

Seesaw/KEK  
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# THE OPEN NEUTRINO QUESTIONS

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# Evidence for Flavor Change

## Neutrinos

Solar

Reactor  
( $L \sim 180 \text{ km}$ )

Atmospheric

Accelerator  
( $L = 250 \text{ km}$ )

Stopped  $\mu^+$  Decay  
(LSND)  
( $L \approx 30 \text{ m}$ )

## Evidence of Flavor Change

Compelling

Very Strong

Compelling

Interesting

Unconfirmed

H.O.]

The observed flavor changes are not due to flavor-changing interactions with matter, but to —

neutrino masses and mixing.

Prob [Atmospheric  $\nu$  flavor change] depends on —

$$\frac{L (\text{Distance } \nu \text{ travels})}{E (\nu \text{ energy})} .$$

Time elapsed in  $\nu$  rest frame during journey

$$= m (\nu \text{ mass}) \times \frac{L}{E} .$$

## A.11 What Would We Like to Know?

What physics is responsible for neutrino masses and mixing?

How many neutrino species are there?  
Are there sterile neutrinos?

What is the neutrino mass spectral pattern?

What is the scale of neutrino mass?

Are neutrinos Majorana particles ( $\bar{\nu} = \nu$ )?

What is the leptonic mixing matrix?

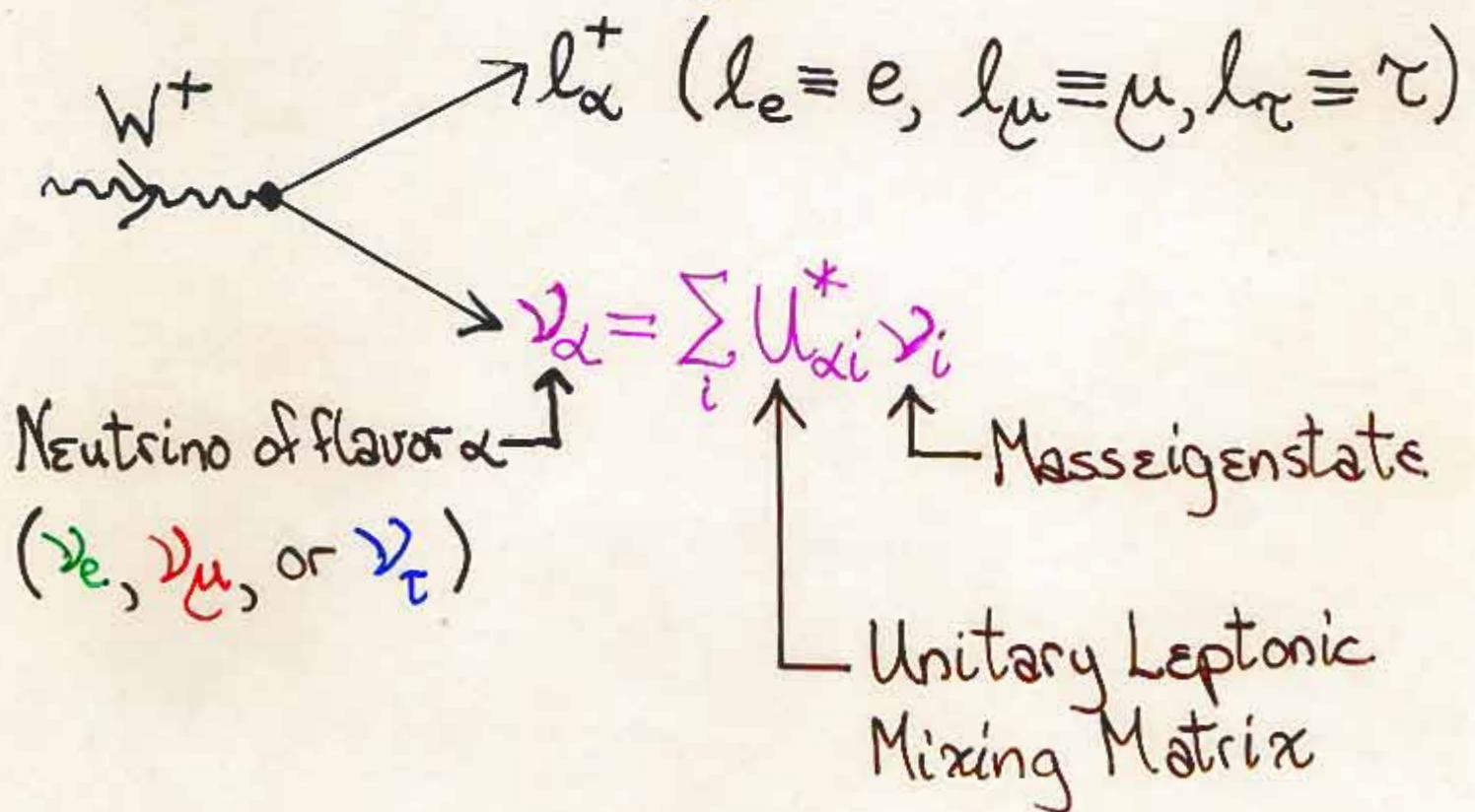
Do neutrino interactions violate CP?

