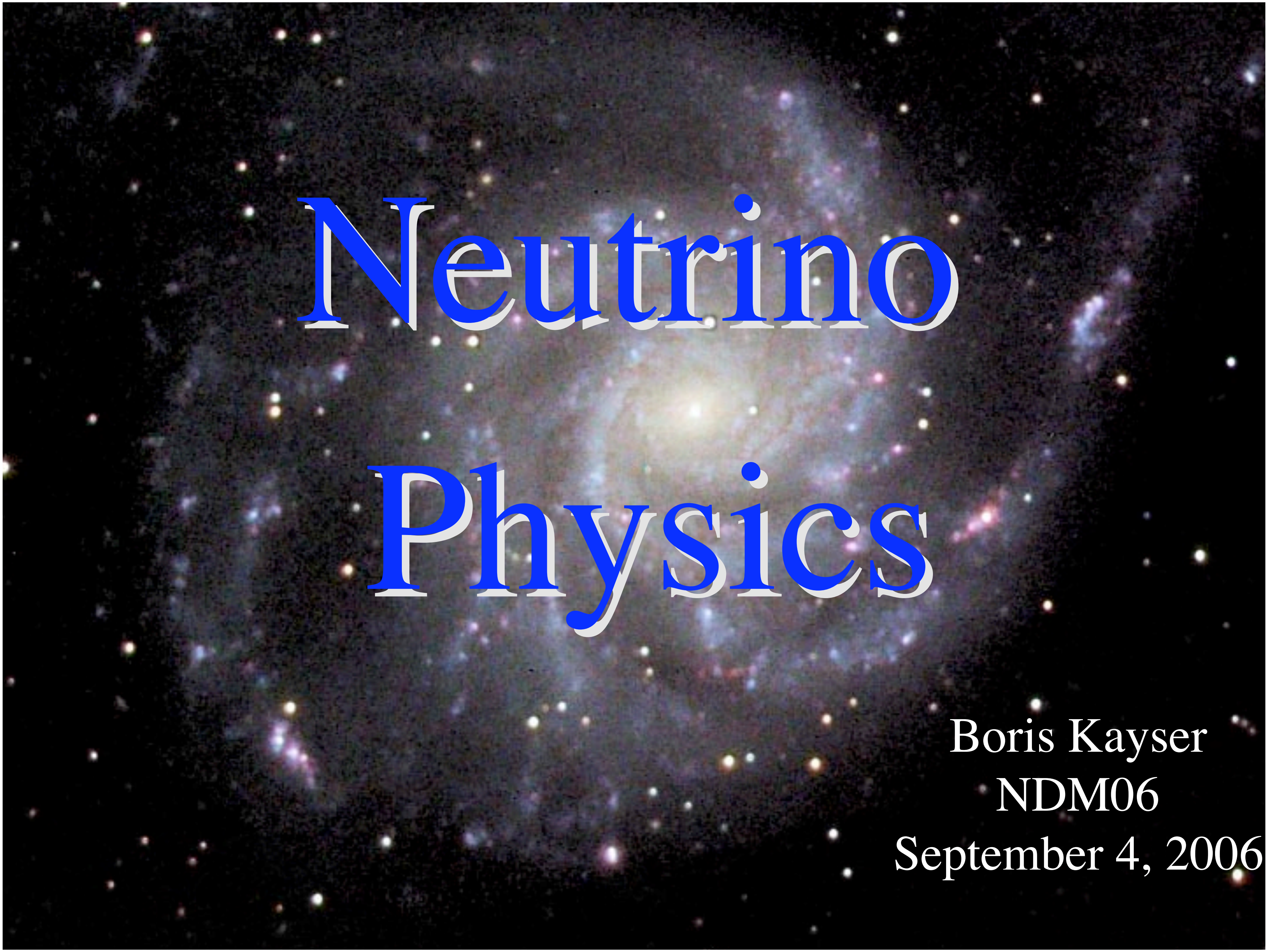
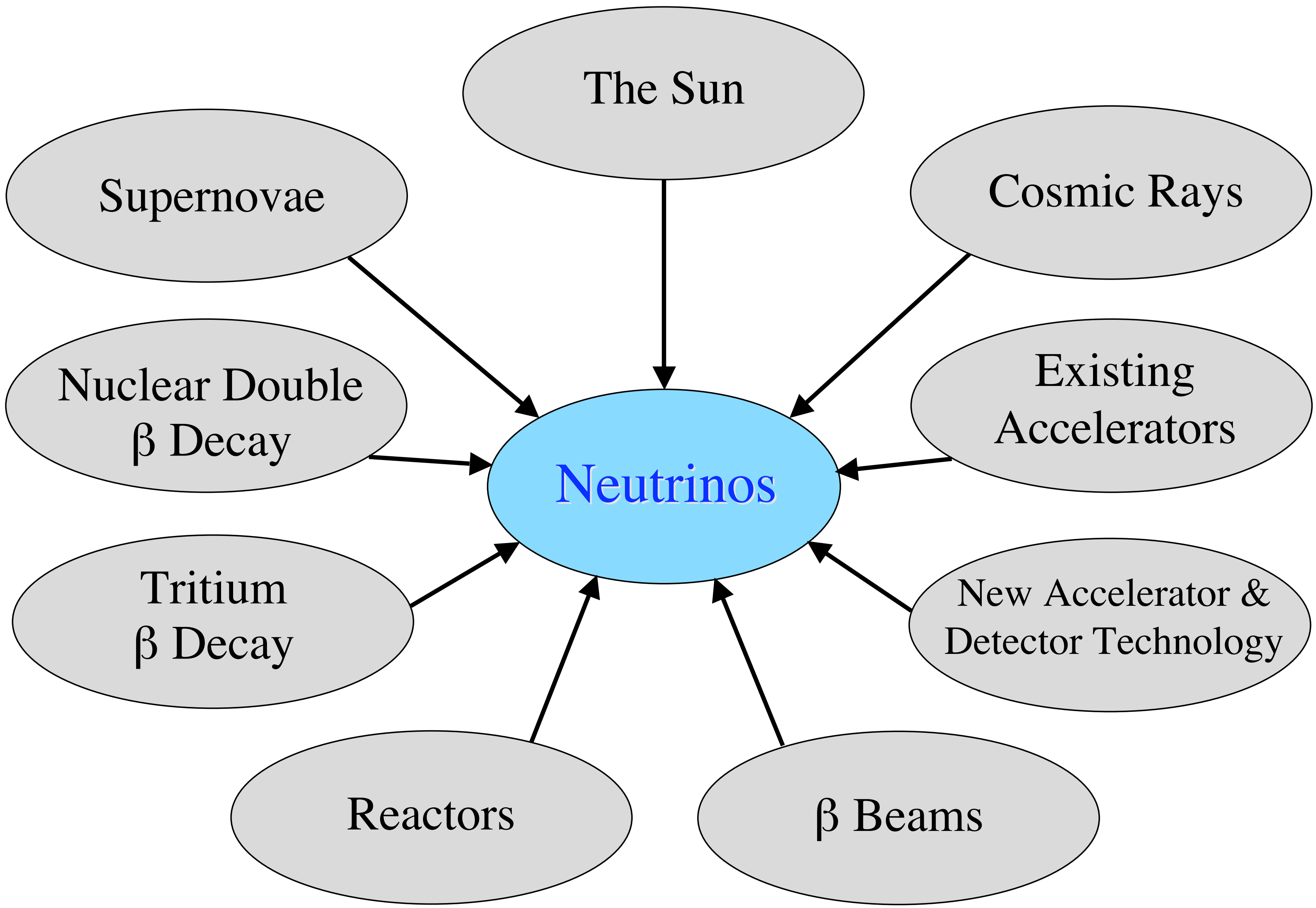

