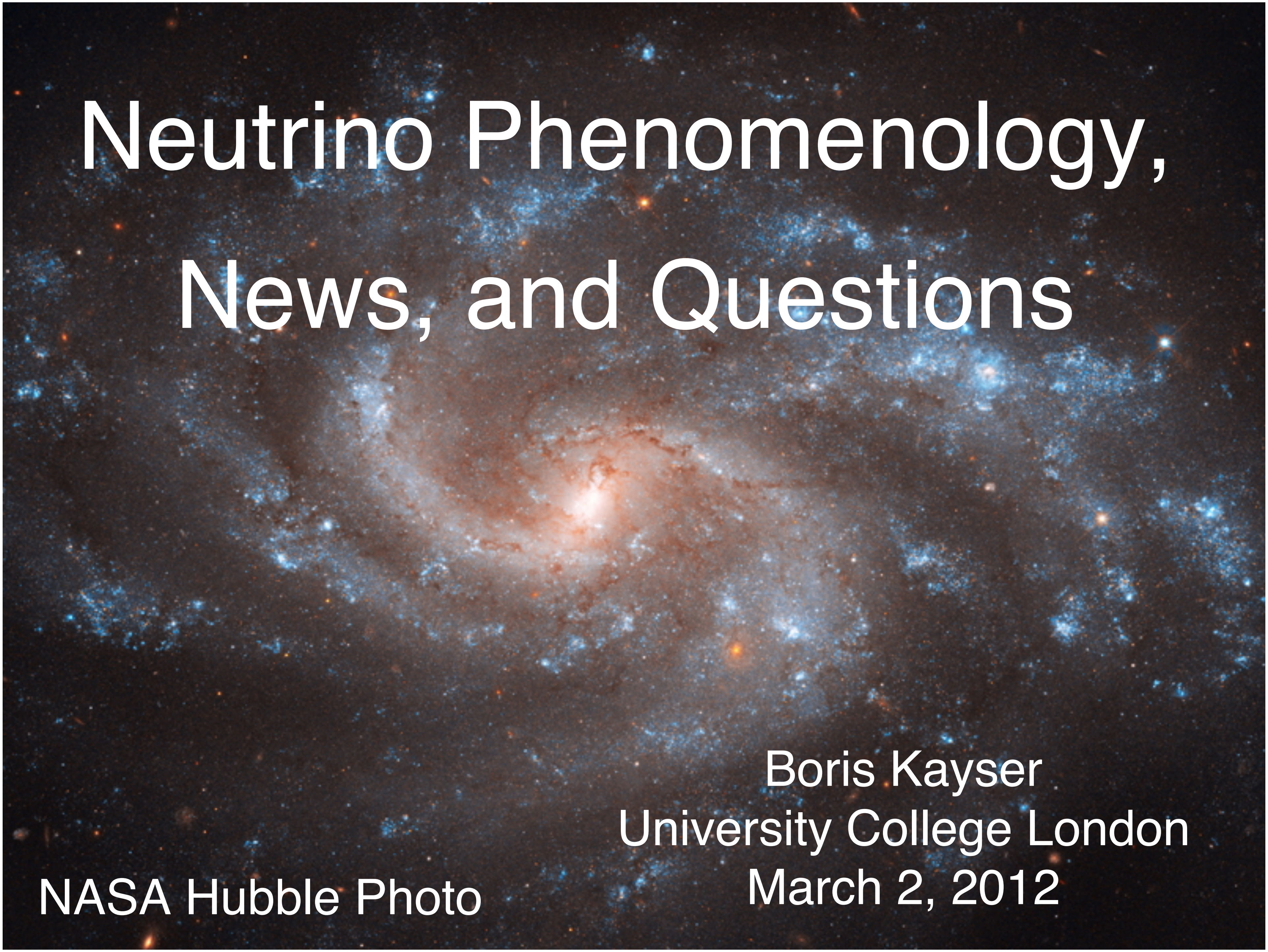
Neutrino Phenomenology, News, and Questions



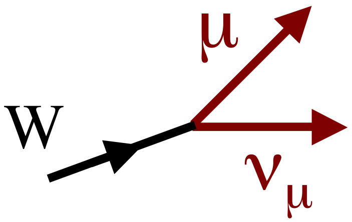
NASA Hubble Photo

Boris Kayser
University College London
March 2, 2012

Neutrino Flavor

The known neutrino flavors: ν_e , ν_μ , ν_τ

Each of these neutrinos is coupled, in the Standard Model (SM) and, as far as we know, also in Nature, only to the charged lepton of the same flavor.



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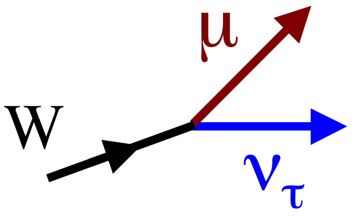

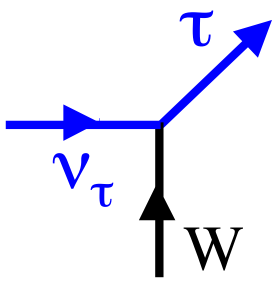

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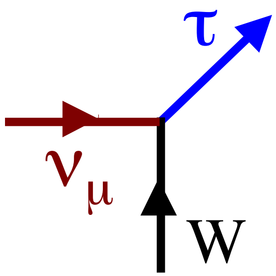
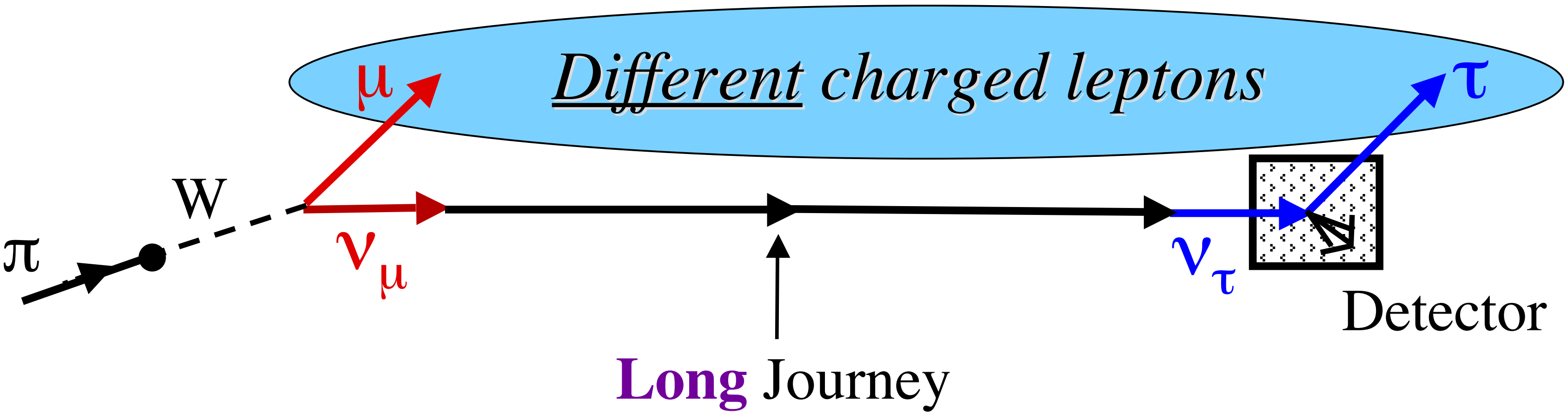


Neutrino Flavor Change (Oscillation)

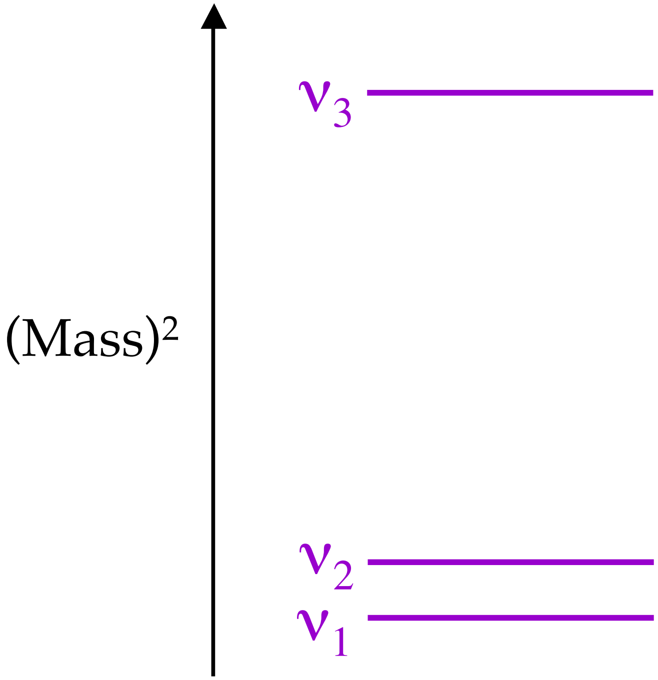
An example —



$$\nu_\mu \longrightarrow \nu_\tau$$

Flavor Change Requires ***Neutrino Masses***

There must be some spectrum
of neutrino mass eigenstates ν_i:



Mass $(\nu_i) \equiv m_i$

Flavor Change Requires ***Leptonic Mixing***

The neutrinos $\nu_{e,\mu,\tau}$ of definite flavor

($W \rightarrow e\nu_e$ or $\mu\nu_\mu$ or $\tau\nu_\tau$)

are superpositions of the neutrinos of definite mass:

