Neutrino Phenomenology, Facts, and Questions

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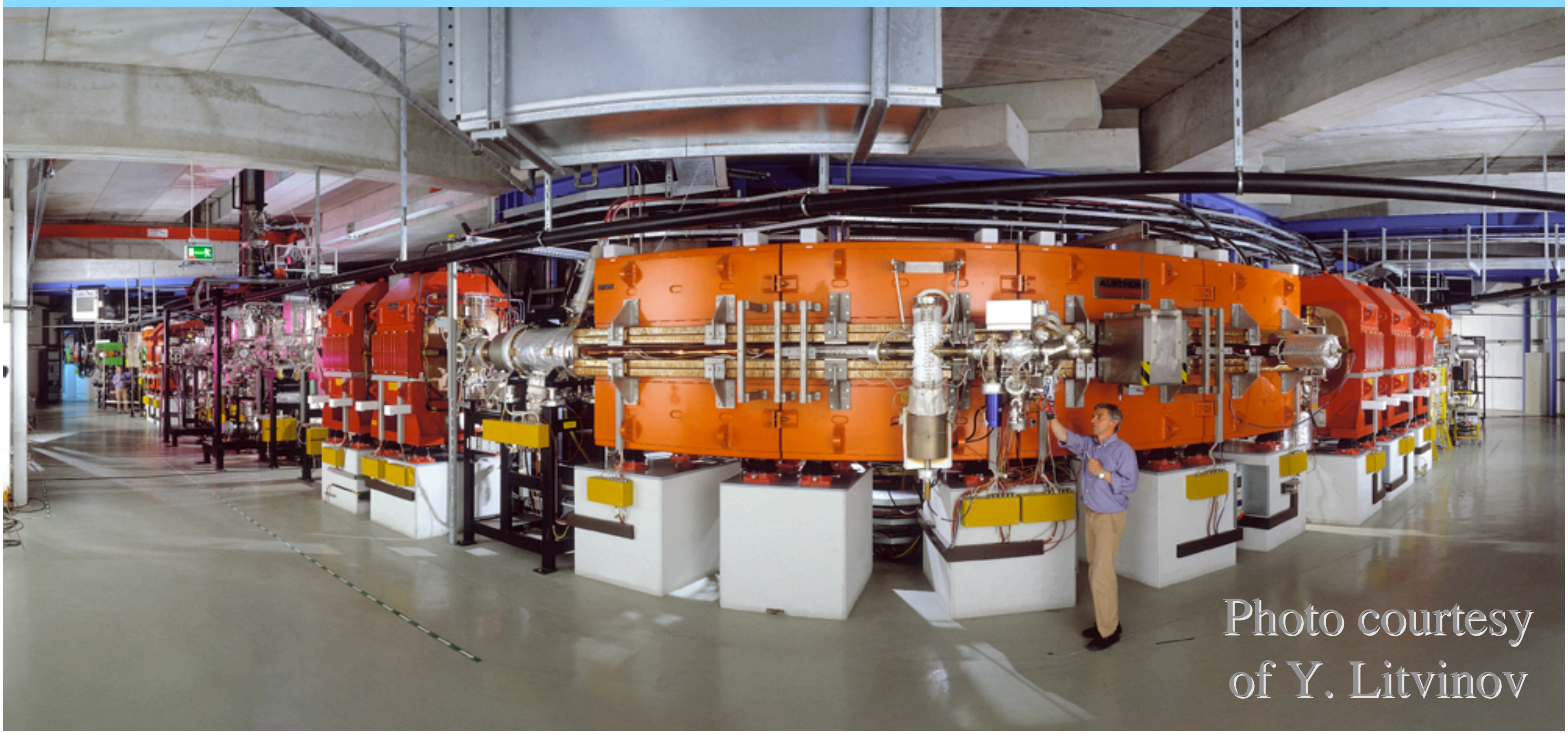
Fermilab, July 2009
Part 3

Coherence *vs.* Incoherence



The reactions —

$$S \to R + \ell_\alpha^+ + \nu \quad \text{and} \quad \ell_\alpha^- + S \to R + \nu$$

always produce $\nu = \nu_\alpha$.

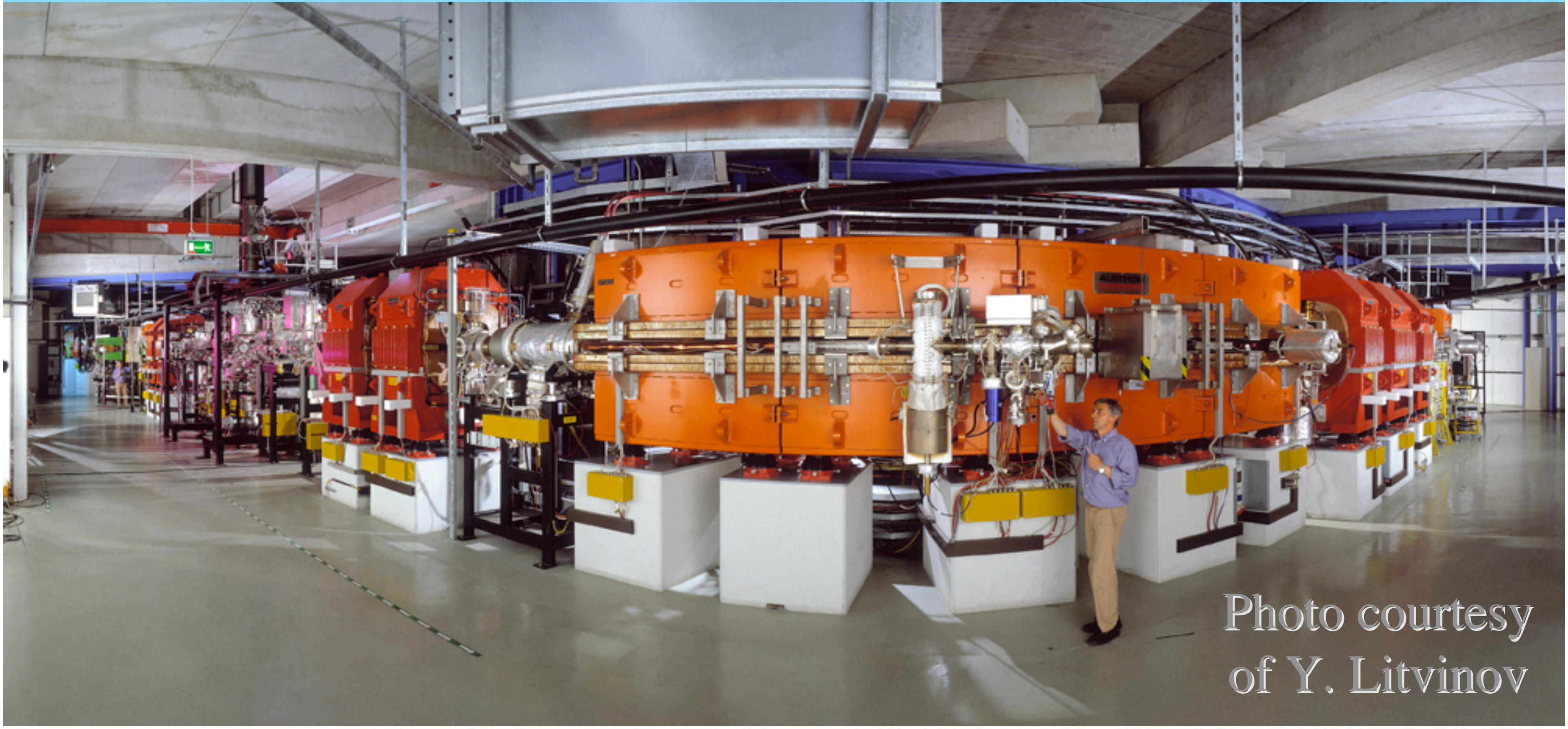
ν_α is a coherent superposition of mass eigenstates ν_i:

$$|\nu_\alpha\rangle = \sum_i U_{\alpha i}^* |\nu_i\rangle$$

Nevertheless, the different ν_i do not contribute coherently to every process.

