Neutrinos: Results and Future

Boris Kayser
DESY
March 4, 2008

Evidence For ν Flavor Change

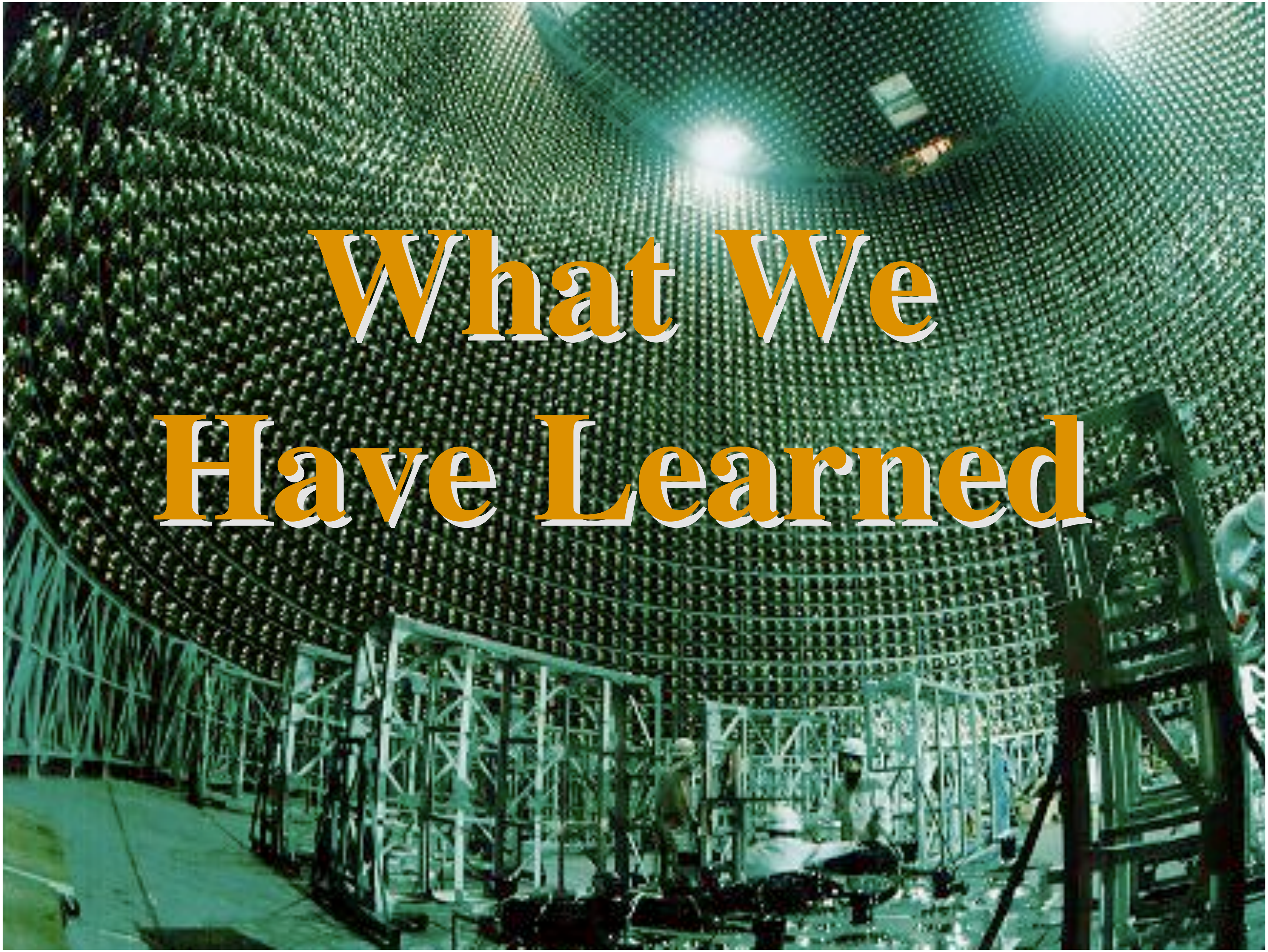
Neutrinos	Evidence of Flavor Change
Solar	Compelling
Reactor (L ~ 180 km)	Compelling
Atmospheric	Compelling
Accelerator (L = 250 and 735 km)	Compelling
Stopped μ^+ Decay $\begin{pmatrix} \text{LSND} \\ L \approx 30\text{ m} \end{pmatrix}$	Unconfirmed by MiniBooNE

The neutrino flavor-change observations imply that —

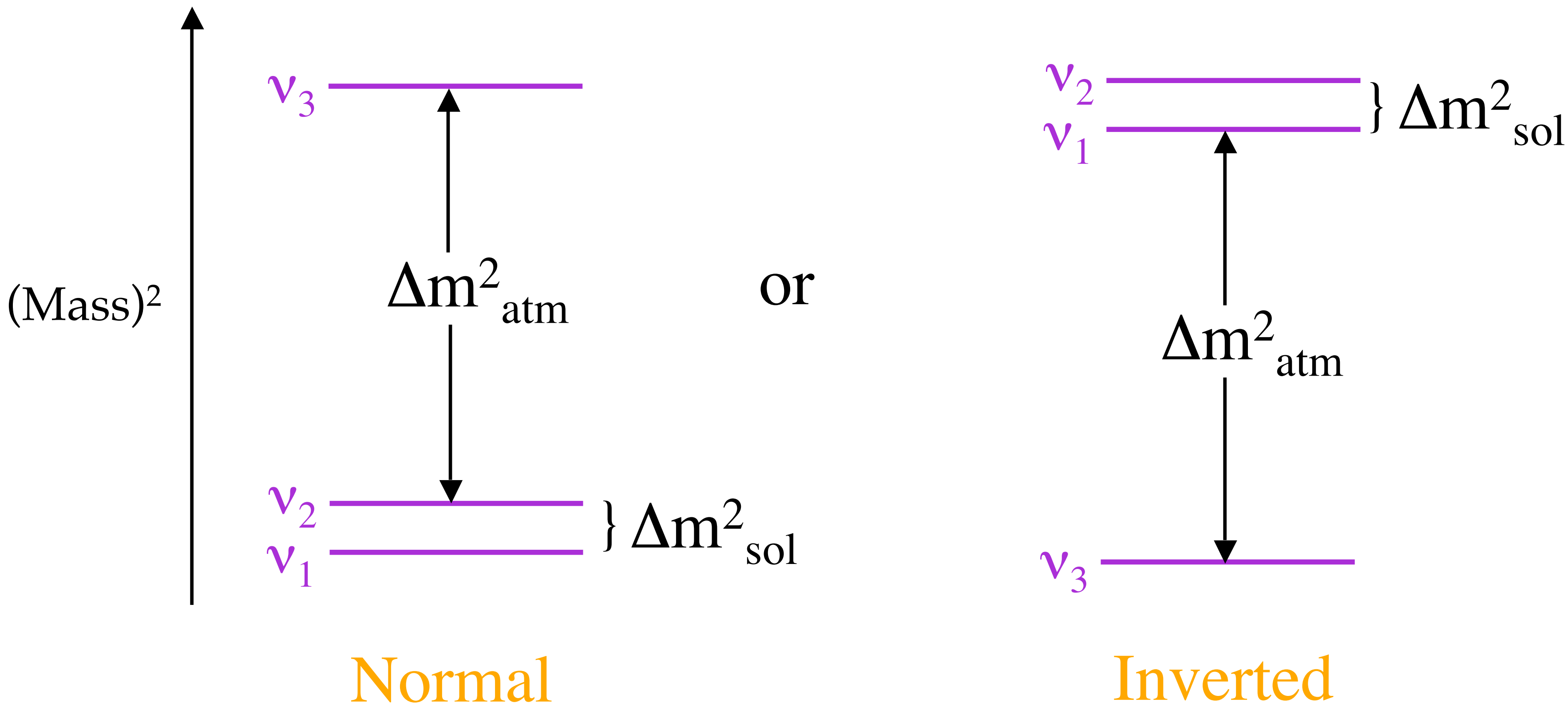
Neutrinos have nonzero masses

and that —

Leptons mix.


What We
Have Learned

The (Mass)^2 Spectrum



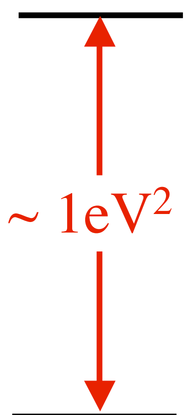
$\Delta m^2_{sol} \cong 7.6 \times 10^{-5}\ eV^2$, $\Delta m^2_{atm} \cong 2.4 \times 10^{-3}\ eV^2$

Are There *More* Than 3 Mass Eigenstates?

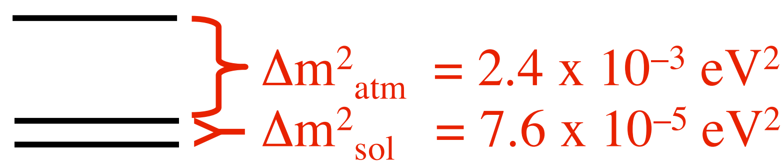
When only two neutrinos count,

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

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



in contrast to

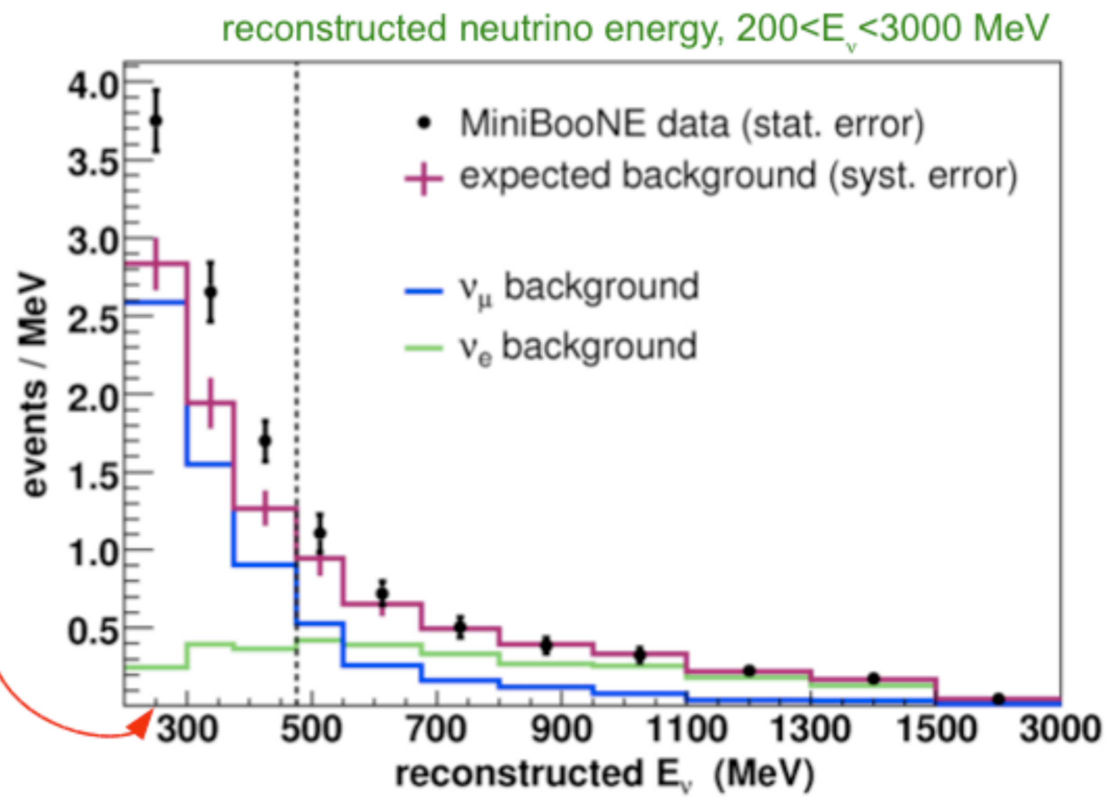


At least **4** mass eigenstates.

