Neutrino Phenomenology

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Part 2

Looking to the Future

The Open Questions

- What is the absolute scale of neutrino mass?

- 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?

What is θ_{13}?
How close to maximal is θ_{23}?

- Is the spectrum like  or  ?

- Do neutrino interactions violate CP?

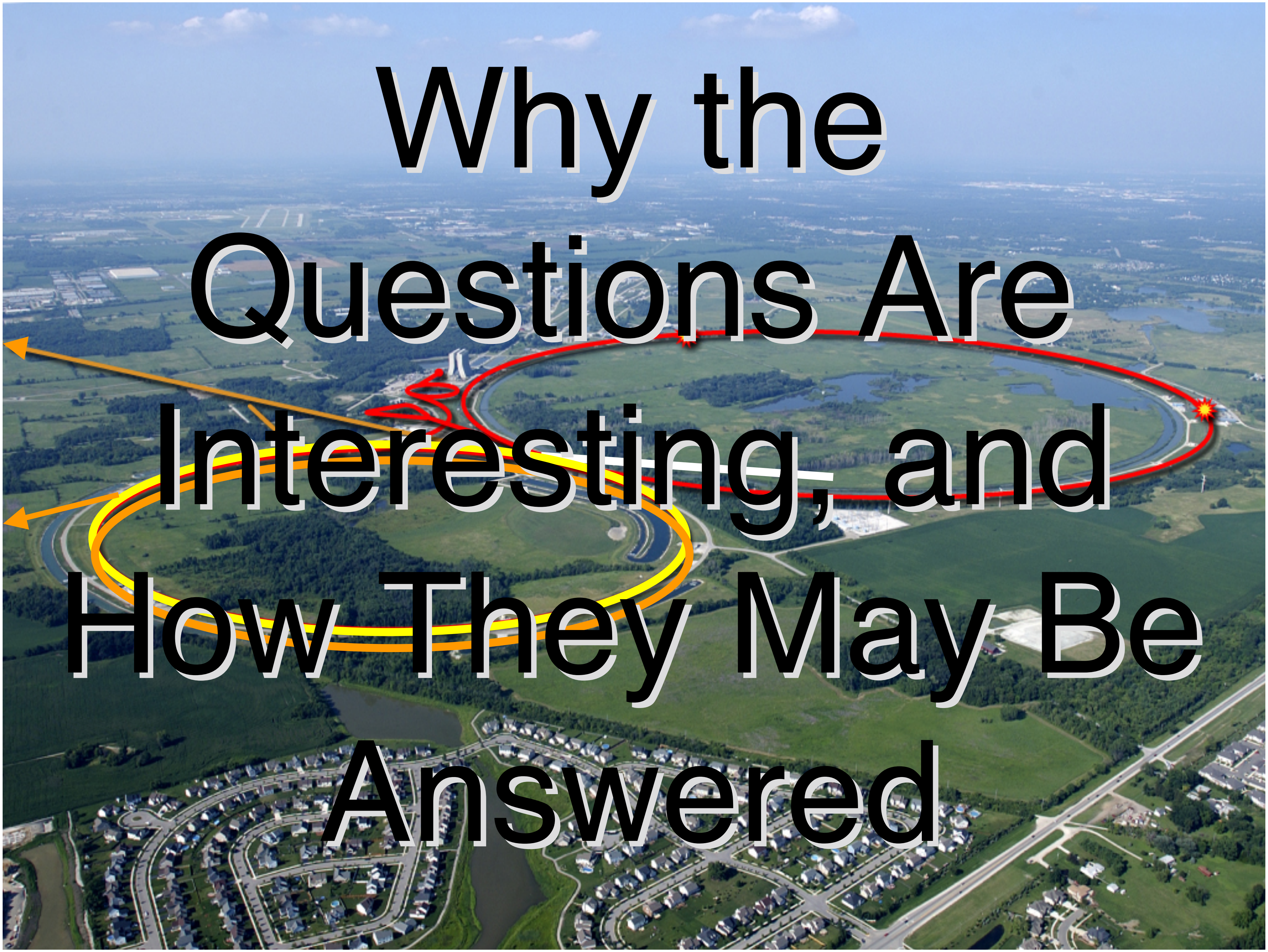
Is $P(\bar{\nu}_\alpha \rightarrow \bar{\nu}_\beta) \neq P(\nu_\alpha \rightarrow \nu_\beta)$?

- 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?



Why the Questions Are Interesting, and How They May Be Answered

What Is the Absolute Scale of Neutrino Mass?

Neutrino Mass From β Decay

Coming: The KArlsruhe TRItium Neutrino (KATRIN) experiment.

5σ signal if $m_i > 0.35$ eV

This requires good β energy resolution.

Good β energy resolution requires a ***BIG*** β spectrometer.

KATRIN'S JOURNEY

Does $\bar{\nu} = \nu$?

What Is the Question?

For each ***mass eigenstate*** ν_i , and ***given helicty*** h, does —

- $\overline{\nu_i}(h) = \nu_i(h)$ (Majorana neutrinos)

or

- $\overline{\nu_i}(h) \neq \nu_i(h)$ (Dirac neutrinos) ?

Equivalently, do neutrinos have *Majorana masses*? If they do, then the mass eigenstates are *Majorana neutrinos*.

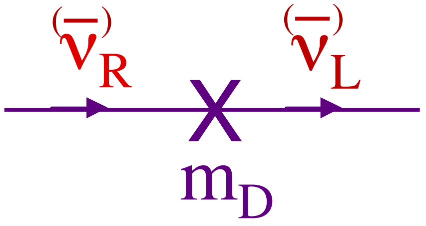
Dirac Masses

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 —

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

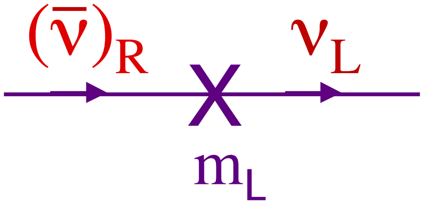


Dirac neutrino masses do not mix neutrinos and antineutrinos.

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 $\mathrm{f} \leftrightarrow \bar{\mathrm{f}}$.