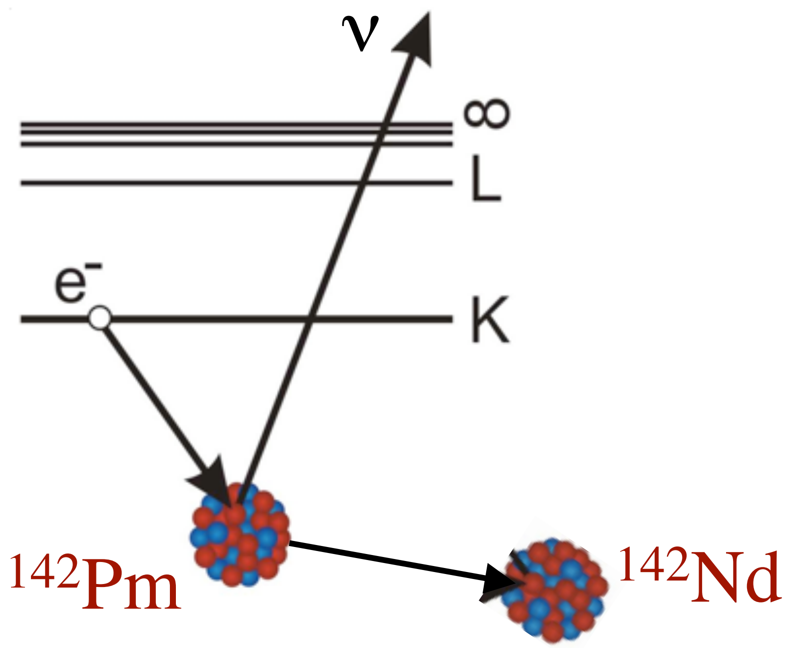
Whether they contribute *coherently* or *incoherently* depends on what you do with them.

Does Neutrino Mass Make *Decay Rates* Oscillate?



Naively, we expect that —

Electron Capture (EC) Decay

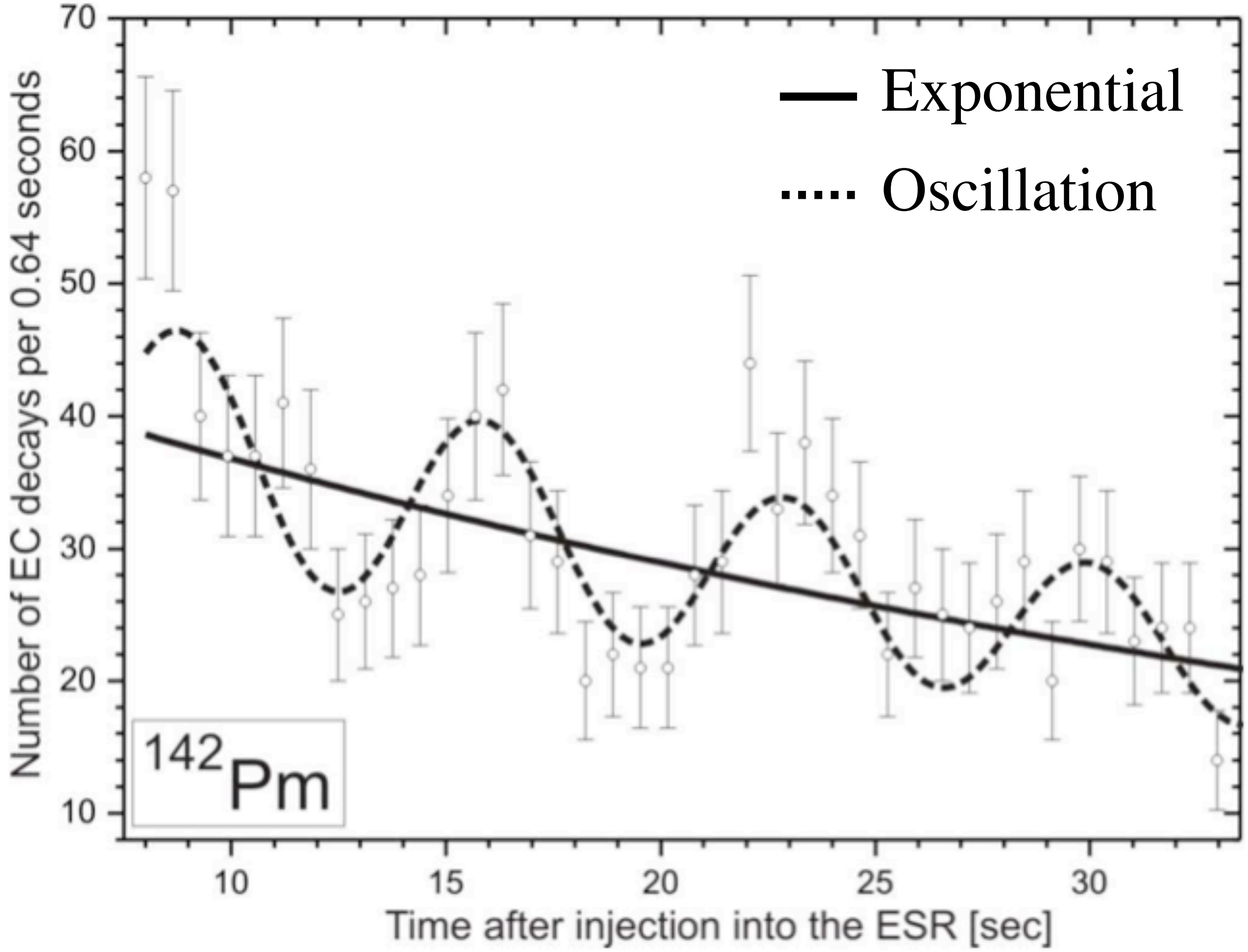


leads to —

$$\frac{dN}{dt}(t) = -\frac{N(0)}{\tau} e^{-t/\tau} \quad ; \tau \equiv \text{meanlife}$$

