The New World of Neutrino Physics

Part One

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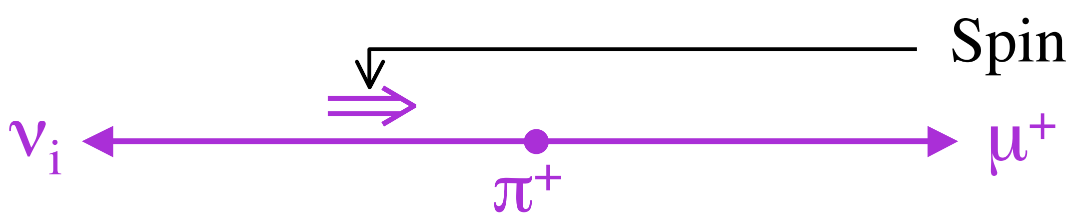
How Can We Demonstrate That $\overline{\nu}_i = \nu_i$?

We assume neutrino interactions are correctly described by the SM. Then the interactions conserve L ($\nu \rightarrow \ell^-$; $\overline{\nu} \rightarrow \ell^+$).

An Idea that Does Not Work
[and illustrates why most ideas do not work]

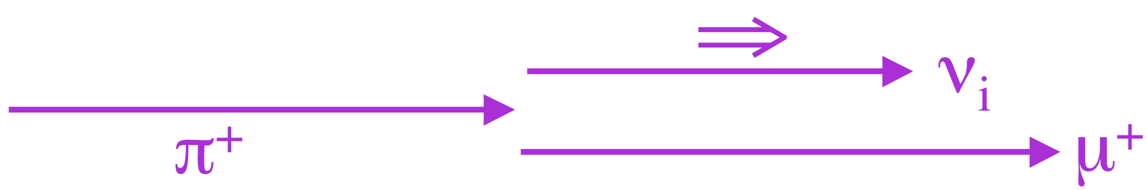
Produce a ν_i via—



Pion Rest Frame

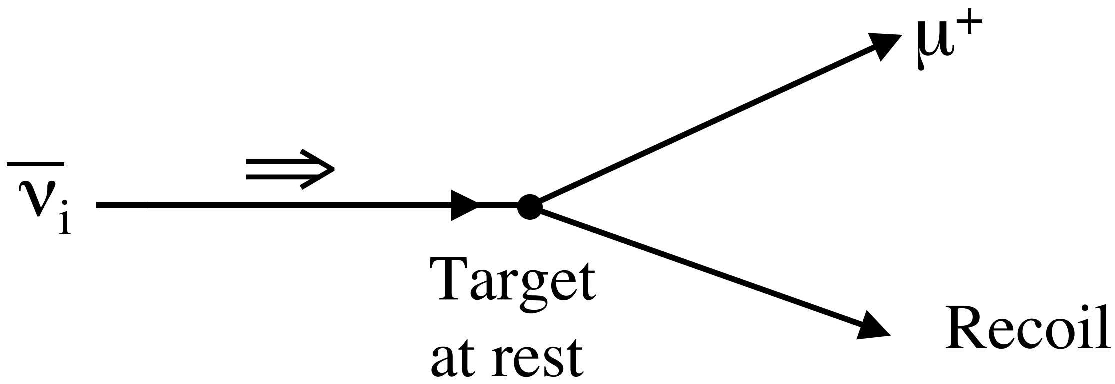
Give the neutrino a Boost:

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



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

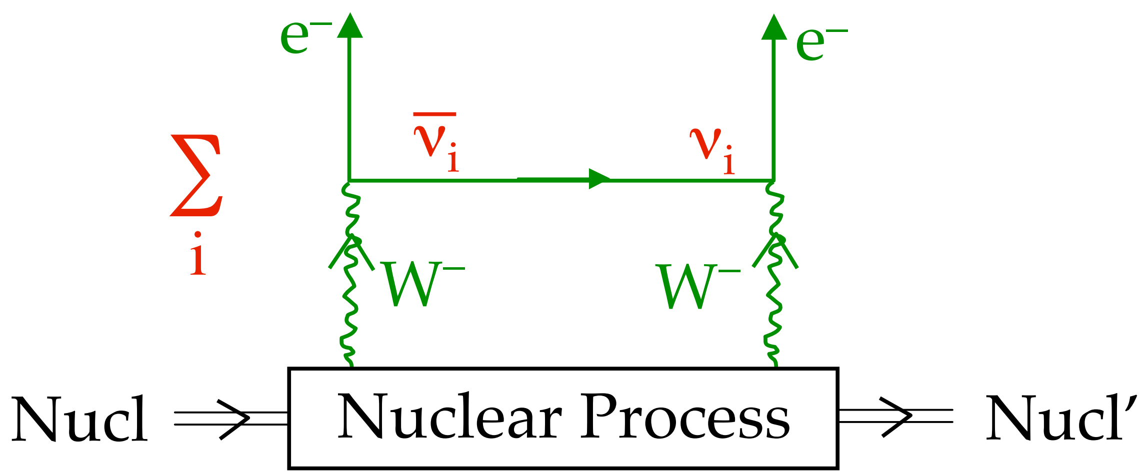
$$\approx \left(\frac{m_{\nu_i}}{E_\nu(\pi \text{ Rest Frame})} \right)^2 \sim 10^{-18} \text{ if } m_{\nu_i} \sim 0.05 \text{ eV}$$

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 [0νββ]

