Neutrino Physics

Boris Kayser
ICRR – CRC Symposium
August 28, 2007

The Neutrino Revolution
(1998 – ...)

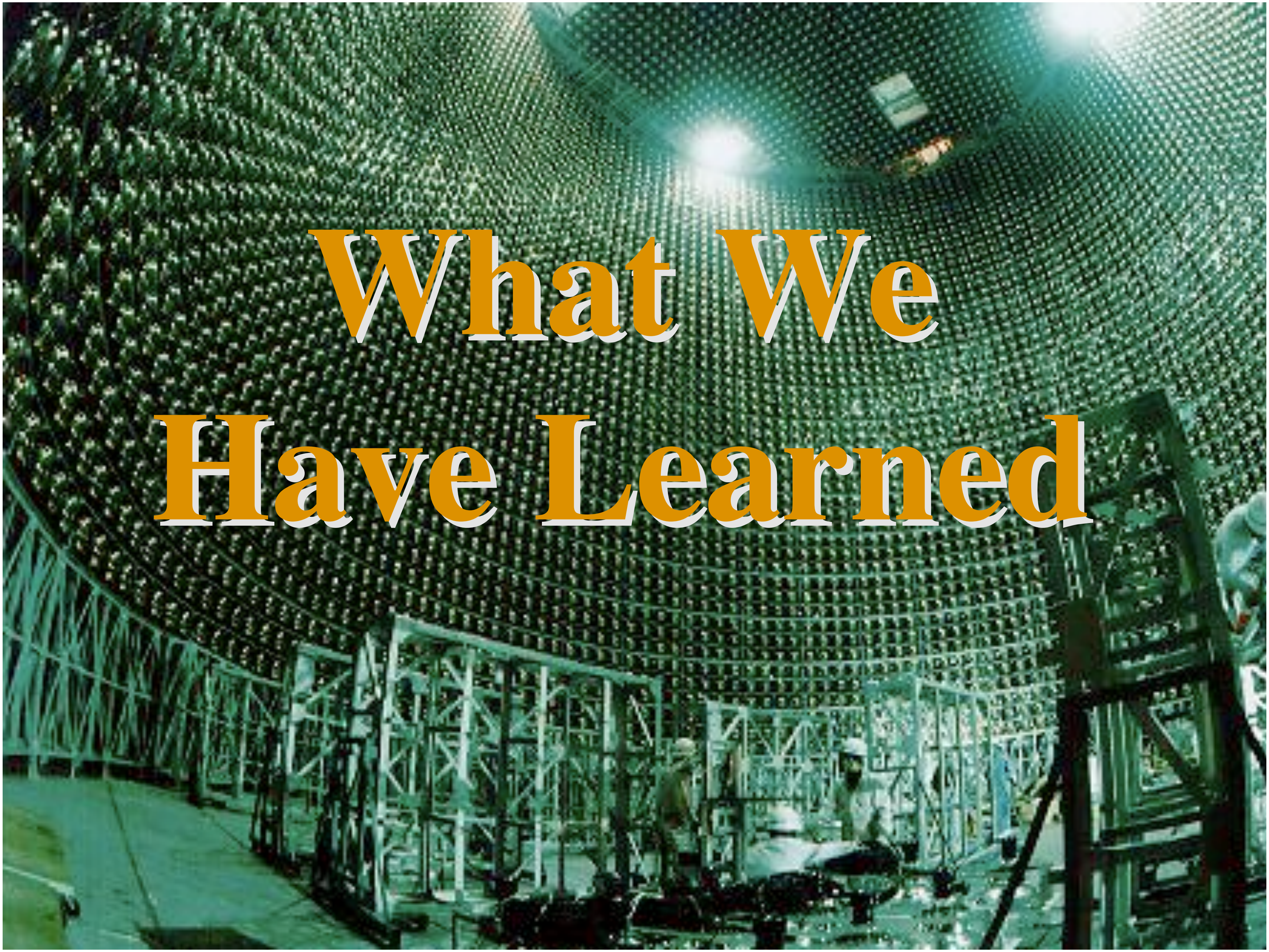
Neutrinos have nonzero masses!

Leptons mix!

This revolution is due, in very
considerable measure, to results from the
Kamiokande detector,
and especially from the
Super-Kamiokande detector.

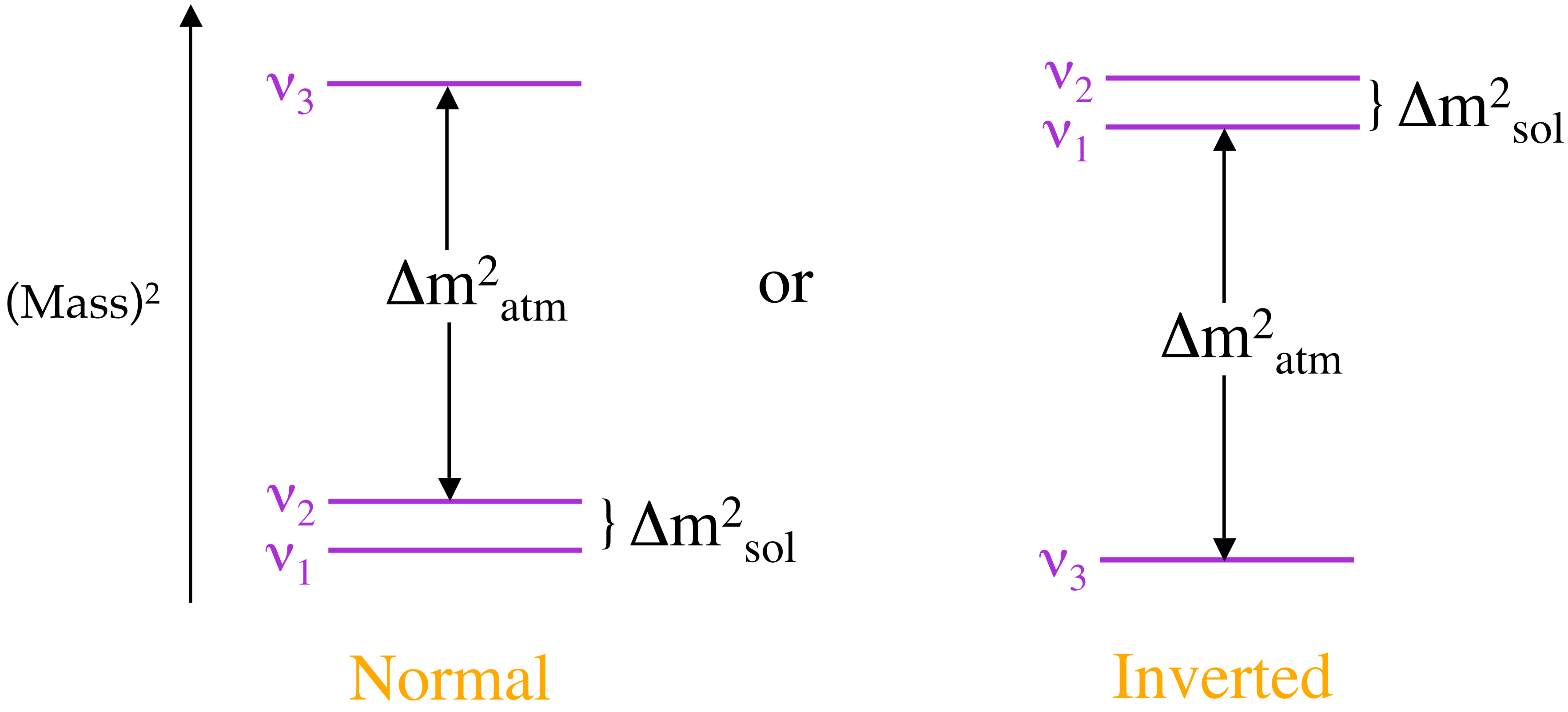
Evidence For Flavor Change

Neutrinos	Evidence of Flavor Change
Solar	Compelling
Reactor (L ~ 180 km)	Compelling
Atmospheric	Compelling
Accelerator (L = 250 and 735 km)	Compelling
Stopped μ^+ Decay $\left(\begin{matrix}\text{LSND}\\ L \approx 30\text{ m}\end{matrix}\right)$	Unconfirmed by MiniBooNE



What We Have Learned

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



$(\text{Mass})^2$

ν_3

Δm^2_{atm}

ν_2

ν_1

$\} \, \Delta m^2_{sol}$

or

ν_2

ν_1

$\} \, \Delta m^2_{sol}$

Δm^2_{atm}

ν_3

Normal

Inverted

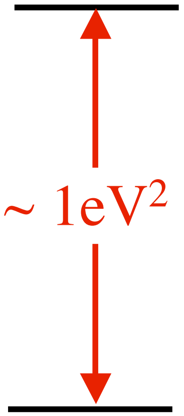
$\Delta m^2_{sol} \cong 8 \text{ x } 10^{-5}$ eV^2, $\Delta m^2_{atm} \cong 2.4 \text{ x } 10^{-3}$ eV^2

Are There *More* Than 3 Mass Eigenstates?

