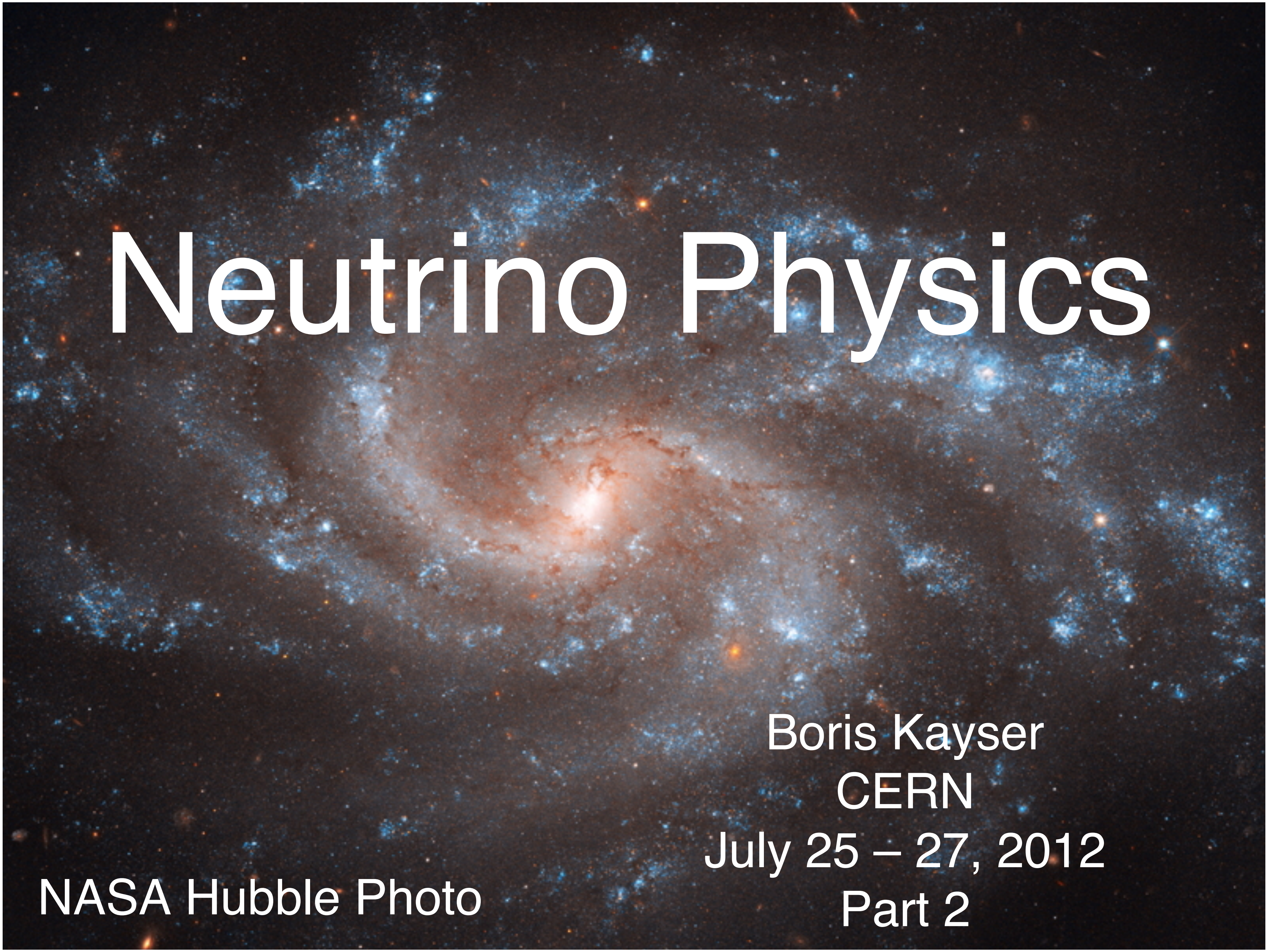
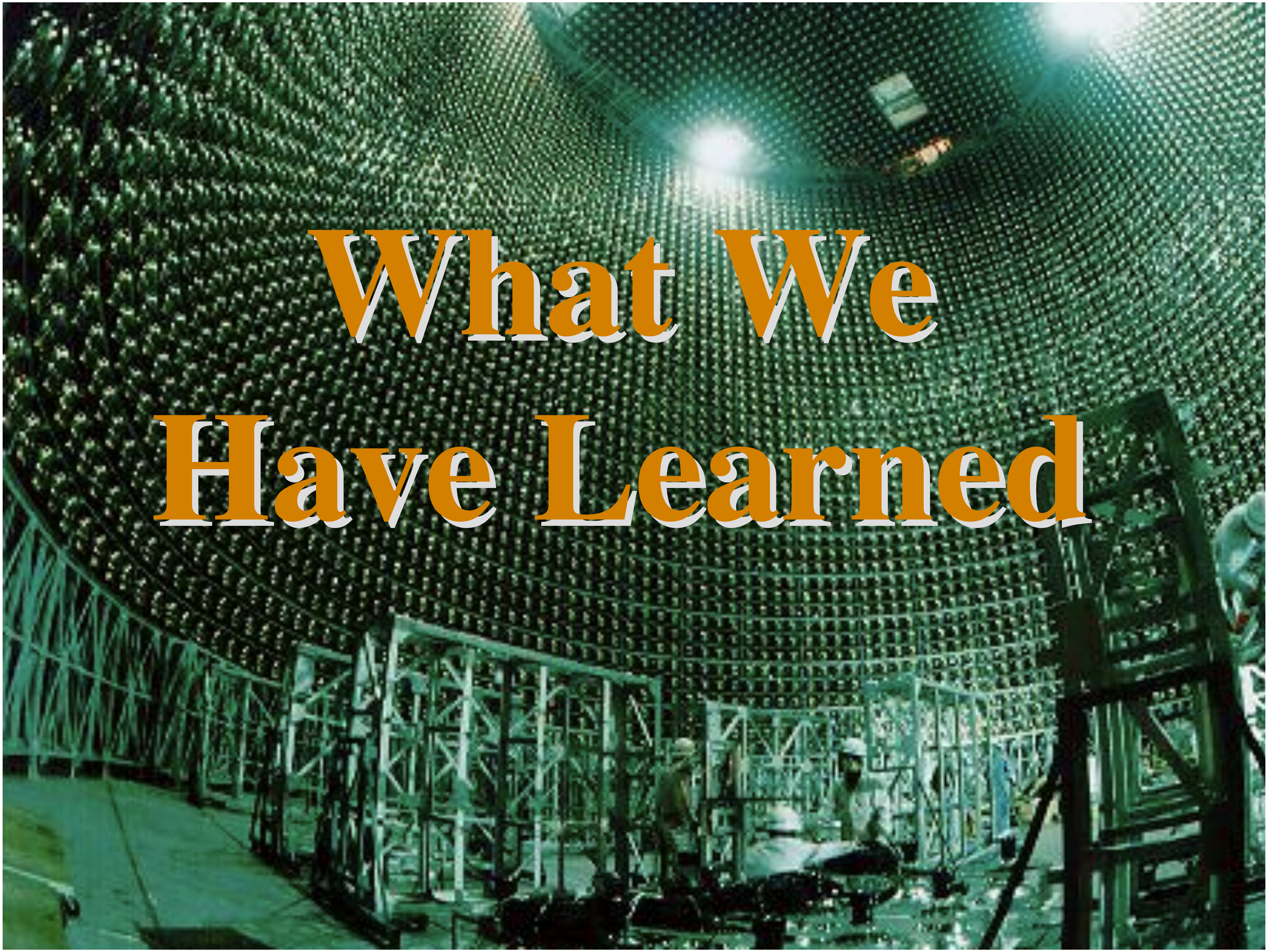


Neutrino Physics

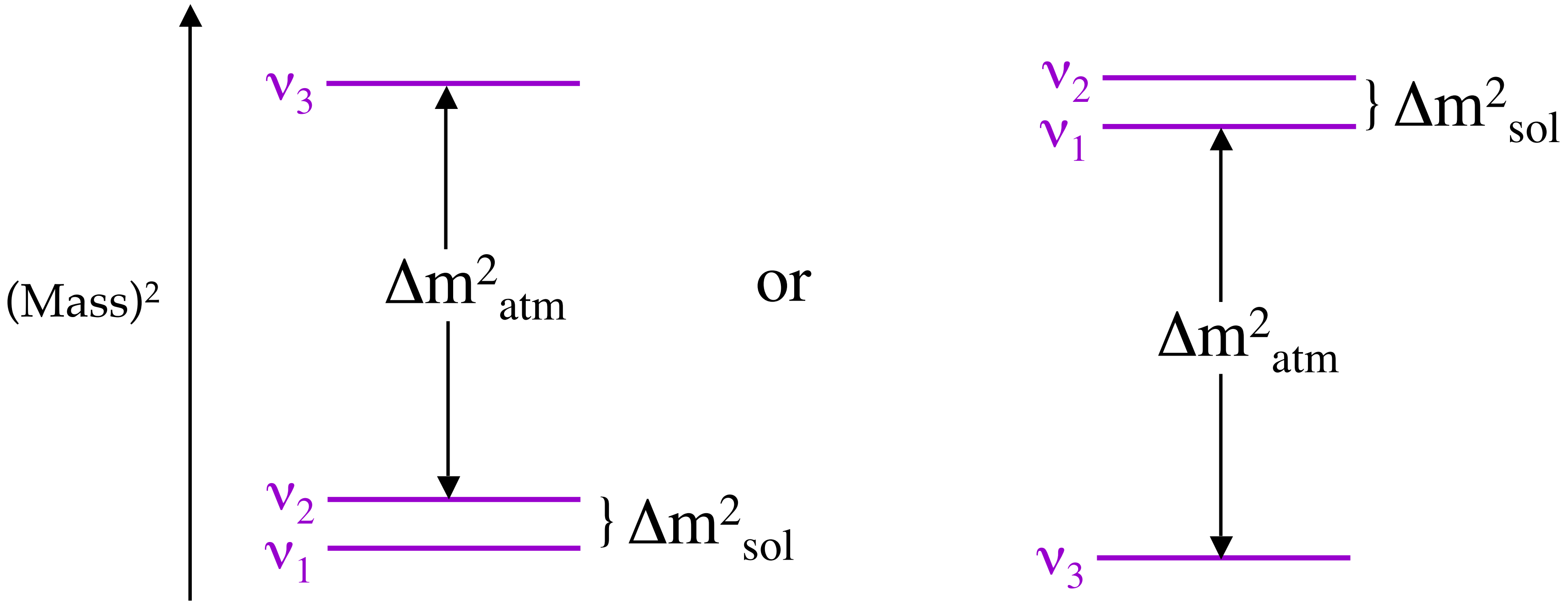
Boris Kayser
CERN
July 25 – 27, 2012
Part 2

NASA Hubble Photo



What We Have Learned

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



Normal

Inverted

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

The Mixing Matrix *U*

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

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

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

$\theta_{12} \approx 34°$, $\theta_{23} \approx 39\text{-}51°$, $\theta_{13} \approx 8\text{-}10°$ ***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 $s_{13} \equiv \sin\theta_{13}$.