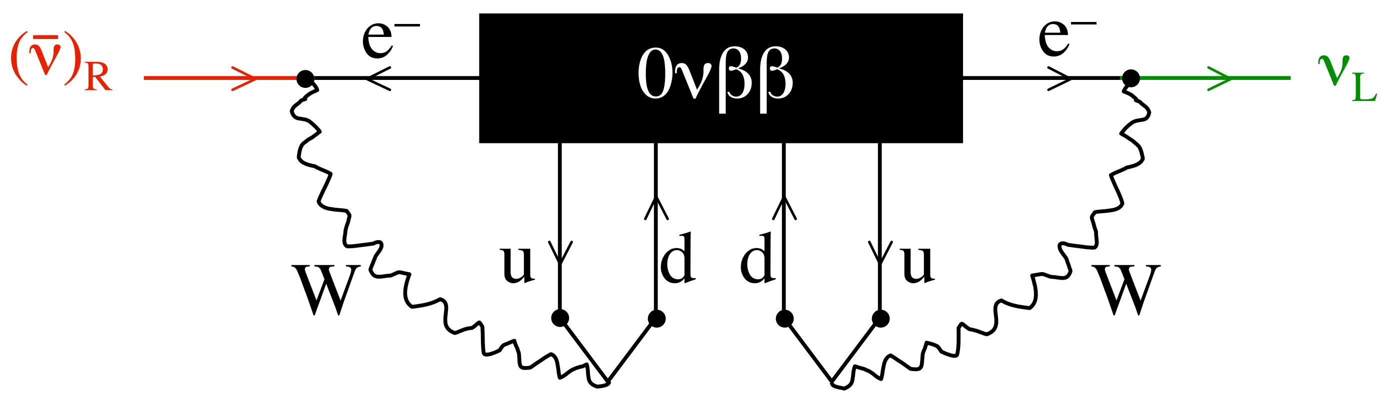


By avoiding competition, this process can cope with the small neutrino masses.

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

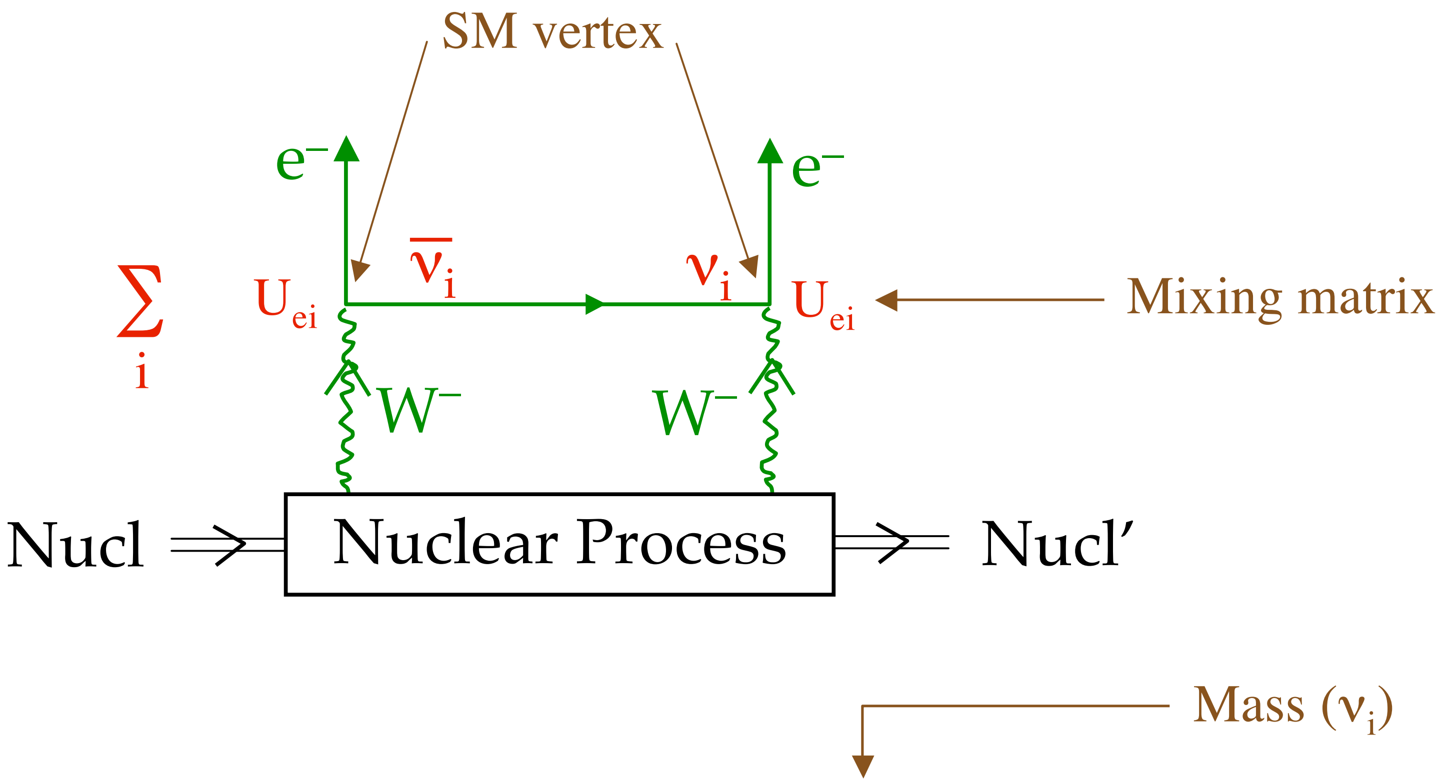
Whatever diagrams cause 0νββ, its observation would imply the existence of a Majorana mass term:

Schechter and Valle



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

In —



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

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

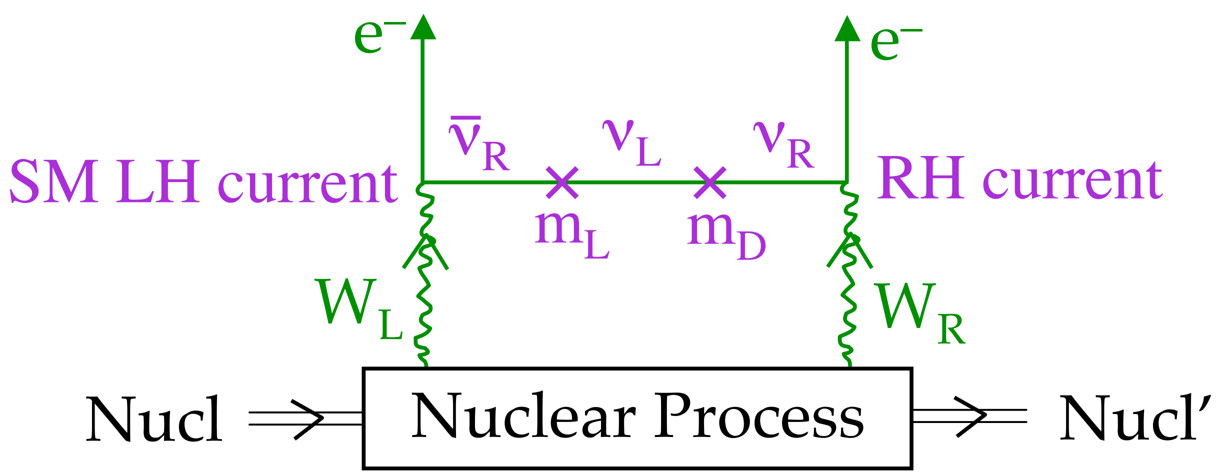
$$\mathrm{Amp}[0\nu\beta\beta] \propto \left| \sum_i m_i U_{ei}^2 \right| \equiv m_{\beta\beta}$$

The proportionality of $0\nu\beta\beta$ to 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.

