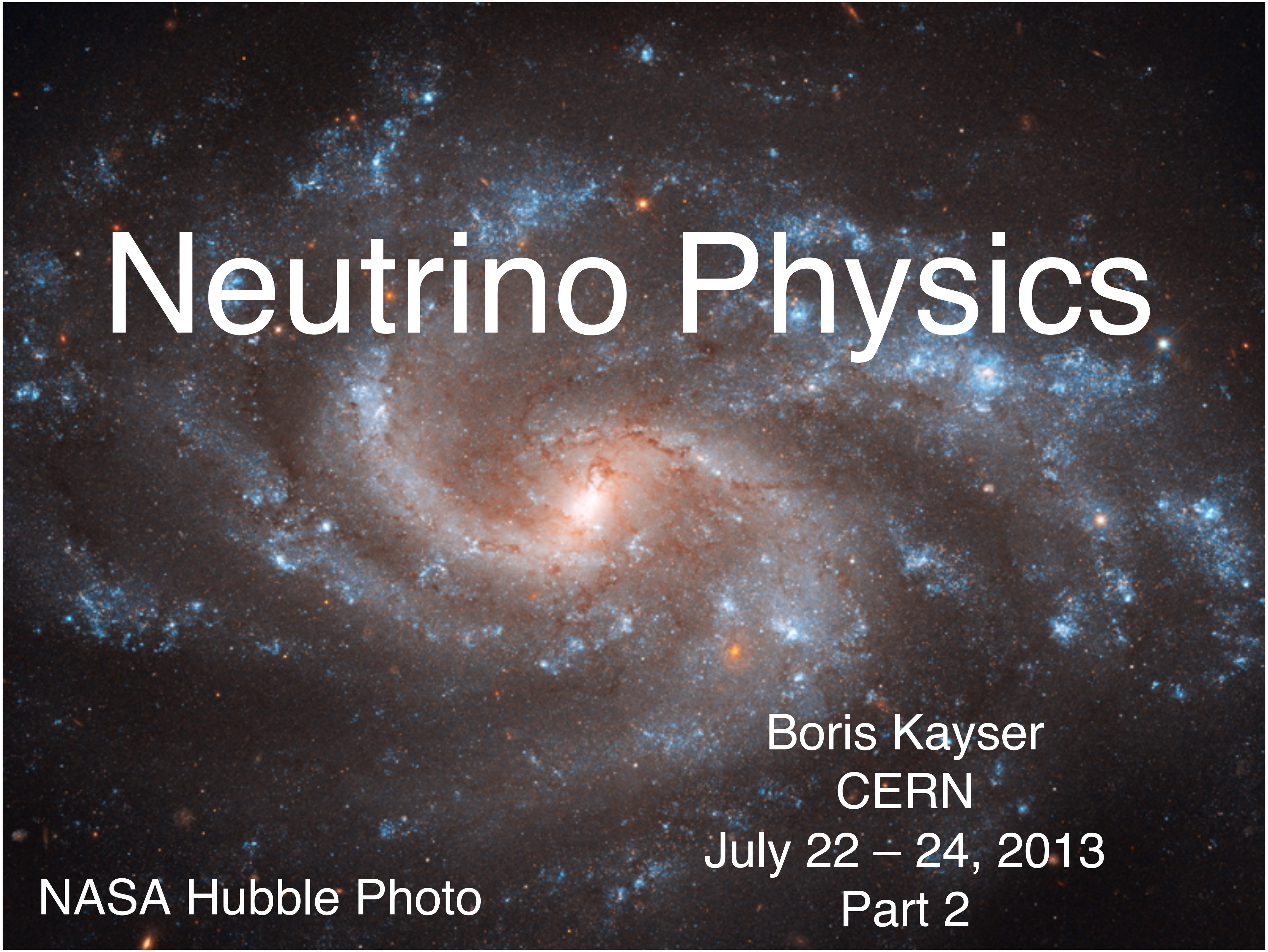
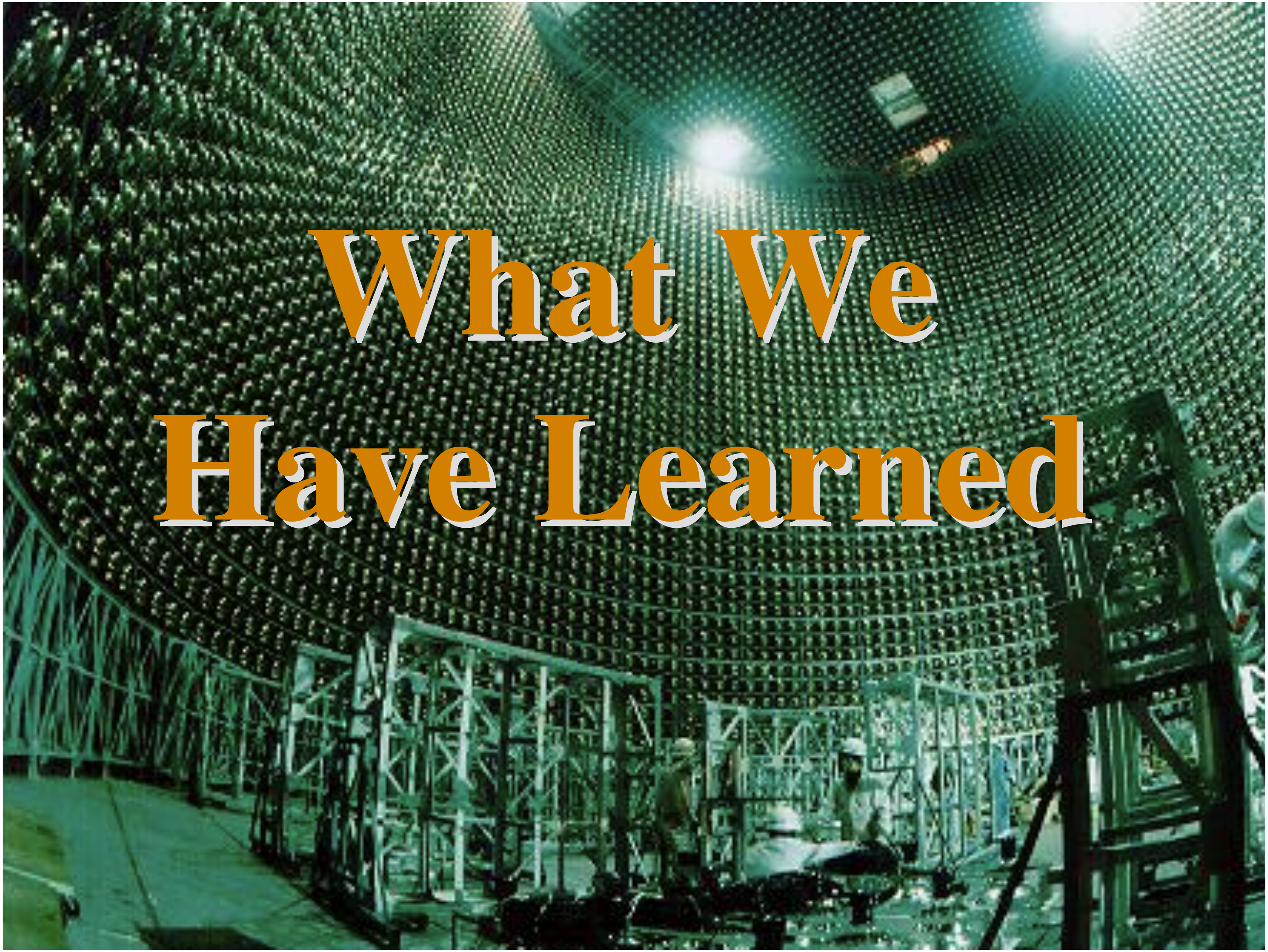


Neutrino Physics

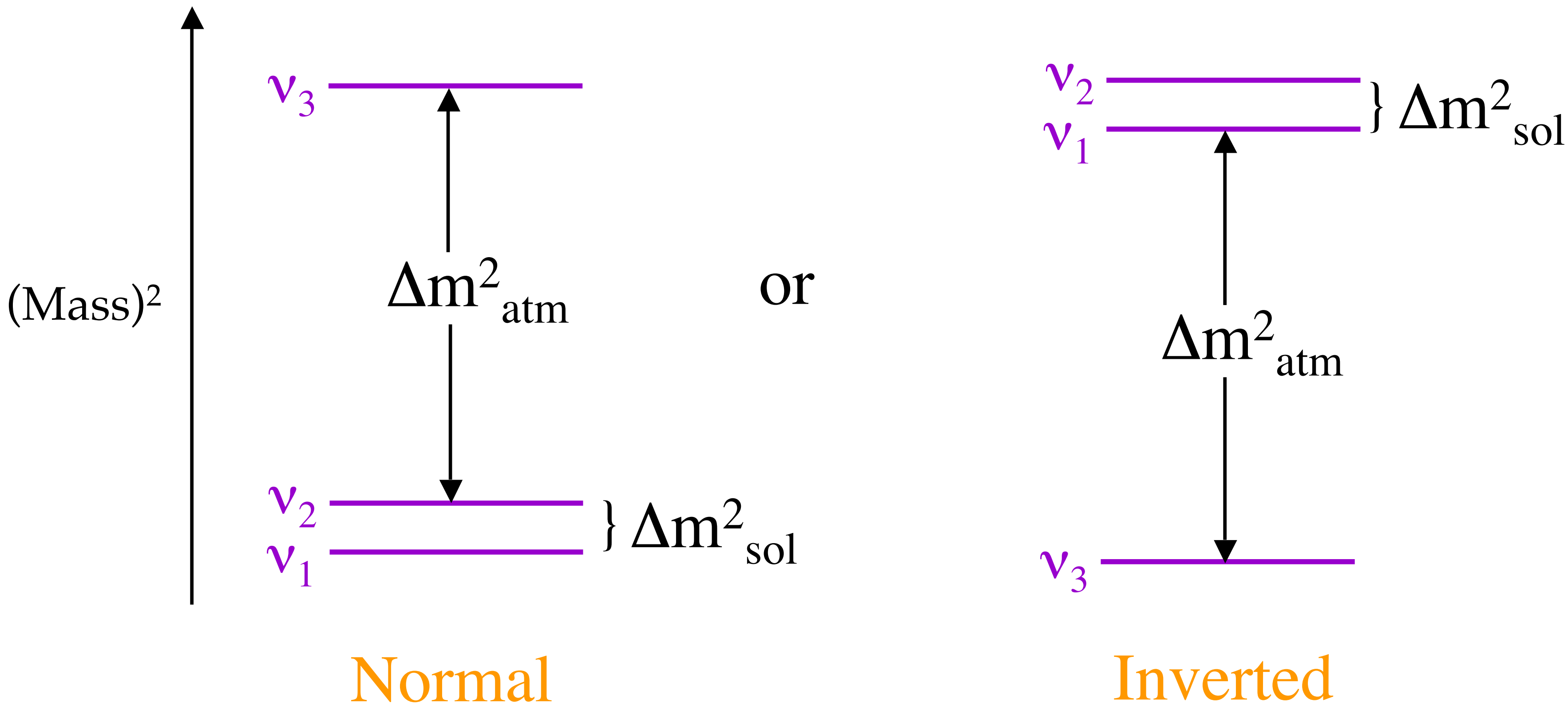
Boris Kayser
CERN
July 22 – 24, 2013
Part 2

