What We Have Learned

and

The Open Questions

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Fermilab
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What Have We Learned ?

We do not know how many neutrino mass eigenstates there are.

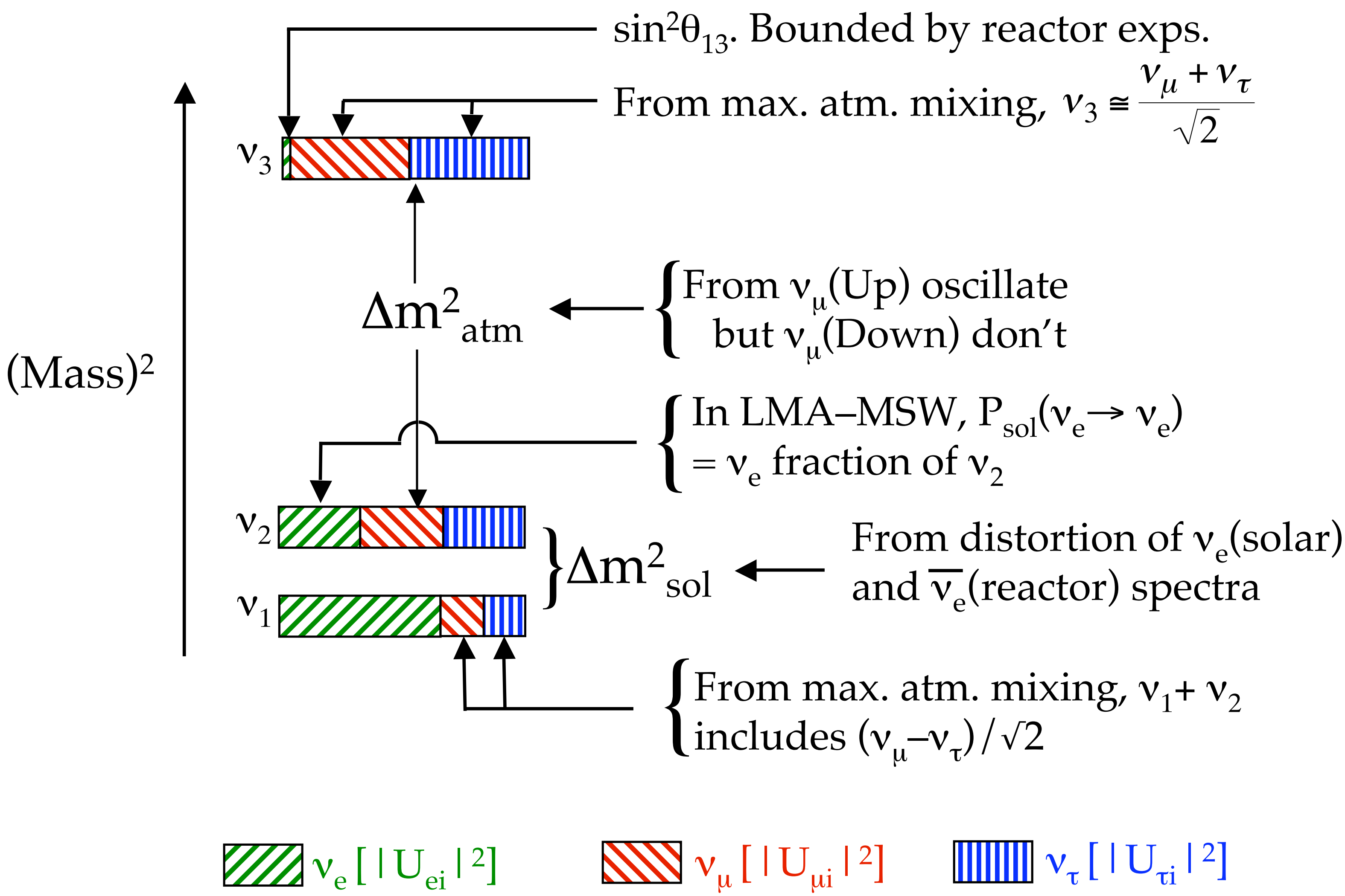
There are at least 3.

If LSND is confirmed, there are more than 3.

4?   6? ∞?

If LSND is not confirmed, nature may contain only 3 neutrinos.

Then, from the existing data, the neutrino spectrum looks like —



$\sin^2\theta_{13}$. Bounded by reactor exps.
From max. atm. mixing, $\nu_3 \cong \frac{\nu_\mu + \nu_\tau}{\sqrt{2}}$
ν_3
Δm^2_{atm}
From ν_μ(Up) oscillate but ν_μ(Down) don't
$(\text{Mass})^2$
In LMA–MSW, $P_{sol}(\nu_e \rightarrow \nu_e)$ = ν_e fraction of ν_2
ν_2
Δm^2_{sol}
From distortion of ν_e(solar) and $\overline{\nu_e}$(reactor) spectra
ν_1
From max. atm. mixing, $\nu_1 + \nu_2$ includes $(\nu_\mu - \nu_\tau)/\sqrt{2}$
$\nu_e\ [\,|U_{ei}|^2]$
$\nu_\mu\ [\,|U_{\mu i}|^2]$
$\nu_\tau\ [\,|U_{\tau i}|^2]$

The Mixing Matrix

The flavor content picture shows the $|U_{\alpha i}|^2$, but not the signs or phases of the $U_{\alpha i}$.

Atmospheric   Cross-Mixing   Solar

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

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

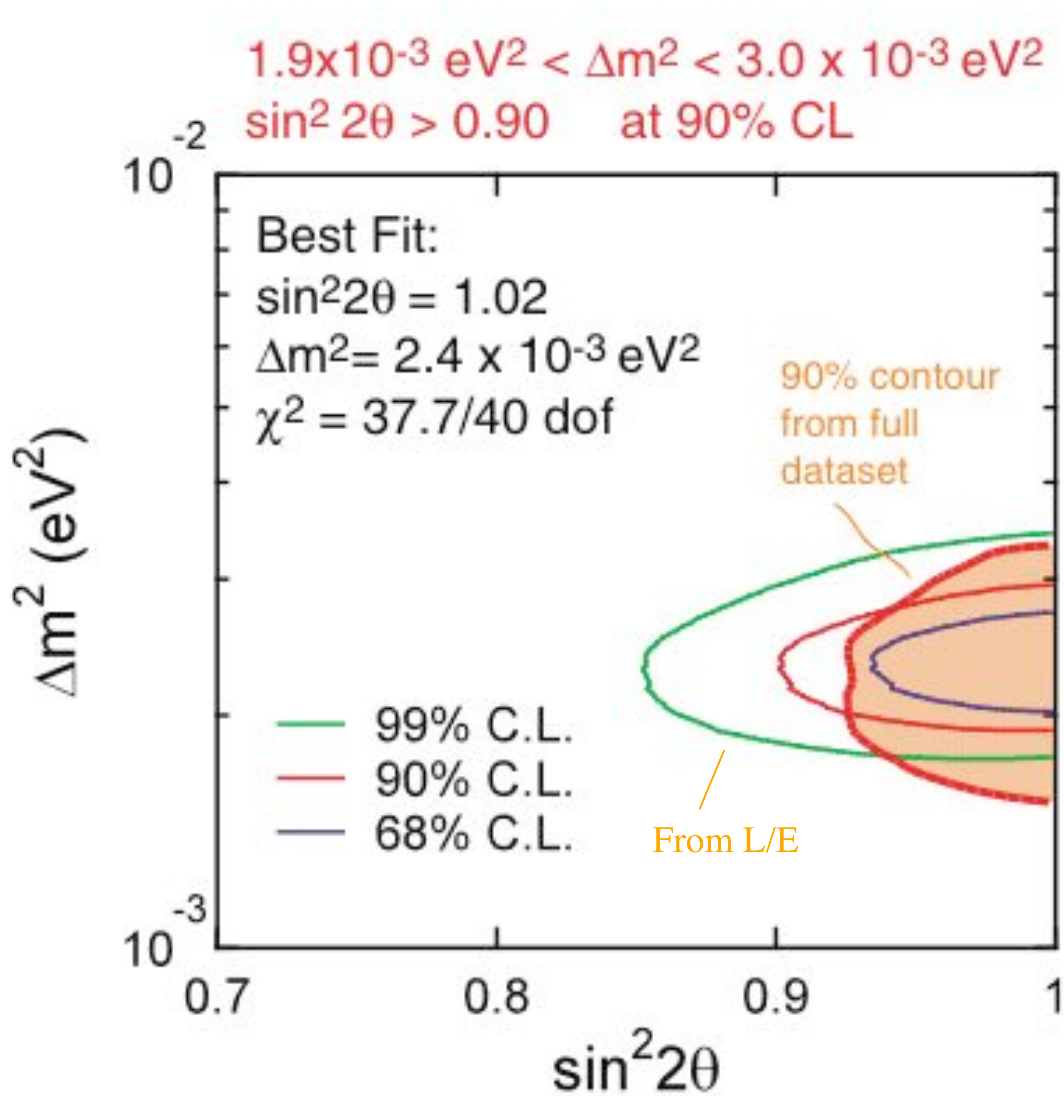
$$\times \begin{bmatrix} e^{i\alpha_1/2} & 0 & 0 \\ 0 & e^{i\alpha_2/2} & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

