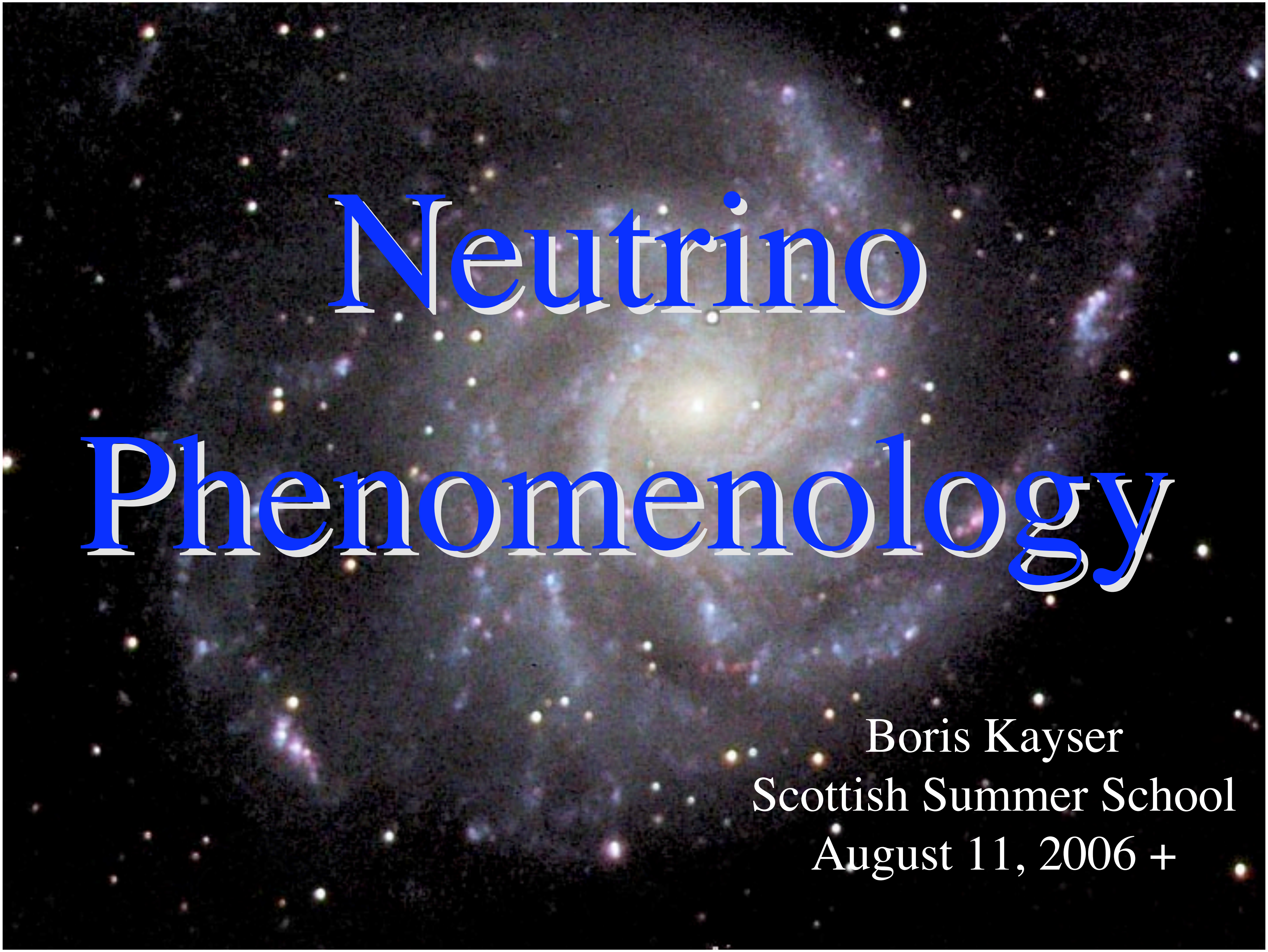

Neutrino Phenomenology

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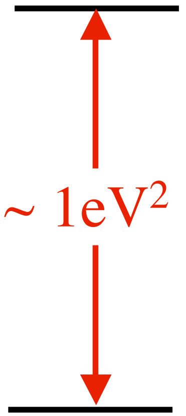
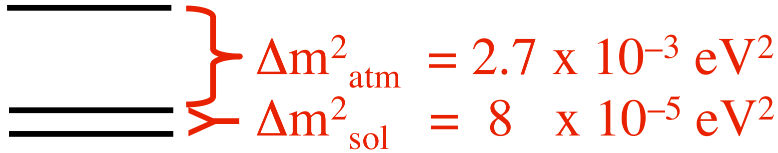
Scottish Summer School
August 11, 2006 +

Are There Sterile Neutrinos?