There Is Nothing Special About θ_{13}

All mixing angles must be nonzero for $\cancel{CP}$ in oscillation.

For example —

$$P\left(\bar{\nu}_\mu \to \bar{\nu}_e\right) - P\left(\nu_\mu \to \nu_e\right) = 2\cos\theta_{13}\sin 2\theta_{13}\sin 2\theta_{12}\sin 2\theta_{23}\sin\delta$$
$$\times \sin\left(\Delta m^2{}_{31}\frac{L}{4E}\right)\sin\left(\Delta m^2{}_{32}\frac{L}{4E}\right)\sin\left(\Delta m^2{}_{21}\frac{L}{4E}\right)$$

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

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 “sterile” neutrinos?

- What are the neutrino magnetic and electric dipole moments?

How close to maximal is θ_{23}?

- Is the spectrum like  or  ?

- Do neutrino interactions violate CP?

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

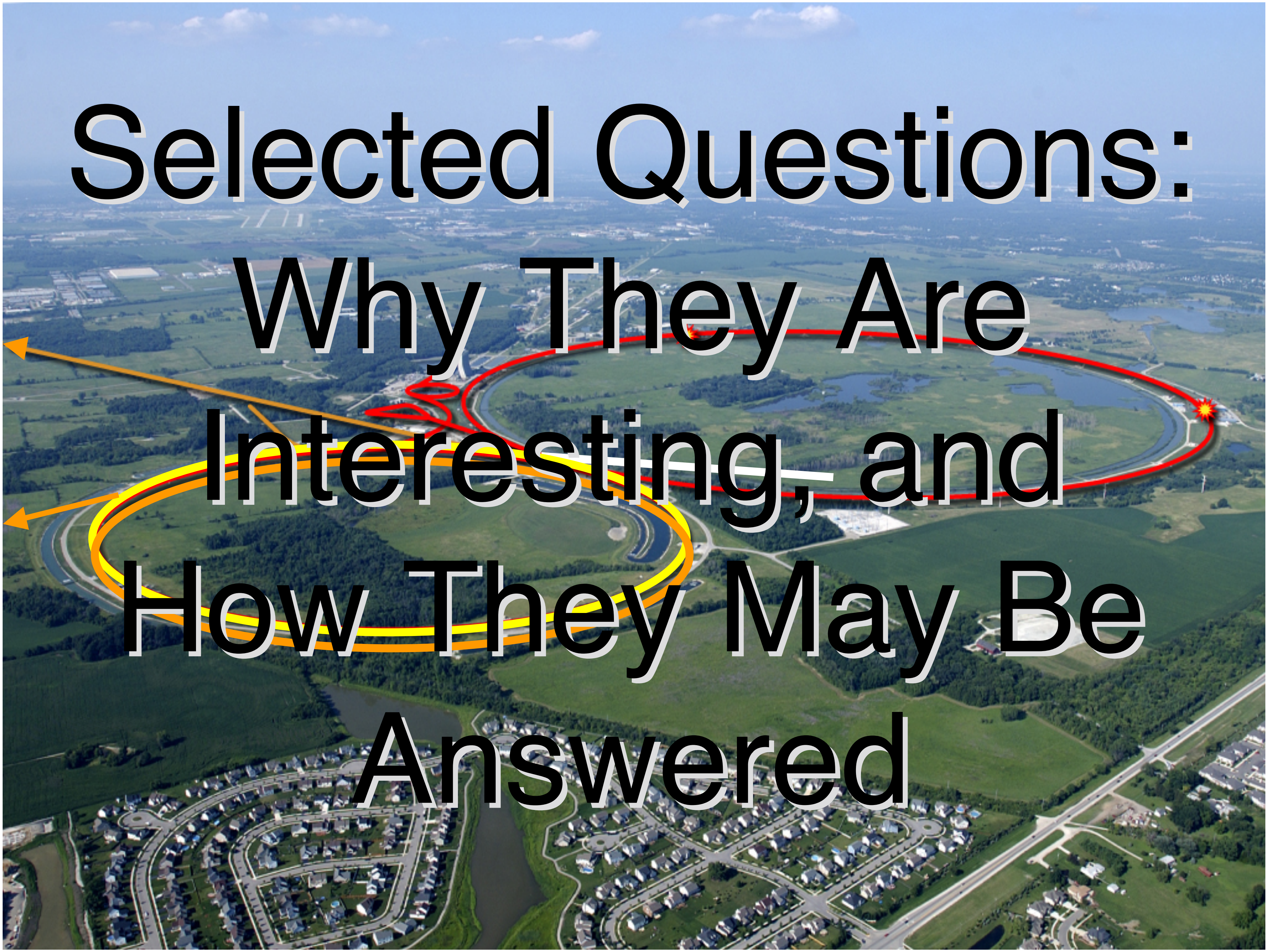
- What can neutrinos and the universe tell us about one another?

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

- What physics is behind neutrino mass?

- 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, does —

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

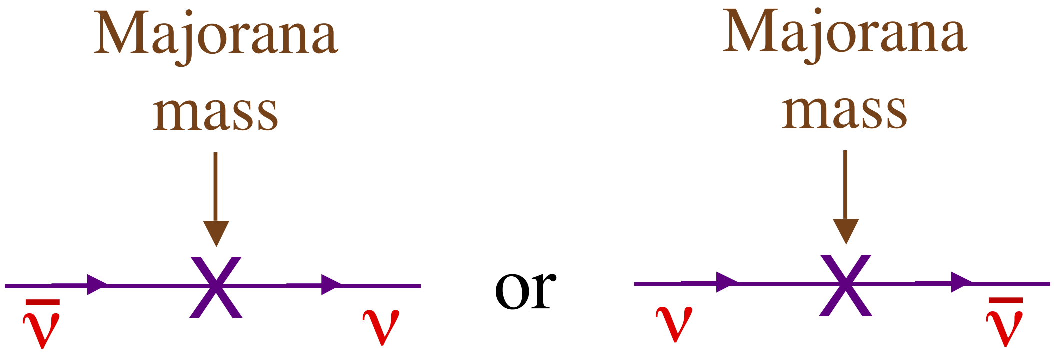
or

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

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

Majorana Masses

Their effect:



Majorana mass

$\bar{\nu}$ ν

or

Majorana mass

ν $\bar{\nu}$

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.**

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 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 $\Rightarrow$ Majorana Neutrinos

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

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

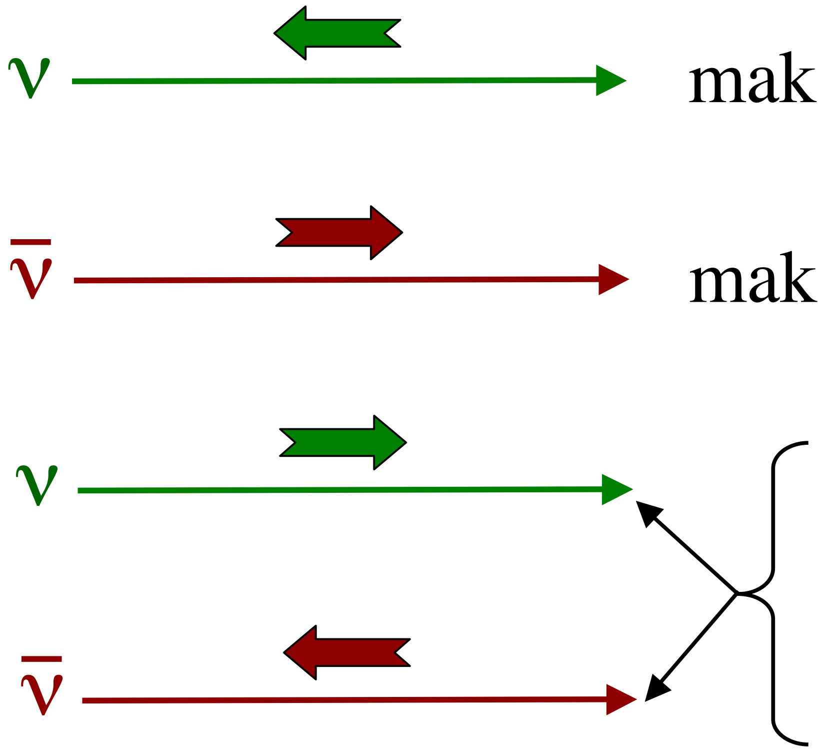
Majorana masses induce $\nu \longleftrightarrow \bar{\nu}$ mixing.

