Neutrinos: Results and Future

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July 1, 2008

Evidence For ν Flavor Change

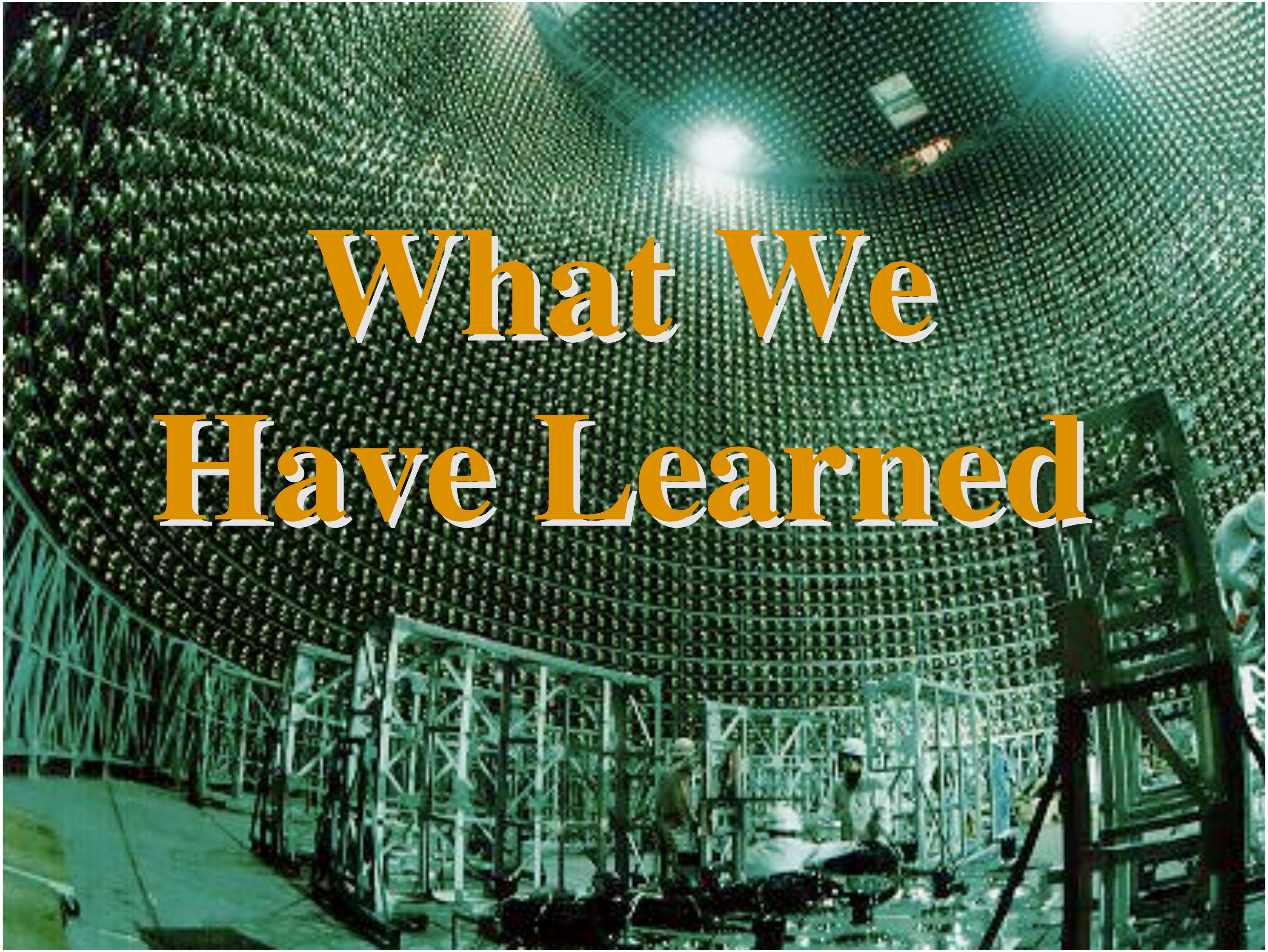
Neutrinos	Evidence of Flavor Change
Solar	Compelling
Reactor (L ~ 180 km)	Compelling
Atmospheric	Compelling
Accelerator (L = 250 and 735 km)	Compelling
Stopped μ^+ Decay $\begin{pmatrix} \text{LSND} \\ L \approx 30\text{ m} \end{pmatrix}$	Unconfirmed by MiniBooNE

The neutrino flavor-change observations imply that —

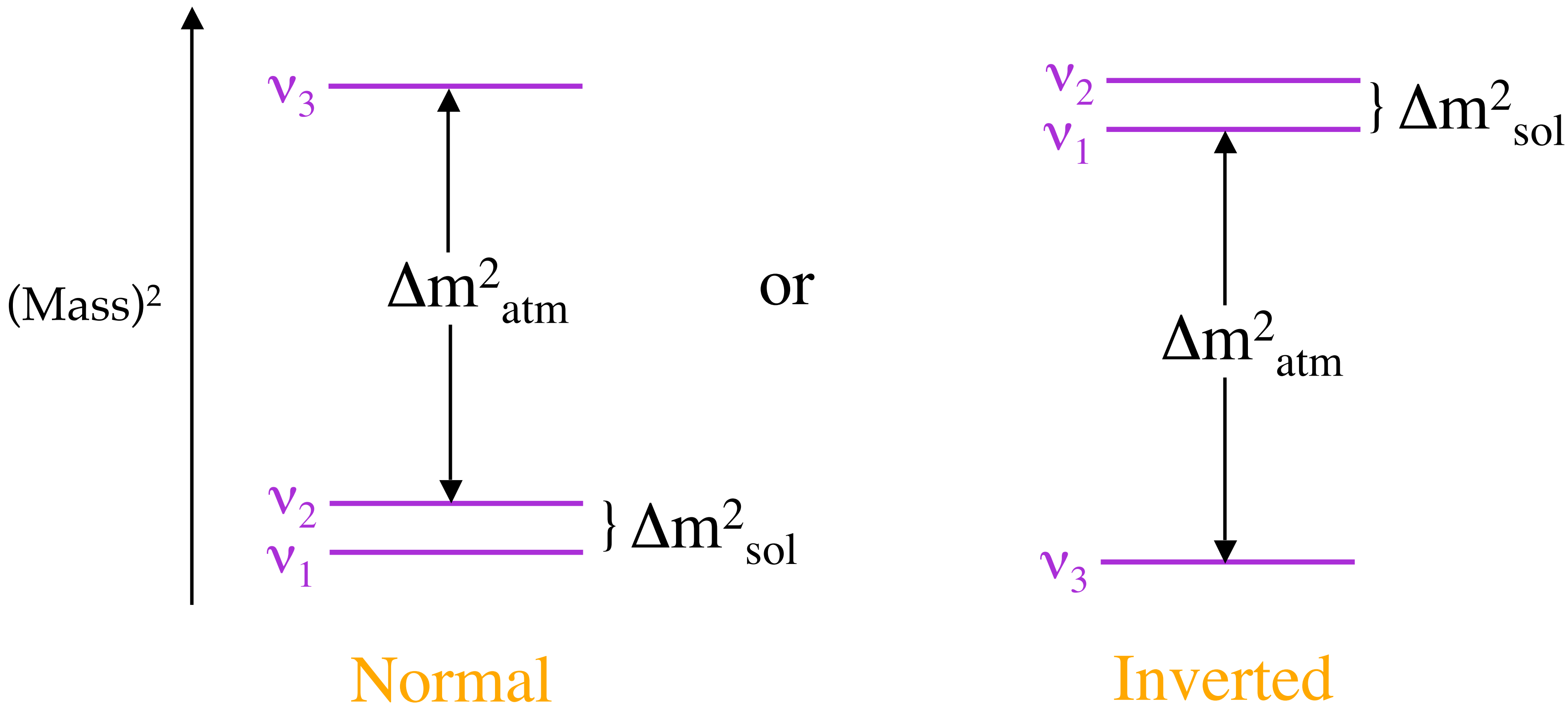
Neutrinos have nonzero masses

and that —

Leptons mix.


What We
Have Learned

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



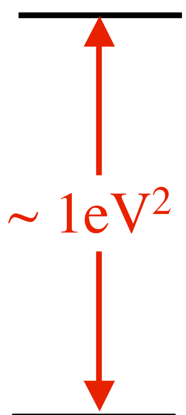
$\Delta m^2_{sol} \cong 7.6 \times 10^{-5}\ \text{eV}^2, \quad \Delta m^2_{atm} \cong 2.4 \times 10^{-3}\ \text{eV}^2$

Are There *More* Than 3 Mass Eigenstates?