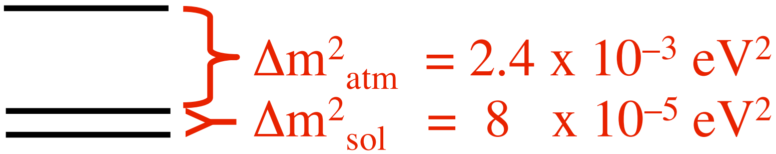
When only two neutrinos count,

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

Rapid neutrino oscillation reported by LSND —

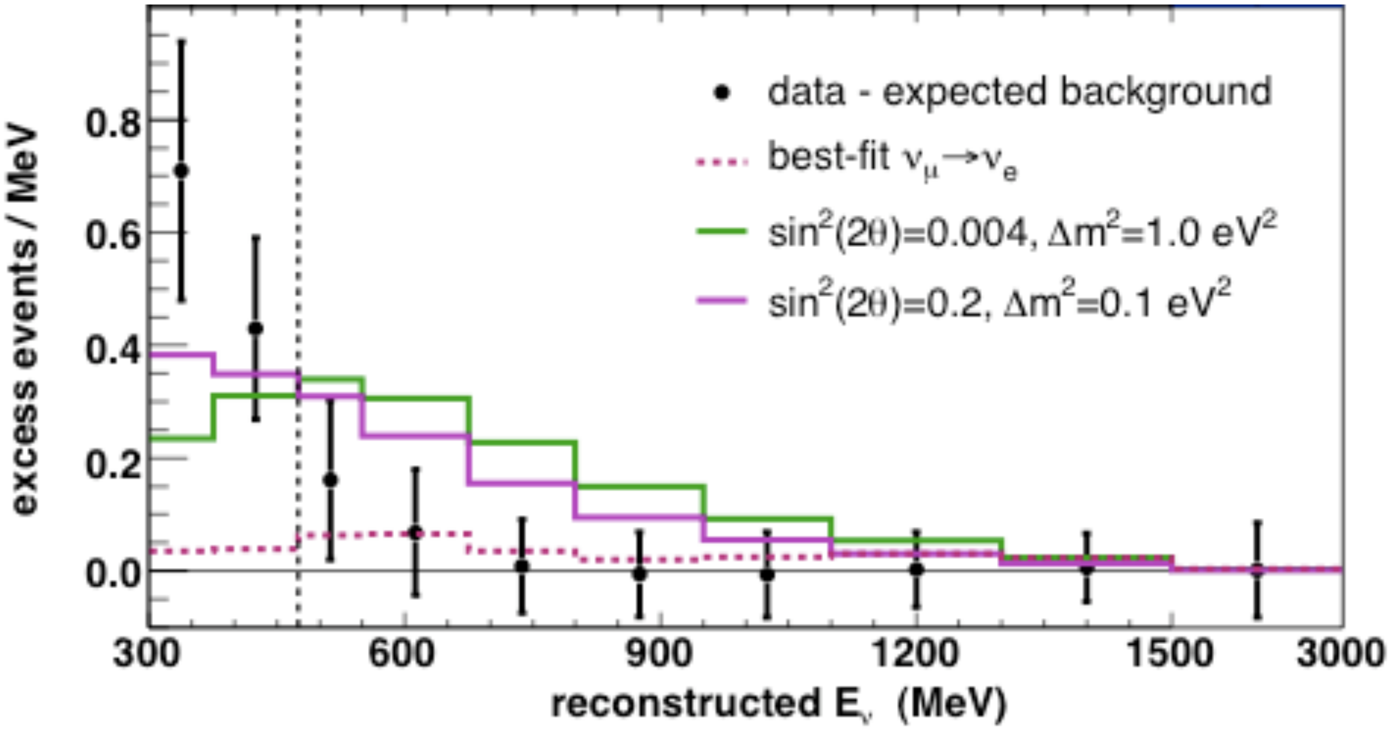


in contrast to



At least **4** mass eigenstates.

MiniBooNE



- 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.
- We shall assume 3 mass eigenstates (but there may be more).

Leptonic Mixing

This has the consequence that —

Mass eigenstate

Flavor eigenstate

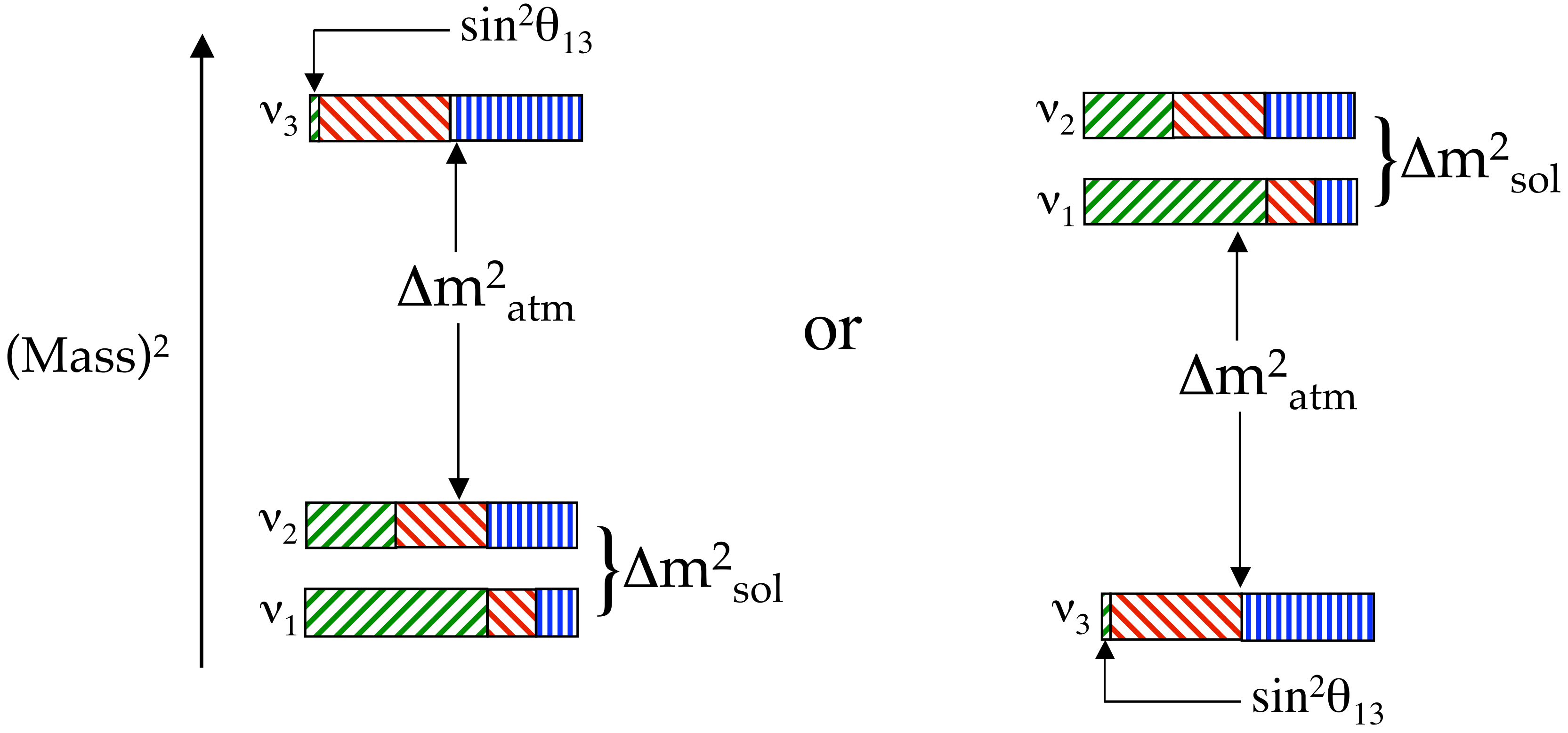
$$|\nu_i> = \sum_{\alpha} U_{\alpha i}\, |\nu_\alpha> .$$

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



Normal Inverted

▨ $\nu_e\,[\,|U_{ei}|^2]$ ▧ $\nu_\mu[\,|U_{\mu i}|^2]$ ▥ $\nu_\tau\,[\,|U_{\tau i}|^2]$

The Mixing Matrix

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

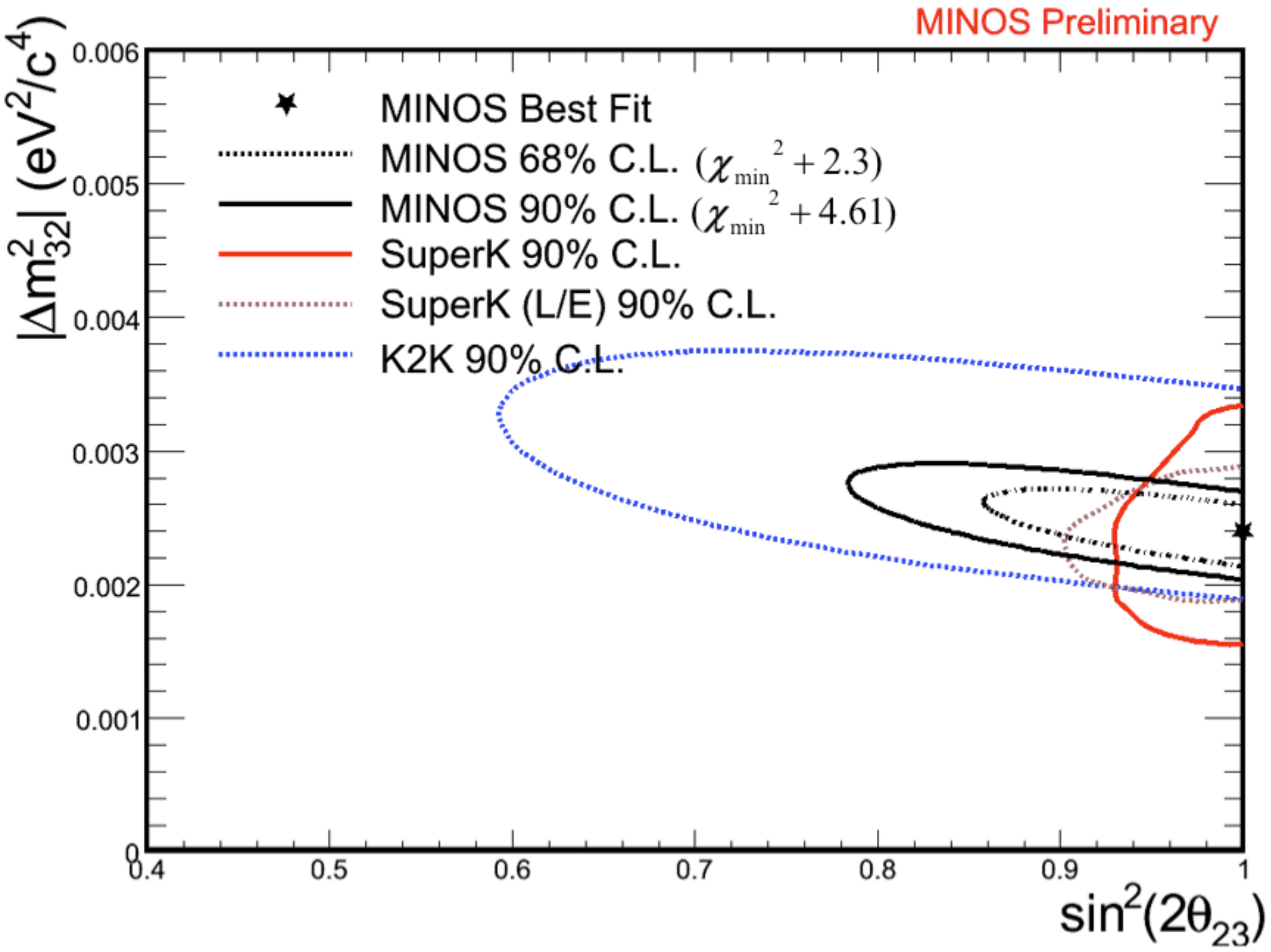
$$c_{ij} \equiv \cos\theta_{ij}$$
$$s_{ij} \equiv \sin\theta_{ij}$$