NASA Hubble Photo

What We Have Learned



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



$\Delta m^2_{sol} \cong 7.5 \times 10^{-5}\ eV^2$, $\Delta m^2_{atm} \cong 2.4 \times 10^{-3}\ eV^2$

The Mixing Matrix *U*

Atmospheric — Reactor (L ~ 1 km) — Solar

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

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

Does not affect oscillation

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

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

Note big mixing!

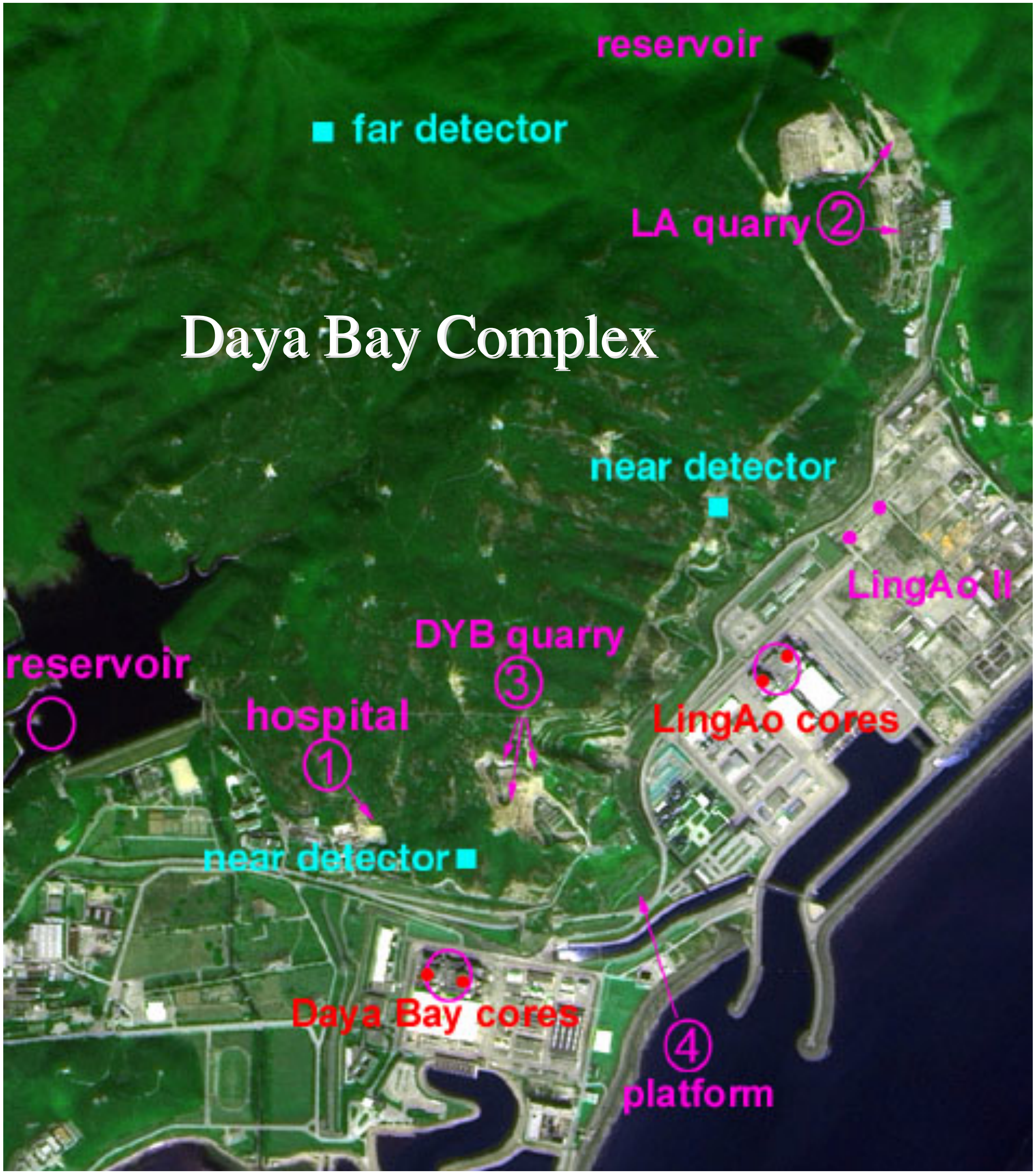
$\theta_{12} \approx 33°$, $\theta_{23} \approx$ 36-42° or 48-54°, $\theta_{13} \approx$ 8-9° *No more worry!*

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

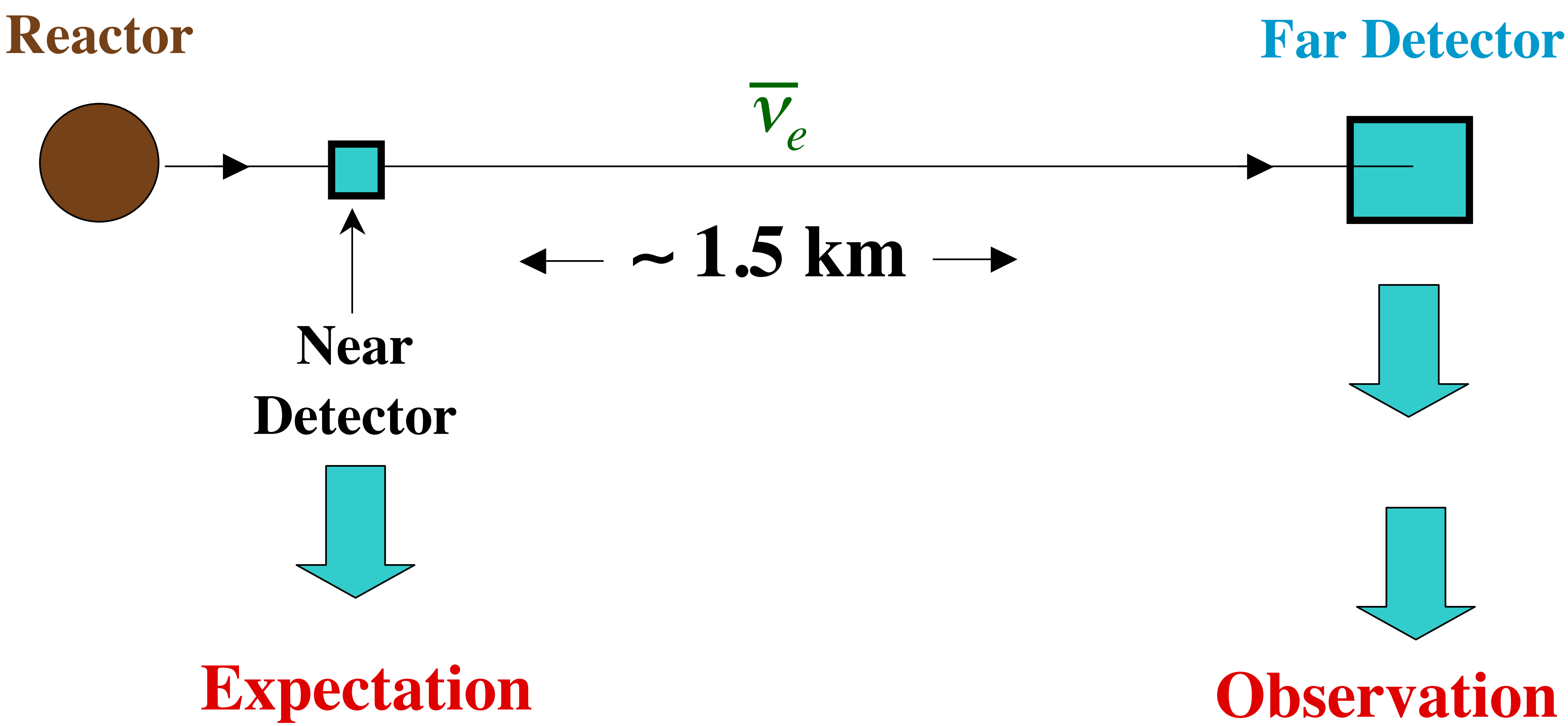
But note the crucial role of $s_{13} \equiv \sin\theta_{13}$.

θ_{13}
was recently
determined by
the Daya Bay,
RENO,
and Double CHOOZ
reactor neutrino
experiments,
and by the T2K*
accelerator neutrino
experiment.

