Neutrino Physics Overview

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ICISE
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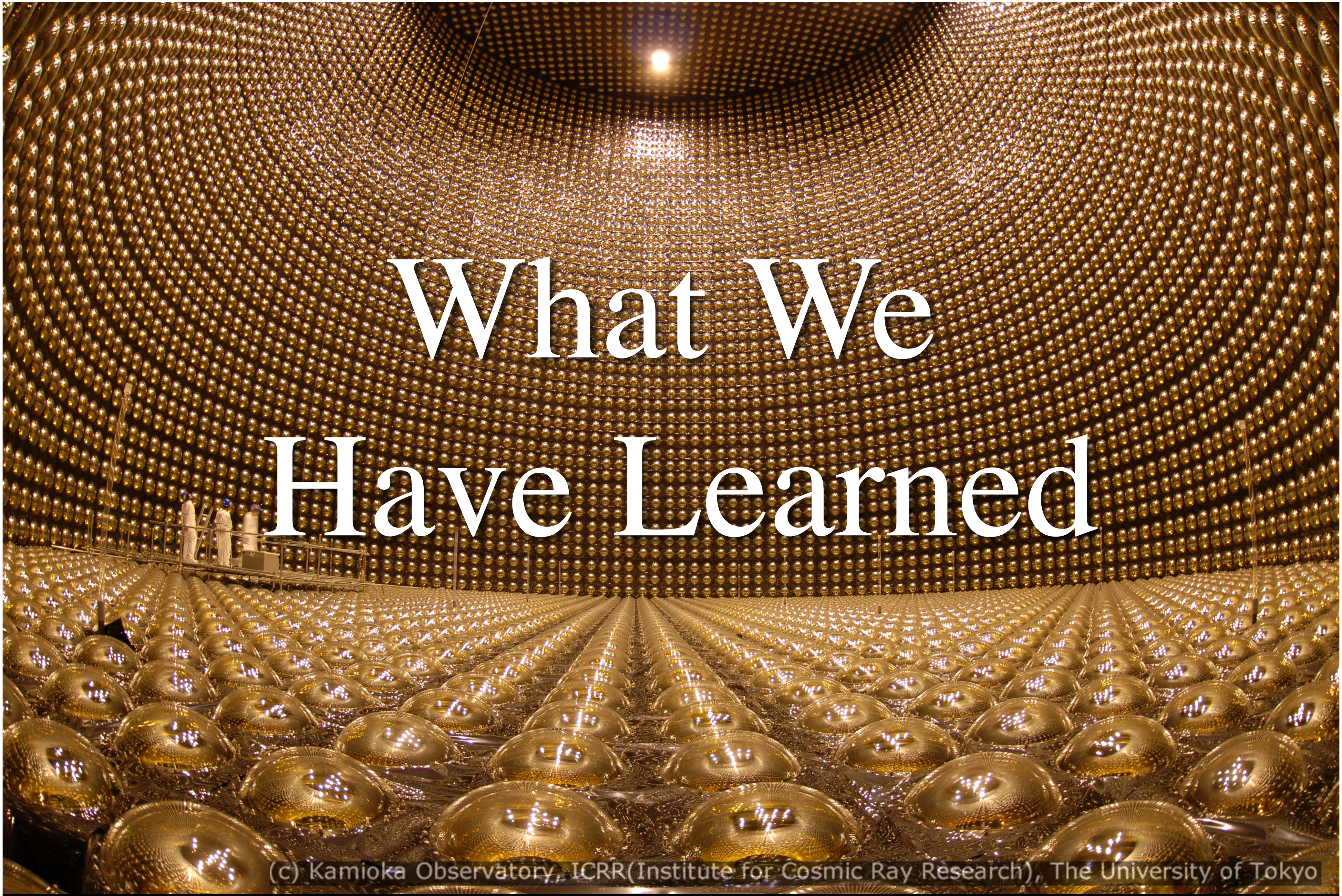
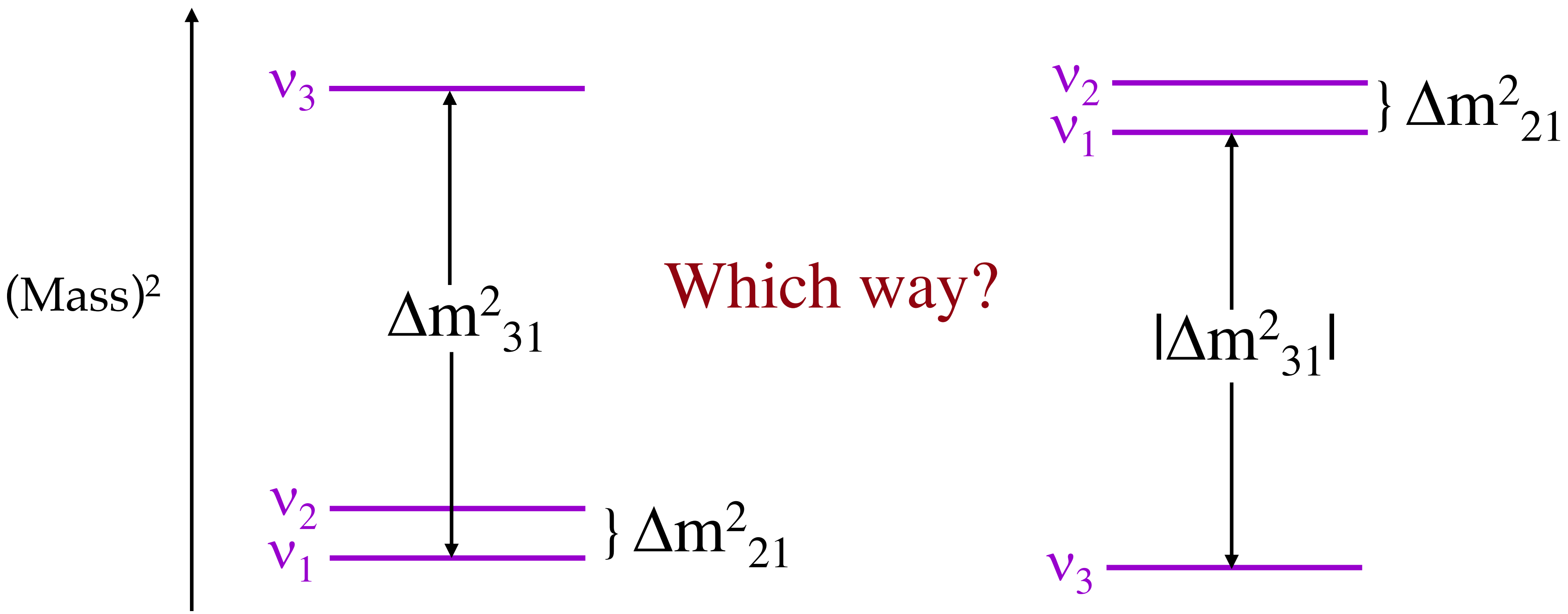
What We Have Learned



(c) Kamioka Observatory, ICRR(Institute for Cosmic Ray Research), The University of Tokyo

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



Which way?