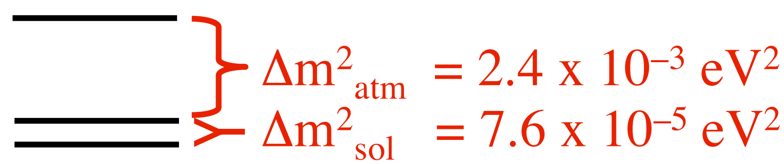
When only two neutrinos count,

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

Rapid $\bar{\nu}_\mu \to \bar{\nu}_e$ oscillation reported by LSND —

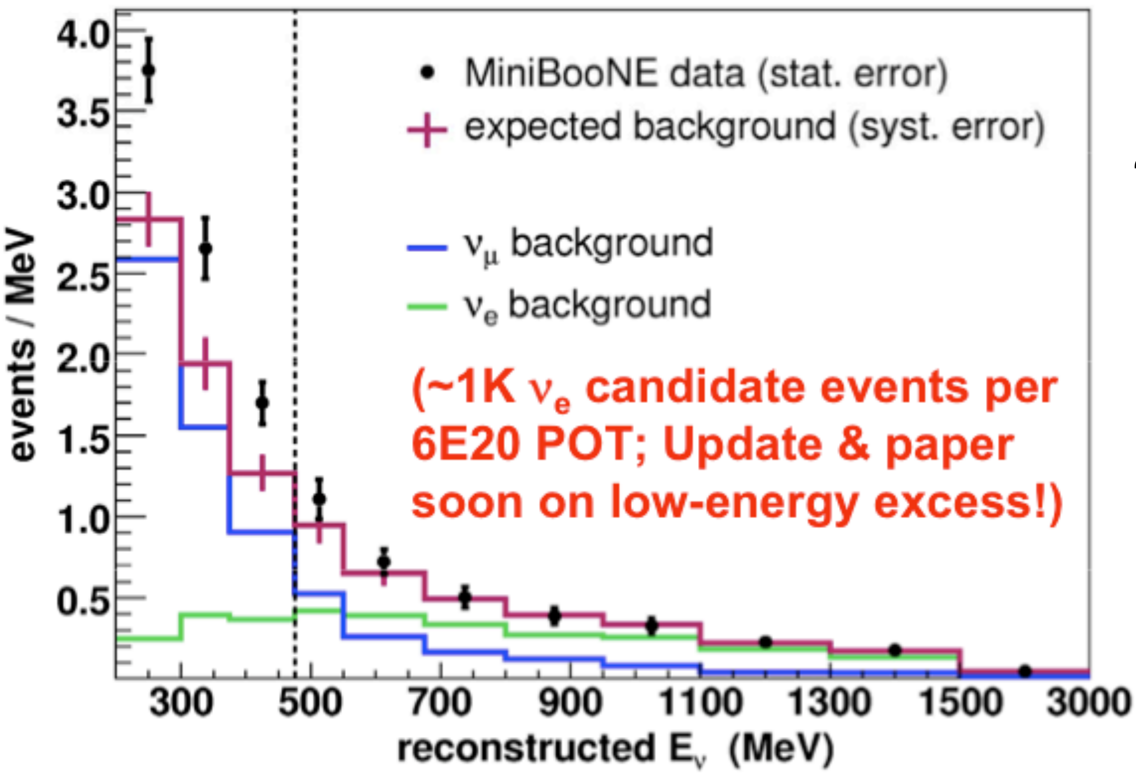


in contrast to



At least **4** mass eigenstates ⇒ At least 1 $\nu_{Sterile}$

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



ν_e Candidate Events

(Bill Louis 19 June 2008)

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

MINOS Neutral Current Analysis

Do the ν_μ that disappear in the MINOS experiment oscillate into ν_e, ν_τ, or $\nu_{Sterile}$?

CHOOZ (and CPT) excludes any appreciable $\nu_\mu \rightarrow \nu_e$.

If $\nu_\mu \rightarrow \nu_\tau$, the MINOS Neutral-Current (NC) event rate will be the same as if there were no oscillation.

If some of the ν_μ disappear via $\nu_\mu \rightarrow \nu_{Sterile}$, the NC event rate will be decreased.

MINOS (At ν 2008) : For E_{vis}< 120 GeV the fraction of NC events that disappear is less than 17% at 90% CL.

Effects of this order are not excluded by MiniBooNE.

While awaiting further news —

We will assume there are only 3 neutrino mass eigenstates.

Leptonic Mixing

This has the consequence that —

Mass eigenstate → $|\nu_i\rangle$; Flavor eigenstate → $|\nu_\alpha\rangle$

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

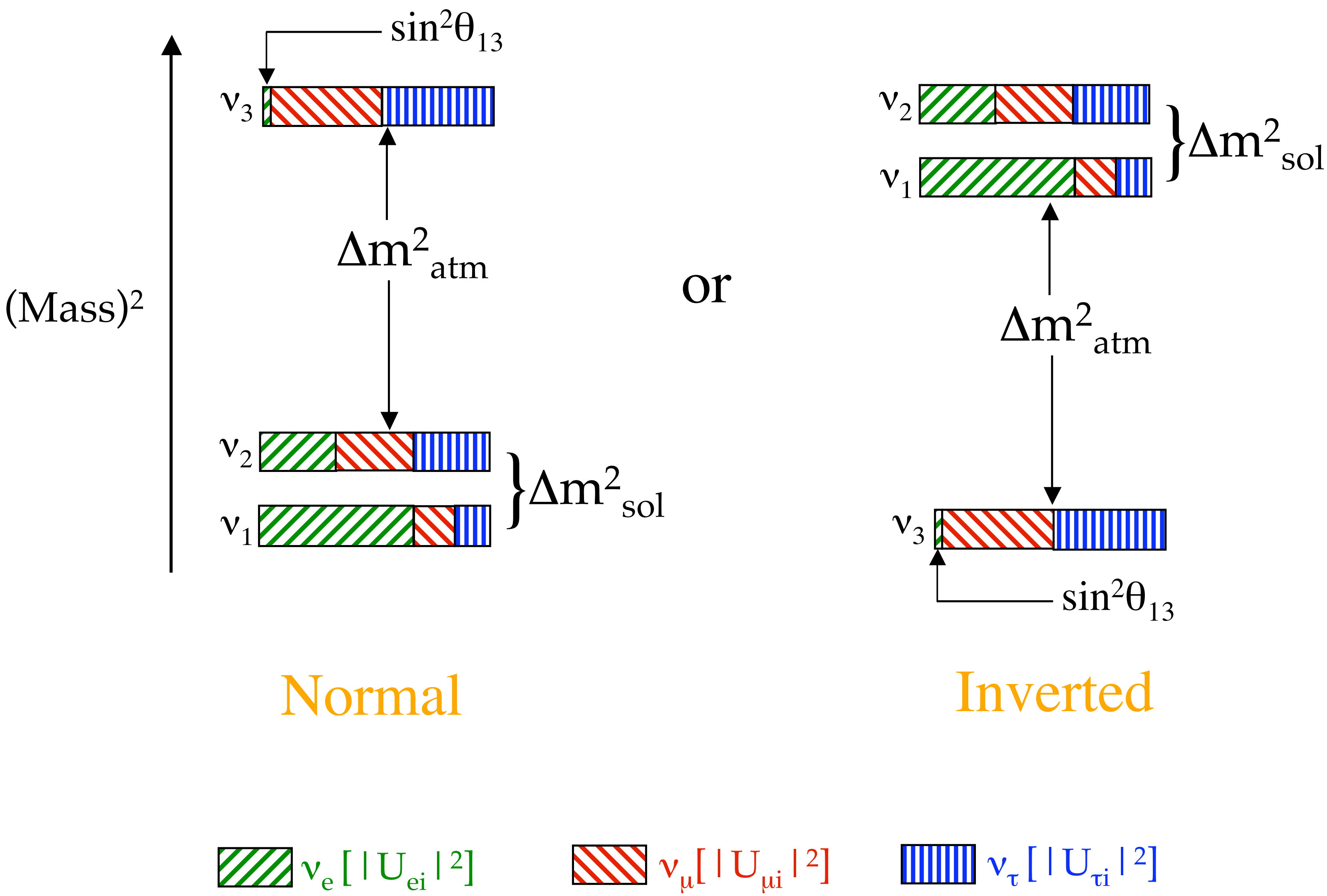
α: e, μ, or τ

$U_{\alpha i}$: PMNS 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

Atmospheric / Cross-Mixing / Solar

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

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

Majorana ~~CP~~ phases

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

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

$\theta_{12} \approx \theta_{sol} \approx 34°$, $\theta_{23} \approx \theta_{atm} \approx 38\text{-}52°$, $\theta_{13} \lesssim 10°$

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 $s_{13} \equiv \sin\theta_{13}$.

Recent Results

^{7}Be Solar Neutrinos

Until recently, only the ^{8}B solar neutrinos, with E ~ 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 —

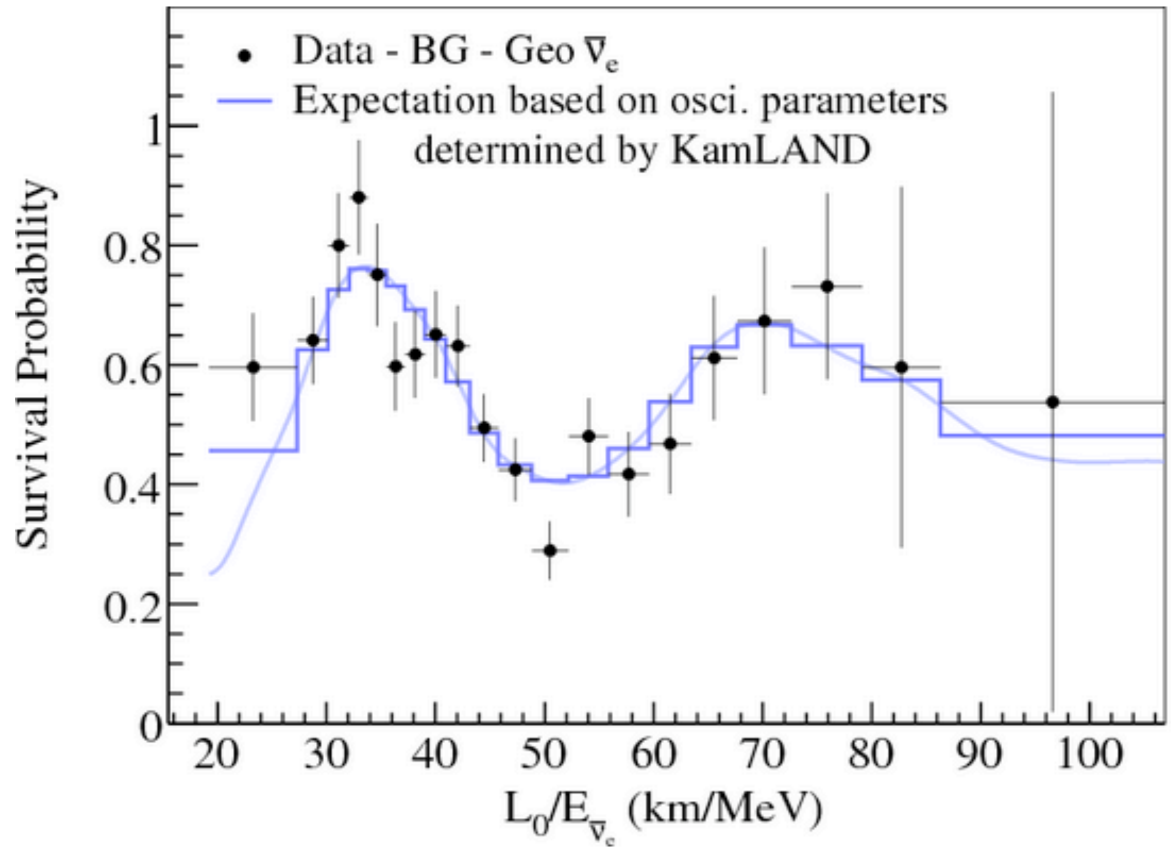
Detects the ^{7}Be solar neutrinos
via $\nu e \to \nu e$ elastic scattering.

