# The Future of Neutrino Oscillation Measurements

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# 3 Flavor Mixing Matrix

## CKM Matrix

$$\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \begin{pmatrix} d \\ s \\ b \end{pmatrix}$$

$$\approx \begin{pmatrix} 1 & \lambda & \lambda^3 \\ \lambda & 1 & \lambda^2 \\ \lambda^3 & \lambda^2 & 1 \end{pmatrix}$$

$$\text{where } \lambda \sim 0.2$$

## MNS Matrix

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

$$\approx \begin{pmatrix} \frac{\sqrt{2}}{2} & \frac{\sqrt{2}}{2} & 0 \\ \frac{-1}{2} & \frac{1}{2} & \frac{\sqrt{2}}{2} \\ \frac{1}{2} & \frac{-1}{2} & \frac{\sqrt{2}}{2} \end{pmatrix}$$

# Mixing Angles

Matrix Components:
- 3 Euler Angles ($\theta_{12}$; $\theta_{13}$; $\theta_{23}$)
- 1 CP phase ($\delta$)
- (+2 Majorana Phases)

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

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

**Atmospheric**
**($\nu_\mu \rightarrow \nu_x$)**

**The Next Big Thing?**

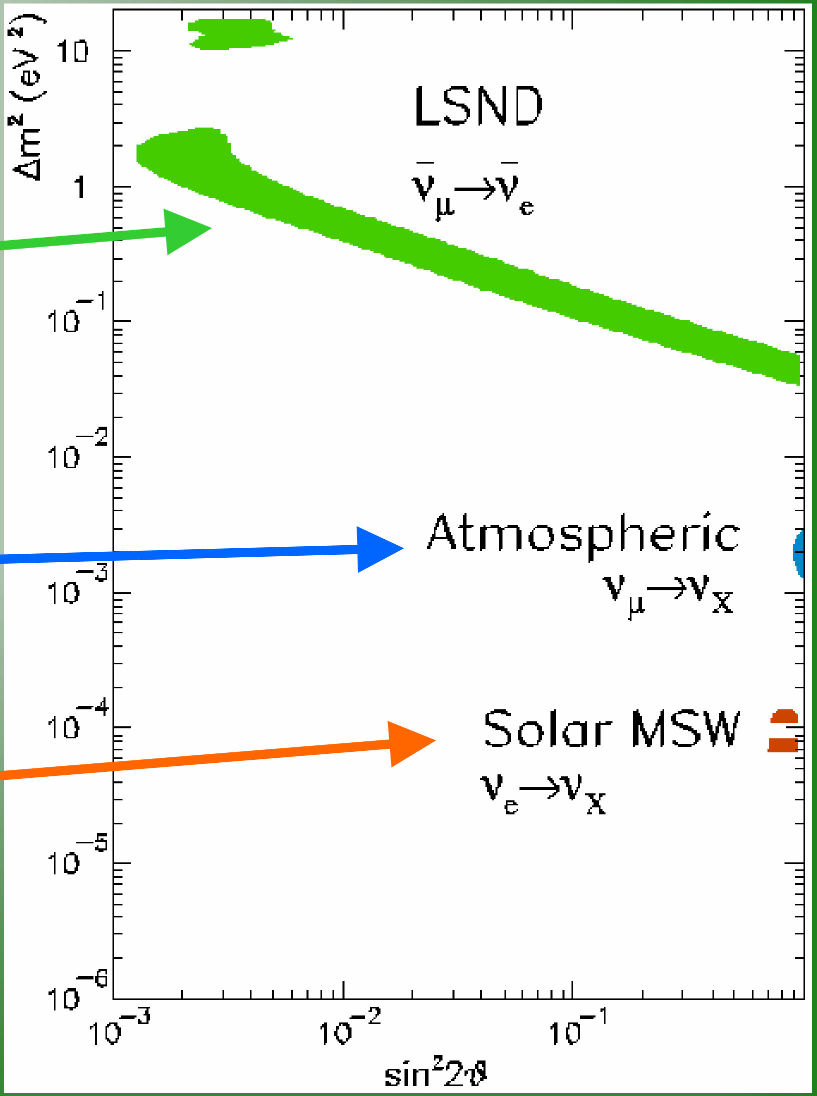
**Solar**
**($\nu_e \rightarrow \nu_x$)**

# Current Experiments

Unconfirmed observation by LSND, currently being investigated by MiniBooNE. Would require the existence of sterile neutrinos or CPT violation.

Measured by Super-K and confirmed by Soudan2 and K2K.

First observed by Ray Davis and collaborators. Measured by Super-K, SNO and KamLAND.