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

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

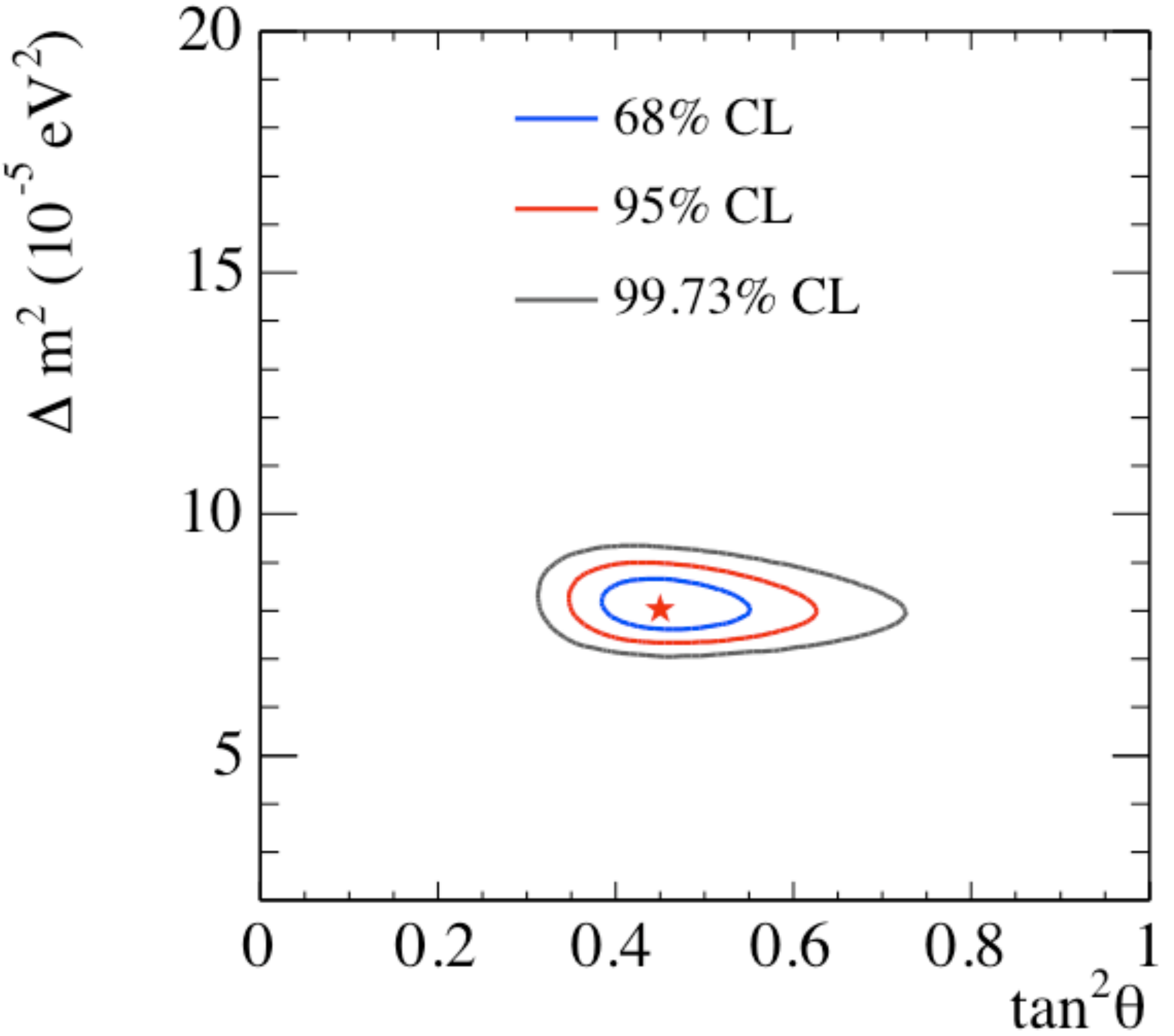
δ would lead to $P(\overline{\nu}_\alpha \rightarrow \overline{\nu}_\beta) \neq P(\nu_\alpha \rightarrow \nu_\beta)$. $\cancel{CP}$

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



From talk by N. Saoulidou

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



From nucl-ex/ 0502021

“Solar” Δm^2 and mixing angle from SNO analysis of solar neutrino and KamLAND data

^{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 Open Questions

- 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 is the absolute scale of neutrino mass?

- Are neutrinos their own antiparticles?

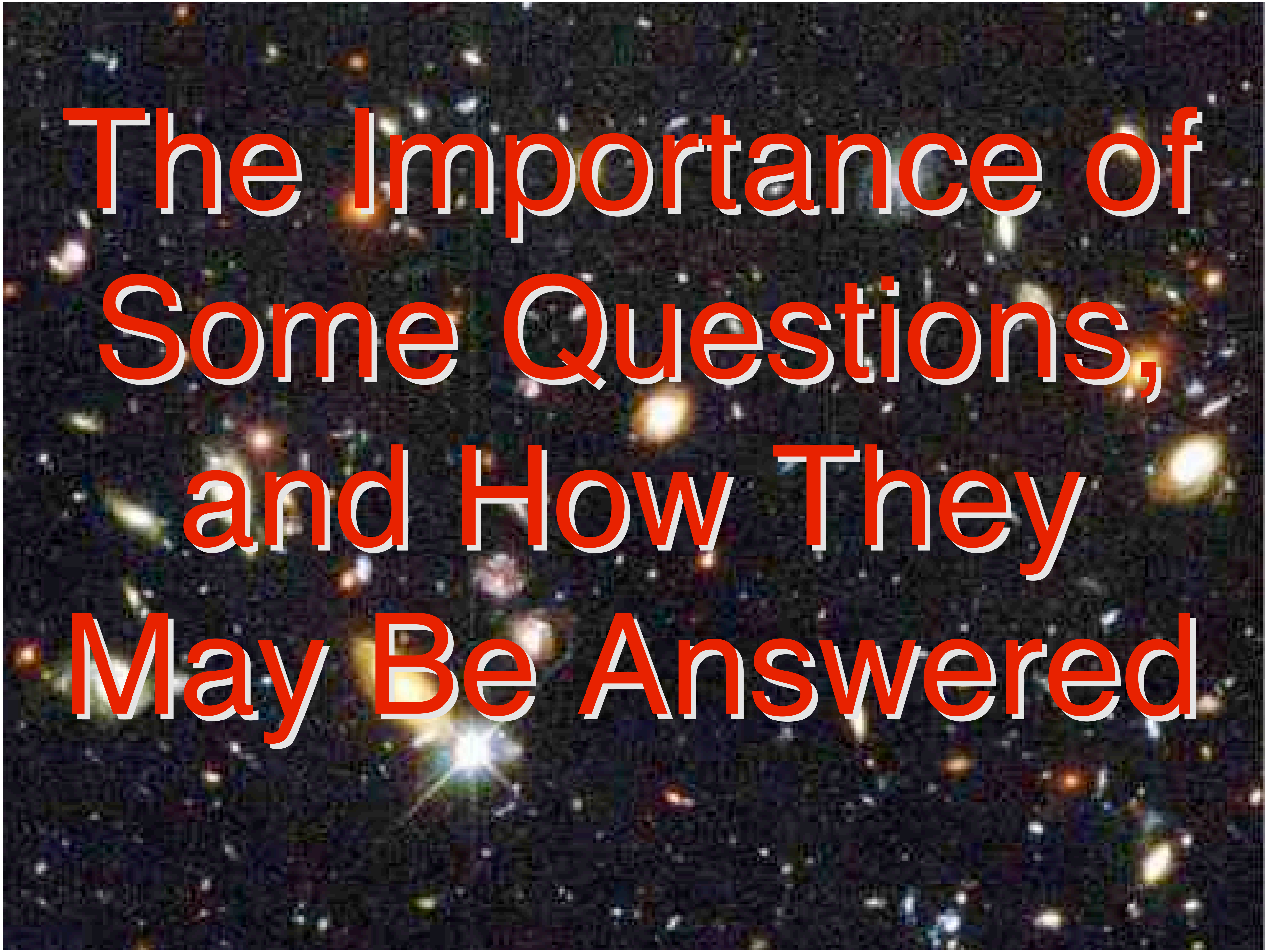
- Are there “sterile” neutrinos?

We must be alert to surprises!

- 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?

