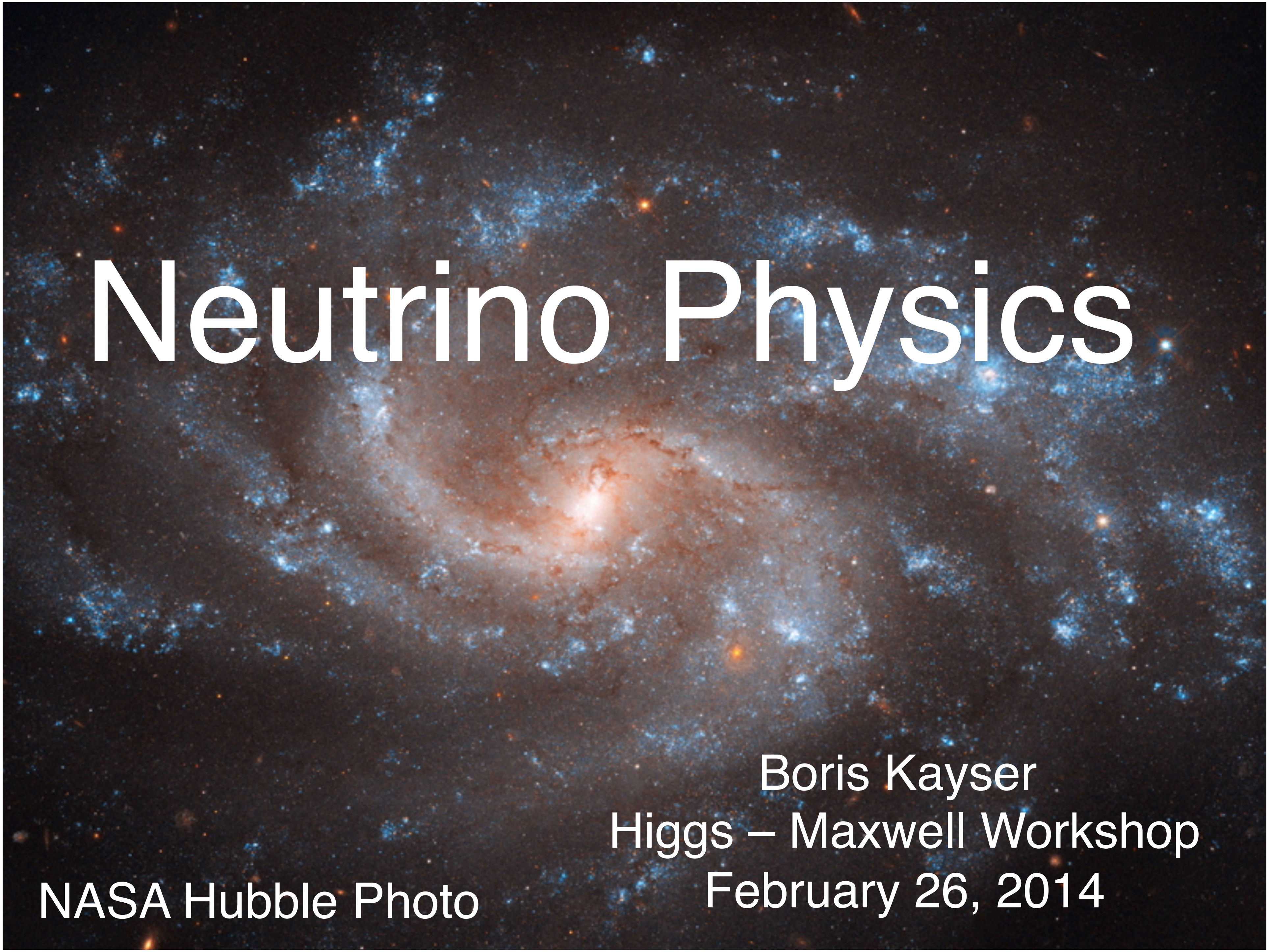
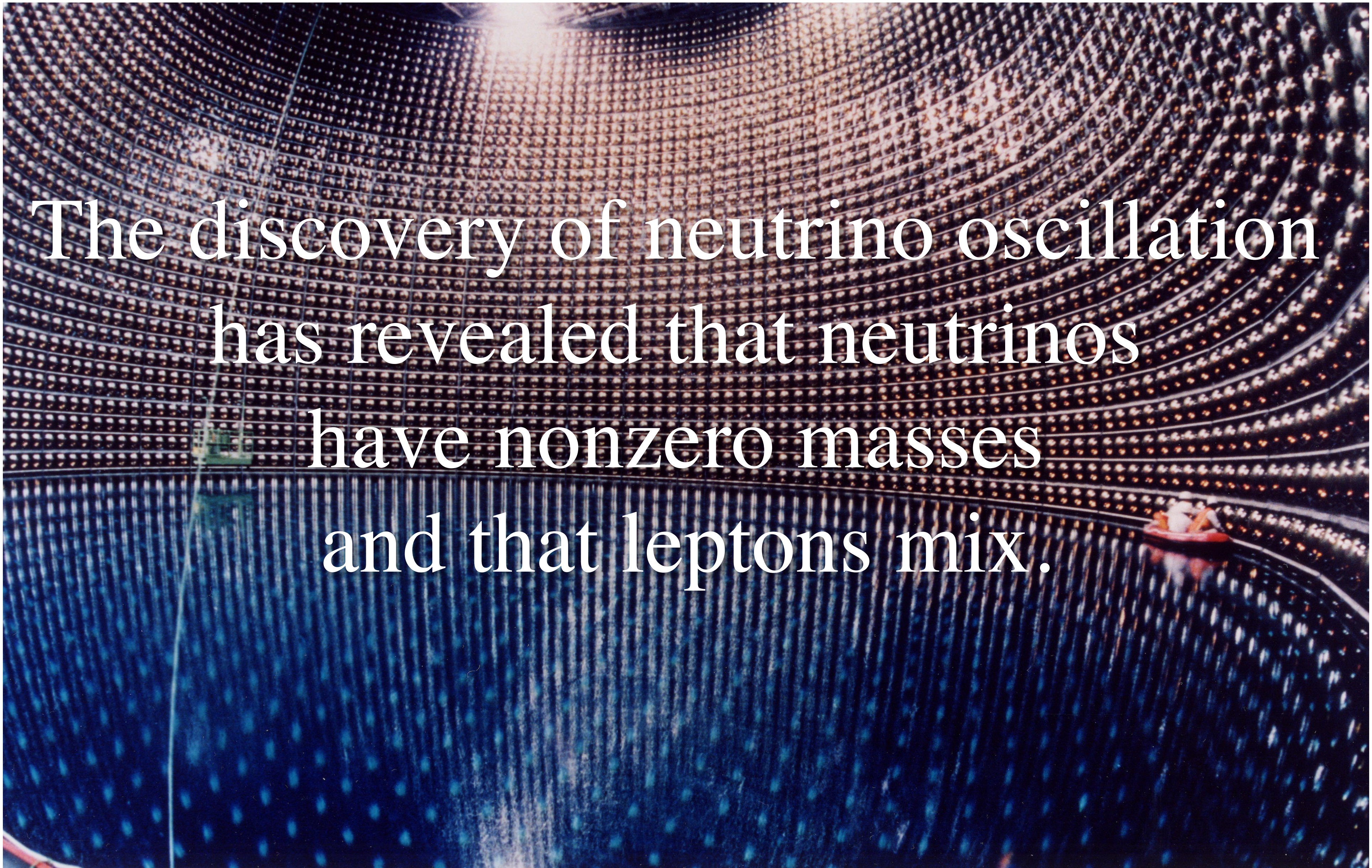