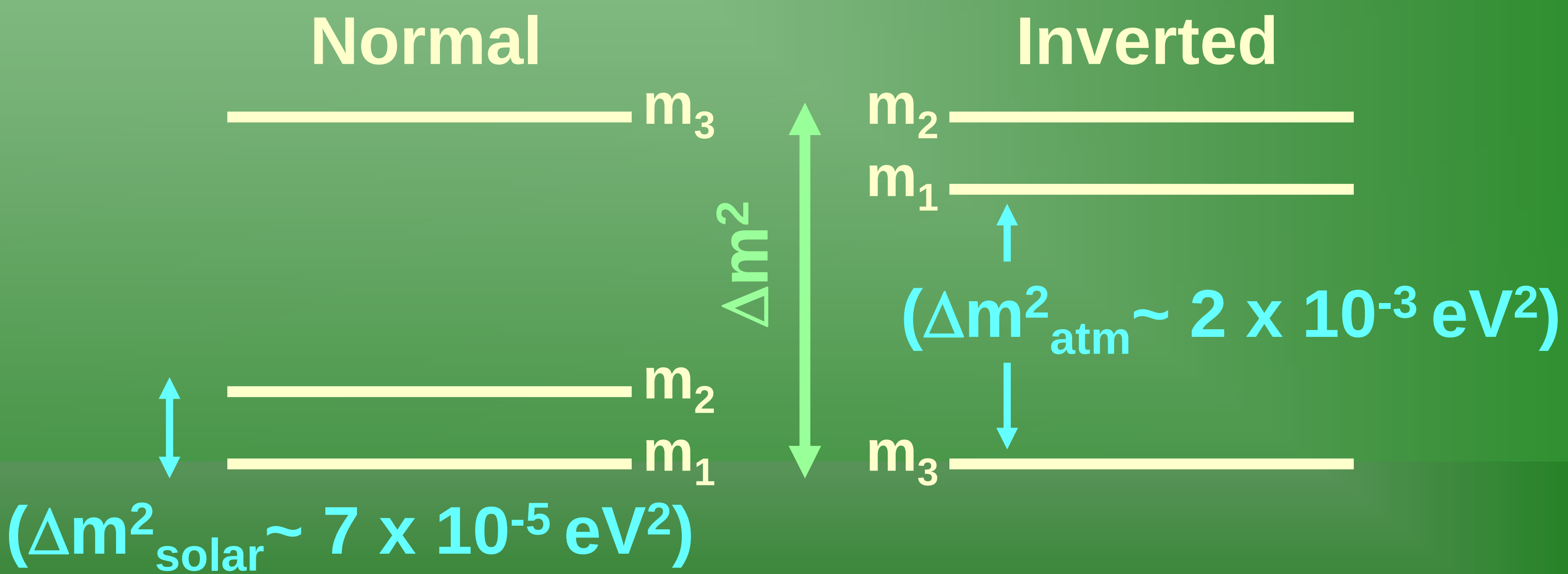


# $\Delta m^2$
# (aka: LSND problem)

- For 3 $\nu$ only 2 independent mass differences

$$\Delta m^2_{13} = \Delta m^2_{12} + \Delta m^2_{23}$$

- Mass hierarchy unknown



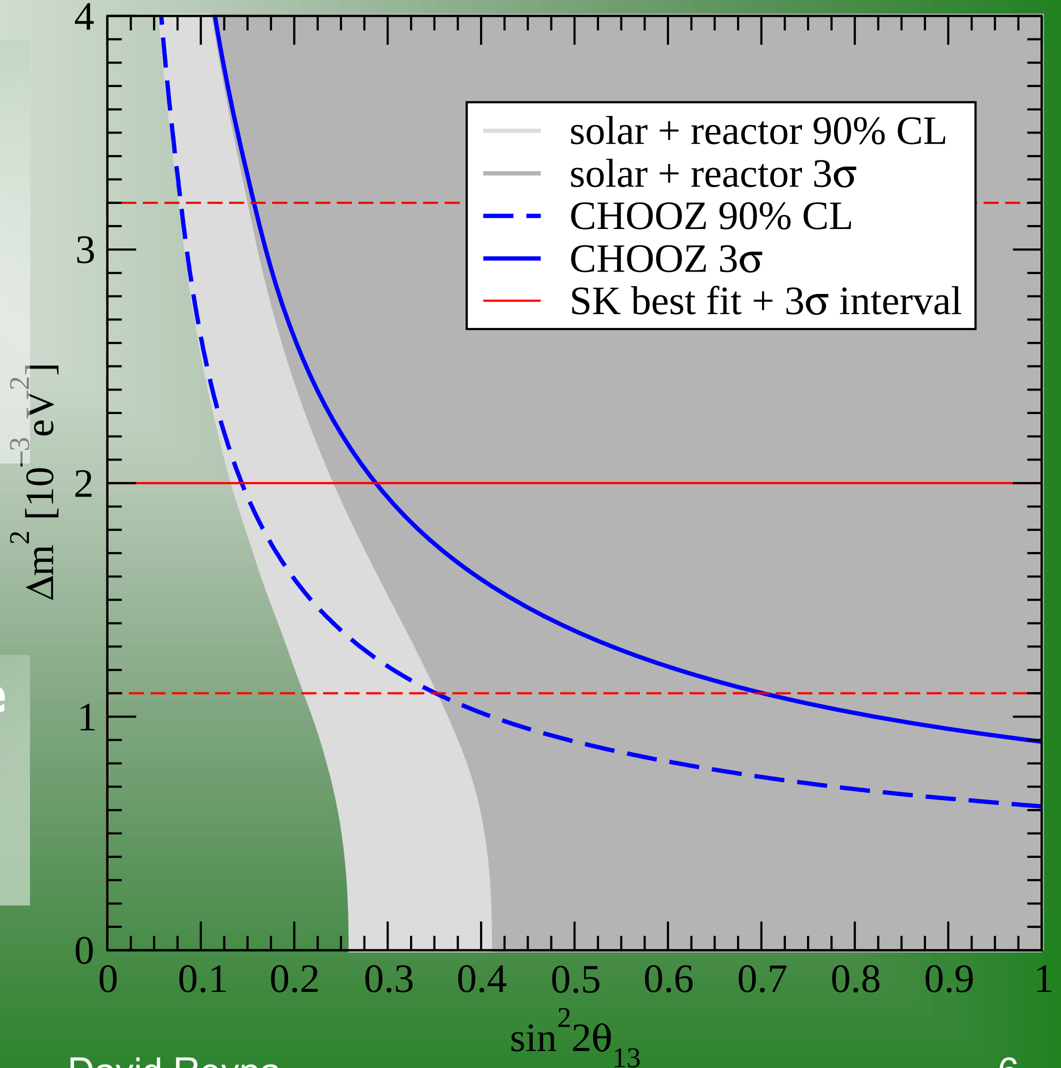
# Current $\theta_{13}$ Bound

**Current Limits are set by experiments which were not trying to measure $\theta_{13}$**

**Optimization of the experiments for this goal was never done**

**In currently allowed range ($\Delta m^2$ =1.3-3 x $10^{-3}$ eV$^2$)**

**$\sin^2(2\theta_{13})$ < 0.19 @ 90% CL**



# How to Measure $\theta_{13}$

- Need for high precision requires 2 detector technique
  - Bugeye, MINOS and K2K
  - Allows errors from neutrino source to be eliminated from experimental results
- Appearance measurement
  - Accelerator "Off-axis" measurements look for small $\nu_e$ appearance in $\nu_\mu$ beam

  $P(\nu_\mu \rightarrow \nu_e) = \sin^2(2\theta_{13})\sin^2(\theta_{23})\sin^2(\Delta m^2_{atm} L/4E)$
- Disappearance measurement
  - Reactor measurements look for small $\overline{\nu}_e$ disappearance from large isotropic flux

  $P(\overline{\nu}_e \rightarrow \overline{\nu}_e) = 1 - \sin^2(2\theta_{13})\sin^2(\Delta m^2_{atm} L/4E)$

# Off-Axis Difficulties

- Signature is electron appearance
  - Requires massive detector with fine granularity
- Backgrounds
  - $\nu_e$ in the beam, (~1%, from $\mu$, $K^{\pm}_{e3}$, $K^0_{e3}$)
  - Fake $\nu_e$ from $\nu_\tau$, $\tau \rightarrow e$, (at high energy)
  - Showers which look like e's, particularly $\nu N \rightarrow \nu N \pi^0$, $\pi^0 \rightarrow \gamma\gamma$
- Measurement has degeneracies due to cp-violation and matter effects

# $\nu_e$ Appearance in a $\nu_\mu$ beam

$$P(\nu_\mu \rightarrow \nu_e) = (2c_{13}s_{13}s_{23})^2 \sin^2\Phi_{31}$$

$$+8c_{13}^2 s_{12} s_{13} s_{23}(c_{12}c_{23}\cos\delta - s_{12}s_{13}s_{23})\cos\Phi_{32}\sin\Phi_{31}\sin\Phi_{21}$$