But, Litvinov *et al*. report that —

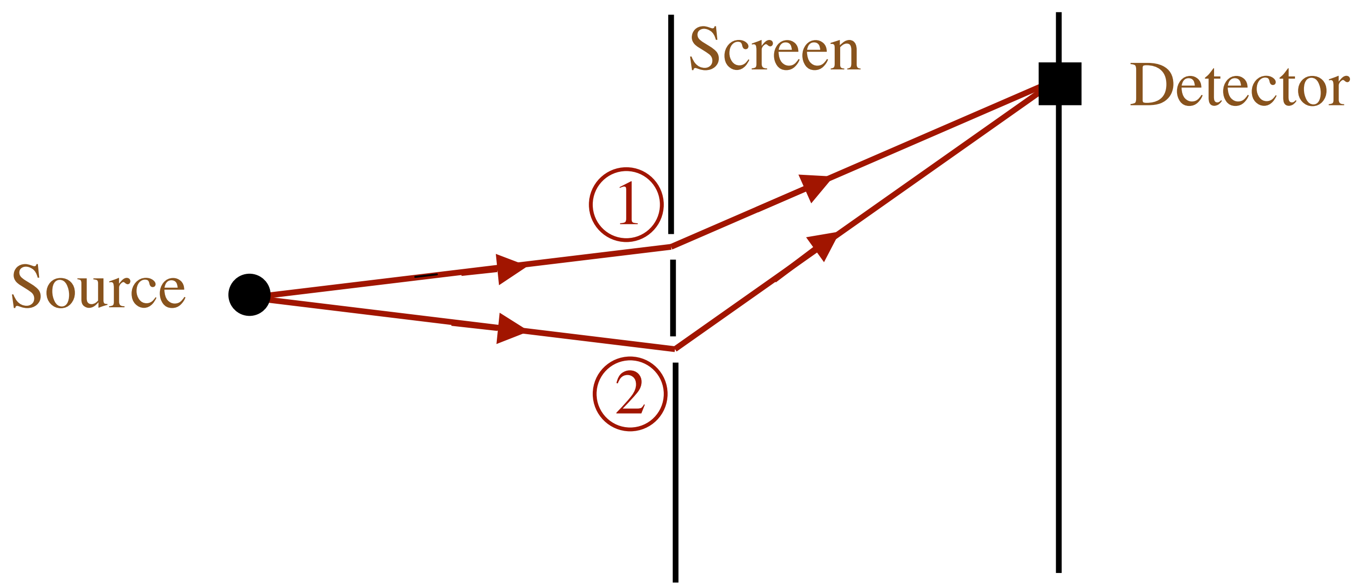
EC decays of H-like ^{142}Pm, ^{140}Pr, and ^{122}I ions in a storage ring at GSI oscillate.



Can the reported oscillatory behavior be due to ***coherent*** interference between neutrino mass eigenstates with different masses??

Quantum Mechanical Rules

If different ***intermediate*** states (or paths) lead to the same final state, and we don't know which path is taken in each event, then the paths contribute to the event rate ***coherently***.

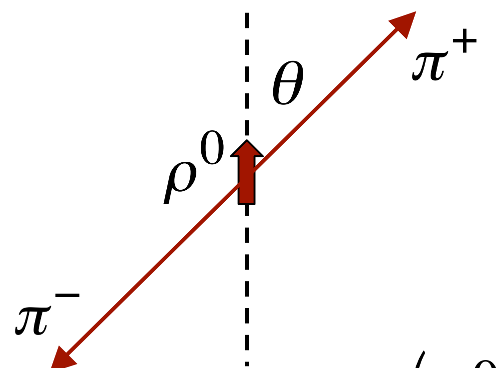


Total Amp = Amp(1) + Amp(2)

The rates to produce different ***final*** states that differ from one another in any way (particle content, kinematical properties, etc.) contribute to the total event rate ***incoherently***.

This is true whether or not we can actually distinguish the different final states in practice.

$$\Gamma_{\text{total}}(\Lambda) = \Gamma\left(\Lambda \to p\pi^-\right) + \Gamma\left(\Lambda \to n\pi^0\right) + \ldots$$

