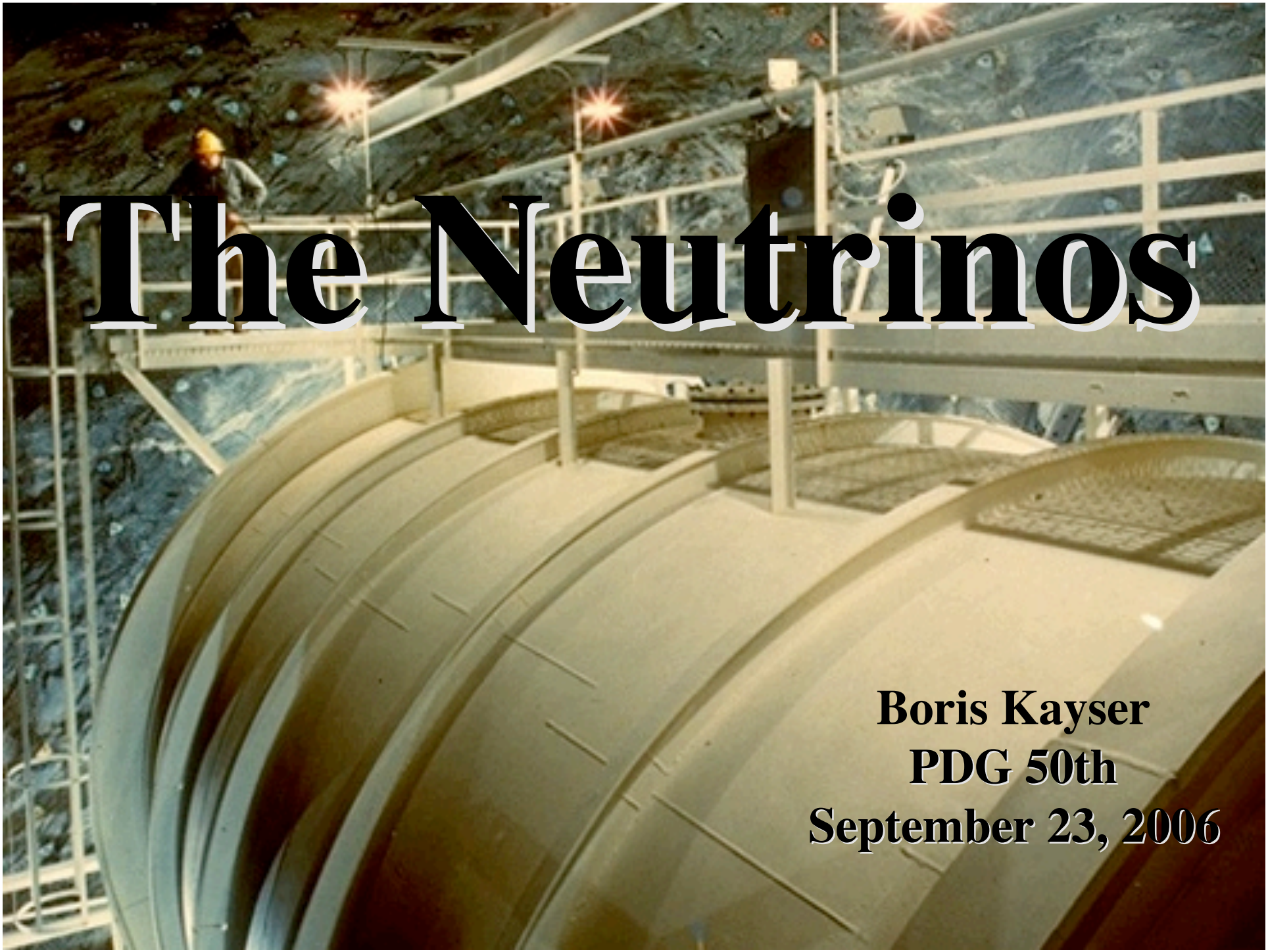


The Neutrinos

Boris Kayser

PDG 50th

September 23, 2006

In the Beginning (of the PDG) —

There were massless neutrinos.

A Few Years Later —

There were ***different kinds*** of massless neutrinos, ν_e and ν_μ.

Then Years Passed ~~~~~~~~~~~~~~~

But In the Last Decade –

The Neutrino Revolution
(1998 – …)

Neutrinos have nonzero masses!

Leptons mix!

What one finds in the Review of Particle Physics has changed.

1995

1995 PARTIAL UPDATE TO THE REVIEW OF PARTICLE PROPERTIES*

ν_e $\quad J = \frac{1}{2}$

Not in general a mass eigenstate. See note on neutrino properties above.

MINIREVIEW GOES HERE

ν_e MASS

Most of the data from which these limits are derived are from β^- decay experiments in which a $\overline{\nu}_e$ is produced, so that they really apply to $m_{\overline{\nu}_1}$. Assuming *CPT* invariance, a limit on $m_{\overline{\nu}_1}$ is the same as a limit on m_{ν_1}. Results from studies of electron capture transitions, given below "$m_{\nu_1} - m_{\overline{\nu}_1}$", give limits on m_{ν_1} itself. See also the Listings in the Neutrino Bounds from Astrophysics and Cosmology section.

VALUE (eV)	CL%	DOCUMENT ID		TECN	COMMENT
OUR LIMIT		[1] PDG	94	RVUE	See the note below.
< 7.2	95	[2] WEINHEIMER	93	SPEC	^{3}H β decay
< 11.7	95	[3] HOLZSCHUH	92B	SPEC	^{3}H β decay
< 13.1	95	[4] KAWAKAMI	91	SPEC	^{3}H β decay
< 9.3	95	[5] ROBERTSON	91	SPEC	^{3}H β decay