↙ CP violating

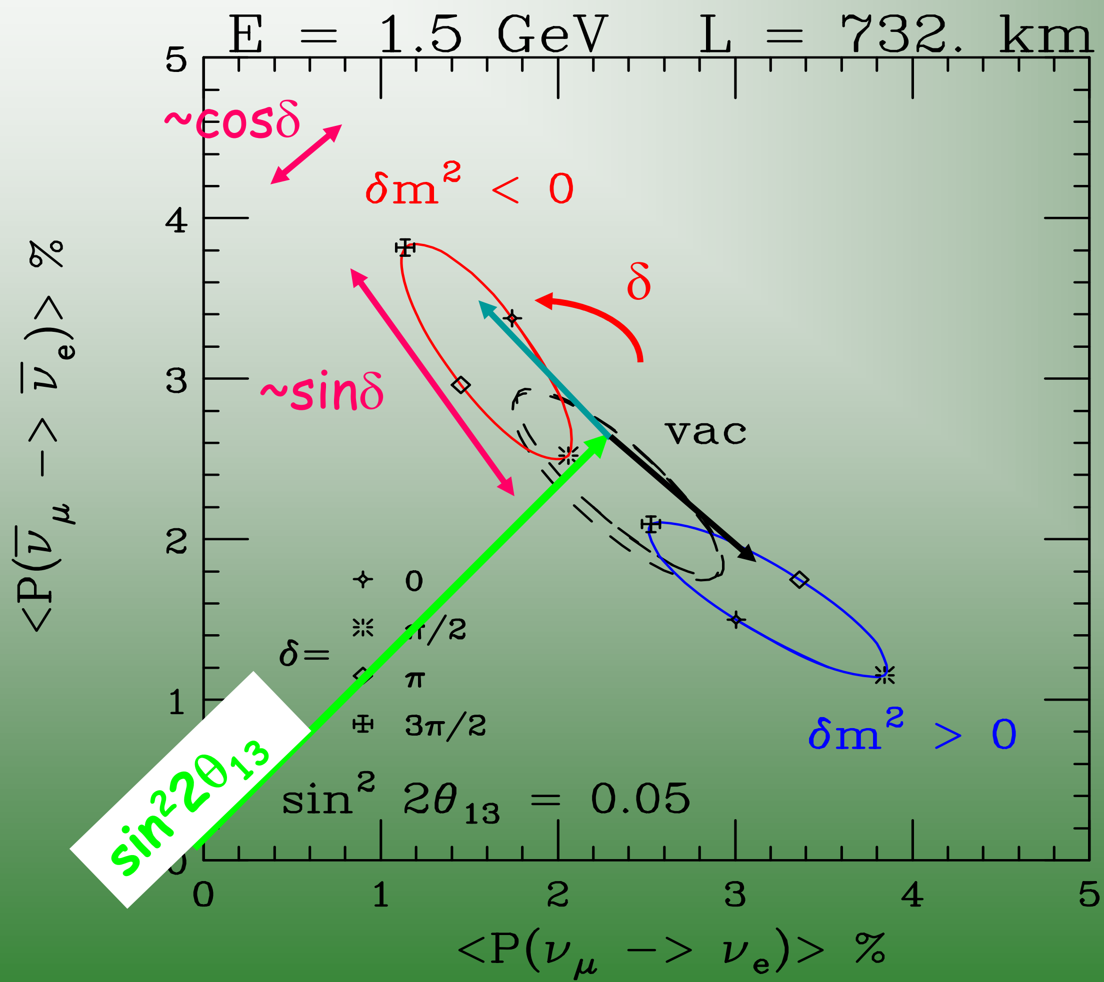
$$-8c_{13}^2 c_{12}^2 c_{23} s_{12} s_{13} s_{23} \sin\delta \sin\Phi_{32}\sin\Phi_{31}\sin\Phi_{21}$$

$$+4s_{12}^2 c_{13}(c_{12}^2 c_{23}^2 + s_{12}^2 s_{23}^2 s_{13}^2 - 2c_{12}c_{23}s_{12}s_{23}s_{13}\cos\delta)\sin^2\Phi_{21}$$

$$-8c_{13}^2 s_{13}^2 s_{23}^2 (1-2s_{13}^2)(aL/4E)\cos\Phi_{32}\sin\Phi_{31}$$

$a$ = constant X $n_e E$ CP: $a \rightarrow -a$, $\delta \rightarrow -\delta$

# Understanding the Degeneracy




Minakata and Nunokawa, hep-ph/0108085

There are 2 Observables

$P(\nu_\mu \rightarrow \nu_e)$

$P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e)$

Interpretation in terms of $\sin^2 2\theta_{13}$, $\delta$ and sign of $\Delta m^2_{23}$ depends on the value of these parameters and on the conditions of the experiment: L and E

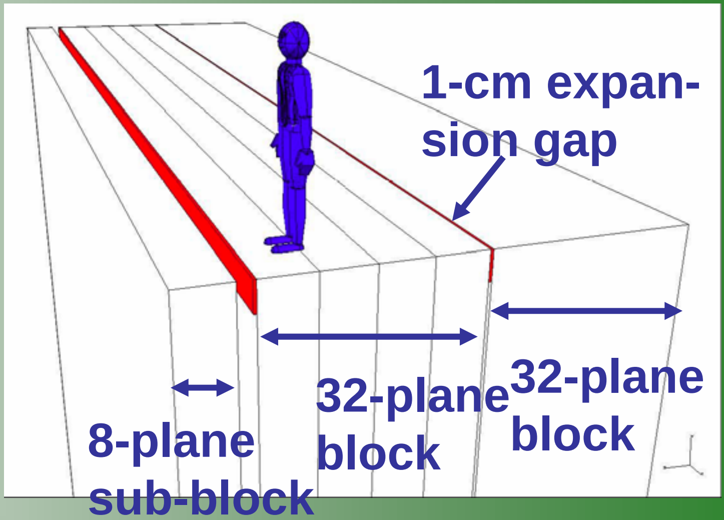
# Experimental Solutions

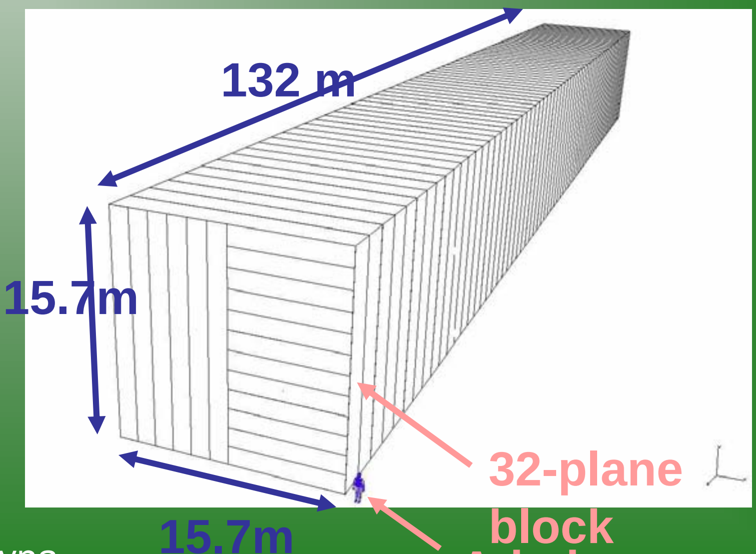
- If $\theta_{13}$ is large, the degeneracy can be broken with off-axis measurements
  - Measure both $\nu$ and anti-$\nu$ rates
  - Multiple experiments with different baselines and different energies
  - Will yield a rich physics program for cp-phase and mass hierarchy
- If $\theta_{13}$ is zero, degeneracies collapse but there's no attainable physics gain
- 2 Proposals underway
  - T2K (Japan)
  - NO$\nu$A (USA)

