Agenda for Meeting

- Neutrino Oscillations Overview - Mike Shaevitz (20 min)
- Offaxis Experiments: Capabilities and Comparisons - Mark Messier (20 min)
- NuMI Offaxis Beam and Detector Performance Requirements - Stan Wojcicki (20 min)
- Detector Technologies - Adam Para
- Plans, Schedules, and Requests - Ed Blucher

Neutrino Oscillations

Near and Far Term Prospective

Michael Shaevitz
Columbia University

- Current Status and Present Program
  - Solar: Kamland, Super-K, SNO, Borexino
  - Atmospheric: K2K, MINOS
  - LSND: MiniBooNE

- Near Term Prospects (this decade) and Possibilities
  - Offaxis experiments: JHF (Japan), NuMI Offaxis
  - Reactor Experiments

- Farther Term Prospects and Possibilities
  - Superbeam experiments (to NUSEL with proton decay?)
  - Neutrino Factory

Neutrino Oscillations

Difficult to probe small neutrino masses (<1 eV) $\Rightarrow$ *Use neutrino oscillations*

- Neutrinos have (different) mass

$$\Rightarrow \Delta m_{12}^2 = m_1^2 - m_2^2,\ \Delta m_{23}^2 = m_2^2 - m_3^2$$

- The ***Weak Eigenstates*** are a mixture of ***Mass Eigenstates***

Experimentally, need to measure the mass differences

$$\Delta m_{12}^2 = \Delta m_{Solar}^2 \approx 7\times 10^{-5}\ \text{eV}^2$$

$$\Delta m_{23}^2 = \Delta m_{Atmospheric}^2 \approx 2.5\times 10^{-3}\ \text{eV}^2$$

and the mixing parameters

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix} = \begin{pmatrix} \sim 0.7 & \sim 0.7 & \mathbf{\sin\theta_{13} e^{i\delta}\ ?} \\ \sim -0.5 & \sim 0.5 & \sim 0.7 \\ \sim 0.5 & \sim -0.5 & \sim 0.7 \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

Key measurements needed : Δm_{23}^2 including sign, $\sin\theta_{13}$, and δ (CP violation)

Why Are Neutrino Oscillation Measurements Important?

- Give a window on physics at high mass scales: unification, physics of flavor, and extra dimensions
  - Why are the neutrino masses so small?
  - Are there additional "sterile" neutrinos?
  - Why are their mixings so large?
  - Is there a connection between the lepton and baryon sector?
  - Is there CP violation, T violation, or CPT violation in the leptons?

- Neutrino masses and mixing are important to understanding astrophysical models of:
  - Supernovae, galactic structure formation, etc.

Should remember that neutrino oscillations only measure mass differences (m_1^2-m_2^2)

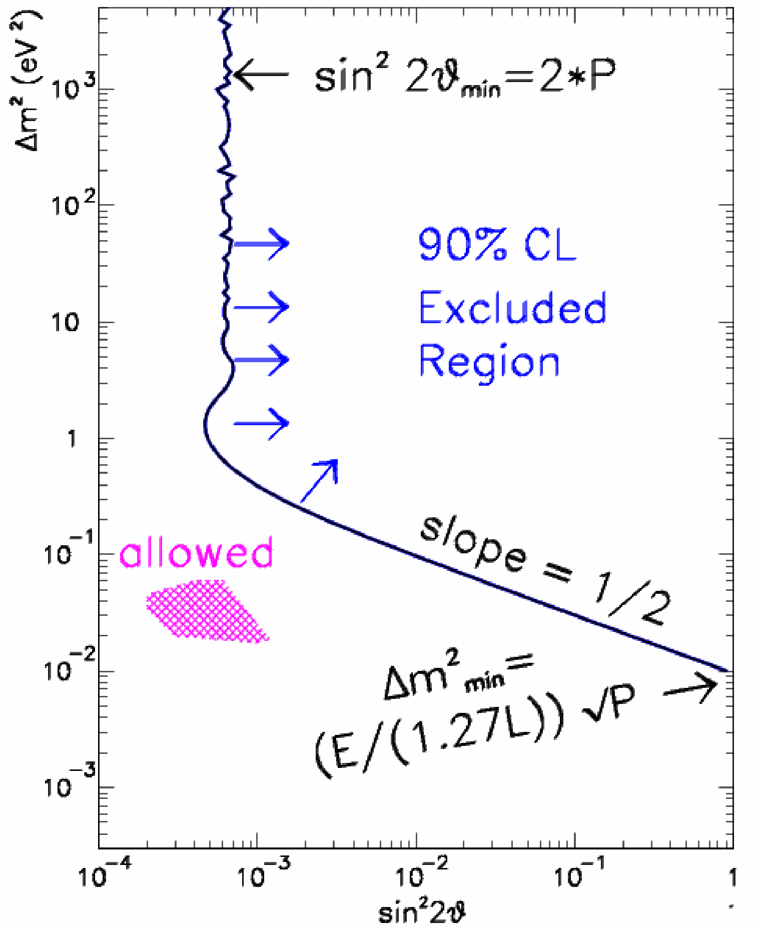
- ***Need tritium decay (KATRIN) or double beta decay to measure one mass $\Rightarrow$ Are ν masses hierarchical or degenerate?***