Event rate (Counts/day/100 tons)

Observed:	49 ± 3(stat) ± 4(syst)
Expected (No Osc):	75 ± 4
Expected (With Osc):	48 ± 4

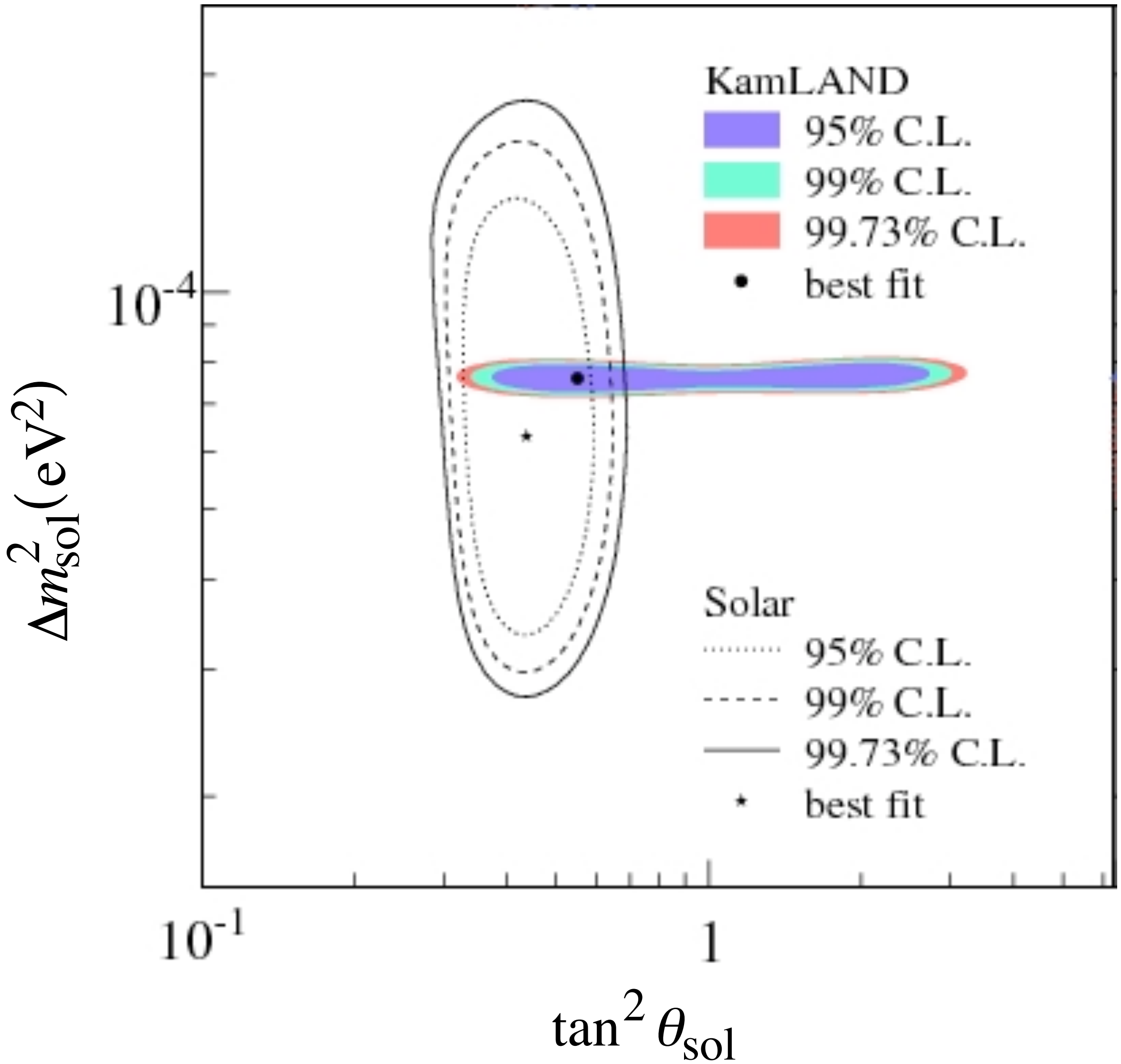
KamLAND Evidence for Oscillatory Behavior

Survival probability $P(\overline{\nu}_e \rightarrow \overline{\nu}_e)$ of reactor $\overline{\nu}_e$



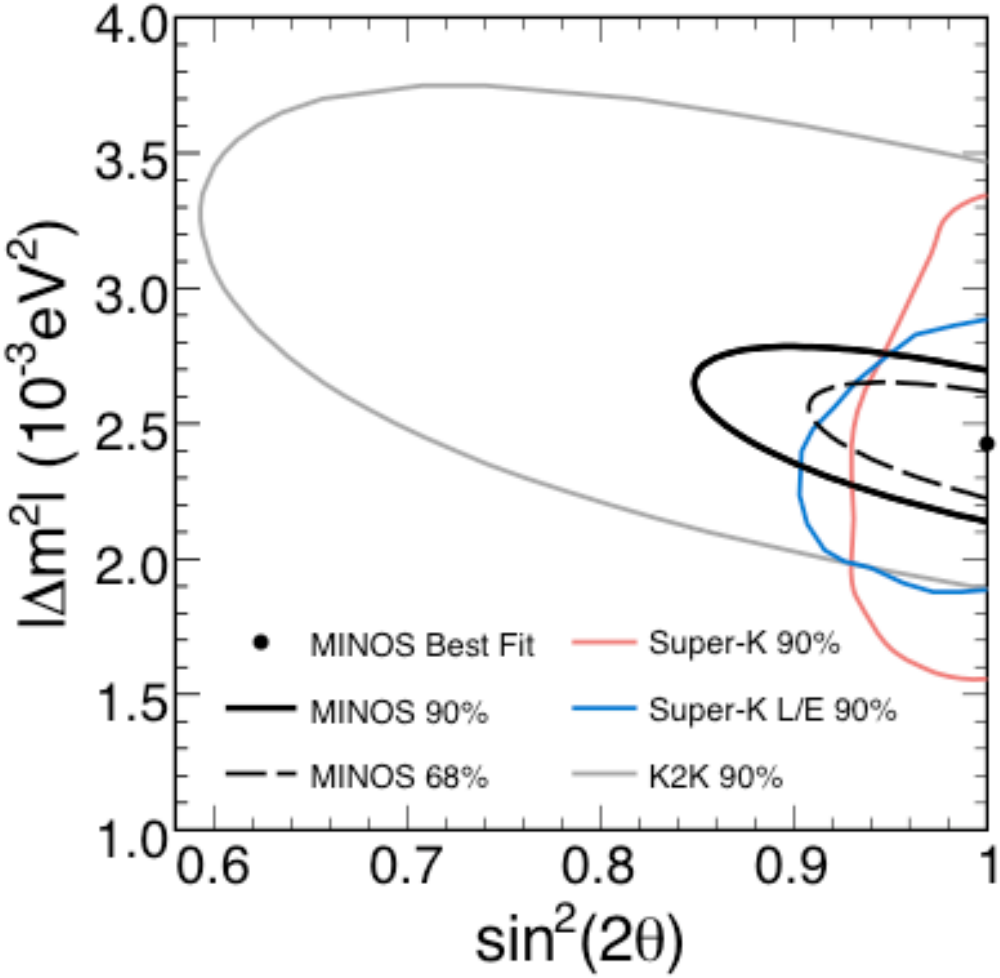
L_0 = 180 km is a flux-weighted average travel distance.

$P(\overline{\nu}_e \rightarrow \overline{\nu}_e)$ actually oscillates!



Presented by KamLAND

"Solar" Δm^2 and mixing angle from KamLAND and solar experiments.



$|\Delta m^2| = (2.43 \pm 0.13) \times 10^{-3}\ eV^2$
(68% C.L.)

$\sin^2(2\theta) > 0.90$
(90% C.L.)

From talk by
H. Gallagher at
Neutrino 2008

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


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  ?

