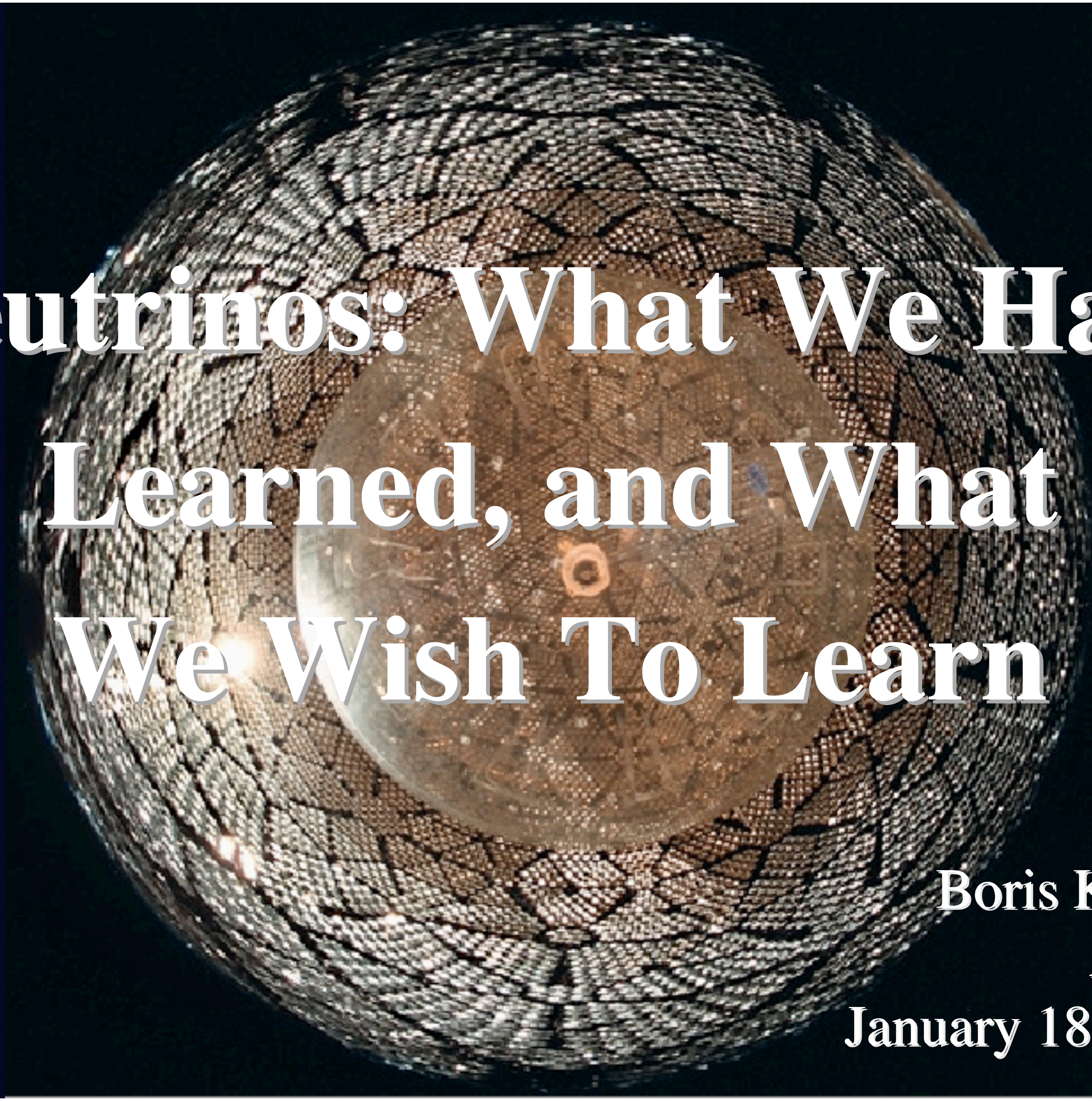
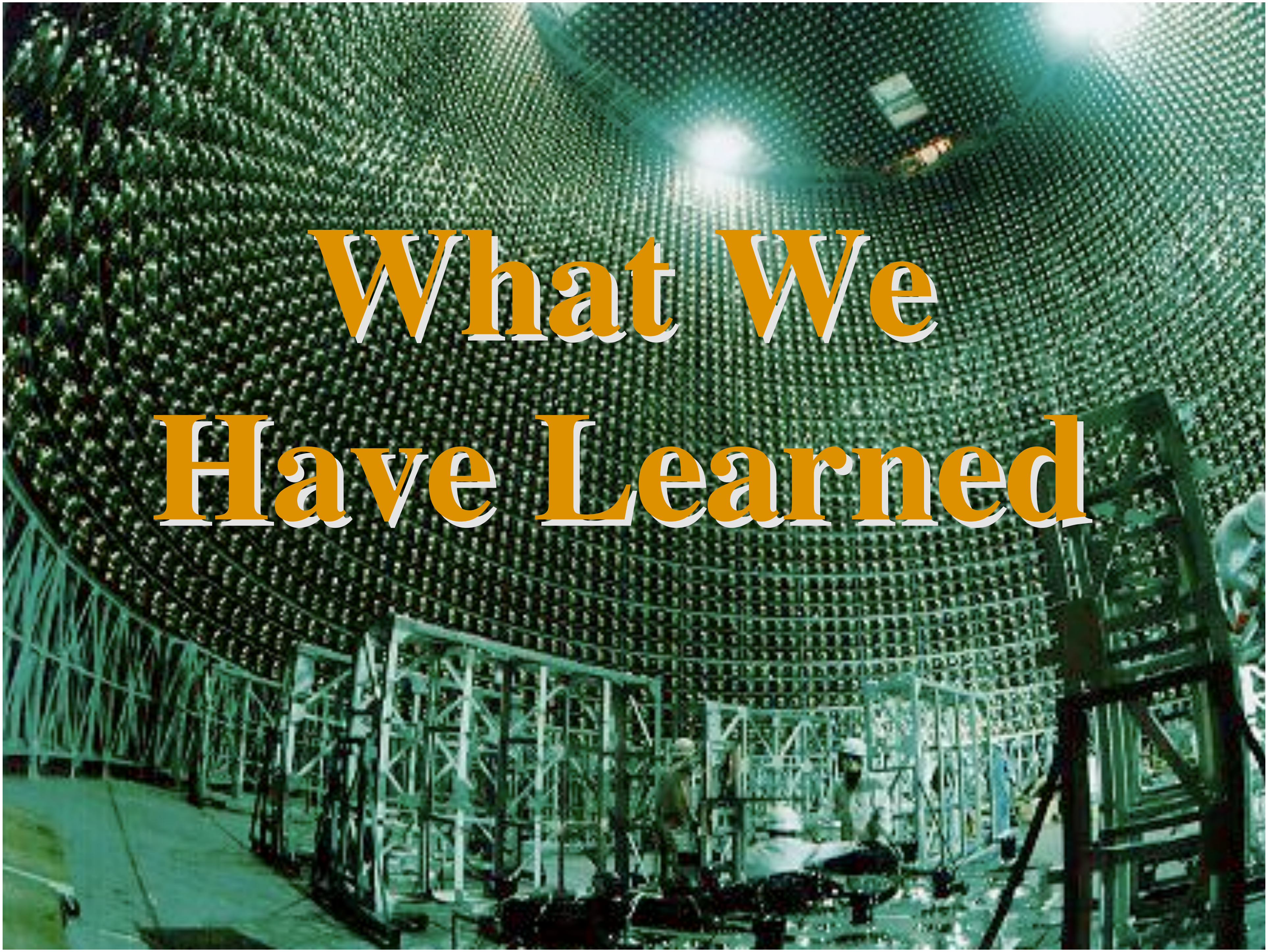
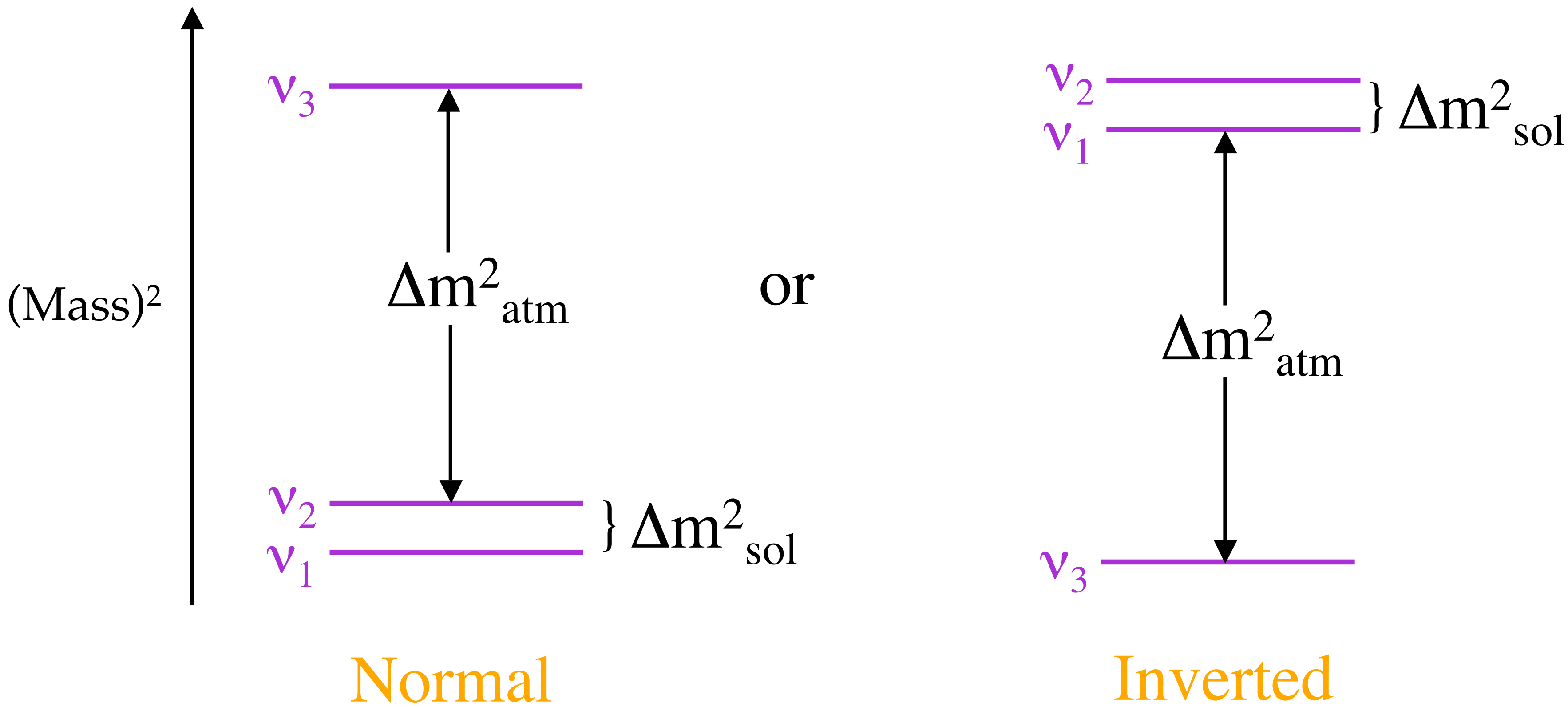


Neutrinos: What We Have Learned, and What We Wish To Learn

Boris Kayser
Aspen
January 18, 2008


What We
Have Learned

The (Mass)^2 Spectrum



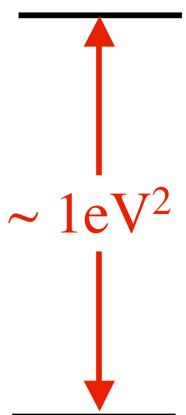
$\Delta m^2_{sol} \cong 7.6 \times 10^{-5}\ eV^2$, $\Delta m^2_{atm} \cong 2.4 \times 10^{-3}\ eV^2$

Are There *More* Than 3 Mass Eigenstates?

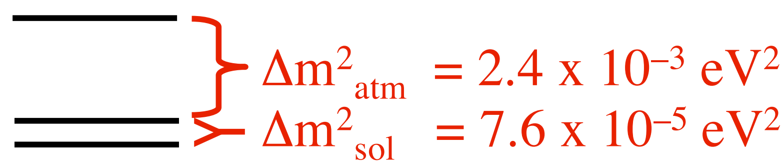
When only two neutrinos count,

$$P\left(\nu_\alpha \to \nu_\beta\right) = \sin^2 2\theta \sin^2\left[1.27\Delta m^2\left(eV^2\right)\frac{L(km)}{E(GeV)}\right]$$

Rapid neutrino oscillation reported by LSND —



in contrast to

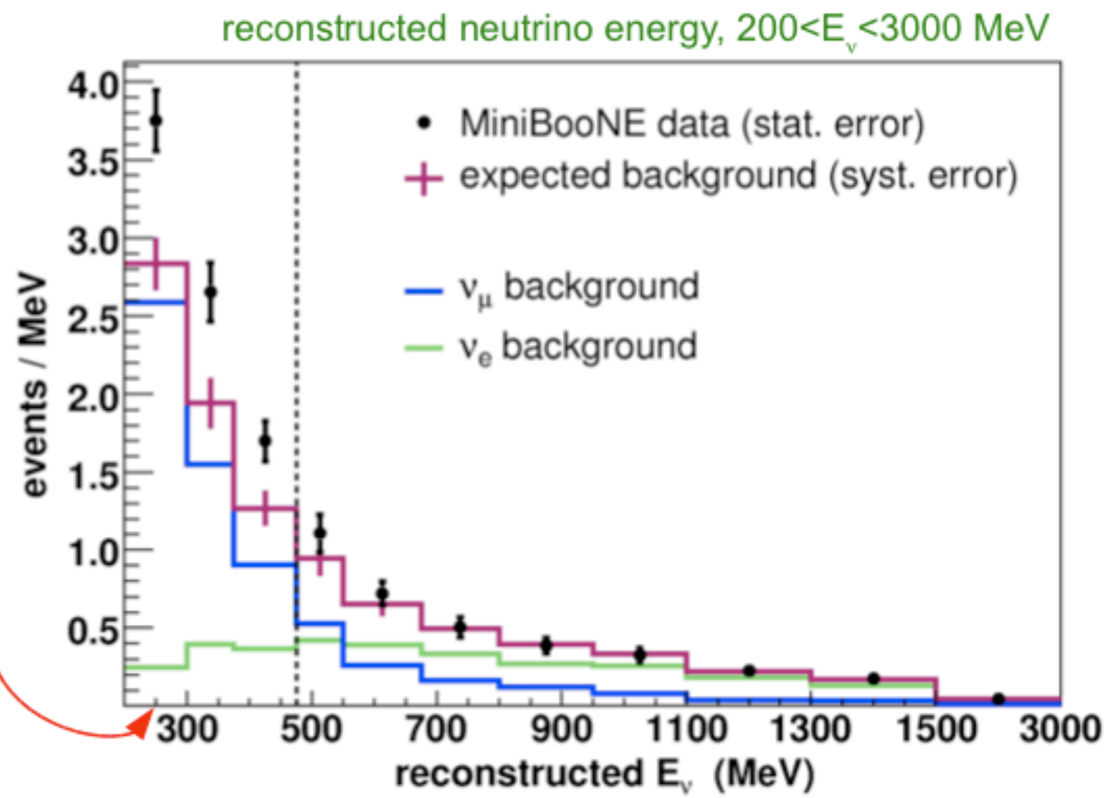


At least **4** mass eigenstates.

MiniBooNE Search for $\nu_\mu \rightarrow \nu_e$

R.Tayloe
at LP07

- NEW:
this energy bin



- No excess above background for energies $E_\nu > 475$ MeV.
- Unexplained excess for $E_\nu < 475$ MeV.
- Two-neutrino oscillation cannot fit LSND *and* MiniBooNE.
- More complicated fits are possible.

MiniBooNE in the NuMI Beam

*The MiniBooNE detector is illuminated by **both***
the MiniBooNE ν_μ beam, and
the NuMI ν_μ beam pointed at MINOS.

