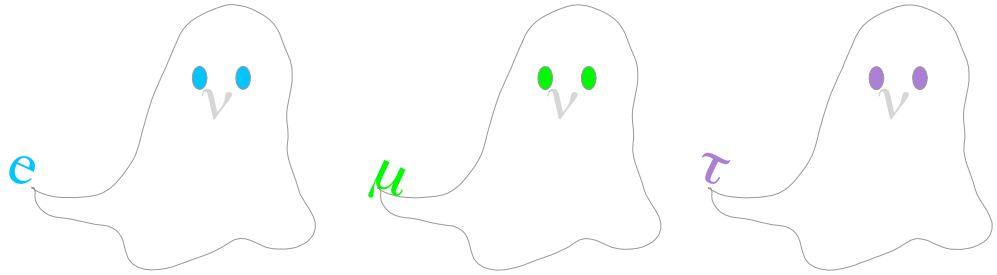
Neutrino Experiments

or...

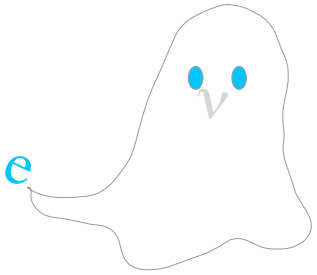


The Ghosts of Experiments
Past
Present
& Future

Janet Conrad,
Columbia University,
New Views Conference,
December 11, 2005

Neutrino Experiments

or...



The Ghosts of Experiments

Past

Present

& Future

Happy 75th Birthday Little Neutrino!

1930 Pauli Predicts the Neutrino

1933 Fermi's theory of weak interactions

1956 Reines & Cowan discover (anti)neutrinos

1968 Davis discovers the solar deficit

1980 2 distinct flavors identified

1989 Kamioka II confirms solar deficit

1990 LEP shows 3 active flavors

1998 SAGE and Gallex see the solar deficit

1998 Kamioka II and IMB see atmospheric neutrino anomaly

2002 Nobel prize for discovery of distinct flavors!

2002 Kamioka II and IMB see supernova neutrinos

2002 LSND sees possible indication of oscillation signal

2002 Nobel Prize for $\bar{\nu}$ discovery!

2002 Super K sees evidence of atmospheric neutrino oscillations

2002 Super K confirms solar deficit and "images" sun

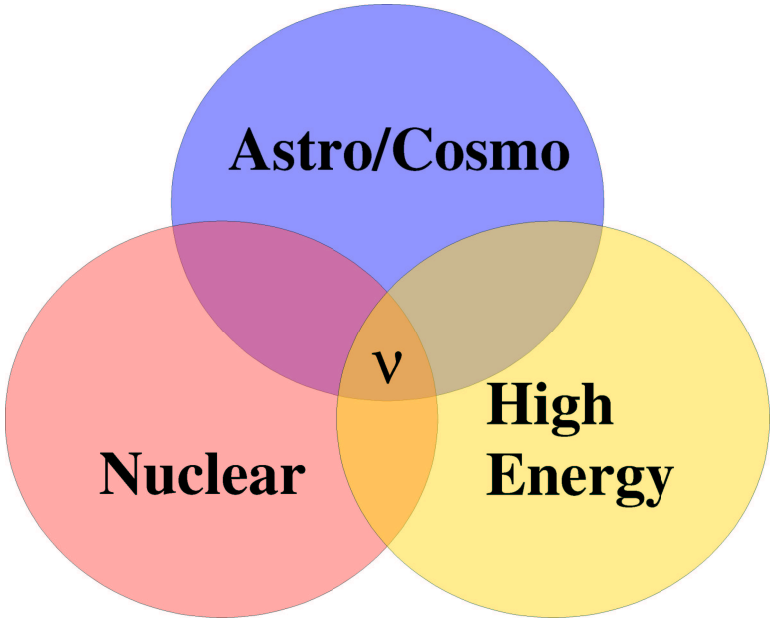
2002 SNO shows solar oscillation to active flavor

2002 Nobel Prize for neutrino astroparticle physics!

2003 KamLAND confirms solar oscillations

2004 K2K confirms atmospheric oscillations

1930 1955 1980 2005



K2K confirms atmospheric oscillations

KamLAND confirms solar oscillations

Nobel Prize for neutrino astroparticle physics!

SNO shows solar oscillation to active flavor

Super K confirms solar deficit and "images" sun

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Nobel prize for discovery of distinct flavors!

Kamioka II and IMB see supernova neutrinos

Kamioka II and IMB see atmospheric neutrino anomaly

SAGE and Gallex see the solar deficit

LEP shows 3 active flavors

Kamioka II confirms solar deficit

2 distinct flavors identified

Pauli Predicts the Neutrino

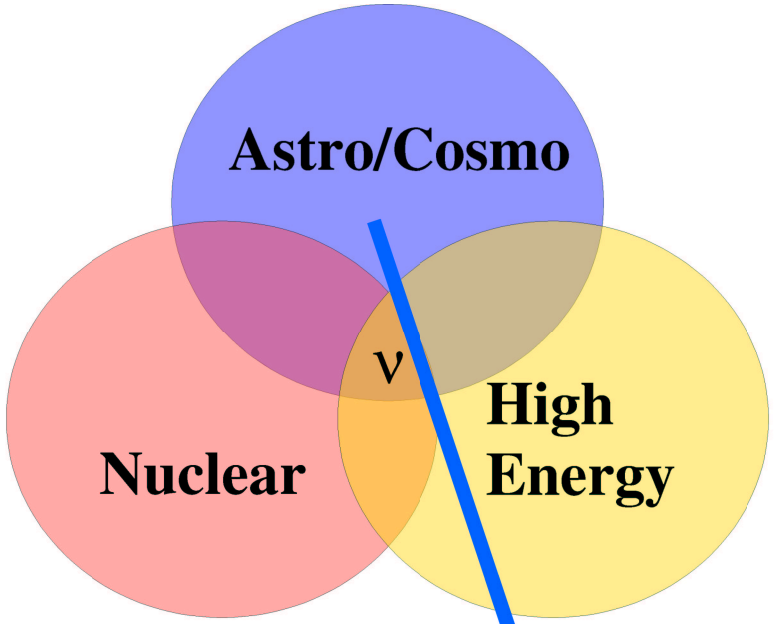
Fermi's theory of weak interactions

Reines & Cowan discover (anti)neutrinos

Davis discovers the solar deficit

1930 1955 1980 2005

Pick one....



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Nobel Prize for neutrino astroparticle physics!

KamLAND confirms solar oscillations

K2K confirms atmospheric oscillations

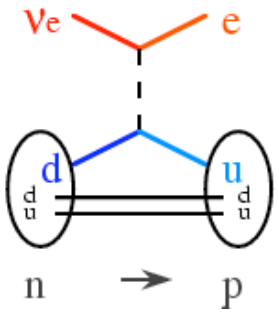
2005

What's so special about neutrinos from the sun?

- They are copiously produced
- They should be only ν_e
- (no other flavors, no antineutrinos)
- Their rate should be predictable...

John Bahcall,
1934 -- 2005

The neutrinos should be detectable...



Ray Davis

$$\frac{\phi_{\nu_e}(\text{Homestake})}{\phi_{\nu_e}(\text{Theory})} = 0.34 \pm 0.06$$

Something was apparently wrong...

- ☐ **A.** The flux calculation
- ☐ **B.** The measurement in the detector
- ☐ **C.** both
- ☐ **D.** neither

Very few people bet....

- ☐ **A.** The flux calculation
- ☐ **B.** The measurement in the detector
- ☐ **C.** both
- ☑ **D.** neither

Sudbury Neutrino Observatory (SNO) could measure the solar flux regardless of the neutrino species:

$$\nu_{sol}\, d \rightarrow \nu\, n\, p \;\Rightarrow \phi_{\nu_e} + \phi_{\nu_\mu} + \phi_{\nu_\tau}$$

SNO: $\phi_{\nu_e} + \phi_{\nu_\mu} + \phi_{\nu_\tau} = (4.94 \pm 0.21 \pm 0.36) \times 10^6/\text{cm}^2\text{sec}$