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

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

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

Possible 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 Majorana Masses ⇒ 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 —

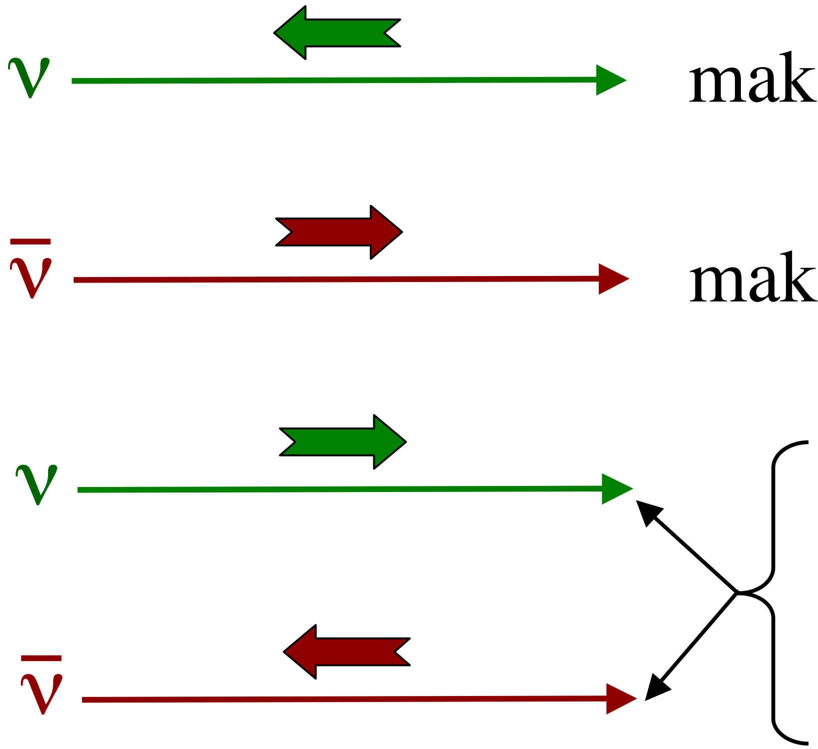
$$K_{S,L} \cong (K^0 \pm \overline{K^0})/\sqrt{2}\ . \qquad \overline{K_{S,L}} = K_{S,L}\ .$$

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:



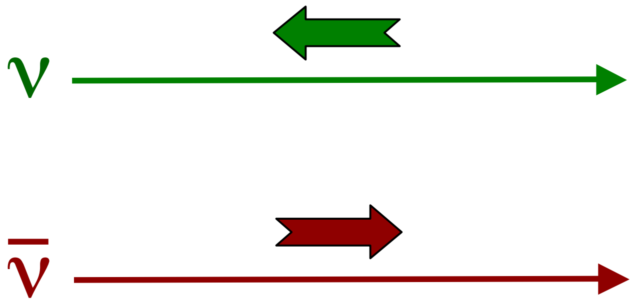
		Conserved L
ν	makes ℓ^-	+1
$\bar{\nu}$	makes ℓ^+	–1

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*.

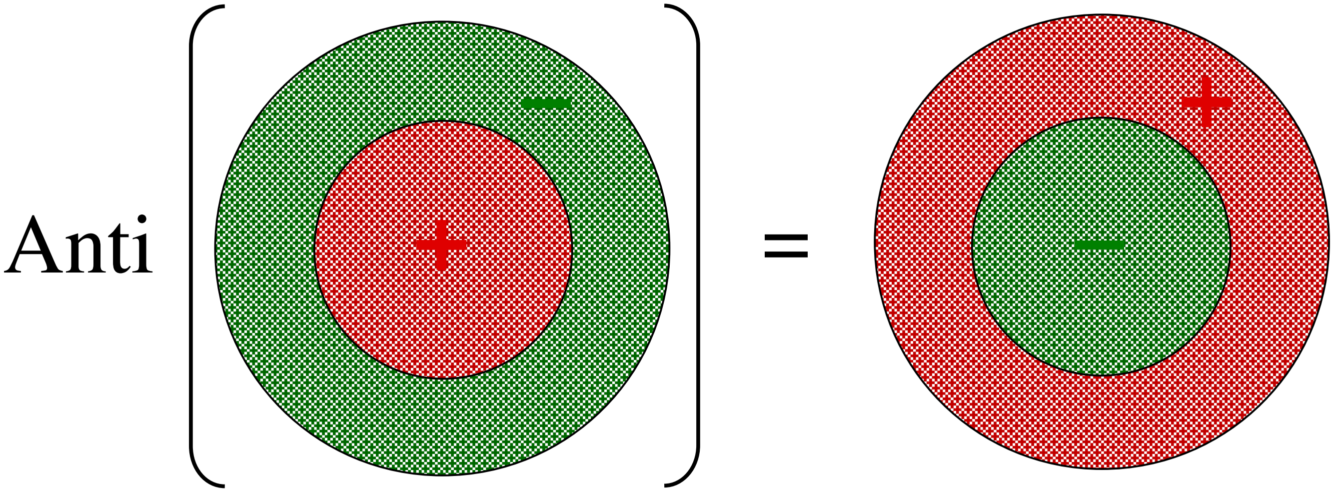
(They can tell *Left* from *Right*.)

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!

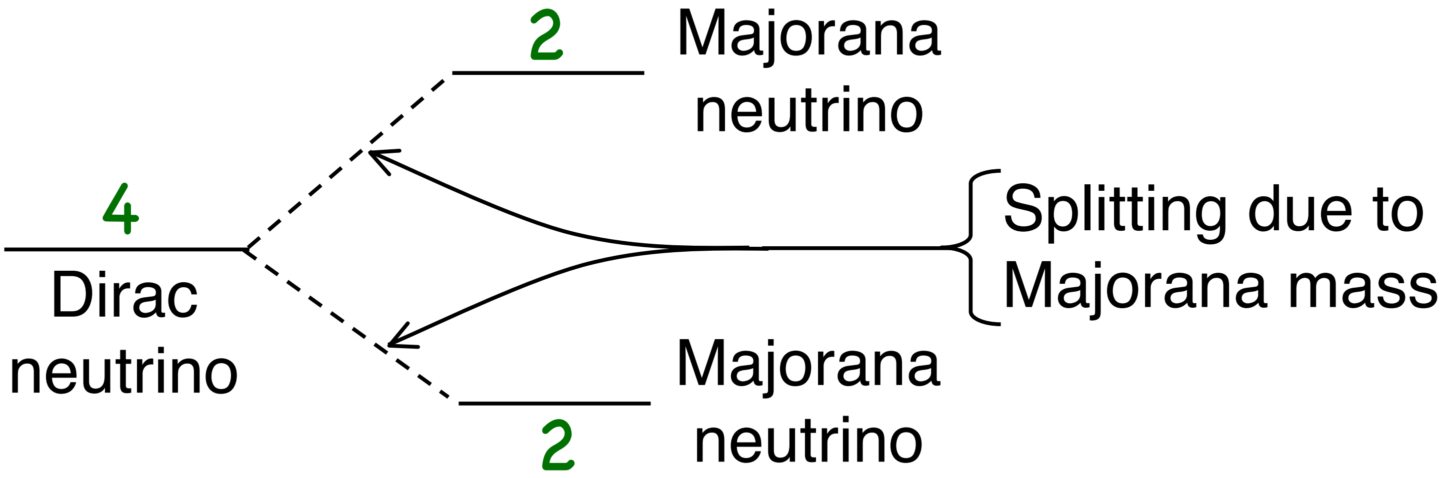


But for a Majorana neutrino —

Anti (ν) = ν

Majorana Masses Split Dirac Neutrinos

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



In the See-Saw picture, the Majorana mass
is much larger than the Dirac mass,
so the splitting is very large as well.