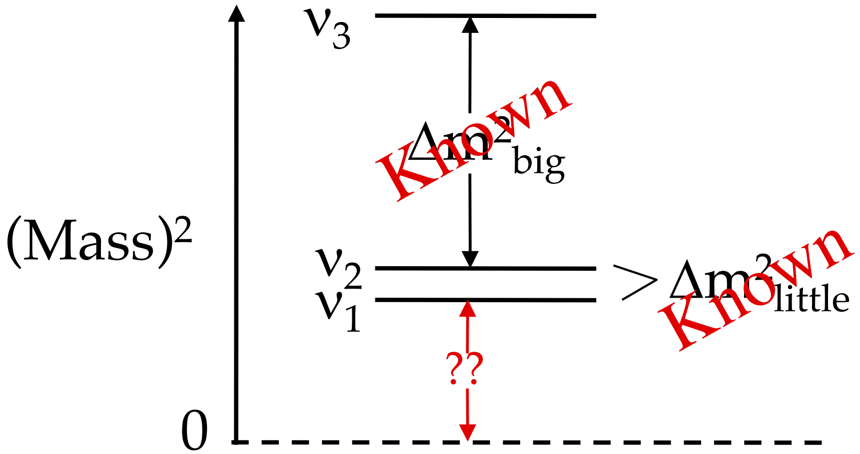
Normal

Inverted

$$\Delta m^2_{21} \cong 7.5 \times 10^{-5}\ \text{eV}^2, \quad |\Delta m^2_{31}| \cong 2.5 \times 10^{-3}\ \text{eV}^2$$

Are there ***more*** mass eigenstates?

Constraints On the Absolute Scale of Neutrino Mass



How far above zero is the whole pattern?

Cosmology, *under certain assumptions* ⇒ $\sum_{\text{All } i} m(\nu_i) < 0.2\text{ eV}$

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

Oscillation ⇒ Mass[Heaviest ν_i] $> \sqrt{\Delta m^2_{big}} > 0.05\text{ eV}$

Leptonic Mixing

Mixing means that —

PMNS mixing matrix

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

Neutrino of flavor

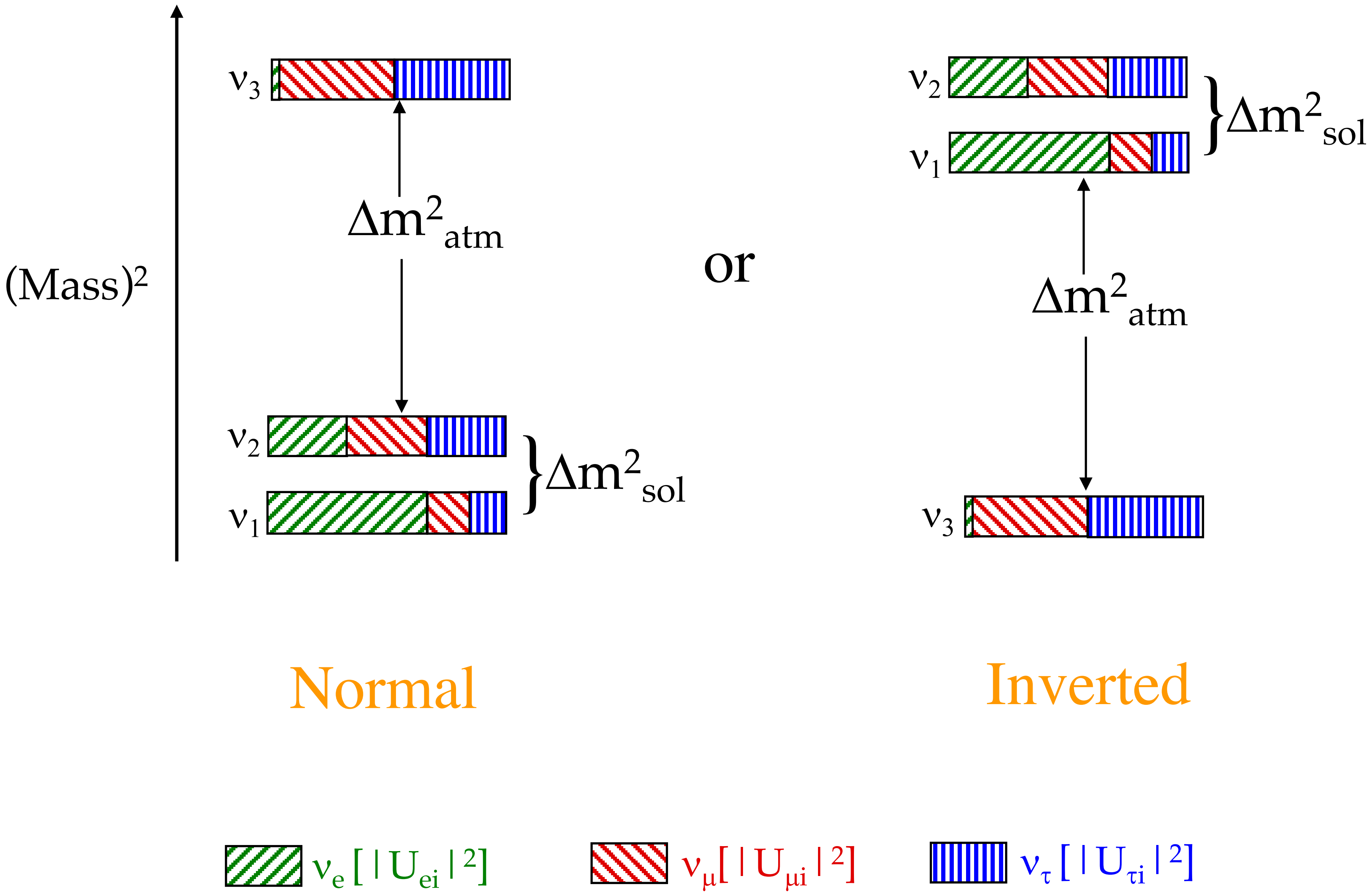
α = e, μ, or τ

Neutrino of definite mass m_i

Inversely, $|\nu_i> = \sum_\alpha U_{\alpha i}\,|\nu_\alpha> \;.$ (***if*** U is unitary)

Flavor-α fraction of $\nu_i = |U_{\alpha i}|^2 \;.$

Experimentally, the flavor fractions are —



(Mass)^2

ν_3

Δm^2_{atm}

ν_2

ν_1

$\}\Delta m^2_{sol}$

or

ν_2

ν_1

$\}\Delta m^2_{sol}$

Δm^2_{atm}

ν_3

Normal

Inverted

▨ ν_e [$|U_{ei}|^2$]

▧ ν_μ [$|U_{\mu i}|^2$]

▥ ν_τ [$|U_{\tau i}|^2$]

