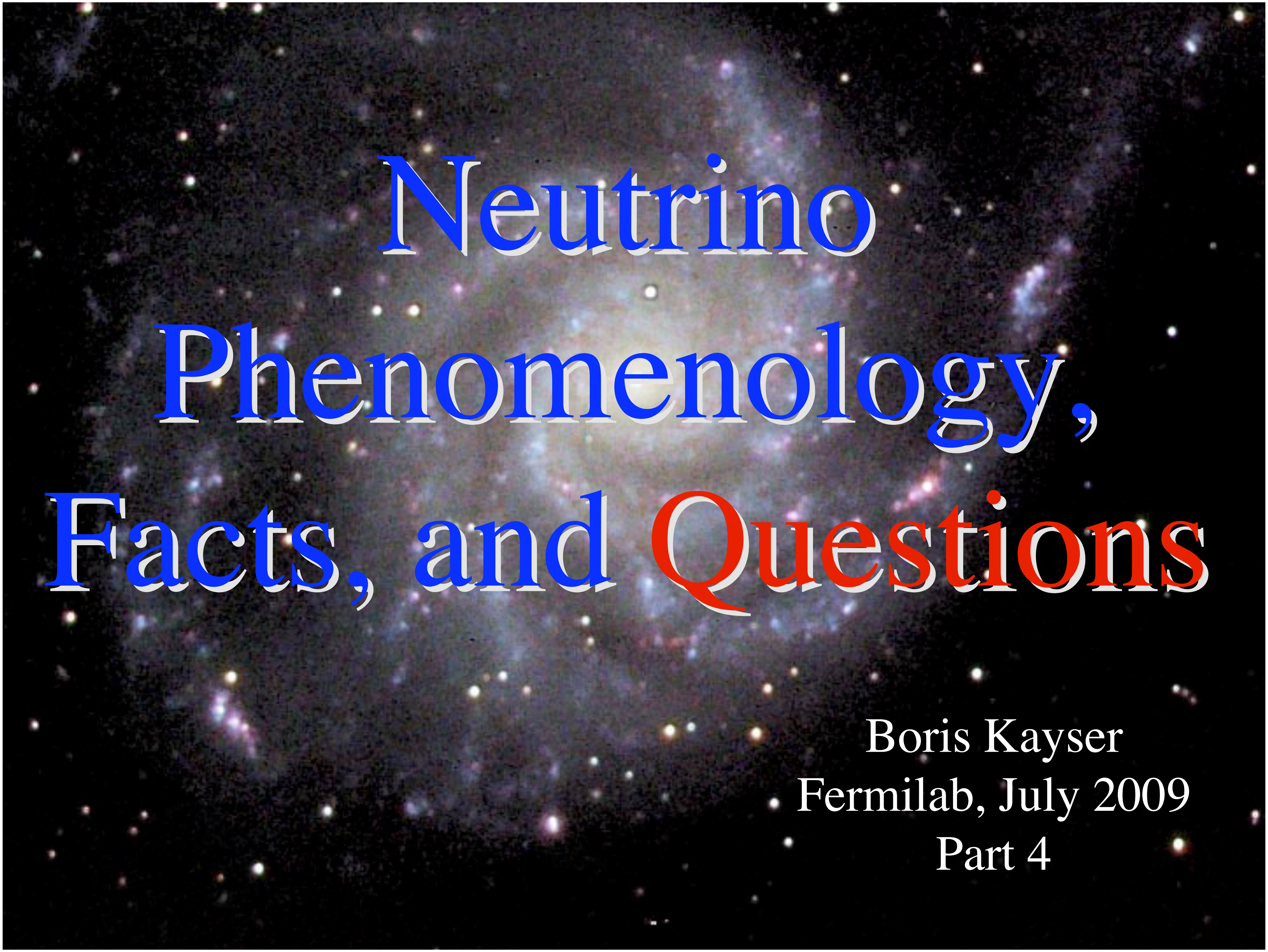


Neutrino Phenomenology, Facts, and Questions

Boris Kayser
Fermilab, July 2009
Part 4

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 the pattern of mixing among the different types of neutrinos?

What is θ_{13}?

- Is the spectrum like  or  ?