2006

Δm^2_{32}

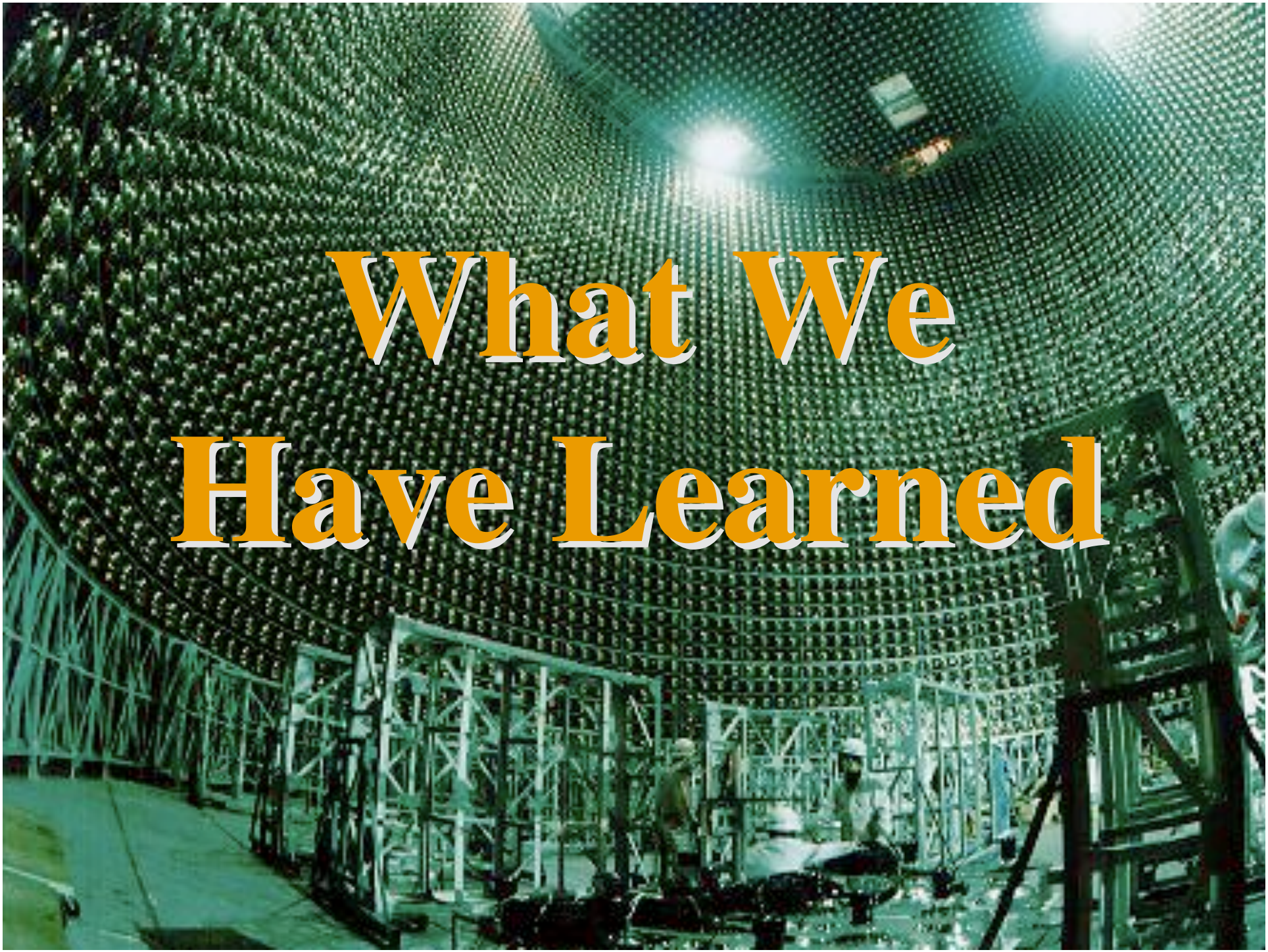
The sign of Δm^2_{32} is not known at this time. Only the absolute value is quoted below. The ranges below correspond to the projection onto the Δm^2_{32} axis of the 90% CL contours in the $\sin^2(2\theta_{23}) - \Delta m^2_{32}$ plane presented by the authors.

VALUE (10^{-3} eV^2)	DOCUMENT ID		TECN	COMMENT
1.9 to 3.0	[93] ASHIE	04	SKAM	L/E distribution
• • • We do not use the following data for averages, fits, limits, etc. • • •				
1.9–3.6	[94] ALIU	05	K2K	KEK to Super-K
0.3–12	[95] ALLISON	05	SOU2	
1.5–3.4	[96] ASHIE	05	SKAM	atmospheric neutrino
0.6–8.0	[97] AMBROSIO	04	MCRO	MACRO
1.5–3.9	[98] AHN	03	K2K	KEK to Super-K
0.25–9.0	[99] AMBROSIO	03	MCRO	MACRO
0.6–7.0	[100] AMBROSIO	03	MCRO	MACRO
0.15–15	[101] SANCHEZ	03	SOU2	Soudan-2 Atmospheric
0.6–15	[102] AMBROSIO	01	MCRO	upward μ
1.0–6.0	[103] AMBROSIO	01	MCRO	upward μ
1.0–50	[104] FUKUDA	99C	SKAM	upward μ
1.5–15.0	[105] FUKUDA	99D	SKAM	upward μ
0.7–18	[106] FUKUDA	99D	SKAM	stop μ / through
0.5–6.0	[107] FUKUDA	98C	SKAM	Super-Kamiokande
0.55–50	[108] HATAKEYAMA	98	KAMI	Kamiokande
4–23	[109] HATAKEYAMA	98	KAMI	Kamiokande
5–25	[110] FUKUDA	94	KAMI	Kamiokande