The Leptonic Mixing Matrix *U*

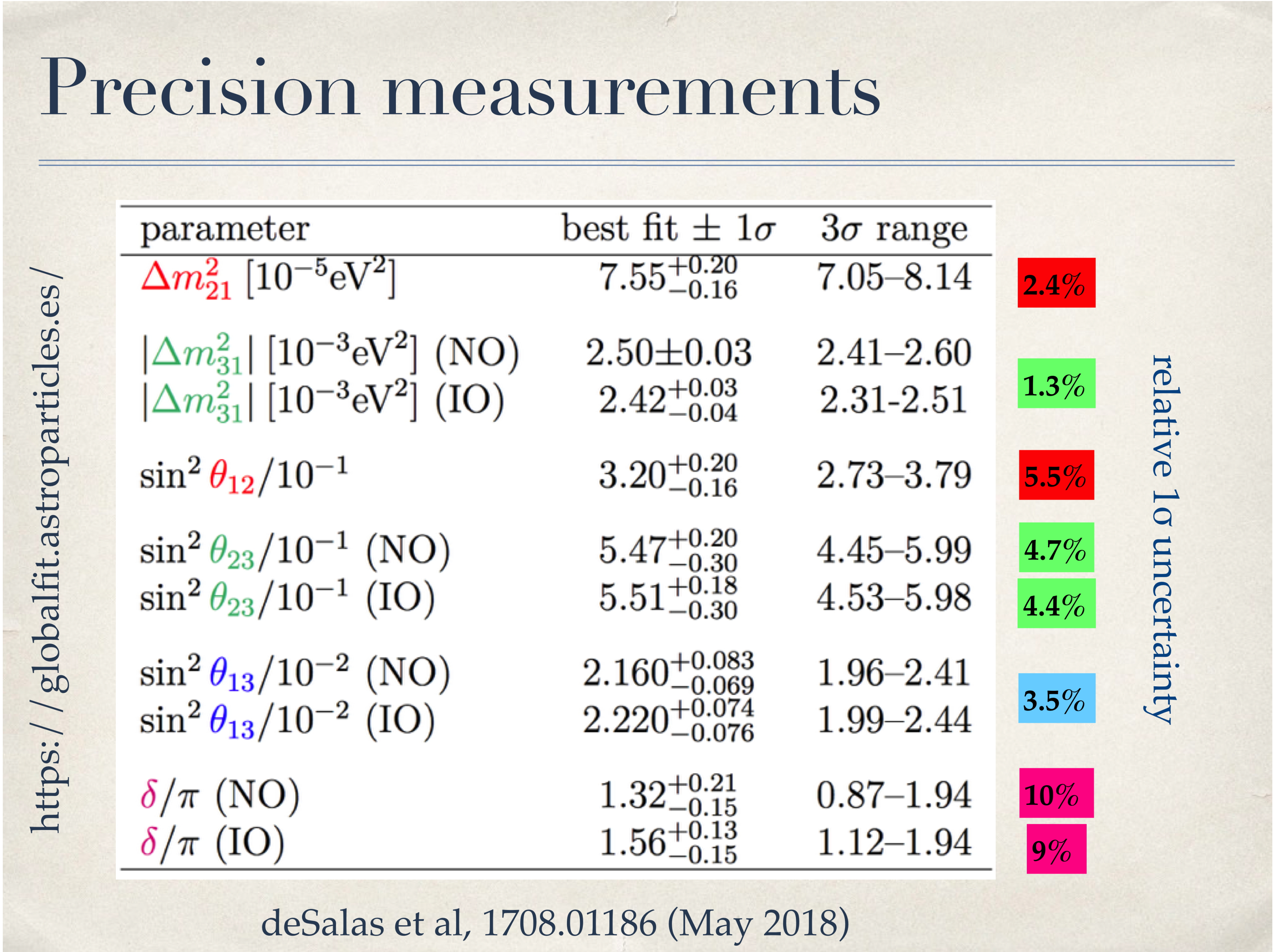
$$U = \begin{bmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{bmatrix} \times \begin{bmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{bmatrix} \times \begin{bmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

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

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

$\theta_{12} \approx 34°$, $\theta_{23} \approx 42\text{-}51°$, $\theta_{13} \approx 8.5°$ $\delta = ??$

(Tortola at ν 2018)



Precision measurements

https://globalfit.astroparticles.es/

parameter	best fit ± 1σ	3σ range	relative 1σ uncertainty
Δm^2_{21} $[10^{-5}\mathrm{eV}^2]$	$7.55^{+0.20}_{-0.16}$	7.05–8.14	2.4%
$\lvert\Delta m^2_{31}\rvert$ $[10^{-3}\mathrm{eV}^2]$ (NO)	2.50±0.03	2.41–2.60	1.3%
$\lvert\Delta m^2_{31}\rvert$ $[10^{-3}\mathrm{eV}^2]$ (IO)	$2.42^{+0.03}_{-0.04}$	2.31-2.51	
$\sin^2\theta_{12}/10^{-1}$	$3.20^{+0.20}_{-0.16}$	2.73–3.79	5.5%
$\sin^2\theta_{23}/10^{-1}$ (NO)	$5.47^{+0.20}_{-0.30}$	4.45–5.99	4.7%
$\sin^2\theta_{23}/10^{-1}$ (IO)	$5.51^{+0.18}_{-0.30}$	4.53–5.98	4.4%
$\sin^2\theta_{13}/10^{-2}$ (NO)	$2.160^{+0.083}_{-0.069}$	1.96–2.41	3.5%
$\sin^2\theta_{13}/10^{-2}$ (IO)	$2.220^{+0.074}_{-0.076}$	1.99–2.44	
δ/π (NO)	$1.32^{+0.21}_{-0.15}$	0.87–1.94	10%
δ/π (IO)	$1.56^{+0.13}_{-0.15}$	1.12–1.94	9%

deSalas et al, 1708.01186 (May 2018)

From M. Tortola, at ν 2018.

What We Would Like To Find Out

NASA Hubble Photo

- Is the physics behind the masses of neutrinos different from that behind the masses of all other known particles?
- Are neutrinos their own antiparticles?

- What is the absolute scale of neutrino mass?

- Is the spectrum like  or  ?

- Is θ_{23} maximal?

- 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 baryon – antibaryon asymmetry of the universe?

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

- What are the electromagnetic properties of neutrinos?

- Are there ***more*** than 3 mass eigenstates?
  - Are there "sterile" neutrinos that don't couple to the W or Z?

- Do neutrinos have Non-Standard-Model interactions?

- Is coherent neutrino – nucleus scattering anomalous?

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

Questions With Current Hints

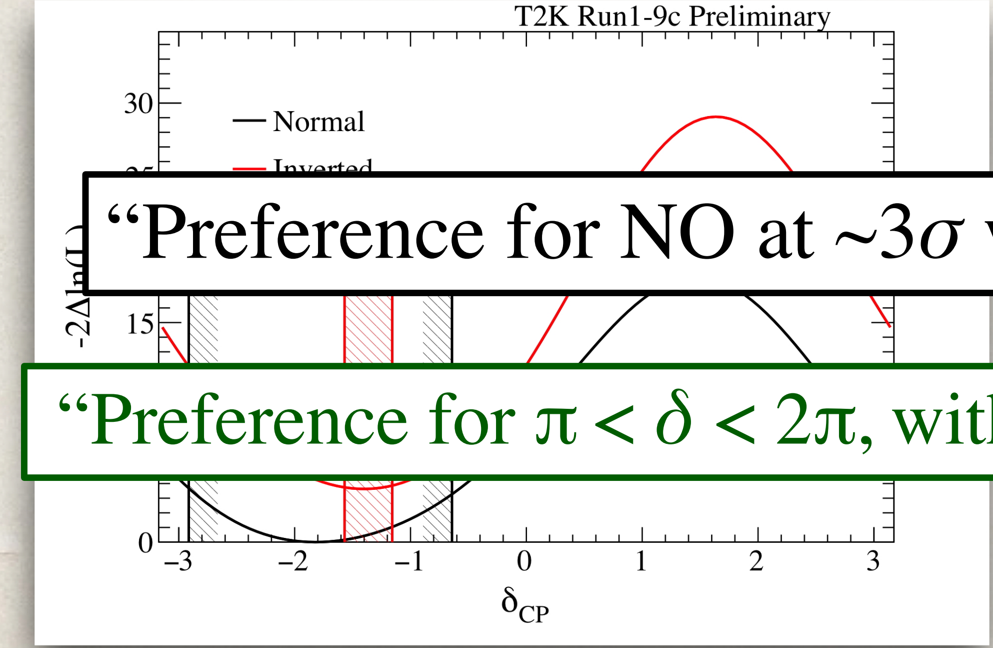
Does the leptonic mixing matrix U violate CP?
That is, is the CP phase $\delta \neq 0$ or π, so that U is not real?