Neutrino
Physics
Boris Kayser
NDM06
September 4, 2006

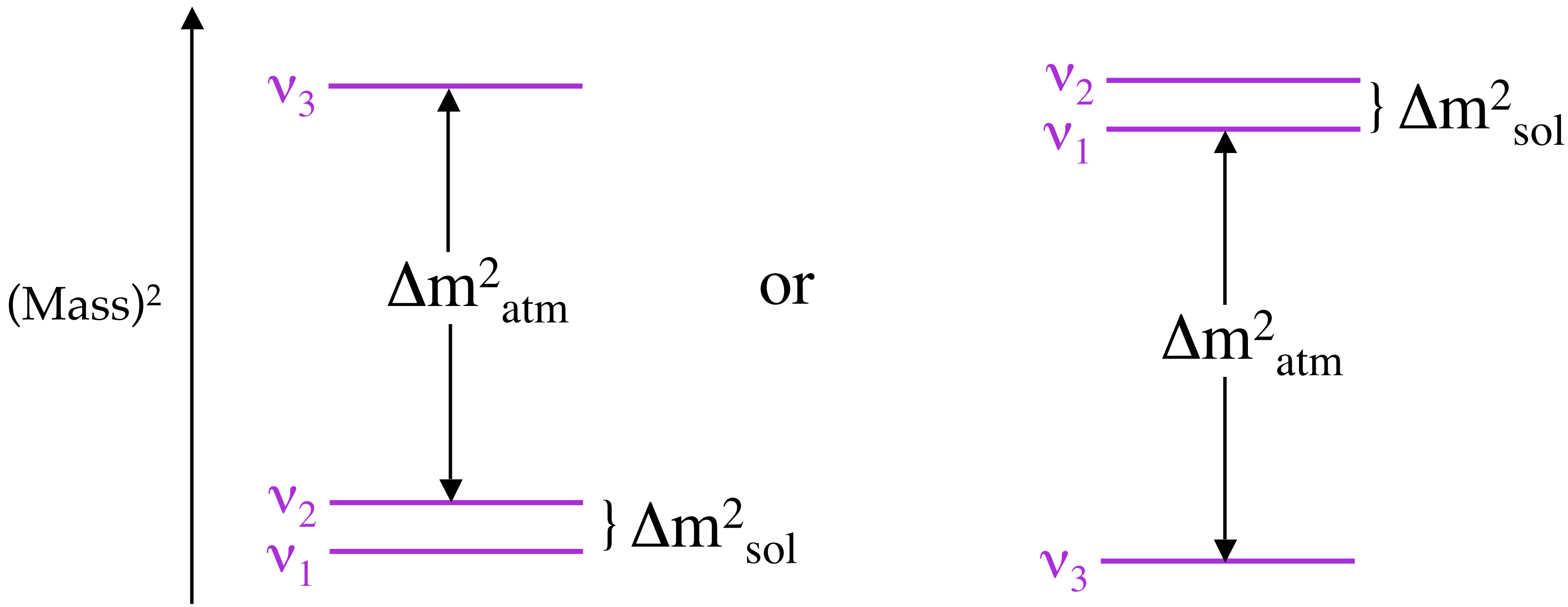

The Sun
Supernovae
Cosmic Rays
Nuclear Double
β Decay
Neutrinos
Existing
Accelerators
Tritium
β Decay
New Accelerator &
Detector Technology
Reactors
β Beams

NDM06

A Special Symposium Reflecting the Many Ties of Neutrinos

What We Have Learned

The (Mass)^2 Spectrum



Normal Inverted

$\Delta m^2_{sol} \cong 8.0 \text{ x } 10^{-5}\ \mathrm{eV}^2$, $\Delta m^2_{atm} \cong 2.7 \text{ x } 10^{-3}\ \mathrm{eV}^2$

Are there *more* mass eigenstates, as LSND suggests?

Leptonic Mixing

The neutrinos $\nu_{e,\mu,\tau}$ of definite flavor

$(W \to e\nu_e$ or $\mu\nu_\mu$ or $\tau\nu_\tau)$

are superpositions of the mass eigenstates:

