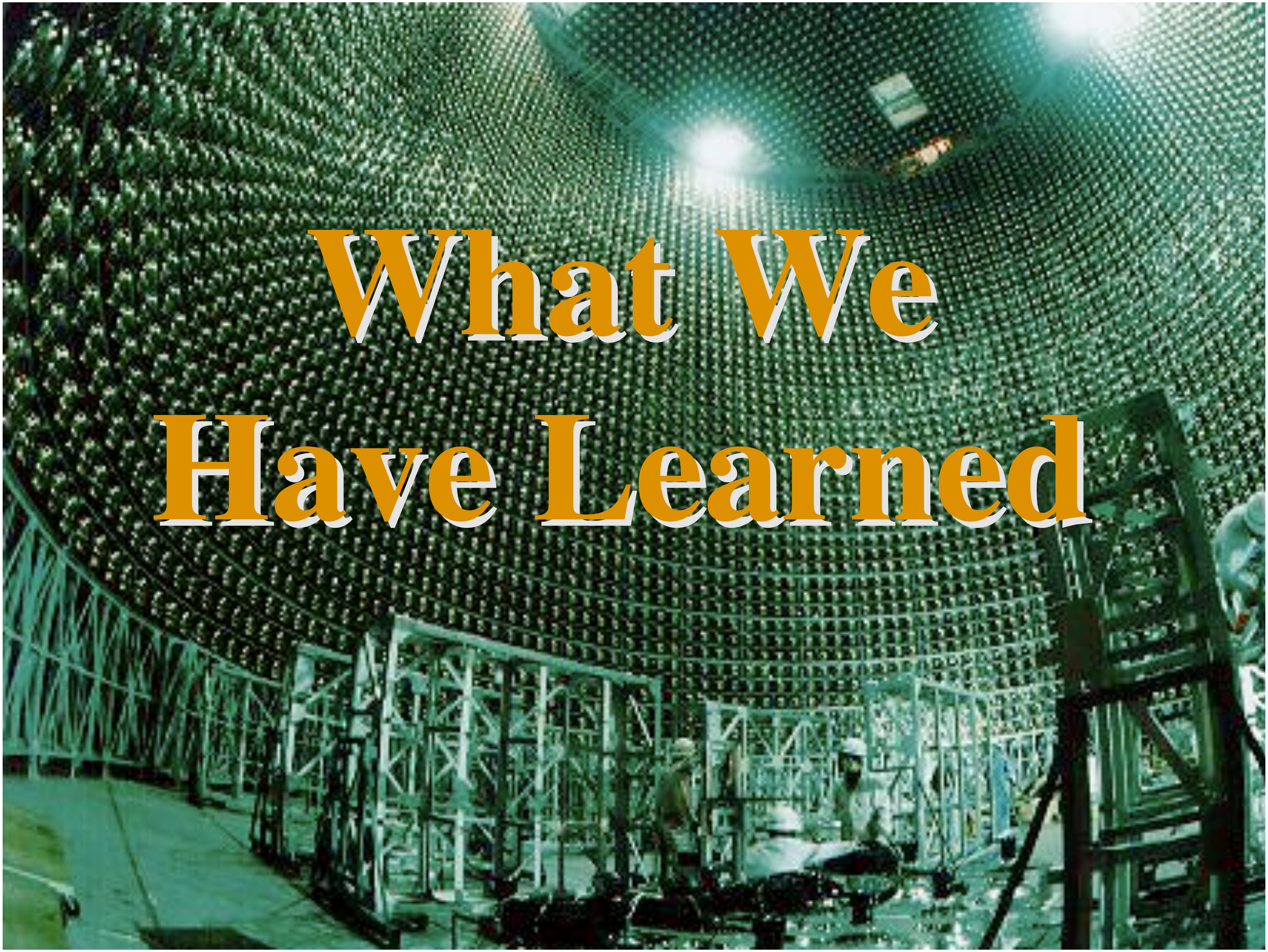
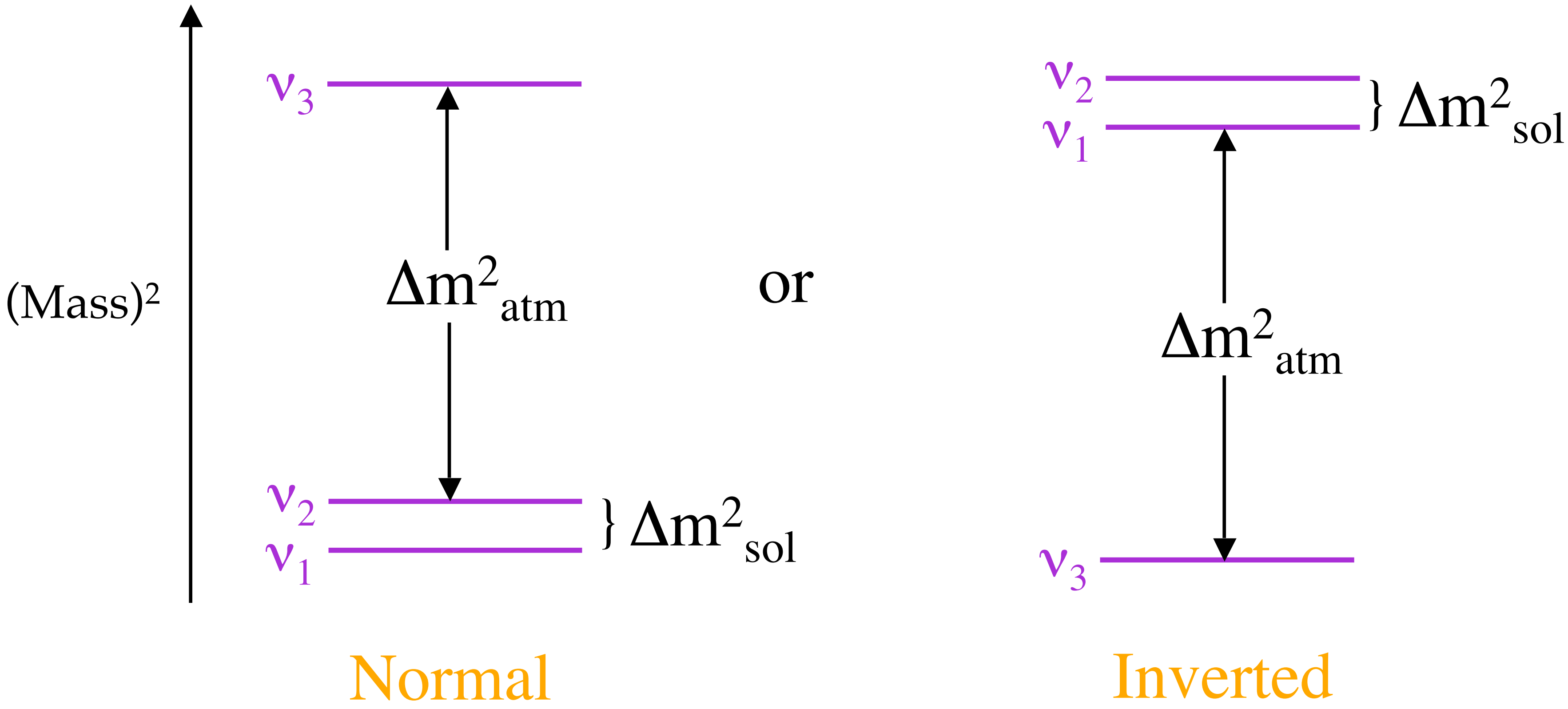
What We Know, and What We Would Like to Find Out

Boris Kayser
ν Horizons
17 April, 2008



What We Have Learned

The (Mass)^2 Spectrum



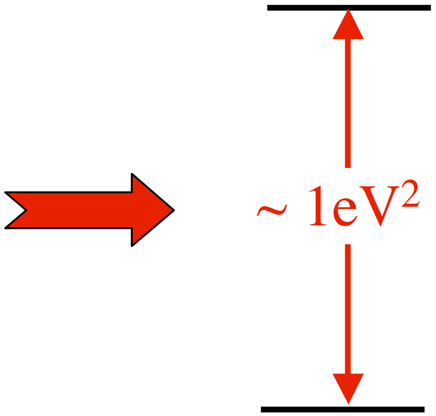
$\Delta m^2_{sol} \cong 7.6 \text{ x } 10^{-5}\ \mathrm{eV}^2$, $\Delta m^2_{atm} \cong 2.4 \text{ x } 10^{-3}\ \mathrm{eV}^2$

Are There *More* Than 3 Mass Eigenstates?

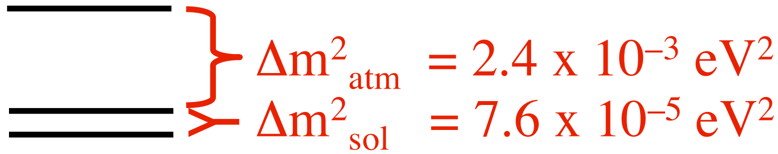
When only two neutrinos count,

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

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



in contrast to



→ At least **4** mass eigenstates → At least 1 ν_{Sterile}

MiniBooNE

Goal: *Confirm* or *Refute* LSND.

Results so far

- Two-neutrino oscillation cannot fit *both* LSND and MiniBooNE.
- More complicated fits are possible ($\bar{\nu}$ vs. ν).
- MiniBooNE will have much more to say.
- We will assume there are only 3 neutrino mass eigenstates.