*Most recent results
last Friday



The Reactor – Neutrino Experiments



Reactor $\overline{\nu}_e$ have $E \sim 3$ MeV, so if $L \sim 1.5$ km,

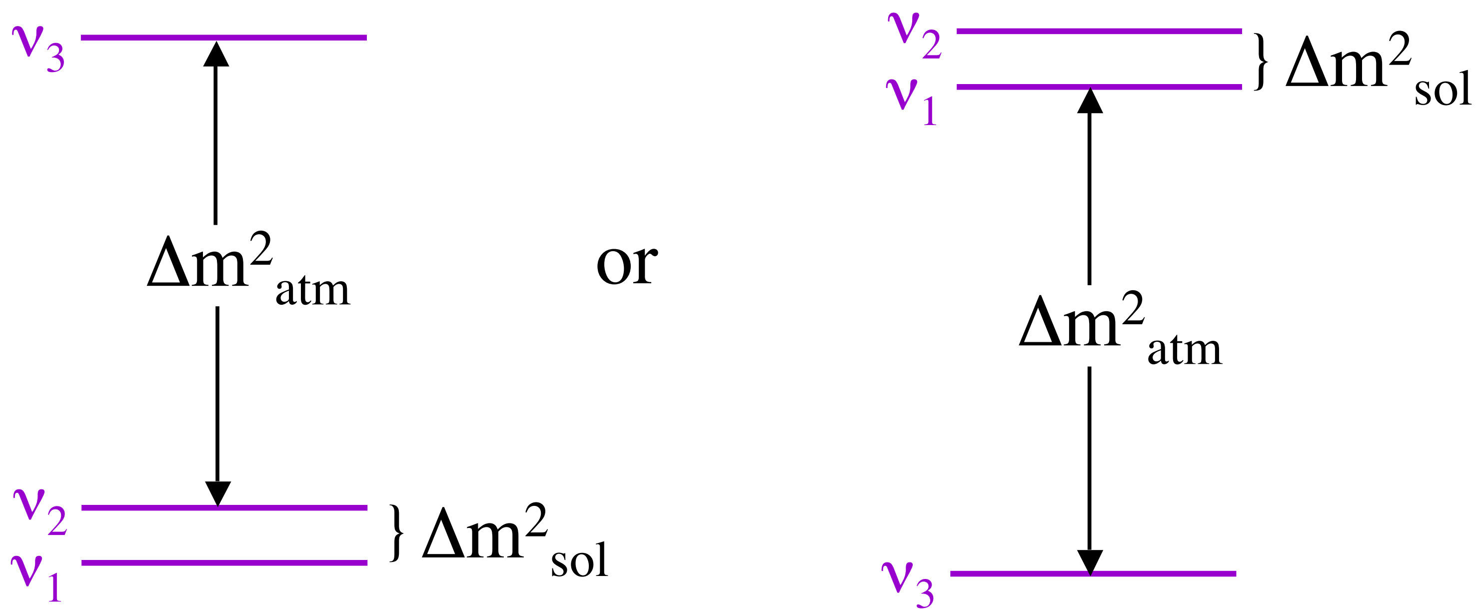
$\sin^2\left[1.27\Delta m^2 \frac{L(\text{km})}{E(\text{GeV})}\right]$ will be sensitive to —

$$\Delta m^2 = \Delta m^2_{\text{atm}} = 2.4 \times 10^{-3}\text{eV}^2 \approx \frac{1}{400}\text{eV}^2$$

but not to —

$$\Delta m^2 = \Delta m^2_{\text{sol}} = 7.5 \times 10^{-5}\text{eV}^2 \approx \frac{1}{13{,}000}\text{eV}^2 .$$

In —



the solar splitting is invisible. Then —

$$P(\bar{\nu}_e \rightarrow \bar{\nu}_e) \cong 1 - 4|U_{e3}|^2\left(1 - |U_{e3}|^2\right)\sin^2\left[1.27\Delta m^2_{atm}\frac{L(\text{km})}{E(\text{GeV})}\right]$$

$$= 1 - \sin^2 2\theta_{13}\sin^2\left[1.27\Delta m^2_{atm}\frac{L(\text{km})}{E(\text{GeV})}\right]$$

There Is Nothing Special About θ_{13}

All mixing angles must be nonzero for $\not{CP}$ in oscillation.

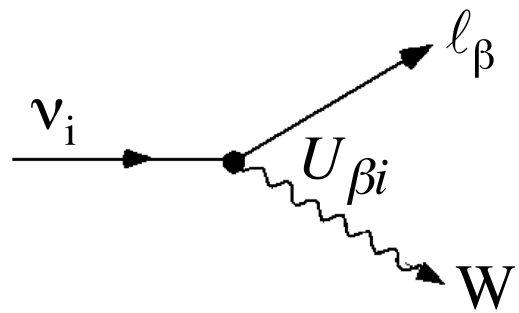
For example —

$$P(\bar{\nu}_\mu \to \bar{\nu}_e) - P(\nu_\mu \to \nu_e) = 2\cos\theta_{13}\sin 2\theta_{13}\sin 2\theta_{12}\sin 2\theta_{23}\sin\delta$$

$$\times \sin\left(\Delta m^2{}_{31}\frac{L}{4E}\right)\sin\left(\Delta m^2{}_{32}\frac{L}{4E}\right)\sin\left(\Delta m^2{}_{21}\frac{L}{4E}\right)$$

In the factored form of U, one can put δ next to θ_{12} instead of θ_{13}.

The Meaning of the Mixing Matrix Elements

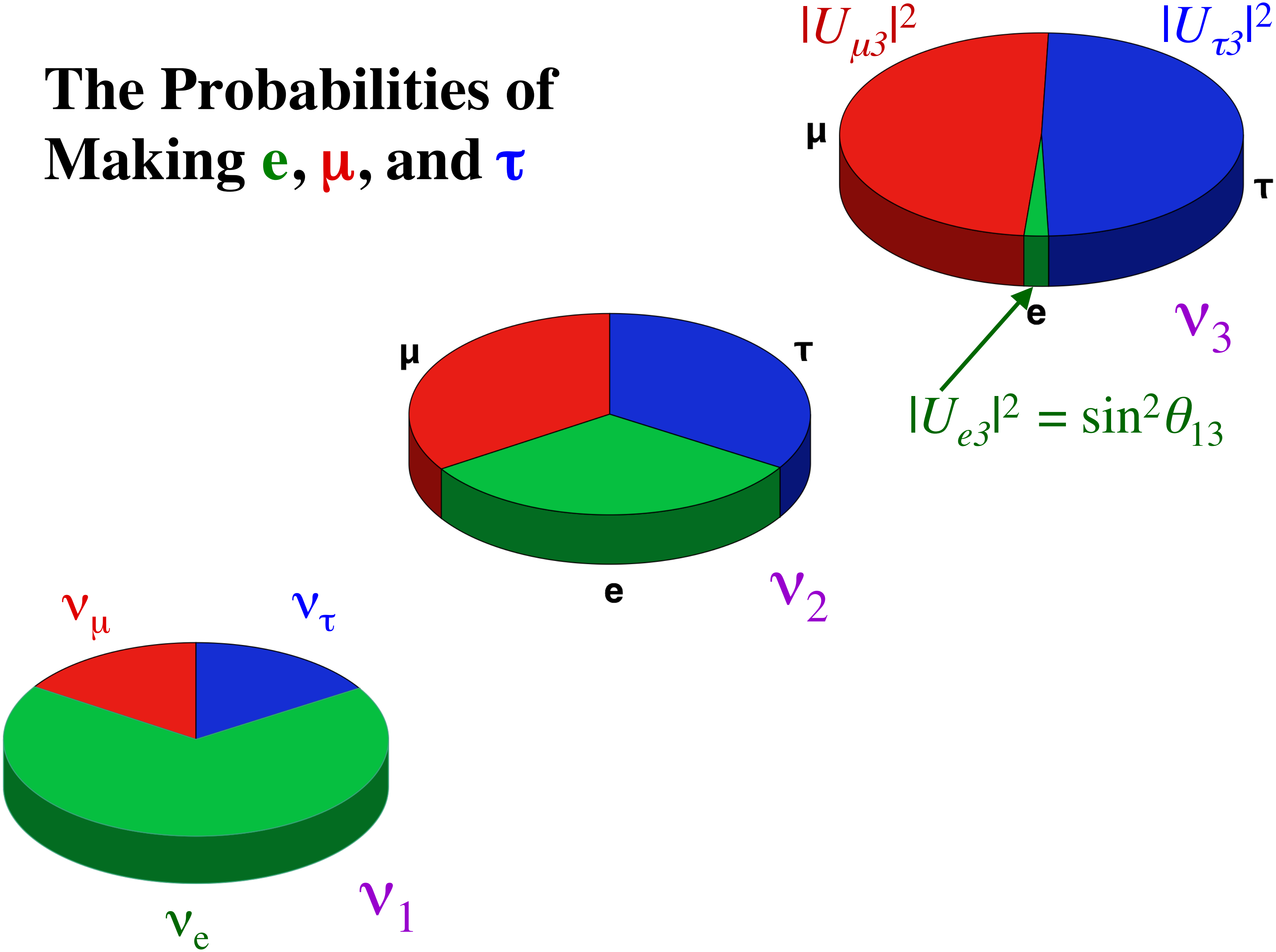


means that when a ν_i creates a charged lepton, the probability that this charged lepton will be, in particular, of flavor β is —