# The NOνA Experiment

"Totally Active Detector"

- 30 kT:
  - 24 kT liquid scintillator
  - 6 kT PVC
- 32 cells/extrusion
- 12 extrusions/plane
- 1984 planes
- Cell dimensions:
  - 3.9 cm x 6 cm x 15.7m
- U-shaped 0.8 mm WLS fiber into APD
- Approved by Fermilab but awaiting funding from DOE
  - Ongoing R&D for detector
  - Expect to start civil construction in 2007



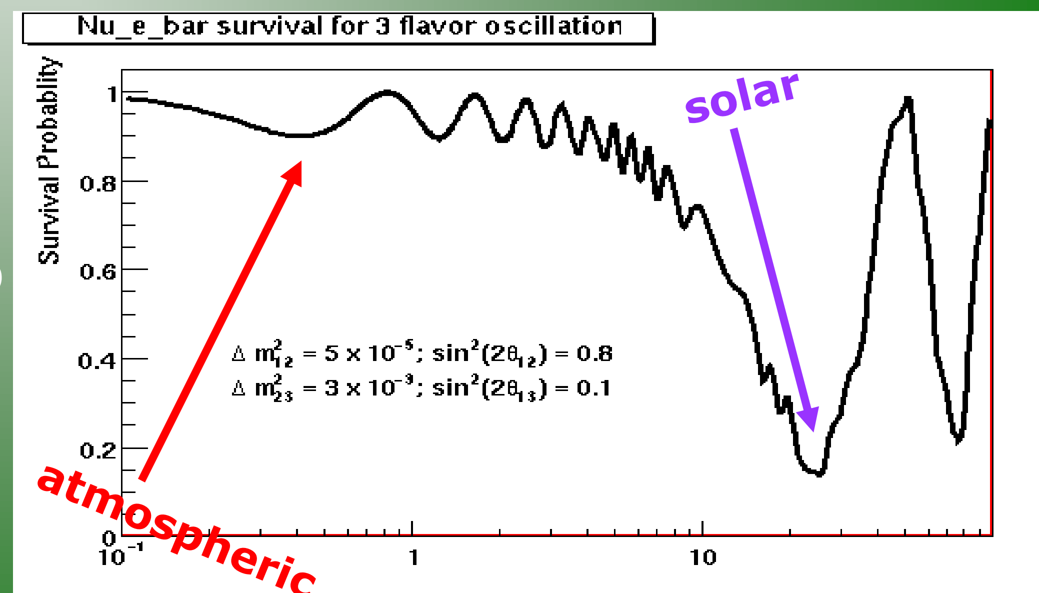



# The Reactor Measurement

$$P(\overline{\nu}_e \rightarrow \overline{\nu}_e) = 1 - \sin^2 2\theta_{13} \sin^2(\Delta m^2_{atm} L/4E) - \cos^4\theta_{13} \sin^2 2\theta_{12} \sin^2(\Delta m^2_{sol} L/4E)$$

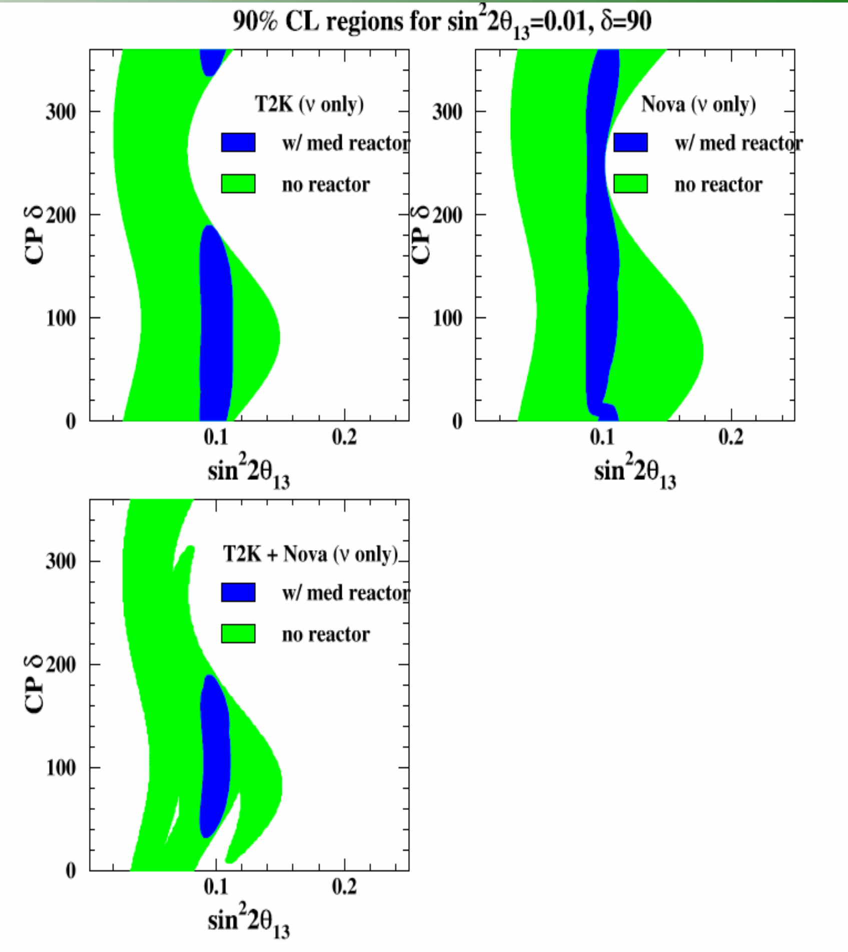
No CP-violation in a disappearance measurement

Distance (~1Km) is too short for matter effects



# Reactor and Off-Axis Work Together

- Reactor experiments can be used to help off-axis experiments constrain the CP violation phase
- Also, the mass hierarchy can be determined in limited regions of parameter space, if $\sin^2 2\theta_{13} > 0.03$