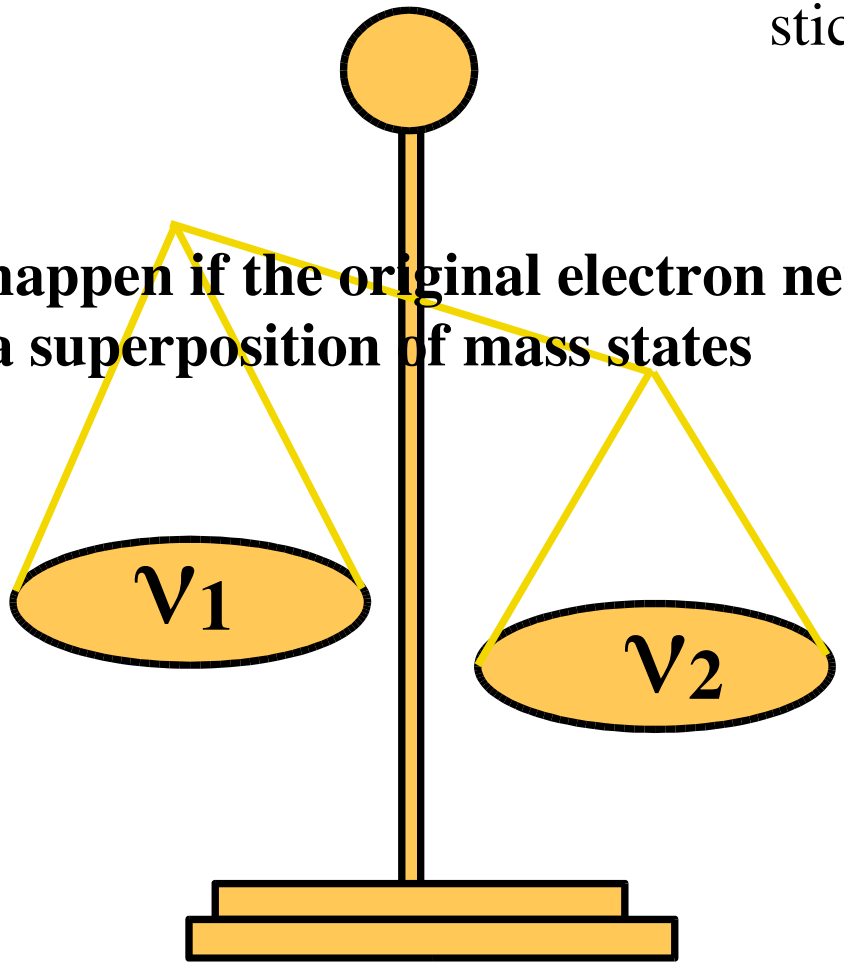
Theory*: $\phi_{\text{total}} = (5.69 \pm 0.91) \times 10^6/\text{cm}^2\text{sec}$

*Bahcall, Basu, Serenelli

The total flux is there! It is just that they are not all ν_e!

As neutrinos travel through the sun, their flavor evolves in the high-density electron environment...
And <u>the mixing is really large</u>!

Bahcall was right to stick to his guns!



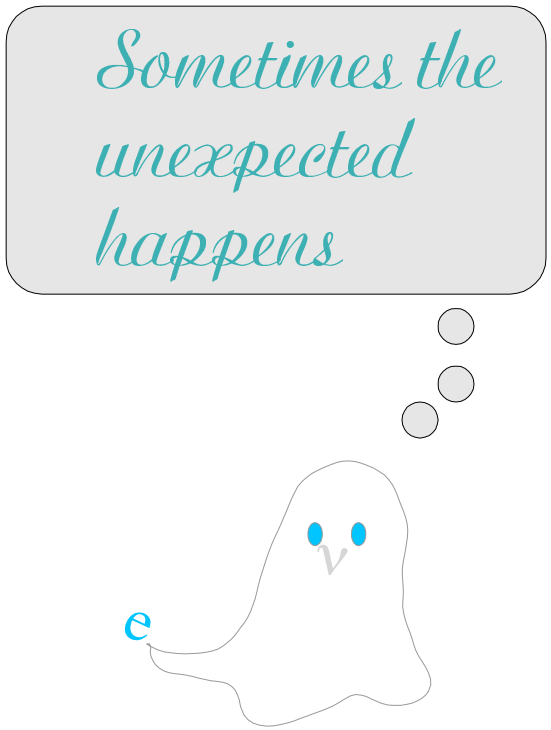
This can only happen if the original electron neutrino was a superposition of mass states

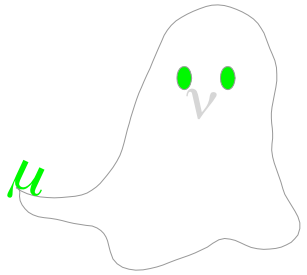
What we know now

Prejudices of experiments past...

- Neutrinos don't have mass. Wrong
- But if they did, then the natural scale is $\Delta m^2 \sim 10 \rightarrow 100\ eV^2$ Wrong

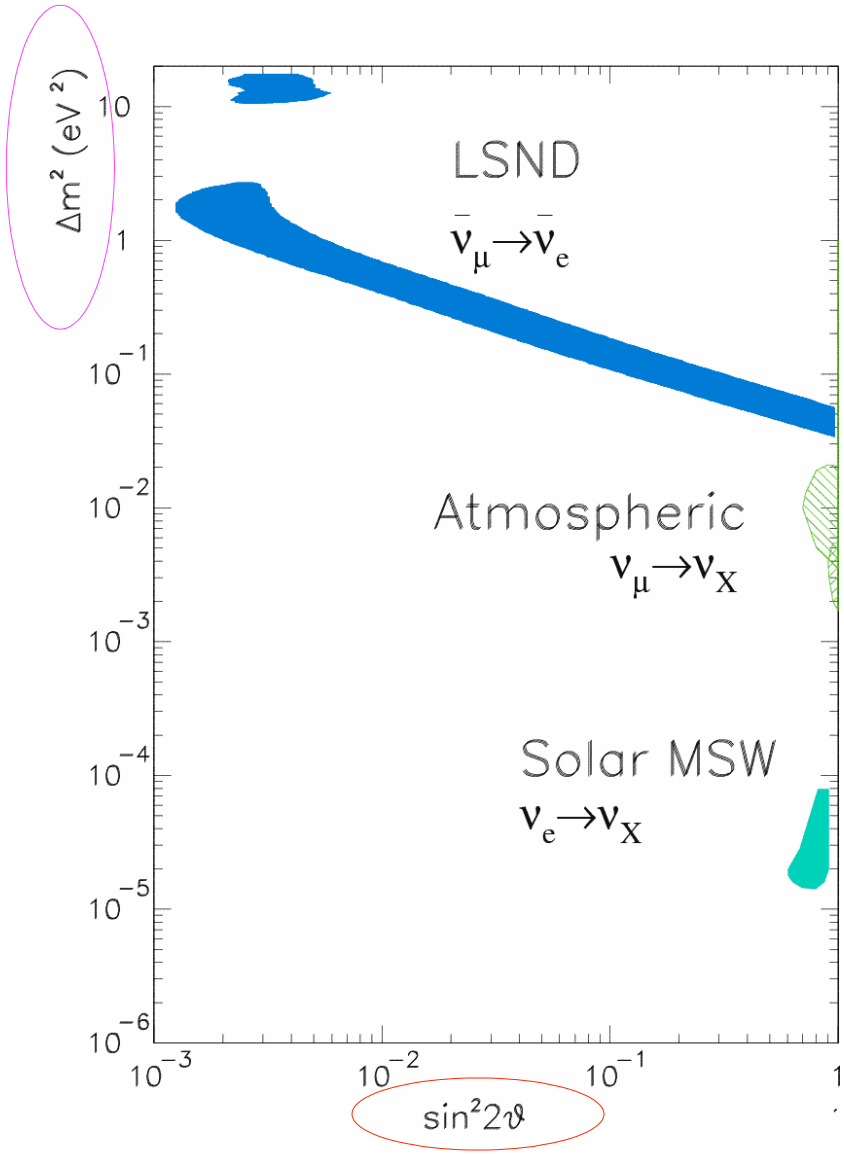
  as is needed to explain dark matter
- Oscillation mixing angles must be small like the quark mixing angles Wrong
- Solar neutrino oscillations must have a small mixing angle solution because we can make that fit with GUTs so nicely Wrong
- Similarly, the atmospheric neutrino deficit must be due to an experimental problem because large mixing doesn't fit our view. Wrong





(Some) *Experiments Present*

This is the status of our knowledge of neutrino oscillations...



$$P_{osc} = \sin^2 2\theta \sin^2(1.27\Delta m^2 L/E)$$

LSND

Kamioka, IMB,
Super K, Soudan II
Macro
Now being tested by Minos!