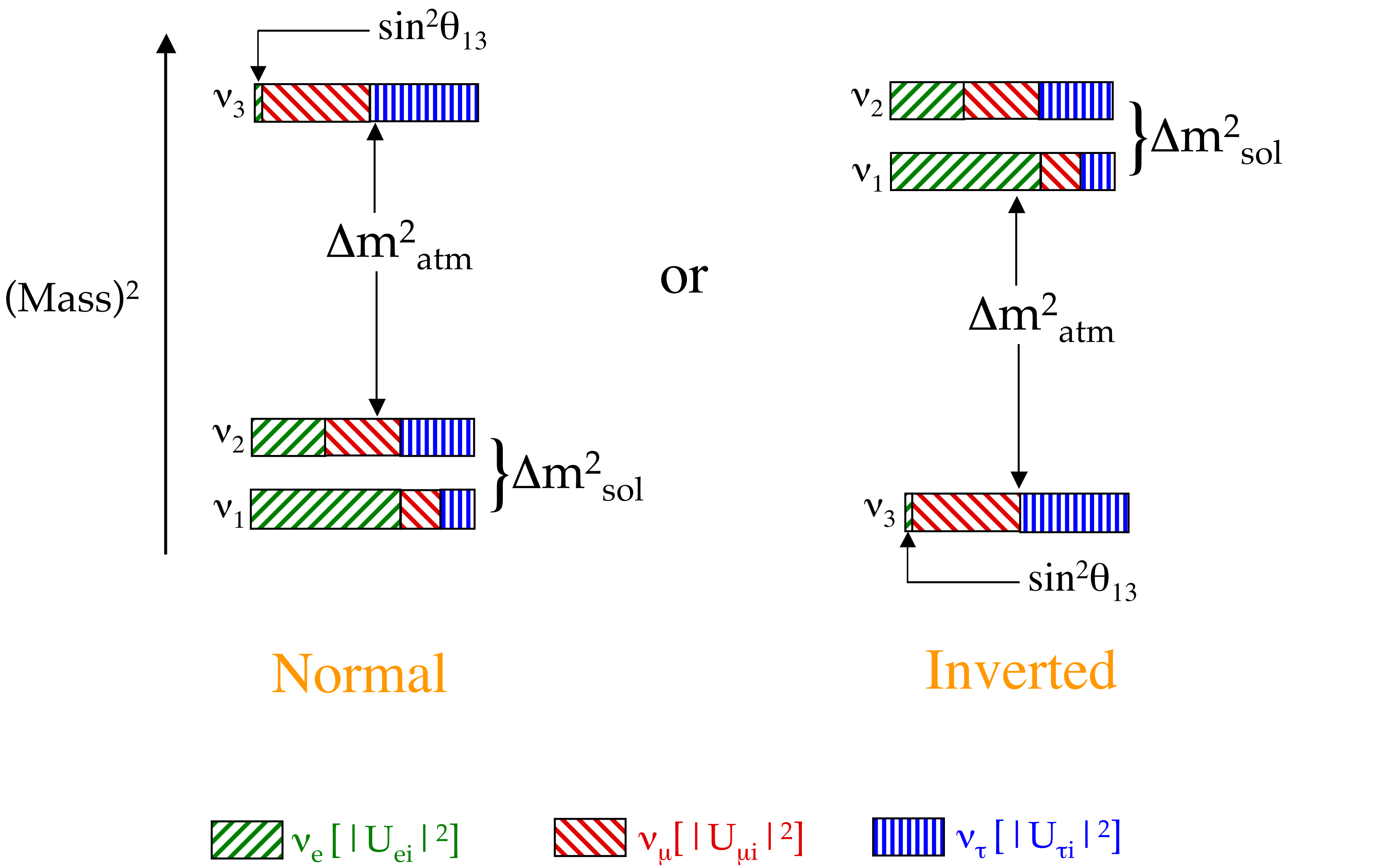
$$\left|U_{\beta i}\right|^2$$

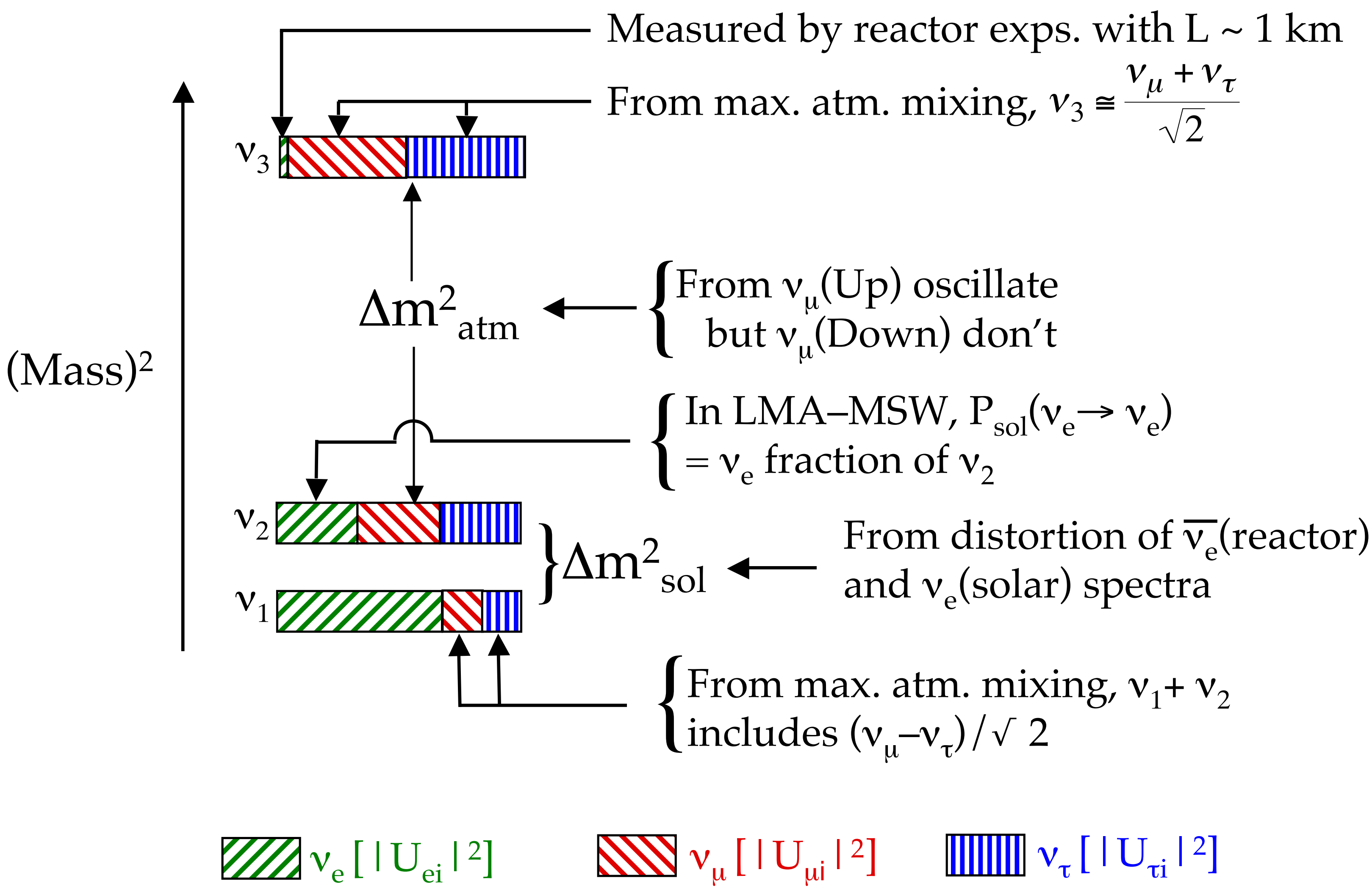
From the measured mixing angles —

The Probabilities of Making e, μ, and τ



A linear version of the same information is —





Measured by reactor exps. with L ~ 1 km
From max. atm. mixing, $\nu_3 \cong \frac{\nu_\mu + \nu_\tau}{\sqrt{2}}$
ν_3
Δm^2_{atm}
From ν_μ(Up) oscillate but ν_μ(Down) don't
(Mass)^2
In LMA–MSW, $P_{sol}(\nu_e \rightarrow \nu_e)$ = ν_e fraction of ν_2
ν_2
Δm^2_{sol}
From distortion of $\overline{\nu_e}$(reactor) and ν_e(solar) spectra
ν_1
From max. atm. mixing, $\nu_1 + \nu_2$ includes $(\nu_\mu - \nu_\tau)/\sqrt{2}$
ν_e [$|U_{ei}|^2$]
ν_μ [$|U_{\mu i}|^2$]
ν_τ [$|U_{\tau i}|^2$]

Looking to the Future

The Open Questions

- What is the absolute scale of neutrino mass?

- Are neutrinos their own antiparticles?

- Are there ***more*** than 3 mass eigenstates?

- Are there non-weakly-interacting "sterile" neutrinos?

- What are the neutrino magnetic and electric dipole moments?

- How close to maximal (45^0) is θ_{23}?

- Is the spectrum like  or  ?

- Do neutrino interactions violate CP?