Leptonic Mixing

This has the consequence that —

Mass eigenstate Flavor eigenstate

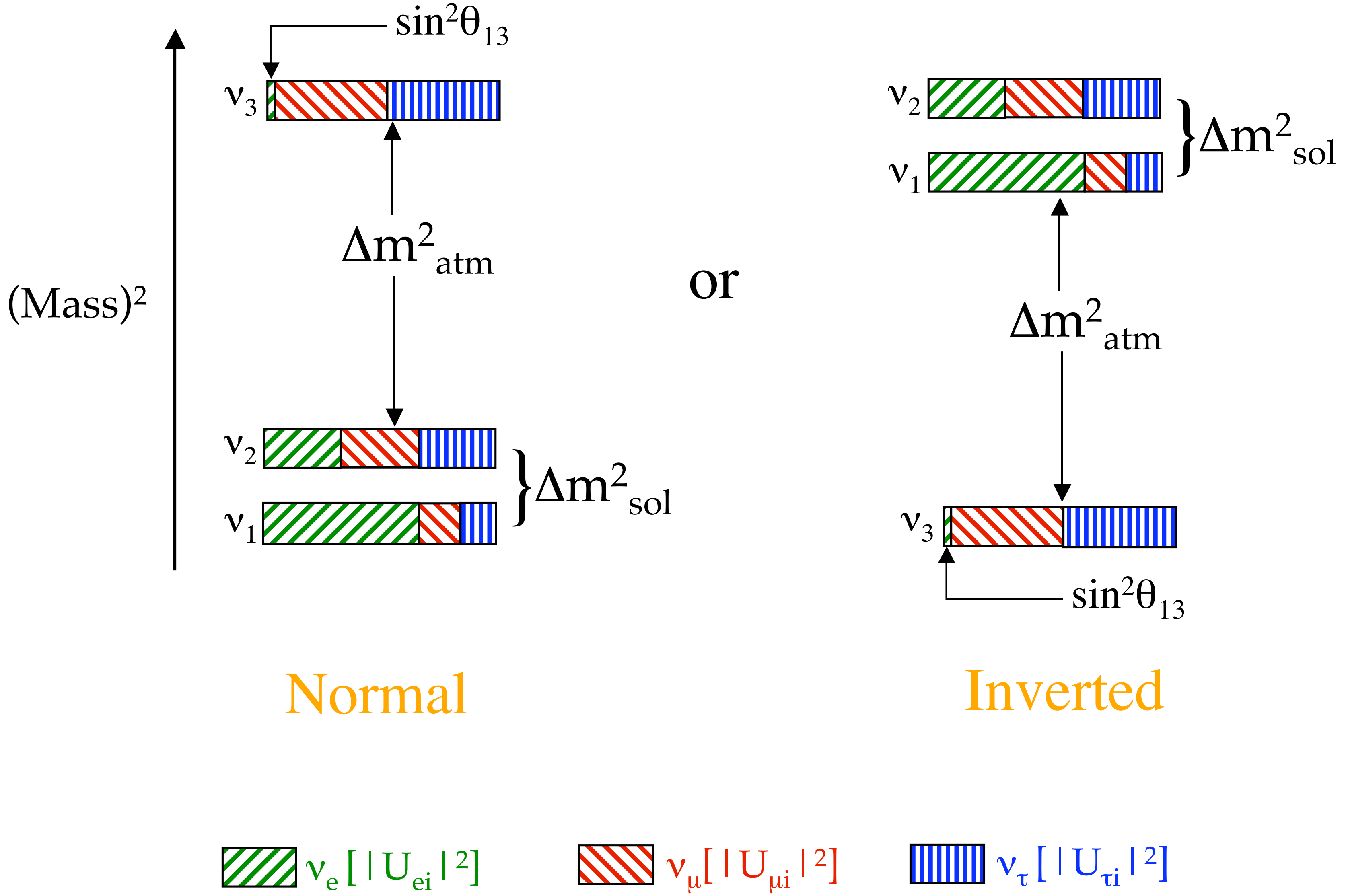
$$|\nu_i\rangle = \sum_{\alpha} U_{\alpha i}\, |\nu_\alpha\rangle \,.$$

e, μ, or τ 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

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

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

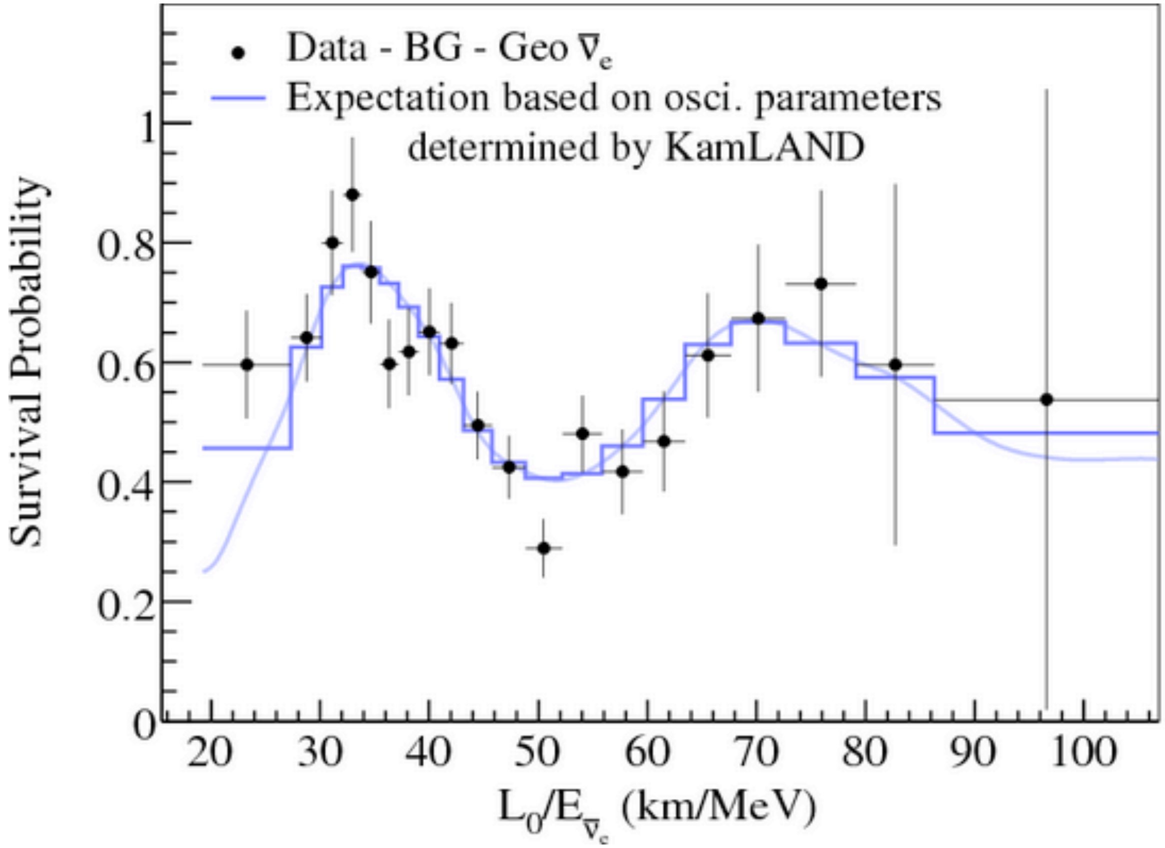
$$\times \underset{\text{Majorana } \cancel{CP} \text{ phases}}{\begin{bmatrix} e^{i\alpha_1/2} & 0 & 0 \\ 0 & e^{i\alpha_2/2} & 0 \\ 0 & 0 & 1 \end{bmatrix}}$$

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

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

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

KamLAND Evidence for Oscillation



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

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

The Open Questions

- What is the absolute scale of neutrino mass?

- Are neutrinos their own antiparticles?

- Are there “sterile” neutrinos?

- **Is our picture right?**

- What is the pattern of mixing among the different types of neutrinos?

What is θ_{13}?

- Is the spectrum like  or  ?

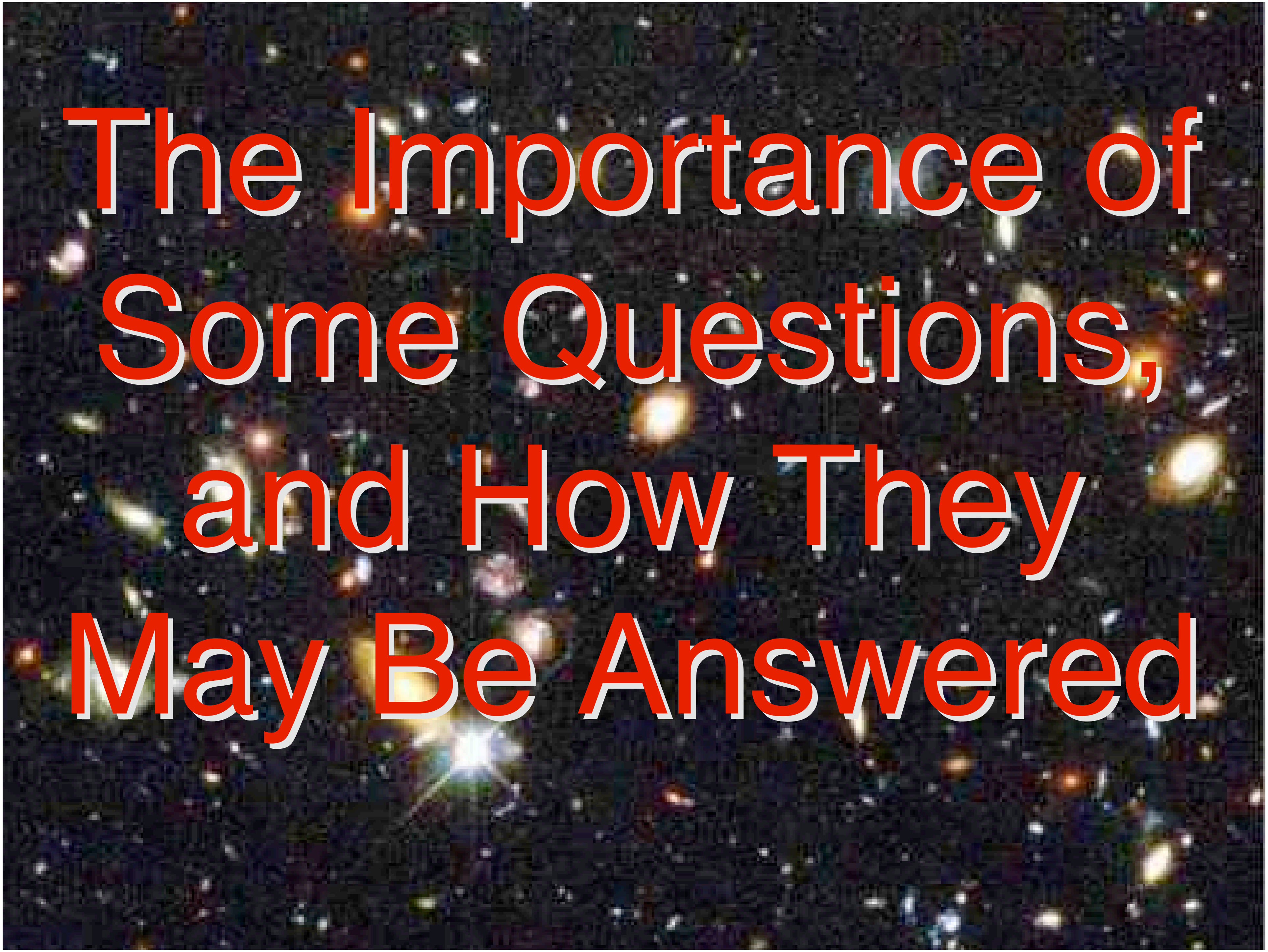
- Do neutrino – matter interactions violate CP?

