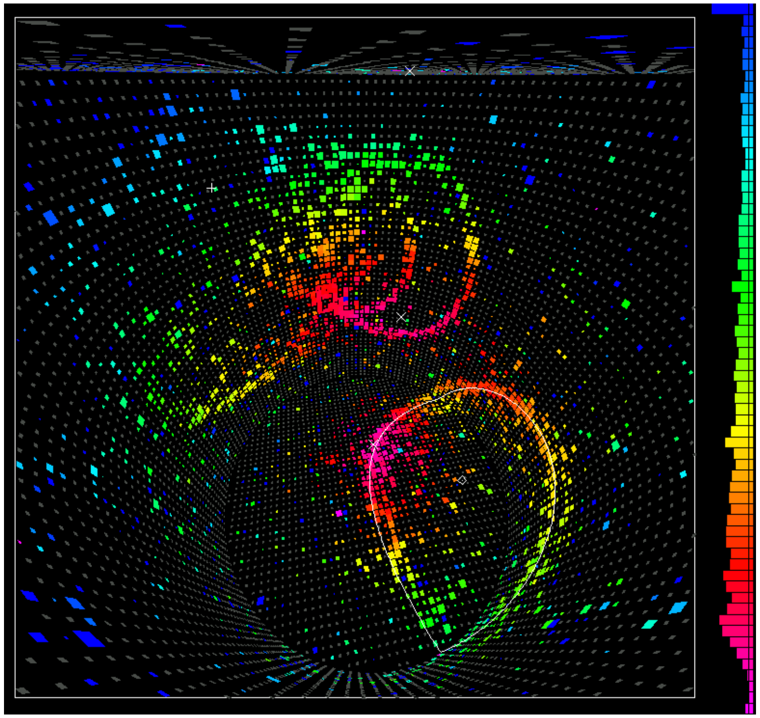
XII MEXICAN WORKSHOP ON PARTICLES AND FIELDS

Present and Future Oscillation Experiments: Lecture 3

M. Shaevitz
Columbia University



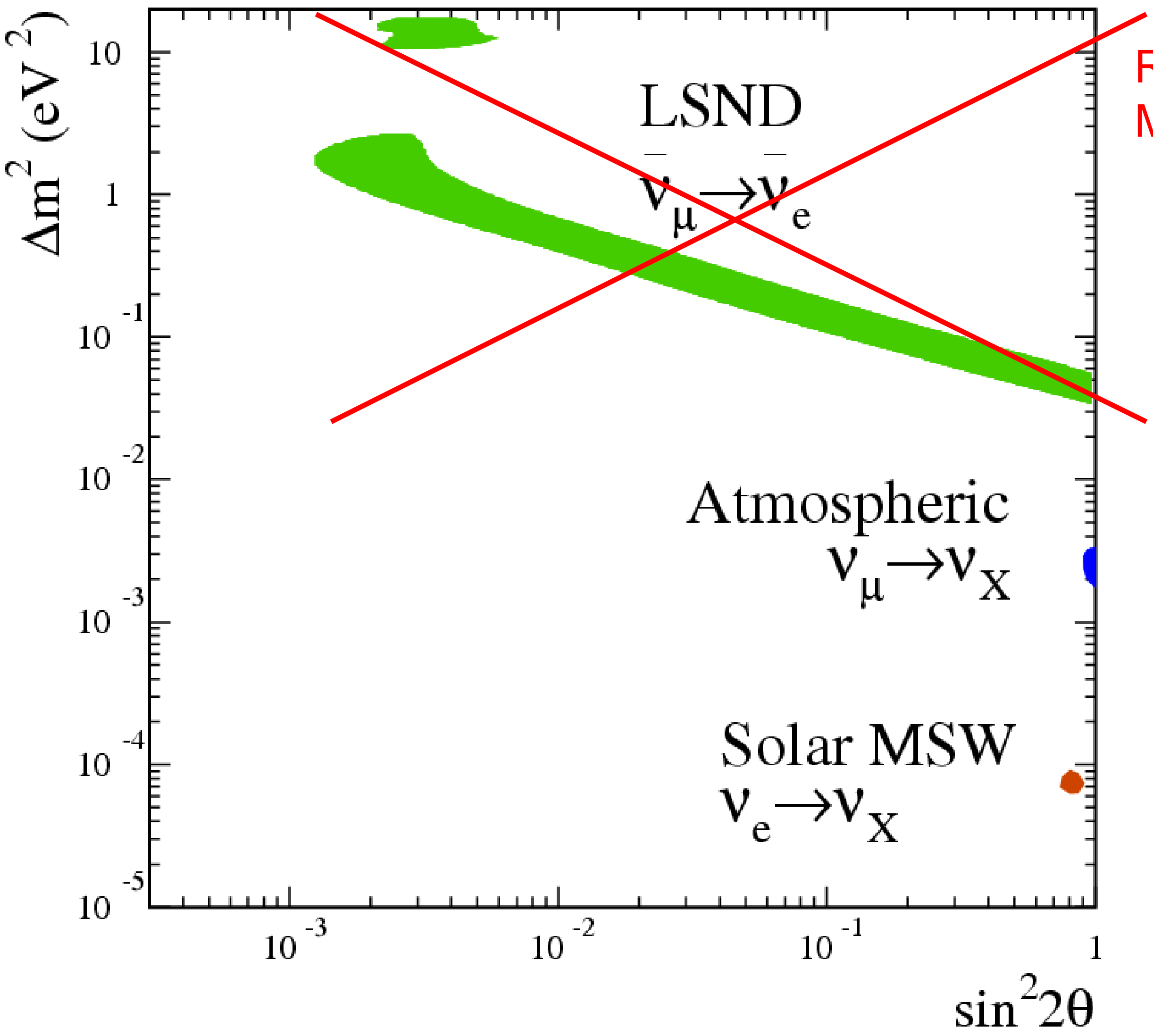
Outline

- Lecture 1: Experimental Neutrino Physics
  - Neutrino Physics and Interactions
  - Neutrino Mass Experiments
  - Neutrino Sources/Beams and Detectors for Osc. Exp's

- Lecture 2: The Current Oscillation Results
  - Solar and Kamland Neutrino Results
  - Atmospheric and Accelerator Neutrino Results
  - Global Oscillation Fits

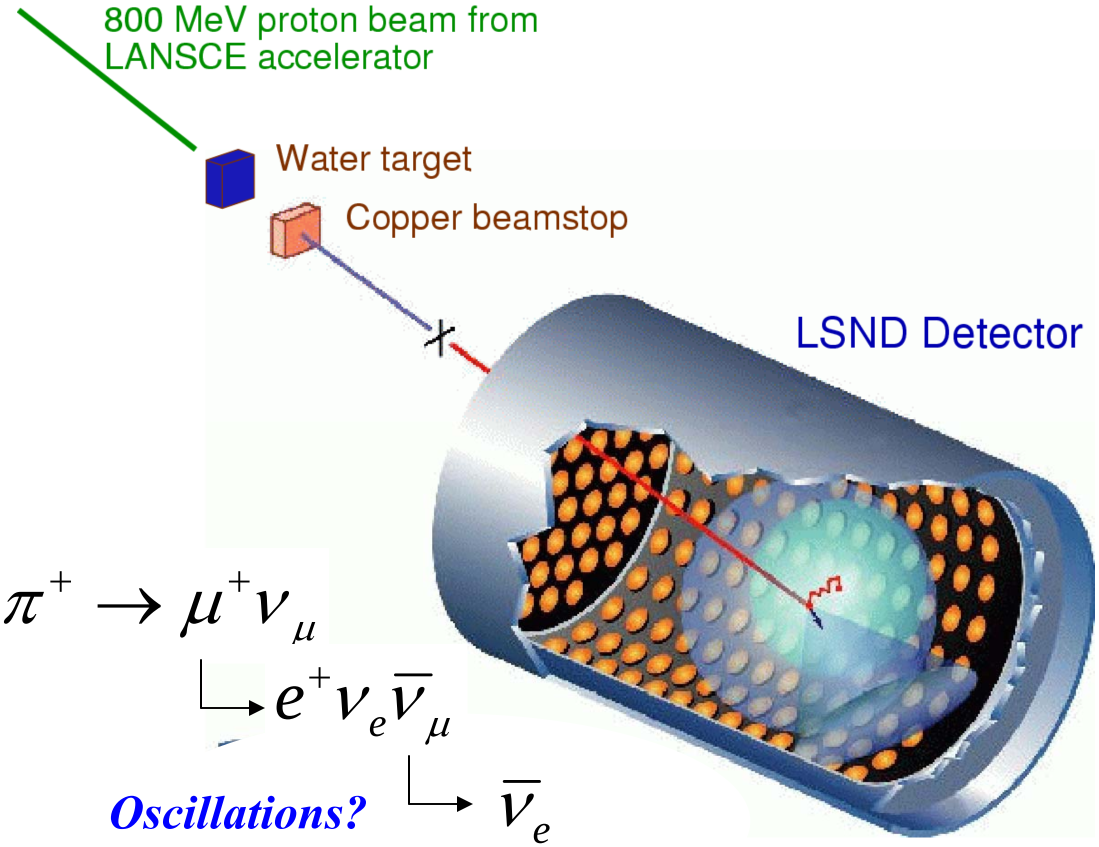
- Lecture 3: Present and Future Oscillation Experiments
  - The Fly in the Ointment: LSND and MiniBooNE
  - Searches for θ_{13} / Mass Hierarchy / CP Violation
    - Current Hints
    - Reactor Experiments
    - Longbaseline experiments
    - Combining Experiments
  - Future Plans for Oscillation Experiments

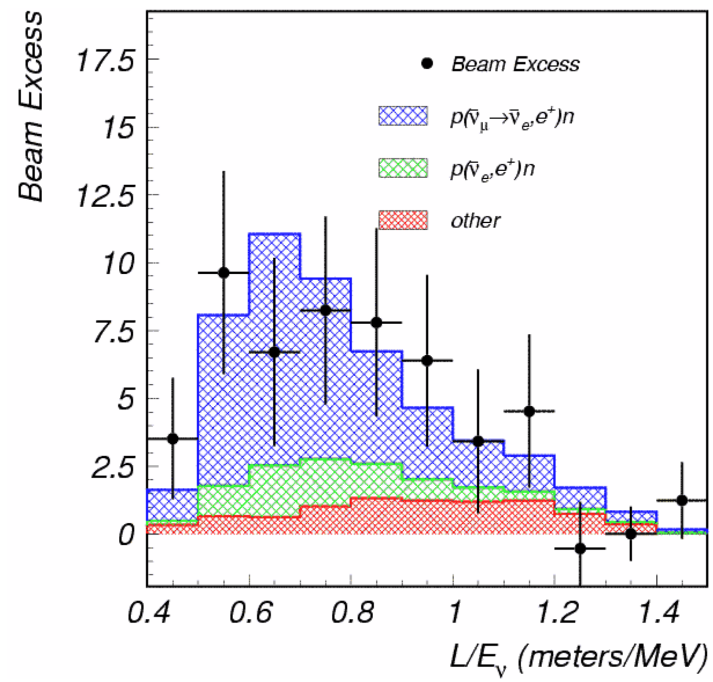
Current Oscillation Summary



Ruled out by MiniBooNE (almost)
($\bar{\nu}$ running; low-E excess)

The Fly in the Ointment – “La mosca en la sopa”
The LSND Anomaly





Saw an excess of:
87.9 ± 22.4 ± 6.0 events.

With an oscillation probability of (0.264 ± 0.067 ± 0.045)%.

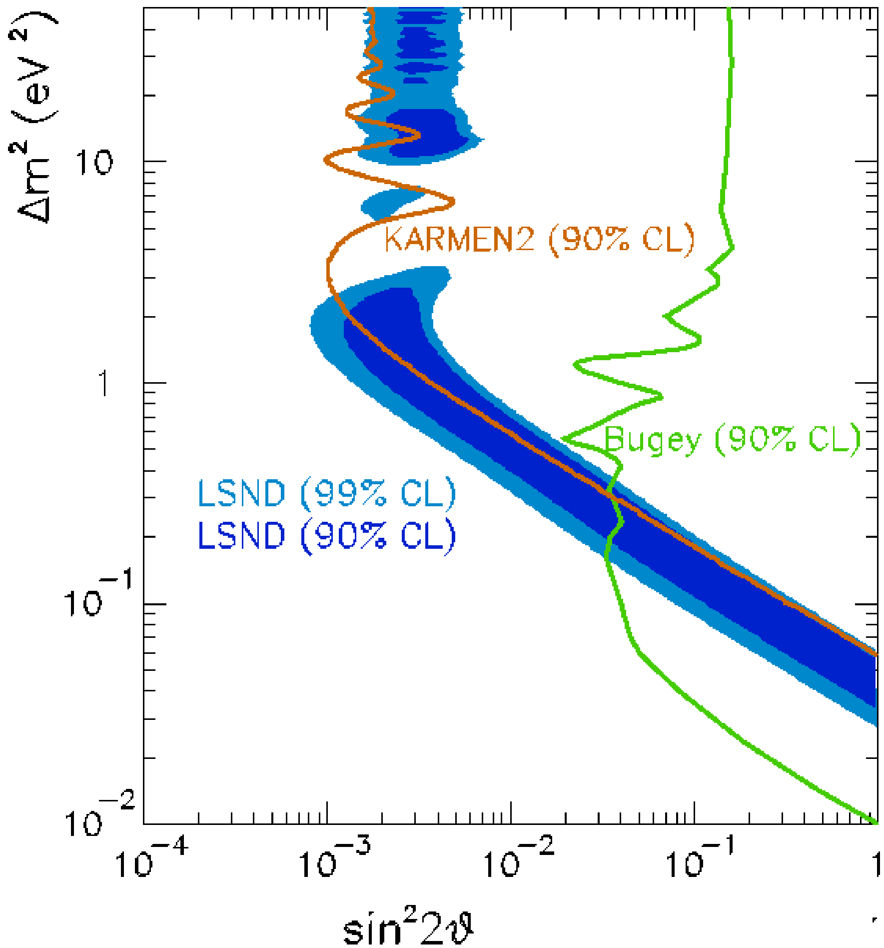
3.8 σ evidence for oscillation.