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)

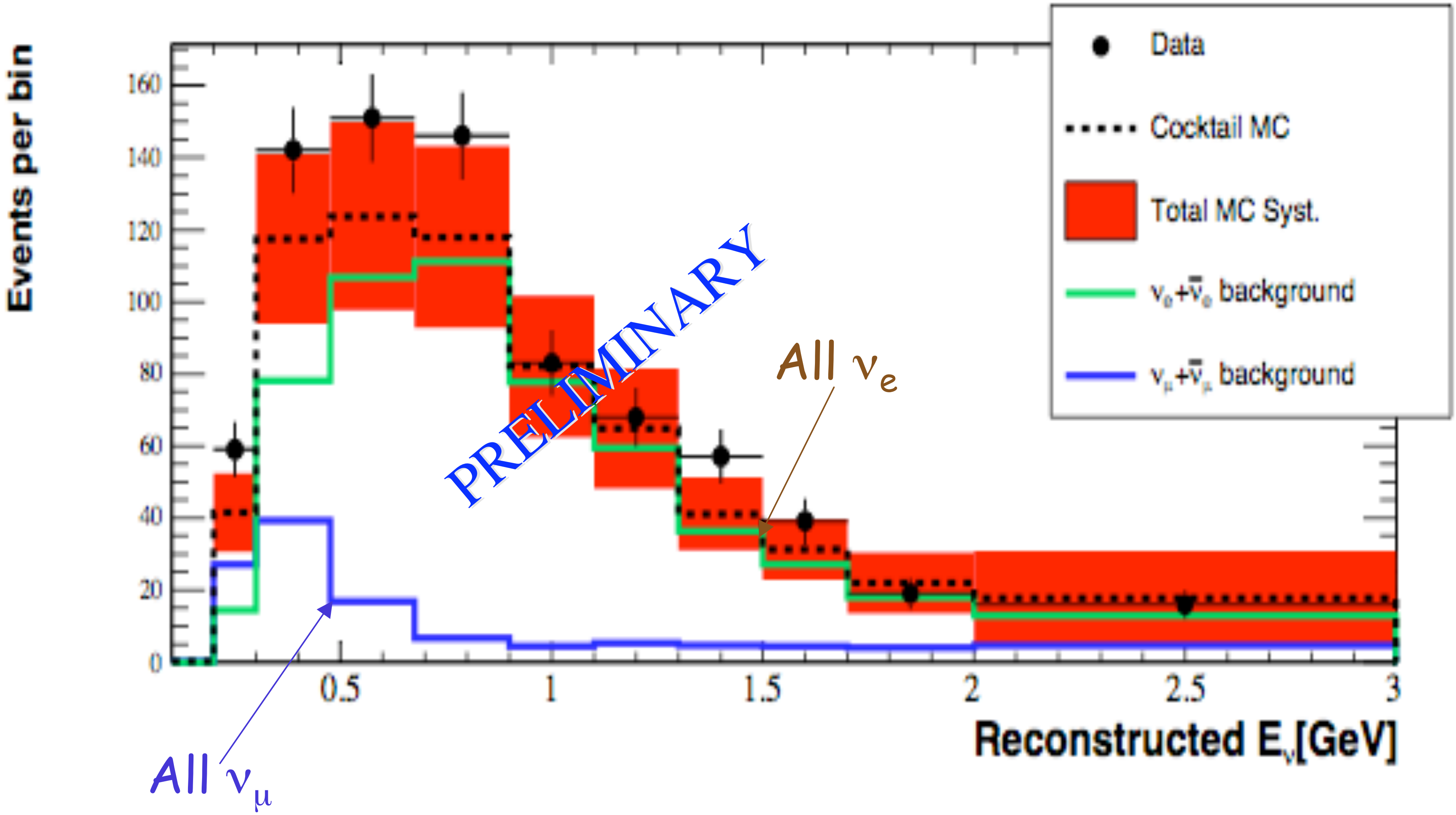
Neutrino oscillation depends on L and E only through L/E.

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 —

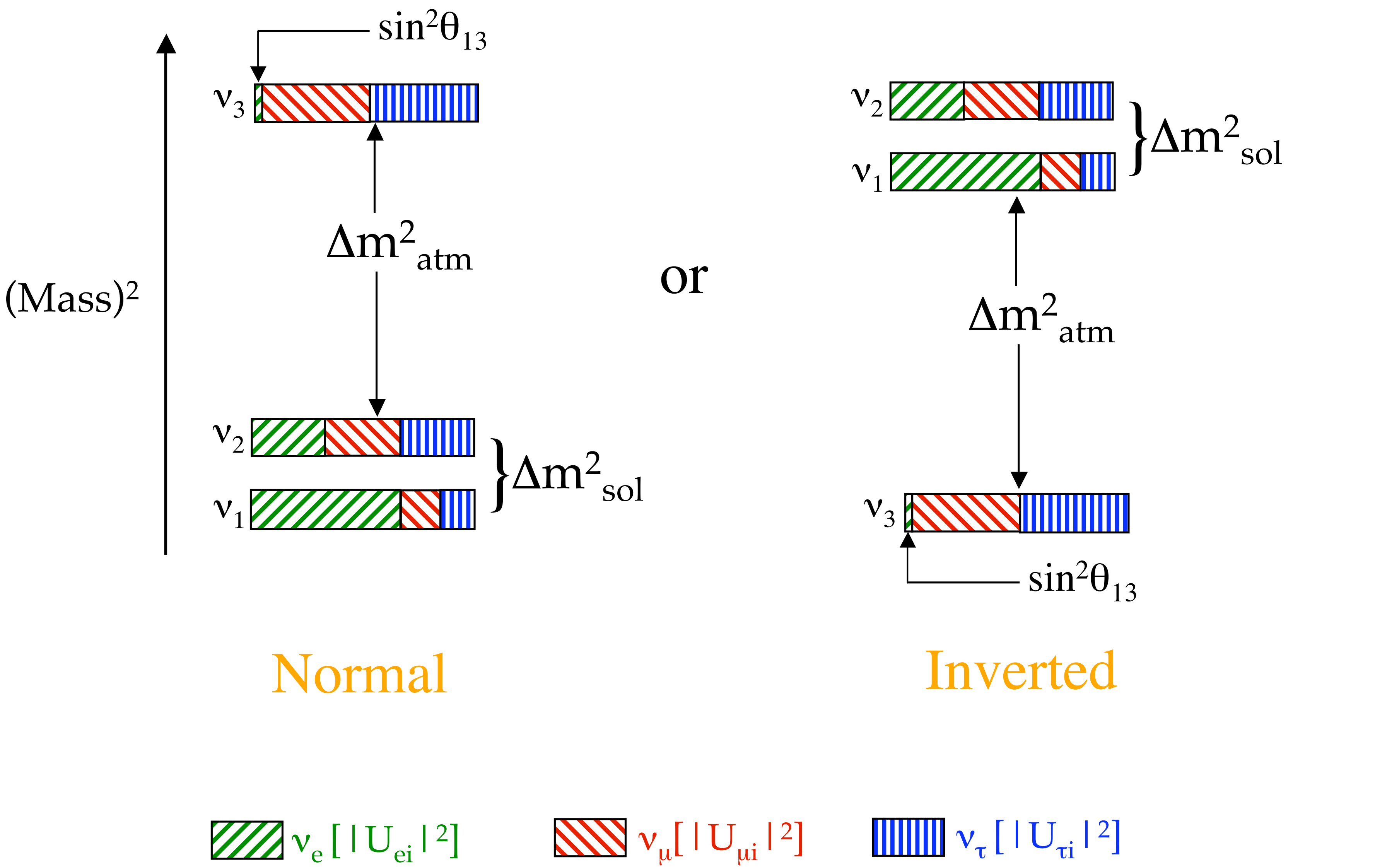
Mass eigenstate → $|\nu_i\rangle = \sum_\alpha U_{\alpha i}\, |\nu_\alpha\rangle$. ← Flavor eigenstate

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

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

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

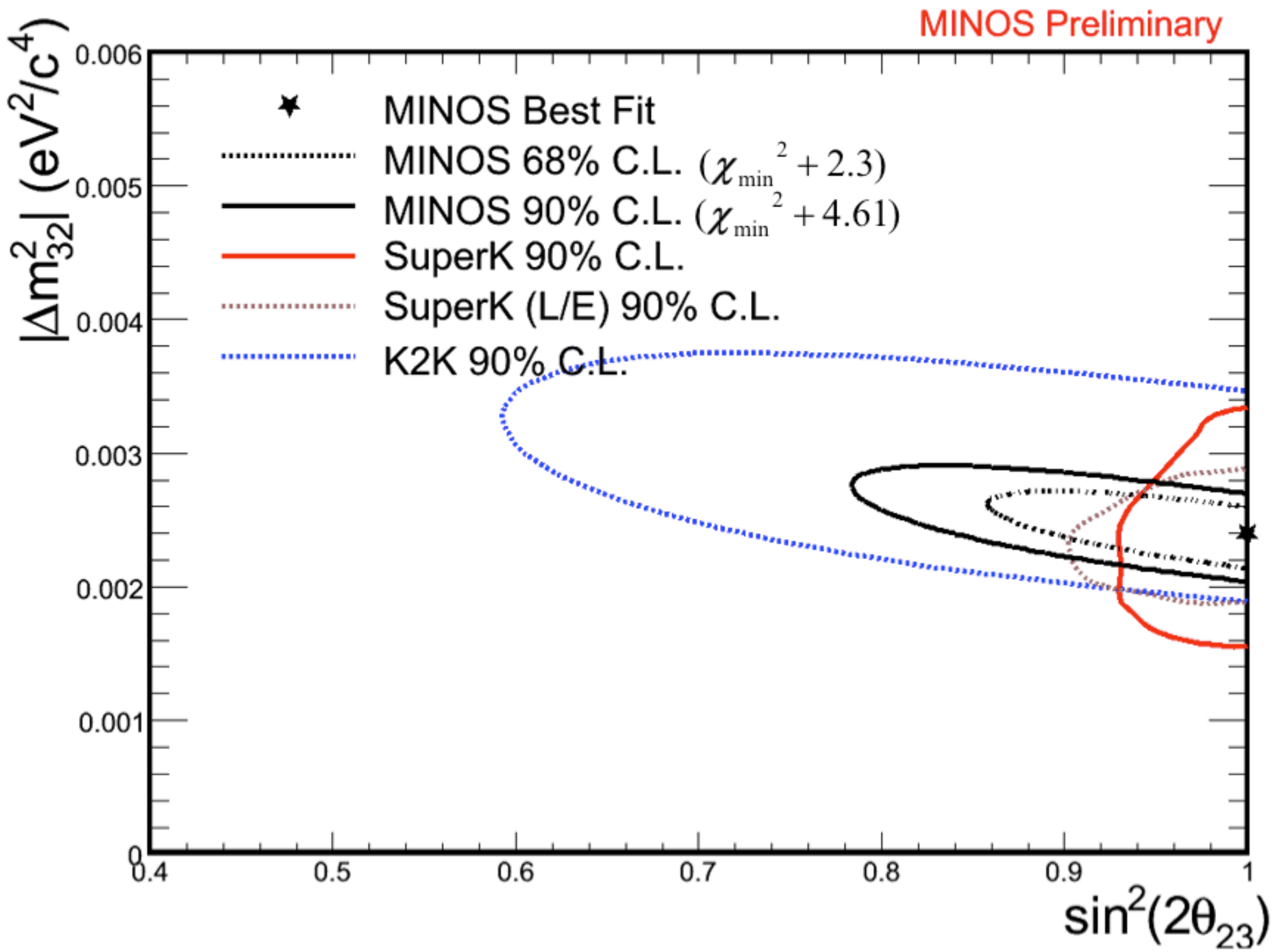
$c_{ij} \equiv \cos\theta_{ij}$
$s_{ij} \equiv \sin\theta_{ij}$