Method to Measure Oscillation Parameters

- Neutrino oscillation method: start with a pure ν_μ beam at L=0, then look for a ν_e component as it travels a distance L.

The Probability for Oscillations...

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



- If you see an oscillation signal with

  $P_{osc} = P \pm \delta P$

  then carve out an **allowed region** in (Δm^2,$\sin^2 2\theta$) plane.

- If you see no signal and limit oscillation with

  $P_{osc} < P$ @ 90% CL

  then carve out an **excluded region** in the (Δm^2,$\sin^2 2\theta$) plane.

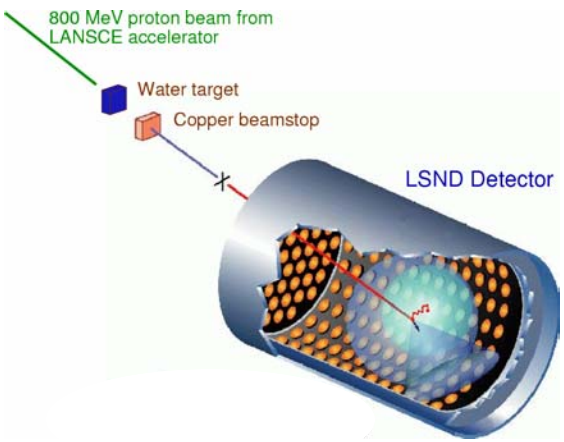
Current Situation: Three Experimental Indications for Neutrino Oscillations