In a scheme where the Majorana mass
is much smaller than the Dirac mass,
a pair of Majorana neutrinos can look
almost like one Dirac neutrino.

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.

Right-Handed Majorana mass terms
are allowed by the SM symmetries.

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

To Determine Whether Majorana Masses Occur in Nature

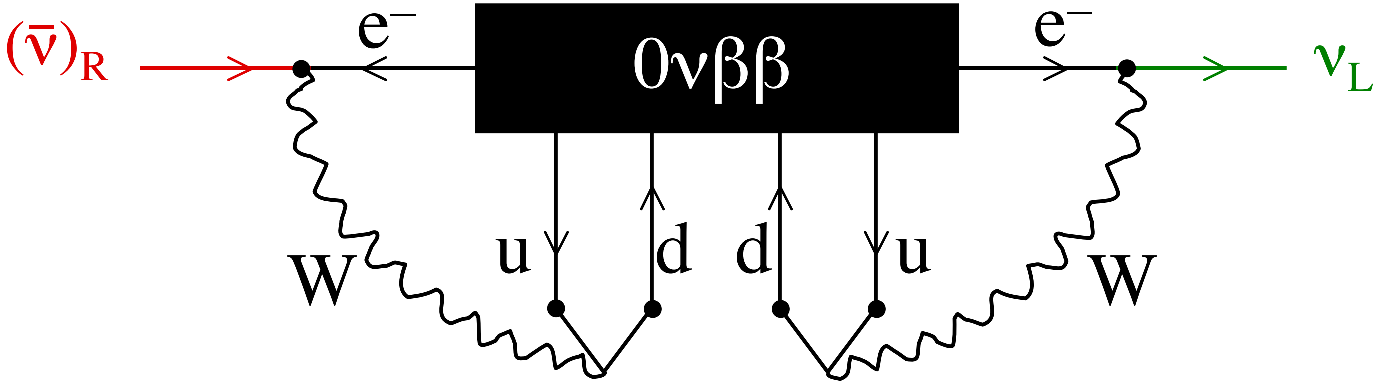
The Promising Approach — Seek

Neutrinoless Double Beta Decay [0νββ]

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

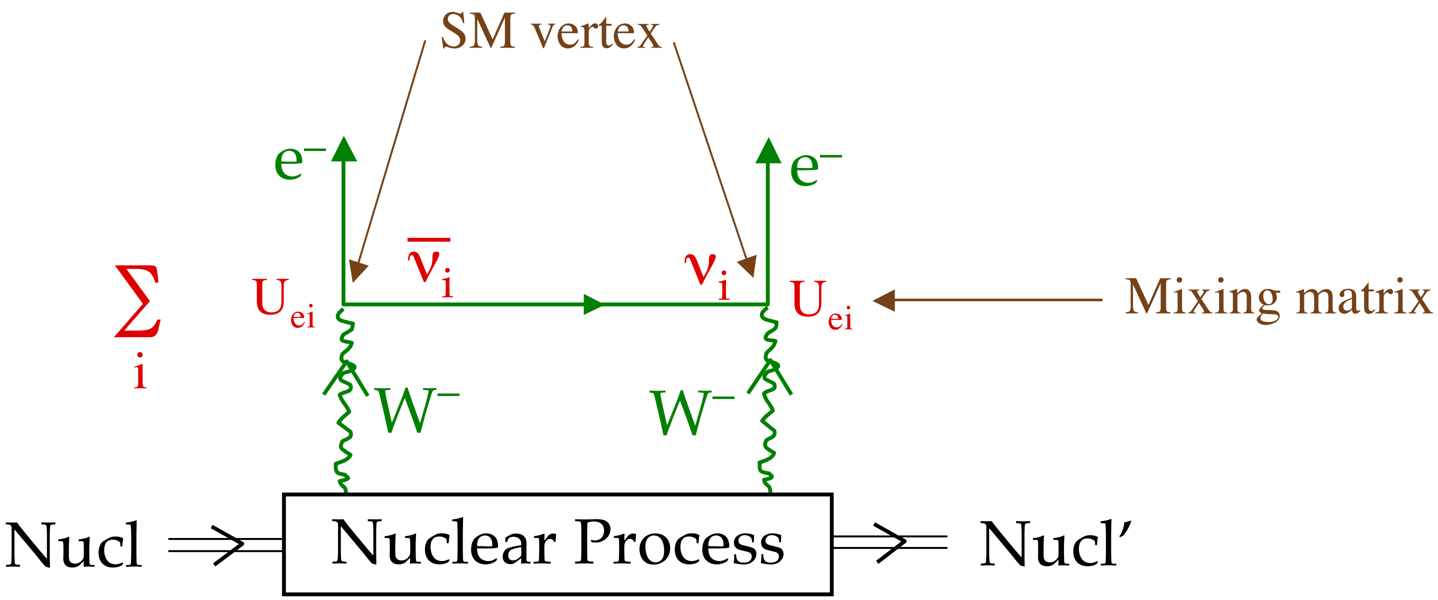
(Schechter and Valle)



