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Big Questions About Neutrinos and Their Connection To Our Existence

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W-1

The Discovery of Neutrino Mass

Neutrinos almost certainly oscillate from one flavor to another.

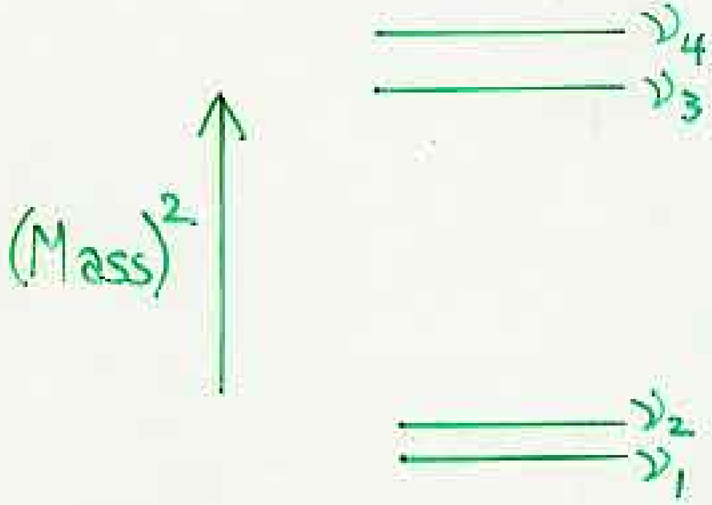
$$\text{Oscillation} \Rightarrow \left\{ \begin{matrix} \text{Neutrino Mass} \\ \text{and Mixing} \end{matrix} \right\}$$

∴ Neutrinos almost certainly have masses and mix.

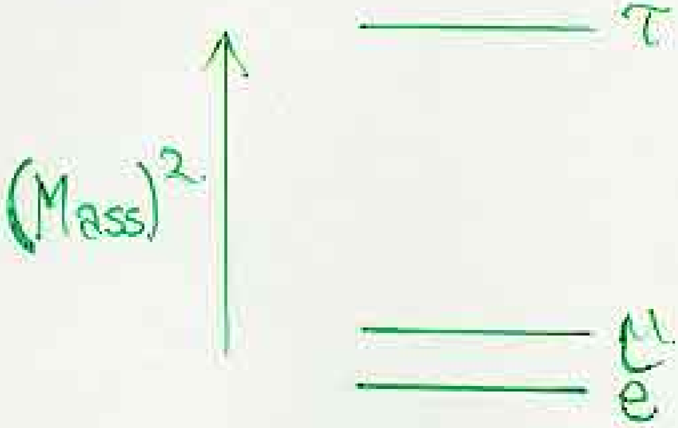
NEUTRINO PROPERTIES

Neutrinos almost certainly have masses and mix.

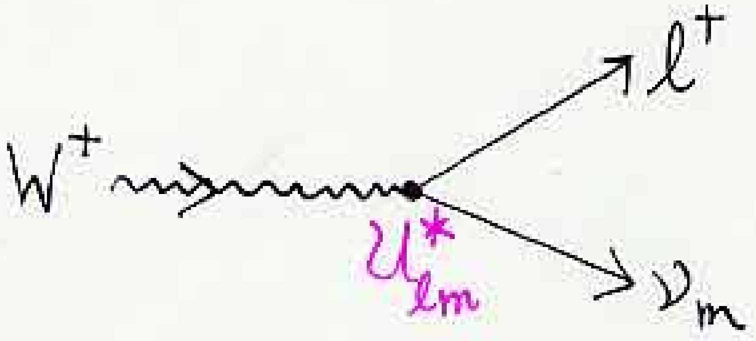
There is some spectrum of three or more neutrino mass eigenstates ν_m:



This is the neutrino analogue of the spectrum of charged-lepton mass eigenstates $\ell = e, \mu$, and τ:



2) Mixing means that the weak interaction couples a given charged lepton of definite mass, ℓ, to more than one neutrino of definite mass, ν_m.



U is the Maki-Nakagawa-Sakata leptonic mixing matrix. $UU^\dagger = 1$.

The neutrino state produced in association with a specific charged lepton ℓ is

$$|\nu_\ell\rangle = \sum_m U^*_{\ell m} |\nu_m\rangle$$

Neutrino of flavor ℓ

Neutrino of mass M_{ν_m}

If there are, say, four neutrino mass eigenstates, then one linear combination of them,

$$|\nu_{\text{sterile}}\rangle = \sum_{m} U^*_{sm} |\nu_m\rangle ,$$

has no normal weak couplings.

The evidence for neutrino masses and mixing comes from the evidence for neutrino flavor oscillation.

Oscillation ⇒ Masses & Mixing

Oscillation cannot determine individual masses, but only the splittings

$$\delta M^2_{mm'} \equiv M^2_{\nu_m} - M^2_{\nu_{m'}} .$$

Evidence for Oscillation

There are 3 pieces of evidence that neutrinos oscillate:

Neutrinos	Evidence of Oscillation	Required δM^2 (eV^2)
$\overset{(-)}{\nu}_\mu$ Atmospheric	Compelling	3×10^{-3}
ν_e Solar	Strong	10^{-12} to 2×10^{-4}
$\bar{\nu}_\mu$ LSND	Unconfirmed	0.2 to 6

If all 3 of these oscillations are genuine, then nature must contain —

- At Least 4 neutrino masses
- Correspondingly, ν_e, ν_μ, ν_τ, $\nu_{s(terile)}$??

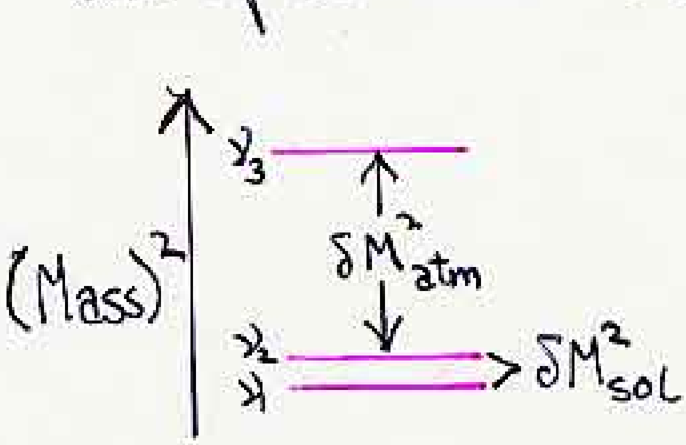
If there are only 3 masses, then we must have

$$\sum \delta M^2 = (M_{\nu_3}^2 - M_{\nu_2}^2) + (M_{\nu_2}^2 - M_{\nu_1}^2) + (M_{\nu_1}^2 - M_{\nu_3}^2) = 0 .$$

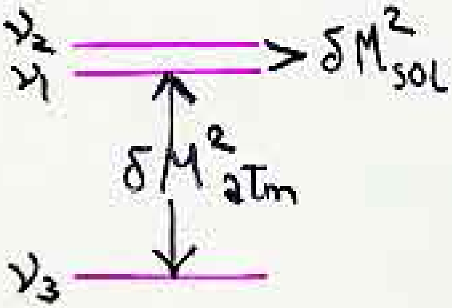
The Neutrino $(\text{Mass})^2$ Spectrum

If only the Atm and Sol oscillations prove to be genuine, nature may contain only 3 neutrinos.