$$|\nu_\alpha> = \sum_i U^*_{\alpha i} \, |\nu_i> \ .$$

Neutrino of flavor
$\alpha = e, \mu,$ or τ

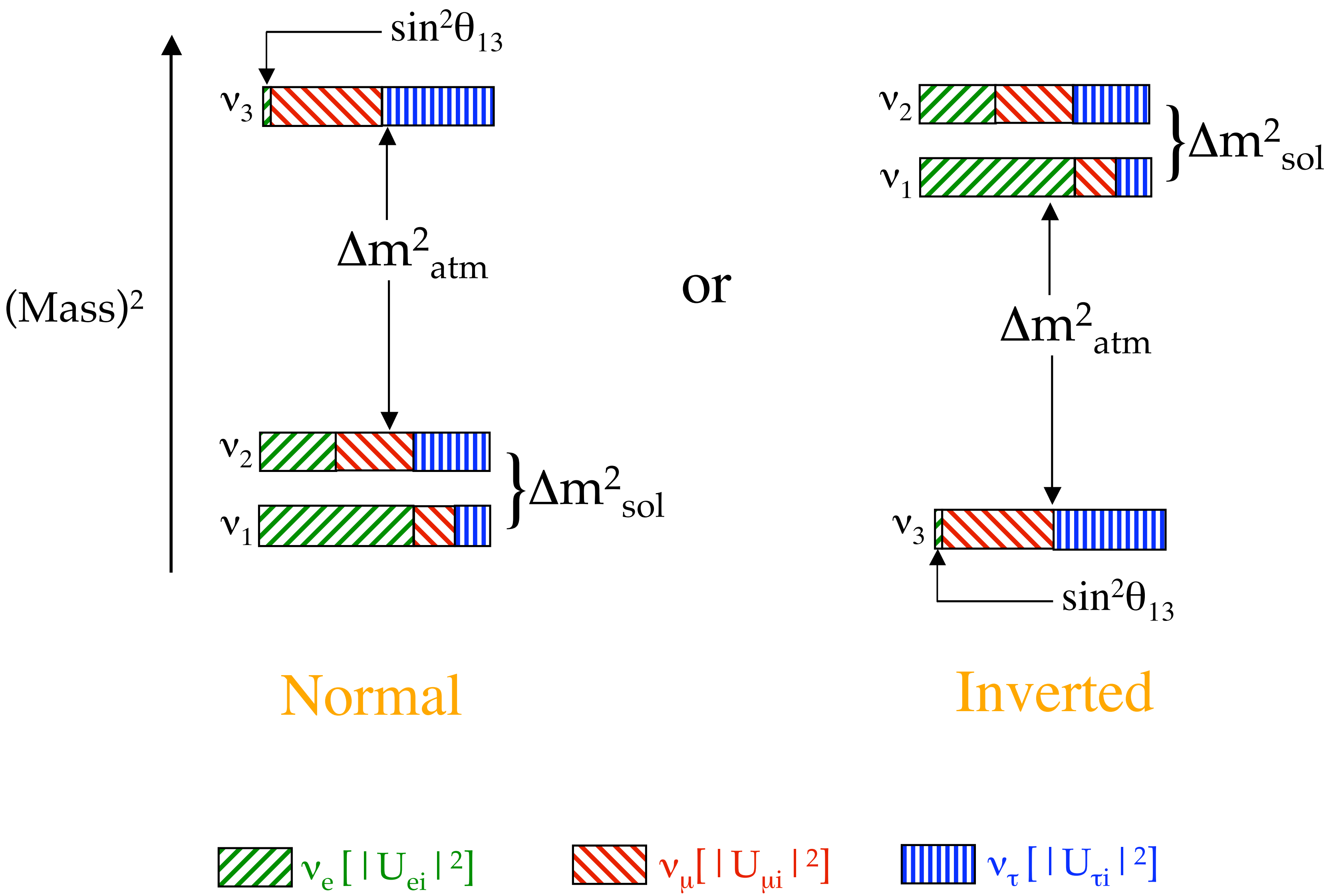
Neutrino of definite mass m_i

Unitary Leptonic Mixing Matrix

Inverting: $|\nu_i> = \sum_\alpha U_{\alpha i} \, |\nu_\alpha> \ .$

Flavor-α fraction of $\nu_i = |U_{\alpha i}|^2$.

The spectrum, showing its approximate flavor content, is



The Mixing Matrix

$$U = \overset{\text{Atmospheric}}{\begin{bmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{bmatrix}} \times \overset{\text{Cross-Mixing}}{\begin{bmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{bmatrix}} \times \overset{\text{Solar}}{\begin{bmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{bmatrix}}$$

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