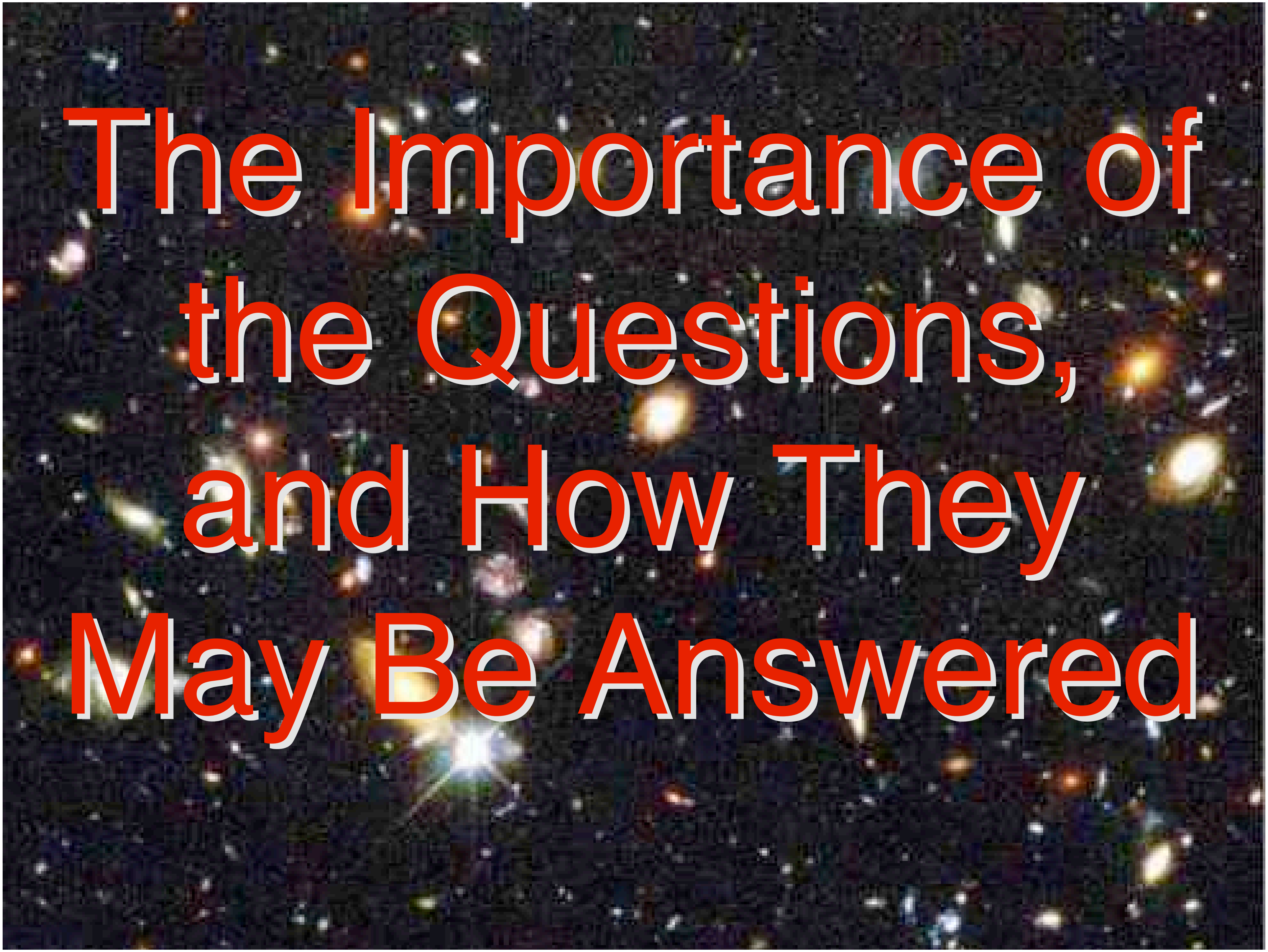
- Do neutrino – matter interactions violate CP?

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?



The Importance of the Questions, and How They May Be Answered

What Is the Absolute Scale of Neutrino Mass?

Theory cannot predict it (yet).

It has to be measured.

Possible approaches include –

- Analysis of cosmological data
- Laboratory study of the beta energy spectrum in nuclear beta decay

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

If so, the neutrinos are ***very*** distinctive, because they have ***very*** distinctive Majorana masses, which are far outside the Standard Model.

Observation of ***neutrinoless double beta decay*** would establish that neutrinos have Majorana masses and are their own antiparticles.

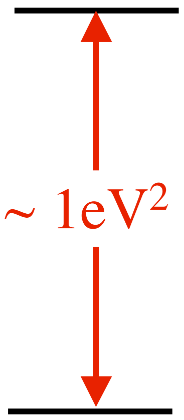
Are There *More* Than 3 Mass Eigenstates?