Distance to MiniBooNE —

L (from NuMI source) ≈ 1.4 L (from MiniBooNE source)

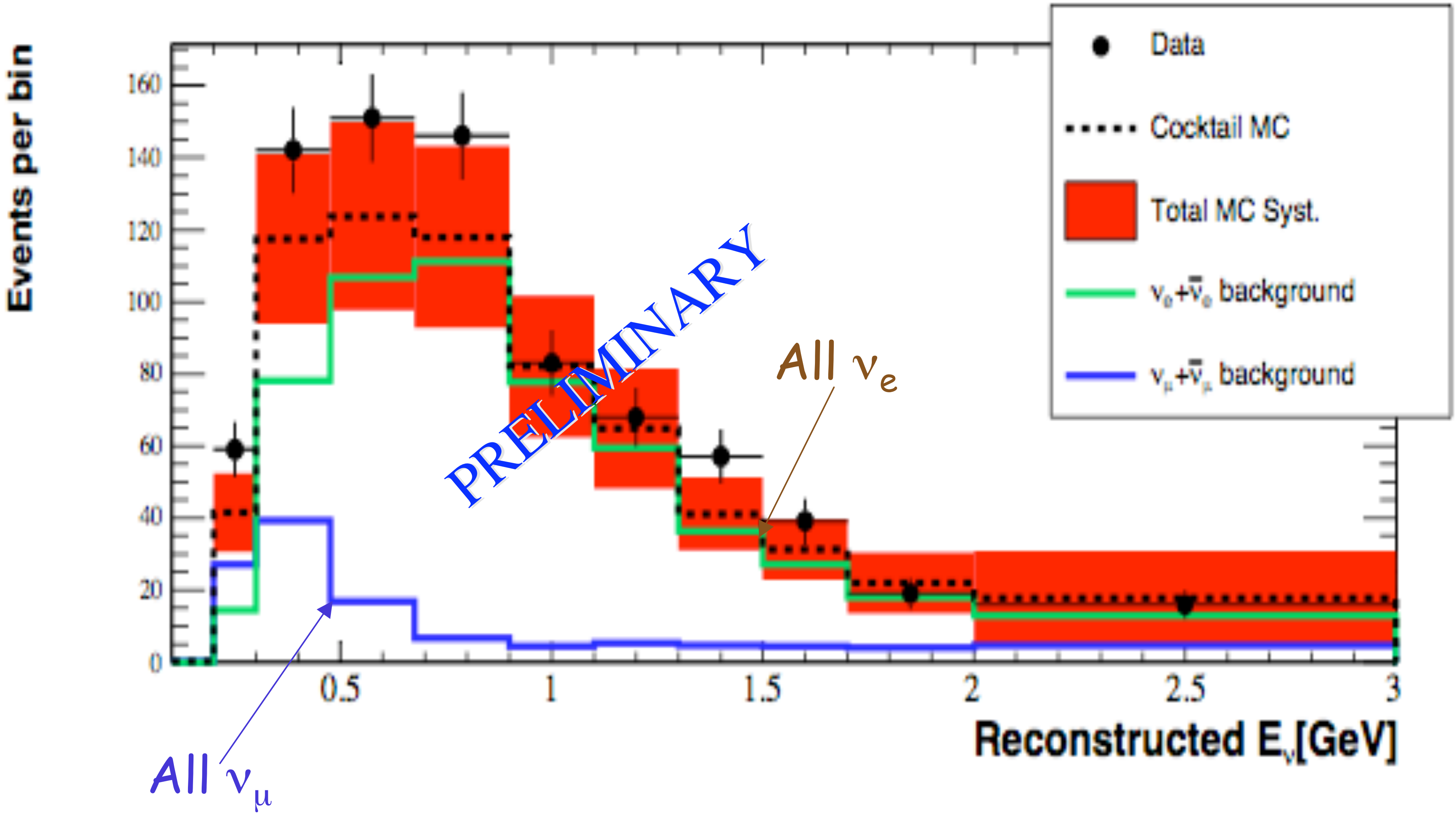
Neutrino oscillation depends on L and E only through L/E.

Therefore, if an anomaly seen at some E in the MiniBooNE-beam data is due to oscillation, it should appear at 1.4 E in the NuMI-beam data.

ν_e CCQE sample: Reconstructed energy E_ν of incoming ν

(Z. Djurcic, Dec. 11, 2007)

$$E_\nu^{QE} = \frac{1}{2}\frac{2M_pE_\ell - m_\ell^2}{M_p - E_\ell + \sqrt{(E_\ell^2 - m_\ell^2)}cos\theta_\ell}$$



To be continued …

Meanwhile, we will assume there are only 3 neutrino mass eigenstates.

Leptonic Mixing

This has the consequence that —

Mass eigenstate — Flavor eigenstate

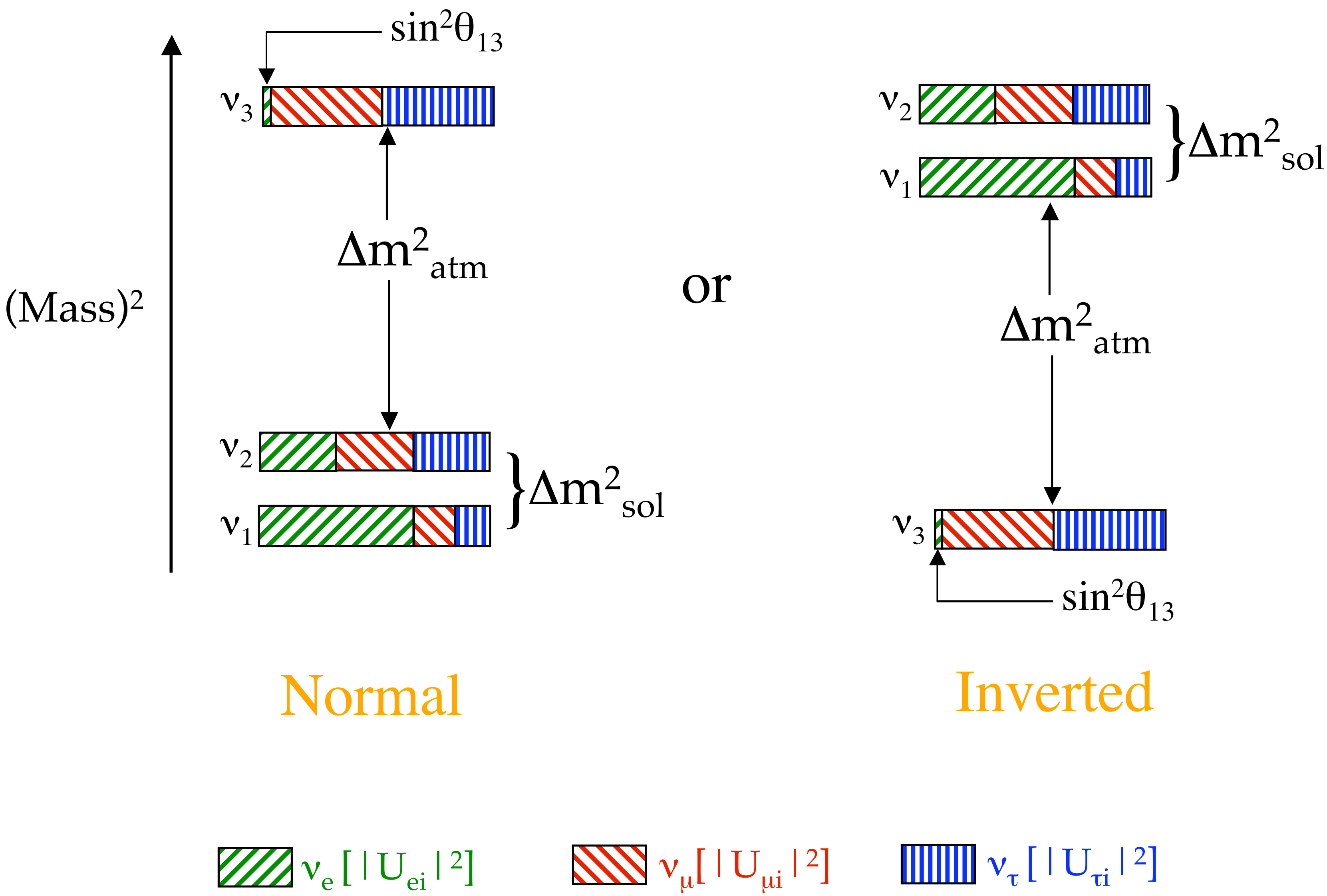
$$|\nu_i> = \sum_\alpha U_{\alpha i} \, |\nu_\alpha> \, .$$

MNS Leptonic Mixing Matrix

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

When a ν_i interacts and produces a charged lepton, the probability that this charged lepton will be of flavor α is $|U_{\alpha i}|^2$.

The spectrum, showing its approximate flavor content, is



The Mixing Matrix

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

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

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

$\theta_{12} \approx \theta_{sol} \approx 35°$, $\theta_{23} \approx \theta_{atm} \approx 37\text{-}53°$, $\theta_{13} \lesssim 10°$

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

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


The Open
Questions

- What is the absolute scale of neutrino mass?

- Are neutrinos their own antiparticles?

- 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 the spectrum like  or  ?

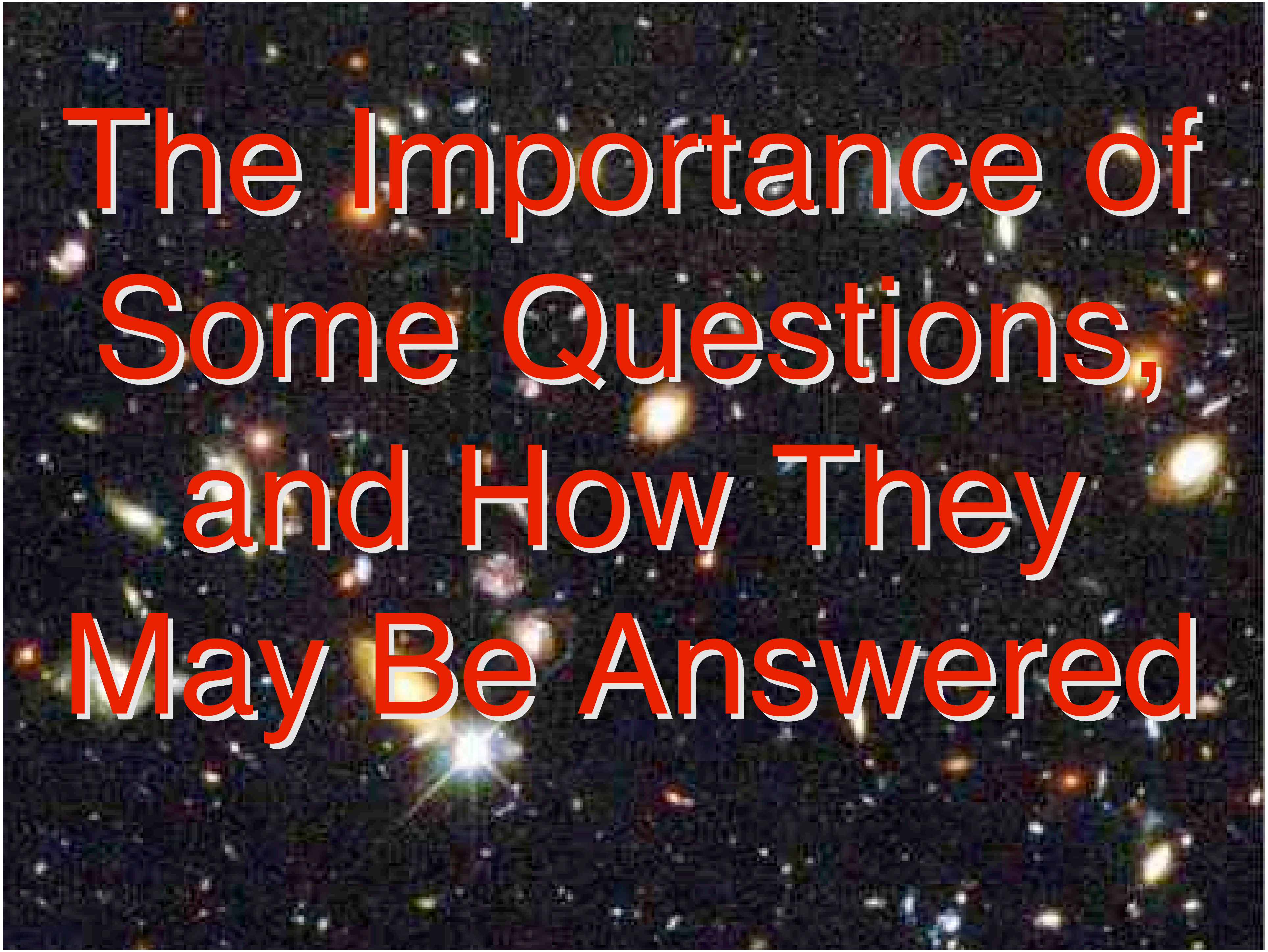
•Do neutrino – matter interactions violate CP?

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

- What physics is behind neutrino mass?


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

Does $\bar{\nu} = \nu$?

That is, for each *mass eigenstate* ν_i , does —

- $\overline{\nu_i} = \nu_i$ (Majorana neutrinos)

or

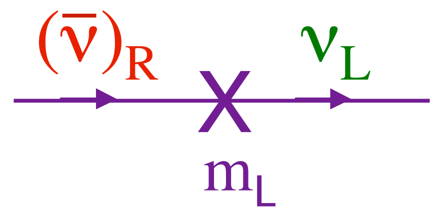
- $\overline{\nu_i} \neq \nu_i$ (Dirac neutrinos) ?

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

Majorana Masses

Out of, say, a left-handed neutrino field, ν_L, and its charge-conjugate, $\nu_L{}^c$, we can build a Majorana mass term —

$$m_L \overline{\nu_L}\, \nu_L{}^c$$



Quark and *charged-lepton* Majorana masses are forbidden by electric charge conservation.

Neutrino Majorana masses would make the neutrinos very distinctive.

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 $\nu_L \longleftrightarrow \nu_L{}^c$ 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 $\nu_L \longleftrightarrow \nu_L{}^c$ mixing, the neutrino mass eigenstate is —

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

To Determine If Neutrinos Have Majorana Masses

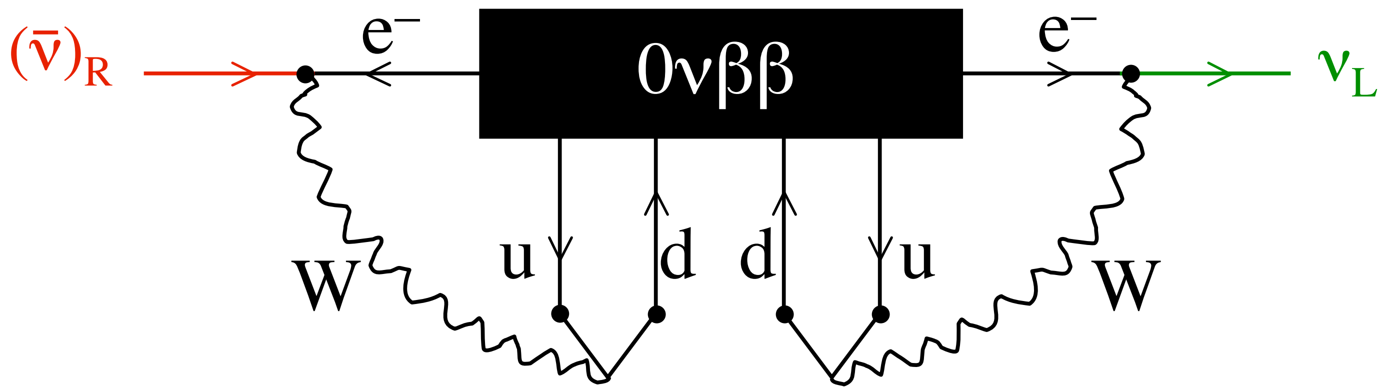
The Promising Approach —

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:

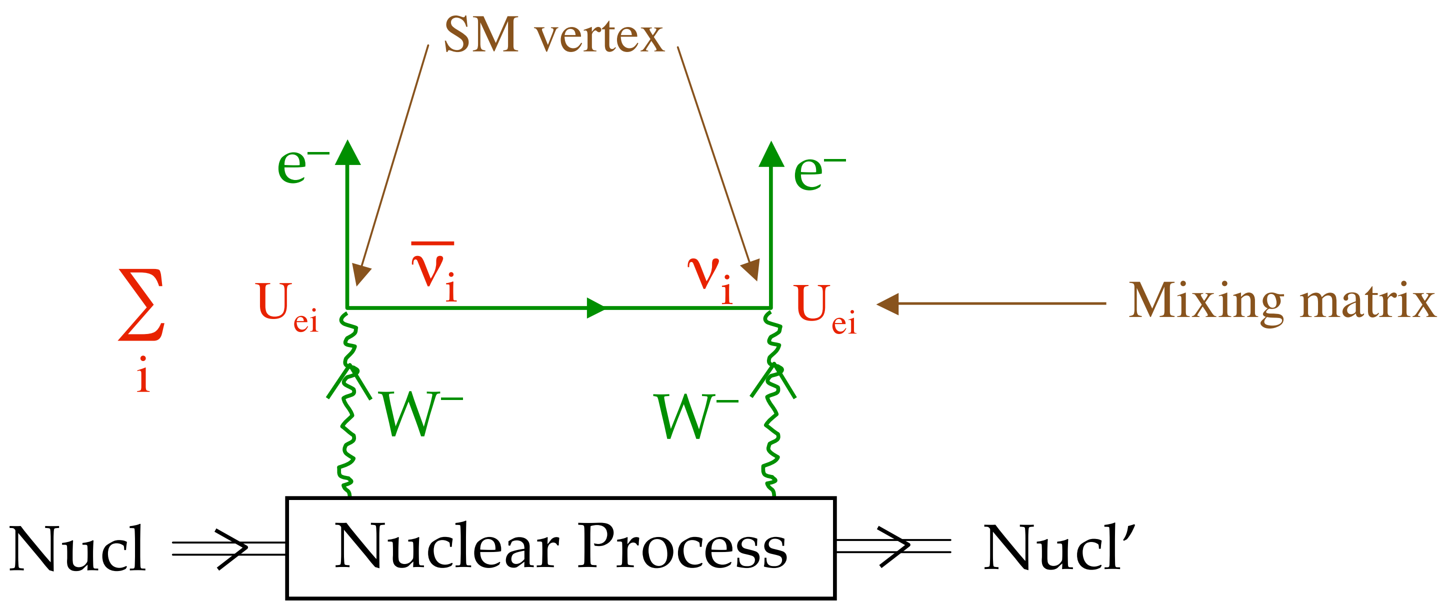
Schechter and Valle



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

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

We anticipate that $0\nu\beta\beta$ is dominated by a diagram with Standard Model vertices:



Then —

Mass (ν_i)

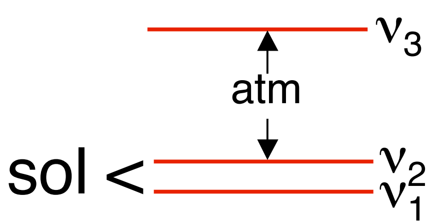
$$\mathrm{Amp}[0\nu\beta\beta] \propto \left| \sum m_i U_{ei}^2 \right| \equiv m_{\beta\beta}$$

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

How sensitive need an experiment be?