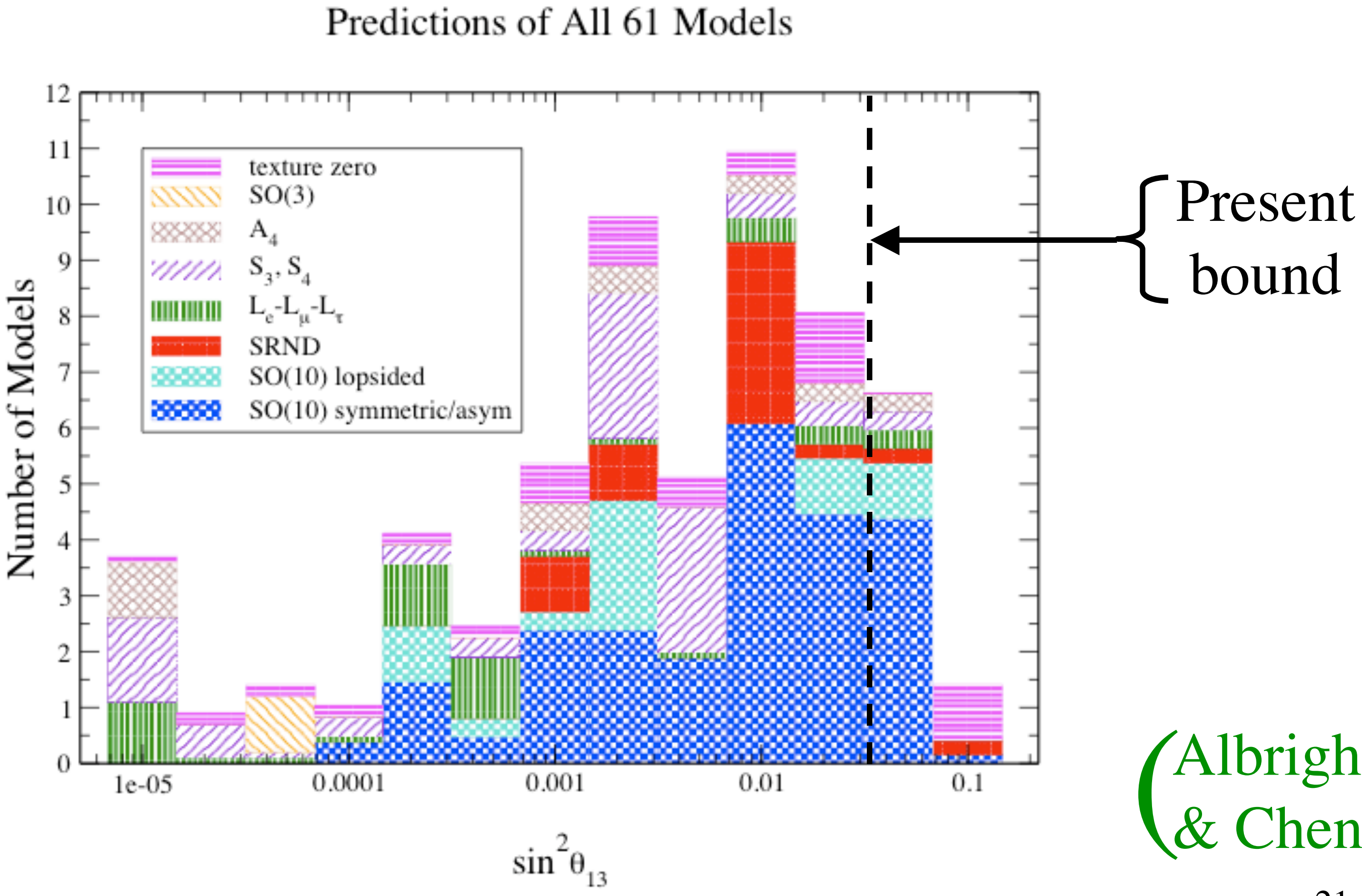


The Importance of Some Questions, and How They May Be Answered

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)

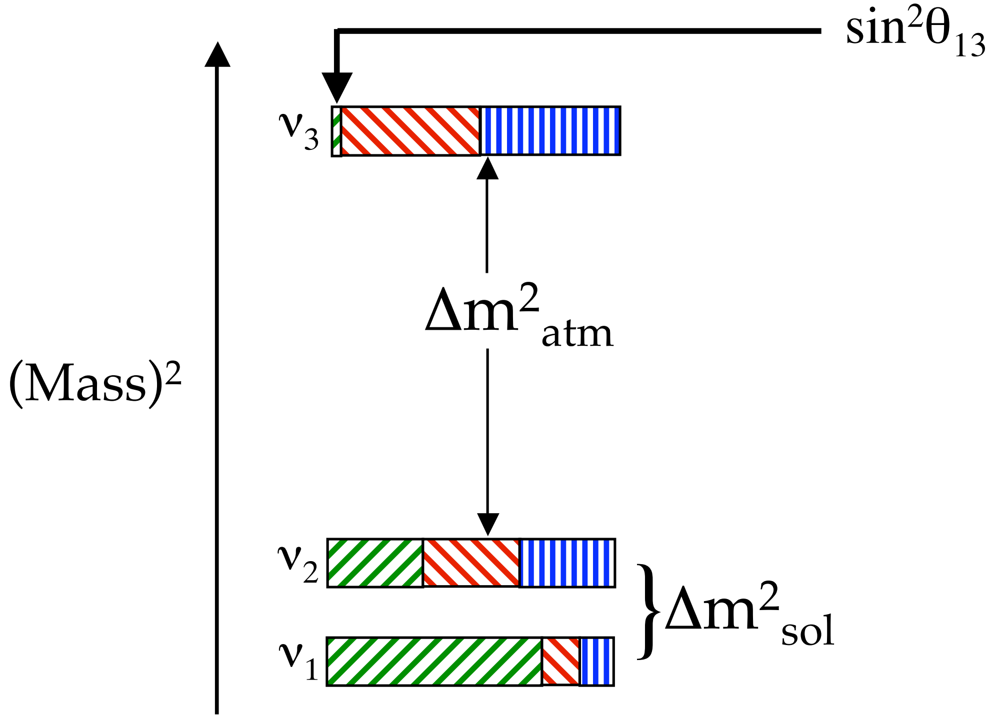
The Central Role of θ_{13}

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

If $\sin^2 2\theta_{13} > (0.01 - 0.02)$, we can study both of these issues with intense but conventional accelerator ν and $\bar{\nu}$ beams, produced via $\pi^+ \to \mu^+ + \nu_\mu$ and $\pi^- \to \mu^- + \bar{\nu}_\mu$.

Determining θ_{13} is an important step.

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?)

Accelerator Experiments

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 $\nu_\mu \rightarrow \nu_e$ and $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$
while the beams travel hundreds of kilometers.

(***T2K will study*** $\nu_\mu \rightarrow \nu_e$)

Further experiments in Japan, or Japan and Korea?

The Mass Spectrum:  or  ?

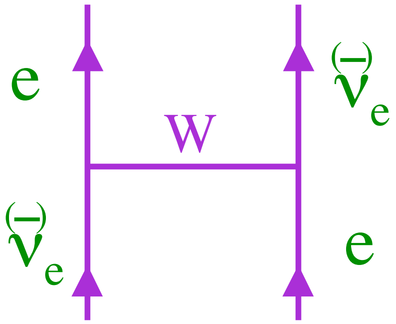
Generically, grand unified models (GUTS) favor —

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 oscillation probabilities
in a way that depends on whether the
spectrum is *Normal* or *Inverted*.

Do Neutrino Interactions Violate CP?

The observed $\not{CP}$ in the weak interactions of ***quarks*** cannot explain the *Baryon Asymmetry* of the universe.

Is ***leptonic*** $\not{CP}$, through *Leptogenesis*, the origin of the *Baryon Asymmetry* of the universe?

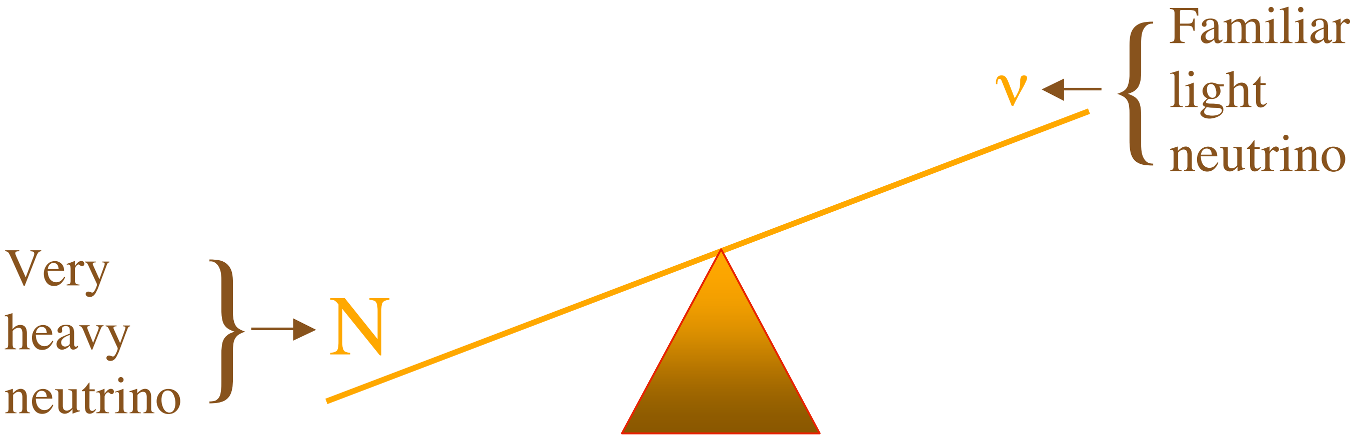
(Fukugita, Yanagida)

Leptogenesis In 60 Seconds

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

Caution: The matter effect can be confused with $\cancel{CP}$.

Separating $\cancel{CP}$ From the Matter Effect

Genuine $\cancel{CP}$ and the matter effect both lead to a difference between ν and $\bar{\nu}$ oscillation.

But genuine $\cancel{CP}$ 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 $\alpha \equiv \Delta m_{21}^2 / \Delta m_{31}^2$, $\Delta \equiv \frac{\Delta m_{31}^2 L}{4E}$, and $x \equiv \frac{2\sqrt{2} G_F N_e E}{\Delta m_{31}^2}$ —

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

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

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

$P\left[\bar{\nu}_\mu \to \bar{\nu}_e\right] \; = \; P\left[\nu_\mu \to \nu_e\right]$ with $\delta \to -\delta$ 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 —

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

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

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

When $L \to 3L$ at given E, $\cancel{CP}$ *is tripled*.
The effect of matter on the ν_e *energy spectrum increases in a revealing way*.