Are There Sterile Neutrinos?

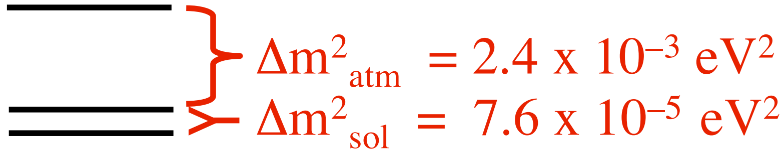
The Hint From LSND

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

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


~ 1eV^2

in contrast to


$\Delta m^2_{\text{atm}} = 2.4 \times 10^{-3}\ \text{eV}^2$

$\Delta m^2_{\text{sol}} = 7.6 \times 10^{-5}\ \text{eV}^2$

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?

Results from the MiniBooNE experiment so far *suggest* that the answer is —

No.

A global analysis of the results of short-baseline experiments finds that even models that include one or two sterile neutrinos do not fit very well.

Karagiorgi *et al.*

The story is not over.

While awaiting further news —

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

Are There Surprises?

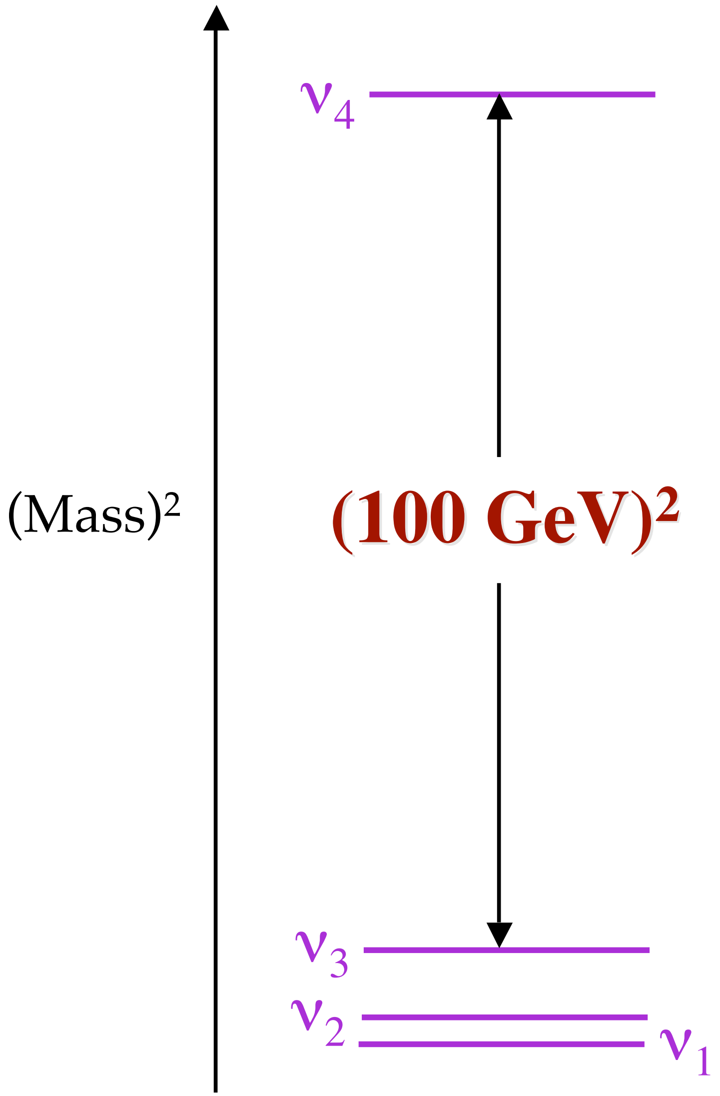
A fourth generation??

With 4 generations, there are 4 charged-lepton mass eigenstates, and 4 neutrino mass eigenstates.

The mixing matrix U is 4 × 4, and unitarity reads —

$$\sum_{i=1}^{\boxed{4}} U_{\alpha i}^{*} U_{\beta i} = \delta_{\alpha\beta}$$

The (Mass)^2 Spectrum??

