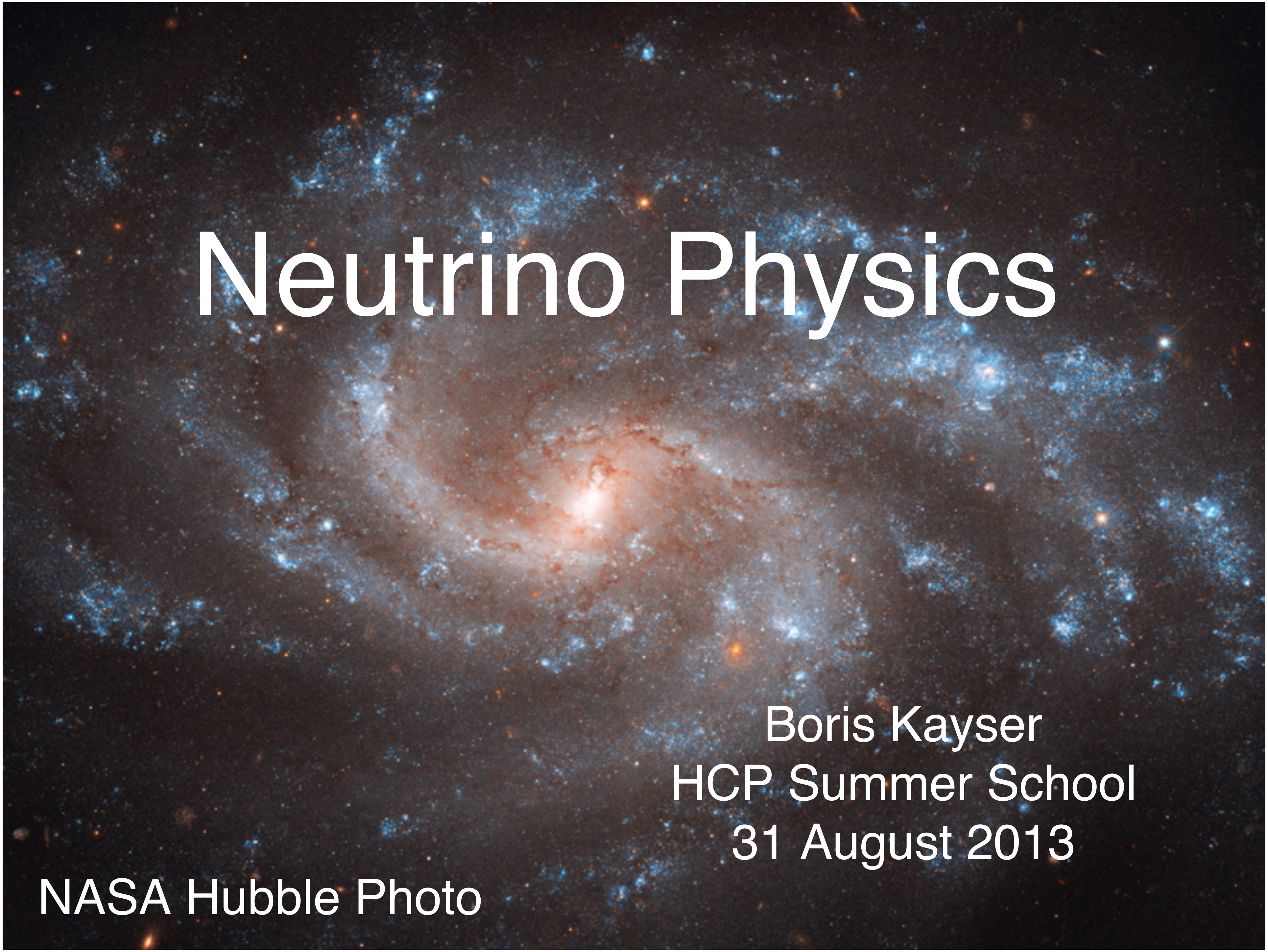


Neutrino Physics

Boris Kayser
HCP Summer School
31 August 2013

NASA Hubble Photo

Neutrinos are Abundant

We humans, and all the everyday objects around us, are made of nucleons and electrons.

But in the universe as a whole —

~ 10^9 neutrinos for each nucleon or electron.

Neutrinos and photons are the most abundant particles in the universe.

If we wish to understand the universe, we must understand neutrinos.

Neutrinos interact very feebly, and thus are hard to study. Intense sources and very large detectors are required. *But* —

The Neutrino Revolution
(1998 – …)

Neutrinos have nonzero masses,
but these masses are really tiny!

Leptons mix,
but differently than the quarks do!

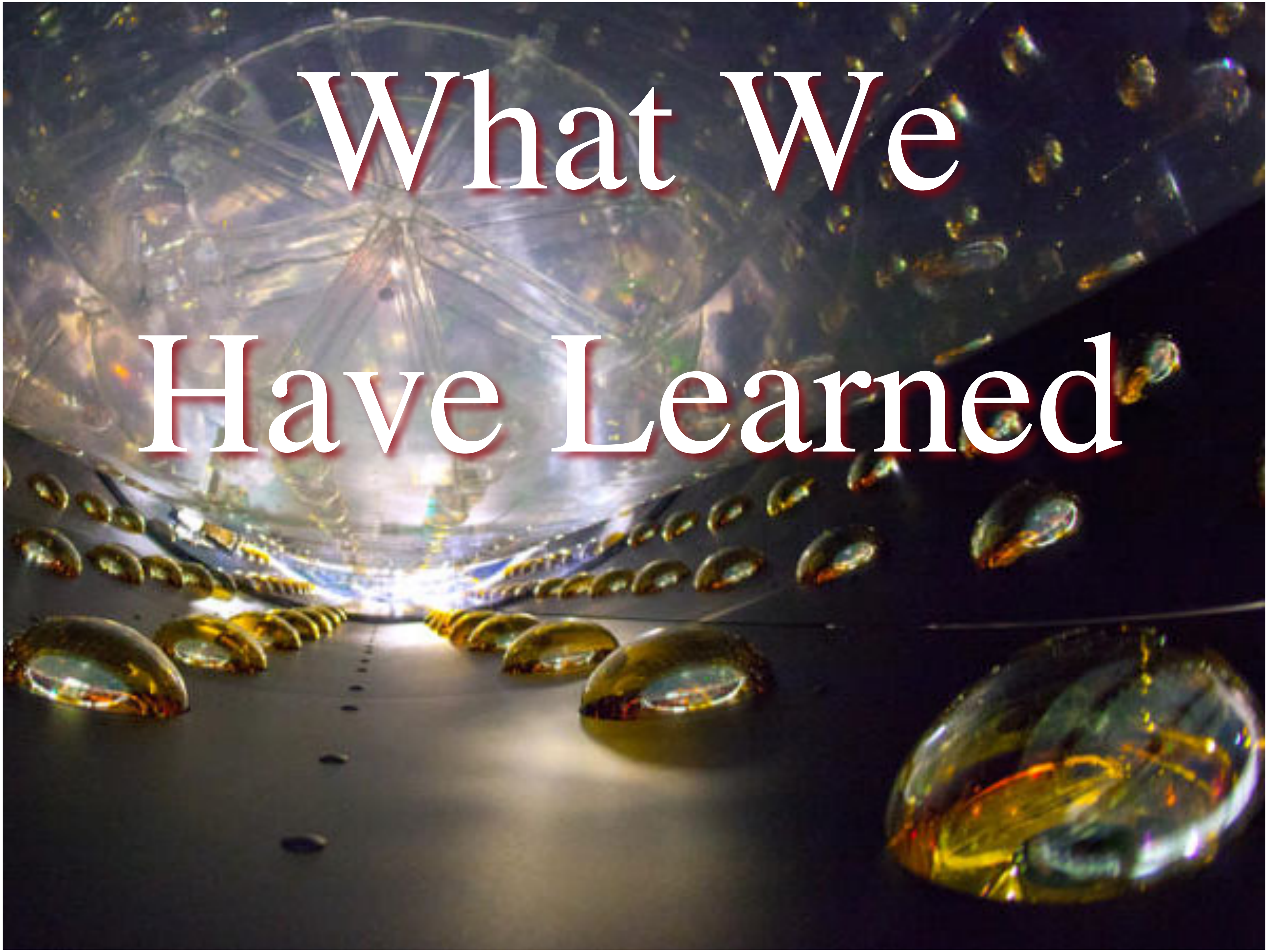
The Origin of Neutrino Mass

The fundamental constituents of matter
are the ***quarks***, the ***charged leptons***,
and the ***neutrinos***.

Most theorists strongly suspect that the origin of the neutrino masses is different from the origin of the quark and charged lepton masses.

The Standard-Model ***Higgs field*** may still be involved,
but not in the same way
as for the quarks and charged leptons.

More later ……….



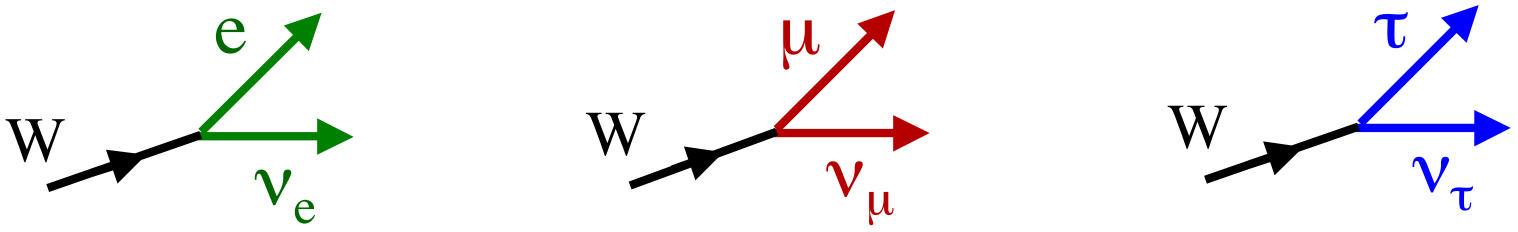
What We Have Learned

Neutrinos Come In (At Least) Three Flavors

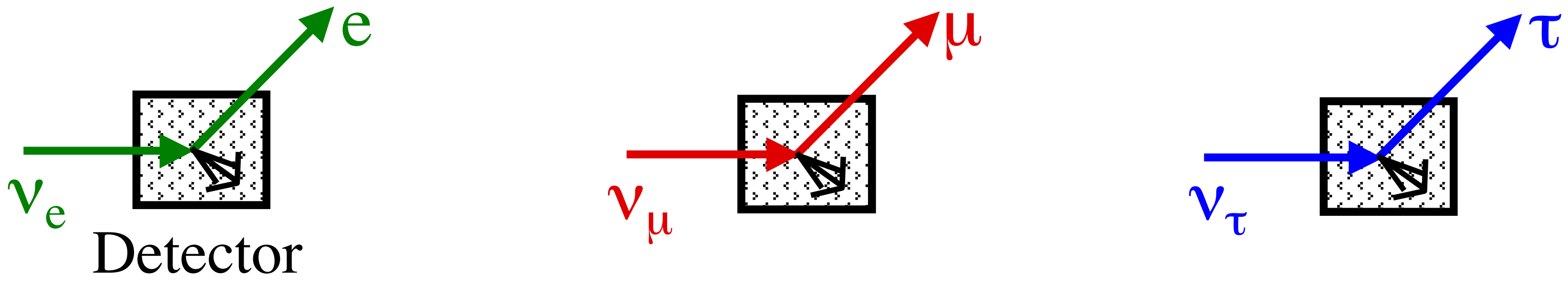
There are three flavors of charged leptons: e , μ , τ

There are three known flavors of neutrinos: ν_e, ν_μ, ν_τ

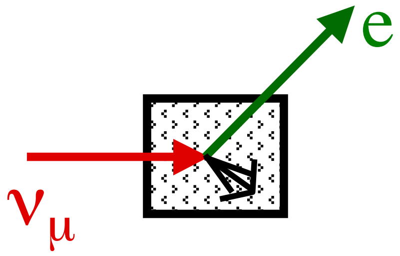
We ***define*** the neutrinos of specific flavor, ν_e, ν_μ, ν_τ, by W boson decays:



As far as we know, when a neutrino of given flavor interacts and creates a charged lepton, that charged lepton will always be of the same flavor as the neutrino.