Is the order of the mass eigenstates  NO or  IO ?

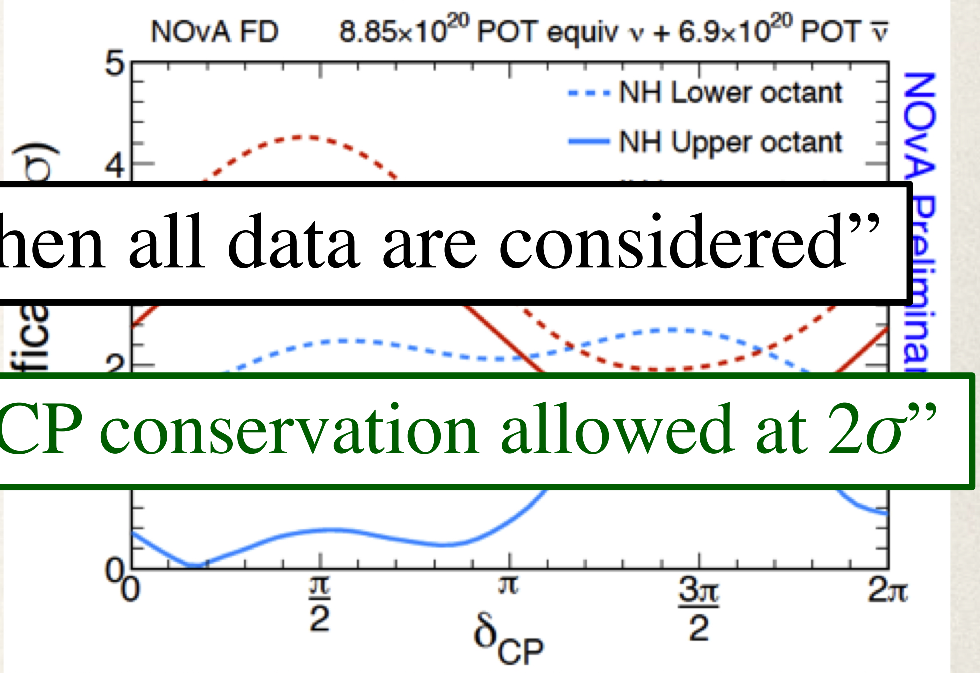
New results on the CP phase

T2K **Talk by M.Wascko**

NOνA **Talk by M. Sánchez**



(fit with reactor constraint)



“Preference for NO at ~3σ when all data are considered”

“Preference for $\pi < \delta < 2\pi$, with CP conservation allowed at 2σ”

Best fit: $\delta_{NO}=0.17\pi$ $\delta_{IO}\sim1.5\pi$

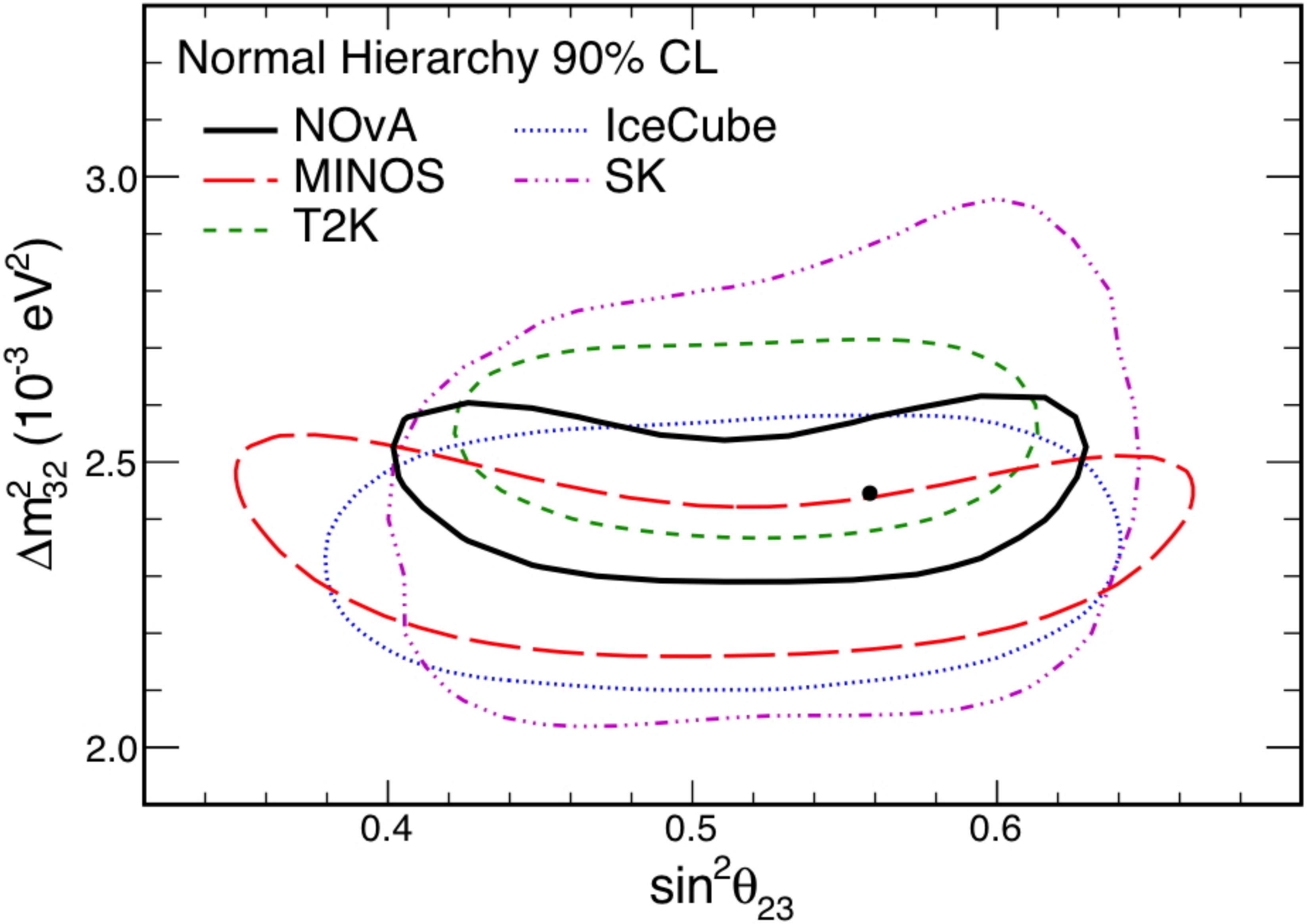
CP conservation more disfavoured
⇒ $\delta=0,\pi$ outside 2σ region for NO & IO

?