Majorana $\cancel{CP}$ phases

$\theta_{12} \approx \theta_{sol} \approx 33°$, $\theta_{23} \approx \theta_{atm} \approx 37\text{-}53°$, $\theta_{13} \lesssim 12°$

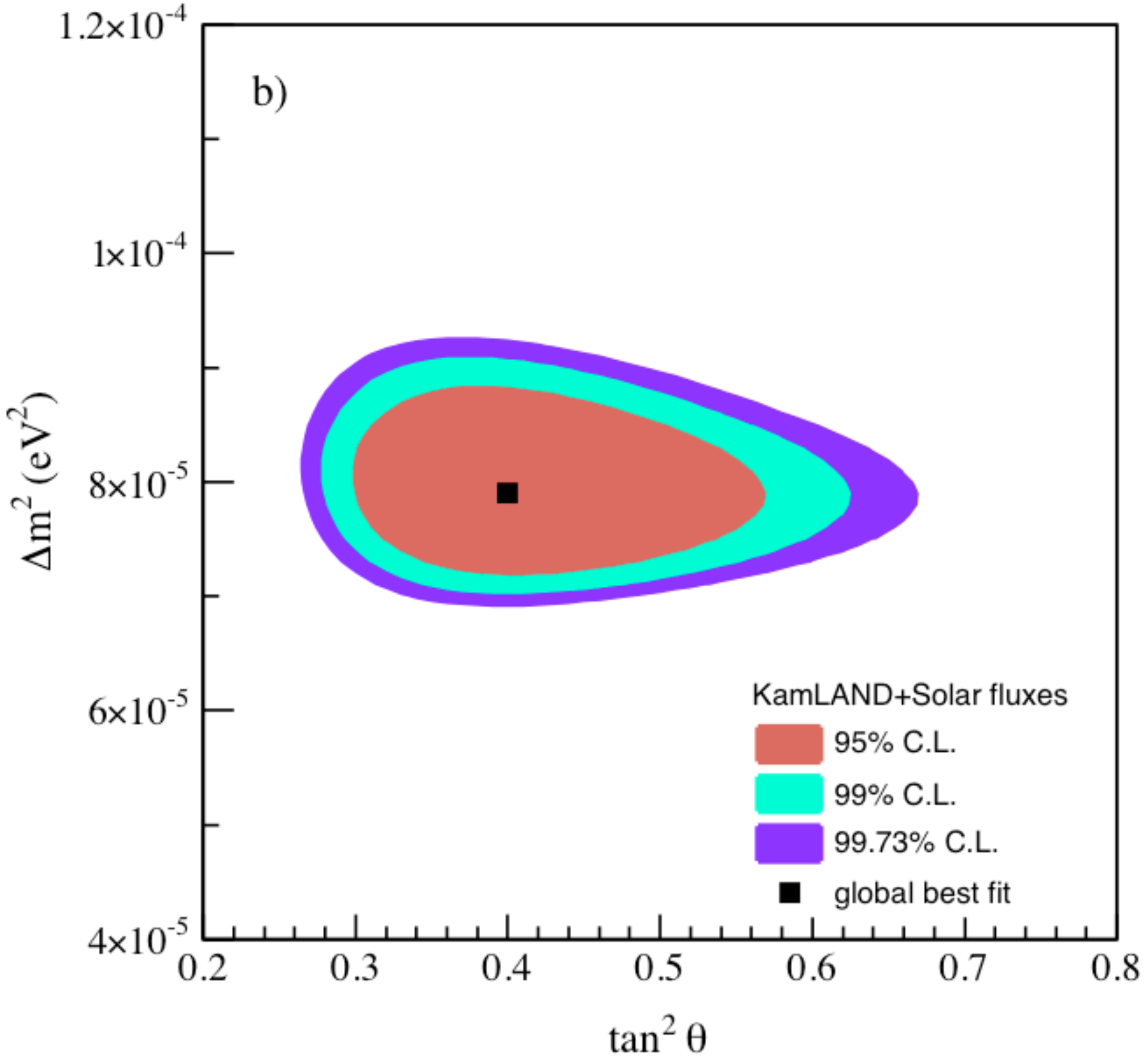
δ would lead to $P(\bar{\nu}_\alpha \rightarrow \bar{\nu}_\beta) \neq P(\nu_\alpha \rightarrow \nu_\beta)$. $\cancel{CP}$

But note the crucial role of $s_{13} \equiv \sin\theta_{13}$.



From Ed Kearns

Atmospheric Δm^2 and mixing angle from SuperKamiokande L/E analysis and full data set



From hep-ex/ 0406035

Solar Δm^2 and mixing angle from KamLAND analysis of KamLAND and solar neutrino data

How Does the Large Mixing Angle MSW Effect Work?

The solar matter effect is important for the high-energy ^{8}B neutrinos, not the low-energy pp neutrinos.

Since ν_3 couples at most feebly to electrons ($\sin^2\theta_{13} < 0.045$), and solar neutrinos are born ν_e, the solar neutrinos are mixtures of just ν_1 and ν_2.

Solar neutrino flavor change is $\nu_e \to \nu_x$, where ν_x is some combination of ν_μ and ν_τ.

This is a 2-neutrino system.

In the sun,

$$H = \frac{\Delta m^2_{sol}}{4E}\begin{bmatrix} -\cos 2\theta_{sol} & \sin 2\theta_{sol} \\ \sin 2\theta_{sol} & \cos 2\theta_{sol} \end{bmatrix} + \sqrt{2} G_F N_e \begin{array}{c} \begin{array}{cc} \nu_e & \nu_x \end{array} \\ \begin{bmatrix} 1 & 0 \\ 0 & 0 \end{bmatrix} \end{array} \begin{array}{c} \\ \nu_e \\ \nu_x \end{array}$$

At the center of the sun,

$$\sqrt{2} G_F N_e \approx 0.75 \times 10^{-5}\ \mathrm{eV}^2 / \mathrm{MeV}\ .$$

For $\Delta m^2_{sol} \approx 8 \times 10^{-5}$ eV^2 and typical ^{8}B neutrino energy of ~8 MeV,

$$\Delta m^2_{sol} / 4E \approx 0.25 \times 10^{-5}\ \mathrm{eV}^2 / \mathrm{MeV}\ .$$

The interaction term in H dominates, and ν_e is approximately an eigenstate of H.

The ^8B solar neutrino propagates outward adiabatically.

It remains the slowly - changing heavier eigenstate of the slowly - changing H.

It emerges from the sun as the heavier eigenstate of H_{Vac}, ν_2.

It stays ν_2 until it reaches the earth. Nothing "oscillates"!

Since $\nu_2 = \nu_e \sin\theta_{sol} + \nu_x \cos\theta_{sol}$, (See U matrix)

Prob[See ν_e at earth] $= \sin^2\theta_{sol}$.

What Would We Like To Find Out?

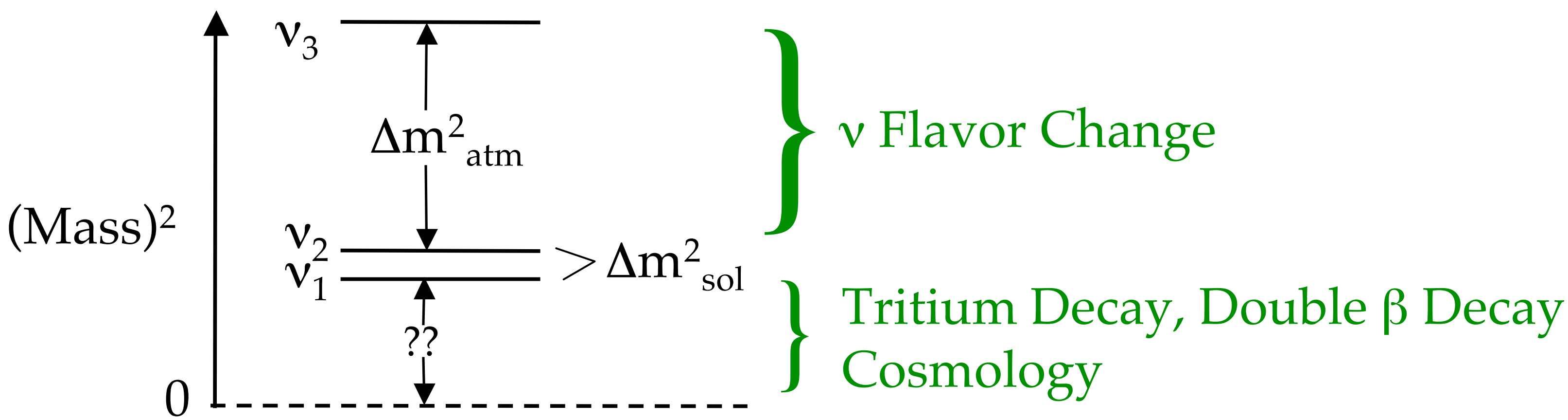
— The Future —

Some of the Open Questions

✠How many neutrino species are there?
Are there sterile neutrinos?

MiniBooNE will confirm or refute LSND.

✠What are the masses of the mass eigenstates ν_i?