Homestake, Sage,
Gallex, Super-K
SNO, Kamland

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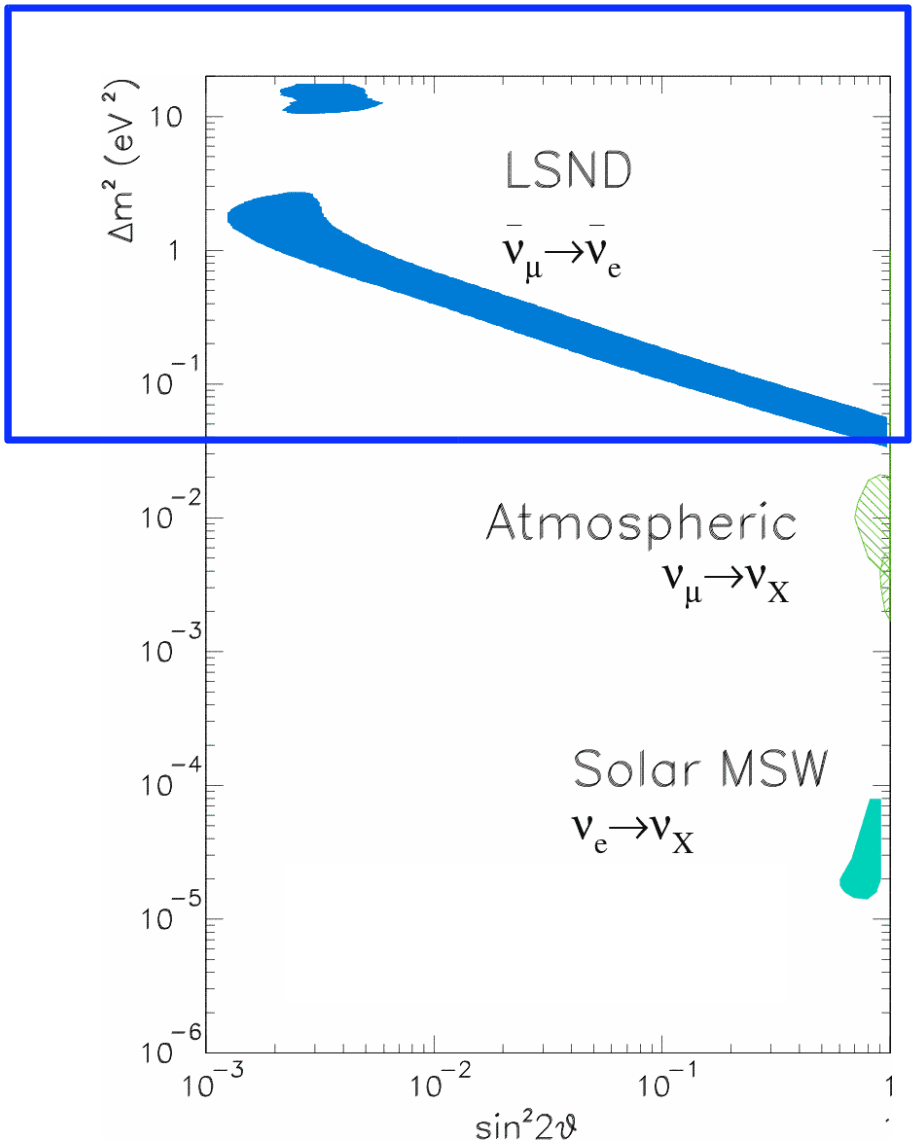

$$P_{osc} = \sin^2 2\theta \sin^2(1.27\Delta m^2 L/E)$$

LSND **WHAT'S THAT???**

Kamioka, IMB,
Super K, Soudan II
Macro, K2K
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Homestake, Sage,
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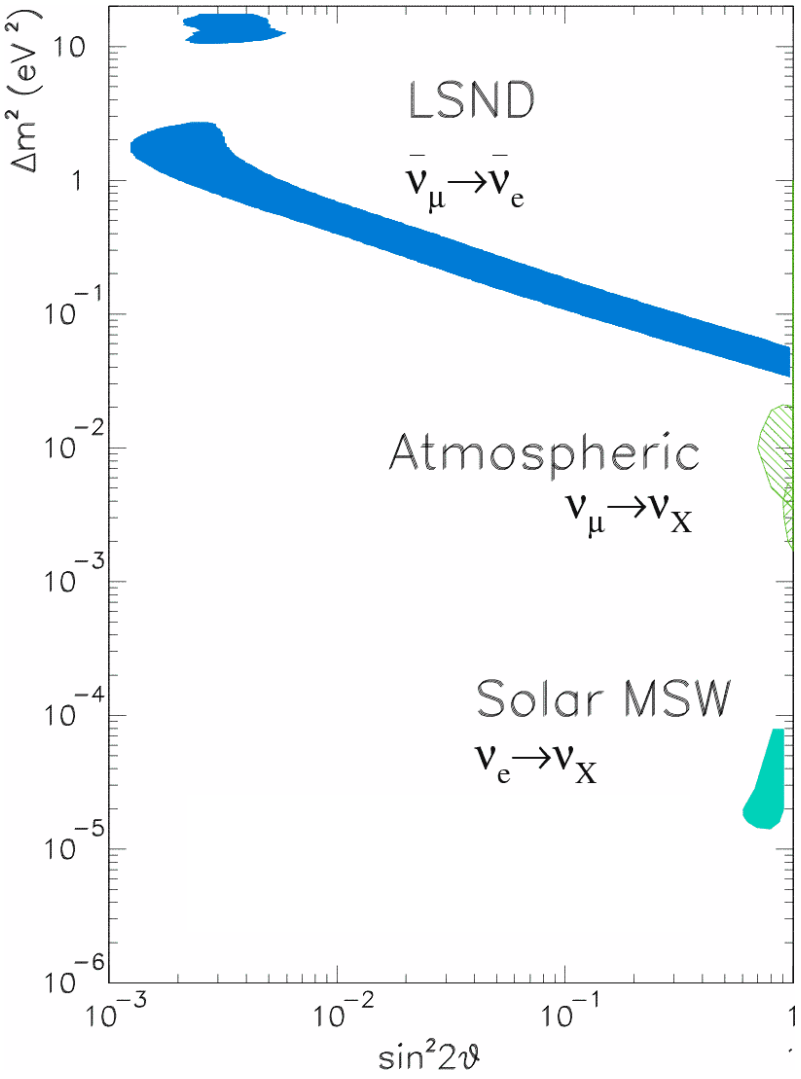
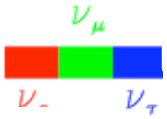
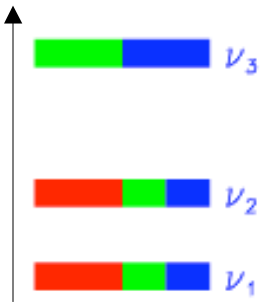
SNO, Kamland



This is a BIG problem:

In SM there are only 3 neutrinos





increasing $(\text{mass})^2$

$\Delta m_{23}^2 = m_2^2 - m_3^2$

$\Delta m_{12}^2 = m_1^2 - m_2^2$

And ... $\Delta m_{13}^2 = \Delta m_{12}^2 + \Delta m_{23}^2$

But ... $1 \neq 0.003 + 0.00005$

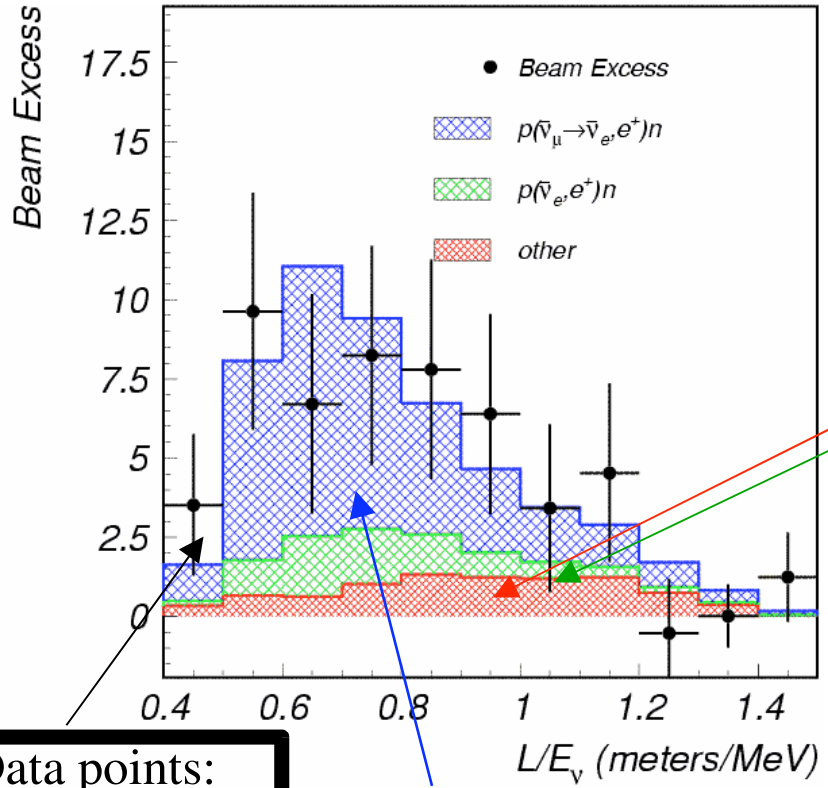
LSND | atmos-pheric | solar

A little simplistic
(you should really apply the full 3 neutrino formalism)
but you get the point

LSND

- neutrinos from a stopped muon beam (~30 MeV)
- liquid scintillator detector

A 4σ excess of electron-like events in a muon-neutrino beam...



Size of the Beam-related backgrounds

Data points: Excess after Beam-off subtraction

Expectation for oscillations (Δm^2=0.24 eV^2)

Something must be wrong...

- ☐ **A.** The flux calculation
- ☐ **B.** The measurement in the detector
- ☐ **C.** both
- ☐ **D.** neither

And there are a few people willing to ask what if the answer is....