Rapid neutrino oscillation reported by LSND —



in contrast to



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?

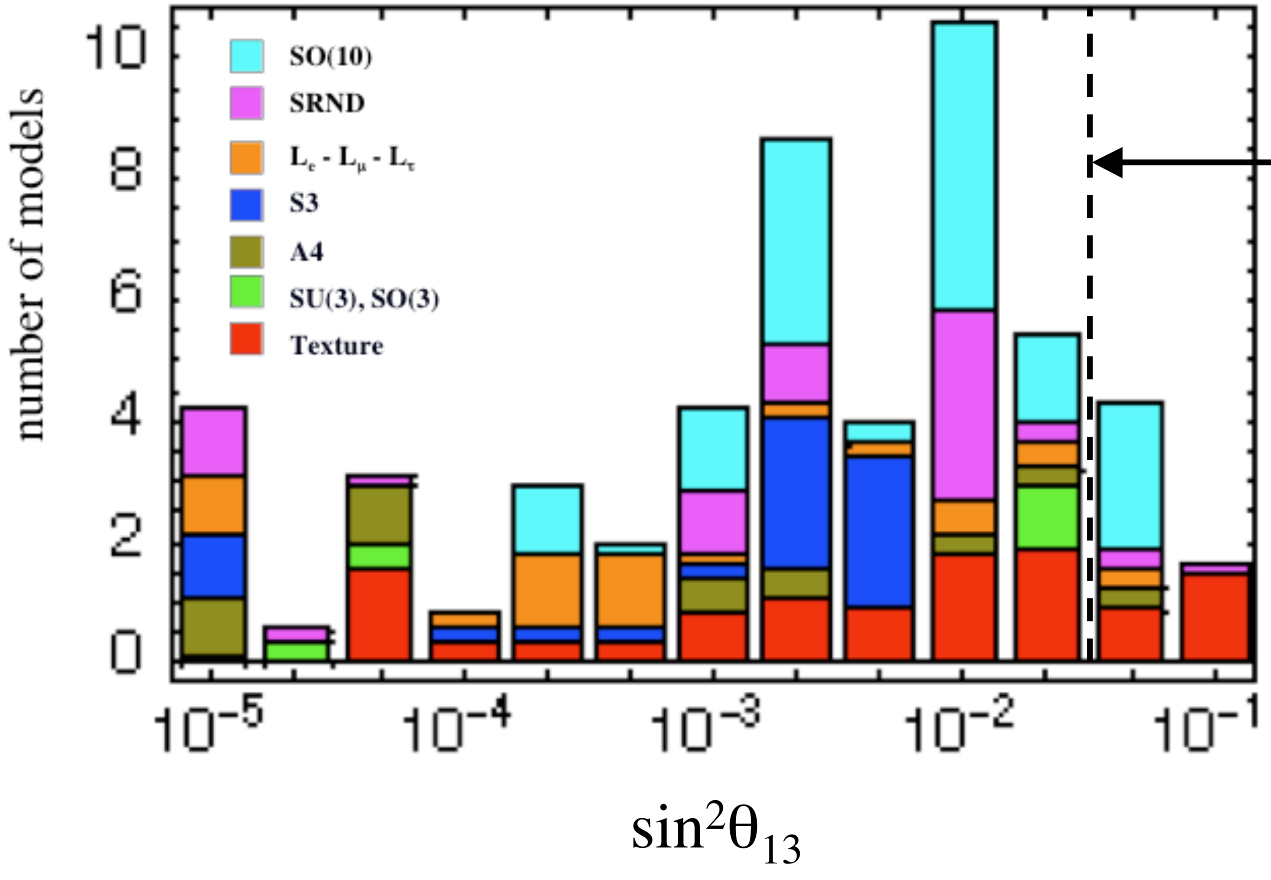
MiniBooNE aims to definitively answer this question.

What Is the Pattern of Mixing?