Is leptonic ~~CP~~ responsible for the baryon asymmetry in the universe?

Are there surprises?

- Rapid  $\nu$  decay?
- Non-Standard-Model  $\nu$  interactions?
- ???

## Leptonic Mixing



$$\nu_i = \sum_\alpha U_{\alpha i} \nu_\alpha$$

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

## c.) What Have We Already Learned?

We do **not** know how many neutrino mass eigenstates  $\nu_i$  there are.

Assuming CPT, confirmation of LSND by MiniBooNE would imply there are more than 3.

The reason:

<u>Neutrinos</u>	<u>Required <math>\Delta m^2</math> (eV<sup>2</sup>)</u>
Solar	$10^{-(4-5)}$
Atmospheric	$\sim 10^{-3}$
LSND	$\sim 1$

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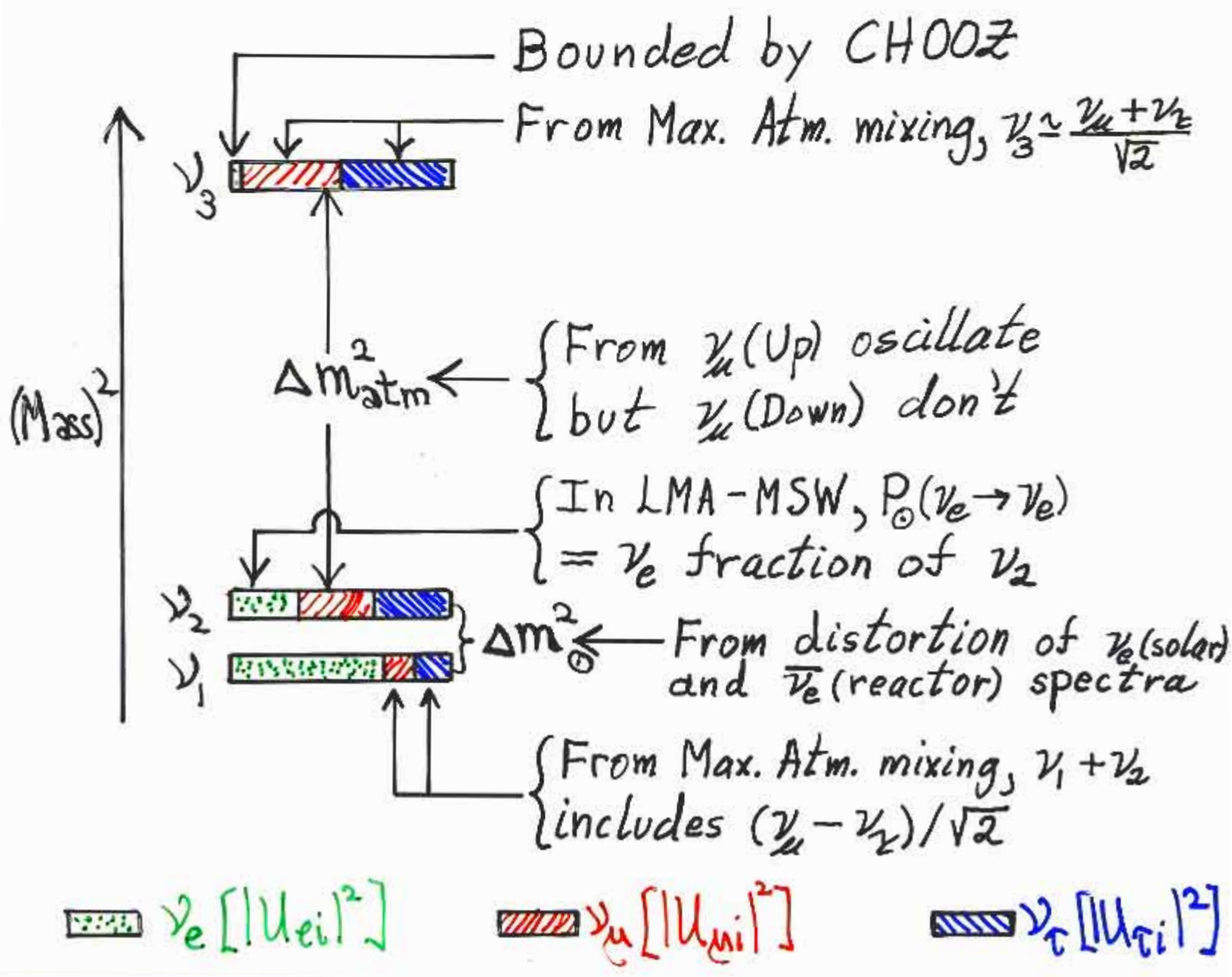
Only 3 neutrinos  $\Rightarrow$  (Mass)<sup>2</sup>  $\uparrow$   $\equiv$