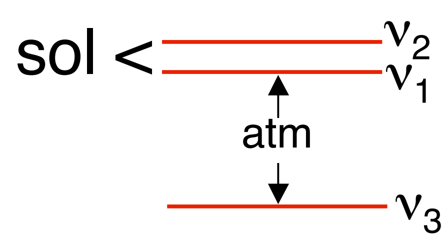
Suppose there are only 3 neutrino mass eigenstates. (More might help.)

Then the spectrum looks like —



Normal hierarchy

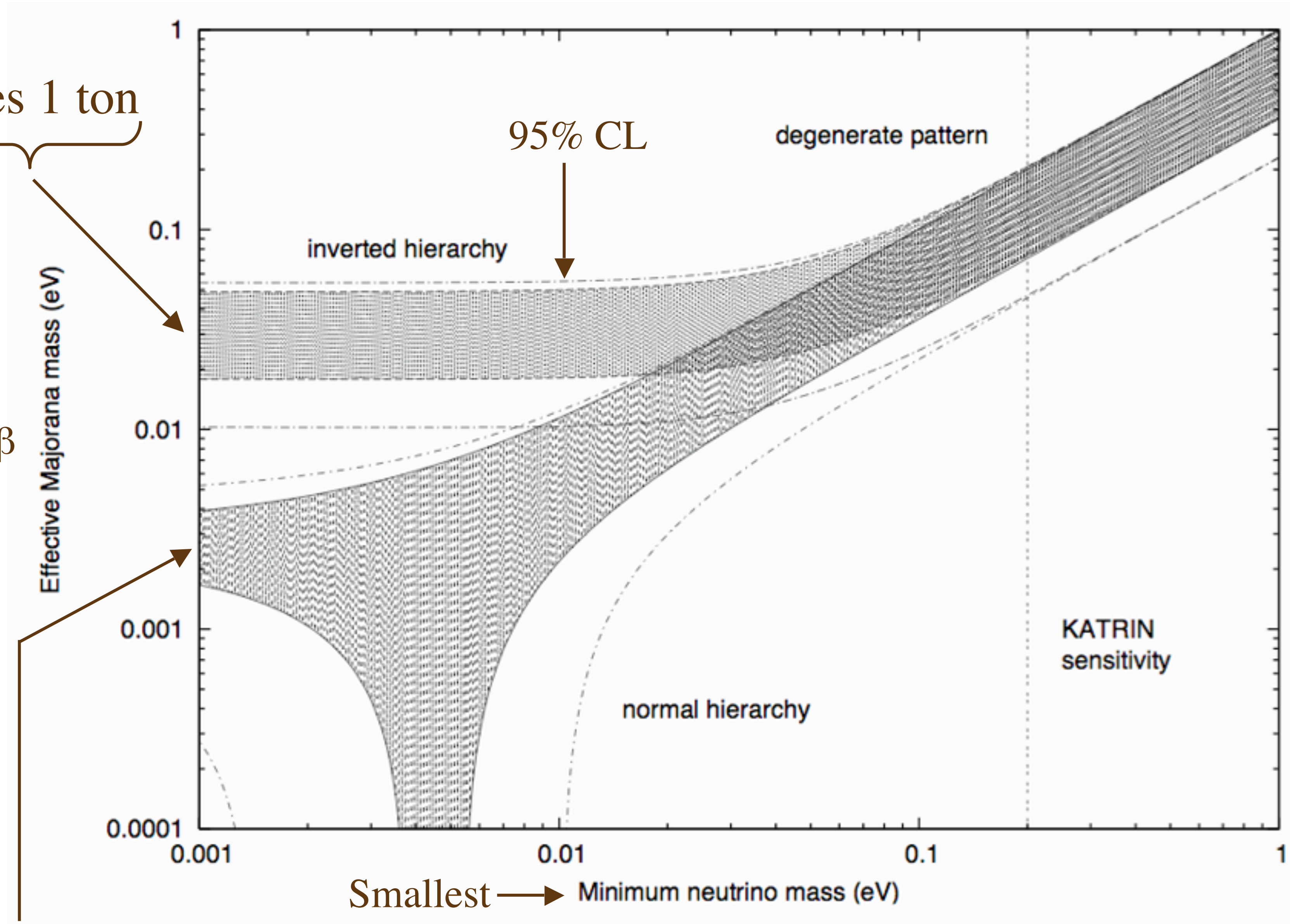
or



Inverted hierarchy

Takes 1 ton

$m_{\beta\beta}$



Takes
100 tons

$m_{\beta\beta}$ For Each Hierarchy

The Central Role of θ_{13}

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

If $\sin^2 2\theta_{13} > 10^{-(2\text{-}3)}$, we can study both of these issues with intense but conventional accelerator ν and $\bar{\nu}$ beams, produced via $\pi^+ \rightarrow \mu^+ + \nu_\mu$ and $\pi^- \rightarrow \mu^- + \bar{\nu}_\mu$.

Determining θ_{13} is an important step.

How θ_{13} May Be Measured

Reactor neutrino experiments are the cleanest way.

Accelerator neutrino experiments can also probe θ_{13} .
Now it is entwined with other parameters.

In addition, accelerator experiments can probe
whether the mass spectrum is normal or inverted,
and look for *CP violation*.

All of this is done by studying $\nu_\mu \to \nu_e$ and $\bar{\nu}_\mu \to \bar{\nu}_e$
while the beams travel hundreds of kilometers.

The Mass Spectrum:  or  ?

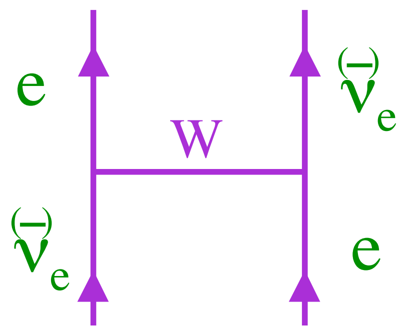
Generically, grand unified models (GUTS) favor

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,



affects ν and $\bar{\nu}$ oscillation ***(differently)***, and leads to —

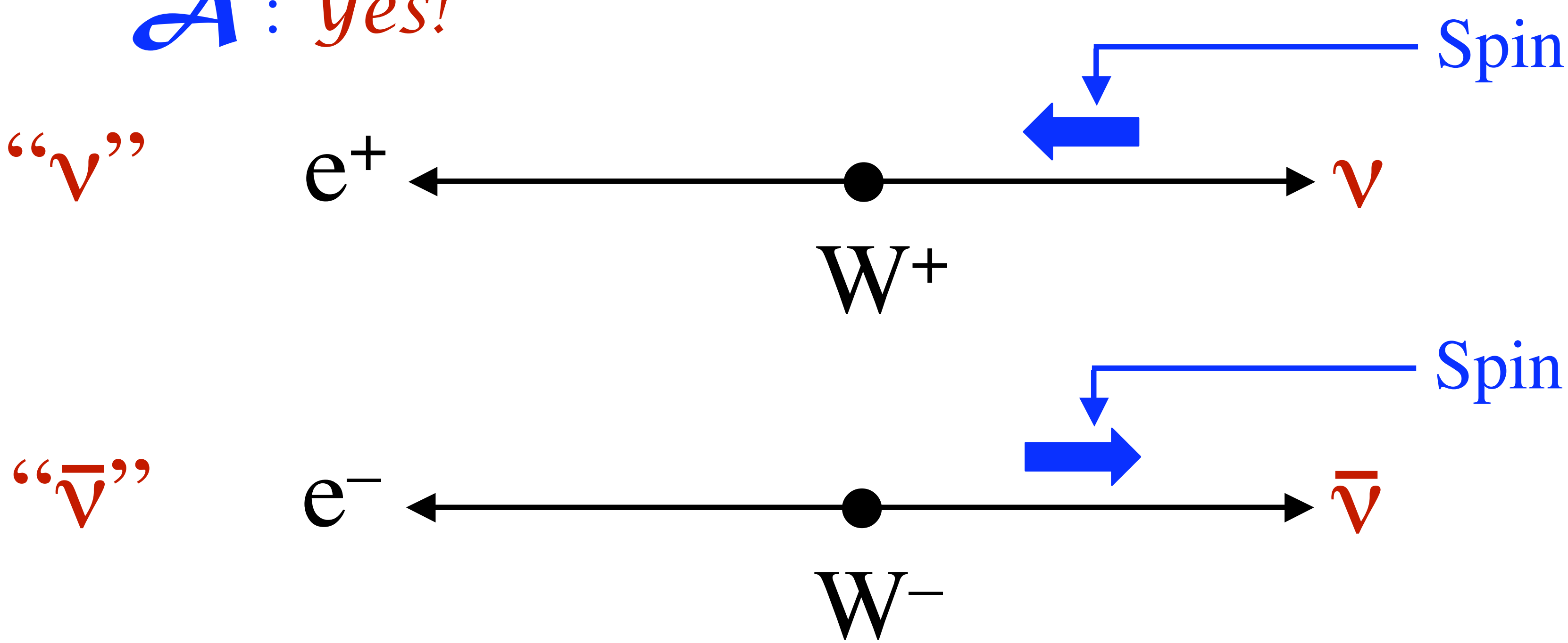
$$\frac{P(\nu_\mu \rightarrow \nu_e)}{P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e)} \begin{cases} > 1 \; ; \\ < 1 \; ; \end{cases}$$

Note fake ~~CP~~

Note dependence on the mass ordering

Q : *Does matter still affect ν and $\bar{\nu}$ differently when $\bar{\nu} = \nu$?*

A : *Yes!*



The weak interactions violate ***parity***. Neutrino – matter interactions depend on the neutrino ***polarization***.

Do Neutrino Interactions Violate CP?

The observed ~~CP~~ in the weak interactions of ***quarks*** cannot explain the *Baryon Asymmetry* of the universe.

Is ***leptonic*** ~~CP~~, through *Leptogenesis*, the origin of the *Baryon Asymmetry* of the universe?

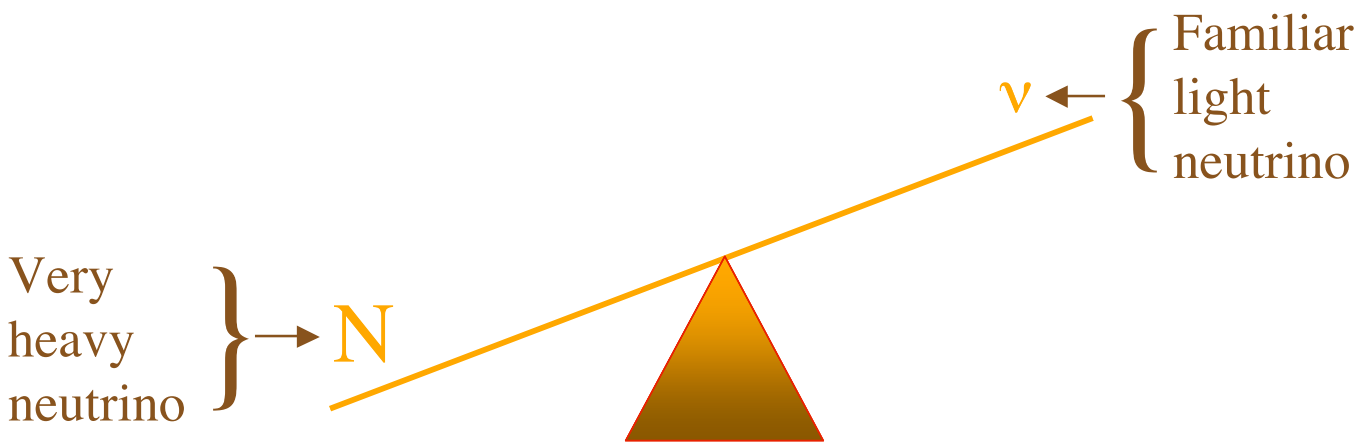
(Fukugita, Yanagida)

Leptogenesis In Brief

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

See-Saw Mechanism

(Yanagida; Gell-Mann, Ramond, Slansky; Minkowski)



The ***very*** 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. In the See-Saw, these two CP violations have a common origin.

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

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

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

Then, Standard-Model ***Sphaleron*** processes would have turned ~ 1/3 of this leptonic asymmetry into a *Baryon Asymmetry*.

How To Search for $\cancel{CP}$ In Neutrino Oscillation

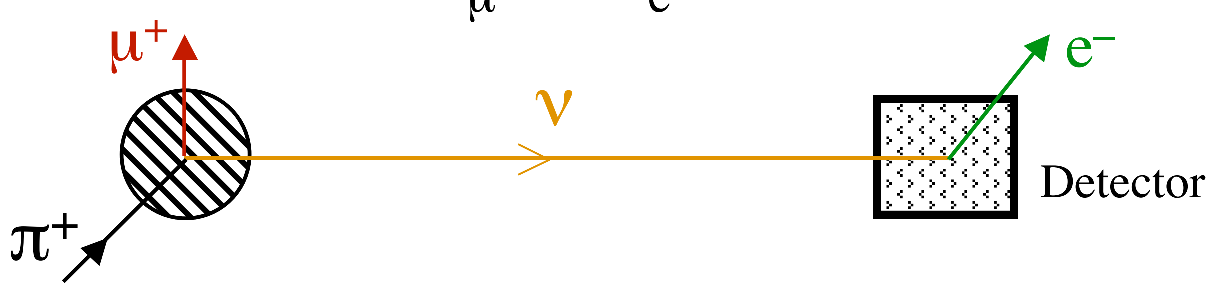
Look for $P(\bar{\nu}_\alpha \rightarrow \bar{\nu}_\beta) \neq P(\nu_\alpha \rightarrow \nu_\beta)$

Q : *Can CP violation still lead to*
$\mathcal{P}(\bar{\nu}_\mu \to \bar{\nu}_e) \neq \mathcal{P}(\nu_\mu \to \nu_e)$ *when* $\bar{\nu} = \nu$?