- ☐ **A.** The flux calculation
- ☐ **B.** The measurement in the detector
- ☐ **C.** both
- ☑ **D.** neither

Sterile Neutrinos
e.g., Sorel, et al, hep-ph/0305255

Mass Varying Neutrinos
e.g., Kaplan, et al, hep-ph/0401099

Lorentz Invariance Violation
e.g., Kostelecky, et al, hep-ph/0406255

Neutrinos & Extra Dimensions
e.g., Pas, et al, hep-ph/0504096

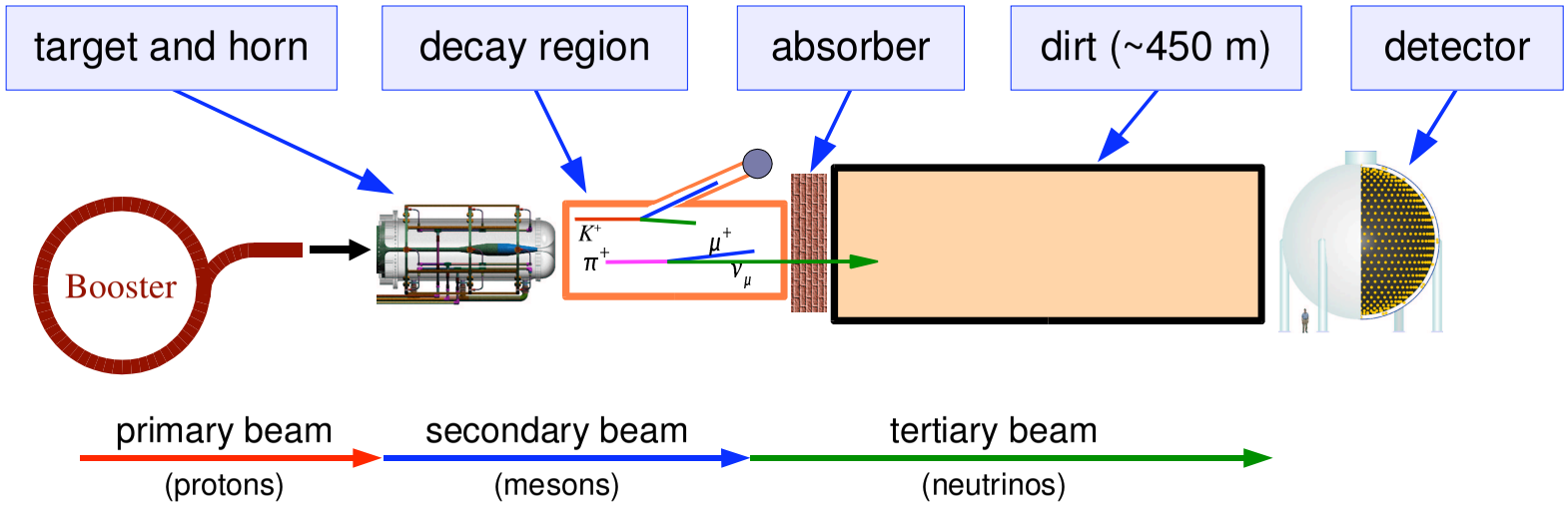
String theories implying Light Dirac Neutrinos
e.g., Giedt, et al, hep-ph/0502032

But really it is an experimental question...

MiniBooNE:

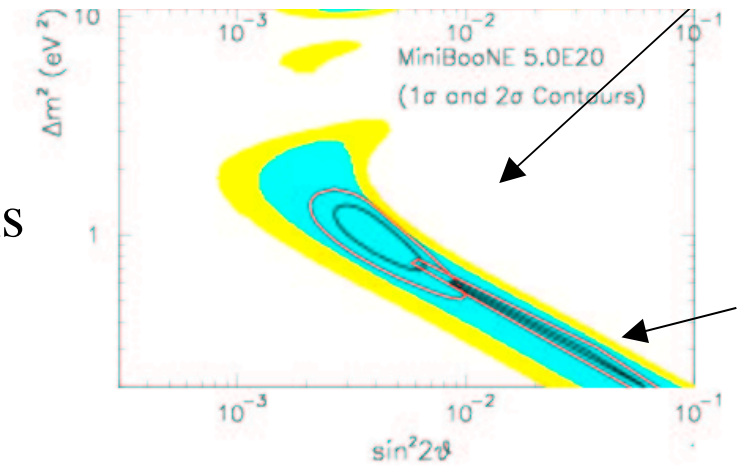
$$P(\nu_\mu \rightarrow \nu_e) = \sin^2 2\theta \, \sin^2(1.27 \Delta m^2 L/E)$$

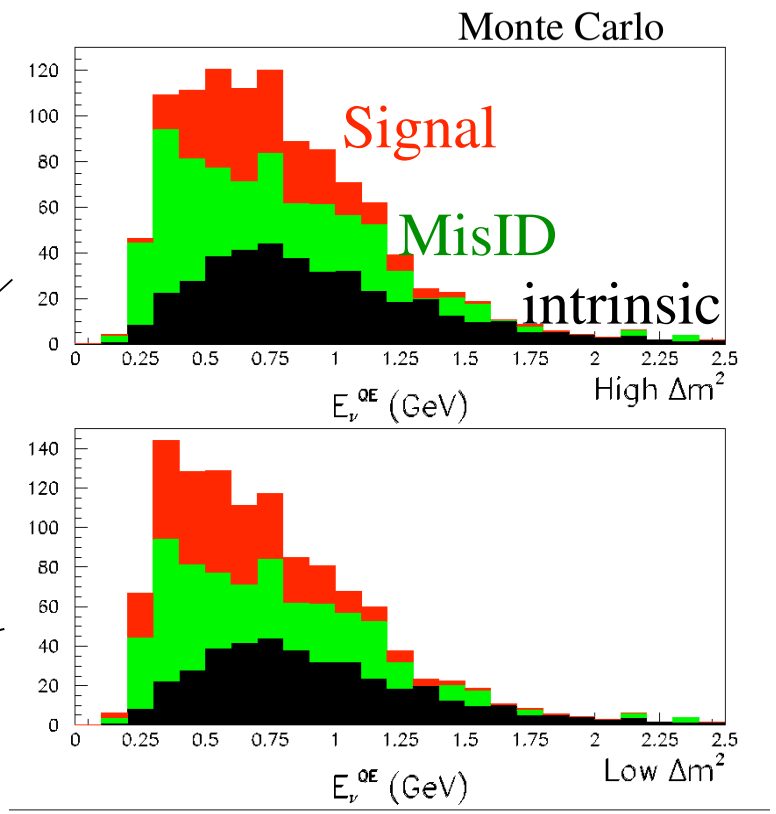
Keep L/E same while changing systematics



What would a signal look like?

Fermilab delivered 5E20 protons on target.





If we see a signal, then some new physics is going on...
Like the presence of sterile neutrinos...

An asset for astrophysics?

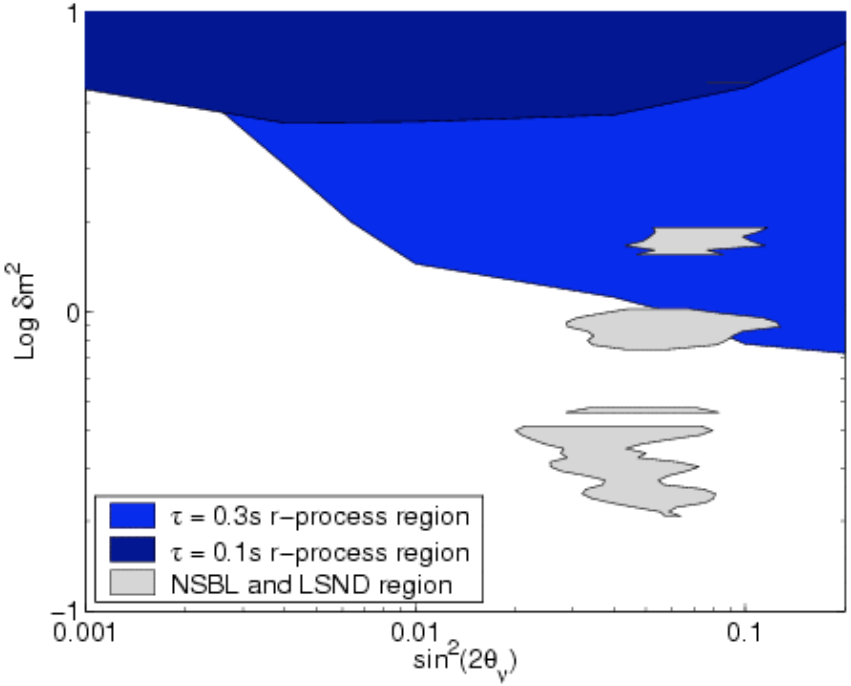
The R-process needs a large neutron imbalance

How do you create a very large neutron-imbalance?
First create an anti-electron neutrino rich environment.

$$\bar{\nu}_e + p \rightleftharpoons e^+ + n,\ \nu_e + n \rightleftharpoons e^- + p$$

... which works if the conditions are right (high electron density, right oscillation parameters) to produce a $\nu_e \rightarrow \nu_s$ resonance

Allowed ranges for oscillation to enable sufficient U production



Beun, Surman, McLaughlin & Hix, preliminary

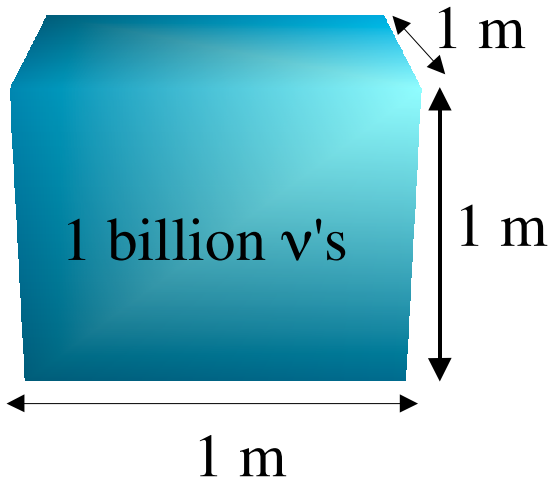
Any extra neutrinos will affect cosmology

Standard Cosmology Assumes

- Only the 3 active neutrino flavors
- Zero neutrino mass
- No neutrino mixings (no oscillations)
- Simple Fermi-Dirac energy distribution (the neutrinos are "thermalized")

number of relic particles of each species testable via:

- expansion rate
- large scale structure



- A small asymmetry in n/p ratio

That will affect:

- *The D/H ratio*
- *The He abundance*
- *The ^{7}Li abundance*

Relic sterile neutrinos affect these predictions!