LSND took data from 1993-98
- 49,000 Coulombs of protons
- L = 30m and 20 < E_ν < 53 MeV

LSND Interpretations

LSND observed a (~3.8σ) excess of $\bar{\nu}_e$ events in a pure $\bar{\nu}_\mu$ beam: 87.9 ± 22.4 ± 6.0 events

$$\text{Oscillation Probability: } P(\bar{\nu}_\mu \to \bar{\nu}_e) = (0.264 \pm 0.067 \pm 0.045)\%$$

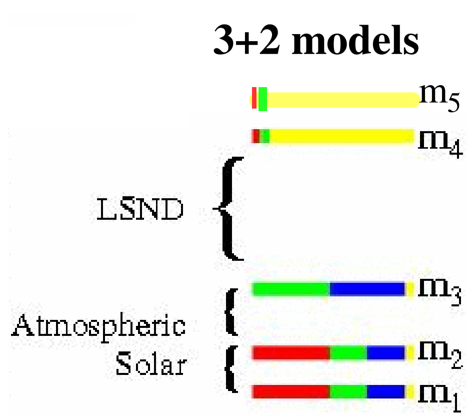


LSND in conjunction with the atmospheric and solar oscillation results needs more than 3 ν's

⇒ Models developed with 2 sterile ν's

or

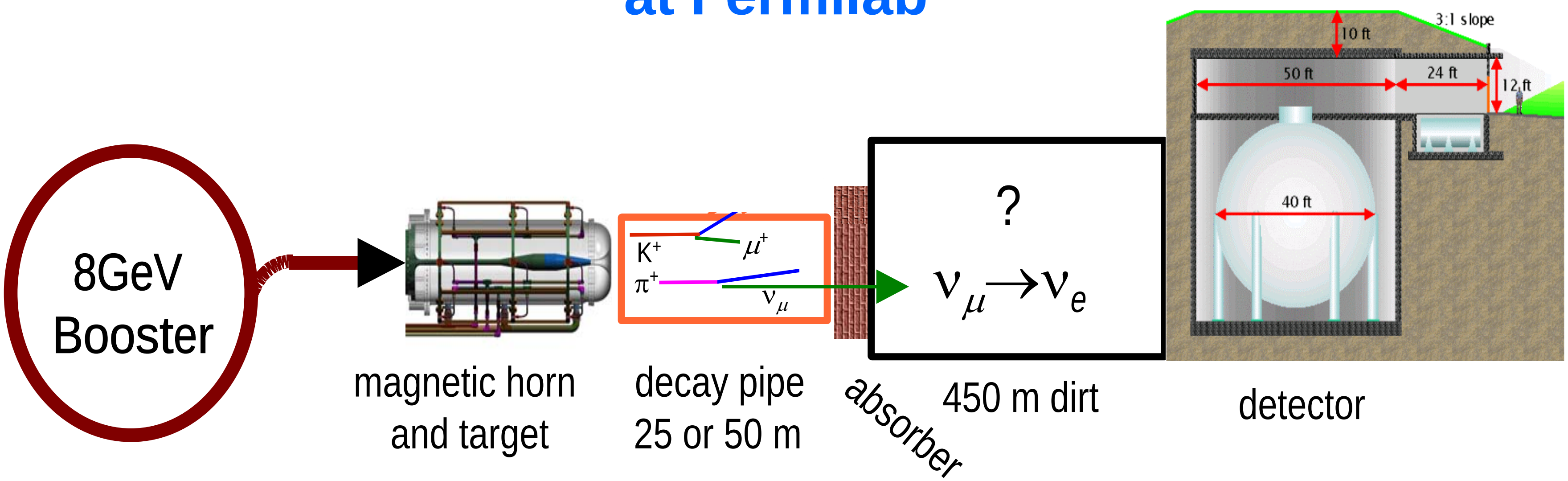
⇒ Other new physics models



(Sorel, Conrad, and Shaevitz, PRD 70(2004)073004 (hep-ph/0305255)

Karagiorgi et al., PRD75(2007)013011 (hep-ph/0609177)

The MiniBooNE Experiment at Fermilab



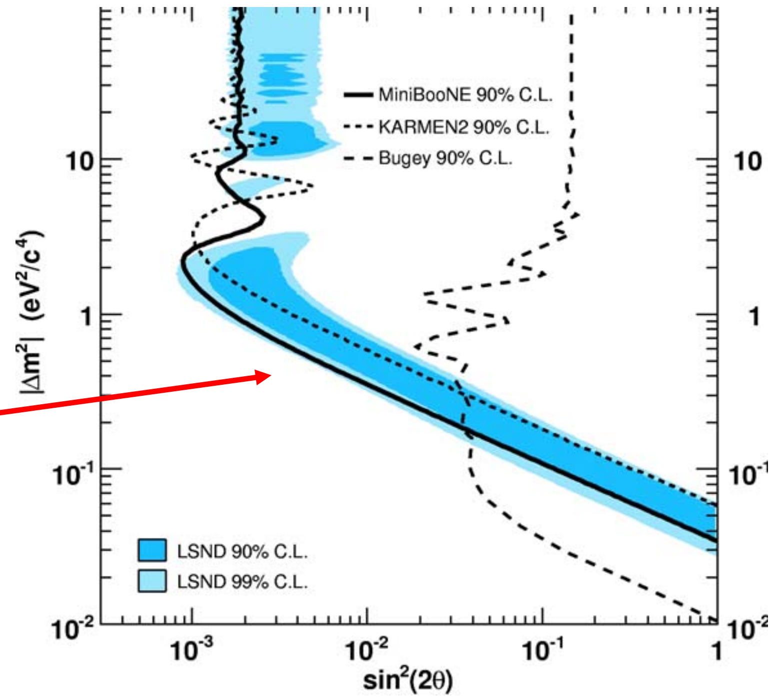
- Proposed in summer 1997, operating since 2002
- Goal to confirm or exclude the LSND result - Similar L/E as LSND
  - Different systematics: event signatures and backgrounds different from LSND
  - High statistics: ~ x5 LSND
- Since August 2002 have collected data:
  - 6.9×10^{20} POT ν
  - 5.1×10^{20} POT $\bar{\nu}$

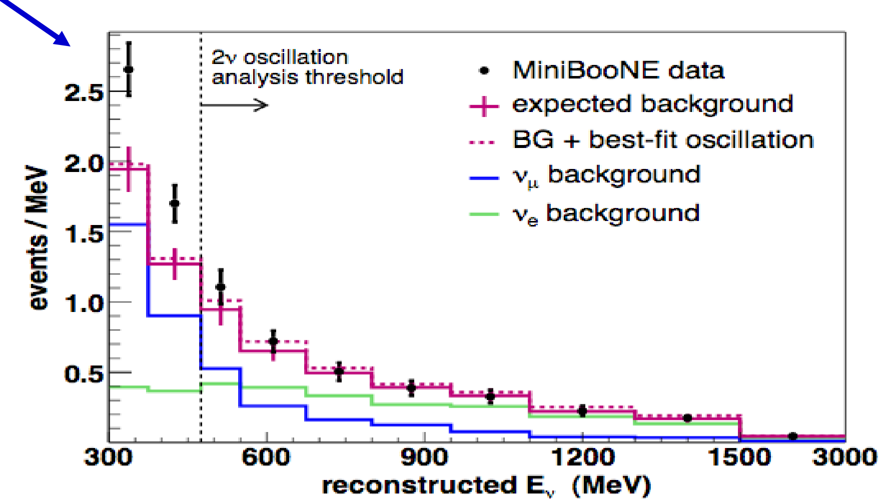
MiniBooNE $\nu_\mu \rightarrow \nu_e$ Appearance Search in LSND Region

- Method: Search for an excess of "ν_e" events over expectation
  $\Rightarrow$ Knowing expectation is key
  Use observed ν_μ events to constrain ν_e physics and background

- In analysis region between 475 < Eν < 3000 MeV, no evidence for oscillation in LSND region
  - Simple 2ν osc excluded at 98% CL

- Unexpected excess of events at low energy < 475 MeV





Phys. Rev. Lett. 98, 231801 (2007), arXiv:0704.1500 [hep-ex]

Also: "Unexplained Excess of Electron-Like Events from a 1 GeV ν Beam", PRL **102**, 101802 (2009)

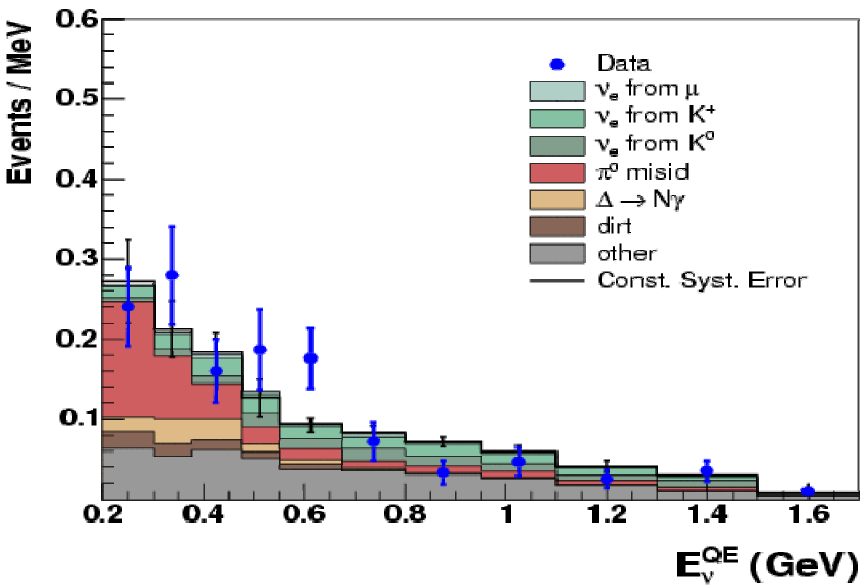
New MiniBooNE $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ Appearance Results

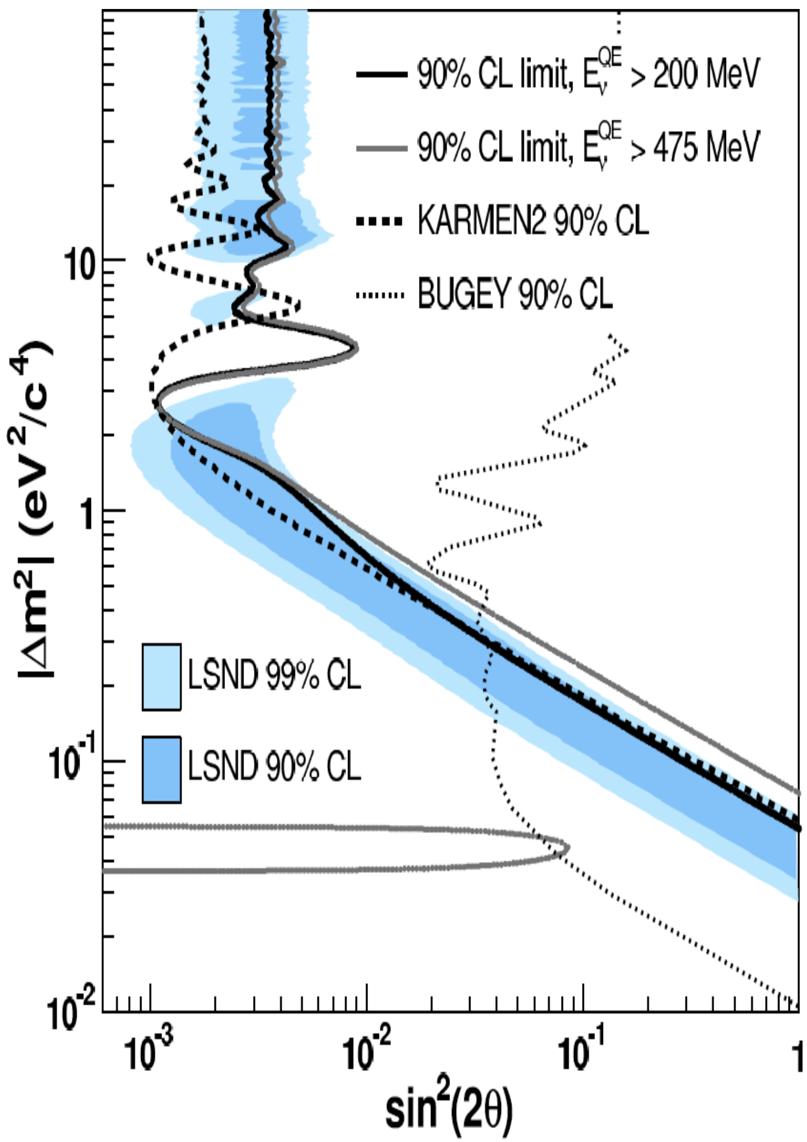
- The antineutrino search important because
  - Provides direct tests of LSND $\bar{\nu}$ appearance
  - More information on low-energy excess
- The backgrounds at low-energy are almost the same for the neutrino and antineutrino data samples.
- Antineutrino analysis is the same as the neutrino analysis.
- First antineutrino result has low statistics
  - 3.4×10^{20} POT giving about 100K event
  - **Inconclusive wrt LSND**

No indication of $\bar{\nu}$ data-MC excess:

200-475 MeV: -0.5 ± 11.7 events

475-1250 MeV: 3.2 ± 10.0 events





(arXiv:0904.1958)

Low Energy Excess Models

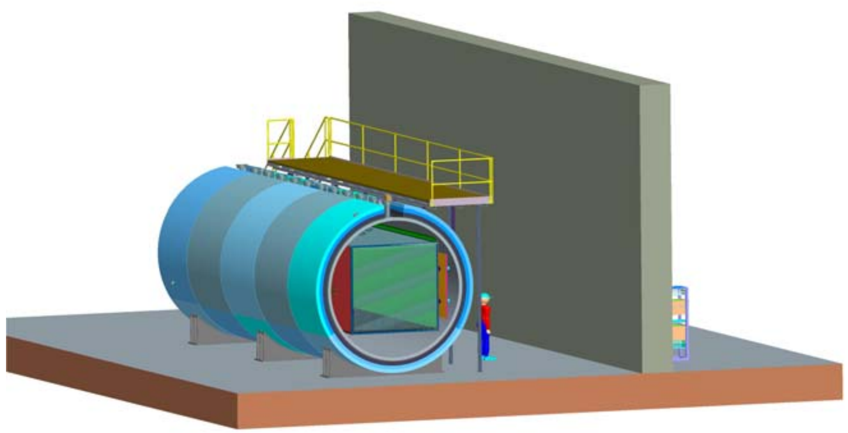
- Few standard model explanations and many new physics ideas
- Many models have equal effects in neutrinos and antineutrinos
  - $\Rightarrow$ These models are "disfavored" by absence of $\bar{\nu}_e$ excess.

Possible explanation	Status
Anomaly Mediated Neutrino-Photon Interactions: *Harvey, Hill, & Hill, arXiv: arXiv:0905.029*	Disfavored
CP-Violation 3+2 Model: *Maltoni & Schwetz, arXiv:0705.0107; T. Goldman, G. J. Stephenson Jr., B. H. J. McKellar, Phys. Rev. D75 (2007) 091301.*	Possible
Lorentz Violation: *Katori, Kostelecky, & Tayloe, Phys. Rev. D74 (2006) 105009*	Possible
CPT Violation 3+1 Model: *Barger, Marfatia, & Whisnant, Phys. Lett. B576 (2003) 303*	Possible
VSBL Electron Neutrino Disappearance: *Giunti and Laveder arXiv:0902.1992*	Disfavored
New Gauge Boson with Sterile Neutrinos: *Ann E. Nelson & Jonathan Walsh, arXiv:0711.1363*	Disfavored

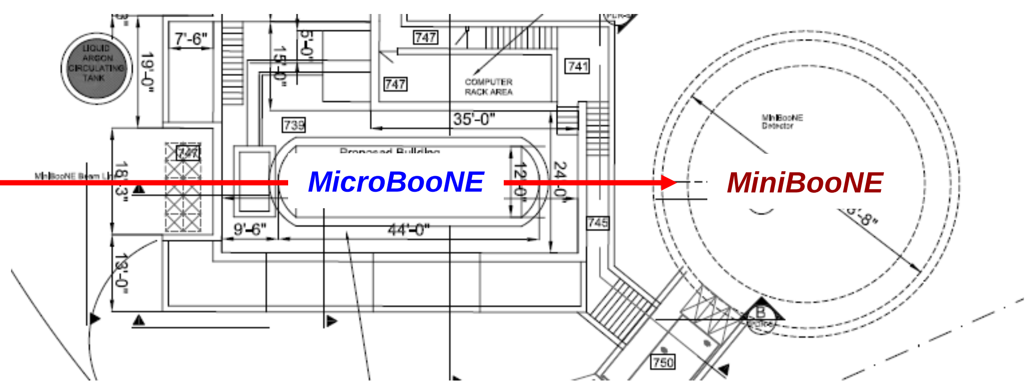
Future Plans and Prospects

- Will triple the MiniBooNE $\bar{\nu}$ data over the next 2 years
  - $\Rightarrow$ Allow better comparison of low-energy excess

- New MicroBooNE Experiment approved at Fermilab
  - Liquid Argon TPC detector which can address the low-energy excess:
    - – Reduced background levels
    - – Is excess due to single electron or photon events?
  - Approximately 70-ton fiducial volume detector, located near MiniBooNE (initial data: end 2011)



Use MiniBooNE Beamline



The Search for the "Little Mixing Angle" (θ_{13}), CP Violation, and the Mass Hierarchy

Oscillations Parameterized by 3x3 Unitary Mixing Matrix

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

$$\begin{pmatrix} \mathit{Flavor} \\ \mathit{Eigenstate} \end{pmatrix} = \begin{pmatrix} \mathit{Mixing} \quad \mathit{Matrix} \end{pmatrix} \begin{pmatrix} \mathit{Mass} \\ \mathit{Eigenstate} \end{pmatrix}$$

Three mass splittings: $\Delta m_{12}^2 = m_1^2 - m_2^2 \quad , \quad \Delta m_{23}^2 = m_2^2 - m_3^2 \quad , \quad \Delta m_{31}^2 = m_3^2 - m_1^2$

But only two are independent since only three masses

If $\delta \neq 0$, then have CP violation $\Rightarrow P(\nu_\mu \to \nu_e) \neq P(\bar{\nu}_\mu \to \bar{\nu}_e)$

solar atmospheric

Current Measurements: $\Delta m_{12}^2 = 8 \times 10^{-5}\ \mathrm{eV}^2 \quad , \quad \Delta m_{13}^2 \approx \Delta m_{23}^2 = 2.5 \times 10^{-3}\ \mathrm{eV}^2$

$$U = \begin{pmatrix} \cos\theta_{12} & \sin\theta_{12} & 0 \\ -\sin\theta_{12} & \cos\theta_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \times \begin{pmatrix} \cos\theta_{13} & 0 & e^{-i\delta_{CP}}\sin\theta_{13} \\ 0 & 1 & 0 \\ -e^{i\delta_{CP}}\sin\theta_{13} & 0 & \cos\theta_{13} \end{pmatrix} \times \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\theta_{23} & \sin\theta_{23} \\ 0 & -\sin\theta_{23} & \cos\theta_{23} \end{pmatrix}$$

3-mixing angles

Solar: $\theta_{12} \sim 33°$

"Little mixing angle, θ_{13}"
$\sin^2 2\theta_{13} < 0.2$ at 90% CL
(or $\theta_{13} < 13°$) and δ = ??