Is $P(\bar{\nu}_\alpha \to \bar{\nu}_\beta) \neq P(\nu_\alpha \to \nu_\beta)$?

- 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) ?

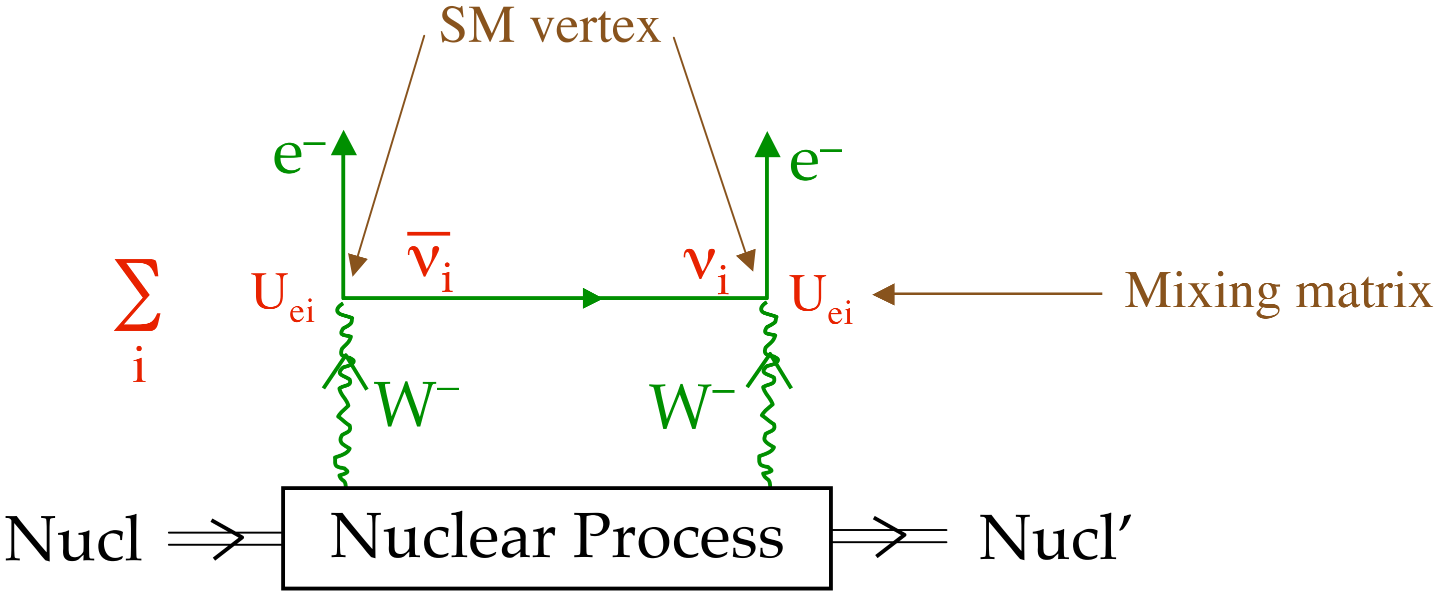
Equivalently, do neutrinos have *Majorana ($\nu \Leftrightarrow \bar{\nu}$ mixing) masses*? They do if the mass eigenstates are *Majorana neutrinos*.

Quarks and charged leptons
cannot have Majorana masses
(q ⇔ $\bar{q}$ would violate
electric charge conservation).

If neutrinos have Majorana masses,
then neutrino mass has a different origin
than the masses of the other
fermionic constituents of matter.

To see whether $\overline{\nu}_i = \nu_i$, seek —

Neutrinoless Double Beta Decay ($0\nu\beta\beta$)



Mass (ν_i)

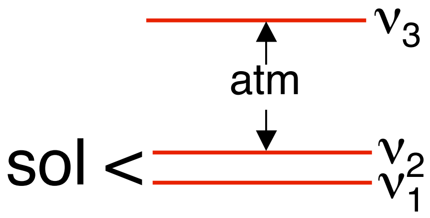
$$\mathrm{Amp}[0\nu\beta\beta] \propto \left|\sum m_i U_{ei}^2\right| \equiv m_{\beta\beta}$$

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

How sensitive need an experiment be?

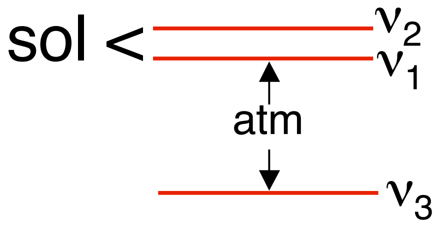
Suppose there are only 3 neutrino mass eigenstates. (More might help.)

Then the spectrum looks like —

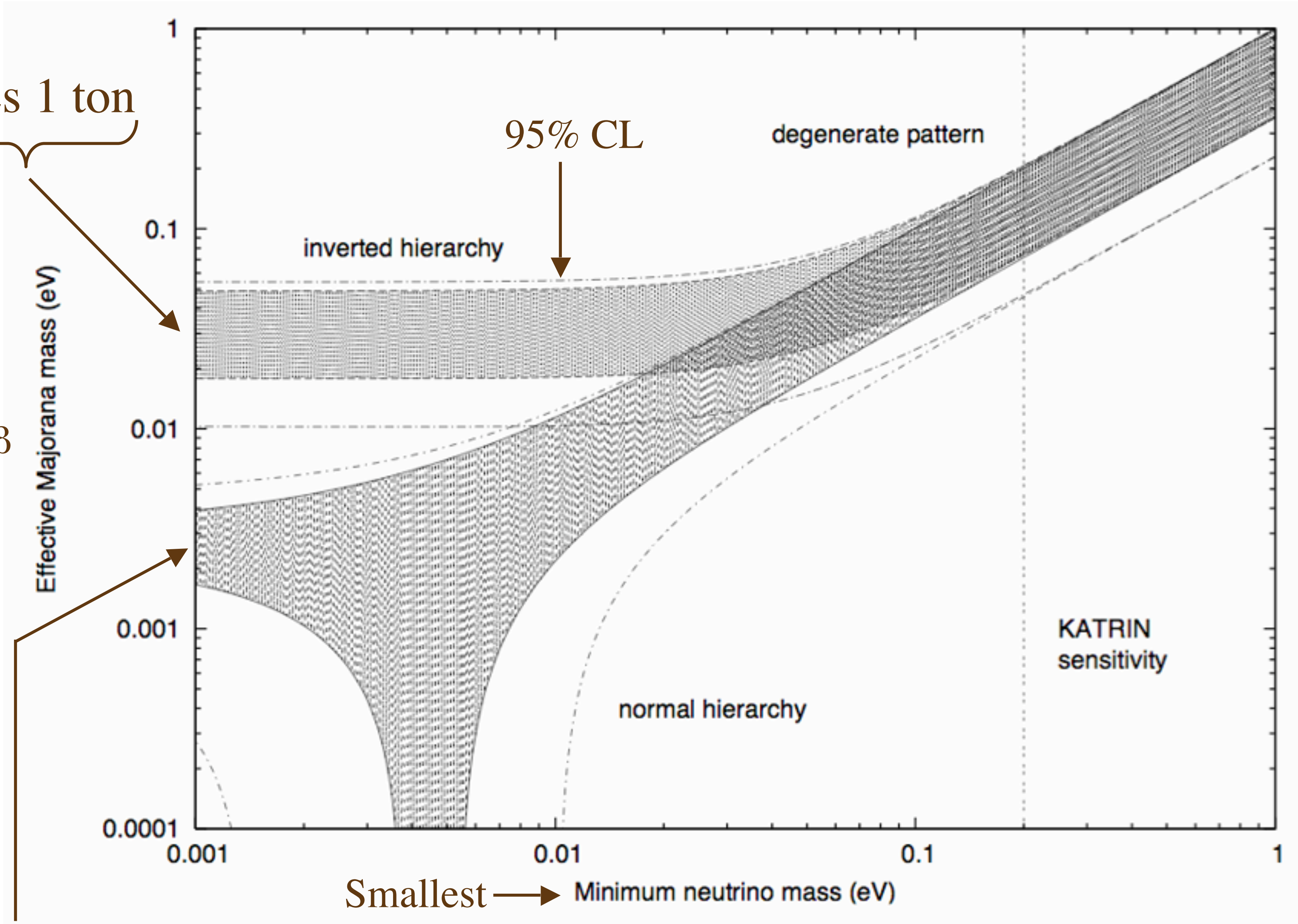


Normal hierarchy

or



Inverted hierarchy



Takes 1 ton

95% CL

$m_{\beta\beta}$

Smallest →

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

The Mass Spectrum:  or  ?

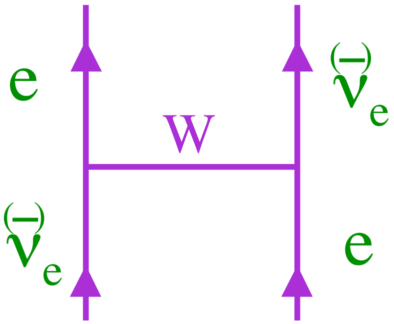
Generically, grand unified models (GUTS) favor —

GUTS relate the Leptons to the Quarks.