"New constraints on the cosmological background of relativistic particles," S. Hannestad, astro-ph/0510582

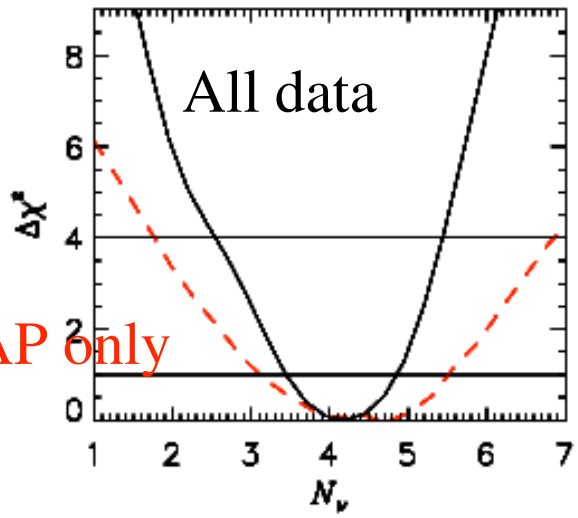
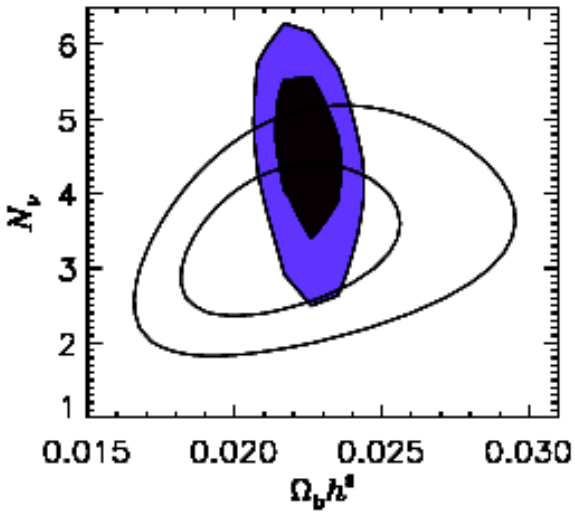


Figure 1. $\Delta\chi^2$ values as a function of N_ν for various data sets. The full line includes all available data, and the dashed line is for WMAP and LSS data only.



BBN

Figure 2. The 68% (dark) and 95% (light) likelihood contours for $\Omega_b h^2$ and N_ν for all available data. The other contours are 68% and 95% regions for BBN, assuming the ^{4}He and D values given in [39].

Cosmology is reaching the point where it might identify new "particle physics" first!

$$N_\nu = 4.2\ ^{+1.2}_{-1.7}$$

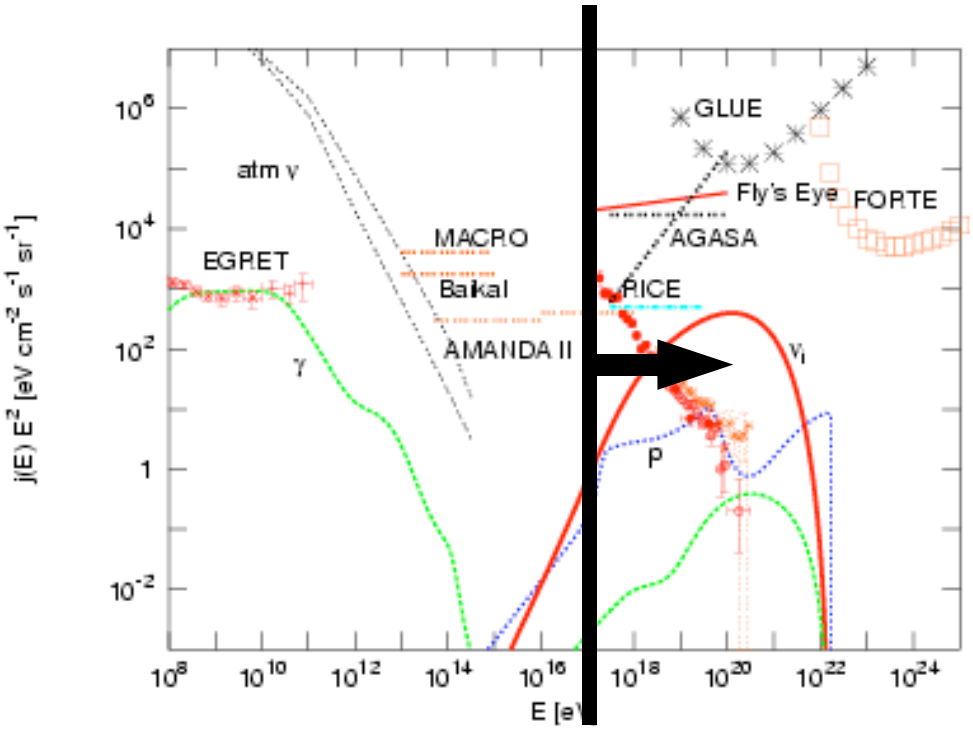
@95% CL

UHE Neutrino Experiments
can definitely give traditional, accelerator-based experiments a run for their money

Experiments that can detect $E_\nu > 10^{17}$ eV are looking beyong LHC energies!

Search for enhancements of $\sigma_{\nu N}$ beyond SM probing...

- extra dimensions,
- black hole production,
- strongly interacting neutrinos,
- ... & *more exotic stuff!*

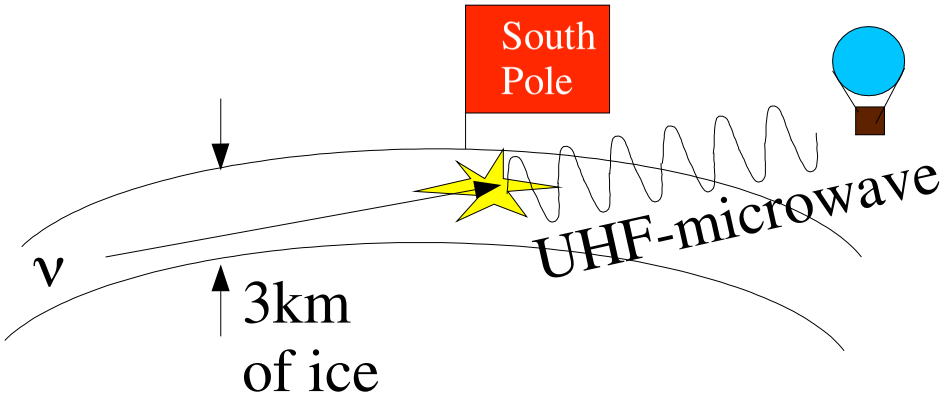


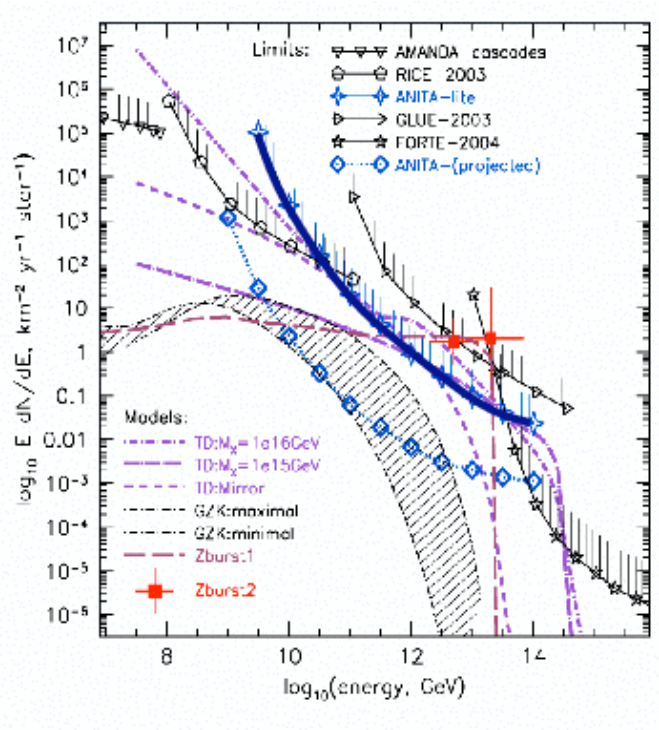
Even a small experiment can do a lot!

Anita-lite has already ruled out "Zburst Models"

ultra-GZK ν + CνB → Z → UHECRs

Kusenko & Weiler, hep-ph/0106071





Prototype for the Anita Experiment, with 18.4 days of flight time

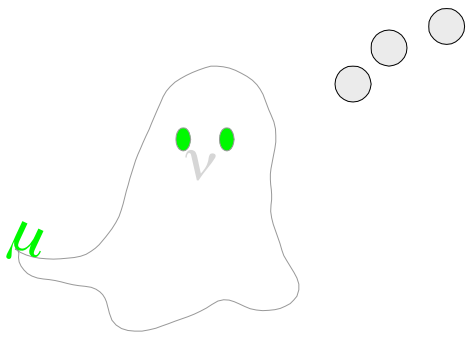
These experiments show that
We are in the process of a change in approach

Last century (i.e. 5 years ago!!!)