➢**How large is the small mixing angle θ_{13}?**

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

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



Present bound

(Albright & Chen)

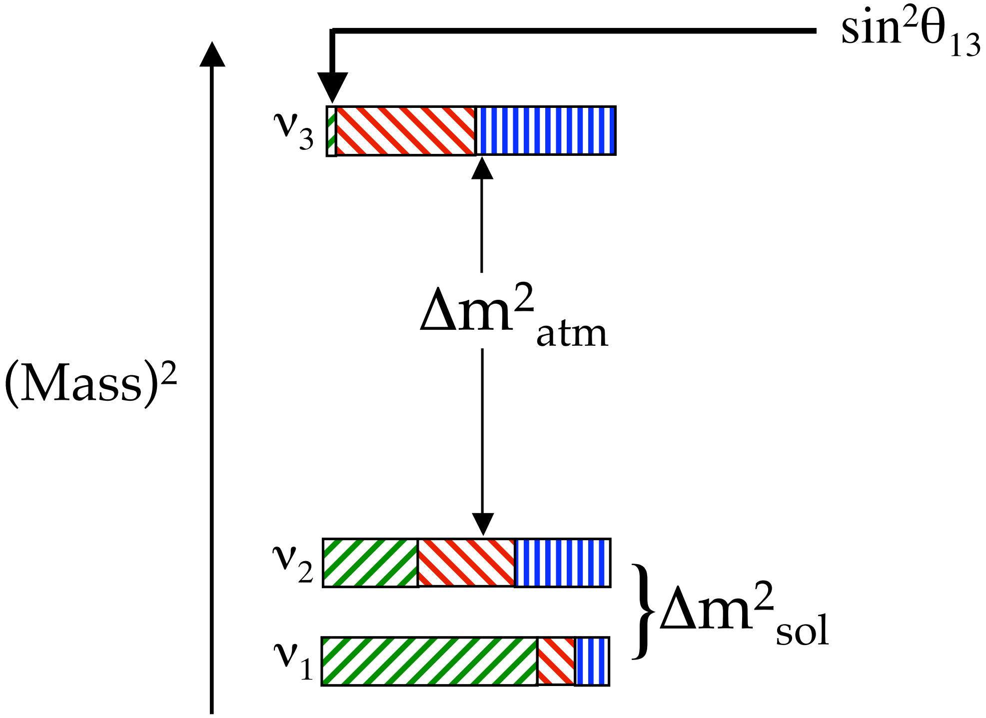
The Central Role of θ_{13}

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}.

∴ 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.

Neglecting matter effects (to keep the formula from getting too complicated):

The accelerator long-baseline $\overset{(-)}{\nu}_e$ appearance experiment measures —

$$P[\overset{(-)}{\nu}_\mu \to \overset{(-)}{\nu}_e] \cong \sin^2 2\theta_{13} \sin^2 \theta_{23} \sin^2 \Delta_{31}$$

$$+ \sin 2\theta_{13} \cos\theta_{13} \sin 2\theta_{23} \sin 2\theta_{12} \sin\Delta_{31} \sin\Delta_{21} \cos(\Delta_{32} \pm \delta)$$

$$+ \sin^2 2\theta_{12} \cos^2 \theta_{23} \cos^2 \theta_{13} \sin^2 \Delta_{21}$$

$$\Delta_{ij} \equiv \Delta m_{ij}^2 L/4E$$

The plus (minus) sign is for neutrinos (antineutrinos).

The Mass Spectrum:  or  ?

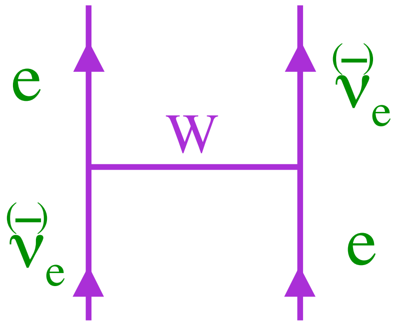
Generically, grand unified models (GUTS) favor —

GUTS relate the Leptons to the Quarks.

 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

Exploit the fact that, in matter,



raises the effective mass of ν_e, and lowers that of $\bar{\nu}_e$.

This changes both the spectrum and the mixing angles.

Matter effects grow with energy E.

At E ~ 1 GeV, matter effects ⇒

$$\sin^2 2\overset{(-)}{\theta}_M \cong \sin^2 2\theta_{13} \left[1 \overset{+}{\underset{(-)}{}} S \frac{E}{6\text{ GeV}} \right] .$$