 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 —

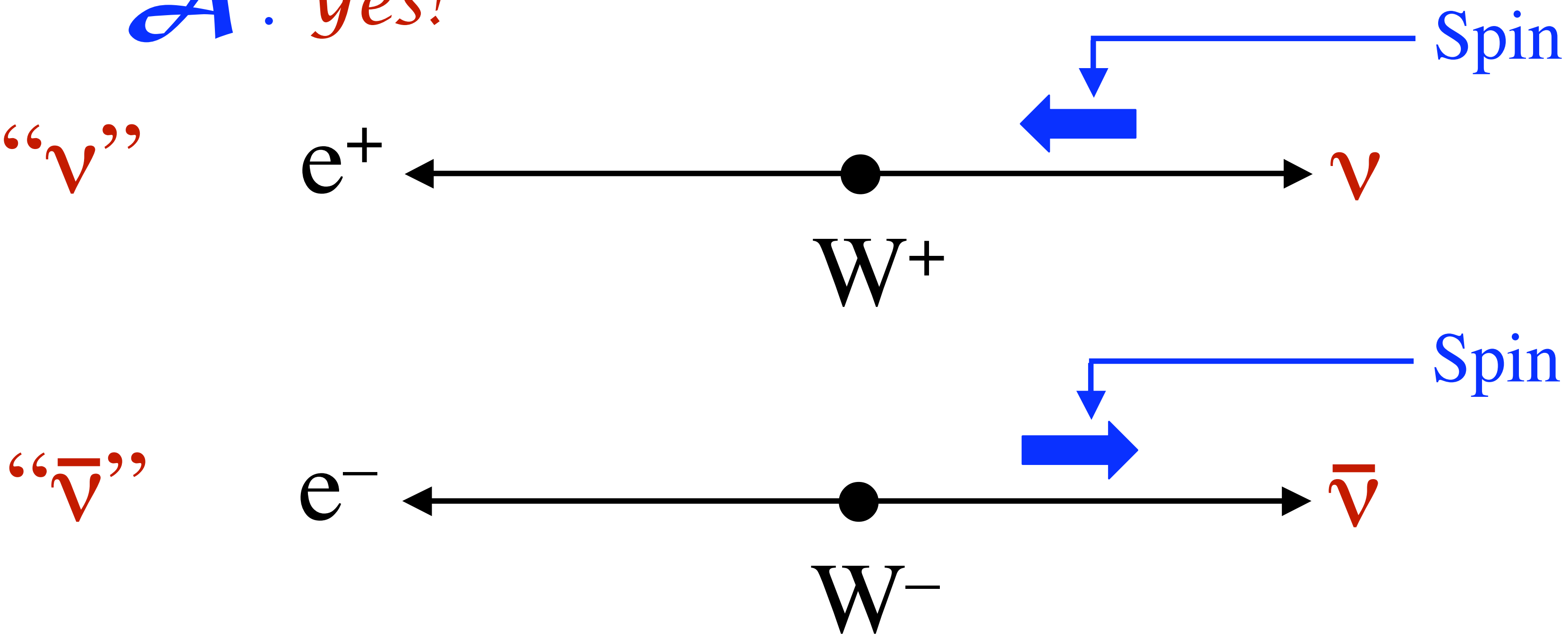
$$\frac{P(\nu_\mu \to \nu_e)}{P(\bar{\nu}_\mu \to \bar{\nu}_e)} \begin{cases} > 1\ ; \\ < 1\ ; \end{cases}$$

Note fake $\not{CP}$

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

Is ***leptonic*** $\cancel{CP}$, through *Leptogenesis*, the origin of the *Baryon Asymmetry* of the universe?

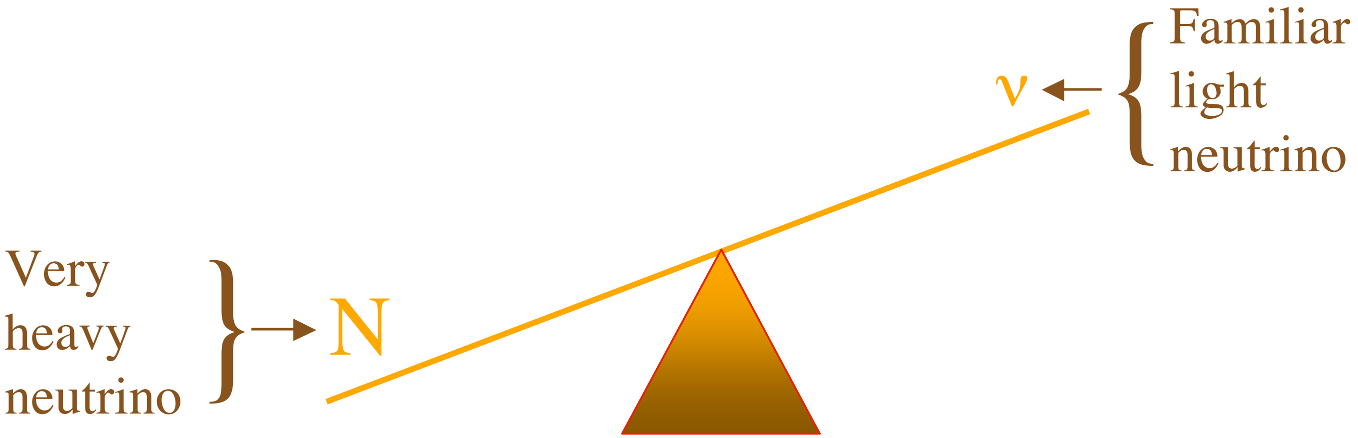
(Fukugita, Yanagida)

Leptogenesis In Brief

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

See-Saw Mechanism

(Yanagida; Gell-Mann, Ramond, Slansky;
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 –

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

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*.

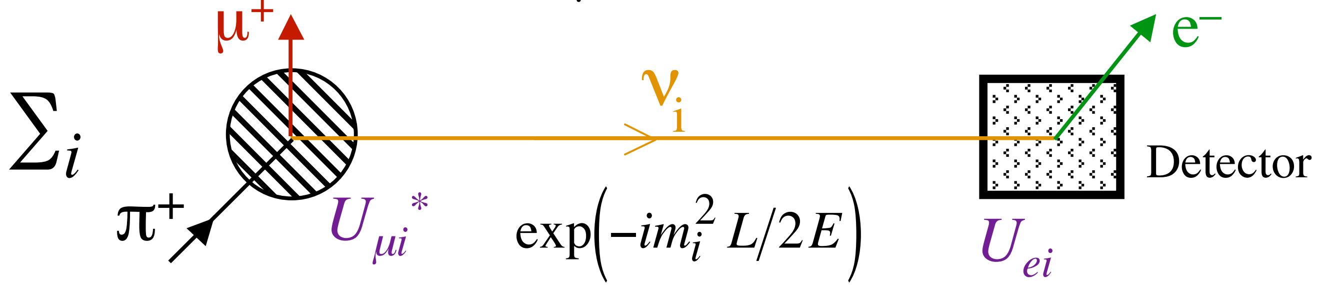
How To Search for ~~CP~~ In Neutrino Oscillation

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

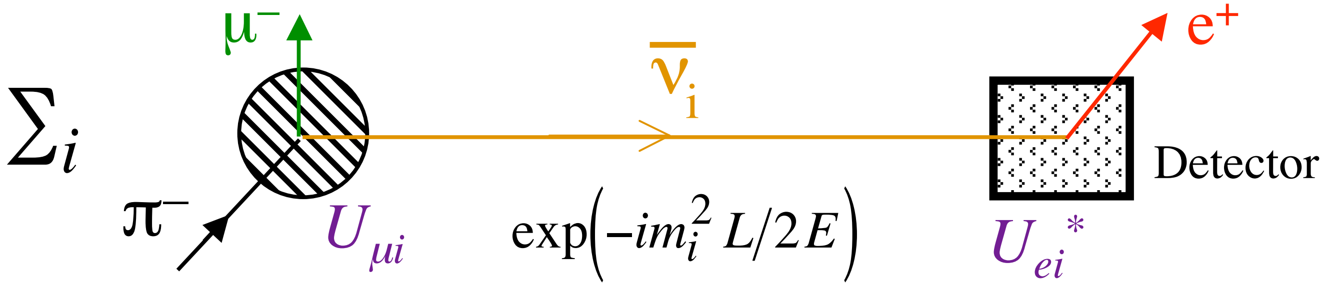
Q : Can CP violation still lead to $\mathcal{P}(\overline{\nu}_\mu \rightarrow \overline{\nu}_e) \neq \mathcal{P}(\nu_\mu \rightarrow \nu_e)$ when $\overline{\nu} = \nu$?

A : Certainly!

Compare $\nu_\mu \rightarrow \nu_e$



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



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.