Majorana ~~CP~~ phases

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

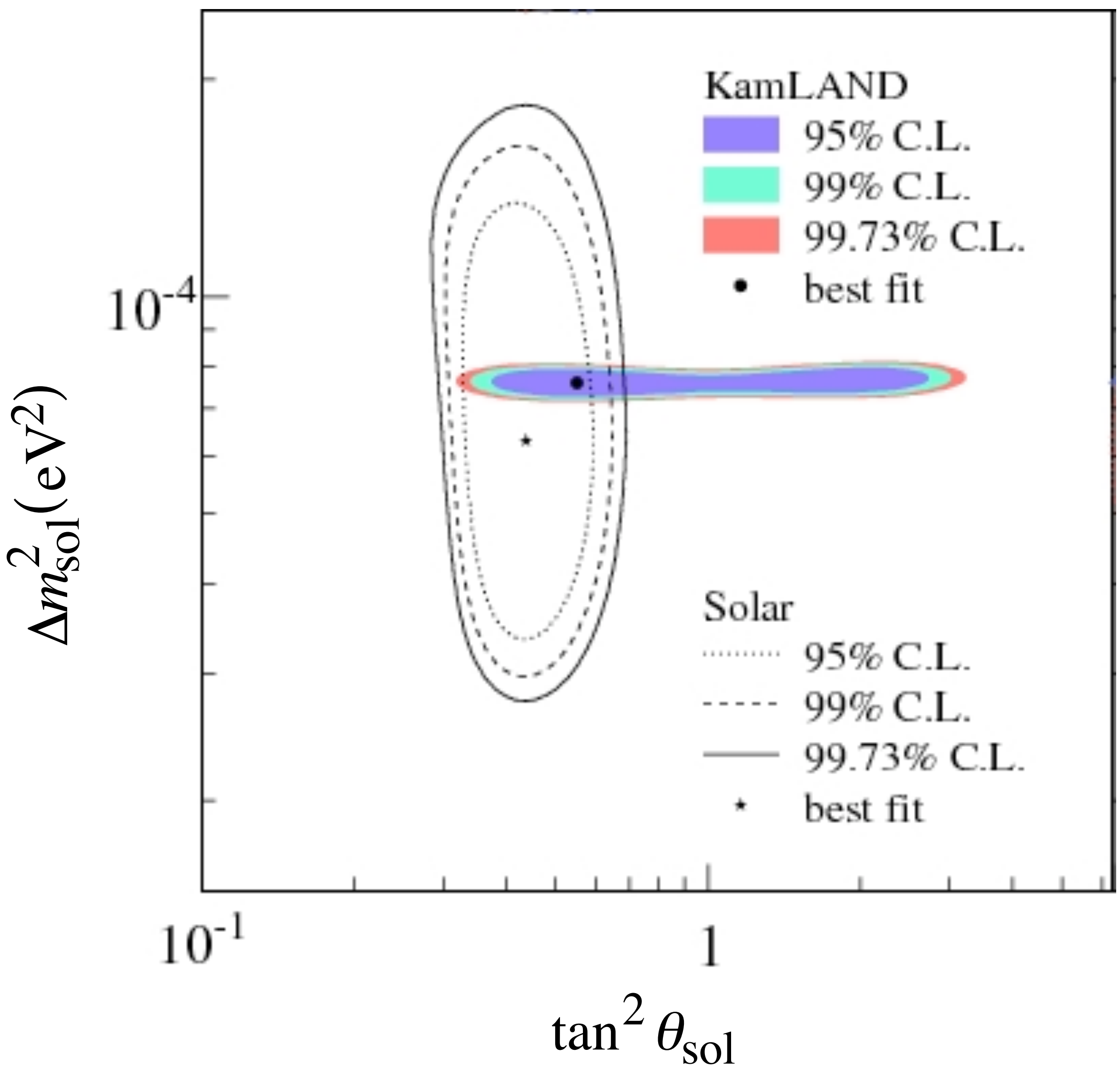
δ would lead to $P(\bar{\nu}_\alpha \rightarrow \bar{\nu}_\beta) \neq P(\nu_\alpha \rightarrow \nu_\beta)$. ~~CP~~

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



From talk by N. Saoulidou

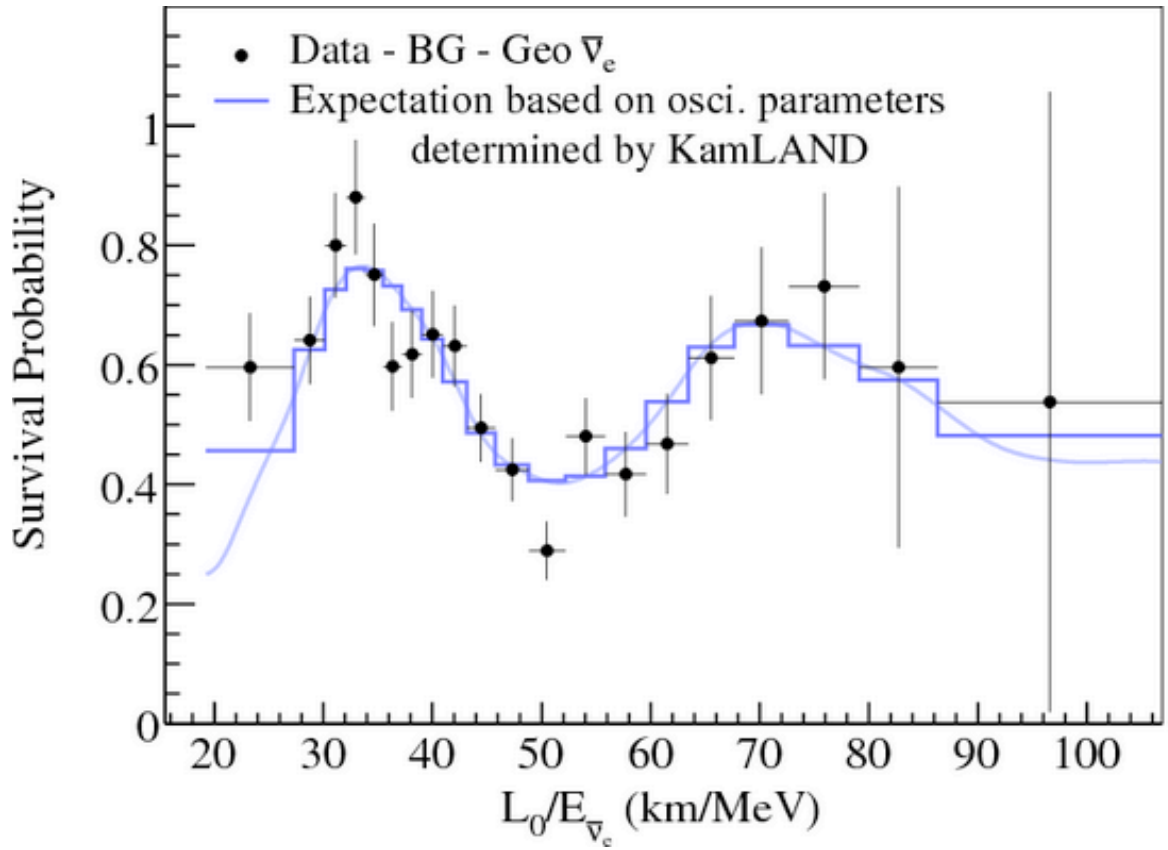
"Atmospheric" Δm^2 and mixing angle from MINOS, Super-K, and K2K.



Presented by KamLAND, a reactor $\overline{\nu}_e$ experiment.

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

KamLAND Evidence for Oscillation



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

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

^{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 ^7Be 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 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  ?

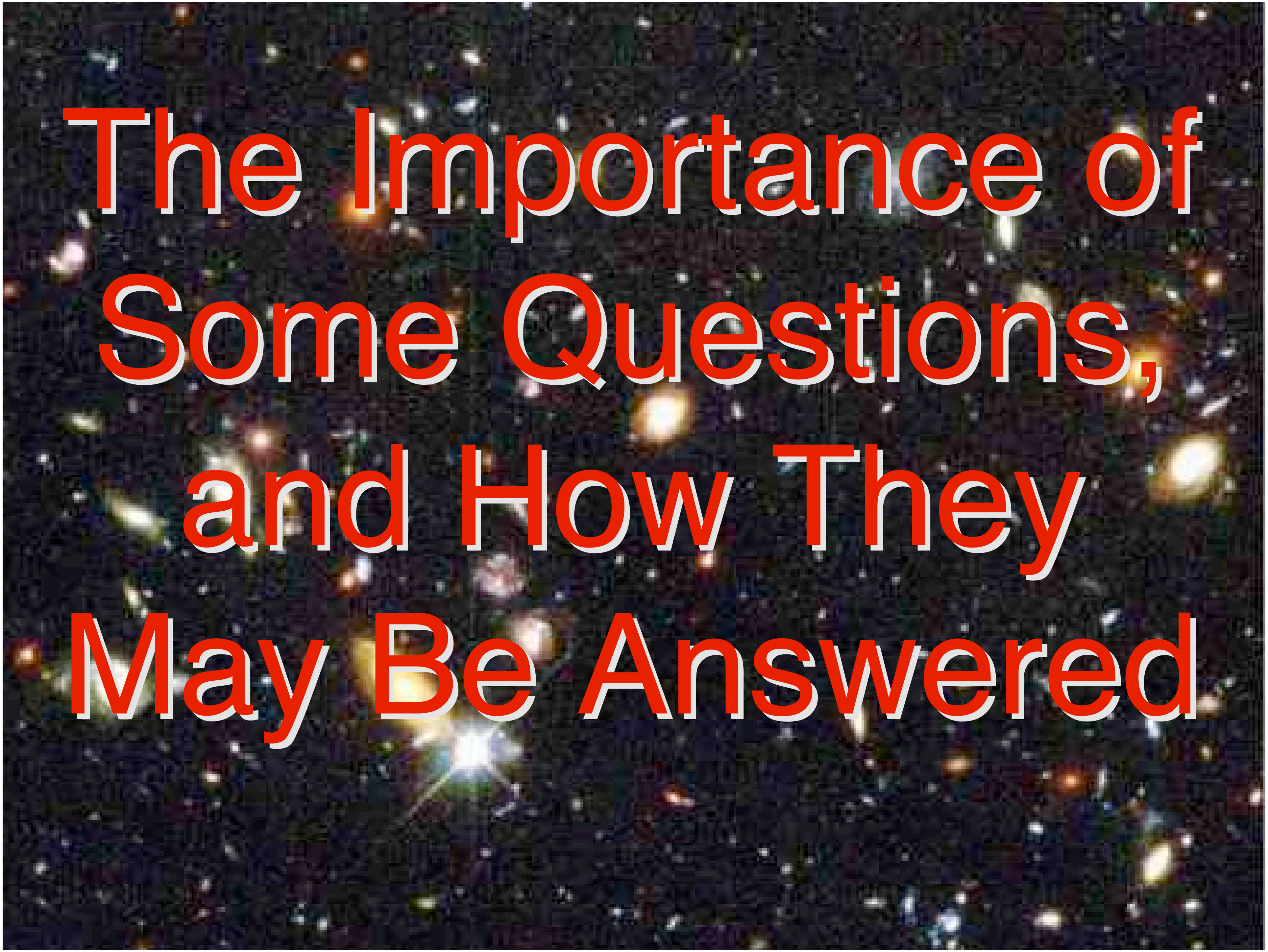
•Do neutrino – matter interactions violate CP?