$$\times \underset{\text{Majorana } \cancel{CP} \text{ phases}}{\begin{bmatrix} e^{i\alpha_1/2} & 0 & 0 \\ 0 & e^{i\alpha_2/2} & 0 \\ 0 & 0 & 1 \end{bmatrix}}$$

$\theta_{12} \approx \theta_{sol} \approx 34°$, $\theta_{23} \approx \theta_{atm} \approx 37\text{-}53°$, $\theta_{13} \lesssim 10°$

δ would lead to $P(\bar{\nu}_\alpha \rightarrow \bar{\nu}_\beta) \neq P(\nu_\alpha \rightarrow \nu_\beta)$. $\cancel{CP}$

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


The Open
Questions

- ***<u>Are neutrinos their own antiparticles?</u>***

- What is the absolute scale of neutrino mass?

- Are there “sterile” neutrinos?

We must be alert to surprises!

•What is the pattern of mixing among the different types of neutrinos?

What is θ_{13}? Is θ_{23} maximal?

•Is the spectrum like  or  ?

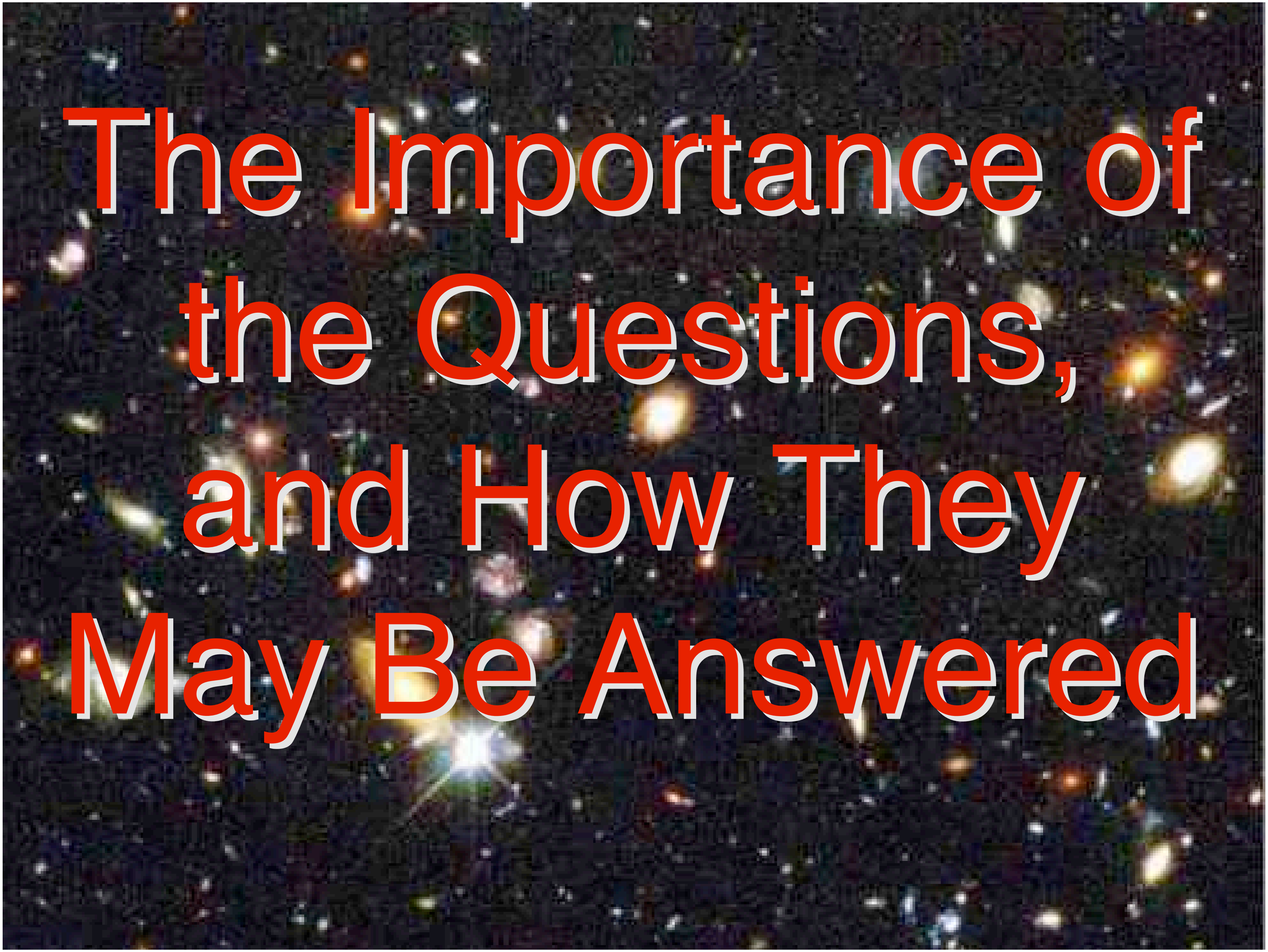
•Do neutrinos violate the symmetry CP?