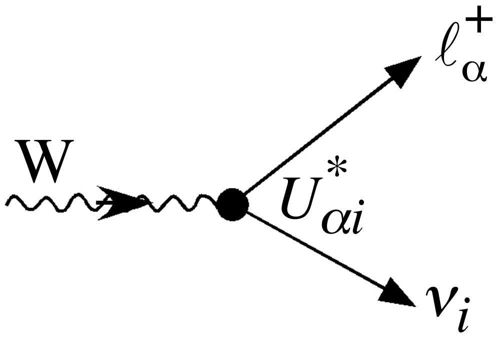
$$|\nu_\alpha> = \sum_i U^*_{\alpha i}\, |\nu_i> \quad .$$

Neutrino of flavor

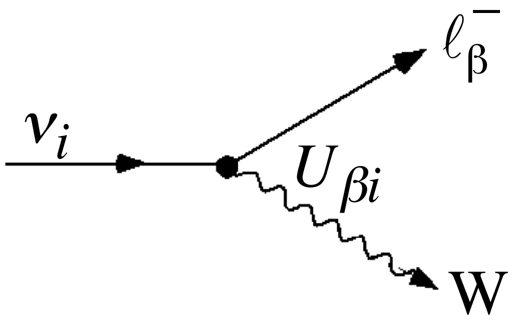
$\alpha = e, \mu$, or τ

Unitary Leptonic Mixing Matrix

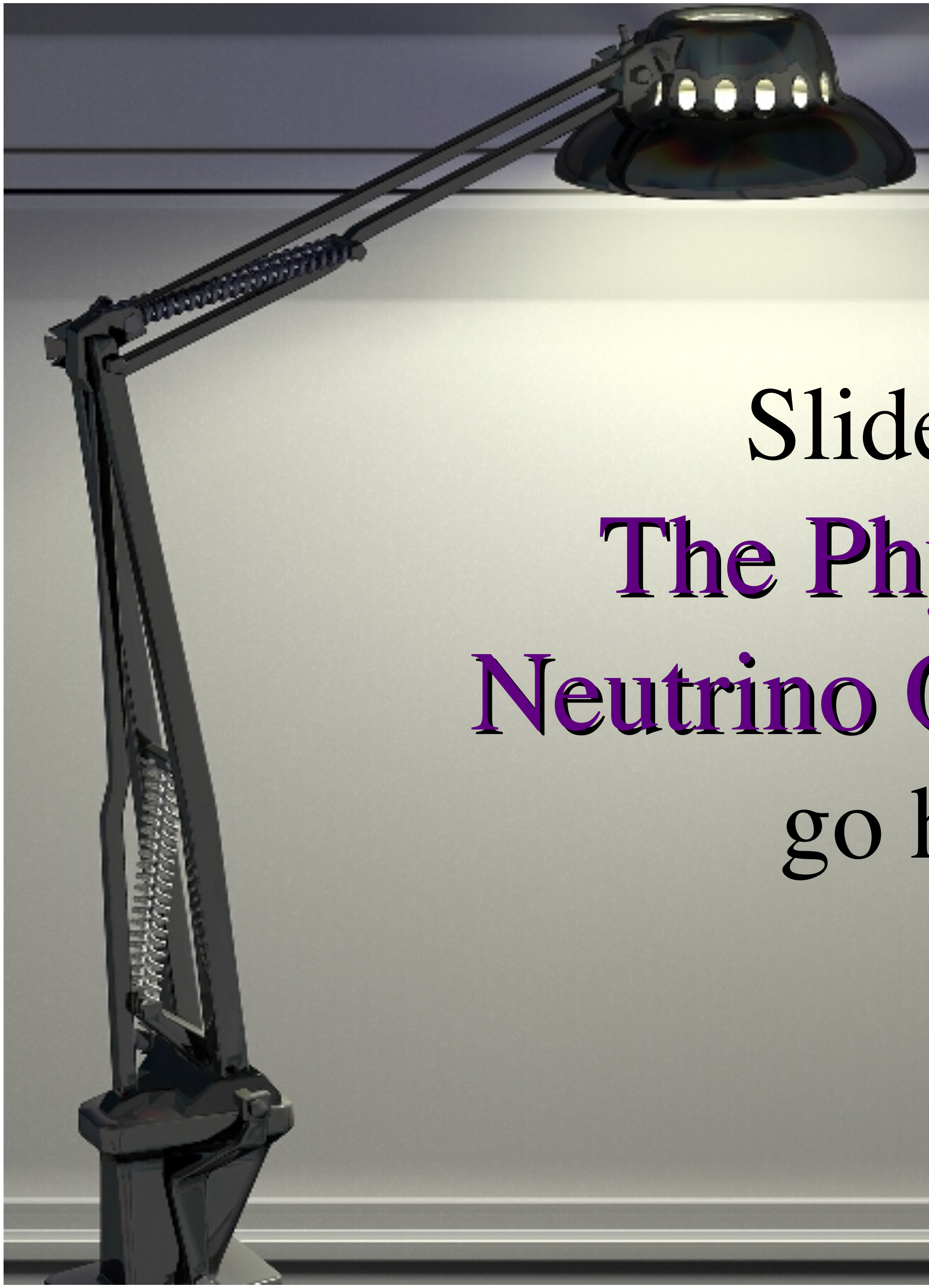
Neutrino of definite mass m_i



and



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

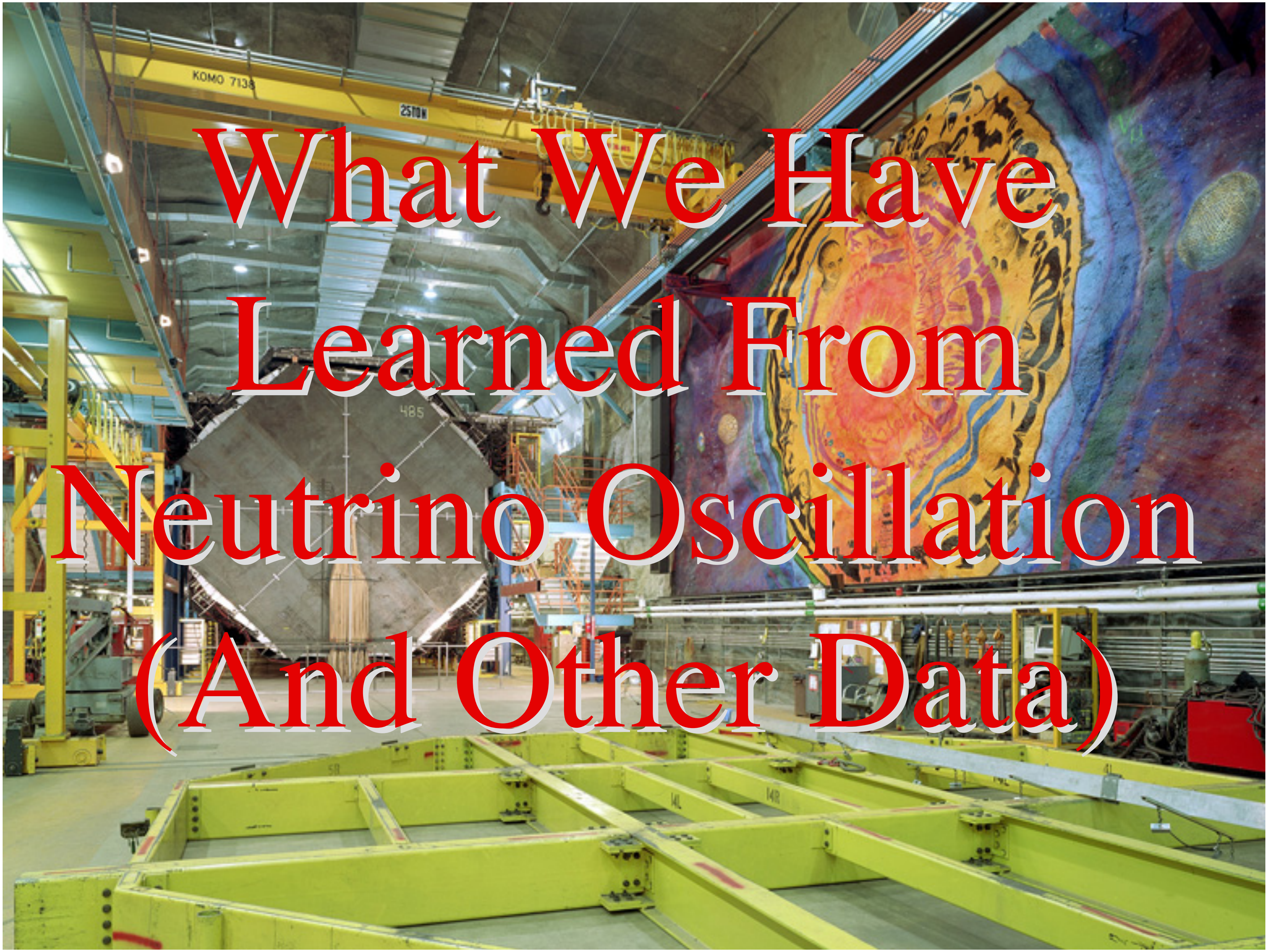


Slides on

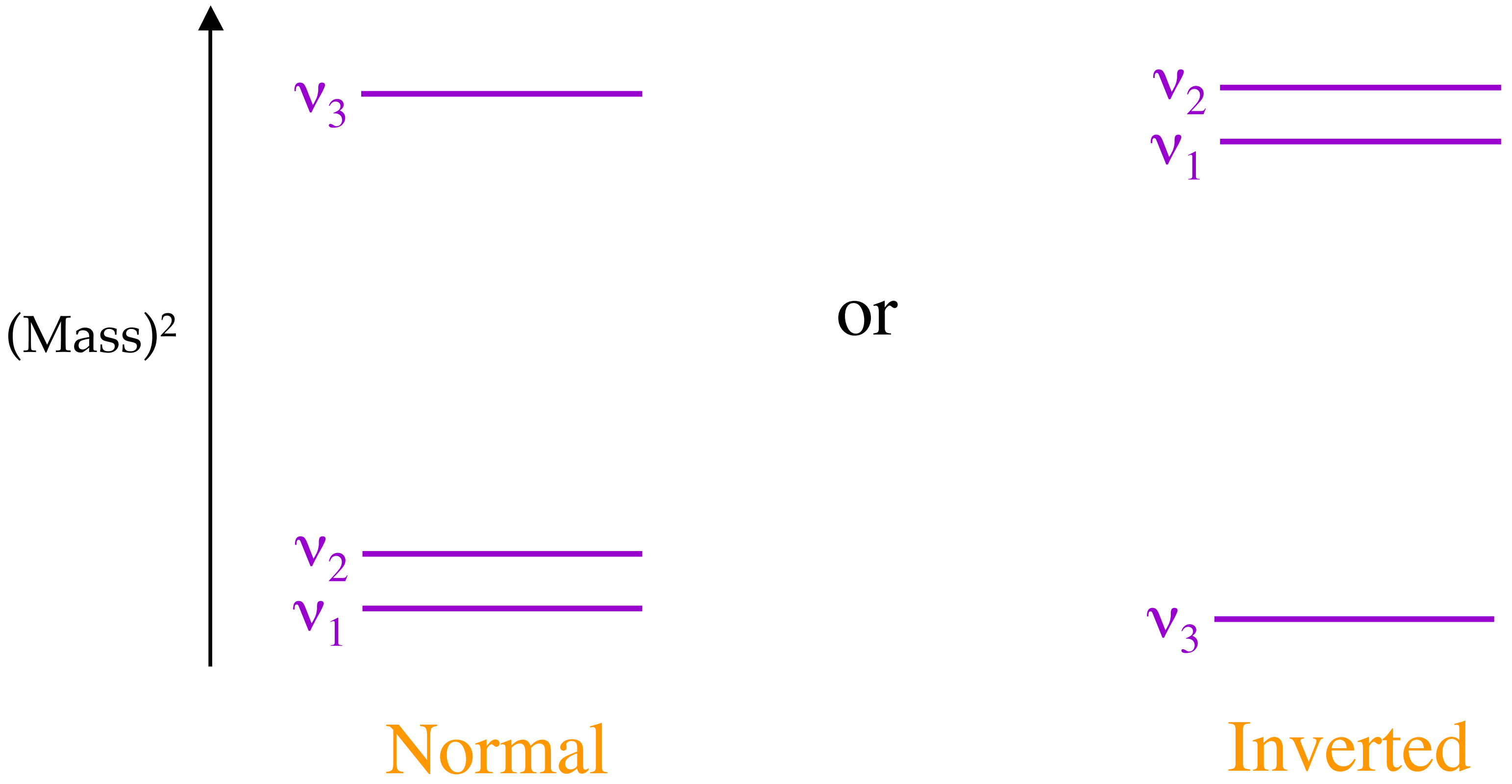
The Physics of Neutrino Oscillation

go here.

What We Have Learned From Neutrino Oscillation (And Other Data)



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



$\Delta m^2_{21} \cong 7.4 \times 10^{-5}\ \text{eV}^2$, $\Delta m^2_{32} \simeq 2.3 \times 10^{-3}\ \text{eV}^2$

Are there *more* mass eigenstates, as LSND suggests, and other experiments may hint?

The Mixing Matrix *U*

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

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

$$\times \underbrace{\begin{bmatrix}e^{i\alpha_1/2} & 0 & 0\\ 0 & e^{i\alpha_2/2} & 0\\ 0 & 0 & 1\end{bmatrix}}_{\text{Doesn't affect oscillation}}$$

$\theta_{12} \approx 34°$, $\theta_{23} \approx 39\text{-}51°$, $\theta_{13} < 12°$ ***News!***