A : *Certainly!*

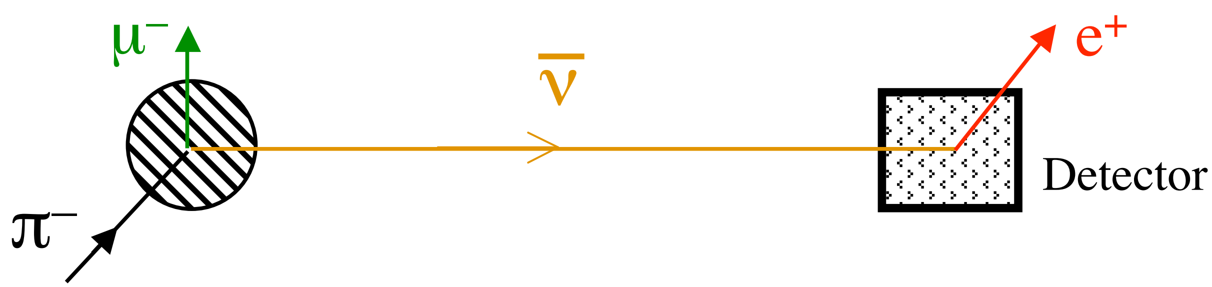
$\nu_\mu \to \nu_e$

Compare



“ $\bar{\nu}_\mu \to \bar{\nu}_e$ ”

with



Separating $\not{CP}$ From the Matter Effect

Genuine $\not{CP}$ and the matter effect both lead to a difference between ν and $\bar{\nu}$ oscillation.

But genuine $\not{CP}$ and the matter effect depend quite differently from each other on L and E.

One can disentangle them by making oscillation measurements at different L and/or E.

Accelerator $\overset{(-)}{\nu}$ Oscillation Probabilities

With $\alpha \equiv \Delta m^2_{21} / \Delta m^2_{31}$, $\Delta \equiv \dfrac{\Delta m^2_{31} L}{4E}$, and $x \equiv \dfrac{2\sqrt{2} G_F N_e E}{\Delta m^2_{31}}$ —

$$P\left[\nu_\mu \to \nu_e\right] \cong \sin^2 2\theta_{13}\, T_1 - \alpha \sin 2\theta_{13}\, T_2 + \alpha \sin 2\theta_{13}\, T_3 + \alpha^2\, T_4 \;;$$

$$T_1 = \sin^2\theta_{23} \frac{\sin^2\left[(1-x)\Delta\right]}{(1-x)^2}, \quad T_2 = \sin\delta \sin 2\theta_{12} \sin 2\theta_{23} \sin\Delta \frac{\sin(x\Delta)}{x} \frac{\sin\left[(1-x)\Delta\right]}{(1-x)},$$

$$T_3 = \cos\delta \sin 2\theta_{12} \sin 2\theta_{23} \cos\Delta \frac{\sin(x\Delta)}{x} \frac{\sin\left[(1-x)\Delta\right]}{(1-x)}, \quad T_4 = \cos^2\theta_{23} \sin^2 2\theta_{12} \frac{\sin^2(x\Delta)}{x^2}$$

$$P\left[\bar{\nu}_\mu \to \bar{\nu}_e\right] = P\left[\nu_\mu \to \nu_e\right] \text{ with } \delta \to -\delta \text{ and } x \to -x.$$

(Cervera *et al.*, Freund, Akhmedov *et al.*)

Strategies

The matter-effect parameter x has $|x| \approx E/12$ GeV.

At L/E of the 1st "atmospheric" oscillation peak, and $E \sim 1$ GeV, the effect of matter on the ***neutrino*** atmospheric oscillation term ($\sin^2 2\theta_{13}\, T_1$) is —

Normal

$$1/(1-x)^2 \cong 1 \pm (E/6\,\text{GeV})$$

Inverted

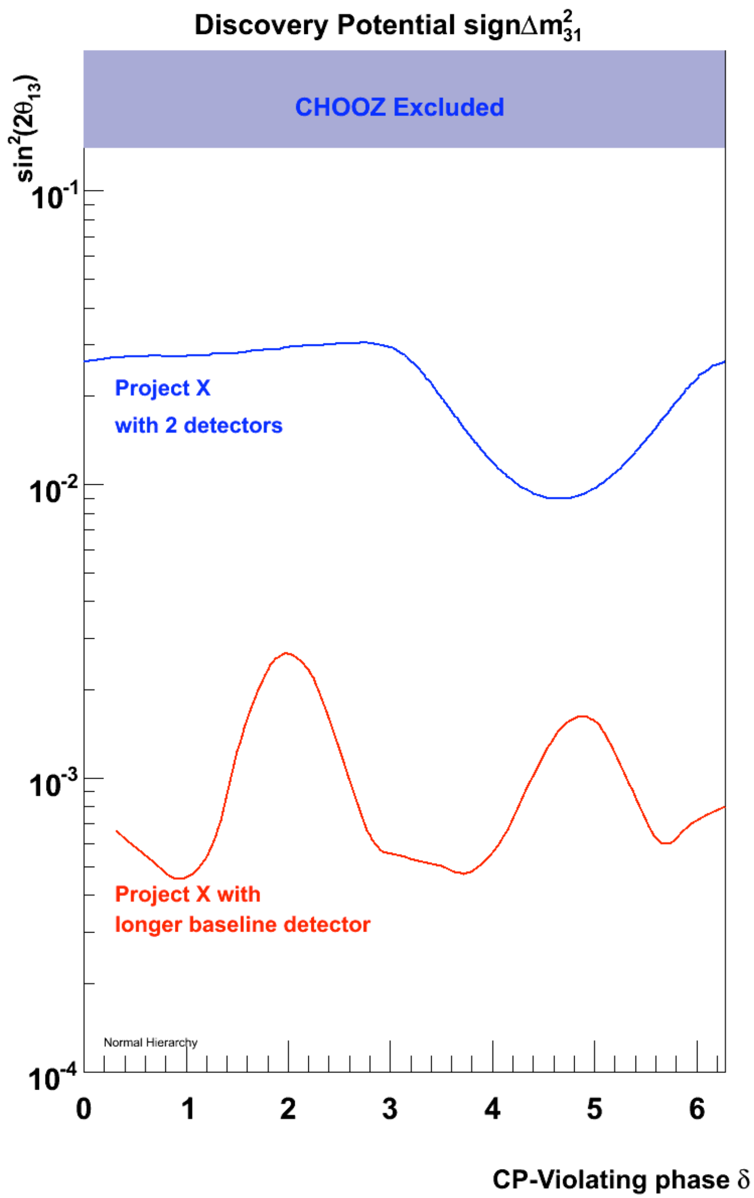
At fixed L/E, genuine $\cancel{CP}$ effects do not change with E, but the matter effect grows, enhancing (suppressing) the oscillation if the hierarchy is Normal (Inverted).

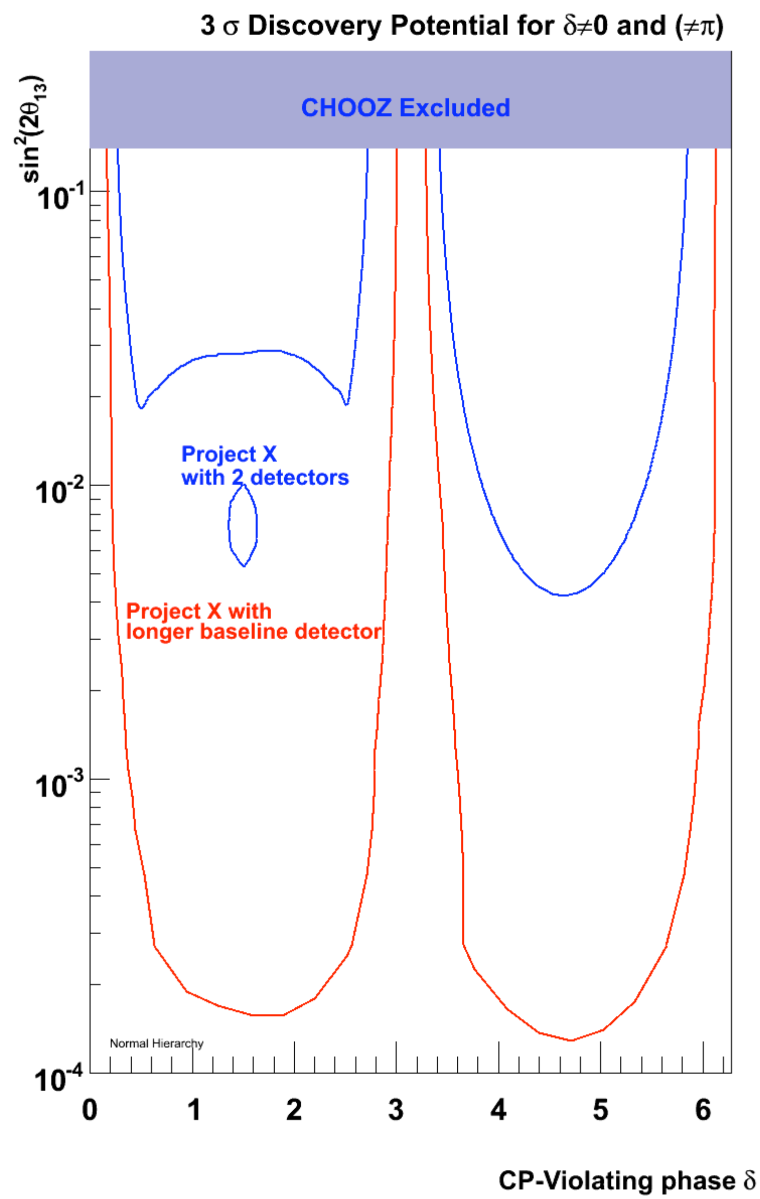
If $E \rightarrow E/3$ at fixed L, we go from the 1st atmospheric oscillation peak to the 2nd one.

When $E \rightarrow E/3$ at fixed L, ~~*CP*~~ *is tripled*, *but the matter effect is reduced by a factor of 3*.

The Impressive Reach of Project X

Mass Ordering and ~~CP~~ Reach of Project X



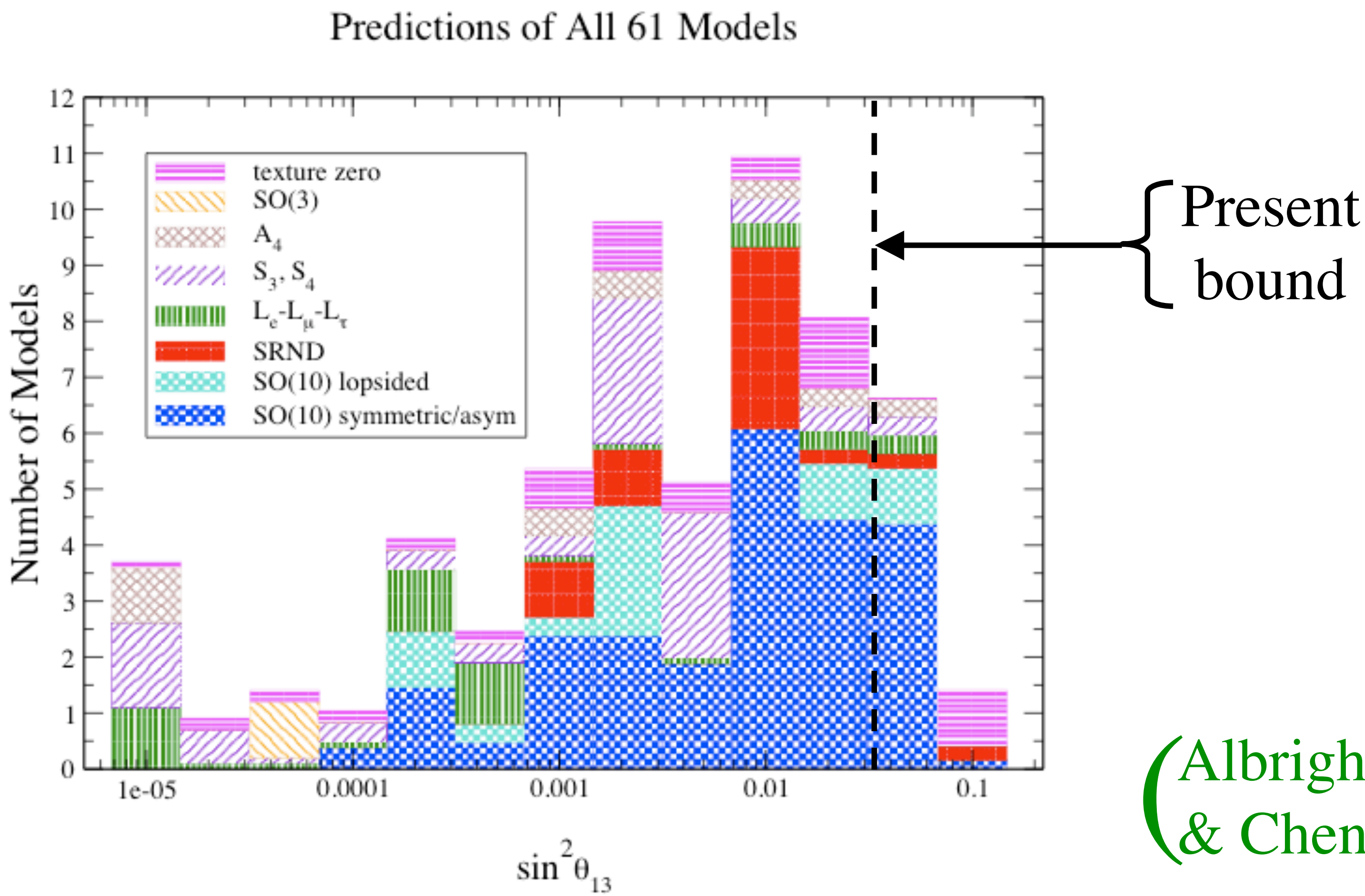


Saoulidou

How Large Is θ_{13}?

We know only that $\sin^2\theta_{13} < 0.032$ (at 2σ).

The theoretical prediction of θ_{13} is not sharp:



(Albright & Chen)

Summary

We have learned a lot about the neutrinos in the last decade.

What we have learned raises some very interesting questions.

We look forward to answering them.

Planning Backup Slides

Evidence For ν Flavor Change

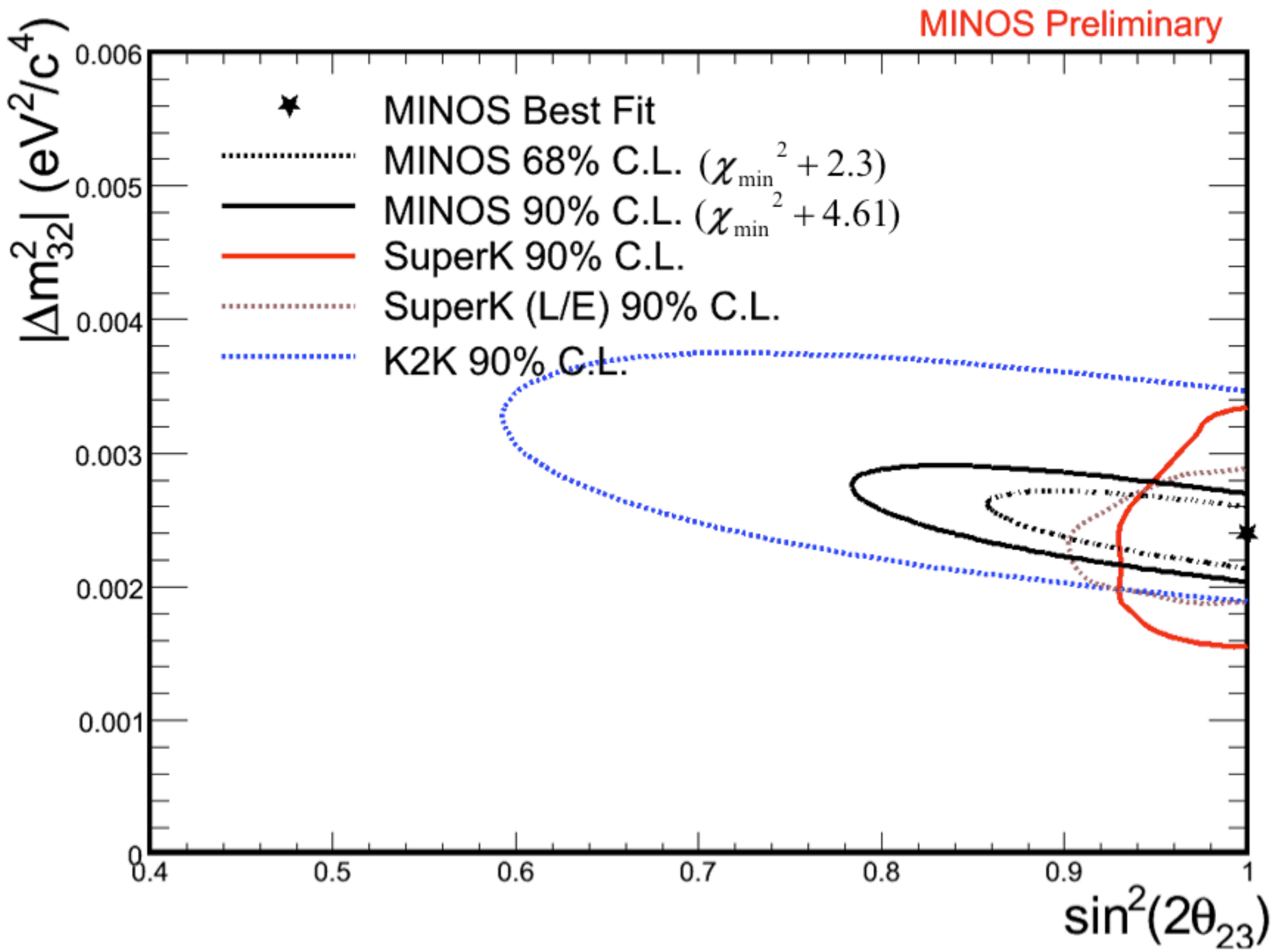
Neutrinos	Evidence of Flavor Change
Solar	Compelling
Reactor (L ~ 180 km)	Compelling
Atmospheric	Compelling
Accelerator (L = 250 and 735 km)	Compelling
Stopped μ^+ Decay (LSND, $L \approx 30$ m)	Unconfirmed by MiniBooNE