If there are only 3 neutrinos the spectrum can look like —



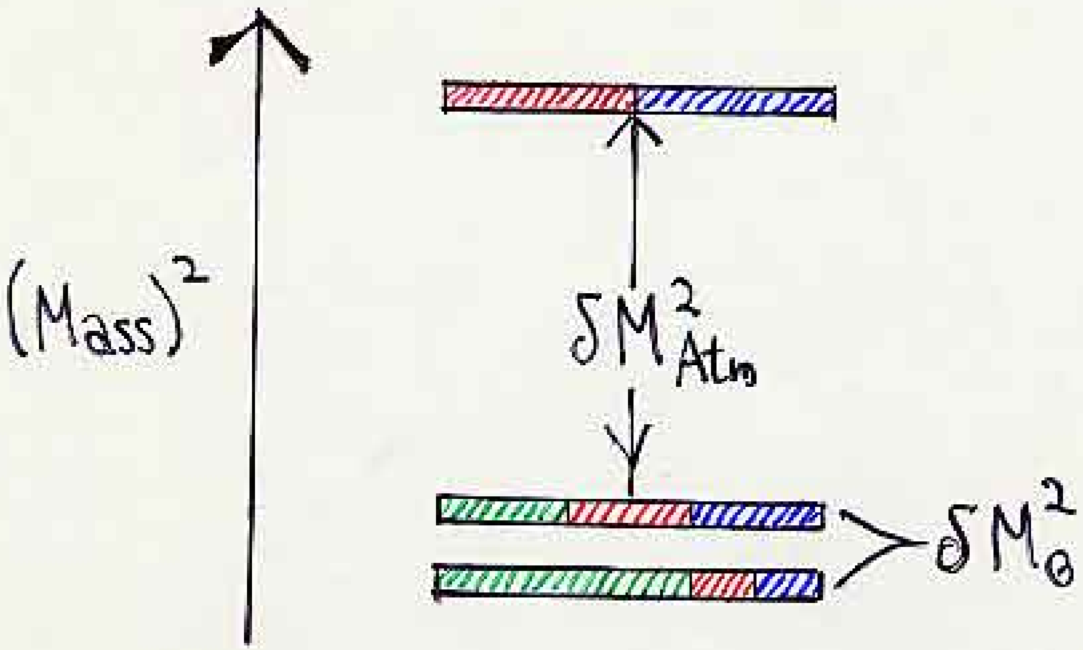
or



Earth matter effects in Long Base Line experiments can tell us which.

Fits to ν_{sol} data somewhat favor the Large Mixing Angle MSW explanation of the ν_{sol} behavior.

If this explanation is correct, then we have approximately —



🟩 $\nu_e\,[|U_{em}|^2]$ 🟥 $\nu_\mu\,[|U_{\mu m}|^2]$ 🟦 $\nu_\tau\,[|U_{\tau m}|^2]$

Or, the solar pair is on top.

The ν_e content will always be $\gtrsim 97\%$ in the solar pair.

(CHOOZ, Palo Verde)

Flavor-ℓ fraction of mass eigenstate ν_m

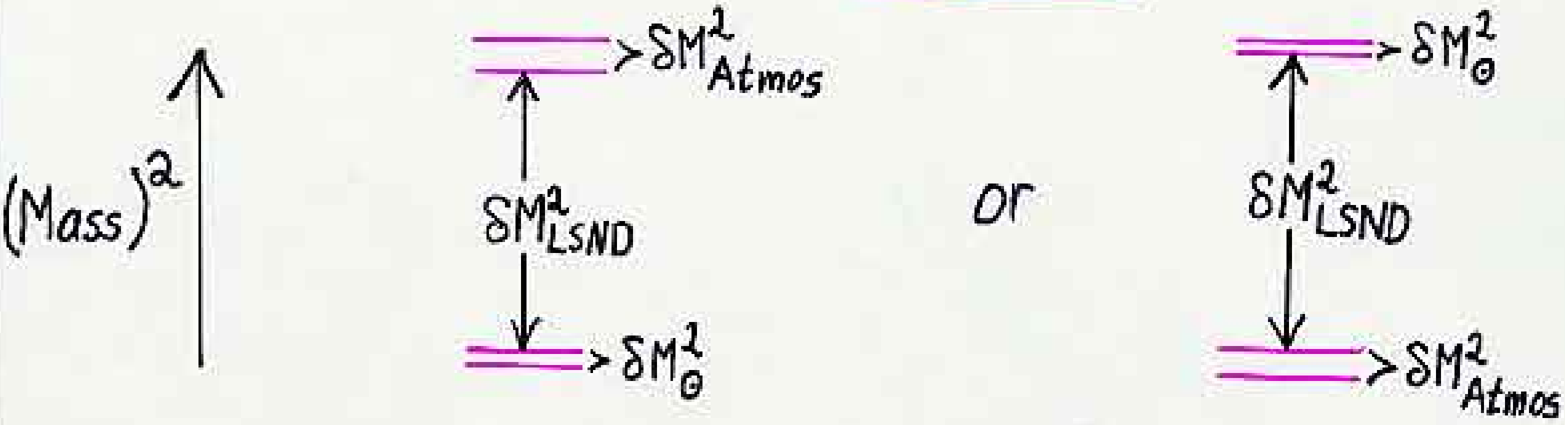
$$\equiv |\langle \nu_\ell | \nu_m \rangle|^2 = |U_{\ell m}|^2 .$$

If LSND is included

Four mass eigenstates are required.

The spectrum can look like —

2 + 2

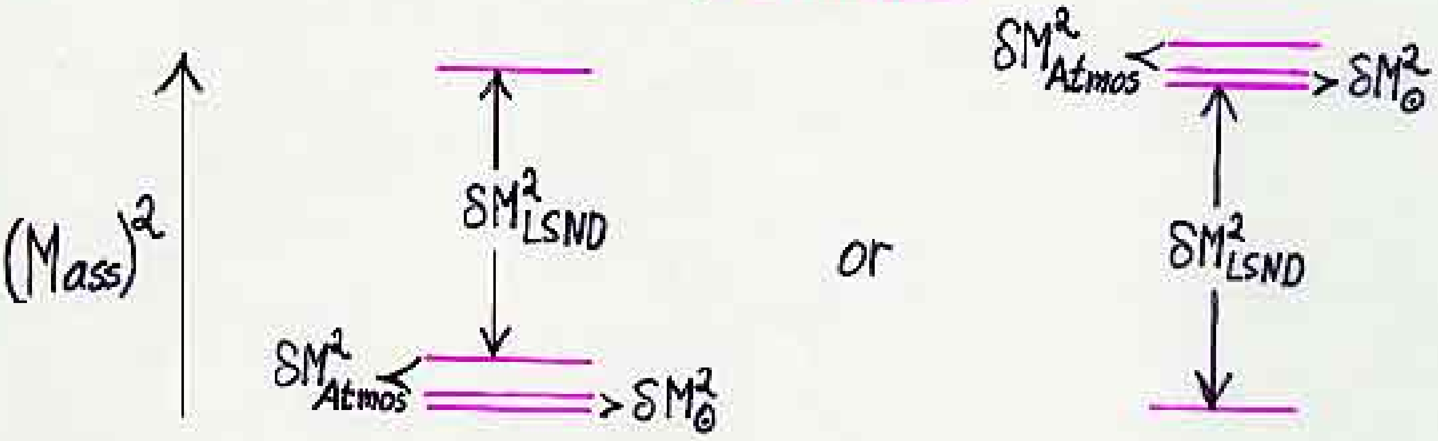


The ν_e content is $>97\%$ in the solar pair.
(Bugey, CHOOZ)