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 $s_{13} \equiv \sin\theta_{13}$.

Recent Evidence For Non-Zero θ_{13}

In an experiment where L/E is too small for the small splitting $\Delta m_{21}^2 \equiv m_2^2 - m_1^2$ to be seen,

$$P(\nu_\mu \rightarrow \nu_e) \cong \boxed{\sin^2 2\theta_{13}} \sin^2 \theta_{23} \sin^2\left(1.27 \Delta m_{32}^2 (\mathrm{eV}^2) \frac{L(\mathrm{km})}{E(\mathrm{GeV})}\right)$$

T2K and MINOS have looked for $\nu_\mu \rightarrow \nu_e$ in long-baseline accelerator-neutrino experiments.

T2K sees 6 candidate events
where 1.5 are expected if $\theta_{13} = 0$.

Global analysis of all data including the T2K and MINOS results ⇨ $\boxed{\sin^2 2\theta_{13} = 0.097 \pm 0.03}$ (Fogli et al.)

Reactor Evidence For Non-Zero θ_{13}

Looking for disappearance of reactor $\overline{\nu}_e$, which have $E \sim 3$ MeV, while they travel $L \sim 1.5$ km is a very different way to determine θ_{13} .

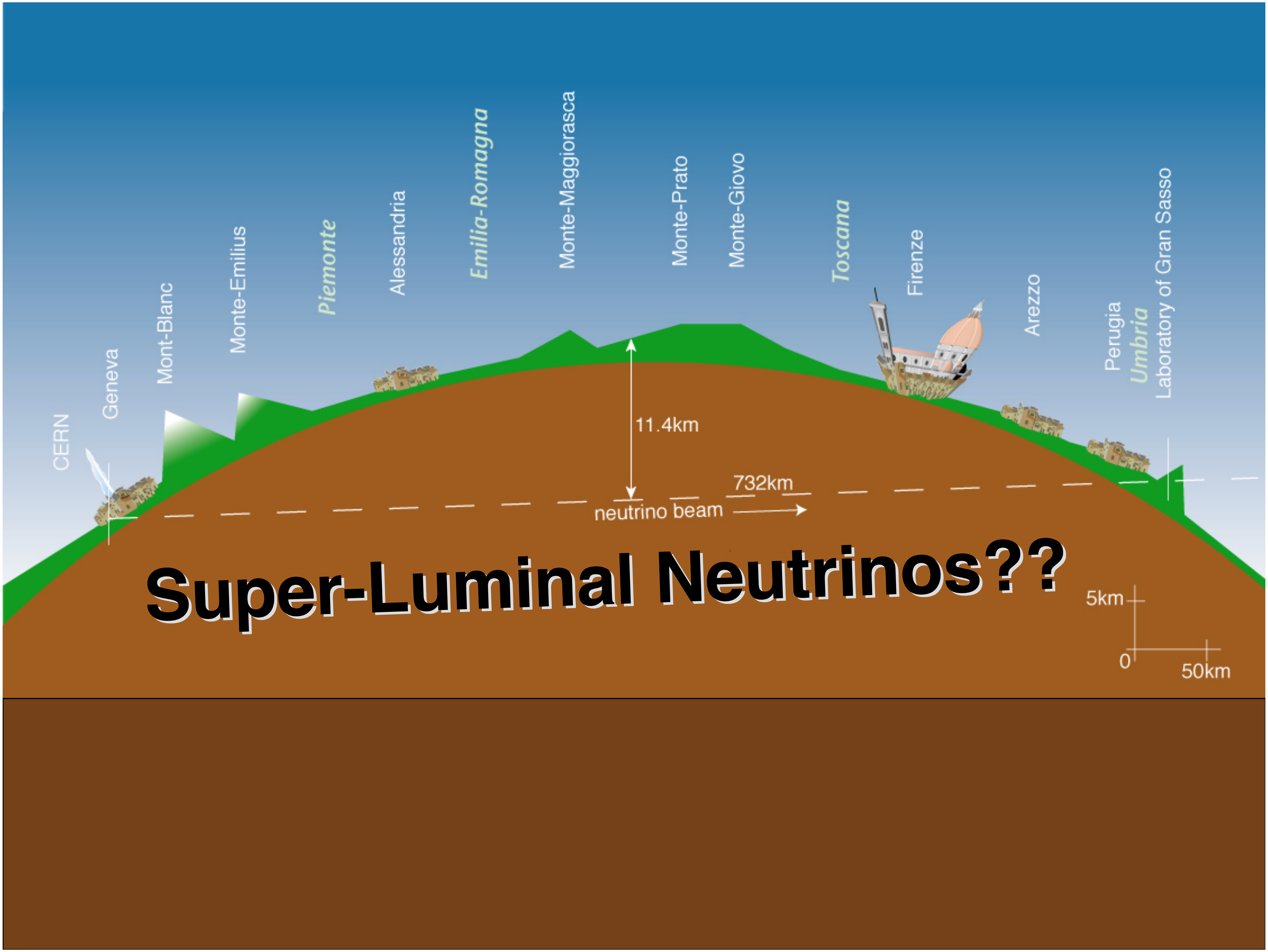
$$P\left(\overline{\nu}_e \ \text{Disappearance}\right) \cong$$

$$\cong \boxed{\sin^2 2\theta_{13}} \sin^2\left(1.27\,\Delta m_{32}^2\left(\text{eV}^2\right)\frac{L(\text{km})}{E(\text{GeV})}\right)$$

Double Chooz → $\boxed{\sin^2 2\theta_{13} = 0.085 \pm 0.051}$

We Must Be
Alert
To **Surprises**!