Atmospheric: $\theta_{23} \sim 45°$

CP Violation in Neutrino Oscillations

- Disappearance measurements cannot see CP violation effect

$$P(\nu_\mu \to \nu_\mu) = P(\bar{\nu}_\mu \to \bar{\nu}_\mu)$$

- Very, very hard to see CP violation effects in exclusive (appearance) measurements.
  - Only can see CP violation effects if an experiment is sensitive to oscillations involving at least three types of neutrinos.

$$P(\nu_\mu \to \nu_e) - P(\bar{\nu}_\mu \to \bar{\nu}_e) = 4\,\mathrm{Im}(U_{\mu 1} U^*_{e1} U^*_{\mu 3} U_{e3})(s_{12} + s_{23} + s_{31})$$

where $s_{ij} = \sin(\delta m^2_{ij} L/2E)$ and $\delta m^2_{ij} = m_i^2 - m_j^2$

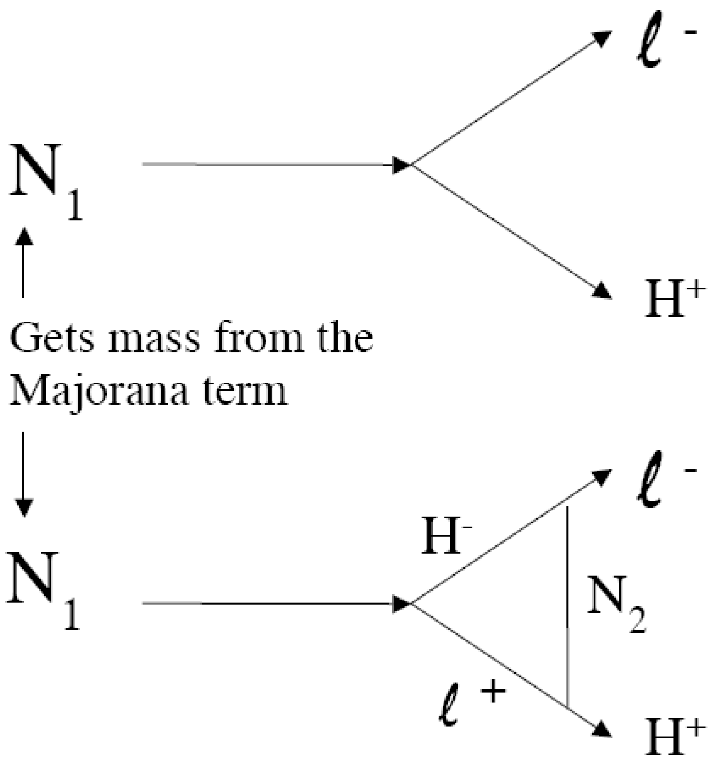
  - All the terms (s_{12}, s_{13}, s_{23}) must not be $\ll 1$ or effectively becomes only two component oscillation
    - For example, if $s_{31} \approx 0$ then $s_{12} \approx -s_{23} \Rightarrow s_{12} + s_{31} + s_{23} \approx 0$

$\Rightarrow$ **To see CP violation must be sensitive to all three neutrino oscillations**

$\Rightarrow$ **Make L/E experiment appropriate for $\Delta m^2_{23} = 2.5 \times 10^{-3}$ eV^2 and look for the small effects from $\Delta m^2_{12} = 8 \times 10^{-5}$ eV^2**

CP violation in the neutrino sector may explain the matter-antimatter asymmetry in the universe

Before the electroweak phase transition…

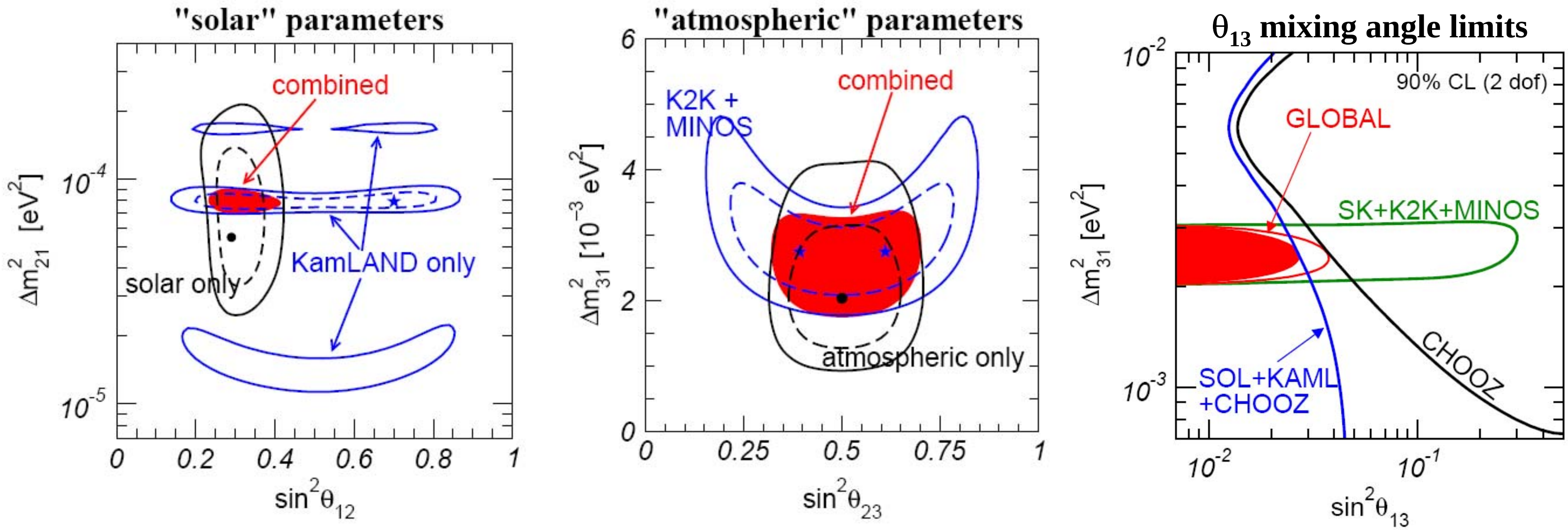


Interference between these two types of diagrams can lead to a different rate of decay to particles than antiparticles

→ **CP Violation**

which seems more plausible if we see CP violation in the light neutrinos

Current Global Fits to Solar, Atmospheric, Accelerator, and Reactor Data

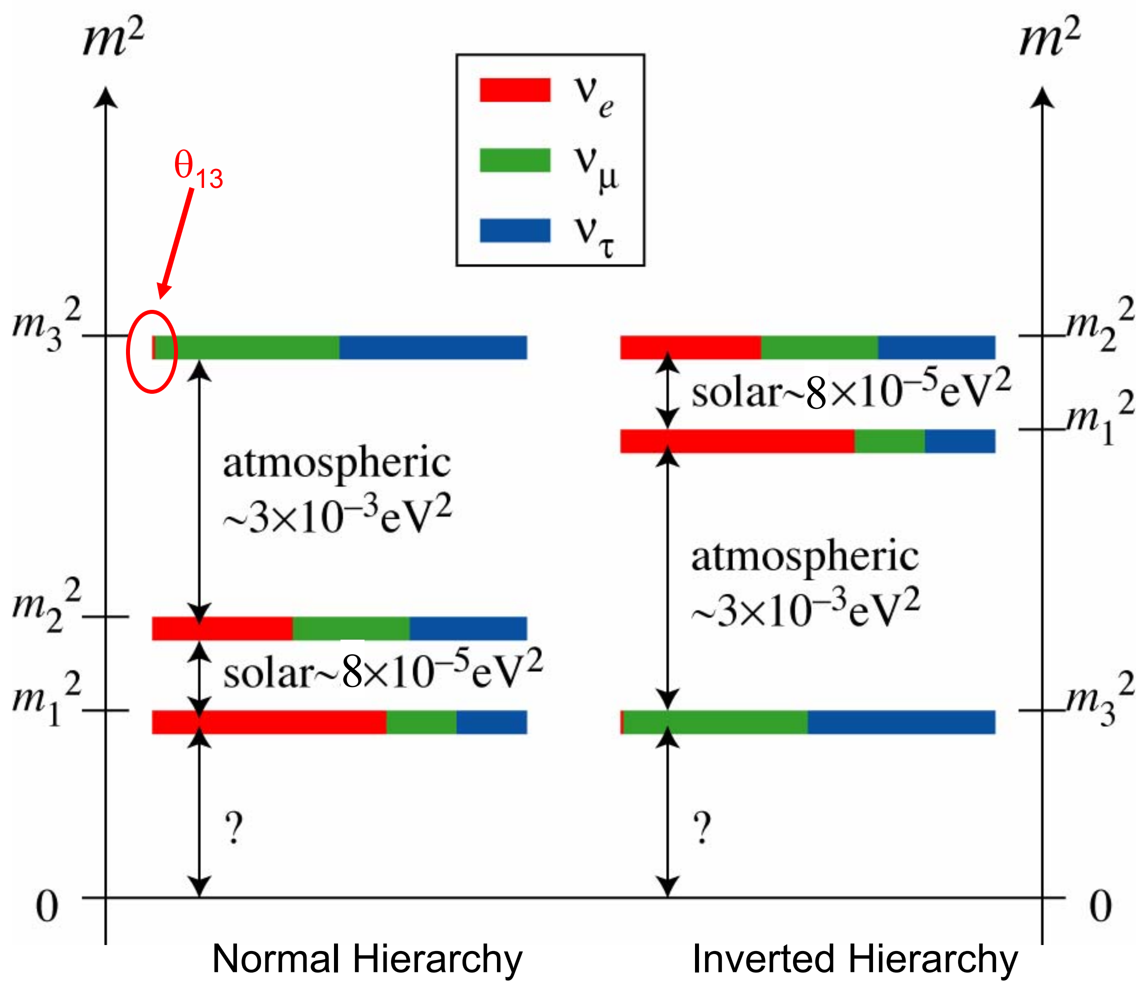


Parameter	Best fit	2σ	3σ
Δm^2_{21} $(10^{-5}\mathrm{eV}^2)$	7.6	7.3–8.1	7.1–8.3
$\lvert\Delta m^2_{31}\rvert$ $(10^{-3}\mathrm{eV}^2)$	2.4	2.1–2.7	2.0–2.8
$\sin^2\theta_{12}$	0.32	0.28–0.37	0.26–0.40
$\sin^2\theta_{23}$	0.50	0.38–0.63	0.34–0.67
$\sin^2\theta_{13}$	0.007	≤ 0.033	≤ 0.050

Big Questions in Neutrino Oscillations

Still missing some information

1. What is ν_e component in the ν_3 mass eigenstate?
   $\Rightarrow$ The size of the "little mixing angle", θ_{13} ?
   – Only know $\theta_{13}<13^0$
2. Is the μ - τ mixing maximal?
   – $35^0 < \theta_{23} < 55^0$
3. What is the mass hierarchy?
   – Is the solar pair the most massive or not?
4. What is the absolute mass scale for neutrinos?
   – We only know Δm^2 values
5. Do neutrinos exhibit CP violation, i.e. is $\delta \neq 0$?



What $\sin^2 2\theta_{13}$ Sensitivity Is Needed?

- Theoretical / Phenomenology
  - Really no solid information or constraints.
    - $U_\nu \neq U_{CKM}$
    - Data driven not theory driven field
    - $\sin^2 2\theta_{13}$ could be very small if associated with some symmetry.
  - Models:
    - Simple models do not fit current oscillation data

      $\Rightarrow$ Put in small? perturbations

      $\theta_{13} = \Delta m_{solar}^2/\Delta m_{atmos}^2$ or $\sqrt{(..)}$

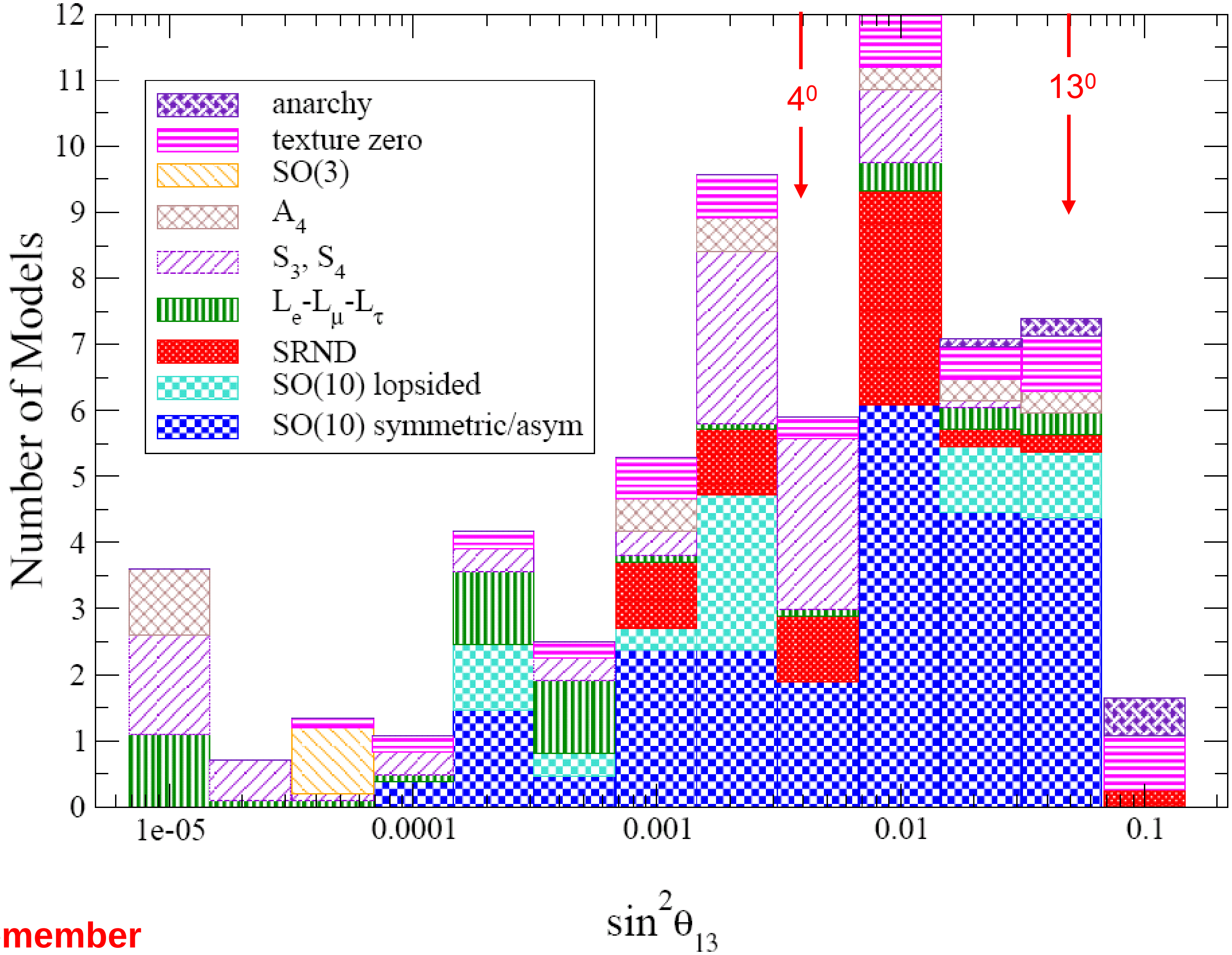
      or $\sqrt{(m_e/m_\mu)}$

      (i.e. Altarelli,Feruglio, hep-ph/0206077)

    ?? $\sin^2 2\theta_{13} \approx$ very small to CHOOZ limit??