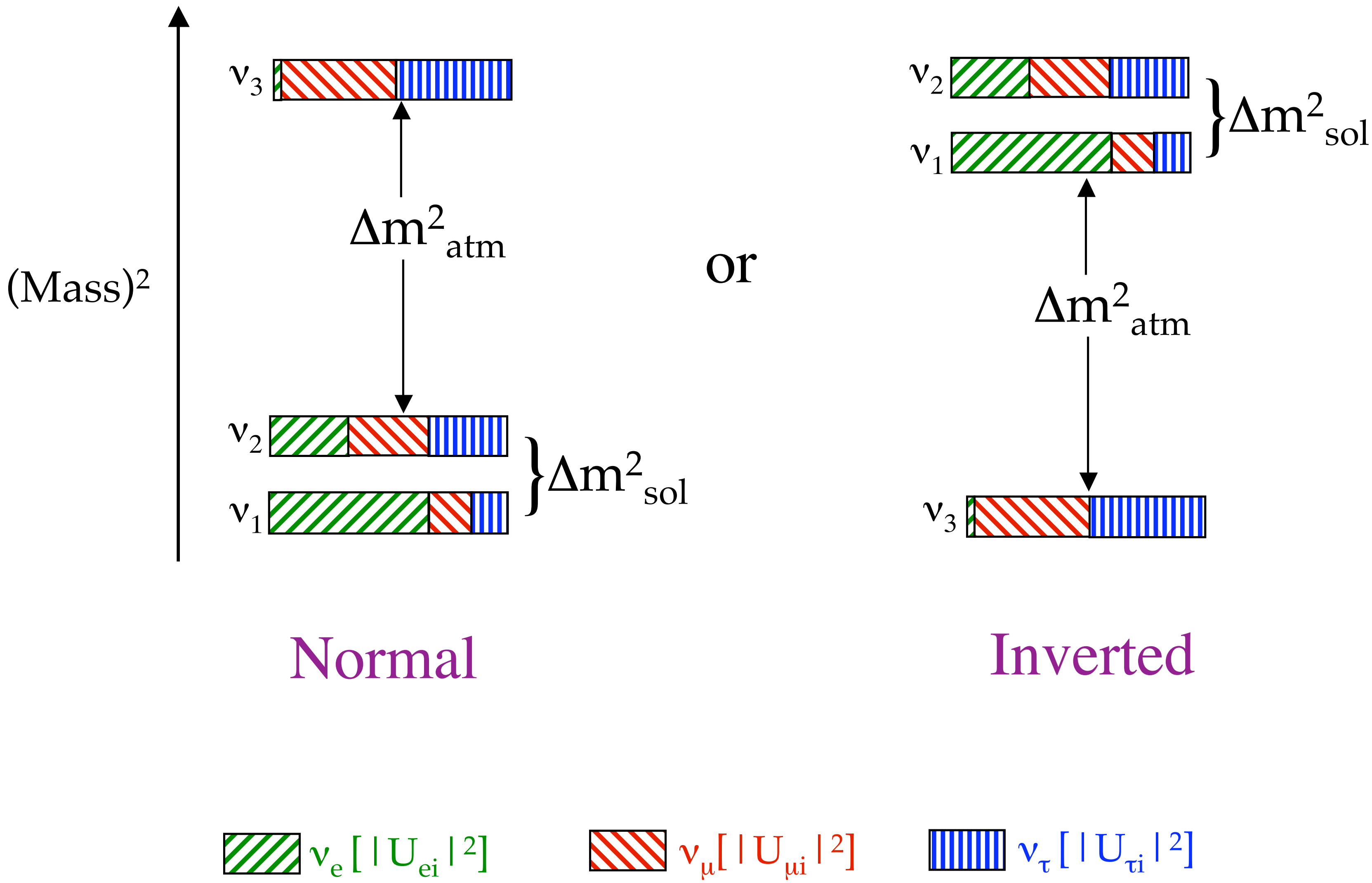


Is the spectral pattern  or  ?

$\overset{(-)}{\nu}$ behavior in earth matter can distinguish.

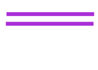
How far above zero is the whole pattern??

Is the spectrum —



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.

To determine whether the spectrum is normal or inverted, study the earth matter effect on $\overset{(-)}{\nu}_\mu \to \overset{(-)}{\nu}_e$.

These oscillations involve Δm^2_{atm} , and are proportional to $\sin^2 2\theta_{13}$.

Sign depends on character of spectrum

$$\sin^2 2\overset{(-)}{\theta}_M = \sin^2 2\theta_{13} \,/\, [\sin^2 2\theta_{13} + (\cos 2\theta_{13} \underset{(+)}{-} x)^2]$$

At superbeam energies,

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

Sign[m²(—) - m²(═)]

$$\frac{P(\nu_\mu \rightarrow \nu_e)}{P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e)} \begin{cases} >1\ ; \\ <1\ ; \end{cases}$$

The effect is $\begin{cases} 30\%\ ;\ E = 2\ \ \ \mathrm{GeV}\ (\mathrm{NO\nu A}) \\ 10\%\ ;\ E = 0.7\ \mathrm{GeV}\ (\mathrm{T2K}) \end{cases}$

A Cosmic Connection

Cosmological Data + Cosmological Assumptions $\Rightarrow$

$$\Sigma\, m_i < (0.4 - 1.0)\ \mathrm{eV}\ .$$

Mass(ν_i)

(Pastor)

If there are only 3 neutrinos,

$$0.04\ \mathrm{eV} \lesssim \mathrm{Mass}[\mathrm{Heaviest}\ \nu_i] < (0.2 - 0.4)\ \mathrm{eV}$$

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

Cosmology

✠ Does —

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

or

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

$e^+ \neq e^-$ since Charge(e^+) = – Charge(e^-).

But neutrinos may not carry any conserved charge-like quantum number.

A conserved Lepton Number L defined by—
$L(\nu) = L(\ell^-) = -L(\overline{\nu}) = -L(\ell^+) = 1$ may not exist.

If it does 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 Electroweak Isospin Invariance), and its renormalizability.

Anything allowed by the symmetries occurs.

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

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: $m_D \overline{\nu}_L \nu_R$.

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

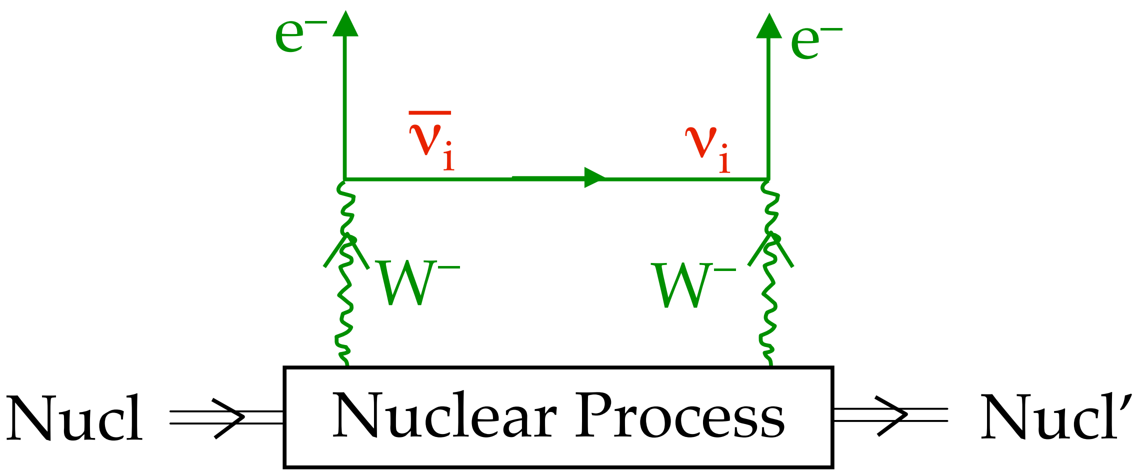
Unlike ν_L , ν_R carries no Electroweak Isospin.

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

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

If L is not conserved, so that neutrinos are their own antiparticles, then we can have —

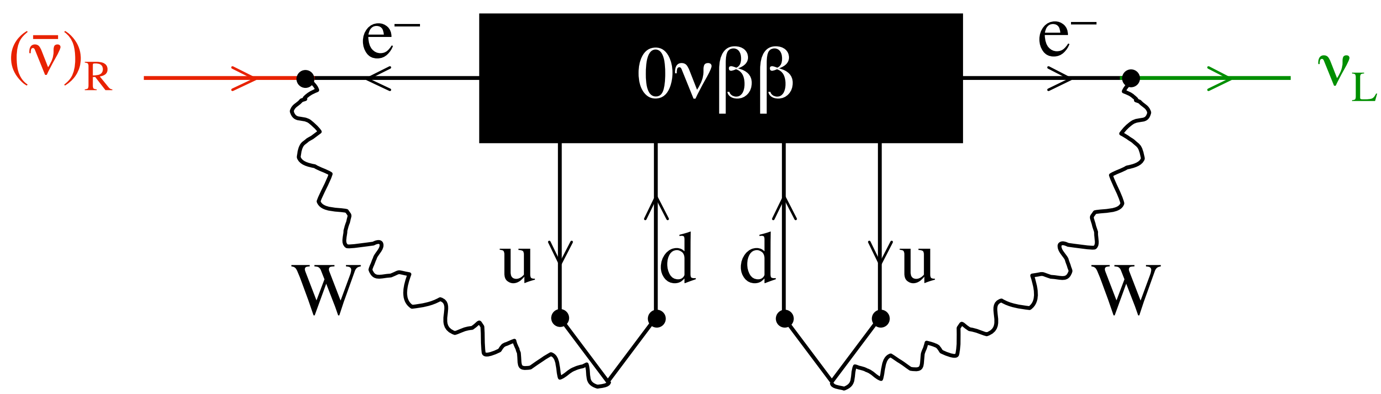
Neutrinoless Double Beta Decay [0νββ]



Observation would imply $\not{L}$ and $\overline{\nu}_i = \nu_i$, making the neutrinos very different from the charged leptons and quarks.