2006

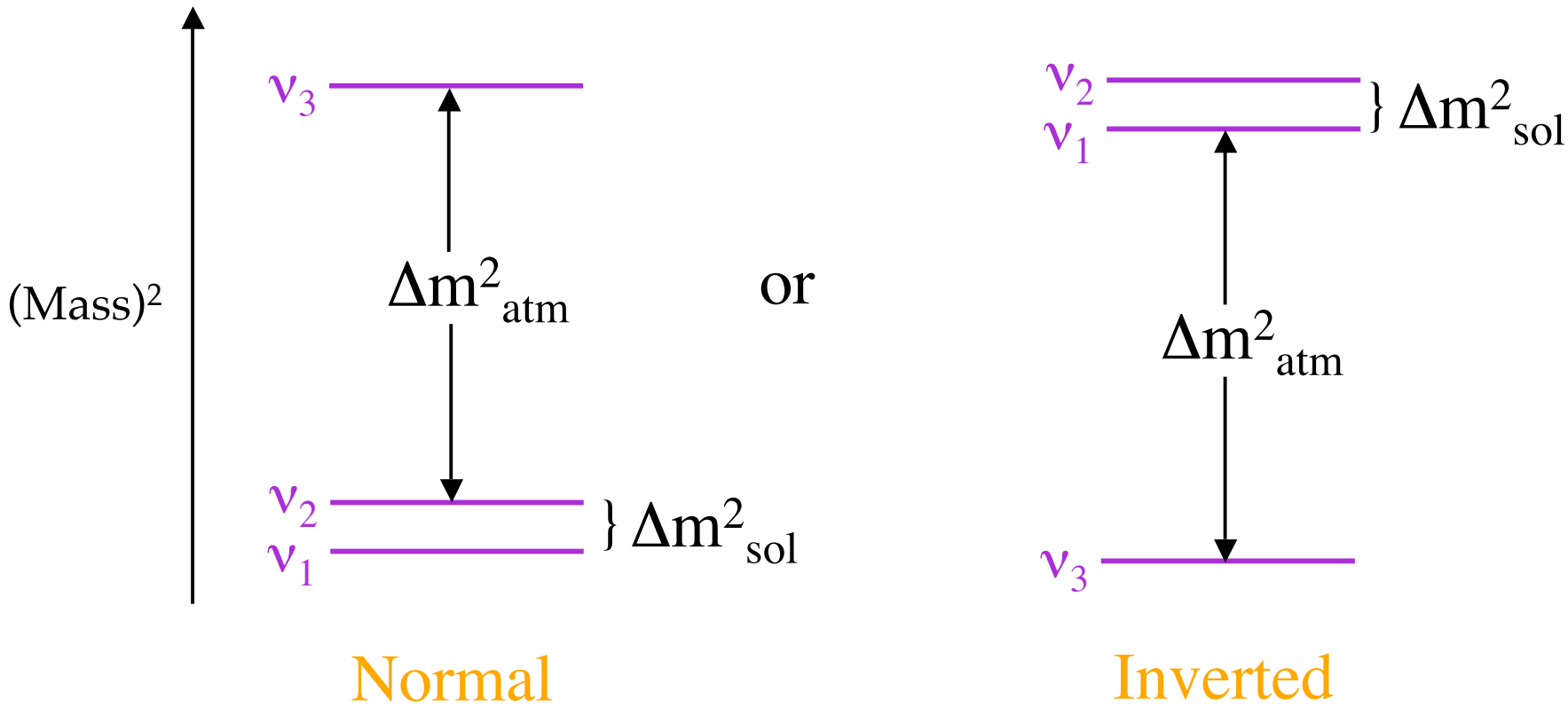
$\sin^2(2\theta_{12})$

VALUE	DOCUMENT ID		TECN	COMMENT
$\mathbf{0.86^{+0.03}_{-0.04}}$	[55] AHARMIM	05A	FIT	KamLAND + global solar
• • • We do not use the following data for averages, fits, limits, etc. • • •				
0.75–0.95	[56] AHARMIM	05A	FIT	global solar
0.82 ± 0.05	[57] ARAKI	05	FIT	KamLAND + global solar
0.82 ± 0.04	[58] AHMED	04A	FIT	KamLAND + global solar
0.71–0.93	[59] AHMED	04A	FIT	global solar
$0.85^{+0.05}_{-0.07}$	[60] SMY	04	FIT	KamLAND + global solar
$0.83^{+0.06}_{-0.08}$	[61] SMY	04	FIT	global solar
$0.87^{+0.07}_{-0.08}$	[62] SMY	04	FIT	SKAM + SNO
0.62–0.88	[63] AHMAD	02B	FIT	global solar
0.62–0.95	[64] FUKUDA	02	FIT	global solar



What We Have Learned

The (Mass)^2 Spectrum



$\Delta m^2_{sol} \cong 8.0 \times 10^{-5}\ eV^2$, $\Delta m^2_{atm} \cong 2.7 \times 10^{-3}\ eV^2$

Are there *more* mass eigenstates, as LSND suggests?

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 mass eigenstates:

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

Neutrino of flavor $\alpha = e, \mu$, or τ

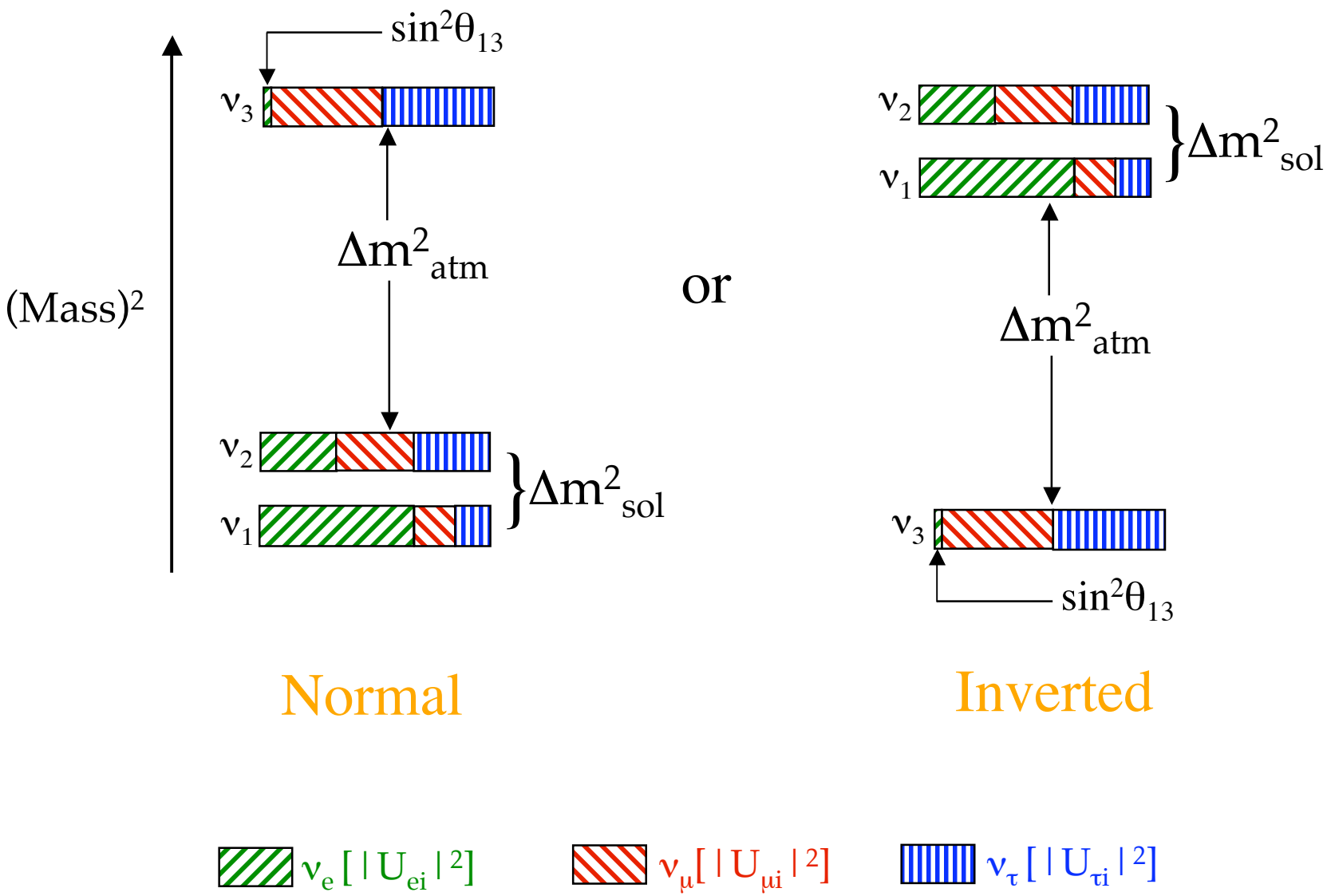
Unitary Leptonic Mixing Matrix

Neutrino of definite mass m_i

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

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

The spectrum, showing its approximate flavor content, is



The Mixing Matrix

Atmospheric Cross-Mixing Solar

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

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

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

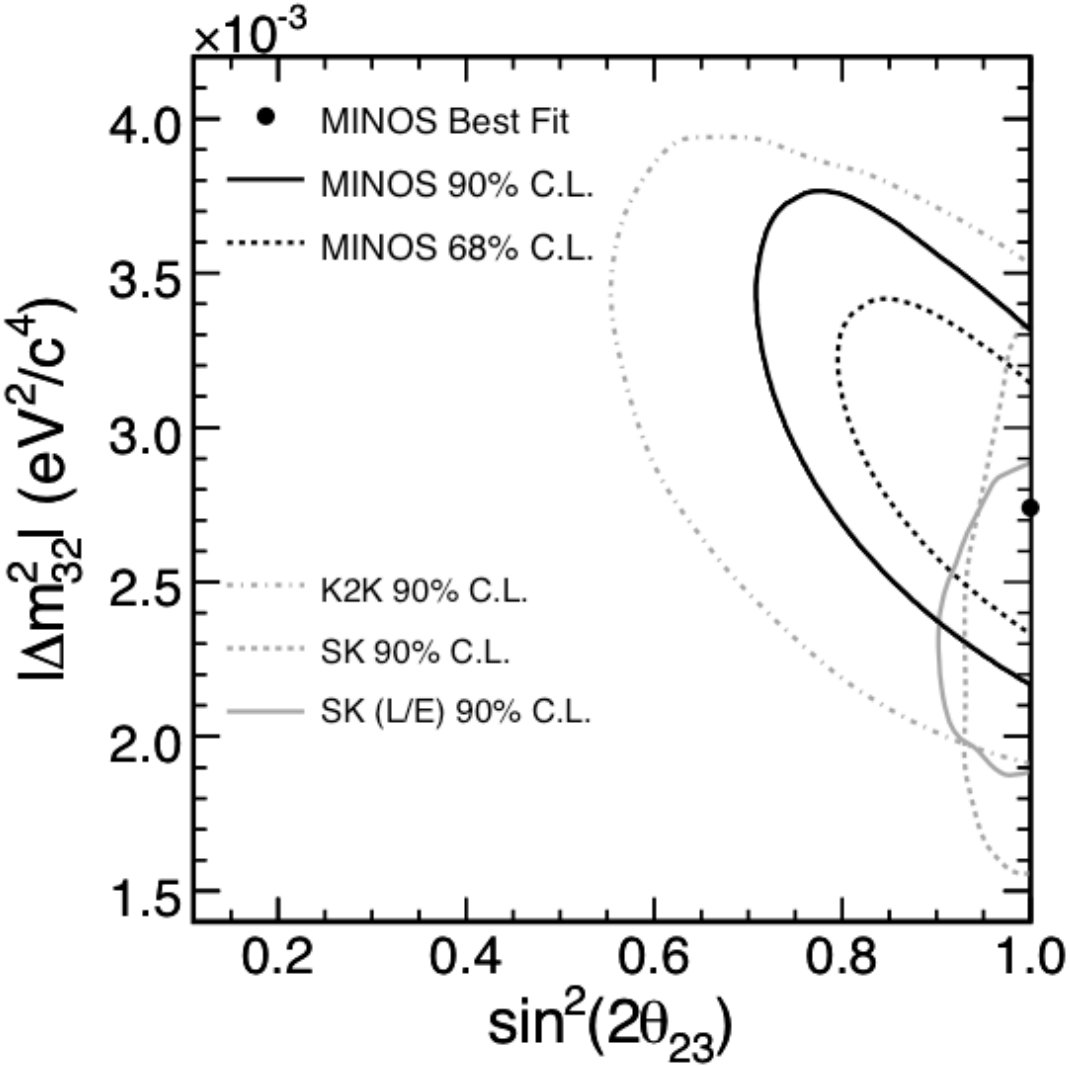
Majorana ~~CP~~ phases

$\theta_{12} \approx \theta_{sol} \approx 34°$, $\theta_{23} \approx \theta_{atm} \approx 37\text{-}53°$, $\theta_{13} \lesssim 10°$

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

Very Recent Findings — MINOS



The Atmospheric Δm^2 and Mixing Angle

The Open
Questions

- What is the absolute scale of neutrino mass?

- Are neutrinos their own antiparticles?

- Are there “sterile” neutrinos?

We must be alert to surprises!

- What is the pattern of mixing among the different types of neutrinos?

  What is θ_{13}? Is θ_{23} maximal?

- Is the spectrum like $\equiv$ or $\equiv$?

- Do neutrinos violate the symmetry CP?
  Is $P(\bar{\nu}_\alpha \rightarrow \bar{\nu}_\beta) \neq P(\nu_\alpha \rightarrow \nu_\beta)$?

