American Physical Society
Multi-Divisional Neutrino Study

Report to the Fermilab PAC

November 11, 2004

The Neutrino Matrix

Reporter:
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The last six years

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Compelling evidence that neutrinos have mass and mix

↓

Open questions about the neutrino world

↓

Need for a coherent strategy for answering them

This need has led to a year-long study of the future of neutrino physics, sponsored by the APS Divisions of –

Nuclear Physics

Particles and Fields

Astrophysics

Physics of Beams

The Process

- Working groups, each defined by an experimental approach to answering the open neutrino questions, explored their defining approaches

- With the working group findings and a general discussion in Snowmass as input, a writing committee prepared a cross-cutting final report

- The draft final report was submitted to the study organizing committee and working group leaders, and then to all the study participants, for comment

- The comments were taken into account

The Status of the Study

Our final report, *The Neutrino Matrix*, is complete.

This contains the study-wide discussion and recommendations, plus executive summaries of the working group reports.

It is posted at the PAC website.

It has been submitted for immediate public posting, accessible from the DNP, DPF, DAP, and DPB websites.

DOE and NSF have been briefed.

What Have We Learned?

What Do We Not Know?

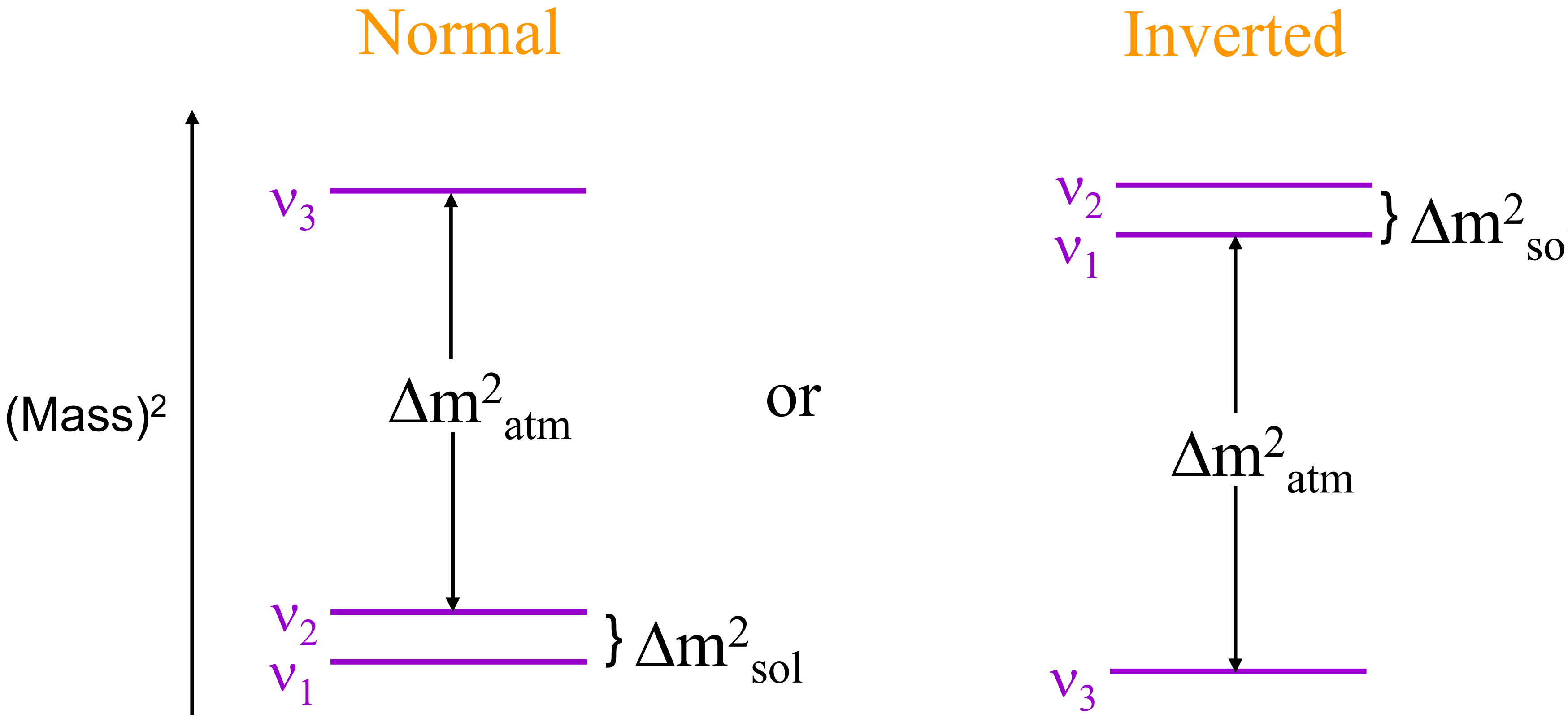
We do not know how many neutrino mass eigenstates there are.

If the Liquid Scintillator Neutrino Detector (LSND) experiment is confirmed, there are more than 3.

Confirmation of LSND would show that our usual assumptions about the neutrino spectrum and neutrino mixing are wrong.