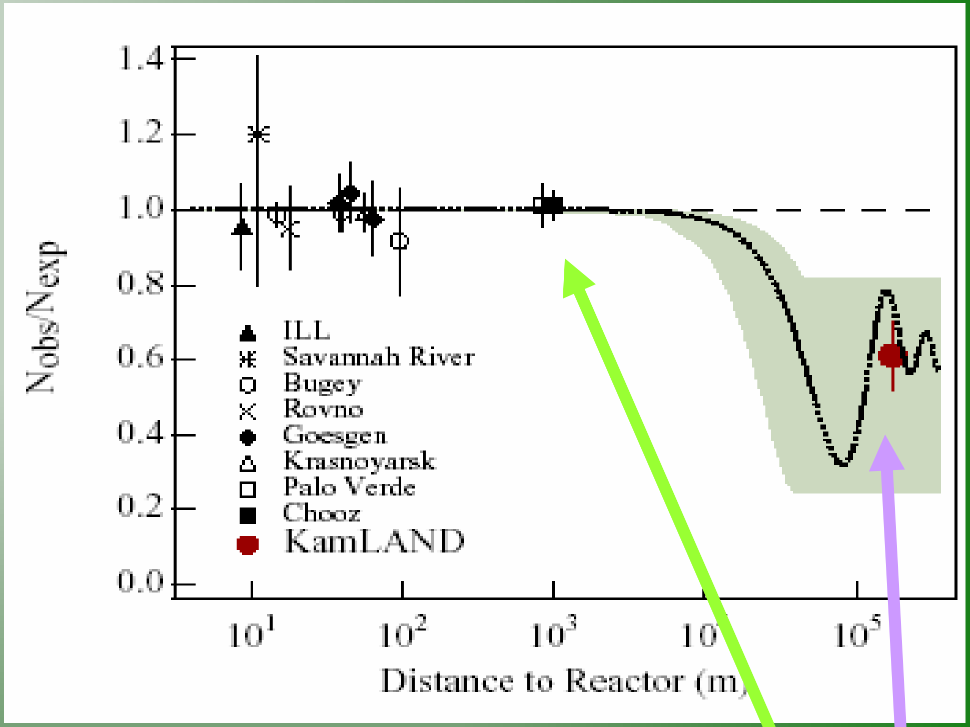


# Reactor Challenges

- Long term stability (Liquid Scintillator)
  - CHOOZ/Palo Verde were few month exp's
  - Next generation must be 3-5 years
- Backgrounds
  - CHOOZ measured ~10% with reactor off
  - Unlikely to duplicate reactor off data
- Systematic Error Control
  - Consistency of mechanical construction
  - Previous exp's were 2-3% (excluding reactor)
  - Needs to be 1% or less

# Previous Reactor Measurements

- All measure the same energy spectrum.
- Previous experiments used single detector and were limited by 3% uncertainty in reactor power.
- KamLAND is first to see positive evidence of oscillation.
- Currently 6 proposed multi-detector experiments




KamLAND sees a 40% deficit/shape at 200km related to $\Delta m^2_{12}$

Search for a 1-5% deficit/shape at ~1 km related to $\Delta m^2_{13}$

# Proposed Reactor Experiments

| Reactor | Power $GW_{th}$ | <Power> $GW_{th}$ | Location | Detectors km/ton/MWE |
|---|---|---|---|---|
| Angra | 6.0 | 5.3 | Brazil | 0.05/1/20<br>0.3/50/250<br>1.5/500/2000 |
| Braidwood | 7.2 | 6.5 | Illinois US | 0.27/[65×2]/464<br>1.51/[65×2]/464 |
| Daya Bay | 11.6<br>(17.4 after 2010) | 9.9<br>(14.8 after 2010) | China | 0.36/40/260<br>0.50/40/260<br>1.75/[40×2]/910 |
| Double Chooz | 8.7 | 7.4 | France | 0.15/10.2/60<br>1.067/10.2/300 |
| KASKA | 24.3 | 19.4 | Japan | 0.35/6/90 [×2]<br>1.6/[6×2]/260 |
| RENO | 17.3 | 16.4 | Korea | 0.15/20/230<br>1.5/20/675 |

# Double Chooz

- Re-use existing Far Laboratory with improved detector
- Construct Near Laboratory at 200-300m.
- Extensive development has been completed
  - 1/5 Scale Prototype is filled with scintillator and undergoing long term testing
  - Engineering/cost estimates of Near Lab by EdF are complete
    - Will have more depth than previously hoped
- Awaiting funding from DOE (since Oct. 2004) to begin construction

# Daya Bay


**Total Tunnel length**
- 3200 m

**Detector swapping**
- in a horizontal tunnel cancels most detector systematic error. Residual error ~0.2%

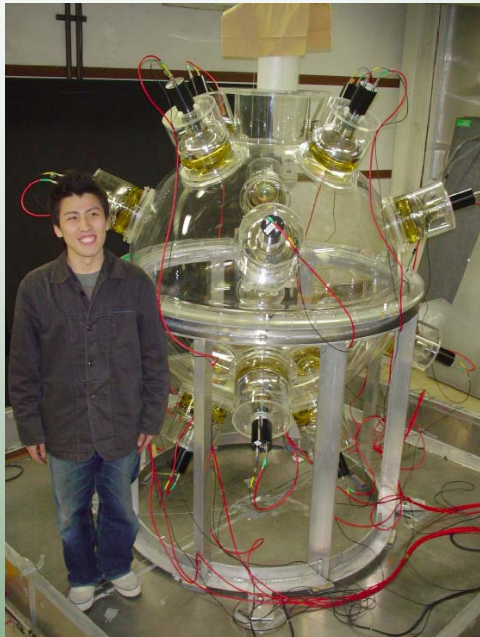
**Backgrounds**
- B/S of DYB,LA ~0.5%
- B/S of Far ~0.2%

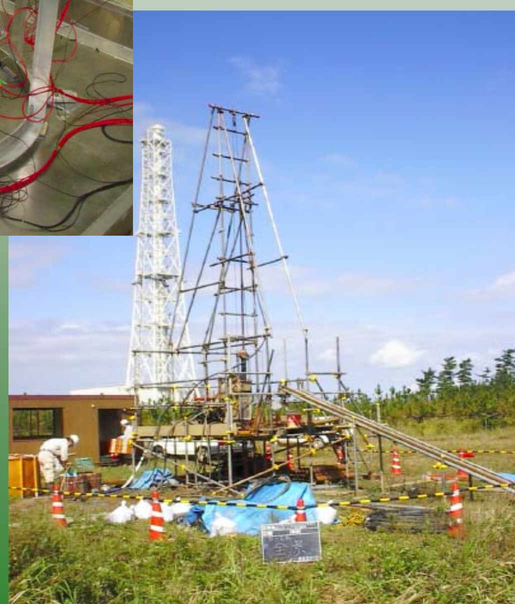
**Fast Measurement**
- DYB+Mid, 2008-2009
- Sensitivity (1 year) ~0.03

**Full Measurement**
- DYB+LA+Far, from 2009
- Sensitivity (3 year) <0.01

**Site Survey**
- Topography: Completed
- Geological Survey: Completed
- Geological Physical Survey: Jun.~Sep.
- Bore-Hole Drilling: Oct.~Dec.