Neutrino Physics

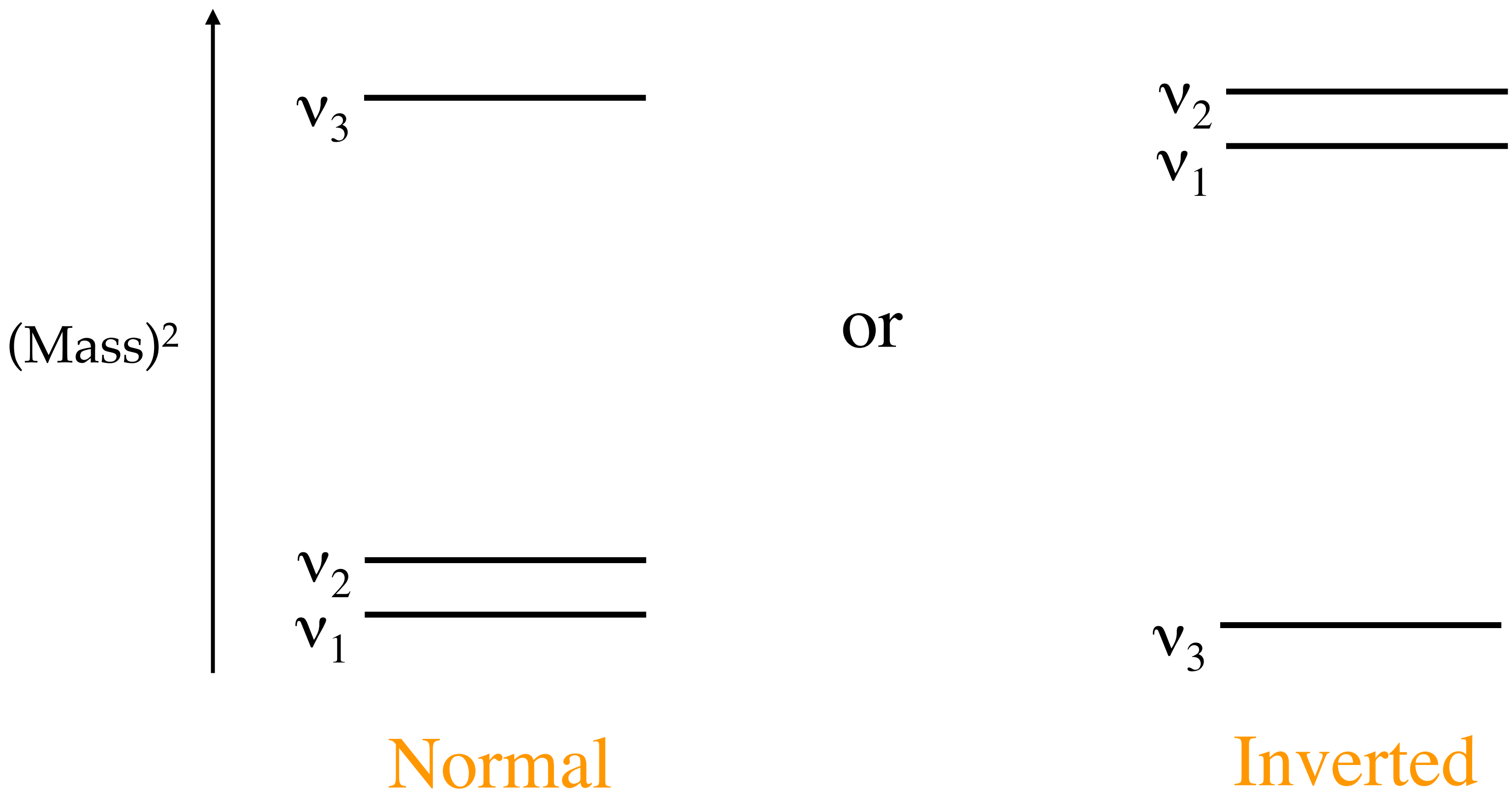
Boris Kayser
Higgs – Maxwell Workshop
February 26, 2014

NASA Hubble Photo


The discovery of neutrino oscillation
has revealed that neutrinos
have nonzero masses
and that leptons mix.

What We Have Learned

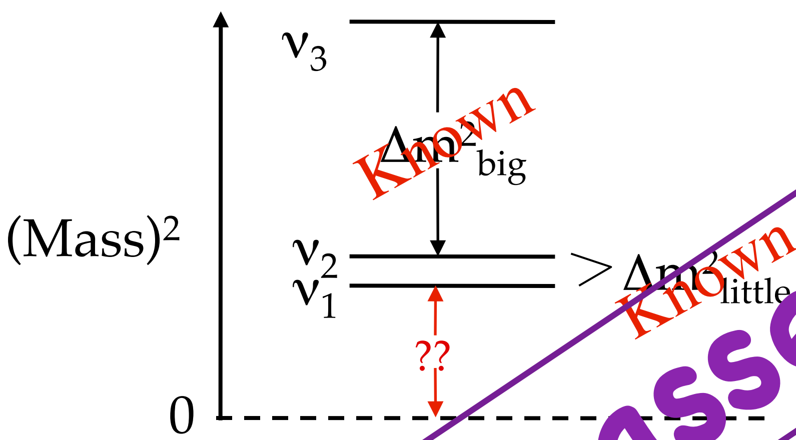
The Three – Neutrino $(\text{Mass})^2$ Spectrum



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

There might be more mass eigenstates.

Constraints On the Absolute Scale of Neutrino Mass



How far above zero is the whole pattern?

Neutrino masses are tiny

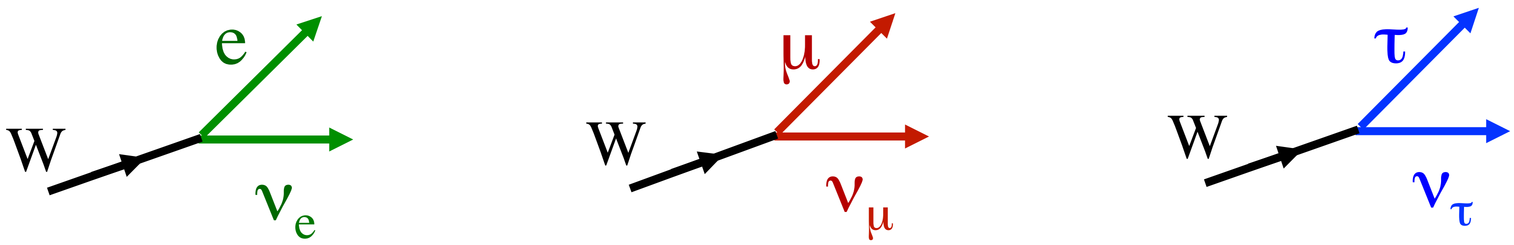
Cosmology, *under certain assumptions* $\Rightarrow$ $\sum m(\nu_i) < 0.23$ eV

All *i*

Tritium beta decay $\Rightarrow$ $\sqrt{0.69m^2(\nu_1)+0.29m^2(\nu_2)+0.02m^2(\nu_3)} < 2$ eV

