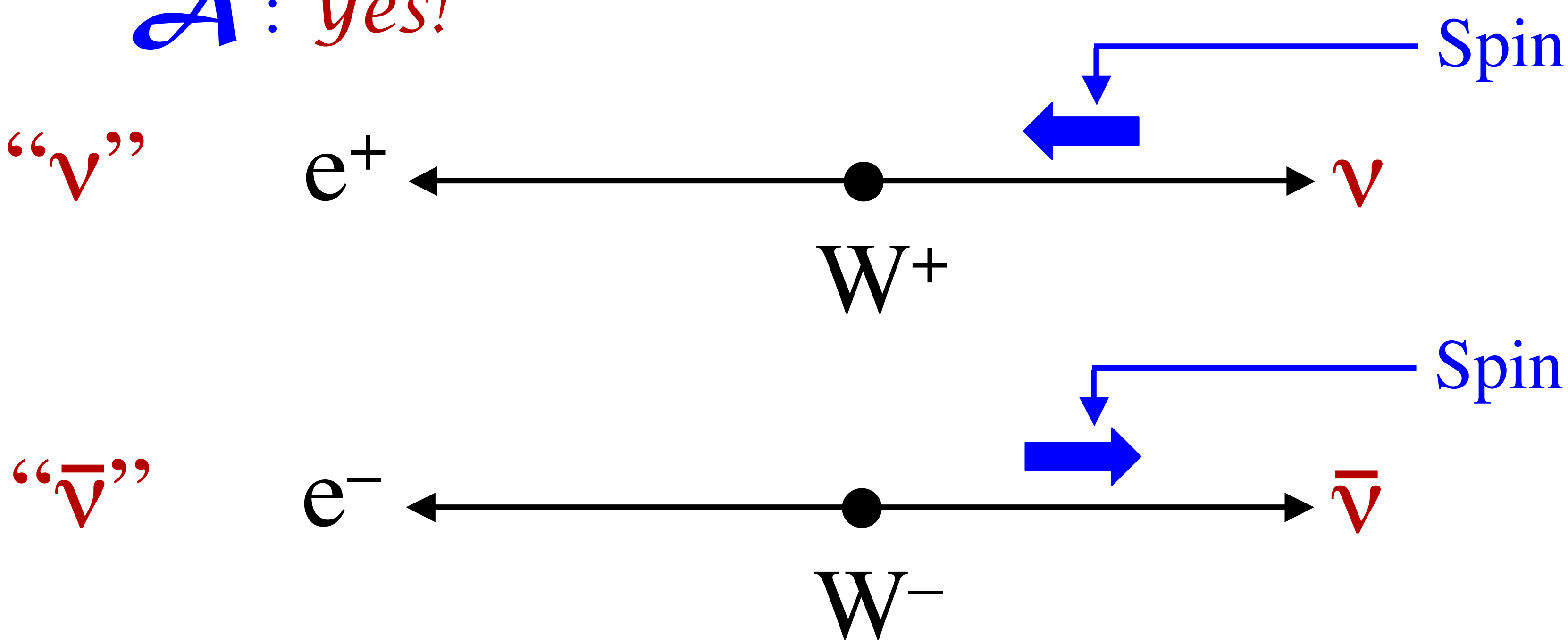
Note dependence on the mass ordering

The matter effect depends on whether the spectrum is Normal or Inverted.



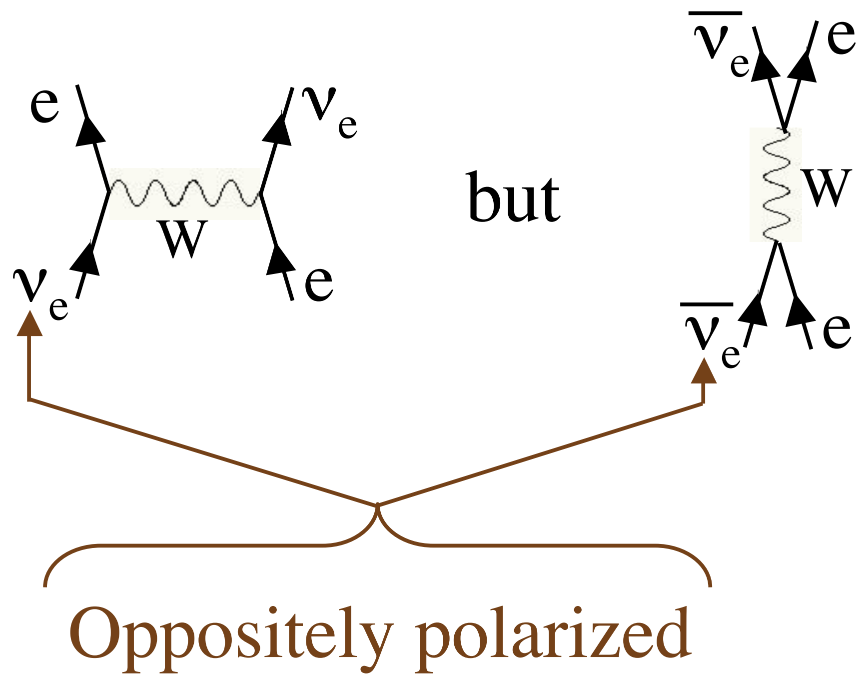
Q : *Does matter still affect* ν *and* $\bar{\nu}$ *differently when* $\bar{\nu} = \nu$*?*

A : *Yes!*



The weak interactions violate ***parity***. Neutrino – matter interactions depend on the neutrino ***polarization***.

Recall that in matter —



The polarization alone is sufficient to determine which diagram will act.

The effective mass of "ν_e" is raised, while that of "$\overline{\nu_e}$" is lowered .

Accelerator $\overset{(-)}{\nu}$ Oscillation Probabilities

With $\alpha \equiv \Delta m^2_{21} / \Delta m^2_{31}$, $\Delta \equiv \frac{\Delta m^2_{31} L}{4E}$, and $x \equiv \frac{2\sqrt{2} G_F N_e E}{\Delta m^2_{31}}$

Δm^2_{31} — $m^2(\text{—}) - m^2(=)$

$$P\left[\nu_\mu \to \nu_e\right] \cong \sin^2 2\theta_{13}\, T_1 - \alpha \sin 2\theta_{13}\, T_2 + \alpha \sin 2\theta_{13}\, T_3 + \alpha^2\, T_4 \;;$$

Atmospheric

CP-odd interference

$$T_1 = \sin^2\theta_{23} \frac{\sin^2\left[(1-x)\Delta\right]}{(1-x)^2} \,, \quad T_2 = \sin\delta \sin 2\theta_{12} \sin 2\theta_{23} \sin\Delta \frac{\sin(x\Delta)}{x} \frac{\sin\left[(1-x)\Delta\right]}{(1-x)} \,,$$

$$T_3 = \cos\delta \sin 2\theta_{12} \sin 2\theta_{23} \cos\Delta \frac{\sin(x\Delta)}{x} \frac{\sin\left[(1-x)\Delta\right]}{(1-x)} \,, \quad T_4 = \cos^2\theta_{23} \sin^2 2\theta_{12} \frac{\sin^2(x\Delta)}{x^2}$$

CP-even interference

Solar

$$P\left[\bar{\nu}_\mu \to \bar{\nu}_e\right] = P\left[\nu_\mu \to \nu_e\right] \text{ with } \delta \to -\delta \text{ and } x \to -x.$$

(Cervera *et al.*, Freund, Akhmedov *et al.*)

Good luck!