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

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



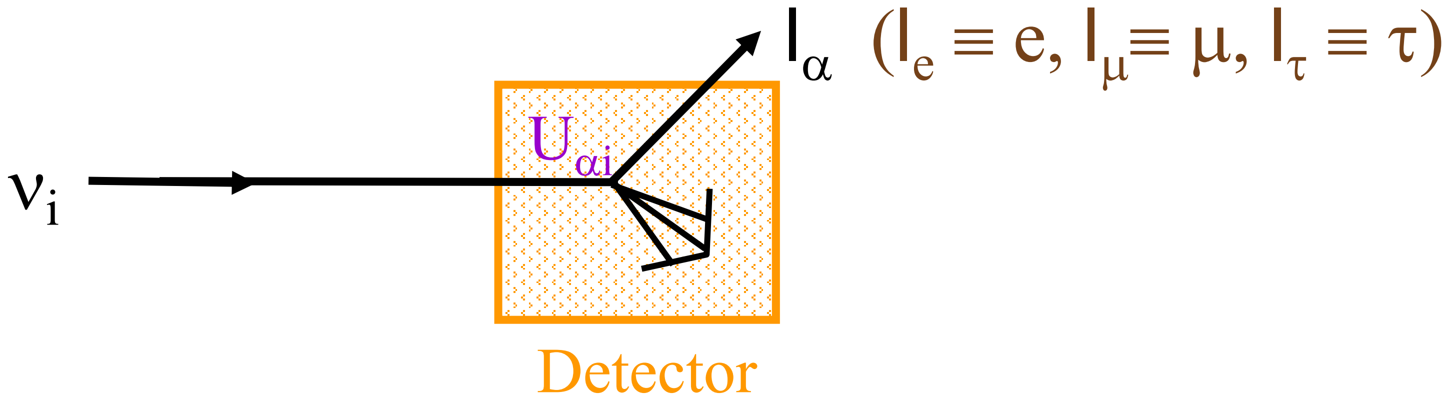
$$\Delta m^2_{sol} \cong 8 \times 10^{-5}\ eV^2, \qquad \Delta m^2_{atm} \cong 2.5 \times 10^{-3}\ eV^2$$

Genericallly, SO(10) grand unified models favor  .

 is un-quark-like, and would probably involve a lepton symmetry with no quark analogue.

The symmetry might be something like $L_e - L_\mu - L_\tau$ conservation.

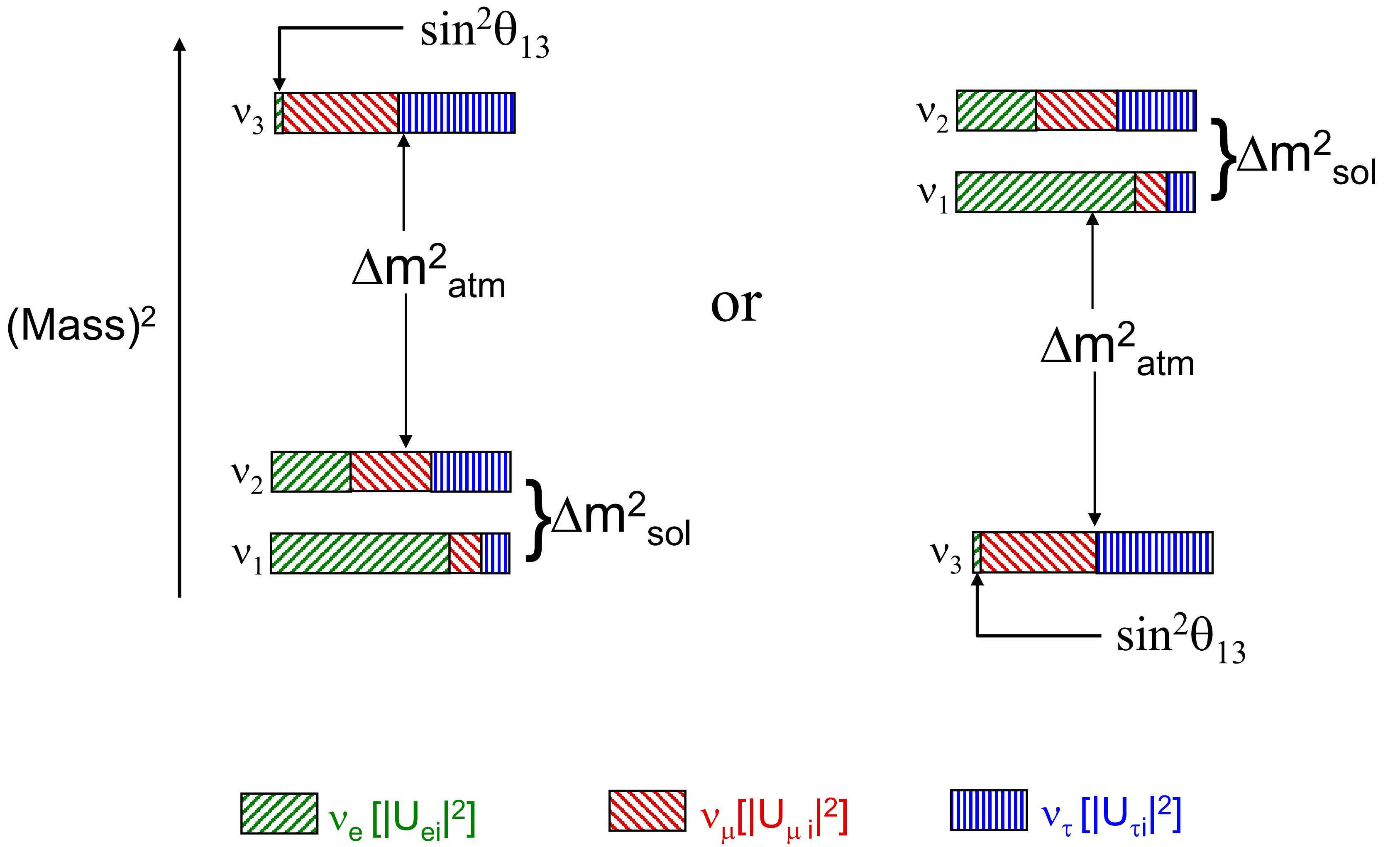
The Unitary Leptonic Mixing Matrix U



The component of ν_i that creates l_α is called ν_α, the neutrino of flavor α.

The ν_α fraction of ν_i is $|U_{\alpha i}|^2$.