Large, identical detectors
in Kamioka and Korea,
both in the J-PARC beam

(Ishitsuka, Kajita, Minakata, Nunokawa)

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

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

U.S. Plans and Hopes

NOνA

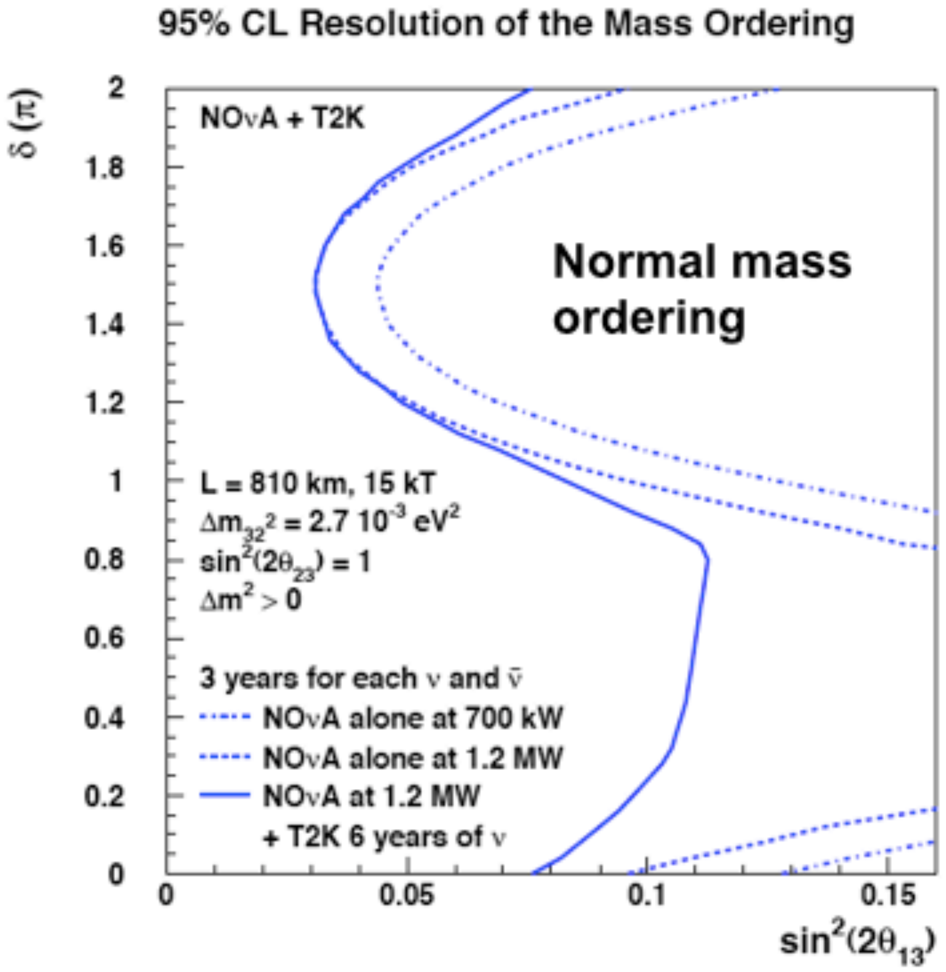
The next Long BaseLine accelerator neutrino oscillation experiment will be the —

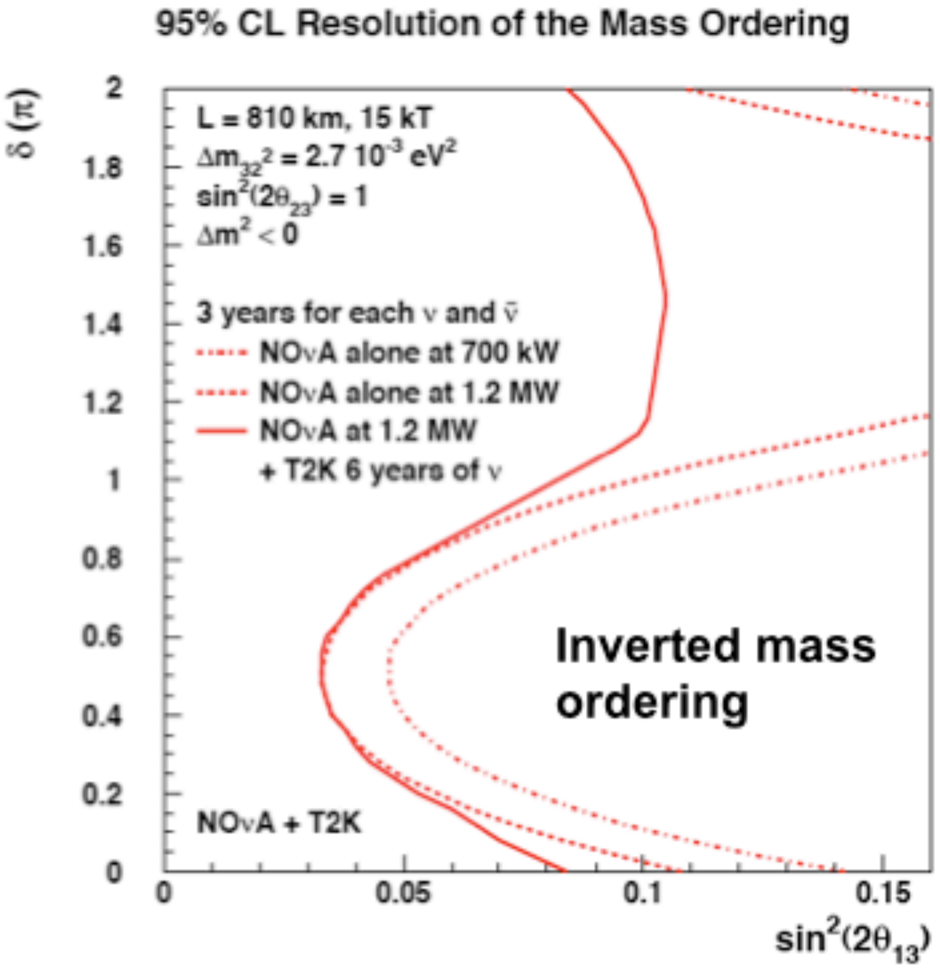
NuMI Off-Axis ν_e Appearance

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
- *Main goal: Try to determine whether the spectrum is Normal or Inverted*

95% CL Resolution of the Mass Ordering


95% CL Resolution of the Mass Ordering


95% CL Resolution of the Mass Ordering

NOνA Timeline

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

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

T2K, Double Chooz, and Daya Bay

The U.S. will participate in —

T2K	accelerator	neutrino	experiment	in Japan
Double Chooz	reactor	“	“	in France
Daya Bay	“	“	“	in China

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

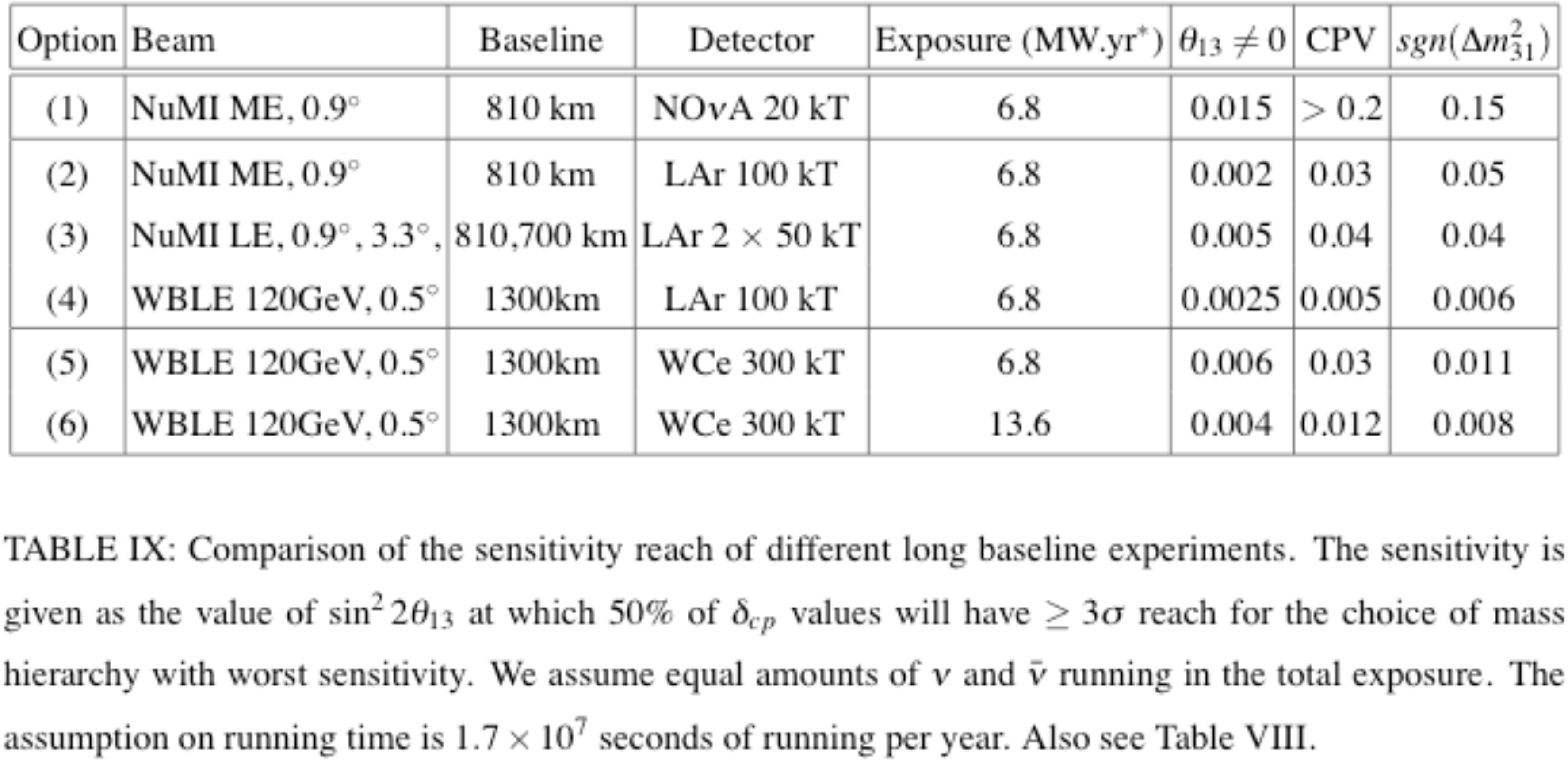
(Brookhaven & Fermilab)

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.