- Practical / Political
  - Information for next step
    - Need $\sin^2 2\theta_{13} > \sim 0.01$ to measure neutrino mass hierarchy and CP violation with longbaseline exp's
      - Probably will not embark on expensive (~500M$) project without a clear measurement of $\sin^2 2\theta_{13}$
  - Competition and Complementarity
    - Proposed experiments have sensitivity in the $> \sin^2 2\theta_{13} \approx 0.01$ region
      - Combination of appearance and disappearance may be powerful if comparable sensitivity

Predicted Values of θ_{13} for Various Models



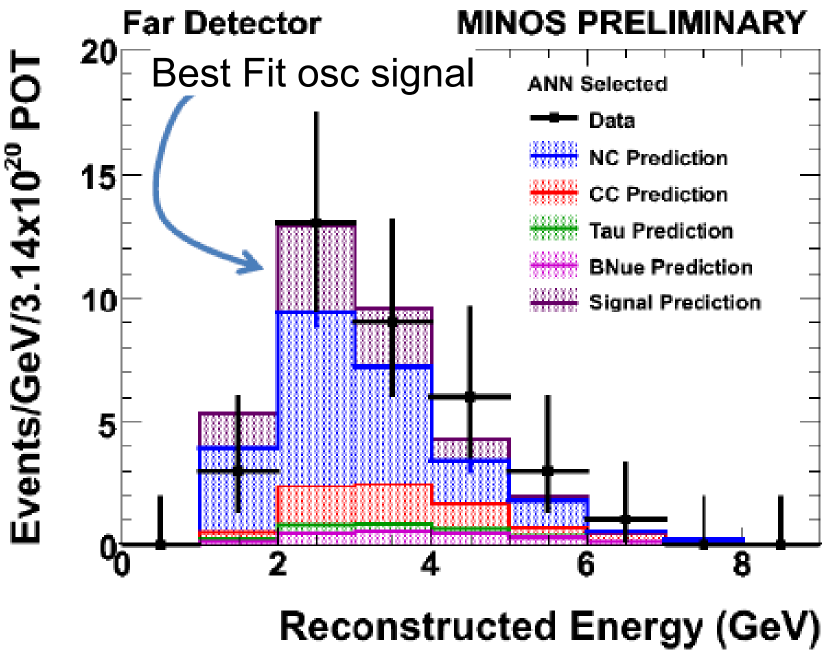
Remember
$\sin^2 2\theta_{13} = 4 \sin^2\theta_{13}$

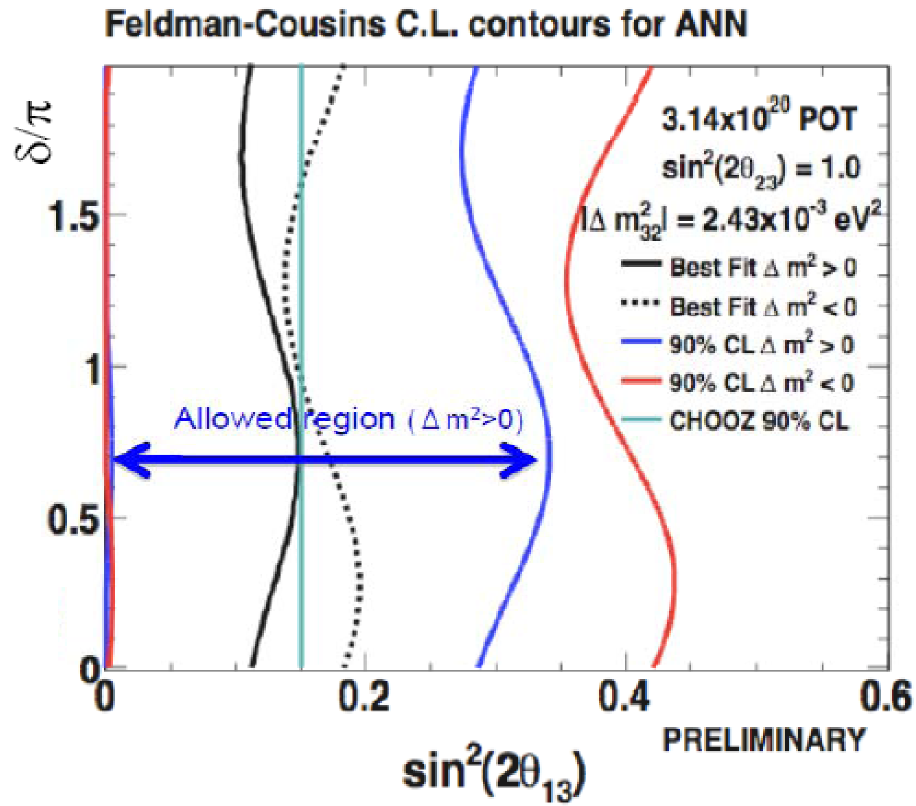
Carl H. Albright,
arXiv:0803.4176v1 [hep-ph] 28 Mar 2008

MINOS ν_e Appearance: Hint of θ_{13}?

A.Habig, TAUP2009

35 ν_e candidate events are selected at the Far detector.
Expected background: 27±5(stat)±2(syst) (1.5 σ)

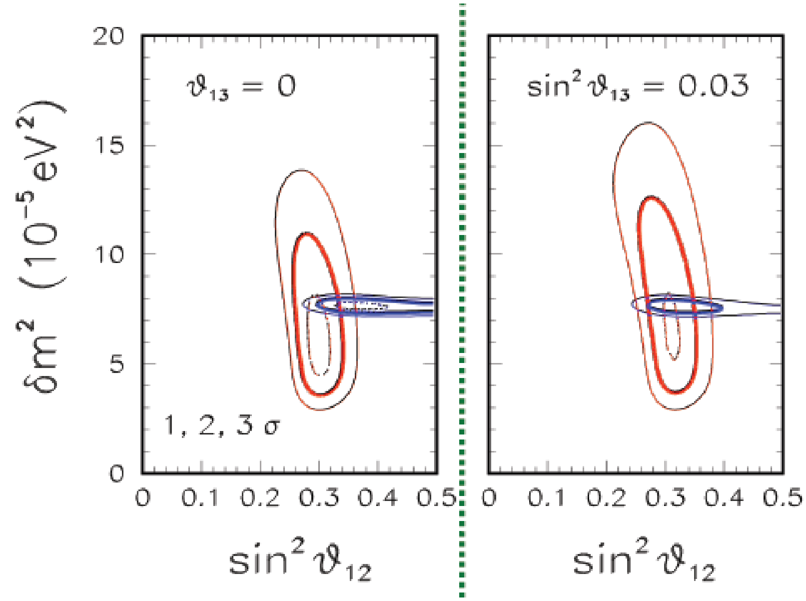




Other Hints of Non-zero θ_{13}

- 3ν analysis Atmospheric region from Super-K, K2K, and Chooz
  - Small excess of sub-GeV electron-like events if solar δm^2 included in the fit
    $\Rightarrow$ 1 sigma effect
- Solar and Kamland prefer a different value of θ_{12} unless $\theta_{13}>0$
  - 1.2 to 1.5 sigma effect
- MINOS sees a 1.5 sigma excess in ν_e appearance search

Solar (red) vs Kamland (blue)

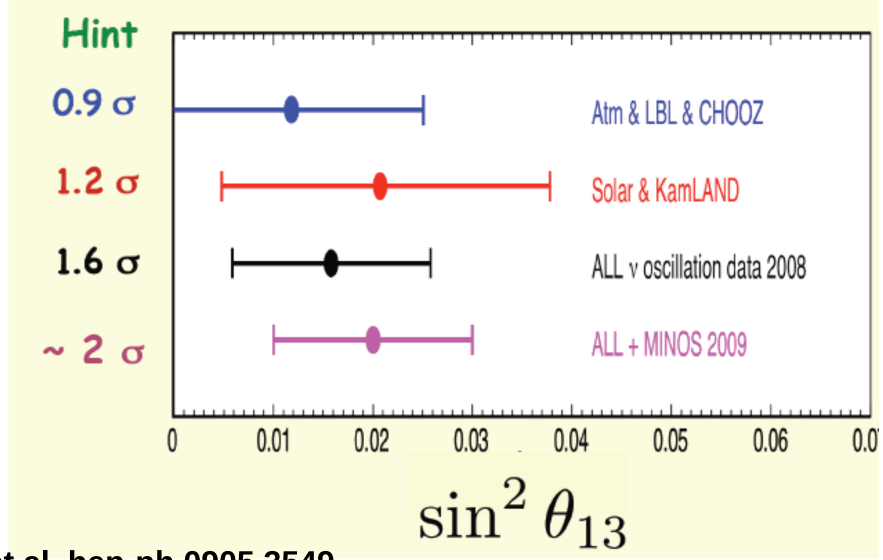


Be careful, these are regions for $\sin^2\theta_{ij}$!!

$\sin^2\theta_{13} = 0.02 \Rightarrow \sin^2 2\theta_{13} = 0.08$

Cheat Sheet:

$U_{e3}^2 = \sin^2\theta_{13} \sim ½ \sin^2\theta_{\mu e} \sim 1/4 \sin^2 2\theta_{13}$



Fogli et al. hep-ph 0905.3549

Experimental Methods to Measure the "Little Mixing Angle", θ_{13}

- Long-Baseline Accelerators: Appearance ($\nu_\mu \rightarrow \nu_e$) at $\Delta m^2 \approx 2.5\times10^{-3}$ eV^2
  - Look for appearance of ν_e in a pure ν_μ beam vs. L and E
    - Use near detector to measure background ν_e's (beam and misid)

NOνA:
$\langle E_\nu \rangle = 2.3$ GeV
L = 810 km

T2K:
$\langle E_\nu \rangle = 0.7$ GeV
L = 295 km

- Reactors: Disappearance ($\bar{\nu}_e \rightarrow \bar{\nu}_e$) at $\Delta m^2 \approx 2.5\times10^{-3}$ eV^2
  - Look for a change in $\bar{\nu}_e$ flux as a function of L and E
    - Look for a non- $1/r^2$ behavior of the ν_e rate
    - Use near detector to measure the un-oscillated flux

Double Chooz:
$\langle E_\nu \rangle = 3.5$ MeV
L = 1100 m

Long-Baseline Accelerator Appearance Experiments

- Oscillation probability complicated and dependent not only on θ_{13} but also:
  1. CP violation parameter (δ)
  2. Mass hierarchy (sign of Δm_{31}^2)
  3. Size of $\sin^2\theta_{23}$

$$
\begin{aligned}
P(\nu_\mu \to \nu_e) &= 4C_{13}^2 S_{13}^2 S_{23}^2 \sin^2 \frac{\Delta m_{31}^2 L}{4E} \times \left(1 + \frac{2a}{\Delta m_{31}^2} \ (1 - 2S_{13}^2)\right) \\
&+8C_{13}^2 S_{12} S_{13} S_{23} (C_{12} C_{23} \cos\delta - S_{12} S_{13} S_{23}) \cos \frac{\Delta m_{32}^2 L}{4E} \sin \frac{\Delta m_{31}^2 L}{4E} \sin \frac{\Delta m_{21}^2 L}{4E} \\
&-8C_{13}^2 C_{12} C_{23} S_{12} S_{13} S_{23} \sin\delta \sin \frac{\Delta m_{32}^2 L}{4E} \sin \frac{\Delta m_{31}^2 L}{4E} \sin \frac{\Delta m_{21}^2 L}{4E} \\
&+4S_{12}^2 C_{13}^2 \left\{C_{12}^2 C_{23}^2 + S_{12}^2 S_{23}^2 S_{13}^2 - 2C_{12} C_{23} S_{12} S_{23} S_{13} \cos\delta\right\} \sin^2 \frac{\Delta m_{21}^2 L}{4E} \\
&-8C_{13}^2 S_{13}^2 S_{23}^2 \cos \frac{\Delta m_{32}^2 L}{4E} \sin \frac{\Delta m_{31}^2 L}{4E} \frac{aL}{4E} \ (1 - 2S_{13}^2)
\end{aligned}
$$

$\Rightarrow$ These extra dependencies are both a "curse" and a "blessing"

Reactor Disappearance Experiments

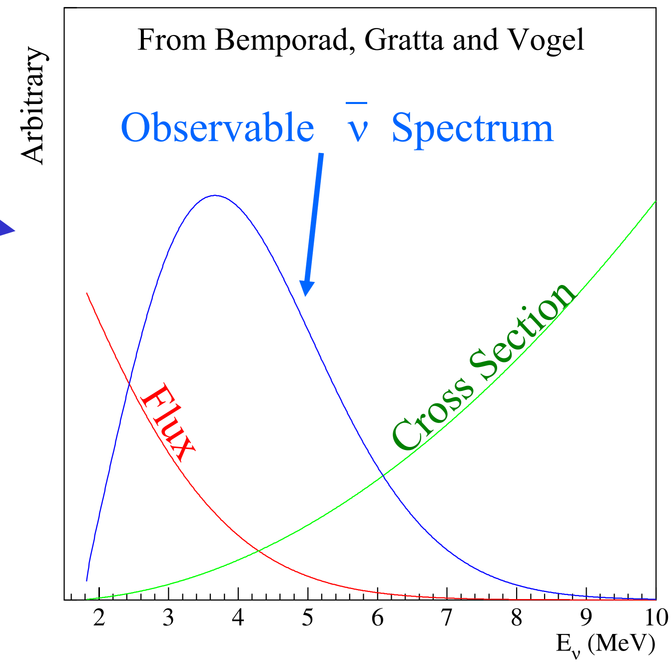
- Reactor disappearance measurements provide a straight forward method to measure θ_{13} with no dependence on matter effects and CP violation

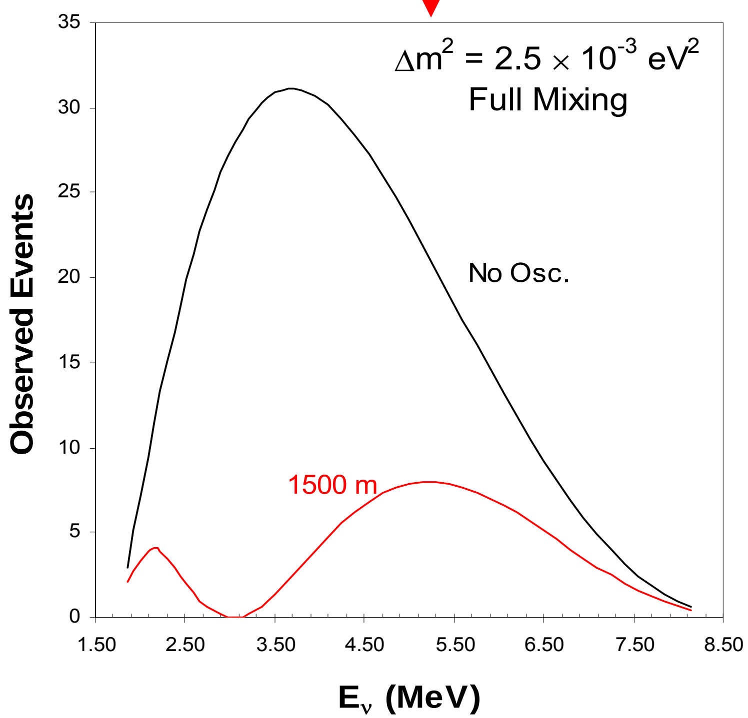
$$P(\overline{\nu}_e \to \overline{\nu}_e) = 1 - \sin^2 2\theta_{13} \sin^2 \frac{\Delta m_{13}^2 L}{4E} + \ small\ terms$$

Reactor Neutrino Experiments

Reactor Measurements of θ_{13}

- Nuclear reactors are very intense sources of $\bar{\nu}_e$ with a well understood spectrum
  - 3 GW → 6×10^{20} $\bar{\nu}_e$/s
    700 events / yr / ton at 1500 m away
  - Reactor spectrum peaks at ~3.7 MeV
  - Oscillation Max. for $\Delta m^2=2.5\times10^{-3}$ eV^2 at L near 1500 m





- Disappearance Measurement:
  Look for small rate deviation from $1/r^2$ measured at near and far baselines
  - Counting Experiment
    - Compare events in near and far detector
  - Energy Shape Experiment
    - Compare energy spectrum in near and far detector

Reactor Disappearance Oscillation Probability

- A reactor disappearance experiment provides a straight forward method to measure $\sin^2 2\theta_{13}$ with no dependence on matter effect and CP violation
  - Only complication is associated with the atmospheric and solar Δm^2 interference terms which is small.