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

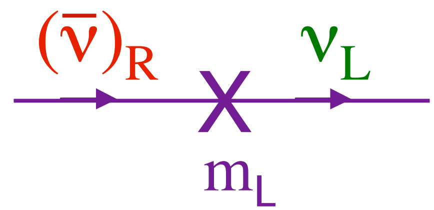
- $\overline{\nu_i} \neq \nu_i$ (Dirac neutrinos) ?

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

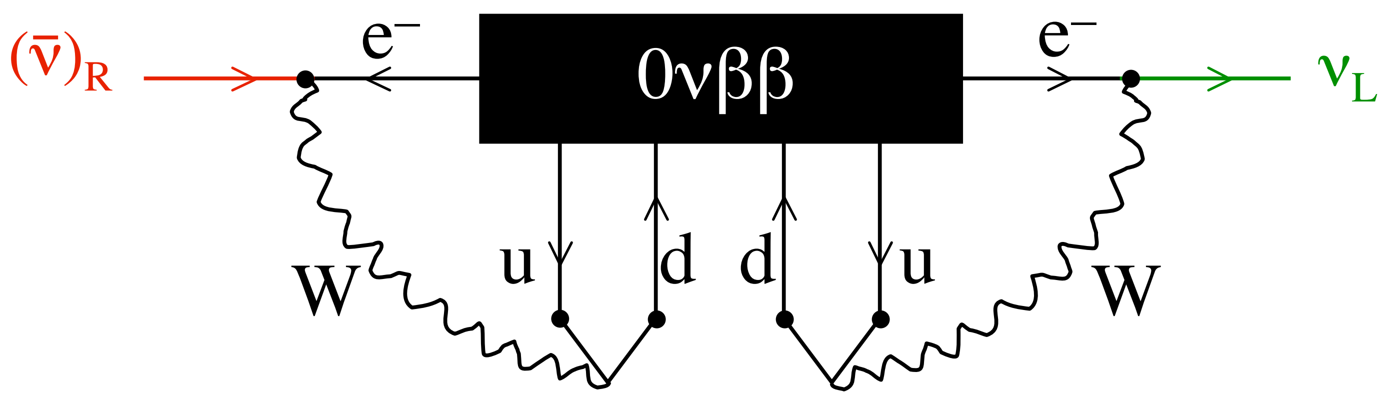
The Promising Approach —

Neutrinoless Double Beta Decay [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 Majorana mass term

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

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  ?

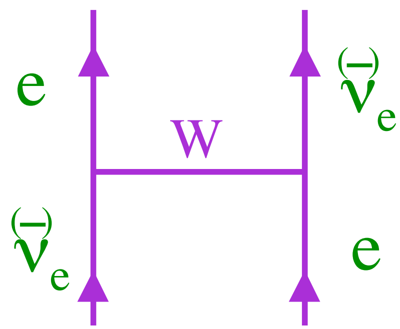
Generically, grand unified models (GUTS) favor —

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 —

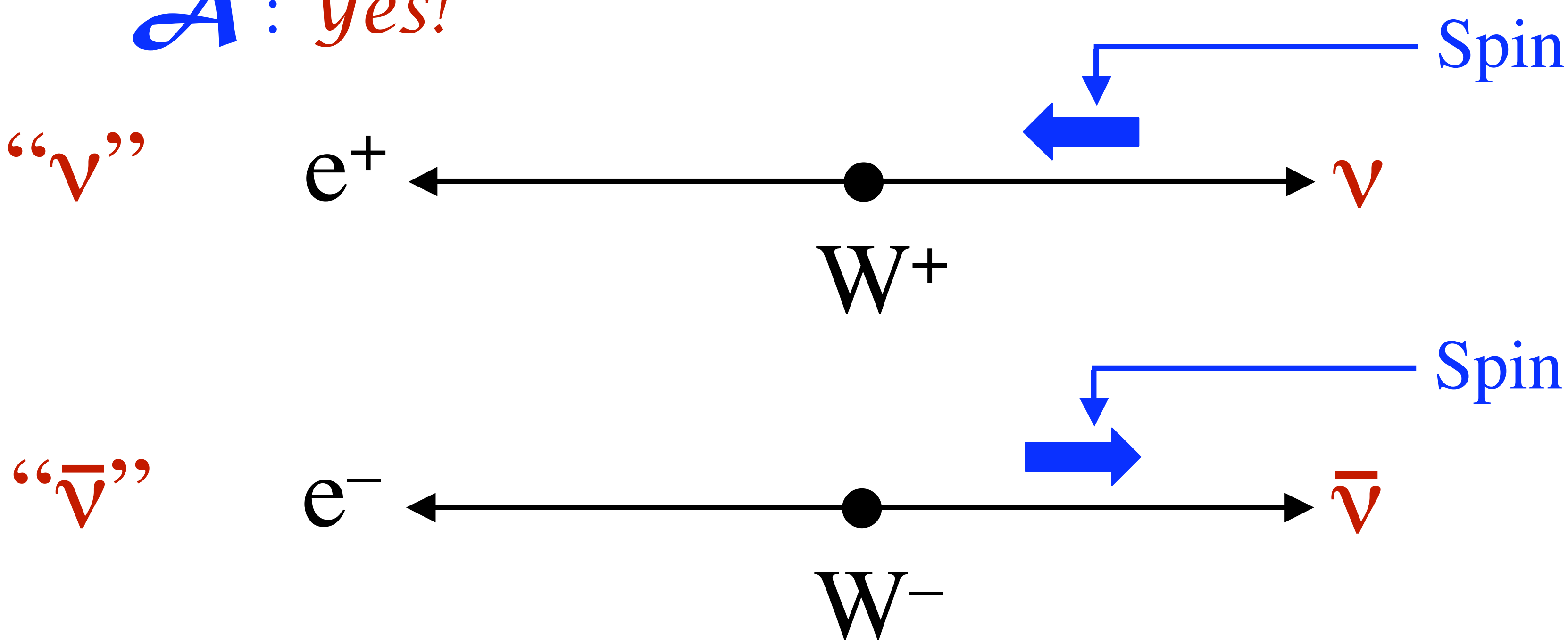
$$\frac{P(\nu_\mu \to \nu_e)}{P(\bar{\nu}_\mu \to \bar{\nu}_e)} \begin{cases} > 1\ ; \\ < 1\ ; \end{cases}$$

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 ~~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?

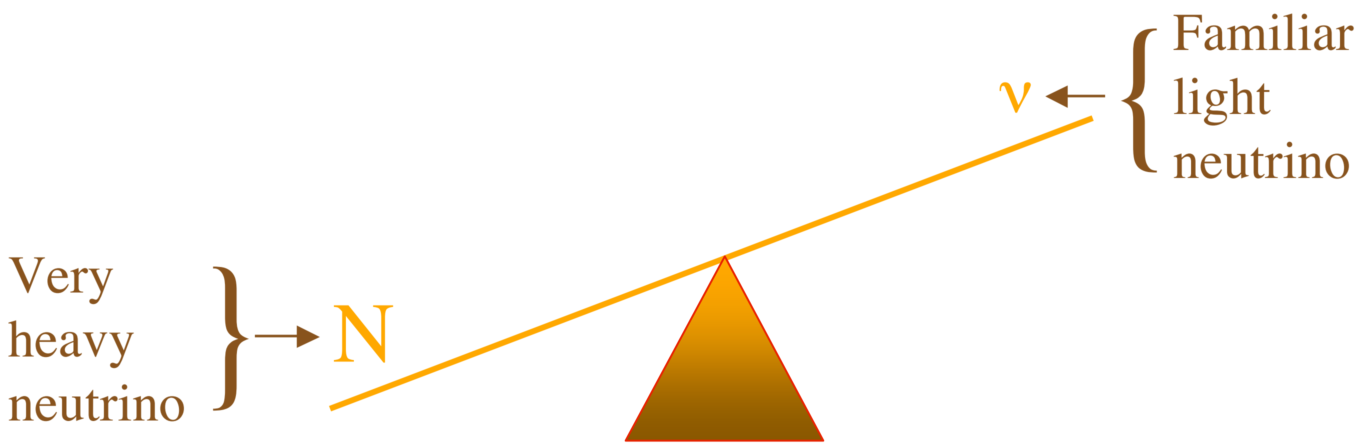
(Fukugita, Yanagida) (Wilfried Buchmueller Leading contributor)

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 ~~CP~~ In Neutrino Oscillation

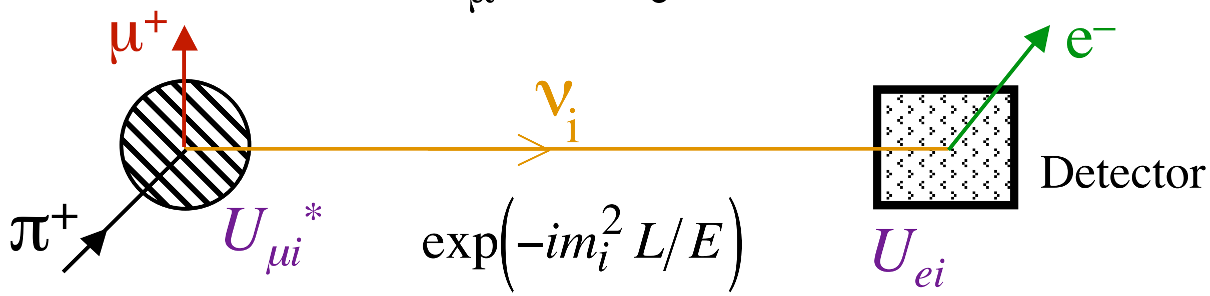
Look for $P(\bar{\nu}_\alpha \rightarrow \bar{\nu}_\beta) \neq P(\nu_\alpha \rightarrow \nu_\beta)$

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!*

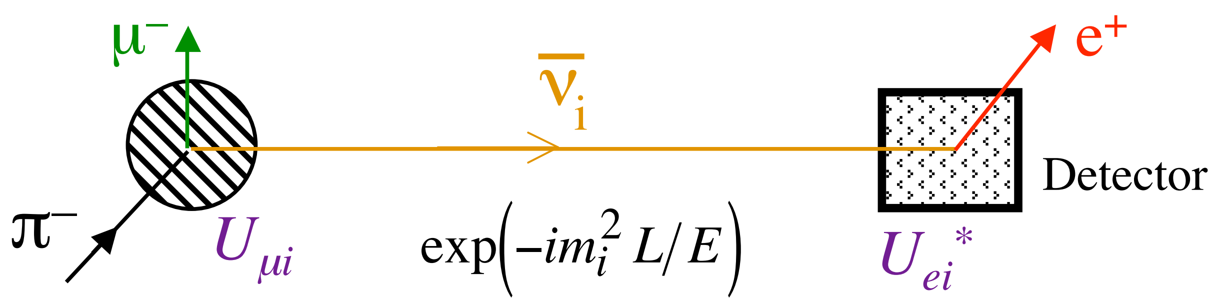
Compare $\nu_\mu \rightarrow \nu_e$

$\sum_i$



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

$\sum_i$



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 $x \equiv \dfrac{2\sqrt{2} G_F N_e E}{\Delta m^2_{31}}$ —

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

Atmospheric

CP-odd interference

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

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

CP-even interference

Solar

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

(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

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

Inverted

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 $E \rightarrow E/3$ 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*.