$$\Rightarrow \Delta m_{\text{LSND}}^2 = \Delta m_{\text{atm}}^2 + \Delta m_{\odot}^2.$$

Q.3) If LSND is not confirmed, nature may contain only 3 neutrinos.

Then the spectrum looks like  $\begin{matrix} \text{---} \\ \text{=} \\ \text{---} \end{matrix}$  or  $\begin{matrix} \text{=} \\ \text{---} \\ \text{---} \end{matrix}$ .

If it is like  $\begin{matrix} \text{---} \\ \text{=} \\ \text{---} \end{matrix}$  :

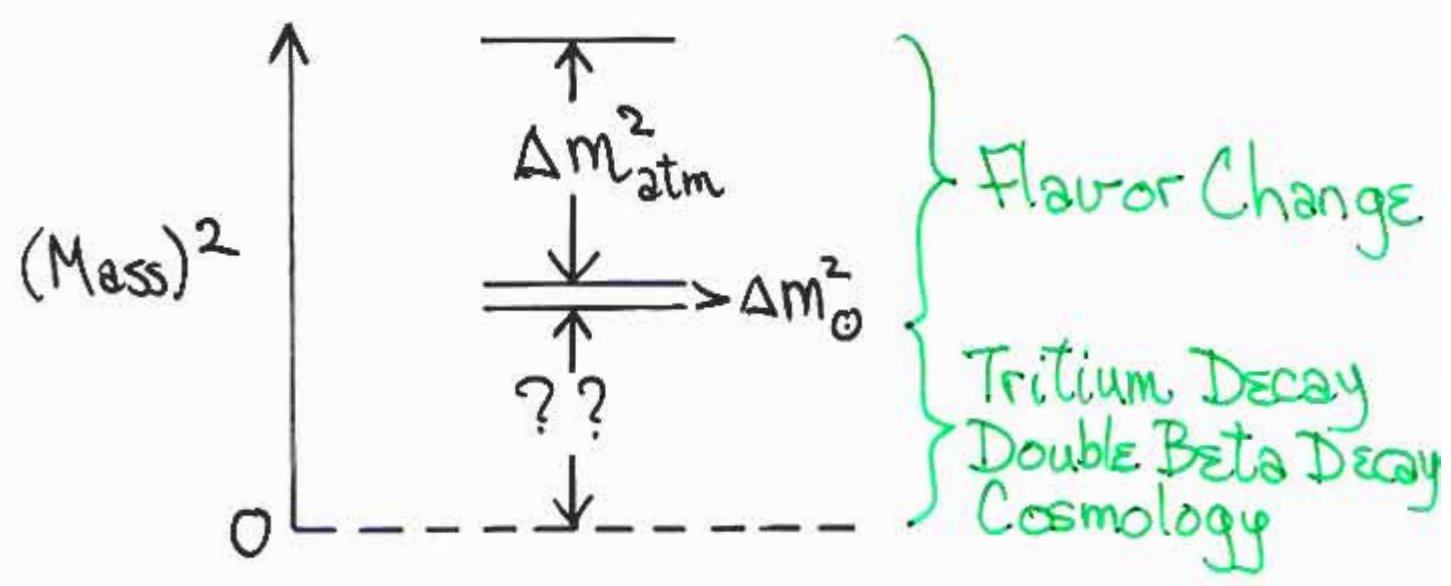


# A.7] The Future — Open Questions

\* How many neutrino species are there?  
Do sterile neutrinos exist?

MiniBooNE

\* What are the masses of the mass eigenstates  $\nu_i$ ?



Is the spectral pattern  $\begin{matrix} - \\ = \end{matrix}$  or  $\begin{matrix} = \\ - \end{matrix}$  ?