Understanding of Particles $\rightarrow \rightarrow \rightarrow$ Understanding of the Universe

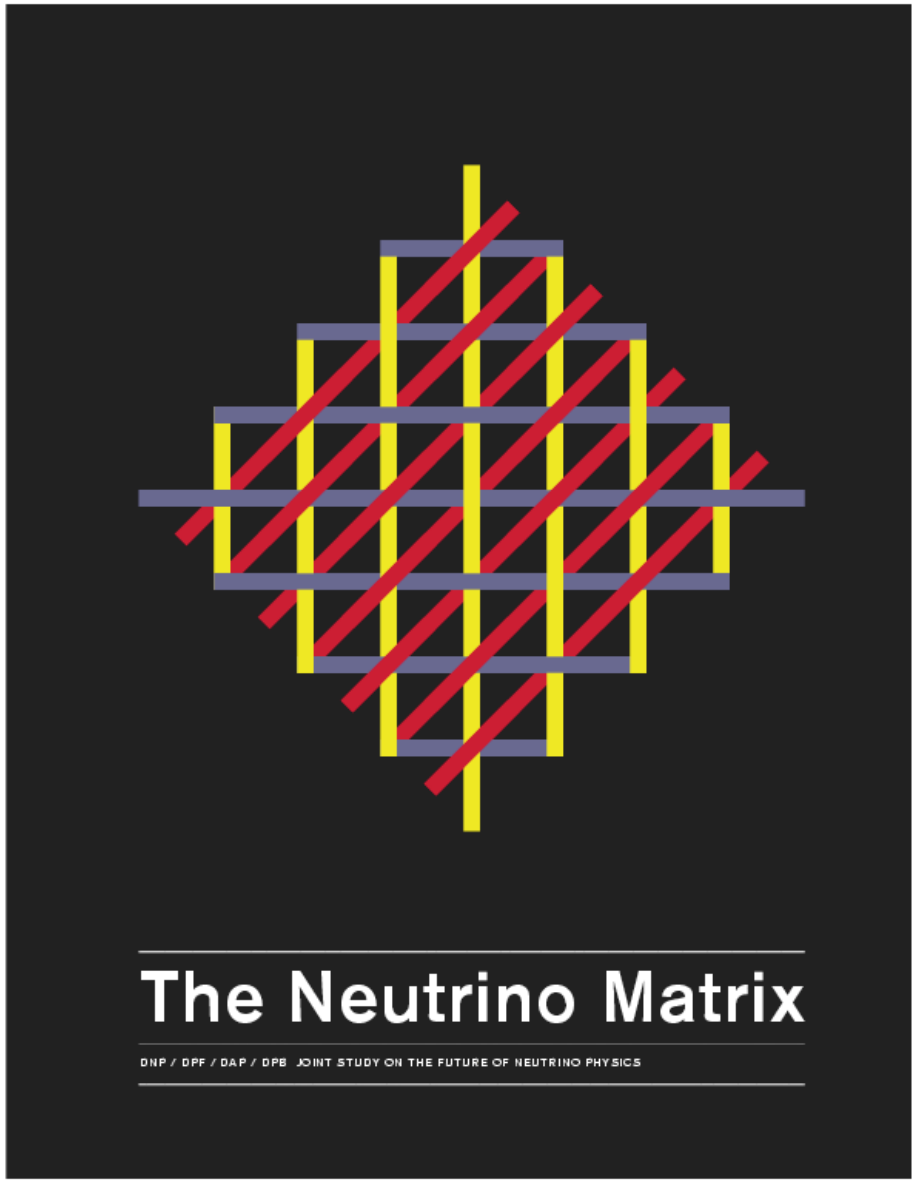
Today

Understanding of Particles $\leftarrow \leftrightarrow \rightarrow$ Understanding of the Universe



A Lesson from David Schramm

(Some) *Experiments Future*



The APS-sponsored
Multidivisional study on...

The Future of Neutrino Physics

Working Groups:

Solar & Atmospheric Neutrinos
Reactor Neutrinos
Super Beams
Neutrino Factory & Beta Beams
Neutrinoless Double Beta Decay
Astrophysics & Cosmology

http://www.aps.org/neutrino

The Big Questions:

1. What is the role of neutrinos in shaping nature?

2. Are neutrinos the key to understanding
   the matter-antimatter asymmetry?

3. What can neutrinos disclose about the deep interiors of
   astrophysical objects, and the mysterious sources
   of ultra high energy cosmic rays?

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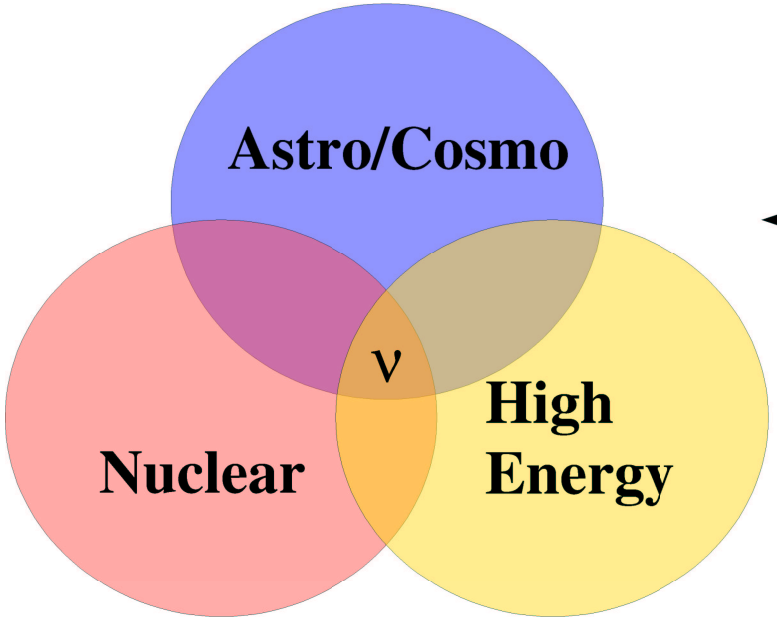
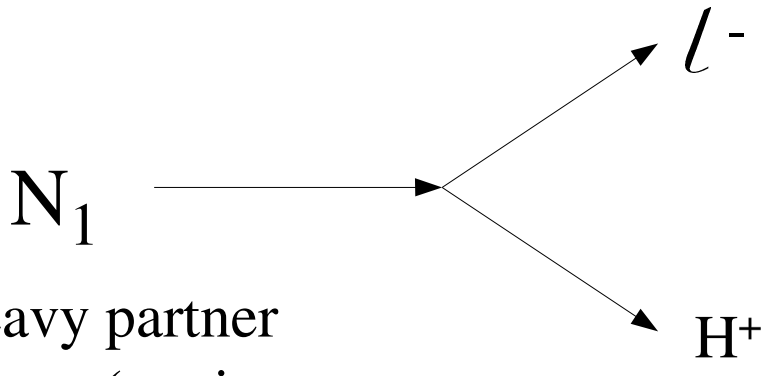
A nice example to again emphasize the overlap!



The idea:

Before the electroweak phase transition...

These are massless:

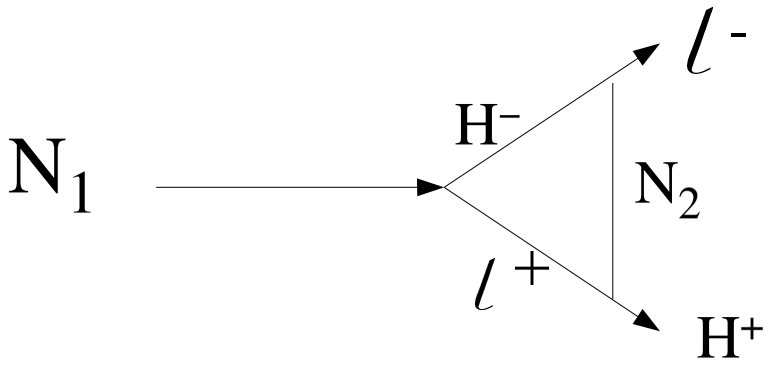


a heavy partner to the ν (getting mass from the Majorana term)

Interference between these two types of diagrams can lead to a different rate of decay to particles than antiparticles

→ **CP Violation**

"Leptogenesis"



Today,
we cannot study the N's
but we can study the ν's...