but not



ν_e, ν_μ, ν_τ Are Not Mass Eigenstates (Leptonic Mixing)

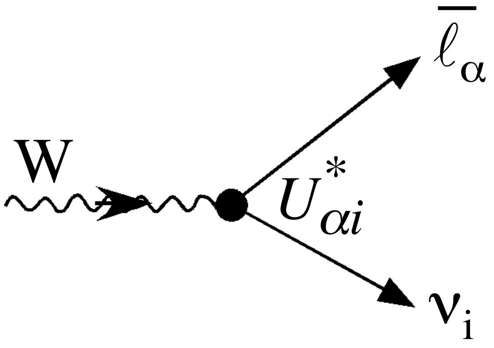
Instead, ν_e, ν_μ, and ν_τ are ***superpositions*** of the mass eigenstates:

$$|\nu_\alpha\rangle = \sum_i U^*_{\alpha i} \, |\nu_i\rangle \quad .$$

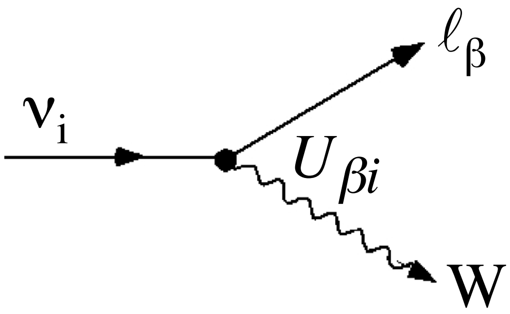
Neutrino of flavor
α = e, μ, or τ

Unitary Leptonic Mixing Matrix

Neutrino of definite mass m_i

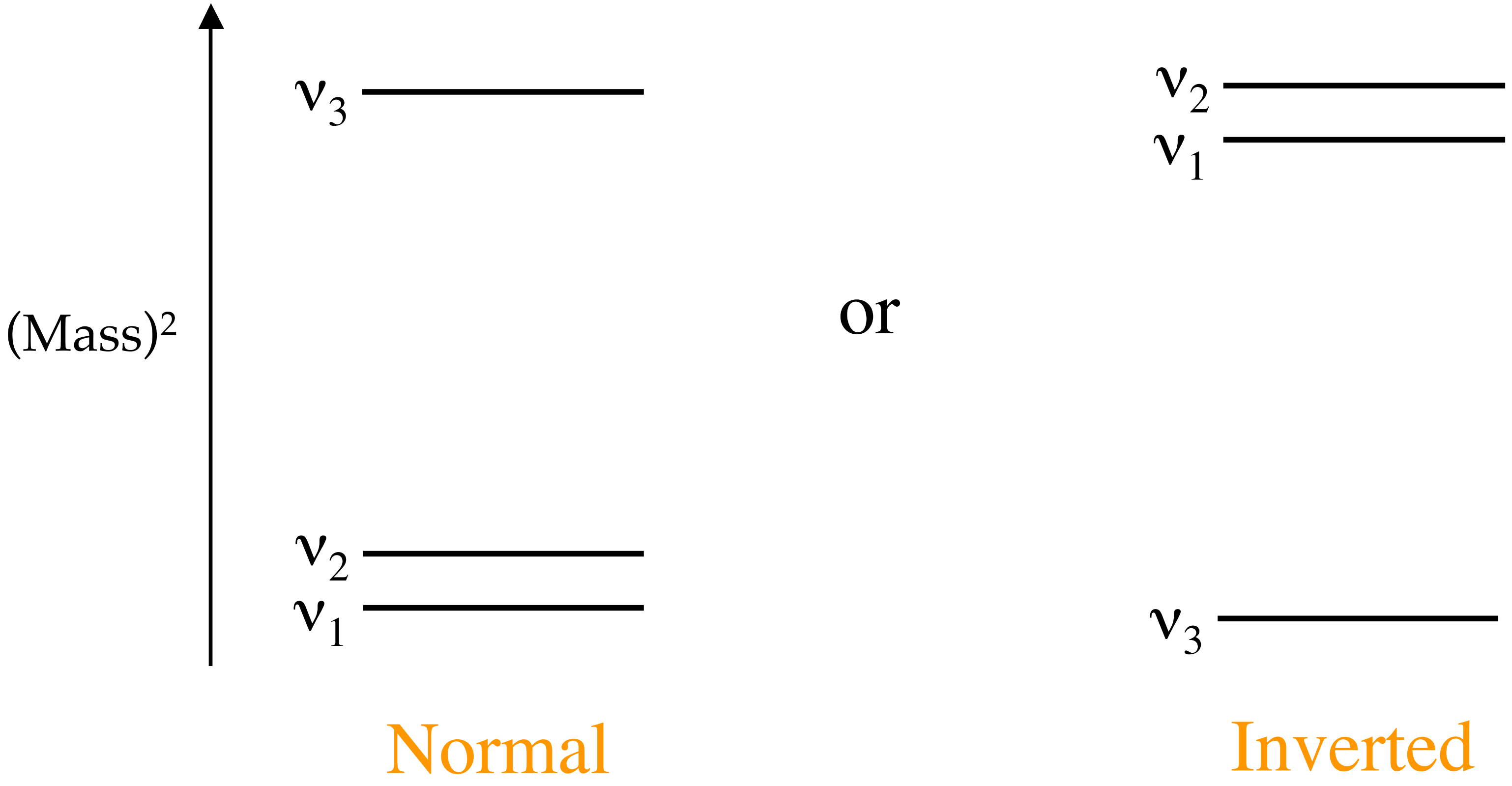


and



ℓ_α is a charged lepton ($\ell_e \equiv e$, $\ell_\mu \equiv \mu$, $\ell_\tau \equiv \tau$).

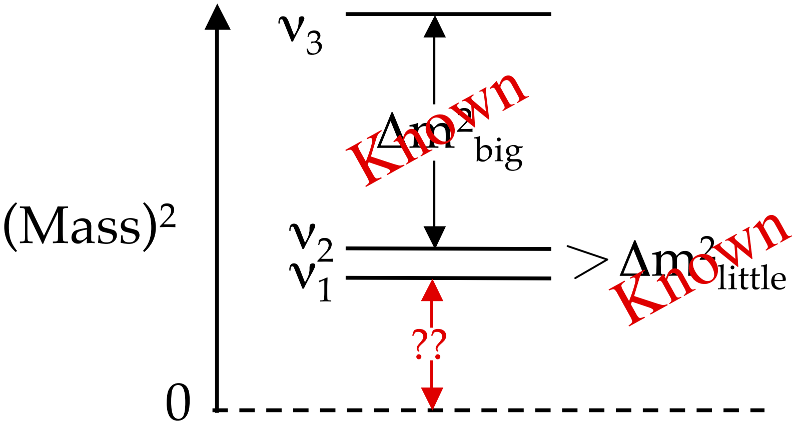
The $(\text{Mass})^2$ Spectrum



$$\Delta m^2_{21} \equiv m^2_2 - m^2_1 \cong 7.5 \text{ x } 10^{-5} \text{ eV}^2, \qquad \Delta m^2_{32} \cong 2.4 \text{ x } 10^{-3} \text{ eV}^2$$

There might be more mass eigenstates.

Constraints On the Absolute Scale of Neutrino Mass



How far above zero is the whole pattern?

Cosmology, under certain assumptions ⟶ $\sum_{\text{All } i} m(\nu_i) < 0.23$ eV

Tritium beta decay ⟶ $\langle m_\beta \rangle \equiv \sqrt{\sum_i |U_{ei}|^2 m(\nu_i)^2} < 2$ eV

$\text{Mass[Heaviest } \nu_i] > \sqrt{\Delta m^2_{\text{big}}} > 0.04$ eV

The Mixing Matrix *U*

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

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

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

$$\overbrace{\theta_{12} \approx 33°,\ \theta_{23} \approx 36\text{-}42°\ \underline{\text{or}}\ 48\text{-}54°,}^{\textit{Note big mixing!}}\ \theta_{13} \approx 8\text{-}9°$$

No more worry!

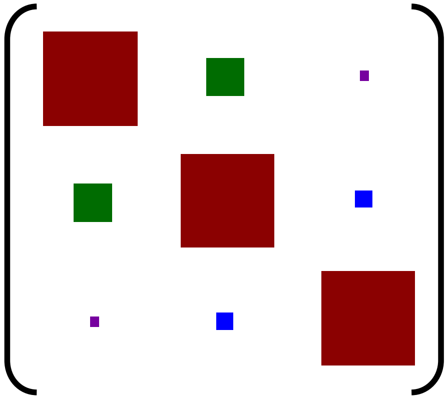
The phases violate CP. δ would lead to $P(\bar{\nu}_\alpha \rightarrow \bar{\nu}_\beta) \neq P(\nu_\alpha \rightarrow \nu_\beta)$.

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

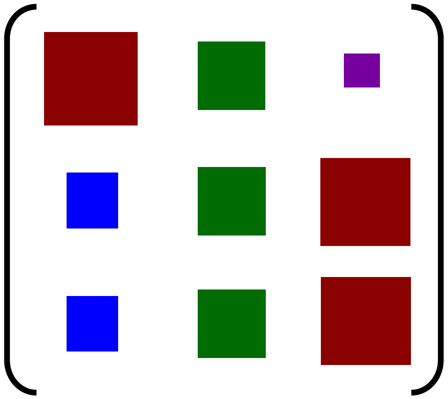
The Quark and Leptonic Mixing Matrices

In terms of the ***sizes*** of their elements, the two matrices look very different:

$V_{\text{quark}} \equiv V_{\text{CKM}} =$



$U_{\text{lepton}} \equiv U_{\text{PMNS}} =$

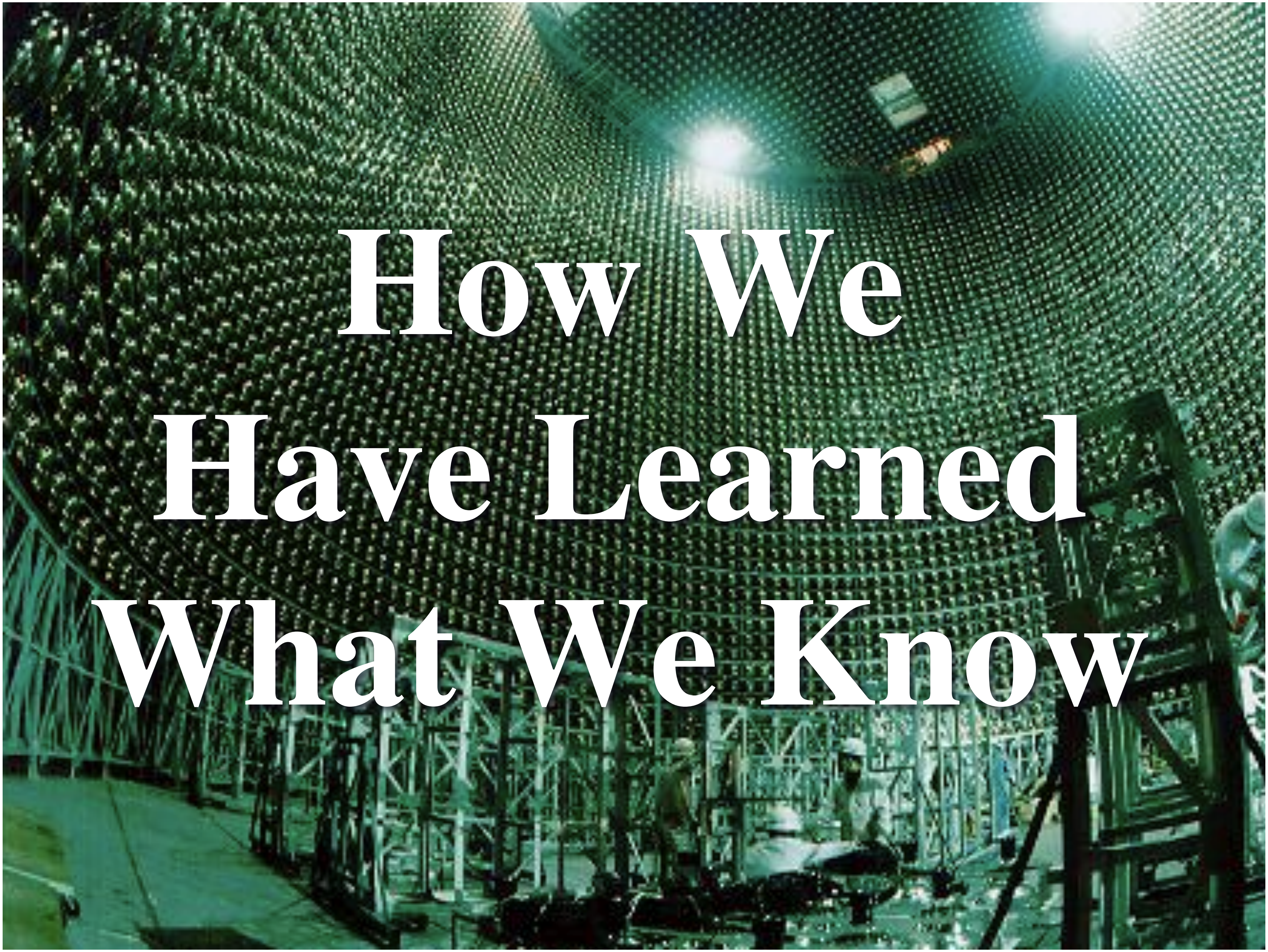


The Extra Leptonic ~~CP~~ Phases

Assuming that $\boldsymbol{V}_{\textbf{quark}}$ and $\boldsymbol{U}_{\textbf{lepton}}$ are 3 x 3 and unitary,
$\boldsymbol{V}_{\textbf{quark}}$ can contain only **1** CP-violating phase factor,
but $\boldsymbol{U}_{\textbf{lepton}}$ may possibly contain **3**.