$$\text{Sign}[m^2(\text{—}) - m^2(\text{=})] \longrightarrow S$$

At oscillation maximum,

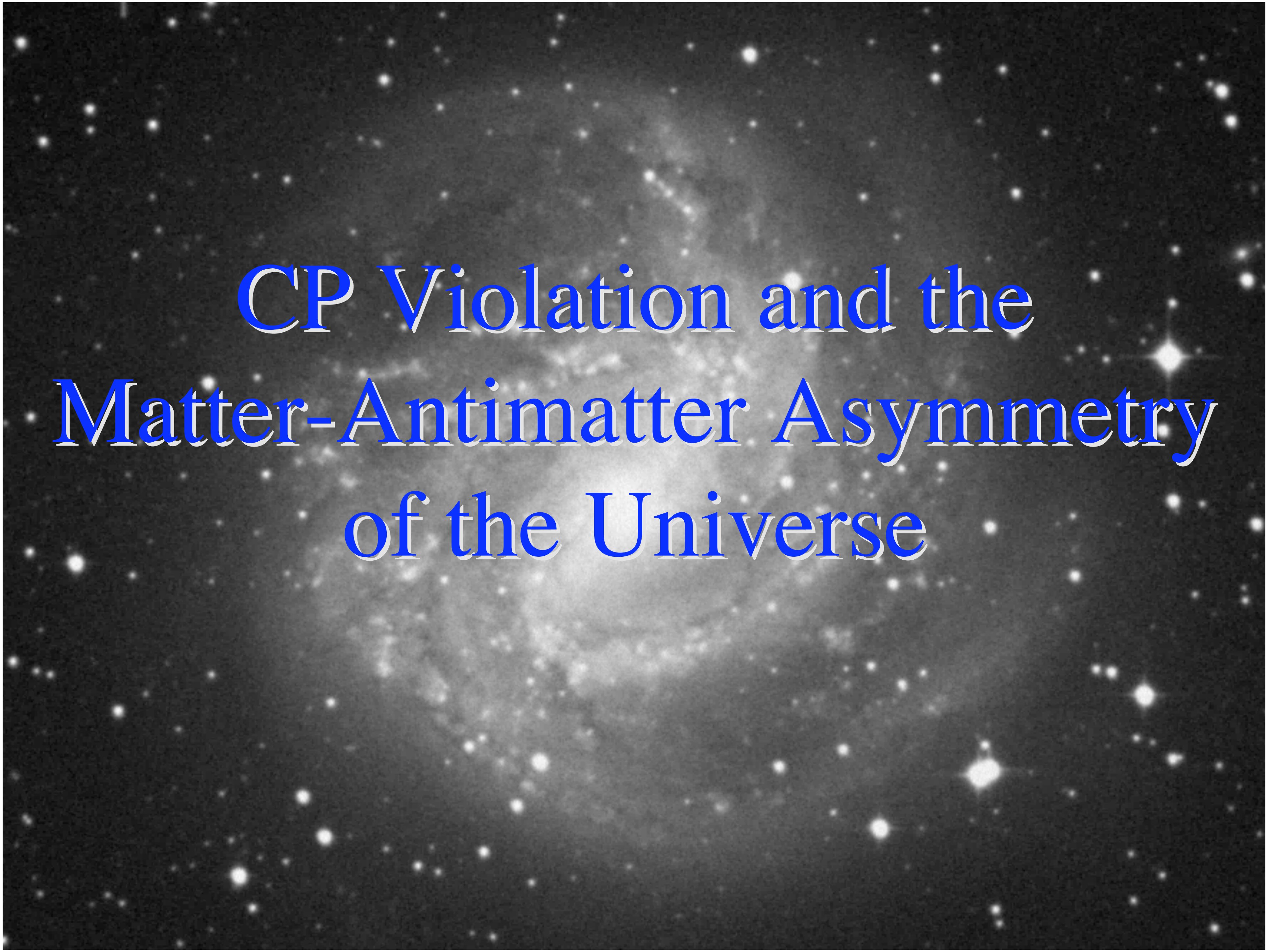
$$\frac{P(\nu_\mu \to \nu_e)}{P(\bar{\nu}_\mu \to \bar{\nu}_e)} \begin{cases} >1 \;; & \begin{matrix} \text{—} \\ \text{=} \end{matrix} \\ <1 \;; & \begin{matrix} \text{=} \\ \text{—} \end{matrix} \end{cases}$$

Note fake CP violation.