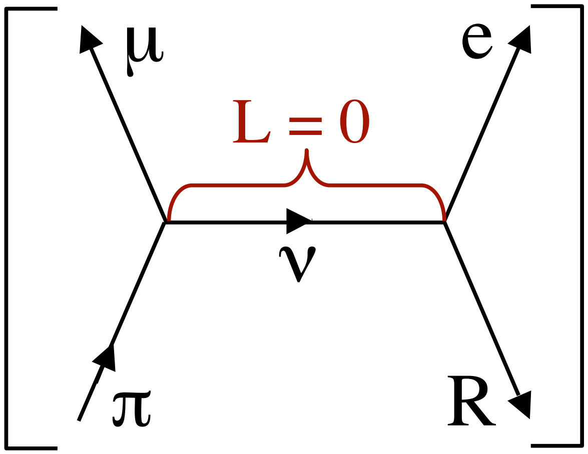


One Consequence:
Instantaneous Flavor Change

$$\text{Unitarity: } \sum_{i=1}^{\boxed{4}} U^*_{\mu i} U_{ei} = 0$$

But the heavy mass eigenstate ν_4 cannot be emitted in pion decay. Thus —

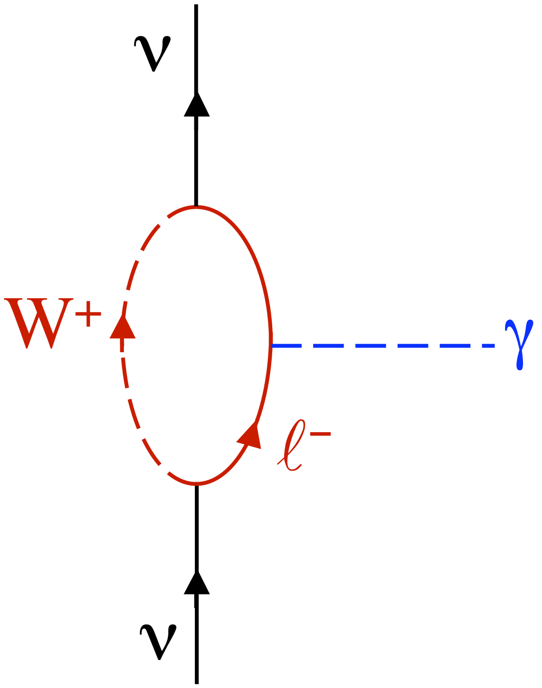
Amp



$$\propto \sum_{i=1}^{\boxed{3}} U^*_{\mu i} U_{ei} \neq 0$$

What Are the Neutrino 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:

$$\vec{\mu}\Big[\underset{e^+}{\uparrow}\Big] = -\,\vec{\mu}\Big[\underset{e^-}{\uparrow}\Big]$$

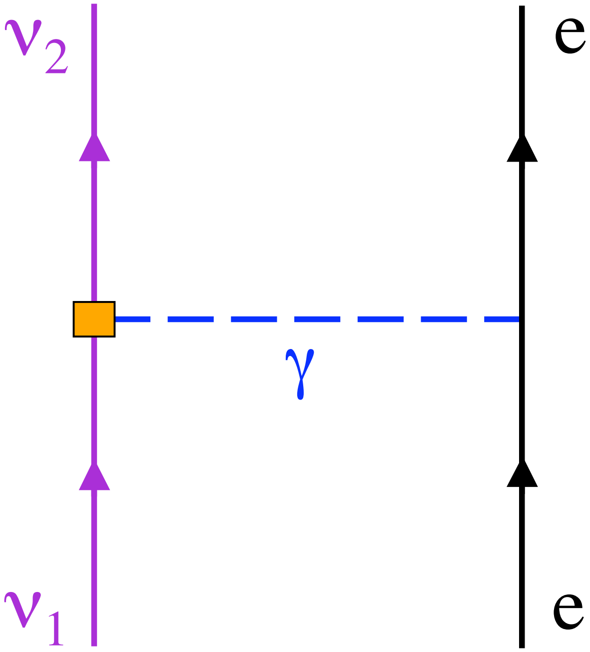
But for a Majorana neutrino,

$$\overline{\nu_i} = \nu_i$$

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.