The extra leptonic phases are physical only if
neutrinos are their own antiparticles.

The quarks are definitely ***not*** their own antiparticles,
so there are no extra phases in quark mixing.



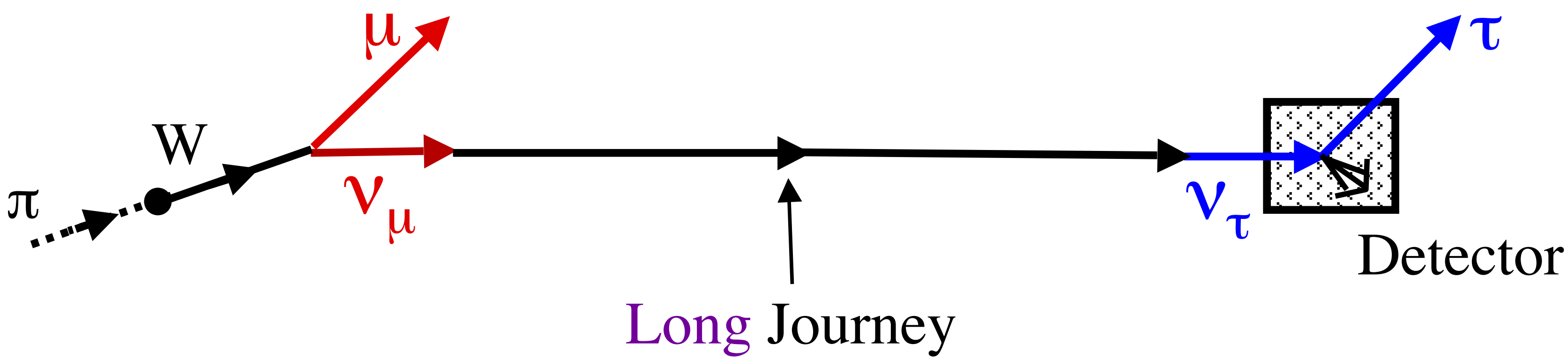
How We Have Learned What We Know

The discoveries of neutrino mass and leptonic mixing have come from the observation of ***neutrino flavor change (neutrino oscillation)***.

So, let us understand the physics of this phenomenon.

What Is Neutrino Flavor Change

If neutrinos have masses, and leptons mix, we can have —



Give a ν time to change character, and you can have

for example: $\nu_\mu \longrightarrow \nu_\tau$

The last 15 years have brought us compelling evidence that such flavor changes actually occur.

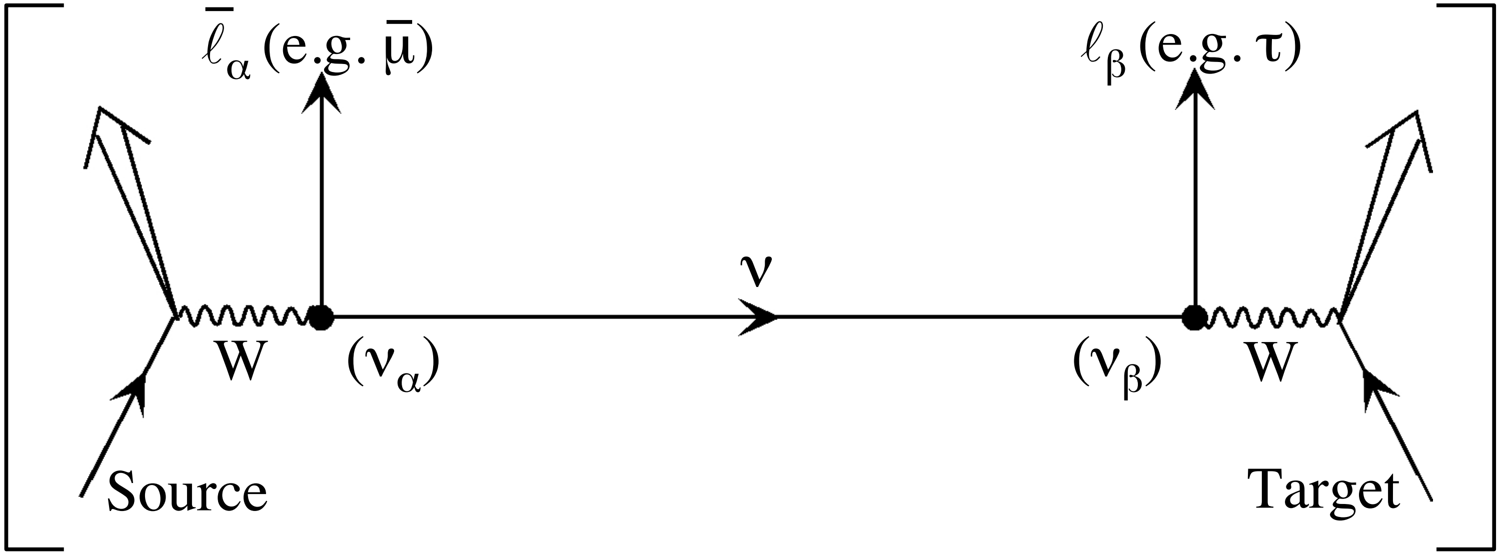
Evidence For Flavor Change

Neutrinos	Evidence of Flavor Change
Solar	Compelling
Reactor (Long-Baseline)	Compelling
Atmospheric	Compelling
Accelerator (Long-Baseline)	Compelling
Accelerator & Reactor (Short-Baseline)	"Interesting"

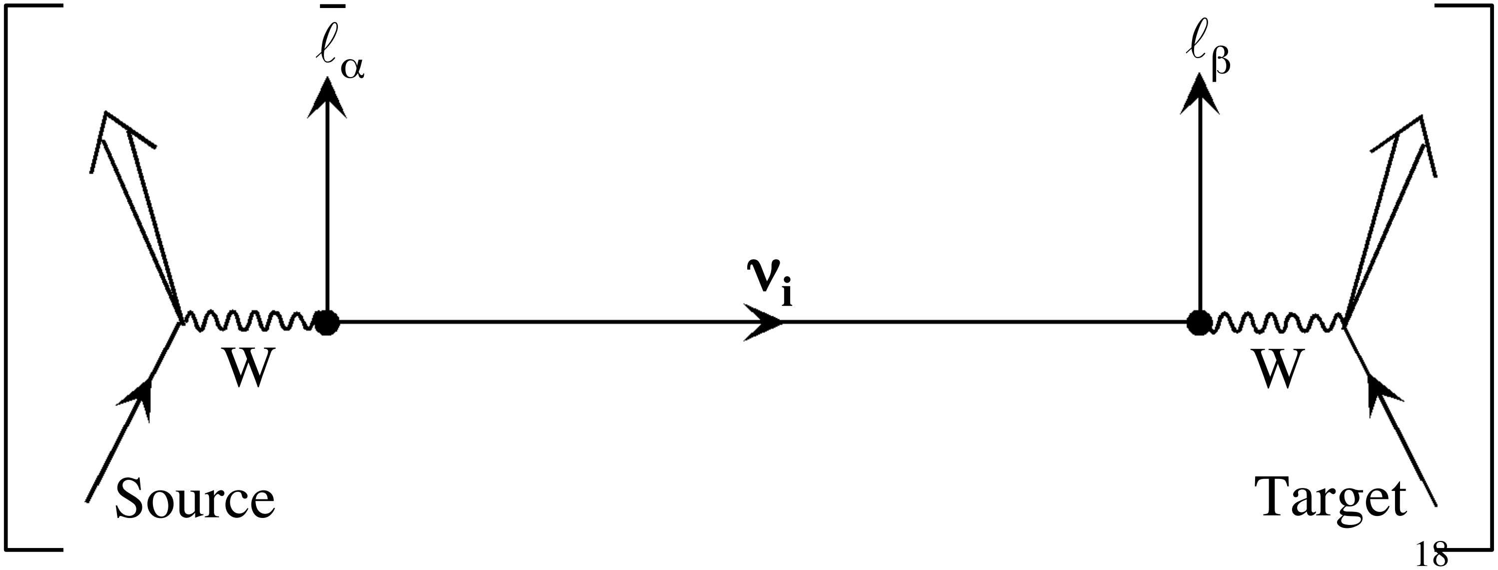
The Physics of Neutrino Flavor Change

(Approach of BK and L. Stodolsky)

Amp

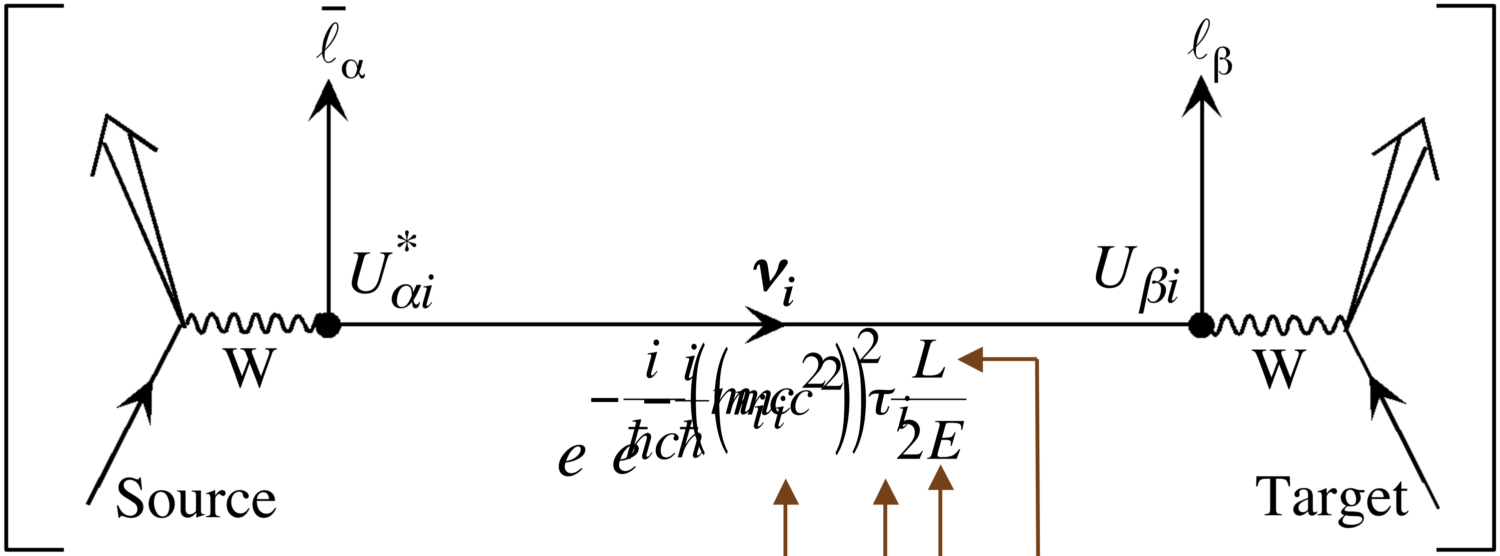


$= \sum_{i}$ Amp



$$\mathrm{Amp}(\nu_\alpha \to \nu_\beta)$$

$$= \sum_{\mathbf{i}} \mathrm{Amp}$$



$$e^{-\frac{i}{\hbar}(m_i c^2)\tau_i}$$

$$e^{-\frac{i}{\hbar c}(m_i c^2)^2 \frac{L}{2E}}$$

Rest energy

Energy

Proper time

Distance

$$= \sum_i U^*_{\alpha i}\, e^{-\frac{i}{\hbar c}(m_i c^2)^2 \frac{L}{2E}}\, U_{\beta i}$$

$$P(\nu_\alpha \to \nu_\beta) = \left|\mathrm{Amp}(\nu_\alpha \to \nu_\beta)\right|^2$$

Probability

Why does $e^{-\frac{i}{\hbar}\left(m_i c^2\right)\tau_i}$ describe neutrino propagation?