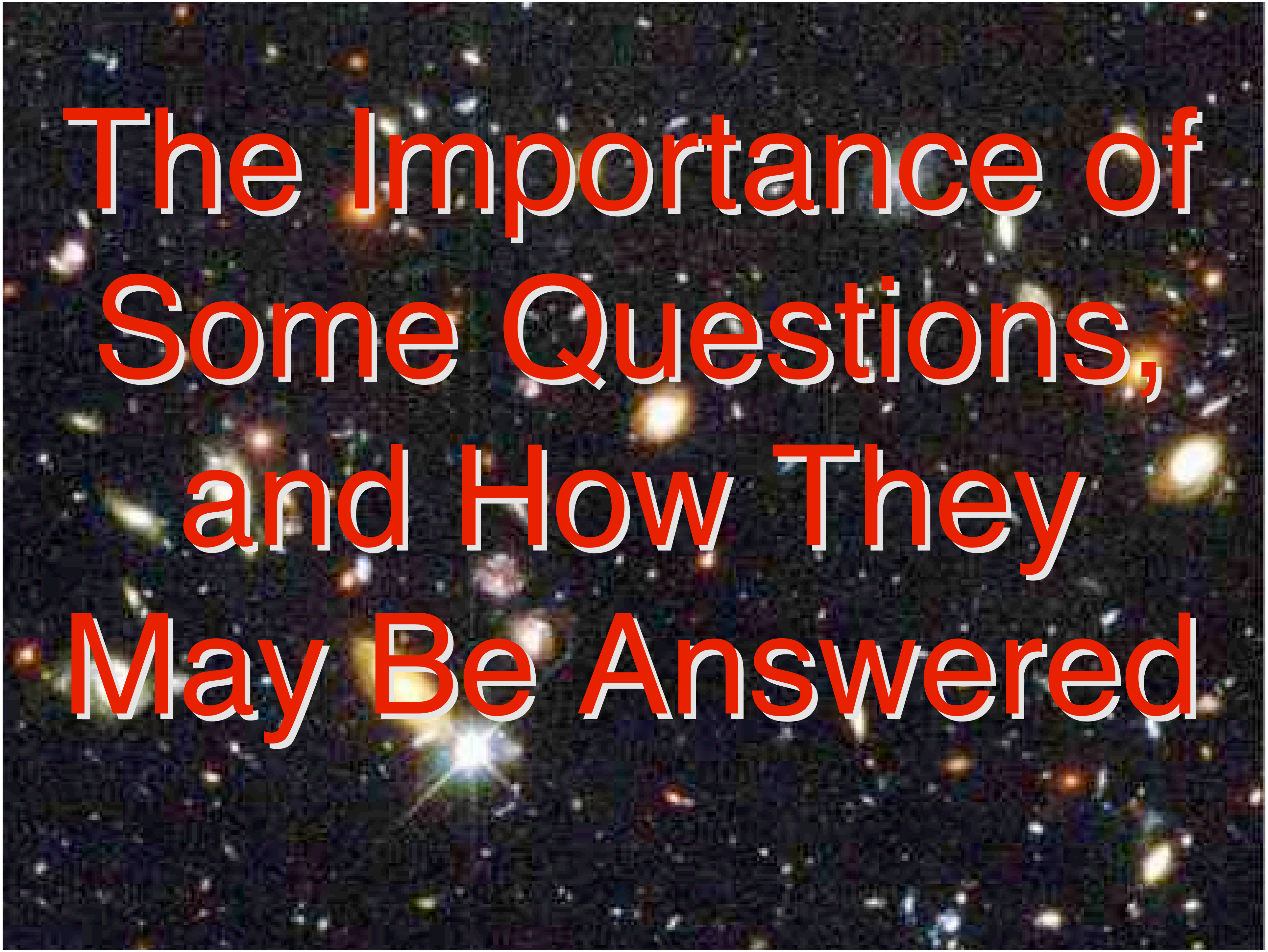
•Do neutrino – matter interactions violate CP?

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

What Is the Question?

For each ***mass eigenstate*** ν_i , and ***given helicty*** h*,* does —

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

or

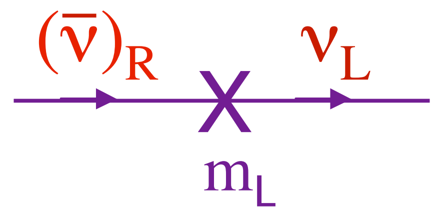
- $\overline{\nu_i}(h) \neq \nu_i(h)$ (Dirac neutrinos) ?

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 Left-Handed Majorana mass term —

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



Majorana masses do not conserve the Lepton Number L defined by —

$$L(\nu) = L(\ell^-) = -L(\bar{\nu}) = -L(\ell^+) = 1.$$

A Majorana mass for any fermion f causes $f \leftrightarrow \bar{f}$.

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

***Neutrino* Majorana masses would make the neutrinos *very* distinctive.**

Majorana ν masses cannot come from $H_{SM}\bar{\nu}_R\nu_L$, the analogue of the q and ℓ mass terms.

Possible Majorana mass terms:

$$H_{SM} H_{SM} \overline{\nu_L^c} \nu_L, \quad H_{I_W=1} \overline{\nu_L^c} \nu_L, \quad m_R \overline{\nu_R^c} \nu_R$$

Not renormalizable

This Higgs not in SM

No Higgs

Majorana neutrino masses must have a different origin than the masses of quarks and charged leptons.

Why Majorana Masses ⟹ Majorana Neutrinos

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

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

Why Most Theorists Expect Majorana Masses

The Standard Model (SM) is defined by the fields it contains, its symmetries (notably weak isospin invariance), and its renormalizability.

Leaving neutrino masses aside, anything allowed by the SM symmetries occurs in nature.

Right-Handed Majorana mass terms
are allowed by the SM symmetries.

Then quite likely *Majorana masses*
occur in nature too.

To Determine Whether Majorana Masses Occur in Nature

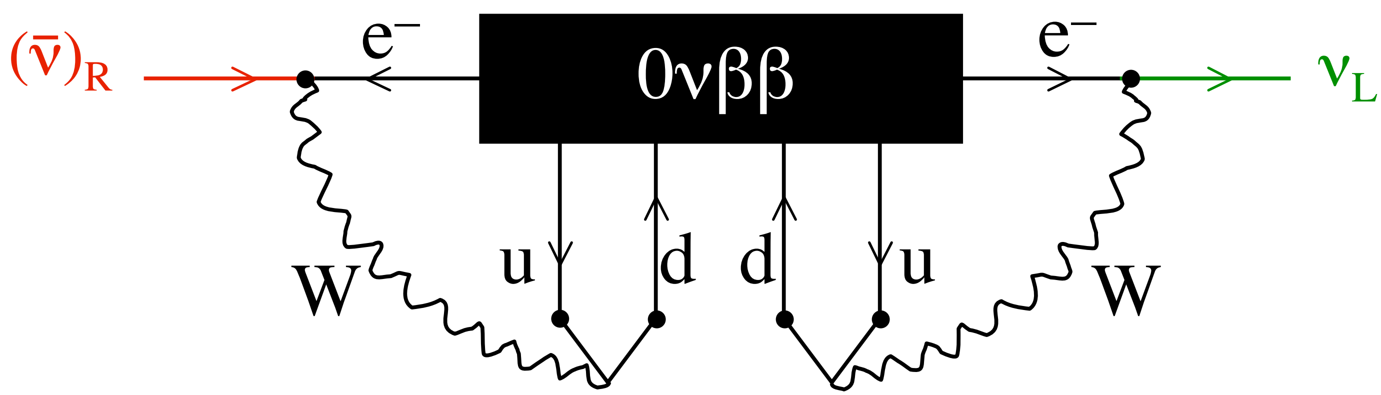
The Promising Approach — Seek

Neutrinoless Double Beta Decay [0νββ]

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:

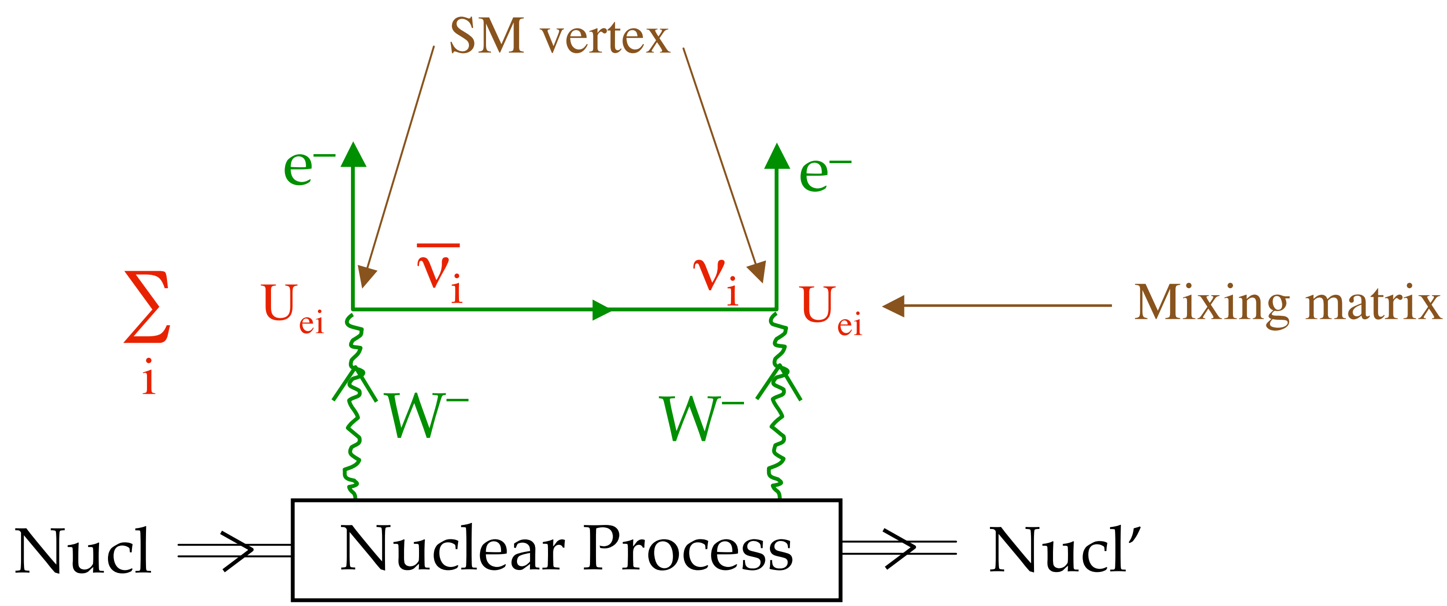
(Schechter and Valle)



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

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

We expect the dominant mechanism to be —



Then —

Mass (ν_i)

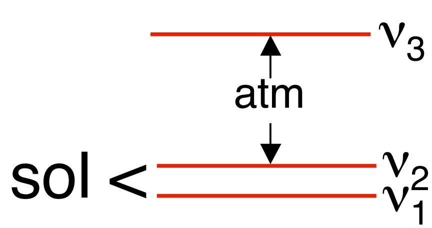
$$\mathrm{Amp}[0\nu\beta\beta] \propto \left| \sum_i m_i U_{ei}^2 \right| \equiv m_{\beta\beta}$$

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

How sensitive need an experiment be?