Neutrino Vision at Fermilab

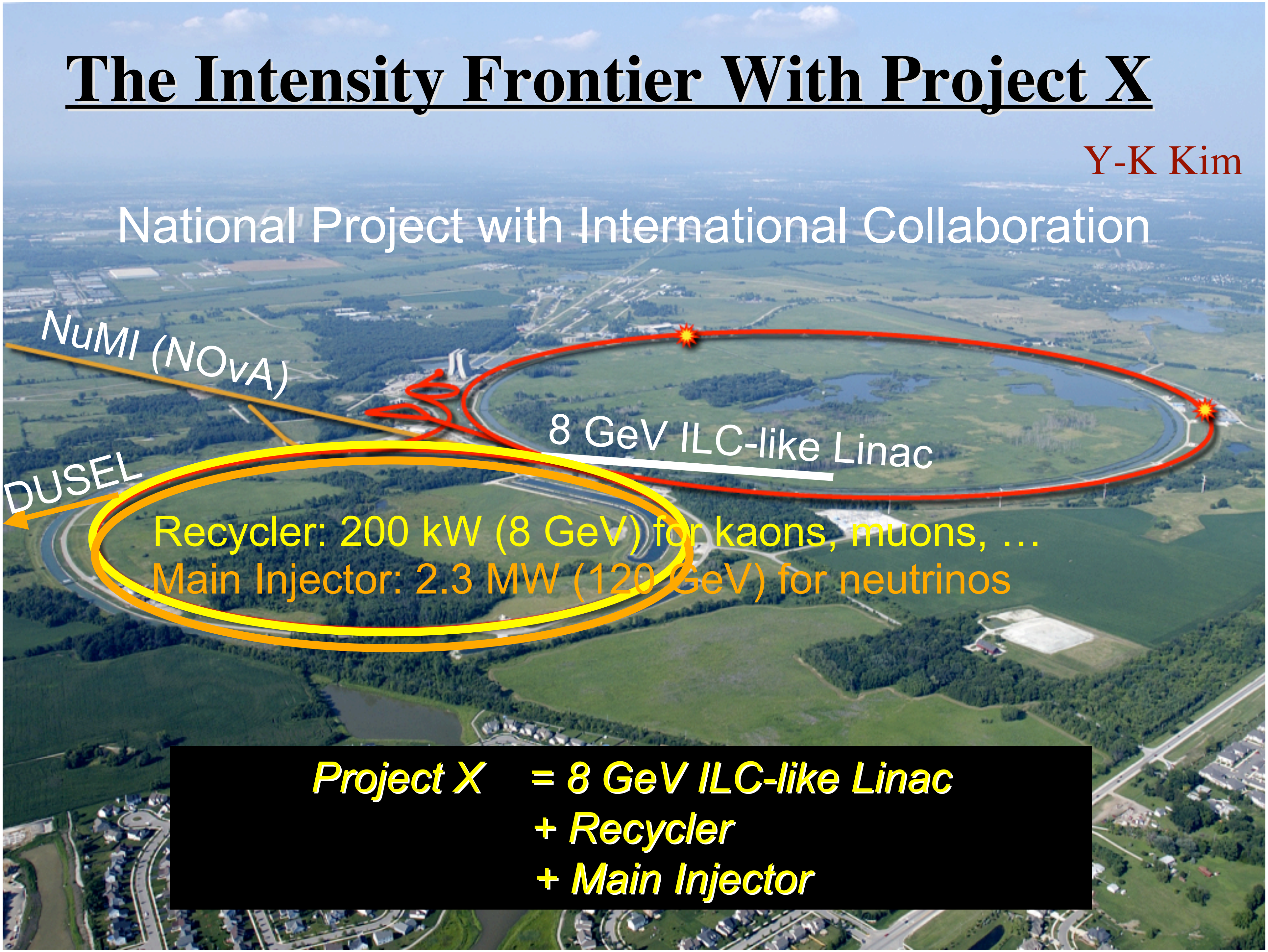
Develop a

phased approach with

ever increasing beam intensities

and ever increasing detector capabilities

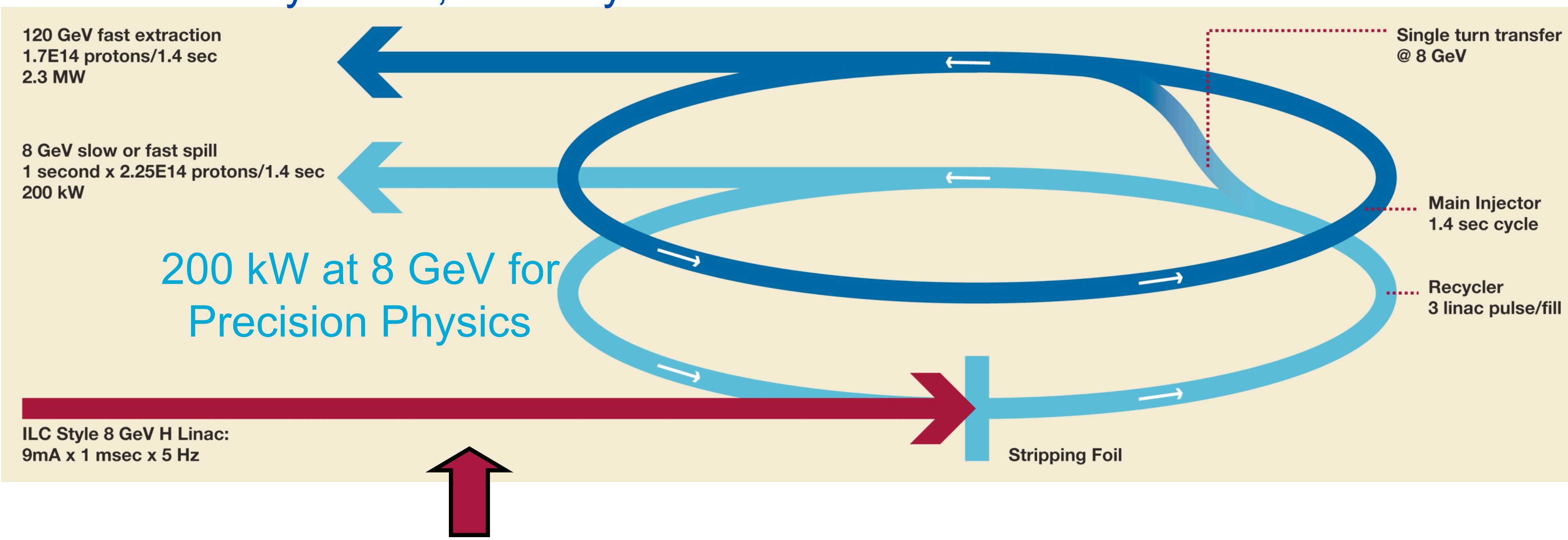
Probe Mixing, Mass Ordering, CP Violation


The Intensity Frontier With Project X
Y-K Kim
National Project with International Collaboration
NuMI (NOvA)
8 GeV ILC-like Linac
DUSEL
Recycler: 200 kW (8 GeV) for kaons, muons, …
Main Injector: 2.3 MW (120 GeV) for neutrinos
Project X = 8 GeV ILC-like Linac
+ Recycler
+ Main Injector

Project X: Properties

(Young-Kee Kim)

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



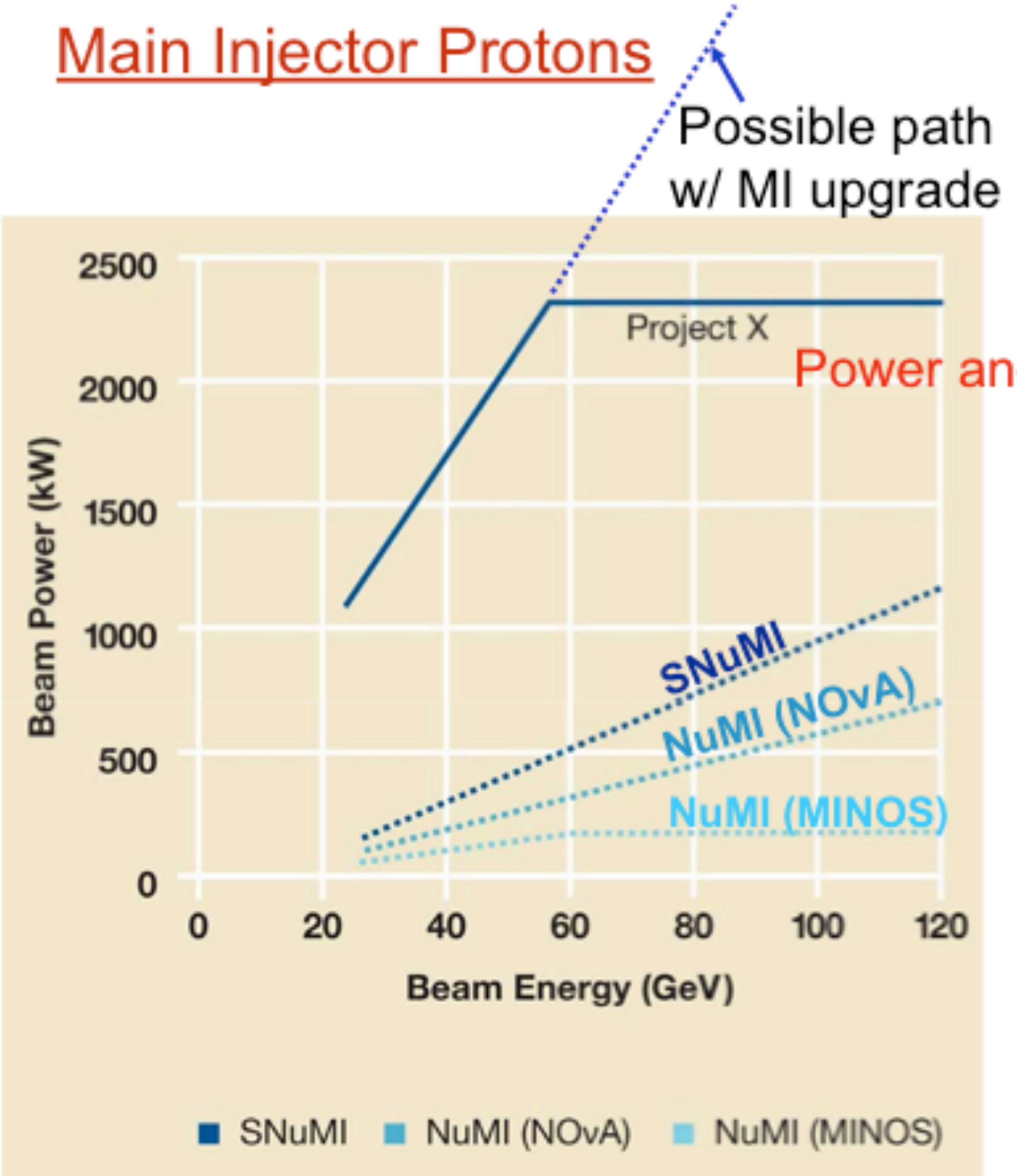
8 GeV H^- Linac with ILC Beam Parameters
(9mA x 1msec x 5Hz)

v < c   v = c (ILC Linac)