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 government-advisory committee)

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.

Fermilab Steering Group

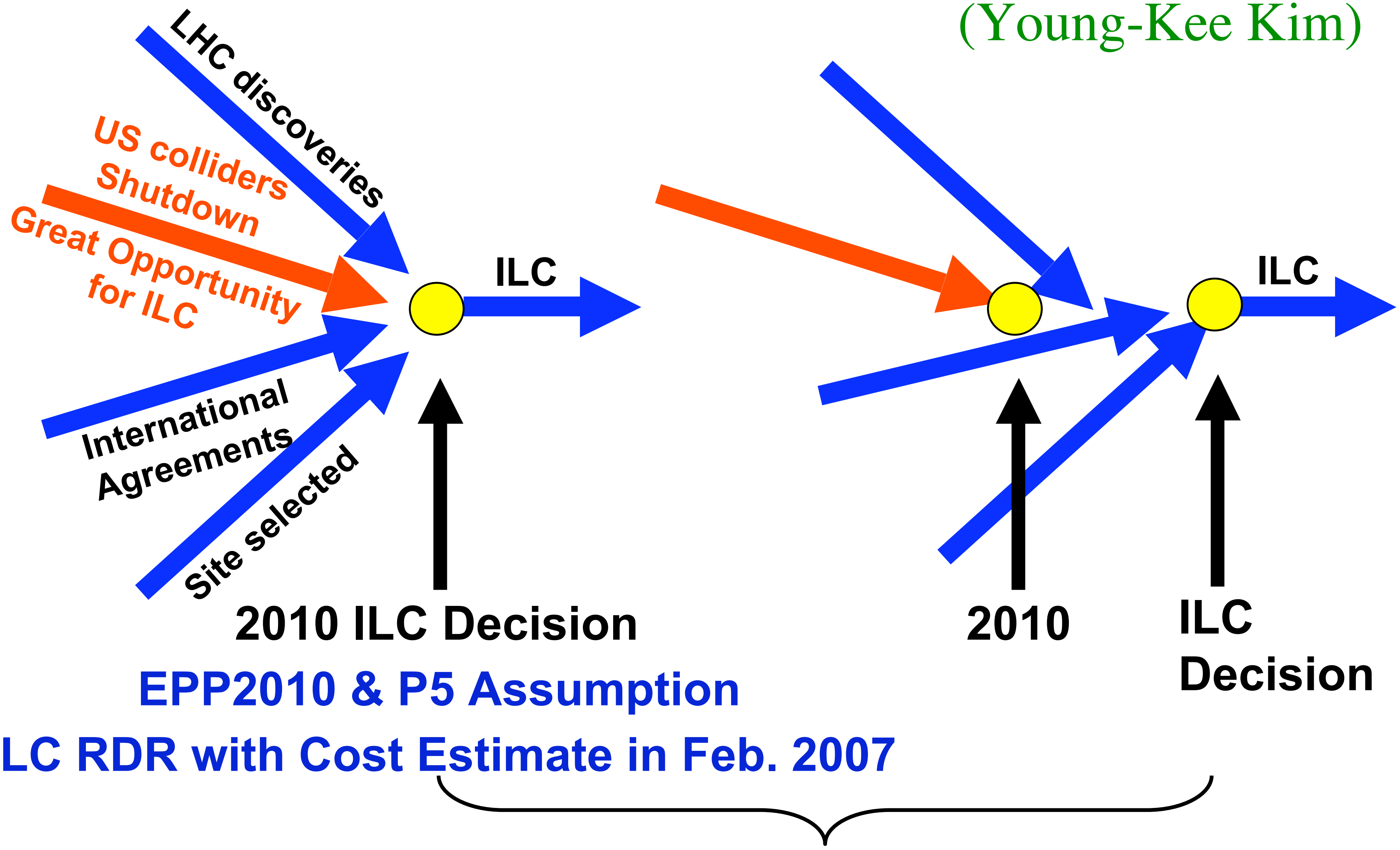
Fermilab's top priority is to bid to host the International Linear Collider (ILC).

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)



LHC discoveries

US colliders Shutdown

Great Opportunity for ILC

International Agreements

Site selected

ILC

2010 ILC Decision

2010

ILC

ILC Decision

EPP2010 & P5 Assumption

ILC RDR with Cost Estimate in Feb. 2007

Possible ILC Decision Timelines

Preliminary Steering Group Report

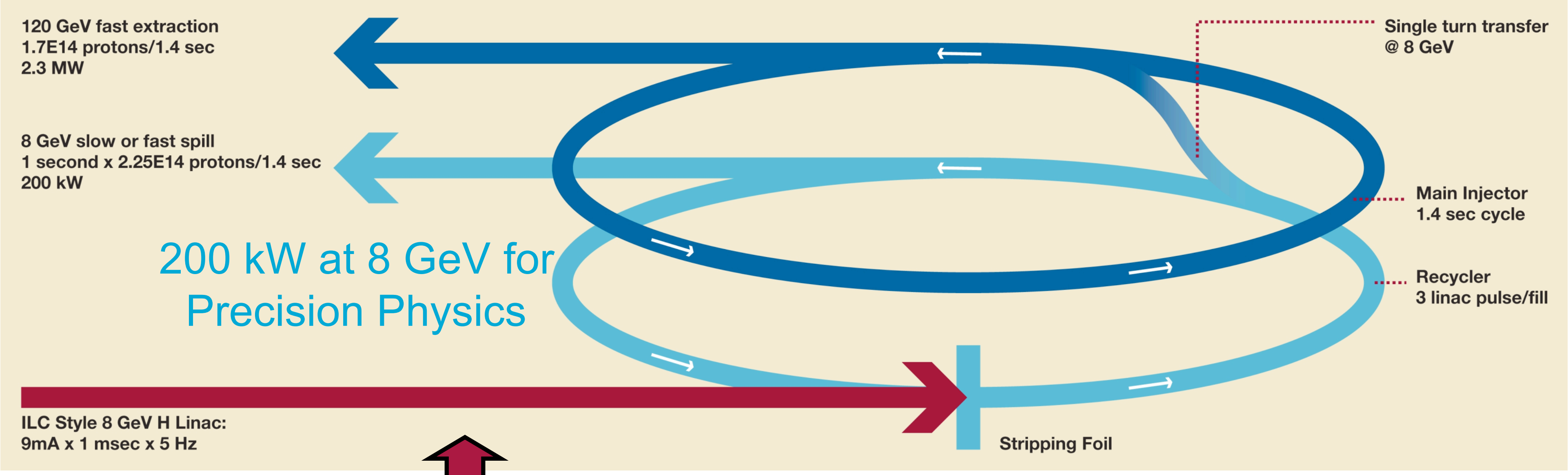
(Points relevant to neutrinos)

- 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 laborabory 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



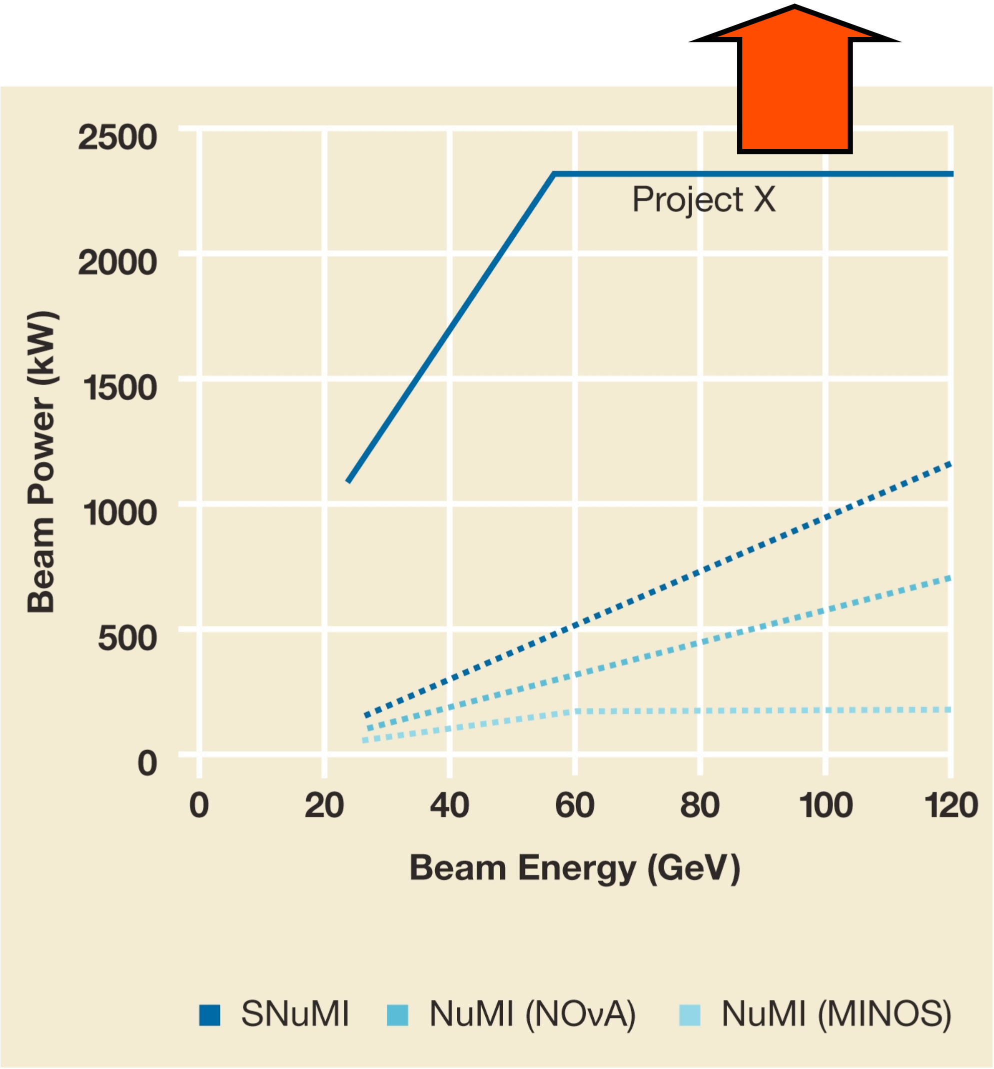
200 kW at 8 GeV for
Precision Physics

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)



with Main Injector Upgrade

Inject into
Main Injector

sNuMI

NuMI (NOvA)