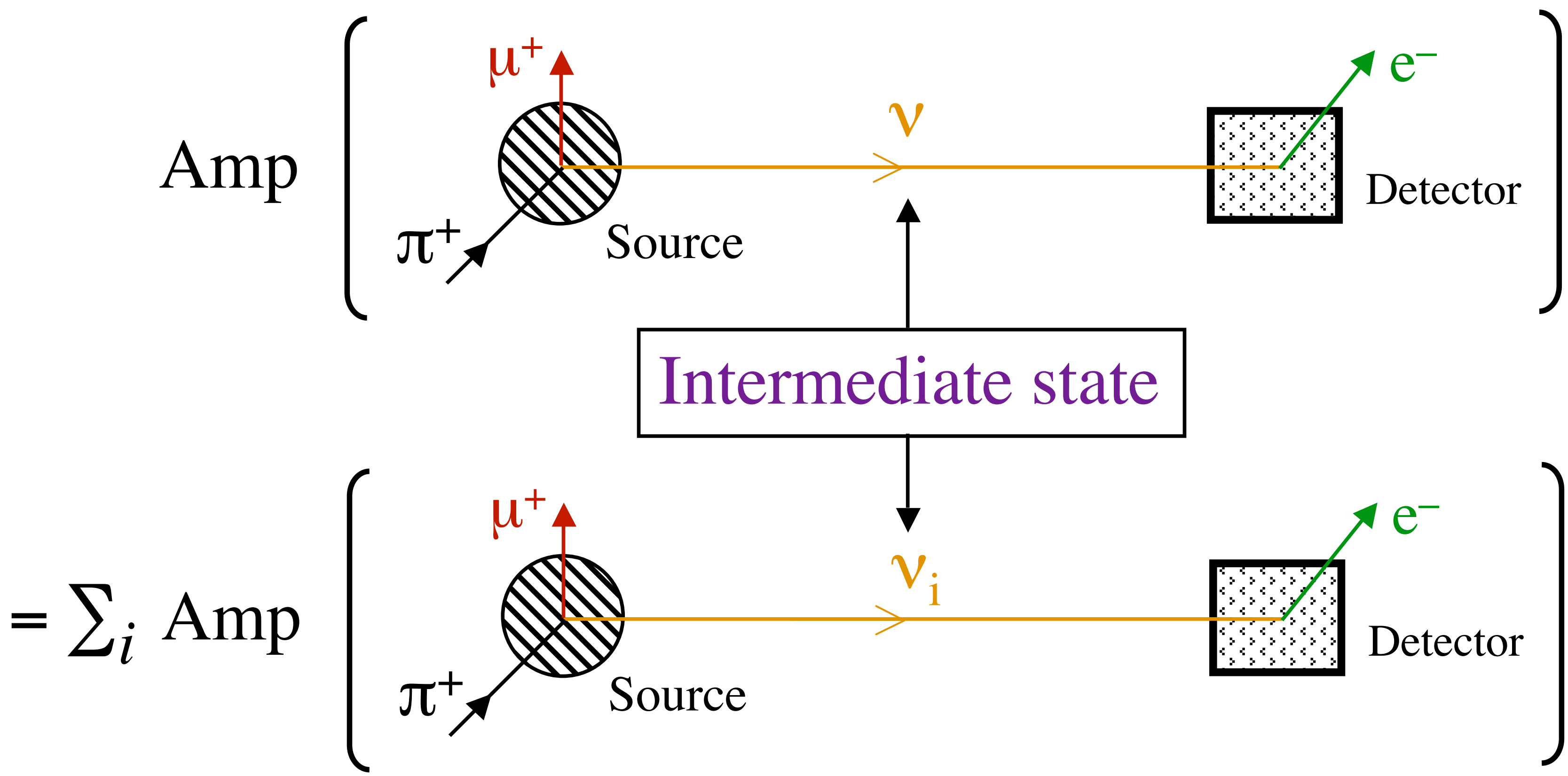


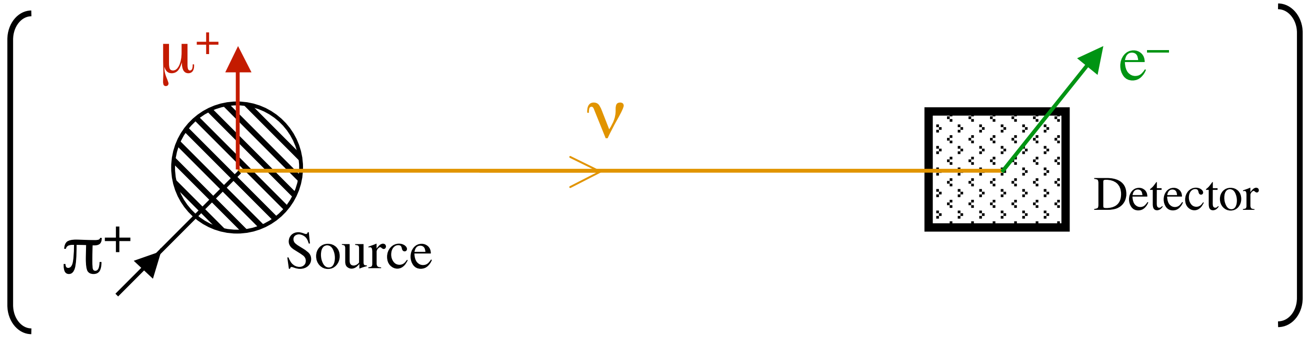
$$\Gamma\left(\rho^0 \to \pi^+\pi^-\right) = \int_{-1}^{+1} d(\cos\theta) \frac{d\Gamma\left(\rho^0 \to \pi^+\pi^-;\, \cos\theta\right)}{d(\cos\theta)}$$

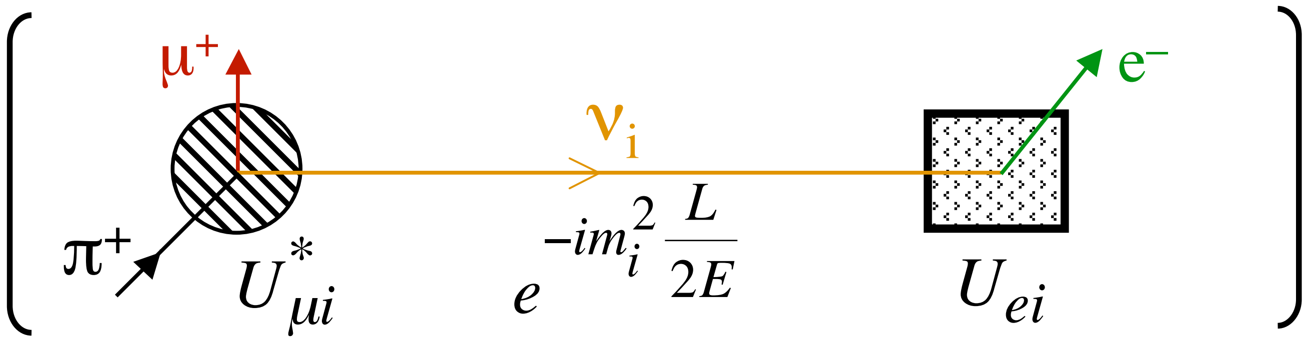
Neutrino Flavor Change (Oscillation)

Flavor change ***oscillates*** because of ***coherent interference*** between different neutrino mass eigensates ν_i with different masses m_i.

The neutrinos are an ***intermediate*** state.



Amp 

$= \sum_i$ Amp 

$$= \sum_i U^*_{\mu i} e^{-im_i^2 \frac{L}{2E}} U_{ei}$$

Neutrino mass-splitting dependence is from *interference*.

Electron Capture Decay

In electron-capture (EC) decays such as —

$$H - like\ {}^{142}Pm \to {}^{142}Nd + \nu\,,$$

in which a parent particle P decays to a daughter particle D plus a neutrino, there are actually 3 distinct decay modes:

$$P \to D + \nu_1$$
$$P \to D + \nu_2$$
$$P \to D + \nu_3$$

$$P \begin{cases} \nearrow D + \nu_1 \\ \rightarrow D + \nu_2 \\ \searrow D + \nu_3 \end{cases}$$

In principle, we can capture the ***final-state*** neutrino and measure its mass.

Then we will know which ν_i it is.

In principle, we can also measure the energy-momentum of the recoil *D*, and that of the neutrino.

None of these measurements affects the decay.

$$
P \begin{array}{l} \nearrow D + \nu_1 \\ \longrightarrow D + \nu_2 \\ \searrow D + \nu_3 \end{array}
$$

The 3 possible final states differ in particle content.

For given *P* energy, they also differ in the energy-momenta of the individual particles.

*The rates for decay to these 3 final states contribute **incoherently** to the total decay rate.*

For example —

$$\frac{dN}{dt}\left(H - like\ ^{142}Pm \rightarrow {}^{142}Nd + \nu; t\right)$$

$$= \sum_i \left[\frac{dN}{dt}\left(H - like\ ^{142}Pm \rightarrow {}^{142}Nd + \nu_i; t\right)\right]$$

Mass eigenstate

An ***incoherent*** *sum*

The Standard-Model Lagrangian for the leptonic couplings to the W boson is —

$$L_{SM} = -\frac{g}{\sqrt{2}} \sum_{\alpha=e,\mu,\tau} \left(\bar{\ell}_{L\alpha} \gamma^{\lambda} \nu_{L\alpha} W_{\lambda}^{-} + \bar{\nu}_{L\alpha} \gamma^{\lambda} \ell_{L\alpha} W_{\lambda}^{+} \right)$$

$$= -\frac{g}{\sqrt{2}} \sum_{\substack{\alpha=e,\mu,\tau \\ i=1,2,3}} \left(\bar{\ell}_{L\alpha} \gamma^{\lambda} U_{\alpha i} \nu_{Li} W_{\lambda}^{-} + \bar{\nu}_{Li} \gamma^{\lambda} U_{\alpha i}^{*} \ell_{L\alpha} W_{\lambda}^{+} \right)$$

$P \rightarrow D + \nu_i$ comes from the term involving $\bar{\nu}_{Li}$.