Putting CP violation into the light neutrino Mixing Matrix:

The CP Violation Parameter

$$U = \begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta} & s_{23}c_{13} \\ s_{12}s_{23} - c_{12}c_{23}s_{13}e^{i\delta} & -c_{12}s_{23} - s_{12}c_{23}s_{13}e^{i\delta} & c_{23}c_{13} \end{pmatrix}$$

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

From Atmospheric and Long Baseline Disappearance Measurements

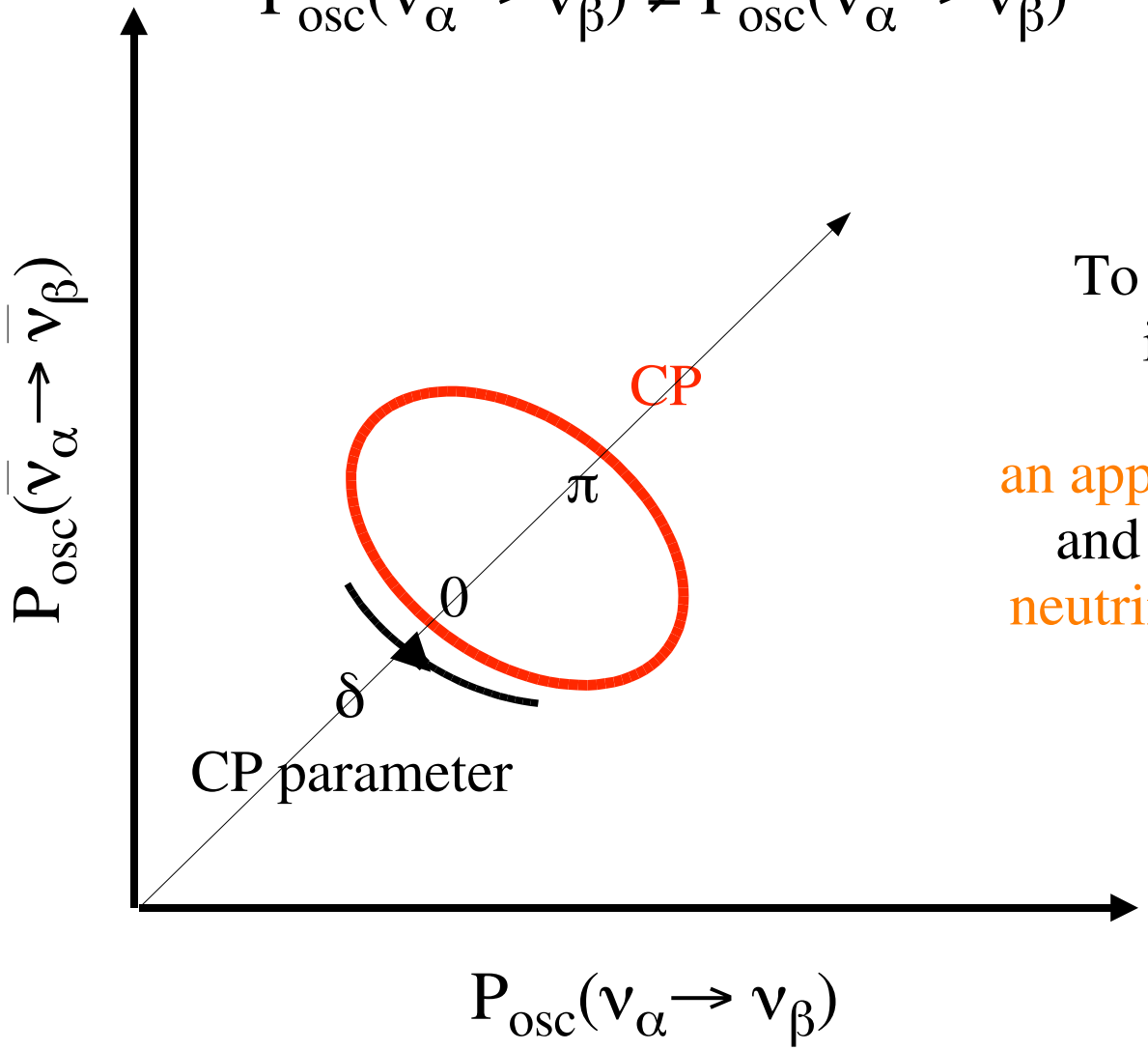
From Reactor Disappearance Measurements

From Long Baseline Appearance Measurements

From Solar Neutrino Measurements

CP violation
& light neutrinos

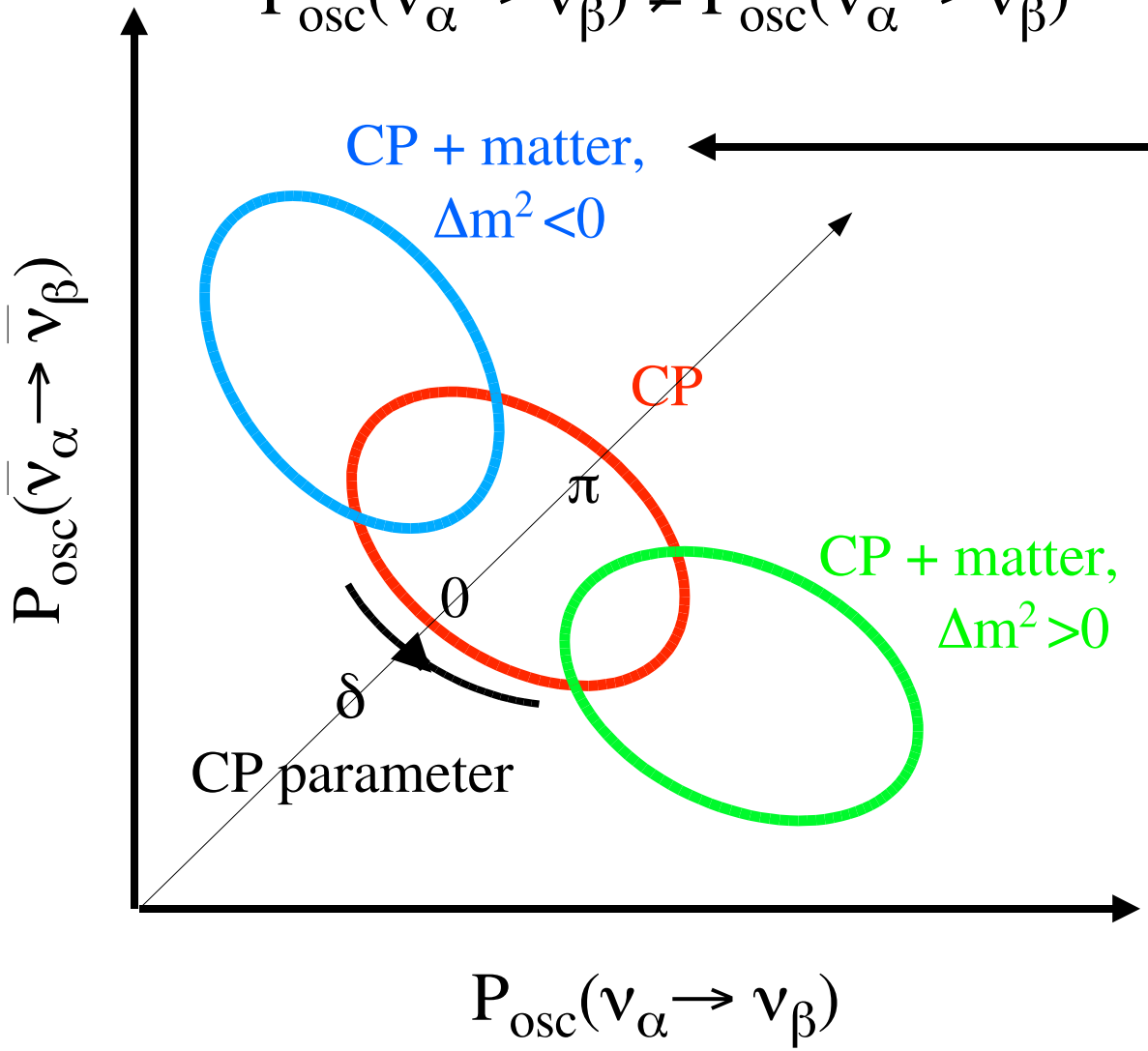
$$P_{osc}(\nu_\alpha \rightarrow \nu_\beta) \neq P_{osc}(\bar{\nu}_\alpha \rightarrow \bar{\nu}_\beta)$$

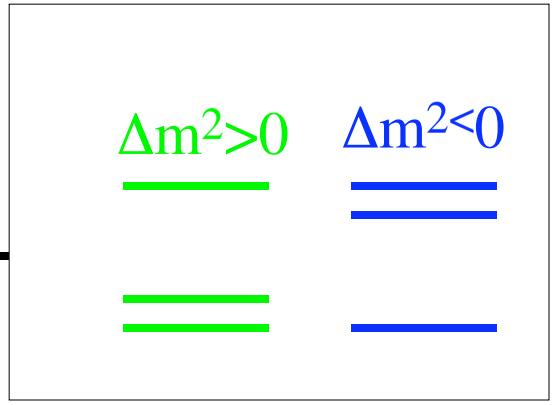


To see CP violation
in oscillations
you need
an appearance experiment
and results from both
neutrino and antineutrino
running

But matter effects mimic
CP Violation!

$$P_{osc}(\nu_\alpha \rightarrow \nu_\beta) \neq P_{osc}(\bar{\nu}_\alpha \rightarrow \bar{\nu}_\beta)$$





Matter effects are
only an issue
for baselines >500 km

Personal opinion:
CP violation is hard.
Avoid matter effects!

Why is measuring CP violation hard?