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

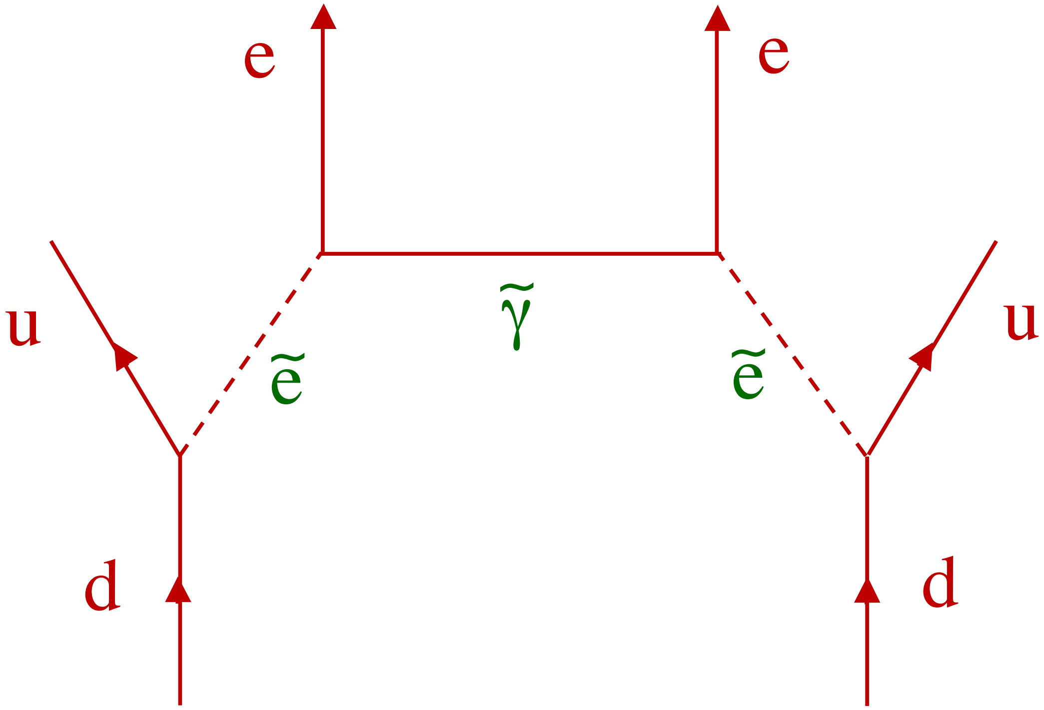
$\therefore$ 0νββ $\Rightarrow$ $\bar{\nu}_i = \nu_i$

We anticipate that 0νββ is dominated by a diagram with Standard Model vertices:

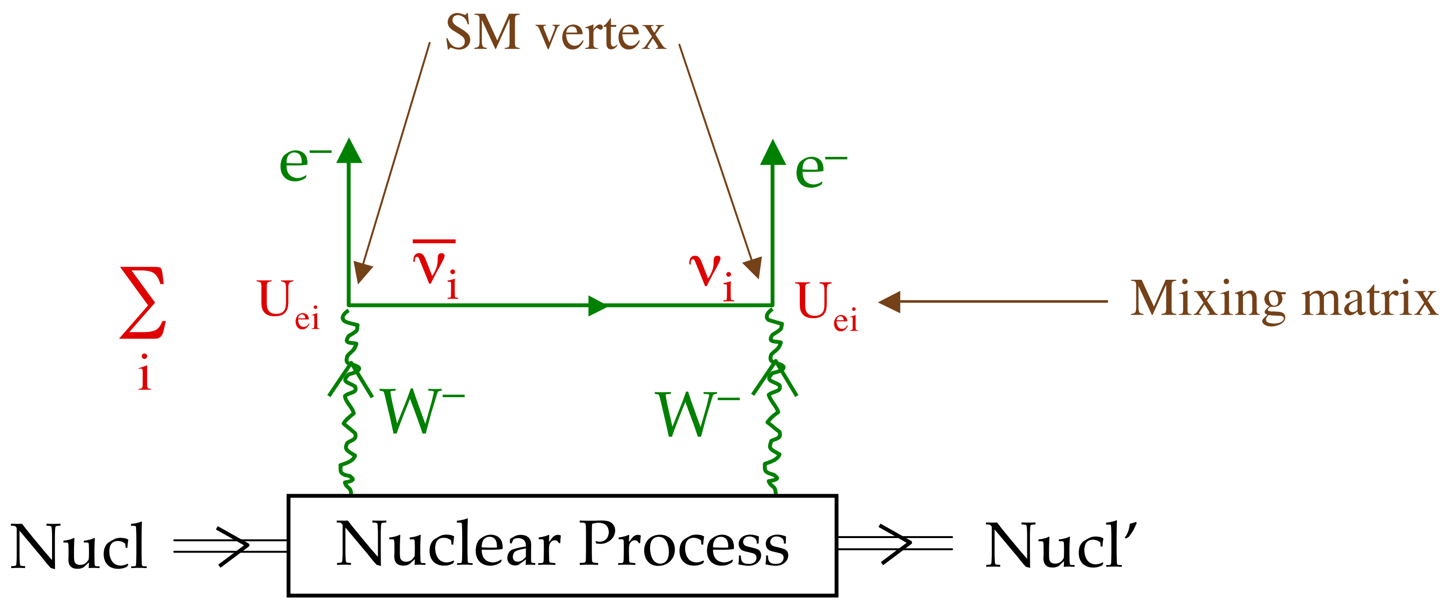


But there could be other contributions to 0νββ, which at the quark level is the process dd → uuee.

An example from Supersymmetry:



Assume the dominant mechanism is –



Mass (ν_i)

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

Thus, Amp [ν_i contribution] ∝ m_i

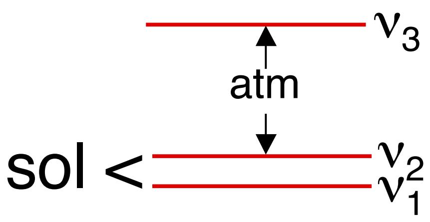
$$\text{Amp}[0\nu\beta\beta] \propto \left| \sum m_i U_{ei}^2 \right| \equiv m_{\beta\beta}$$

How Large is $m_{\beta\beta}$?

How sensitive need an experiment be?

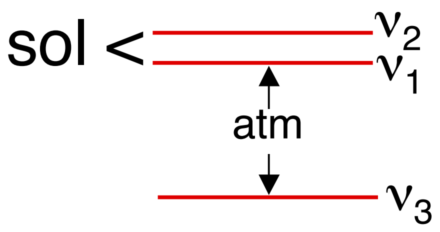
Suppose there are only 3 neutrino mass eigenstates. (More might help.)