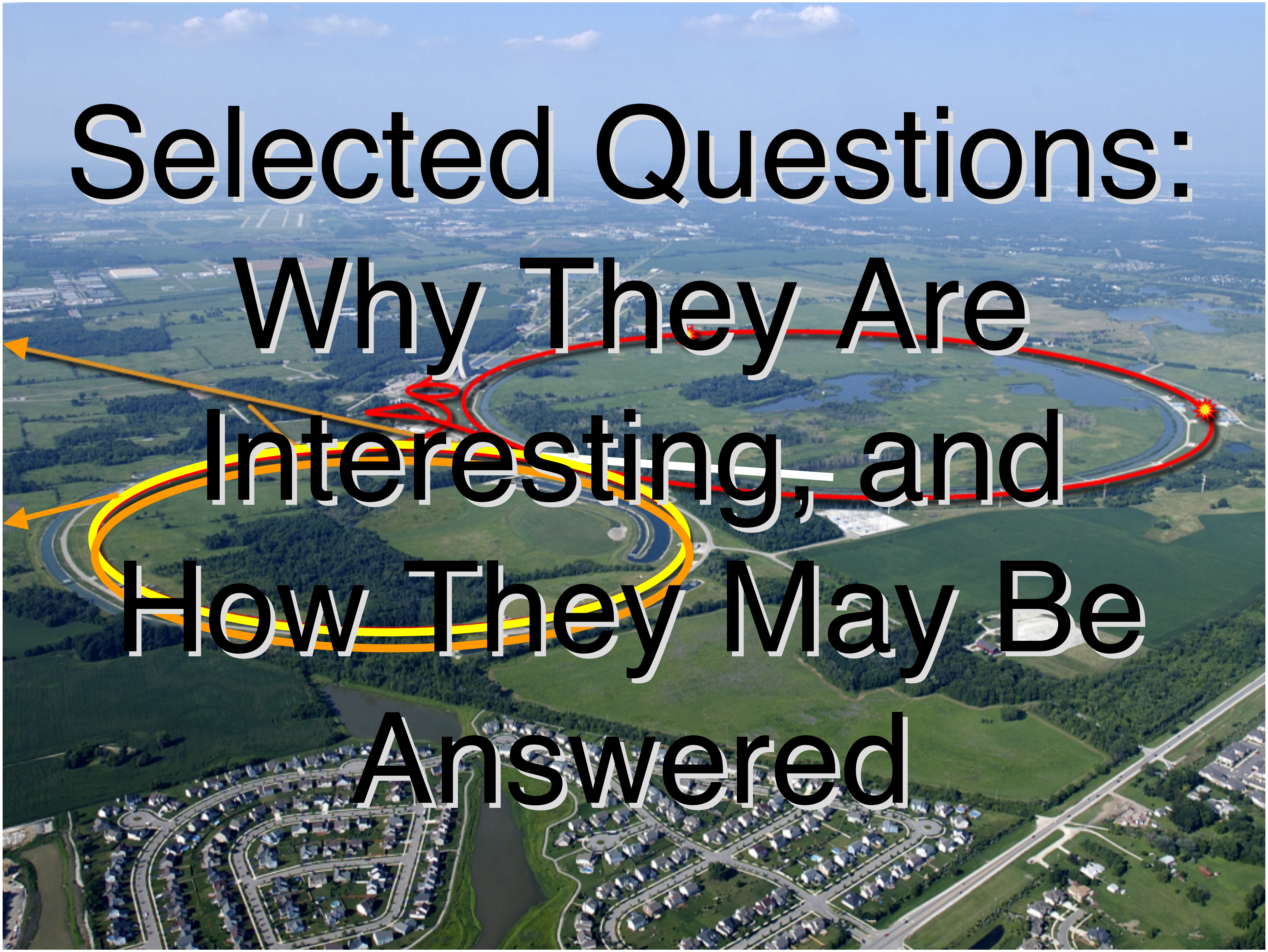
Is $P(\bar{\nu}_\alpha \rightarrow \bar{\nu}_\beta) \neq P(\nu_\alpha \rightarrow \nu_\beta)$?

- 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?

- Where does neutrino mass come from?

- What *surprises* are in store?


Selected Questions:
Why They Are
Interesting, and
How They May Be
Answered

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

What Is the Question?

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

(h ≡ $\overrightarrow{\text{Spin}} \bullet \widehat{\text{Momentum}}$), does —

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

or

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

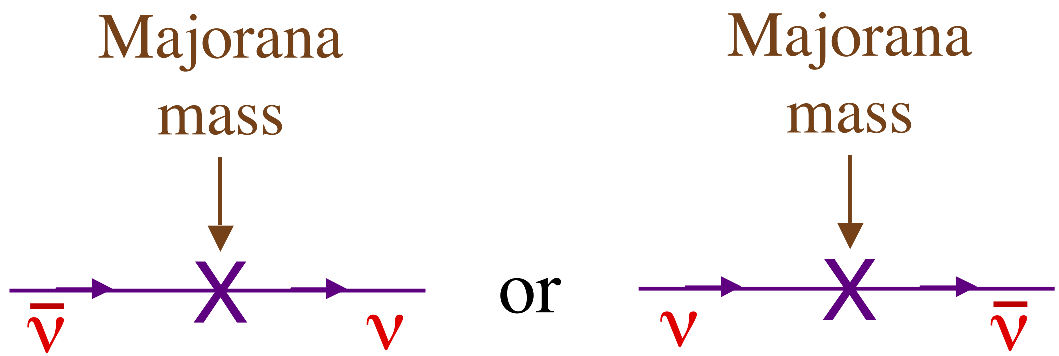
Equivalently, do neutrinos have *Majorana masses*? If they do, then the mass eigenstates are *Majorana neutrinos*.

Majorana Masses

They are not what you normally think of when you say the word "mass".

We start with neutrino states ν and $\bar{\nu}$ that are not mass eigenstates and are distinct from each other.

The effect of the Majorana masses:



Majorana masses mix ν and $\bar{\nu}$, so they do not conserve the Lepton Number L that distinguishes leptons from antileptons:

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

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, because —**

Majorana neutrino masses have a different origin than the quark and charged-lepton masses.

Fermion Masses Without Field Theory

According to the Standard Model —

Quark and charged lepton masses arise from an interaction with the Higgs field.

Neutrino masses ***could*** arise in the same way.

But not ***Majorana*** neutrino masses.

Majorana neutrino masses are from physics way outside the Standard Model.

A ***Majorana*** neutrino mass can arise
without interaction with any Higgs field,

— or through interaction with a Higgs-like field
which is not in the Standard Model,
and carries a different value of the "weak isospin"
quantum number than the Standard Model Higgs,

— or through interaction with the Standard Model Higgs,
but not the same kind of interaction
as would generate the quark masses.

***The study of neutrino masses is part of the quest
to understand the*** *origins* ***of all mass.***

Why Majorana Masses ➡ Majorana Neutrinos

As a result of $K^0 \longleftrightarrow \overline{K^0}$ mixing, the neutral K mass eigenstates are —

$$K_{S,L} \cong (K^0 \pm \overline{K^0})/\sqrt{2}\ . \qquad \overline{K_{S,L}} = K_{S,L}\ .$$

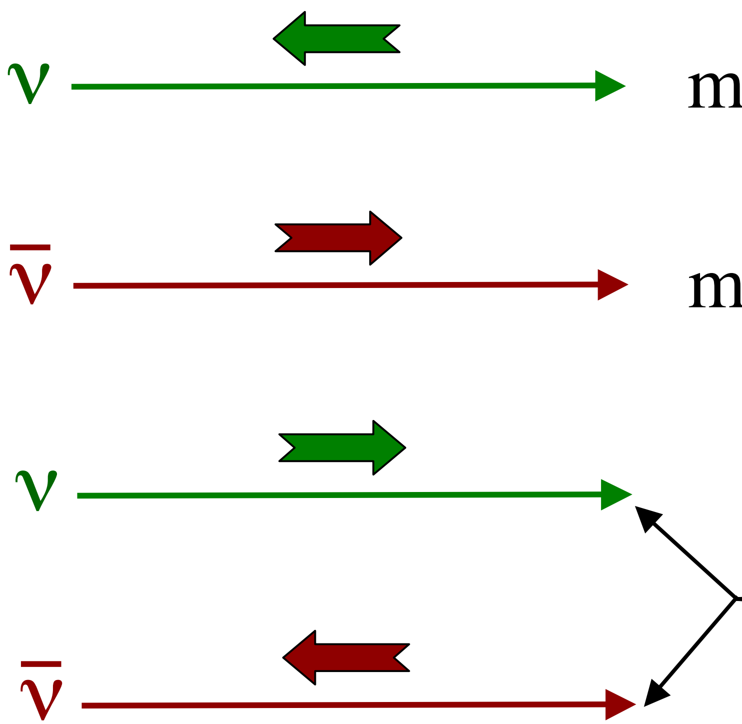
Majorana masses induce $\nu \longleftrightarrow \bar{\nu}$ mixing.

As a result of $\nu \longleftrightarrow \bar{\nu}$ mixing, the neutrino mass eigenstate is —

$$\nu_i = \nu + \bar{\nu}\ . \qquad \bar{\nu}_i = \nu_i\ .$$

SM Interactions Of A Dirac Neutrino

We have 4 mass-degenerate states:



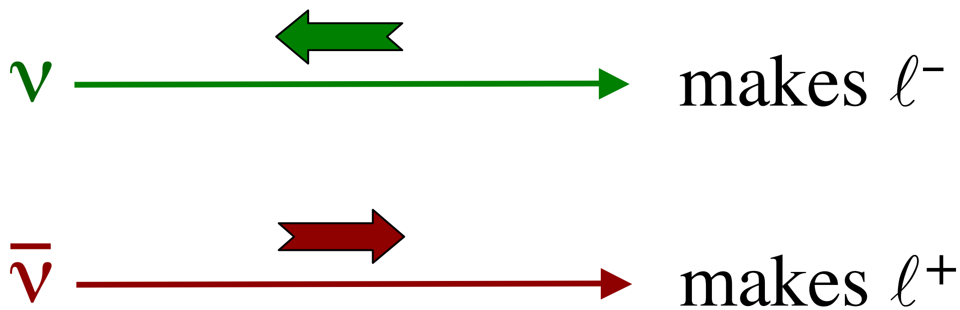
	Conserved L
ν makes ℓ^-	+1
$\bar{\nu}$ makes ℓ^+	–1

These states, when Ultra Rel., do not interact.

(The weak interaction is Left Handed.)

SM Interactions Of A Majorana Neutrino

We have only 2 mass-degenerate states:



The weak interactions violate *parity*.
(They can tell *Left* from *Right*.)

An incoming left-handed neutral lepton makes ℓ^-.