GUTS:  $\begin{matrix} - \\ = \end{matrix}$  (Albright)       $\begin{matrix} = \\ - \end{matrix}$  : Symmetry (Babu & Mohapatra)

## A.12] Why Is $\equiv$ vs. $\equiv$ Interesting?

For a given center of gravity,

$\equiv$  involves more **degeneracy** than  $\equiv$ .

**Degeneracy** could be caused by an underlying **symmetry**.

In the simplified limit of  $\equiv$  with  $\equiv$

- $\Delta m_{21}^2 = 0$  &  $m_3 = 0$
- $\theta_{atm}$  &  $\theta_{\odot}$  maximal;  $\theta_{13} = 0$
- Only Majorana masses

$\tilde{L} \equiv L_e - L_{\mu} - L_{\tau}$  is conserved.  
(Babu & Mohapatra)

$\tilde{L}$  conservation forbids  $\text{Nucl} \rightarrow \text{Nucl}' + 2e^-$ .

But don't worry:  $\theta_{\odot}$  is not maximal.

## How $\overset{\text{---}}{=}$ vs. $\overset{=}{\text{---}}$ May Be Determined

We determined that  $m(K_L) > m(K_S)$  by  $\text{---}$

- Passing kaons through matter (Regenerator)
- Beating the unknown  $\text{Sign}[m(K_L) - m(K_S)]$  against the known  $\text{Sign}[\text{Regeneration Amp.}]$

We will determine

$$\text{Sign}[m^2(\text{---}) - m^2(\overset{=}{\text{---}})] = S$$

by  $\text{---}$

- Passing neutrinos through matter (Earth)
- Beating the unknown sign  $S$  against the known  $\text{Sign}[\text{forward } \nu_e e \rightarrow \nu_e e \text{ Amp.}]$

At superbeam energies  $E \approx 2 \text{ GeV}$ ,

$$\sin^2 2\theta_{13} [\text{In Earth}] \cong \sin^2 2\theta_{13} \left[ \overset{\nu}{\downarrow} \underset{\bar{\nu}}{\uparrow} \left( 1 \pm S \frac{E}{6 \text{ GeV}} \right) \right].$$

## B.8] A Cosmic Connection

WMAP + Other Cosmological Data  
+ Cosmological Assumptions

$$\Rightarrow \sum_i m_i < 0.71 \text{ eV.}$$

Mass ( $\nu_i$ )

(95% CL  
Spergel et al.)