NuMI (MINOS)

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

It should also make possible such experiments as —

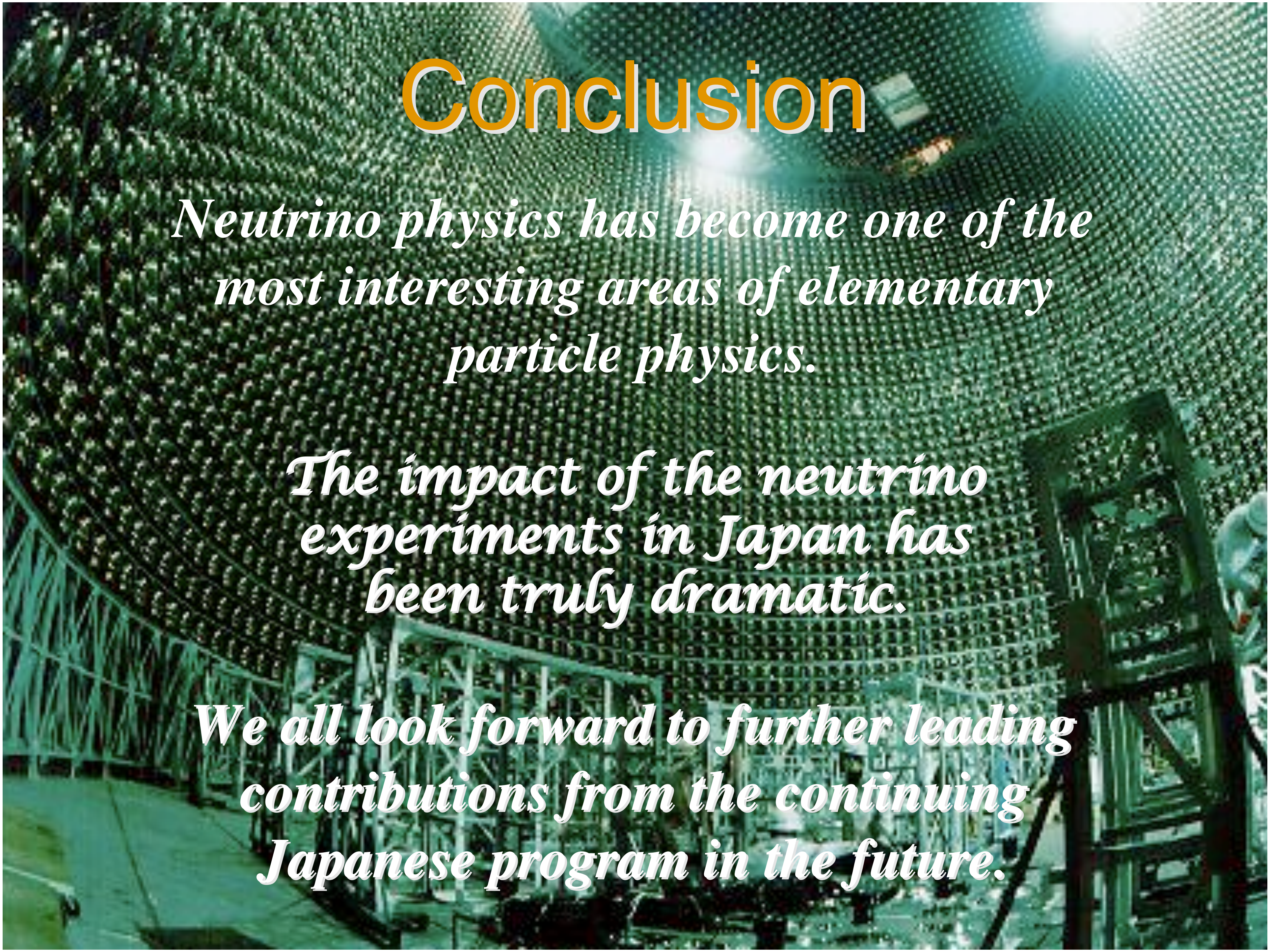
high-statistics $\nu_\mu e \rightarrow \nu_\mu e$ scattering, *using neutrinos from 800 GeV protons produced by the TeVatron*, for a precision measurement of θ_W *that does not involve a nuclear target*

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

Conclusion



Neutrino physics has become one of the most interesting areas of elementary particle physics.

The impact of the neutrino experiments in Japan has been truly dramatic.

We all look forward to further leading contributions from the continuing Japanese program in the future.

Backup Slides

Are Neutrinos Their Own Antiparticles?

Does —

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

or

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

Equivalently, is the Lepton Number L defined by—
$L(\nu) = L(\ell^-) = -L(\overline{\nu}) = -L(\ell^+) = 1$ conserved?

If not, then nothing distinguishes $\overline{\nu}_i$ from ν_i . We then have Majorana neutrinos.

Why Many Theorists Think L Is Not Conserved

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.

This SM conserves the lepton number L.

But now we know the neutrino has mass.

If we try to preserve L, we accommodate this mass by adding a Dirac, L - conserving, mass term: $m_D\overline{\nu}_L\nu_R$.

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

Unlike ν_L , ν_R carries no Weak Isospin.

Thus, no SM symmetry prevents the occurrence of the Majorana mass term $m_M\overline{\nu_R{}^c}\nu_R$.

This mass term causes $\nu \rightarrow \overline{\nu}$. It does not conserve L.

If anything allowed by the *extended* SM occurs in nature, then L is not conserved.

The Promising Approach —

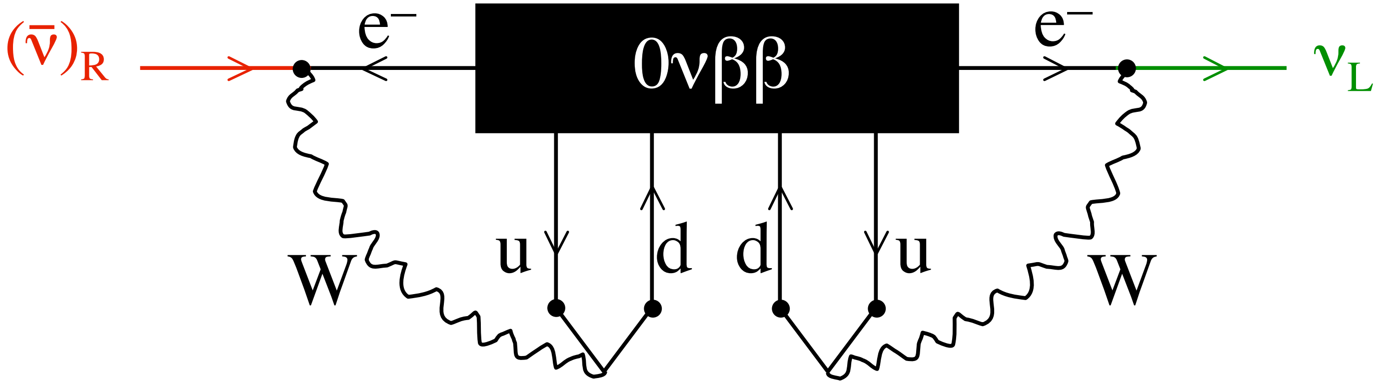
Neutrinoless Double Beta Decay [0νββ]

If we start with ***a lot*** of parent nuclei (say, one ton of them), we can cope with the smallness of $\not{L}$.

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

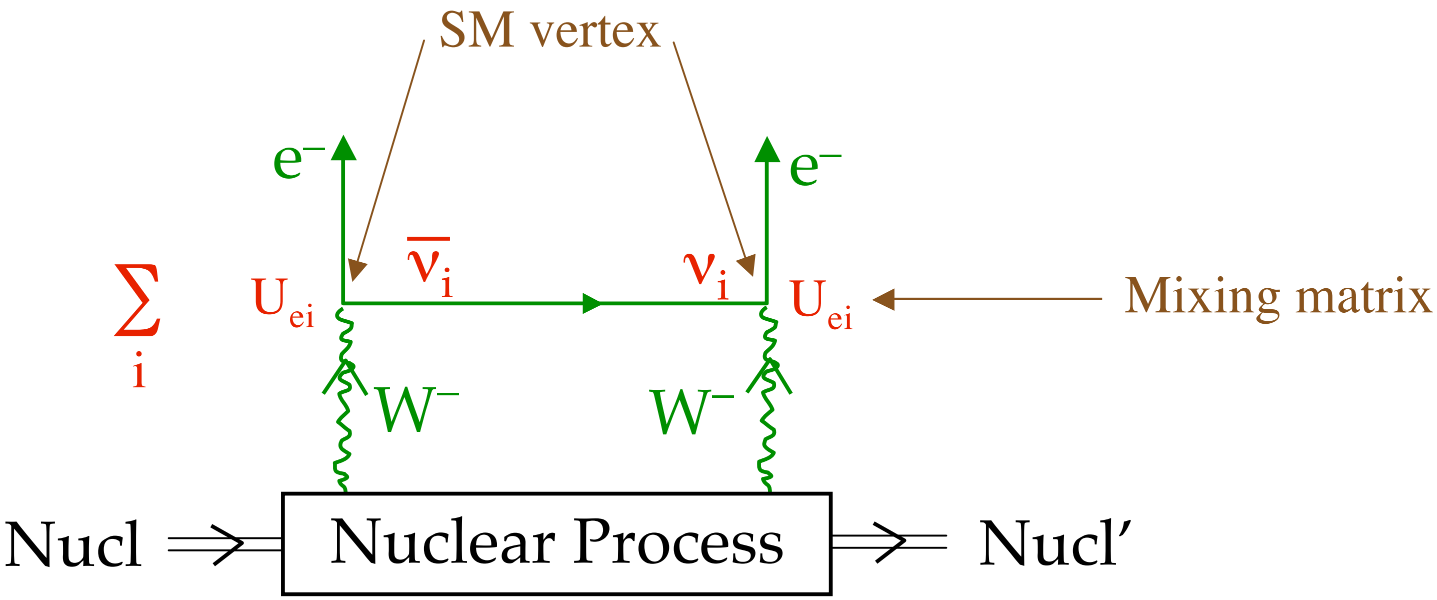
Whatever diagrams cause 0νββ, its observation would imply the existence of a Majorana mass term:

Schechter and Valle

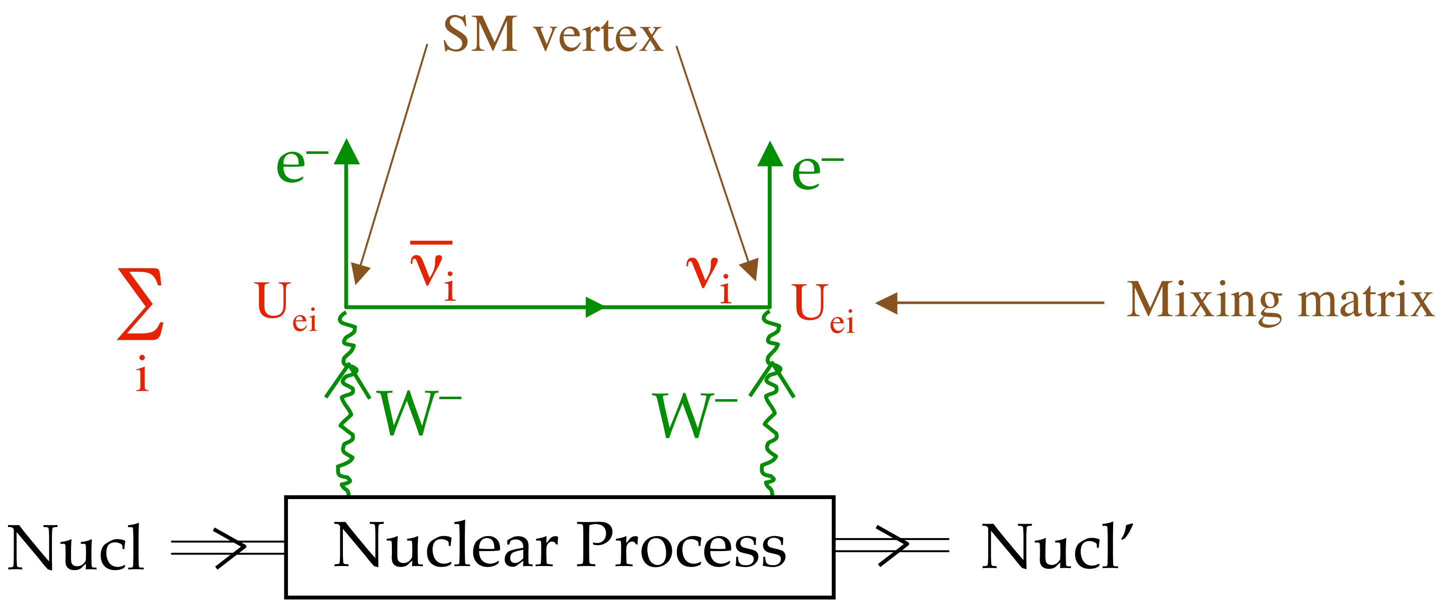


$(\bar{\nu})_R \rightarrow \nu_L$: A Majorana mass term

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



In —



Mass (ν_i)

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

Thus, Amp [ν_i contribution] ∝ 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 0νββ to ν mass is no surprise.

0νββ violates L. But the SM interactions conserve L.

The L – violation in 0νββ comes from underlying **Majorana** neutrino mass terms.

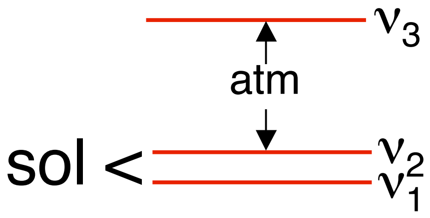
The 0νββ amplitude would be proportional to neutrino mass even if there were no helicity mismatch.

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

How sensitive need an experiment be?

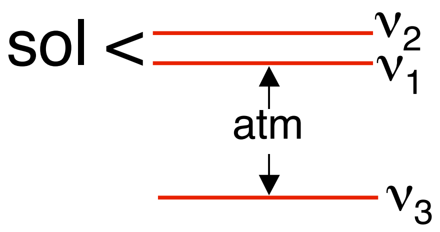
Suppose there are only 3 neutrino mass eigenstates. (More might help.)

Then the spectrum looks like —

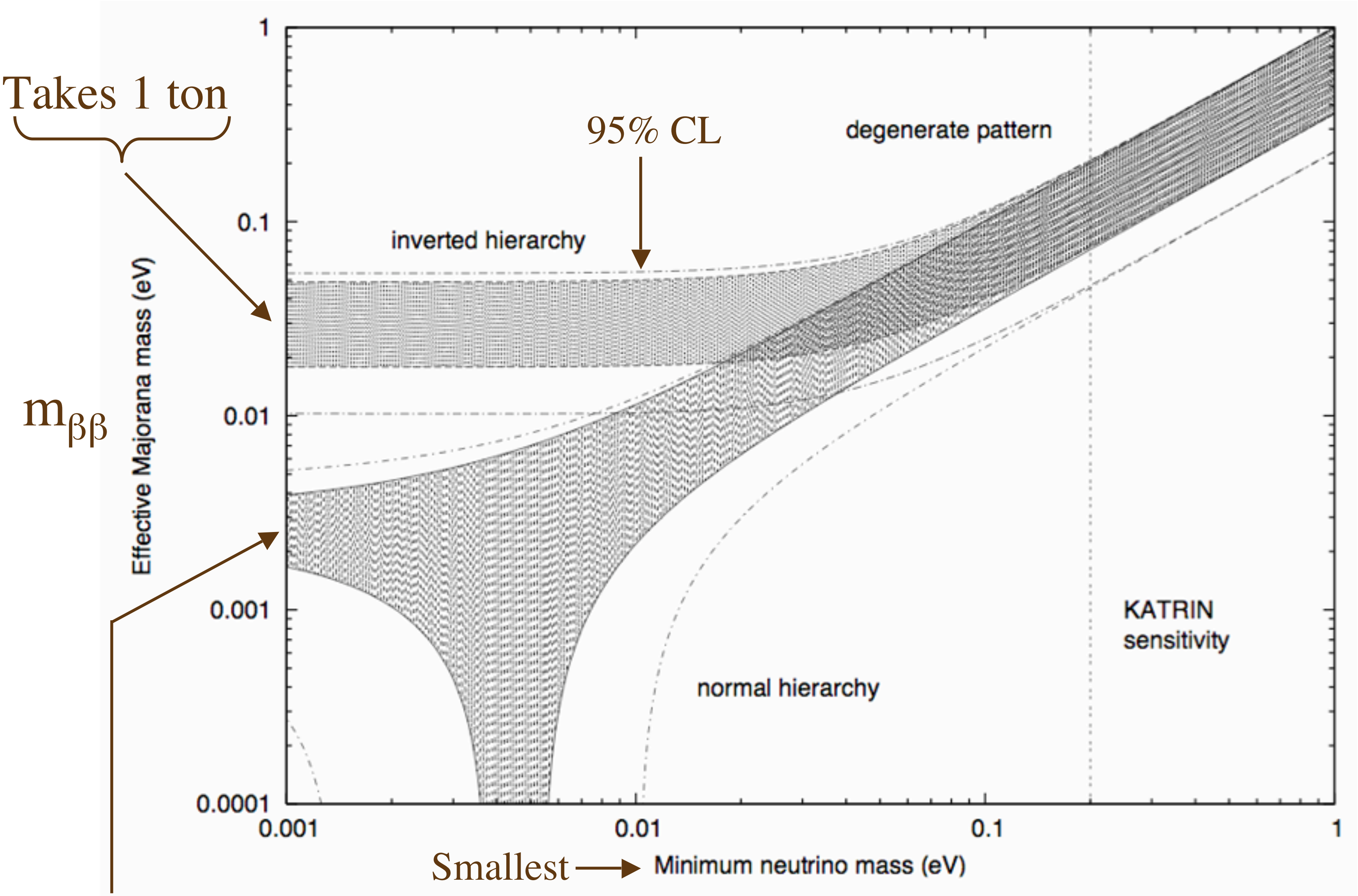


Normal hierarchy

or



Inverted hierarchy



Takes 1 ton

95% CL

$m_{\beta\beta}$

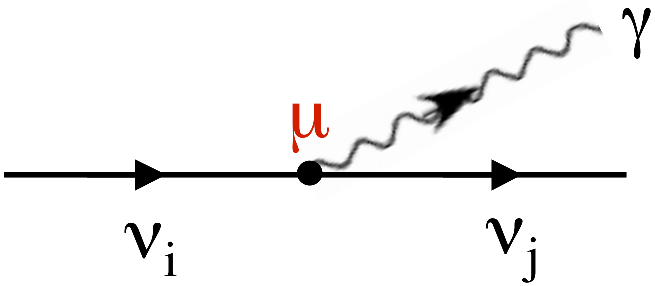
Smallest →

Takes
100 tons

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

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} μ_{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.