LSND Experiment

L = 30m

E = ~40 MeV

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



Δm^2 = .3 to 3 eV^2

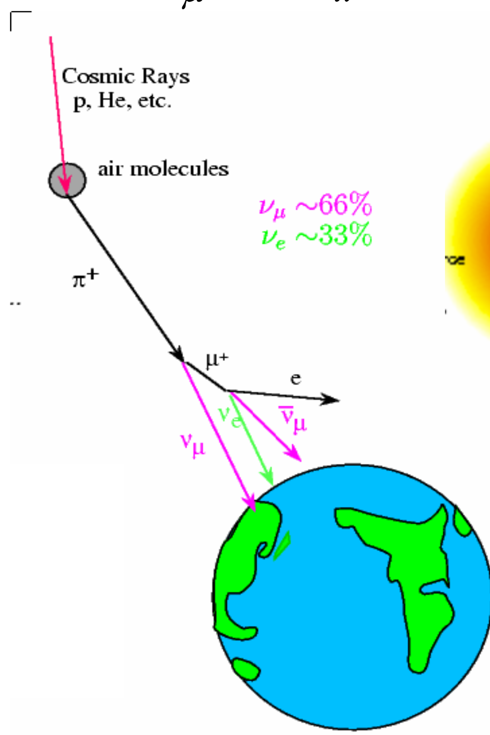
$Prob_{OSC}$ = 0.3 %

Atmospheric Neutrinos

L = 15 to 15,000 km

E =300 to 2000 MeV

$$\nu_\mu \rightarrow \nu_x$$



Δm^2 = ~ 1 to 7 × 10^{-3} eV^2

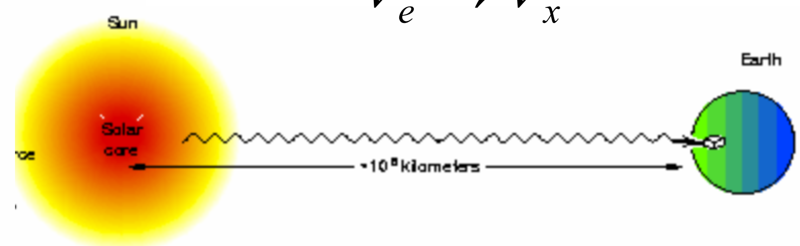
$Prob_{OSC}$ = ~100%

Solar Neutrinos

L = 10^8 km

E =0.3 to 3 MeV

$$\nu_e \rightarrow \nu_x$$

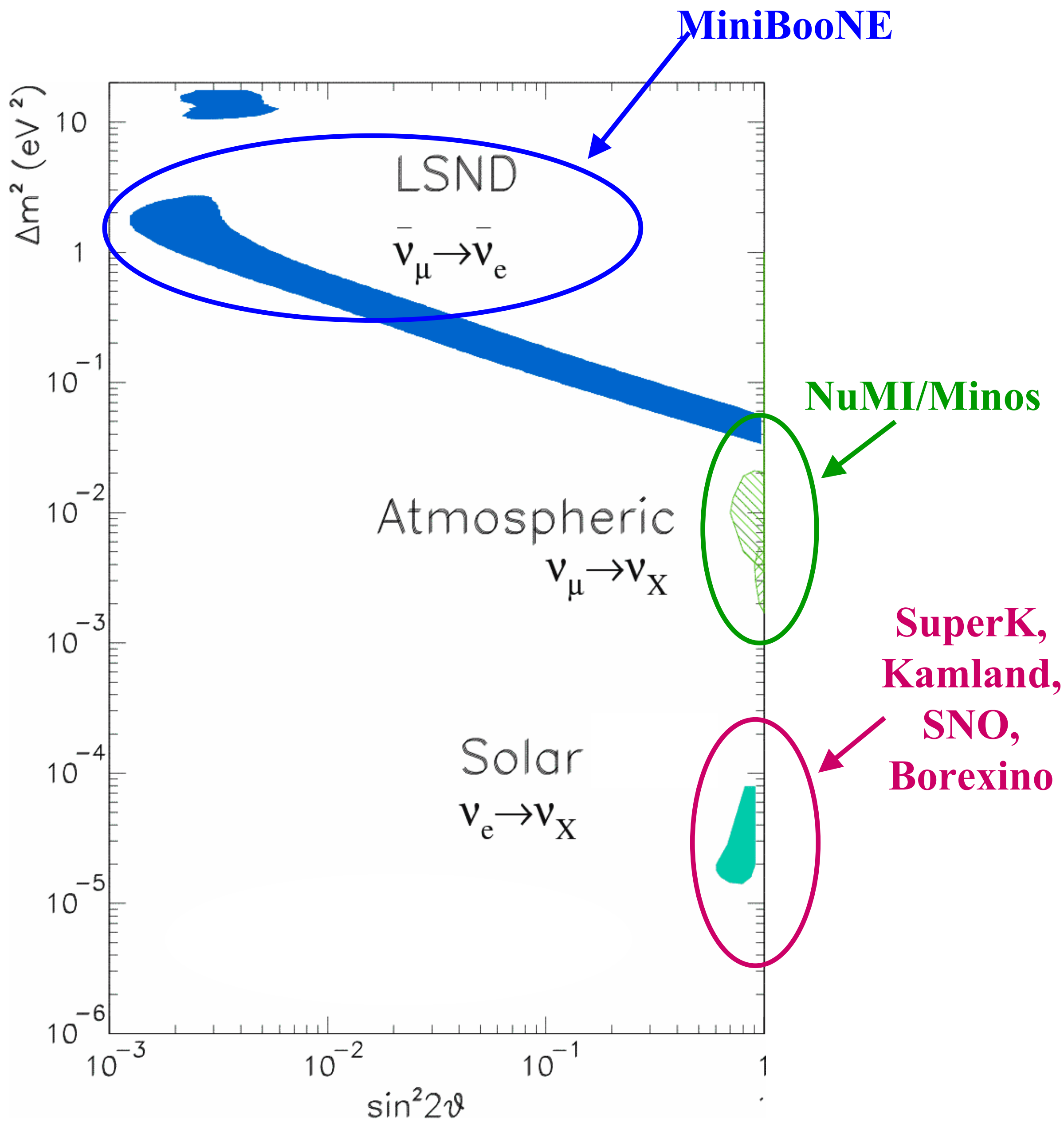


Δm^2 = ~ 2 to 8 × 10^{-5} eV^2

$Prob_{OSC}$ = ~100%

Questions addressed by Current Experiments:

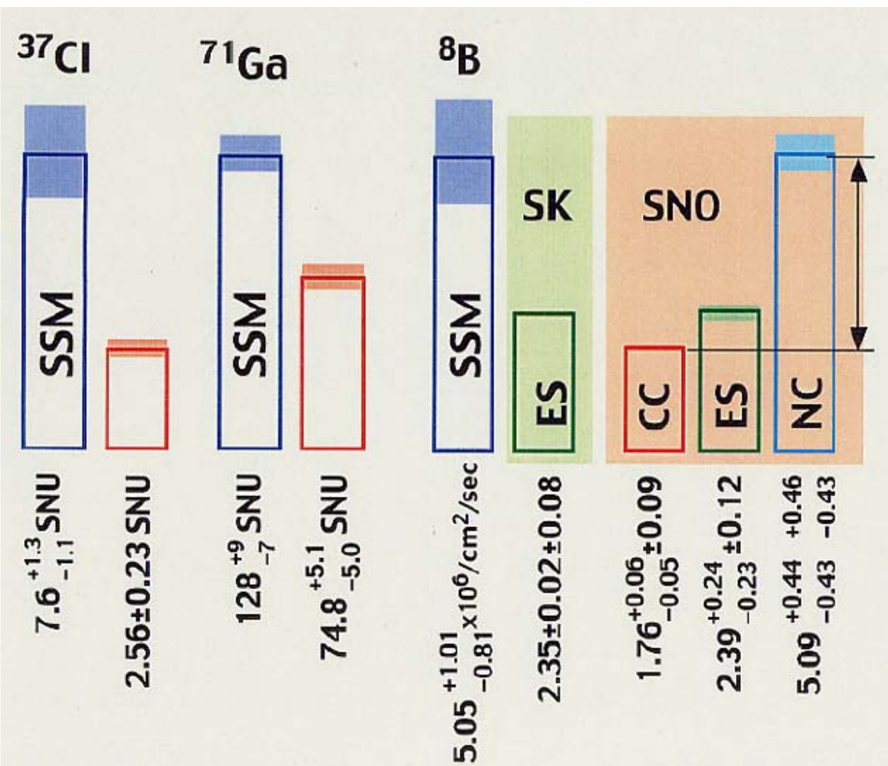
- LSND Δm^2
  - Determination if osc.
  - Measure $\Delta m^2/\sin^2 2\theta$
- Atmospheric Δm^2
  - Know if $\nu_\mu \rightarrow \nu_\tau$ or ν_s
  - Measure $\Delta m^2/\sin^2 2\theta$
  - Maybe see $\nu_\mu \rightarrow \nu_e$
- Solar Δm^2
  - Restrictions to one solar solution
  - Know if $\nu_e \rightarrow \nu_{\mu,\tau}$ or ν_s
  - Measure Δm^2

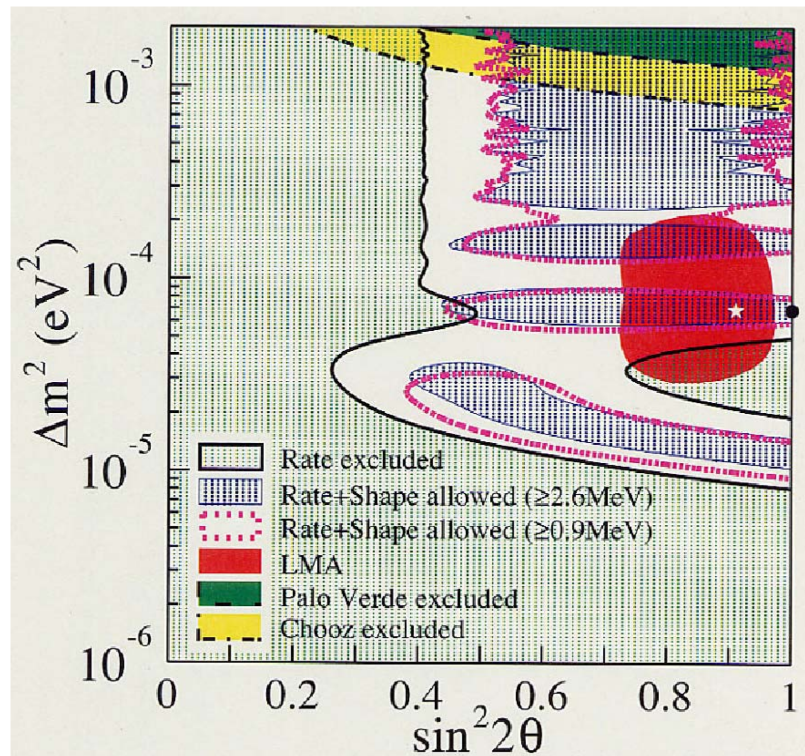


Solar Oscillation Experiments

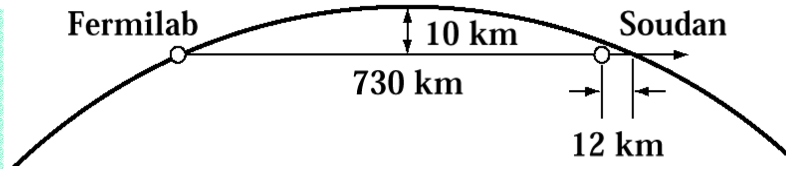
- All solar experiments see too few solar neutrinos
  - SNO sees expected total neutrino flux $(\nu_e+\nu_\mu+\nu_\tau)$ $\Rightarrow \nu_e \rightarrow \nu_\mu+\nu_\tau$ mostly