⇒ improved status for $\delta=0$

M. Tortola at ν 2018

Is θ_{23} maximal (45°)?



(NOνA; 1806.00096)

Are there eV-mass sterile neutrinos?

$$\text{Probability}\left(\text{Oscillation}\right) \propto \sin^2\left[1.27\Delta m^2\left(\text{eV}^2\right)\frac{L\left(\text{m}\right)}{E\left(\text{MeV}\right)}\right]$$

There are several hints of oscillation with L(m)/E(MeV) ~ 1.

These suggest that there is a Δm^2 larger than the 2 established ones. If so, there must be a 4th mass eigenstate, hence a 4th flavor.

Since only 3 neutrino flavors couple to the Z or W, this new flavor must be sterile (≡ does not couple to Z or W).

The Hints of eV^2-Scale Δm^2

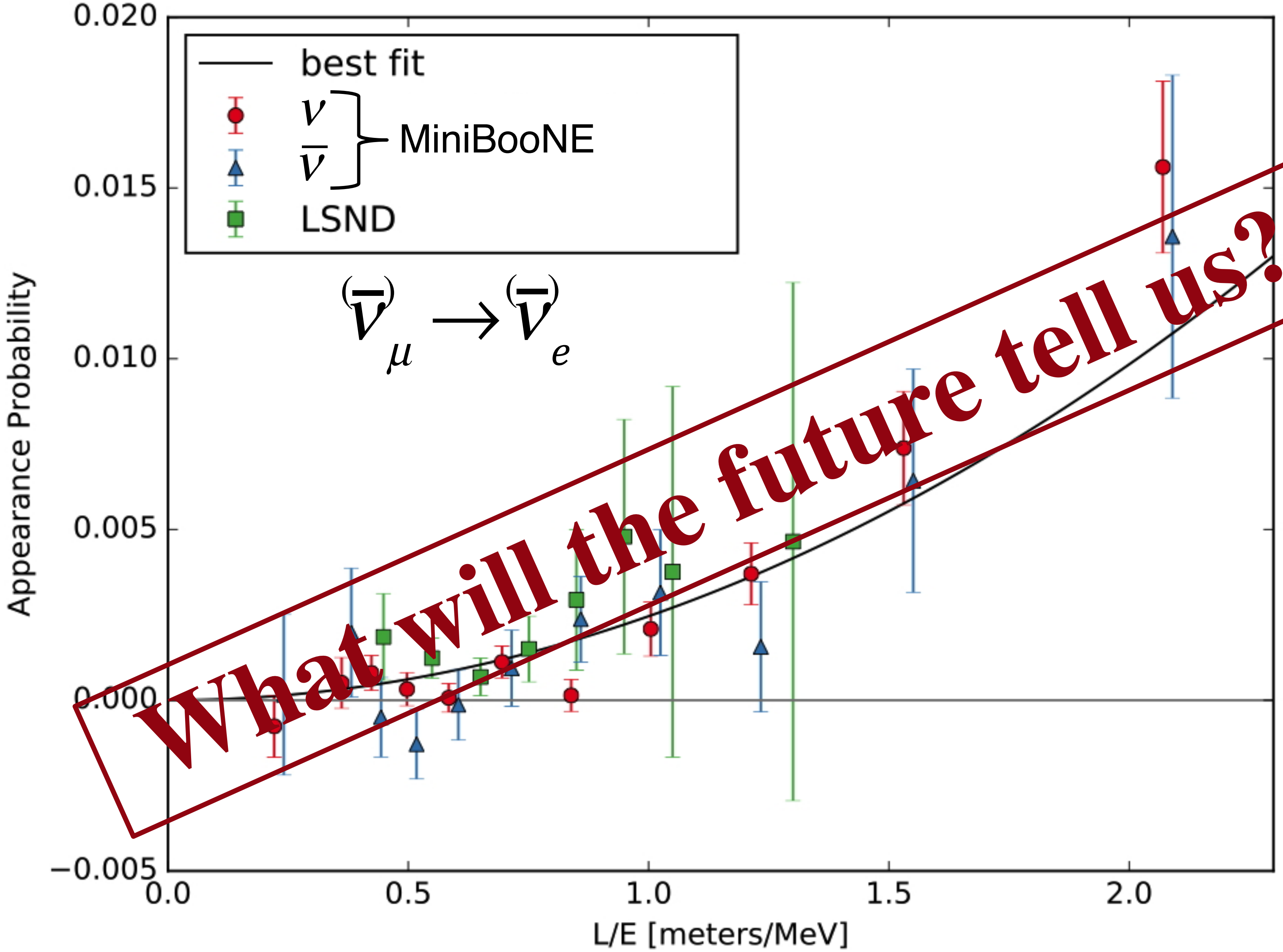
Experiment	**Possible Oscillation**	**Comment**
LSND	$\bar{\nu}_\mu \rightarrow \bar{\nu}_e$	Interesting
MiniBooNE	$\nu_\mu \rightarrow \nu_e$	Low energy excess?
MiniBooNE	$\bar{\nu}_\mu \rightarrow \bar{\nu}_e$	Low energy excess?
Reactor Exps.	$\bar{\nu}_e \rightarrow \text{Not } \bar{\nu}_e$	Flux uncertainty ~ 6% size of effect
^{51}Cr and ^{37}Ar Source Exps.	$\nu_e \rightarrow \text{Not } \nu_e$	Detection efficiency?

There is strong tension between the evidence for rapid $\nu_\mu \rightarrow \nu_e$ and $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$, and the limits on rapid $\nu_\mu \rightarrow \nu_{\cancel{\mu}}$ and $\bar{\nu}_e \rightarrow \bar{\nu}_{\cancel{e}}$.

(M. Dentler et al., 1803.10661)

A recent paper shows that the MiniBooNE and LSND positive indications of ***something*** going on ***(a sterile neutrino???)*** are not inconsistent.

(MiniBooNE, 1805.12028)



What will the future tell us?