Super-Luminal Neutrinos??



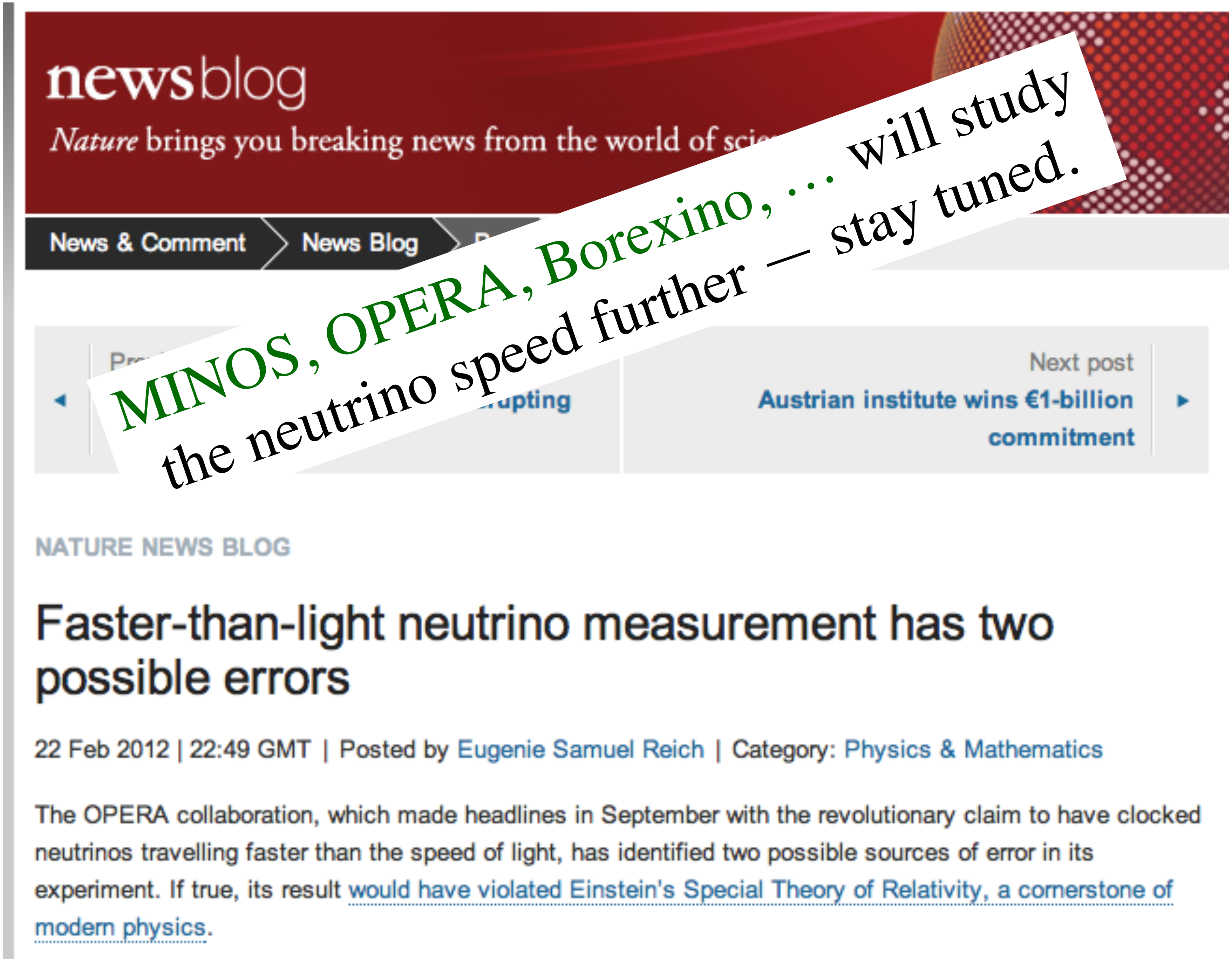
OPERA: Neutrinos from CERN arrive at Gran Sasso
$57.8 \pm 7.8\ (\text{stat})\ ^{+8.3}_{-5.9}\ (\text{sys})$ ns before a light beam would.

$$v_\nu = c\ \{1 + [2.37 \pm 0.32\ (\text{stat})\ ^{+0.34}_{-0.24}\ (\text{sys}) \times 10^{-5}]\}$$

“Extraordinary claims require extraordinary evidence.”

Q: How come the neutrinos from Supernova 1987A, 168,000 light years away, did not arrive here 4 years before the light did?

A: Good point, but maybe the speed of neutrinos is energy-dependent.



NATURE NEWS BLOG

Faster-than-light neutrino measurement has two possible errors

22 Feb 2012 | 22:49 GMT | Posted by Eugenie Samuel Reich | Category: Physics & Mathematics

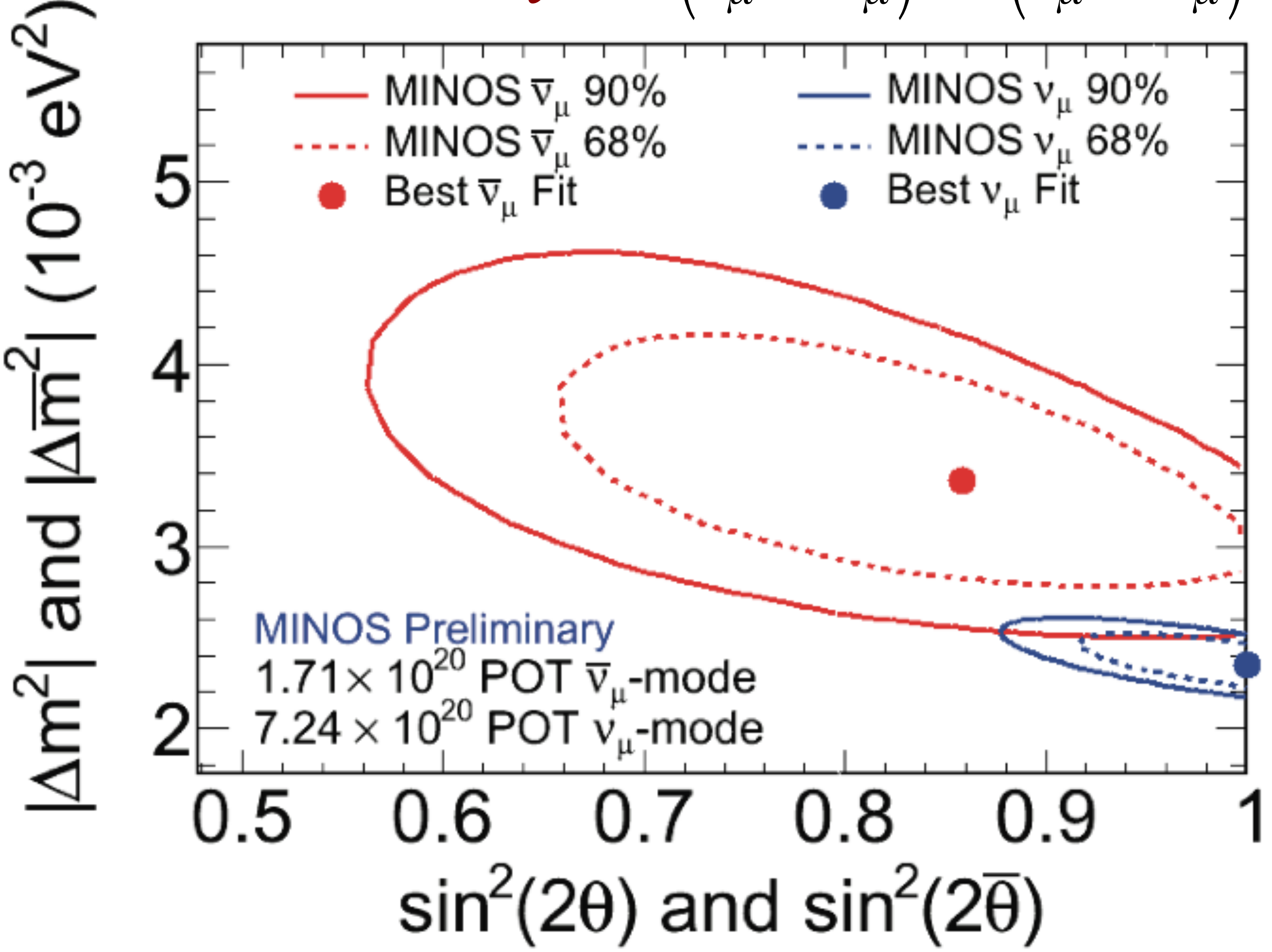
The OPERA collaboration, which made headlines in September with the revolutionary claim to have clocked neutrinos travelling faster than the speed of light, has identified two possible sources of error in its experiment. If true, its result would have violated Einstein's Special Theory of Relativity, a cornerstone of modern physics.

MINOS, OPERA, Borexino, … will study the neutrino speed further — stay tuned.

Surprises

Can Go Away!