Neutrino Vision at Fermilab

Develop a

phased approach with

ever increasing beam intensities

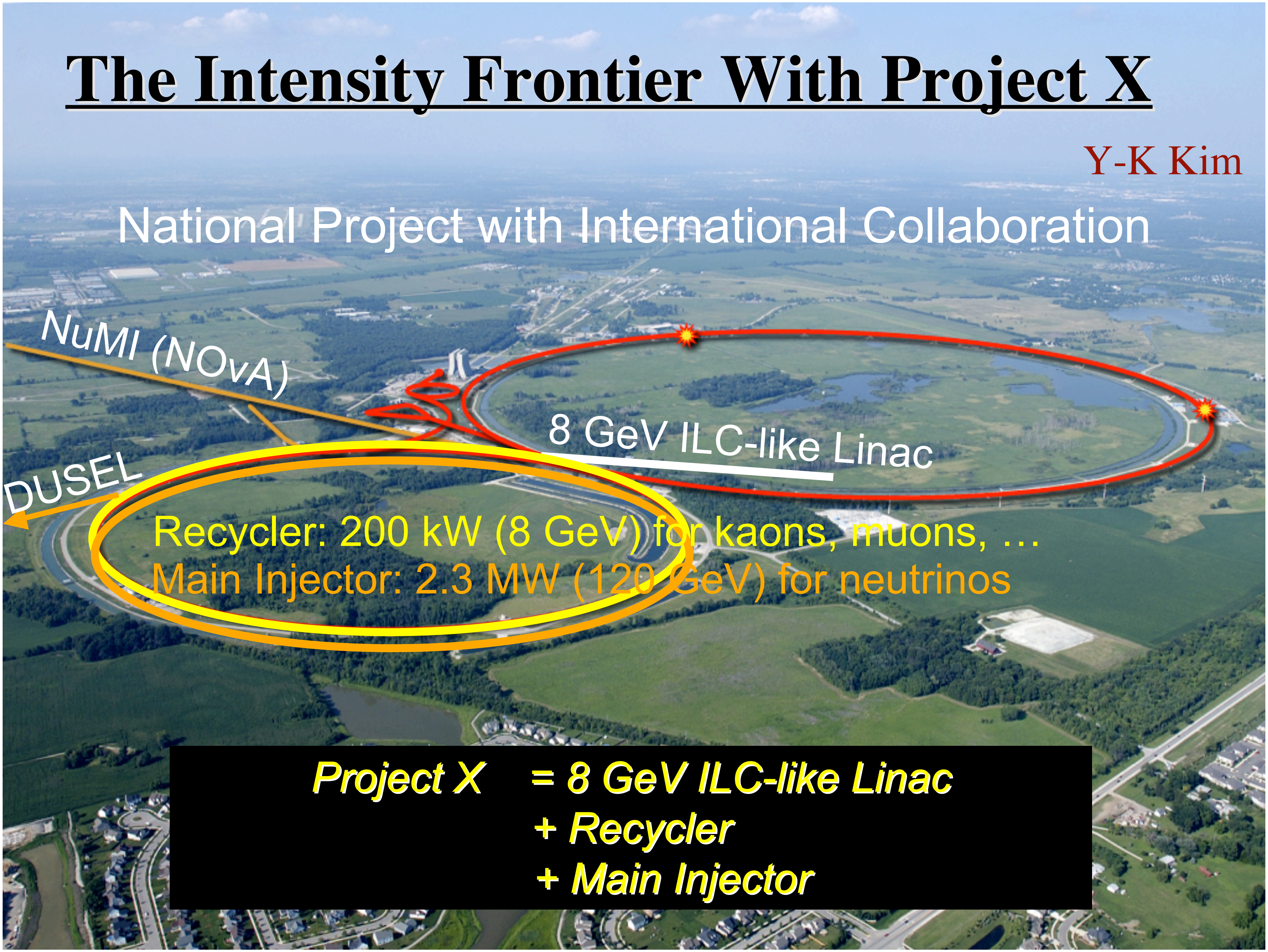
and ever increasing detector capabilities

Probe Mixing, Mass Ordering, CP Violation

The Intensity Frontier With Project X

Y-K Kim

National Project with International Collaboration

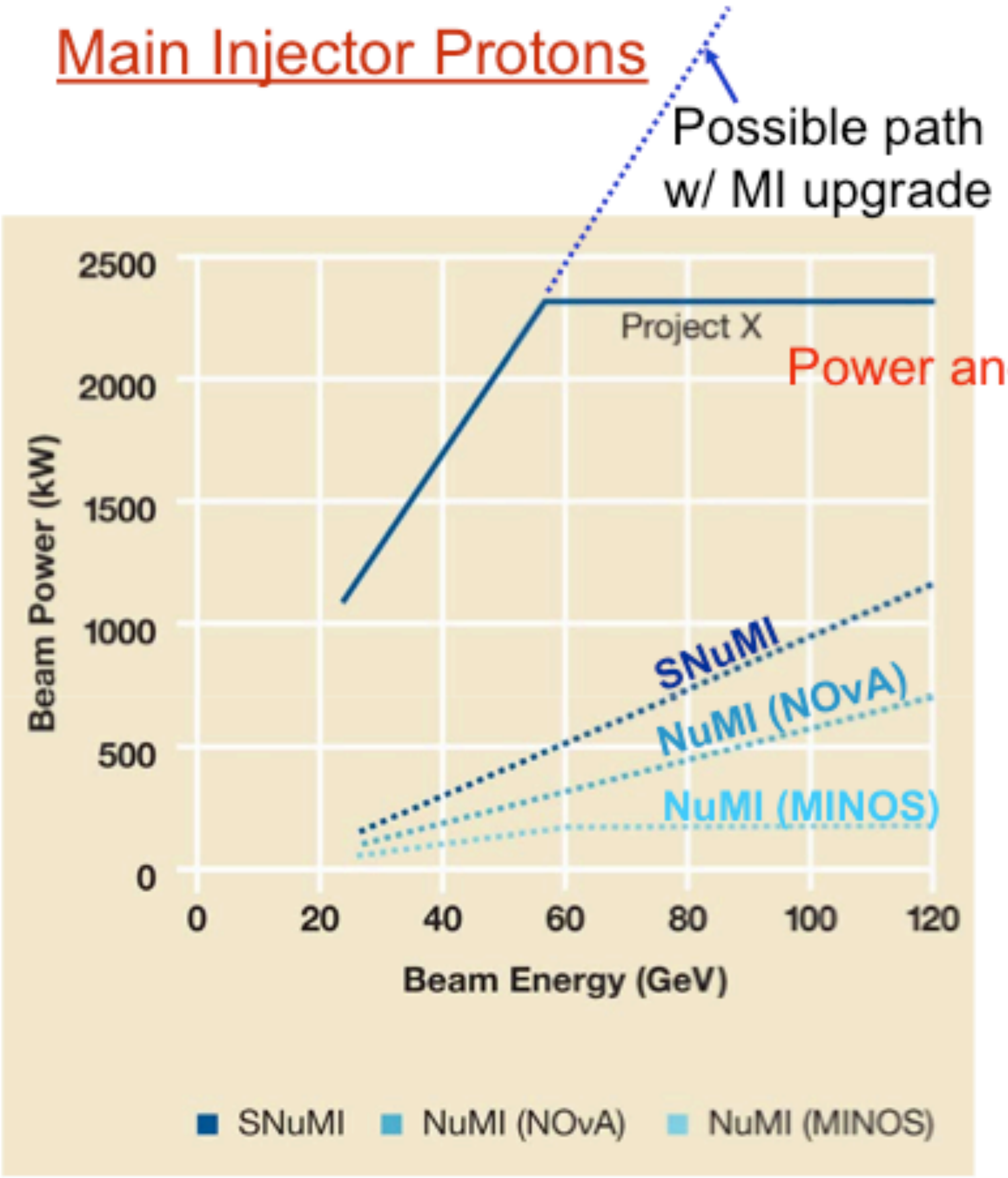


Project X = 8 GeV ILC-like Linac
+ Recycler
+ Main Injector

Project X: Proton Beam Power

(Y-K Kim)

Main Injector Protons



Possible path w/ MI upgrade

Power and Flexibility

Recycler 8 GeV Protons

with 120GeV MI protons

200 kW (Project X)

0* (SNuMI)

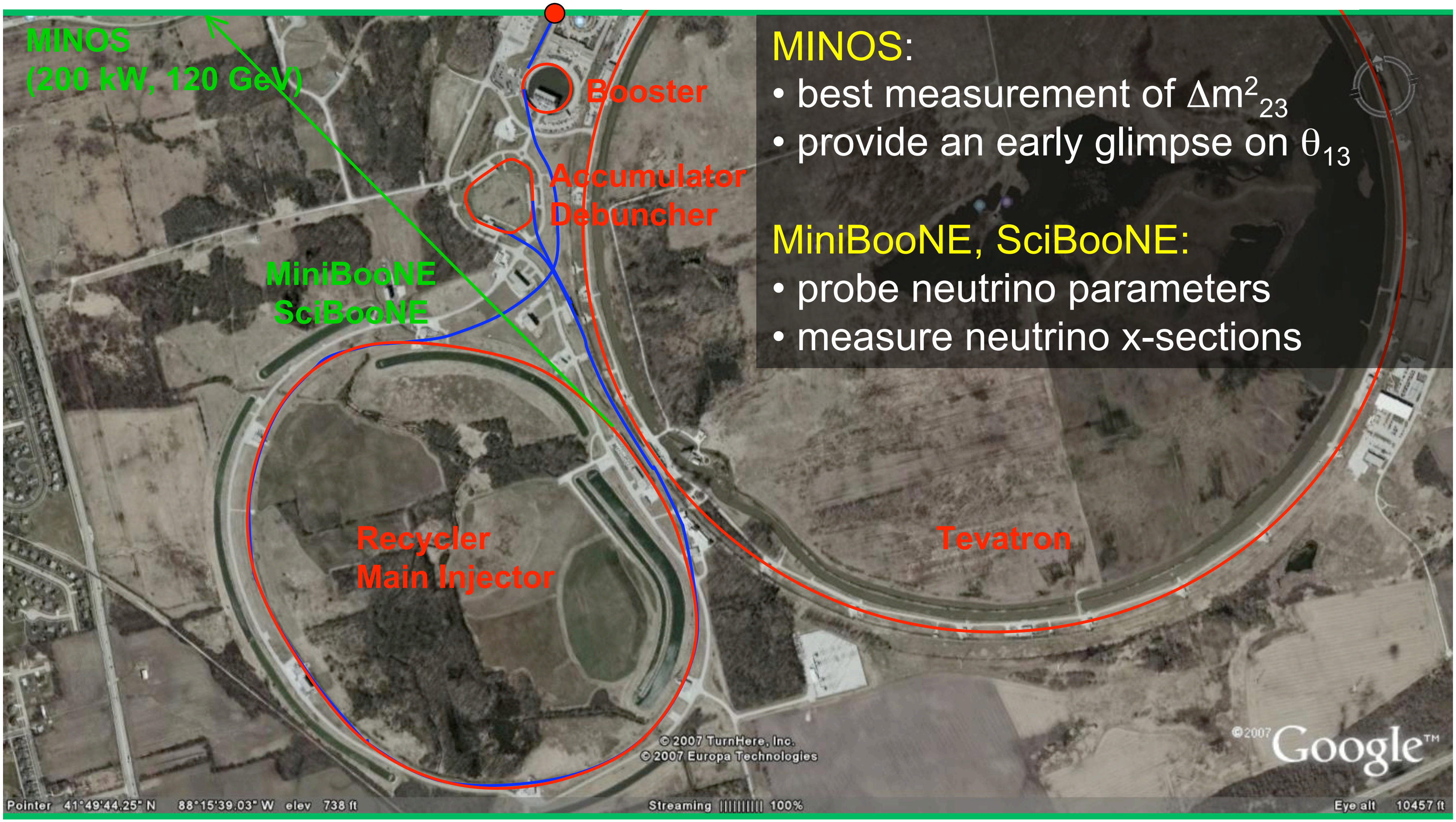
16 kW (NuMI-NOvA)