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

ν

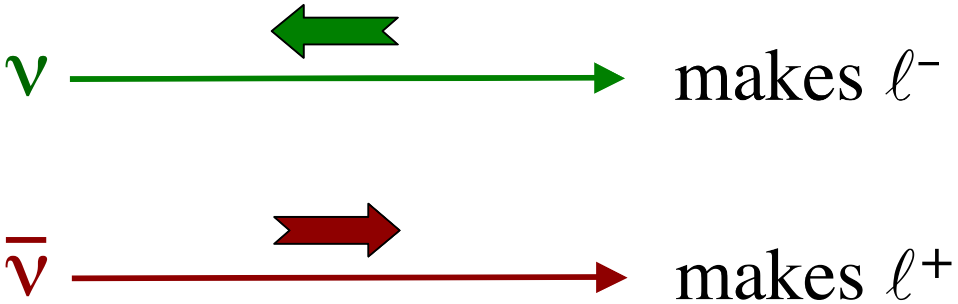
$\bar{\nu}$

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

$\left(\begin{array}{c}\text{The weak interaction}\\ \text{is Left Handed.}\end{array}\right)$

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

The Promising Approance — Seek

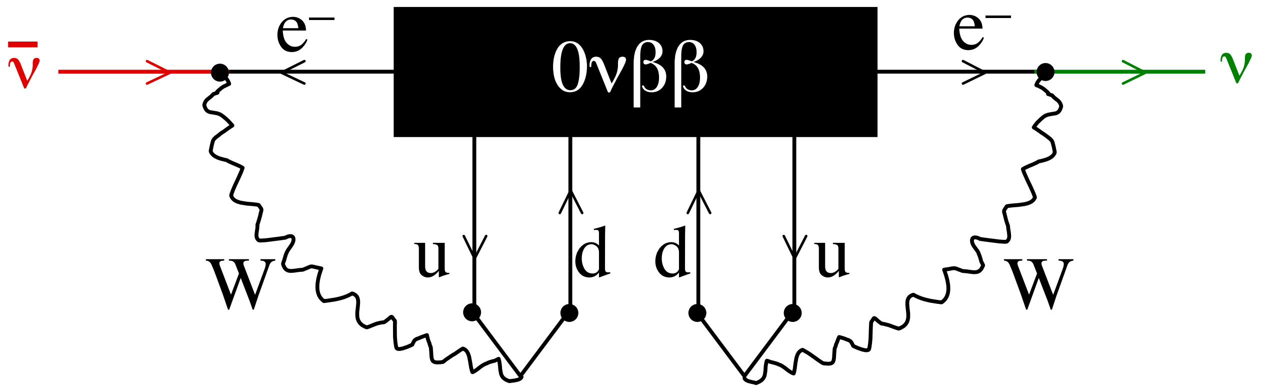
Neutrinoless Double Beta Decay [$0\nu\beta\beta$]

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 diagrams cause 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,
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: $n_{\overline{B}} = n_B \Longrightarrow n_{\overline{B}} << n_B$ requires ~~CP~~.

The ~~CP~~ in the quark mixing matrix, seen in B and K decays, leads to much too small a $B-\overline{B}$ asymmetry.

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

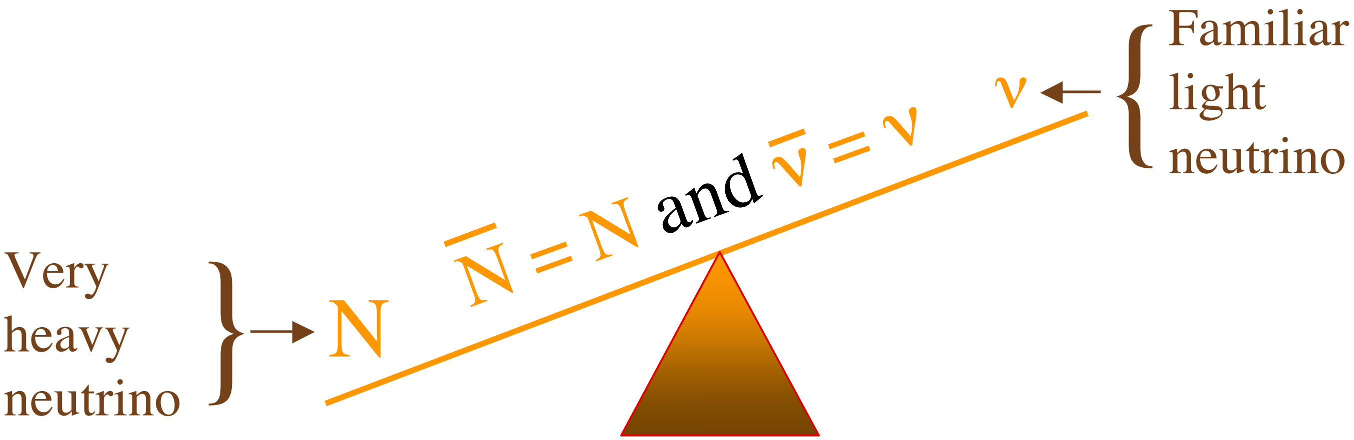
The candidate scenario: *Leptogenesis*.

(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



Very heavy neutrino → N

$\overline{N} = N$ and $\overline{\nu} = \nu$

ν ← Familiar light neutrino

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 —

$$m_N \sim 10^{(9\text{–}10)}\ \text{GeV} \quad .$$

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 —

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

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.

$\cancel{CP}$ phases in the matrix y will 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 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,
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**.**

There are baryons, but ~ no antibaryons.

Reasonable parameters give the observed n_B / n_γ **.**

Generically, leptogenesis and light-neutrino $\cancel{CP}$ imply each other.

Seeking $\cancel{CP}$ 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.

Good luck!

Backup Slides

Leptonic Mixing

This has the consequence that —

Mass eigenstate Flavor eigenstate

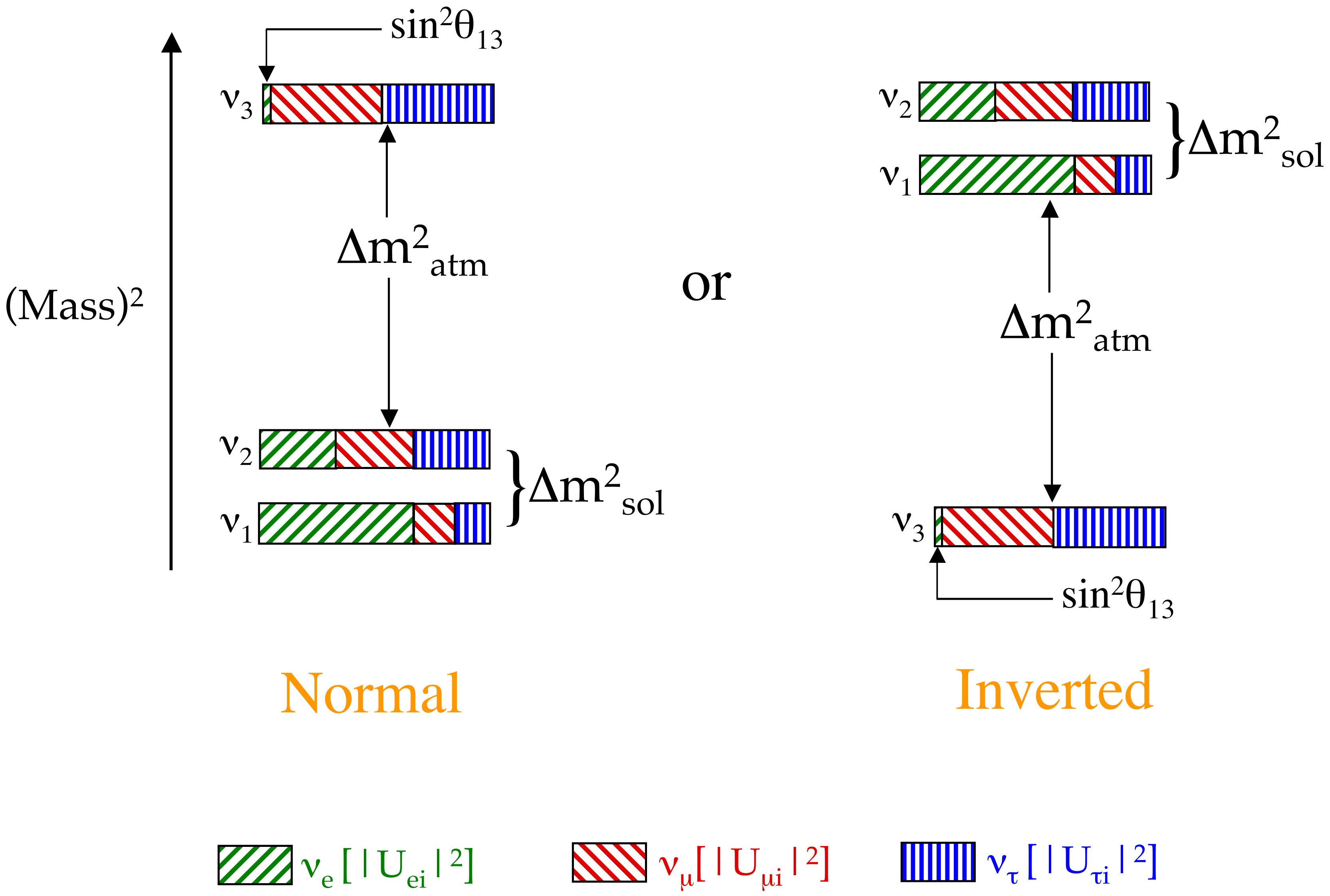
$$|\nu_i> = \sum_\alpha U_{\alpha i}\, |\nu_\alpha> .$$