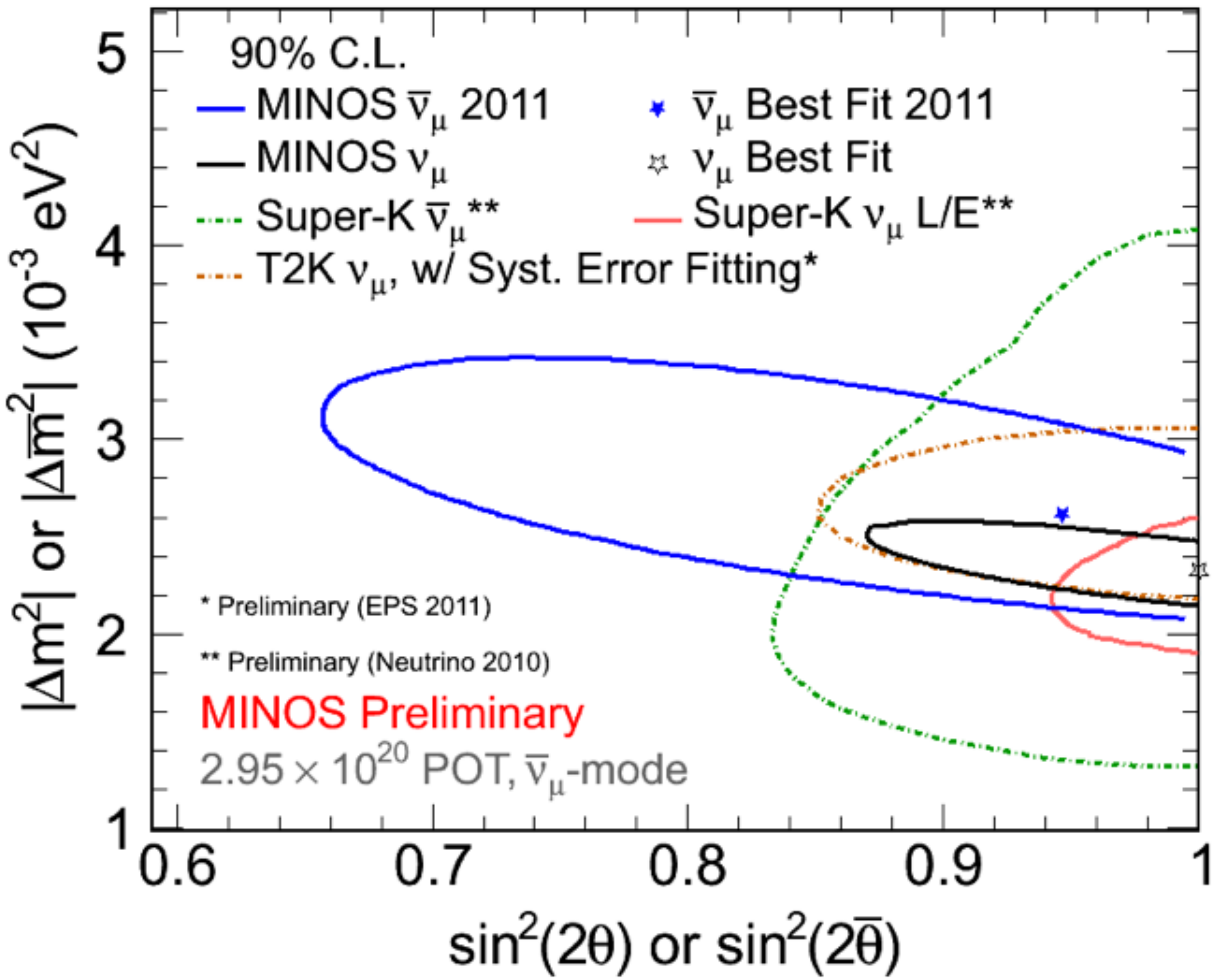
MINOS: ***Maybe*** $P\left(\bar{\nu}_\mu \rightarrow \bar{\nu}_\mu\right) \neq P\left(\nu_\mu \rightarrow \nu_\mu\right)$



P. Vahle, Neutrino 2010

Non-SM neutrino interactions??

MINOS: *With 70% More $\bar{\nu}$ Data*



We Must Be Alert To Surprises!

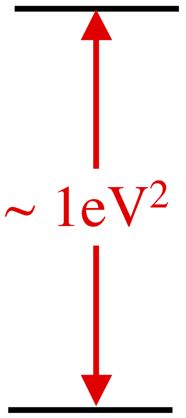
Are There *More* Than 3 Mass Eigenstates?

Are There Sterile Neutrinos?

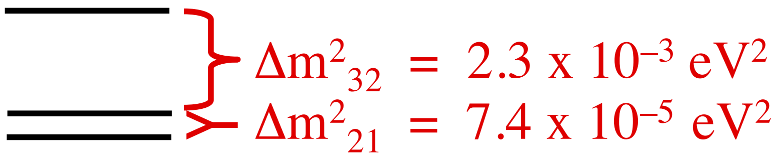
The Hint From LSND

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

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



in contrast to



At least **4** mass eigenstates

(From the **Z** width) At least **1** sterile neutrino

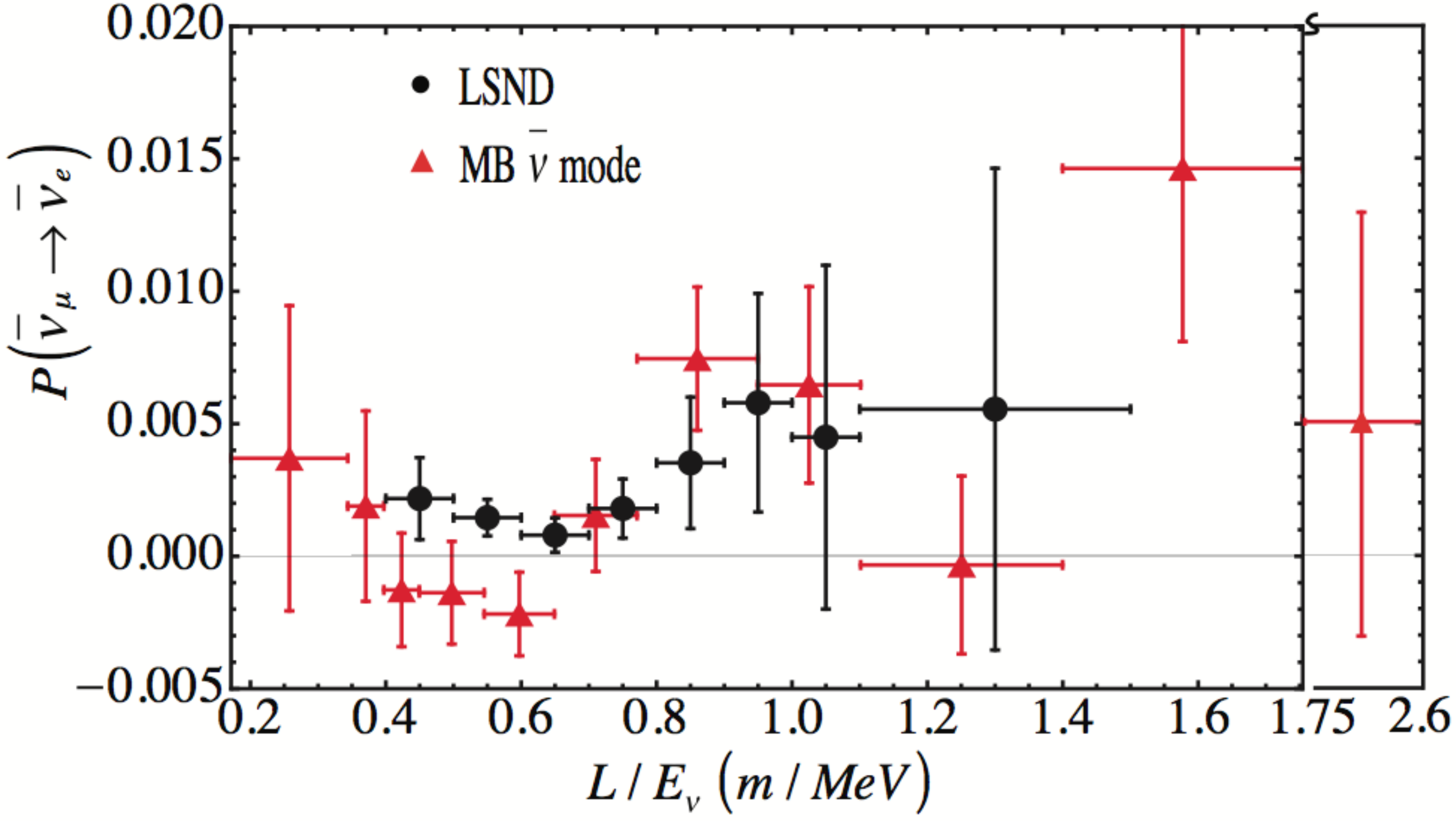
Is the LSND Signal Genuine Neutrino Oscillation?

The MiniBooNE experiment is
trying to confirm or refute LSND.

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

MiniBooNE has reported
its $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ results so far.