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 by neutrinos the key to understanding the matter – antimatter asymmetry of the universe?

- What physics is behind neutrino mass?

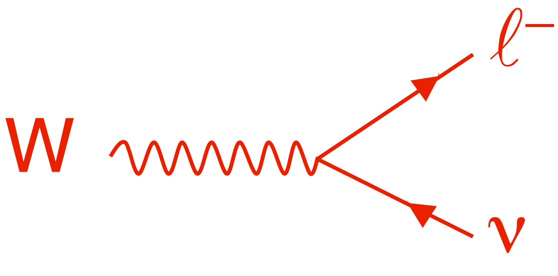

The Importance of the Questions, and How They May Be Answered

Are Neutrinos Majorana Particles? (Does $\bar{\nu} = \nu$?)

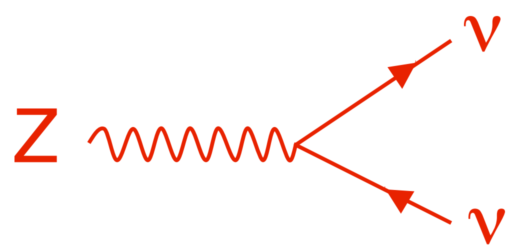
How Can the Standard Model be Modified to Include Neutrino Masses?

Majorana Neutrinos or Dirac Neutrinos?

The S(tandard) M(odel)



and

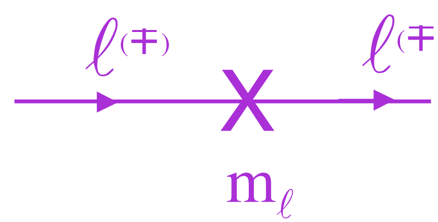


couplings conserve the Lepton Number L defined by—

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

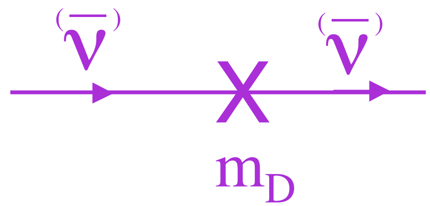
So do the Dirac charged-lepton mass terms

$$m_\ell \bar{\ell}_L \ell_R$$



- Original SM: $m_\nu = 0$.
- Why not add a Dirac mass term,

$$m_D \overline{\nu}_L \nu_R$$



Then everything conserves L, so for each mass eigenstate ν_i,

$$\overline{\nu}_i \neq \nu_i \qquad \text{(Dirac neutrinos)}$$

$$[L(\overline{\nu}_i) = -L(\nu_i)]$$

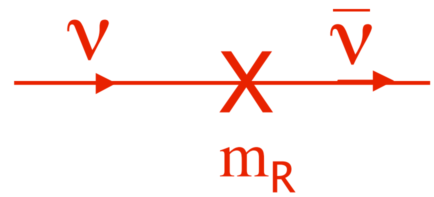
- The SM contains no ν_R field, only ν_L.

To add the Dirac mass term, we had to add ν_R to the SM.

Unlike ν_L, ν_R carries no Electroweak Isospin.

Thus, no SM principle prevents the occurrence of the Majorana mass term

$$m_R \overline{\nu_R{}^c}\, \nu_R$$



But this does not conserve L, so now

$$\bar{\nu}_i = \nu_i \qquad \text{(Majorana neutrinos)}$$

[No conserved L to distinguish $\bar{\nu}_i$ from ν_i]

We note that $\bar{\nu}_i = \nu_i$ means —

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

helicity

Many Theorists Expect Majorana Masses

The Standard Model (SM) is defined by the fields it contains, its symmetries (notably Electroweak Isospin Invariance), and its renormalizability.