An incoming right-handed neutral lepton makes ℓ^+.

To Determine Whether Majorana Masses Occur in Nature

The Promising Approach — Seek

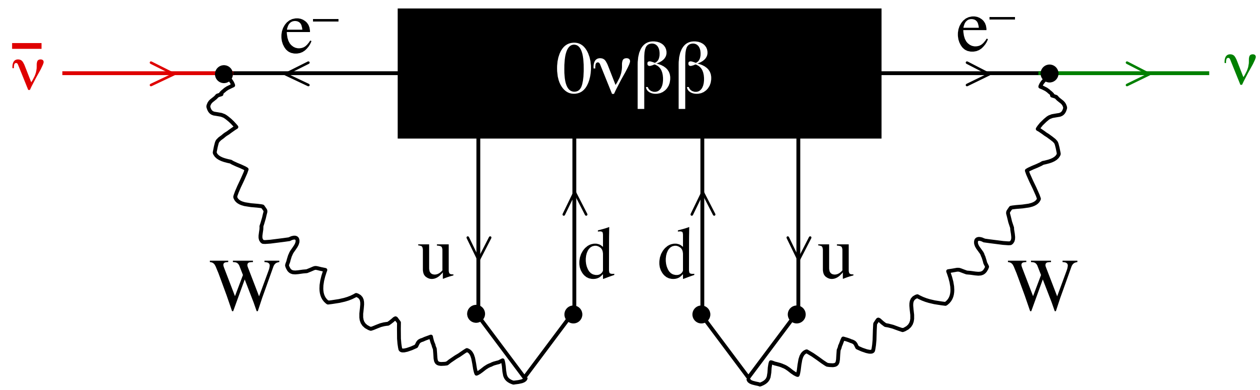
Neutrinoless Double Beta Decay [$0\nu\beta\beta$]

We are looking for a ***small*** Majorana neutrino mass. Thus, we will need ***a lot*** of parent nuclei (say, one ton of them).

Note that $0\nu\beta\beta$ violates conservation of lepton number L by $\Delta L = 2$.

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

(Schechter and Valle)



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

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


Do Neutrino Interactions
Violate CP?
Are we descended
from heavy neutrinos?

The Challenge — A Cosmic Broken Symmetry

The universe contains baryons (nucleons), but essentially no antibaryons.

$$\frac{n_B}{n_\gamma} = 6 \times 10^{-10} \quad ; \quad \frac{n_{\overline{B}}}{n_B} \sim 0\,(< 10^{-6})$$

Standard cosmology: Any initial baryon – antibaryon asymmetry would have been erased.

How did $n_{\overline{B}} = n_B$ ➡ $n_{\overline{B}} << n_B$?

Sakharov: $n_{\overline{B}} = n_B$ $\Rightarrow$ $n_{\overline{B}} << n_B$ requires $\not{CP}$.

The $\not{CP}$ in the quark mixing matrix, seen in B and K decays, leads to much too small a $B-\bar{B}$ asymmetry.

If ***quark*** $\not{CP}$ cannot generate the observed $B-\bar{B}$ asymmetry, can some scenario involving ***leptons*** do it?

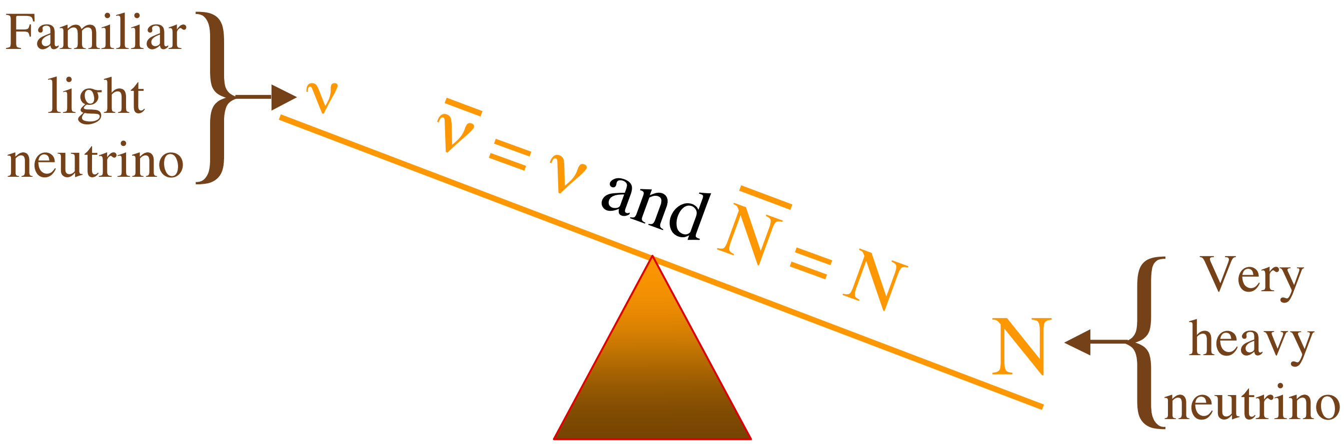
The candidate scenario: *Leptogenesis*.

(Fukugita, Yanagida)

Leptogenesis – A Two-Step Process

Leptogenesis is an outgrowth of the most popular theory of why neutrinos are so light —

The See-Saw Mechanism



$$M_\nu \propto 1/M_N$$

(***Yanagida; Gell-Mann, Ramond, Slansky; Mohapatra, Senjanovic; Minkowski***)

In standard leptogenesis, to account for the observed cosmic baryon – antibaryon asymmetry, ***and*** to explain the tiny light neutrino masses, we must have —

$$m_N \sim 10^{(9-10)}\ \mathrm{GeV} \quad .$$

This puts the heavy neutrinos N far beyond LHC range.

But these heavy neutrinos would have been made in the ***hot*** Big Bang.

In the see-saw picture —

$$N \to \ell^{\mp} + H^{\pm} \quad \text{and} \quad N \to \overset{(-)}{\nu} + \overset{(\overline{\quad})}{H^0}$$

SM Higgs particle

Assume 3 heavy neutrinos N_i to match the number (3) of light lepton (ℓ_α, ν_α) families.

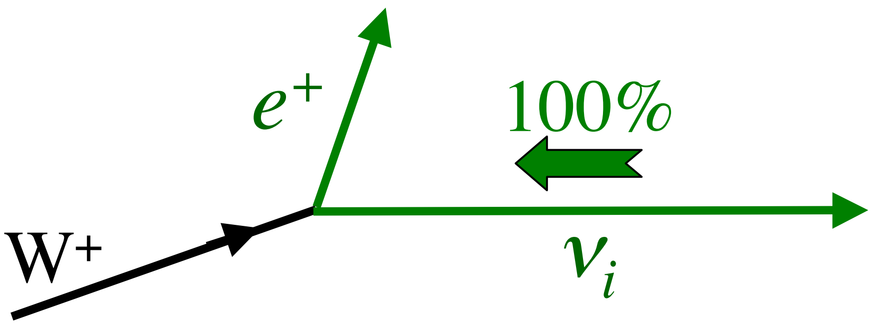
By SM weak-isospin symmetry —

$$\Gamma\left(N_i \to \ell_\alpha^- + H^+\right) = \Gamma\left(N_i \to \nu_\alpha + H^0\right)$$

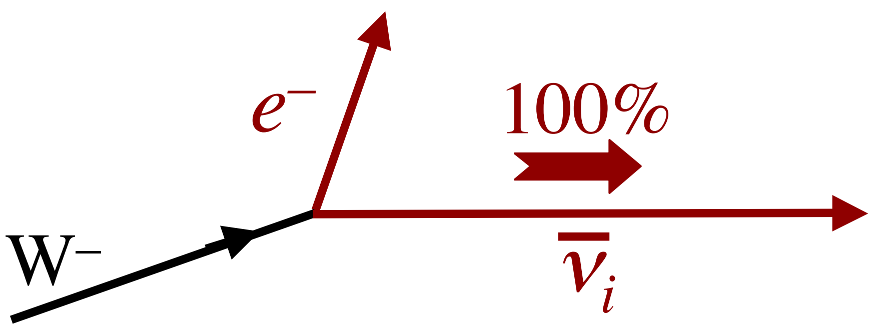
There are 3 × 3 = 9 independent "coupling constants" (lowest order decay amplitudes) $y_{\alpha i}$, forming a matrix y.

The decays $N \rightarrow \ell^{\mp} + H^{\pm}$ and $N \rightarrow \overset{(-)}{\nu} + \overset{(-)}{H^0}$ occur when the temperature $T \sim m_N$. When T >> 100 GeV, all particles are massless, except the N.

When the ν_i are massless, they are **100%** polarized.



and



whether the neutrinos are Dirac or Majorana.

This 100% polarization completely determines how the neutrinos will interact.

The distinction between Dirac and Majorana neutrinos has disappeared.

We will think of the light neutrinos as Dirac in what follows.

$\not{CP}$ phases in the matrix y will lead to —

$$\Gamma\left(N \to \ell^- + H^+\right) \neq \Gamma\left(N \to \ell^+ + H^-\right)$$

and

$$\Gamma\left(N \to \nu + H^0\right) \neq \Gamma\left(N \to \bar{\nu} + \overline{H^0}\right)$$

This produces a universe with unequal numbers of leptons (ℓ^- and ν) and antileptons (ℓ^+ and $\bar{\nu}$).

In this universe the lepton number L, defined by $L\left(\ell^-\right) = L(\nu) = -L\left(\ell^+\right) = -L(\bar{\nu}) = 1$, is not zero.

This is Leptogenesis — Step 1

Leptogenesis — Step 2

The Standard-Model ***Sphaleron*** process,
which does not conserve Baryon Number $B \equiv n_B - n_{\bar{B}}$,
or Lepton Number L, but does conserve $B - L$, acts.

$$B_i = 0$$
$$L_i \neq 0$$

Initial state from N decays

→ **Sphaleron Process** →

$$B_f \cong -\frac{1}{3} L_i$$
$$L_f \cong \frac{2}{3} L_i \cong -2B_f$$

Final state

There is now a nonzero Baryon Number.