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

Schechter and Valle



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

Majorana mass terms either directly involve New Physics not in the Standard Model, or else imply its existence.

Observation of $0\nu\beta\beta$ would imply that —

The origin of neutrino mass involves physics different from that which gives masses to the charged leptons, quarks, nucleons, humans, the earth, and galaxies.

The Quest for the Origin of Mass

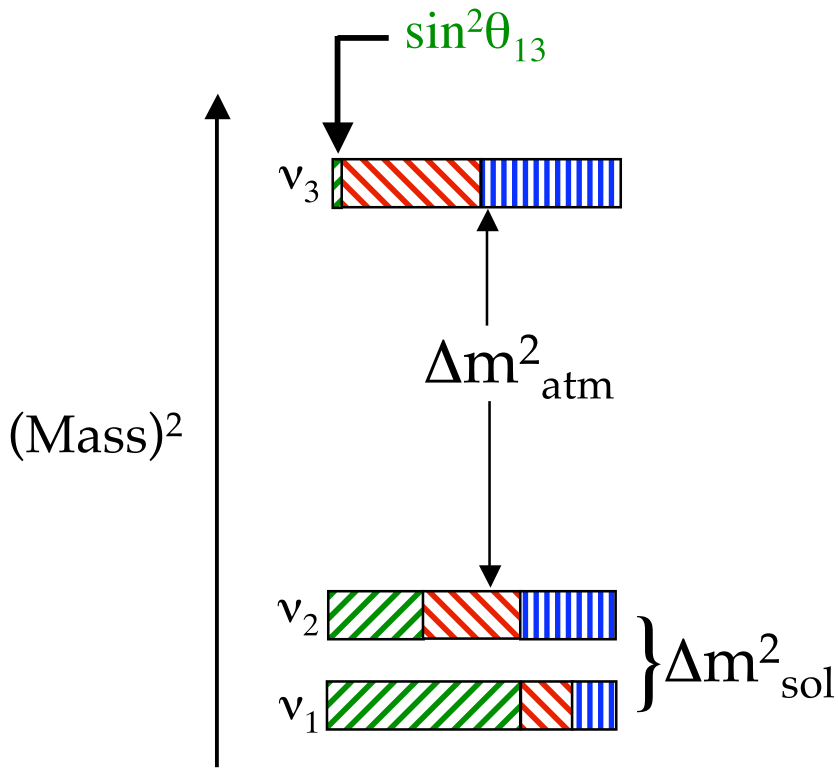
Neutrino experiments and the search for the Higgs boson both probe the origin of mass.

The see-saw mechanism suggests that the physics behind neutrino mass resides at 10^{15} GeV, which is approximately where Grand Unified Theories (GUTS) say the elementary particle forces between unified.

In Pursuit of θ_{13}

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

How may θ_{13} 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}, and involving ν_e.

Complementary Approaches

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

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

✠ Do neutrino interactions violate CP?

Do the leptonic interactions, like the quark interactions, violate the fundamental symmetry of CP?

Is leptonic $\not{CP}$ responsible for the

MATTER antimatter

asymmetry of the universe?

✠ Is neutrino ~~CP~~ the reason we exist?

The universe contains **MATTER**, but essentially no antimatter.
Good thing for us:

This preponderance of **MATTER** over antimatter could not have developed unless the two behave differently.

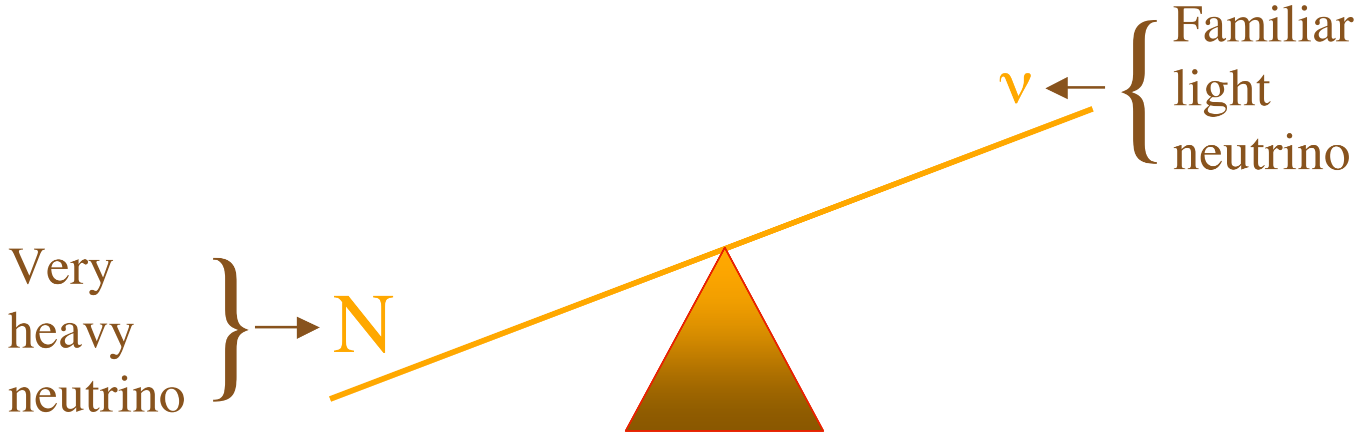
The observed difference between **QUARK** and antiquark behavior, as described by the Standard Model, is inadequate.

Could the interactions of **MATTER** and antimatter with neutrinos provide the crucial difference?

There is a natural way in which they could.

The most popular theory of why neutrinos are so light is the —

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 e^- or e^+.

But if, in violation of CP, **MATTER** and antimatter couple differently to these heavy neutrinos N, then we can have —

$$\text{Probability}\,[\,N \rightarrow \underbrace{e^-}_{\textbf{MATTER}} + \ldots\,] \neq \text{Probability}\,[\,N \rightarrow \underbrace{e^+}_{\text{antimatter}} + \ldots\,]$$

in the early universe.

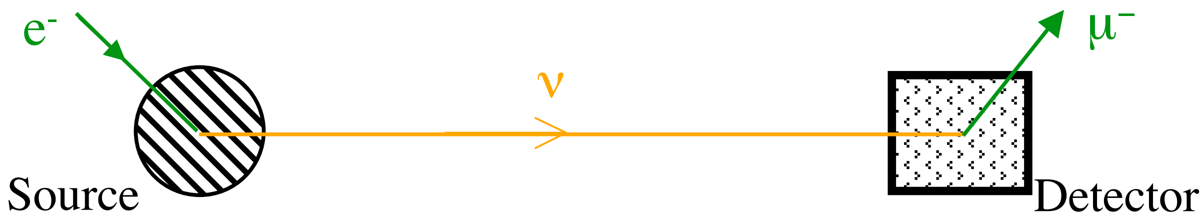
This phenomenon (leptogenesis) would have led to a universe containing unequal amounts of leptonic **MATTER** and antimatter.

SM sphaleron processes would then have converted some of the leptonic asymmetry into a baryon asymmetry.

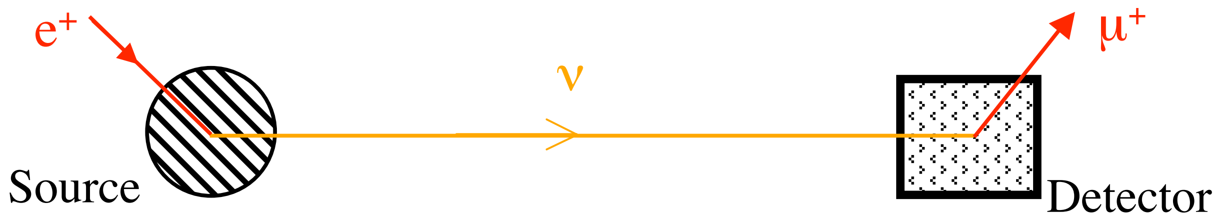
We cannot repeat the early universe.

But we can lend credibility to the hypothesis of leptogenesis by showing that **MATTER** and antimatter couple differently to the light neutrinos ν.

A neutrino flavor change involving **MATTER**:



A neutrino flavor change involving antimatter:



If these two flavor changes have different probabilities, then quite likely so do —

$$N \to e^- + \ldots \qquad \text{and} \qquad N \to e^+ + \ldots$$

If N decays led to the present preponderance of **MATTER** over antimatter, then we are all descendants of heavy neutrinos.