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

ν_e, ν_μ, ν_τ Are Not the Mass Eigenstates



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

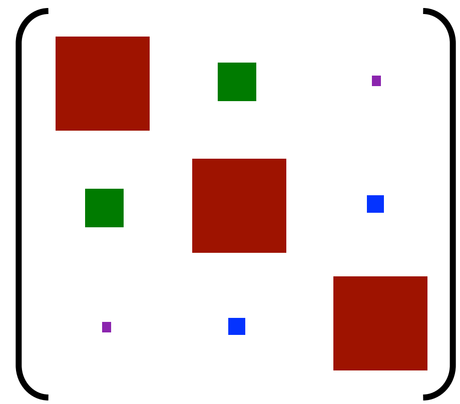
Neutrino of definite mass m_i

Unitary Leptonic Mixing Matrix

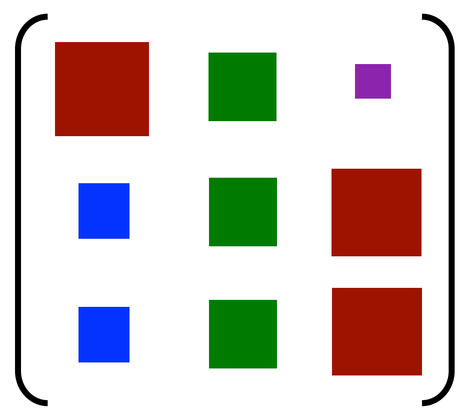
Leptonic Mixing

The Quark and Lepton Mixing Matrices

Quark mixing matrix =



Lepton mixing matrix =



The Lepton Mixing Matrix *U*

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

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

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

Note big mixing!

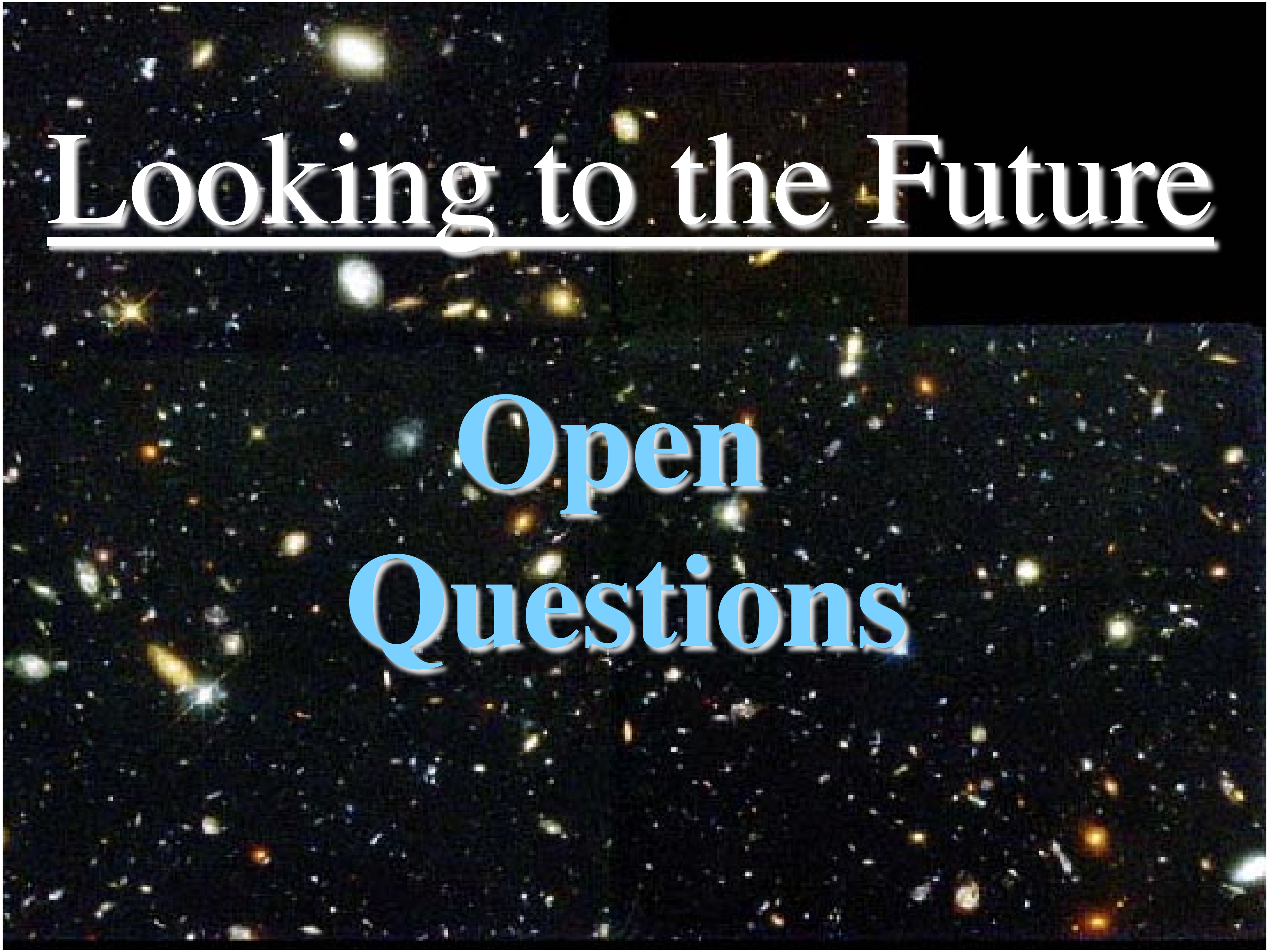
$\underbrace{\theta_{12} \approx 33°,\ \theta_{23} \approx 36\text{-}42° \ \underline{\text{or}}\ 48\text{-}54°,}$ $\theta_{13} \approx 8\text{-}9°$ ← *Not very small!*

The phases violate CP. 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 $s_{13} \equiv \sin\theta_{13}$.

We know nothing about the phases.


Looking to the Future
Open
Questions

• What is the absolute scale
of neutrino mass?

•Is the physics behind the masses of neutrinos
different from that behind the masses
of all other known particles?

•Are neutrinos their own antiparticles?

•Is the spectrum like  or  ?

- Do neutrino interactions violate CP?