There are baryons, but ~ no antibaryons.

Reasonable parameters give the observed n_B / n_γ .

Generically, leptogenesis and light-neutrino ~~CP~~ imply each other.

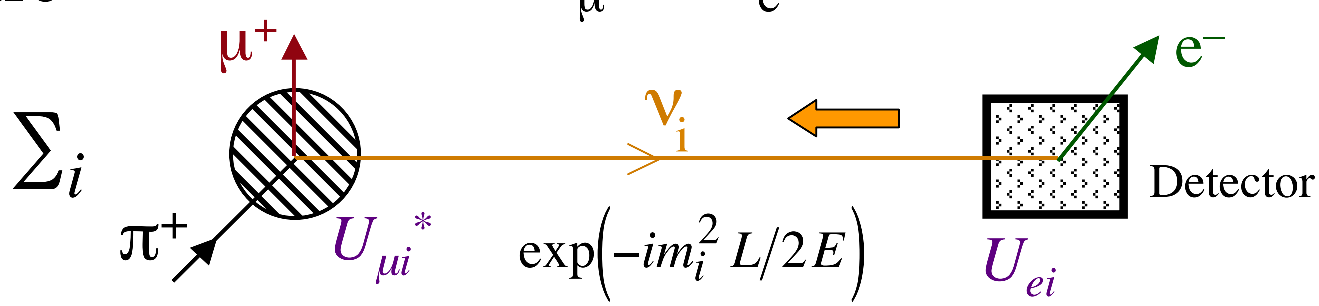
Seeking ~~CP~~ in neutrino oscillation is now a worldwide goal.

The search will use long-baseline accelerator neutrino beams to study $\nu_\mu \rightarrow \nu_e$ and $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$, or their inverses.

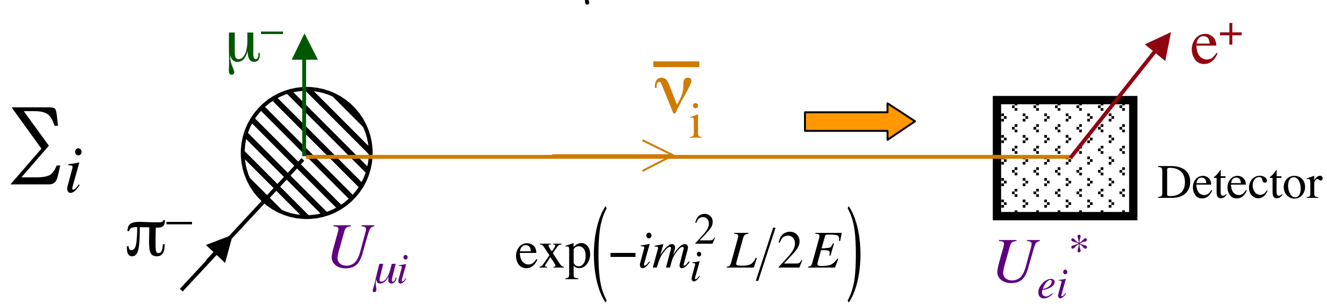
Q : *Can CP violation still lead to*
$\mathcal{P}(\bar{\nu}_\mu \to \bar{\nu}_e) \neq \mathcal{P}(\nu_\mu \to \nu_e)$ *when* $\bar{\nu} = \nu$*?*

A : *Certainly!*

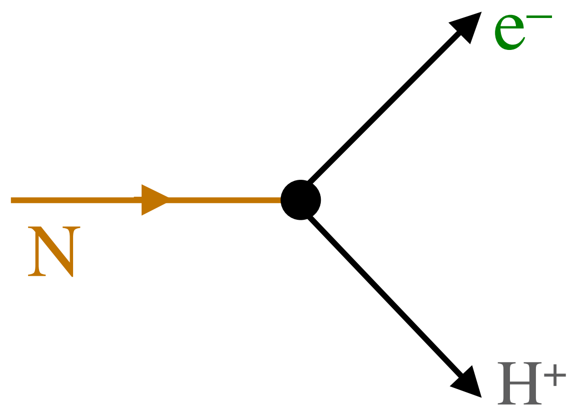
Compare $\nu_\mu \to \nu_e$



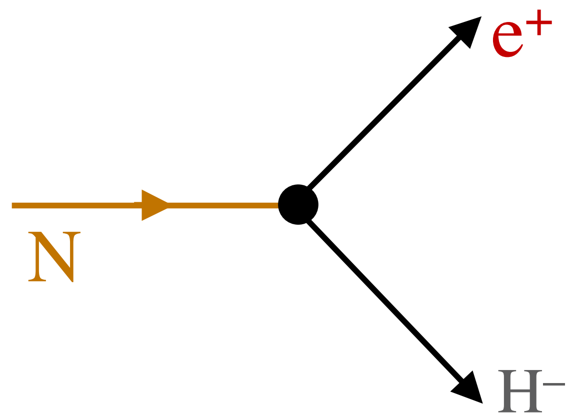
with "$\bar{\nu}_\mu \to \bar{\nu}_e$"



This is today’s version of comparing —



with —



Are There Sterile Neutrinos?

Sterile Neutrino

One that does not couple to the SM W or Z boson

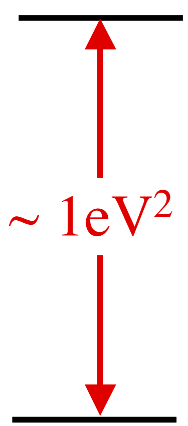
A "sterile" neutrino may well couple to some non-SM particles. These particles could perhaps be found at LHC or elsewhere.

The Hint From LSND

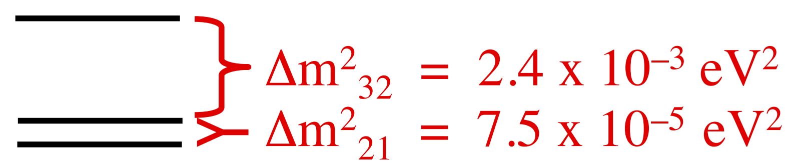
The LSND experiment at Los Alamos reported a ***rapid*** $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ oscillation at $L(km)/E(GeV) \sim 1$.

$$P\left(\overline{\nu_\mu} \rightarrow \overline{\nu_e}\right) = \sin^2 2\theta \, \sin^2\left[1.27\Delta m^2\left(eV^2\right)\frac{L(km)}{E(GeV)}\right] \sim 0.26\%$$

From μ^+ decay at rest; E ~ 30 MeV



in contrast to



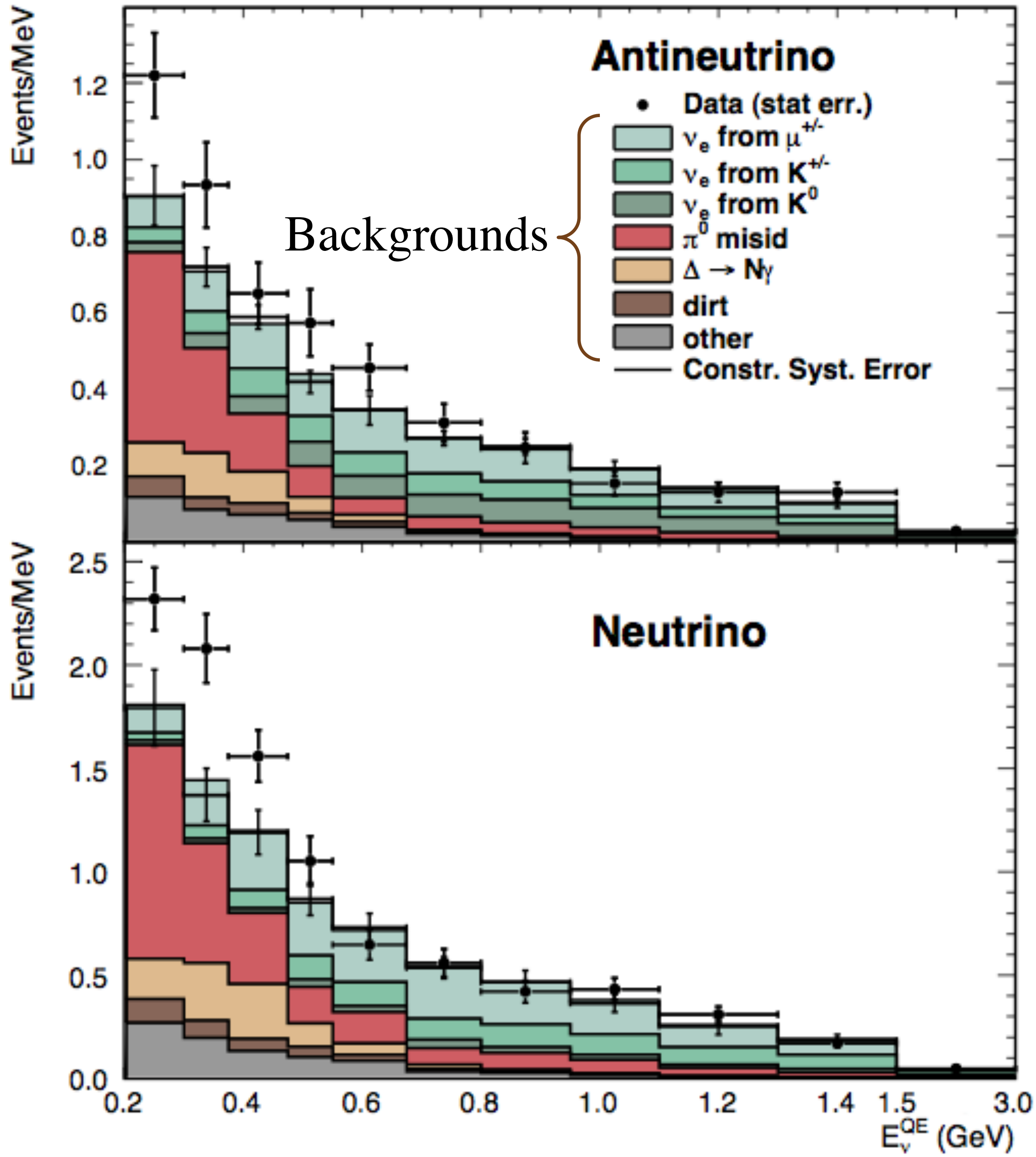
At least **4** mass eigenstates

{from measured $\Gamma(Z \rightarrow \nu\bar{\nu})$} At least **1** sterile neutrino

The Hint From MiniBooNE

In MiniBooNE, both L and E are ~ 17 times larger than they were in LSND, and L/E is comparable.