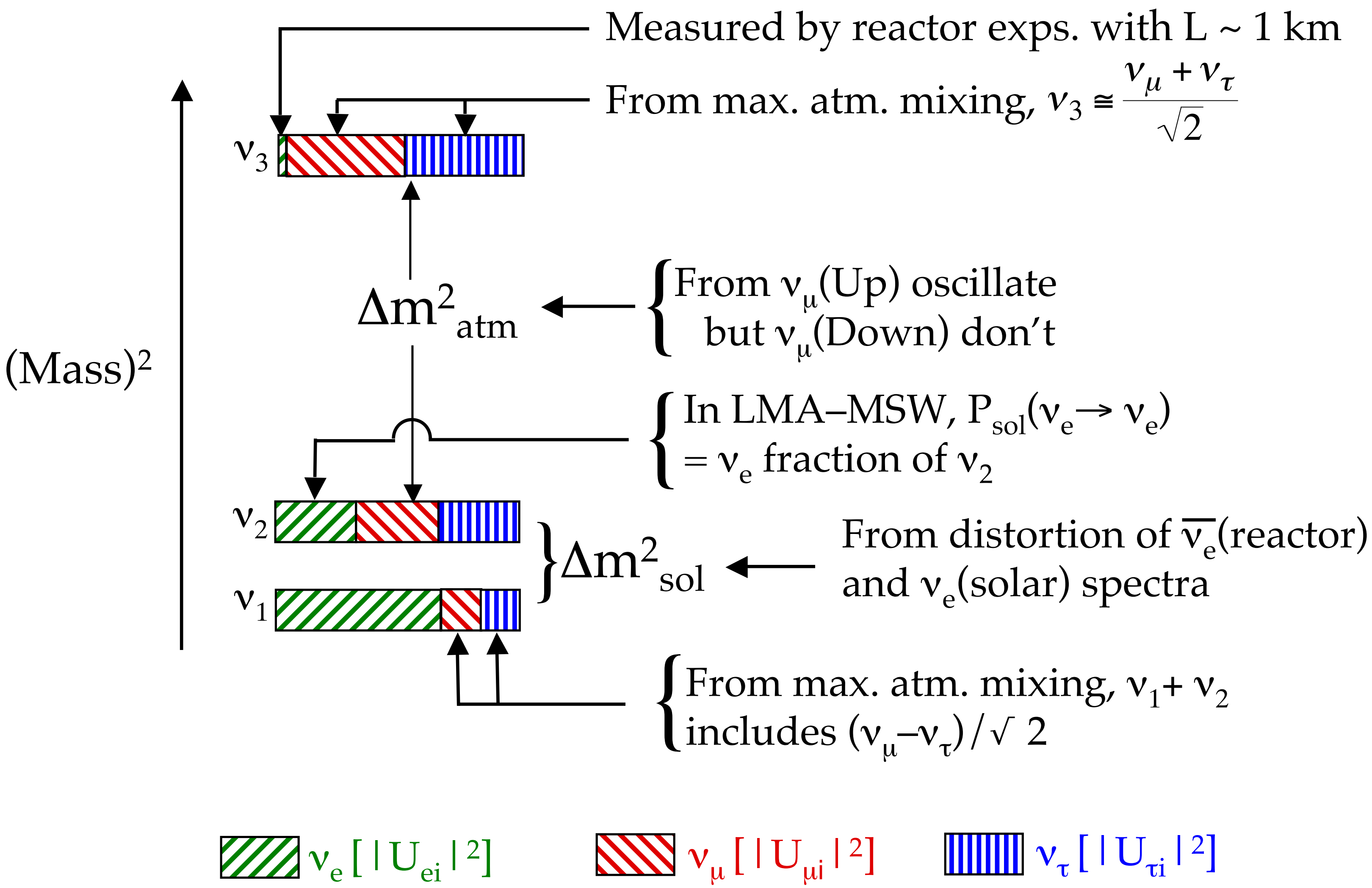
e, μ, or τ Leptonic Mixing Matrix

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





Measured by reactor exps. with L ~ 1 km

From max. atm. mixing, $\nu_3 \cong \frac{\nu_\mu + \nu_\tau}{\sqrt{2}}$

From ν_μ(Up) oscillate but ν_μ(Down) don't

In LMA–MSW, $P_{sol}(\nu_e \rightarrow \nu_e)$ = ν_e fraction of ν_2

From distortion of $\overline{\nu_e}$(reactor) and ν_e(solar) spectra

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 [$|U_{\tau i}|^2$]

The Measurement of θ_{13}

The T2K accelerator-neutrino experiment

➡ $$\sin^2 2\theta_{13} = 0.104^{+0.060}_{-0.045}$$

assuming $\theta_{23} = 45^0$ and $\delta_{CP} = 0$.

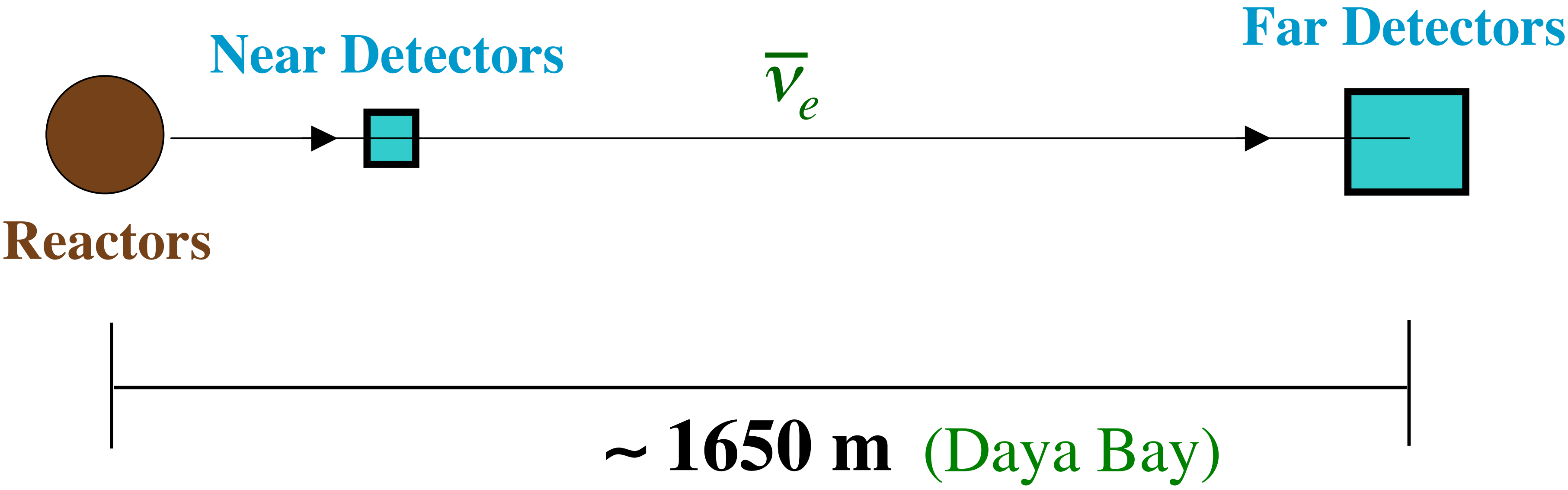
There was also an indication of nonzero θ_{13} from MINOS.

Then reactor-neutrino experiments weighed in,
with Double CHOOZ first.

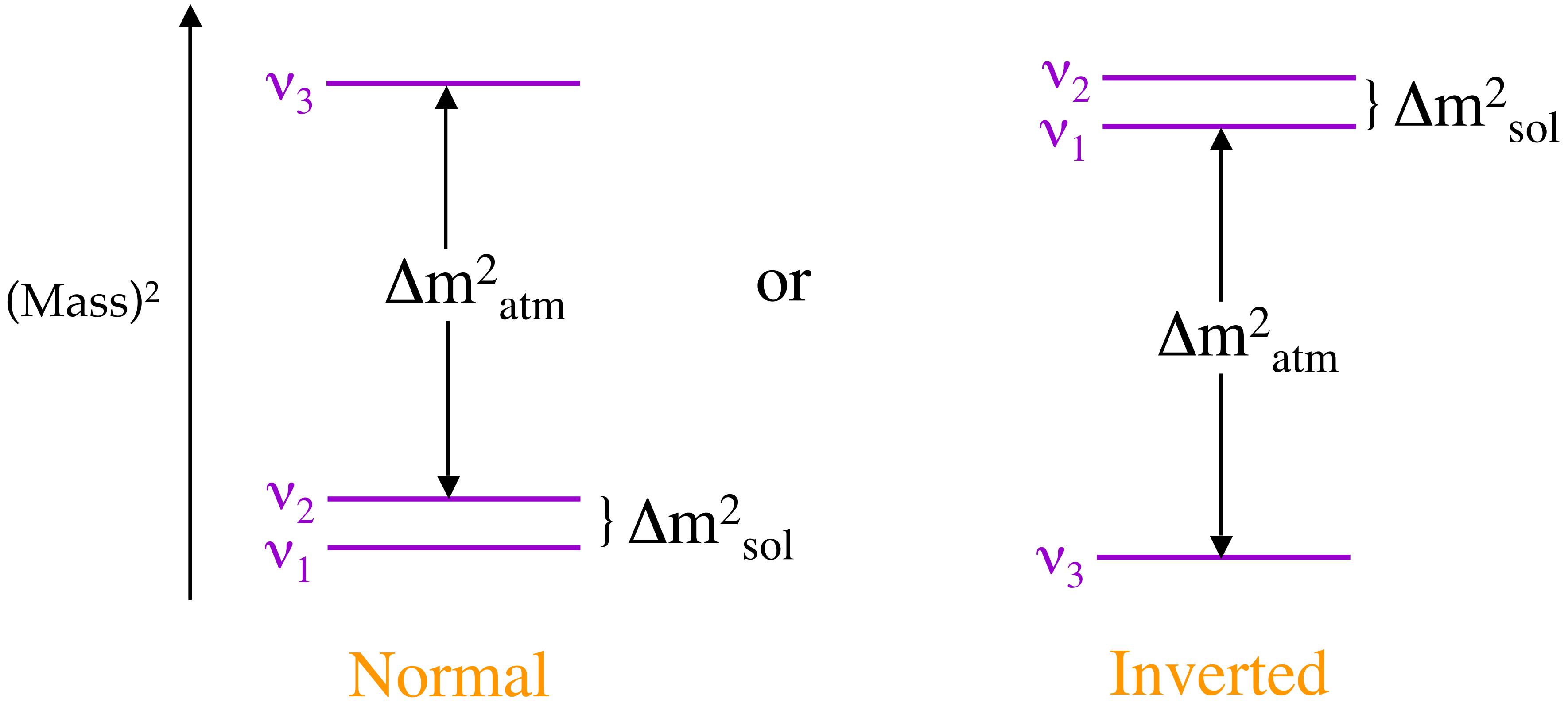
The most accurate determinations of θ_{13}
have come from the Daya Bay and RENO
reactor experiments.

These are reactor $\overline{\nu}_e$ disappearance experiments.

The Idea



Recall that the neutrino squared-mass spectrum looks like —


(Mass)^2

ν_3

Δm^2_{atm}

ν_2

ν_1

} Δm^2_{sol}

or

ν_2

ν_1

} Δm^2_{sol}

Δm^2_{atm}

ν_3

Normal

Inverted

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

$\Delta m^2_{sol} / \Delta m^2_{atm} \sim 1/30$

If L/E is too small for us to see the small Δm^2_{sol},

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

$$= \sin^2 2\theta_{13}\sin^2\left[1.27\Delta m^2_{atm}\left(eV^2\right)\frac{L(m)}{E(MeV)}\right]$$

Since $\Delta m^2_{atm} = \left(2.41^{+0.11}_{-0.10}\right)\times 10^{-3} eV^2$ (MINOS)

$\approx \frac{1}{400} eV^2$, and $E \sim 3\ MeV$,

we need $L \sim 1600\ m$ to get $\left[1.27\Delta m^2_{atm}\left(eV^2\right)\frac{L(m)}{E(MeV)}\right] \sim \frac{\pi}{2}$.