If, in the lab. frame, a neutrino ν of mass m,
with momentum p and energy E,
travels a distance L in time t,
its wave function picks up a factor —

$$\exp\left[\frac{i}{\hbar}\left(pL - Et\right)\right] = \exp\left[-\frac{i}{\hbar}\left(mc^2\right)\tau\right]$$

By the Lorentz
transformation

$$P\left(\nu_\alpha \to \nu_\beta\right) = \left|\mathrm{Amp}\right|^2 =$$

$$\delta_{\alpha\beta} - 4\sum_{i>j} \mathrm{Re}\left(U_{\alpha i}^* U_{\beta i} U_{\alpha j} U_{\beta j}^*\right) \sin^2\left(1.27\,\Delta m_{ij}^2\left(\mathrm{eV}^2\right)\frac{L(\mathrm{km})}{E(\mathrm{GeV})}\right)$$

$$+2\sum_{i>j} \mathrm{Im}\left(U_{\alpha i}^* U_{\beta i} U_{\alpha j} U_{\beta j}^*\right) \sin\left(2.54\,\Delta m_{ij}^2\left(\mathrm{eV}^2\right)\frac{L(\mathrm{km})}{E(\mathrm{GeV})}\right)$$

where $\Delta m_{ij}^2 \equiv m_i^2 - m_j^2$

Note that neutrino flavor change requires neutrino mass and leptonic mixing (U ≠ I).

Antineutrinos vs. Neutrinos

Because the neutrinos we encounter in the lab.
are always of left-handed helicity, while the
antineutrinos are always of right-handed helicity,

$$\bar{\nu}_\alpha \rightarrow \bar{\nu}_\beta = \mathrm{CP}\left(\nu_\alpha \rightarrow \nu_\beta\right)$$

Similarly,

$$\bar{\nu}_\alpha \rightarrow \bar{\nu}_\beta = \mathrm{CPT}\left(\nu_\beta \rightarrow \nu_\alpha\right)$$

If CPT-invariance holds,

$$P\left(\bar{\nu}_\alpha \rightarrow \bar{\nu}_\beta\right) = P\left(\nu_\beta \rightarrow \nu_\alpha\right) = P\left(\nu_\alpha \rightarrow \nu_\beta ; U \Rightarrow U^*\right)$$

Thus —

$$P\left(\overset{(-)}{\nu}_\alpha \rightarrow \overset{(-)}{\nu}_\beta\right) =$$

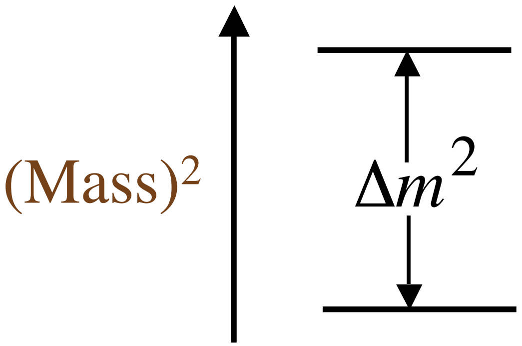
$$\delta_{\alpha\beta} - 4\sum_{i>j} \mathrm{Re}\left(U_{\alpha i}^* U_{\beta i} U_{\alpha j} U_{\beta j}^*\right) \sin^2\left(1.27\,\Delta m_{ij}^2\left(\mathrm{eV}^2\right)\frac{L(\mathrm{km})}{E(\mathrm{GeV})}\right)$$

$$\underset{(-)}{+}2\sum_{i>j} \mathrm{Im}\left(U_{\alpha i}^* U_{\beta i} U_{\alpha j} U_{\beta j}^*\right) \sin\left(2.54\,\Delta m_{ij}^2\left(\mathrm{eV}^2\right)\frac{L(\mathrm{km})}{E(\mathrm{GeV})}\right)$$

The phase δ in U would lead to the CP violation

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

When there are effectively only
2 mass eigenstates and 2 flavors

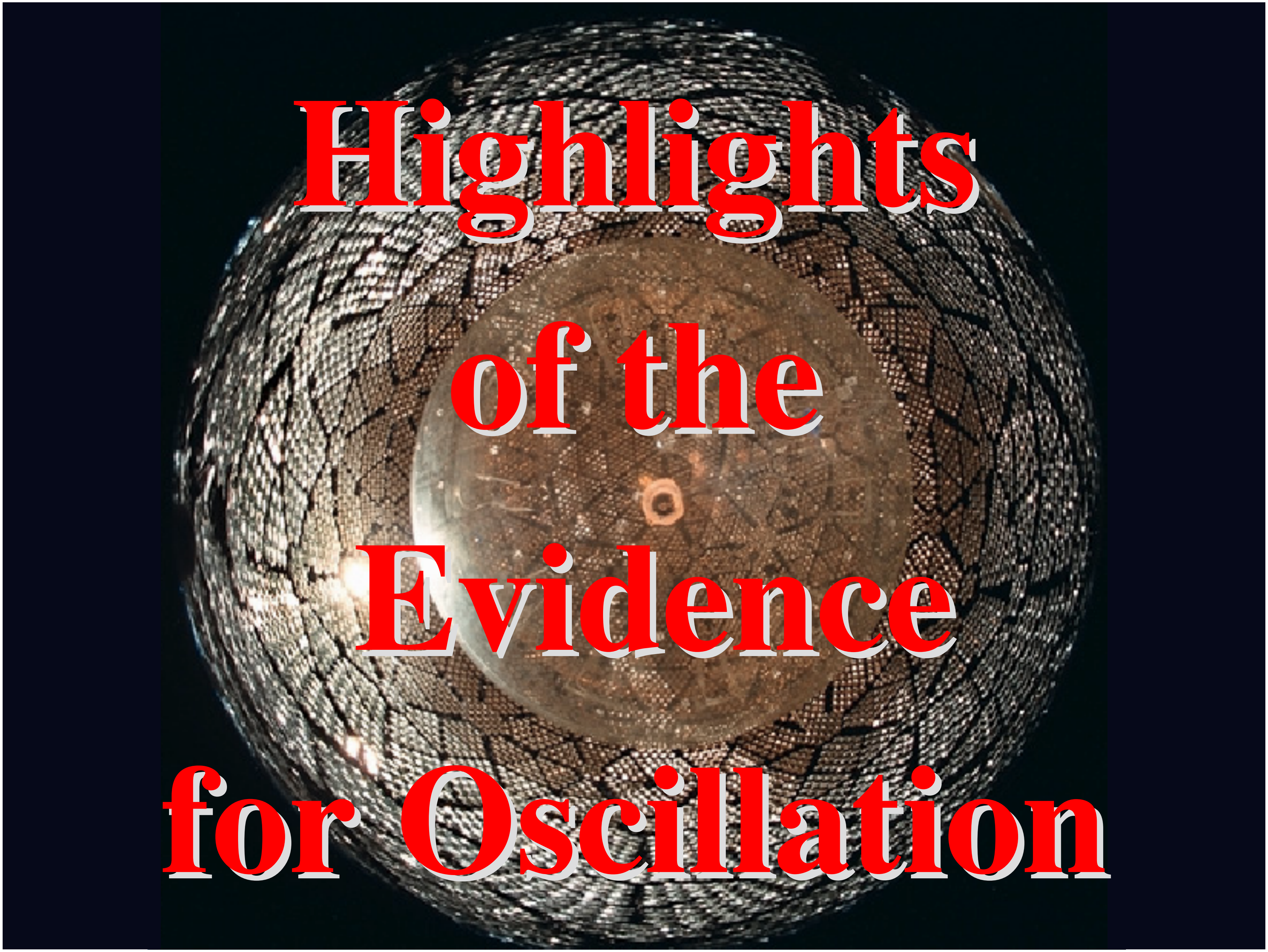


$$U = \begin{bmatrix} U_{\alpha 1} & U_{\alpha 2} \\ U_{\beta 1} & U_{\beta 2} \end{bmatrix} = \begin{bmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{bmatrix}$$

Mixing angle

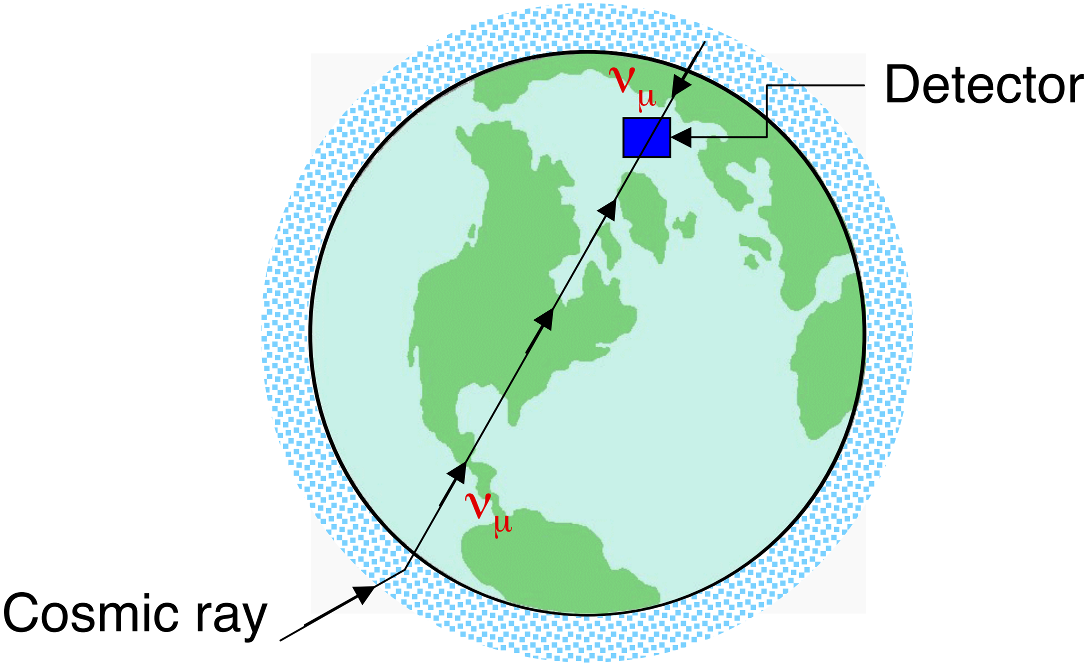
$$P\left(\overset{(-)}{\nu}_\alpha \rightarrow \overset{(-)}{\nu}_{\beta\neq\alpha}\right) = \sin^2 2\theta \, \sin^2\left[1.27\Delta m^2\left(eV^2\right)\frac{L(km)}{E(GeV)}\right]$$

$$P\left(\overset{(-)}{\nu}_\alpha \rightarrow \overset{(-)}{\nu}_\alpha\right) = 1 - \sin^2 2\theta \, \sin^2\left[1.27\Delta m^2\left(eV^2\right)\frac{L(km)}{E(GeV)}\right]$$