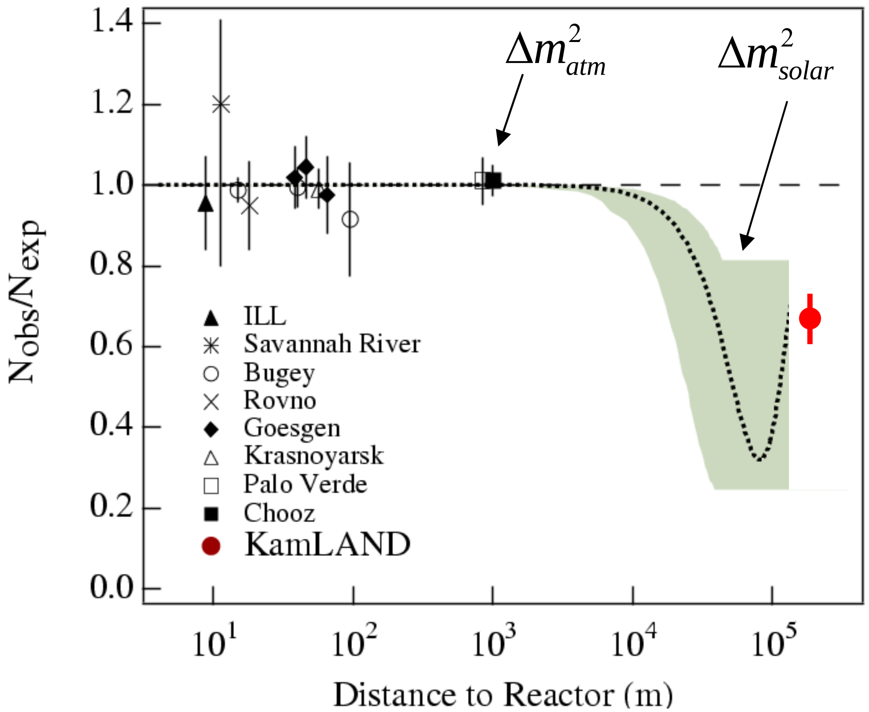
Measure θ_{13}

Measure Δm^2_{12} : Kamland

$$
\begin{aligned}
P_{\bar{\nu}_e \to \bar{\nu}_e} &= 1 - 2\sin^2\theta_{13}\cos^2\theta_{13}\sin^2\left(\frac{\Delta m^2_{31} L}{4E}\right) \\
&- \frac{1}{2}\cos^4\theta_{13}\sin^2(2\theta_{12})\sin^2\left(\frac{\Delta m^2_{21} L}{4E}\right) \\
&+ 2\sin^2\theta_{13}\cos^2\theta_{13}\sin^2\theta_{12}\left(\cos\left(\frac{\Delta m^2_{31} L}{2E} - \frac{\Delta m^2_{21} L}{2E}\right) - \cos\left(\frac{\Delta m^2_{31} L}{2E}\right)\right)
\end{aligned}
$$

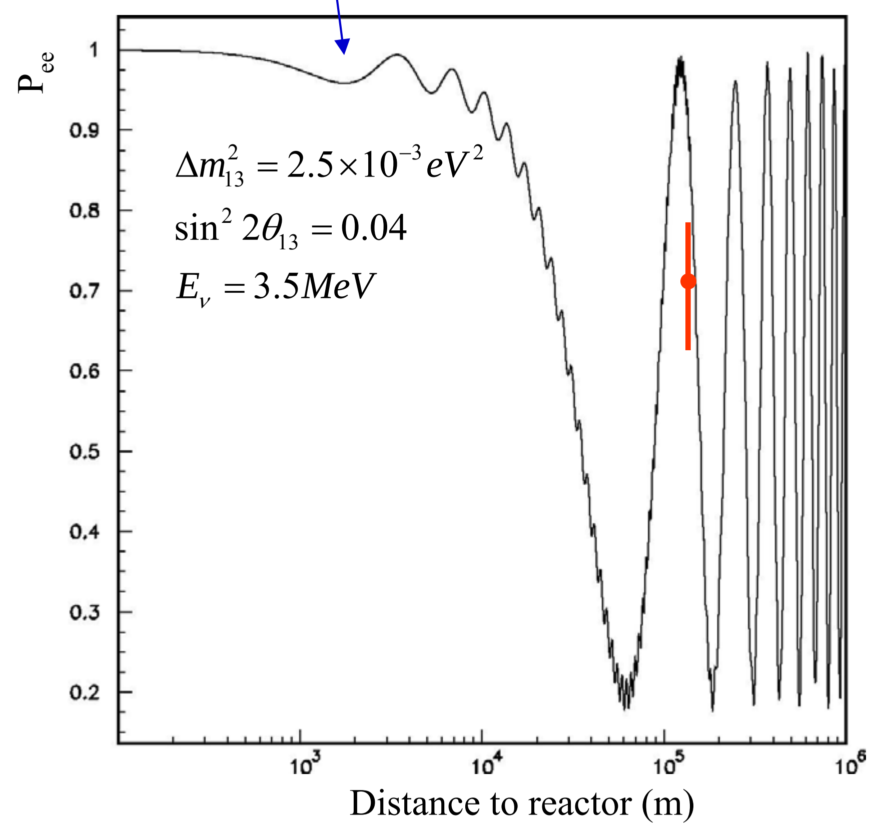
Reactor Measurements of $P(\bar{\nu}_e \rightarrow \bar{\nu}_e)$

Past measurements:



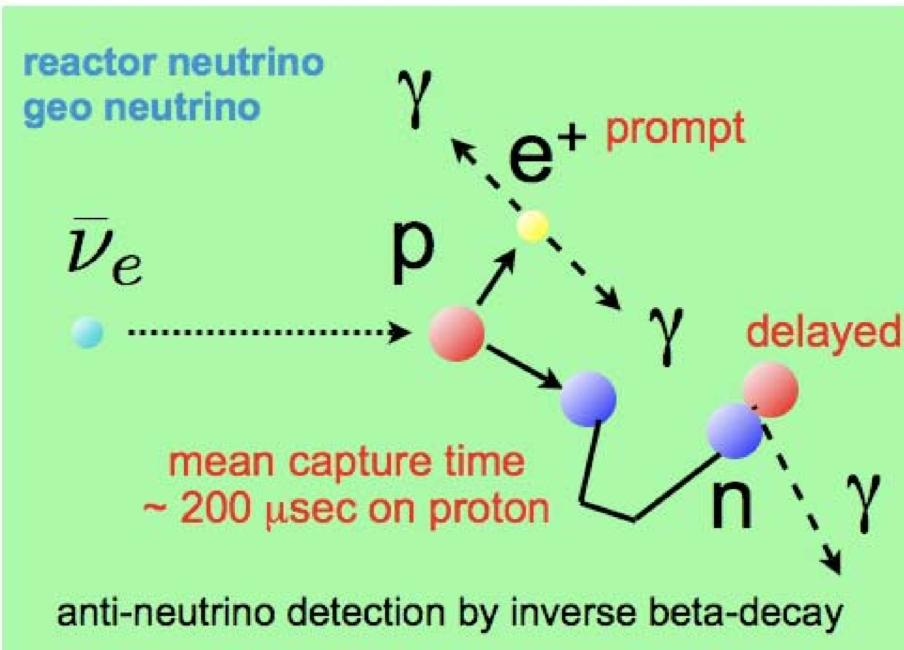
Next: Search for small oscillations at 1-2 km distance (corresponding to Δm^2_{atm}).

$$P(\bar{\nu}_e \rightarrow \bar{\nu}_e) \approx 1 - \sin^2 2\theta_{13} \sin^2 \frac{\Delta m^2_{13} L}{4E} - \sin^2 2\theta_{12} \sin^2 \frac{\Delta m^2_{12} L}{4E}$$

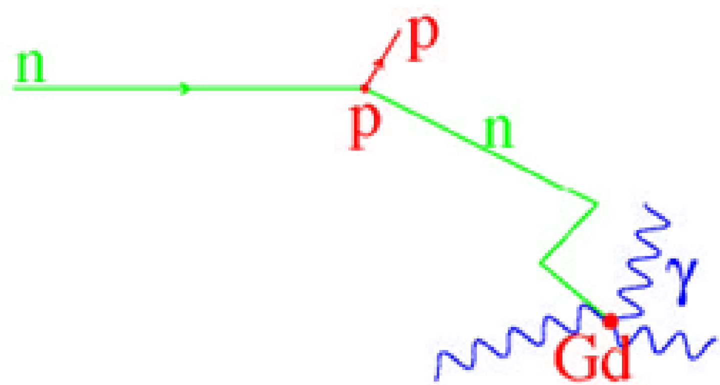


Reactor Neutrino Detection

Inverse Beta Decay (IBD) Signal



Correlated Background



Neutrons from cosmic ray muon interactions in rock ⇒ Fake signal

1) Scattered proton looks like positron
2) Neutron then gets captured

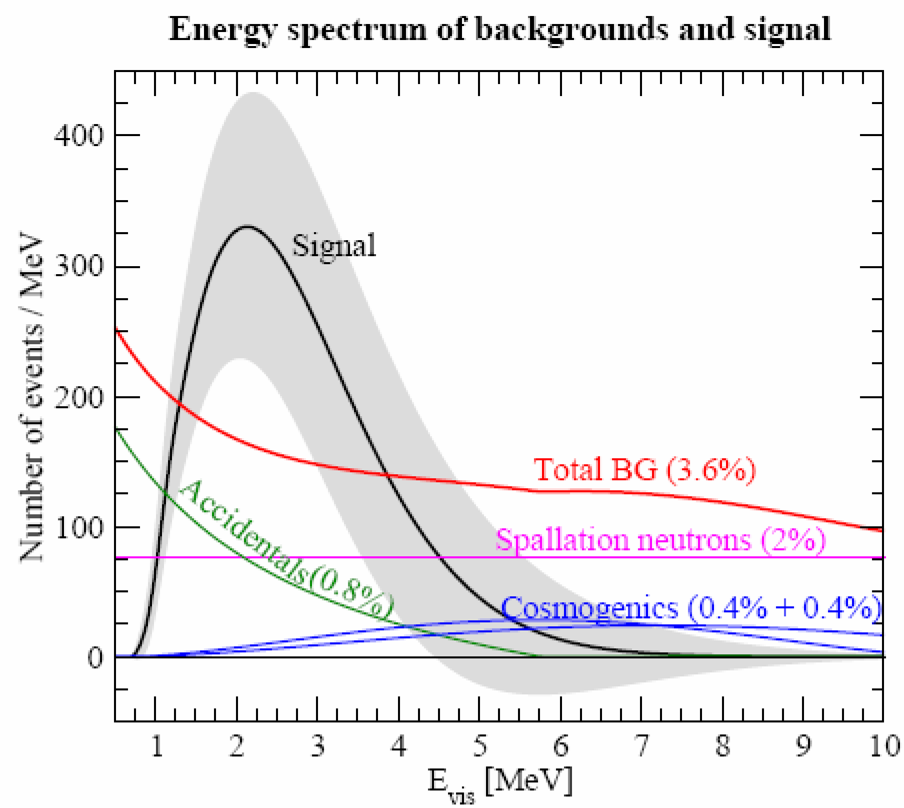
Backgrounds for Reactor Disappearance Exp's

- Backgrounds to the e^+ - n coincidence signal

  Uncorrelated Backgrounds
  - ambient radioactivity
  - accidentals
  - cosmogenic neutrons

  Correlated Backgrounds
  - cosmic rays induce neutrons in the surrounding rock and buffer region of the detector
  - cosmogenic radioactive nuclei that emit delayed neutrons in the detector

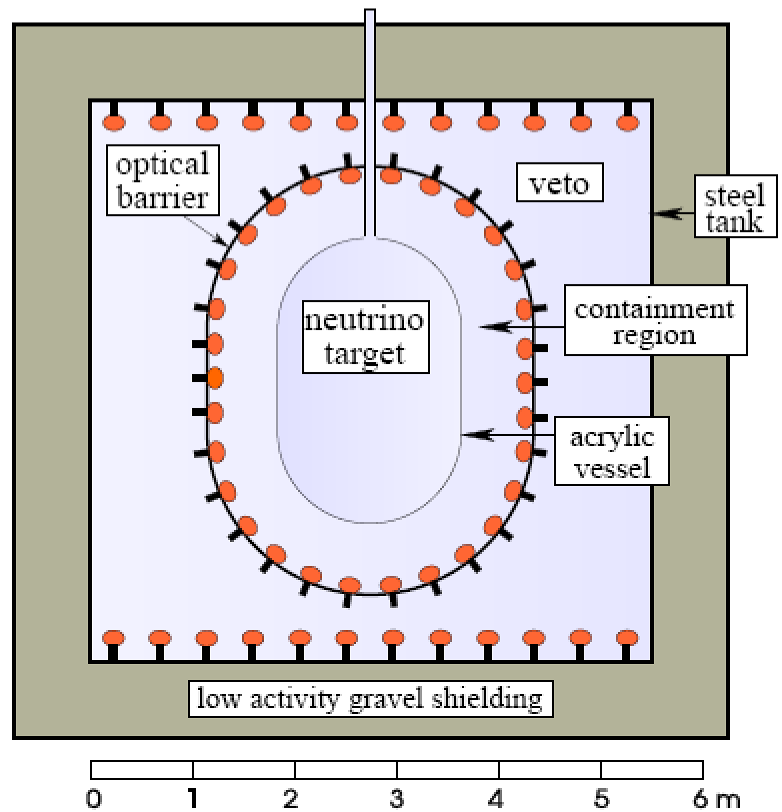
    eg. ^{8}He (T1/2=119ms)
    ^{9}Li (T1/2=178ms)



Previous CHOOZ Reactor Experiment

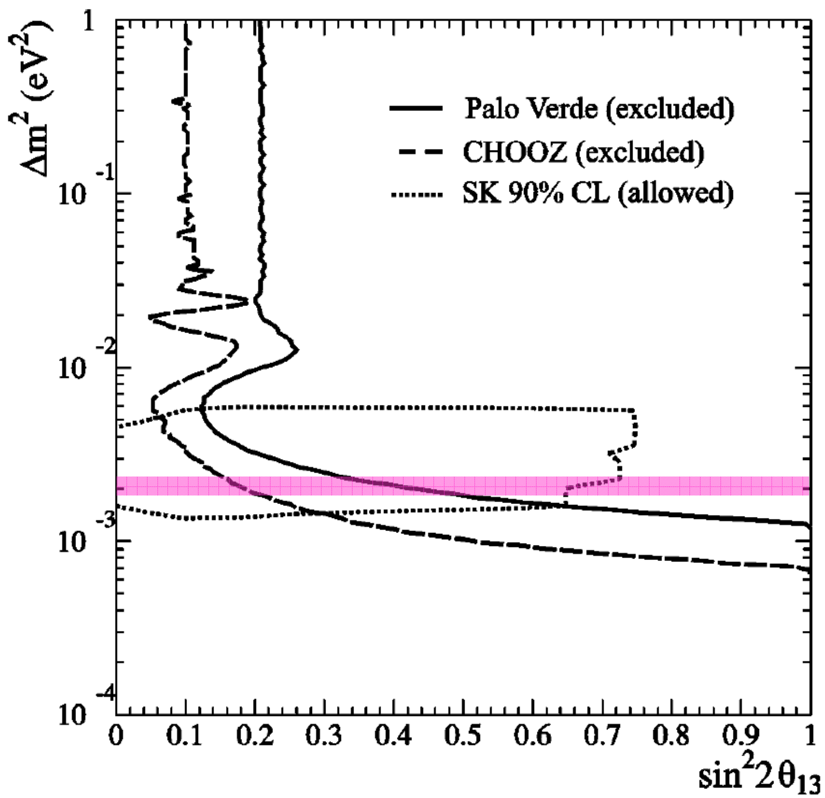
- CHOOZ Experiment probed this region
  - One detector experiments
    - Major systematic associated with reactor flux
  - Detectors used liquid scintillator with gadolinium and buffer zones for background reduction
  - Shielding:
    - CHOOZ: 300 mwe
  - Fiducial mass:
    - CHOOZ: 5 tons @ 1km, 5.7 GW
      - ~2.2 evts/day/ton with 0.2-0.4 bkgnd evts/day/ton
      - ~3600 $\bar{\nu}$ events