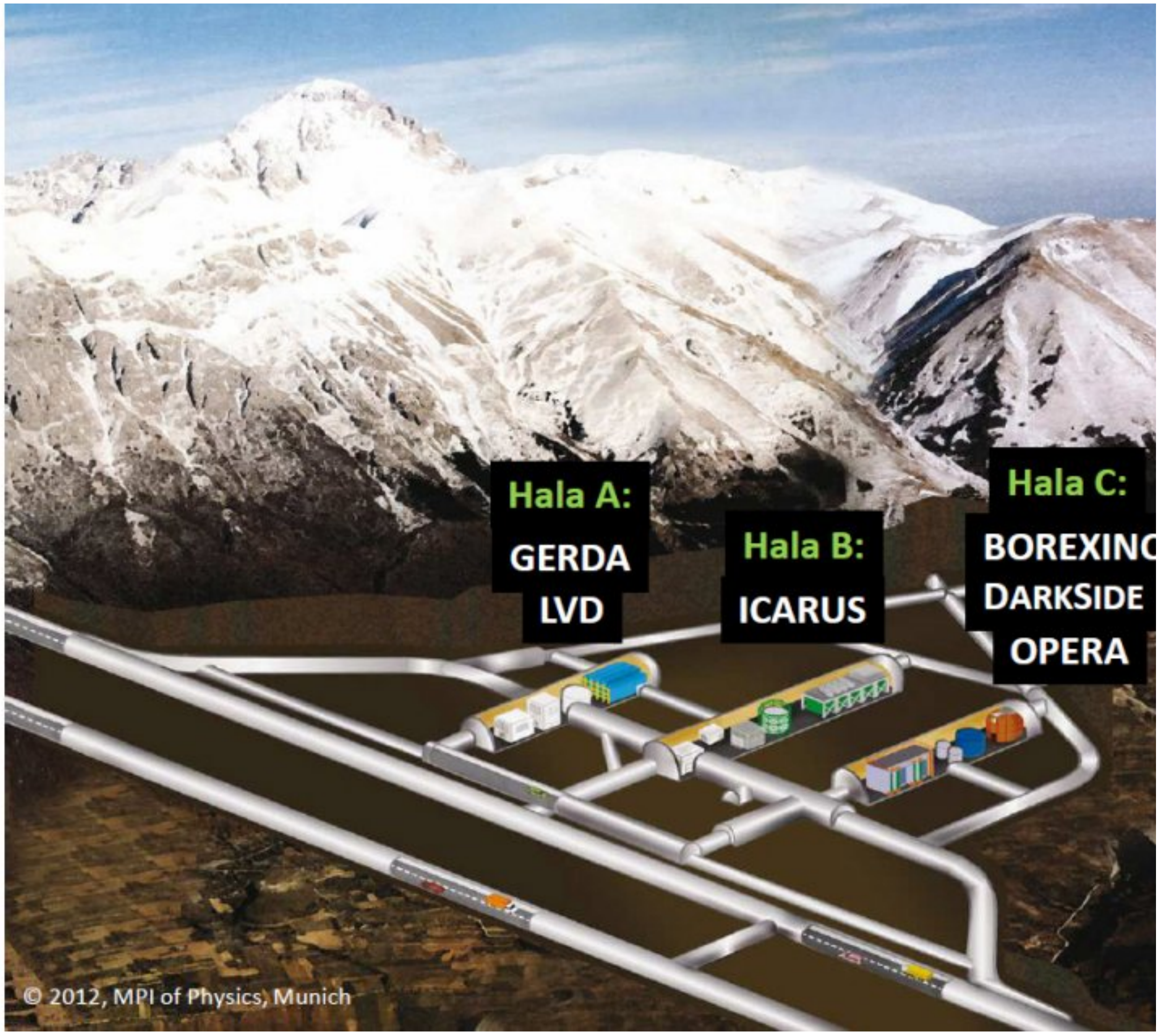
  Is $P(\bar{\nu}_\alpha \rightarrow \bar{\nu}_\beta) \neq P(\nu_\alpha \rightarrow \nu_\beta)$?

- Is CP violation involving neutrinos the key to understanding the matter – antimatter asymmetry of the universe?

- What can neutrinos and the universe tell us about one another?

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

- Do neutrinos break the rules?
  - Non-Standard-Model interactions?
  - Violation of Lorentz invariance?
  - Violation of CPT invariance?
  - Departures from quantum mechanics?



Are Neutrino Masses Different?

Perhaps, neutrino masses have the same source as the quark and charged lepton masses:

The Standard Model (SM) Brout – Englert – Higgs mechanism for fermion masses.

Coupling constant

Must add to the SM

$$\mathcal{L}_{SM} = y\overline{H}^0\overline{\nu}_L\nu_R \Rightarrow y\underbrace{\left\langle \overline{H}^0 \right\rangle_0}_{\text{Vacuum expectation value}}\overline{\nu}_L\nu_R \equiv m_\nu\overline{\nu}_L\nu_R$$

SM Higgs field

$$\left\langle \overline{H}^0 \right\rangle_0 \equiv v = 174\text{ GeV}\ ,\ \text{so}\ \ y = \frac{m_\nu}{v} \sim \frac{0.1\,\text{eV}}{174\text{ GeV}} \sim 10^{-12}$$

A coupling constant this much smaller than unity leaves many theorists skeptical.

— An alternative possibility —

Majorana masses and the **See-Saw** picture

The See-Saw model is the most popular theory of why neutrinos are so light.

The straightforward (type-I) See-Saw model adds to the SM 3 heavy neutrinos N_i, with —

Large Majorana masses

SM lepton doublet

$$\mathcal{L}_{\text{new}} = -\frac{1}{2}\sum_i m_{N_i} N_{iR}^2 \quad + \sum_{\substack{\alpha=e,\mu,\tau \\ i=1,2,3}} y_{\alpha i}\left[\bar{\nu}_{\alpha L}\overline{H^0} - \bar{\ell}_{\alpha L} H^-\right] N_{iR} + h.c.$$

SM Higgs doublet

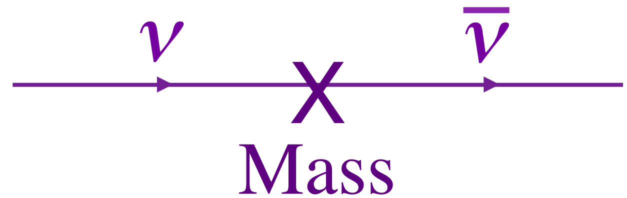
Yukawa coupling matrix

In this picture, there is still a coupling of the neutrinos to the SM Higgs field.

In addition, there is a new ingredient: large Majorana masses, whose origin is unknown physics.

Majorana masses cannot come from the standard, linear Yukawa coupling of neutrinos to the SM Higgs field.

Majorana mass terms have the effect —



(Or the reverse)

Because they mix neutrino and antineutrino,
they do not conserve $L \equiv$ #(Leptons) – #(Antileptons).

There is then no conserved quantum number
to distinguish antineutrinos from neutrinos.

Consequence: The neutrino mass eigenstates ν_1, ν_2, ν_3 are their own antiparticles.

$$\bar{\nu}_i \equiv \nu_i$$

Majorana neutrinos

- **Presence of Majorana masses**
- **Non-conservation of *L***
- **Self-conjugacy of neutrinos ($\bar{\nu} = \nu$)**

— are all signature predictions of the See-Saw picture.

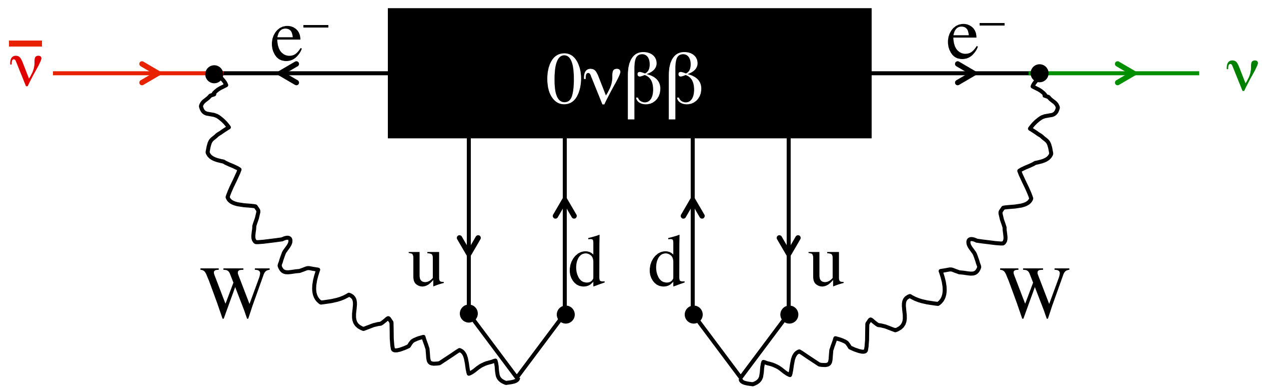
All three predictions would be confirmed by the observation of neutrinoless double beta decay (0νββ)

$\Delta L = 2$

does not conserve L.