Highlights of the Evidence for Oscillation

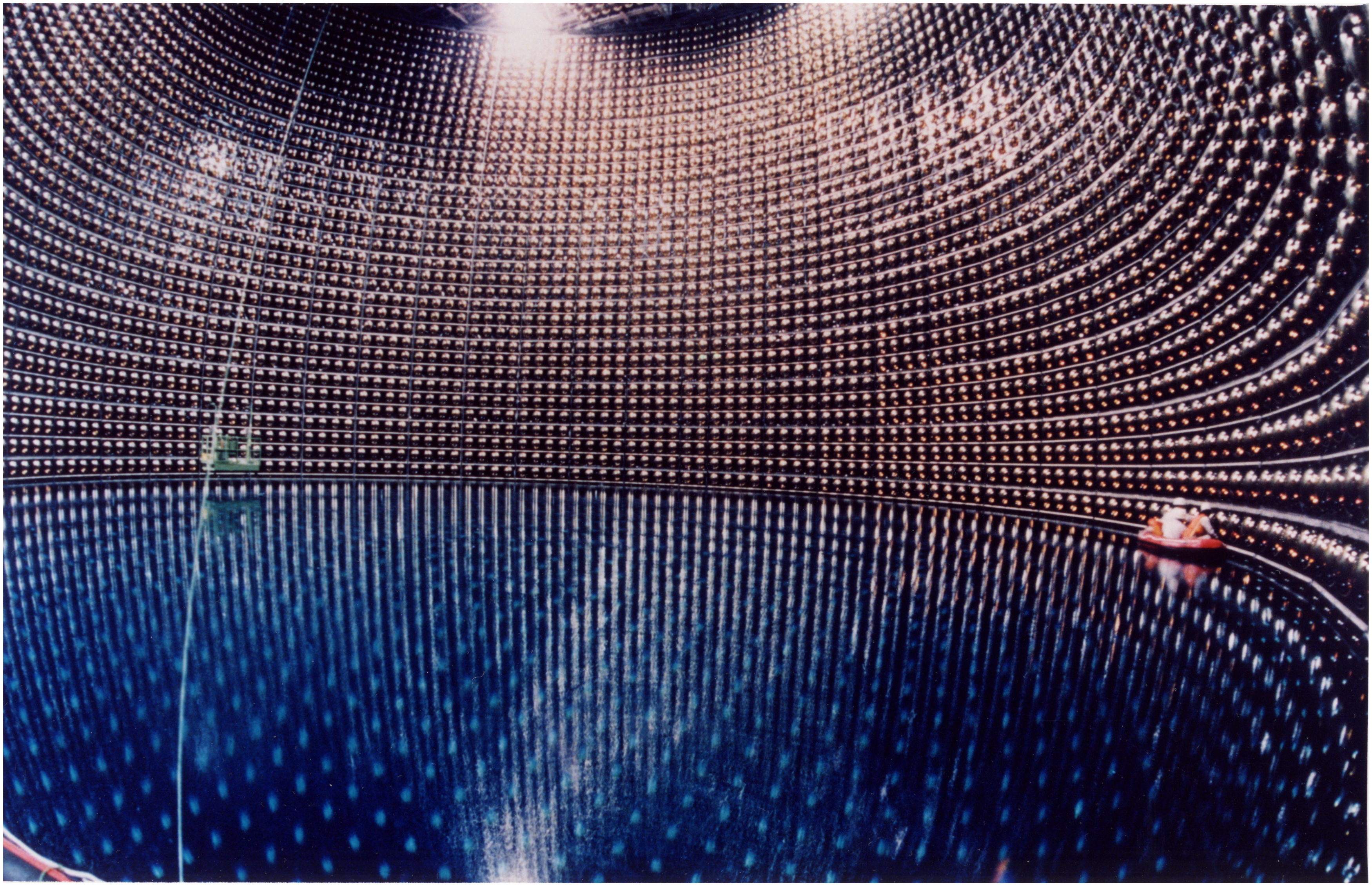
— Atmospheric Neutrinos —
The First Compelling Evidence



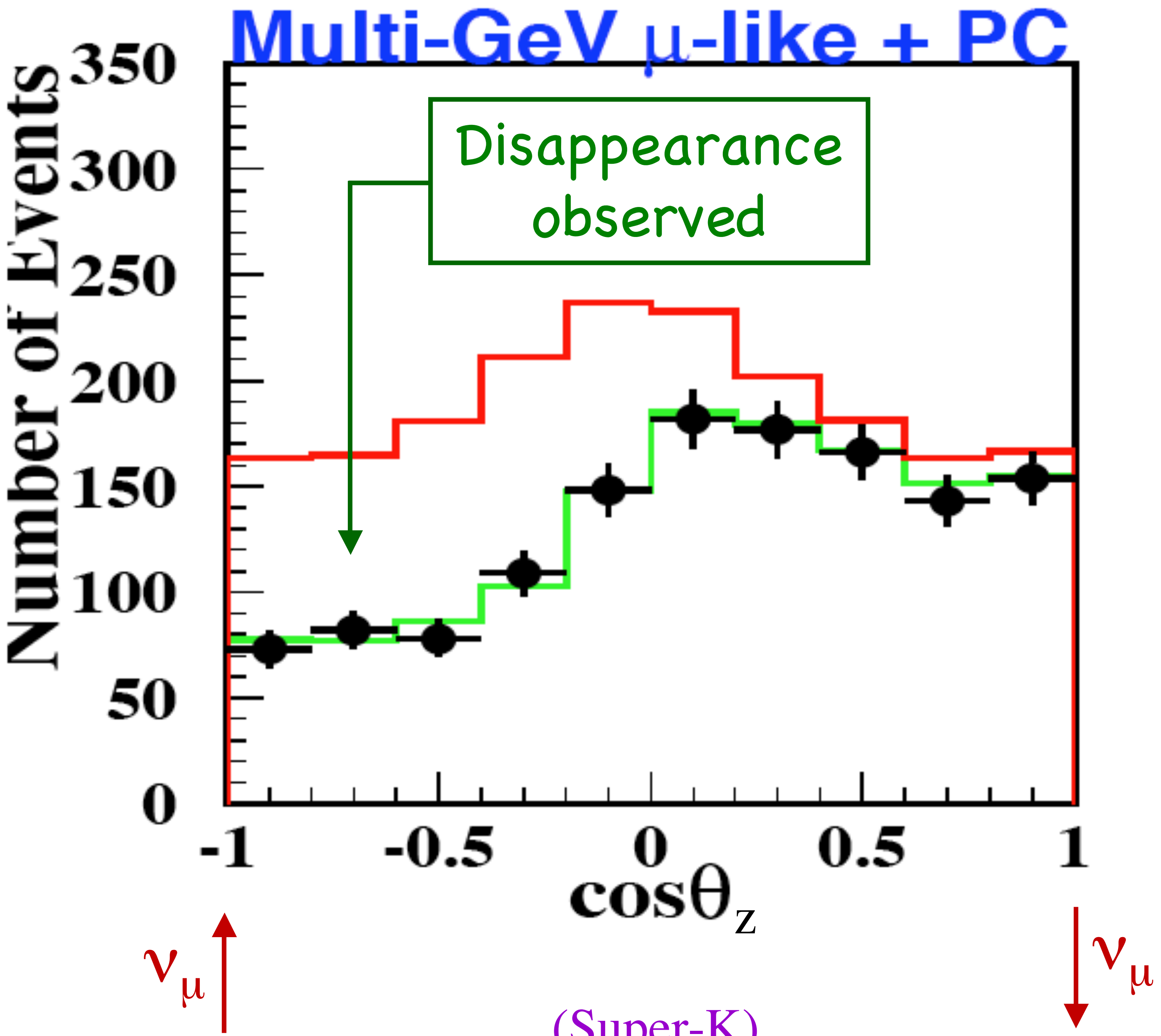
Isotropy of the $\gtrsim$ 2 GeV cosmic rays + Gauss' Law + No ν_μ disappearance

$$\Longrightarrow \quad \frac{\phi_{\nu_\mu}(\mathrm{Up})}{\phi_{\nu_\mu}(\mathrm{Down})} = 1 \ .$$

But Super-Kamiokande finds for $E_\nu > 1.3$ GeV, $\dfrac{\phi_{\nu_\mu}(\mathrm{Up})}{\phi_{\nu_\mu}(\mathrm{Down})} \cong 1/2$.



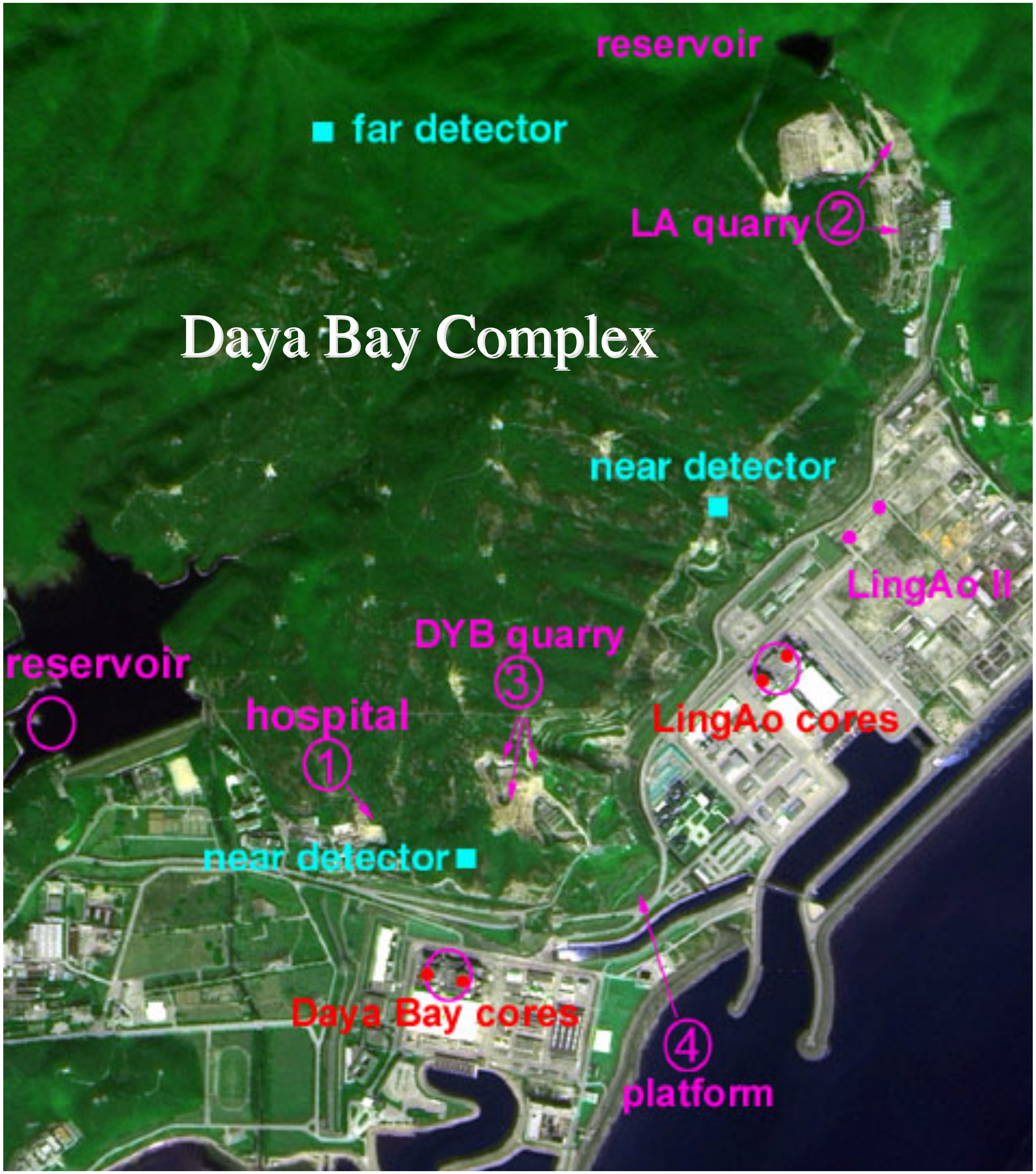
Super-Kamiokande: 50 ktons of water, surrounded by 11k phototubes that detect Cerenkov light from a μ or e