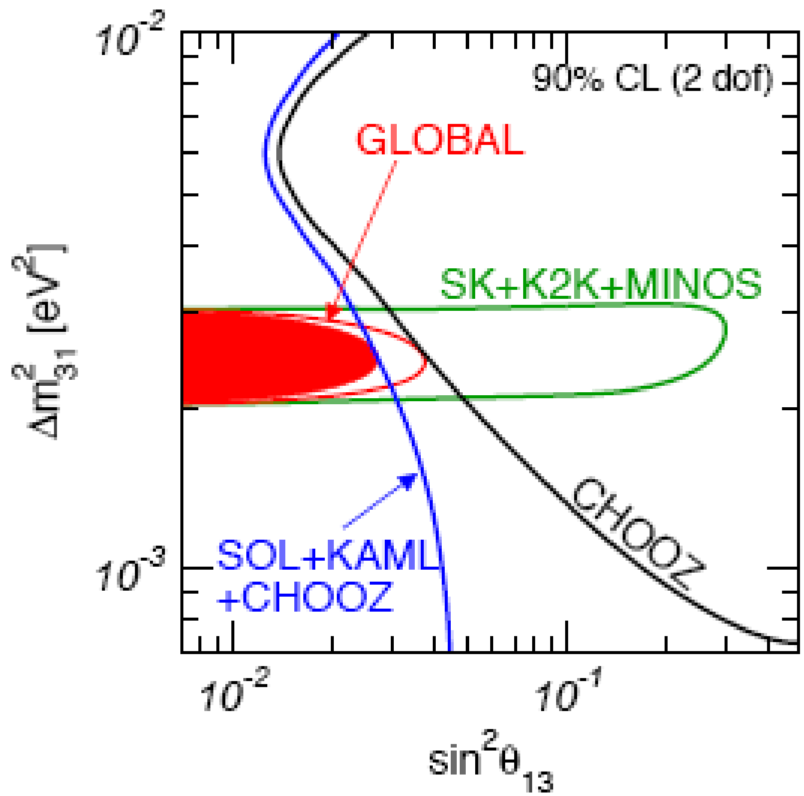
parameter	relative error (%)
reaction cross section (flux)	1.9%
number of protons	0.8%
detection efficiency	1.5%
reactor power	0.7%
energy released per fission	0.6%
combined	2.7%



Current Limits on $\sin^2\theta_{13}$

Best current limit from:
CHOOZ (single detector experiment)
$\sin^2(2\theta_{13})<0.2$
$(\sin^2(\theta_{13})<0.05)$



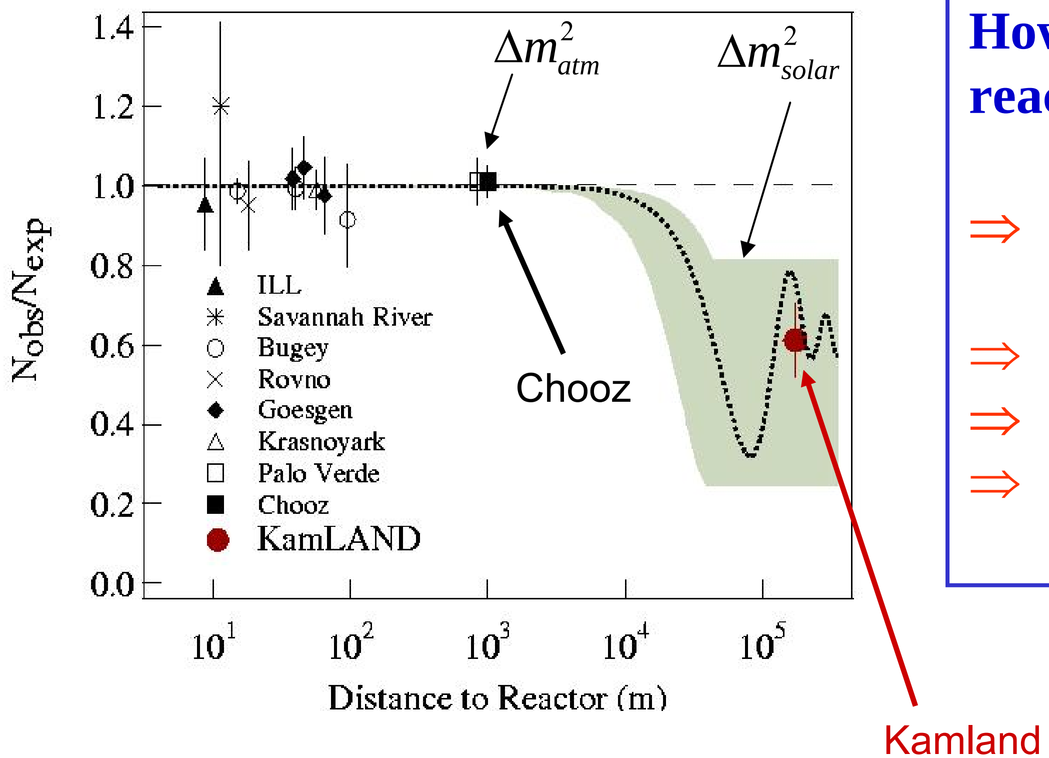


Upcoming Multi-Detector Reactor Experiments

Precision Reactor Disappearance Exp. Are Difficult

- Looking for a small change in the expected rate and/or shape of the observed event

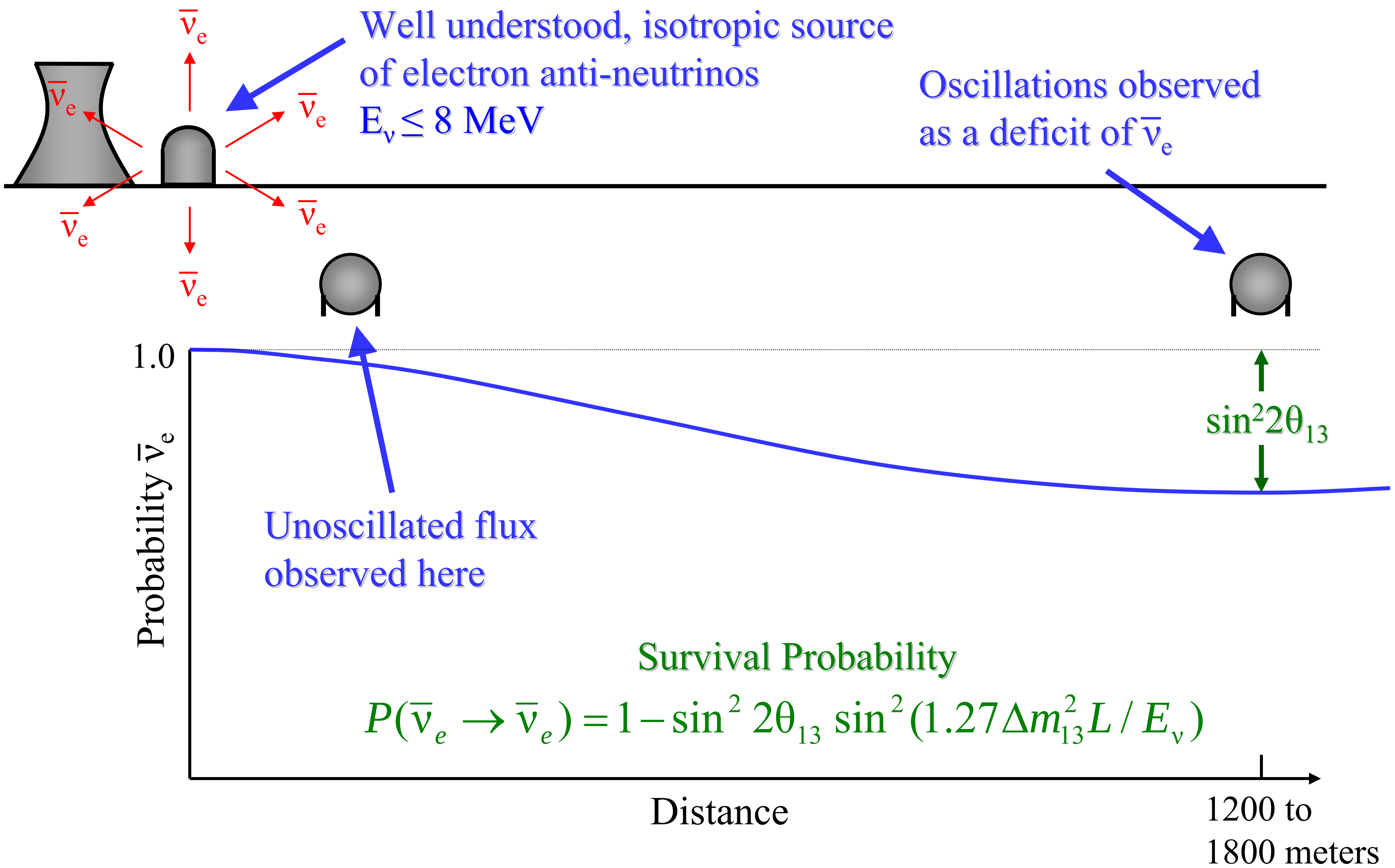
Past reactor measurements:



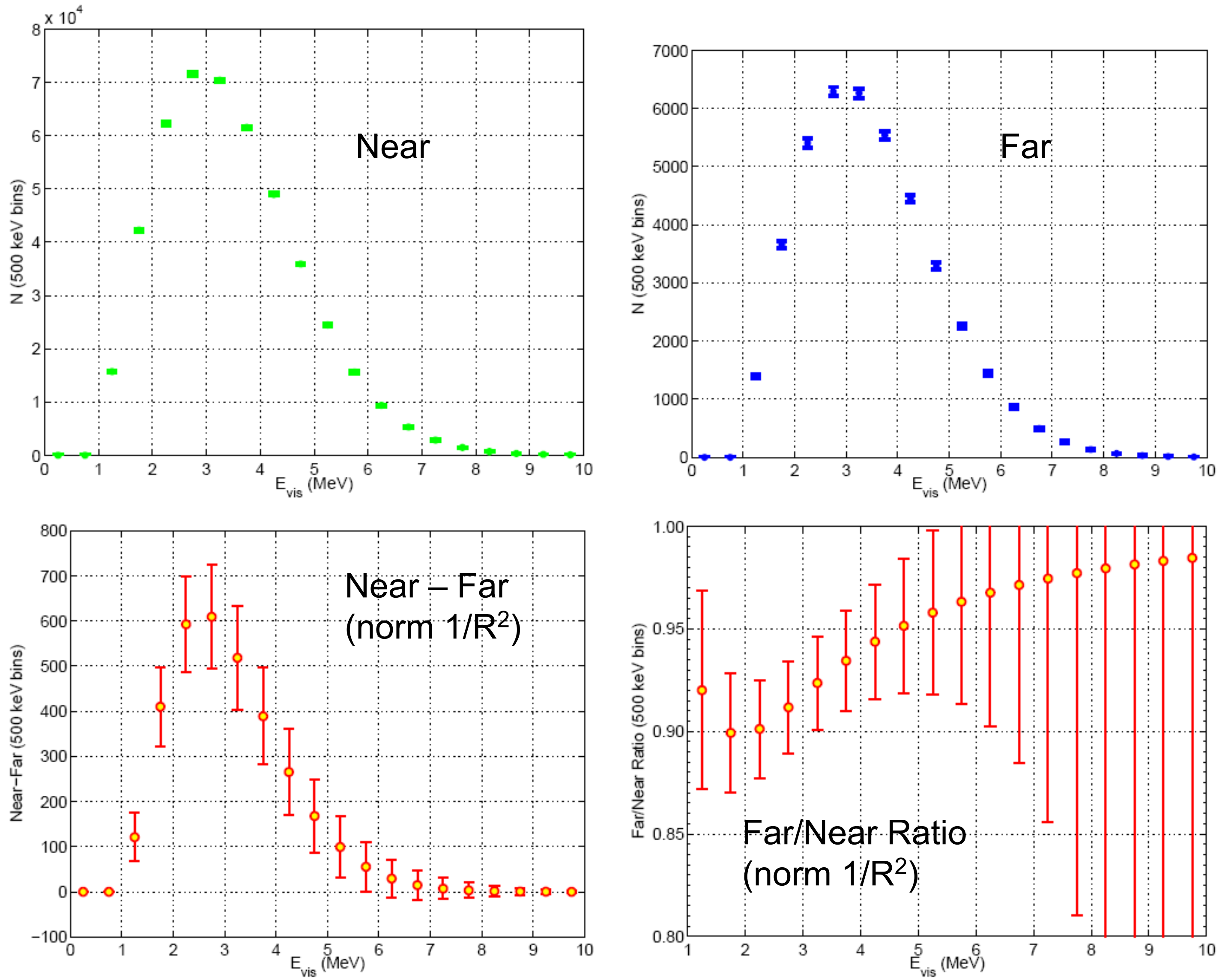
How to do better than previous reactor experiments?

⇒ **Reduce systematic uncertainties due to reactor flux and detector**
⇒ **Larger detectors**
⇒ **Reduce and control backgrounds**
⇒ **Use Near/Far Detectors**

Two Detector Reactor Experiment

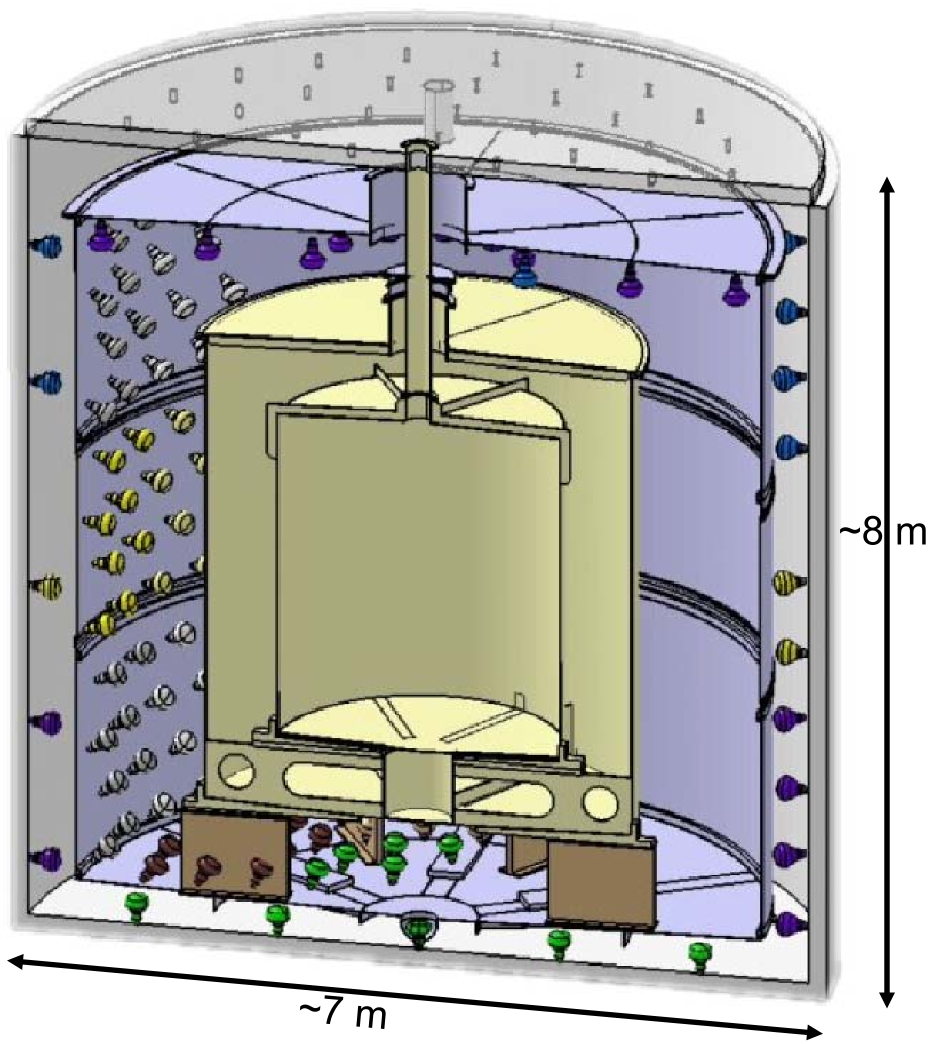


Example Measurement (Double Chooz 3 yrs)



$$\sin^2(2\theta_{13}) = 0.1 \text{ and } \Delta m^2_{31} = 2.5 \times 10^{-3}\ eV^2$$