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

If this is also true for neutrino masses, then neutrinos have Majorana masses.

- The presence of Majorana masses
- $\overline{\nu}_i = \nu_i$ (Majorana neutrinos)
- L not conserved

— are all equivalent

Any one implies the other two.

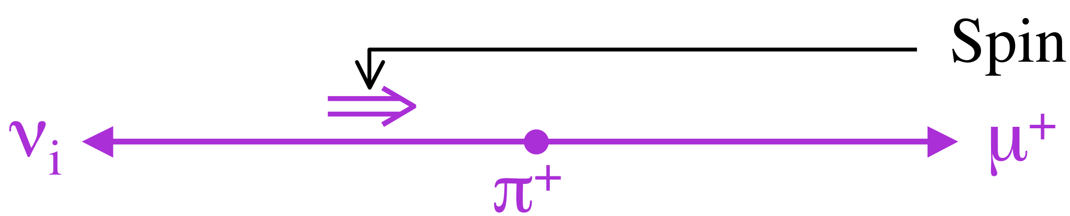
(Recent work: Hirsch, Kovalenko, Schmidt)

How Can We Demonstrate That $\bar{\nu}_i = \nu_i$?

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]

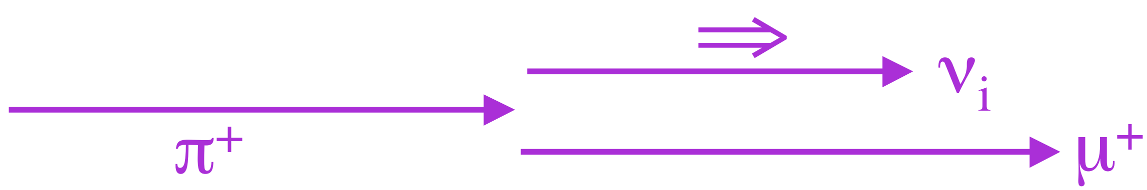
Produce a ν_i via—



Pion Rest Frame

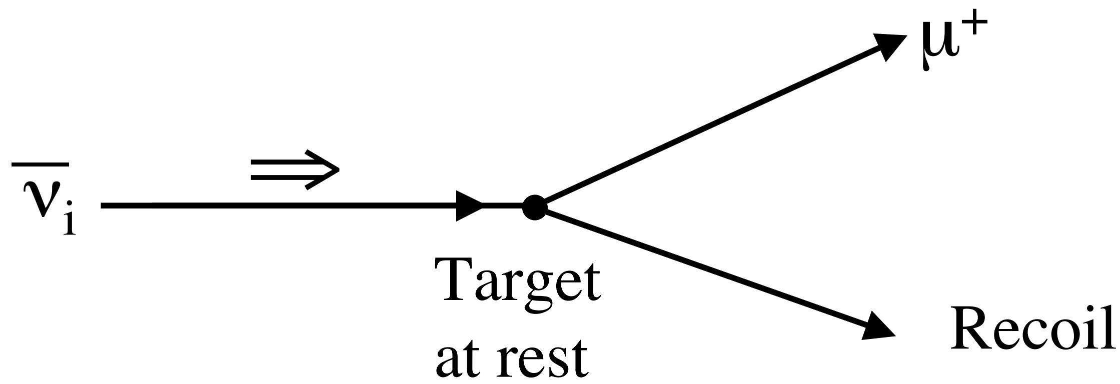
Give the neutrino a Boost:

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



Lab. Frame

The SM weak interaction causes—



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

helicity

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

our $\nu_i \xrightarrow{\Rightarrow}$ will make μ^+ too.

Minor Technical Difficulties

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

$$\Rightarrow \frac{E_\pi(\text{Lab})}{m_\pi} > \frac{E_\nu(\pi \text{ Rest Frame})}{m_{\nu_i}}$$

$$\Rightarrow E_\pi(\text{Lab}) \gtrsim 10^5 \text{ TeV if } m_{\nu_i} \sim 0.05 \text{ eV}$$