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

$\theta_{12} \approx \theta_{sol} \approx 32°$, $\theta_{23} \approx \theta_{atm} \approx 36\text{-}54°$, $\theta_{13} \lesssim 15°$

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

The Open Questions

Neutrinos and the New Paradigm

- What are the masses of the neutrinos?
- What is the pattern of mixing among the different types of neutrinos?
- Are neutrinos their own antiparticles?
- Do neutrinos violate the symmetry CP?

Neutrinos and the Unexpected

- Are there “sterile” neutrinos?
- Do neutrinos have unexpected or exotic properties?
- What can neutrinos tell us about the models of new physics beyond the Standard Model?

Neutrinos and the Cosmos

- What is the role of neutrinos in shaping the universe?
- Is CP violation by neutrinos the key to understanding the matter – antimatter asymmetry of the universe?
- What can neutrinos reveal about the deep interior of the earth and sun, and about supernovae and other ultra high energy astrophysical phenomena?

Recommendations for Future Experiments

High Priority: A comprehensive U.S. program to –

- Complete our understanding of neutrino mixing
- Determine whether the neutrino mass spectrum is normal or inverted
- Search for CP violation among the neutrinos

Components of this Program

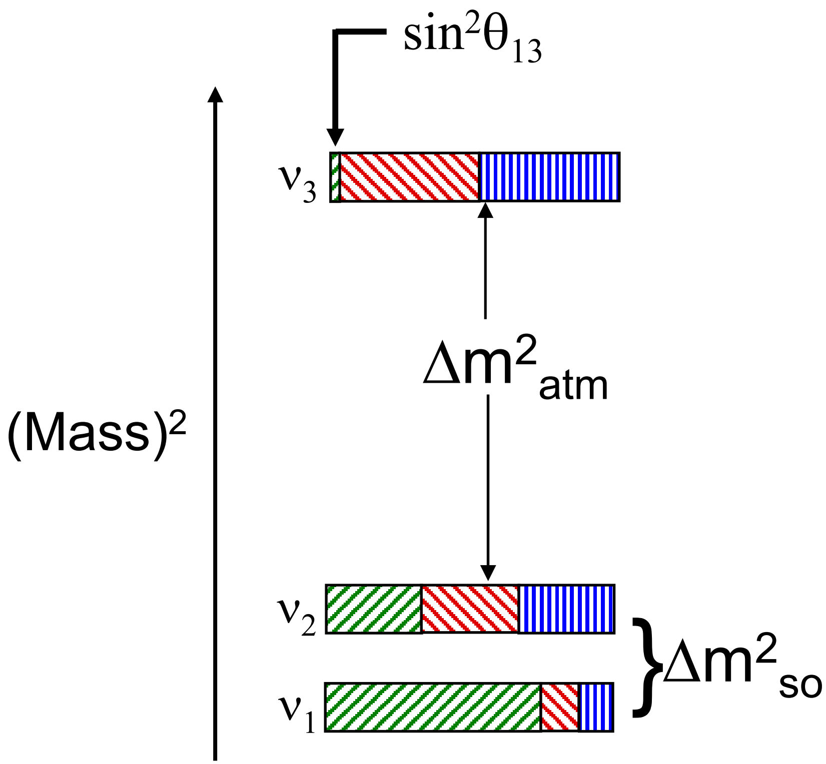
1. An expeditiously– deployed reactor experiment with sensitivity down to $\sin^2 2\theta_{13} = 0.01$
2. A timely accelerator experiment with comparable θ_{13} sensitivity, and the possibility of determining the character of the mass hierarchy
3. A megawatt-class proton driver and neutrino superbeam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

In Pursuit of θ_{13}

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

If $\sin^2 2\theta_{13} < 0.01$, a neutrino factory will be needed to study both of these issues.

How may θ_{13} be measured?



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

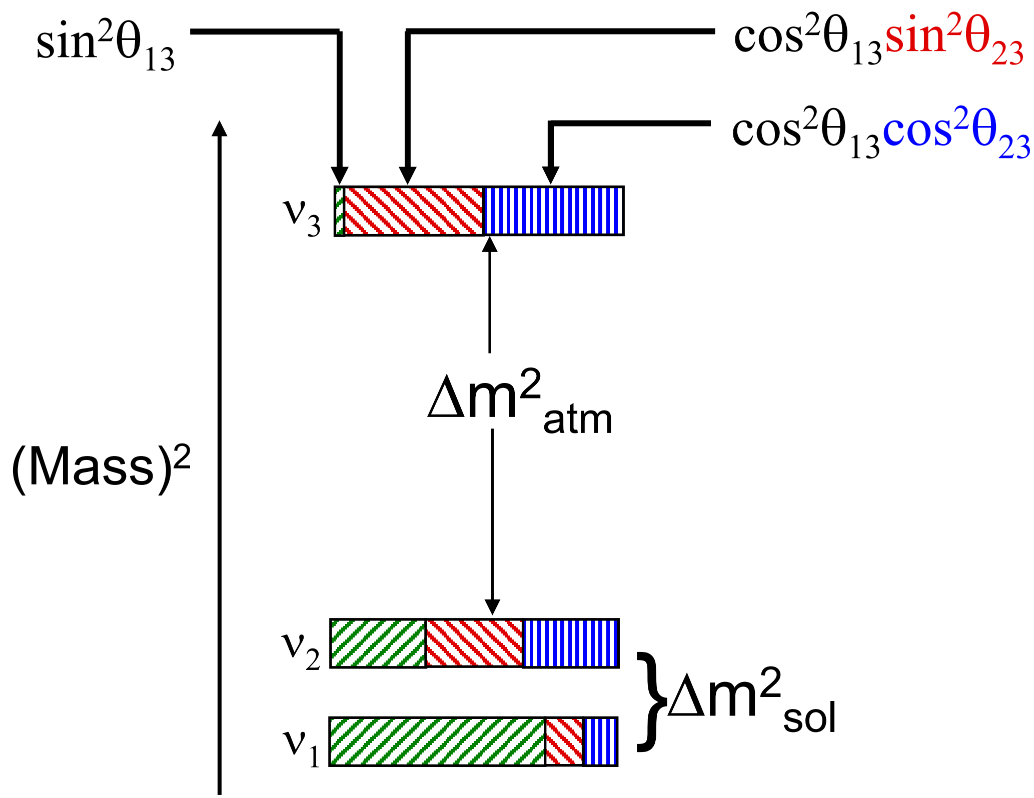
ν_3 is at one end of Δm^2_{atm}.