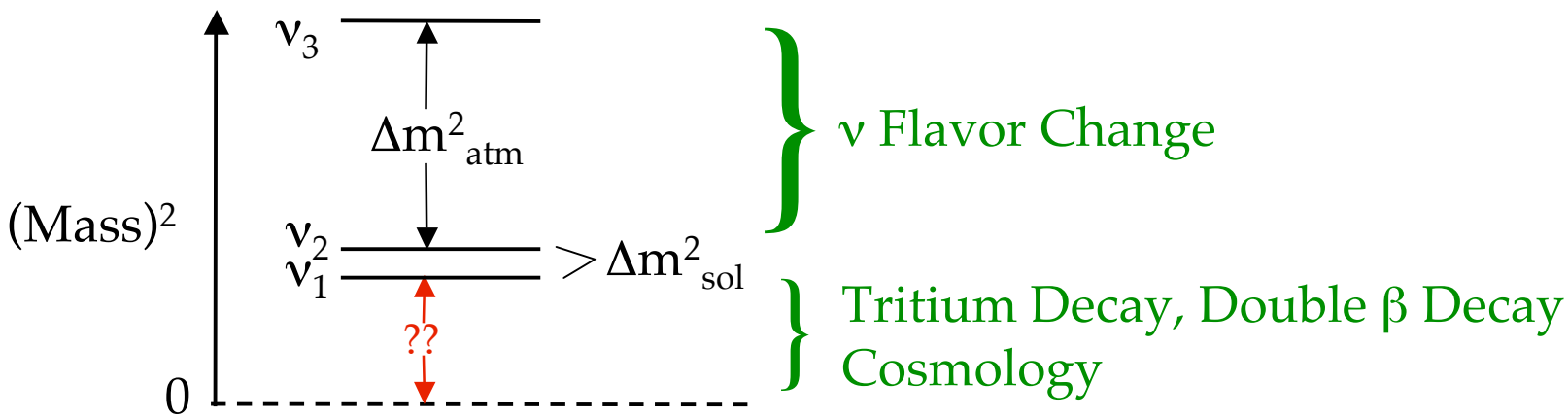
- What can neutrinos and the universe tell us about one another?

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

- What physics is behind neutrino mass?

The Importance of the Questions, and How They May Be Answered

What Is the Absolute Scale of Neutrino Mass?



How far above zero is the whole pattern?

A Cosmic Connection

Oscillation Data $\Rightarrow \sqrt{\Delta m^2_{atm}} <$ Mass[Heaviest ν_i]

Cosmological Data + Cosmological Assumptions $\Rightarrow$

$$\Sigma\, m_i < (0.17 - 1.0)\ \text{eV}\ .$$

Mass(ν_i)

(Seljak, Slosar, McDonald
Pastor)

If there are only 3 neutrinos,

$$0.04\ \text{eV} \lesssim \text{Mass[Heaviest } \nu_i] < (0.07 - 0.4)\ \text{eV}$$

$\sqrt{\Delta m^2_{atm}}$ Cosmology

Are Neutrinos Their Own Antiparticles?

Does —

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

or

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

Equivalently, is the Lepton Number L defined by—
$L(\nu) = L(\ell^-) = -L(\overline{\nu}) = -L(\ell^+) = 1$ conserved?

If not, then nothing distinguishes $\overline{\nu}_i$ from ν_i . We then have Majorana neutrinos.

Why Many Theorists Think L Is Not Conserved

The Standard Model (SM) is defined by the fields it contains, its symmetries (notably Weak Isospin Invariance), and its renormalizability.

Anything allowed by the symmetries occurs in nature.

The SM contains no ν mass, and no ν_R field, only ν_L.

This SM conserves the lepton number L.

But now we know the neutrino has mass.

If we try to preserve L, we accommodate this mass by adding a Dirac, L - conserving, mass term: $m_D \bar{\nu}_L \nu_R$.

To add a Dirac mass term, we had to add ν_R to the SM.

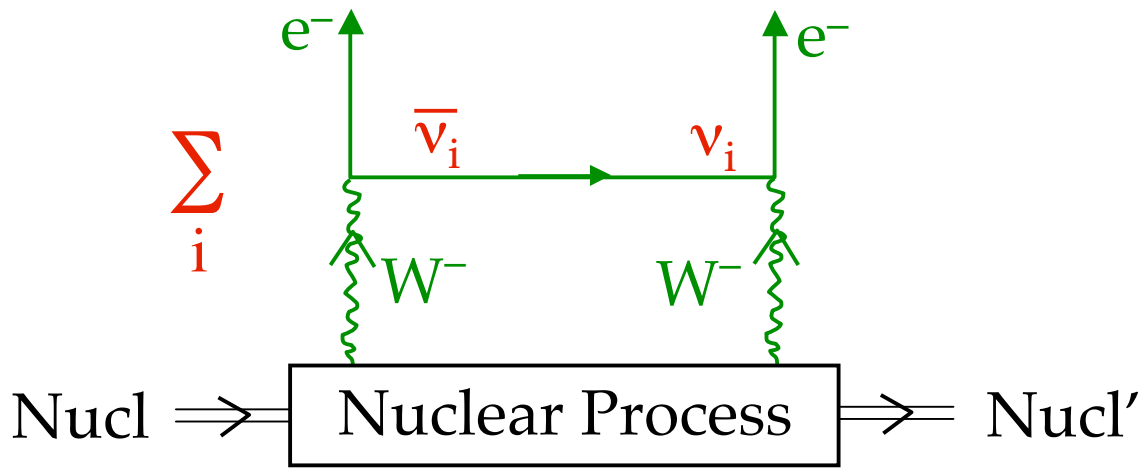
Unlike ν_L , ν_R carries no Weak Isospin.

Thus, no SM symmetry prevents the occurrence of the Majorana mass term $m_M \overline{\nu_R{}^c} \nu_R$.

This mass term causes $\nu \rightarrow \overline{\nu}$. It does not conserve L.

If anything allowed by the *extended* SM occurs in nature, then L is not conserved.