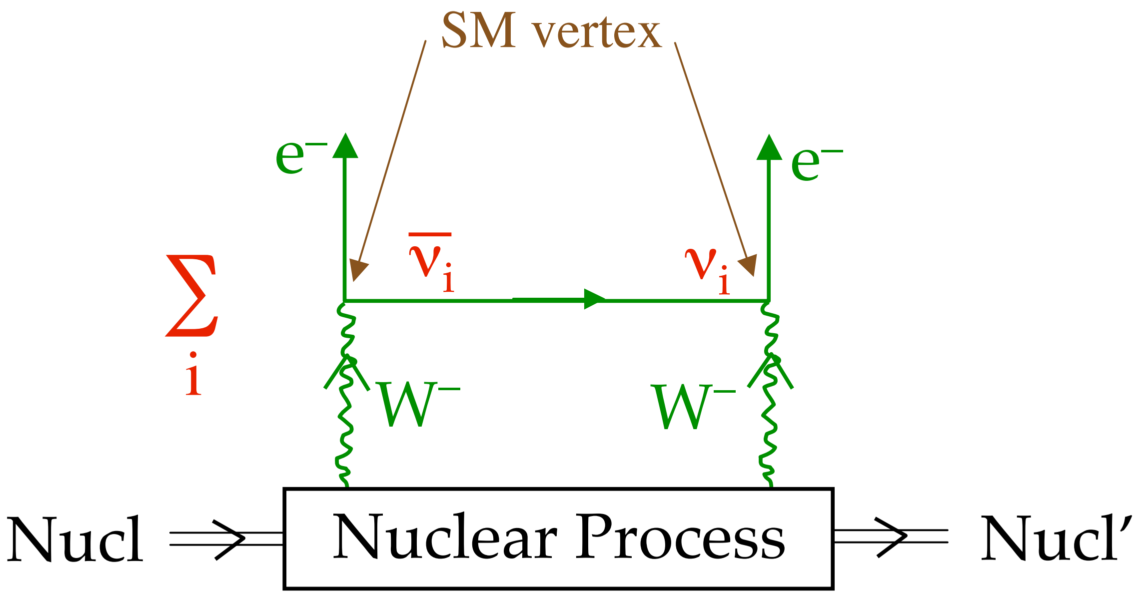
Fraction of all π – decay ν_i that get helicity flipped

$$\approx \left(\frac{m_{\nu_i}}{E_\nu(\pi \text{ Rest Frame})}\right)^2 \sim 10^{-18} \text{ if } m_{\nu_i} \sim 0.05 \text{ eV}$$

Since L-violation comes only from Majorana neutrino *masses*, any attempt to observe it will be at the mercy of the neutrino masses.

(BK & Stodolsky)

The Idea That Can Work — Neutrinoless Double Beta Decay [$0\nu\beta\beta$]



By avoiding competition, this process can cope with the small neutrino masses.

Observation would imply $\not{L}$ and $\overline{\nu}_i = \nu_i$.

The pictured mechanism is expected to dominate.

Then —

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

Mass (ν_i)

(See S. Petcov's talk)

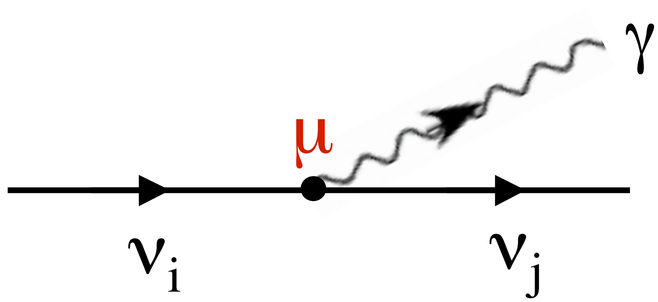
The proportionality of $0\nu\beta\beta$ to ν mass is no surprise.

$0\nu\beta\beta$ violates L. But the SM interactions conserve L.

The L – violation in $0\nu\beta\beta$ comes from underlying **Majorana** mass terms.

Possible Information From Neutrino Magnetic Moments

Both Majorana and Dirac neutrinos can have *transition* magnetic dipole moments μ:



For *Dirac* neutrinos, $\mu < 10^{-15}\,\mu_{Bohr}$

For *Majorana* neutrinos, $\mu <$ Present bound

$$\text{Present bound} = \begin{cases} 7 \times 10^{-11}\,\mu_{Bohr}\text{ ; Wong et al. (Reactor)} \\ 3 \times 10^{-12}\,\mu_{Bohr}\text{ ; Raffelt (Stellar E loss)} \end{cases}$$

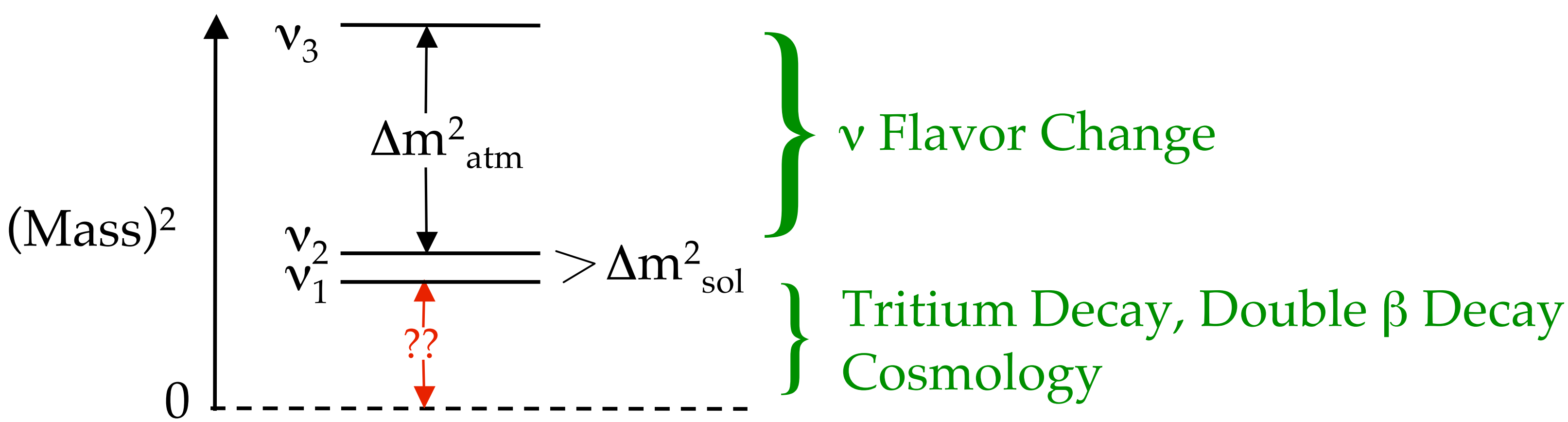
An observed μ below the present bound but well above $10^{-15}\ \mu_{Bohr}$ would imply that neutrinos are Majorana particles.