- New Kamland Reactor Results:
  - Detect too few anti-ν_e events from reactors around Japan
  - 54 events observed, 86±6 expected $\Rightarrow$ Osc. Probability = 0.39 ± 0.09
  - Accurate measurement of $\Delta m^2_{Solar} \approx 7\times10^{-5}$ eV^2

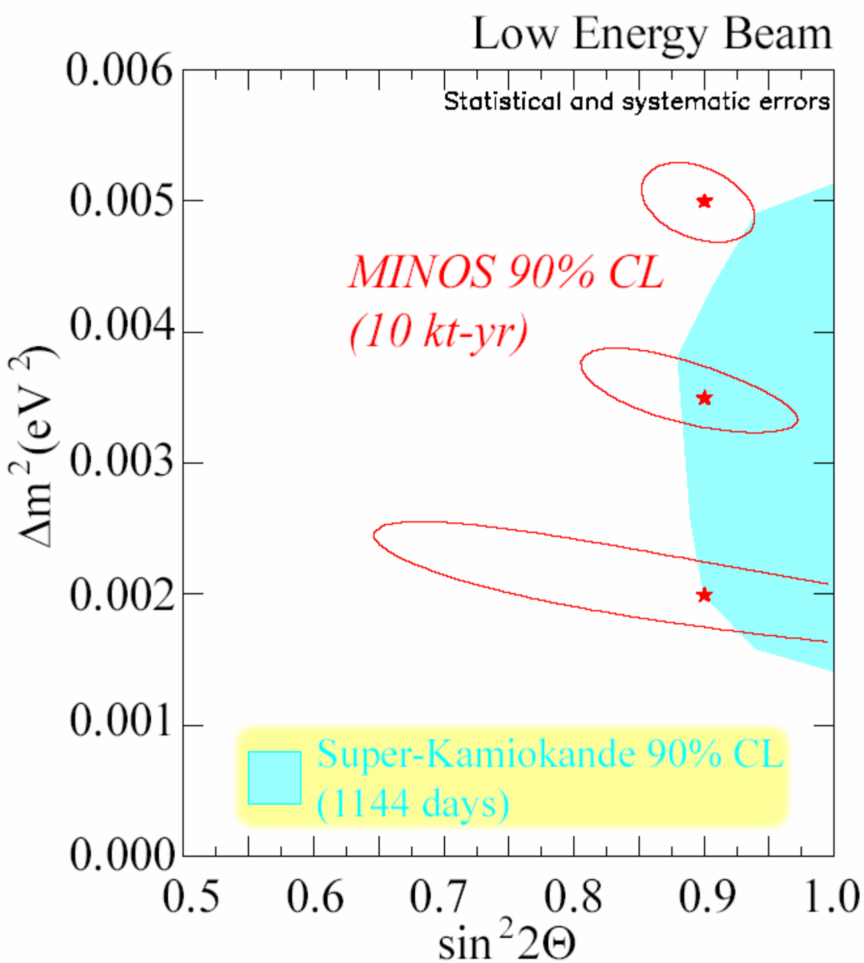




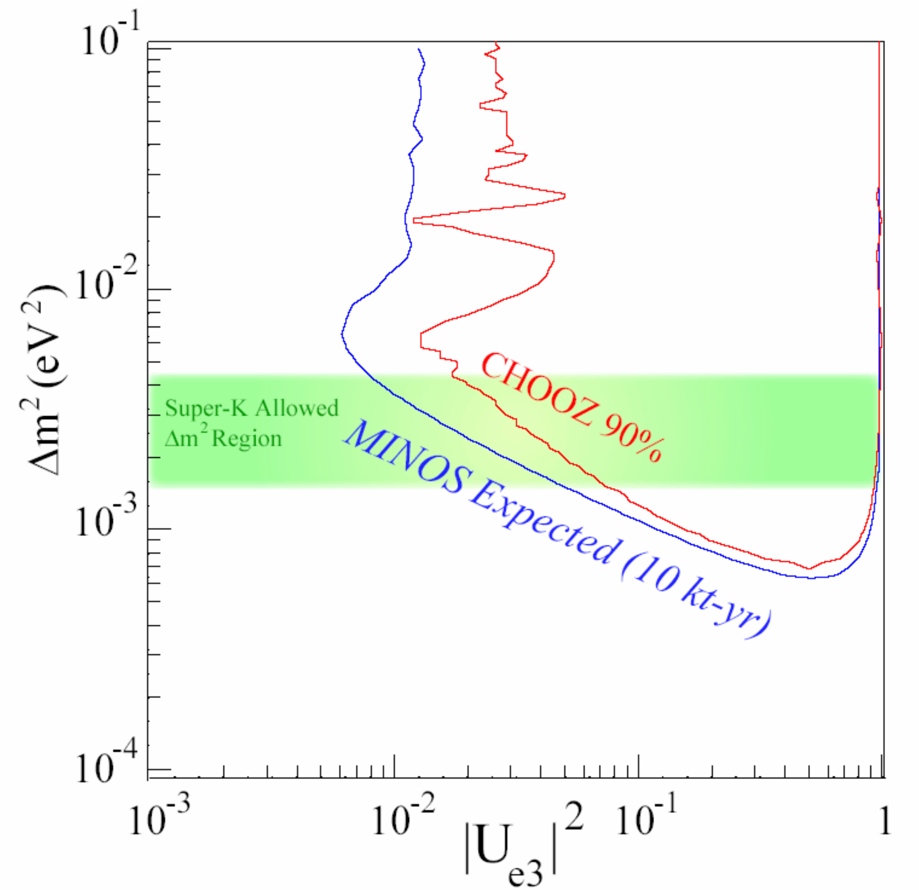
Atmospheric Oscillation Region: NuMI/MINOS Experiment