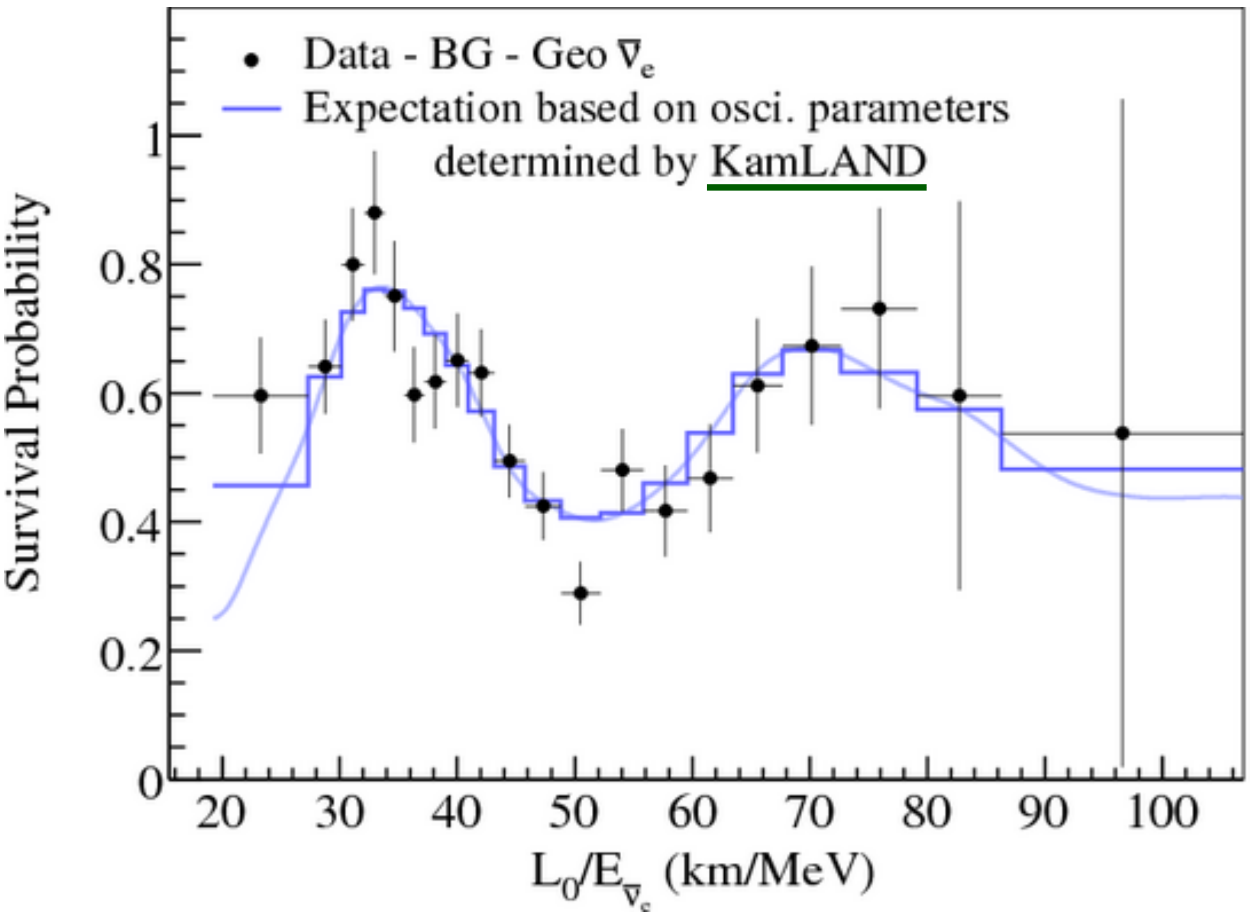
1 eV scale sterile neutrinos, if real, could greatly affect the interpretation of the CP-violation studies of the long-baseline experiments.

For example, long-baseline data that, when analyzed disregarding the possibility of sterile neutrinos, indicate that CP violation is very small or absent, could in fact hide quite large CP violation.

(R. Gandhi, B.K., M. Masud, S. Prakash)

The presence or absence of 1 eV scale sterile neutrinos needs to be settled experimentally, and many experiments to do that, using neutrinos from sources, reactors, accelerators, or elsewhere, are in progress or planned.

To confirm their existence, it would be nice to see actual Oscillatory Behavior a la



DANSS and NEOS do see hints of wiggles, but make no claims.

A theoretical issue that should not cause any worries

Much of what we know about the neutrinos was learned from studies of neutrino flavor change, using such formulas as —

Probability of Flavor Change In Vacuum

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

Mixing matrix

Distance

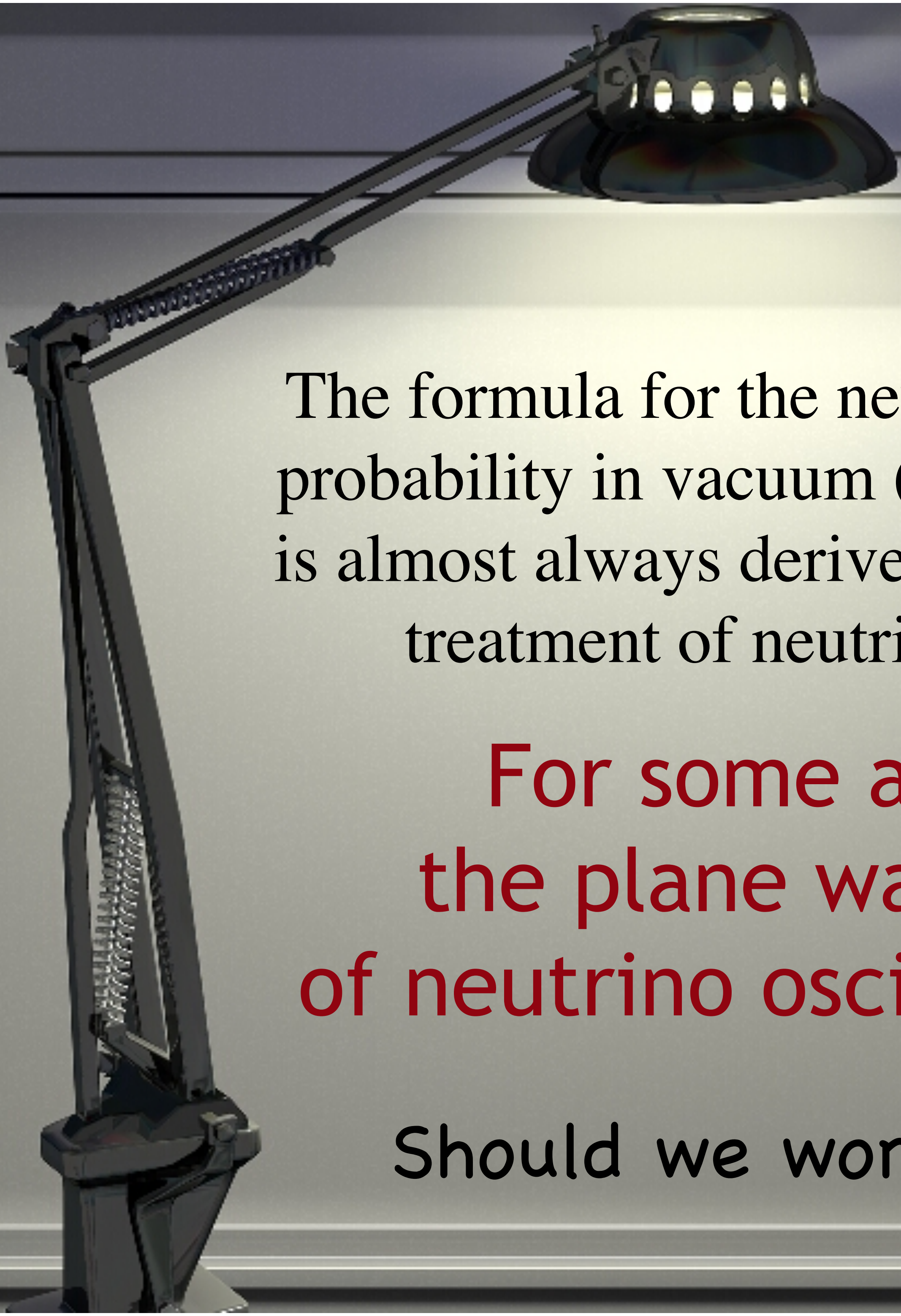
Energy

e, μ, or τ

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

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

where $\Delta m^2_{ij} \equiv m^2_i - m^2_j$.