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

Possibilities

Reactor $\bar{\nu}_e$ disappearance while traveling L ~ 1.5 km. L/E ~ 500 km/GeV. This process depends on θ_{13} alone.

Accelerator $\nu_\mu \rightarrow \nu_e$ while traveling L > Several hundred km. L/E ~ 400 km/GeV. This process depends on θ_{13}, θ_{23}, the ~~CP~~ phase δ, and on whether the spectrum is normal or inverted.



$\bar{\nu}_e$ 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 $\sin^2 2\theta_{13} > 0.01$, measure it if it is, and help break the $\theta_{23} \leftrightarrow 90^o - \theta_{23}$ degeneracy.

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

An accelerator ν experiment can probe several neutrino properties:

- θ_{13}
- θ_{23}
- Whether the spectrum is normal or inverted
- CP violation

Only the U.S. can have baselines long enough to probe whether the spectrum is normal or inverted.

Why are long baselines needed?

At superbeam energies,

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

Sign[m^2(—) - m^2(═)] → S

At oscillation maximum,

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

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

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 unique contribution of the U.S. program.

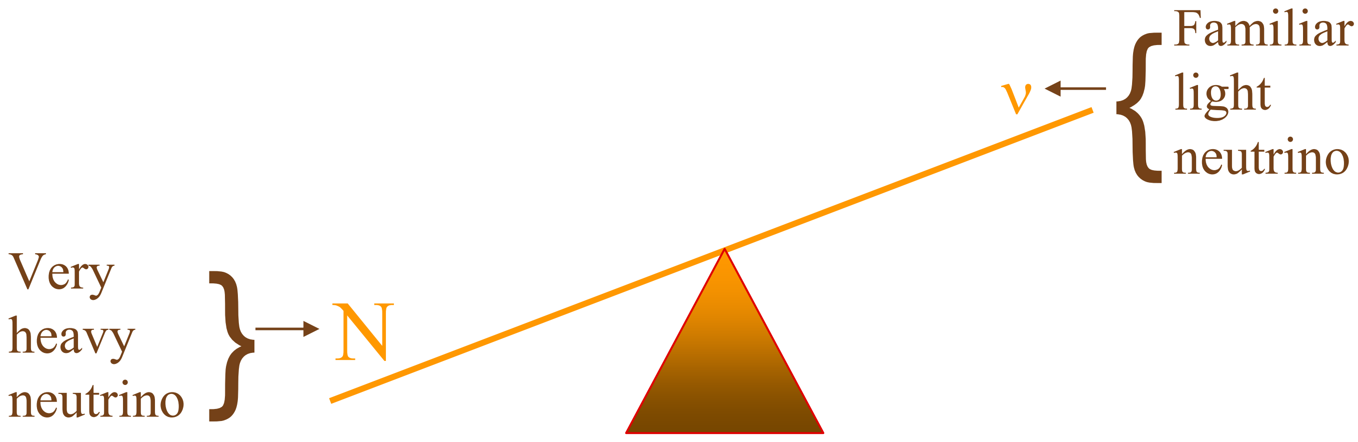
3. The Proton Driver and Large Detector

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 $\sin^2 2\theta_{13} > (0.01 - 0.02)$.

Why would $\not{CP}$ in ν oscillation be interesting?

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.

If neutrino oscillation violates CP, then quite likely so does N decay.