The APS Multi-Divisional Neutrino Study

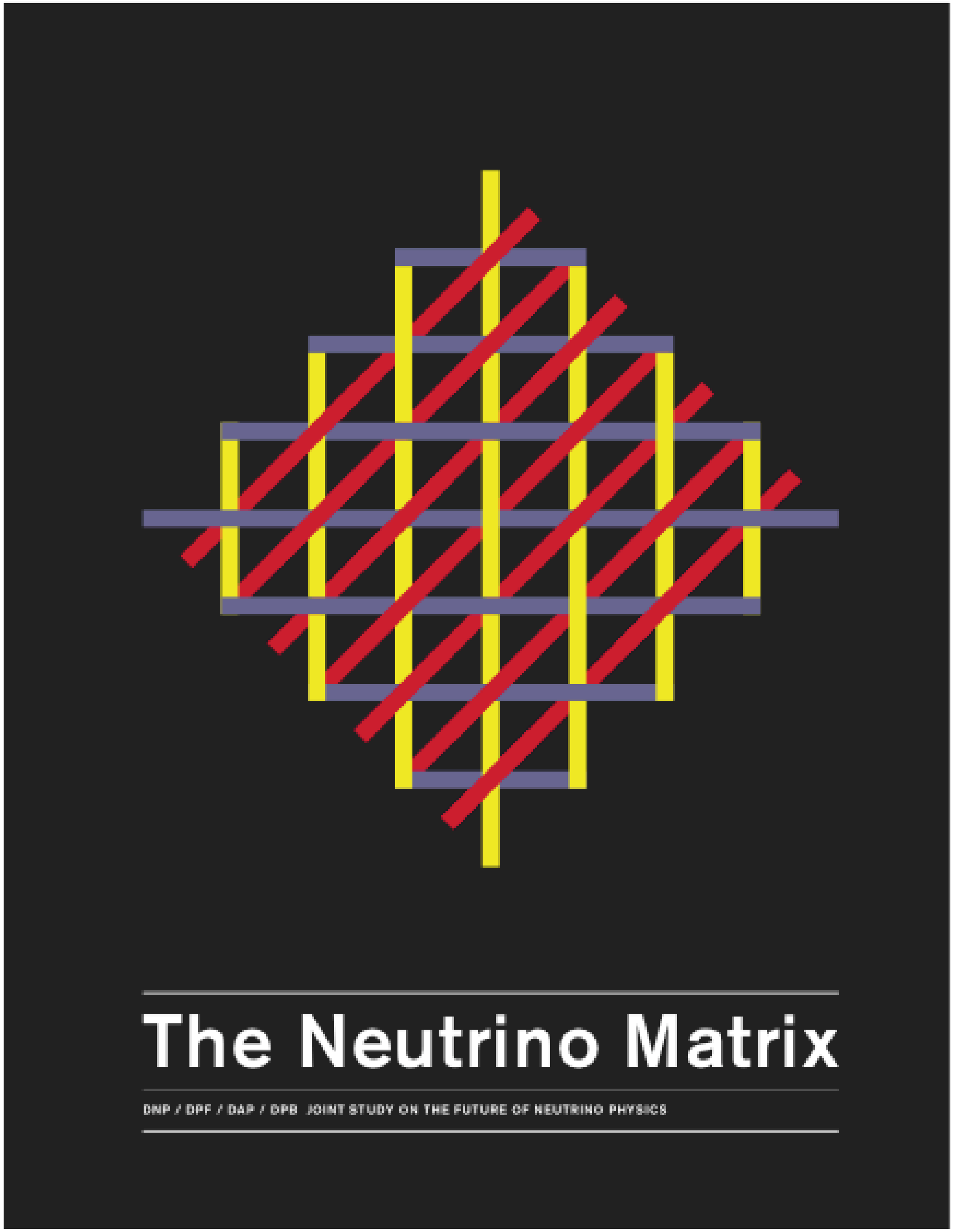
- Over 200 Participants
- Seven Working Groups
- Organizing Committee (Four members from abroad): Janet Conrad, Guido Drexlin, Belen Gavela, Takaaki Kajita, Paul Langacker, Keith Olive, Bob Palmer, Georg Raffelt, Hamish Robertson, Stan Wojcicki, Lincoln Wolfenstein
- Co-Chairpersons: Stuart Freedman, Boris Kayser

The aim: To develop a strategy for the U.S. role in a global neutrino program.

The U.S. effort should complement, and cooperate with, the efforts in Europe and Asia.

Our Main Report,
The Neutrino Matrix,
and the reports of the Working Groups, may be found at –

www.aps.org/neutrino




Recommendations for
Future Experiments

We recommend, as a high priority, that a phased program of increasingly sensitive searches for —

neutrinoless nuclear double beta decay ($0\nu\beta\beta$)

— be initiated as soon as possible.

We recommend, as a high priority, a comprehensive U.S. program to —

- Complete our understanding of neutrino mixing
- Determine the character of the neutrino mass spectrum
- Search for CP violation among neutrinos

Components of this Program

1. An expeditiously– deployed reactor experiment with sensitivity down to $\sin^2 2\theta_{13} = 0.01$
2. A timely accelerator experiment with comparable θ_{13} sensitivity, and sensitivity to the mass hierarchy through matter effects
3. A megawatt-class proton driver and neutrino superbeam with an appropriate very large detector capable of observing CP violation

We recommend the development of a solar neutrino experiment capable of measuring the energy spectrum of neutrinos from the primary pp fusion process in the sun.

- Confirm the Mikheyev-Smirnov-Wolfenstein explanation of solar neutrino behavior
- Test, at last, whether the pp fusion chain is the only source of solar energy

Conclusion

Wonderful experiments, involving the beautiful physics of flavor change, have led to the discovery of neutrino mass.

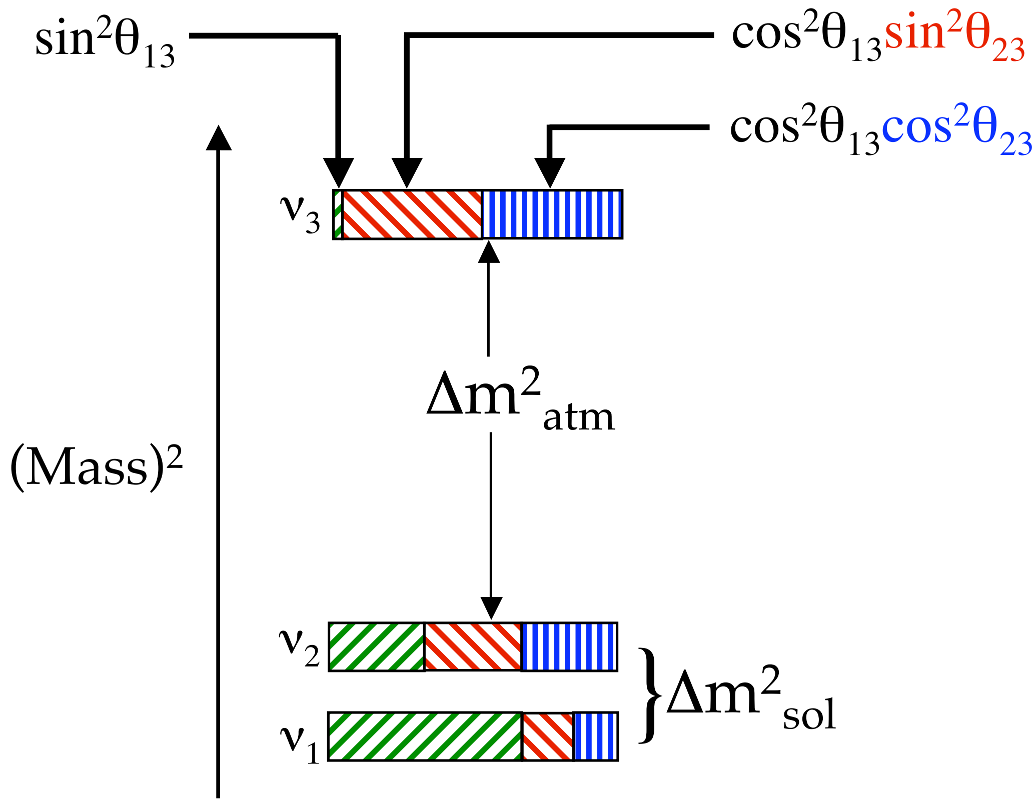
This discovery has raised very interesting questions that we must now try to answer.

Backup Slides

Lifetime $[0\nu\beta\beta] \propto 1/[m_{\beta\beta}]^2$. A phased $0\nu\beta\beta$ program addressing three possible $m_{\beta\beta}$ ranges:

Range (meV)	Spectrum Covered	Required Mass	Status
100 – 500	Quasi - Degenerate	200 kg	Close
20 – 50	Inverted	1 ton	"Proposed"
2 – 5	"Any"	100 tons	Future Tech.

In the first two stages, more than one experiment is desirable, worldwide, both to permit confirmation and to explore the underlying physics.



$\bar{\nu}_e$ disappearance depends on $\sin^2 2\theta_{13}$.

$\nu_\mu \rightarrow \nu_e$ depends on $\sin^2 2\theta_{13}\sin^2\theta_{23}$.

ν_μ disappearance depends essentially on $\sin^2\theta_{23}\cos^2\theta_{23}$.

1. The Reactor Experiment

A relatively modest-scale reactor experiment can cleanly determine whether $\sin^2 2\theta_{13} > 0.01$, and measure it if it is.

Sensitivity:

Experiment	$\sin^2 2\theta_{13}$
Present CHOOZ bound	0.2
Double CHOOZ	0.03 (In ~ 2011)
Future "US" experiment (Detectors at ~200 m and ~ 1.5 km)	0.01

2. The Accelerator Experiment

Without a proton driver, an accelerator ν experiment can —

- Probe θ_{13}
- Probe θ_{23}
- Have **some** sensitivity to whether the mass spectrum is normal or inverted

For θ_{13}: $\nu_\mu \rightarrow \nu_e$ in T2K (Japan) and NOνA (US)

For θ_{23}: $\nu_\mu \rightarrow \nu_x$ ” ”

Larger E is better.