17 kW (NuMI-MINOS)

35-year-old injection (technical risk)

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

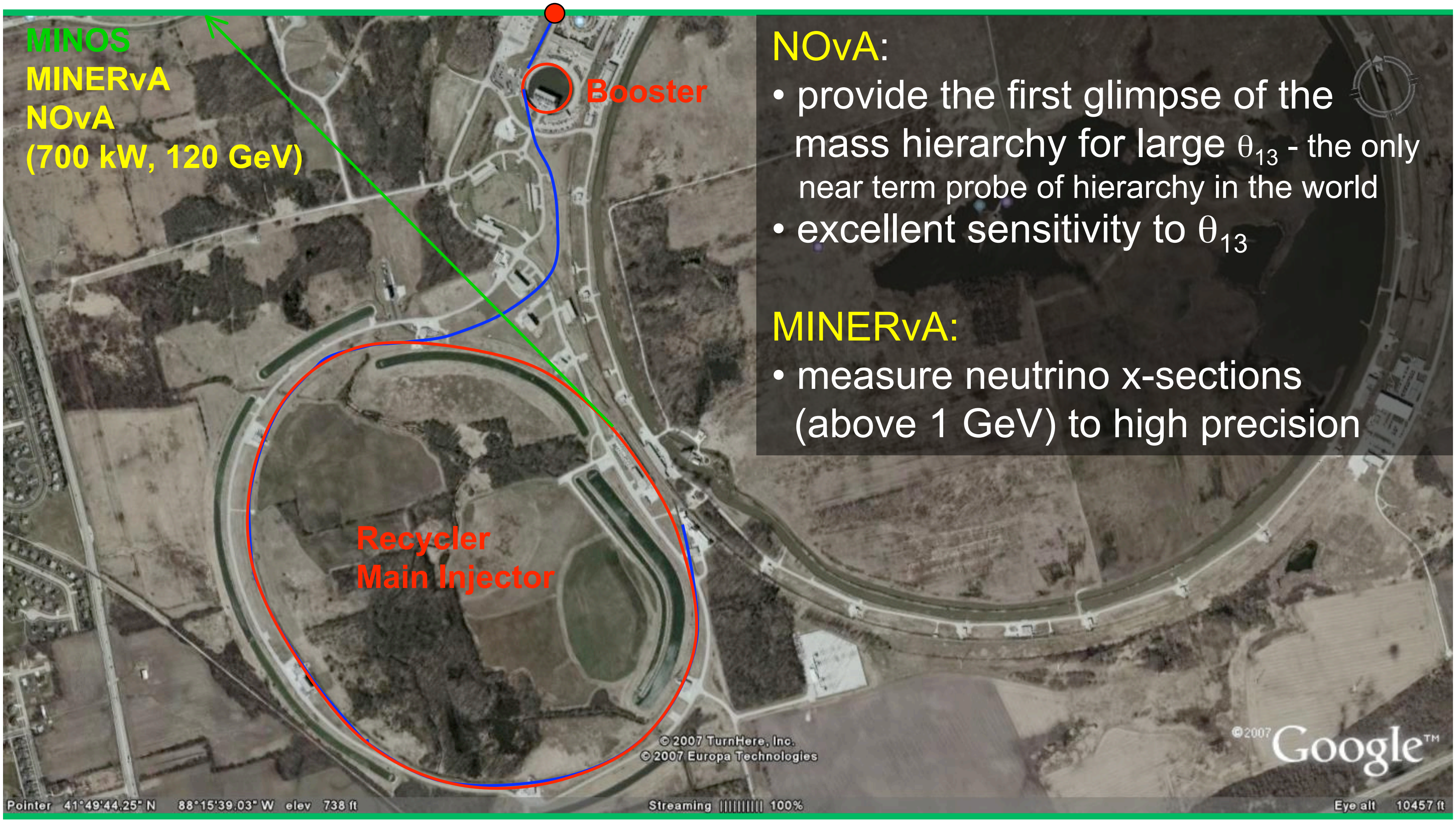
Present:



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:

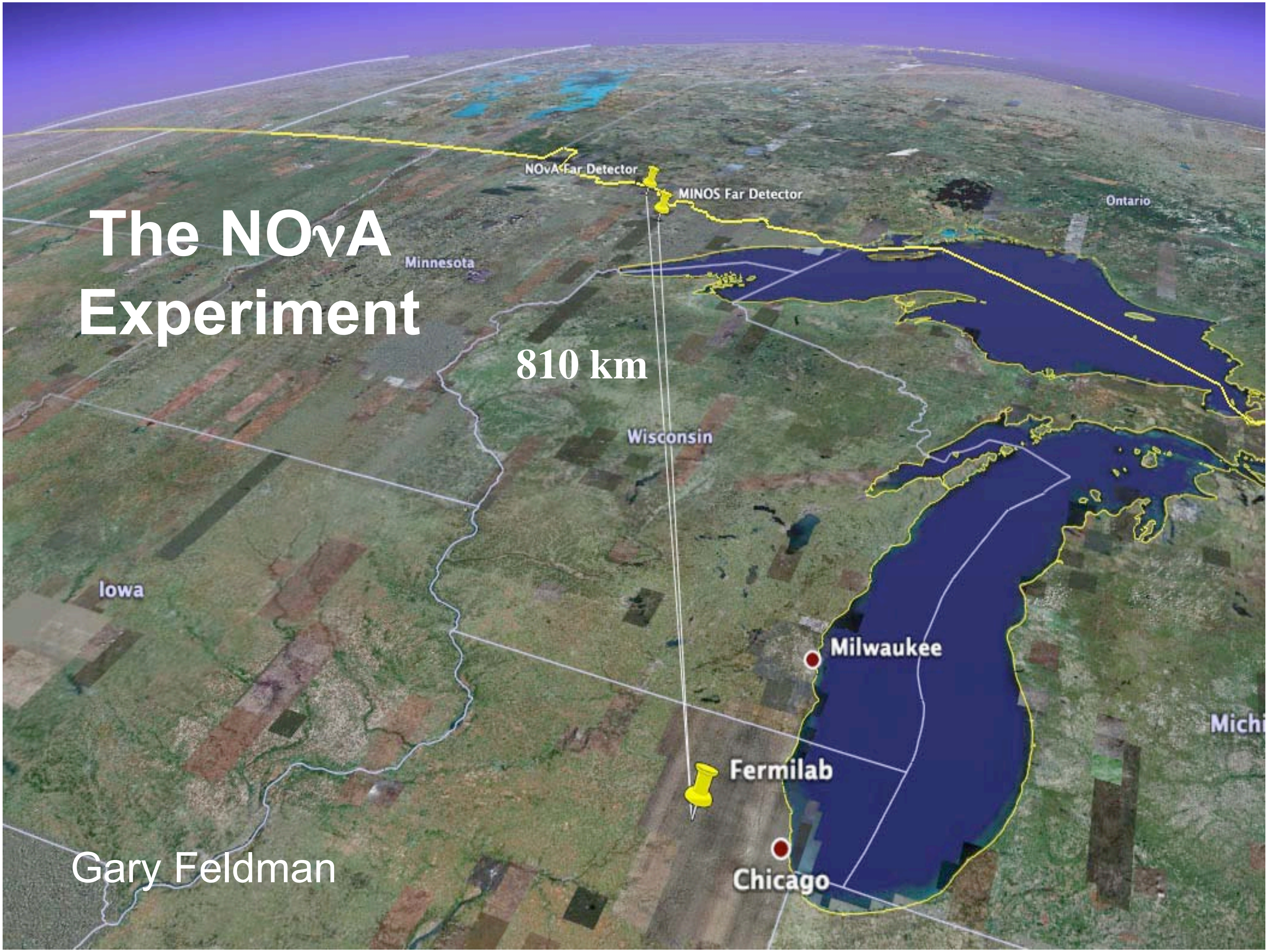
- provide the first glimpse of the mass hierarchy for large θ_{13} - the only near term probe of hierarchy in the world
- excellent sensitivity to θ_{13}

MINERvA:

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

The NOνA Experiment

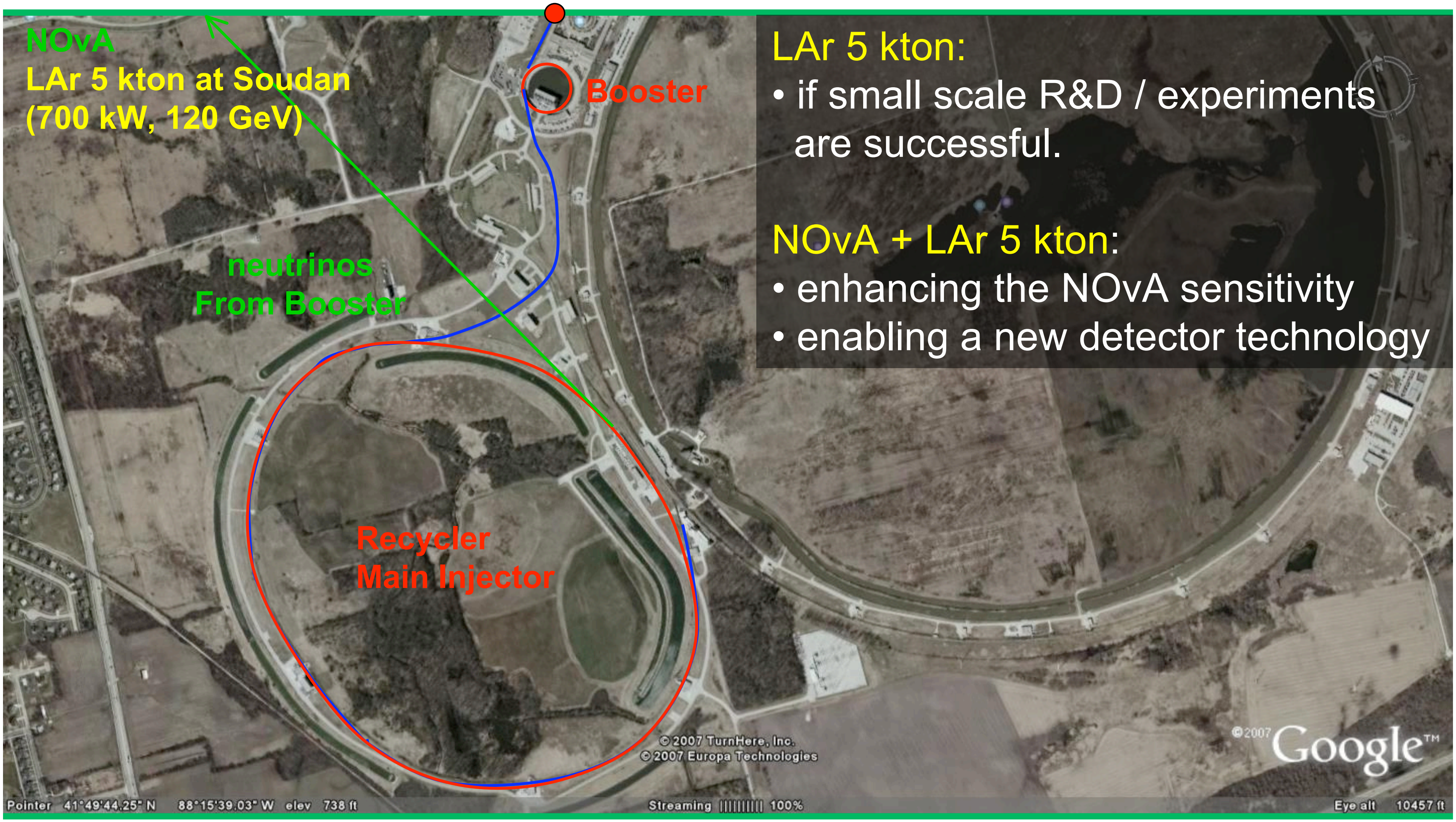
Gary Feldman



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:



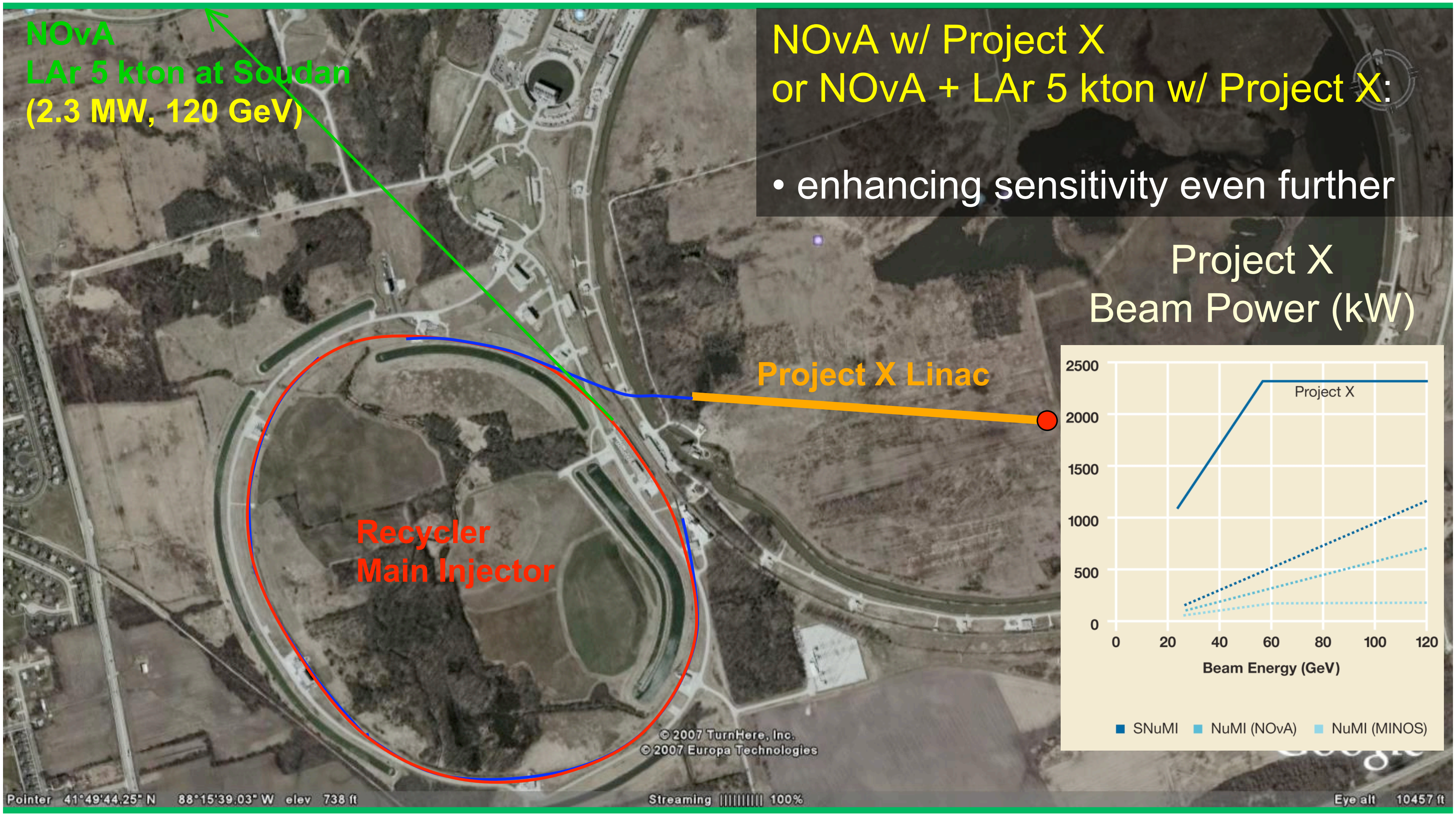
LAr 5 kton:

- if small scale R&D / experiments are successful.

NOvA + LAr 5 kton:

- enhancing the NOvA sensitivity
- enabling a new detector technology

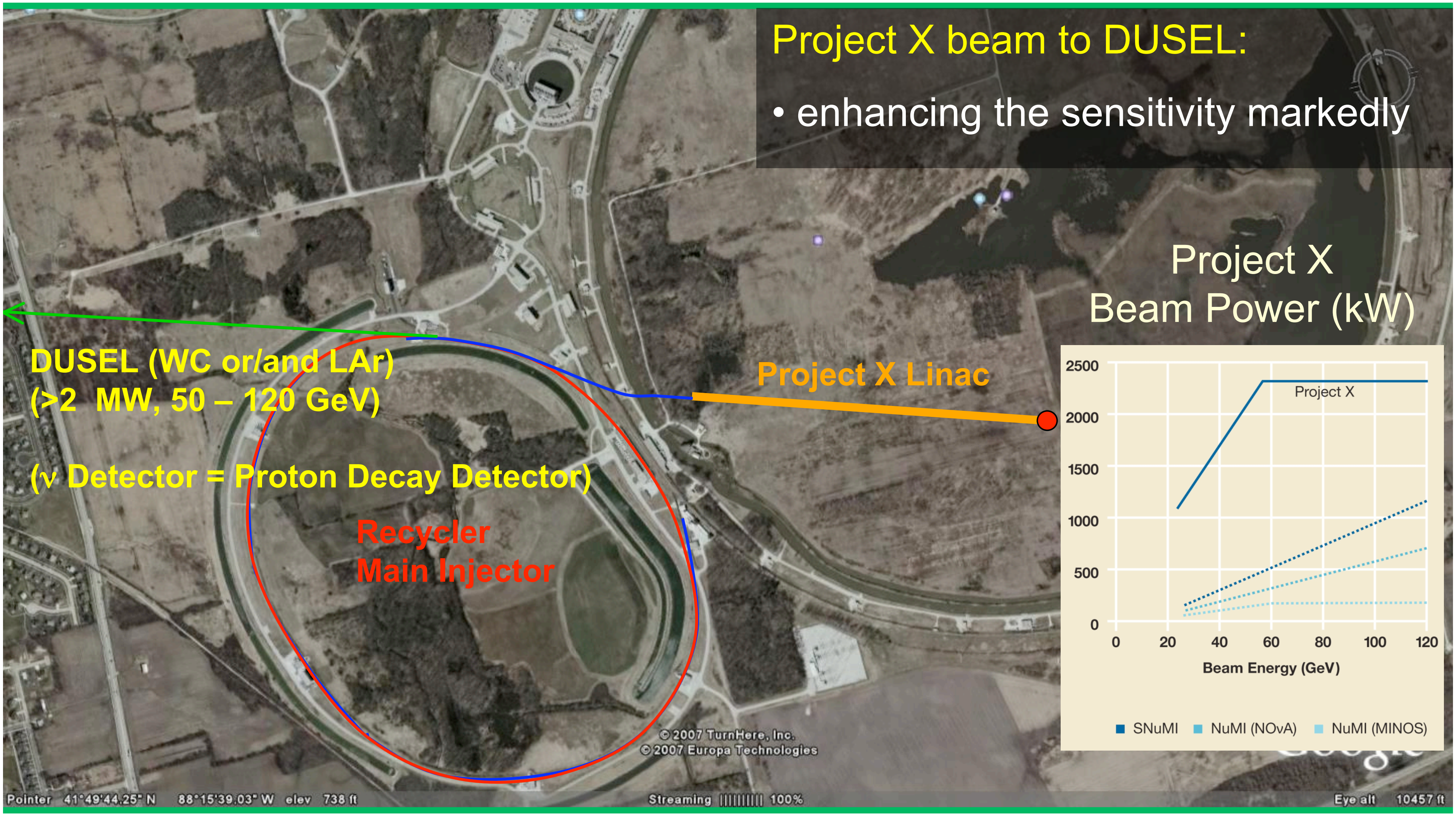
Phase 2:



NOvA w/ Project X
or NOvA + LAr 5 kton w/ Project X:

- enhancing sensitivity even further

Phase 3



Project X beam to DUSEL:

- enhancing the sensitivity markedly

DUSEL (WC or/and LAr)
(>2 MW, 50 – 120 GeV)

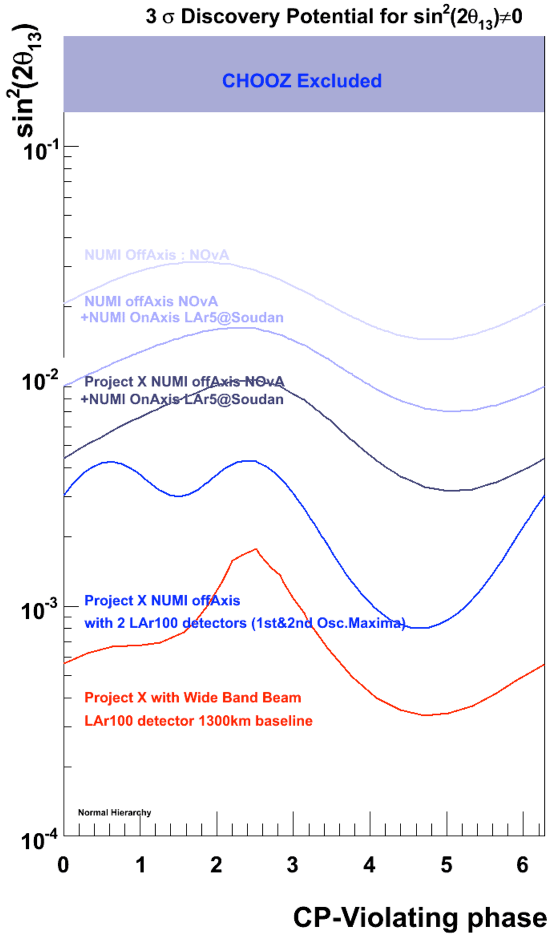
(ν Detector = Proton Decay Detector)

Project X
Beam Power (kW)

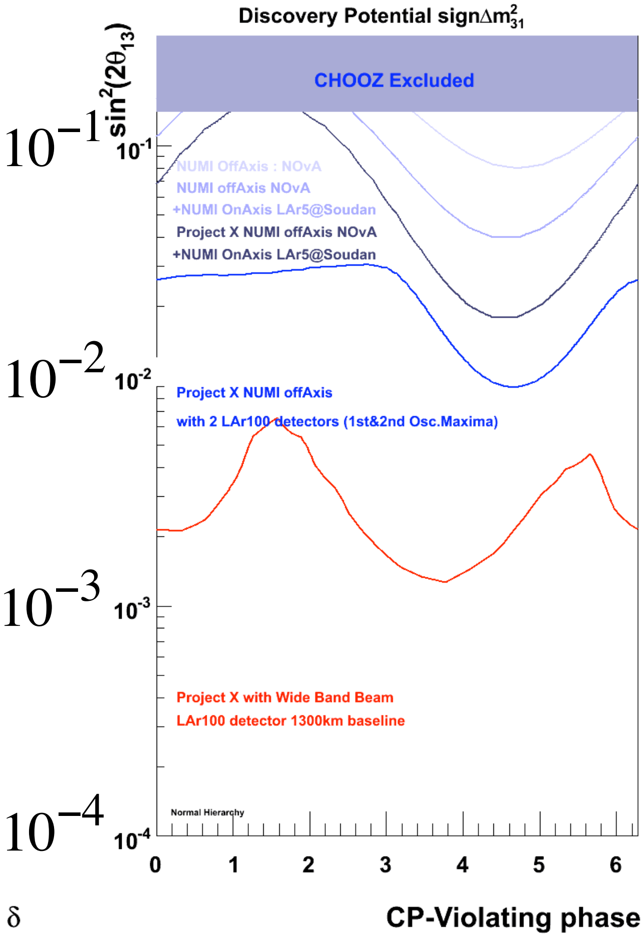
Y-K Kim

The 3σ Reach of the Successive Phases

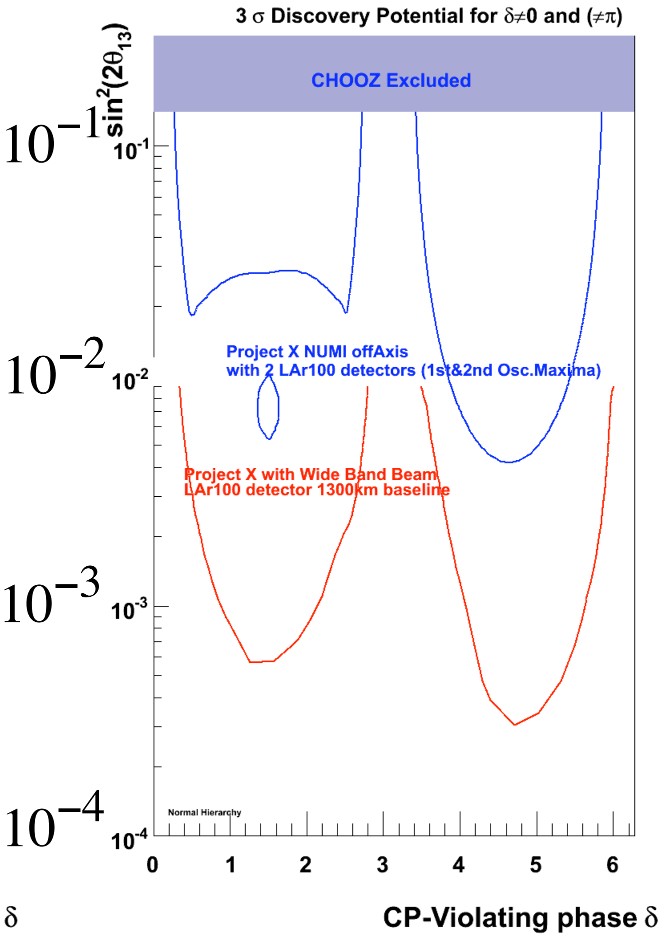
$\sin^2 2\theta_{13}$



Mass Ordering

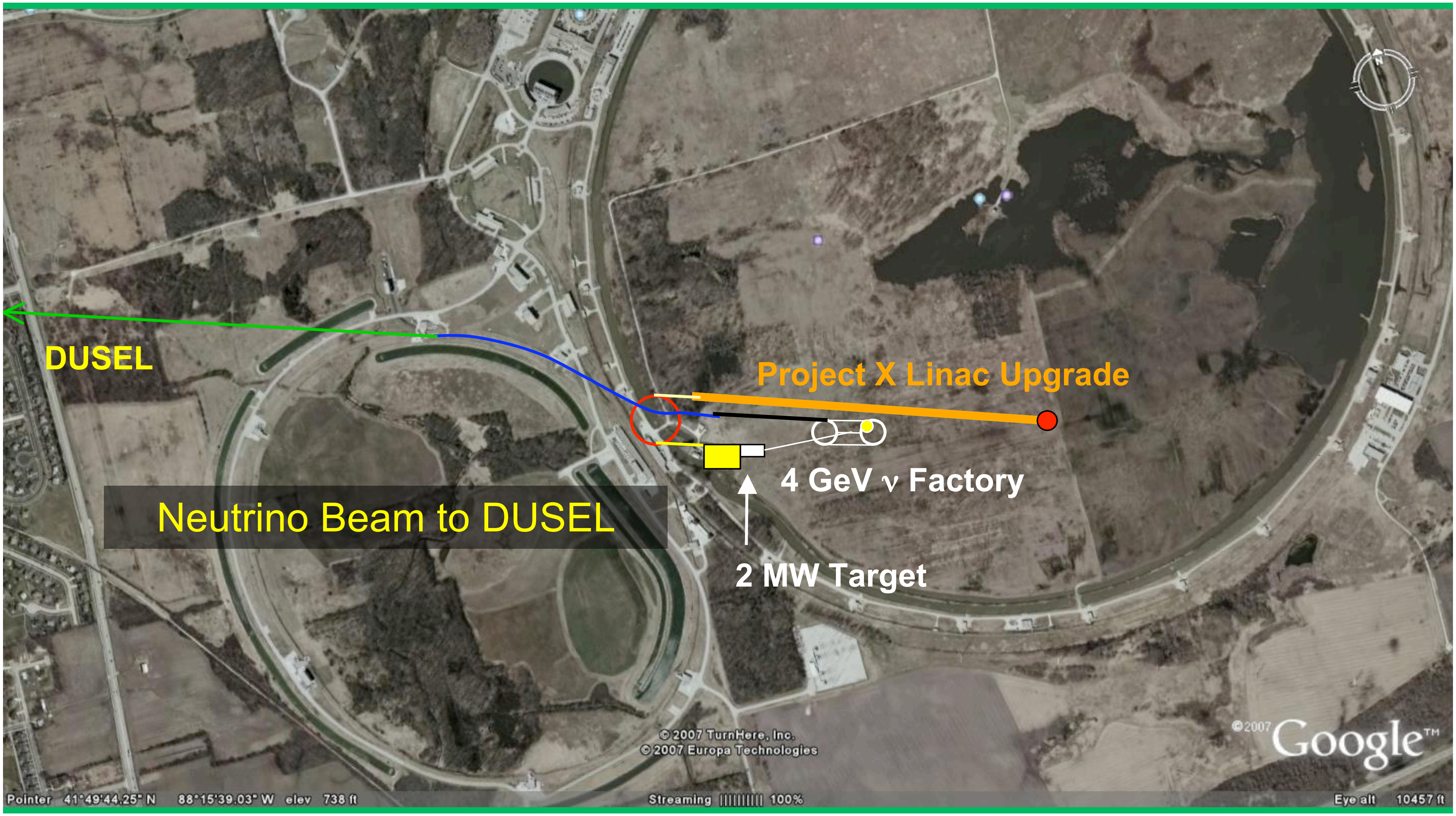


CP Violation



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.