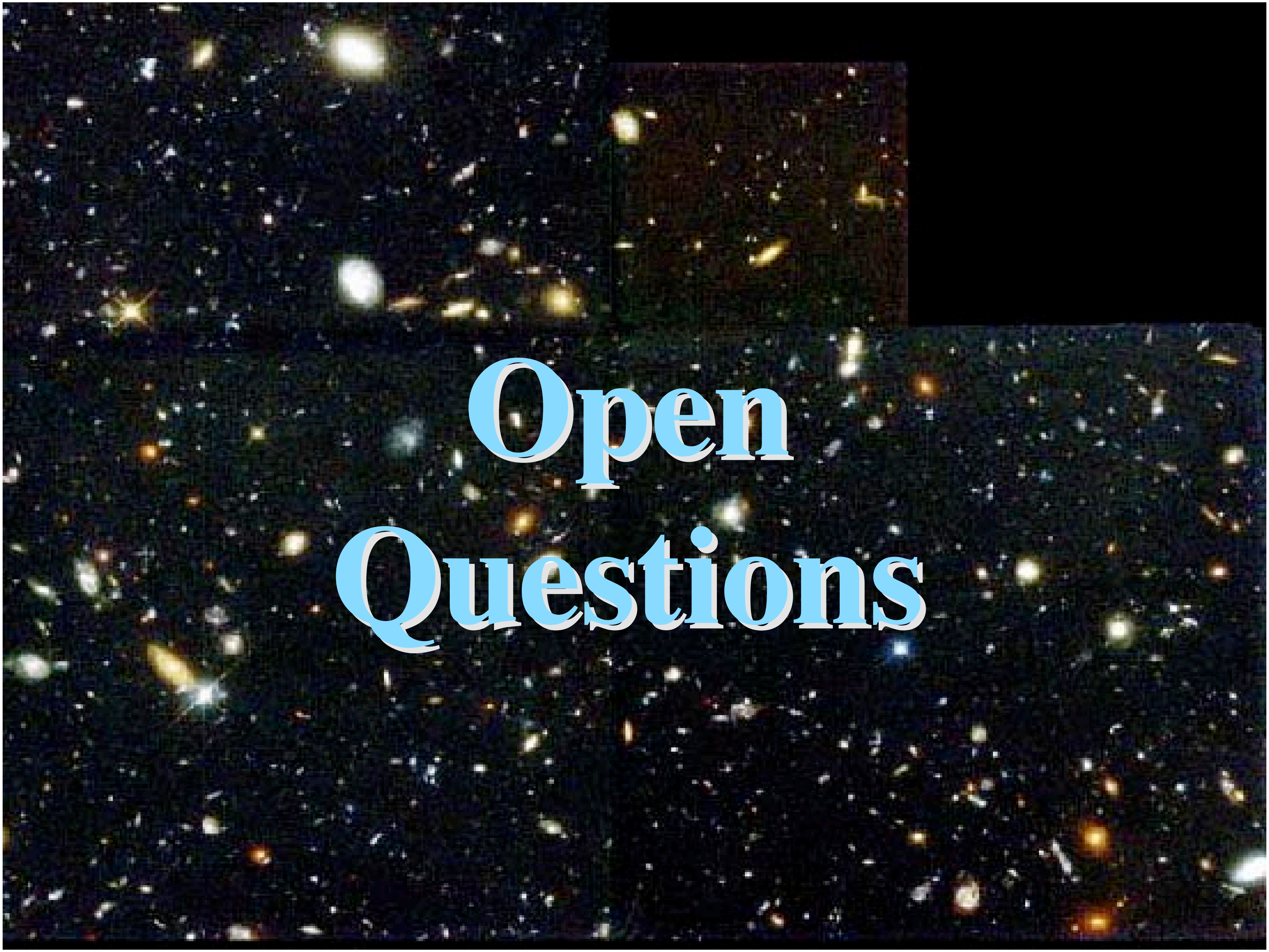
This term doesn't know about the ***other*** neutrino mass eigenstates or their masses.

$$\frac{dN}{dt}\left(P \rightarrow D + \nu; t\right) = \sum_i \left[\frac{dN}{dt}\left(P \rightarrow D + \nu_i; t\right) \right]$$

does not depend on neutrino mass splittings.

Neither does the rate for tritium decay:

$$\frac{dN}{dt}\left({}^3H \rightarrow {}^3He + e^- + \bar{\nu}; t\right) = \sum_i \left[\frac{dN}{dt}\left({}^3H \rightarrow {}^3He + e^- + \overline{\nu_i}; t\right) \right]$$



Open Questions

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) ?

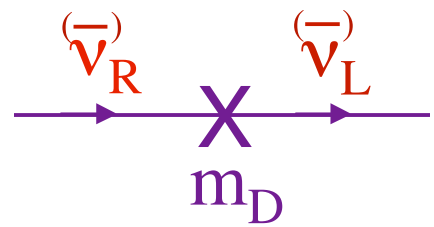
Equivalently, do neutrinos have *Majorana masses*? If they do, then the mass eigenstates are *Majorana neutrinos*.

Dirac Masses

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 —

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



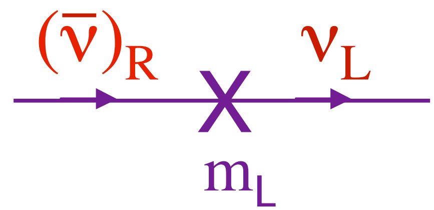
Dirac neutrino massses are the neutrino analogues of the SM quark and charged lepton masses.

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 $f \leftrightarrow \bar{f}$.

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 $H_{SM}\bar{\nu}_R\nu_L$, the progenitor of the Dirac mass term, and the ν analogue of the Higgs coupling that leads to the q and ℓ masses.

Possible 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 $\Longrightarrow$ 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 —

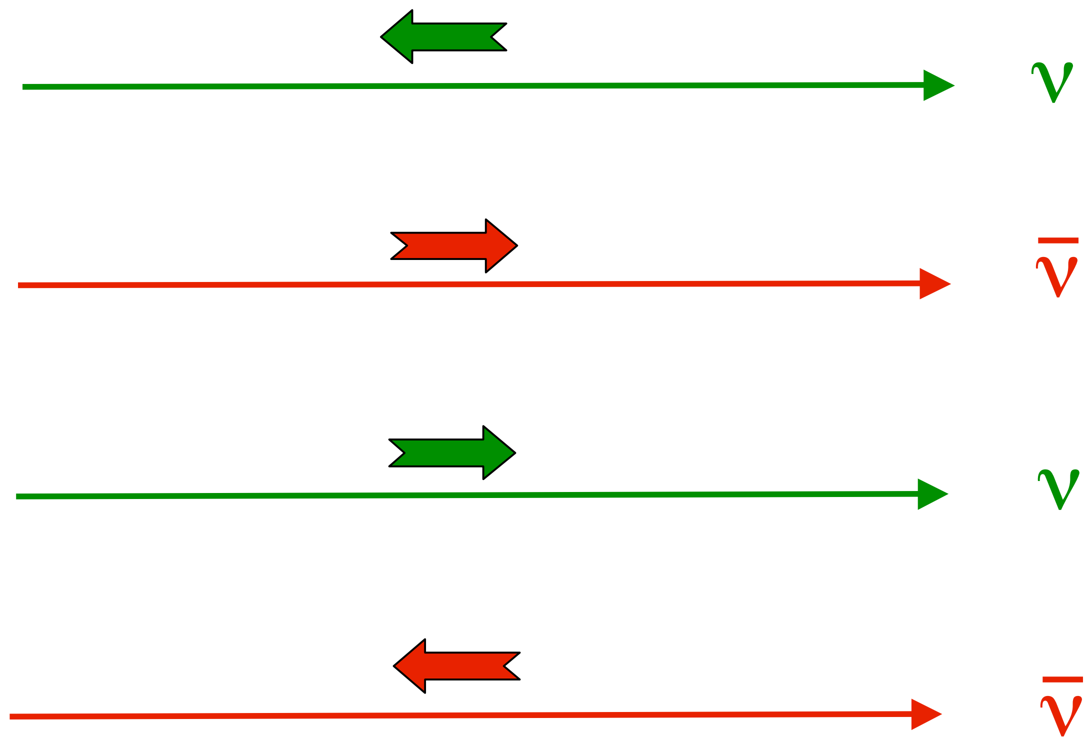
$$K_{S,L} \cong (K^0 \pm \overline{K^0})/\sqrt{2}\ . \qquad \overline{K_{S,L}} = K_{S,L}\ .$$