If there are only 3 neutrinos,

$$0.04 \text{ eV} \lesssim \text{Mass [Heaviest } \nu_i] < 0.23 \text{ eV}$$

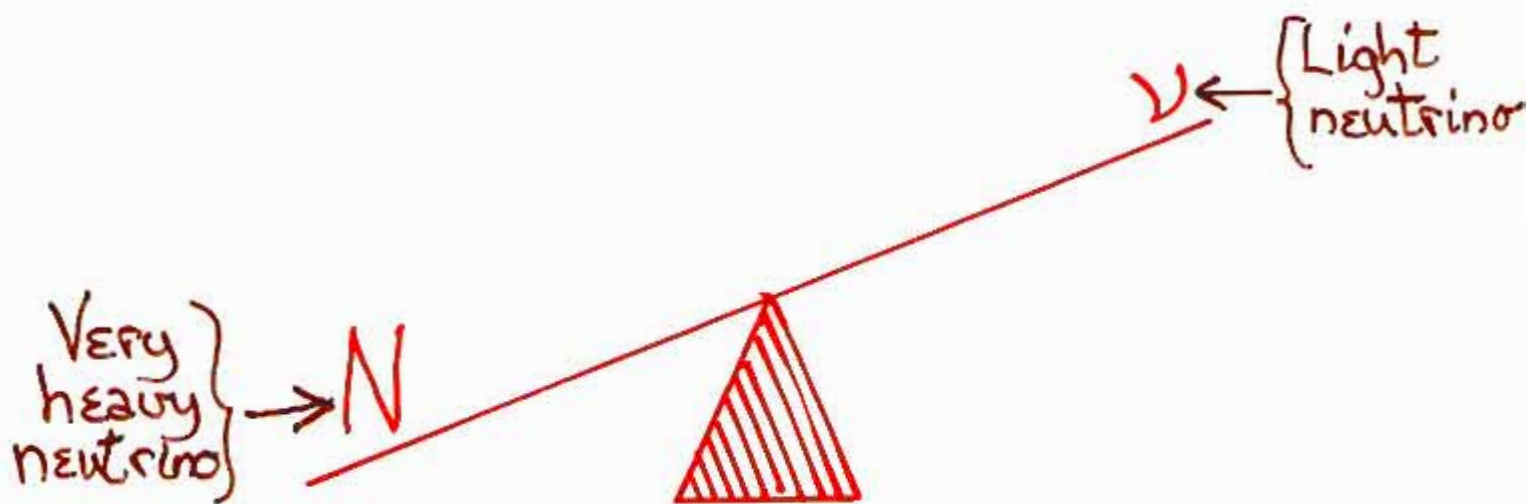
$$\sqrt{\Delta m_{\text{atm}}^2}$$

Cosmology

\* Why are  $\nu$  masses  $\ll$  quark and charged lepton masses?

An outstanding answer  $\rightarrow$

The See-Saw mechanism



$$m_\nu m_N \sim m_{\text{quark or charged lepton}}^2$$

(Gell-Mann, Ramond, Slansky; Yanagida)

Perhaps  $\cancel{CP}$  in  $N$  decays led to the baryon asymmetry of the universe.

(Fukugita & Yanagida)

SK.2)

The see-saw mechanism grows out of naturally expected

Majorana ( $\nu \leftrightarrow \bar{\nu}$ ) mass terms.

Majorana mass terms violate  $L$ , the lepton number that distinguishes antileptons from leptons.

Then there is no conserved  $L$  to distinguish a mass eigenstate  $\nu_i$  from  $\bar{\nu}_i$ , or  $N_i$  from  $\bar{N}_i$ . Hence —

$$\bar{\nu}_i = \nu_i$$

$$\bar{N}_i = N_i$$

Majorana Neutrinos

With this in mind —

SK3 \* Is each light mass eigenstate —

- A Majorana particle  
( $\bar{\nu}_i = \nu_i$ ; No conserved  $L$ )

or

- A Dirac particle  
( $\bar{\nu}_i \neq \nu_i$ ;  $L(\bar{\nu}_i) = -L(\nu_i)$ ) ?

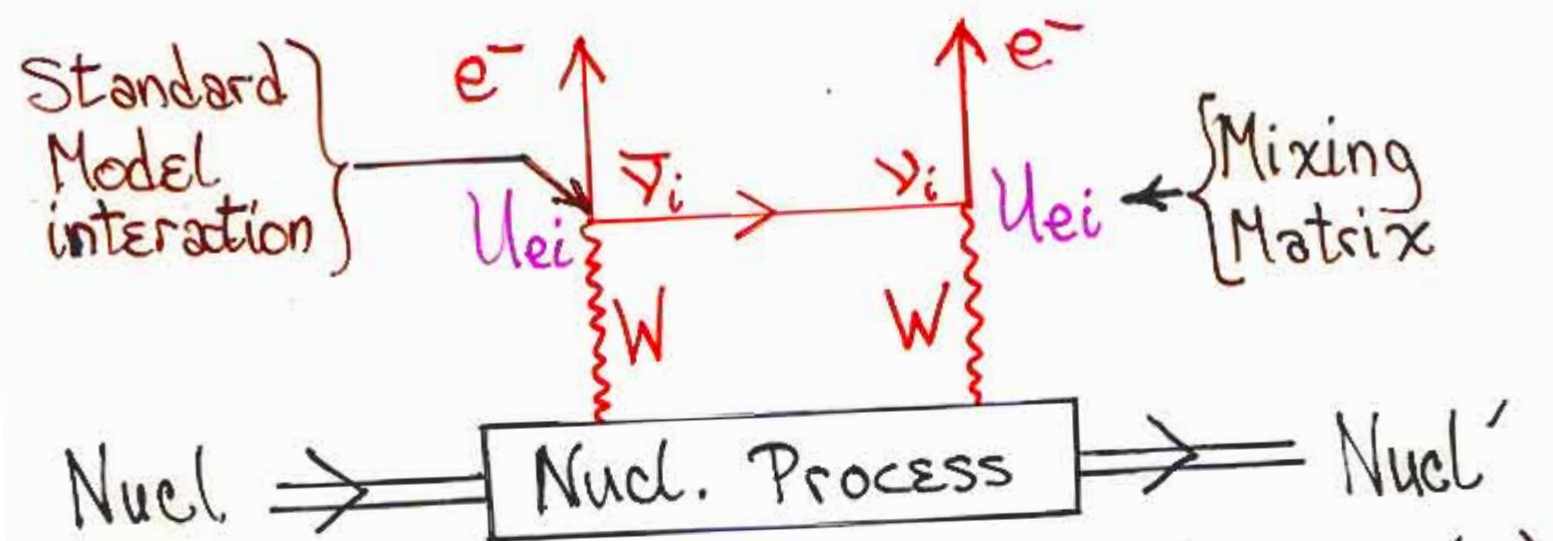
$0\nu\beta\beta$  [Nucl  $\rightarrow$  Nucl' +  $2e^-$ ]

$\Rightarrow$   ~~$L$~~ ;  $\bar{\nu}_i = \nu_i$ ; a Majorana mass term

Quarks and charged leptons cannot have Majorana mass terms, since  $q \leftrightarrow \bar{q}$  would not conserve electric charge.