Wouldn't the dependence on neutrino mass be eliminated by a Right-Handed Current?



The SM LH current does not violate L.

An identical current, but of opposite handedness, wouldn't violate L either.

We still need the L-violating Majorana neutrino mass to make this process occur.

With a RH current at one vertex,

$$\text{Amp}[0\nu\beta\beta] \propto (\nu \text{ mass})^2 .$$

Contributions with a RH current at one vertex are not likely to be significant.

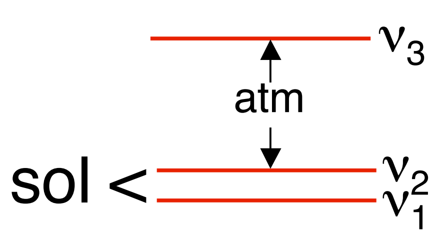
$\left\{ \begin{array}{c} \text{BK, Petcov, Rosen} \\ \text{Enqvist, Maalampi, Mursula} \end{array} \right\}$

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

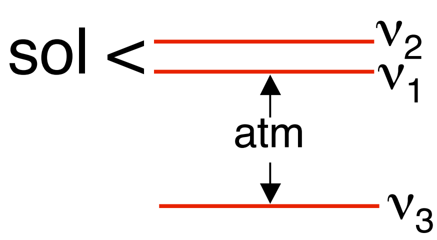
How sensitive need an experiment be?

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

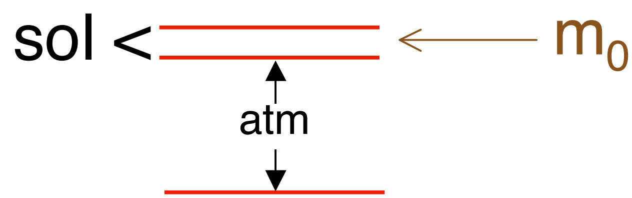
Then the spectrum looks like —



or



If the spectrum looks like—



then–

Majorana
~~CP~~ phases

$$m_{\beta\beta} \cong m_0[1 - \sin^2 2\theta_\odot \sin^2(\frac{\alpha_2-\alpha_1}{2})]^{1/2} \quad .$$

Solar mixing angle

$$m_0 \cos 2\theta_\odot \leq m_{\beta\beta} \leq m_0$$

At 90% CL,

$m_0 > 40$ meV (SuperK); $\cos 2\theta_\odot > 0.28$ (SNO),

so

$$m_{\beta\beta} > 11 \text{ meV} \; .$$

The Mixing Matrix

Atmospheric — Cross-Mixing — Solar

$$U = \begin{bmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{bmatrix} \times \begin{bmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{bmatrix} \times \begin{bmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

$$\times \begin{bmatrix} e^{i\alpha_1/2} & 0 & 0 \\ 0 & e^{i\alpha_2/2} & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

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

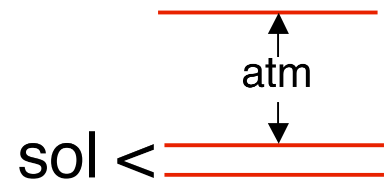
Majorana ~~CP~~ phases

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

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

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

If the spectrum looks like →



then —

$0 < m_{\beta\beta} <$ Present Bound [(0.3–1.0) eV] .

(Petcov *et al.*)

<u>Analyses of $m_{\beta\beta}$ vs. Neutrino Parameters</u>

Barger, Bilenky, Farzan, Giunti, Glashow, Grimus, BK, Kim, Klapdor-Kleingrothaus, Langacker, Marfatia, Monteno, Murayama, Pascoli, Päs, Peña-Garay, Peres, Petcov, Rodejohann, Smirnov, Vissani, Whisnant, Wolfenstein,

Review of ββ Decay: Elliott & Vogel

Evidence for 0νββ with $m_{\beta\beta} = (0.05 – 0.84)$ eV?

Klapdor-Kleingrothaus

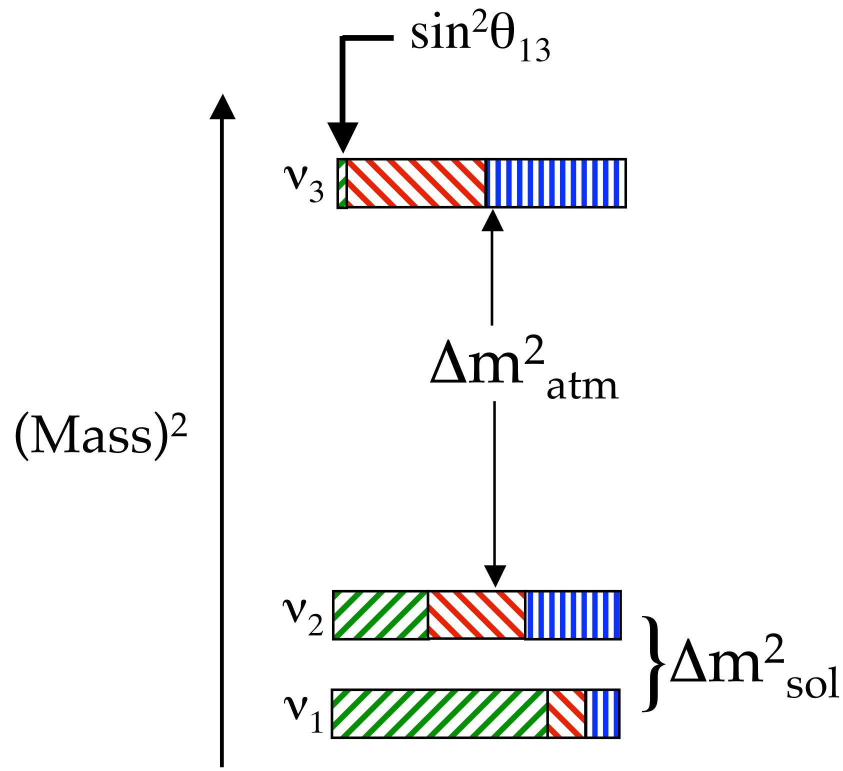
How Neutrino Questions May Be Answered

In Pursuit of θ_{13}

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

If $\sin^2 2\theta_{13} < 0.01$, a neutrino factory will be needed to study both of these issues.