Whatever diagrams cause $0\nu\beta\beta$, its observation would imply the existence of a Majorana mass term:

(Schechter and Valle)



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

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

The See-Saw picture leads to —

The See-Saw Relation

Leptonic mixing matrix

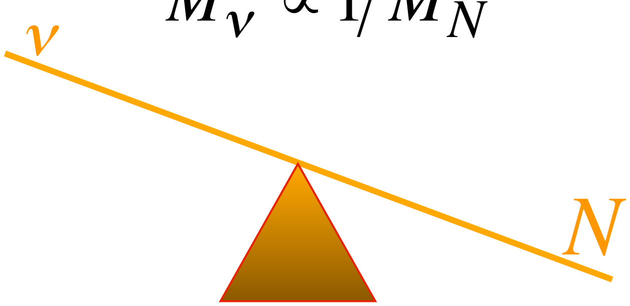
Heavy N mass eigenvalues

$$UM_\nu U^T = -v^2\left(y\, M_N^{-1} y^T\right)$$

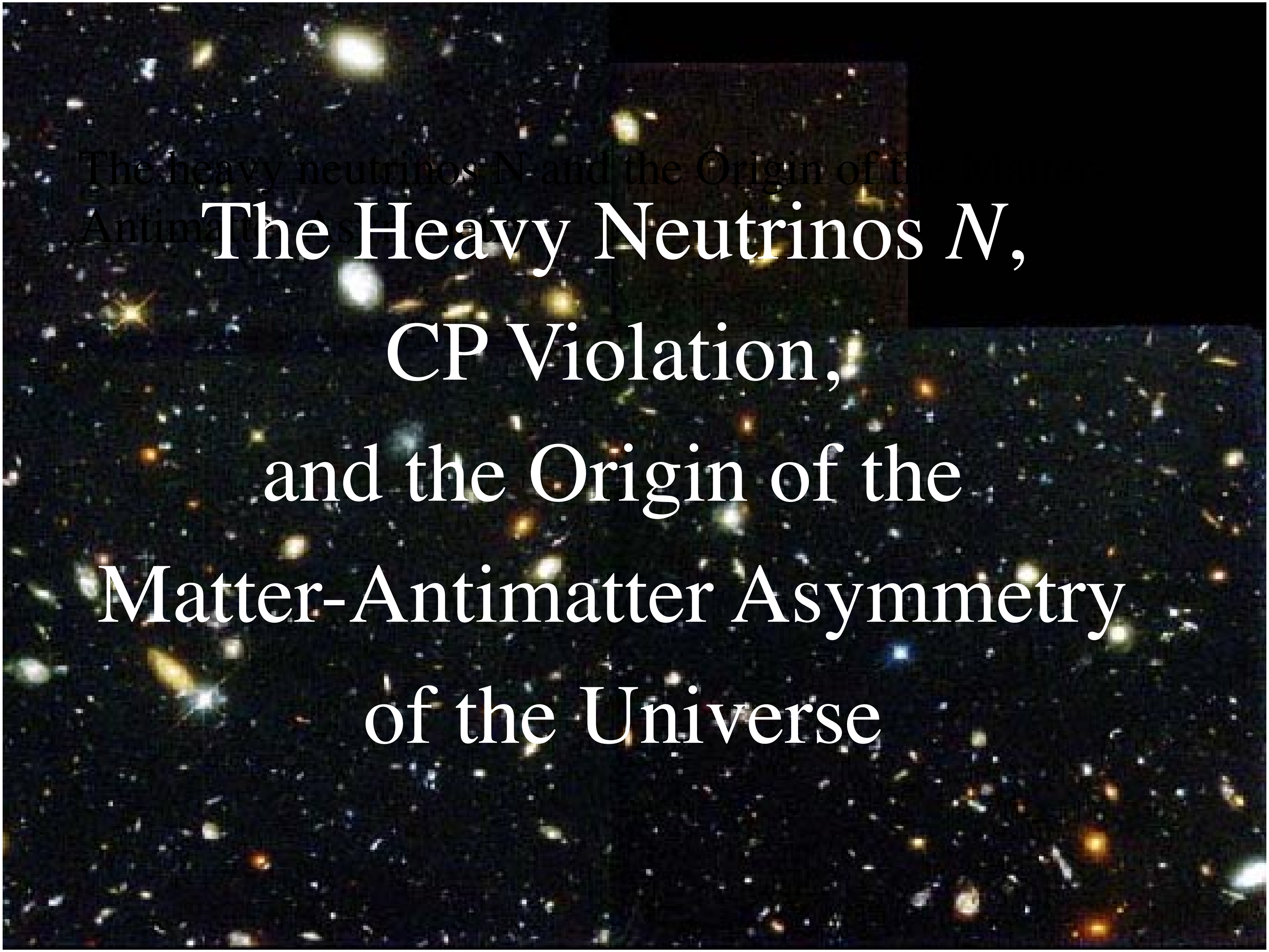
Light ν mass eigenvalues

The Higgs vev, 174 GeV

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



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


The Heavy Neutrinos *N*,
CP Violation,
and the Origin of the
Matter-Antimatter Asymmetry
of the Universe

The 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 $B = 0 \Longrightarrow B \neq 0$?

Sakharov: $B = 0 \Longrightarrow B \neq 0$ requires $\not{C}$ and $\cancel{CP}$.

$\not{C}$ is easy to achieve, but the required degree and kind of $\not{CP}$ is harder.

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

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

The candidate scenario: *Leptogenesis*, a very natural consequence of the See-Saw picture.

(Fukugita, Yanagida)

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

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

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

and

CP mirror image modes

In the See-Saw, $\overline{N} = N$

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

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 $L \neq 0$.

Next —

The Standard-Model ***Sphaleron*** process,
which does not conserve Baryon Number B,
or Lepton Number L, but does conserve $B - L$, acts.

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

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 B.

There are baryons, but ~ no antibaryons.

Reasonable couplings y give the observed value of B.

The heavy neutrinos N must be **very** heavy.

The see-saw relation $M_\nu \sim \dfrac{v^2 y^2}{M_N}$ and the y^2 called for

by the observed cosmic $B - \overline{B}$ asymmetry

$$\Rightarrow \quad M_N \gtrsim 10^{(9-10)}\ \text{GeV}.$$

This places the heavy neutrinos N far out of reach of the LHC.

$\Rightarrow$ ***The possibility of Leptogenesis must be explored by experiments that do not produce an N.***

Number of leptonic parameters in the See-Saw picture: 21

Number of these parameters that can be measured without producing the heavy neutrinos N: 12

Since 21 > 12, laboratory measurements today cannot pin down what happened in the early universe.

Can there be $\cancel{CP}$ in ν oscillation but no leptogenesis? Yes.

Can there be leptogenesis but no $\cancel{CP}$ in ν oscillation? Yes.

Is either of these possibilities likely? ***NO!***

An Argument

(B.K.)

The See-Saw Relation

Leptonic mixing matrix

Heavy N mass eigenvalues

$$UM_\nu U^T = -v^2\left(y\, M_N^{-1} y^T\right)$$

Light ν mass eigenvalues

The Higgs vev, a real number

$$\left(\underbrace{UM_\nu U^T}_{\text{Outputs}} = -v^2 \underbrace{\left(y\, M_N^{-1} y^T\right)}_{\text{Inputs, in } \mathcal{L}}\right)$$

Through ***U***, the phases in ***y*** lead to $\cancel{CP}$ in light neutrino oscillation.