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

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

When $\bar{\nu} \neq \nu$

We have 4 mass-degenerate states:



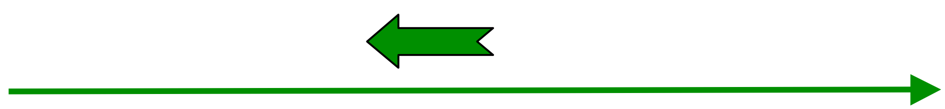
This collection of 4 states is a Dirac neutrino plus its antineutrino.

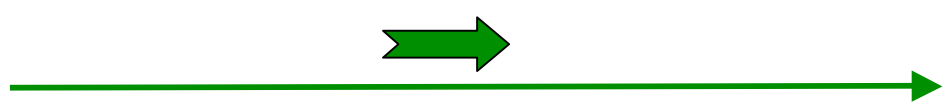
The SM $\ell\nu$W interaction is —

Left-handed

$$L_{SM} = -\frac{g}{\sqrt{2}}\,\bar{\ell}_L \gamma^{\lambda} \nu_L W_{\lambda}^{-} + \bar{\nu}_L \gamma^{\lambda} \ell_L W_{\lambda}^{+}$$

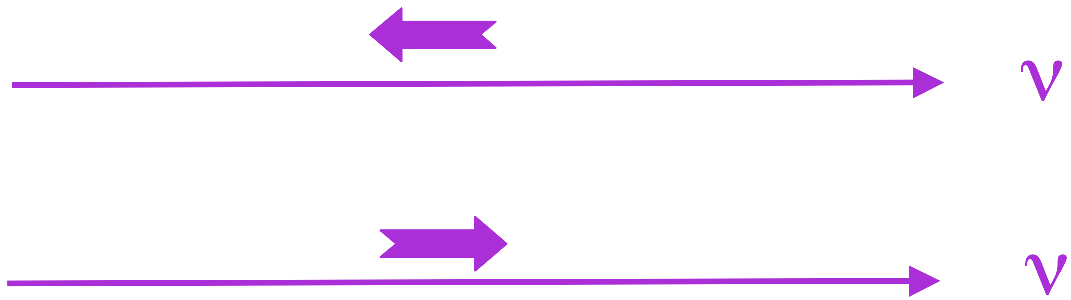
When $\bar{\nu} \neq \nu$

ν  makes ℓ^-

ν  makes nothing

When $\bar{\nu} = \nu$

We have only 2 mass-degenerate states:



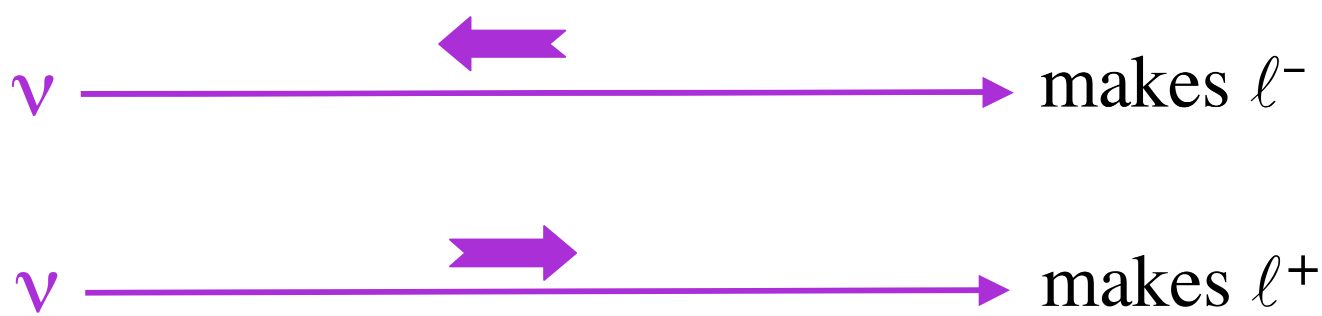
This collection of 2 states is a Majorana neutrino.

The SM $\ell\nu W$ interaction is —

Left-handed

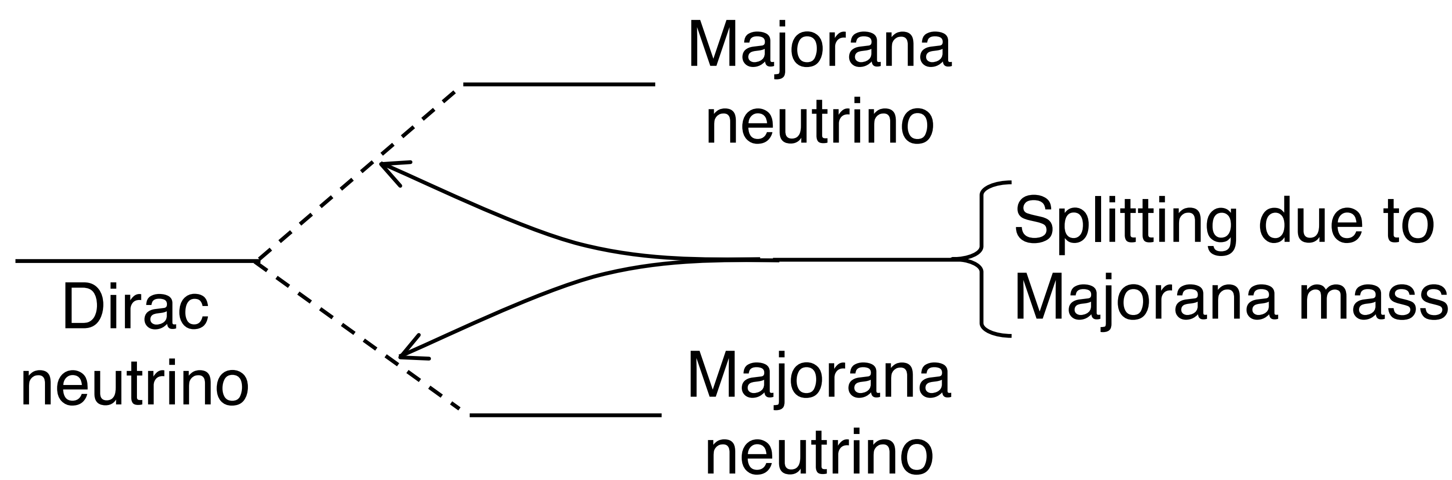
$$L_{SM} = -\frac{g}{\sqrt{2}}\left[\bar{\ell}_L \gamma^\lambda \nu_L W_\lambda^- + \bar{\nu}_L \gamma^\lambda \ell_L W_\lambda^+\right]$$