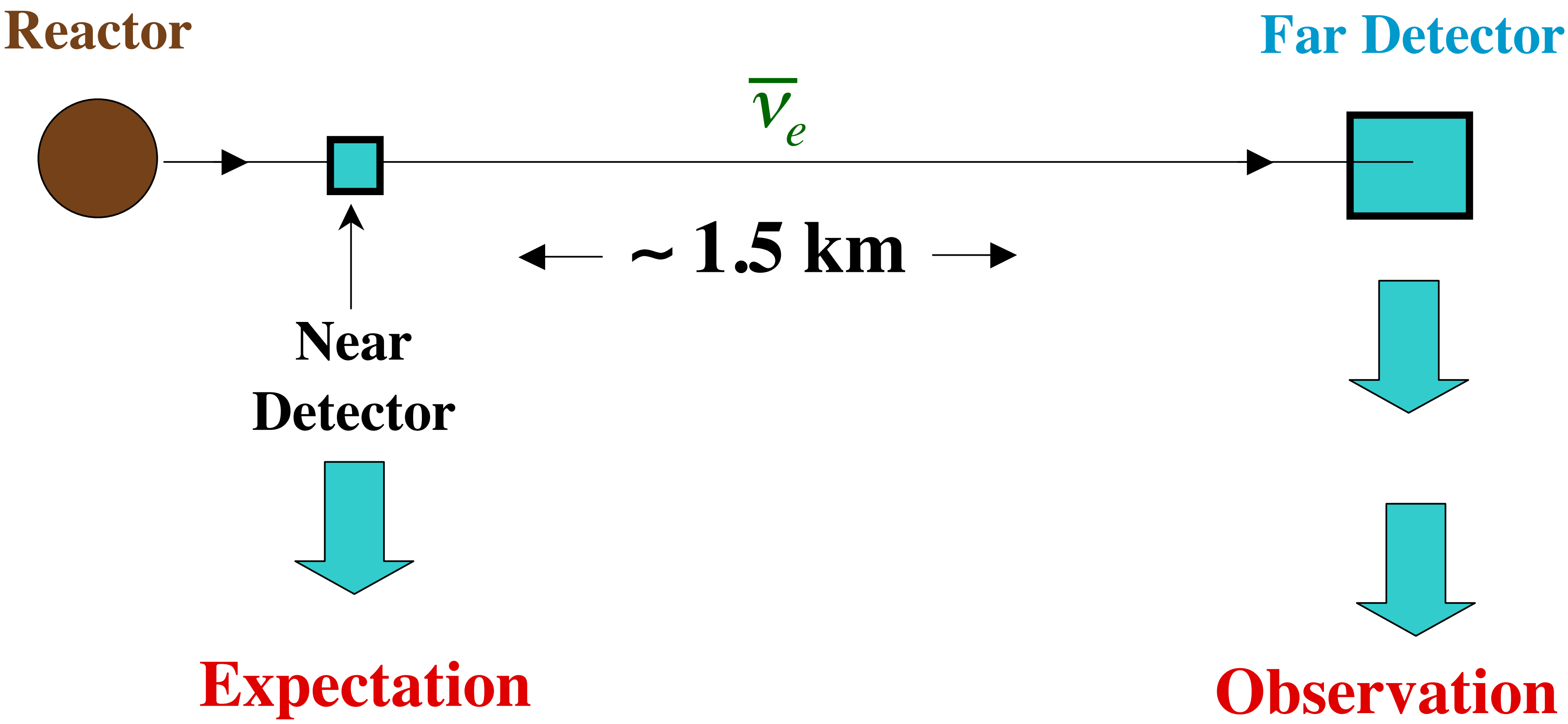
Disappearance observed

(Super-K)

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



The Reactor – Neutrino Experiments


Reactor

Far Detector

$\bar{\nu}_e$

~ 1.5 km

Near Detector

Expectation

Observation

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

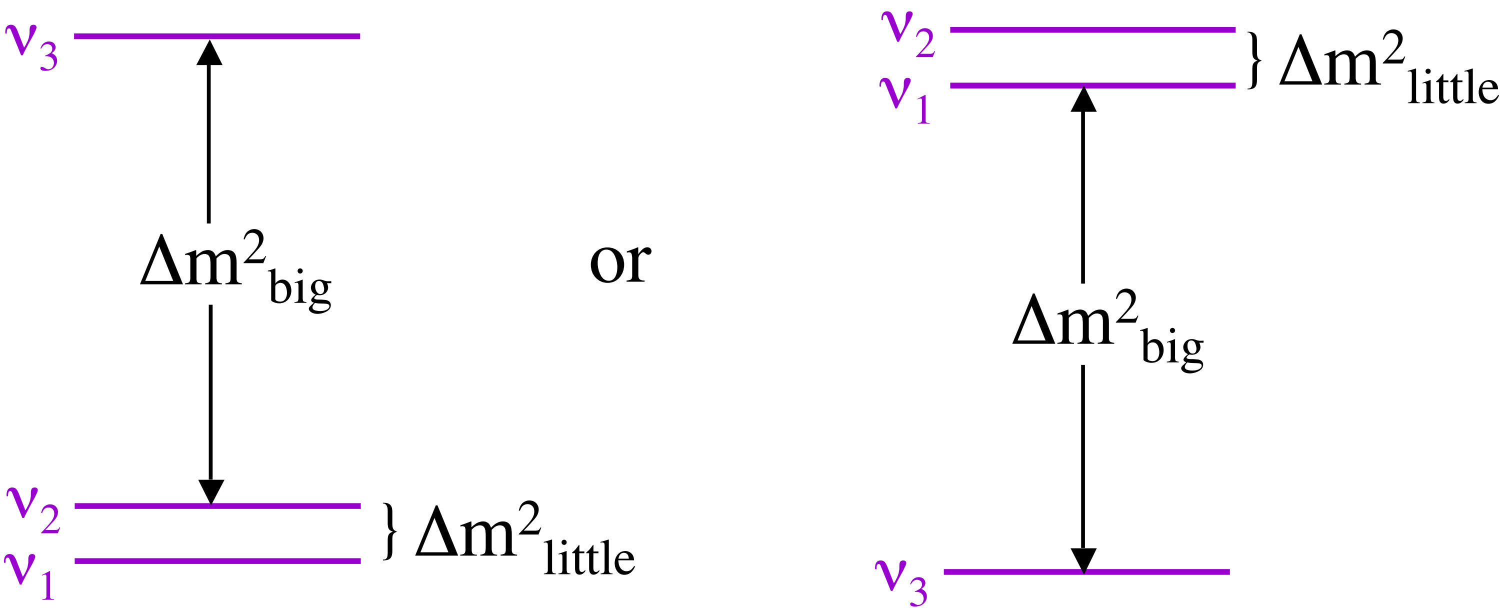
$$\sin^2\left[1.27\Delta m^2 \frac{L(\mathrm{km})}{E(\mathrm{GeV})}\right]$$ will be sensitive to —

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

but not to —

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

In —



the little splitting is invisible. Then —

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

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

Looking to the Future

The Open Questions

- What is the absolute scale of neutrino mass?

- Are neutrinos their own antiparticles?
- Do neutrinos have Majorana masses?

- Are there ***more*** than 3 mass eigenstates?
- Are there non-weakly-interacting “sterile” neutrinos?

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

- Is the spectrum like  or  ?

- Do neutrino interactions violate CP?

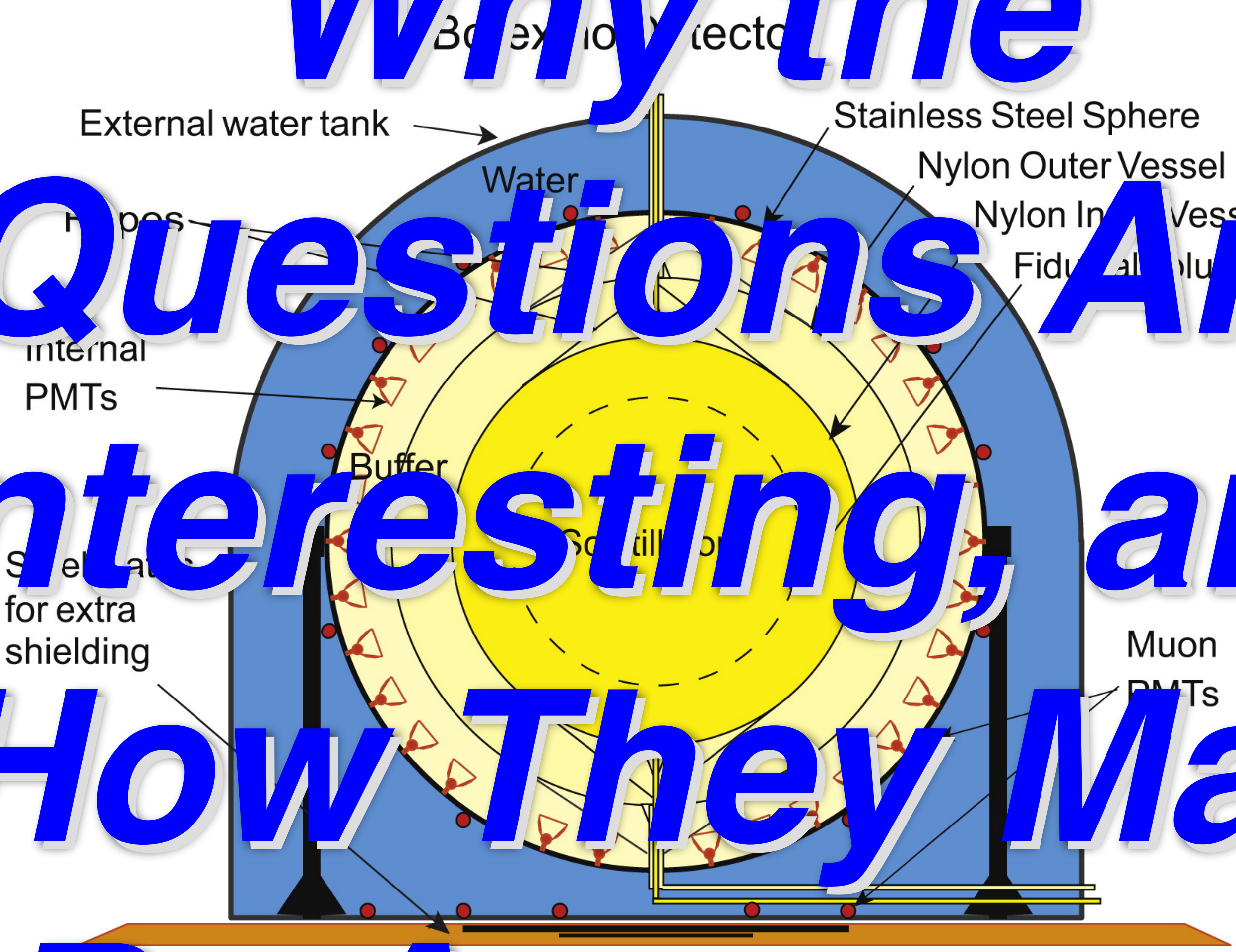
Is $P(\bar{\nu}_\alpha \rightarrow \bar{\nu}_\beta) \neq P(\nu_\alpha \rightarrow \nu_\beta)$?

- 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?

- What **surprises** are in store?

Why the Questions Are Interesting, and How They May Be Answered



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

Do Neutrinos Have Majorana Masses?

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

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*.

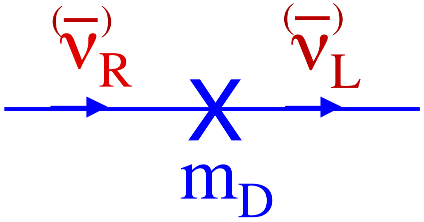
Dirac Masses

Dirac neutrino masses are the neutrino analogues of the SM quark and charged lepton masses.

To build a Dirac mass for the neutrino ν, we require not only the left-handed field ν_L in the Standard Model, but also a right-handed neutrino field ν_R.

The Dirac neutrino mass term is —

$$m_D \overline{\nu_L}\, \nu_R$$

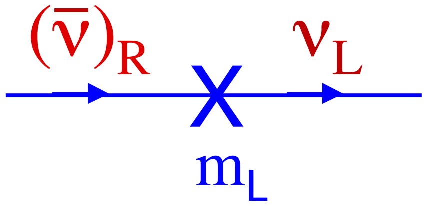


Dirac neutrino masses do not mix neutrinos and antineutrinos.

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 mix ν and $\bar{\nu}$, so they 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 ↔ $\bar{\text{f}}$.

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 arise via the Higgs mechanism:

$$\mathcal{L}_{SM} = f\underset{\substack{\uparrow\\ \text{SM Higgs field}}}{H_{SM}}\bar{\nu}_L\nu_R \Rightarrow f\underbrace{\langle H_{SM}\rangle_0}_{\text{Vacuum expectation value}}\bar{\nu}_L\nu_R \equiv m_D\bar{\nu}_L\nu_R$$

This, the ν analogue of the mechanism that produces
the q and ℓ masses, leads only to a **Dirac** ν mass term.