But want L/E to correspond roughly to the peak of the oscillation.

Therefore, larger E should be matched by larger L.

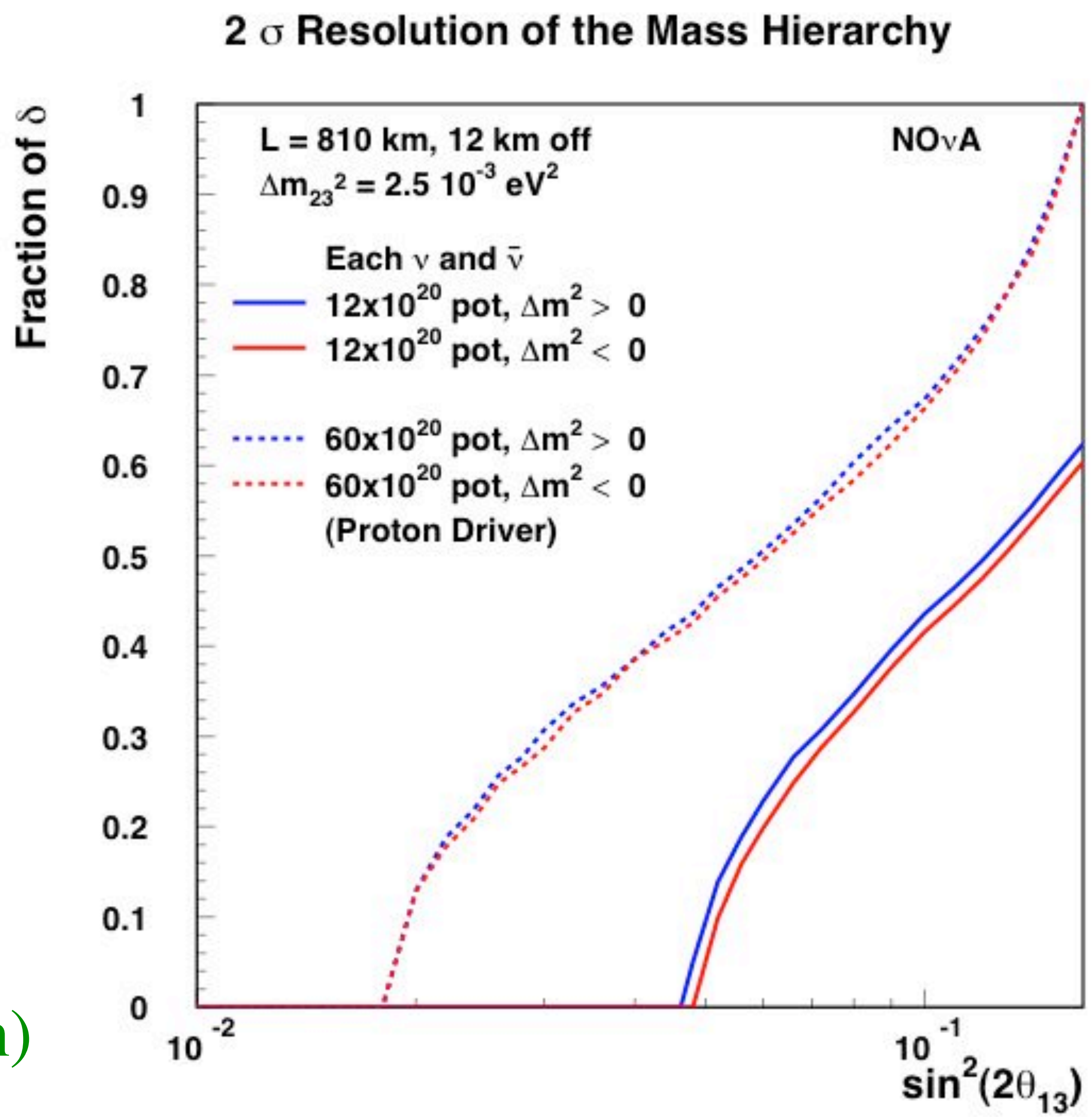
Using larger L to determine whether the spectrum is normal or inverted could be a special contribution of the U.S. to the global program.

3. The Proton Driver and Large Detector

These facilities are needed if we are to be able to determine whether the spectrum is normal or inverted, and to observe CP violation, for any $\sin^2 2\theta_{13} > (0.01 - 0.02)$.

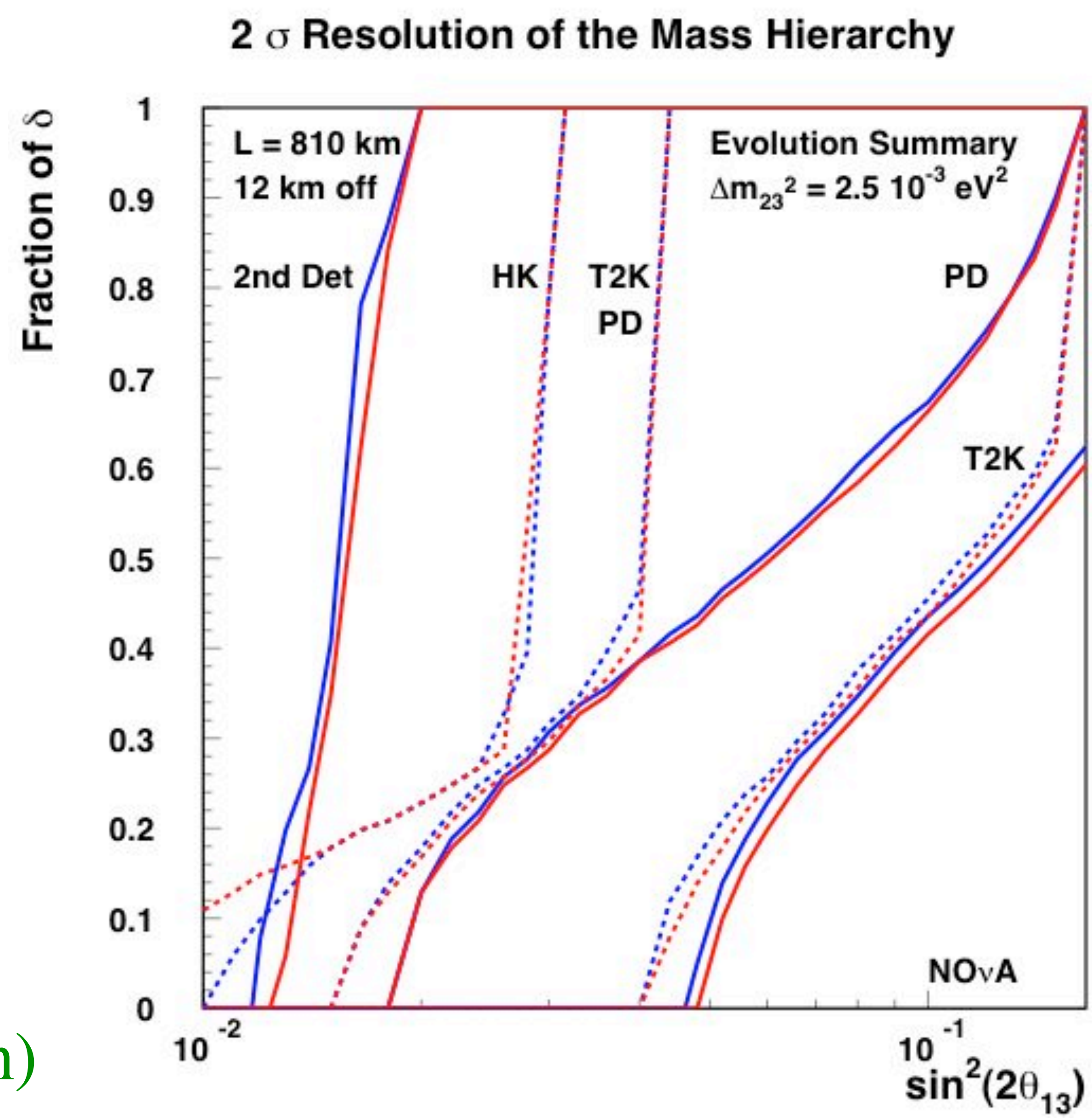
The Difference a Proton Driver Can Make

The spectral hierarchy without a proton driver



(Feldman)

The spectral hierarchy with a proton driver



(Feldman)