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

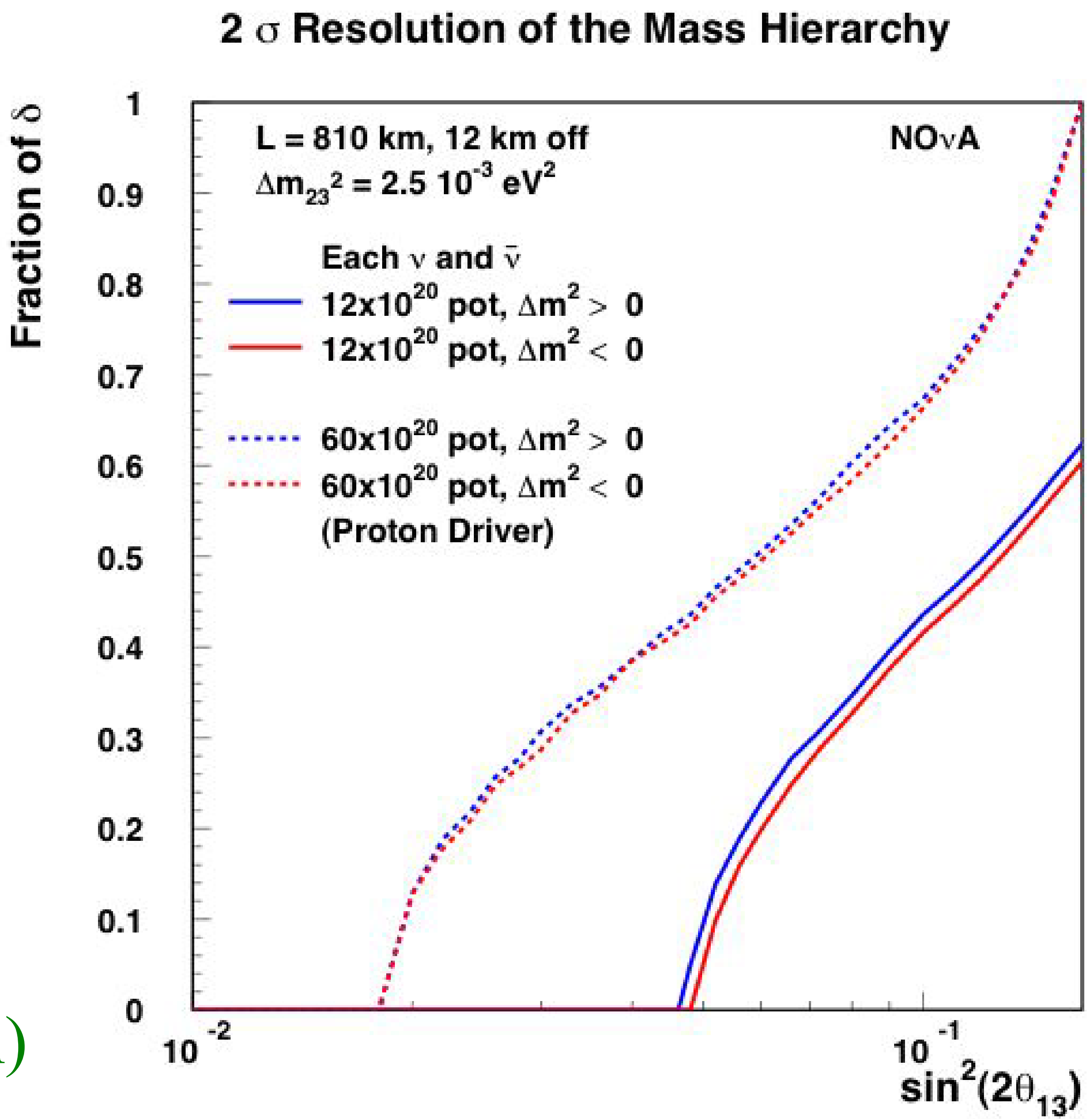
$$N \to l^- + \ldots \qquad \text{and} \qquad N \to l^+ + \ldots$$

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.

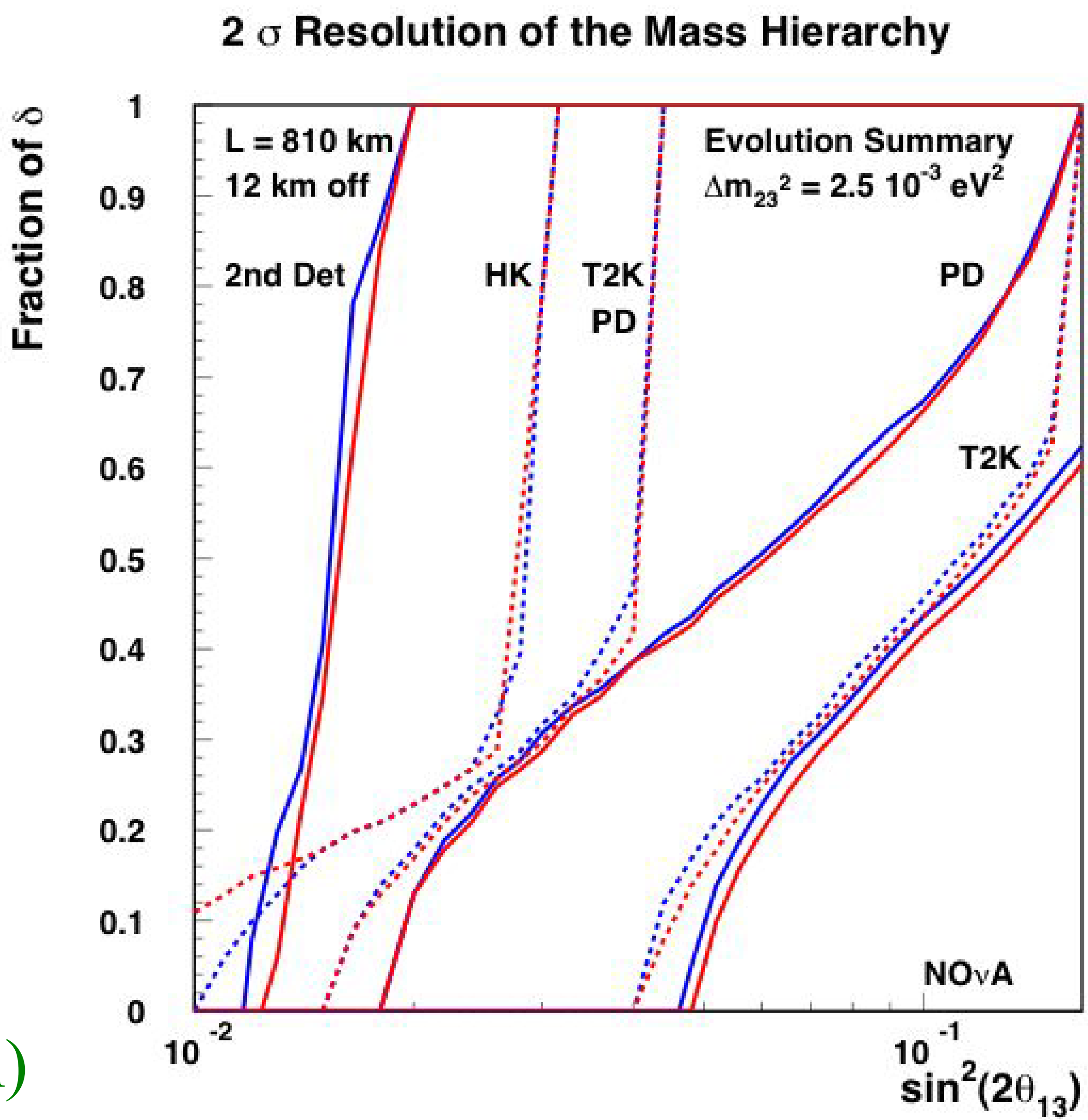
The Difference a Proton Driver Can Make

The spectral hierarchy without a proton driver



(Feldman)