How may θ_{13} be measured?



$\sin^2\theta_{13} = |U_{e3}|^2$ is the small ν_e piece of ν_3.

ν_3 is at one end of Δm^2_{atm}.

$\therefore$ We need an experiment with L/E sensitive to Δm^2_{atm} (L/E ~ 500 km/GeV) , and involving ν_e.

Recall that for a spectrum with one big Δm^2, which here is Δm^2_{atm},

$$P(\nu_\mu \rightarrow \nu_e) \cong S_{\mu e} \sin^2\left(\Delta m^2{}_{atm} \frac{L}{4E}\right)$$

with —

$$S_{\mu e} \equiv 4\left|\sum_{i \text{ in Clump}} U^*{}_{\mu i} U_{ei}\right|^2 = 4\left|U_{\mu 3} U_{e3}\right|^2$$

and —

$$P(\bar{\nu}_e \rightarrow \bar{\nu}_e) \cong 1 - 4T_e(1 - T_e)\sin^2\left(\Delta m^2{}_{atm} \frac{L}{4E}\right)$$

with —

$$T_e \equiv \sum_{i \text{ in Clump}} |\mathrm{U_{ei}}|^2 = |U_{e3}|^2$$

Complementary Approaches

We use the abbreviation —

$$1.27\ \Delta m^2_{ij}(eV^2)\ L(km)/E(GeV) \equiv \Delta_{ij}$$

Reactor Experiments

Reactor $\bar{\nu}_e$ disappearance while traveling L ~ 1.5 km. This process depends on θ_{13} alone:

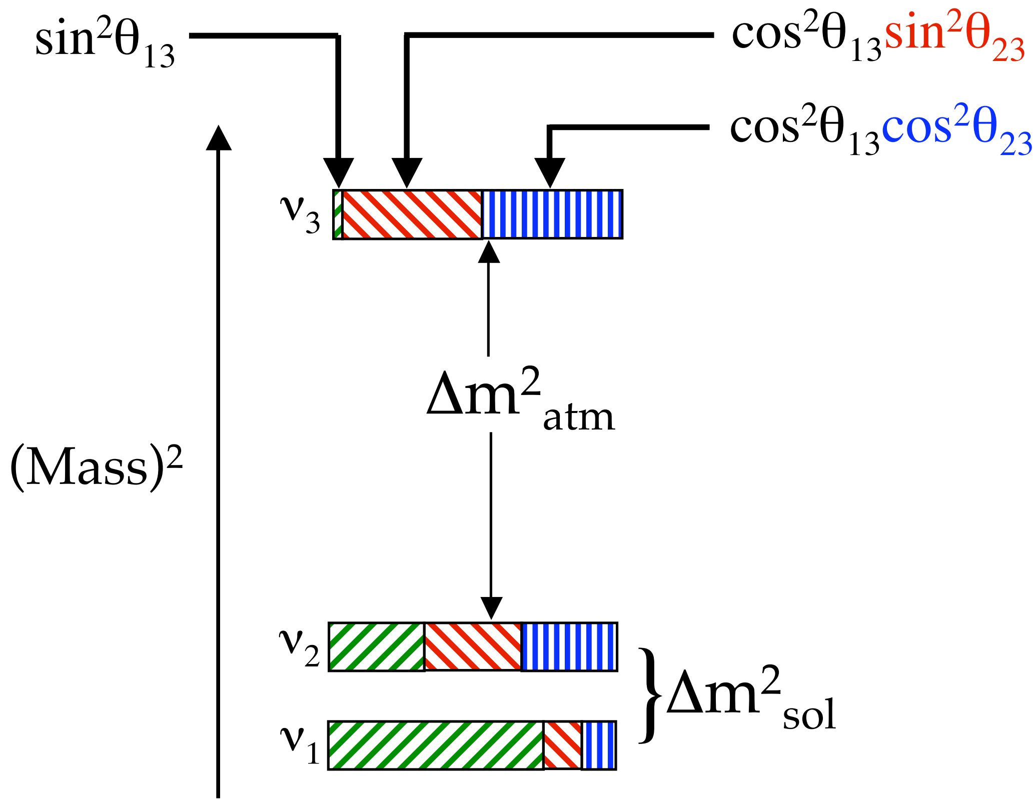
$$P[\overline{\nu_e} \rightarrow \text{Not } \overline{\nu_e}] \cong \sin^2 2\theta_{13} \sin^2 \Delta_{31} + \cos^4 \theta_{13} \sin^2 2\theta_{12} \sin^2 \Delta_{21}$$

For $\sin^2 2\theta_{13} > 0.01$, the first term dominates at the first atmospheric (Δ_{31}) oscillation maximum, where the far detector will be situated.

Given a measured value of Δ_{31} (from MINOS), a positive reactor experiment determines θ_{13}.

Accelerator Experiments

Accelerator $\nu_\mu \rightarrow \nu_e$ while traveling L > Several hundred km. This process depends on θ_{13}, θ_{23}, on whether the spectrum is normal or inverted, and on whether CP is violated through the phase δ.



$\bar{\nu}_e$ disappearance depends on $\sin^2 2\theta_{13}$.

$\nu_\mu \rightarrow \nu_e$ depends on $\sin^2 2\theta_{13} \sin^2\theta_{23}$.

ν_μ disappearance depends essentially on $\sin^2\theta_{23}\cos^2\theta_{23}$.

Neglecting matter effects (to keep the formula from getting too complicated):

The accelerator long-baseline $\overset{(-)}{\nu}_e$ appearance experiment measures —

$$P[\overset{(-)}{\nu}_\mu \rightarrow \overset{(-)}{\nu}_e] \cong \sin^2 2\theta_{13} \sin^2 \theta_{23} \sin^2 \Delta_{31}$$
$$+ \sin 2\theta_{13} \cos \theta_{13} \sin 2\theta_{23} \sin 2\theta_{12} \sin \Delta_{31} \sin \Delta_{21} \cos(\Delta_{32} \pm \delta)$$
$$+ \sin^2 2\theta_{12} \cos^2 \theta_{23} \cos^2 \theta_{13} \sin^2 \Delta_{21}$$

The plus (minus) sign is for neutrinos (antineutrinos).