Probability of the oscillation $\overset{(-)}{\nu}_\alpha \to \overset{(-)}{\nu}_\beta$

$$P(\overset{(-)}{\nu}_\alpha \to \overset{(-)}{\nu}_\beta) =$$

Distance

e, μ, or τ

$$= \delta_{\alpha\beta} - 4\sum_{i>j} \Re(U^*_{\alpha i} U_{\beta i} U_{\alpha j} U^*_{\beta j}) \sin^2(\Delta m^2_{ij} \frac{L}{4E})$$

$$\underset{(-)}{+} 2\sum_{i>j} \Im(U^*_{\alpha i} U_{\beta i} U_{\alpha j} U^*_{\beta j}) \sin(\Delta m^2_{ij} \frac{L}{2E})$$

Neutrino (Mass)^2 splitting

Energy

$\cancel{CP}$ phases in U, which produce $\cancel{CP}$ in ν oscillation, and influence the rate for neutrinoless double beta decay, also lead in general to a baryon-antibaryon asymmetry.

(Abada, Davidson, Ibarra, Josse-Michaux, Losada, Nardi, Nir, Racker, Riotto, Roulet; Pascoli, Petcov, Riotto, Rodejohann)

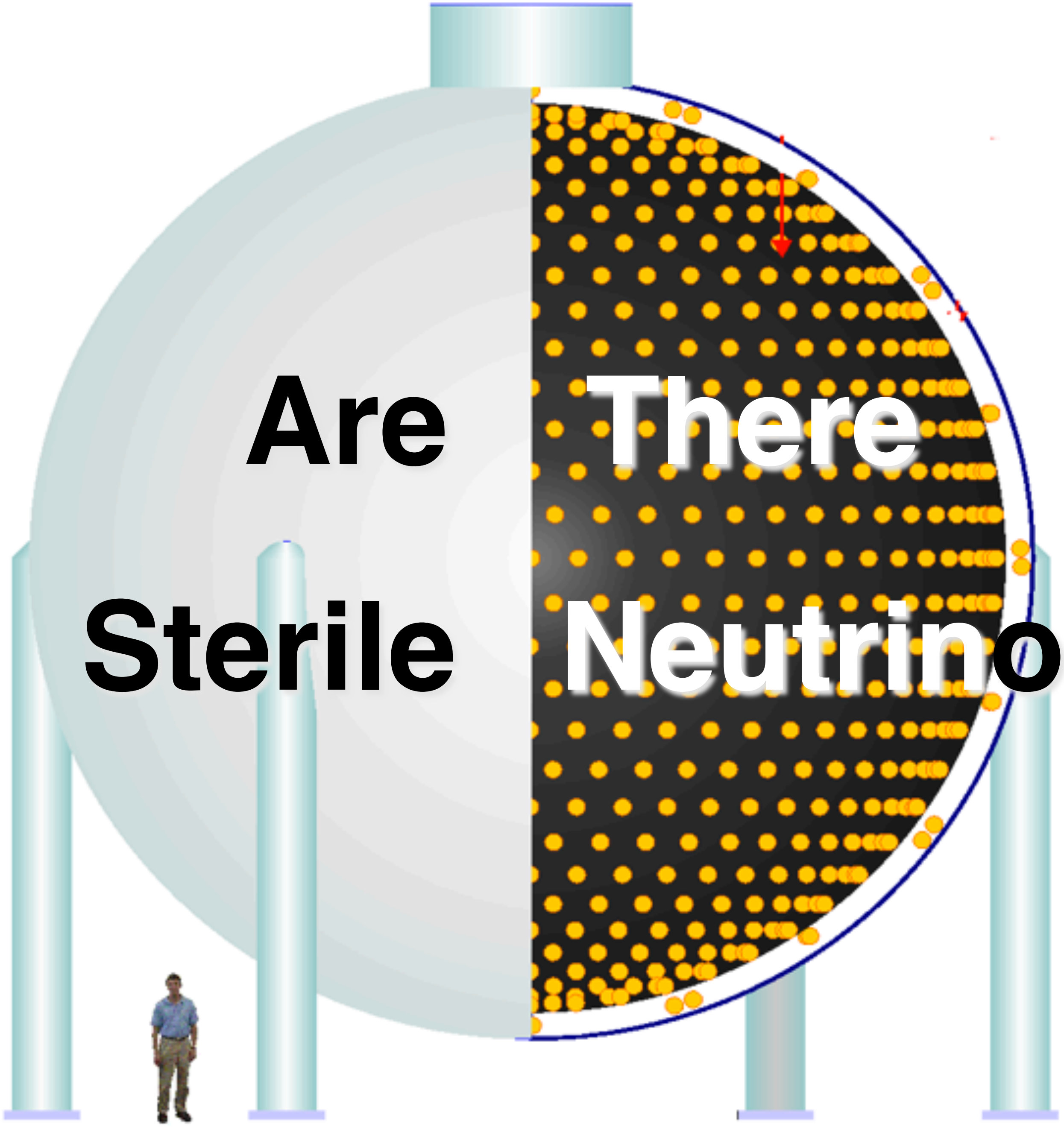
Given that θ_{13} is relatively large, the phase δ that drives $\cancel{CP}$ in ν oscillation can be sufficient, all by itself, to account for the whole observed cosmic $B - \overline{B}$ asymmetry.

(Pascoli, Petcov, Riotto)

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

Seeking ~~CP~~ violation in light neutrino oscillation is now a major global goal.

Are There Sterile Neutrinos?



Sterile Neutrino

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

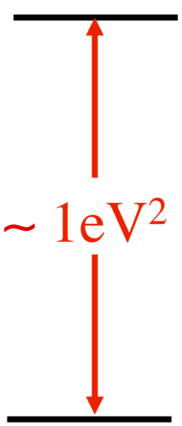
A “sterile” neutrino may well couple to some non-SM particles. These particles could perhaps be found at LHC or elsewhere.

Some Hints — First LSND

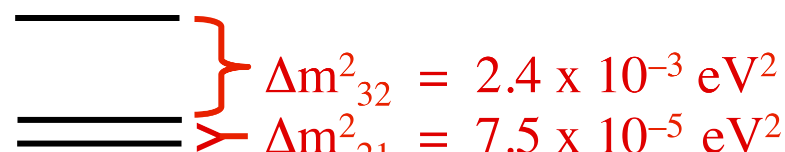
The LSND experiment at Los Alamos reported a ***rapid*** $\bar{\nu}_\mu \to \bar{\nu}_e$ oscillation at $L(km)/E(GeV) \sim 1$.