To Demonstrate That $\overline{\nu}_i = \nu_i$: Neutrinoless Double Beta Decay [$0\nu\beta\beta$]

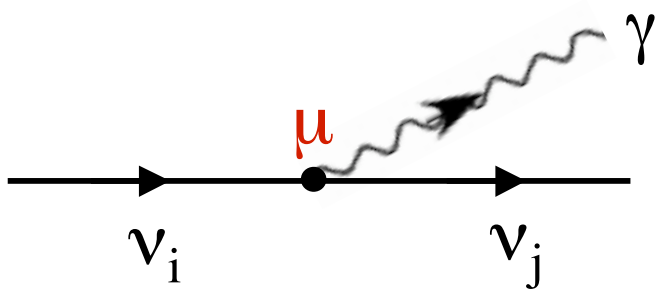


Observation would imply $\not{L}$ and $\overline{\nu}_i = \nu_i$.

$\not{L}$ is tiny. But by starting with a ***large*** number of parent nuclei and suppressing backgrounds, we can search for it.

Possible Information From Neutrino Magnetic Moments

Both Majorana and Dirac neutrinos can have *transition* magnetic dipole moments μ:



For *Dirac* neutrinos, $\mu < 10^{-15}\ \mu_{Bohr}$

For *Majorana* neutrinos, $\mu <$ Present bound

$$\text{Present bound} = \begin{cases} 7 \times 10^{-11}\ \mu_{Bohr}\ ; \text{Wong et al. (Reactor)} \\ 3 \times 10^{-12}\ \mu_{Bohr}\ ; \text{Raffelt (Stellar E loss)} \end{cases}$$

An observed μ below the present bound but well above 10^{-15} μ_{Bohr} would imply that neutrinos are Majorana particles.

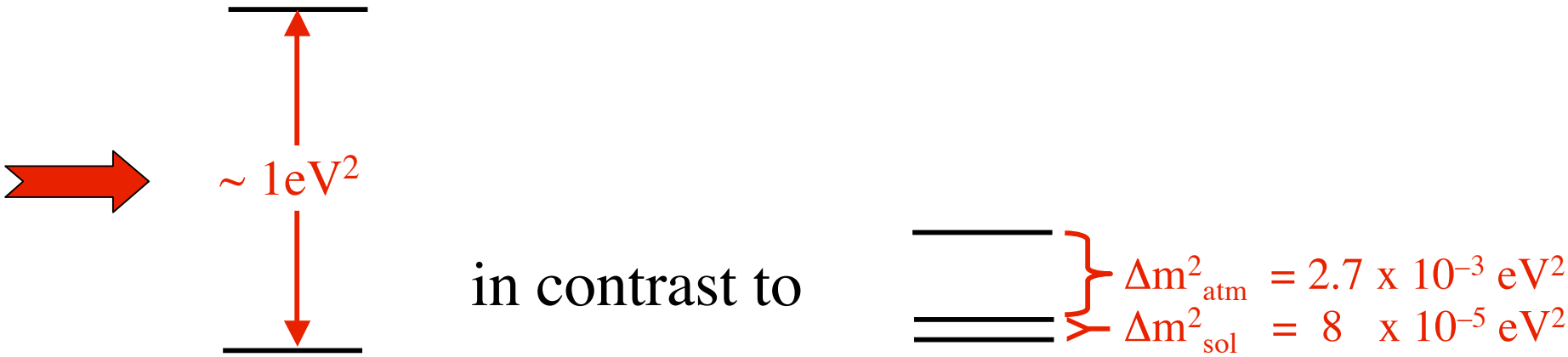
However, a dipole moment that large requires L-violating new physics below 100 TeV.

(Bell, Cirigliano, Davidson, Gorbahn, Gorchtein, Ramsey-Musolf, Santamaria, Vogel, Wise, Wang)

Neutrinoless double beta decay at the planned level of sensitivity only requires this new physics at ~ 10^{15} GeV, near the Grand Unification scale.

Are There Sterile Neutrinos?

Rapid neutrino oscillation reported by LSND —



At least **4** mass eigenstates, hence at least **4** flavors.

Measured $\Gamma(Z \rightarrow \nu\bar{\nu})$ → only **3** different *active* neutrinos.

→ At least **1** *sterile* neutrino.

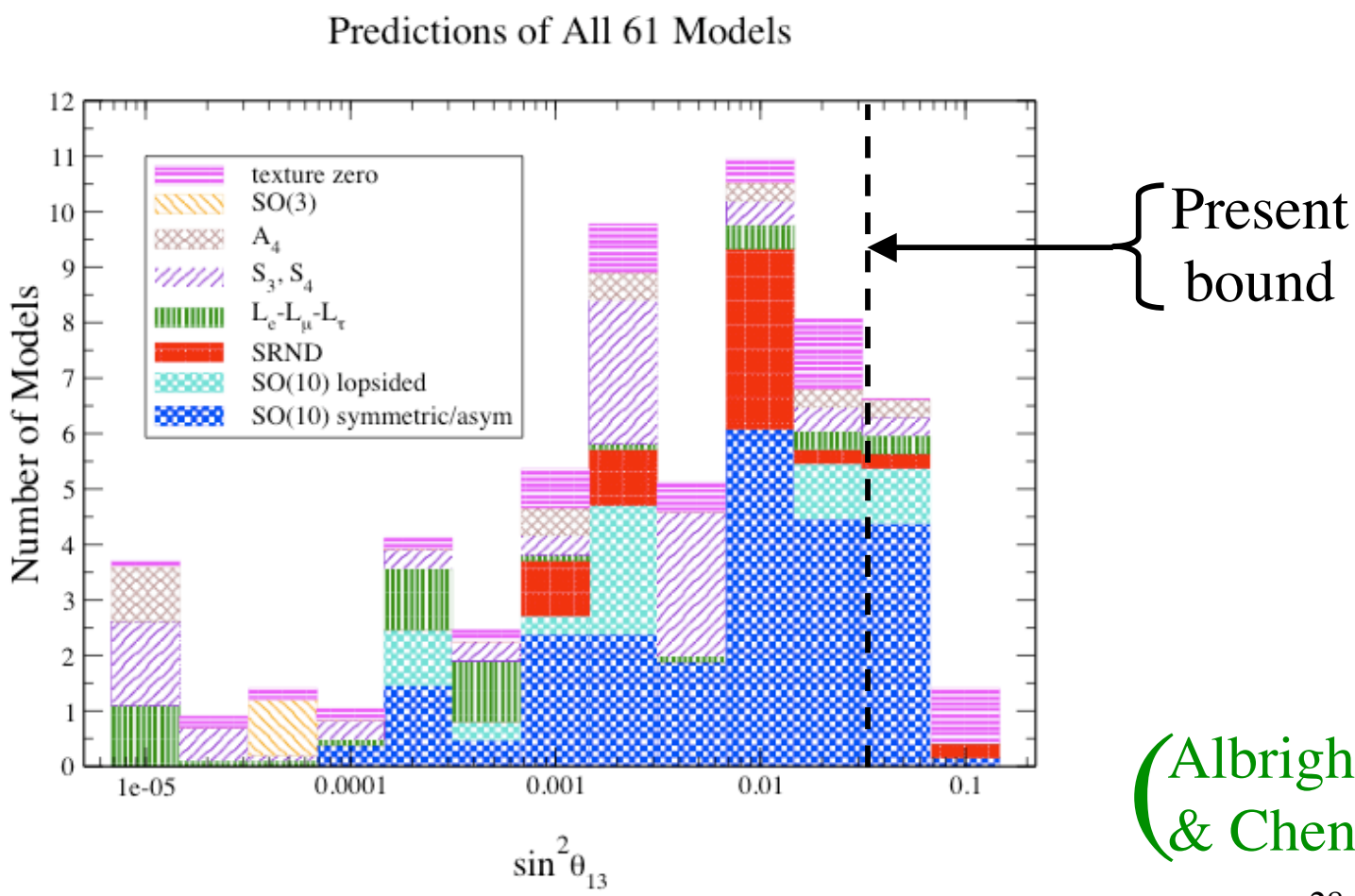
Is the so-far unconfirmed oscillation reported by LSND genuine?