- From ν_μ disappearance signal
  - Measure Δm_{23}^2 to ~10%



- Probe for $\nu_\mu \rightarrow \nu_e$ appearance
  - Sensitivity at the level of $\sin^2 2\theta_{13} > 0.06$ @ 90%CL

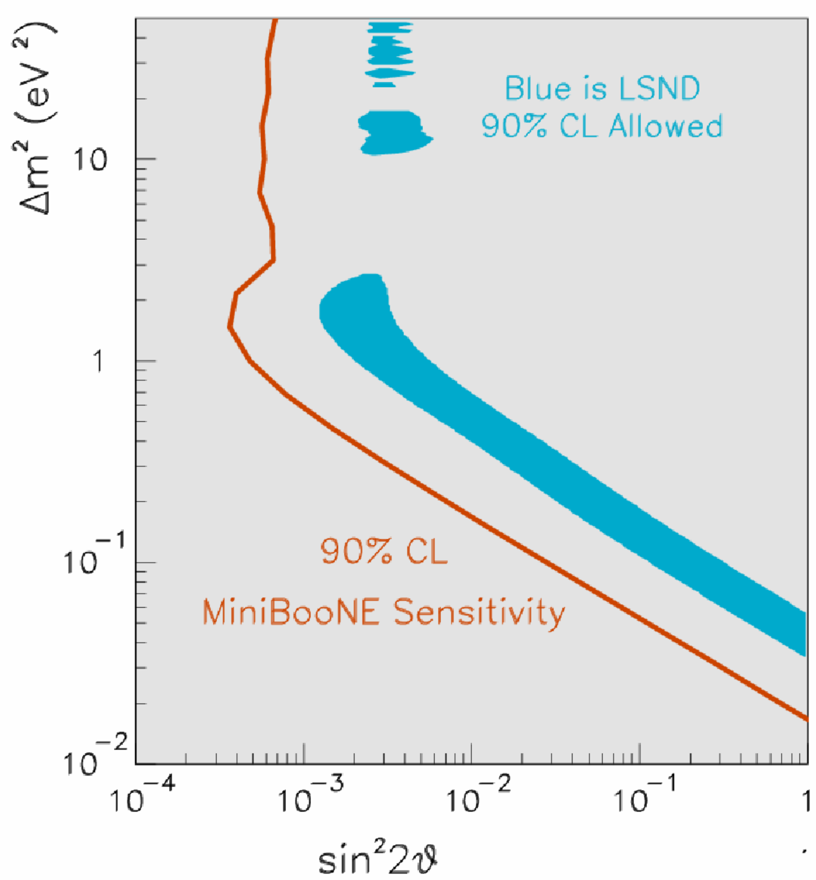


MiniBooNE

With ~two years of running MiniBooNE will completely include or exclude the entire LSND signal region at the 5σ level.