Possible (Weak-Isospin-Conserving) couplings that can lead to Majorana mass terms:

$$\underbrace{H_{SM}H_{SM}\overline{\nu_L^c}\nu_L}_{\text{Not renormalizable}},\quad \underbrace{H_{I_W=1}}_{\text{This Higgs not in SM}}\overline{\nu_L^c}\nu_L,\quad \underbrace{m_R\overline{\nu_R^c}\nu_R}_{\text{No Higgs}}$$

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

Searching for Majorana neutrino masses is part of the effort to determine the origin of mass.

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. ν_L and $\nu_L{}^c$ are distinct.

$m_L\overline{\nu_L}\,\nu_L{}^c$ 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 —

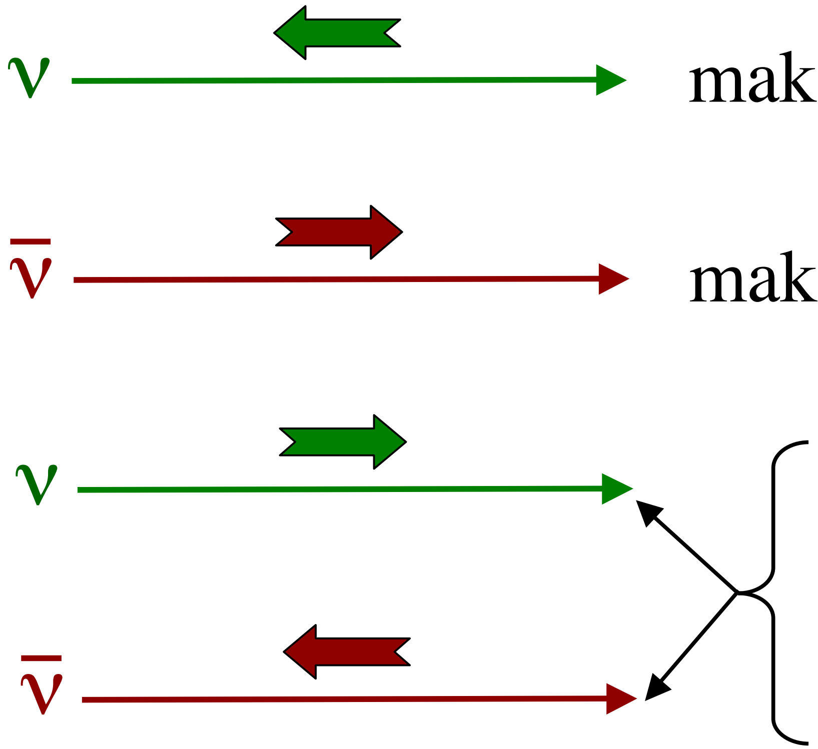
$$K_{S,L} \cong (K^0 \pm \overline{K^0})/\sqrt{2}\ . \qquad \overline{K_{S,L}} = K_{S,L}\ .$$

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

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

SM Interactions Of A Dirac Neutrino

We have 4 mass-degenerate states:

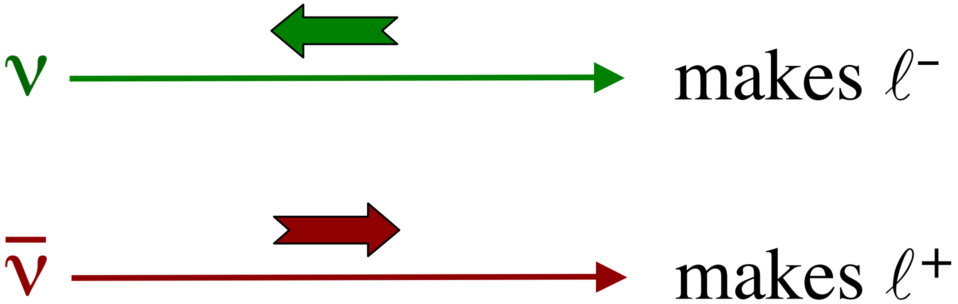


		Conserved L
ν	makes ℓ^-	+1
$\bar{\nu}$	makes ℓ^+	–1
ν		
$\bar{\nu}$		

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:



ν makes ℓ^-

$\bar{\nu}$ makes ℓ^+

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, So That $\bar{\nu} = \nu$

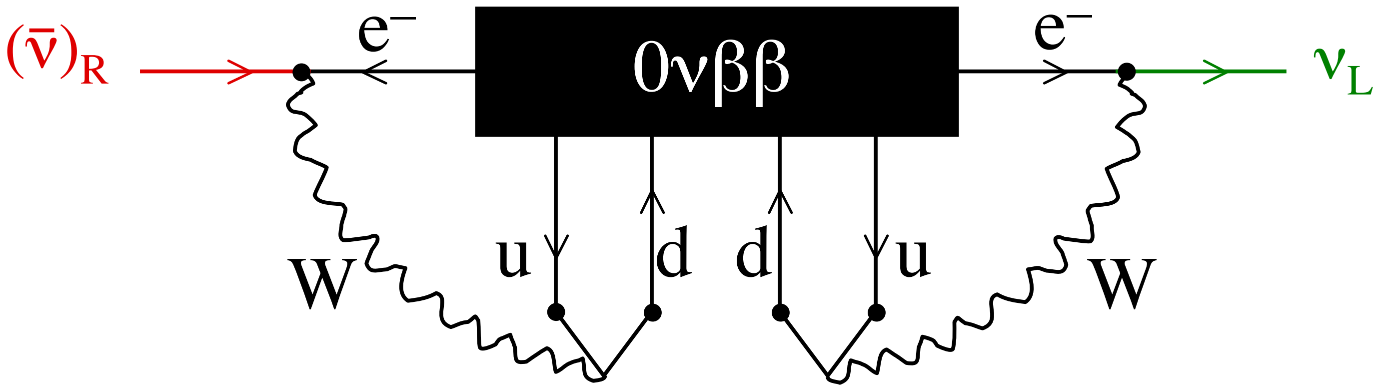
The Promising Approach — Seek Neutrinoless Double Beta Decay [0νββ]

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

Note that 0νββ does not conserve Lepton Number L. It has $\Delta L = 2$.

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 (tiny) Majorana mass term

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

Do Neutrinos Violate CP?

Are We Descended From Heavy Neutrinos?

CP is a fundamental symmetry.

Is CP violation
special to quark mixing?

Or, does it occur in both
quark and lepton mixing,
as suggested by Grand Unified Theories,
which unify the quarks and the leptons?

Look For CP Violation By Neutrinos

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

$$P\left(\overset{(-)}{\nu}_\alpha \rightarrow \overset{(-)}{\nu}_\beta\right) = \left|\mathrm{Amp}\right|^2 =$$

$$\delta_{\alpha\beta} - 4 \sum_{i>j} \mathrm{Re}\left(U_{\alpha i}^{*} U_{\beta i} U_{\alpha j} U_{\beta j}^{*}\right) \sin^2\left(1.27 \Delta m_{ij}^2 \left(\mathrm{eV}^2\right) \frac{L(\mathrm{km})}{E(\mathrm{GeV})}\right)$$

$$\overset{+}{(-)} 2 \sum_{i>j} \mathrm{Im}\left(U_{\alpha i}^{*} U_{\beta i} U_{\alpha j} U_{\beta j}^{*}\right) \sin\left(2.54 \Delta m_{ij}^2 \left(\mathrm{eV}^2\right) \frac{L(\mathrm{km})}{E(\mathrm{GeV})}\right)$$

Are We Descended From Heavy Neutrinos?

NASA Hubble Photo

A Cosmic Puzzle

Today: $B \equiv \#(\text{Baryons}) - \#(\text{Antibaryons}) \neq 0.$

Standard cosmology: Right after the Big Bang, $B = 0.$

Also, $L \equiv \#(\text{Leptons}) - \#(\text{Antileptons}) = 0.$

How did $B = 0$ → $B \neq 0$?

An appealing possible answer is **Leptogenesis**.

(Fukugita, Yanagida)

Leptogenesis is a very natural consequence of the **See-Saw** picture, the most popular explanation of why neutrinos are so light.

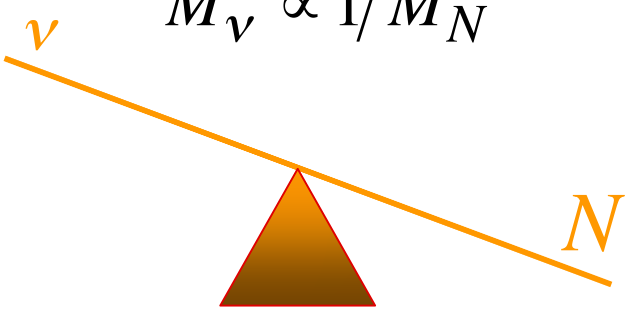
The straightforward See-Saw adds to the Standard Model (SM) 3 very ***heavy*** neutrinos N_i, $i = 1, 2, 3$, to match the 3 ***light*** lepton families $(\nu_\alpha, \ell_\alpha)$, $\alpha = e, \mu, \tau$.

The heavy neutrinos N_i are coupled to the rest of the world only through the Yukawa interaction —

$$\mathcal{L}_{\text{Yukawa}} = \underset{\text{SM lepton doublets}}{\overline{L}}\,\underset{\text{SM Higgs doublet}}{\overline{H}}\,\overset{\text{Yukawa coupling matrix}}{y}N + h.c.$$

A consequence of this picture is —

$M_\nu \propto 1/M_N$



See-Saw Relation

$$\left\{\begin{array}{c}\textit{Yanagida;}\\ \textit{Gell-Mann, Ramond, Slansky;}\\ \textit{Mohapatra, Senjanovic;}\\ \textit{Minkowski}\end{array}\right\}$$

Another consequence is that $\overline{N} = N$ and $\overline{\nu} = \nu$.

Leptogenesis is quite likely another consequence.

During the ***hot*** Big Bang, the N_i were made.

$\cancel{CP}$ phases in the matrix y would have lead to —

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

and

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

This violates CP in the leptonic sector,
and violates lepton number L.

Starting with a universe with $L = 0$,
these decays would have produced one with $L \neq 0$.

The Standard-Model ***Sphaleron*** process, which does not conserve B or L, would then have converted some of this $L \neq 0$ into $B \neq 0$.

$$B_i = 0$$

$$L_i \neq 0$$

Sphaleron Process

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

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

Initial state
from N decays

Final state

There is now a nonzero *Baryon Number*.

During the ***hot*** Big Bang, the N_i were made.

~~CP~~ phases in the matrix y would have lead to —

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

and

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

This violates CP in the leptonic sector,
and violates lepton number L.

These are the key ingredients of Leptogenesis.

Starting with a universe with $L = 0$,
these decays would have produced one with $L \neq 0$.

To establish that there is CP violation in the leptonic sector:

Show that there is CP violation in neutrino oscillation.

To establish that there is lepton number violation:

Show that neutrinoless double beta decay occurs.

This is one more reason we want to do both of these experiments.