# KASKA

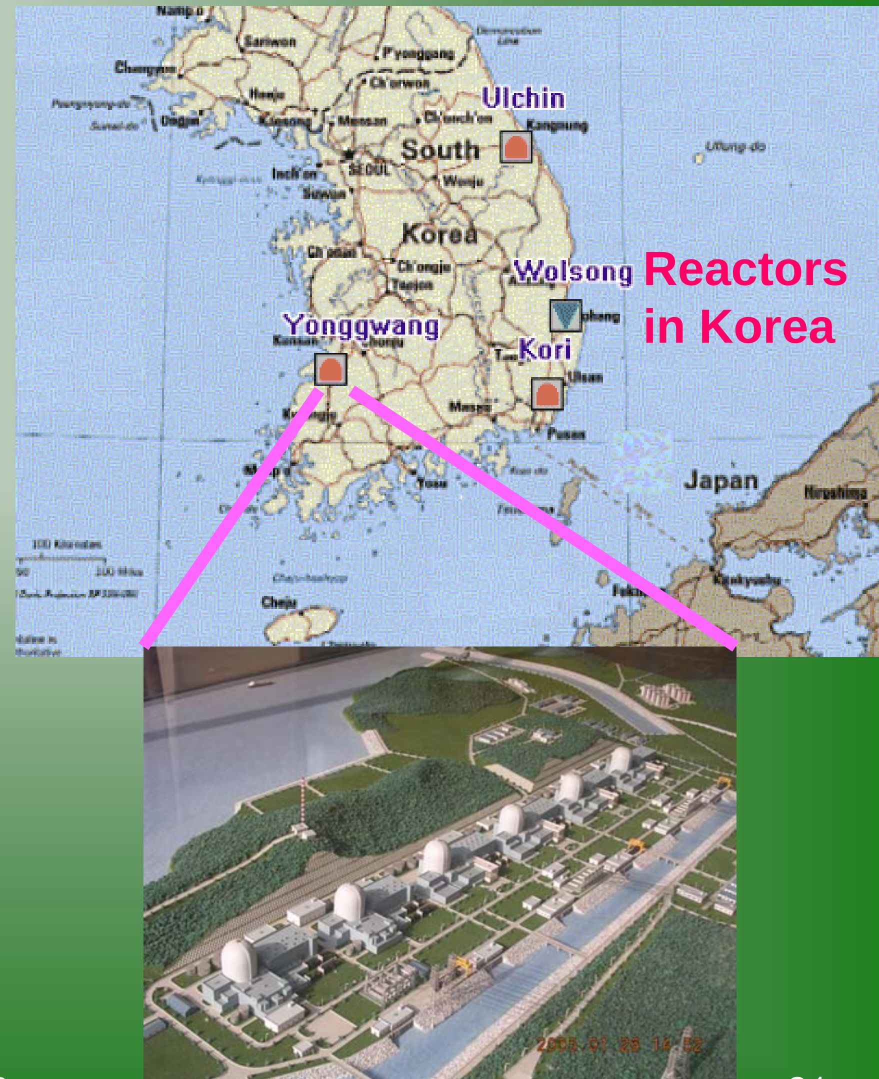




- Use Worlds most powerful reactor complex (7 cores)
- 3 detectors to compensate source uncertainties
- R&D Budgets have been obtained to perform
  - Prototype development
  - On site geology/ background study
- Requesting a full budget for JFY2006
- If approved this year, KASKA will take data from March/2009.

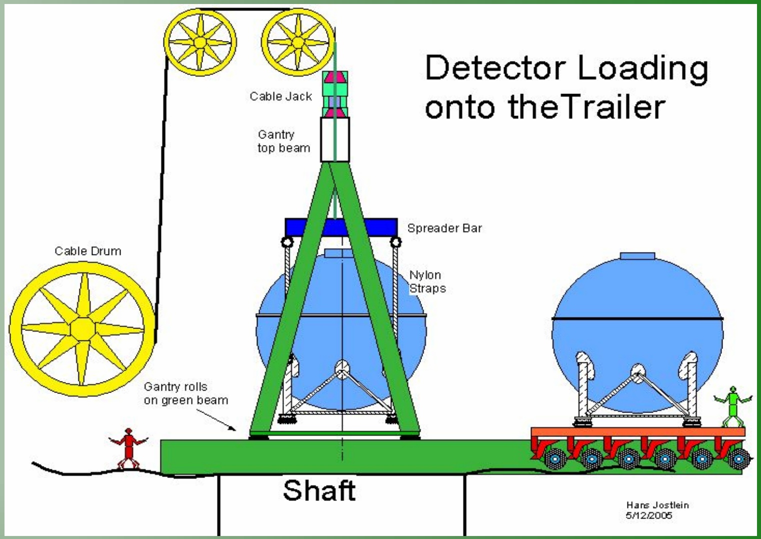
# RENO

- Small scale project at a 6-core reactor complex
  - Studied experimental feasibility ($\sin^2(2\theta_{13}) > 0.03$)
- Ministry Of Science and Technology (MOST) has chosen the RENO project and included in the list of government budget request for 2006
- The Ministry of Finance approved the US $9M proposal in Dec. 2005 after Congress review
  - RENO is now funded higher than any other reactor proposals
- Contacted the power plant and its local government → Promised their best cooperation upon approval
- A prototype with 40 liters of Gd liquid scintillator is under construction



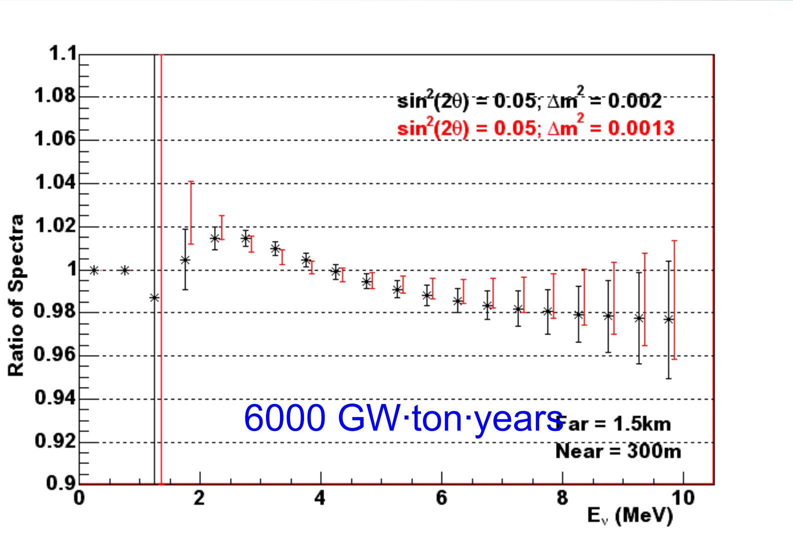
# Braidwood

- Focused on movable detectors to reduce systematic errors
- Initial geological surveys have been completed on site
  - Civil costs dominate for an experiment in the US (~ x10 detector cost)
- Development of scintillator at BNL is progressing
- Uncertain impact of recent news on tritium leak by Excelon in 2000.