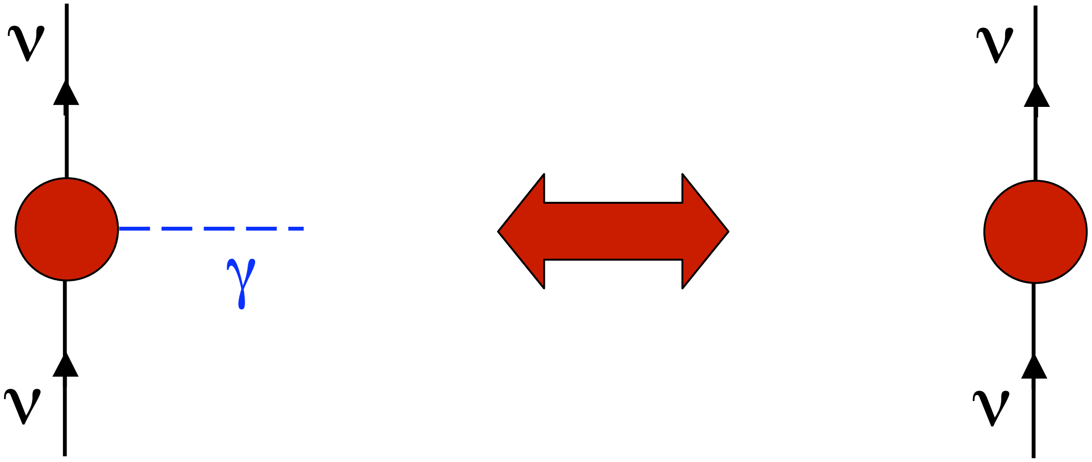
Present Bounds On Dipole Moments

$$\text{Upper bound} = \begin{cases} 7 \text{ x } 10^{-11}\,\mu_B & ;\ \text{Wong et al. (Reactor)} \\ 5.4 \text{ x } 10^{-11}\,\mu_B & ;\ \text{Borexino (Solar)} \\ 3 \text{ x } 10^{-12}\,\mu_B & ;\ \text{Raffelt (Stellar E loss)} \end{cases}$$

New Physics can produce larger dipole moments than the $\sim 10^{-20}\mu_B$ SM ones.

But the dipole moments cannot be arbitrarily large.

The Dipole Moment – Mass Connection



Dipole Moment

Mass Term

$$\mu_\nu \sim \frac{eX}{\Lambda}$$

$$m_\nu \sim X\Lambda$$

Scale of New Physics

$$\Rightarrow \quad m_\nu \sim \frac{\Lambda^2}{2m_e}\frac{\mu_\nu}{\mu_B} \sim \left(\frac{\mu_\nu}{10^{-18}\mu_B}\right)\left(\frac{\Lambda}{1\mathrm{TeV}}\right)^2 \mathrm{eV}$$

(Bell *et al.*)

Any dipole moment leads to a contribution to the neutrino mass that grows with the scale Λ of the new physics behind the dipole moment.

The dipole moment must not be so large as to lead to a violation of the upper bound on neutrino masses.

The constraint —

$$m_\nu \sim \frac{\Lambda^2}{2m_e}\frac{\mu_\nu}{\mu_B} \sim \left(\frac{\mu_\nu}{10^{-18}\mu_B}\right)\left(\frac{\Lambda}{1\,\mathrm{TeV}}\right)^2 \mathrm{eV}$$

can be evaded by some new physics.

But the evasion can only go so far.

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}.

If $\sin^2 2\theta_{13} > 10^{-(2\text{-}3)}$, we can study both of these issues with intense but conventional accelerator ν and $\bar{\nu}$ beams, produced via $\pi^+ \rightarrow \mu^+ + \nu_\mu$ and $\pi^- \rightarrow \mu^- + \bar{\nu}_\mu$.

Determining θ_{13} is an important step.

Reactor Experiments To Determine θ_{13}

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

$$P(\bar{\nu}_e \text{ Disappearance}) =$$

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

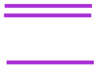
Accelerator Experiments

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 $\bar{\nu}_\mu \to \bar{\nu}_e$
while the beams travel hundreds of kilometers.

(Lectures by Stephen Parke)

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.