The neutrino flavor-change observations imply that —

Neutrinos have nonzero masses

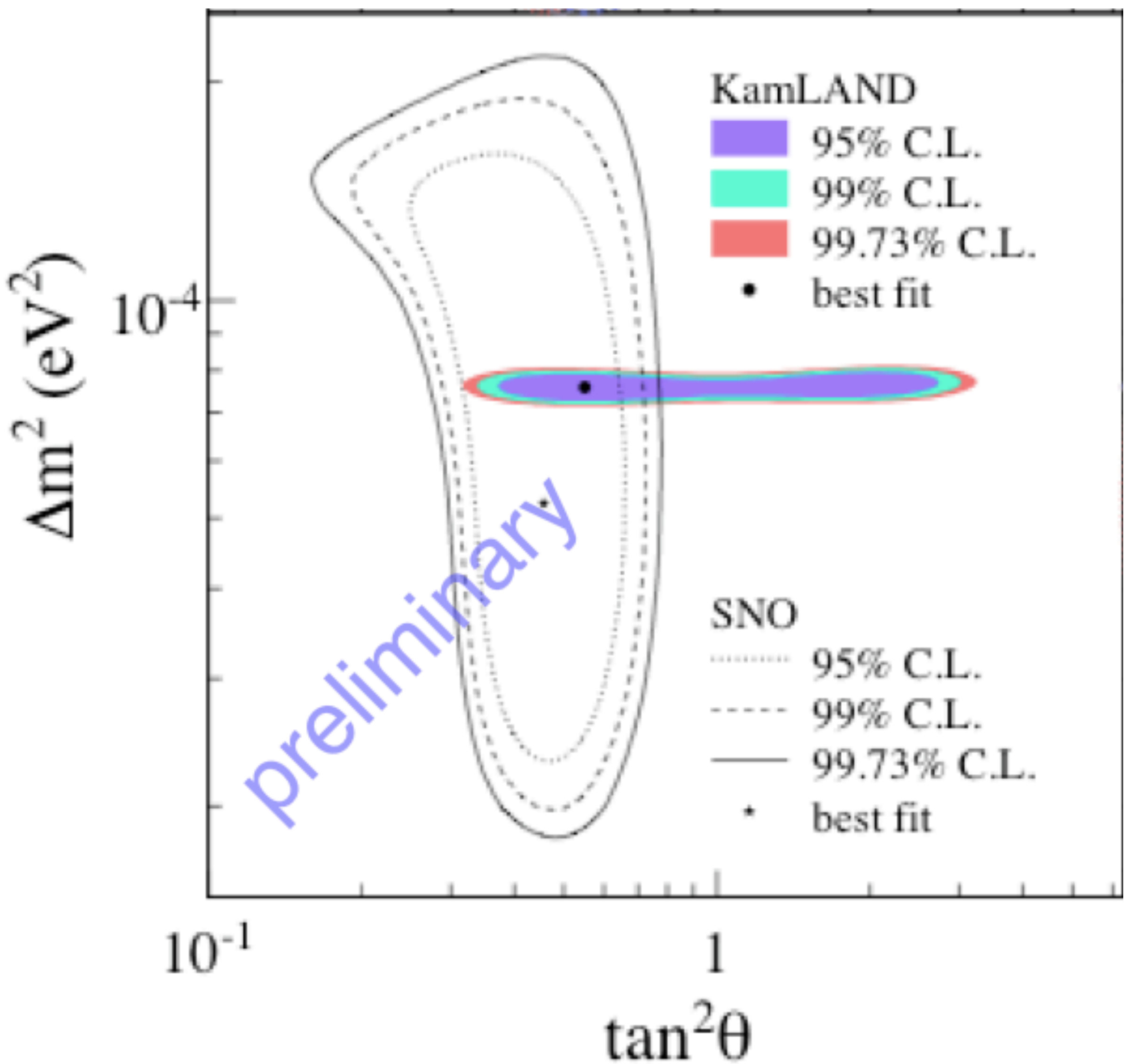
and that —

Leptons mix.



From talk by N. Saoulidou

"Atmospheric" Δm^2 and mixing angle from MINOS, Super-K, and K2K.



From
K. Heeger at
TAUP 2007

"Solar" Δm^2 and mixing angle from KamLAND and SNO.

^{7}Be Solar Neutrinos

Until recently, only the ^{8}B solar neutrinos, with $E \sim 7$ MeV, had been studied in detail.

The Large Mixing Angle MSW (***matter***) effect boosts the fraction of the ^{8}B solar ν_e that get transformed into neutrinos of other flavors to roughly 70%.

At the energy $E = 0.862$ MeV of the ^{7}Be solar neutrinos, the matter effect is expected to be very small. Only about 45% of the ^{7}Be solar ν_e are expected to change into neutrinos of other flavors.

Borexino —

Detects the ^{7}Be solar neutrinos
via $\nu e \rightarrow \nu e$ elastic scattering.

Event rate (Counts/day/100 tons)

Observed:	47 ± 7(stat) ± 12(syst)
Expected (No Osc):	75 ± 4
Expected (With 45% Osc):	49 ± 4
Expected (With 70% Osc):	~ 31

The Present, and a Part of the Future

American researchers participate in —

MINOS, MiniBooNE, SciBooNE, and (soon) MINERνA, in R&D on EXO and Majorana,

and, beyond the U.S. border, in —

KamLAND, SNO, and Super-Kamiokande.

They will participate in NOνA, and, offshore, in —

Cuore, Daya Bay, Double Chooz, and T2K.

NOνA

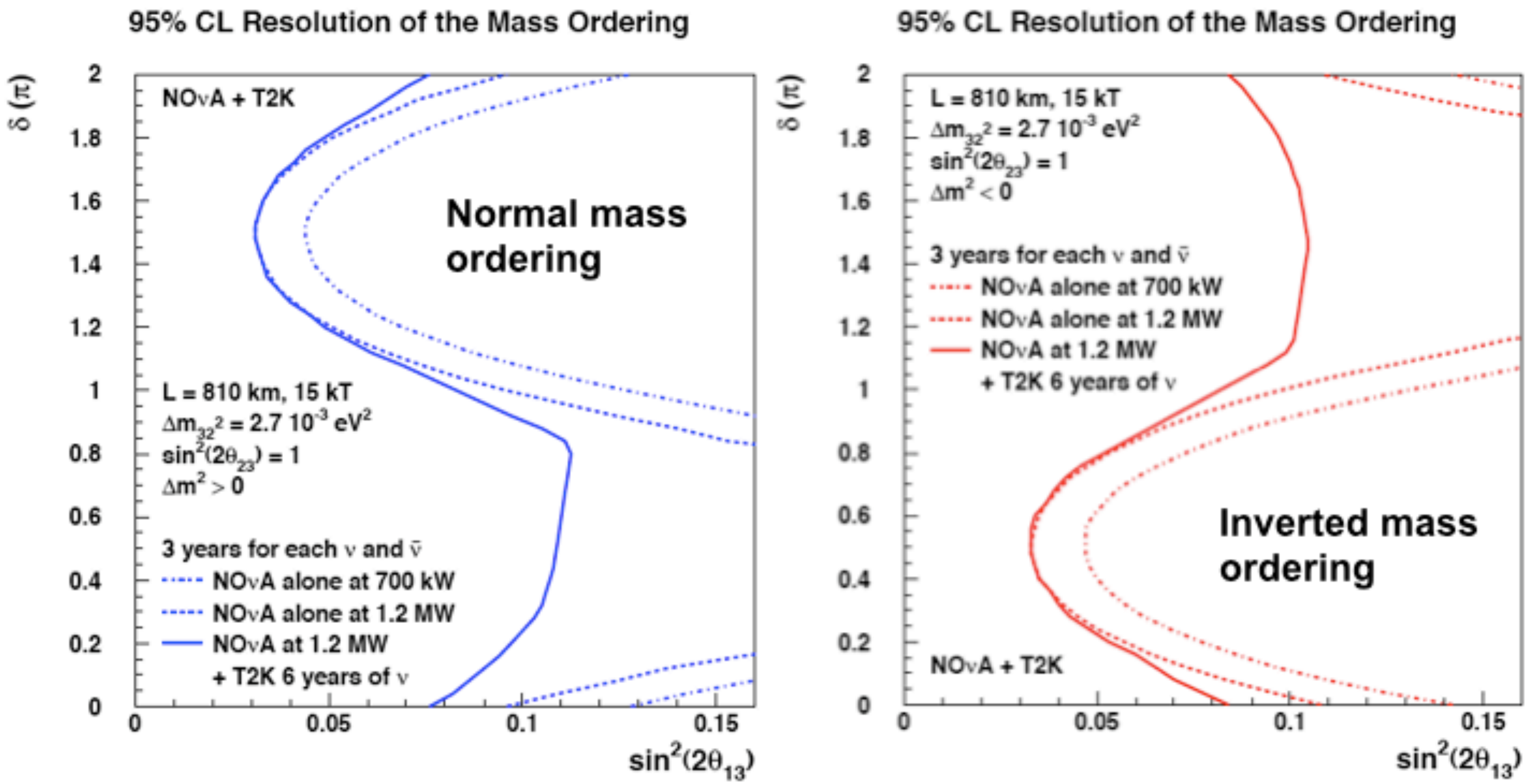
The next Long BaseLine accelerator neutrino oscillation experiment will be the —

NuMI Off-Axis ν_e Appearance

experiment **(NOνA)**.

- A study of $\nu_\mu \rightarrow \nu_e$ and $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$
- ~ 15 kton liquid scintillator detector
- Off the axis of Fermilab's NuMI neutrino beamline, total 4E21 pot each for ν and $\bar{\nu}$
- L = 810 km; E ~ 2 GeV *(L/E near 1st osc. peak)*
- *Main goal: Try to determine whether the spectrum is Normal or Inverted*

95% CL Resolution of the Mass Ordering



Beyond NOνA

Although it is not certain, it appears quite likely that the U.S. will mount a substantial program of accelerator neutrino experiments beyond NOνA.

The goals include determining whether neutrino oscillation violates CP.

The details of this program are not yet known, but several studies have been carried out:

U.S. Long Baseline Neutrino Study

(Brookhaven & Fermilab)

Explored two approaches:

1. Add detector mass, beyond NOνA, in Fermilab's NuMI beamline

2. Build at Fermilab a new, wide-band beam aimed at a very large (ν and p-decay) detector more than 1000 km away, possibly in a Deep Underground Science and Engineering Laboratory (DUSEL)

The 2nd approach has greater physics reach, particularly for determining whether the spectrum is Normal or Inverted, and greater cost.

Fermilab Steering Group

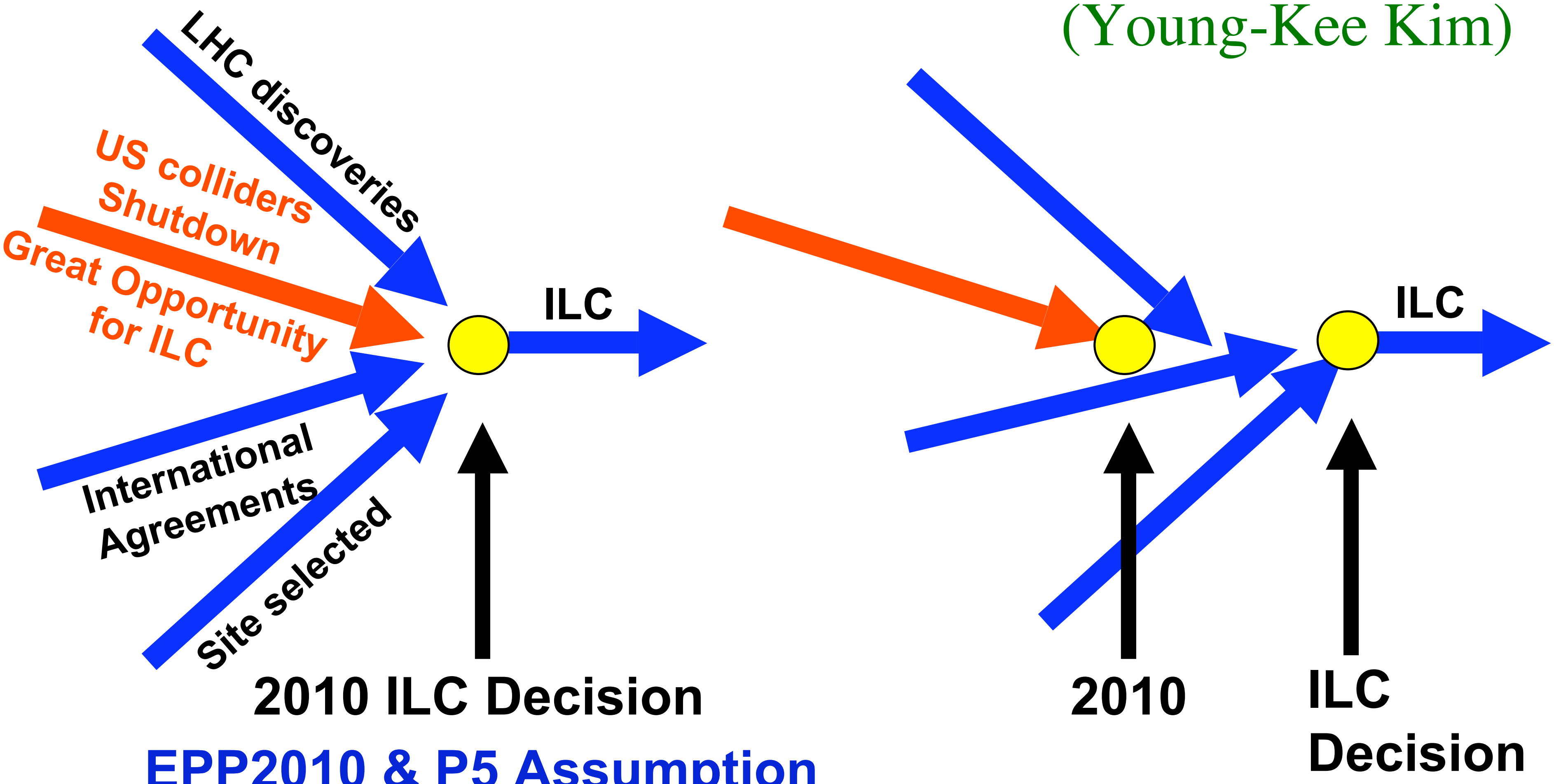
Fermilab's top priority is to bid to host the International Linear Collider (ILC).

But it is recognized that even if the ILC comes to Fermilab, it may not be taking data before ~ 2025.

What would be the best scientific program for Fermilab until then?