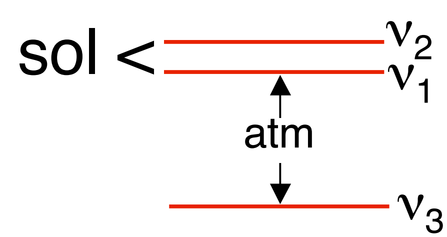
Suppose there are only 3 neutrino mass eigenstates. (More might help.)

Then the spectrum looks like —

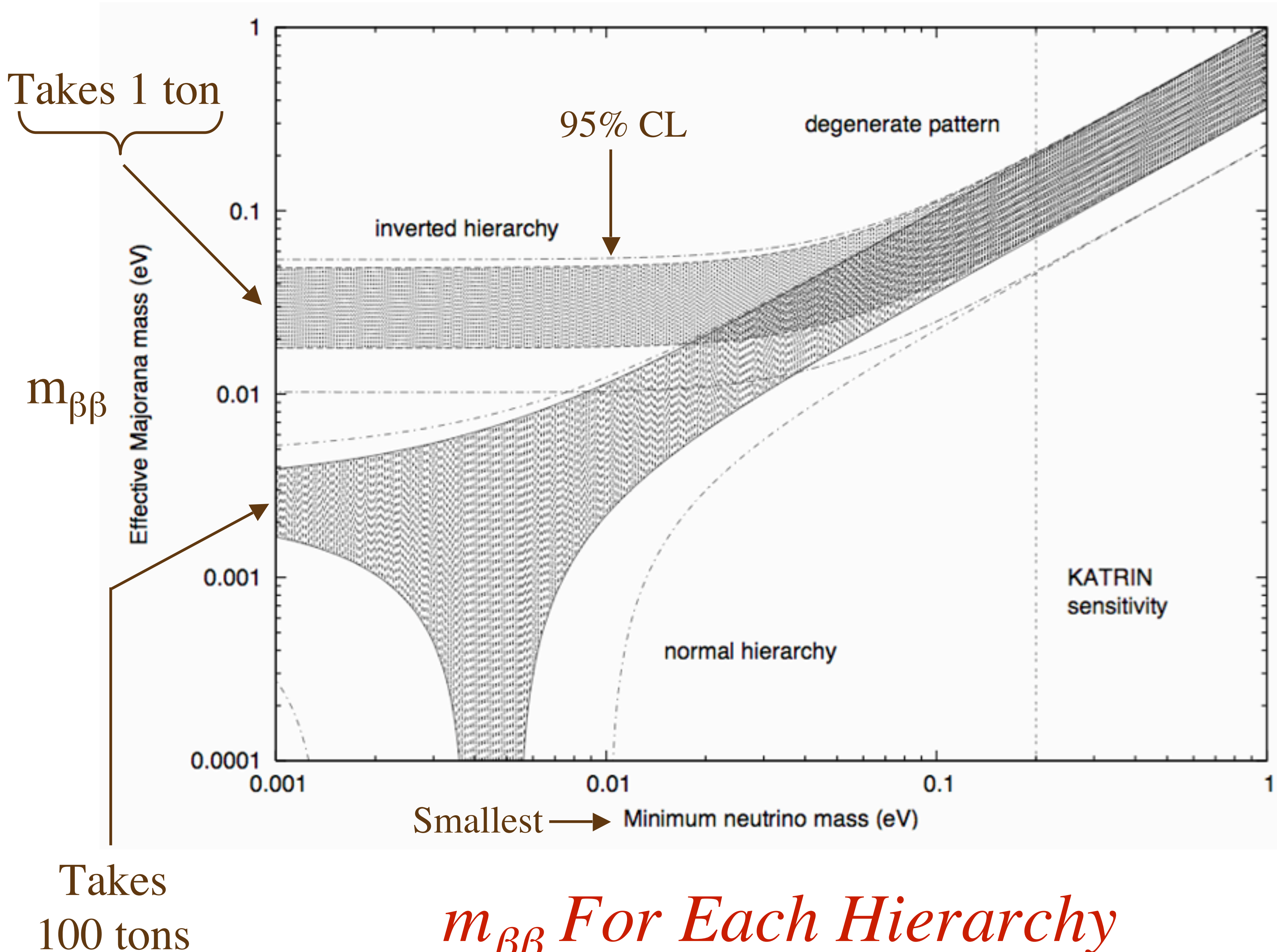


Normal hierarchy

or



Inverted hierarchy



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

There is no clear theoretical preference for either hierarchy.

If the hierarchy is **inverted**—

then $0\nu\beta\beta$ searches with sensitivity to $m_{\beta\beta} = 0.01$ eV have a very good chance to see a signal.

Sensitivity in this range is a good target for the next generation of experiments.

Mixing, Mass Ordering, and ~~CP~~

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

The Mass Spectrum:  or  ?

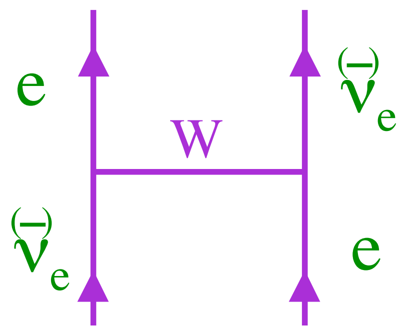
Generically, grand unified models (GUTS) favor —

GUTS relate the Leptons to the Quarks.

However, ***Majorana masses***, with no quark analogues, could turn  into  .

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 —

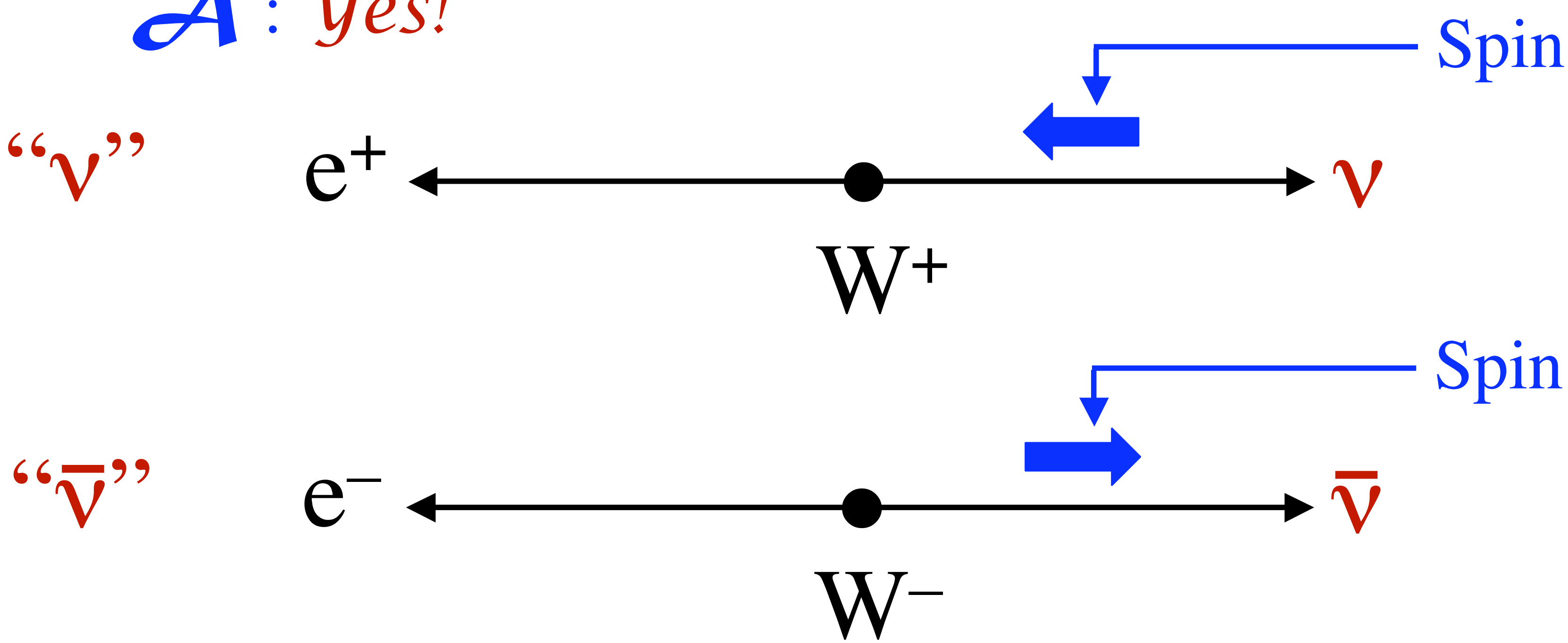
$$\frac{P(\nu_\mu \to \nu_e)}{P(\bar{\nu}_\mu \to \bar{\nu}_e)} \begin{cases} > 1\,; \\ < 1\,; \end{cases}$$

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 $\not{C}\not{P}$ in the weak interactions of ***quarks*** cannot explain the *Baryon Asymmetry* of the universe.