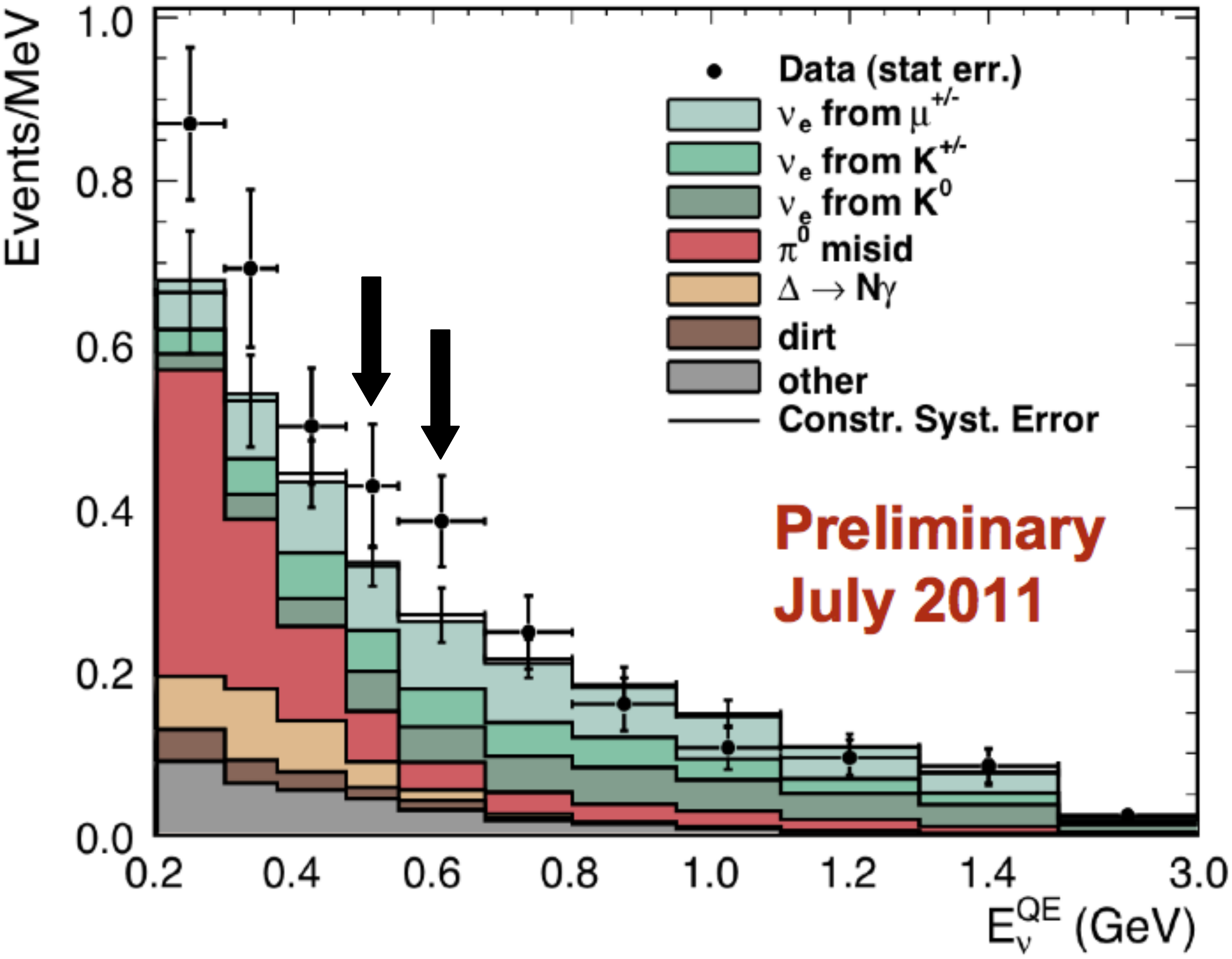
Direct MiniBooNE-LSND Comparison of $\bar{\nu}$ Data



(Phys.Rev.Lett.105:181801, 2010)

Latest from MiniBooNE (July, 2011 at PANIC):
Significance of $\bar{\nu}_\mu \to \bar{\nu}_e$ signal reduced.

MiniBooNE



E. Zimmerman and M. Shaevitz at PANIC 2011

The Reactor $\overline{\nu}_e$ Flux Surprise

The prediction for the un-oscillated $\overline{\nu}_e$ flux
from reactors has increased by about 3%.

(Mueller et al.)

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

(Mention et al.)

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

Fits to all data with 2 extra neutrinos are improved.

(Kopp et al.)

The ^{51}Cr and ^{37}Ar ν_e Flux Surprise

These radioactive sources were used to
calibrate Gallium solar ν_e detectors.

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

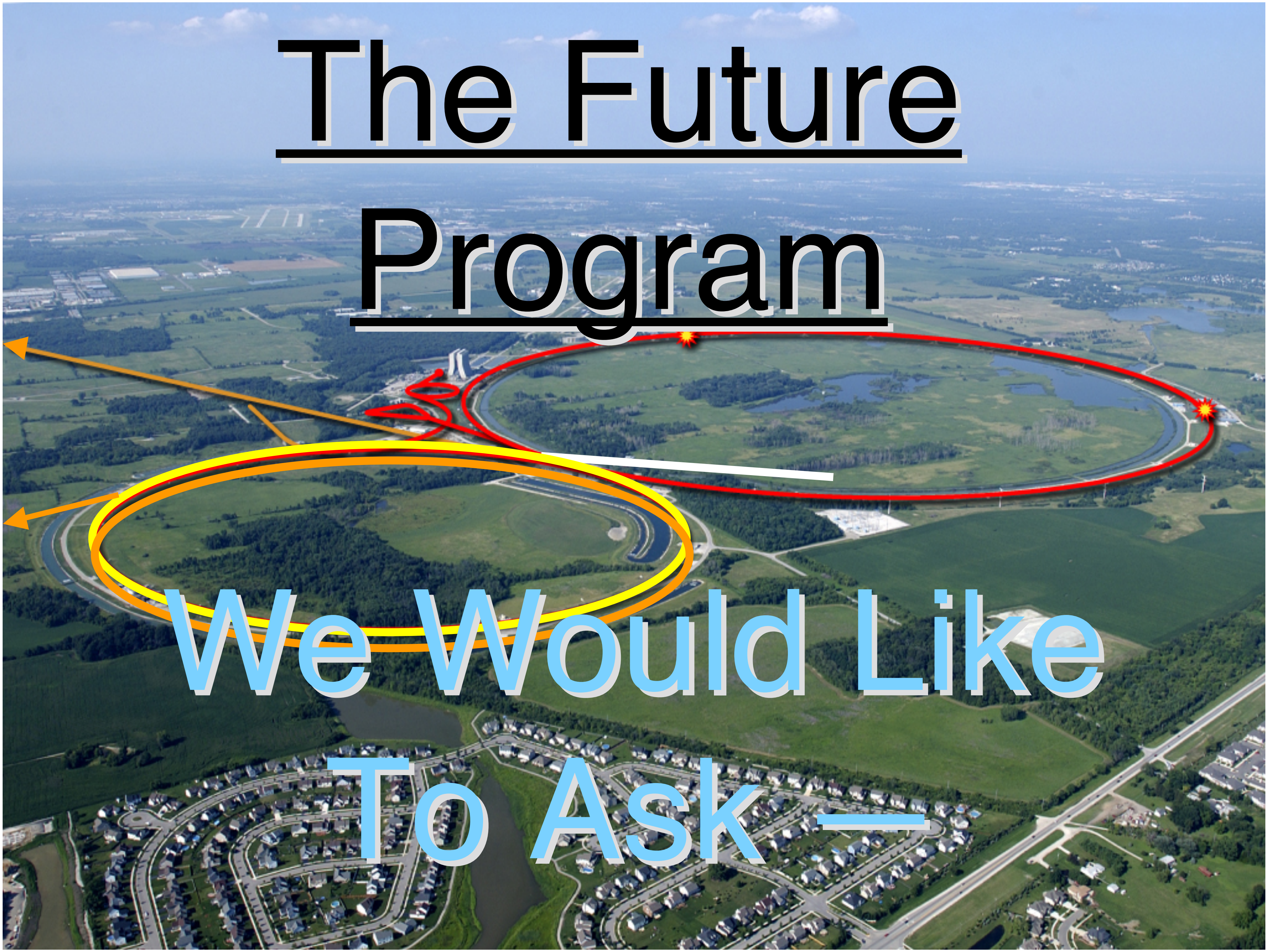
(Giunti, Laveder)

Rapid disappearance of ν_e flux with
$\Delta m^2 \sim 1\ \text{eV}^2$, like LSND and MiniBooNE??

Best-fit point excluded by
LSND and MiniBooNE data.

(Conrad, Shaevitz)

The Future Program



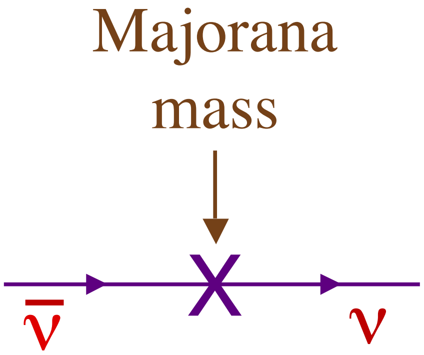
We Would Like To Ask —

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

Do Neutrinos Have ***Majorana*** Masses?

Majorana Masses

Their effect:



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 causes $\Delta L = 2$.

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.