Then we can measure θ_{13}.

The results —

$$\sin^2 2\theta_{13} = 0.089 \pm 0.010(stat) \pm 0.005(syst)$$ Daya Bay

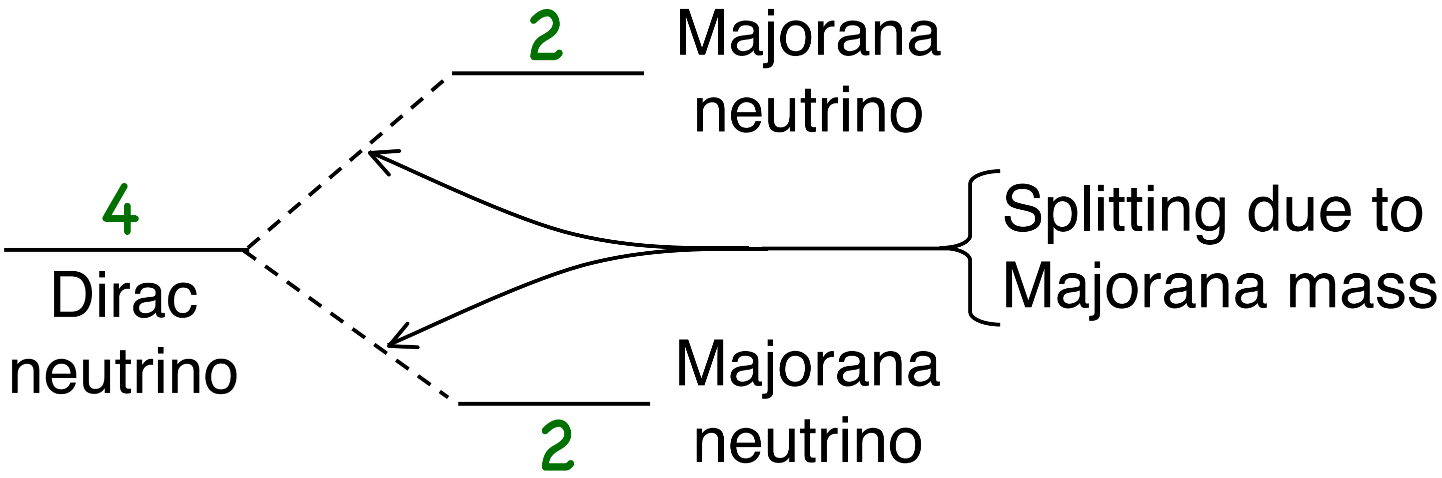
$$\sin^2 2\theta_{13} = 0.113 \pm 0.013(stat) \pm 0.019(syst)$$ RENO

We need no longer worry that θ_{13} may be very small.

All the mixing angles that need to be nonvanishing in order for neutrino oscillation to violate CP are indeed nonvanishing.

Majorana Masses Split Dirac Neutrinos

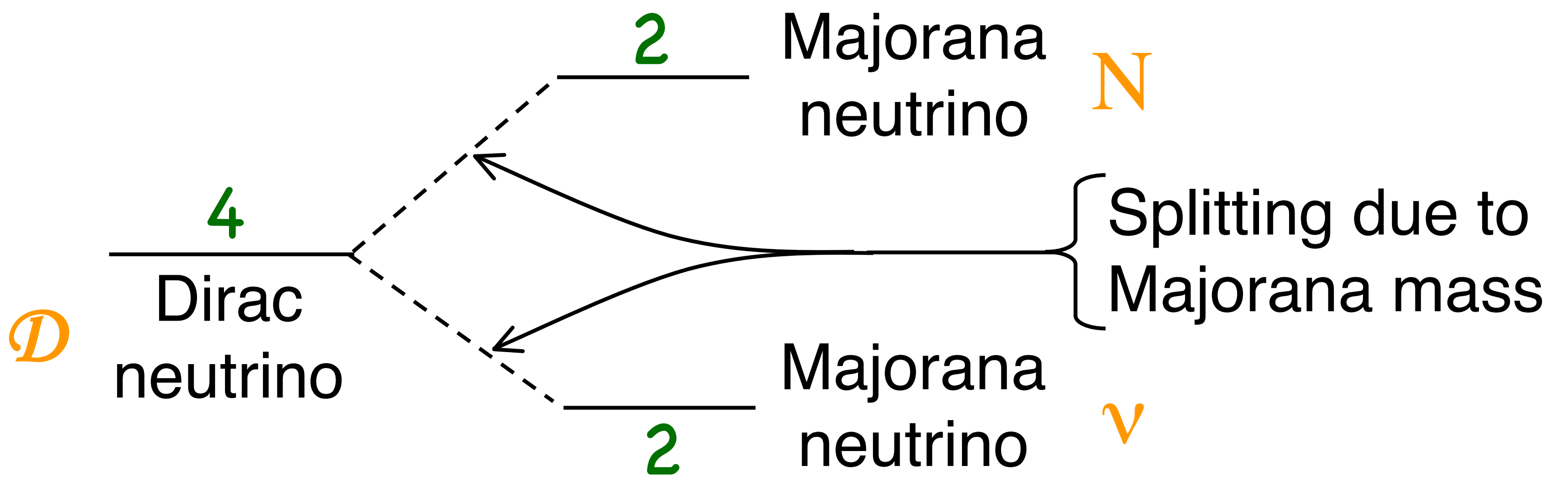
A Majorana mass term splits a Dirac neutrino into two Majorana neutrinos.



The See-Saw Mechanism

The most popular theory of why m_ν is so small.

A ***BIG*** Majorana mass term splits a Dirac neutrino into two ***widely-spaced*** Majorana neutrinos.



2 Majorana neutrino N

Splitting due to Majorana mass

4

$\mathcal{D}$ Dirac neutrino

2 Majorana neutrino ν

$m_\nu m_N \approx m_{\mathcal{D}}^2$ ***The See-Saw Relation***

If $m_{\mathcal{D}}$ *is a typical fermion mass,* m_N *will be very large.*

Leptogenesis and ~~CP~~ In ν Oscillation

In a convenient basis, the coupling matrix
y is the only source of CP violation among the leptons.

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

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

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

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

e, μ, or τ

Distance

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

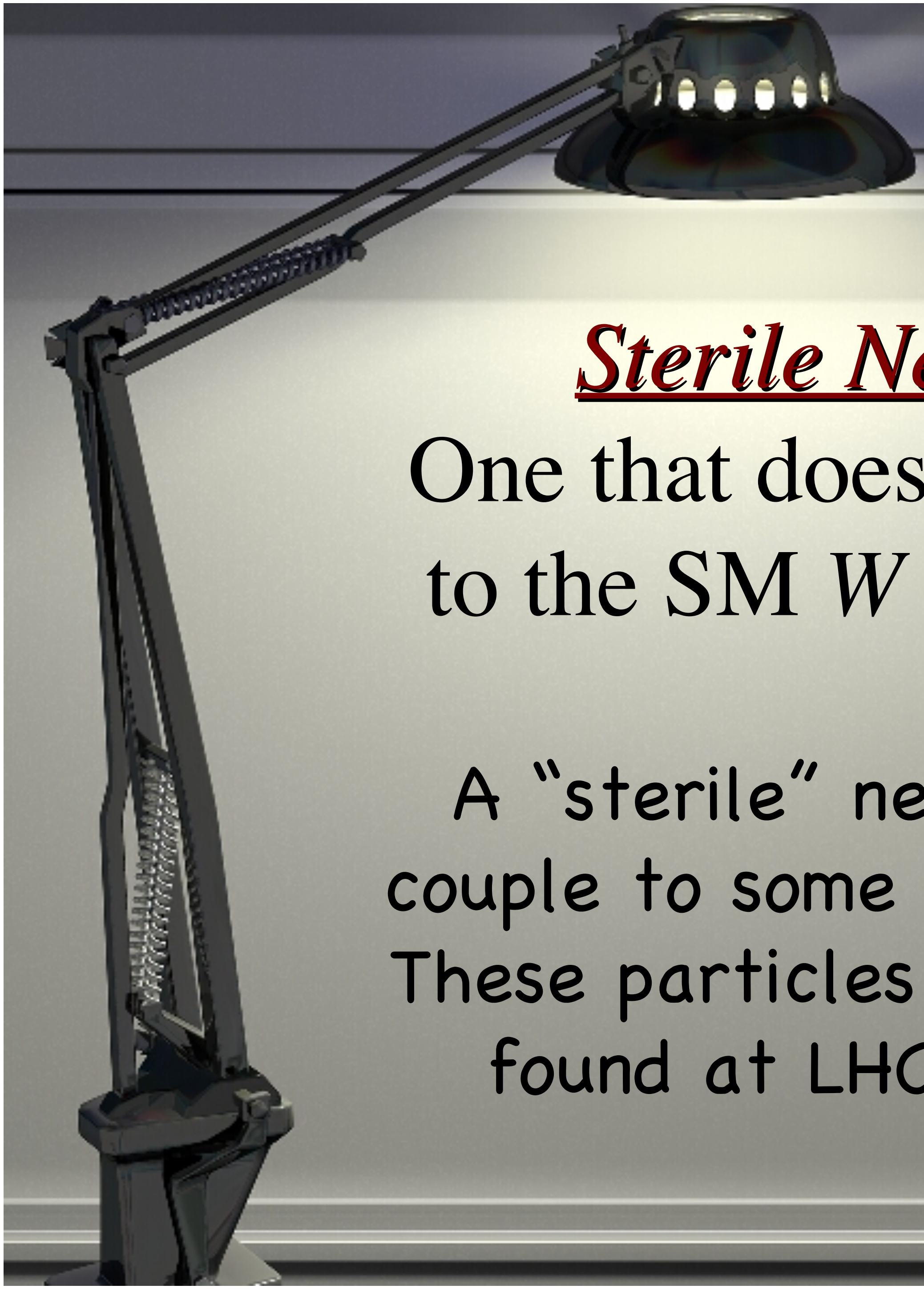
$$\underset{(-)}{+}2\sum_{i>j} \Im(U^*_{\alpha i}U_{\beta i}U_{\alpha j}U^*_{\beta j})\sin(\Delta m^2_{ij}\frac{L}{2E})$$

Neutrino (Mass)^2 splitting

Energy

Are There ***More*** Than 3 Mass Eigenstates?