The ν_μ content is $\gtrsim 97\%$ in the atmos. pair.
(CDHS)

or

3 + 1



The ν_e content is $>97\%$ in the close-spaced trio. Similarly for ν_μ. (CDHS, Bugey, CHOOZ)

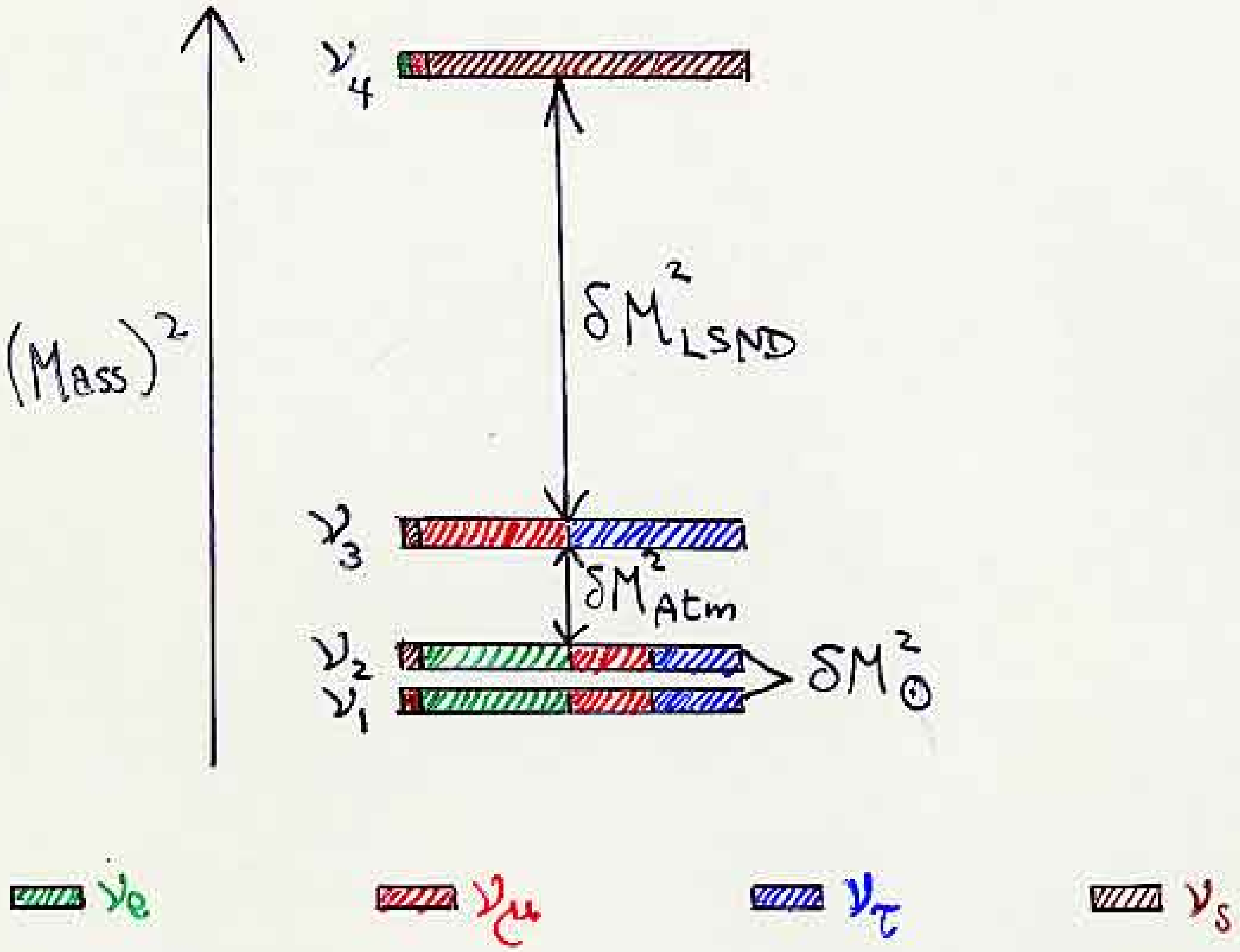
With L = distance a neutrino travels,
and E = neutrino energy,
the oscillation probability amplitude is —

$$\mathrm{Amp}(\nu_\ell \to \nu_{\ell'}) = \sum_m U^*_{\ell m} U_{\ell' m} e^{-iM^2_{\nu_m}\frac{L}{2E}} .$$

A mass eigenstate ν_m with small U_{em} and $U_{\mu m}$ will not contribute to $\nu_e(\odot)$ or $\nu_\mu(\mathrm{Atm})$ oscillations.

With this in mind —

An Example of a 3+1 Spectrum



The $\nu_\odot$ and ν_{Atm} oscillations ≈ do not involve ν_4, and produce dominantly active neutrinos.

(Barger, B.K., Learned, Weiler, Whisnant; Peres & Smirnov; Giunti; Fogli, Lisi, Marrone; Grimus & Schwetz

3+1

Neither atmospheric nor solar oscillation need produce ν_s.

Agreement with data not great.
(Barger et al.; Peres & Smirnov; Guinti;
Fogle, Lisi, Marrone; Grimus & Schwetz)

2+2

Agreement with pre-2001 data good.

Either atmospheric or solar oscillation, or both, must produce ν_s with significant probability.

If

$$f_s^{Atm} \equiv \left.\frac{P(\nu_\mu \to \nu_s)}{\sum\limits_{\ell\neq\mu} P(\nu_\mu \to \nu_\ell)}\right|_{Atm}, \quad f_s^{\odot} \equiv \left.\frac{P(\nu_e \to \nu_s)}{\sum\limits_{\ell\neq e} P(\nu_e \to \nu_\ell)}\right|_{\odot},$$

then

$$f_s^{Atm} + f_s^{\odot} = 1 .$$

(Peres & Smirnov)

Sterile flavor cannot hide.