Detector Design Basics

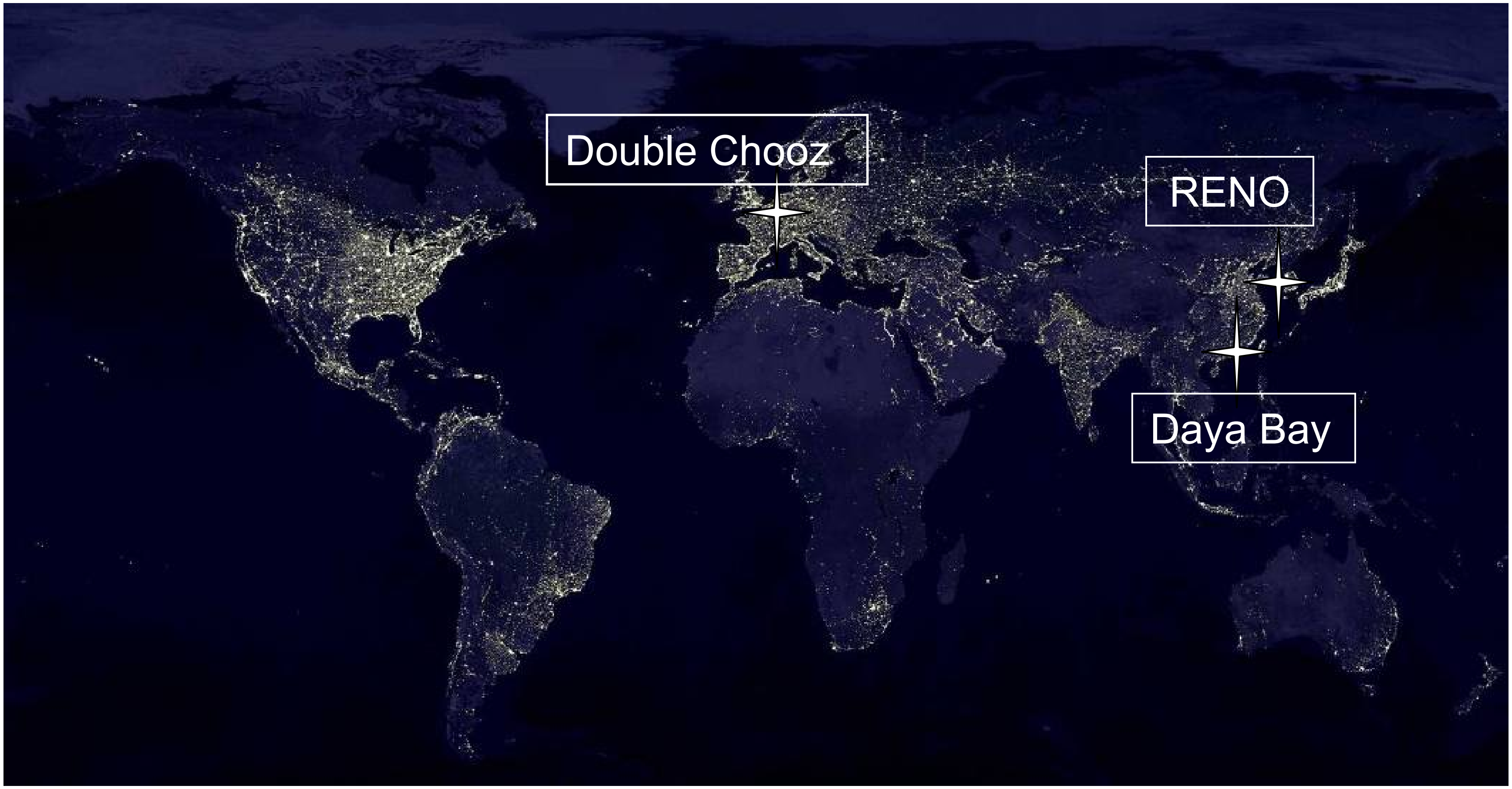


- Multi-layer, high efficiency veto system

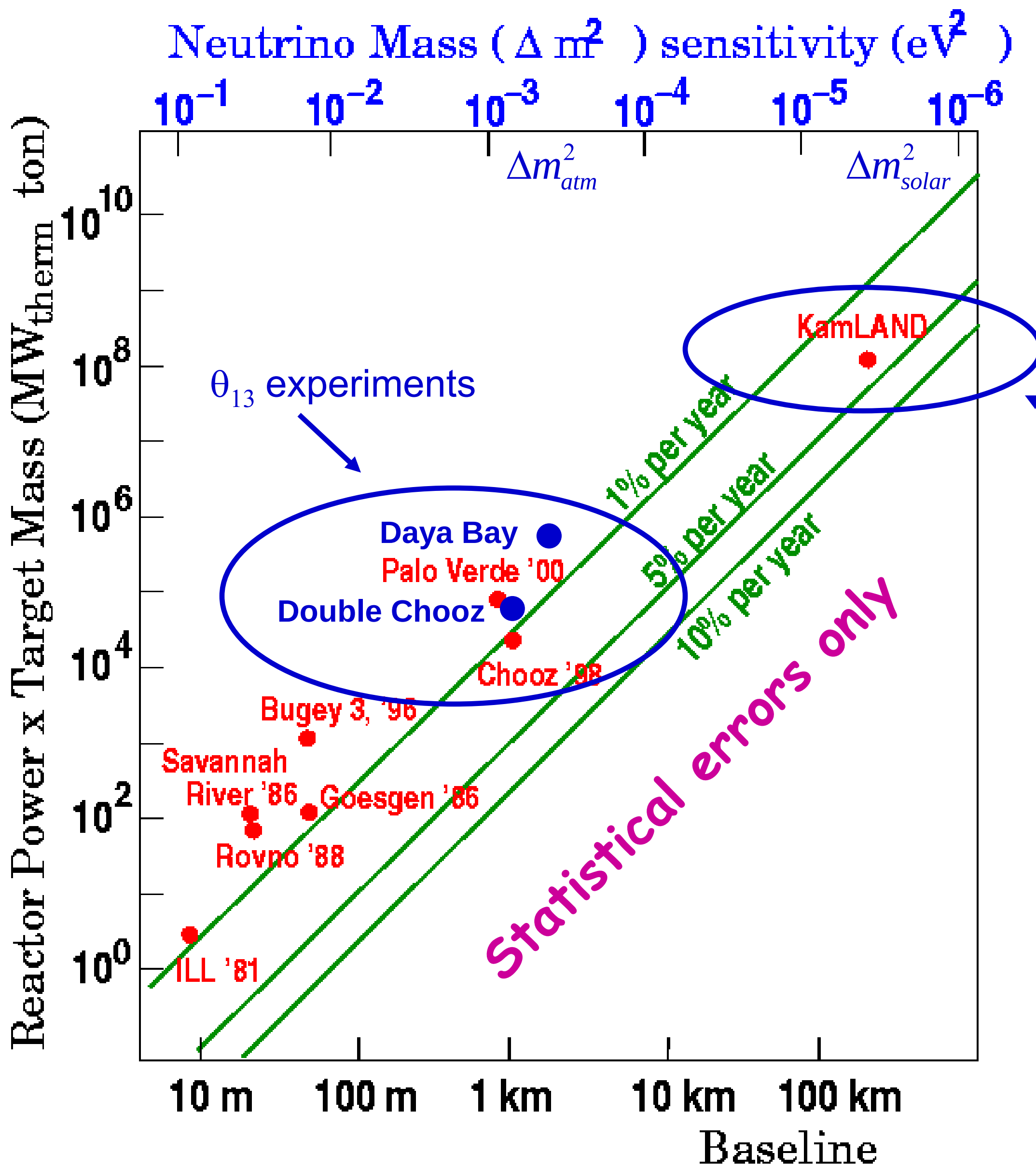
- Homogenous Volume
- Viewed by PMT's
  - Coverage of 10% or better
- Gadolinium Loaded, Liquid Scintillator Target (10 – 20 tons)
  - Enhances neutron capture
- Extra scintillator region to capture gammas that might leak out from Gd target region
- Pure Mineral Oil Buffer
  - To shield the scintillator from radioactivity in the PMT glass.

Proposed Reactor Oscillation Experiments (2005)

Current Reactor θ_{13} Projects

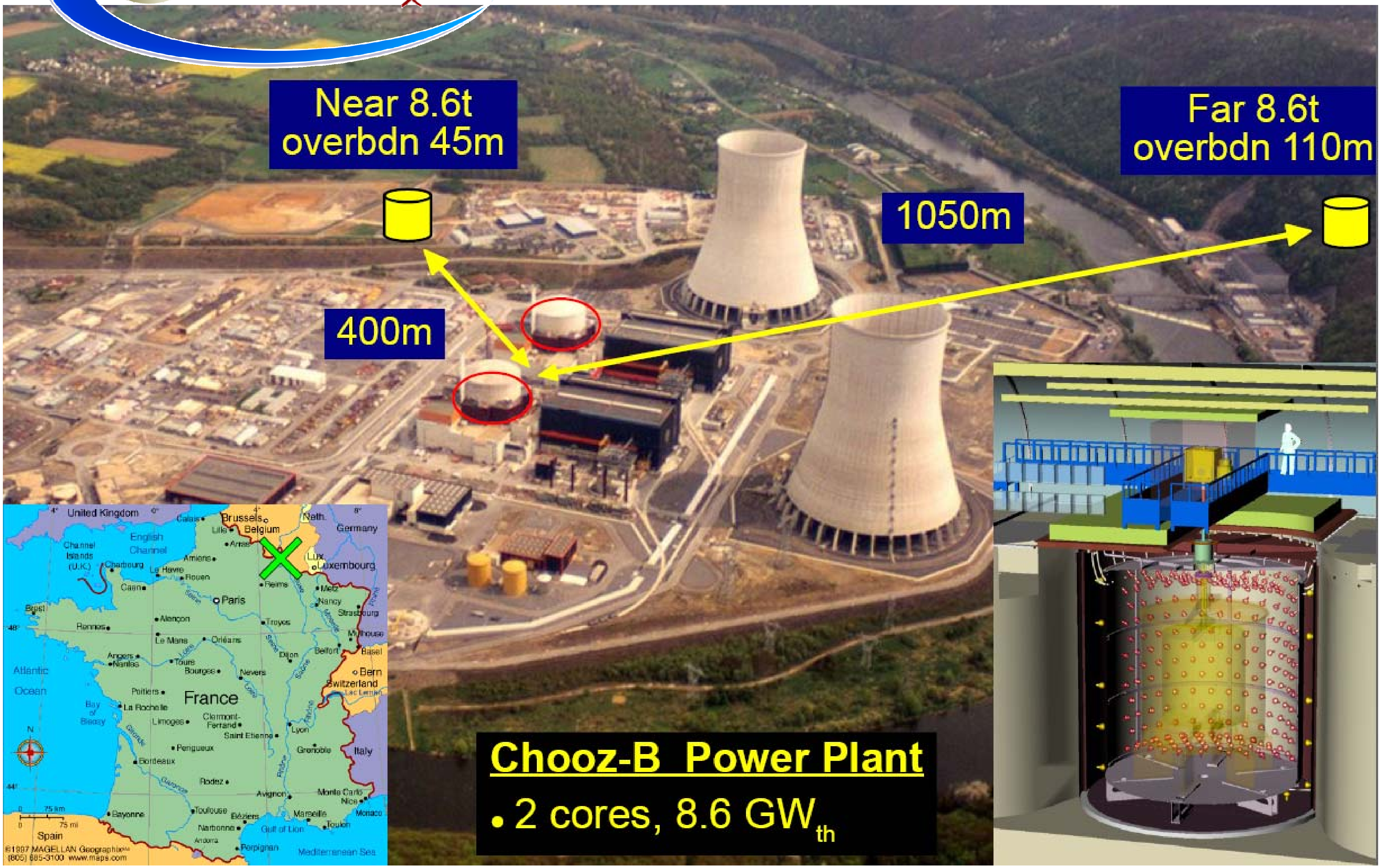


Event Rate (power x mass) vs Distance



KamLAND unique in distance, power, and mass.

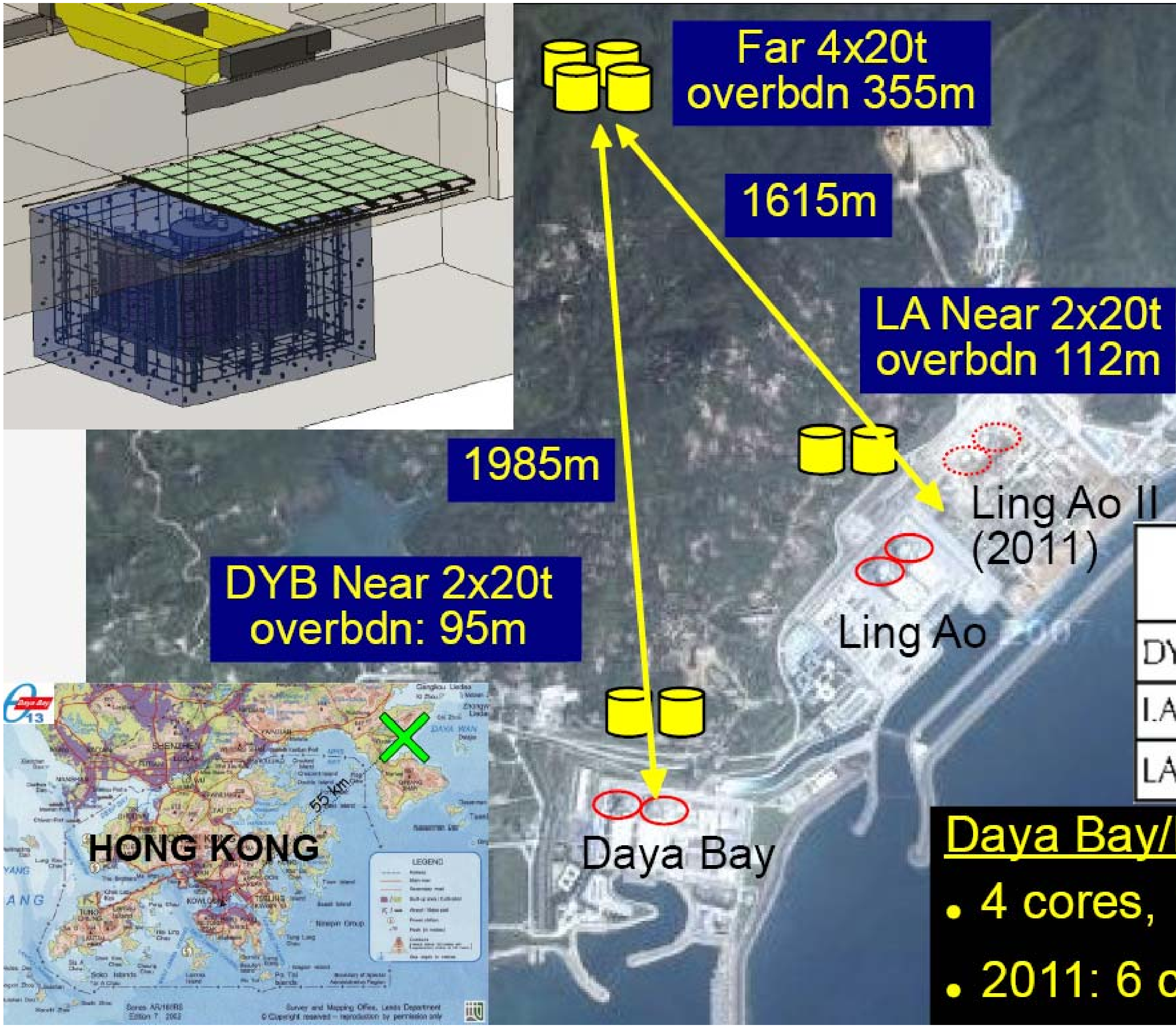
Double Chooz Reactor Experiment in Ardennes, France

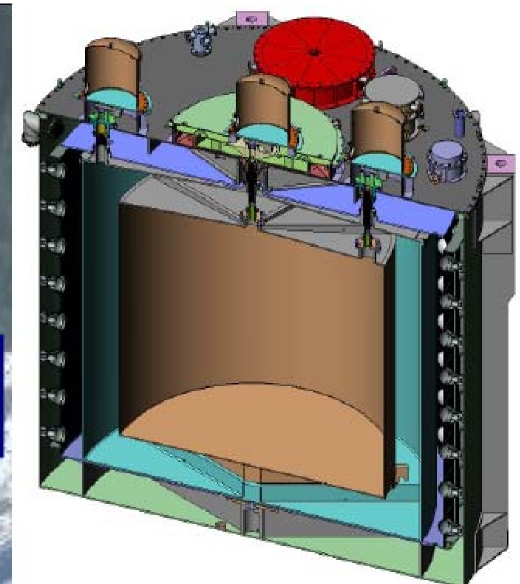


Systematic uncertainties

		Chooz	Double-Chooz	
Reactor-induced	ν flux and σ	1.9 %	<0.1 %	Two ''identical'' detectors, Low bkg
	Reactor power	0.7 %	<0.1 %	
	Energy per fission	0.6 %	<0.1 %	
Detector - induced	Solid angle	0.3 %	<0.1 %	Distance measured @ 10 cm + monitor core barycenter
	Volume	0.3 %	0.2 %	Precise control of detector filling
	Density	0.3 %	<0.1 %	Accurate T control (near/far)
	H/C ratio & Gd concentration	1.2 %	<0.1 %	Same scintillator batch + Stability
	Spatial effects	1.0 %	<0.1 %	Identical detectors and monitoring
	Live time	-----	0.25 %	Special electronic systems and monitoring
Analysis	From 7 to 3 cuts	1.5 %	0.2 - 0.3 %	Simplified cuts due to detector design
	Total	2.7 %	< 0.6 %	