MiniBooNE aims to definitively answer this question.

How Large Is θ_{13}?

We know only that $\sin^2\theta_{13} < 0.032$ (at 2σ).

The theoretical prediction of θ_{13} is not sharp:



(Albright & Chen)

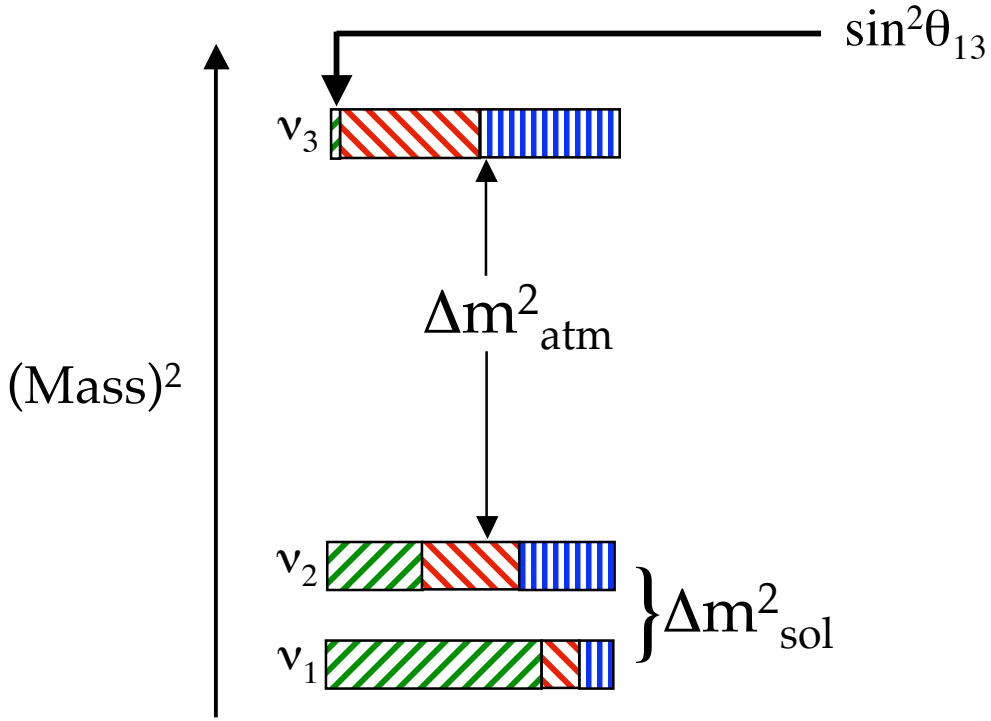
The Central Role of θ_{13}

Both CP violation and our ability to tell whether the spectrum is normal or inverted depend on θ_{13}.

If $\sin^2\theta_{13} > (0.0025 - 0.0050)$, we can study both of these issues with intense but conventional ν and $\bar{\nu}$ beams.

Determining θ_{13} is an important stepping-stone.

How θ_{13} May Be Measured



$\sin^2\theta_{13} = |U_{e3}|^2$ is the small ν_e piece of ν_3.

ν_3 is at one end of Δm^2_{atm}.

$\therefore$ We need an experiment with L/E sensitive to Δm^2_{atm} (L/E ~ 500 km/GeV) , and involving ν_e.

Complementary Approaches

Reactor Experiments

Reactor $\bar{\nu}_e$ disappearance while traveling L ~ 1.5 km. This process depends on θ_{13} alone:

$$P(\bar{\nu}_e \text{ Disappearance}) =$$

$$= \sin^2 2\theta_{13} \sin^2[1.27\Delta m^2_{atm}(eV^2)L(km)/E(GeV)]$$

Accelerator Experiments

Accelerator $\nu_\mu \rightarrow \nu_e$ while traveling L > Several hundred km. This process depends on θ_{13}, θ_{23}, on whether the spectrum is normal or inverted, and on whether CP is violated through the phase δ.

The Mass Spectrum: $\overline{\overline{}}$ or $\overline{\overline{}}$?

Generically, grand unified models (GUTS) favor —

$$\overline{\overline{}}$$

GUTS relate the Leptons to the Quarks.

$\overline{\overline{}}$ is un-quark-like, and would probably involve a lepton symmetry with no quark analogue.

How To Determine If The Spectrum Is Normal Or Inverted

Due to the matter effect, at oscillation maximum,

Sign[m^2(—) - m^2(═)]

$$\frac{P(\nu_\mu \to \nu_e)}{P(\bar{\nu}_\mu \to \bar{\nu}_e)} \cong \frac{1 + S(E/6GeV)}{1 - S(E/6GeV)}$$

$$\begin{cases} > 1\ ; & \text{—} \\ & \text{═} \\ < 1\ ; & \text{═} \\ & \text{—} \end{cases}$$

Note the $\nu - \bar{\nu}$ *asymmetry that is not from CP violation.*

The matter effect, which depends on the spectrum, grows with energy.