Constraints on $f_s^{Atm} + f_s^{\odot}$

Atmospheric Neutrinos

$$f_s^{Atm} < 0.25 \quad @ \; 90\% \text{ CL}$$

(Super-K)

Solar Neutrinos

If no sterile neutrinos are being produced by oscillation,

$$\underbrace{\left[\phi_{\nu_e} + (\phi_{\nu_\mu} + \phi_{\nu_\tau})\right]\Big|_{\substack{\text{At}\\ \text{earth}}}}_{(5.44 \pm 0.99) \times 10^6/\text{cm}^2\text{sec}} = \underbrace{\phi_{\text{Tot}}\Big|_{\substack{\text{Produced in}\\ \text{solar core}}}}_{(5.93 \pm 0.89) \times 10^6/\text{cm}^2\text{sec}}$$

[SNO + SK]

[Bahcall, Pinsonneault, Basu
with new $\sigma(p + {}^7\text{Be} \rightarrow {}^8\text{B} + \gamma)$]

The finding that $\phi_{\nu_\mu} + \phi_{\nu_\tau} \neq 0$

$$\Longrightarrow f_s^{\odot} < 1.$$

But how big can it be?

$$f_s^{\odot} = \frac{\phi_{\nu_s}}{\phi_{\nu_{\mu,\tau}} + \phi_{\nu_s}} = \frac{\phi_{Tot} - 6.5\,\phi_{SK} + 5.5\,\phi_{SNO}}{\phi_{Tot} - \phi_{SNO}}$$

$$= 0.12 \pm 0.30$$

(Snowmass-style calculation)

While the hints are that $f_s^{Atm} + f_s^{\odot} < 1$,

$f_s^{Atm} + f_s^{\odot} = 1$ is <u>not</u> confidently excluded.

$=$

spectra are alive.

$=$

3(active) + 3(sterile) = 6 neutrino spectra are alive too.

LSND is alive.

Big Questions

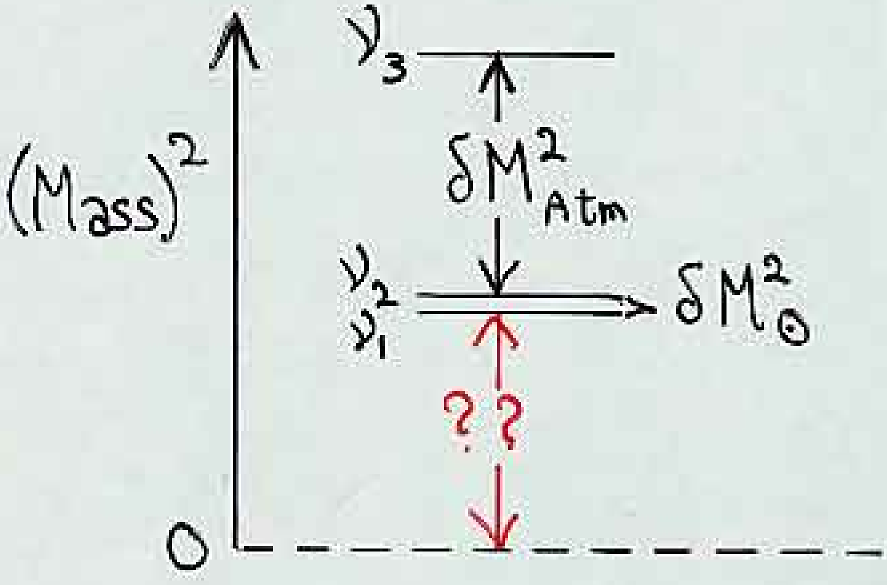
- * How many neutrino flavors, active and sterile, are there? Equivalently, how many neutrino mass eigenstates are there?

- * What are the masses, M_{ν_m}, of the mass eigenstates ν_m?

Oscillation experiments can measure only mass splittings $\delta M^2_{mm'} \equiv M^2_{\nu_m} - M^2_{\nu_{m'}}$:

$$\mathrm{Amp}(\nu_\ell \to \nu_{\ell'}) = \sum_m U^*_{\ell m} U_{\ell' m} e^{-i M^2_{\nu_m} \frac{\overset{\text{Distance}}{L}}{\underset{\text{Energy}}{2E}}}$$

W.3]



* Does –

$$\bar{\nu}_m = \nu_m \quad \text{(Majorana neutrinos)}$$

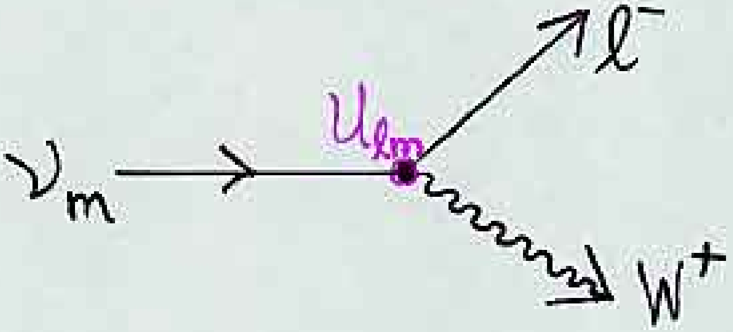
or

$$\bar{\nu}_m \neq \nu_m \quad \text{(Dirac neutrinos)}$$

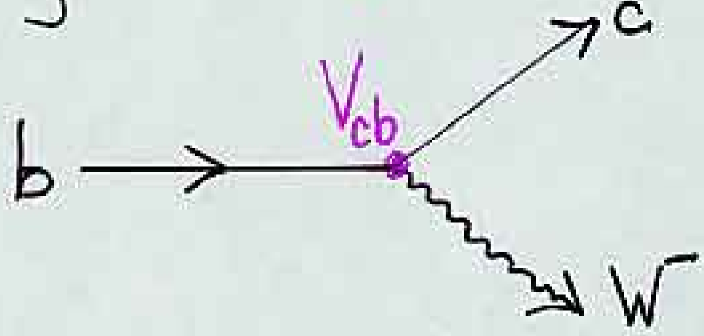
* What is the leptonic mixing matrix U? How does it compare with the quark mixing matrix?

** Does the behavior of neutrinos violate CP? If so, is this $\cancel{CP}$ the reason we are here?

In the Standard Model, extended to include ν masses, leptonic $\cancel{CP}$ comes from phases in the couplings $U_{\ell m}$:



Similarly, quark $\cancel{CP}$, seen in K and B decays, comes from phases in the quark mixing matrix V:



Exploring the Questions

* How many neutrinos are there?

MiniBooNE will find out whether the LSND oscillation is genuine.

If it is not, 3 neutrinos suffice.
If it is, ???

* How much do the neutrinos weigh?

KATRIN will study $^3H \rightarrow {}^3He + e^- + \bar{\nu}_m$ with a sensitivity to $M_{\nu_m} \gtrsim 0.3$ eV.

How much sensitivity is needed?

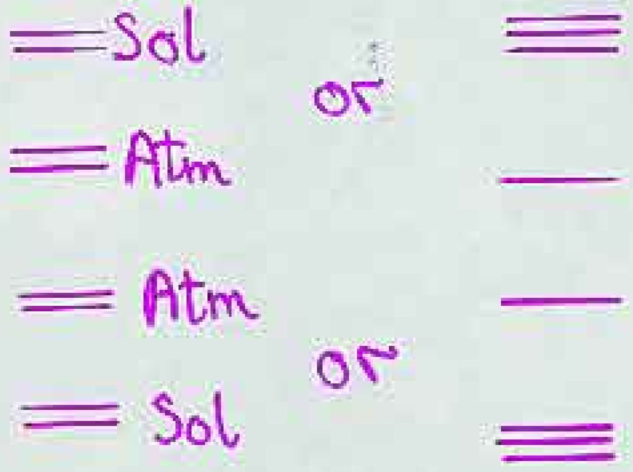
Suppose the neutrinos are no heavier than required by their splittings.