The effect you are looking for is small

and

$\nu_\mu \rightarrow \nu_e$ is complicated by many poorly known parameters

$$P_{long-baseline} \simeq \sin^2 2\theta_{13} \sin^2 \theta_{23} \sin^2 \Delta$$
$$\mp \alpha \sin 2\theta_{13} \sin \delta_{CP} \cos \theta_{13} \sin 2\theta_{12} \sin 2\theta_{23} \sin^3 \Delta$$
$$+ \alpha \sin 2\theta_{13} \cos \delta_{CP} \cos \theta_{13} \sin 2\theta_{12} \sin 2\theta_{23} \cos \Delta \sin^2 \Delta$$
$$+ \alpha^2 \cos^2 \theta_{23} \sin^2 2\theta_{12} \sin^2 \Delta$$

θ_{13} -- not yet measured ($\sin^2 2\theta_{13}<0.2$ @90% CL from Chooz)

θ_{23} -- Minos will measure $d(\sin^2 2\theta_{23})\sim 5\%$ (6 years)

T2K will measure $d(\sin^2 2\theta_{23})\sim 1\%$ (4+5 years)

but you cannot tell if $\theta_{23}>45°$ or $<45°$!!! -- it's degenerate

and matter effects only make this worse!...

Why do we need a reactor experiment in order to search for CP violation?

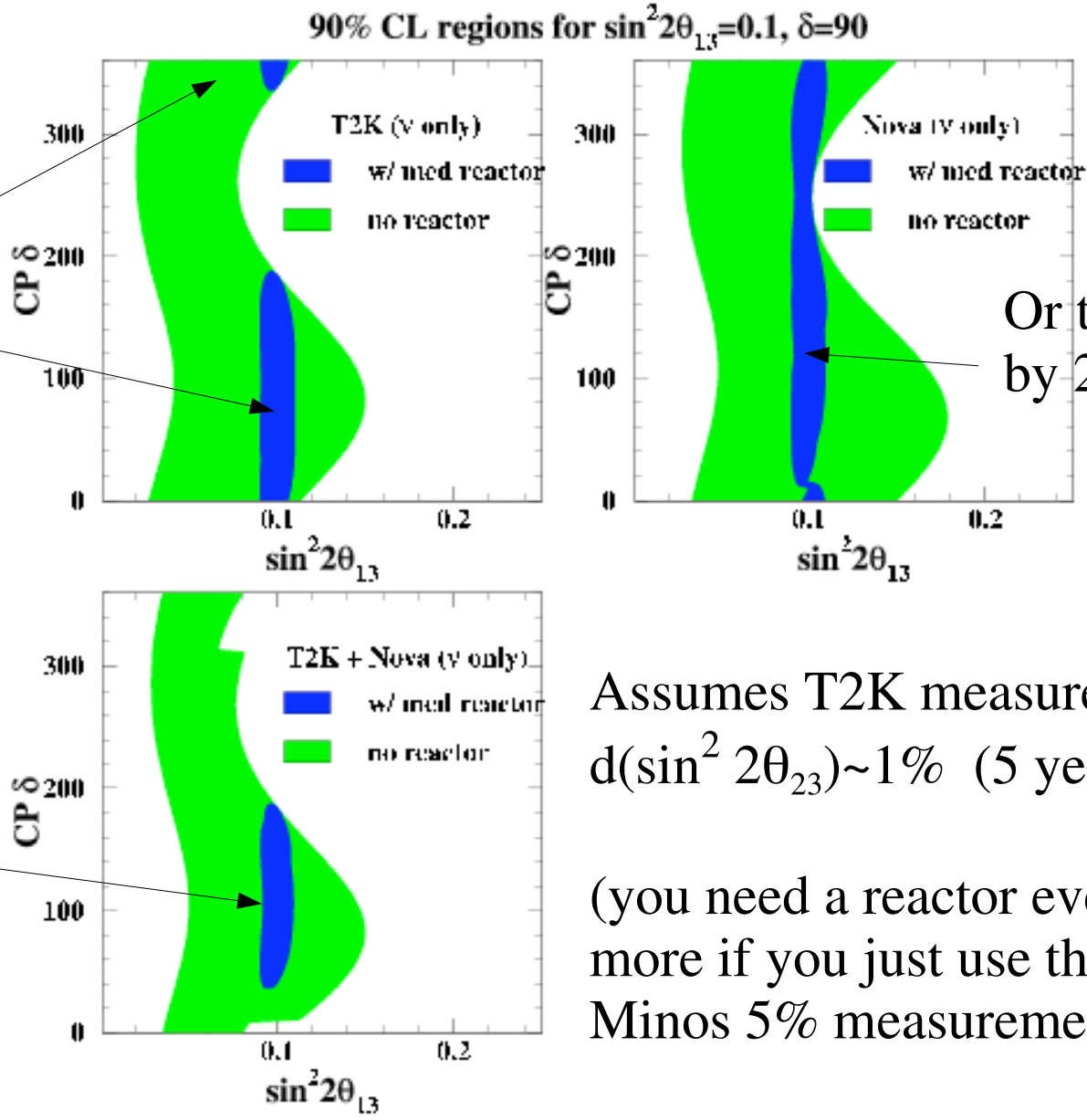
McConnel-Mahn & Shaevitz, hep-ex/0409028

$$P_{reactor} \simeq \sin^2 2\theta_{13} \sin^2 \Delta_{31} + \alpha^2 \Delta_{31}^2 \cos^4 \theta_{13} \sin^2 2\theta_{12},$$

θ_{13} -- Can be measured at the 3σ level for $\sin^2 2\theta_{13} > 0.01$

θ_{23} -- the correct choice of the 2 degenerate solutions can be picked out of the long baseline running once θ_{13} is known

And once you have a clean slice in θ_{13} , you have the chance to nail down the CP violation parameter...



You could have just these regions by 2015

If θ_{13} is too small, the long-baseline experiments have no sensitivity)

Or this region by 2020

Or this by 2020 with both LB experiments....

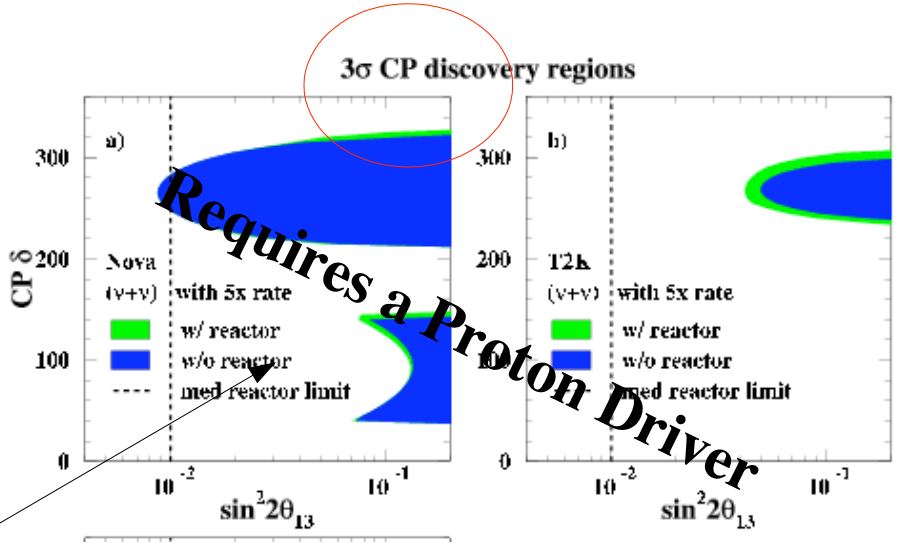
Assumes T2K measures $d(\sin^2 2\theta_{23}) \sim 1\%$ (5 years)

(you need a reactor even more if you just use the Minos 5% measurement)

If θ_{13} is large enough, the reactor slice allows non-zero CP to be distinguished.

That was 90% CL...

What about discovery?



Requires a Proton Driver

You can have this in 2030 (100th Birthday of the neutrino!) **if** nature is good to you...

Reactor experiment tells you whether nature is here...

or here...

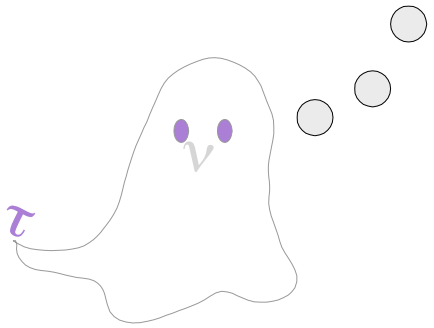
...Before you invest in the CP Search Experiment

Searching for CP violation is...

... hard

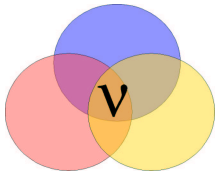
... worth doing!

... worth doing in a thoughtful and organized manner!



This was just one facet of the noted needs from the astro/cosmo group
Also explicitly recommended....

- Development of techniques for detecting atmospheric neutrinos in the $>10^{15}$ eV range
- Measurements of neutrino-nucleus cross sections in the few 10's of MeV range
- Support for long-term running of existing neutrino detectors for supernova neutrino detection
- Further establishment of a wide range of experimental methods to precisely measure the CνB
- Timely construction of a suite of experiments pursuing galactic and extra-galactic neutrino sources.
- Precision measurement of low-energy solar neutrino rates
- Development of techniques for dark matter detection in concert with these neutrino experiments.



= *The Future!*

and lastly,
'Tis the season to wish..

Happy ν year,

Everyone!