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

From μ^+ decay at rest; E ~ 30 MeV



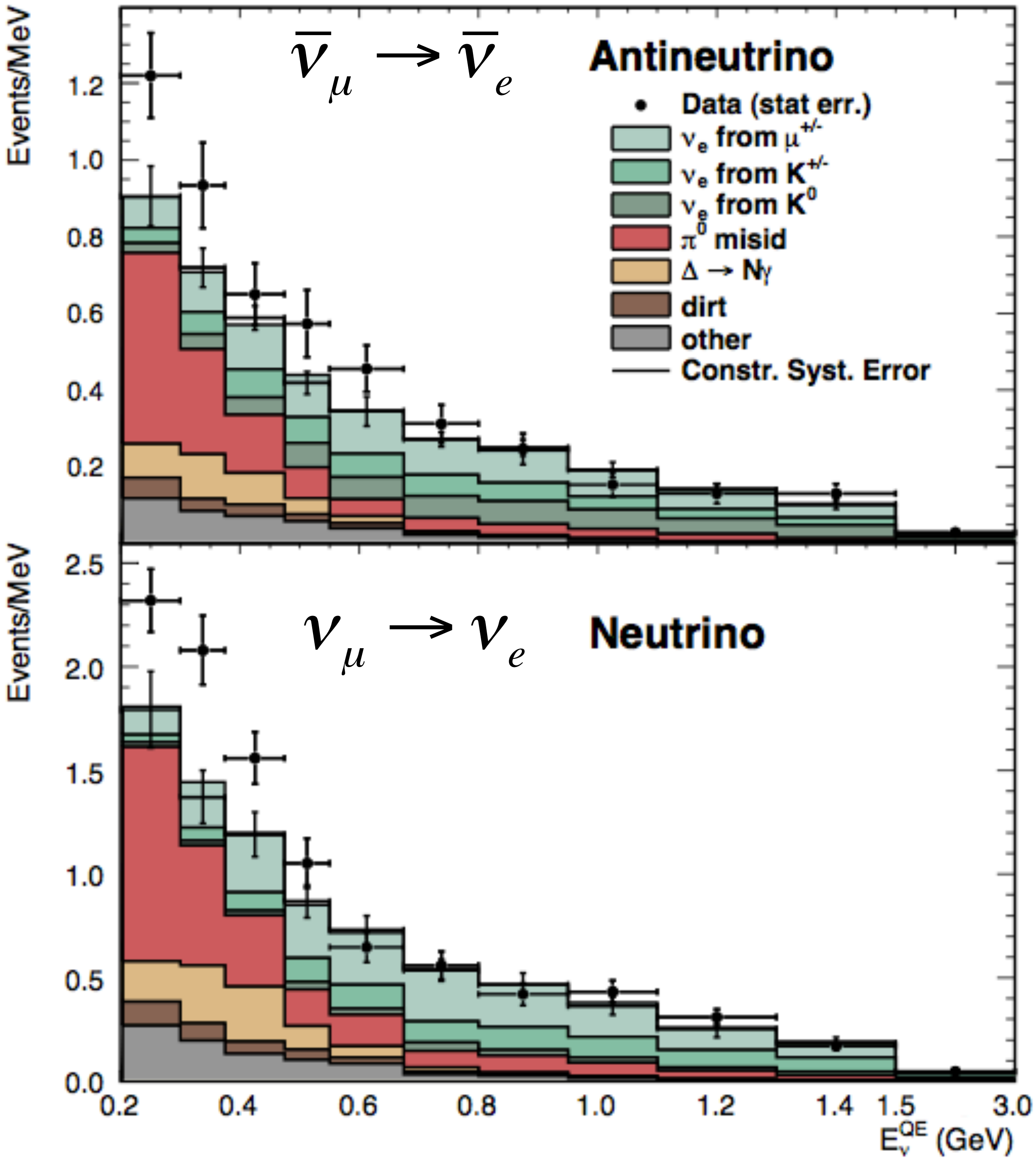
in contrast to



At least **4** mass eigenstates

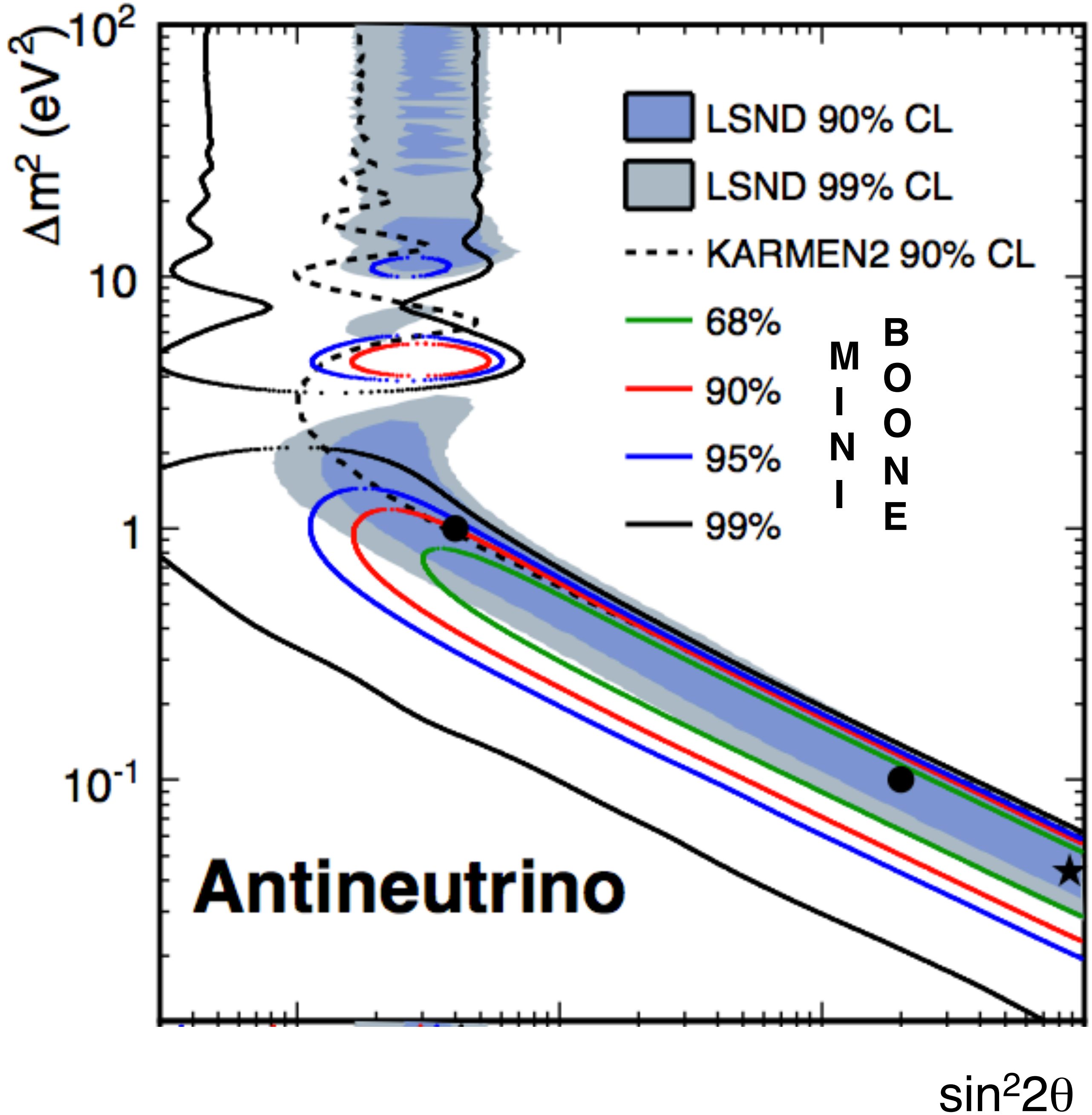
{from measured $\Gamma(Z \to \nu\bar{\nu})$} At least **1** sterile neutrino

The Hint From MiniBooNE



78.4 ± 28.5 excess events

162.0 ± 47.8 excess events



LSND and MiniBooNE allowed regions overlap.