In addition,

$$\frac{P_{\text{Hi E}}(\nu_\mu \to \nu_e)}{P_{\text{Lo E}}(\nu_\mu \to \nu_e)} \begin{cases} >1 \;; & \begin{matrix} \text{—} \\ \text{=} \end{matrix} \\ <1 \;; & \begin{matrix} \text{=} \\ \text{—} \end{matrix} \end{cases}$$

(Mena, Minakata,
Nunokawa, Parke)



CP Violation and the Matter-Antimatter Asymmetry of the Universe

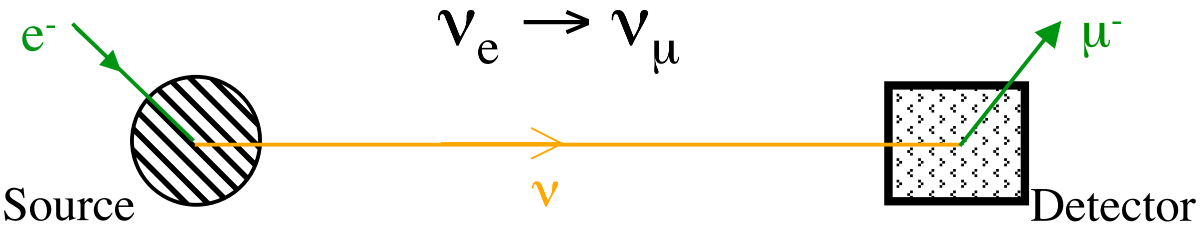
Leptonic CP Violation

- Is there leptonic $\cancel{CP}$, or is $\cancel{CP}$ special to quarks?
- Is leptonic $\cancel{CP}$, through *Leptogenesis*, the origin of the **MATTER**-antimatter asymmetry of the universe?

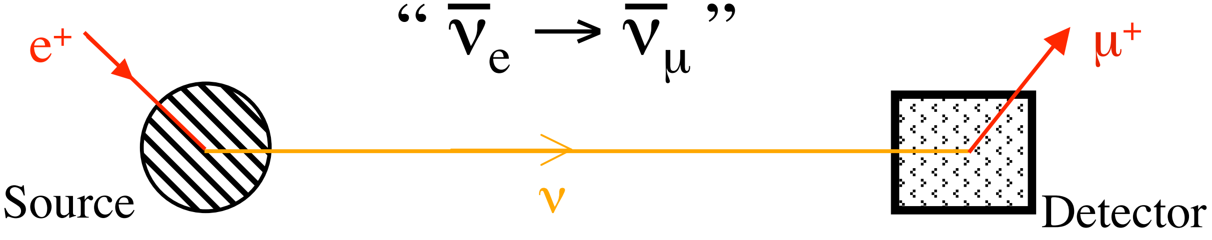
How To Search for Leptonic $\cancel{CP}$

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



$\nu_e \rightarrow \nu_\mu$



“ $\bar{\nu}_e \rightarrow \bar{\nu}_\mu$ ”

$$\text{CPT: } P(\nu_\alpha \to \nu_\beta) = P(\bar{\nu}_\beta \to \bar{\nu}_\alpha)$$

$$\therefore \quad P(\nu_\alpha \to \nu_\alpha) = P(\bar{\nu}_\alpha \to \bar{\nu}_\alpha)$$

No CP violation in a *disappearance* experiment.

But if δ is present, $P(\nu_\mu \to \nu_e) \neq P(\bar{\nu}_\mu \to \bar{\nu}_e)$:

$$P\left(\bar{\nu}_\mu \to \bar{\nu}_e\right) - P\left(\nu_\mu \to \nu_e\right) = 2\cos\theta_{13}\sin 2\theta_{13}\sin 2\theta_{12}\sin 2\theta_{23}\sin\delta$$

$$\times \sin\left({\Delta m^2}_{31}\frac{L}{4E}\right)\sin\left({\Delta m^2}_{32}\frac{L}{4E}\right)\sin\left({\Delta m^2}_{21}\frac{L}{4E}\right)$$

Note that all mixing angles must be nonzero for ~~CP~~.

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 may make oscillation measurements at different L and/or E.

What Physics Is Behind Neutrino Mass?

The See-Saw Mechanism
— A Summary —

This assumes that a neutrino has *both*
a Majorana mass term $m_R \overline{\nu_R{}^c}\, \nu_R$
and a Dirac mass term $m_D \overline{\nu}_L \nu_R$.