Rate[ $0\nu\beta\beta$ ]  $\neq 0 \Rightarrow$  The physics of  $\nu$  masses is unlike the physics of the masses of all other fermions.

1.8] The dominant mechanism is expected to be—



$\bar{\nu}_i$  is emitted  $[RH + \mathcal{O}(\frac{m_i}{E}) LH]$   $\xrightarrow{\text{Mass}(\nu_i)}$

$\therefore \text{Amp}[\nu_i \text{ contribution}] \propto m_i$

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

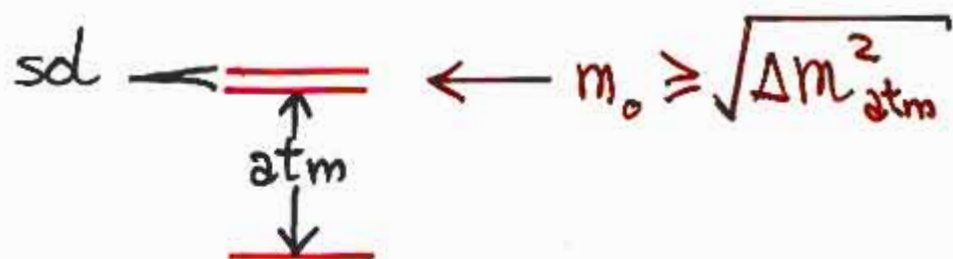
$0\nu\beta\beta$  violates  $L$ . Standard Model interactions conserve  $L$ . The  $L$  in  $0\nu\beta\beta$  comes from underlying Majorana mass terms.

$\therefore \text{Amp}[0\nu\beta\beta] \propto \nu \text{ mass}$

SK.4]

Desirable sensitivity:  $m_{\beta\beta} \sim 10$  meV.

If the spectrum looks like —



then —

$$m_{\beta\beta} \geq m_0 \cos 2\theta_0.$$

At 90% CL,

$$m_0 > 43 \text{ meV} \quad (\text{SuperK L/E analysis})$$

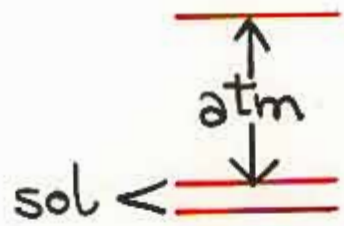
$$\cos 2\theta_0 > 0.28 \quad (\text{SNO}),$$

so

$$m_{\beta\beta} > 12 \text{ meV}.$$

10

If the spectrum looks like -



then

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

(Petcov et al.)

### Analyses of $m_{\beta\beta}$ vs. Neutrino Parameters

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

Review of  $\beta\beta$  Decay: Elliott & Vogel

\* What is the leptonic mixing matrix  $U$ ?

For 3 neutrinos -

$$U = \begin{matrix} \text{Atmospheric} \\ \begin{bmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{bmatrix} \end{matrix} \times \begin{matrix} \text{Cross-Mixing} \\ \begin{bmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{bmatrix} \end{matrix} \\
 \times \begin{matrix} \text{Solar} \\ \begin{bmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{bmatrix} \end{matrix} \times \begin{matrix} \text{Majorana } \cancel{\text{CP}} \text{ Phases} \\ \begin{bmatrix} e^{i\frac{\alpha_1}{2}} & 0 & 0 \\ 0 & e^{i\frac{\alpha_2}{2}} & 0 \\ 0 & 0 & 1 \end{bmatrix} \end{matrix}$$

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

$$\theta_{23} \approx \theta_{\text{atm}} \quad , \quad \theta_{12} \approx \theta_{\odot}$$

$\delta, \alpha_1, \alpha_2$  are  $\cancel{\text{CP}}$  phases.