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

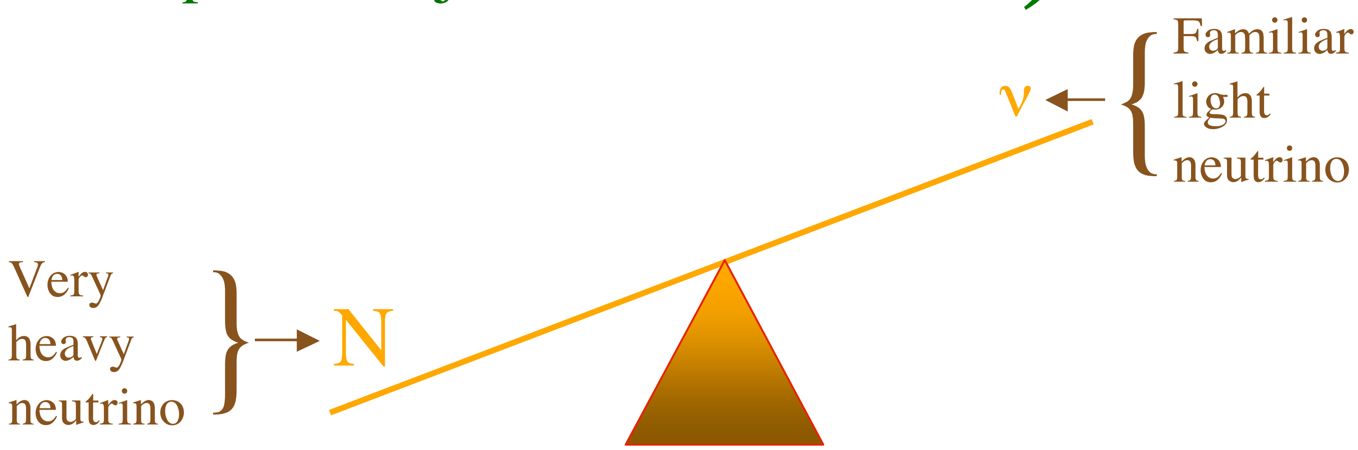
(Fukugita, Yanagida)

Leptogenesis In Brief

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

See-Saw Mechanism

(Yanagida; Gell-Mann, Ramond, Slansky; Mohapatra, Senjanovic; 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: One Yukawa coupling matrix.

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

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

Standard-Model Higgs

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*.

Electromagnetic Leptogenesis

(Bell, B.K., Law)

A new leptogenesis scenario in which the leptonic asymmetry arises from —

$$\Gamma(N \to \nu + \gamma) \neq \Gamma(N \to \bar{\nu} + \gamma)$$

Decay via CP-violating transition dipole moments

This too can produce the observed *Baryon Asymmetry* of the universe.

Neutrino dipole moments lead to neutrino masses.

If leptogenesis is driven by the dipole moments, then the neutrino masses probably are too.

CP-violating dipole moments will lead to CP-violating mass matrices, which in turn will lead to CP violation in oscillation.

As in standard leptogenesis, CP in neutrino oscillation and CP in the early universe are linked.

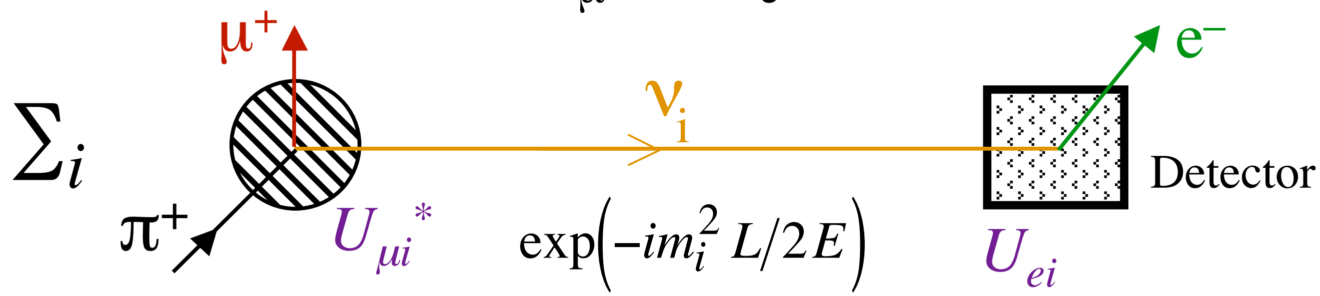
How To Search for ~~CP~~ In Neutrino Oscillation

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

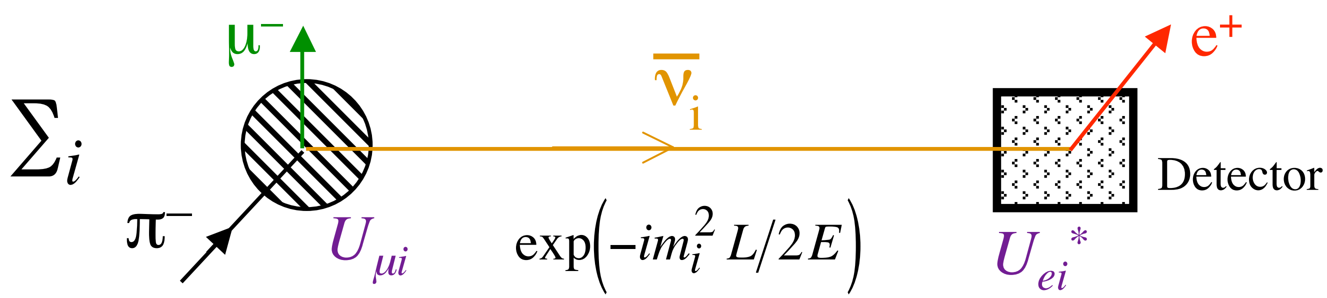
Q : *Can CP violation still lead to*
$\mathcal{P}(\bar{\nu}_\mu \rightarrow \bar{\nu}_e) \neq \mathcal{P}(\nu_\mu \rightarrow \nu_e)$ *when* $\bar{\nu} = \nu$*?*

A : *Certainly!*

Compare $\nu_\mu \rightarrow \nu_e$



with "$\bar{\nu}_\mu \rightarrow \bar{\nu}_e$"



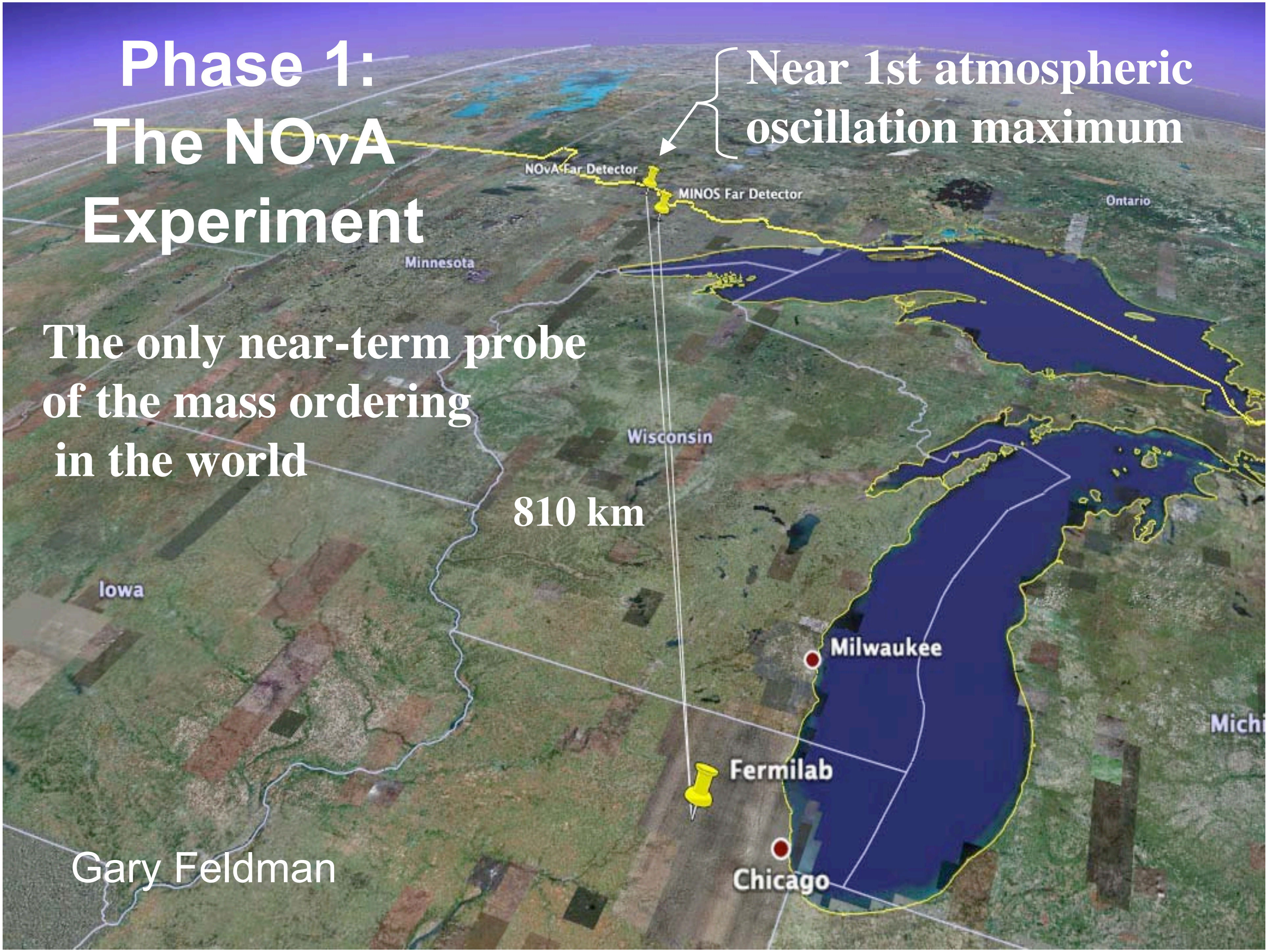
Separating ~~CP~~ From the Matter Effect