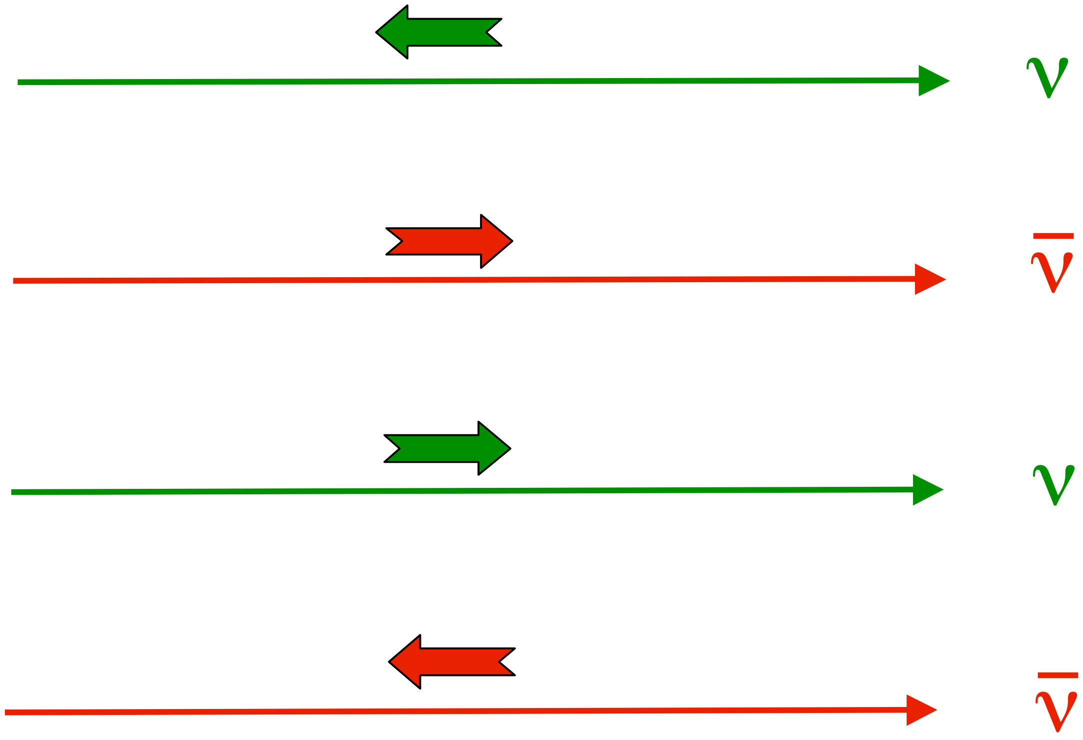
No SM principle prevents m_R from being extremely large.

But we expect m_D to be of the same order as the masses of the quarks and charged leptons.

Thus, we assume that $m_R >> m_D$.

When $\bar{\nu} \neq \nu$

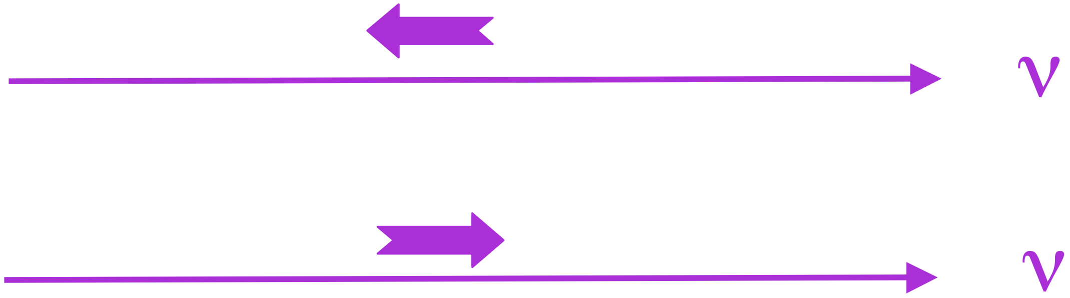
We have 4 mass-degenerate states:



This collection of 4 states is a Dirac neutrino plus its antineutrino.

When $\bar{\nu} = \nu$

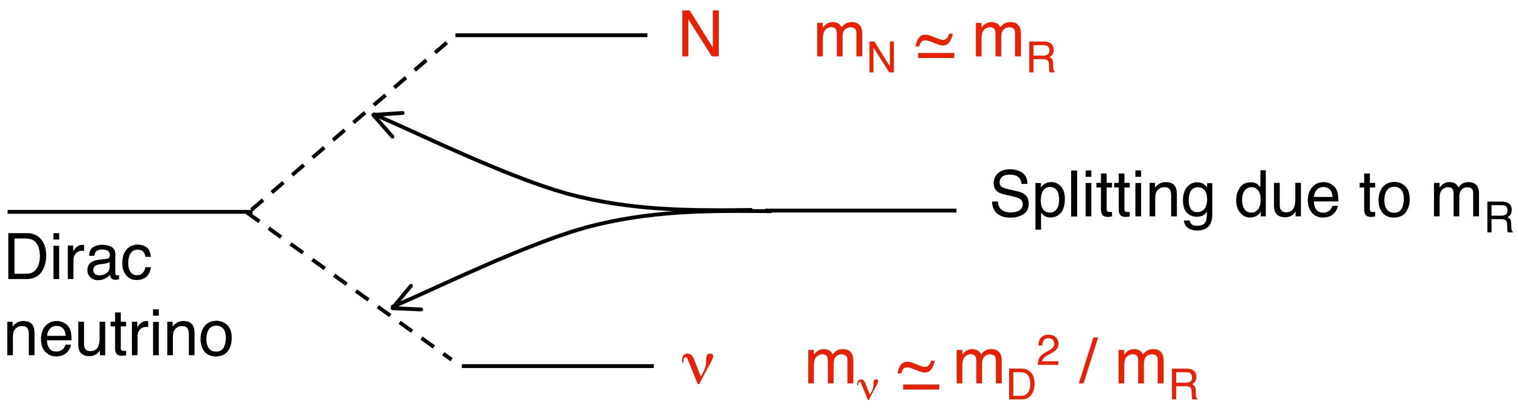
We have only 2 mass-degenerate states:



This collection of 2 states is a Majorana neutrino.

What Happens In the See-Saw?

The Majorana mass term splits a *Dirac* neutrino into two *Majorana* neutrinos.



N $m_N \simeq m_R$

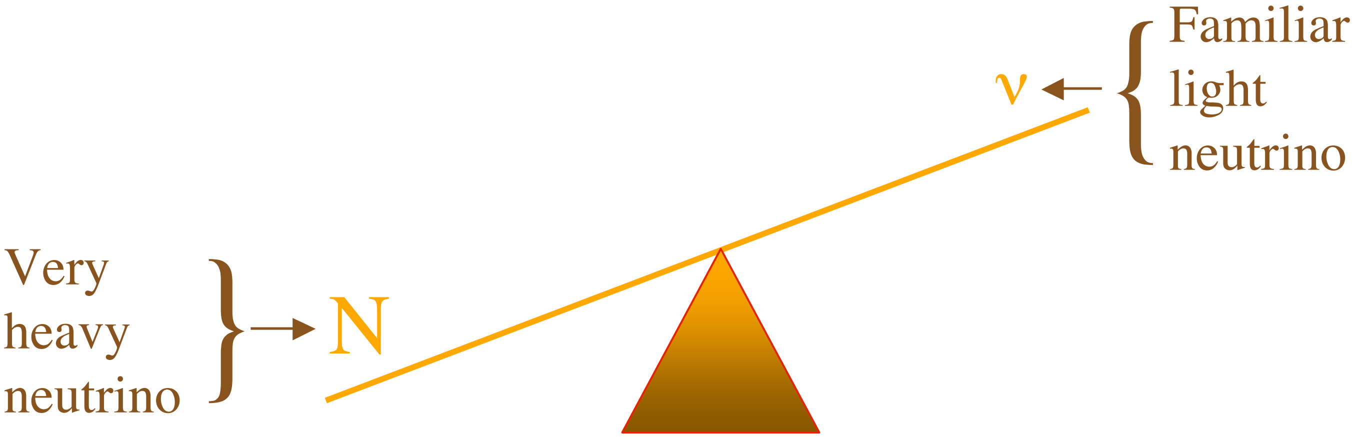
Splitting due to m_R

Dirac neutrino

ν $m_\nu \simeq m_D^2 / m_R$

Note that $m_\nu m_N \sim m_D^2 \sim m_{q \text{ or } l}^2$. ***See-Saw Relation***

The See-Saw Relation



ν ← { Familiar light neutrino

Very heavy neutrino } → N

Predictions of the See-Saw

- Each $\bar{\nu}_i = \nu_i$ (Majorana neutrinos)
- The light neutrinos have heavy partners N

How heavy??

$$m_N \sim \frac{m^2_{top}}{m_\nu} \sim \frac{m^2_{top}}{0.05\text{ eV}} \sim 10^{15}\text{ GeV}$$

Near the GUT scale.

Coincidence??

A Possible Consequence of the See-Saw — *Leptogenesis*

The heavy see-saw partners N would have been made in the hot Big Bang.

Then, being very heavy, they would have decayed.

The see-saw model predicts —

$N \to \ell^- + \ldots$ and $N \to \ell^+ + \ldots$

If there was $\cancel{CP}$ in these leptonic processes, then unequal numbers of leptons and antileptons would have been produced.

Perhaps this was the origin of today's **matter-antimatter** asymmetry.

Enjoy The Rest Of The School!

Backup Slides

➢What is the atmospheric mixing angle θ_{23}?