| Period | Near | Far |
|---|---|---|
| Initial 3 months | A B | |
| 3 year data run | A C | B D |
| Final check | A D | B C |

# Angra dos Reis




- **Make High Luminosity Measurement to See Oscillation in Energy Spectrum (KamLAND at 1.5km)**
- Optimal Geology allows reduction of backgrounds to negligible level
  - Background ~1-2 ev/day
  - Signal ~1000 ev/day
- Working with reactor company and outside agencies to develop small prototype of a very near detector (65m from reactor core)
  - Outside funding already provided for geological surveys and construction cost estimates
  - Want to Develop needed technologies and demonstrate viability of energy spectrum techniques
  - Beginning setup of experimental site and prototype detector
  - Additional interest and assistance from Nuclear Non-Proliferation Agencies
- 3-5 year R&D program
- Full Experiment could begin in 2013

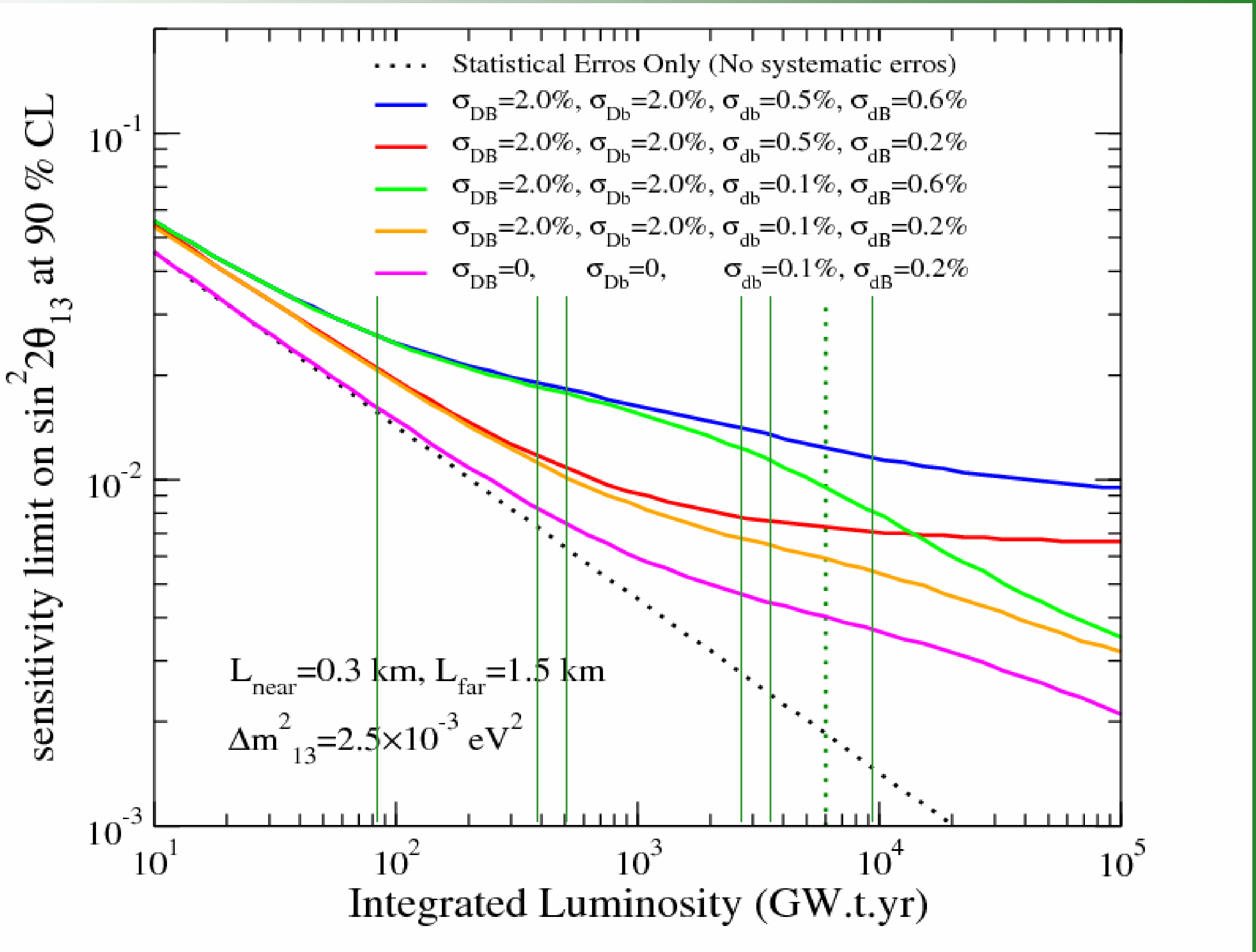
# Proposed Schedules and Sensitivities

| Reactor | Optimistic start date | GW-t-yr (yr) | 90% CL $Sin^2 2\theta_{13}$ sensitivity | for $\Delta m^2$ ($10^{-3}eV^2$) | efficiencies | Far event rate |
|---|---|---|---|---|---|---|
| Double Chooz | Oct 07(far)<br>Oct 08(near) | 29(1)<br>29(1+1)<br>80(1+3) | 0.08<br>0.04<br>0.025 | 2.5 | 0.8 ×0.9 | 15,000/yr |
| Daya Bay | 08(fast)<br>09(full) | 3700(3) | 0.008 | 2.5 | 0.75×0.83 | 70,000/yr<br>110,000/yr<br>(before/after 2010) |
| KASKA | Mar 09 | 493(3) | 0.015 | 2.5 | 0.8×0.88 | 24,000/yr |
| RENO | Late 09 | 340(1) | 0.03 | 2.0 | 0.8 | 18,000/yr |
| Braidwood | 2010 | 845(1)<br>2535(3)<br>7605(9) | 0.007<br>0.005<br>0.0035 | 2.5 | 0.75 | 41,000/yr |
| ANGRA | 2013(full) | 3900(1)<br>9000(3)<br>15000(5) | 0.0070<br>0.0060<br>0.0055 | 2.5 | 0.8×0.9 | 350,000/yr |