Are There **Sterile** Neutrinos?



Sterile Neutrino

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

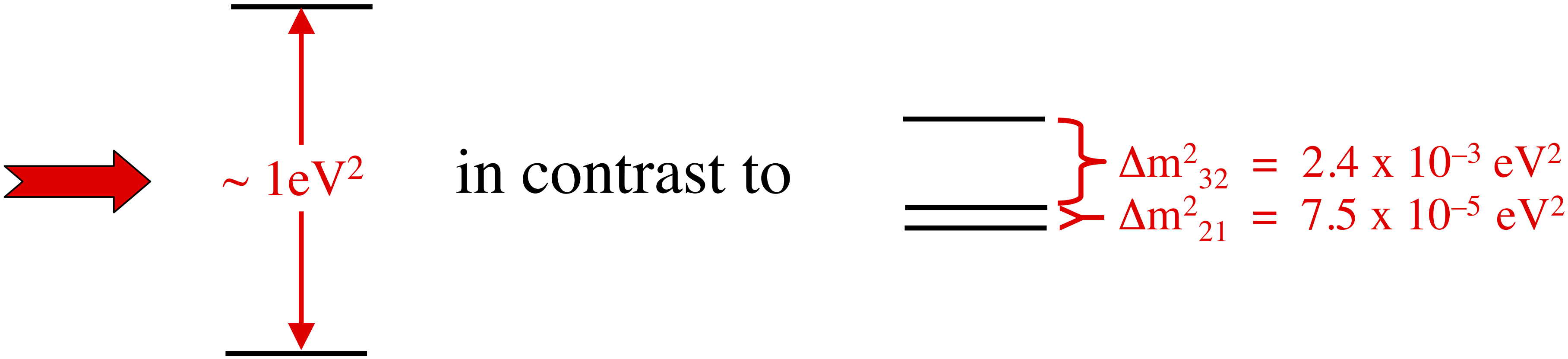
A "sterile" neutrino may well
couple to some non-SM particles.
These particles could perhaps be
found at LHC or elsewhere.

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



At least **4** mass eigenstates

Are There Sterile Neutrinos?

At least **4** mass eigenstates ⇒ At least **4** flavors.

Measured $\Gamma(Z \to \nu\bar{\nu})$ ⇒ only **3** different flavor neutrinos made of light mass eigenstates couple to the Z.

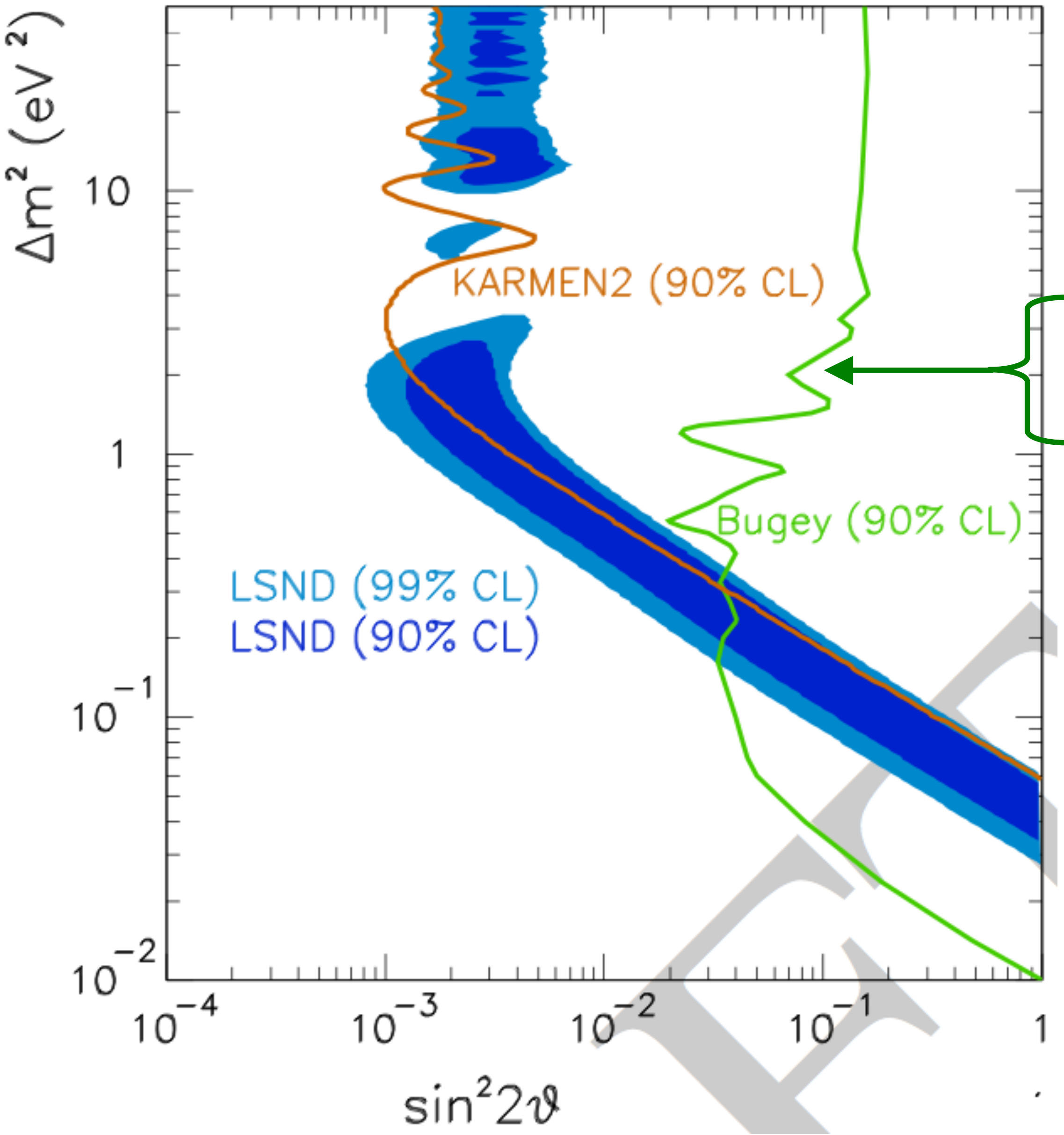
If there are > 3 light mass eigenstates, as hinted by LSND, then the extra flavors do not couple to the Z.

In the Standard Model, flavor neutrinos that do not couple to the Z do not couple to the W either.

Such neutrinos, with no SM interactions, are what we call ***sterile*** neutrinos.

LSND hints at the existence of sterile neutrinos.