However, a dipole moment that large requires L-violating new physics below 100 TeV.

(Bell, Cirigliano, Gorchtein, Ramsey-Musolf, Vogel, Wise, Wang)

Neutrinoless double beta decay at the planned level of sensitivity only requires this new physics at $\sim 10^{15}$ GeV, near the Grand Unification scale.

What Is the Absolute Scale of Neutrino Mass?



How far above zero
is the whole pattern?

The Mass Spectrum: or ?

Generically, grand unified models (GUTS) favor —

GUTS relate the Leptons to the Quarks.

is un-quark-like, and would probably involve a lepton symmetry with no quark analogue.

How To Determine If The Spectrum Is Normal Or Inverted

Due to matter effects, at oscillation maximum,

Sign[m^2(—) - m^2(═)]

$$\frac{P(\nu_\mu \to \nu_e)}{P(\bar{\nu}_\mu \to \bar{\nu}_e)} \cong \frac{1 + S(E/6\,GeV)}{1 - S(E/6\,GeV)}$$

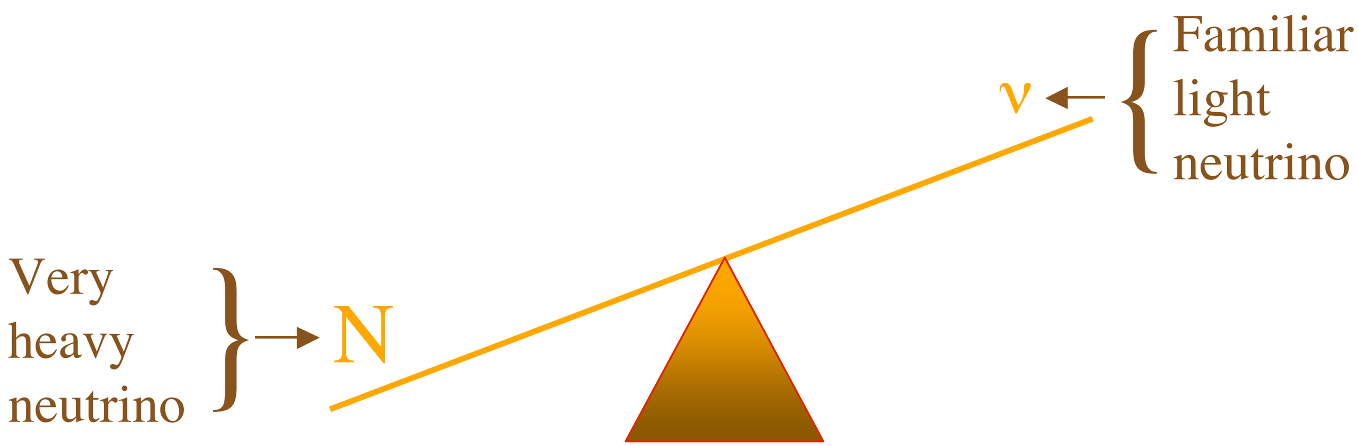
$$\begin{cases} > 1\ ; \\ < 1\ ; \end{cases}$$

Note the $\nu - \bar{\nu}$ asymmetry that is not from CP violation.

Do Neutrinos Violate CP?

The most popular theory of why neutrinos are so light is the —

See-Saw Mechanism



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

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

If neutrino oscillation violates CP, then quite likely so does N decay, even though one can decouple the two.

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

$$N \to \ell^- + \ldots \qquad \text{and} \qquad N \to \ell^+ + \ldots$$

This would have led to unequal numbers of leptons and antileptons *(Leptogenesis)*.

Perhaps this was the original source of the present preponderance of Matter over Antimatter in the universe.

How To Search for $\not{C}\not{P}$

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

But genuine $\not{C}\not{P}$ and the matter effect must be disentangled.

Genuine $\not{C}\not{P}$ and the matter effect depend quite differently from each other on L and E.

To disentangle them, one must make oscillation measurements at different L and/or E.

Conclusion

We have a very rich opportunity to do exciting physics.

Answering the questions raised by the discovery of neutrino mass should prove **very** interesting!