The spectral hierarchy with a proton driver



(Feldman)

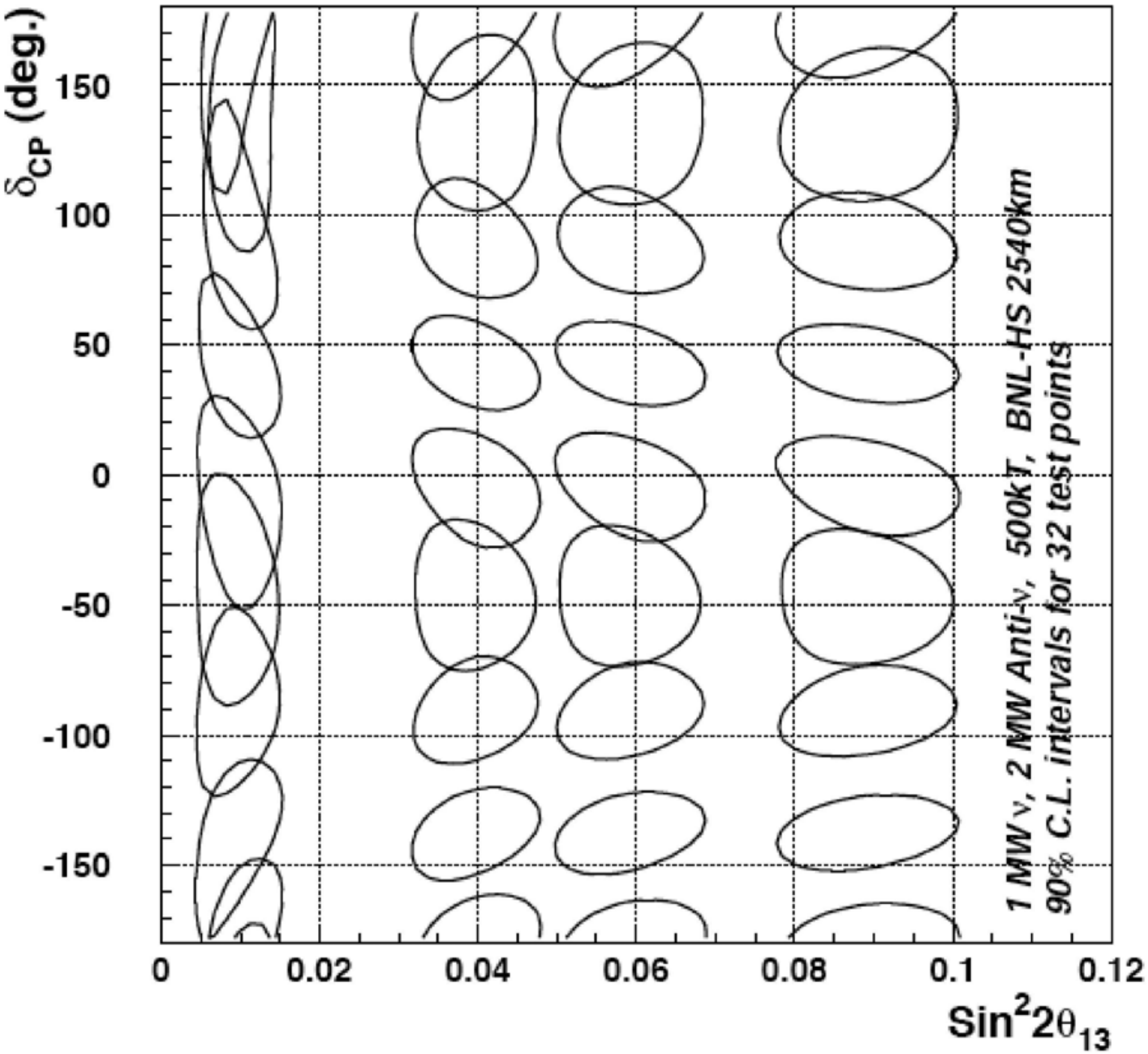
CP violation without a proton driver

"… 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)

High Priority: A phased program of searches for neutrinoless double beta decay ($0\nu\beta\beta$)

Observation of $0\nu\beta\beta$ would establish that –

- Lepton number L is not conserved
- Neutrinos are Majorana particles ($\bar{\nu} = \nu$)
- Nature *(but not the Standard Model)* contains Majorana neutrino masses

Important: An Experiment That Can Measure the Energy Spectrum of the pp Solar Neutrinos

The pp neutrinos are almost *all* the neutrinos.

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

The Context

Our recommendations for a strong future program are predicated on fully capitalizing on our investments in the current program:

- Accelerator ν experiments within the U.S.
- American participation in experiments in Antarctica, Argentina, Canada, Germany, Italy, and Japan

The current/near-future program should include –

- Determination of the ^{7}Be solar neutrino flux to 5%.
- Clear-cut confirmation or refutation of LSND.
- R&D on techniques for detecting astrophysical neutrinos above 10^{15} eV.
- Measurements of neutrino cross sections needed for the interpretation of neutrino experiments.

An Important Observation

Future experiments that we feel are particularly important rely on suitable **underground facilities**. Having these facilities will be crucial.

The Large Δm^2 Oscillation (LSND) Question

If MiniBooNE confirms LSND, we will want to know —

- How many extra neutrinos, beyond 3, are there?
- What are the splittings Δm^2 between them?
- How should long-baseline and reactor experiments be interpreted?
- Are there new, short-baseline CP-violating effects?