Then the spectrum looks like —

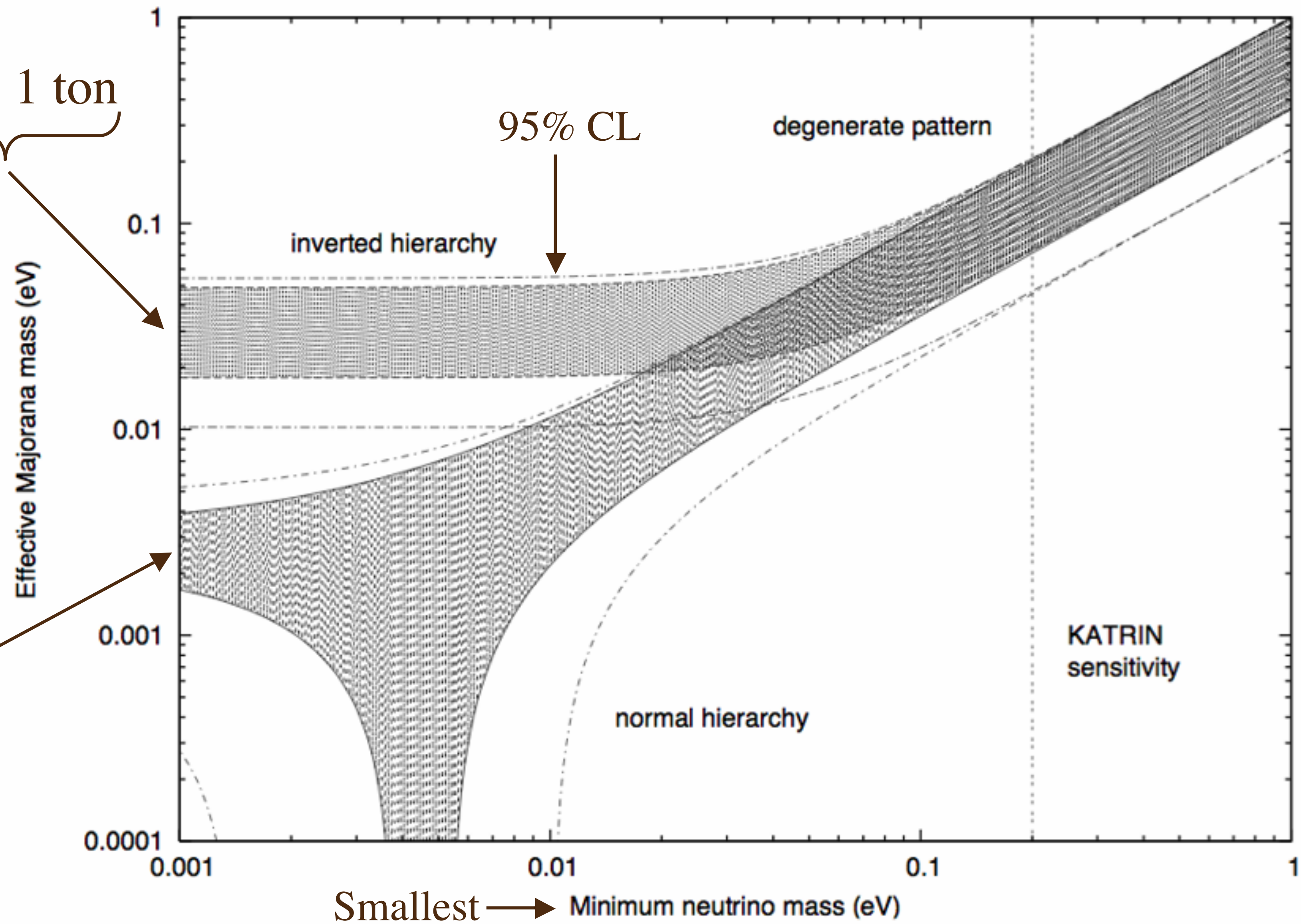


Normal hierarchy

or



Inverted hierarchy



95% CL

Takes 1 ton

$m_{\beta\beta}$

Takes 100 tons

Smallest →

$m_{\beta\beta}$ *For Each Hierarchy*

There is no clear theoretical preference
for either hierarchy.

If the hierarchy is **inverted**—

then $0\nu\beta\beta$ searches with sensitivity
to $m_{\beta\beta} = 0.01$ eV have
a very good chance to see a signal.

Sensitivity in this range is the target
for the next generation of experiments.

We Must Be Alert To **Surprises**!

Are There

More Than 3

Mass Eigenstates?

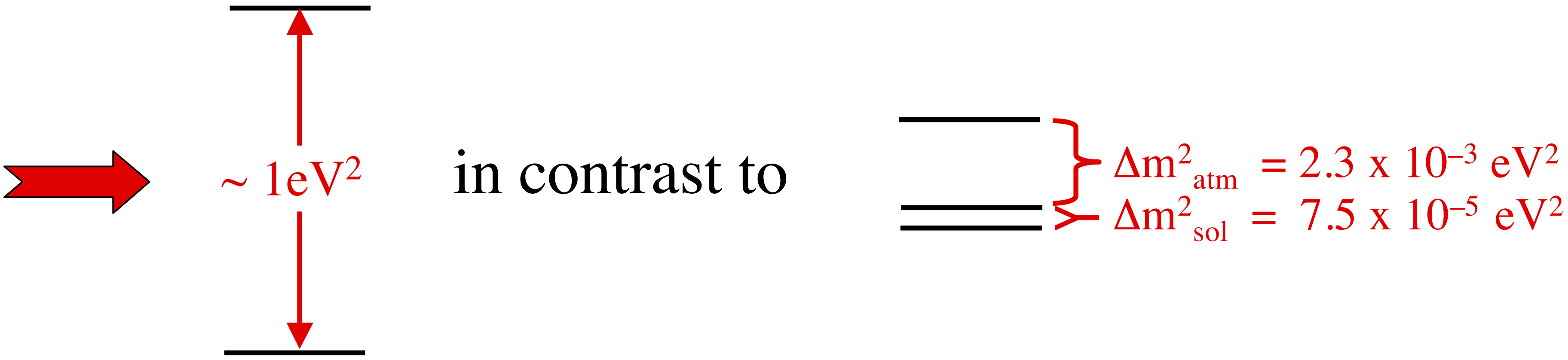
Are There

Sterile Neutrinos?

The Hint From LSND

Rapid $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ neutrino oscillation reported by the L(iquid) S(cintillator) N(eutrino) D(etector) —

$$P\left(\overline{\nu_\mu} \rightarrow \overline{\nu_e}\right) = \sin^2 2\theta \, \sin^2\left[1.27\,\Delta m^2\left(eV^2\right)\frac{L(km)}{E(GeV)}\right]$$



$\sim 1\text{eV}^2$

in contrast to

$\Delta m^2_{atm} = 2.3 \times 10^{-3}\ \text{eV}^2$

$\Delta m^2_{sol} = 7.5 \times 10^{-5}\ \text{eV}^2$

At least **4** mass eigenstates.