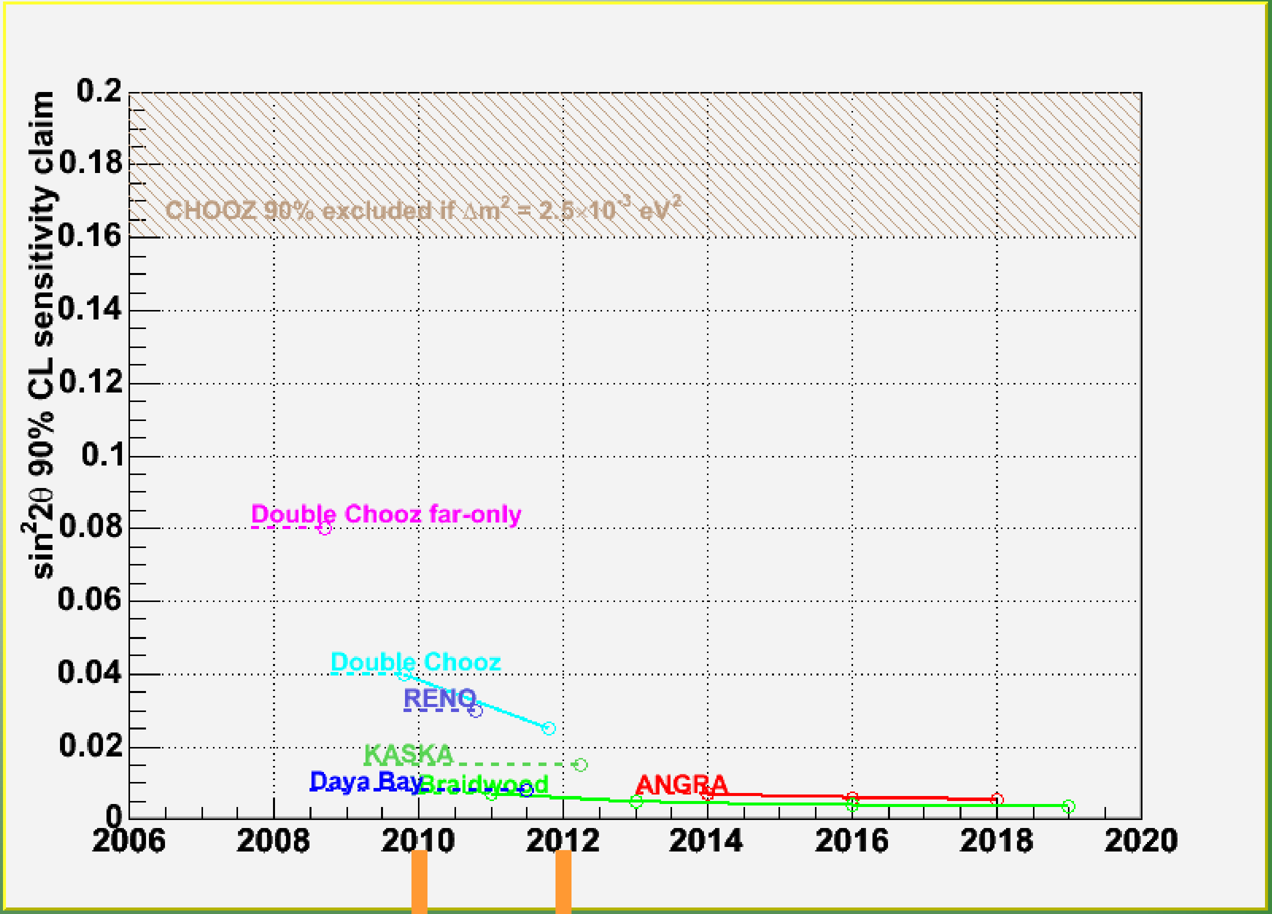
# Systematic Errors Matter

conventions

- d/D: detectors
- b/B: bin (energy)
- capital: correlated
- small: uncorrelated



# Proposed Schedules




Nova at Full Luminosity

T2K at Full Luminosity

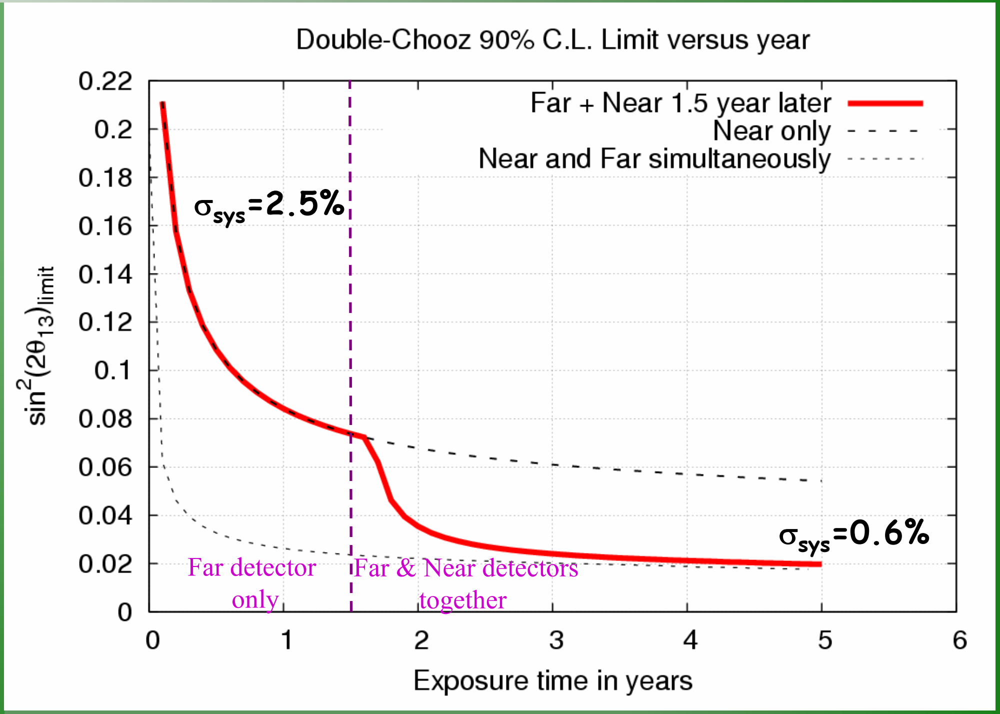
# Funding in the US

- Reactor experiments made proposals to DOE and NSF in October of 2004
- A Neutrino Scientific Assessment Group (NuSAG) has heard proposals from US groups to work on T2K, NOvA, and Double Chooz, and R&D proposals for groups working on Braidwood and Daya Bay.
- A recommendation to DOE/NSF was expected in September-October 2005.

….*still waiting*

# First Data expected from Double Chooz

- Europeans are not allowing delays to the schedule
- Far Detector begins data taking in 2007
- Near detector follows 16 months later
- Double Chooz can surpass the original CHOOZ bound in 6 months
- $\Delta m^2_{atm}$ = 2.8 $10^{-3}$ $eV^2$ is supposed to be known at 20% by MINOS




05/2007 05/2008 05/2009 05/2010

# Conclusions

- The future of the neutrino community is very bright
  - Focus on $\theta_{13}$ has produced a wealth of new proposals
- Off-Axis and Reactor measurements are complementary and each will help the other to gain maximum results
- Given the minimal costs ($5-50 Million), multiple reactor experiments with different systematic approaches and different background conditions will provide redundancy and better confidence
- We look forward to exciting results within the next 3 years.