The formula for the neutrino flavor-change probability in vacuum (neutrino oscillation) is almost always derived using a plane-wave treatment of neutrino propagation.

For some applications, the plane wave treatment of neutrino oscillation is **wrong**.

Should we worry about that?

The probability of neutrino oscillation depends on the distance L between the neutrino source and the point of detection.

To determine L, we must know where the neutrino started, and where it was detected.

A plane wave has a definite, precise momentum p.

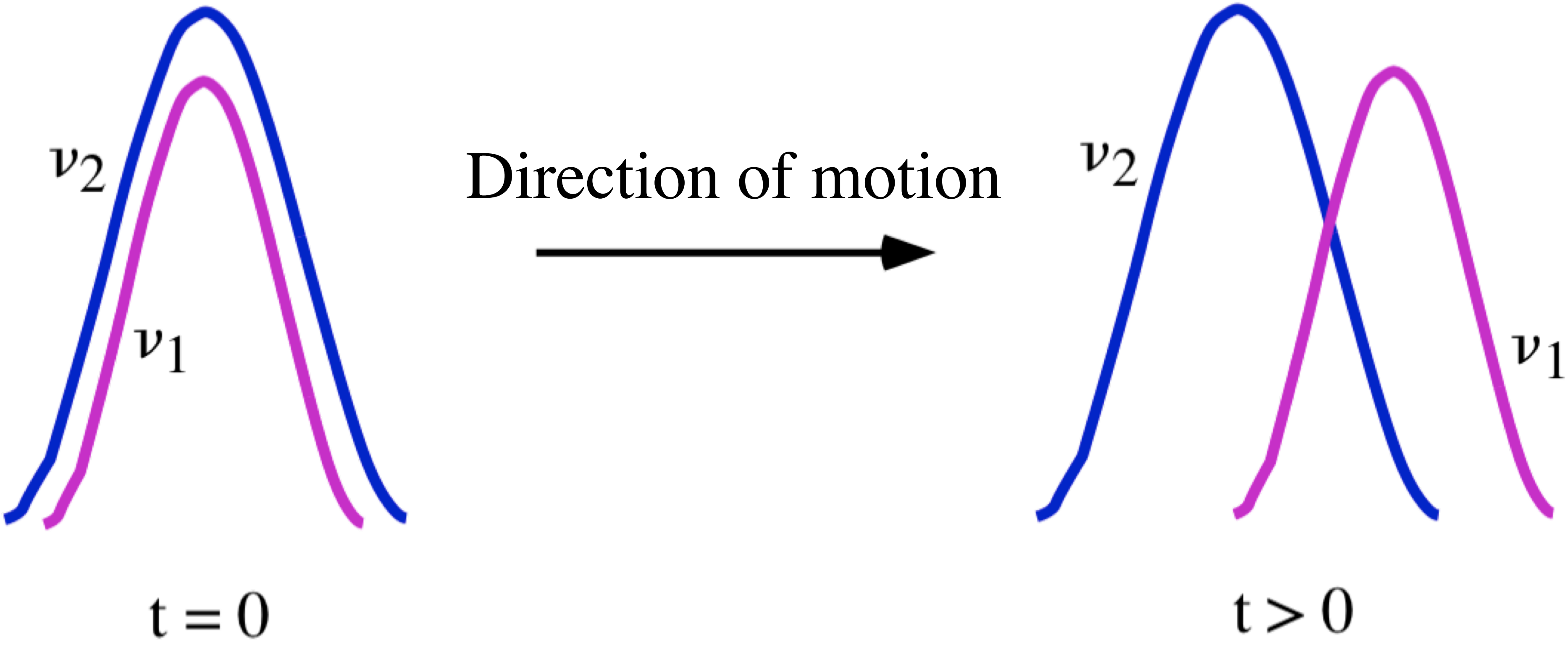
Heisenberg: $\Delta x \Delta p \geq \hbar/2$.

If we know precisely the momentum with which a neutrino was born, we know nothing about <u>*where*</u> *it was born.*

The Wave Packet Picture

Each mass eigenstate is described by a wave packet.

Suppose ν_2 is heavier than ν_1.



Eventually the wave packets will separate.

No more oscillation.

How soon do the wave packets separate??

For accelerator neutrinos with energy $E = 1$ GeV, and a wave packet width equal to the length of the pion decay region where the neutrinos are born, the bigger $\Delta m^2 = 2.5 \times 10^{-3}$ eV^2 leads to wave packet separation in

10^{20} km.

This separation may be safely ignored!

However, for supernova neutrinos from SN 1987A, with energy $E \sim 10$ MeV, and a wave packet width equal to an *estimated* inter-nucleon distance within the star, separation occurs in

10^{3} km.

Supernova neutrinos are no longer oscillating when they reach us.

Different mass eigenstates <u>produced at the same instant</u> arrive at separate times, depending on their individual speeds.

The arrival time difference for the SN 1987 A neutrinos could have been $\sim 10^{-4}$ sec.

Probability of Flavor Change In Vacuum

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

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

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

For experiments with terrestrial neutrinos, use this formula with confidence.

Theoretical Ideas

Most theorists suspect that neutrinos, and only neutrinos, have **Majorana masses.**

If this suspicion is right, then the origin of neutrino masses is different from the origin of the masses of all other known particles.

A majorana mass term, such as —

$$\mathcal{L}_{\text{Mass}} = -\frac{\overset{\substack{\text{Mass}\\ \downarrow}}{m_R}}{2}\left[\overline{\left(\nu_R\right)^c}\,\nu_R + \overline{\nu_R}\left(\nu_R\right)^{\overset{\substack{\text{charge conjugation}\\ \downarrow}}{c}}\right],$$

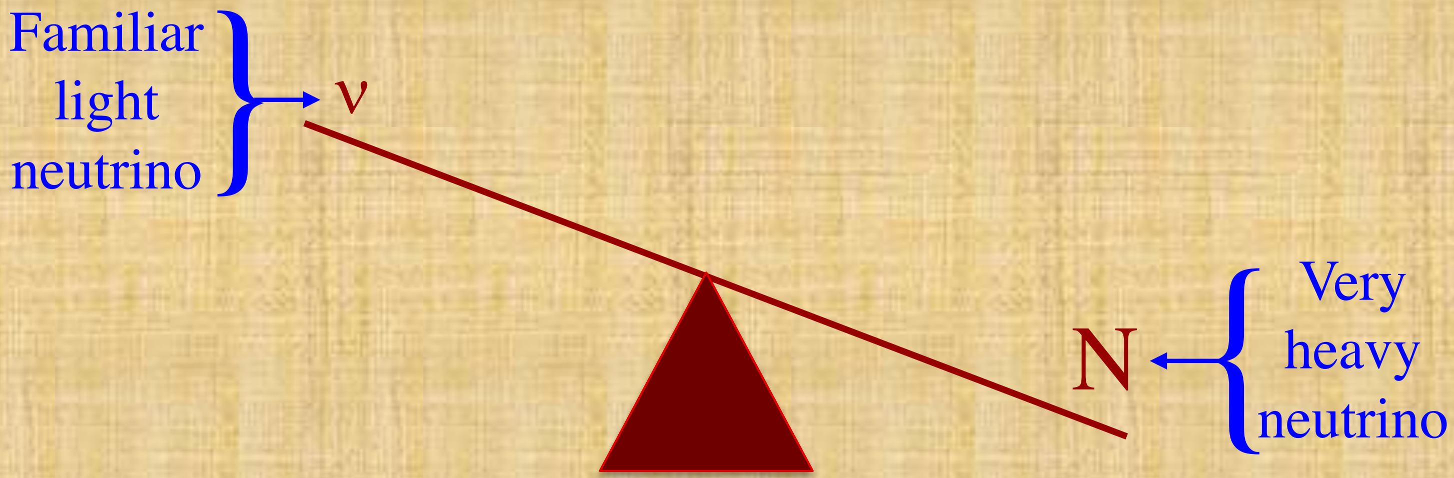
causes the transitions $\nu \to \bar{\nu}$ and $\bar{\nu} \to \nu$ between the underlying neutrino ν and its antiparticle.