The accelerator long-baseline experiment also measures —

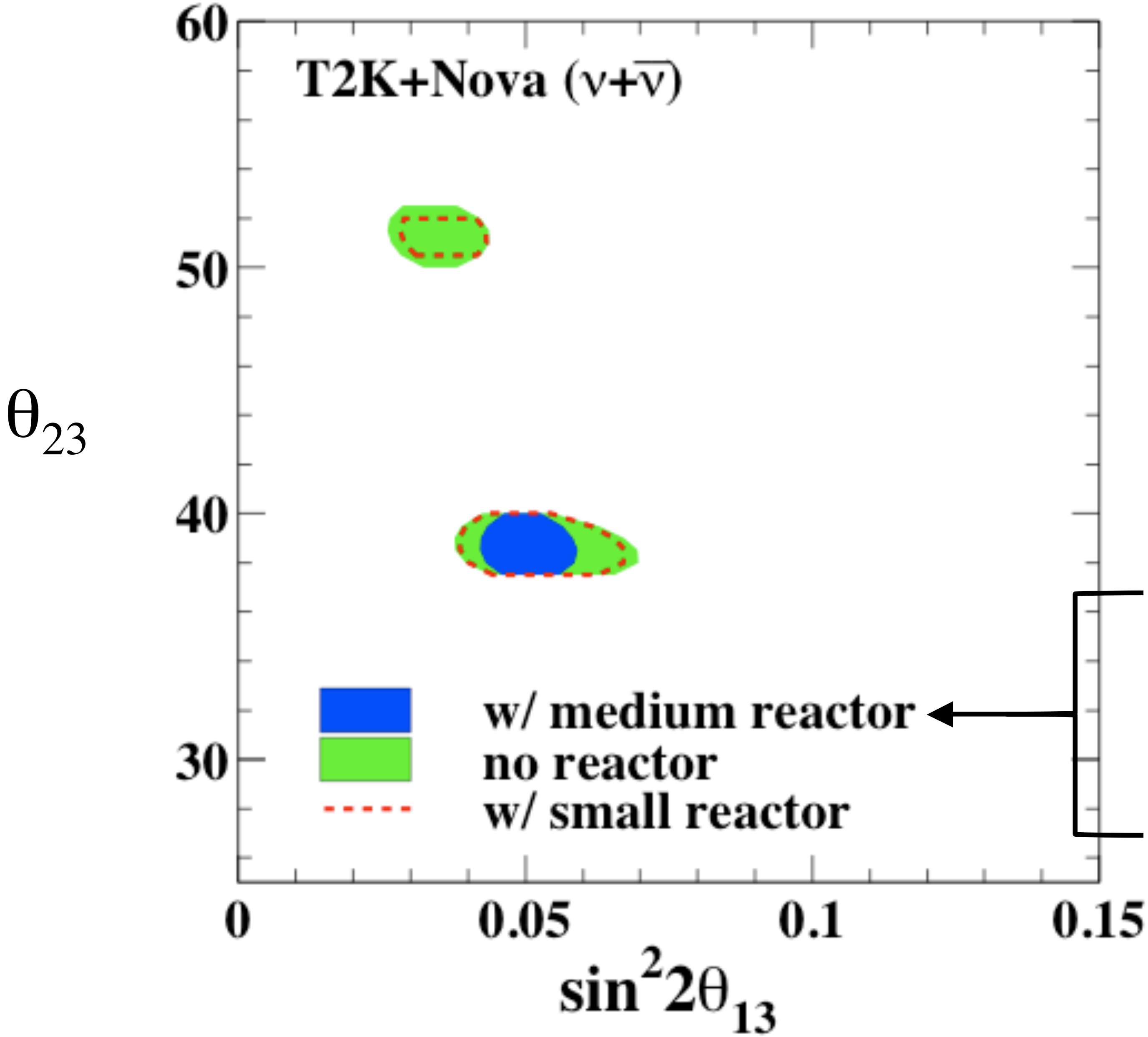
$$P[\nu_\mu \rightarrow \text{Not } \nu_\mu] \cong \sin^2 2\theta_{23} \sin^2 \Delta_{atm}$$

Here Δ_{atm} lies between the (very nearly equal) Δ_{31} and Δ_{32}.

This measurement determines $\sin^2 2\theta_{23}$, but if $\theta_{23} \neq 45°$, there are two solutions for θ_{23}:

$$\theta_{23} \text{ and } 90° - \theta_{23}.$$

A reactor experiment may be able to resolve this ambiguity.



Assumes $\sin^2 2\theta_{23}$ = .95 ± .01

Sensitive to $\sin^2 2\theta_{13}$ = 0.01

(Mahn, Shaevitz)

The Mass Spectrum:  or  ?

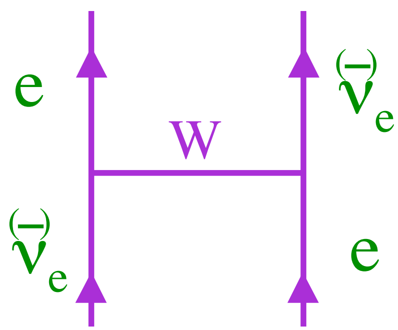
Generically, grand unified models (GUTS) favor —

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

Exploit the fact that, in matter,



raises the effective mass of ν_e, and lowers that of $\bar{\nu}_e$.

This changes both the spectrum and the mixing angles.

Matter effects grow with energy E.

At E ~ 1 GeV, matter effects ⇒

$$\sin^2 2\overset{(-)}{\theta}_M \cong \sin^2 2\theta_{13} \left[1 \underset{(-)}{+} S \frac{E}{6\ \text{GeV}} \right].$$

Sign[m^2(—) - m^2(═)] → S

At oscillation maximum,

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

Note fake CP violation.

The effect is $\begin{cases} 30\% \ ; \ E = 2 \quad \text{GeV (NuMI)} \\ 10\% \ ; \ E = 0.7\ \text{GeV (T2K)} \end{cases}$

T2K cannot address the mass hierarchy.