Only  $\delta$  can affect neutrino oscillation.  
All effects of  $\delta$  depend on  $\sin \theta_{13}$ .

c.4] The 90% CL mixing-angle ranges —

$$\sin^2 2\theta_{\text{atm}} > 0.9 \quad (\text{Super-K})$$

$$0.73 \lesssim \sin^2 2\theta_{\odot} \lesssim 0.92 \quad (\text{SNO})$$

$$\sin^2 2\theta_{13} \lesssim 0.2 \quad (\text{CHOOZ})$$

Clearly,  $\theta_{\text{atm}}$  and  $\theta_{\odot}$  are large, unlike any quark mixing angles.

But what is  $\theta_{13}$ ? How small is it??

Both  $\mathcal{CP}$  in oscillation and the possibility of telling  $\overline{\nu\nu}$  from  $\nu\nu$  depend on  $\theta_{13}$ .

SK.5]

How Big Do We Expect  $\theta_{13}$  To Be?

Sorry —

The size of  $\theta_{13}$  is an  
experimental question.

## H.10 How $\theta_{13}$ May Be Measured

$\sin^2 \theta_{13} = |U_{e3}|^2$  is the small  $\nu_e$  piece of  $\nu_3$ .  $\nu_3$  is at one end of  $\Delta m_{atm}^2$ .

$\therefore$  We need an experiment with  $L/E$  sensitive to  $\Delta m_{atm}^2$ , and involving  $\nu_e$ .

### Possibilities

Reactor  $\bar{\nu}_e$  disappearance while traveling  $L \sim 1 \text{ km}$ .

Accelerator  $\nu_\mu \rightarrow \nu_e$  or  $\nu_e \rightarrow \nu_\mu$  while traveling  $L > \text{Several hundred km}$ .

W.9 \* Do neutrino interactions violate CP?

$$\text{Prob}(\bar{\nu}_\alpha \rightarrow \bar{\nu}_\beta) = \text{Prob}(\nu_\alpha \rightarrow \nu_\beta; U \rightarrow U^*)$$

$\delta$  leads to -

$$\text{Prob}(\bar{\nu}_\alpha \rightarrow \bar{\nu}_\beta) \neq \text{Prob}(\nu_\alpha \rightarrow \nu_\beta).$$

↑ CP

Demonstrating that ~~CP~~ in oscillation is nonzero would establish that ~~CP~~ is not a peculiarity of quarks.

Leptonic ~~CP~~ might have been the ~~CP~~ that made baryogenesis possible.

## SK.7] Nature May Surprise Us

MiniBooNE is exploring the number of neutrino species.

MiniBooNE is a Short Baseline (SBL)  $\nu_\mu \rightarrow \nu_e$  oscillation search sensitive to  $\Delta m^2 \gtrsim \mathcal{O}(1 \text{ eV}^2)$ . It seeks to confirm or refute LSND.

Most theorists today:

MiniBooNE will refute LSND.

Most theorists five years ago:

Leptonic mixing angles will prove to be small.

## Suppose MiniBooNE Sees a $\nu_{\mu} \rightarrow \nu_e$ Signal (B.K. & S. Parke)

There will be questions to answer, such as —

- \* Is the  $\nu_{\mu} \rightarrow \nu_e$  signal consistent with the LSND  $\bar{\nu}_{\mu} \rightarrow \bar{\nu}_e$  signal?
- \* How many large oscillation frequencies  $\Delta m^2$  are involved? Just one ( $4\nu_i$ ), or more ( $>4\nu_i$ )?

There will be implications for the Long Baseline (LBL) and reactor experiments:

SK.9]

LBL  $\nu_\mu \rightarrow \nu_e$  experiments may see oscillation coming from both  $\Delta m_{atm}^2$  and  $\Delta m_{LSND}^2$ .

Reactor  $\bar{\nu}_e$  disappearance experiments sensitive to  $\Delta m_{atm}^2$  effects may see disappearance due to  $\Delta m_{LSND}^2$  as well.

If there are  $N$  mass eigenstates  $\nu_i$  —

- $U$  is  $N \times N$

- There are  $N-1$  independent

$$\Delta m_{ij}^2 \equiv m_i^2 - m_j^2$$

## III Implications for CP

CP in  $\nu$  oscillation requires at least 3 nondegenerate  $\nu_i$ .

When there are only 3  $\nu_i$ ,  $\text{CP} \propto \Delta m_{21}^2$ .

When there are 4  $\nu_i$ , there are new CP effects that remain even when  $\Delta m_{21}^2 \rightarrow 0$ .

Where are these new effects most significant?

SK.101

Suppose there are 4  $\nu_i$ .