Study participants' view of MiniBooNE $\bar{\nu}$ running:

If MiniBooNE running with ν sees no signal, one must try, if at all practicable, to check LSND (whose signal was in the $\bar{\nu}$ channel) with $\bar{\nu}$ running.

What will this take in protons and time?

Looking Ahead

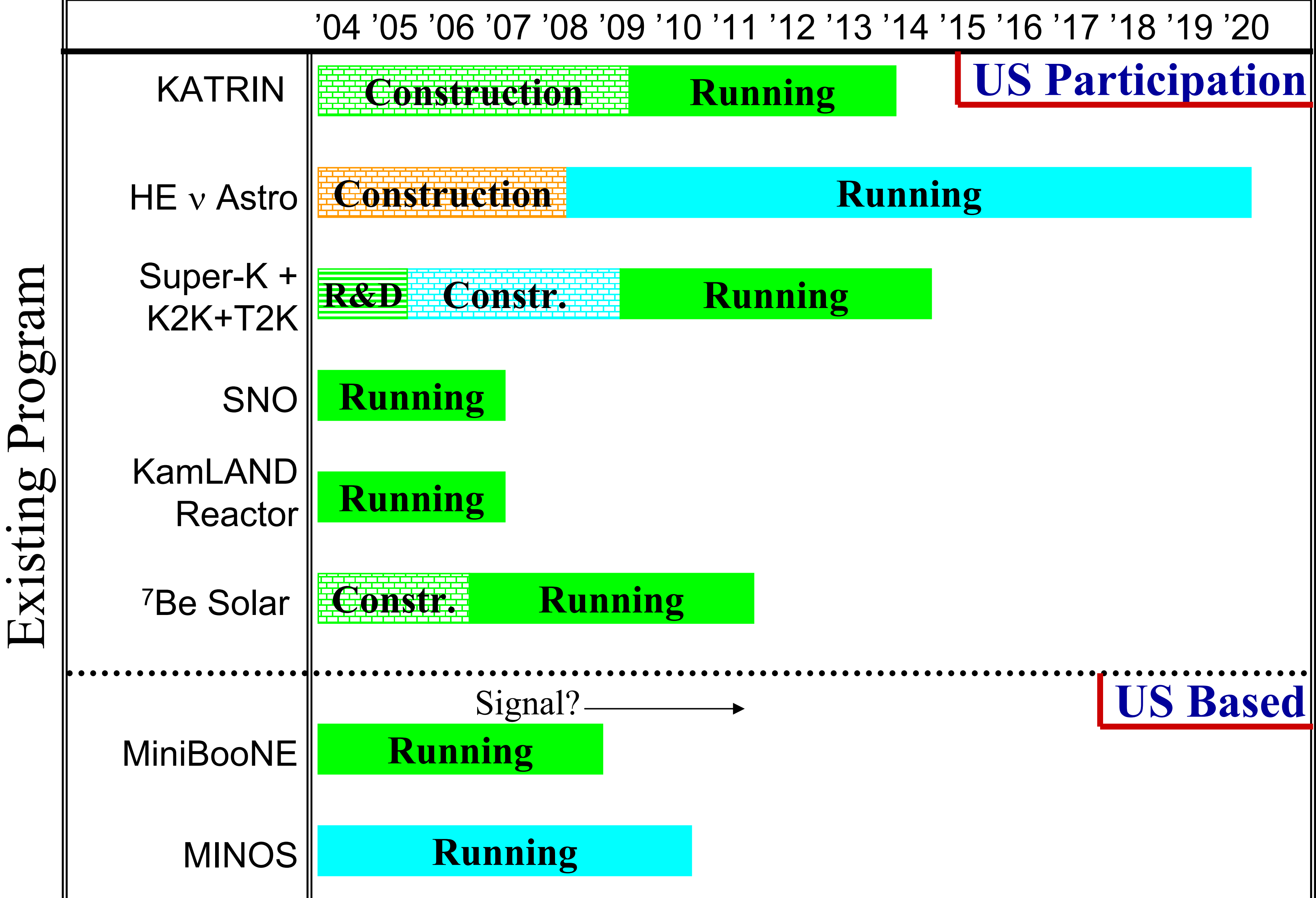
A neutrino factory (or beta beam) is the ultimate tool in neutrino physics. It may be the *only* way to study CP violation and other issues. Substantial neutrino factory R&D is needed if this facility is to be possible in the long term.

Conclusion

We have a very rich opportunity to do exciting physics.