If the LSND oscillation is real, there are one or more neutrinos ν_m with masses M_{ν_m} obeying

$$M_{\nu_m} \gtrsim \sqrt{\delta M^2_{LSND}} \gtrsim \sqrt{0.2 eV^2} \simeq 0.4\, eV.$$

$$\sum_{Heavies} BR(^3H \to {}^3He + e^- + \bar{\nu}_m) \sim \sum_{Heavies} |U_{em}|^2$$

$$= \begin{cases} \sim 1 \; ; \\ \text{Small} \; ; \end{cases}$$



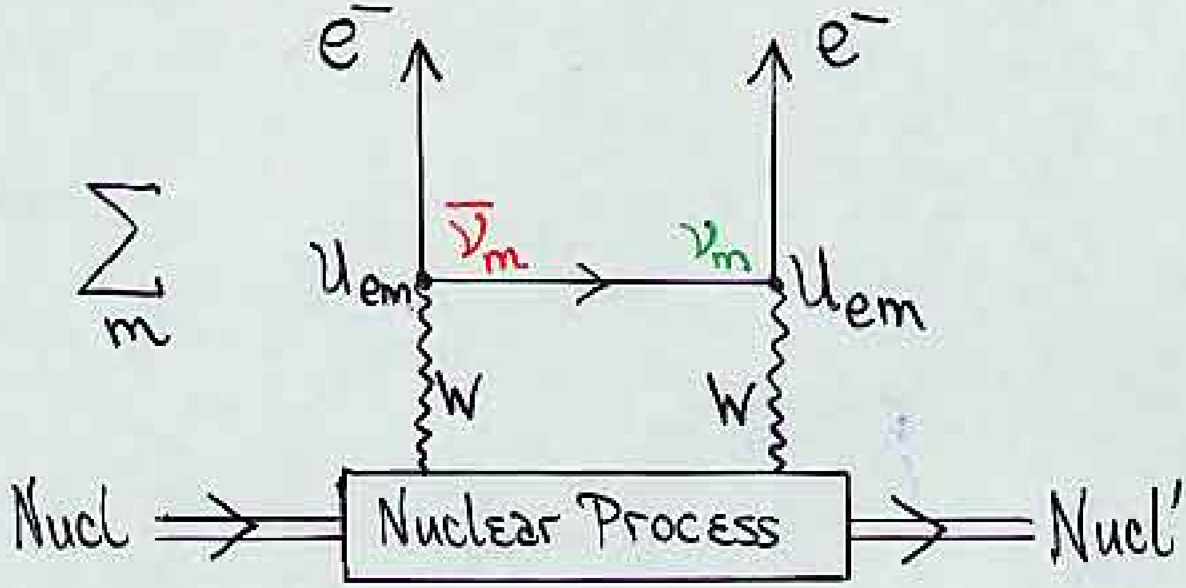
,

If the LSND oscillation is not real, the heaviest mass eigenstate need be no heavier than

$$\sqrt{\delta M^2_{Atm}} \sim \sqrt{2.5 \times 10^{-3} eV^2} = 0.05\, eV.$$

Some information on masses at this level might come from future searches for —

Neutrinoless Double Beta Decay ($\beta\beta_{0\nu}$)



If $\overline{\nu}_m = \nu_m$, this process can go.

Observation of $\beta\beta_{0\nu} \Rightarrow \overline{\nu}_m = \nu_m$.

Recent report of evidence for $\beta\beta_{0\nu}$ (^{76}Ge).

(Klapdor-Kleingrothaus, Dietz, Harney, Krivosheina)

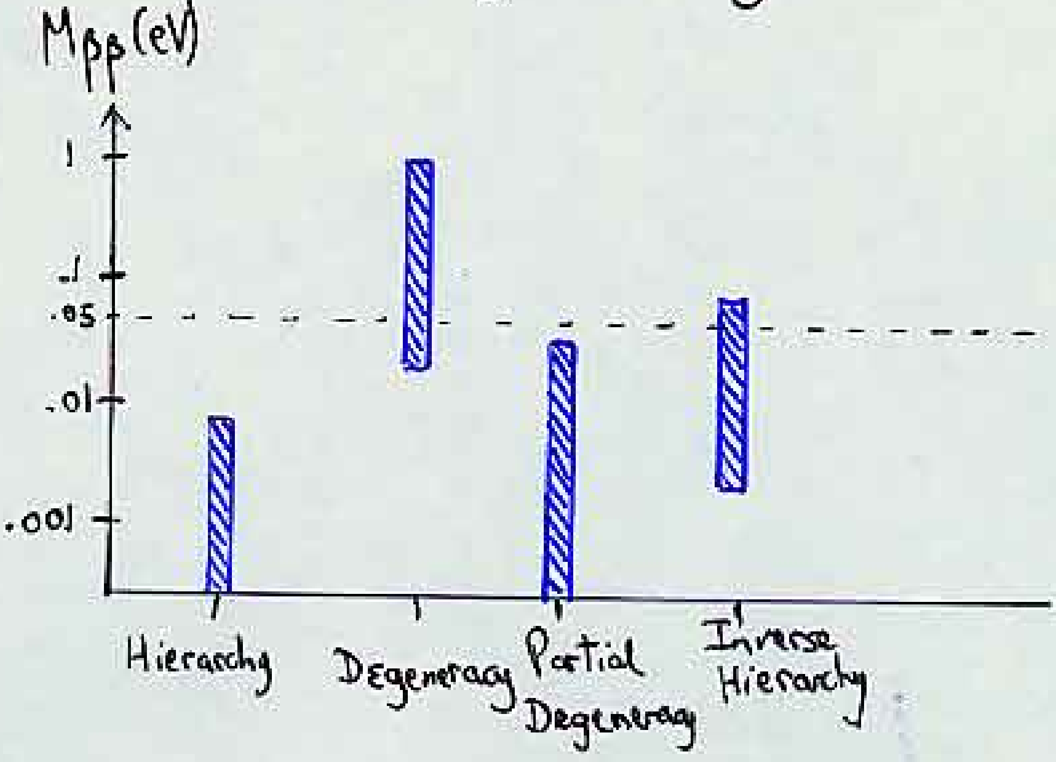
If $\overline{\nu}_m = \nu_m$,

$$|\text{Amp}[\beta\beta_{0\nu}]| = \Big|\sum_m \underset{\substack{\uparrow \\ \text{Can contain phases}}}{U_{em}^2} \overset{\substack{\text{From helicity} \\ \downarrow}}{M_{\nu_m}}\Big| \equiv M_{\beta\beta} \leq \text{Biggest } M_{\nu_m}$$

$M_{\beta\beta}$

- A measure of the ν mass scale
- A constraint on the ν mass spectrum
- Desirable sensitivity: $M_{\beta\beta} \sim 0.01$ eV
- $M_{\beta\beta}$(recent report) $= (0.11 - 0.56)$ eV.

Large Mixing MSW



(Klapdor-Kleingrothaus, Päs, Smirnov)

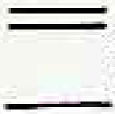
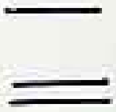
Recent studies of the $M_{\beta\beta}$- spectrum connection:

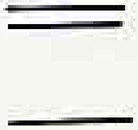
Farzan, Peres, Smirnov; Bilenky, Pascoli, Petcov; Klapdor-Kleingrothaus, Päs, Smirnov; Bilenky, Giunti, Grimus, BK, Petcov

To determine a specific M_{ν_m} accurately, we have to be lucky.