Larger E is better.

But want L/E to correspond roughly to the peak of the oscillation.

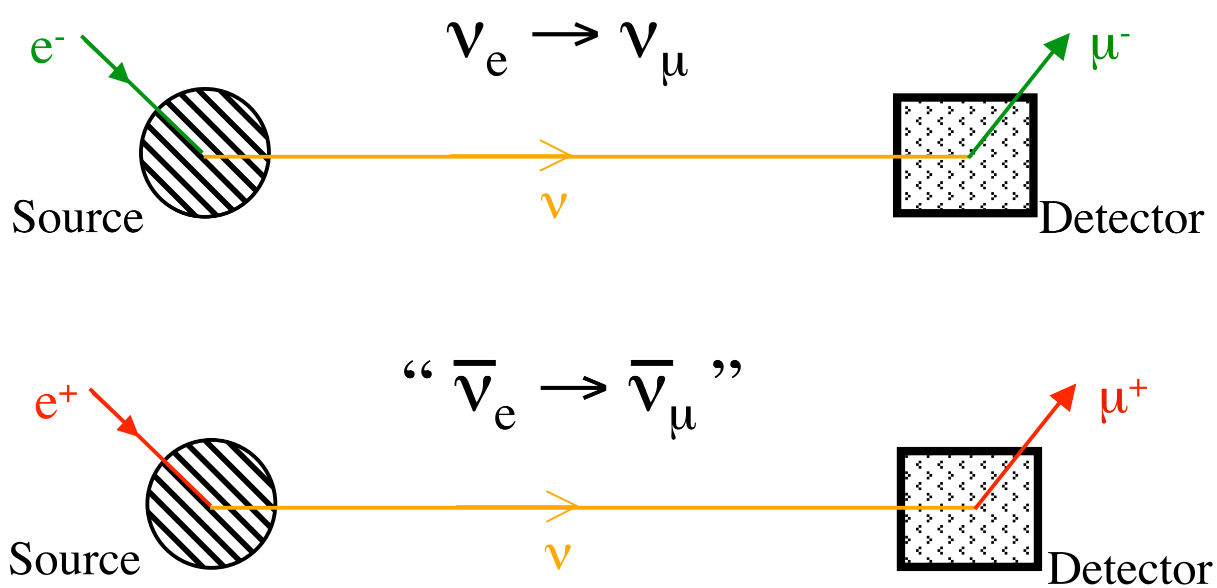
Therefore, larger E should be matched by larger L.

Using larger L to determine whether the spectrum is normal or inverted could be a special contribution of the U.S. to the global program.

How To Search for $\not{CP}$

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

" $\bar{\nu}_\alpha \rightarrow \bar{\nu}_\beta$ " is a different process from $\nu_\alpha \rightarrow \nu_\beta$ even when $\bar{\nu}_i = \nu_i$



CPT: $P(\nu_\alpha \rightarrow \nu_\beta) = P(\bar{\nu}_\beta \rightarrow \bar{\nu}_\alpha)$

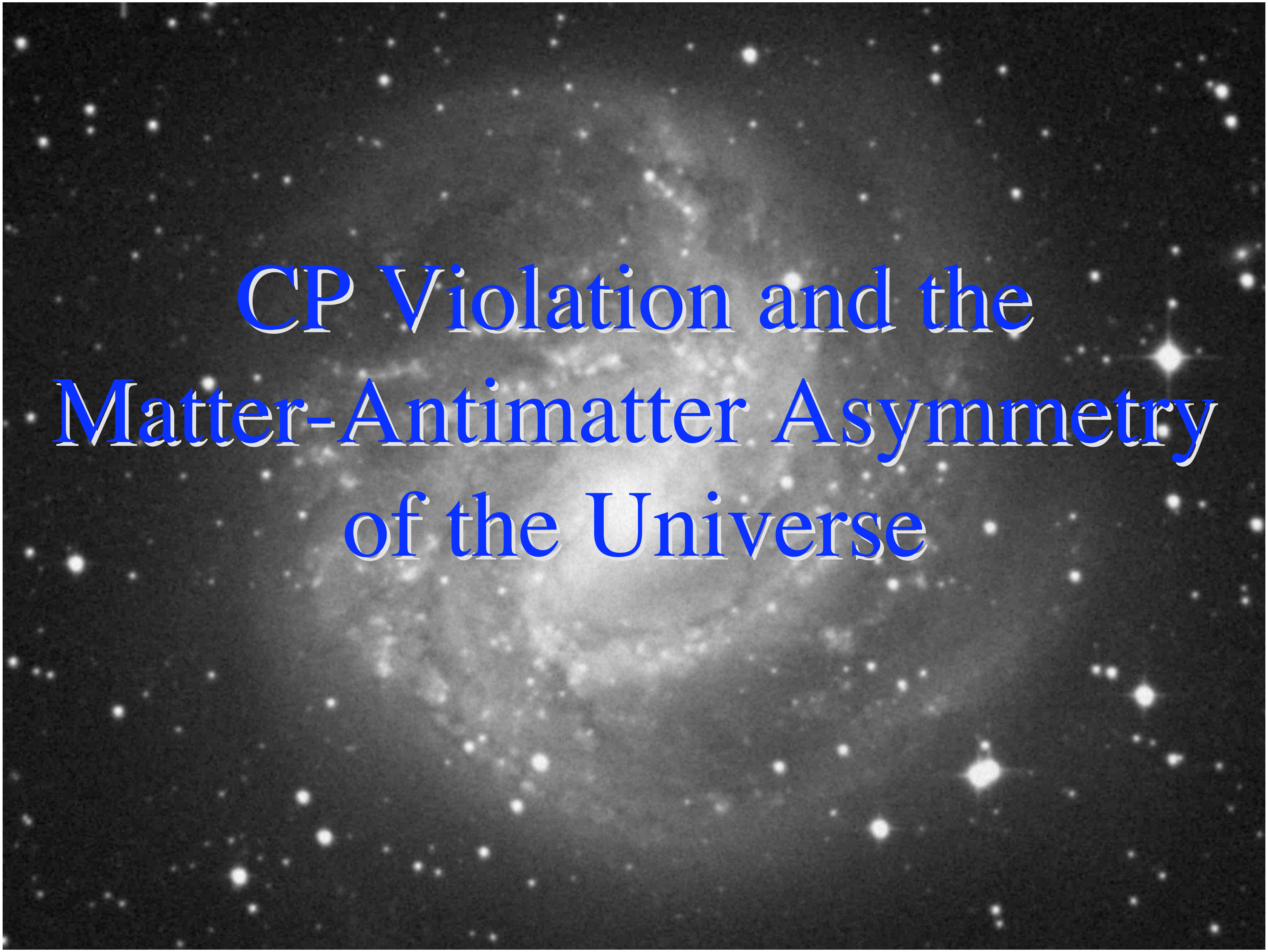
$\therefore \quad P(\nu_\alpha \rightarrow \nu_\alpha) = P(\bar{\nu}_\alpha \rightarrow \bar{\nu}_\alpha)$

No CP violation in a *disappearance* experiment.