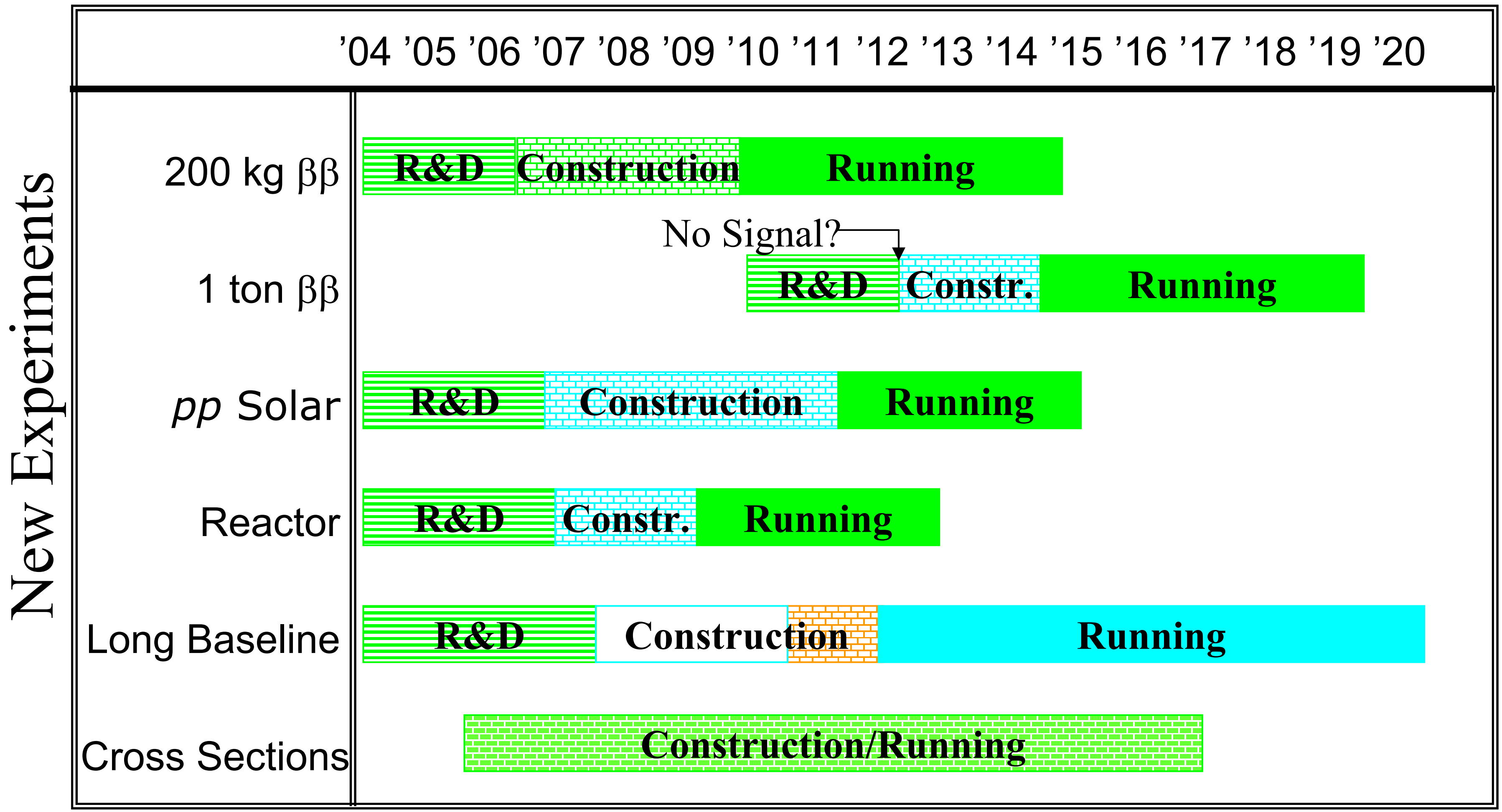
We hope our study, and its report, will help the community chart a sensible, fruitful, future course.

Backup Slides



Green < $10M/yr
Blue $10M - $40M/yr
Orange $40M -$100M/yr
Red > $100M/yr

New Experiments



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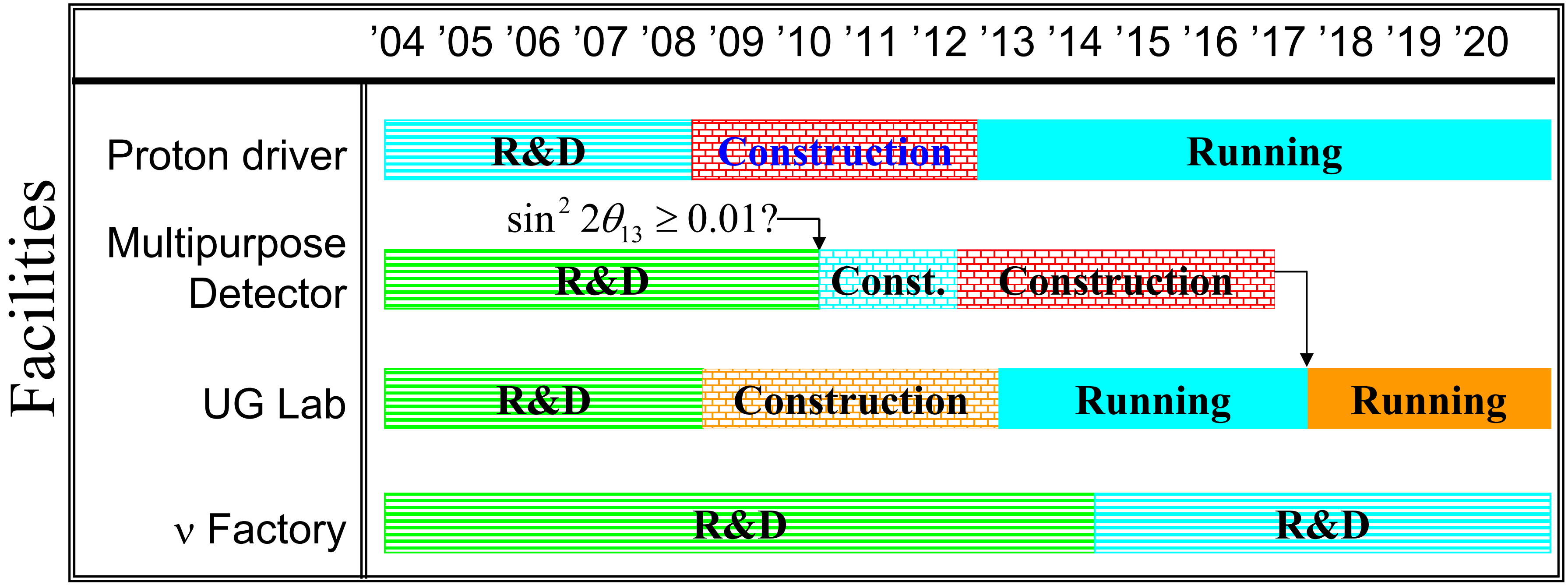
Facilities



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