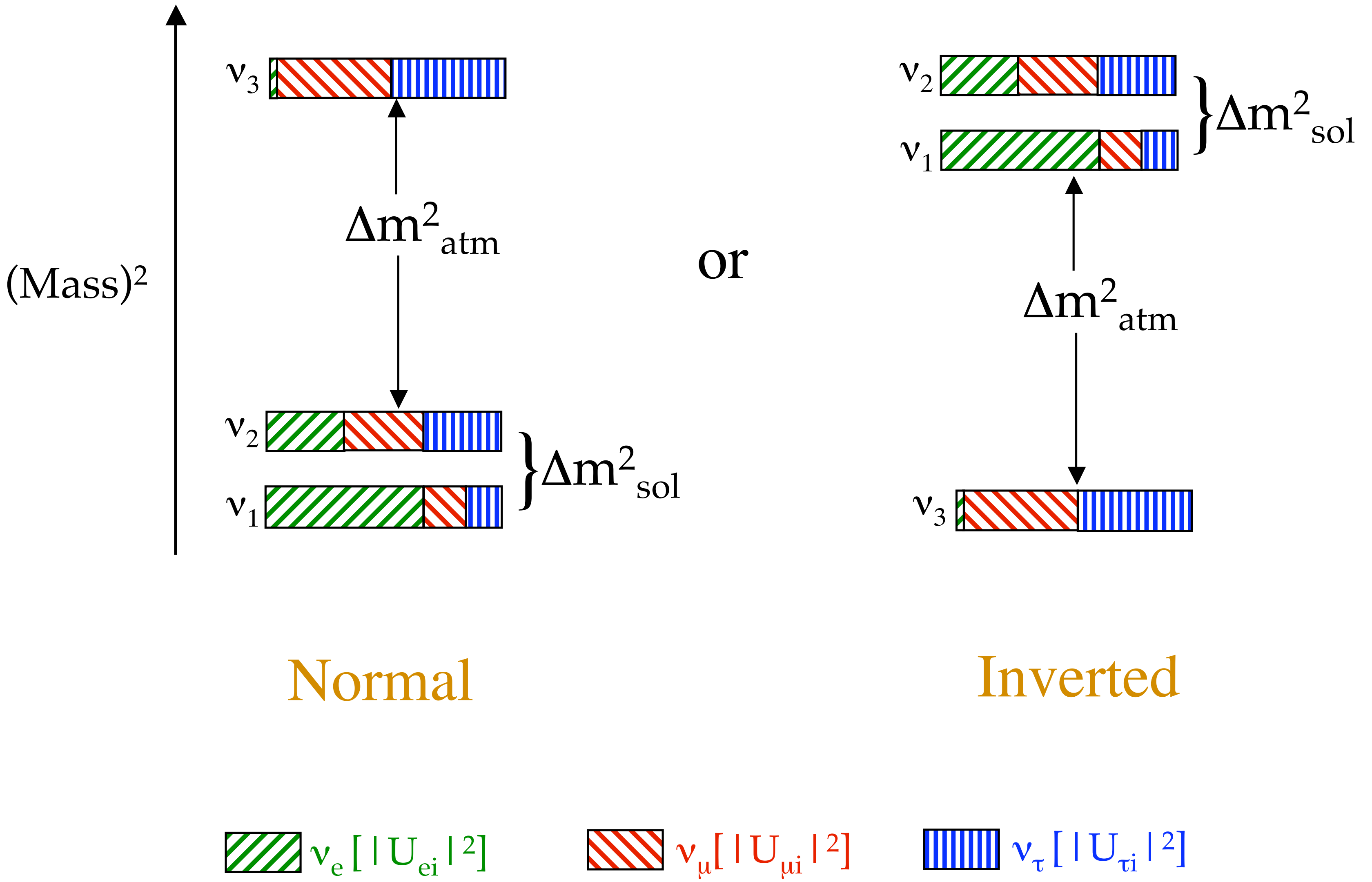
Recall that the matter effect ***raises*** the effective mass of ν_e, but ***lowers*** that of $\bar{\nu}_e$. Thus, it affects ν and $\bar{\nu}$ oscillation ***differently***, leading to:

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

Note fake ~~CP~~

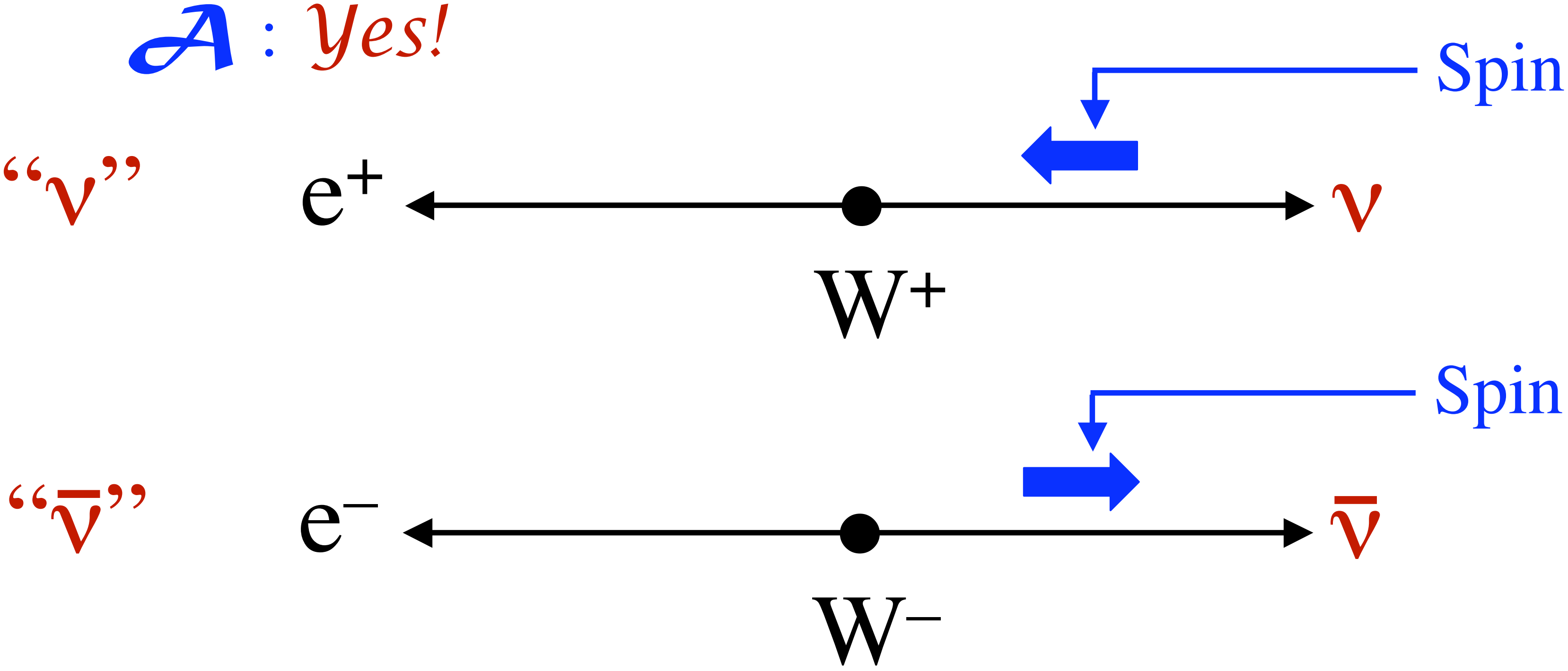
Note dependence on the mass ordering

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!*



Spin

“ν” e^+ ν

W^+

Spin

“$\bar{\nu}$” e^- $\bar{\nu}$

W^-

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

Do Neutrino Interactions Violate CP?

The observed $\cancel{CP}$ in the weak interactions of ***quarks*** cannot explain the *Baryon Asymmetry* of the universe.

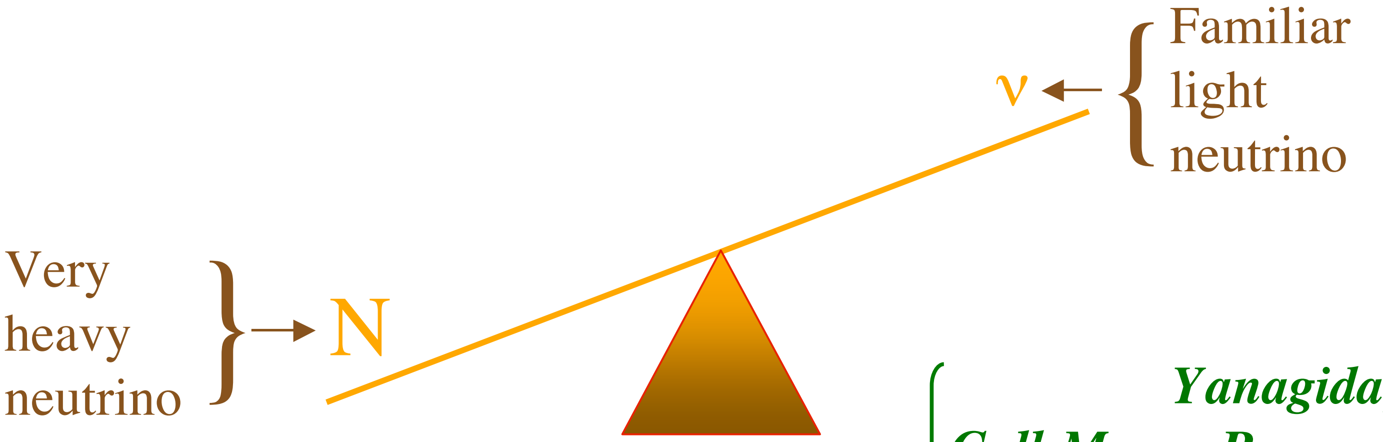
Is ***leptonic*** $\cancel{CP}$, through *Leptogenesis*, the origin of the *Baryon Asymmetry* of the universe?