Are There Sterile Neutrinos?

At least **4** mass eigenstates ⇒ At least **4** flavors.

Measured $\Gamma(Z \rightarrow \nu\bar{\nu})$ ⇒ only **3** different flavor neutrinos made of light mass eigenstates couple to the Z.

If there are > 3 light mass eigenstates, as hinted by LSND, then the extra flavors do not couple to the Z.

In the Standard Model, flavor neutrinos that do not couple to the Z do not couple to the W either.

Such neutrinos, with no SM interactions, are called ***sterile*** neutrinos.

LSND hints at the existence of sterile neutrinos.

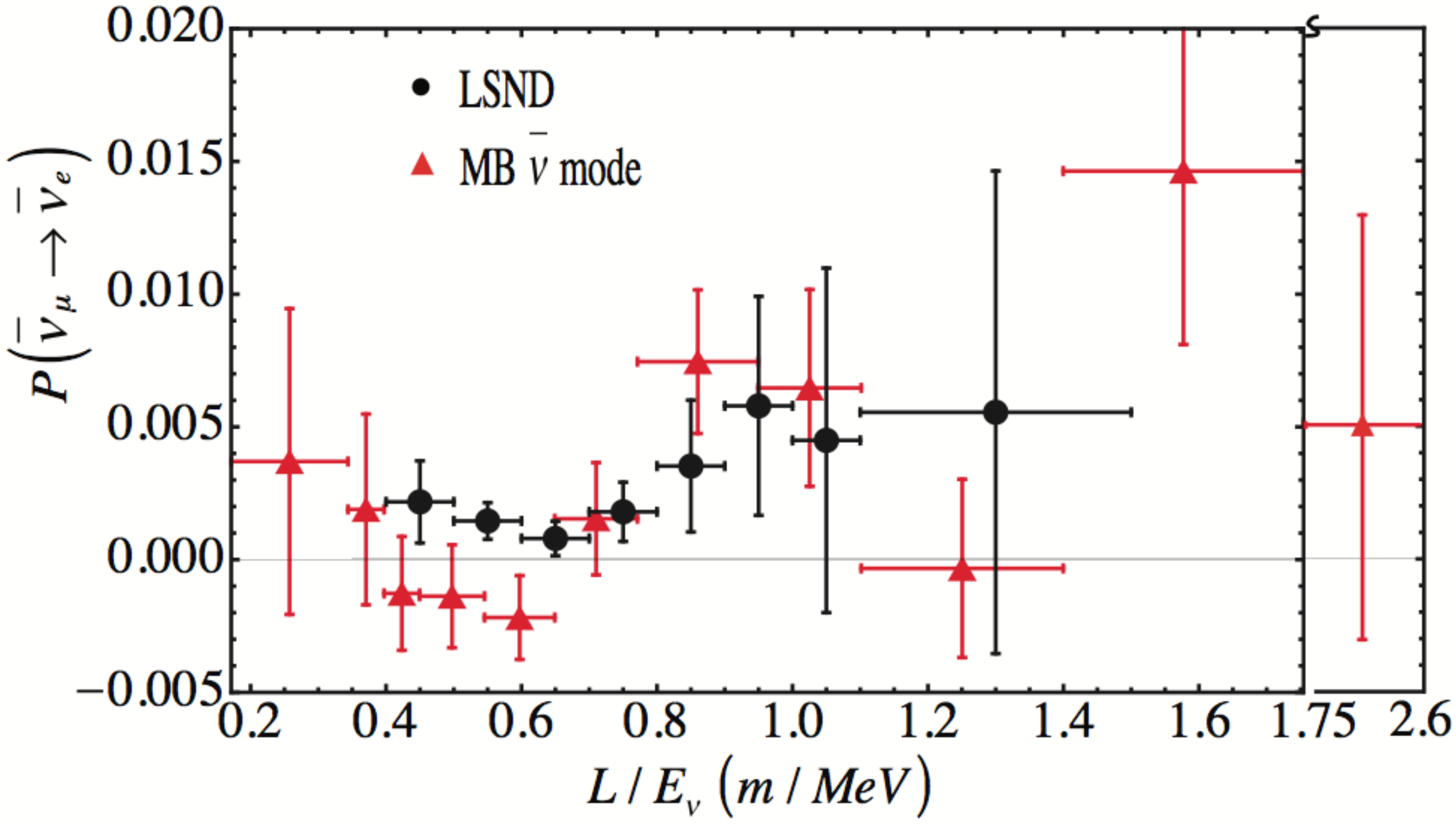
Is the LSND Signal Genuine Neutrino Oscillation?

The MiniBooNE experiment is
trying to confirm or refute LSND.

In MiniBooNE, both L and E are ~ 17 times
larger than they were in LSND,
and L/E is comparable.

MiniBooNE has recently reported
its $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ results.

Direct MiniBooNE-LSND Comparison of $\bar{\nu}$ Data



(Phys.Rev.Lett.105:181801, 2010)

Do LSND and MiniBooNE see the same thing???

The Reactor $\overline{\nu}_e$ Flux Surprise

The prediction for the un-oscillated $\overline{\nu}_e$ flux
from reactors has increased by about 3%.

(Mueller et al.)

Measurements of the $\overline{\nu}_e$ flux at (10 – 100)m from reactor
cores now show a ~ 6% disappearance.

(Mention et al.)

Disappearance at L(m)/E(MeV) ~ 1 suggests oscillation
with $\Delta m^2 \sim 1$ eV^2, like LSND and MiniBooNE.

Fits to all data with 2 extra neutrinos are improved.

(Kopp et al.)

Clearly, more information is needed.

While awaiting further news —

We will assume there are
only 3 neutrino mass eigenstates,
and no sterile neutrinos.

Mixing,
Mass Ordering,
and ~~CP~~

The Central Role of θ_{13}

Both CP violation and our ability to tell whether the spectrum is normal or inverted depend on θ_{13}.

Determining θ_{13} is
an important step.

Reactor Experiments To Determine θ_{13}

Looking for disappearance of reactor $\bar{\nu}_e$, which have $E \sim 3$ MeV, while they travel $L \sim 1.5$ km is the cleanest way to determine θ_{13} .

P($\bar{\nu}_e$ Disappearance) $\cong$

$$\sin^2 2\theta_{13} \sin^2[1.27\Delta m^2_{\mathrm{atm}}(\mathrm{eV}^2)L(\mathrm{km})/E(\mathrm{GeV})]$$

Accelerator Experiments

Accelerator neutrino experiments can also probe θ_{13} .
Now it is entwined with other parameters.