ILC Decision Timelines

(Young-Kee Kim)



EPP2010 & P5 Assumption

ILC RDR with Cost Estimate in Feb. 2007

Possible ILC Decision Timelines

Steering Group Report

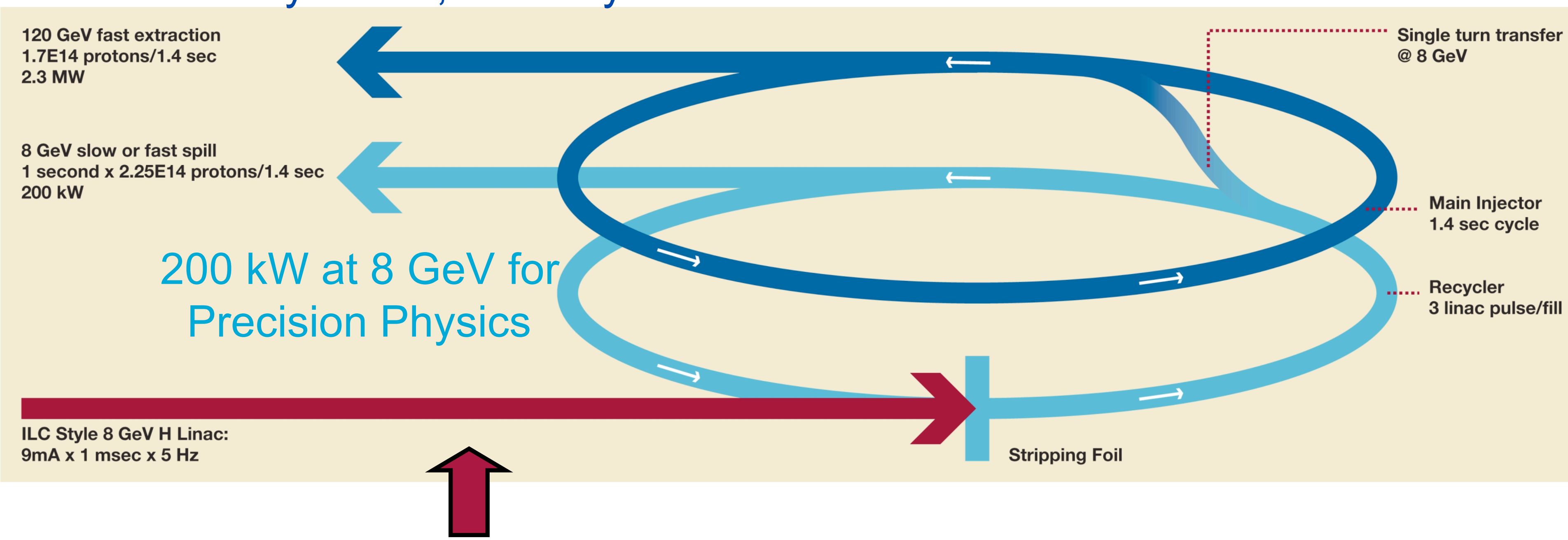
(Points relevant to neutrinos)

- If ILC remains near the proposed timeline, the Fermilab neutrino program will focus on ***NOνA*** and several small experiments.
- If ILC start is delayed a couple of years, Fermilab should undertake ***SNuMI***, an upgrade of the NuMI beamline.
- If ILC postponement would accommodate an interim major project, the laboratory should undertake ***Project X***, an ILC-related high-intensity proton source.

Project X: Properties

(Young-Kee Kim)

~2.3 MW at 120 GeV for Neutrino Science
Initially NOvA, Possibly DUSEL later



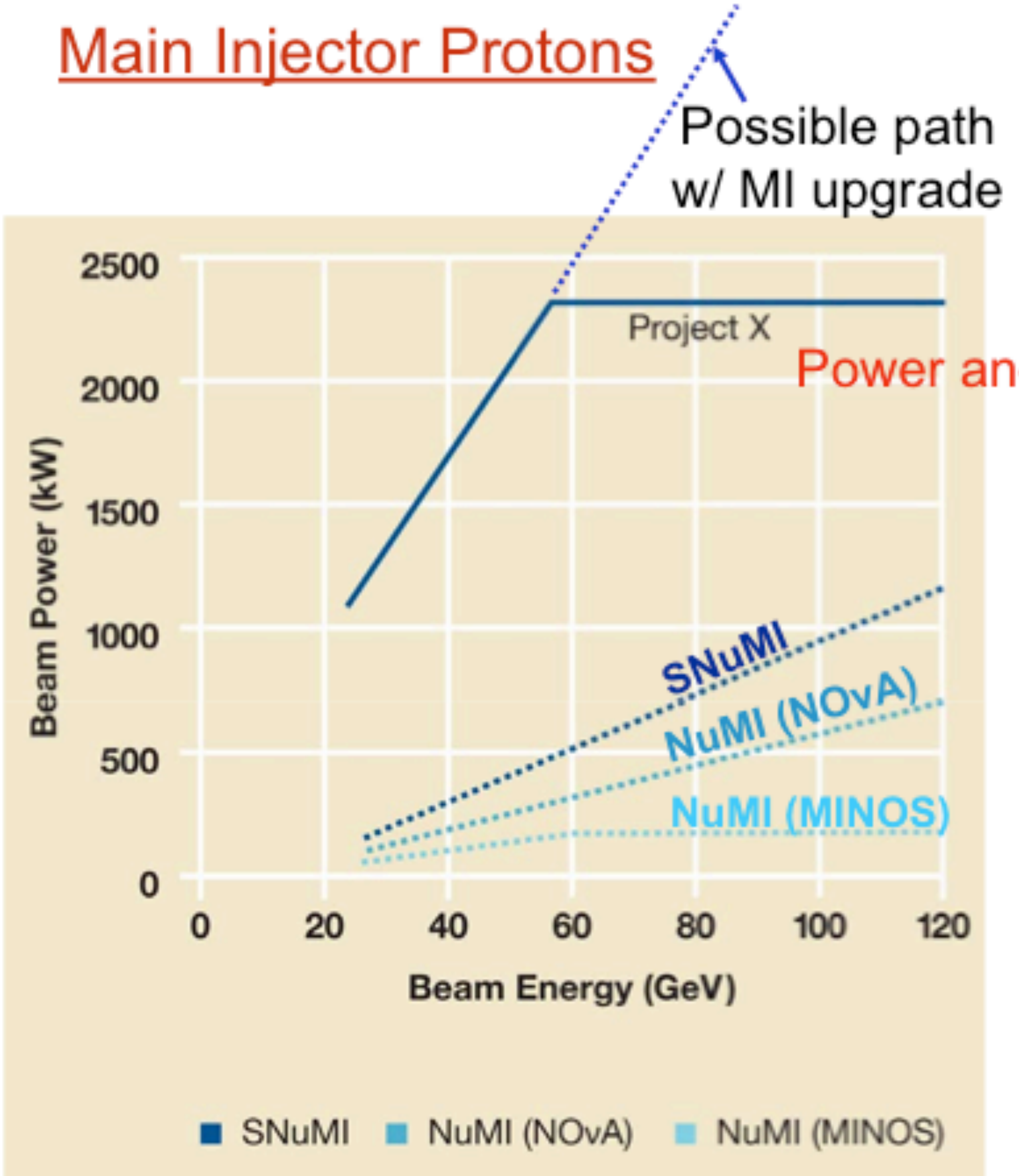
200 kW at 8 GeV for
Precision Physics

8 GeV H^- Linac with ILC Beam Parameters
(9mA x 1msec x 5Hz)

v < c   v = c (ILC Linac)

Project X: Proton Beam Power (Young-Kee Kim)

Main Injector Protons



Power and Flexibility

Recycler 8 GeV Protons

with 120GeV MI protons

200 kW (Project X)

0* (SNuMI)

16 kW (NuMI-NOvA)

17 kW (NuMI-MINOS)

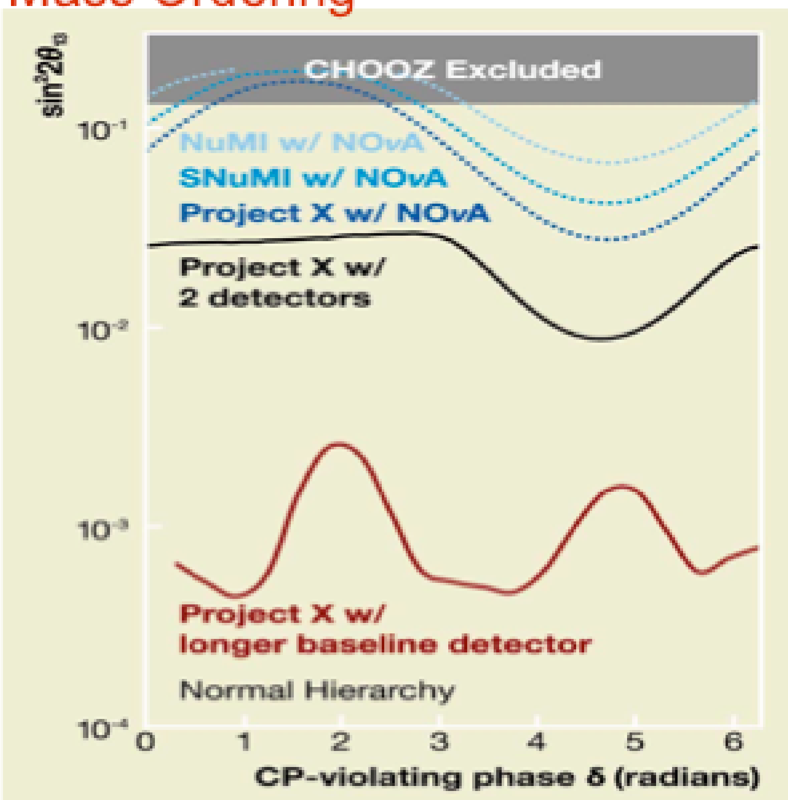
35-year-old injection
(technical risk)

* Protons could be made available at the expense of 120 GeV power.

Neutrino Oscillation (Simulations: Niki Saoulidou)

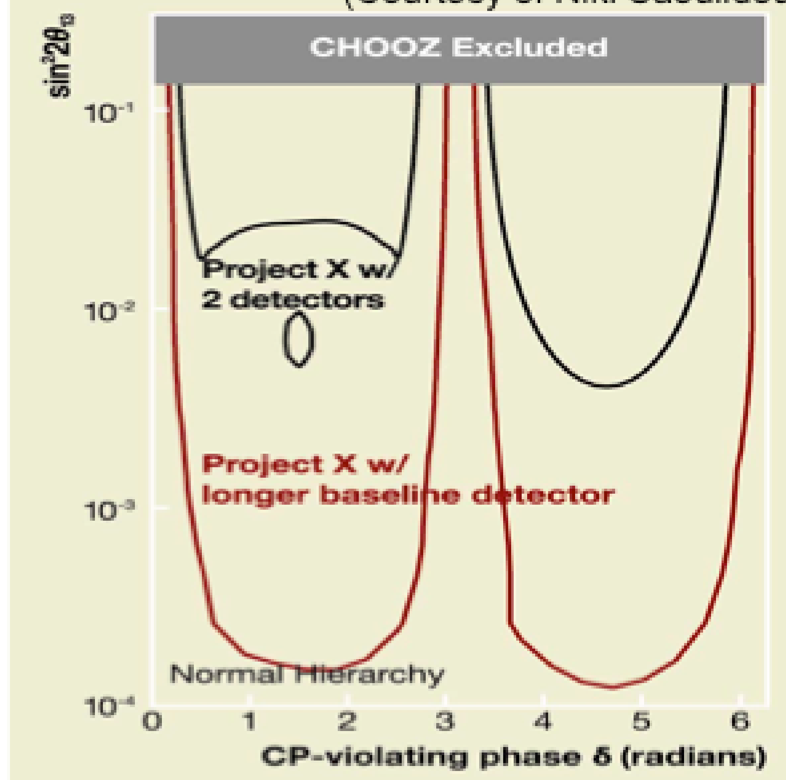
95% CL (dotted) and 3σ (solid) sensitivity with 3 years of each ν and $\overline{\nu}$

Mass Ordering



CP Violation

(Courtesy of Niki Saoulidou)



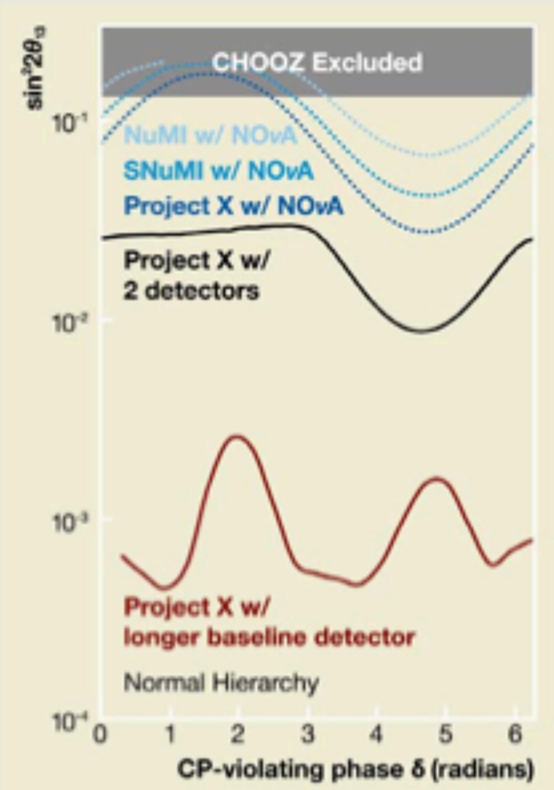
2 100kt LAr detectors at 1st(700 km) & 2nd(810 km) oscil. maxima w/ NuMI beamline

One 100 kt LAr (or 300 kt water Cerenkov) at 1300 km using a wide-band ν beam

A large ν detector in DUSEL would also be a world-class proton decay detector, addressing *"Do all the forces become one?"*

Neutrino Oscillation (Mass Ordering) (Y2K)

Project X



(Courtesy of Niki Saoulidou)

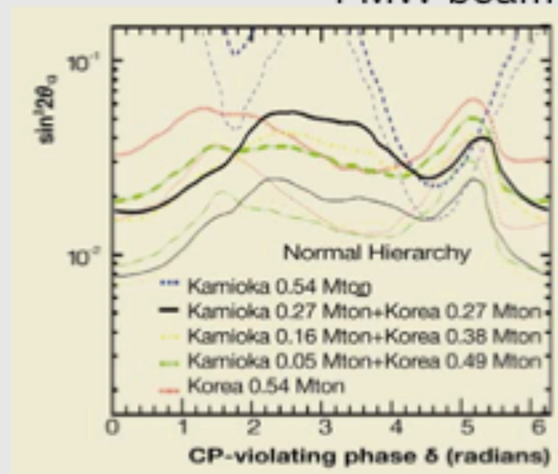
2 100kt LAr detectors at 1st (700 km) & 2nd (810 km) oscillation maxima using NuMI beamline

100 kt LAr (or 300 kt water Cerenkov) at 1300 km using a wide-band ν beam

3σ sensitivity.
3 years of ν + 3 years of $\bar{\nu}$ run

J-PARC Upgrades

4 MW beam

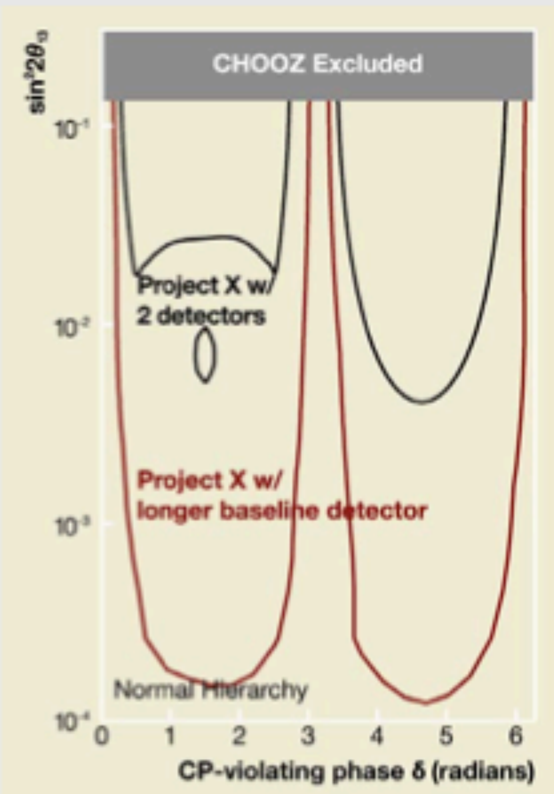


Phys. Rev. D72, 033003 (2005)

2σ (thin lines),
3σ (thick lines) sensitivity.
4 years of ν + 4 years of $\bar{\nu}$ run

Neutrino Oscillation (CP Violation) (Y2K)

Project X



(Courtesy of Niki Saoulidou)

2 100kt LAr detectors at
1st (700 km) & 2nd (810 km)
oscillation maxima
using NuMI beamline