(Fukugita, Yanagida)

Leptogenesis – The General Idea

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

The See-Saw Mechanism



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

The ***very*** heavy neutrinos N would have been made in the hot Big Bang.

Leptogenesis — Step 1

The heavy neutrinos N, like the light ones ν, are Majorana particles. Thus, an N can decay into ℓ^- or ℓ^+.

If ν oscillation violates CP, then quite likely so does N decay. In the See-Saw, these two CP violations have a common origin: One Yukawa coupling matrix, y.

Then, in the early universe, we would have had different rates for the CP-mirror-image decays –

$$N \rightarrow \ell^- + \varphi^+ \qquad \text{and} \qquad N \rightarrow \ell^+ + \varphi^-$$

Standard-Model Higgs

This produces a universe with unequal numbers of leptons and antileptons.

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 Baryon Asymmetry.

We may be descended from heavy neutrinos.

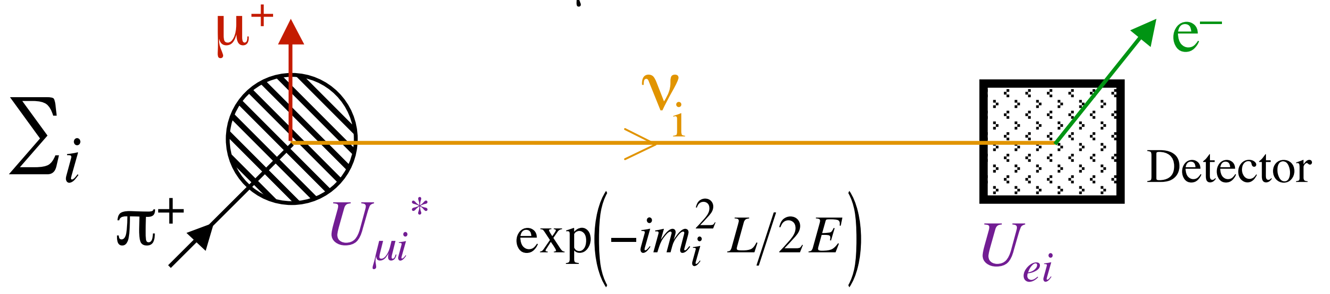
How To Search for $\not{CP}$ In Neutrino Oscillation

Look for $P(\bar{\nu}_\alpha \rightarrow \bar{\nu}_\beta) \neq P(\nu_\alpha \rightarrow \nu_\beta)$

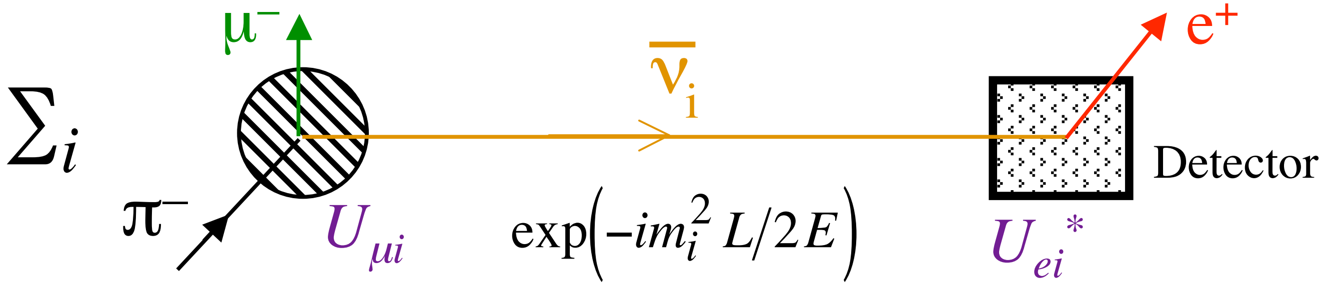
$\mathcal{Q}$: *Can CP violation still lead to $\mathcal{P}(\bar{\nu}_\mu \to \bar{\nu}_e) \neq \mathcal{P}(\nu_\mu \to \nu_e)$ when $\bar{\nu} = \nu$?*

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

Compare $\nu_\mu \to \nu_e$



with “$\bar{\nu}_\mu \to \bar{\nu}_e$”



Enjoy the rest of the School!