In addition, accelerator experiments can probe
whether the mass spectrum is normal or inverted,
and look for *CP violation*.

All of this is done by studying $\nu_\mu \to \nu_e$ and $\bar{\nu}_\mu \to \bar{\nu}_e$,
or their inverses, while the beams travel
hundreds or thousands of kilometers.

The Mass Spectrum:  or  ?

Generically, grand unified models (GUTS) favor —

GUTS relate the Leptons to the Quarks.

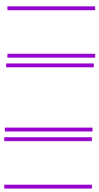
However, ***Majorana masses***, with no quark analogues, could turn  into  .

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:

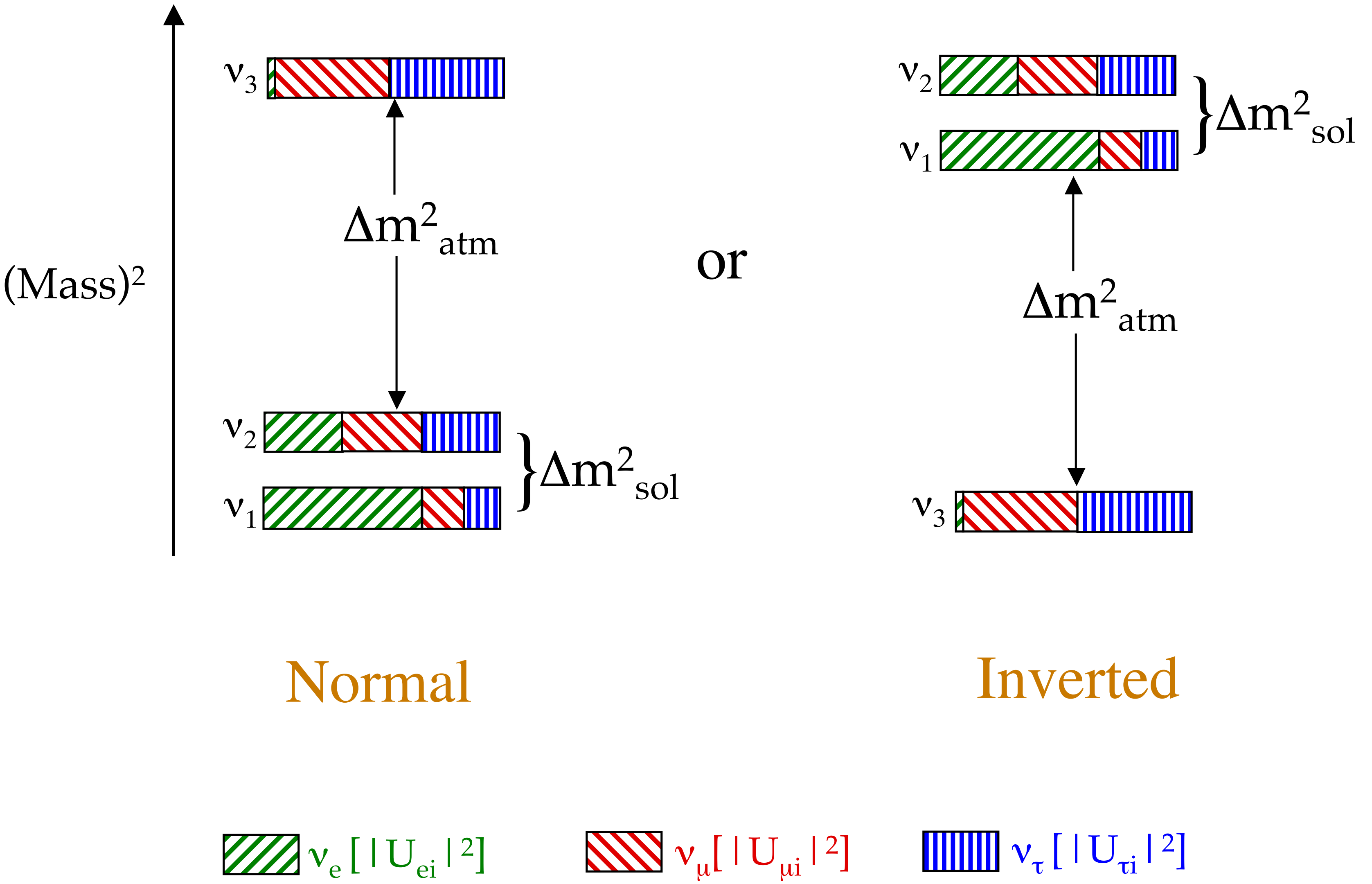
$$\frac{P(\nu_\mu \rightarrow \nu_e)}{P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e)} \begin{cases} > 1\ ; \\ < 1\ ; \end{cases}$$