When $\bar{\nu} = \nu$



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

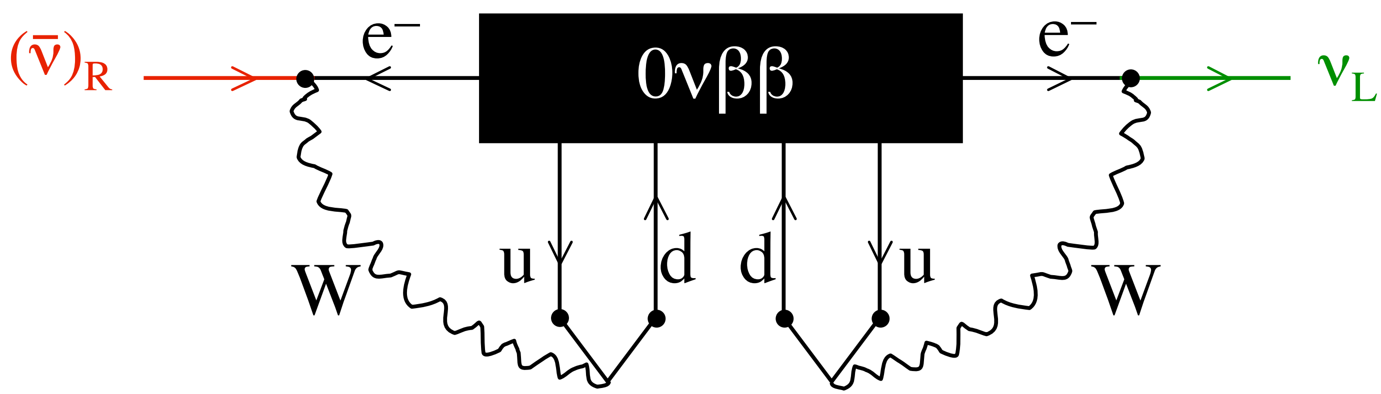
The Promising Approach — Seek

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

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

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

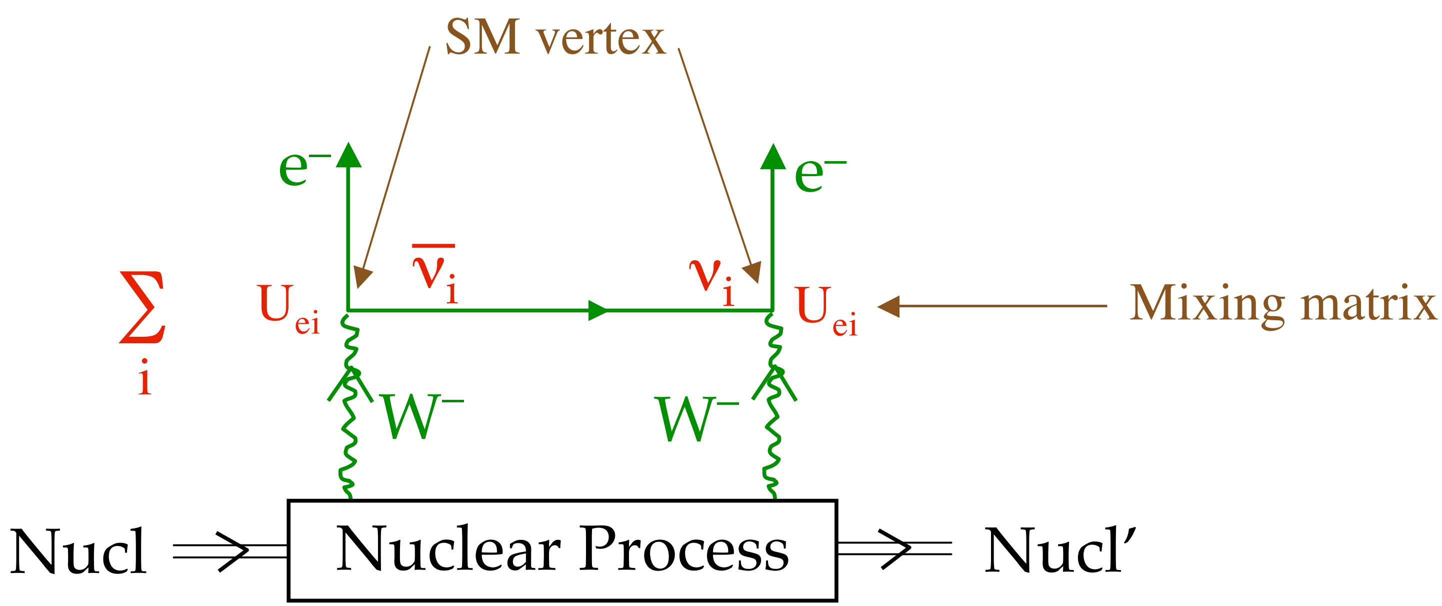
(Schechter and Valle)



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

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

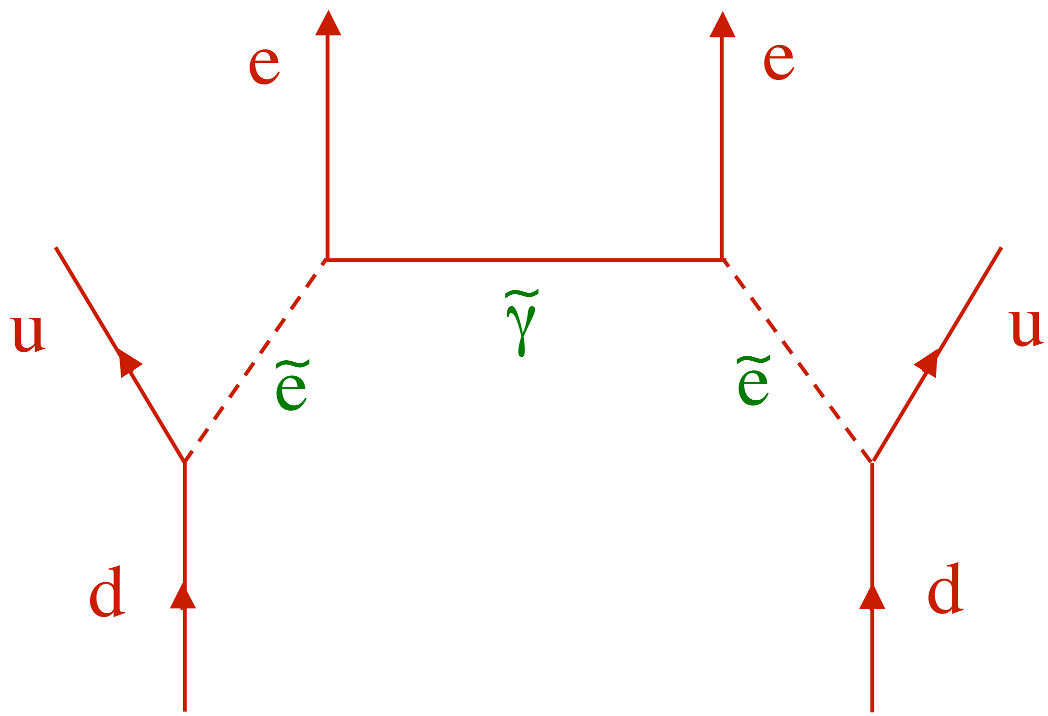
We anticipate that 0νββ is dominated by a diagram with Standard Model vertices:



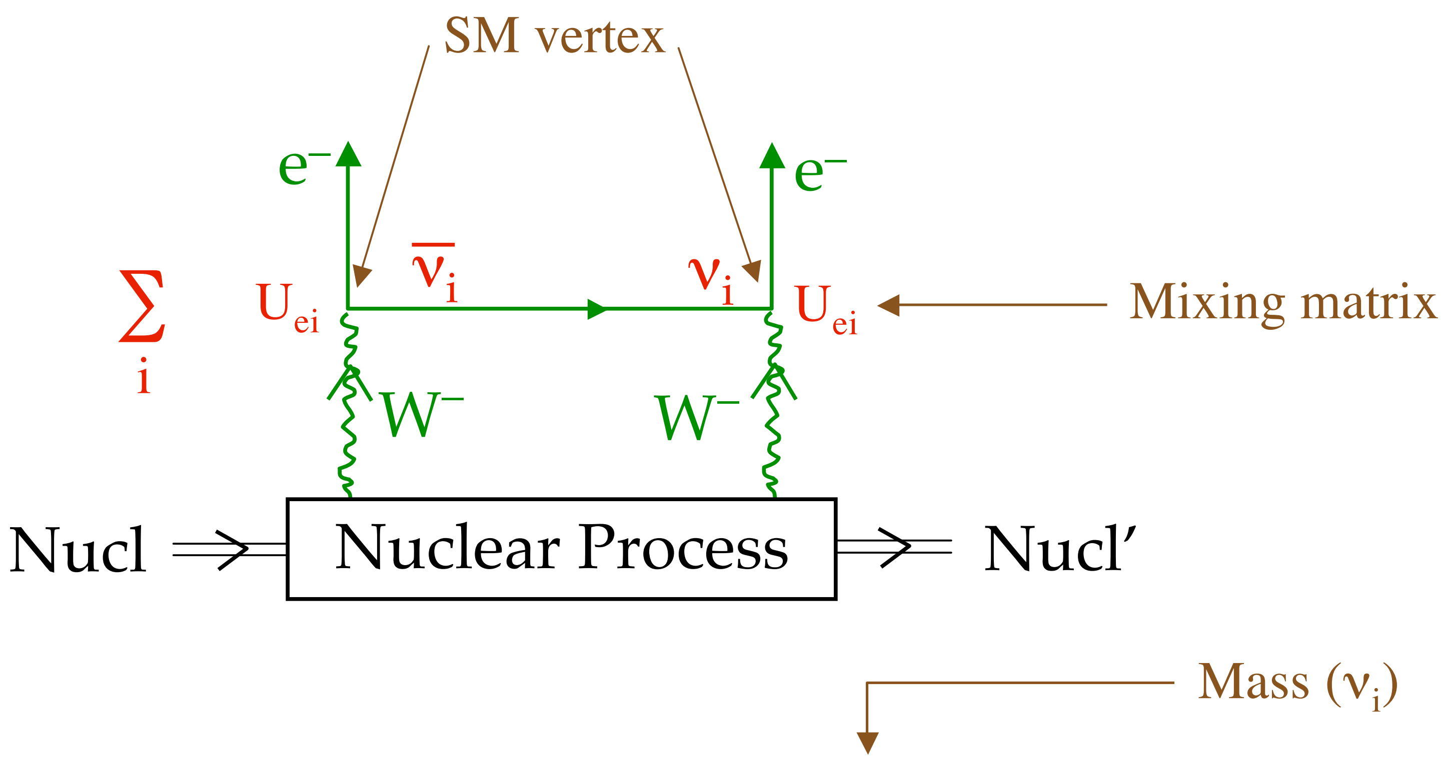
But there could be other contributions to $0\nu\beta\beta$, which at the quark level is the process

$dd \rightarrow uuee$.

An example from Supersymmetry:



Assume the dominant mechanism is —



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

Thus, Amp [ν_i contribution] $\propto$ m_i

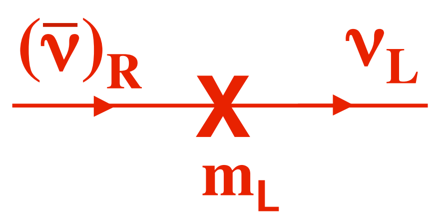
$$\mathrm{Amp}[0\nu\beta\beta] \propto \left| \sum m_i U_{ei}^2 \right| \equiv m_{\beta\beta}$$

Why Amp[0νββ] Is ∝ Neutrino Mass

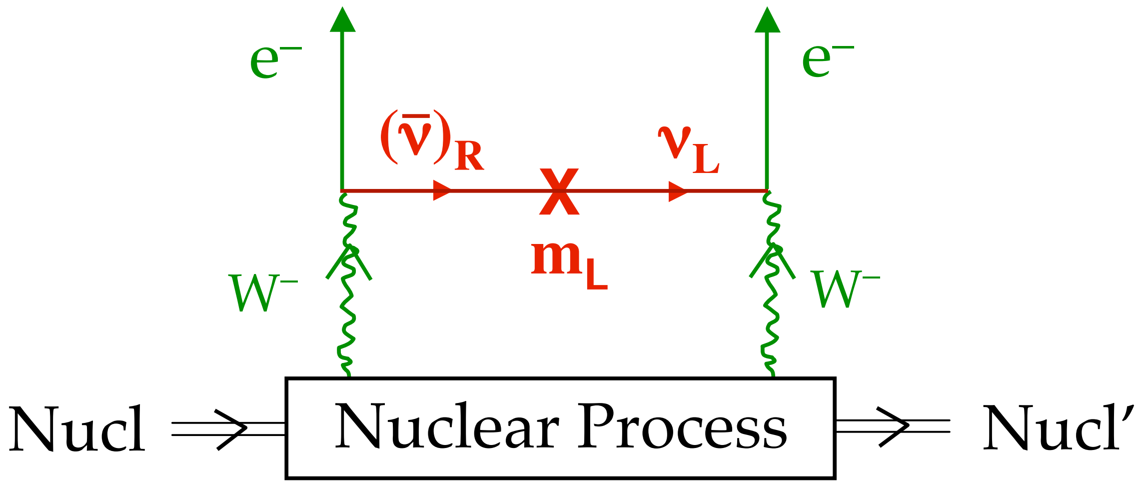
— manifestly does not conserve L.

But the Standard Model (SM) weak interactions *do* conserve L. Absent any non-SM L-violating interactions, the $\Delta L = 2$ of 0νββ can only come from *Majorana neutrino masses*, such as —

$$m_L(\overline{\nu_L{}^c}\,\nu_L + \overline{\nu_L}\,\nu_L{}^c)$$



Treating the neutrino masses perturbatively,
we have —



A Left-Handed Majorana mass term is just what
is needed to —

1) Violate L

2) Flip handedness

— and allow the decay to occur.