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

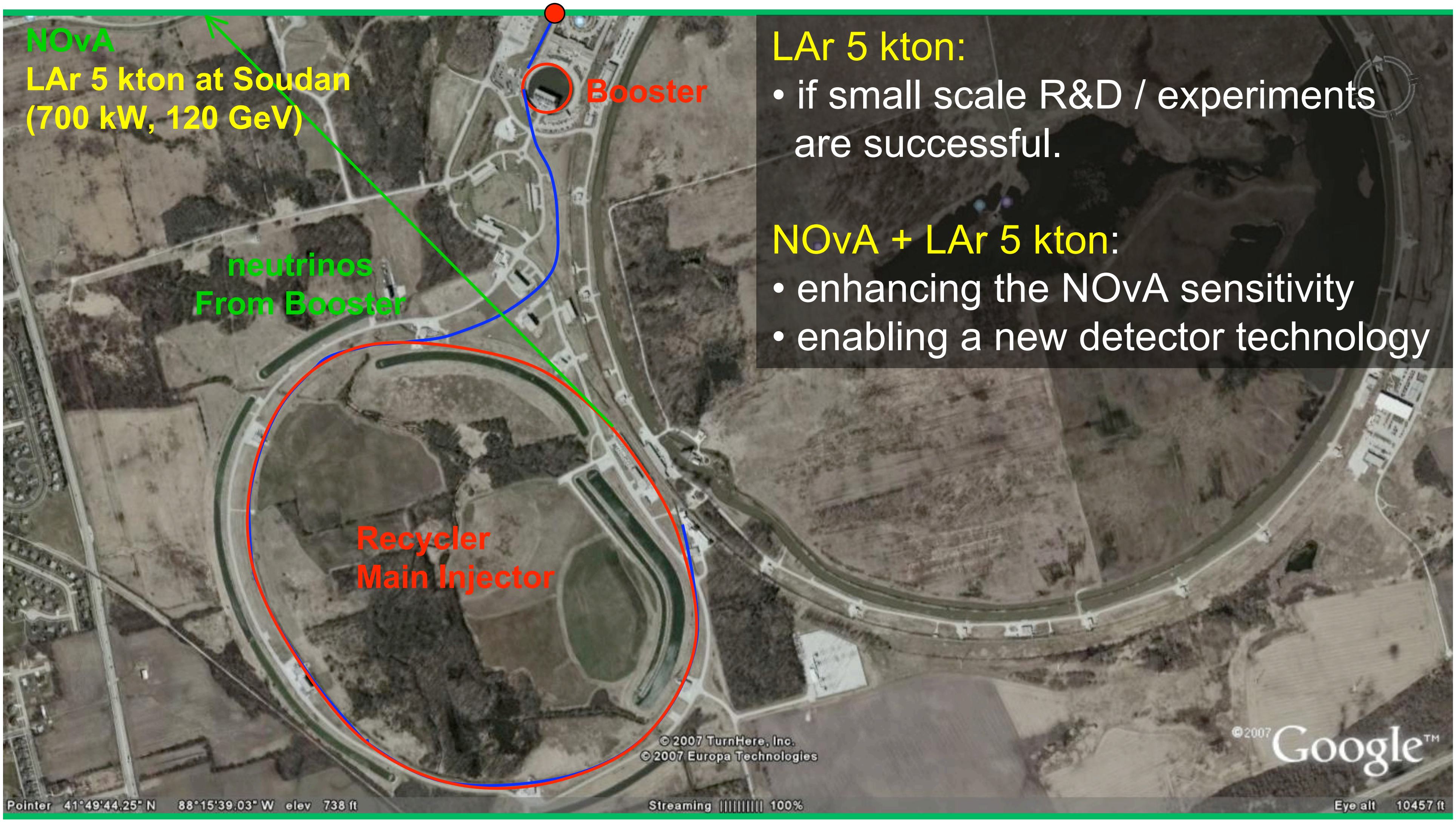
But genuine ~~CP~~ and the matter effect depend quite differently from each other on L and E.

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

Neutrino Vision at Fermilab


Phase 1:
The NOνA
Experiment
Near 1st atmospheric
oscillation maximum
NOνA Far Detector
MINOS Far Detector
Ontario
Minnesota
The only near-term probe
of the mass ordering
in the world
Wisconsin
810 km
Iowa
Milwaukee
Michi
Fermilab
Chicago
Gary Feldman

Phase 1.5:



LAr 5 kton:
- if small scale R&D / experiments are successful.

NOvA + LAr 5 kton:
- enhancing the NOvA sensitivity
- enabling a new detector technology

Y-K Kim

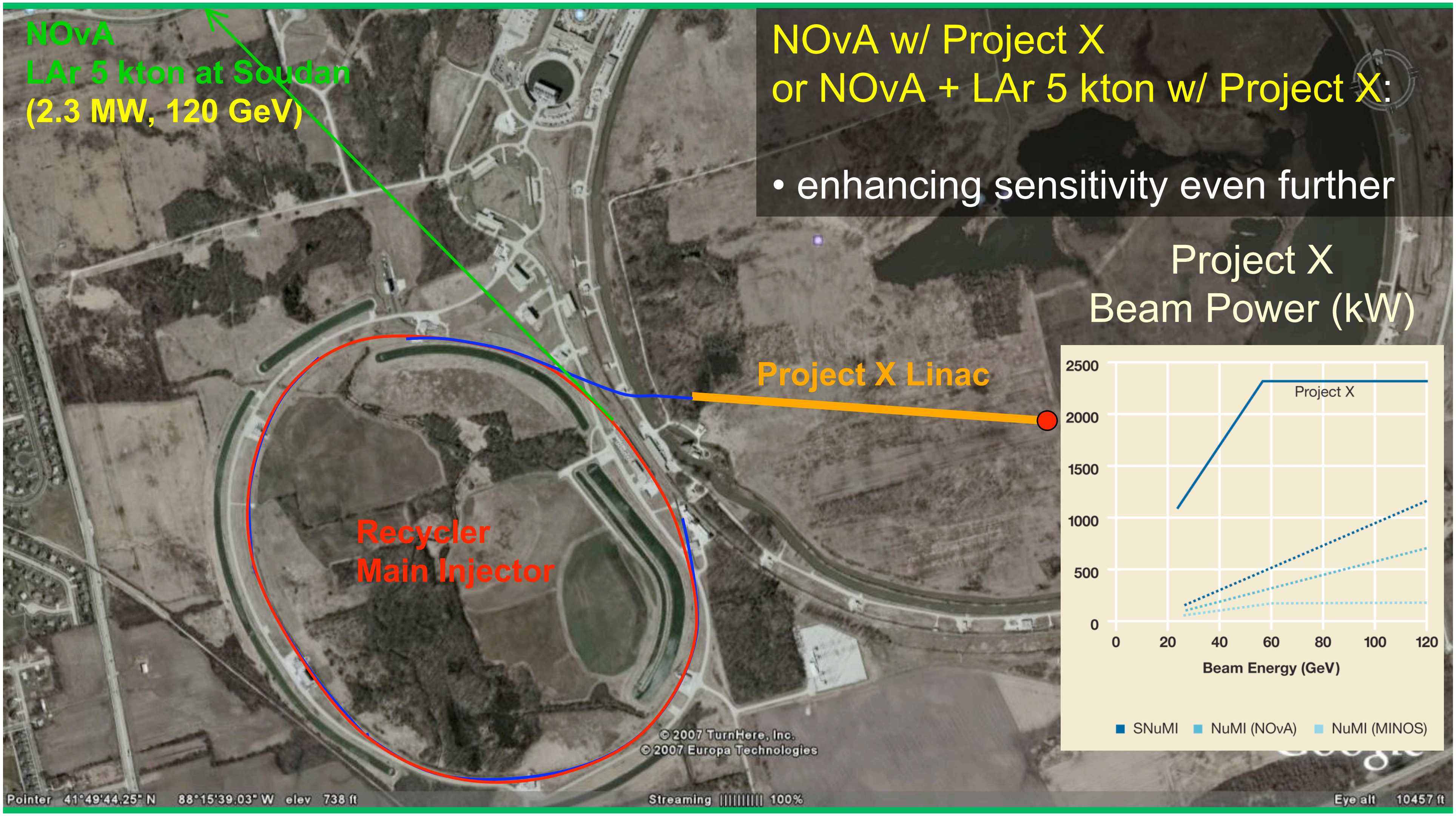
The Intensity Frontier With Project X

Y-K Kim

National Project with International Collaboration

Project X = 8 GeV ILC-like Linac
+ Recycler
+ Main Injector

Phase 2:


NOvA
LAr 5 kton at Soudan
(2.3 MW, 120 GeV)
NOvA w/ Project X
or NOvA + LAr 5 kton w/ Project X:
• enhancing sensitivity even further
Project X
Beam Power (kW)
Project X Linac
Recycler
Main Injector
2500
2000
1500
1000
500
0
0
20
40
60
80
100
120
Beam Energy (GeV)
Project X
SNuMI
NuMI (NOvA)
NuMI (MINOS)
© 2007 TurnHere, Inc.
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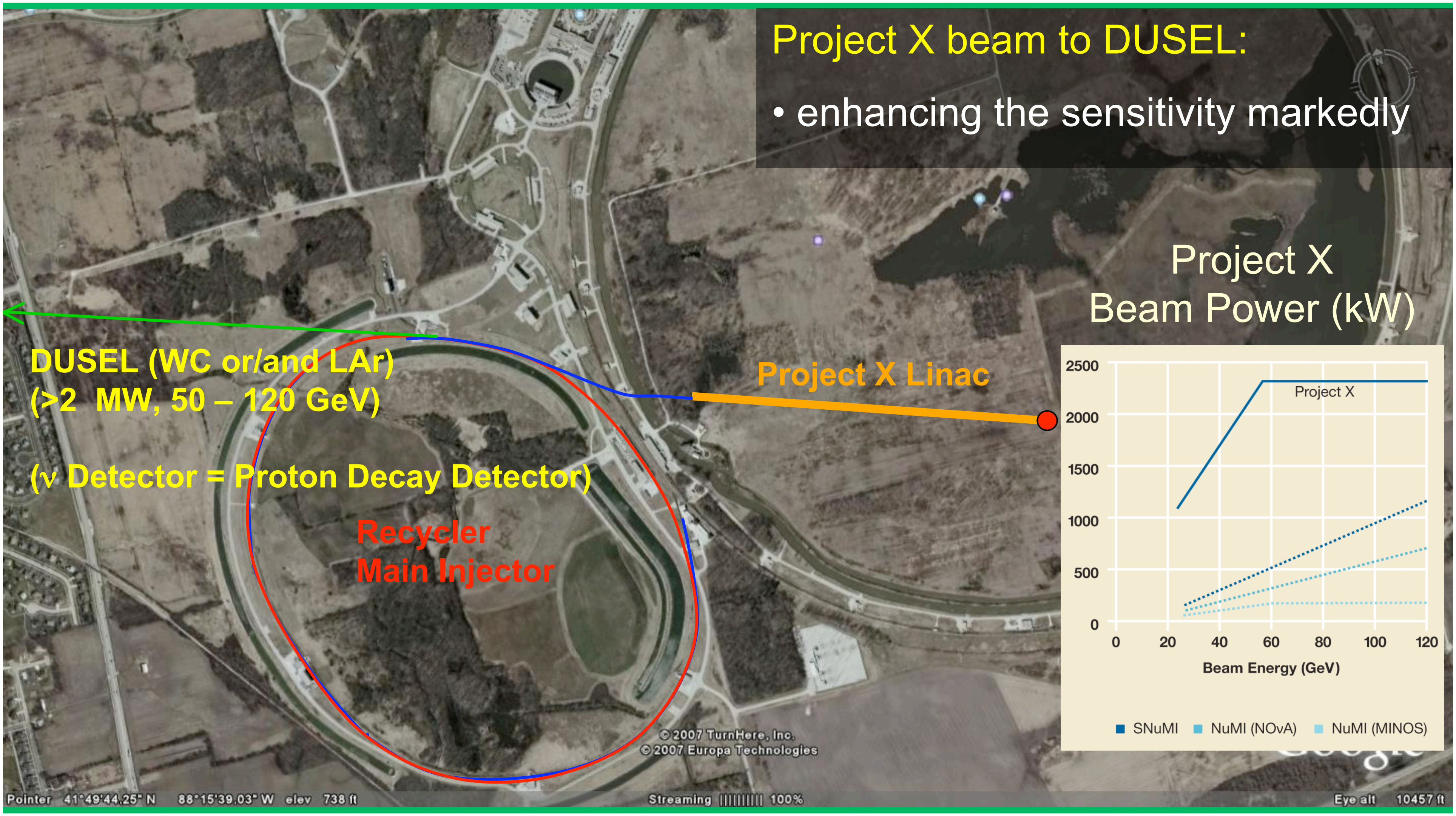
Pointer 41°49'44.25" N 88°15'39.03" W elev 738 ft
Streaming 100%
Eye alt 10457 ft

Phase 3



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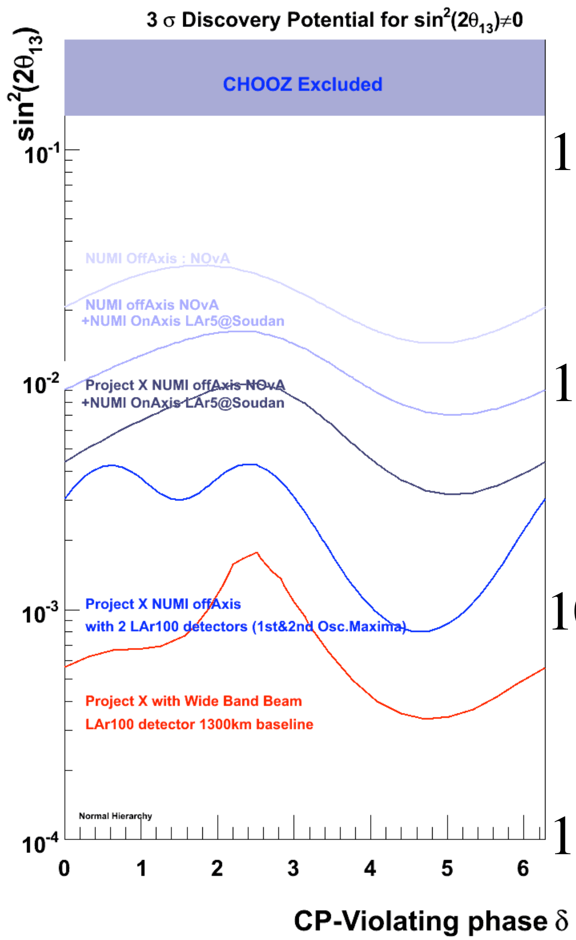
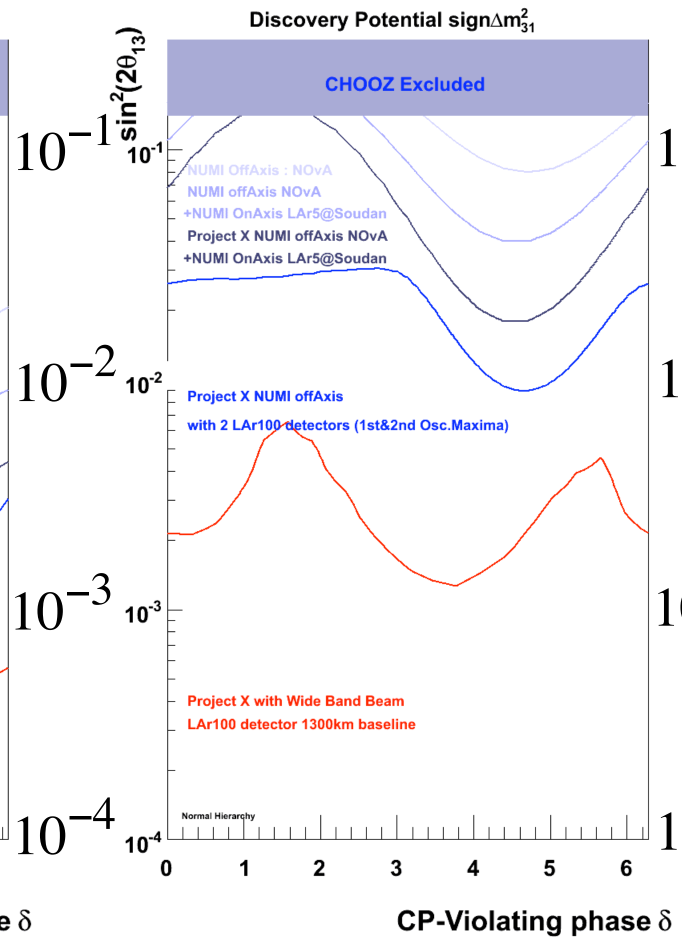
The 3σ Reach of the Successive Phases

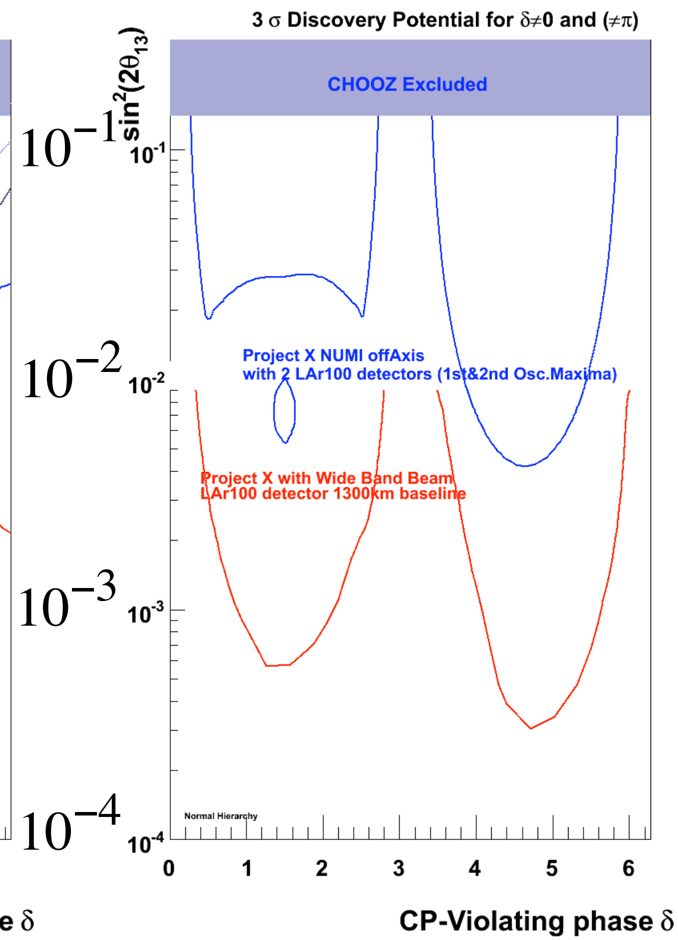
$\sin^2 2\theta_{13}$



Mass Ordering



CP Violation



N. Saoulidou

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.