The LSND-favored region

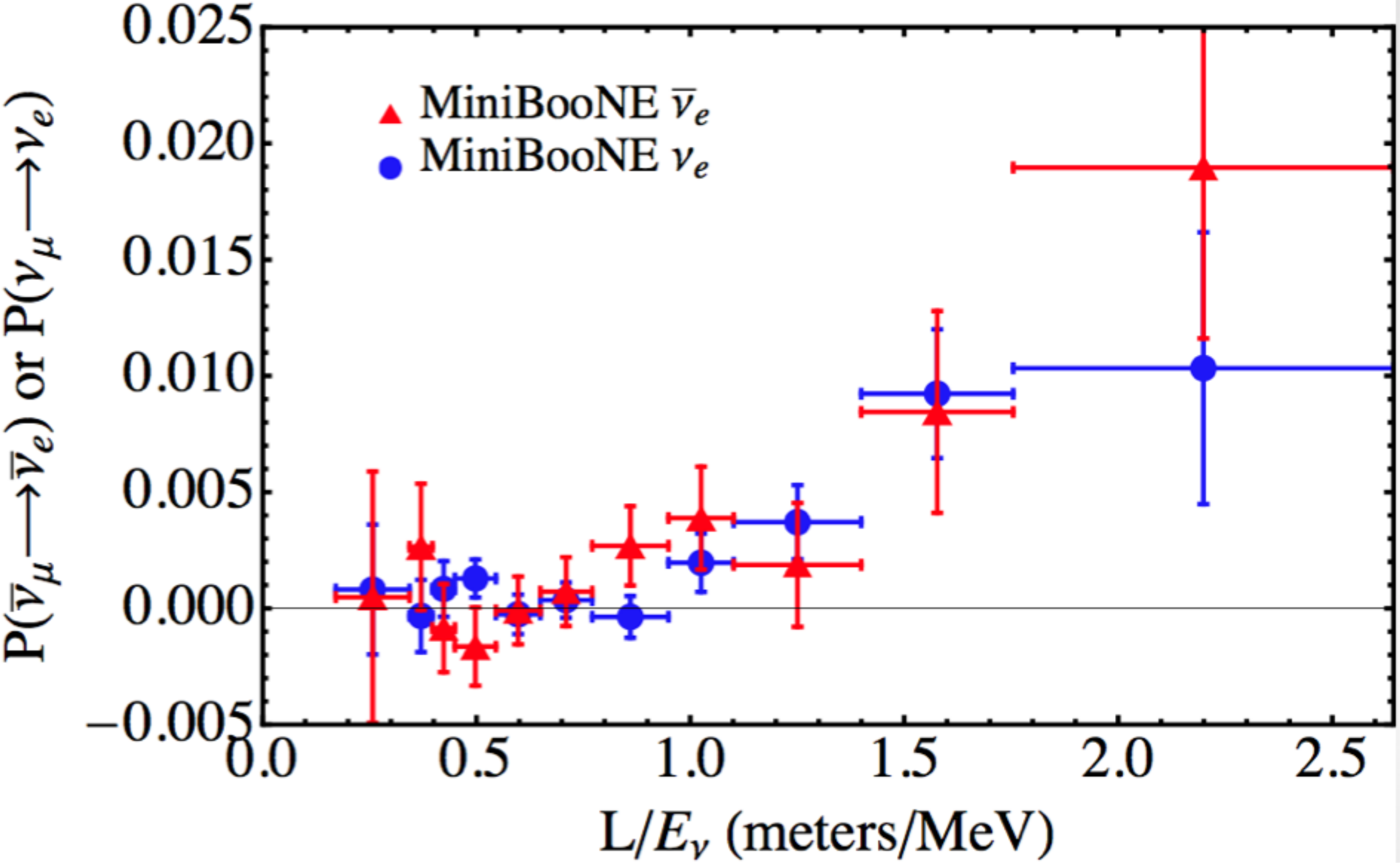


Relevant if CPT holds

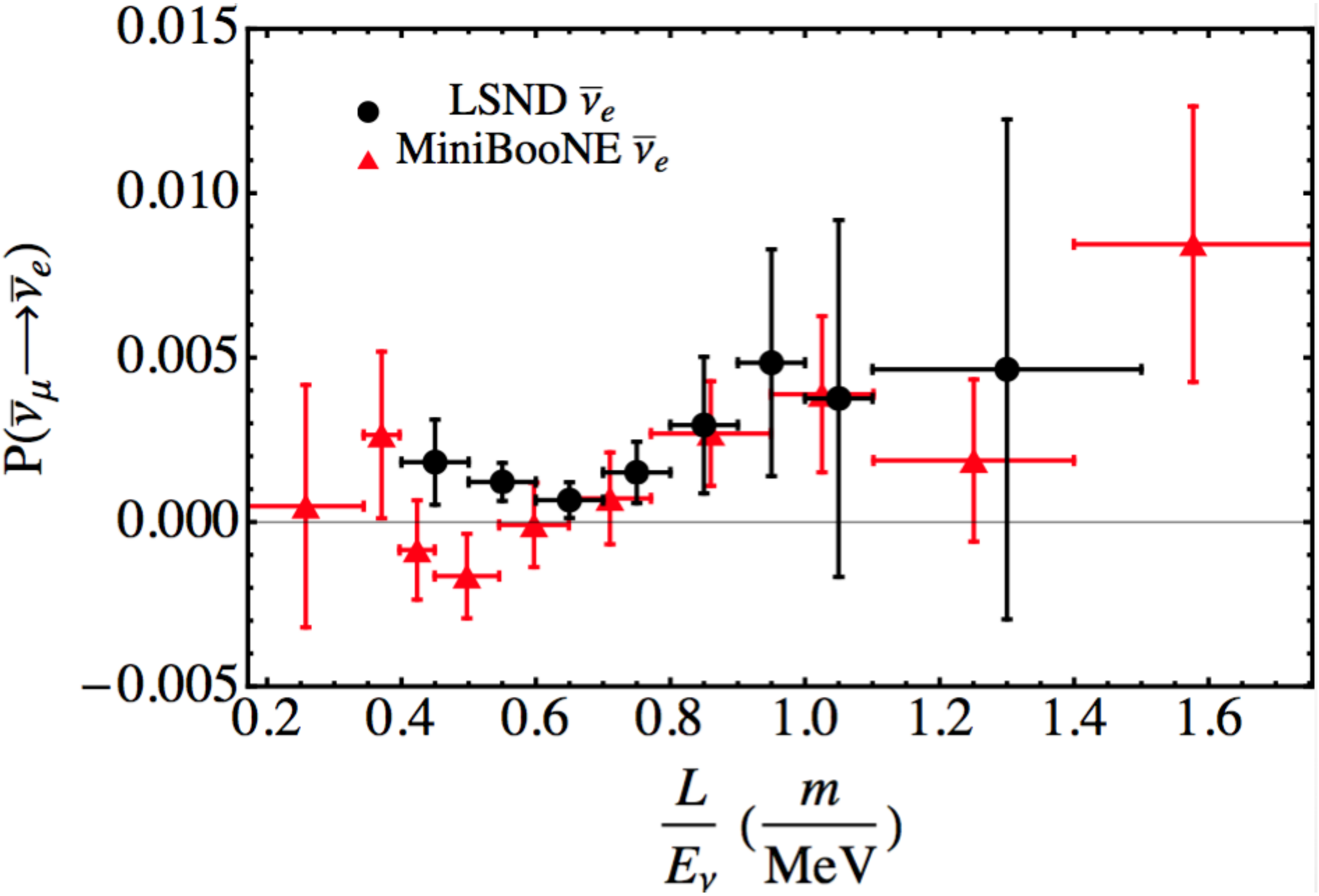
The Hint From MiniBooNE

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

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



Chris Polly at Neutrino 2012



Chris Polly at Neutrino 2012

The Hint From Reactors

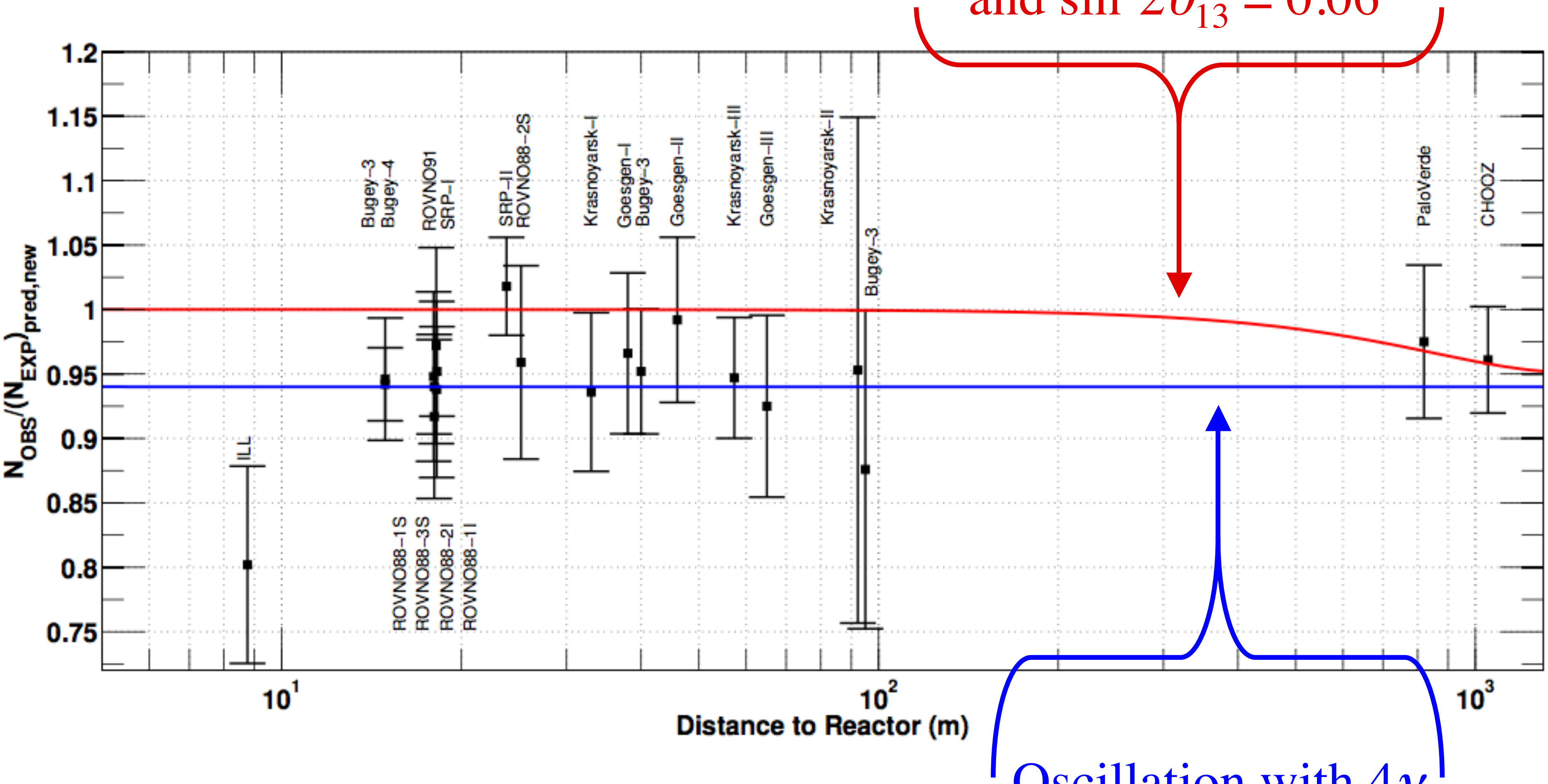
The prediction for the un-oscillated $\overline{\nu}_e$ flux from reactors, which has $\langle E \rangle \sim 3$ MeV, has increased by about 3%.

(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 $\sin^2 2\theta_{13} = 0.06$



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 placed
inside 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??

The Hint From Cosmology

(Yvonne Wong)

Big Bang Nucleosysthesis (BBN) and CMB anisotropies count the effective number of relativistic degrees of freedom, N_{eff}, at early times.