At fixed L/E but two different energies —

$$\frac{P_{\text{Hi E}}(\nu_\mu \to \nu_e)}{P_{\text{Lo E}}(\nu_\mu \to \nu_e)} \begin{cases} >1 \ ; & \overline{\overline{\overline{\

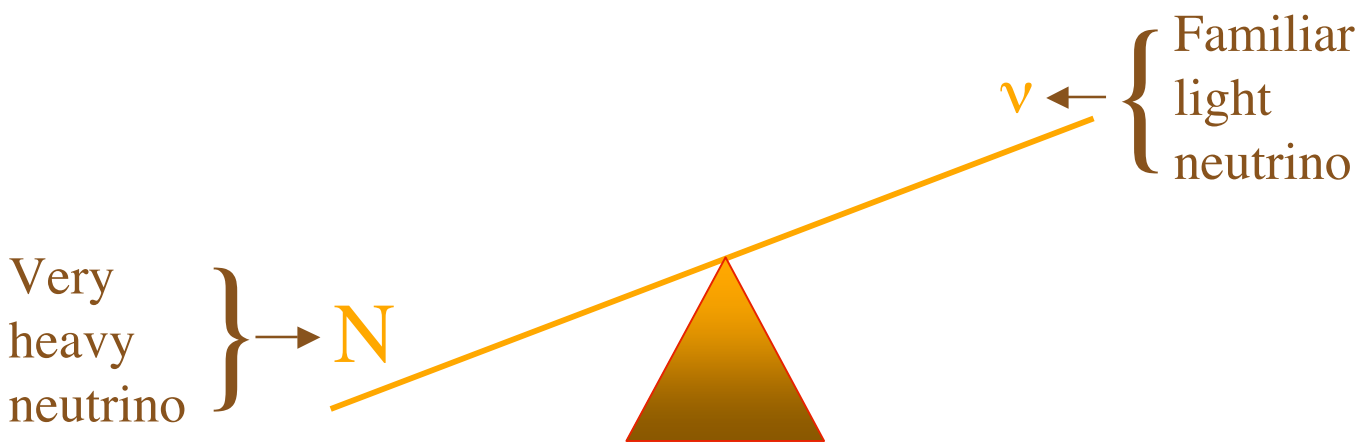
Do Neutrino Interactions Violate CP?

Quark mixing violates CP. Does *leptonic* mixing also violate CP, or is CP violation something special to the quark sector?

Is leptonic CP violation, via *leptogenesis*, the origin of the matter-antimatter asymmetry of the universe?

Leptogenesis In 30 Seconds

See-Saw Mechanism



The heavy neutrinos N would have been made in the hot Big Bang.

The heavy neutrinos N, like the light ones ν, are Majorana particles. Thus, an N can decay into ℓ^- or ℓ^+.

If neutrino oscillation violates CP, then quite likely so does N decay, even though one can decouple the two.

Then, in the early universe, we would have had different rates for the CP-mirror-image decays –

$$N \rightarrow \ell^- + \ldots \qquad \text{and} \qquad N \rightarrow \ell^+ + \ldots$$

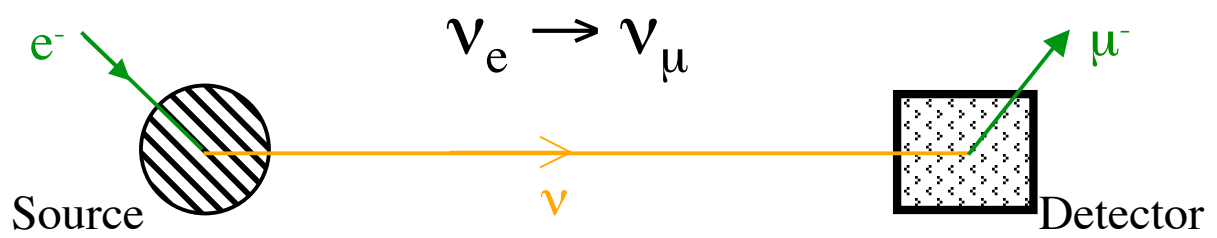
This would have led to unequal numbers of leptons and antileptons (Leptogenesis).

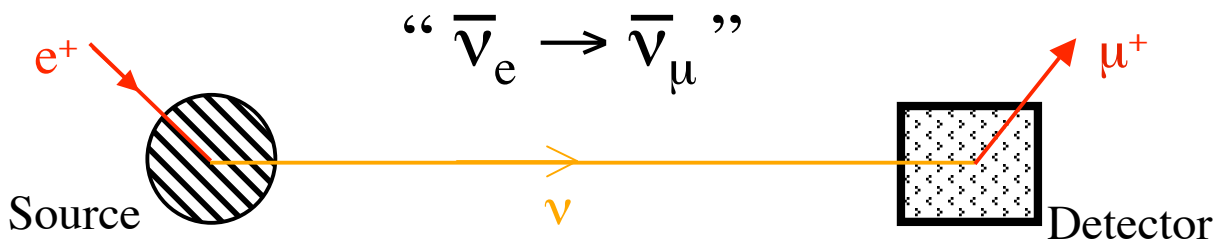
Perhaps this was the original source of the present preponderance of Matter over Antimatter in the universe.

How To Search for $\not{C}\not{P}$

Look for $P(\bar{\nu}_\alpha \rightarrow \bar{\nu}_\beta) \neq P(\nu_\alpha \rightarrow \nu_\beta)$

" $\bar{\nu}_\alpha \rightarrow \bar{\nu}_\beta$ " is a different process from $\nu_\alpha \rightarrow \nu_\beta$ even when $\bar{\nu}_i = \nu_i$





Separating $\not{CP}$ From the Matter Effect

Genuine $\not{CP}$ and the matter effect both lead to a difference between ν and $\bar{\nu}$ oscillation.

But genuine $\not{CP}$ and the matter effect depend quite differently from each other on L and E.

To disentangle them, one must make oscillation measurements at different L and/or E.

Happy 50th Anniversary, PDG!

Answering the open neutrino questions will yield exciting results to report!