Expected events

- 500,000 ν_μ CC quasi-elastic
- **~1000 extra ν_e's if LSND correct**



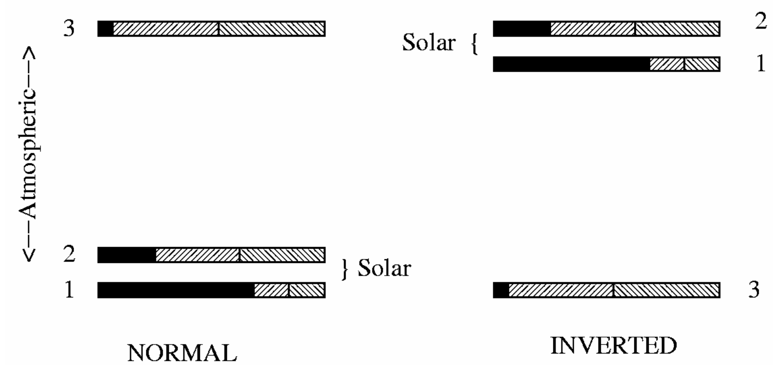
- If MiniBooNE sees $\nu_\mu \rightarrow \nu_e$ oscillations then need to modify oscillation program
  - Three distinct Δm^2 values
    $\Rightarrow$ Indicates some unexpected physics
    - More than three types of neutrinos – extra "sterile" neutrino types
    - Neutrinos and antineutrinos have different masses
  - Need more long and short-baseline probing high Δm^2
    - Terrestrial ν_μ and ν_e beams and reactor sources
    - Measure Δm^2 and see oscillatory behavior

Near Term Steps of a Neutrino Oscillation Program

1. Measure $\sin^2 2\theta_{13}$
   - Last unmeasured element in the mixing matrix
   - Sets the scale for being able to observe CP violation and matter effects
   - Off-axis experiments
     - Off-axis gives beam with narrow energy distribution that is tunable osc. max
       - Japanese JHF to SuperK experiment
       - Fermilab NuMI to Offaxis detector
   - Reactor Experiments
     - Provides complementary information to offaxis searches
       - Proposals being developed in US, Japan, and Europe

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} \sim 0.7 & \sim 0.7 & \mathbf{\sin\theta_{13} e^{i\delta}\ ?} \\ \sim -0.5 & \sim 0.5 & \sim 0.7 \\ \sim 0.5 & \sim -0.5 & \sim 0.7 \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

$$\Delta m_{12}^2 << \Delta m_{23}^2$$



2. Determine the sign of Δm^2_{23} from matter effects in the earth
   - Only available with NuMI off axis measurements

3. Probe for CP Violation (δ parameter)
   - Compare measurements for neutrinos with antineutrinos

Measurements of $\sin^2 2\theta_{13}$

Goal: Design experiments with sensitivity at the $\sin^2 2\theta_{13} \approx 0.01$ **level**

- Appearance (Offaxis Exps.)

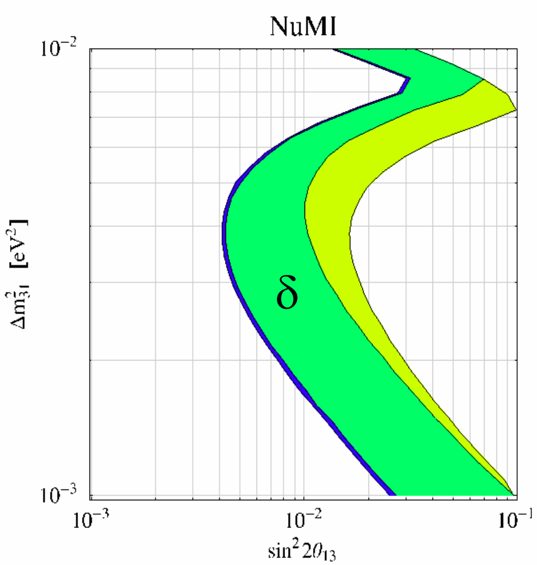
$$P[\nu_\mu(\bar{\nu}_\mu) \to \nu_e(\bar{\nu}_e)] = s_{23}^2 \sin^2 2\theta_{13} \sin^2 \frac{\Delta_{31}}{2}$$

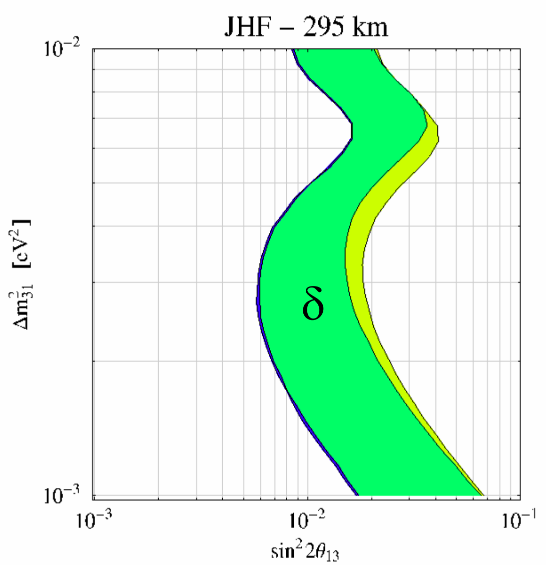
  - Measurement difficult:
    - Look for small number of events over comparable background