Summary

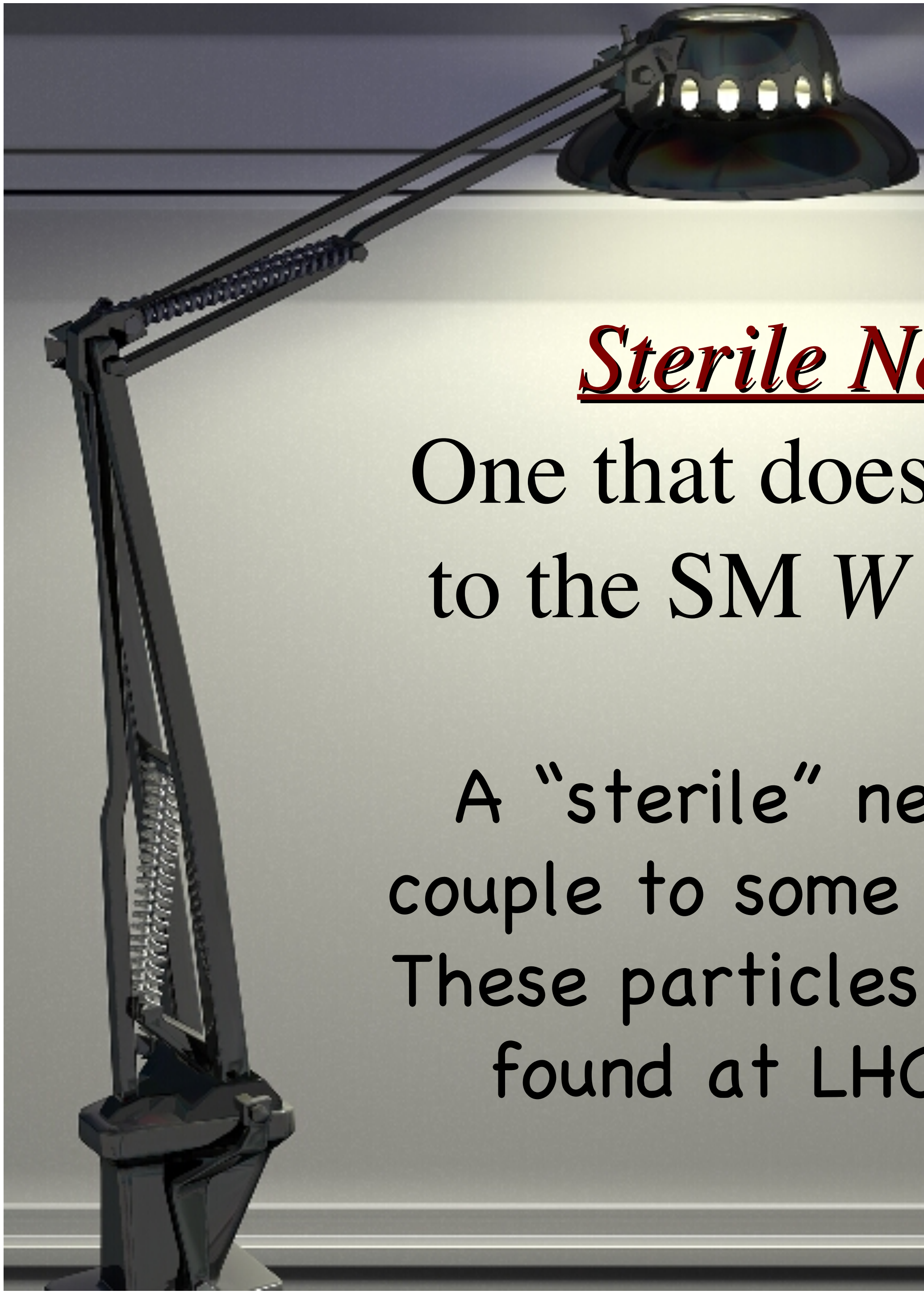
We have learned a lot about the neutrinos in the last 15 years.

What we've learned has raised very interesting questions.

We look forward to answering them!

Backup/Resource Slides

Are There Sterile Neutrinos?



Sterile Neutrino

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

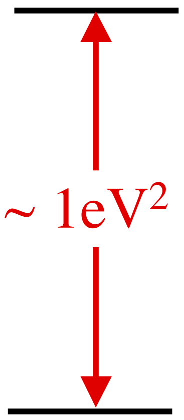
A “sterile” neutrino may well couple to some non-SM particles. These particles could perhaps be found at LHC or elsewhere.

The Hint From LSND

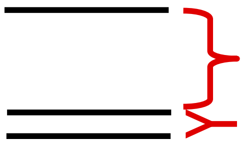
The LSND experiment at Los Alamos reported a ***rapid*** $\bar{\nu}_\mu \to \bar{\nu}_e$ oscillation at $L(km)/E(GeV) \sim 1$.

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

From μ^+ decay at rest; E ~ 30 MeV



⇒ $\sim 1\text{eV}^2$ in contrast to



$\Delta m^2_{32} = 2.4 \times 10^{-3}\ \text{eV}^2$

$\Delta m^2_{21} = 7.5 \times 10^{-5}\ \text{eV}^2$

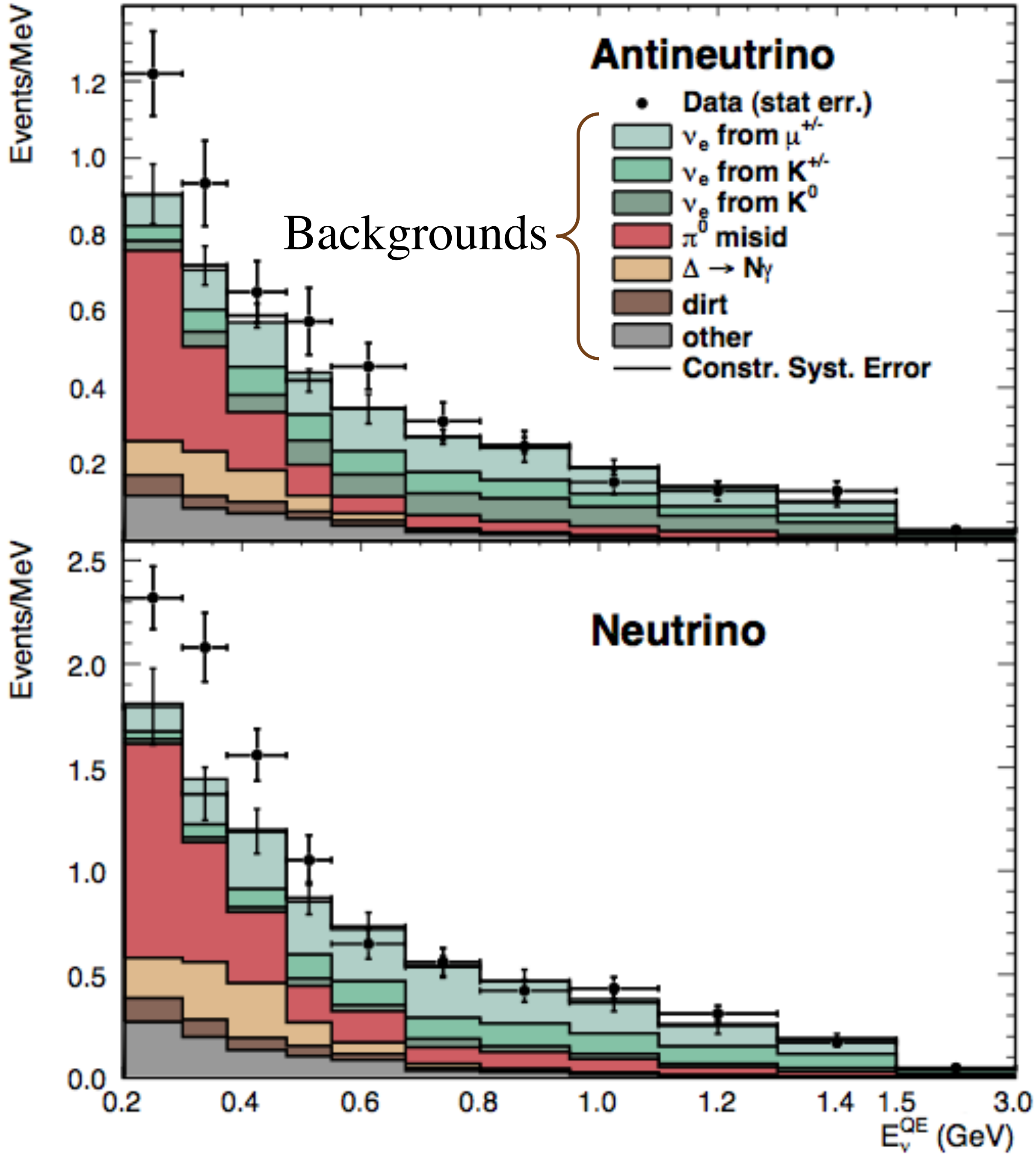
⇒ At least **4** mass eigenstates

⇒ {from measured $\Gamma(Z \to \nu\bar{\nu})$} 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 $\overline{\nu}_\mu \rightarrow \overline{\nu}_e$ results.



MiniBooNE

1303.2588

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

The Hint From Reactors

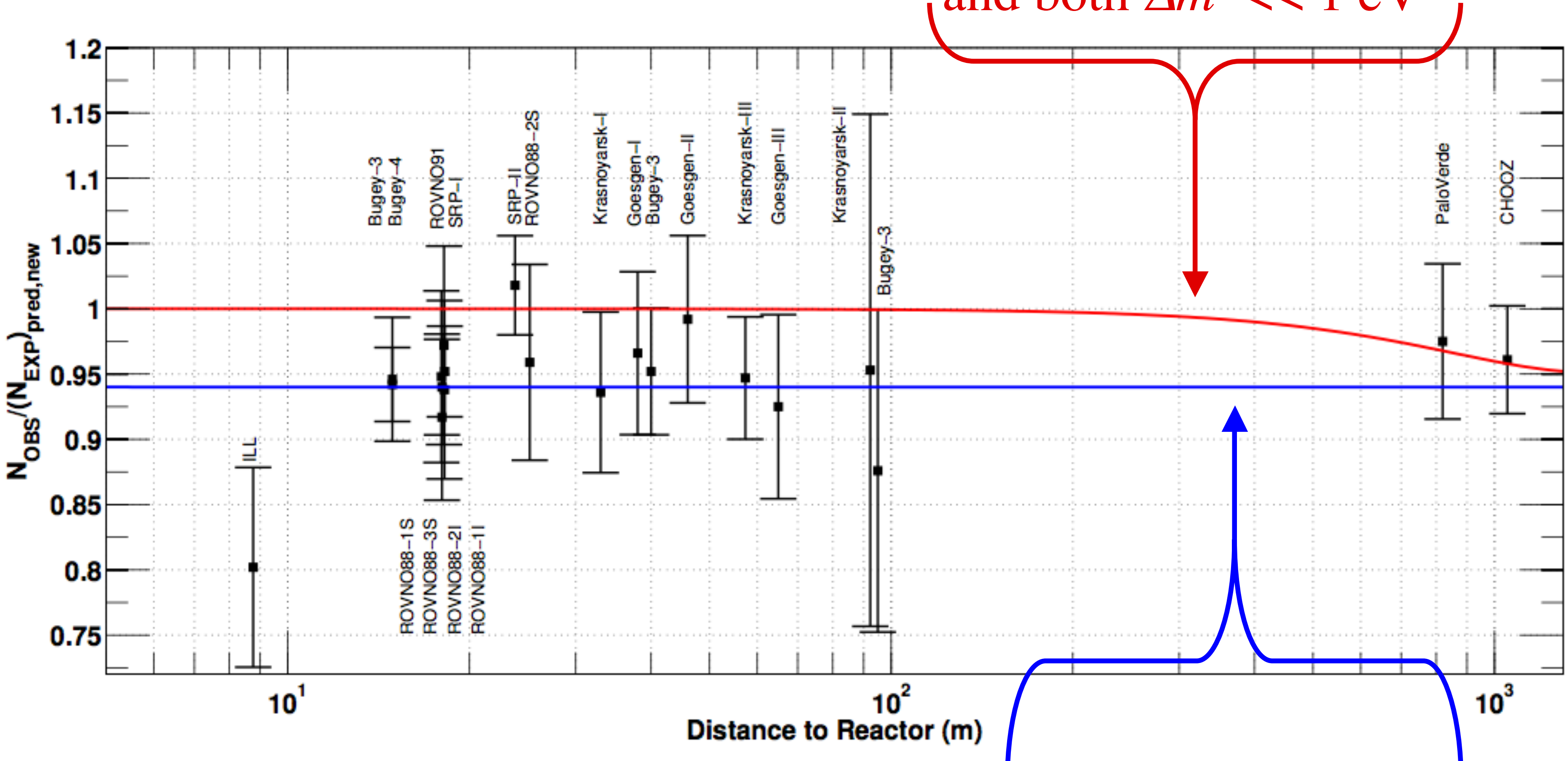
The prediction for the un-oscillated $\overline{\nu}_e$ flux from reactors, which has $\langle E \rangle \sim 3$ MeV, has increased by about 3%.

(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 $\Delta m^2 << 1\ \text{eV}^2$



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

Disappearance at L(m)/E(MeV) $\gtrsim 1$ suggests oscillation with $\Delta m^2 \gtrsim 1\ \text{eV}^2$, 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??