They cannot come from a Yukawa coupling $\bar{f}\,H\,f$
to the Standard Model Higgs field **H.**

Majorana Masses ➡ $\bar{\nu}_i = \nu_i$

For Mass Eigenstates

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 —

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

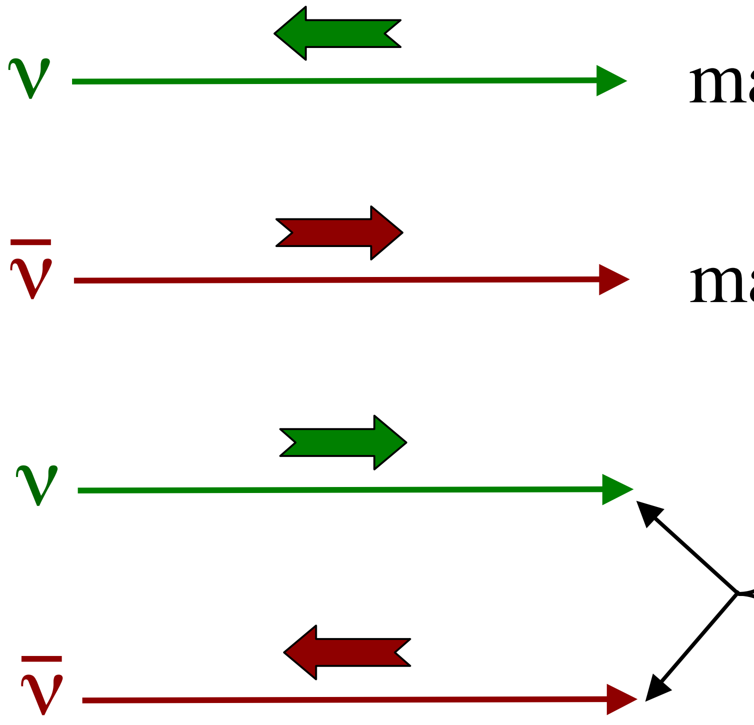
What $\overline{\nu}_i = \nu_i$ Means

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

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

SM Interactions Of A Dirac Neutrino

We have 4 mass-degenerate states:



<u>Conserved L</u>

ν makes ℓ^- $+1$

$\bar{\nu}$ makes ℓ^+ -1

ν

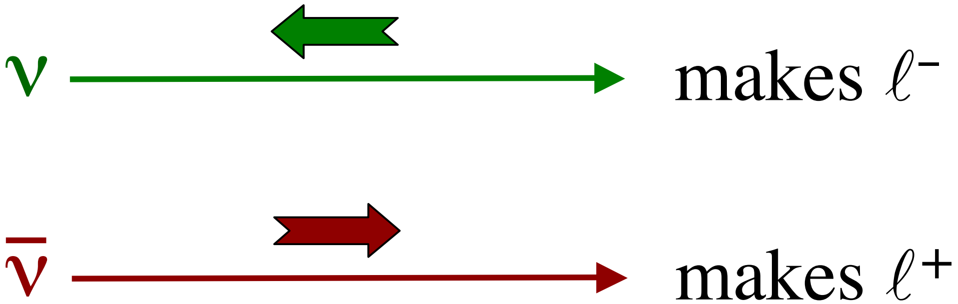
$\bar{\nu}$

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

(The weak interaction is Left Handed.)

SM Interactions Of A Majorana Neutrino

A Majorana neutrino has 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 Approach — Seek

Neutrinoless Double Beta Decay [0νββ]

0νββ

Clearly does not conserve L: ΔL = 2.

Non-perturbative ***Sphaleron*** processes in the Standard Model (SM) do not conserve L.

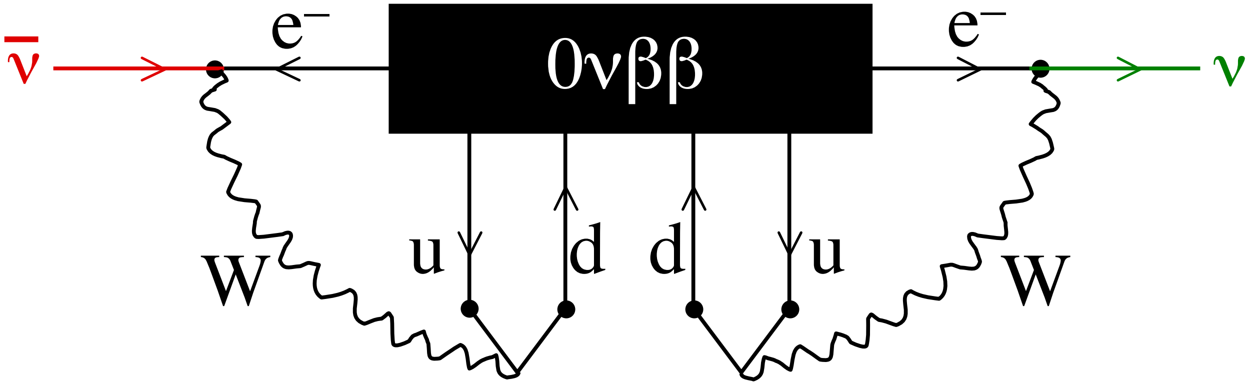
But Sphaleron processes can only change L by a multiple of 3.

2 is not a multiple of 3.

The ΔL = 2 of 0νββ is outside the SM.

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

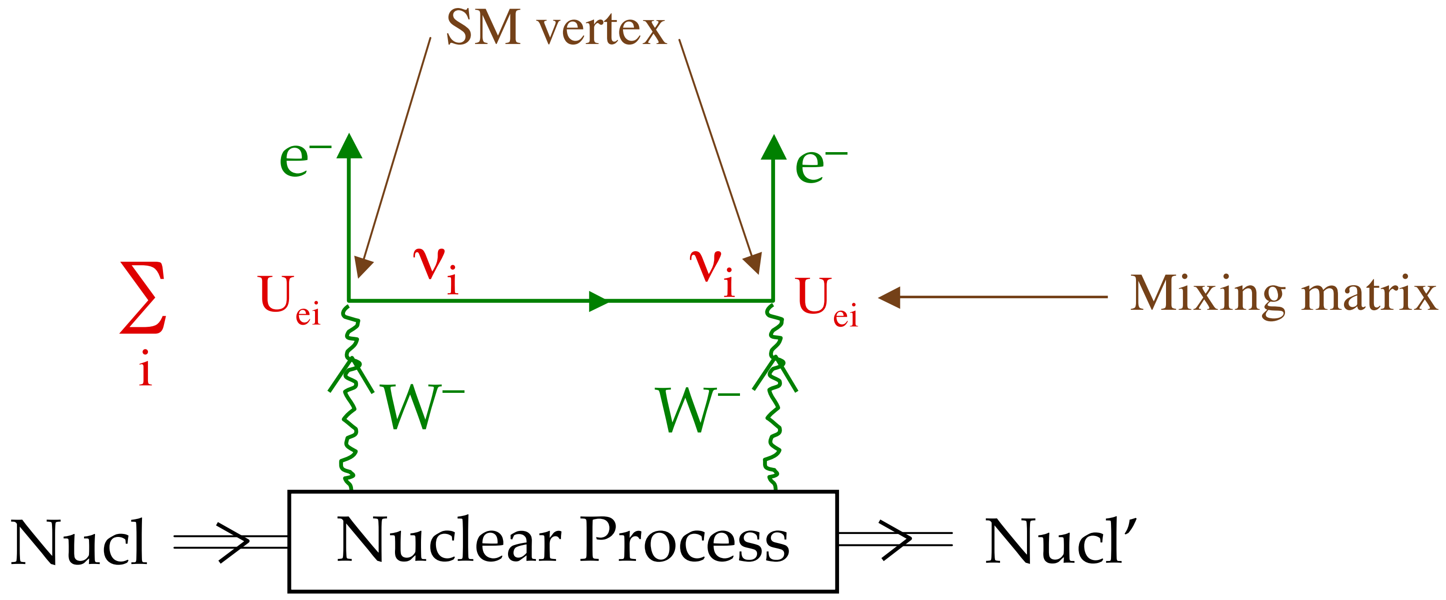
(Schechter and Valle)



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

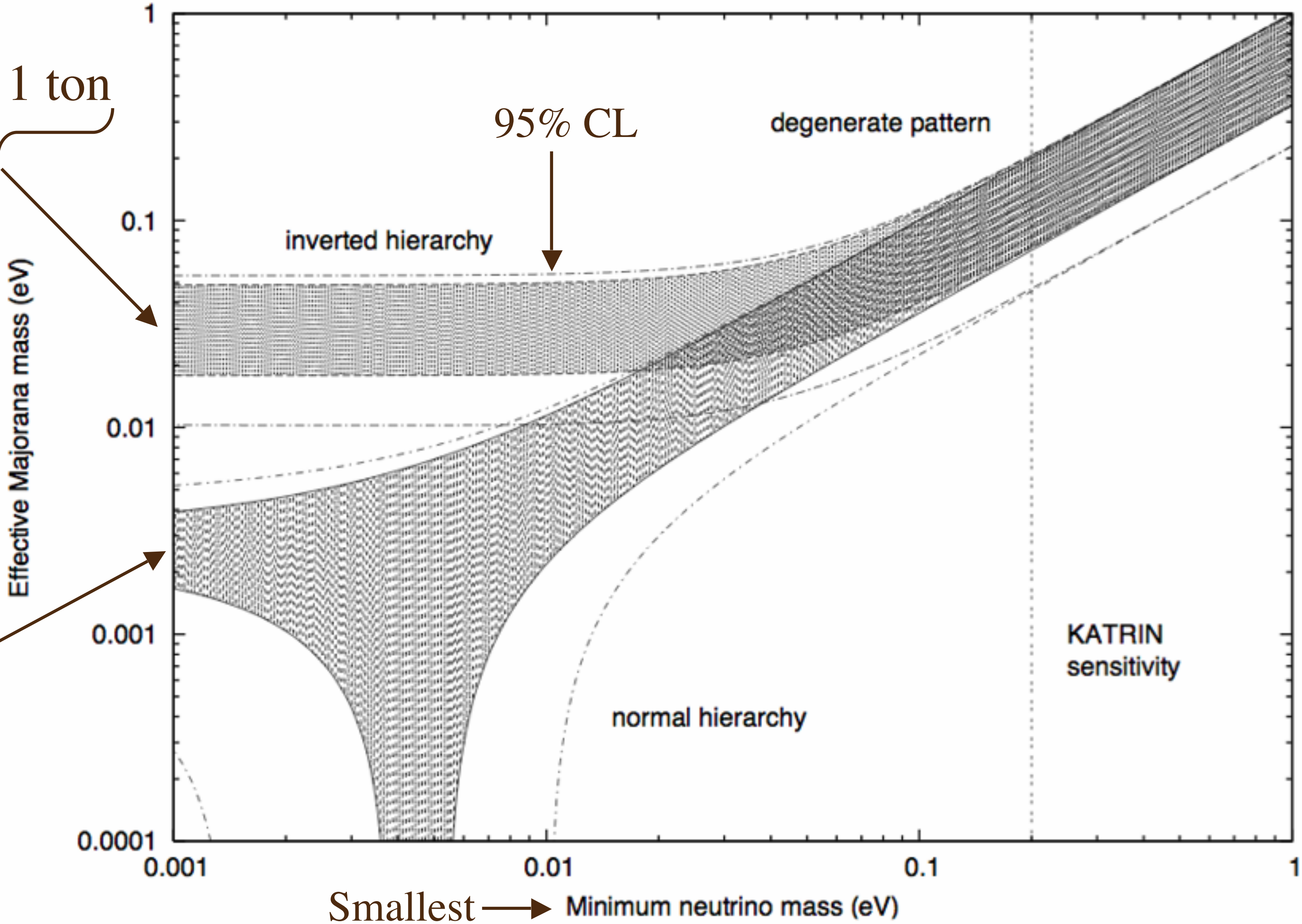
$\therefore$ 0$\nu\beta\beta$ ➡ $\bar{\nu}_i = \nu_i$