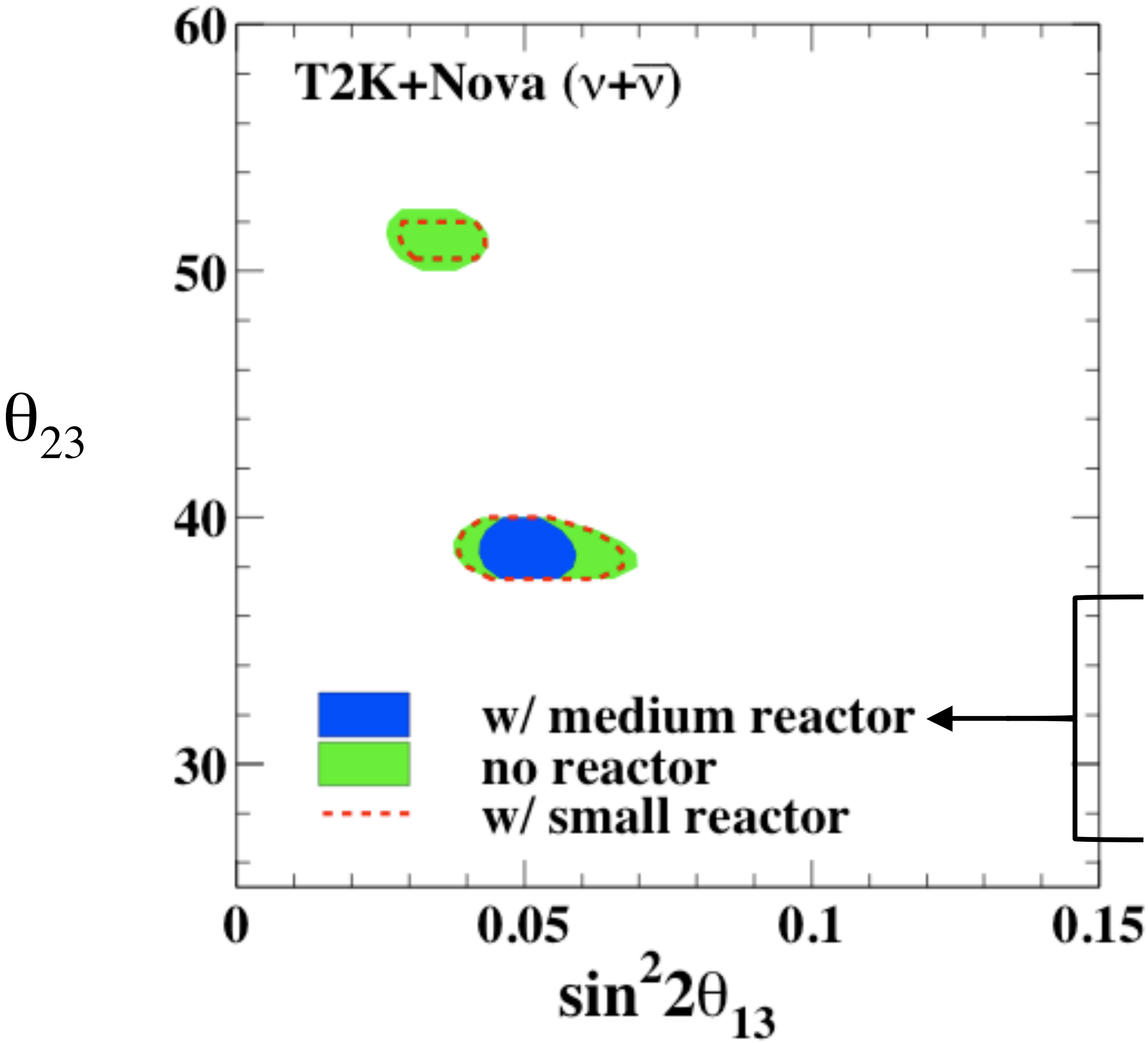
$$P[\nu_\mu \rightarrow \text{Not } \nu_\mu] \cong \sin^2 2\theta_{23} \sin^2 \Delta_{atm}$$

Here Δ_{atm} lies between the (very nearly equal) Δ_{31} and Δ_{32}.

This measurement determines $\sin^2 2\theta_{23}$, but if $\theta_{23} \neq 45°$, there are two solutions for θ_{23}:

$$\theta_{23} \text{ and } 90° - \theta_{23}.$$

A reactor experiment may be able to resolve this ambiguity.



Assumes $\sin^2 2\theta_{23}$ = .95 ± .01

Sensitive to $\sin^2 2\theta_{13}$ = 0.01

(McConnel, Shaevitz)