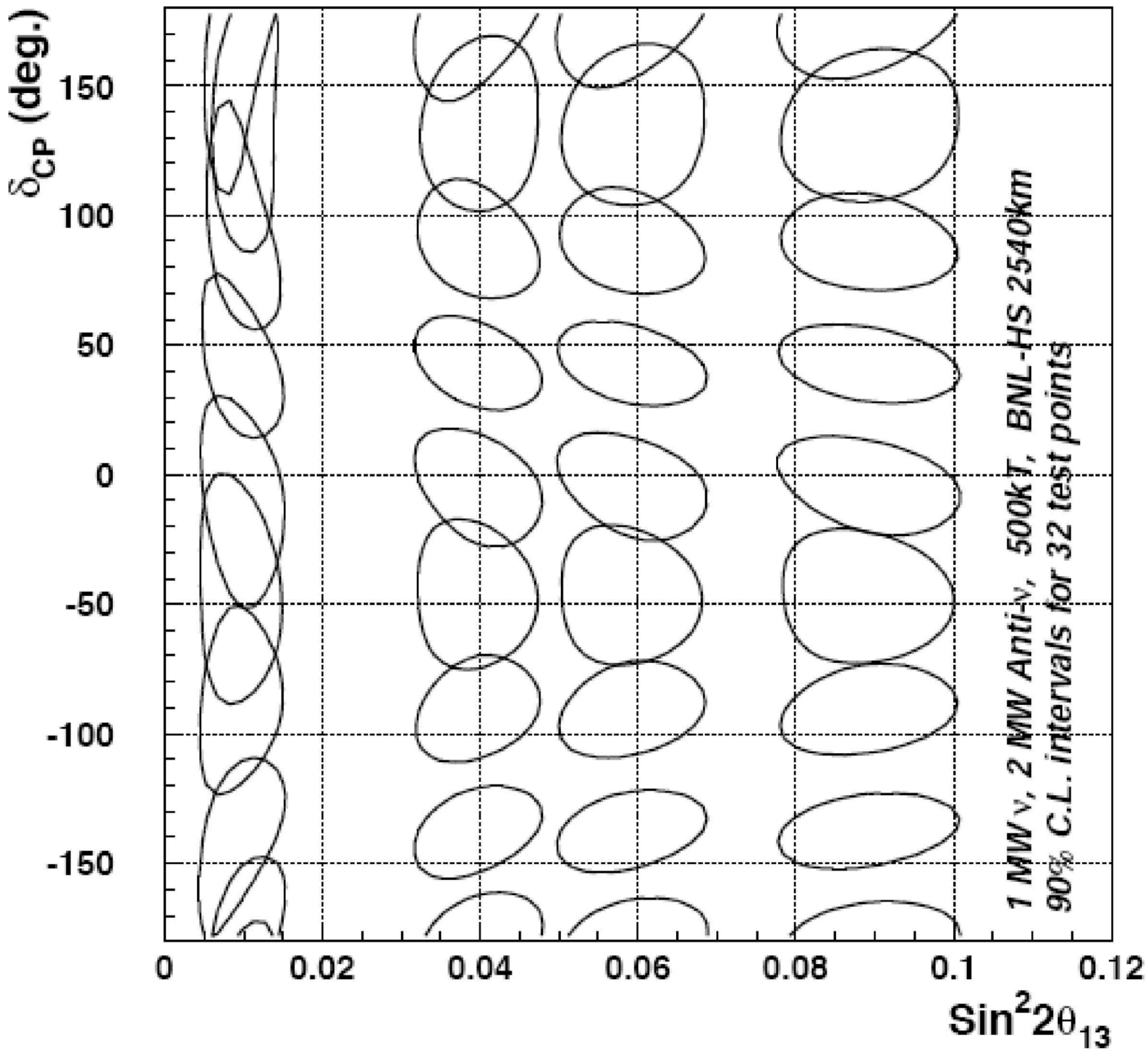
CP violation without a proton driver

"… one cannot demonstrate CP violation for any delta without a proton driver." (Feldman)

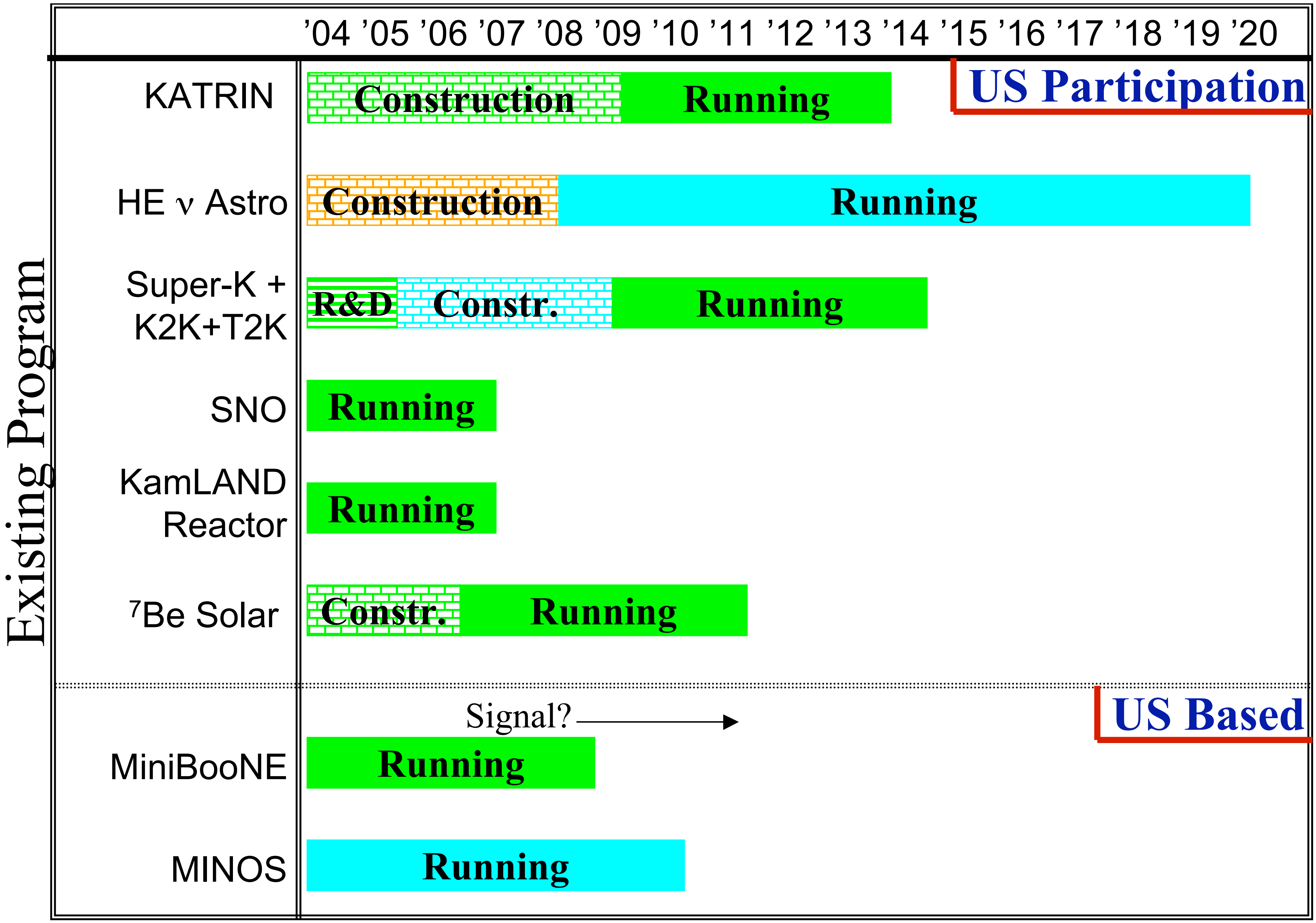
"Without a proton driver, one cannot make a 3 sigma CP discovery." (Shaevitz)

CP violation with a proton driver

90% CL contours for 5 yr ν + 5 yr $\bar{\nu}$ running



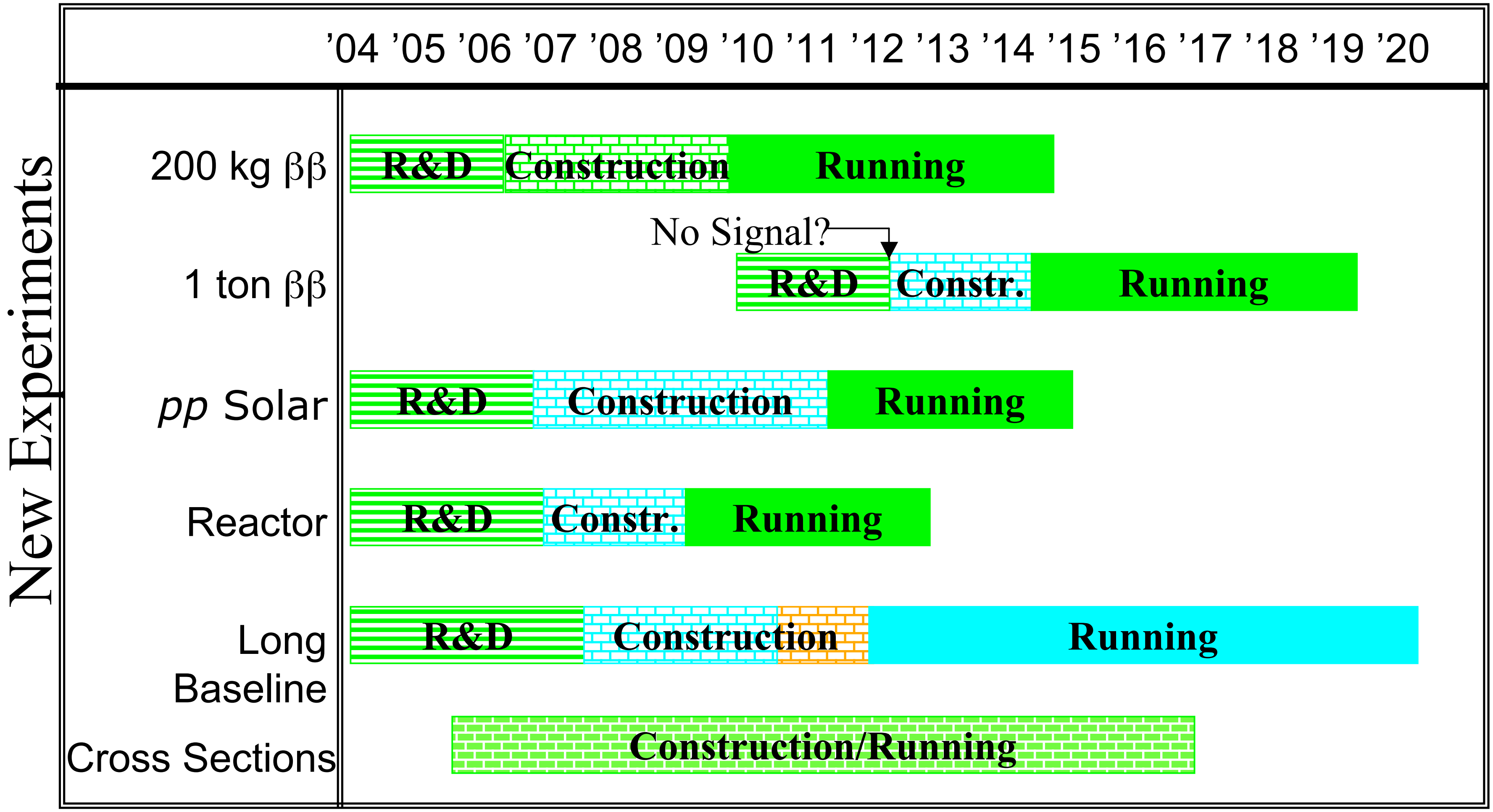
(BNL)