But if δ is present, $P(\nu_\mu \rightarrow \nu_e) \neq P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e)$.

This $\not{C}\not{P}$, coming from a phase (δ), requires an **interference** between the oscillations involving $(\sin 2\theta_{13}\ \Delta m^2_{atm})$ and Δm^2_{sol}.

$\{\Delta m^2_{sol} / \Delta m^2_{atm} \cong 1/30\}$


CP Violation and the
Matter-Antimatter Asymmetry
of the Universe

The universe is presently

MATTER-antimatter asymmetric:

It contains **MATTER** (of which we are made), but essentially no antimatter (which would annihilate us).

Any initial asymmetry would have been washed out by baryon-number (B) and lepton-number (L) violating processes expected from Grand Unified TheorieS.

Therefore, we have to understand how the present **MATTER**-antimatter asymmetry developed from a matter-antimatter-symmetric universe.

This development requires CP violation ($\not{CP}$).

That is, antimatter must behave differently from matter.

Otherwise, a universe containing **equal** amounts of the two will **continue** to contain **equal** amounts of the two.

Sakharov

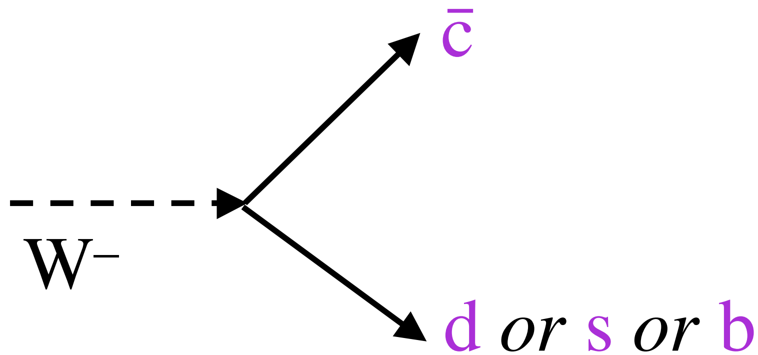
In Standard Model weak processes involving *quarks*, the $\not{CP}$ phases are in the quark mixing matrix —

$$V = \begin{bmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{bmatrix}$$

$\not{CP}$ coming from phases in this matrix is far too small to explain the **MATTER**-antimatter asymmetry of the universe.

One reason: **It's too darn hot** in the early universe.

In —



the middle row of $V = \begin{bmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{bmatrix}$ determines the

relative amplitudes for emitting d, s, and b
in combination with c̄.

The thinking was that perhaps the matter-antimatter asymmetry was generated by phases in V as the universe cooled through the Electroweak Phase Transiton ($kT \sim m_W$).

But it was **hot** then, compared with the masses of all the quarks except top. The masses of d, s, and b were negligible.

Then one could not tell d from s from b.

The quark mixing matrix did not yet have any meaning.

Hence, it had no consequences.

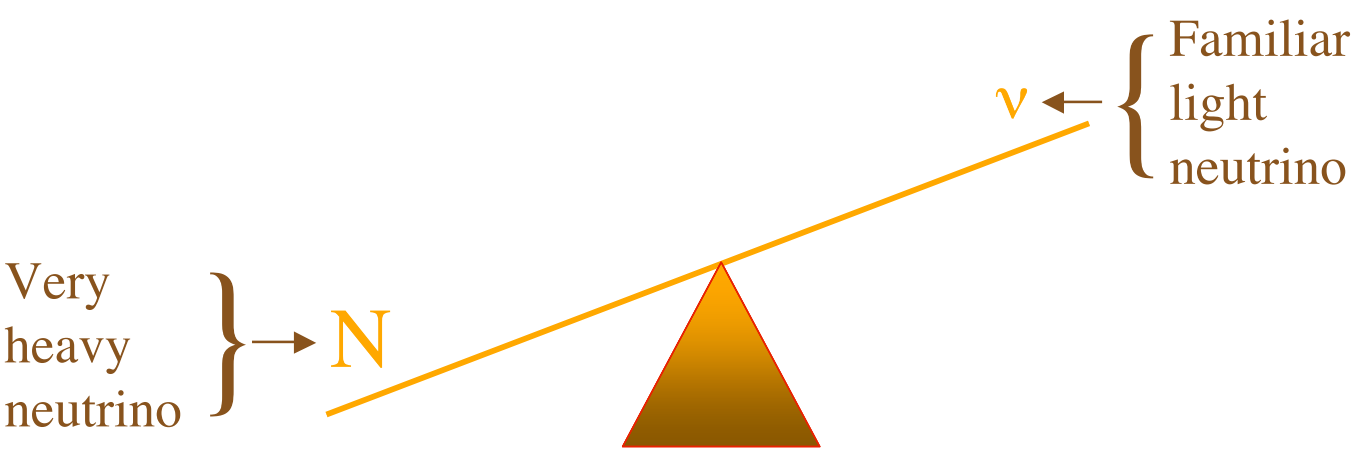
It could not cause ~~CP~~. {At least, not much.}

Leptogenesis

If the quarks can't generate the observed **MATTER**-antimatter asymmetry, maybe the **leptons** can!

Remember the —

See-Saw Mechanism



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

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

In the early universe, before the neutral Higgs field develops its vacuum expectation value, the Higgs particles φ^+ and φ^0 in —

$$\begin{pmatrix} \varphi^+ \\ \varphi^0 \end{pmatrix}$$

are ordinary massless particles. We can have —

$$N \to \ell^- + \varphi^+ \quad \text{and} \quad N \to \ell^+ + \varphi^-$$

If CP is violated in N decays, we will have —

$$\Gamma(N \rightarrow \ell^- + \varphi^+) \neq \Gamma(N \rightarrow \ell^+ + \varphi^-),$$

producing a universe with unequal amounts of leptonic matter and antimatter.