To illustrate:

Suppose we know that—

- There are only 3 neutrinos
- The spectrum looks like , not 
- Large-mixing MSW governs $\nu_\odot$ behavior.
- The solar mixing angle, $\theta_\odot$

Then, if the mass of the pair →  is M_0,

$$M_{\beta\beta} \cong M_0 \overbrace{\sqrt{1 - \sin^2 2\theta_\odot \, \sin^2\left(\frac{\alpha_2-\alpha_1}{2}\right)}}^{\text{Presently between} \sim .25 \text{ and } 1}$$

↑ Unknown CP phase

$M_{\beta\beta}$ would leave M_0 uncertain by a factor of 4. Future $\theta_\odot$ knowledge may improve this.

However, there is another, wonderful scenario:

Tritium finds M_0.

Then —

$$M_{\beta\beta} = M_0 \sqrt{1 - \sin^2 2\theta_0 \times \sin^2\left(\frac{\alpha_2-\alpha_1}{2}\right)}$$

must lie in the range

$$M_0 \cos 2\theta_0 \leq M_{\beta\beta} \leq M_0$$

An $M_{\beta\beta}$ in this range $\Rightarrow$ $\alpha_2 - \alpha_1$

$M_{\beta\beta}$ not in this range $\Rightarrow$ $\bar{\nu} \neq \nu$

* Does neutrino behavior violate CP?
Is this $\cancel{CP}$ why we are here?

Leptonic $\cancel{CP}$ would come from complex phase factors in U.

Suppose there are only 3 neutrinos, and the behavior of solar neutrinos is due to the Large Mixing Angle MSW effect. Then—

$$\mathcal{U} \approx \begin{array}{c} \\ e \\ \mu \\ \tau \end{array} \begin{array}{c} \begin{array}{ccc} \nu_1 & \nu_2 & \nu_3 \end{array} \\ \left[\begin{array}{ccc} c\,e^{i\frac{\alpha_1}{2}} & s\,e^{i\frac{\alpha_2}{2}} & s_{13}e^{-i\delta} \\ -\frac{s}{\sqrt{2}}e^{i\frac{\alpha_1}{2}} & \frac{c}{\sqrt{2}}e^{i\frac{\alpha_2}{2}} & \frac{1}{\sqrt{2}} \\ \frac{s}{\sqrt{2}}e^{i\frac{\alpha_1}{2}} & -\frac{c}{\sqrt{2}}e^{i\frac{\alpha_2}{2}} & \frac{1}{\sqrt{2}} \end{array} \right] \end{array}$$

$c \equiv \cos\theta_\odot$, $s \equiv \sin\theta_\odot$, $s_{13} \equiv \sin\theta_{13}$

With Large-Mixing MSW,

$$0.21 < \sin^2\theta_\odot < 0.37 \quad (90\%\,\mathrm{CL}).$$

(Fogli, Lisi, Montanino, Palazzo

From bounds on reactor $\overline{\nu_e}$ oscillation,

$$\sin^2\theta_{13} \lesssim 0.03 \quad (90\%\,\mathrm{CL}).$$

(CHOOZ; Palo Verde

Consequences for Neutrino Oscillation

$$\mathrm{Amp}(\nu_\ell \to \nu_{\ell'}) = \sum_m U^*_{\ell m} U_{\ell' m}\, e^{-iM^2_{\nu_m} \frac{\overset{\text{Distance}}{L}}{\underset{\text{Energy}}{2E}}}$$

CPT invariance then implies that–

$$\mathrm{Amp}(\bar{\nu}_\ell \to \bar{\nu}_{\ell'}) = \sum_m U_{\ell m} U^*_{\ell' m}\, e^{-iM^2_{\nu_m} \frac{L}{2E}} .$$

∴ If δ and s_{13} are nonvanishing, we will have CP-violating inequalities

$$P(\nu_\ell \to \nu_{\ell'}) = |\mathrm{Amp}(\nu_\ell \to \nu_{\ell'})|^2$$

$$\neq P(\bar{\nu}_\ell \to \bar{\nu}_{\ell'}) = |\mathrm{Amp}(\bar{\nu}_\ell \to \bar{\nu}_{\ell'})|^2 .$$

If observed, this $\cancel{CP}$ would establish that $\cancel{CP}$ is not a peculiarity of quarks

Let $P(\nu_\ell \to \nu_{\ell'}) - P(\bar{\nu}_\ell \to \bar{\nu}_{\ell'}) \equiv \Delta_{\cancel{CP}}(\ell\ell')$.

If there are only 3 neutrinos,

$$\Delta_{\cancel{CP}}(e\mu) = \Delta_{\cancel{CP}}(\mu\tau) = \Delta_{\cancel{CP}}(\tau e)$$

$$= 16 J \, k_{12} k_{23} k_{31} ,$$

where

$$J \equiv \mathrm{Im}(U_{e1}^* U_{e3} U_{\mu 1} U_{\mu 3}^*) \cong \frac{1}{4} \sin 2\theta_\odot \sin\theta_{13} \sin\delta$$

and

$$k_{mm'} \equiv \sin\left[1.27 \, \delta M^2_{mm'}(\mathrm{eV}^2) \frac{L(\mathrm{km})}{E(\mathrm{GeV})}\right] .$$

- Just one $\cancel{CP}$ difference
- No hadronic uncertainties
- But, small due to $\sin\theta_{13}$ and $\delta M^2_\odot$

W.9]

Where can the phases $\alpha_{1,2}$ play a role?

If $\overline{\nu}_m \neq \nu_m$, nowhere!

But if $\overline{\nu}_m = \nu_m$, $\alpha_{1,2}$ influence neutrinoless double beta decay:

$$\Gamma_{\beta\beta 0\nu} \propto M_{\beta\beta}^2 = \left| \sum_m U_{em}^2 M_{\nu_m} \right|^2$$

We have already seen how $\alpha_2 - \alpha_1$ can appear in $M_{\beta\beta}$.

The α_i: Majorana $\cancel{CP}$ phases.

They occur only for Majorana particles.

Majorana $\cancel{CP}$ phases and our existence

Why does the universe contain much more matter (of which we are made) than antimatter?

Why is $\Delta B \equiv \#(\text{Baryons}) - \#(\text{Antibaryons}) \neq 0$?

Symmetry suggests that $\Delta B = 0$ at $t = 0$.

How did $\Delta B \neq 0$ subsequently arise?

Sakharov: $\cancel{CP}$ is required.

Example: $(X^+ \to p + \ldots) \overset{CP}{\Longrightarrow} (X^- \to \bar{p} + \ldots)$

If no $\cancel{CP}$, the rates are equal.

Is the observed $\Delta B \neq 0$ due to $\cancel{CP}$ in Leptonic interactions?