Green < $10M/yr   Blue $10M - $40M/yr

Orange $40M -$100M/yr   Red > $100M/yr

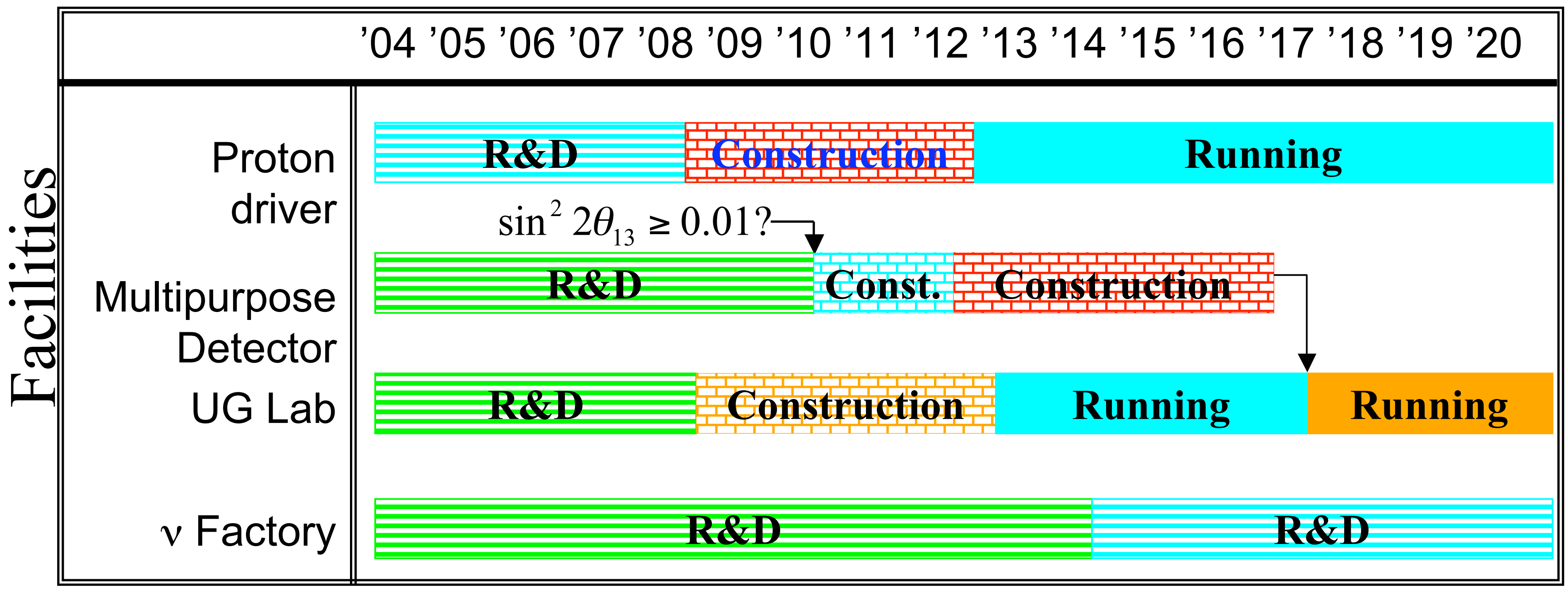
New Experiments



Green < \$10M/yr Blue \$10M - \$40M/yr

Orange \$40M -\$100M/yr Red > \$100M/yr

Facilities



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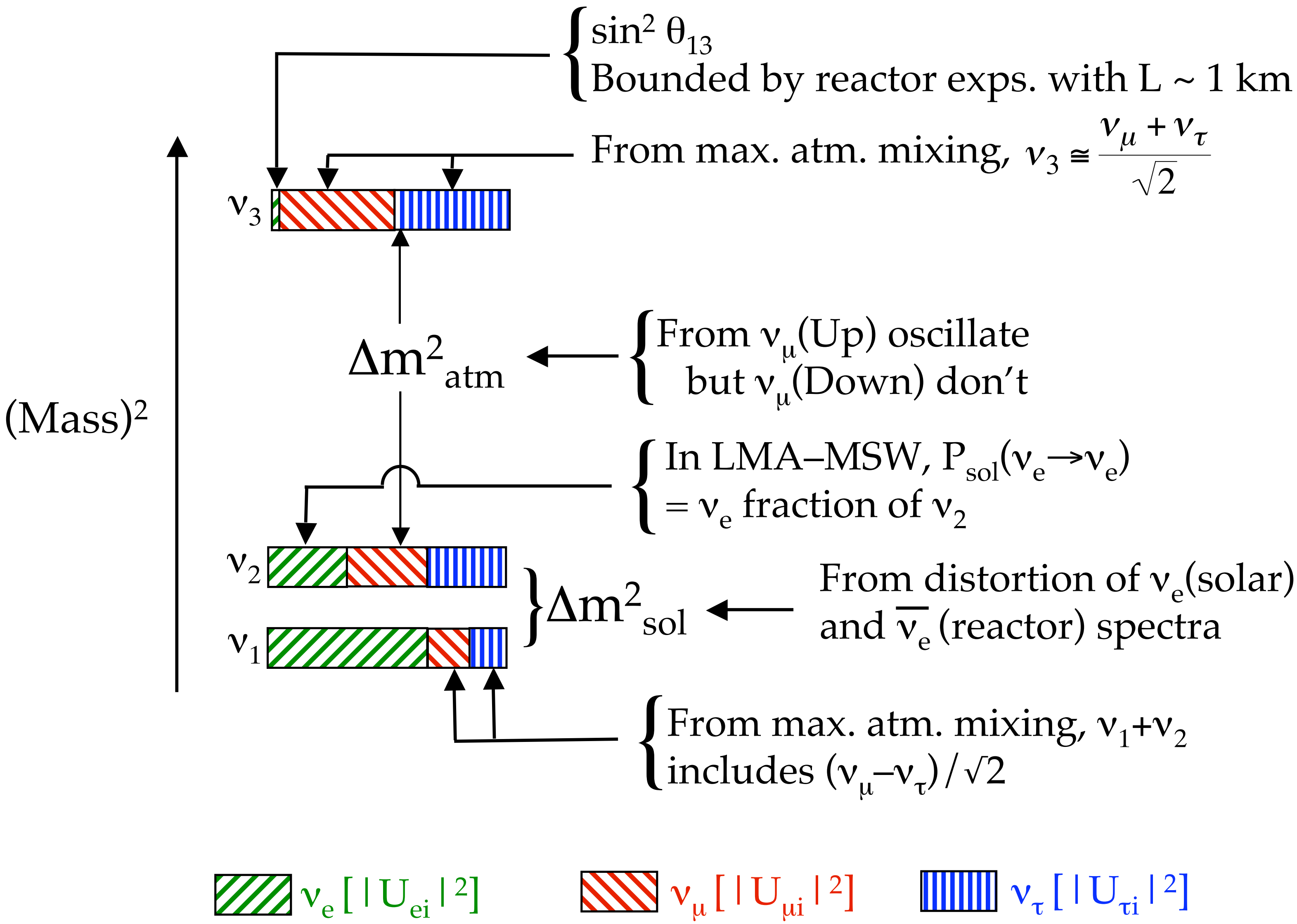

$\sin^2\theta_{13}$
Bounded by reactor exps. with L ~ 1 km
From max. atm. mixing, $\nu_3 \cong \frac{\nu_\mu + \nu_\tau}{\sqrt{2}}$
ν_3
Δm^2_{atm}
From ν_μ(Up) oscillate
but ν_μ(Down) don't
(Mass)^2
In LMA–MSW, $P_{sol}(\nu_e \rightarrow \nu_e)$
= ν_e fraction of ν_2
ν_2
Δm^2_{sol}
ν_1
From distortion of ν_e(solar)
and $\overline{\nu_e}$ (reactor) 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 $[\,|U_{\tau i}|^2]$