Note fake ~~CP~~

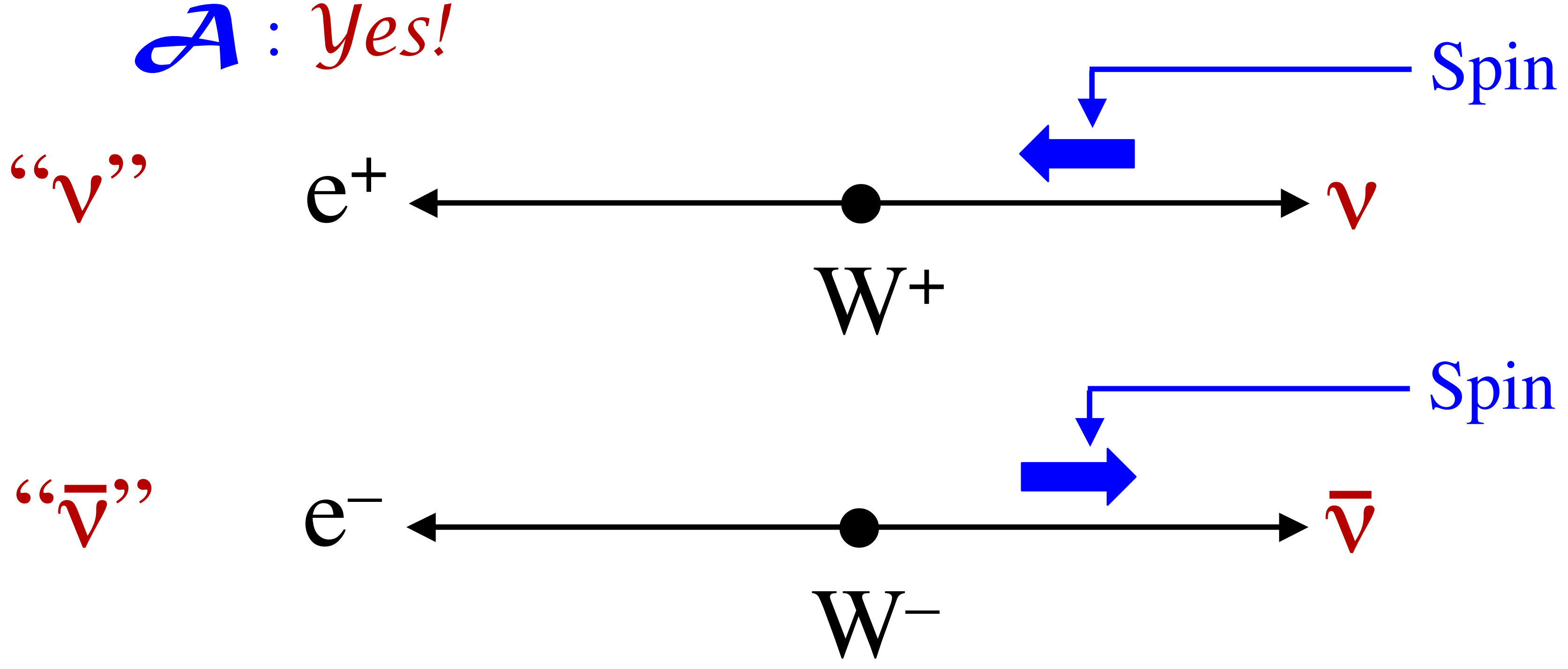
Note dependence on the mass ordering

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***.

Do Neutrino Interactions Violate CP?

CP violation involving the neutrinos would show that CP violation is not peculiar to quarks.

CP violation involving the neutrinos may be related, through ***leptogenesis***, to why the universe contains matter but no antimatter.

(See Concha Gonzalez-Garcia)

(I will talk about the relationship later.)

*The observation of CP violation in neutrino oscillation would make it more plausible that **leptogenesis** occurred in the early universe.*

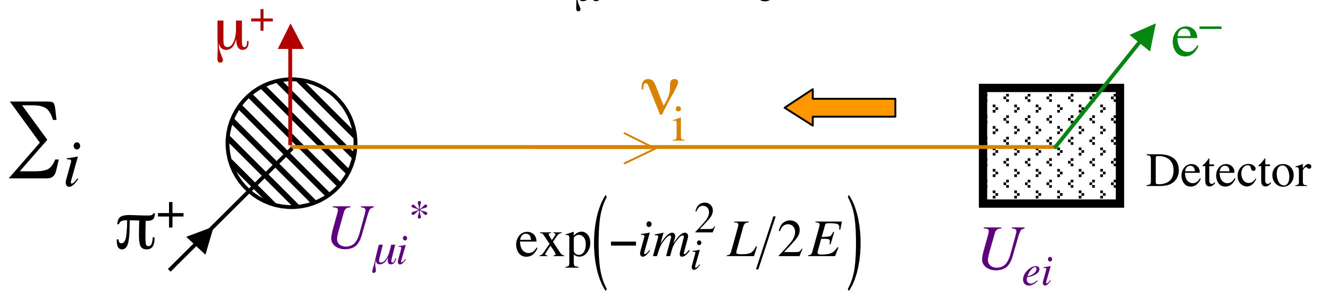
Seeking CP violation in neutrino oscillation is now a worldwide goal.

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.

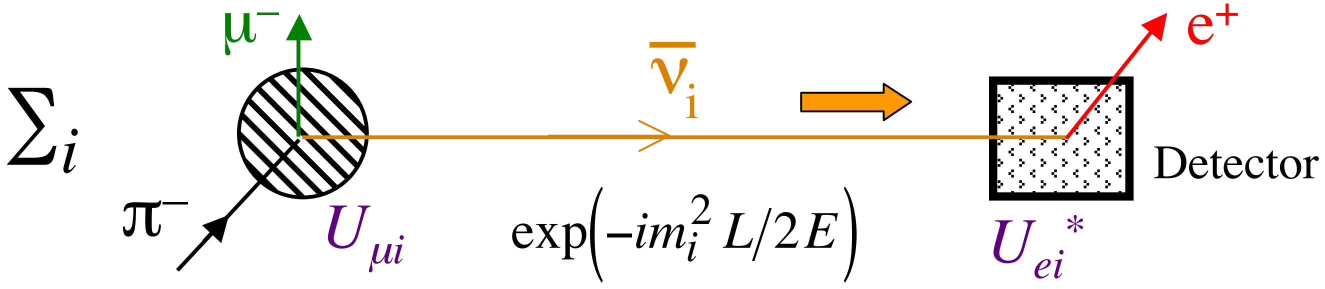
Q : *Can CP violation still lead to* $\mathcal{P}(\overline{\nu}_\mu \to \overline{\nu}_e) \neq \mathcal{P}(\nu_\mu \to \nu_e)$ *when* $\overline{\nu} = \nu$*?*

A : *Certainly!*

Compare $\nu_\mu \to \nu_e$



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



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

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

Δm^2_{31}: $m^2(—) - m^2(═)$

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

Atmospheric

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

CP-odd interference

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

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

CP-even interference

$$T_4 = \cos^2\theta_{23} \sin^2 2\theta_{12} \frac{\sin^2(x\Delta)}{x^2}$$

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*.)

What Facility Is Needed?

$$P\left(\nu_\mu \to \nu_e\right) \sim \sin^2 2\theta_{13}$$

A conventional accelerator neutrino beam from π and K decay is mostly ν_μ, but has a ~1% ν_e contamination.

Studying $\nu_\mu \to \nu_e$ with a conventional beam would be difficult if $\sin^2 2\theta_{13} < 0.01$.

More Powerful Facilities

β Beam: β^+ emitting nuclei in a storage ring produce a flavor-pure ν_e beam. Look for $\nu_e \to \nu_\mu$.

ν Factory: The decays $\mu^+ \to e^+ \nu_e \overline{\nu}_\mu$ of muons in a storage ring, plus a magnetized detector with μ^+/μ^- discrimination, yields an effectively flavor-pure ν_e beam. Look for $\nu_e \to \nu_\mu$.

$\sin^2 2\theta_{13}$	Use
$> 10^{-(2\text{-}3)}$	Conventional “Superbeam”
$< 10^{-(2\text{-}3)}$	β Beam or ν Factory

From the T2K and MINOS evidence, there is at least a good change that θ_{13} puts the search for CP violation in the Superbeam range.

A β Beam or ν Factory will then carry out the precision measurements.