If we neglect  $m_2^2 - m_1^2 \equiv \Delta m_{21}^2$  and small matter effects,

$$\begin{aligned}
P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e) = & 4 \left\{ |U_{\mu 4} U_{e 4}|^2 \sin^2 \Delta_{41} + |U_{\mu 3} U_{e 3}|^2 \sin^2 \Delta_{31} \right. \\
& + 2 |U_{\mu 4} U_{e 4} U_{\mu 3} U_{e 3}| \sin \Delta_{41} \sin \Delta_{31} \cos \Delta_{43} \cos \delta_{CP} \\
& \left. + 2 |U_{\mu 4} U_{e 4} U_{\mu 3} U_{e 3}| \sin \Delta_{41} \sin \Delta_{31} \sin \Delta_{43} \sin \delta_{CP} \right\}.
\end{aligned}$$

Here,

$$\Delta_{ij} \equiv \Delta m_{ij}^2 \frac{L}{4E} \quad \text{and} \quad \delta_{CP} \equiv \arg(U_{\mu 4} U_{e 4}^* U_{\mu 3}^* U_{e 3}).$$

SK.111

Example: 3+1

— 4

$$\Delta_{41} = \Delta_{\text{LSND}}$$

1+2 = 3

$$\Delta_{31} = \Delta_{\text{atm}}$$

The CP-odd term is maximal, and potentially quite significant, where

$$\Delta_{\text{atm}} = \Delta_{31} = \frac{\pi}{4}.$$

$$-2 \langle \sin \Delta_{41} \sin \Delta_{31} \sin \Delta_{43} \rangle_E \sin \delta_{\text{CP}}$$

$$= -\frac{1}{2} \langle \sin 2\Delta_{43} + \sin 2\Delta_{31} - \sin 2\Delta_{41} \rangle_E \sin \delta_{\text{CP}}$$

$$\approx -\frac{1}{2} \sin \delta_{\text{CP}} \quad \text{at} \quad \Delta_{31} = \frac{\pi}{4}.$$

Practical considerations such as the  $\sim \frac{1}{L^2}$  falling of beam fluxes may make another point a better place to work.

Inspired by the exciting discoveries in neutrino physics,  
But keenly aware of the need for a coherent plan for the future,

The American Physical Society Divisions of —

- ◆ **Particles and Fields**
- ◆ **Nuclear Physics**
- ◆ **Astrophysics**
- ◆ **Physics of Beams**

are sponsoring a year-long

## **STUDY OF THE PHYSICS OF NEUTRINOS**

Background information at: [www.neutrinooscillation.org/studyaps/](http://www.neutrinooscillation.org/studyaps/)

# The Structure of the Study

## Chairmen

Stuart Freedman, Boris Kayser

## Organizing Committee

Janet Conrad, Guido Drexlin,

Belen Gavella, Takaaki Kajita,

Paul Langacker, Keith Olive,

Bob Palmer, Georg Raffelt,

Hamish Robertson, Stan Wojcicki

Lincoln Wolfenstein

# Working Groups — The Central Element

Each working group is defined by an experimental approach.

The groups and their leaders —

## Solar and Atmospheric Neutrino Experiments

John Bahcall <jnb@ias.edu>, Josh Klein <jrk@physics.utexas.edu>

## Reactor Neutrino Experiments

Gabriela Barenboim <gabriela@fnal.gov>, Ed Blucher <blucher@hep.uchicago.edu>

## Superbeam Experiments and Development

Bill Marciano <marciano@bnl.gov>, Doug Michael <michael@hep.caltech.edu>

## Neutrino Factory and Beta Beam Experiments and Development

Stephen Geer <sgeer@fnal.gov>, Michael Zisman <mszisman@lbl.gov>

## Neutrinoless Double Beta Decay and Direct Searches for Neutrino Mass

Steve Elliott <elliotts@lanl.gov>, Petr Vogel <pxv@caltech.edu>

## What Cosmology/Astrophysics and Neutrino Physics can Teach Each Other

Steve Barwick <barwick@HEP.ps.uci.edu>, John Beacom <beacom@fnal.gov>

Theorists participate in all working groups.

They will also discuss issues like how best to use future measurements to discriminate among theoretical models.

Coordinator of theoretical discussions:

Rabi Mohapatra <[rmohapat@physics.umd.edu](mailto:rmohapat@physics.umd.edu)>

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International participation in the study is warmly encouraged!

To join any working group, just contact its leaders.

Contact information at —

[home.fnal.gov/~boris/NeutrinoStudy2.ppt](http://home.fnal.gov/~boris/NeutrinoStudy2.ppt)

## Summary

The discovery of  $\nu$  mass and mixing has raised very interesting questions.

Let's go answer them!

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