A two-step process:

1) Generate $\Delta L \equiv \#(\text{Leptons}) - \#(\text{Antileptons}) \neq 0$ before the electroweak phase transition, when the universe cooled through ~100 Ge

2) Convert the $\Delta L \neq 0$ to $\Delta B \neq 0$ by expected B-L conserving processes at the electroweak phase transition

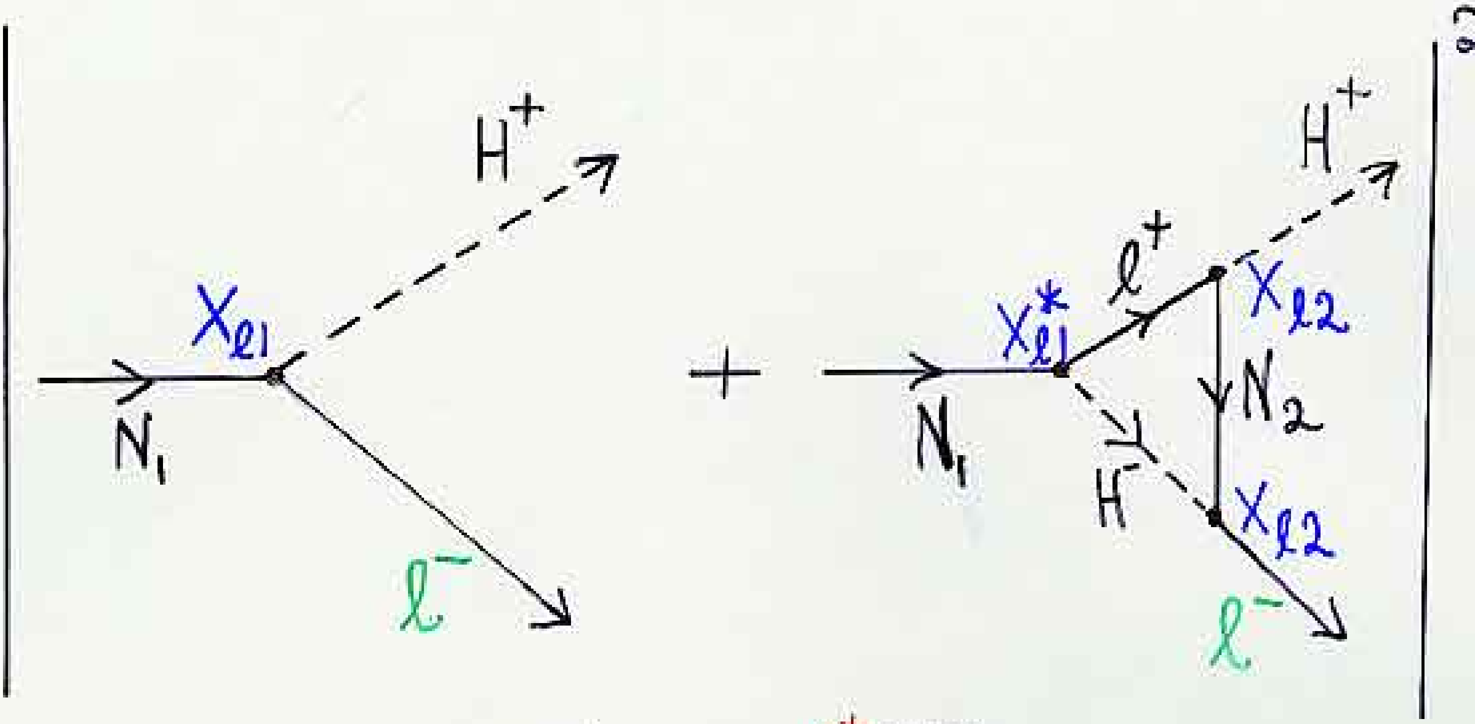
$\Delta L \neq 0$ can be generated by $\cancel{CP}$ in the decays of very heavy Majorana neutral leptons N.

(Fukugita & Yanagida
Buchmüller & Plümacher,

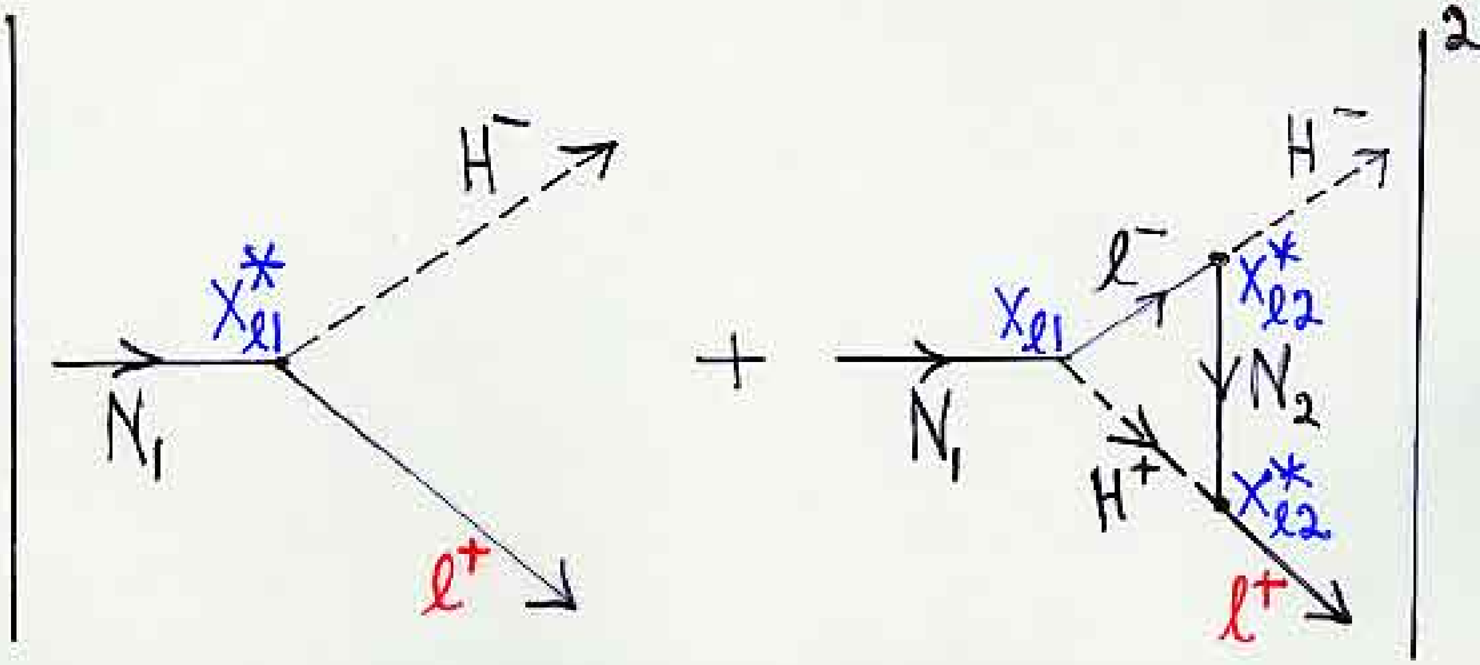
With $N_{1,2}$ two such leptons, and $H^{\pm}$ a charged Higgs particle —

$$\Gamma(N_1 \to \ell^- H^+) \;=$$

=



Then CPT $\Rightarrow \Gamma(N_1 \to \ell^+ H^-) =$



X is a $\mathcal{U}$ matrix for heavy neutral leptons.