A Hint From Reactors

The measured $\overline{\nu}_e$ flux at (10 – 100)m from reactor cores is ~ 6% below the theoretically expected value.

Are the $\overline{\nu}_e$ disappearing by oscillating into another flavor?

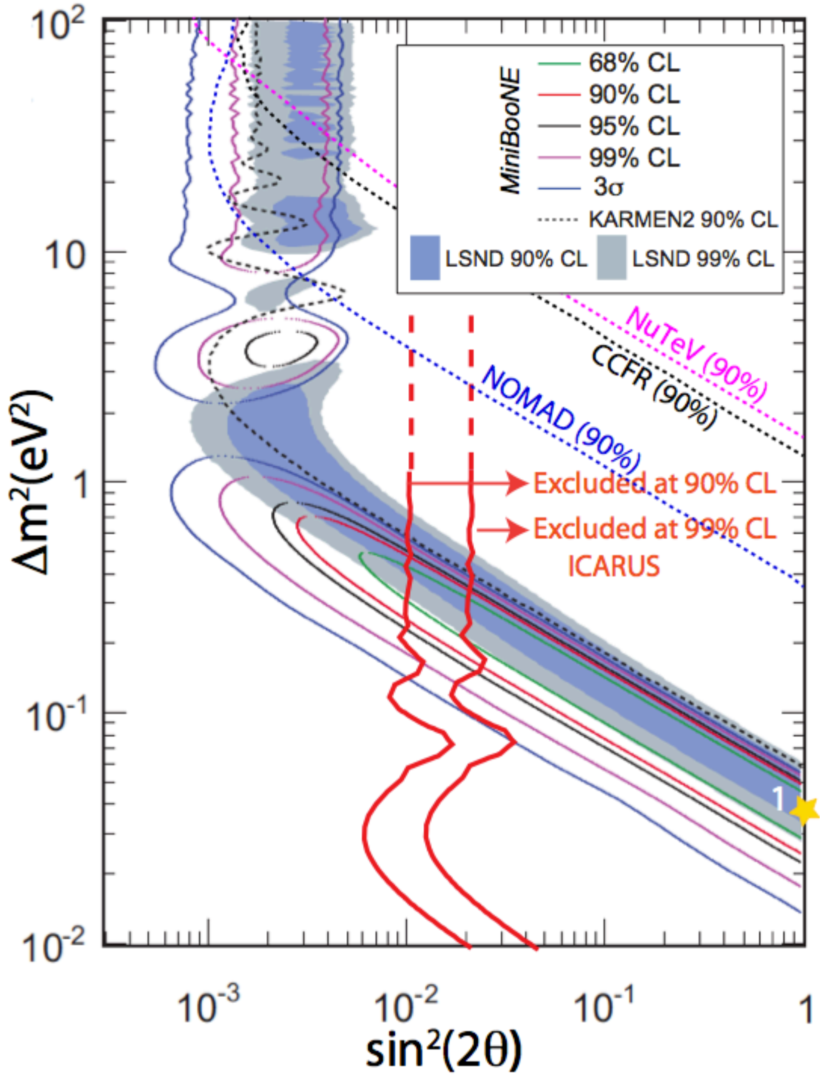
The $\overline{\nu}_e$ energy is ~ 3 MeV, so at, say, 15m,

$$L(\mathrm{m})/E(\mathrm{MeV}) = L(\mathrm{km})/E(\mathrm{GeV}) \sim 5.$$

If the $\overline{\nu}_e$ are oscillating away,

$$\sin^2\left[1.27\Delta m^2\left(eV^2\right)\frac{L(km)}{E(GeV)}\right] \sim 1 \Longrightarrow \Delta m^2\left(eV^2\right) \sim 1 \cdot$$

ICARUS and OPERA, at $L/E \approx 35$ km/GeV, have not seen $\nu_\mu \rightarrow \nu_e$. This disfavors a $\nu_\mu \rightarrow \nu_e$ interpretation of the low-energy MiniBooNE ν_e excess.



ICARUS exclusion

So, are there sterile neutrinos?

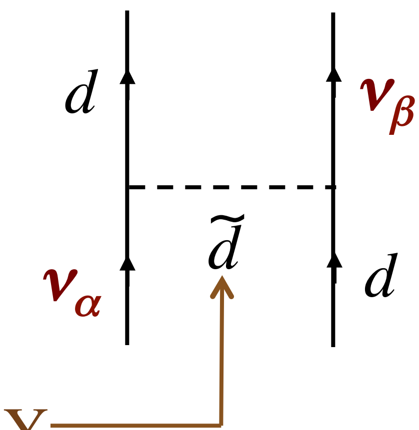
Stay tuned.

Do Neutrinos Break the Rules?

Non–SM Neutrino Interactions (NSI)?

Surely, there are new interactions beyond the SM, and neutrinos participate in (at least some of) them.

Example of a ***flavor – changing*** NSI from Supersymmetry



Squark from $\not{R}$ SUSY

Potentially, NSI can have significant effects on neutrino oscillation.

A Story

A few years ago, MINOS reported that ***maybe*** —

$$P\left(\bar{\nu}_\mu \to \bar{\nu}_\mu\right) \neq P\left(\nu_\mu \to \nu_\mu\right) .$$

For neutrinos traveling in vacuum (unlike the neutrinos of MINOS), this would violate CPT invariance.

But we do not even need to invoke interactions with matter en route to explain the early MINOS result.

The NSI $\nu_\tau + N \to X + \mu$ at the detector will do it.

(Kopp, Machado, Parke)

MINOS: With 70% more $\bar{\nu}_\mu$ data,
the $\bar{\nu}_\mu - \nu_\mu$ discrepancy went away.

But —

The Model and the Moral

A measurement of "$P(\nu_\mu \to \nu_\mu)$" is really a measurement of the μ^- production rate in a far detector.

Similarly for "$P(\bar{\nu}_\mu \to \bar{\nu}_\mu)$" and the μ^+ production rate.

Kopp et al. included not only the possibility of ν_μ survival, but also the possibility of $\nu_\mu \xrightarrow[\text{Osc.}]{} \nu_\tau + N \to X + \mu^-$.

Interference between the amplitudes for these two processes led to a CP-violating difference between the μ^- and the μ^+ production rates. No CPT violation was involved!

The moral: A difference between the μ^- production rate in an initially ν_μ beam, and the corresponding μ^+ production rate in an initially $\bar{\nu}_\mu$ beam, is not necessarily a violation of CPT.

Such a difference may be a striking effect of NSI.

Lorentz-Invariance Violation (LIV)?

Suppose —

SM lepton doublet

$$\mathcal{L} \supset \left(a_\mu\right)_{\alpha\beta} \bar{L}_\alpha \gamma^\mu L_\beta + \frac{1}{2} i \left(c_{\mu\nu}\right)_{\alpha\beta} \bar{L}_\alpha \gamma^\mu \overleftrightarrow{D}_\nu L_\beta$$

Frame independent LIV numbers

$\alpha, \beta =$ e, μ, τ

(Kostelecky & Mewes)

This contributes terms ~ aL and cEL to the phases of neutrino oscillation.

If $L = 10^3$ km, and $E = 1$ GeV, $a = 10^{-13}$ eV and $c = 10^{-22}$ can lead to visibly-large phases ~ 1.

Summary

Neutrino oscillation has proved that neutrinos have nonzero masses.

These masses may have a quite different origin than the quark and charged lepton masses.

We, and all matter, may be descended from heavy neutrinos.

Surprises may well be coming.