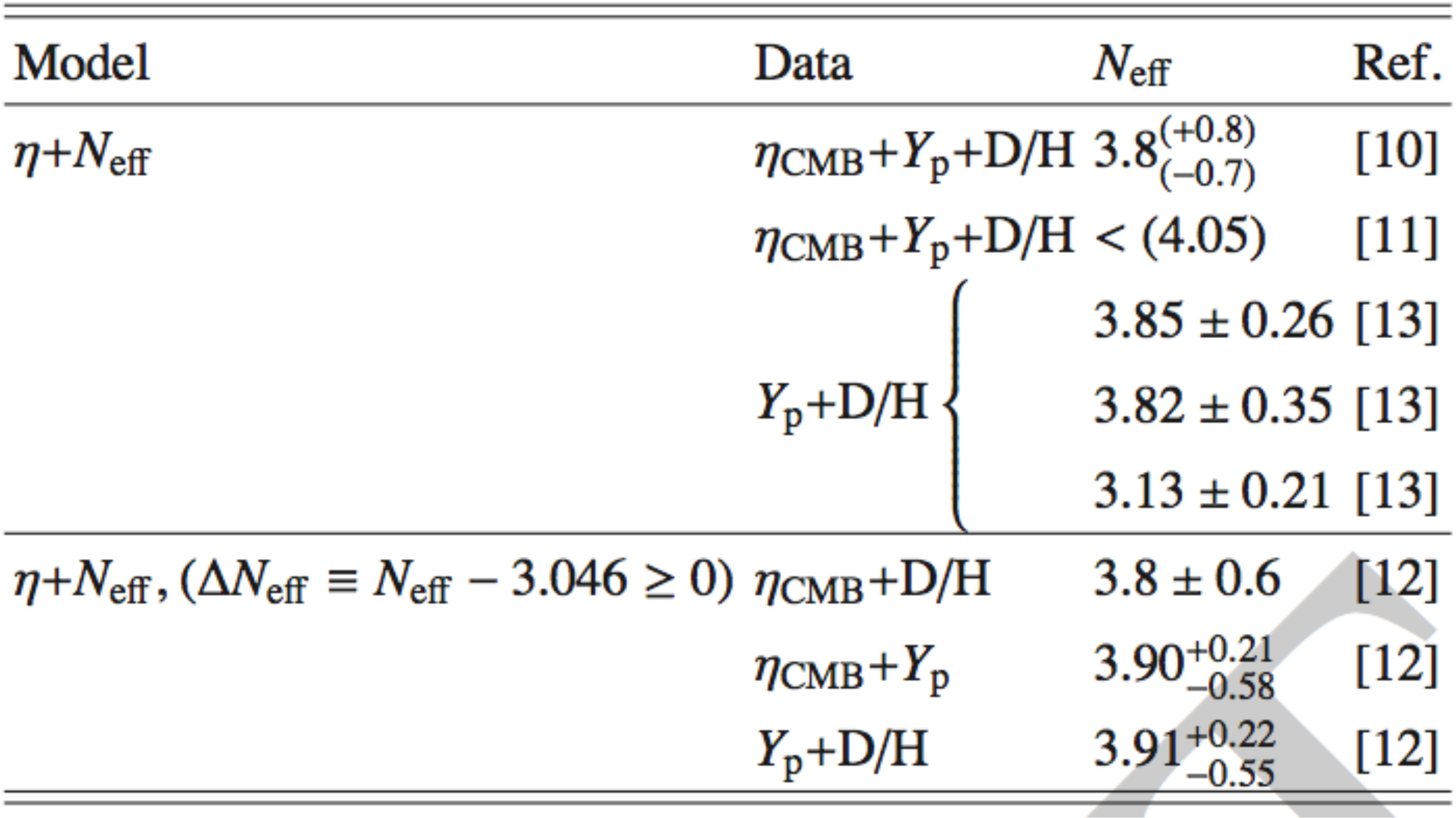
Light neutrinos would have been at least somewhat relativistic then.

Light sterile neutrinos mixed with the active ones as required by the terrestrial anomalies would very likely have thermalized in the early universe.

Then each sterile species contributes 1 to N_{eff}.

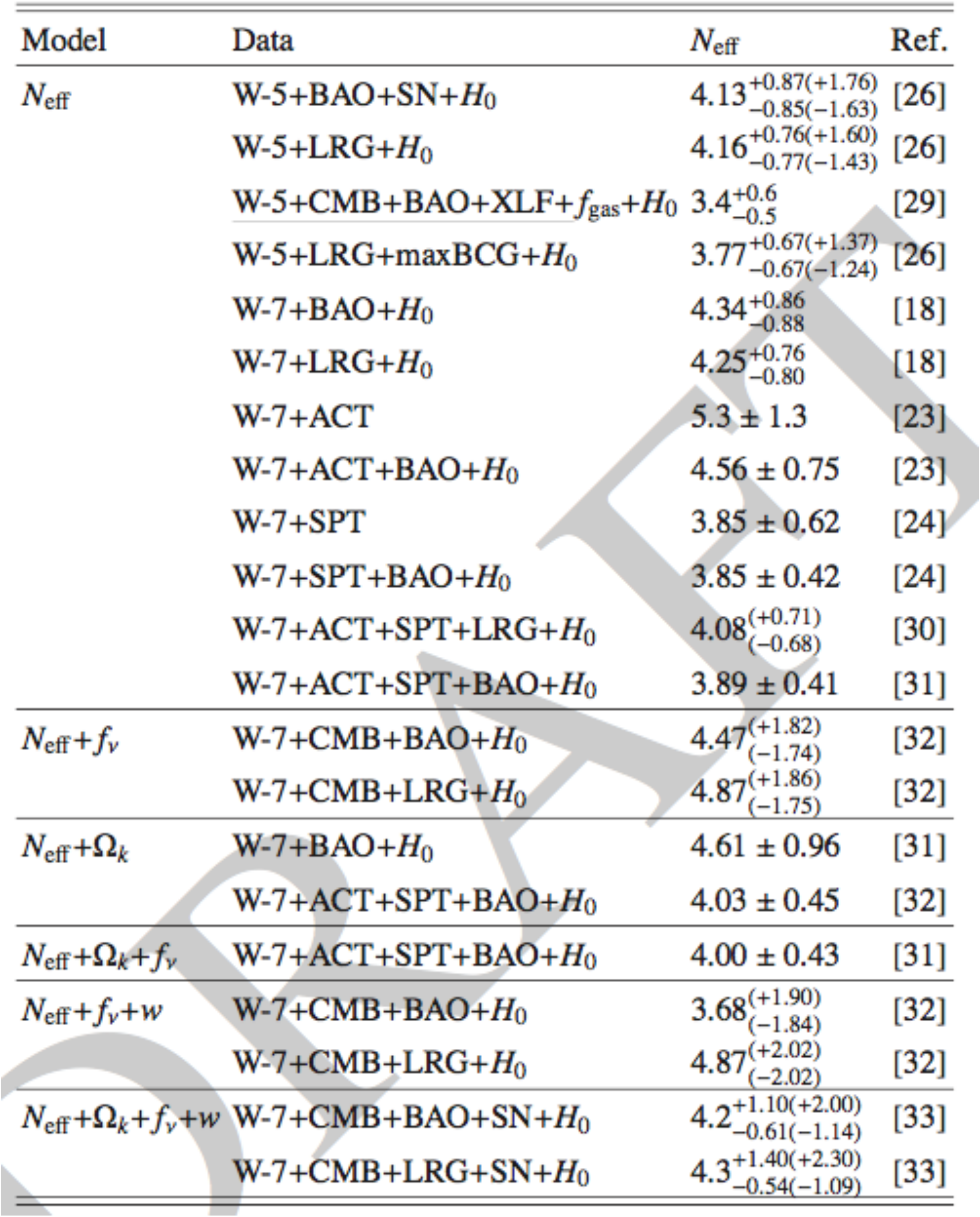
The evidence suggests that perhaps N_{eff} is closer to 4 than 3.

N_{eff} From BBN



Model	Data	N_{eff}	Ref.
$\eta+N_{\text{eff}}$	$\eta_{\text{CMB}}+Y_{\text{p}}+\text{D/H}$	$3.8^{(+0.8)}_{(-0.7)}$	[10]
	$\eta_{\text{CMB}}+Y_{\text{p}}+\text{D/H}$	$<(4.05)$	[11]
	$Y_{\text{p}}+\text{D/H}$	3.85 ± 0.26	[13]
		3.82 ± 0.35	[13]
		3.13 ± 0.21	[13]
$\eta+N_{\text{eff}}, (\Delta N_{\text{eff}} \equiv N_{\text{eff}} - 3.046 \geq 0)$	$\eta_{\text{CMB}}+\text{D/H}$	3.8 ± 0.6	[12]
	$\eta_{\text{CMB}}+Y_{\text{p}}$	$3.90^{+0.21}_{-0.58}$	[12]
	$Y_{\text{p}}+\text{D/H}$	$3.91^{+0.22}_{-0.55}$	[12]

$N_{\rm eff}$ From CMB



Model	Data	$N_{\rm eff}$	Ref.
$N_{\rm eff}$	W-5+BAO+SN+H_0	$4.13^{+0.87(+1.76)}_{-0.85(-1.63)}$	[26]
	W-5+LRG+H_0	$4.16^{+0.76(+1.60)}_{-0.77(-1.43)}$	[26]
	W-5+CMB+BAO+XLF+$f_{\rm gas}$+H_0	$3.4^{+0.6}_{-0.5}$	[29]
	W-5+LRG+maxBCG+H_0	$3.77^{+0.67(+1.37)}_{-0.67(-1.24)}$	[26]
	W-7+BAO+H_0	$4.34^{+0.86}_{-0.88}$	[18]
	W-7+LRG+H_0	$4.25^{+0.76}_{-0.80}$	[18]
	W-7+ACT	5.3 ± 1.3	[23]
	W-7+ACT+BAO+H_0	4.56 ± 0.75	[23]
	W-7+SPT	3.85 ± 0.62	[24]
	W-7+SPT+BAO+H_0	3.85 ± 0.42	[24]
	W-7+ACT+SPT+LRG+H_0	$4.08^{(+0.71)}_{(-0.68)}$	[30]
	W-7+ACT+SPT+BAO+H_0	3.89 ± 0.41	[31]
$N_{\rm eff}+f_\nu$	W-7+CMB+BAO+H_0	$4.47^{(+1.82)}_{(-1.74)}$	[32]
	W-7+CMB+LRG+H_0	$4.87^{(+1.86)}_{(-1.75)}$	[32]
$N_{\rm eff}+\Omega_k$	W-7+BAO+H_0	4.61 ± 0.96	[31]
	W-7+ACT+SPT+BAO+H_0	4.03 ± 0.45	[32]
$N_{\rm eff}+\Omega_k+f_\nu$	W-7+ACT+SPT+BAO+H_0	4.00 ± 0.43	[31]
$N_{\rm eff}+f_\nu+w$	W-7+CMB+BAO+H_0	$3.68^{(+1.90)}_{(-1.84)}$	[32]
	W-7+CMB+LRG+H_0	$4.87^{(+2.02)}_{(-2.02)}$	[32]
$N_{\rm eff}+\Omega_k+f_\nu+w$	W-7+CMB+BAO+SN+H_0	$4.2^{+1.10(+2.00)}_{-0.61(-1.14)}$	[33]
	W-7+CMB+LRG+SN+H_0	$4.3^{+1.40(+2.30)}_{-0.54(-1.09)}$	[33]

Tables taken from the White Paper at arXiv:1204.5379

More precise information will come from the Planck satellite.