We anticipate that 0νββ is dominated by a diagram with Standard Model vertices:



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

Mass of ν_i



Takes 1 ton

95% CL

$m_{\beta\beta}$

Smallest →

Takes
100 tons

$m_{\beta\beta}$ For Each Hierarchy

There is no clear theoretical preference
for either hierarchy.

If the hierarchy is **inverted**—

then $0\nu\beta\beta$ searches with sensitivity
to $m_{\beta\beta} = 0.01$ eV have
a very good chance to see a signal.

Sensitivity in this range is the target
for the next generation of experiments.

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 $n_{\overline{B}} = n_B \Longrightarrow n_{\overline{B}} << n_B$?

Sakharov: $n_{\overline{B}} = n_B \Longrightarrow n_{\overline{B}} << n_B$ requires $\cancel{CP}$.

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

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

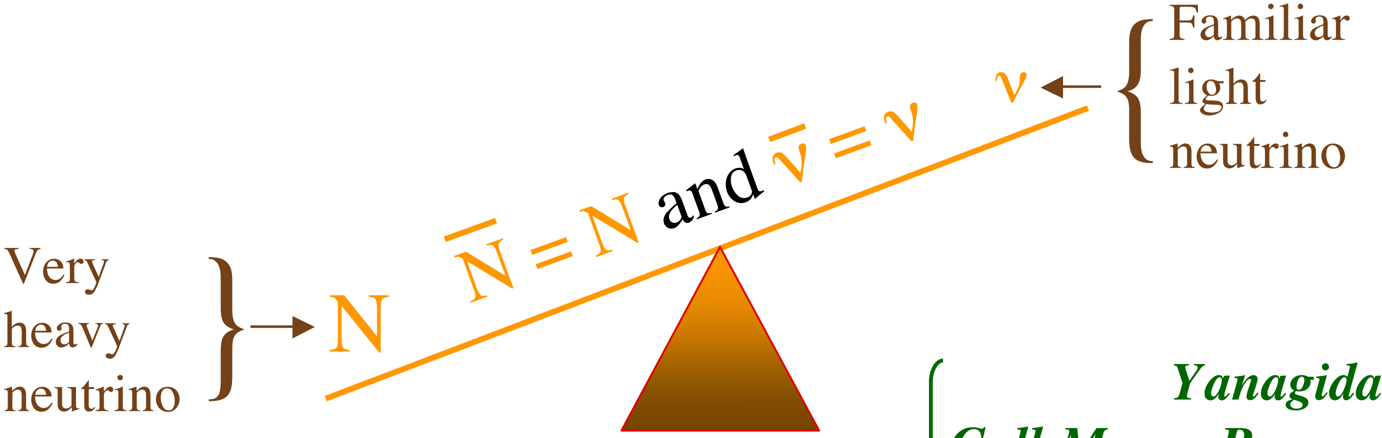
The candidate scenario: *Leptogenesis*.

(Fukugita, Yanagida)

Leptogenesis – A Two-Step Process

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

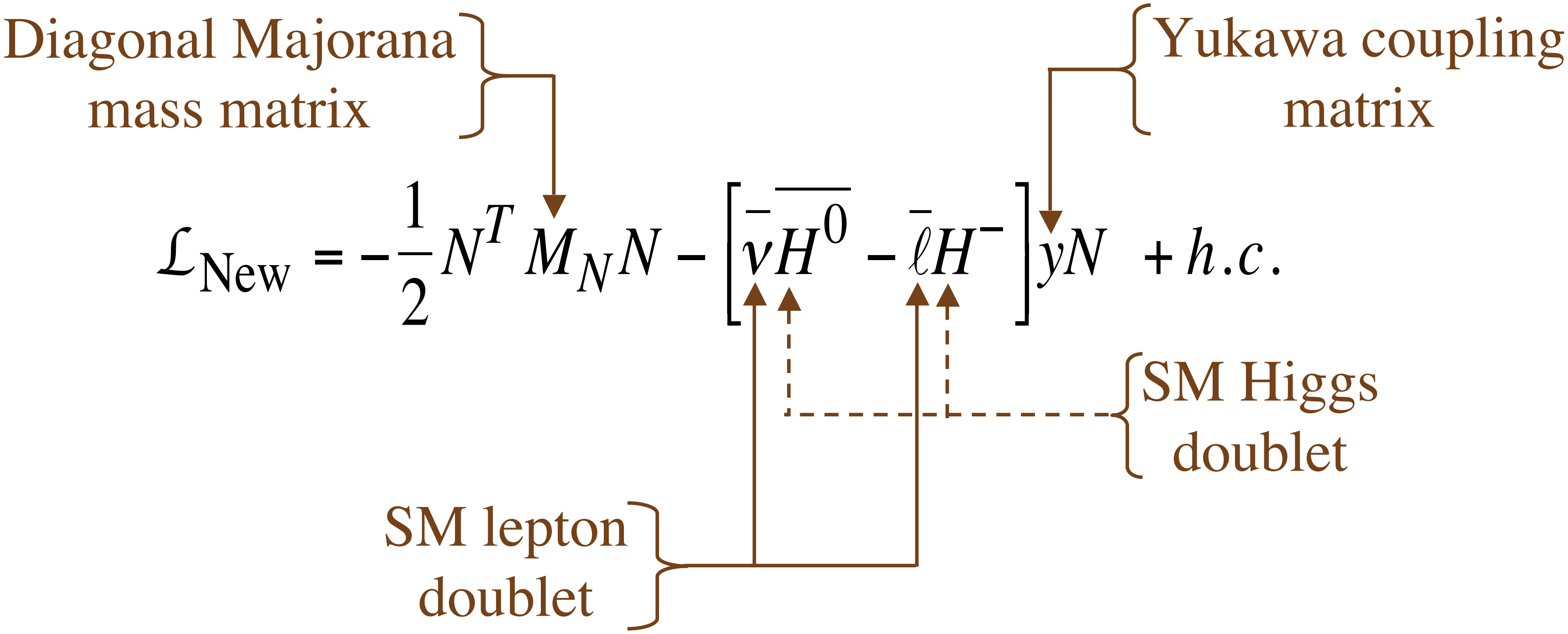
The See-Saw Mechanism



Yanagida;
Gell-Mann, Ramond, Slansky;
Mohapatra, Senjanovic;
Minkowski

The ***very*** heavy neutrinos N are far beyond LHC range, but would have been made in the hot Big Bang.

In the straightforward (Type-I) see-saw model —



Diagonal Majorana mass matrix

Yukawa coupling matrix

$$\mathcal{L}_{\text{New}} = -\frac{1}{2}N^T M_N N - \left[\bar{\nu}\overline{H^0} - \bar{\ell}H^-\right] y N \; + h.c.$$

SM Higgs doublet

SM lepton doublet

Here, N, ν, and ℓ are three-component vectors, corresponding to the three particle families.

The heavy neutrinos decay through the Yukawa coupling:

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

$\cancel{CP}$ phases in y will lead to —

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

and

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

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

In this universe the lepton number L, defined by $L\left(\ell^-\right) = L(\nu) = -L\left(\ell^+\right) = -L(\overline{\nu}) = 1$, 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 .

Leptogenesis and ~~CP~~ In Light ν Oscillation

(BK, arXiv:1012.4469)

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.

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

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

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

The observation of CP violation in neutrino oscillation would make it more plausible that ***leptogenesis*** *occurred in the early universe.*

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

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

Summary

Neutrino oscillation is a beautiful consequence of quantum mechanics.

We have very interesting questions to ask about the neutrinos.

Very likely, more surprises are in store!