100 kt LAr
(or 300 kt water Cerenkov)
at 1300 km
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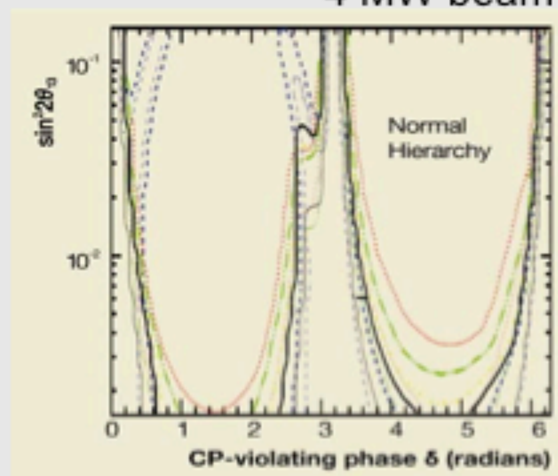


Phys. Rev. D72, 033003 (2005)

2σ (thin lines),
3σ (thick lines) sensitivity.
4 years of ν + 4 years of $\bar{\nu}$ run

Neutrino Oscillation (Y2K)

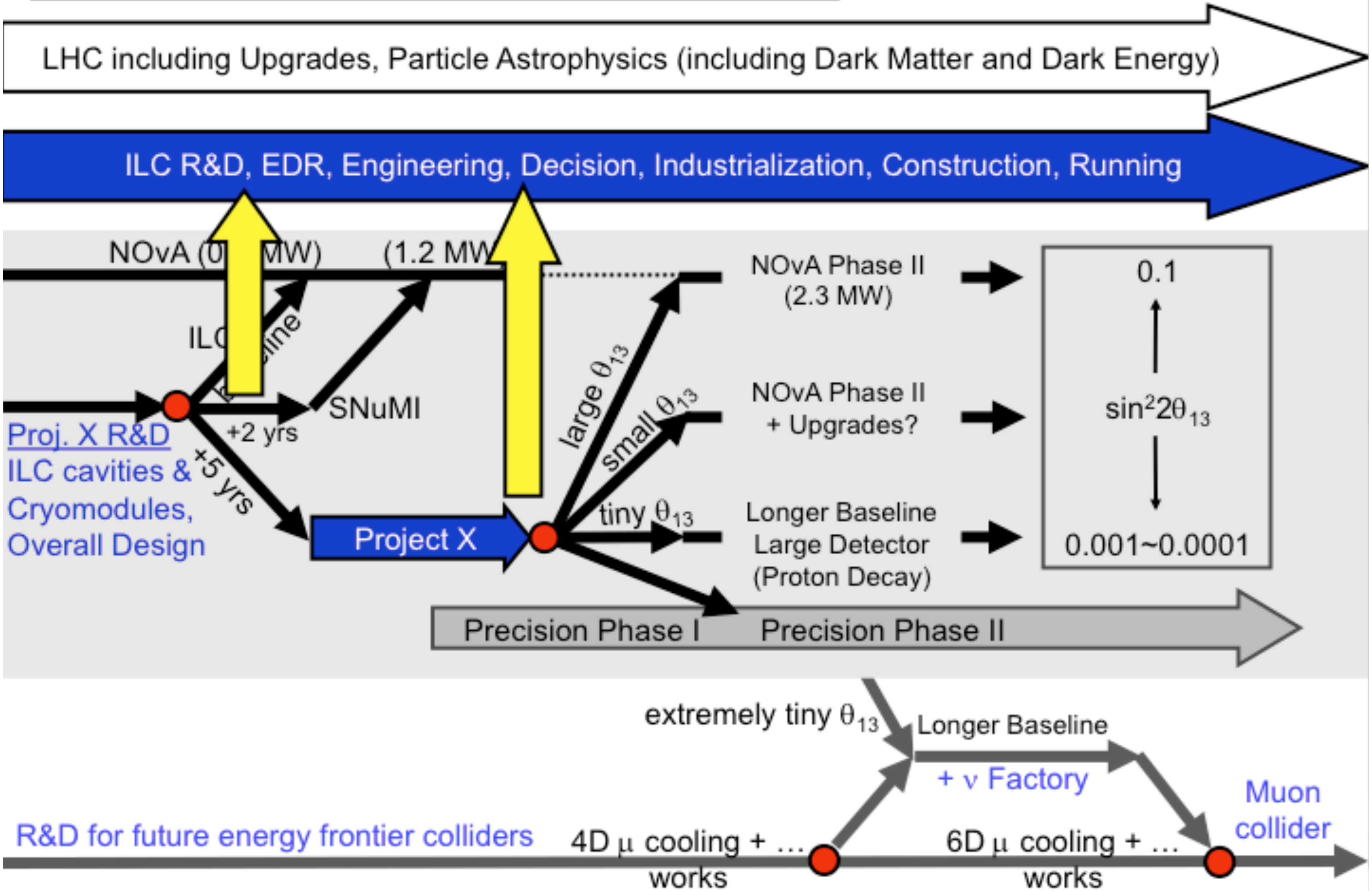
- Quite apart from their relative sensitivities,
  - the Japanese and U.S. programs would operate under different physical conditions.

  - In the U.S. program, there could be
    - higher beam energy
    - a wide-band-beam
    - a single large detector, possibly using liquid-argon technology
    - 1300 km away.

  - In the Japanese program, there could be
    - lower beam energy
    - a narrower-band beam
    - a single large water-Cerenkov detector, 300 km away
      or, a split version of this detector, with part of it 300 km away and the rest in Korea, about 1000 km away

Sketch of Integrated Plan

(Young-Kee Kim)



NOνA Timeline

Construction: 2008 – 2012 (US$36.5M requested in President's budget for 2008)

Data taking : 2012 – 2021, evenly split between ν and $\bar{\nu}$

Sensitivity reach of different long baseline experiments

Option	Beam	Baseline	Detector	Exposure (MW.yr*)	$\theta_{13} \neq 0$	CPV	$sgn(\Delta m^2_{31})$
(1)	NuMI ME, 0.9°	810 km	NOνA 20 kT	6.8	0.015	> 0.2	0.15
(2)	NuMI ME, 0.9°	810 km	LAr 100 kT	6.8	0.002	0.03	0.05
(3)	NuMI LE, 0.9°, 3.3°,	810,700 km	LAr 2×50 kT	6.8	0.005	0.04	0.04
(4)	WBLE 120GeV, 0.5°	1300km	LAr 100 kT	6.8	0.0025	0.005	0.006
(5)	WBLE 120GeV, 0.5°	1300km	WCe 300 kT	6.8	0.006	0.03	0.011
(6)	WBLE 120GeV, 0.5°	1300km	WCe 300 kT	13.6	0.004	0.012	0.008

TABLE IX: Comparison of the sensitivity reach of different long baseline experiments. The sensitivity is given as the value of $\sin^2 2\theta_{13}$ at which 50% of δ_{cp} values will have $\geq 3\sigma$ reach for the choice of mass hierarchy with worst sensitivity. We assume equal amounts of ν and $\bar{\nu}$ running in the total exposure. The assumption on running time is 1.7×10^7 seconds of running per year. Also see Table VIII.

(U.S. Long Baseline Neutrino Study)

Neutrino Scientific Assessment Group (NuSAG)

(A subpanel of HEPAP and NSAC)

Recommends preparation for a U.S. long baseline neutrino program, including R&D on both of the approaches explored by the U.S. Long Baseline Neutrino Study.

Detector R&D should include both water Cerenkov and liquid argon detectors.

Points out that, because of the different matter effects in Japan and the U.S., a cooperative program with T2K could help determine the mass ordering.

Project X *would make possible a high-intensity, flexible-energy, neutrino beam aimed at a distant (L > 1000 km) large detector.*

It would also be a high-intensity source of muons and quarks for experiments in precision physics.

If the ILC is constructed outside of the U.S., Fermilab should pursue additional neutrino science with ***SNuMI*** at a minimum, and ***Project X*** if possible.

In all scenarios —

- R&D on ***Project X*** should start now
- R&D on future accelerator options, concentrating on a ***Neutrino Factory*** and a ***Muon Collider***, should be increased

Backup Slides

Why Many Theorists Think Majorana Mass Terms Are Likely

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

Anything allowed by the symmetries occurs in nature.

The SM contains no ν mass, and no ν_R field, only ν_L.

Now that we know the neutrino has mass, we must somehow extend the SM to accommodate it. In doing this, we can either add ν_R, or not add it.

If we *do not* add ν_R, then the only neutrino mass term we can construct is $m_L \overline{\nu_L{}^c} \nu_L$, a Majorana mass term.

If we *do* add ν_R, then we can construct the Dirac mass term $m_D \bar{\nu}_L \nu_R$. If this term is all there is, the neutrino gets its mass the same way that a quark or charged lepton does. No Majorana neutrino masses.

However —

Unlike ν_L , ν_R carries no Weak Isospin.

Thus, once ν_R has been added, no SM symmetry prevents the occurrence of the Majorana mass term $m_R \overline{\nu_R{}^c} \nu_R$.

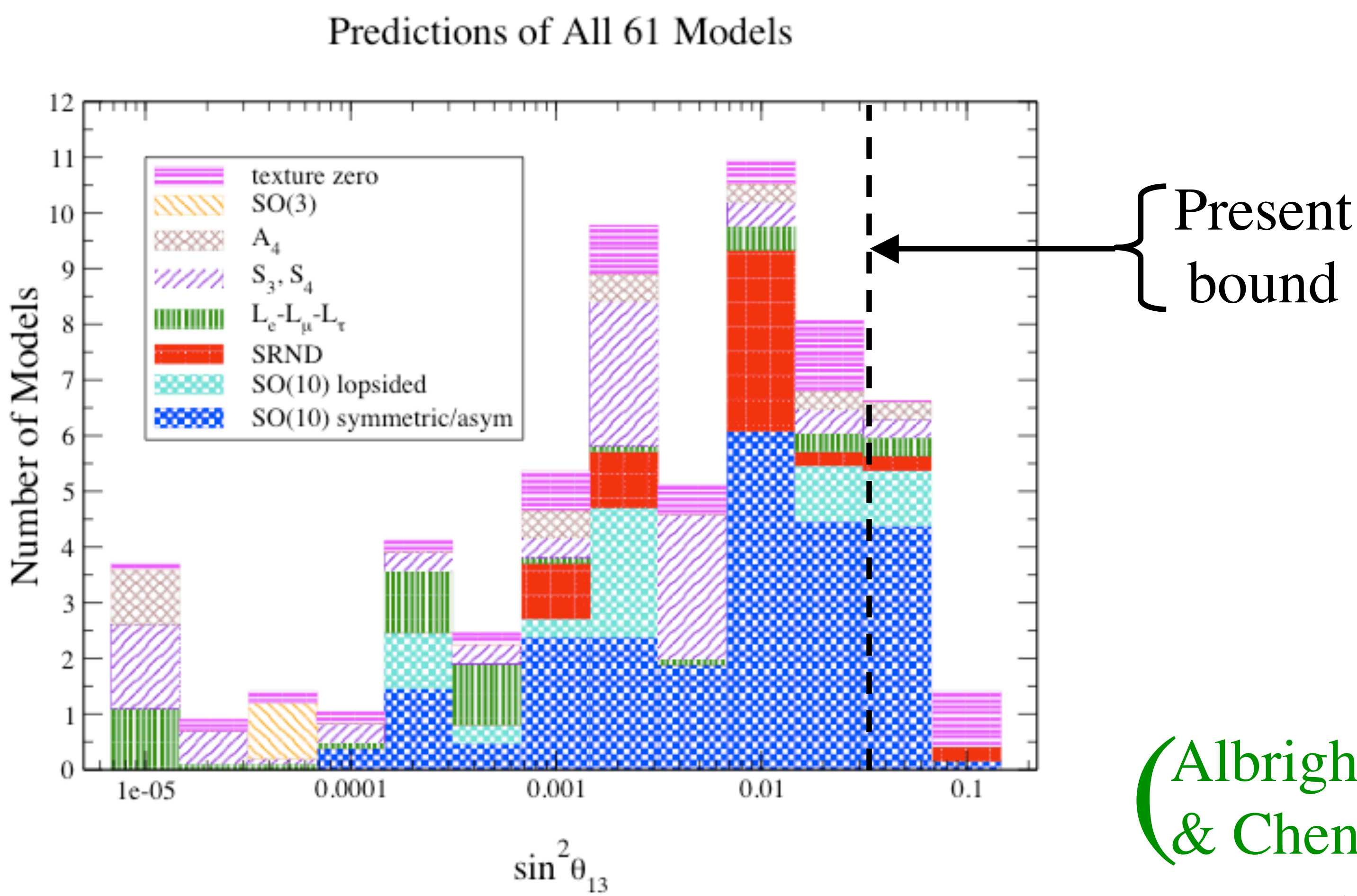
If anything allowed by the *extended* SM occurs in nature, then neutrinos have *Majorana masses*.

Hence, the neutrino mass eigenstates are their own antiparticles.

How Large Is θ_{13}?

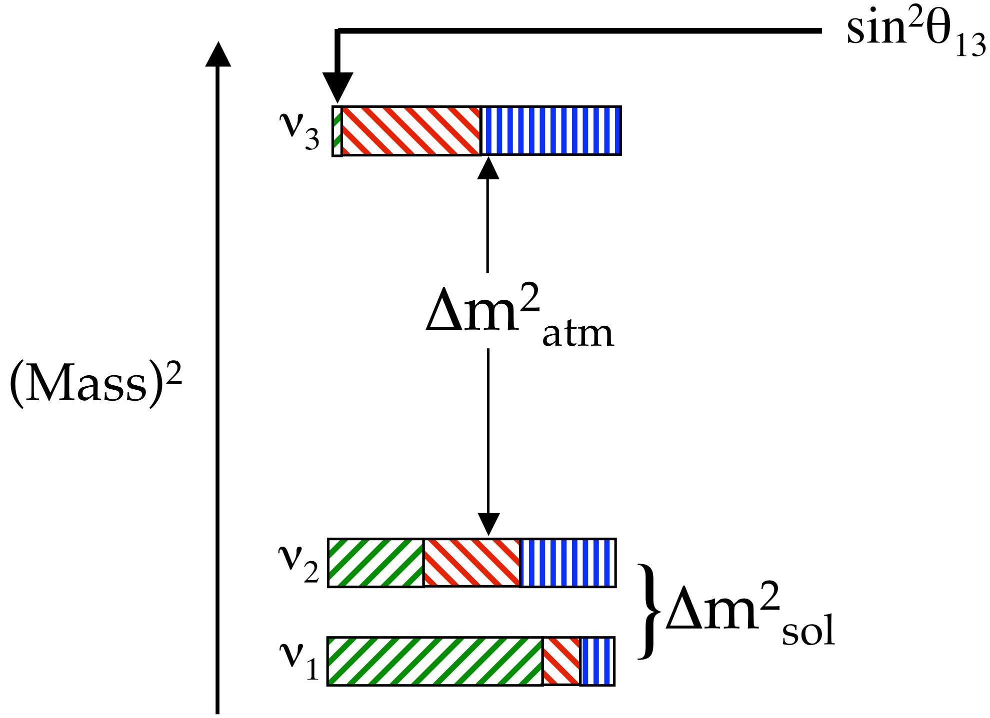
We know only that $\sin^2\theta_{13} < 0.032$ (at 2σ).

The theoretical prediction of θ_{13} is not sharp:



(Albright & Chen)

How θ_{13} May 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.

Reactor Experiments

Looking for disappearance of reactor $\bar{\nu}_e$ while they travel L ~ 1.5 km with energy E ~ 3 MeV is the cleanest way to determine θ_{13} .

$$P(\bar{\nu}_e \text{ Disappearance}) =$$

$$= \sin^2 2\theta_{13} \sin^2[1.27\Delta m^2_{atm}(eV^2)L(km)/E(GeV)]$$

(Possible experiment in Japan?)

Does Leptogenesis Require Neutrino Mass?

Could leptogenesis occur even if the light neutrinos were massless??

(André de Gouvêa, B.K., and Paul Langacker)

Leptogenesis is an outgrowth of the see-saw picture.

In a straightforward (i.e., Type I) see-saw picture,

Real, positive

Yukawa couplings

$$\mathcal{L}_{\text{new}} = -\sum_{i=1}^{3} \frac{M_i}{2} \overline{N_{iR}{}^{c}} N_{iR} - \sum_{\alpha, i=1}^{3} y_{\alpha i} \left[\overline{\nu_{\alpha L}}\, \overline{\varphi^0} - \overline{\ell_{\alpha L}} \varphi^- \right] N_{iR} + h.c.$$

Diagonal basis

SM Higgs doublet

The Yukawa couplings $y_{\alpha i}$ play two roles:

- ➢They cause the heavy neutrinos to decay
- ➢They give masses to the light neutrinos

The light neutrino masses can have implications for Leptogenesis.