$\Gamma(N_1 \to \ell^- H^+)$ and $\Gamma(N_1 \to \ell^+ H^-)$ can differ if X breaks CP by being complex.

$\Gamma(N_1 \to \ell^- H^+) - \Gamma(N_1 \to \ell^+ H^-)$ depends on —

$$\arg\left[X_{\ell 1}^2 / X_{\ell 2}^2\right].$$

In

$$\Gamma(\beta\beta_{0\nu}) \propto M_{\beta\beta}^2 = \left|\sum_m M_{\nu_m} \mathcal{U}_{em}^2\right|^2,$$

$\not{CP}$ depends on —

$$\arg\left[\mathcal{U}_{e1}^2 / \mathcal{U}_{e2}^2\right].$$

In both cases, $\not{CP}$ is coming from Majorana $\not{CP}$ phases.

$\Gamma(\beta\beta_{0\nu})$ violates CP

$\Rightarrow$ Nature contains the kind of $\not{CP}$ phases that can generate $\Delta L \neq 0$

(L.N. Chang, J. Ellis, Gavela,
B.K., Langacker, Murayama

Ar.111

Baryogenesis via Leptonic ~~CPT~~

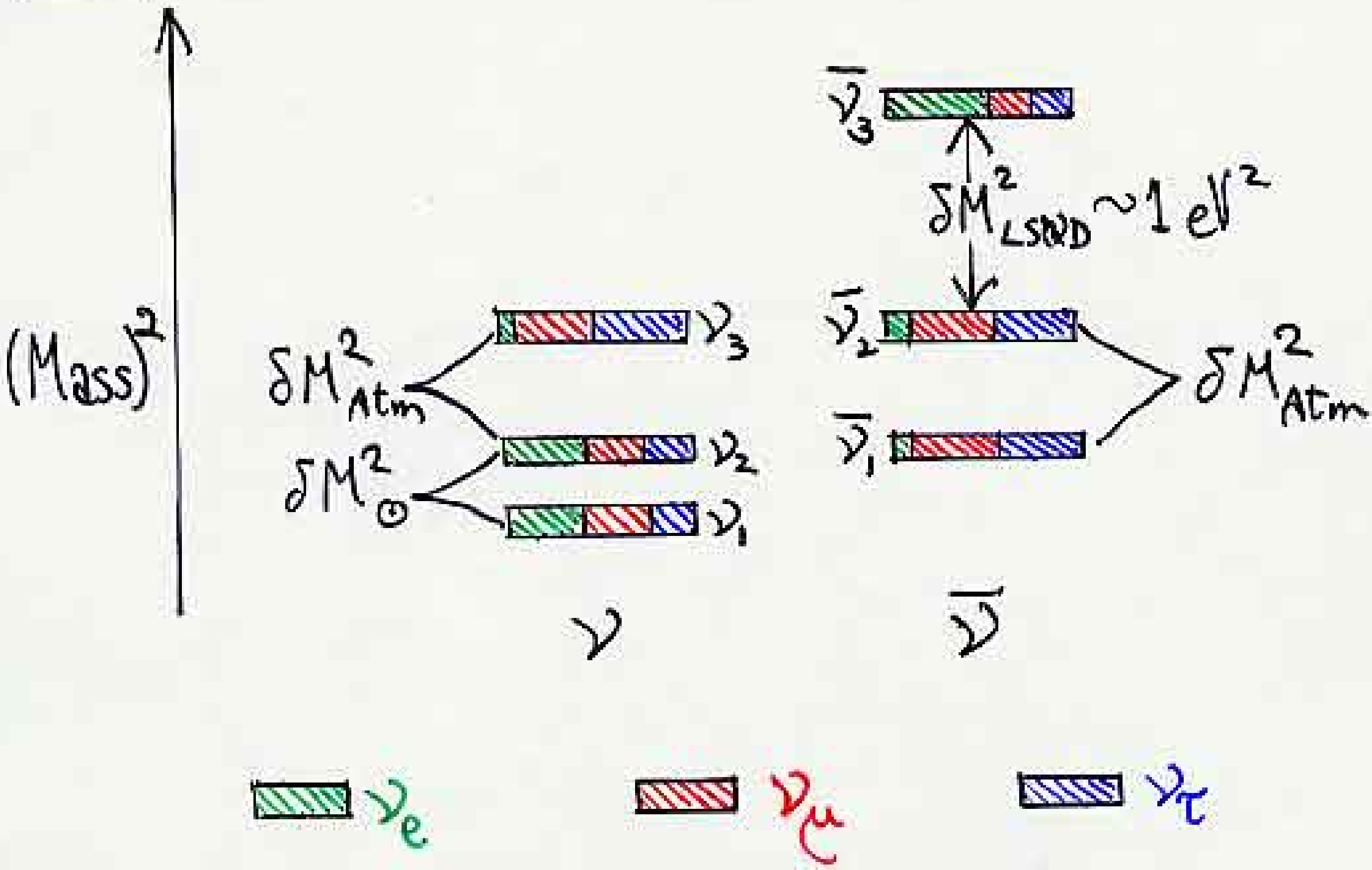
$$\text{CPT} \Longrightarrow \text{Mass}(\bar{\nu}_m) = \text{Mass}(\nu_m).$$

Suppose CPT is broken by neutrinos.

Then, if we suppose LSND sees $\bar{\nu}_\mu \to \bar{\nu}_e$ but not $\nu_\mu \to \nu_e$, we can accommodate the solar, atmospheric, and LSND oscillations without sterile neutrinos.

Just allow $M_{\bar{\nu}_m} \neq M_{\nu_m}$, and assume that the $\bar{\nu}_m$ have a bigger δM^2 than the ν_m:

Ac.12



(Barenboim, Borissov, Lykken, Smirnov
Murayama, Yanagida)

At the EW phase transition, the ν and $\bar{\nu}$ masses turn on.

Since the ν are lighter than the $\bar{\nu}$, after equilibrium is reached, $\#(\nu) > \#(\bar{\nu})$.

Then B−L conserving processes convert this ν excess into a B excess.

Note that the sign is right: $\Delta B = B - \bar{B} > 0$.
(Thanks to LSND)

The estimated size of ΔB is right too.

A problem:

Without affecting any oscillation, we can slide the whole ν or $\bar{\nu}$ spectrum up or down in $(\text{Mass})^2$.

Raise the ν spectrum to $\sim 2\,\text{eV}^2$.

Tritium: ${}^3\text{H} \to {}^3\text{He} + e^- + \bar{\nu}_e$ won't see it.

$\beta\beta_{0\nu}$: If L is conserved, this won't see anything.

ΔB: Now the sign is wrong.

Still, the most natural ν and $\bar{\nu}$ spectra predict the right ΔB.

Without any $\not{CP}$!

Related Studies of $\not{CPT}$ Among the Neutrinos

Barger, Pakvasa, Weiler, Whisnant
Pakvasa
Skadhauge
Bilenky, Freund, Lindner, Ohlsson, Winter
Barenboim, Borissov, Lykken

Conclusion

The compelling evidence for ν masses opens a whole ν world to explore.

We have much to discuss at this Workshop.