The mass eigenstate is then $\nu + \bar{\nu}$, since $\nu + \bar{\nu} \to \bar{\nu} + \nu$.

We see that the mass eigenstate is a Majorana (self-conjugate) neutrino.

Majorana mass terms make possible the simple version of the See-Saw Mechanism for neutrino masses.

The See-Saw Mechanism

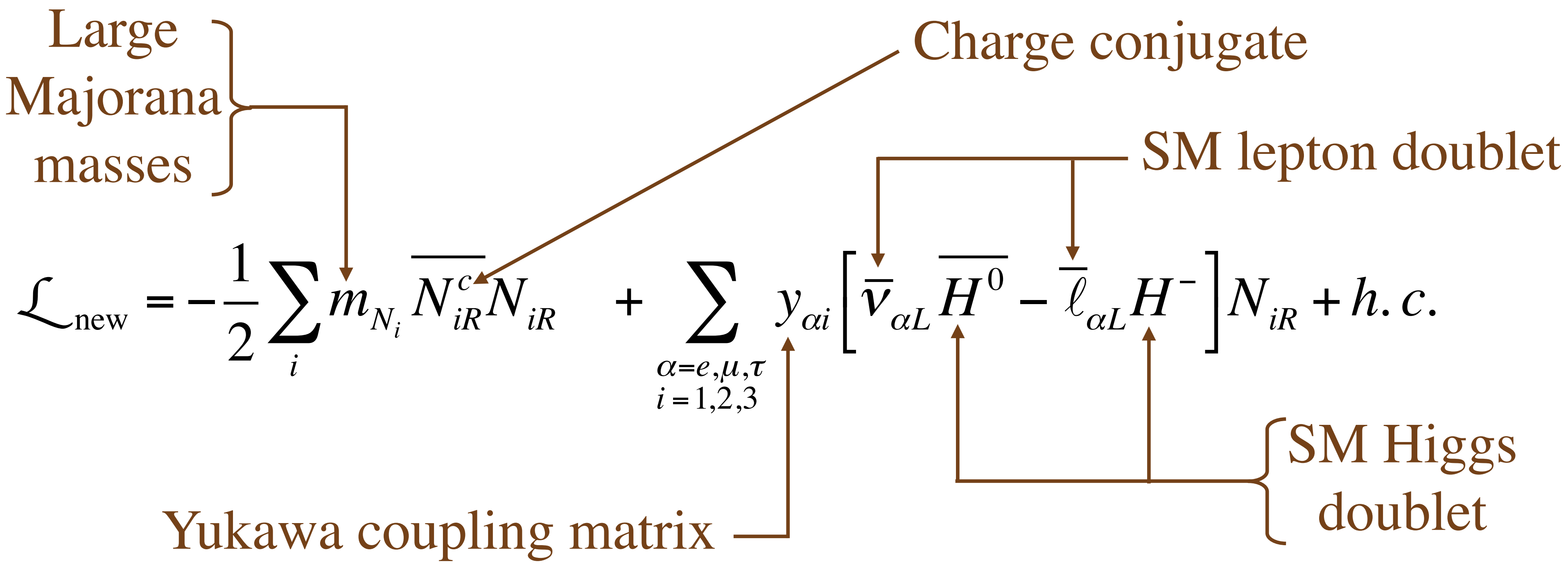


Familiar light neutrino → ν

N ← Very heavy neutrino

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

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



Large Majorana masses

Charge conjugate

SM lepton doublet

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

SM Higgs doublet

Yukawa coupling matrix

Exploring the physics of this model leads to The See-Saw Relation.

The See-Saw Relation

Leptonic mixing matrix

Heavy N mass eigenvalues

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

Light ν mass eigenvalues

The Higgs vev

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

The See-Saw partner neutrinos N_i, although heavy, would have been made during the *hot* Big Bang.

This makes possible —

Leptogenesis

(an explanation of the baryon-antibaryon asymmetry of the universe)

First, CP violation in N_i decays converts $L = 0$ into $L \neq 0$.

Then, the Standard Model Sphaleron process converts part of this non-zero lepton number into a non-zero baryon number B.

The key ingredients of Leptogenesis are —

CP violation among the leptons

Confirm via observation of
CP violation in neutrino oscillation.

Non-conservation of Lepton Number L

Confirm via observation of
neutrinoless double beta decay.

The heavy neutrinos N_i may well be far too heavy to observe experimentally.

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

They both come from phases in the same Yukawa coupling matrix y.

The Oscillation — Leptogenesis Connection

(B.K.)

The See-Saw Relation

Leptonic mixing matrix

Heavy N mass eigenvalues

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

Light ν mass eigenvalues

The Higgs vev, a real number

Through ***U***, the phases in ***y*** lead to
~~CP~~ in light neutrino oscillation.

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

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

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

If the oscillation $\cancel{CP}$ phase δ proves to be large, it could explain almost the entire Baryon – Antibaryon asymmetry by itself.

(Pascoli, Petcov, Riotto)

Future and Ongoing Experiments

Long Baseline Accelerator Neutrinos

CP Violation, Neutrino Mass Ordering, θ_{23}, Non-Standard Interactions, Sterile Neutrinos, Extra Dimensions, Lorentz or CPT Violation, Atmospheric, Solar, and Supernova Neutrinos

Long Baseline Reactor Neutrinos

Neutrino Mass Ordering, Atmospheric, Solar, and Supernova Neutrinos

Short Baseline Accelerator, Reactor, and Radioactive-Source Neutrinos

1 eV Sterile Neutrinos: Yes or No?

Neutrinoless Double Beta Decay

Neutrinos: Dirac or Majorana?

Beta Spectrum in Beta Decay

Neutrino Mass Determination

Coherent Neutrino-Nucleus Scattering

Non-Standard Interactions?

Searches for Heavy Neutrinos

keV, MeV, GeV, TeV Neutrinos?

Neutrino Telescopes

Astronomy with Neutrinos,
General Neutrino Physics

Cosmological Observations

Sum of Neutrino Masses,
Number of Neutrino Flavors

The future program
is rich.

We look forward
to the results.