Leptogenesis In a Minimal Model

A minimal model:

Two heavy RH neutrinos, N_{1R} and N_{2R}

One light LH lepton doublet, (ν_L, ℓ_L)

In the basis where the Majorana mass term is diagonal, with real positive eigenvalues,

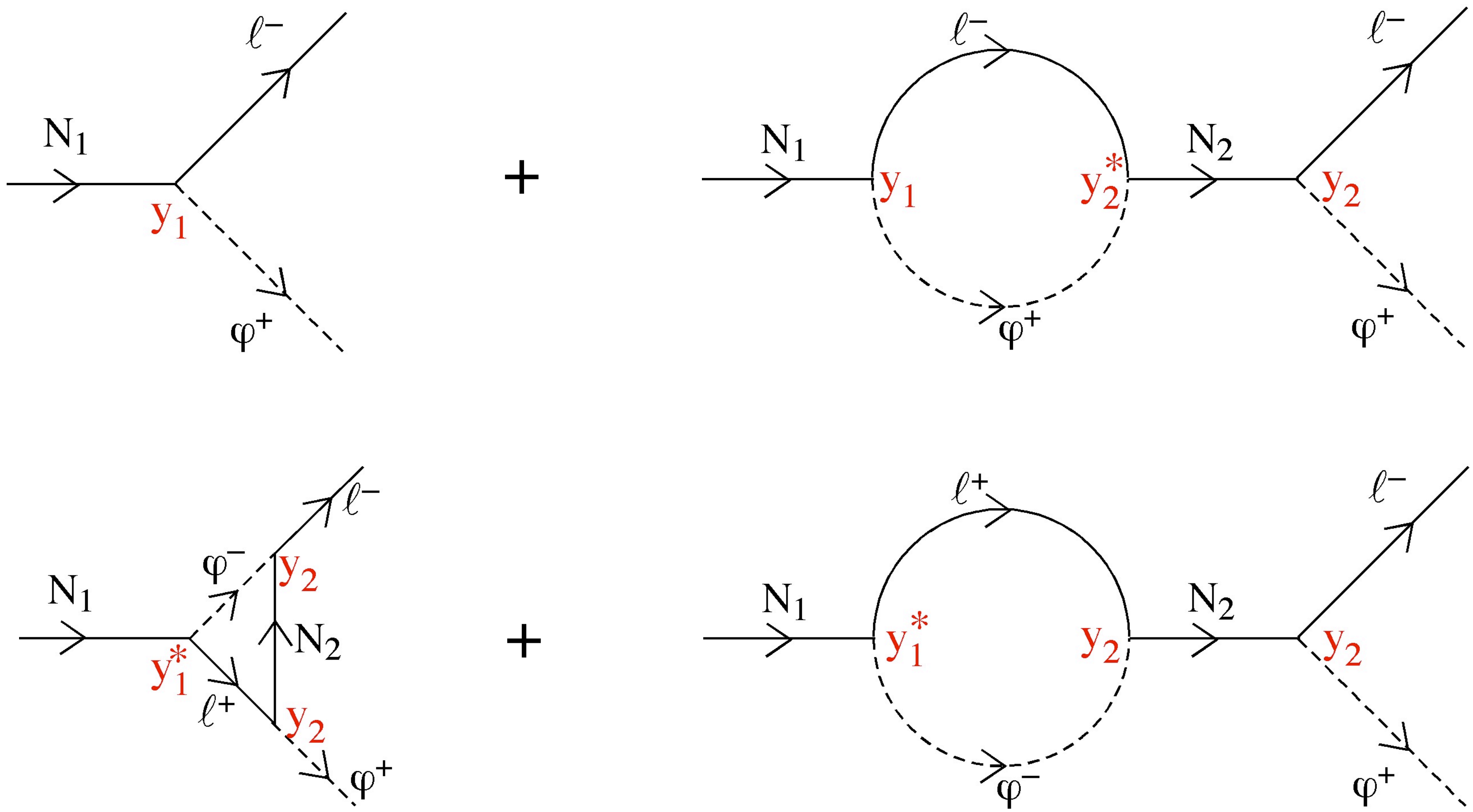
Yukawa couplings

$$\mathcal{L}_{\text{new}} = -\sum_{i=1}^{2} \frac{M_i}{2} \overline{N_{iR}{}^c} N_{iR} - \sum_{i=1}^{2} y_i \left[\overline{\nu_L} \overline{\varphi^0} - \overline{\ell_L} \varphi^- \right] N_{iR} + h.c.$$

SM Higgs doublet

Long ago —

$$N_1 \rightarrow \ell^- + \phi^+$$



The decay rates were —

$$\Gamma(N_1 \to \ell^- + \varphi^+) = |ay_1 + by_1{}^*y_2{}^2|^2$$

and

$$\Gamma(N_1 \to \ell^+ + \varphi^-) = |ay_1{}^* + by_1y_2{}^{*2}|^2$$

These rates produced a matter – antimatter asymmetry if —

$$\Delta \equiv \Gamma(N_1 \to \ell^- + \varphi^+) - \Gamma(N_1 \to \ell^+ + \varphi^-)$$

$$\propto \Im m(ab^*)\ \Im m(y_1{}^{*2}y_2{}^2) \neq 0.$$

(***Leptogenesis***)

Today —

$$\langle \varphi^0 \rangle_{vac} \equiv v \neq 0$$

The light neutrino now has a nonzero mass *unless* —

Mass matrix

$$Det(\mathcal{M}) = 0 \; .$$

The product P of all the heavy and light neutrino eigenmasses satisfies —

$$P^2 = Det(\mathcal{M}\mathcal{M}^*) = |Det(\mathcal{M})|^2 \; .$$

$$Det(\mathcal{M}) = 0 \quad \Rightarrow \quad \frac{y_1^{\,2}}{M_1} + \frac{y_2^{\,2}}{M_2} = 0$$

Masses of N_1, N_2

The only natural solution to this constraint is —

$$y_1 = y_2 = 0.$$

Then N_1 and N_2 do not decay, and there is no Leptogenesis.

The loophole —

$$\frac{y_1{}^2}{M_1} + \frac{y_2{}^2}{M_2} = 0$$

can be satisfied by a *cancellation* between the terms.

This requires a *conspiracy* between the Yukawa sector and the Majorana sector of the theory.

But suppose this conspiracy happens:

Then $y_1{}^2$ and $y_2{}^2$ must be relatively *real*, so that —

$$\Im\mathrm{m}(y_1{}^{*2} y_2{}^2) = 0$$

Thus, there is still no Leptogenesis!

In the minimal model that can give Leptogenesis, the light neutrino must have a nonzero mass or Leptogenesis cannot occur.

Perhaps neutrino mass ***<u>is</u>*** *essential to our existence.*

When There Are Three Light Doublets and Three Heavy Neutrinos

$$\mathcal{L}_{\text{new}} = -\sum_{i=1}^{3} \frac{M_i}{2} \overline{N_{iR}{}^c} N_{iR} - \sum_{\alpha,\, i=1}^{3} y_{\alpha i} \left[\overline{\nu_{\alpha L}}\, \overline{\varphi^0} - \overline{\ell_{\alpha L}}\, \varphi^- \right] N_{iR} + h.c.$$

The condition that all 3 light neutrinos be massless is —

$$\sum_{i=1}^{3} y_{\alpha i} \frac{1}{M_i} y_{\beta i} \cong 0 \quad ; \quad \alpha, \beta = 1, 3$$

The only natural solution to these 6 constraints is —

The Yukawa coupling matrix $y = 0$.

Then the N_i do not decay, and there is no Leptogenesis.

The loophole —

$$\sum_{i=1}^{3} y_{\alpha i} \frac{1}{M_i} y_{\beta i} = 0 \quad ; \quad \alpha, \beta = 1, 3$$

can be satisfied by a *cancellation* between the terms.

This requires a *conspiracy* between the Yukawa sector and the Majorana sector of the theory.

In addition, the Yukawa coupling matrix y must be *singular*.

While mathematically possible, these circumstances are quite unnatural.

However, suppose they occur:

For hierarchical heavy neutrino masses ($M_{2,\,3} >> M_1$) —

$$\Delta \equiv \Gamma(N_1 \rightarrow \ell^- + \varphi^+) - \Gamma(N_1 \rightarrow \ell^+ + \varphi^-)$$

$$\propto \Im\mathrm{m}\left[\sum_{\alpha,\beta=1}^{3} y_{\alpha 1}^{*}\, y_{\beta 1}^{*}\left(\sum_{i=1}^{3} y_{\alpha i}\,\frac{1}{M_i}\,y_{\beta i}\right)\right]$$

(Dutta & Mohapatra)

Then there is still no Leptogenesis.

If the three light neutrinos are all massless, Leptogenesis is possible, but quite unlikely.

Double beta decay backup slides

This leads many theorists to expect Majorana masses, hence $\not{L}$ *and* $\bar{\nu}_i = \nu_i$.

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.

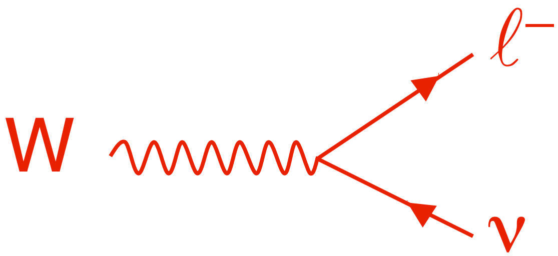
If this is also true for neutrino masses, then neutrinos have *Majorana masses*.

Do We Expect That $\bar{\nu}_i = \nu_i$?

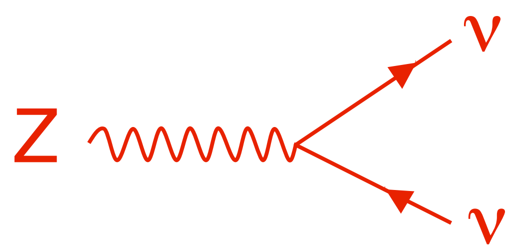
How can the S(tandard) M(odel) be extended to include neutrino masses?

How does the SM become the νSM?

The S(tandard) M(odel)



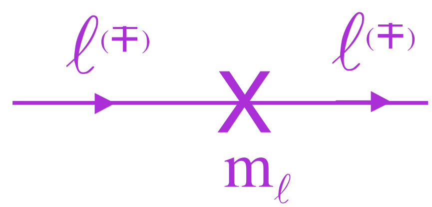
and



couplings conserve the Lepton Number L.

So do the Dirac charged-lepton mass terms

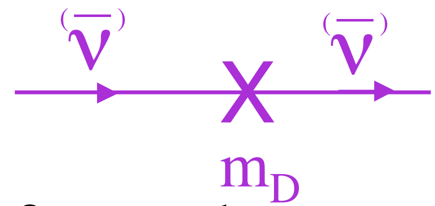
$$m_\ell \bar{\ell}_R \ell_L$$



R(L) ≡ Right(Left) Handed

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

$$m_D \overline{\nu}_R \nu_L$$



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. (Only Left-Handed fermions couple to the W boson.)

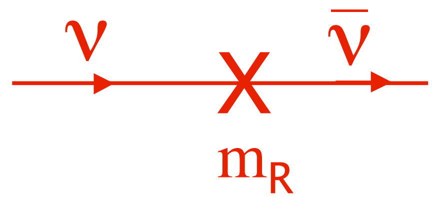
But to add the Dirac mass term, we had to add ν_R to the SM.

Unlike ν_L, ν_R carries no Electroweak Isospin.

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

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

Charge conjugate



Charge-conjugate fields:

$$\psi c = \psi(\text{Particle} \leftrightarrow \text{Antiparticle})$$

The Majorana mass does not conserve L, so now

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

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

This leads many theorists to expect Majorana masses, hence $\not{L}$ *and* $\bar{\nu}_i = \nu_i$.

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*.

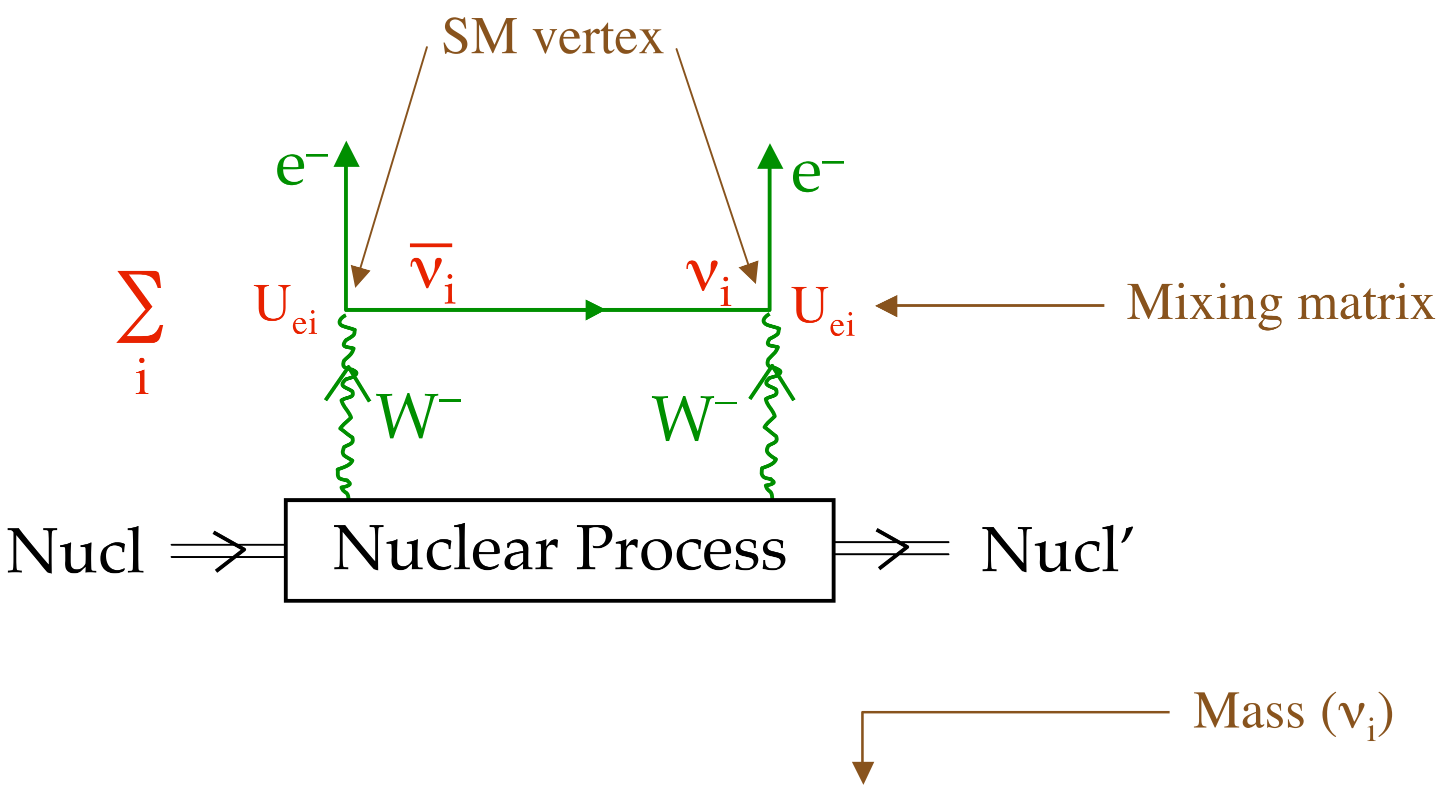
- The presence of Majorana masses
- $\overline{\nu_i} = \nu_i$ (Majorana neutrinos)
- L not conserved

— are all equivalent

Any one implies the other two.

(Recent work: Hirsch, Kovalenko, Schmidt)

In —



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

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

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

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

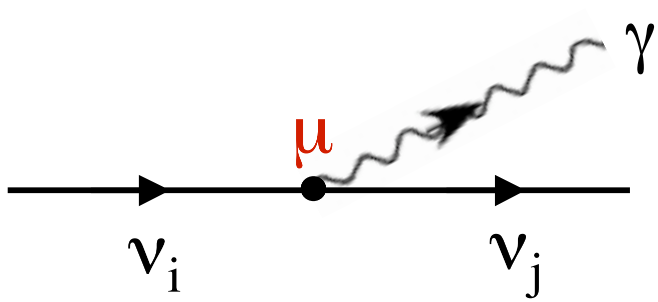
$0\nu\beta\beta$ violates L. But the SM interactions conserve L.

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

The $0\nu\beta\beta$ amplitude would be proportional to neutrino mass even if there were no helicity mismatch.

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, Davidson, Gorbahn, Gorchtein, Ramsey-Musolf, Santamaria, Vogel, Wise, Wang)

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