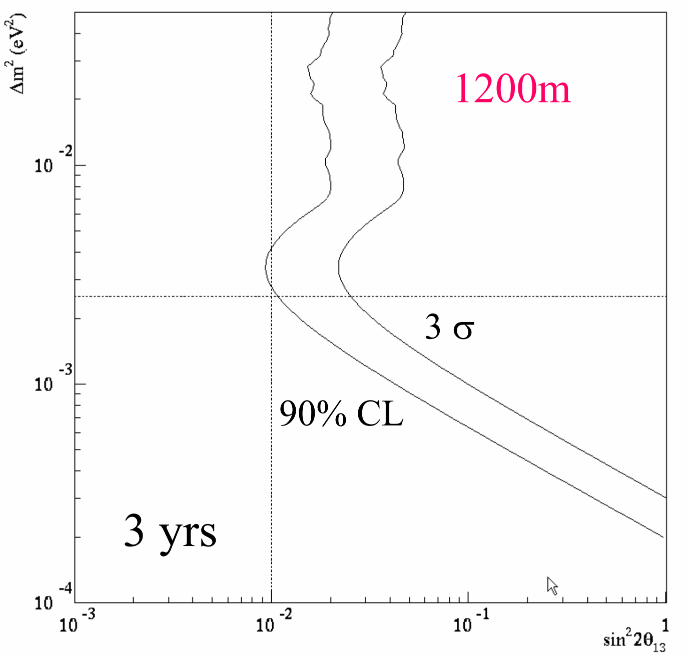
- Disappearance (Reactor Exps)

$$1 - P(\bar{\nu}_e \to \bar{\nu}_e) = \sin^2 2\theta_{13} \sin^2 \frac{\Delta_{31}}{2}$$

  - Measurement difficult:
    - Look for slight change in overall neutrino rate







Farther Term: Neutrino Superbeam Experiments

If $\sin^2 2\theta_{13}$> 0.01, design experiment to measure δ (CP violation parameter) and the sign of Δm^2_{23} through matter effects

- Need high intensity proton sources coupled with very large underground combined function detectors
- Current ideas for experiments:
  - JHF Phase II to HyperK detector
    - $<E_\nu> \approx 700$ MeV beam using 4MW JHF to 1000kton water Cerenkov
    - CP violation 3σ discovery reach for $\sin^2 2\theta_{13}>0.02$ (2yr for nu's and 6 yrs for nubars)
  - BNL Upgraded AGS to NUSL
    - Very longbaseline with wide-band beam gives dramatically large effects Use 1MW AGS beam with $0.5<E_\nu<5$ GeV and 500 kton water Cerenkov
  - Fermilab Proton Driver to NUSL
    - Upgrade proton driver to 1-4MW combined with 500kton detector
      $\Rightarrow$ Fit first and second maximum for neutrinos and antineutrinos
    - Possibly also NuMI to Canada

Neutrino Oscillation Roadmap

- Stage 0: Current near term program
  - Solar neutrino Δm^2_{12} measured to 5-10%
  - NuMI (K2K) checks atmospheric oscillations and measures Δm^2_{23} to about 10%
  - MiniBooNE makes definitive check of LSND and measures associated Δm^2
- Stage 1 - Constrain / measure $\sin^2 2\theta_{13}$ - Maybe observe initial matter and CP violation effects
  - NuMI /MINOS on-axis probes $\sin^2 2\theta_{13} > 0.06$ @ 90%CL
  - NuMI/JHF offaxis with 20-50 kton detectors to probe $\sin^2 2\theta_{13} > 0.01$ @ 3σ level
  - Two-detector, longbaseline reactor experiments probe at the $\sin^2 2\theta_{13} > 0.01$ level
- Stage 2 - Observe CP violation and determine the sign of Δm^2_{23} with conventional superbeams and very large detectors (>500 ktons) - May be coupled with underground lab (NUSEL...) and proton decay
  - Must have $\sin^2 2\theta_{13} > 0.01$
  - Need to measure $P(\nu_\mu \to \nu_e)$ then $P(\bar{\nu}_\mu \to \bar{\nu}_e)$ or use constraints from a precision reactor $\bar{\nu}_e \to \bar{\nu}_e$
  - Need increased rate (especially for $\bar{\nu}$'s) $\Rightarrow$ Need high intensity proton sources
- Stage 3 - Measurements with a Neutrino Factory
  - Map out CP violation with precision for $\sin^2 2\theta_{13} > 0.01$
  - Probe $\nu_\mu \to \nu_e$ transitions down to $\sin^2 2\theta_{13} > 0.001$