The detailed mechanism for $\not{C}\not{P}$ in these decays makes it very natural.

$$\Gamma(N \to \ell^- + \varphi^+) \neq \Gamma(N \to \ell^+ + \varphi^-)$$

generates a LEPTON asymmetry.

What about the BARYON asymmetry that we also see?

Non-perturbative Standard Model **sphaleron processes**, occuring after N decay, will change the total baryon number B, and the total lepton number L, while conserving B – L.

If N decay produced more ℓ^+ than ℓ^-, then some of this antilepton excess will be reprocessed by the (B – L) conserving sphaleron processes into a baryon excess and a lepton excess — what we see today.

Leptogenesis and Today's Neutrinos

Under reasonable assumptions, Leptogenesis requires that the masses m_i of the light neutrinos satisfy —

$$0.001 \text{ eV} < m_i < 0.1 \text{ eV}.$$

Together, cosmology and neutrino oscillation data tell us that —

$$0.04 \text{ eV} < \text{Largest } m_i < (0.2 - 0.4) \text{ eV}.$$

Notice the coincidence!

If ν oscillation violates CP, then quite likely so does N decay.

Thus, observing CP violation in neutrino oscillation would lend credence to the hypothesis that Leptogenesis was the original source of the

MATTER-antimatter asymmetry

Backup Slides

How CP Violation Comes About

$\not{CP}$ in a decay would mean that —

$$\Gamma\left(P \to f\right) \neq \Gamma\left(\overline{P} \to \bar{f}\right)$$

How can this come about?

$\not{CP}$ comes from phases. Therefore, it always involves an interference between amplitudes.

Strong, CP-even, phases

Suppose that —

$$\mathrm{Amp}(P \to f) = a_1 e^{i\varphi_1} e^{i\delta_1} + a_2 e^{i\varphi_2} e^{i\delta_2}$$

Weak, CP-odd, phases

while —

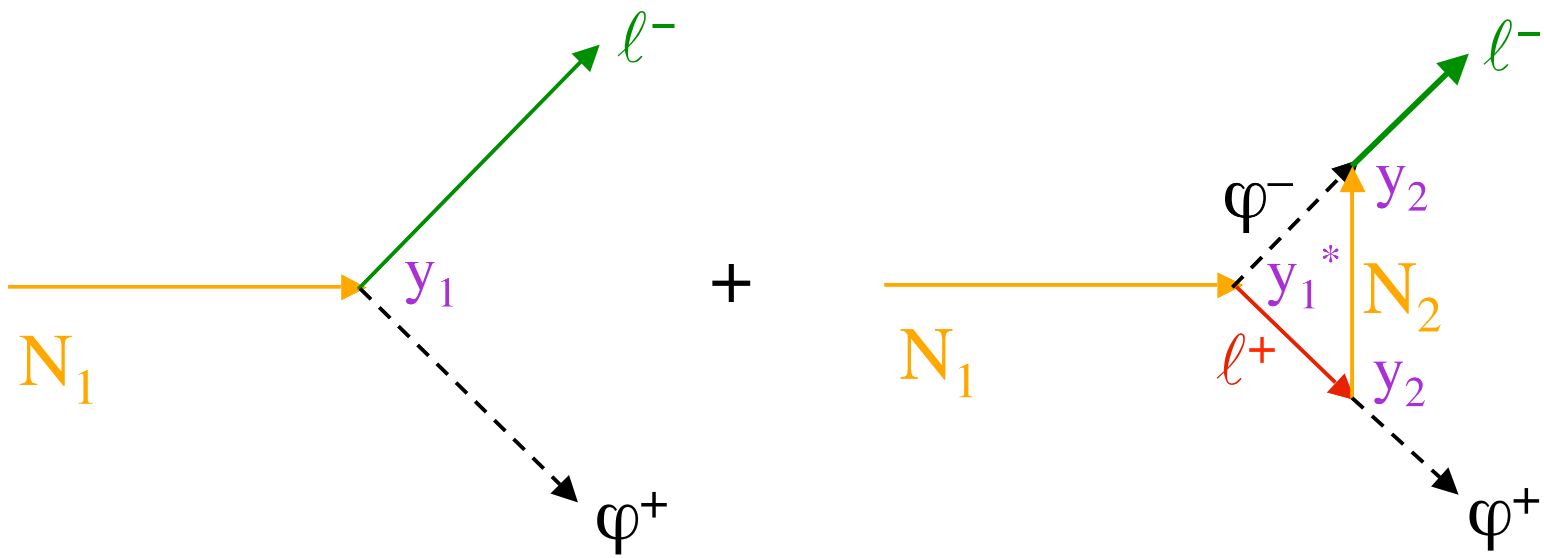
$$\mathrm{Amp}(\overline{P} \to \bar{f}) = a_1 e^{i\varphi_1} e^{-i\delta_1} + a_2 e^{i\varphi_2} e^{-i\delta_2}$$

Then —

$$\Gamma\left(P \to f\right) - \Gamma\left(\overline{P} \to \bar{f}\right) = |\,\mathrm{Amp}(P \to f)\,|^2 - |\,\mathrm{Amp}(\overline{P} \to \bar{f})\,|^2$$
$$= -\,4 a_1 a_2 \sin\left(\varphi_1 - \varphi_2\right) \sin\left(\delta_1 - \delta_2\right)$$

Corresponding to the 3 light neutrinos, ν_1, ν_2, and ν_3, there are 3 heavy see-saw partners, N_1, N_2, and N_3.

The decay $N_1 \rightarrow \ell^- + \varphi^+$ involves an interference between the diagrams —



Here, y_1 and y_2 are elements of a mixing matrix for the heavy neutrinos N, analogous to the mixing matrix U for the light neutrinos ν.

$$\mathrm{Amp}(N \rightarrow \ell^+ + \varphi^-) = \mathrm{Amp}(N \rightarrow \ell^- + \varphi^+;\ y \Rightarrow y^*)$$

Complex y_i will lead via interference to ~~CP~~.