MiniBooNE has reported both $\nu_\mu \rightarrow \nu_e$ and $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ results.



MiniBooNE

1303.2588

78.4 ± 28.5 excess $\bar{\nu}$ events, and 162.0 ± 47.8 excess ν events

The Hint From Reactors

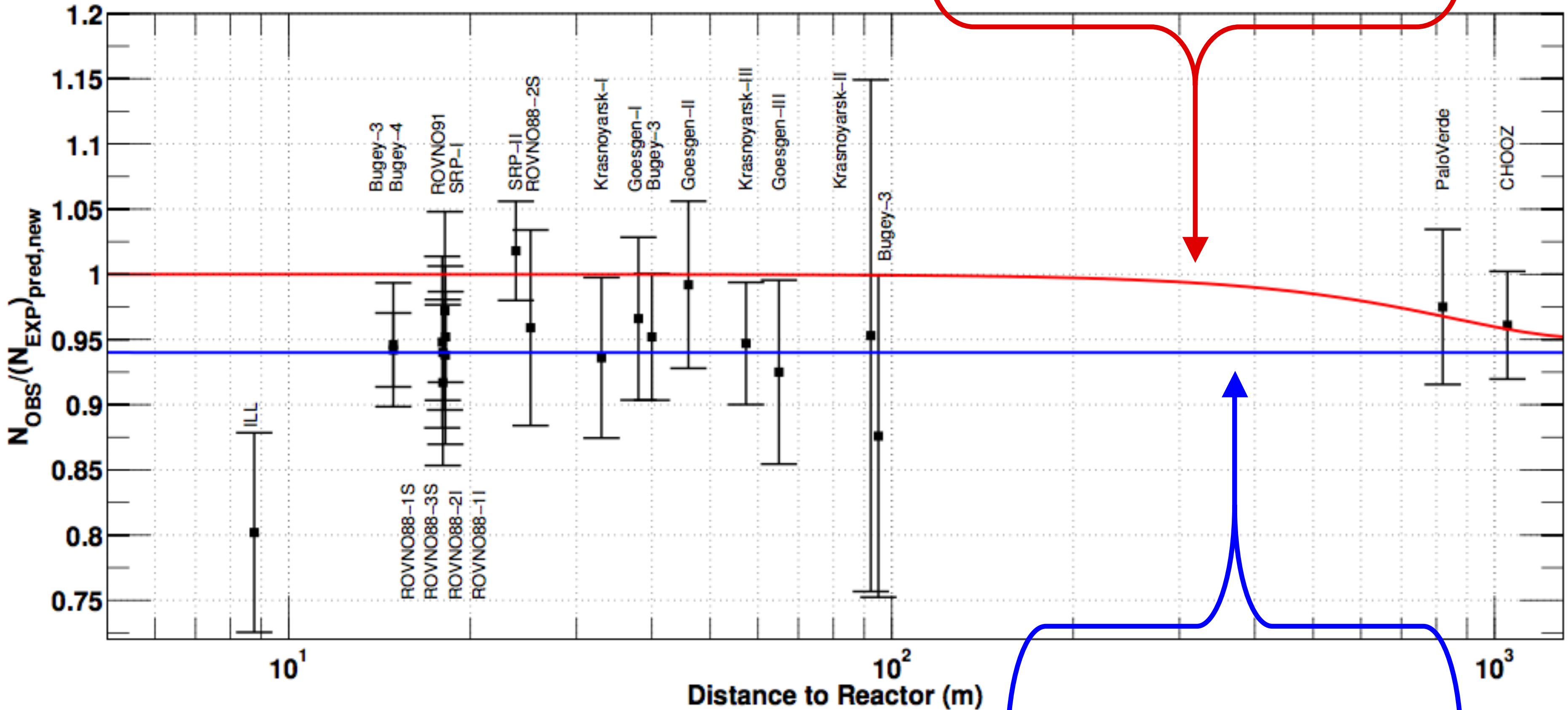
The prediction for the un-oscillated $\overline{\nu}_e$ flux from reactors, which has $\langle E \rangle \sim 3$ MeV, has increased by about 3%.

(Mueller et al., Huber)

Measurements of the $\overline{\nu}_e$ flux at (10 – 100)m from reactor cores now show a ~ 6% disappearance.

(Mention et al.)

Oscillation with only 3ν
and both $\Delta m^2 << 1$ eV^2



Oscillation with 4ν
and one $\Delta m^2 >> 1$ eV^2

Disappearance at L(m)/E(MeV) $\gtrsim 1$ suggests oscillation with $\Delta m^2 \gtrsim 1$ eV^2, like LSND and MiniBooNE.

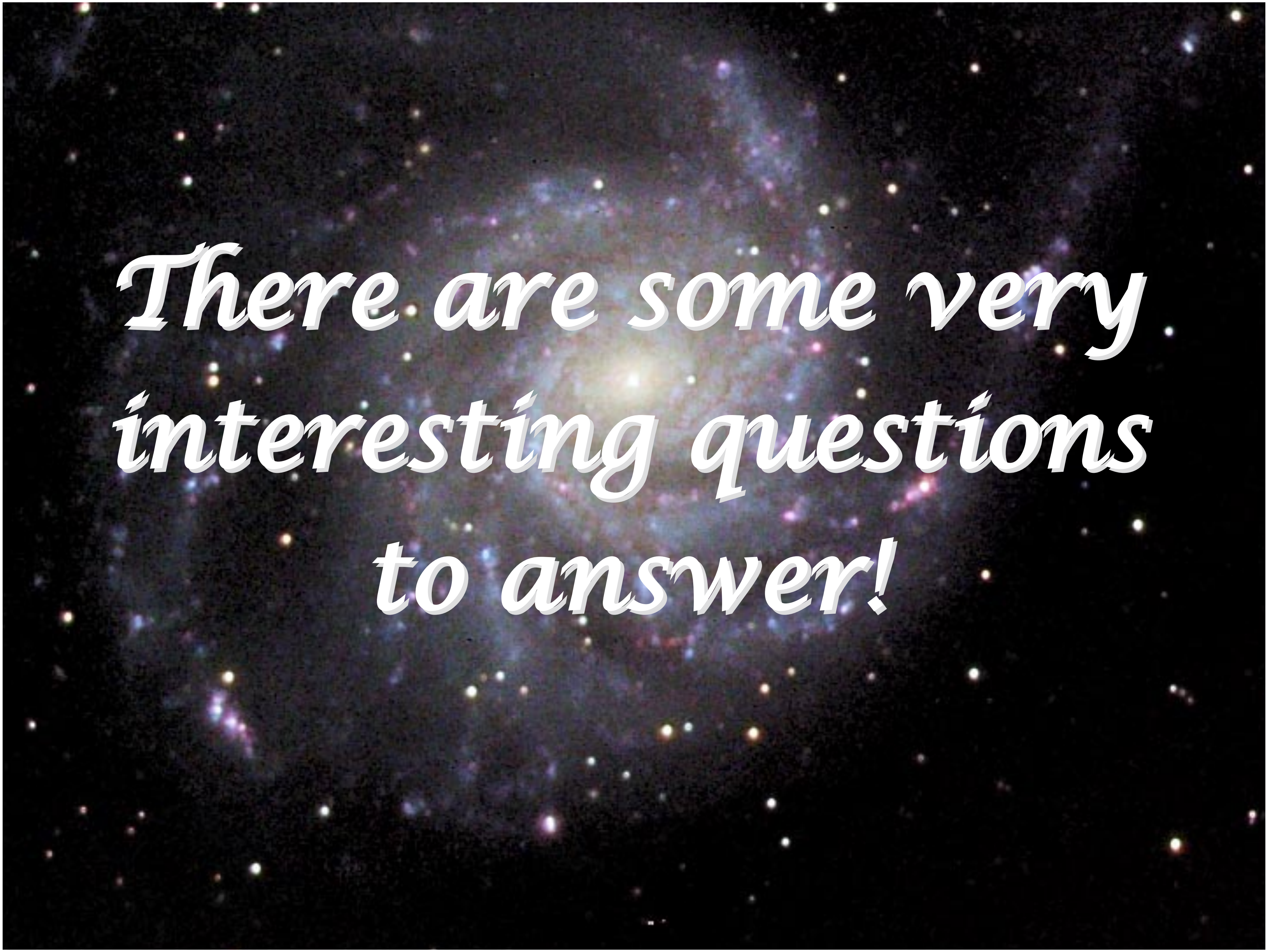
The Hint From ^{51}Cr and ^{37}Ar Sources

These radioactive sources were used to test gallium solar ν_e detectors.

$$\frac{\text{Measured event rate}}{\text{Expected event rate}} = 0.86 \pm 0.05$$

(Giunti, Laveder)

Rapid disappearance of ν_e flux due to oscillation with a large Δm^2??


There are some very interesting questions to answer!

Good luck!