Project X: Proton Beam Power

(Y-K Kim)

Main Injector Protons



Power and Flexibility

Recycler 8 GeV Protons

with 120GeV MI protons

200 kW (Project X)

0* (SNuMI)

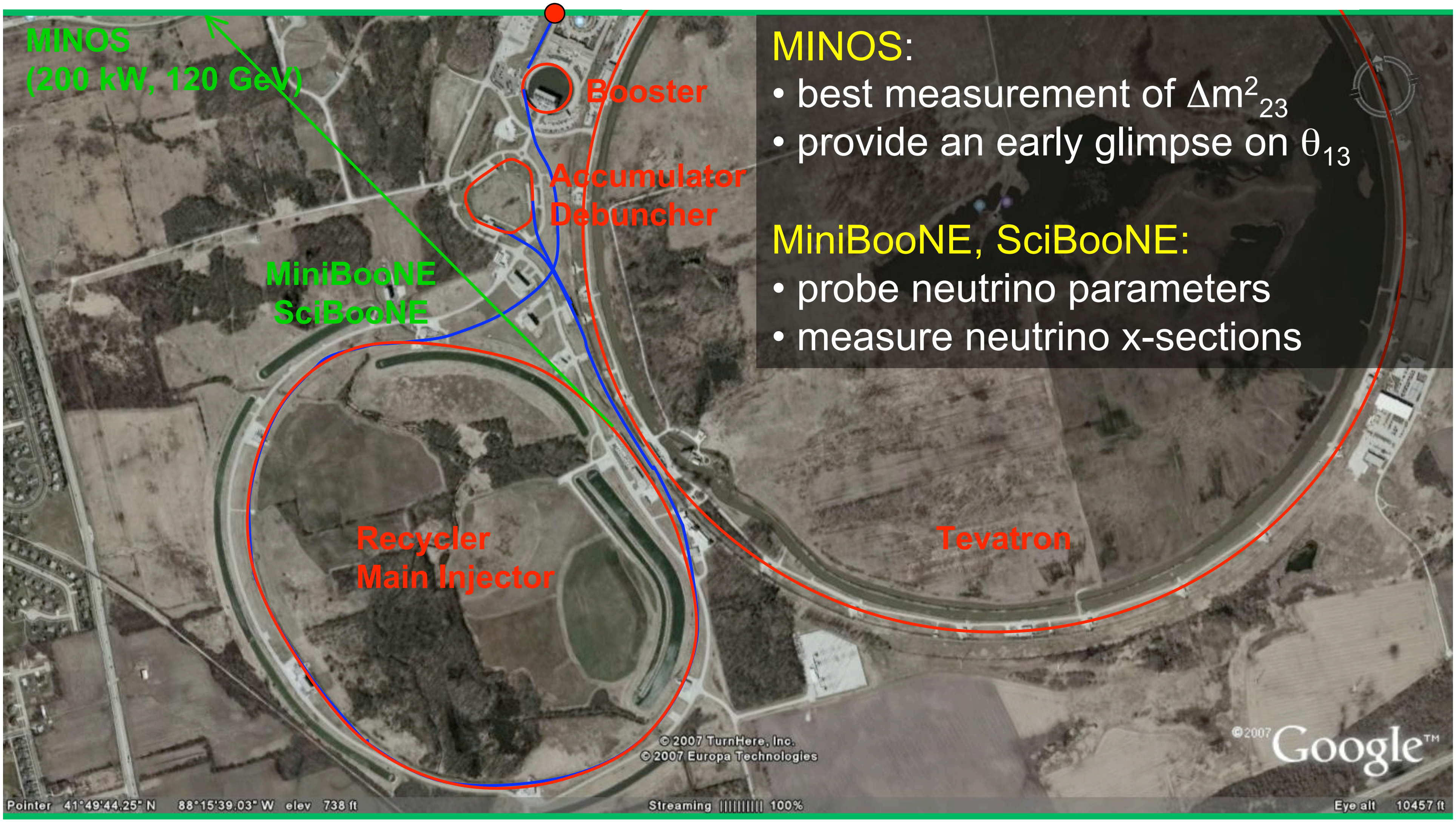
16 kW (NuMI-NOvA)

17 kW (NuMI-MINOS)

35-year-old injection
(technical risk)

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

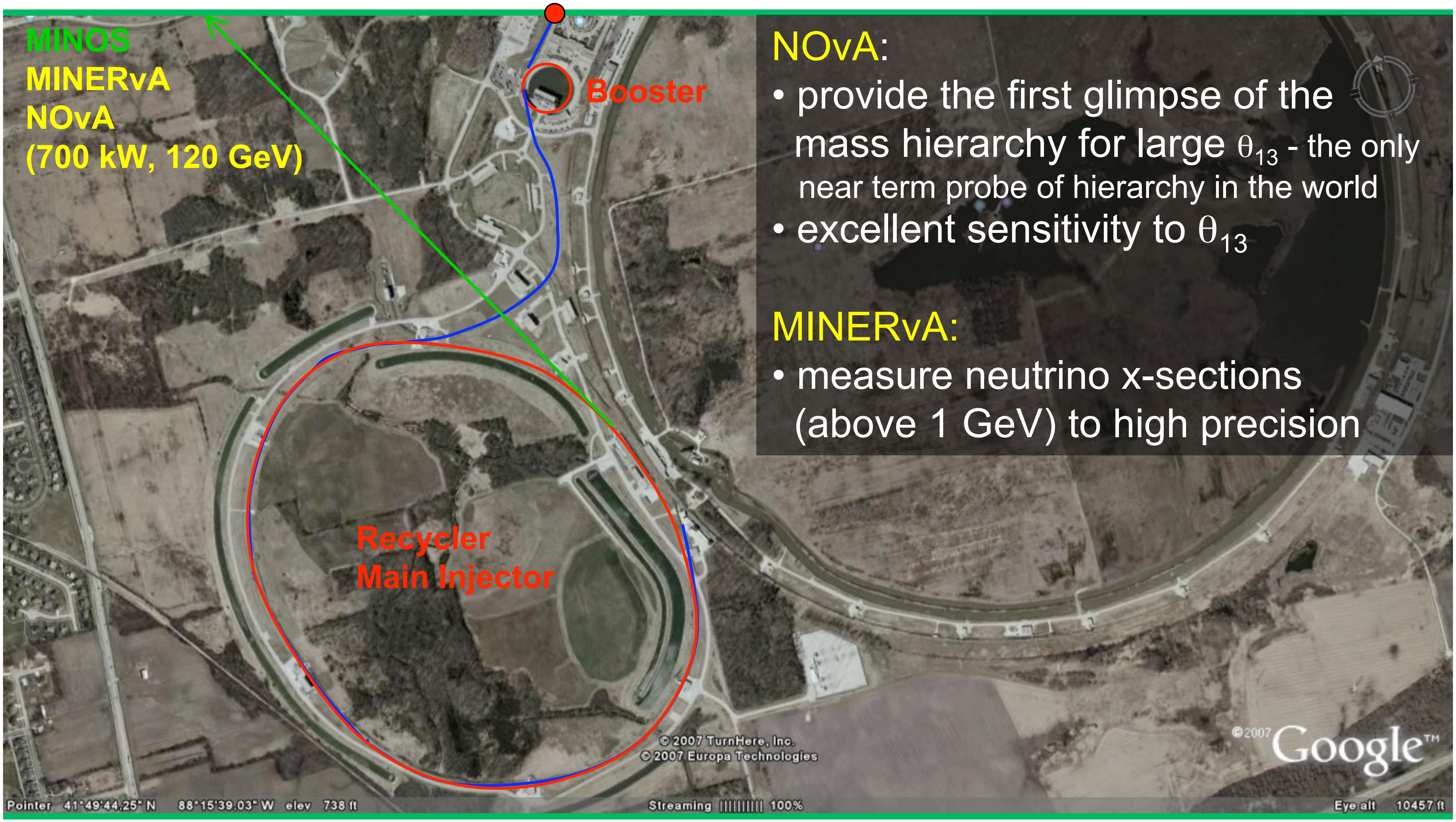
Present:



MINOS:
- best measurement of Δm^2_{23}
- provide an early glimpse on θ_{13}

MiniBooNE, SciBooNE:
- probe neutrino parameters
- measure neutrino x-sections

Phase 1:



NOvA:

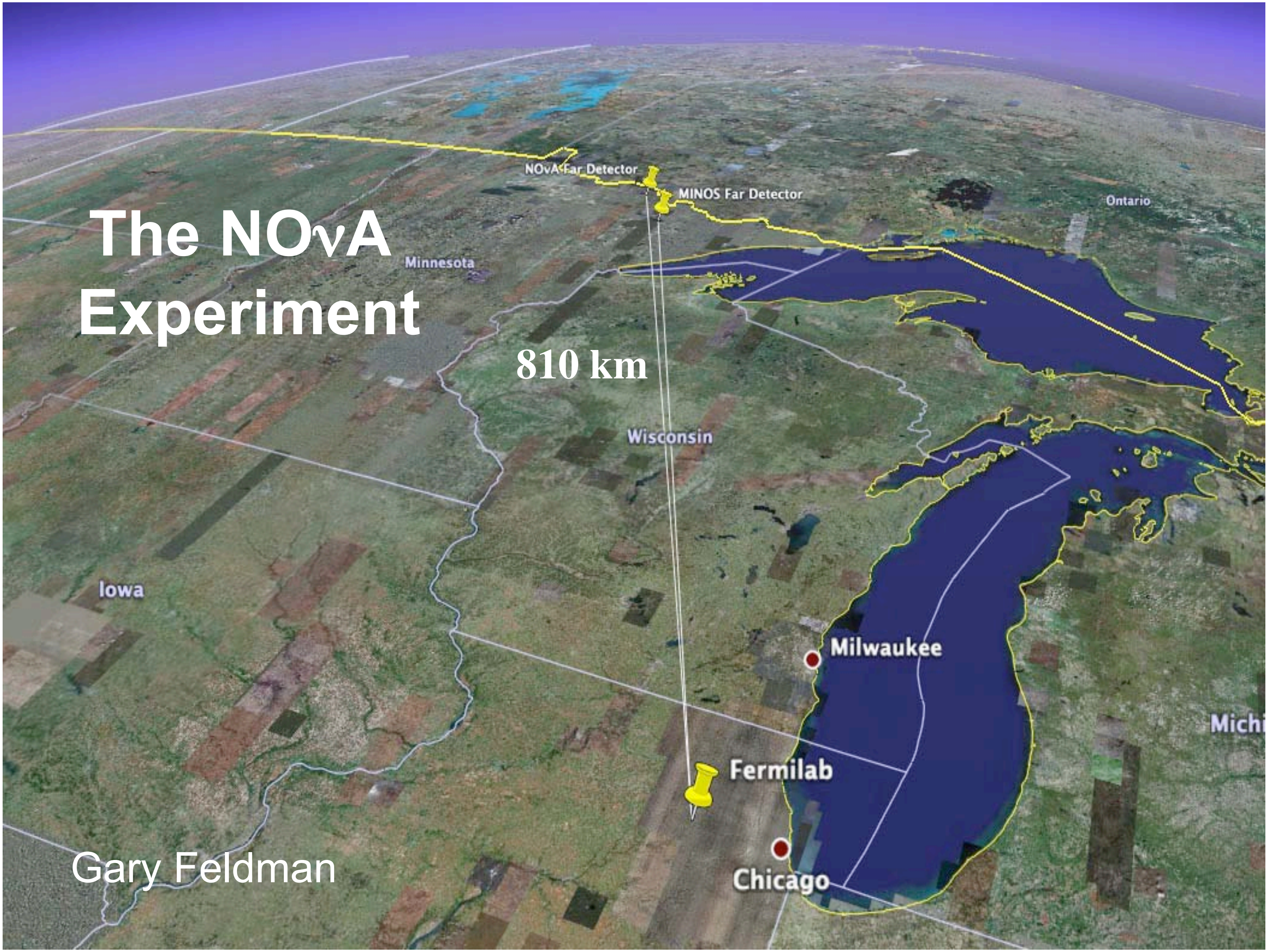
- provide the first glimpse of the mass hierarchy for large θ_{13} - the only near term probe of hierarchy in the world
- excellent sensitivity to θ_{13}

MINERvA:

- measure neutrino x-sections (above 1 GeV) to high precision

Y-K Kim

The NOνA Experiment

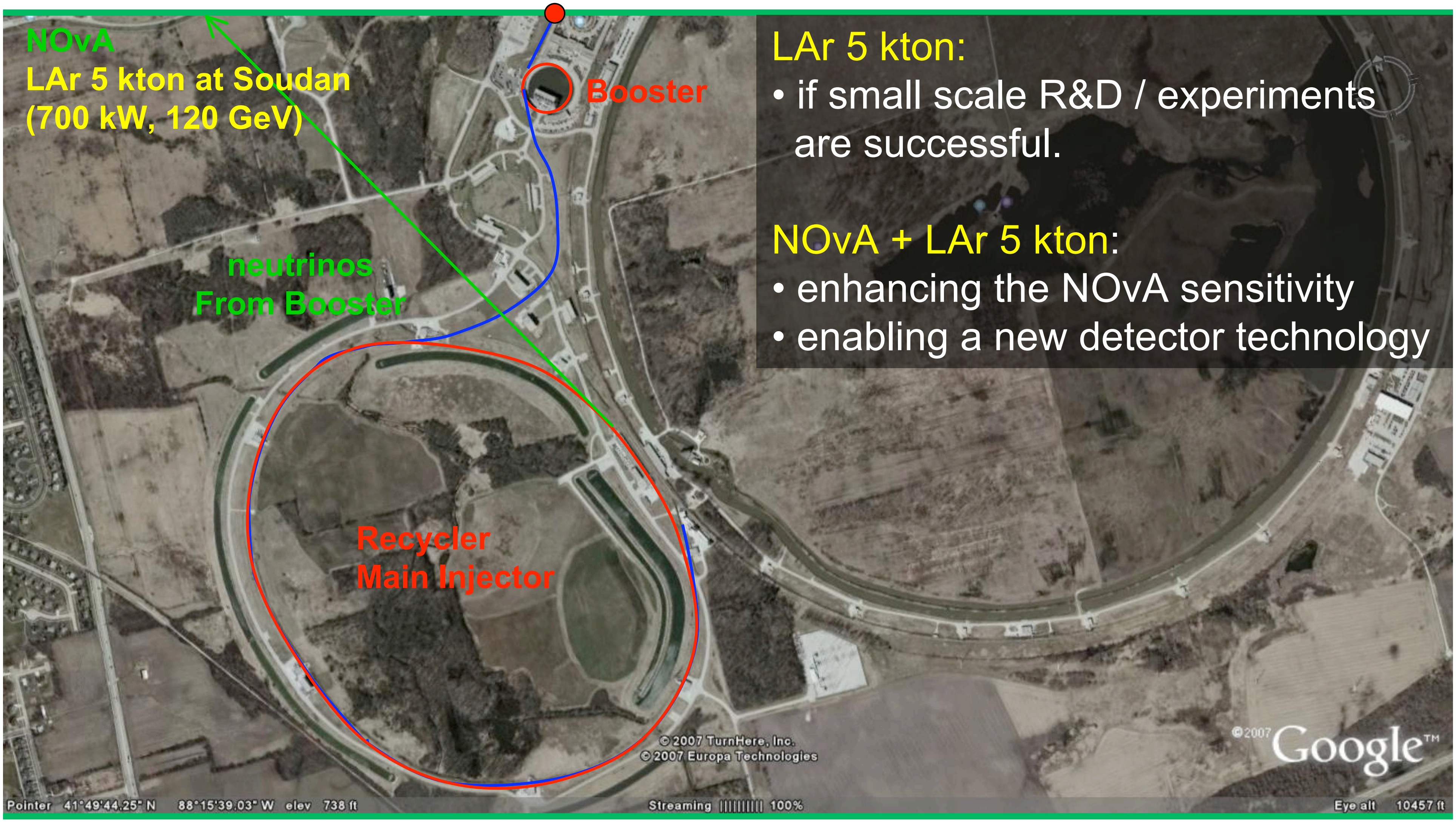


Gary Feldman

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
- L = 810 km; E ~ 2 GeV *(L/E near 1st osc. peak)*
- *Main goal: Try to determine whether the spectrum is* ***Normal*** *or* ***Inverted***

Phase 1.5:



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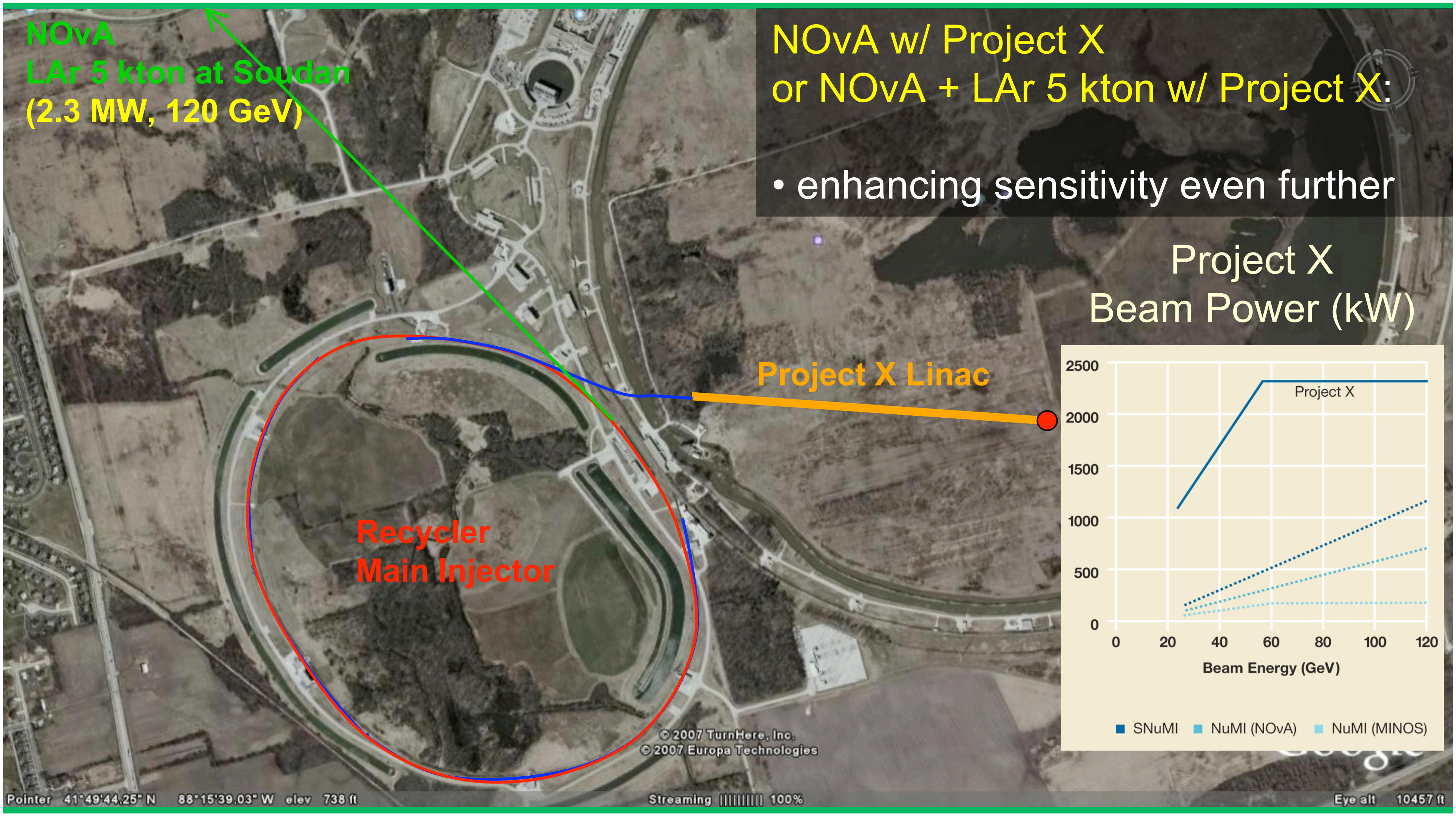
Phase 2:



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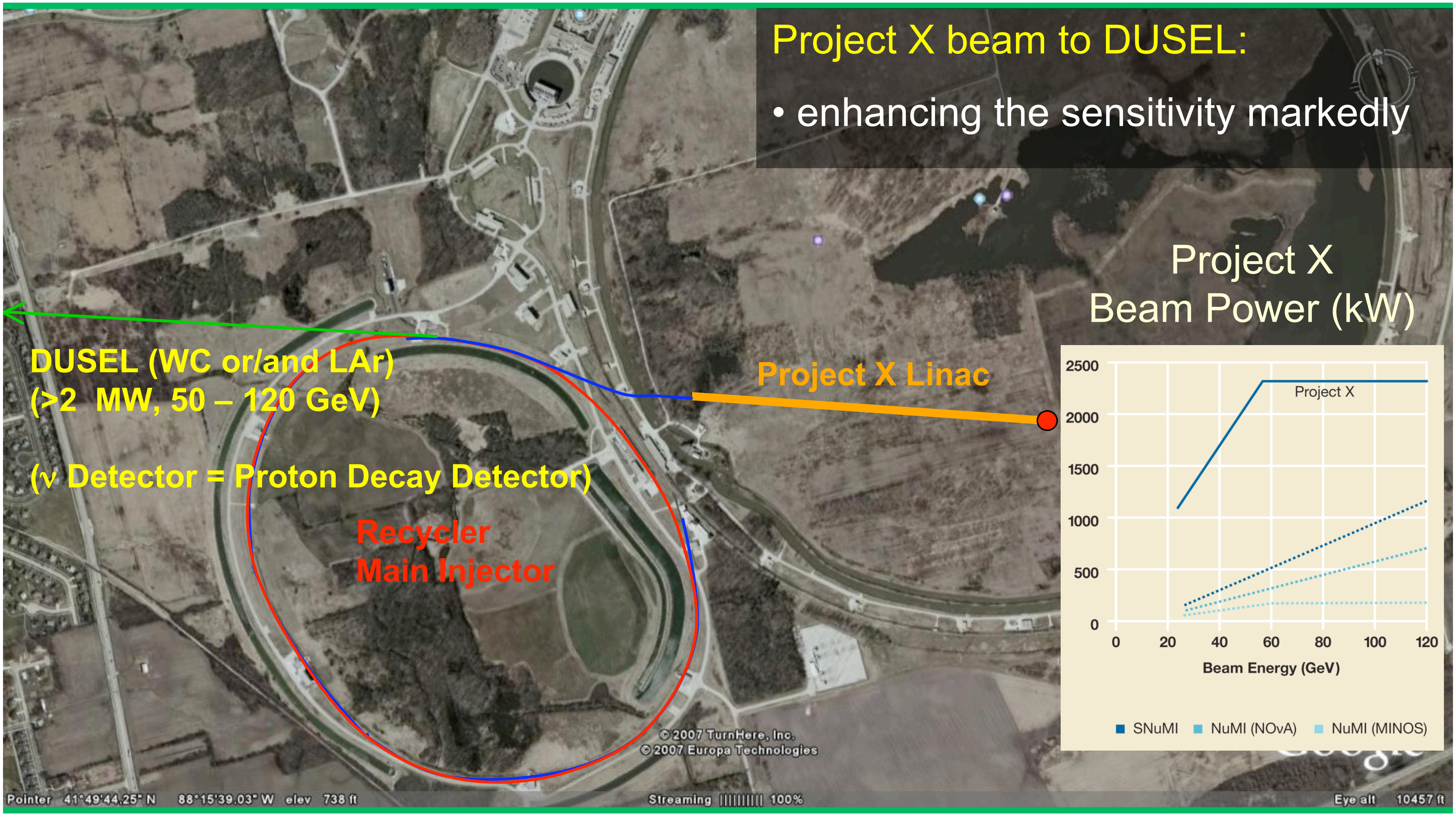
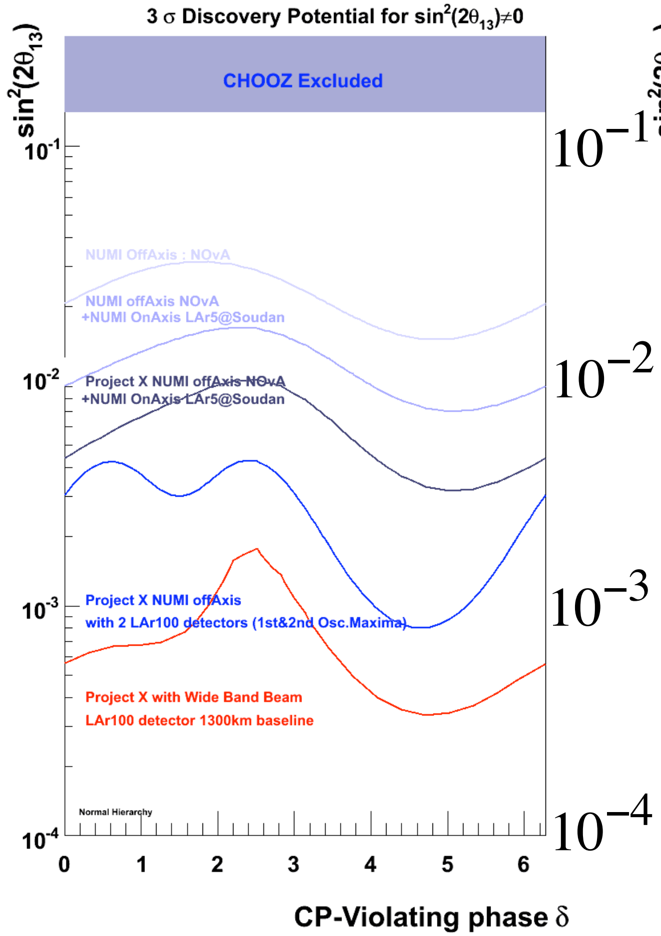
Phase 3



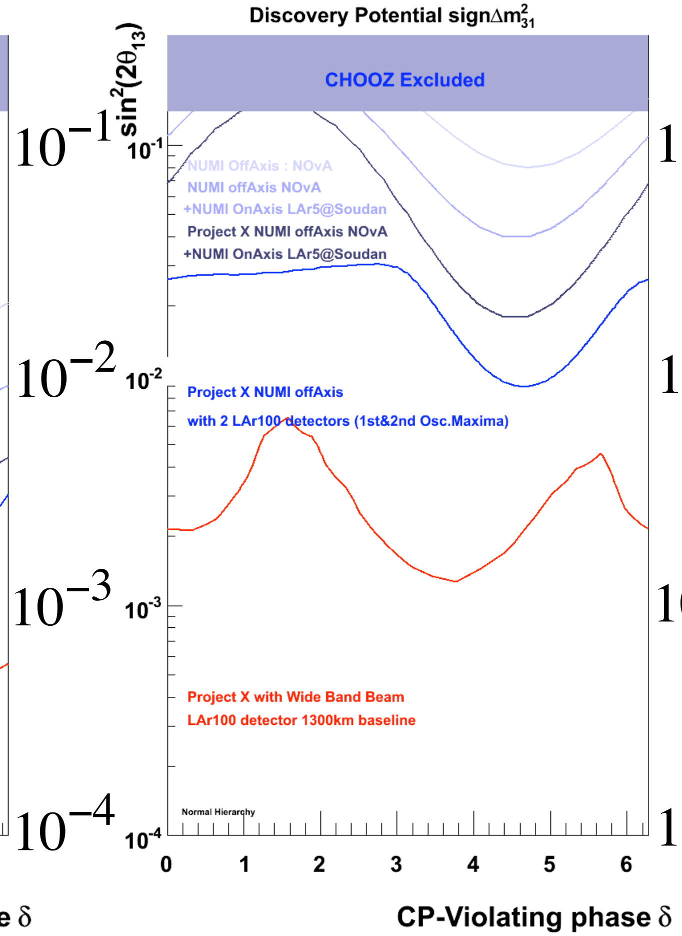
Y-K Kim

The 3σ Reach of the Successive Phases

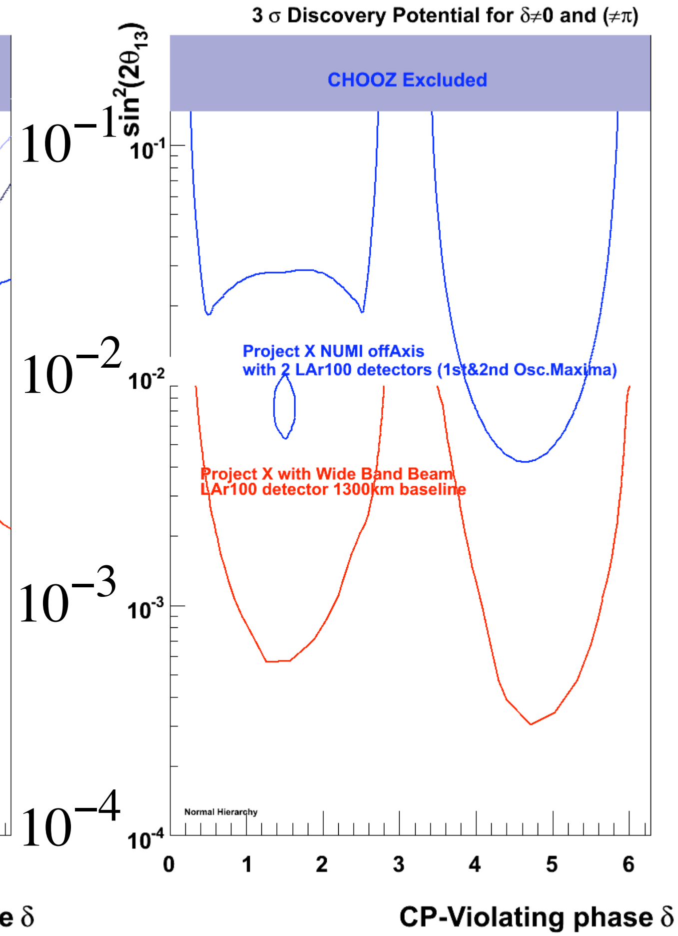
$\sin^2 2\theta_{13}$



Mass Ordering

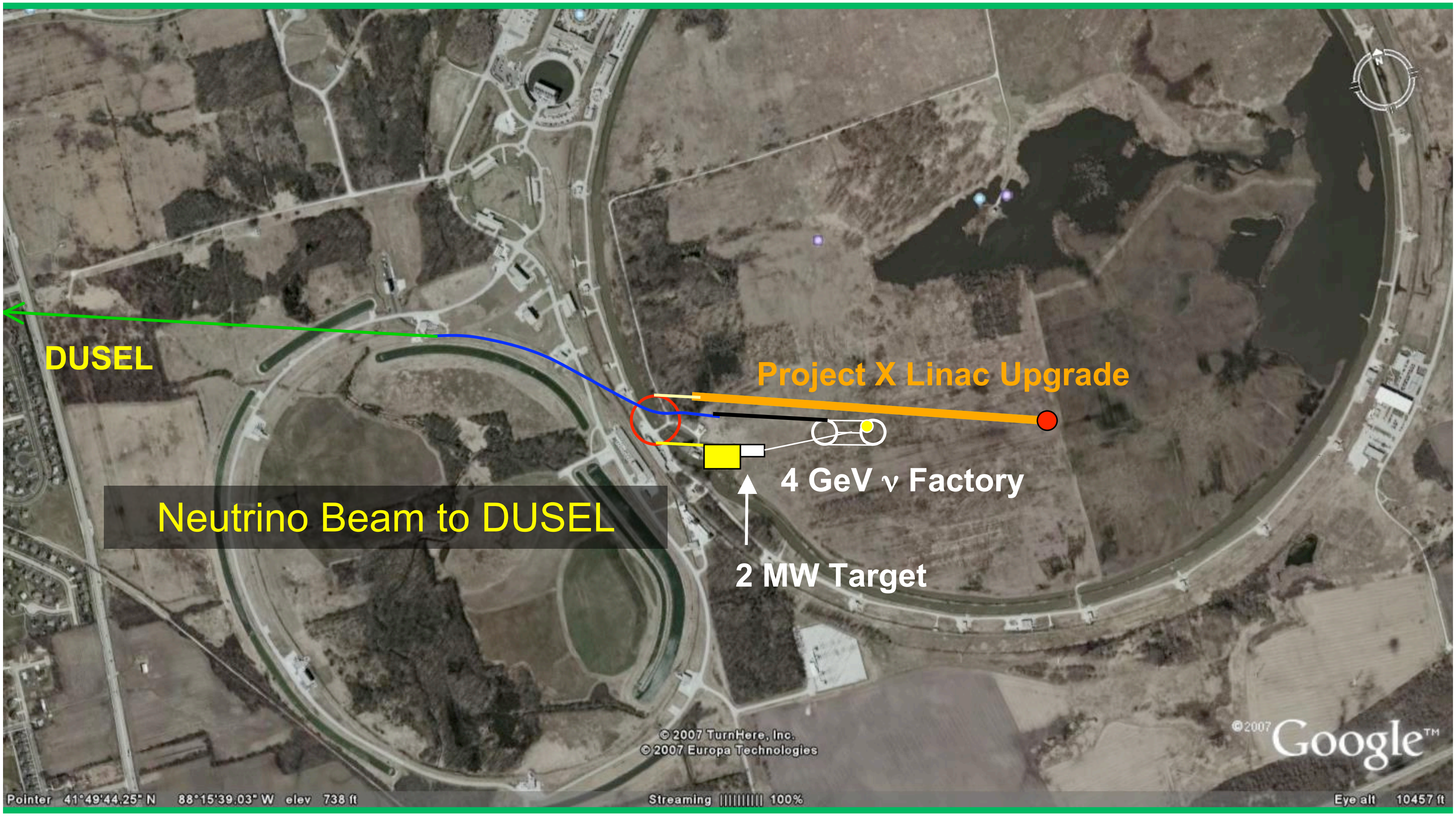


CP Violation



N. Saoulidou

Toward "Proton Intensity Upgrade"
Evolutionary Path to a Neutrino Factory



Y-K Kim

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.