Daya Bay Experiment



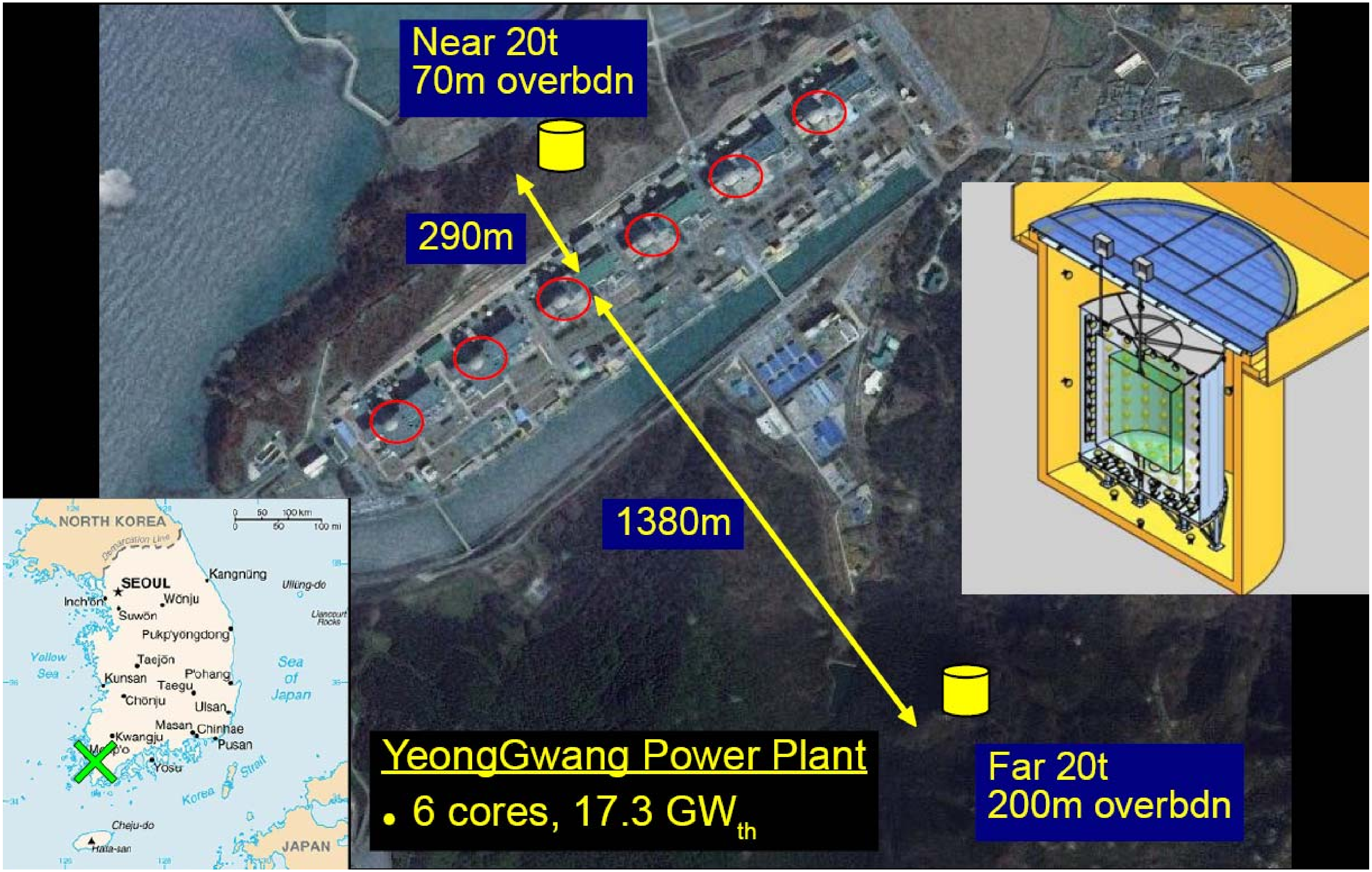


	DYB Site (m)	LA Site (m)	Far Site (m)
DYB	363	1347	1985
LA	857	481	1618
LA II	1307	526	1613

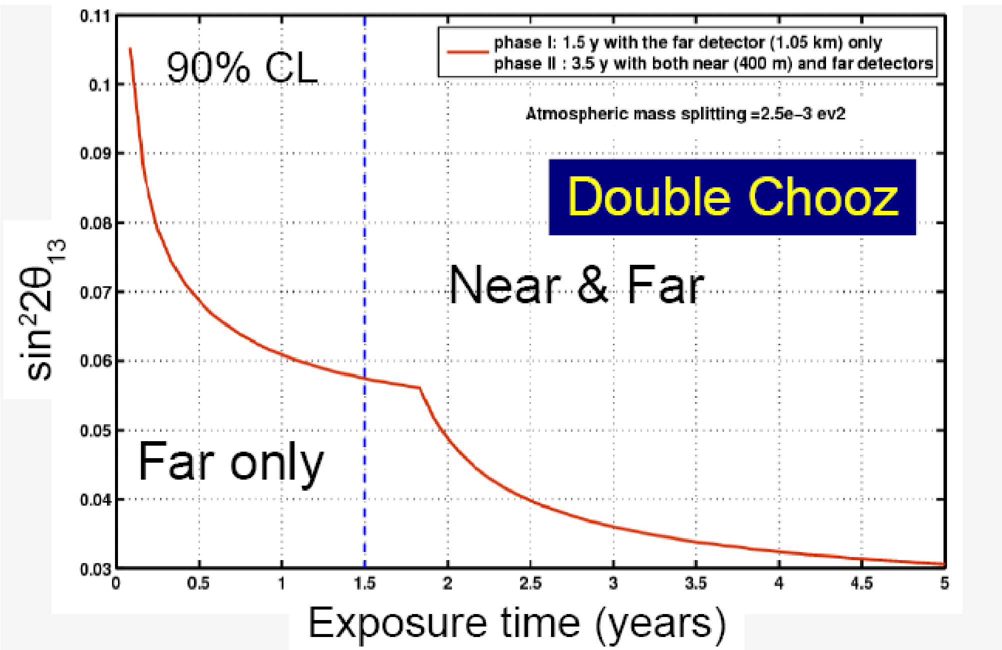
<u>Daya Bay/Ling Ao Power Plant</u>

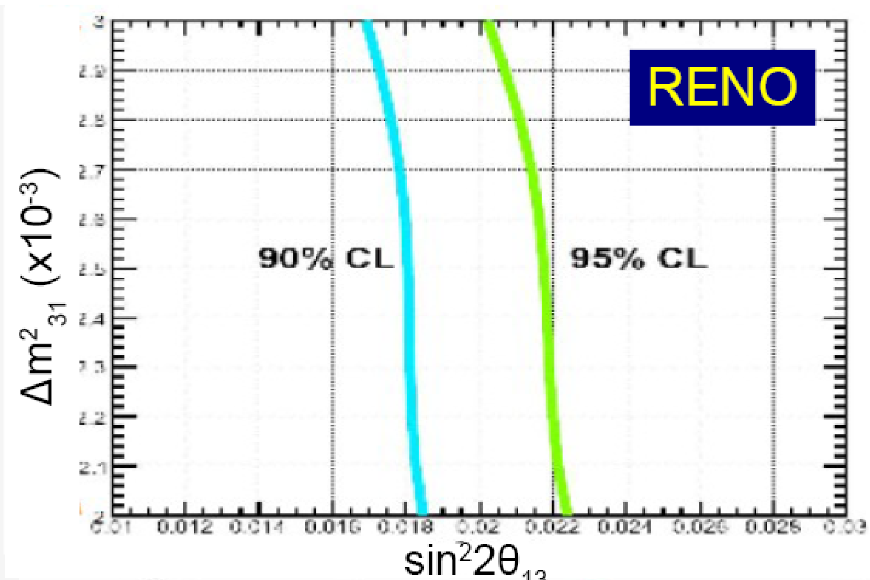
- 4 cores, 11.6 GW_{th}
- 2011: 6 cores, 17.4 GW_{th}

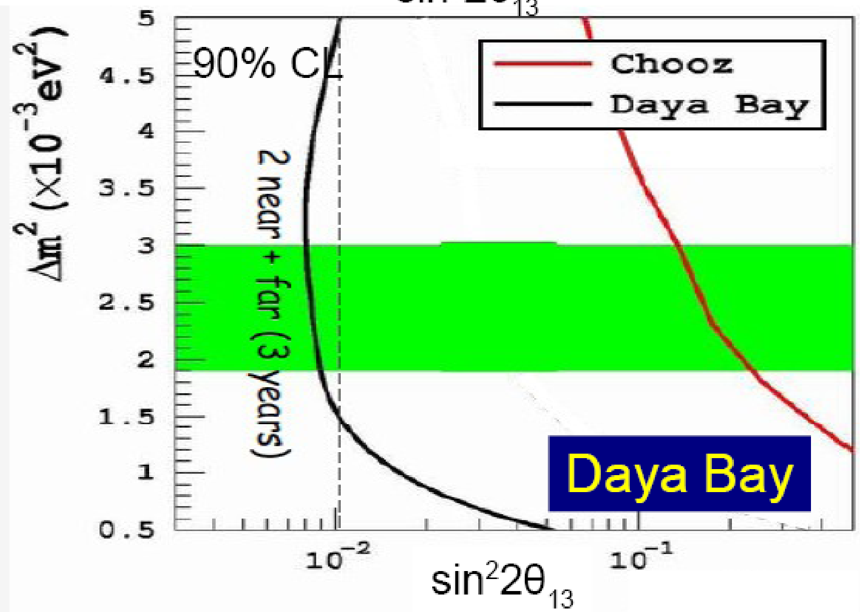
Reactor Experiment for Neutrino Oscillations at YoungGwang in Korea



Expected Sensitivities

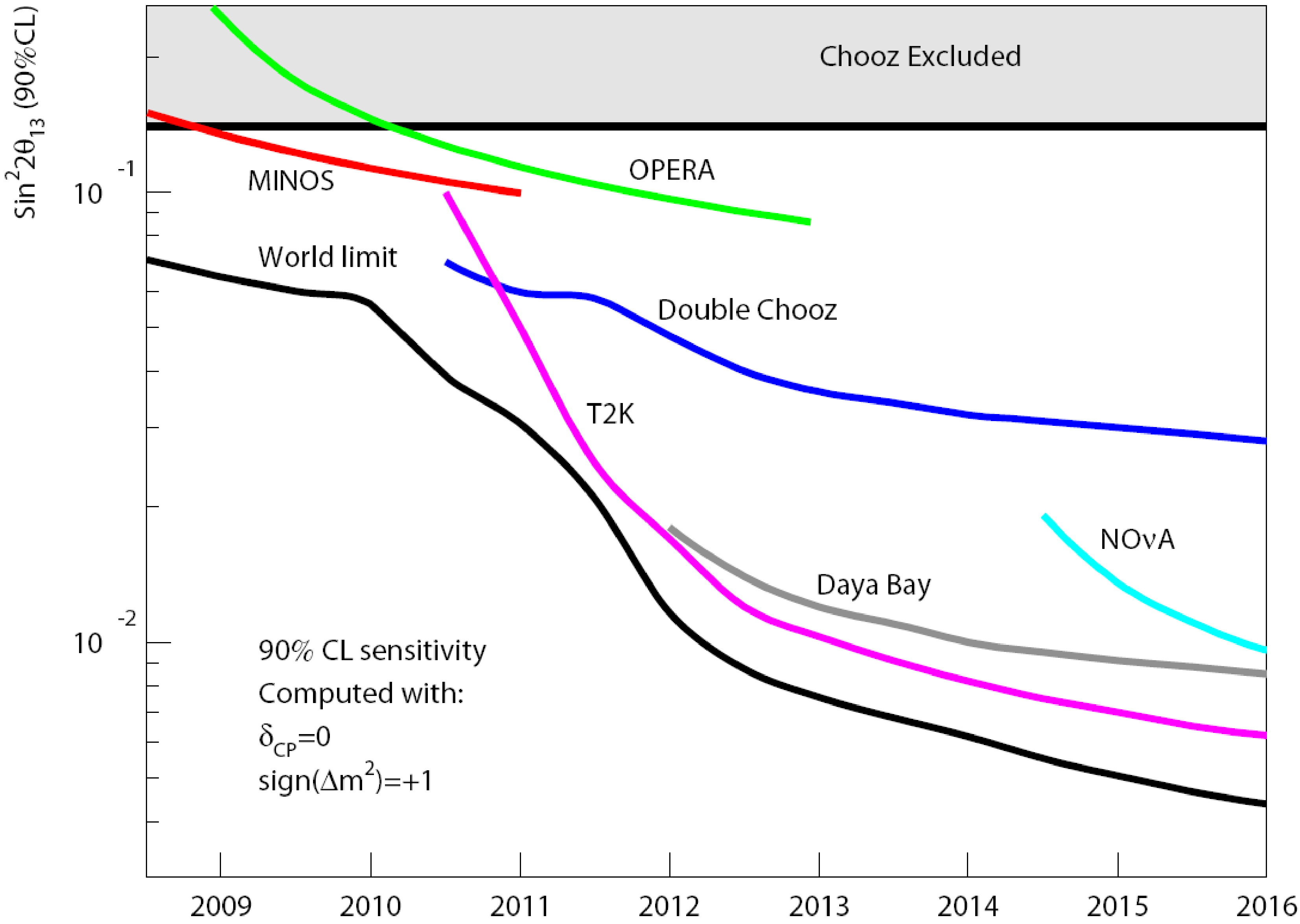






Expt	σ_{stat} [%]	σ_{syst} rel. [%]	$\sin^2 2\theta_{13}$ > (90% CL)
Double Chooz	0.5	0.6	0.03
RENO	0.3	0.5	0.02
Daya Bay	0.2	0.4	0.01

Sensitivity Estimates for θ_{13} vs Time



From Mauro Mezzetto NT 2009

Longbaseline ν_e Appearance Experiments

Long-Baseline Accelerator Appearance

- Oscillation probability dependent not only on mixing angles but also:
  1. CP violation parameter (δ)
  2. Mass hierarchy (sign of Δm_{31}^2)
  3. Size of $\sin^2\theta_{23}$ (as opposed to the measured $\sin^2 2\theta_{23}$)

- These are both complications and an opportunity to measure these parameters
  – Use information from other oscillation measurements: reactors, solar/atmospheric/accelerator disappearance
  – Use combinations of appearance measurements for neutrinos and antinuetrinos at different baselines to determine CP δ and mass hierarchy

$$P(\nu_\mu \to \nu_e) = 4C_{13}^2 S_{13}^2 S_{23}^2 \sin^2 \frac{\Delta m_{31}^2 L}{4E} \times \left(1 + \frac{2a}{\Delta m_{31}^2} \;(1 - 2S_{13}^2)\right)$$
$$+8C_{13}^2 S_{12} S_{13} S_{23}(C_{12}C_{23}\cos\delta - S_{12}S_{13}S_{23}) \cos\frac{\Delta m_{32}^2 L}{4E} \sin\frac{\Delta m_{31}^2 L}{4E} \sin\frac{\Delta m_{21}^2 L}{4E}$$
$$-8C_{13}^2 C_{12}C_{23}S_{12}S_{13}S_{23} \sin\delta \sin\frac{\Delta m_{32}^2 L}{4E} \sin\frac{\Delta m_{31}^2 L}{4E} \sin\frac{\Delta m_{21}^2 L}{4E}$$
$$+4S_{12}^2 C_{13}^2 \left\{C_{12}^2 C_{23}^2 + S_{12}^2 S_{23}^2 S_{13}^2 - 2C_{12}C_{23}S_{12}S_{23}S_{13}\cos\delta\right\} \sin^2\frac{\Delta m_{21}^2 L}{4E}$$
$$-8C_{13}^2 S_{13}^2 S_{23}^2 \cos\frac{\Delta m_{32}^2 L}{4E} \sin\frac{\Delta m_{31}^2 L}{4E} \frac{aL}{4E} \left(1 - 2S_{13}^2\right)$$

where

$S_{ij} = \sin\theta_{ij}$

$C_{ij} = \cos\theta_{ij}$

Ambiguities and Correlations in Appearance Measurements

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

Mass Hierarchy

CP Violation

Expansion to second order in α and Δ

with $\alpha \equiv \Delta m^2_{21}/\Delta m^2_{23}$ and $\Delta \equiv \Delta m^2_{31} L/(4E_\nu)$

Ambiguities due to:

Measured by Atmos

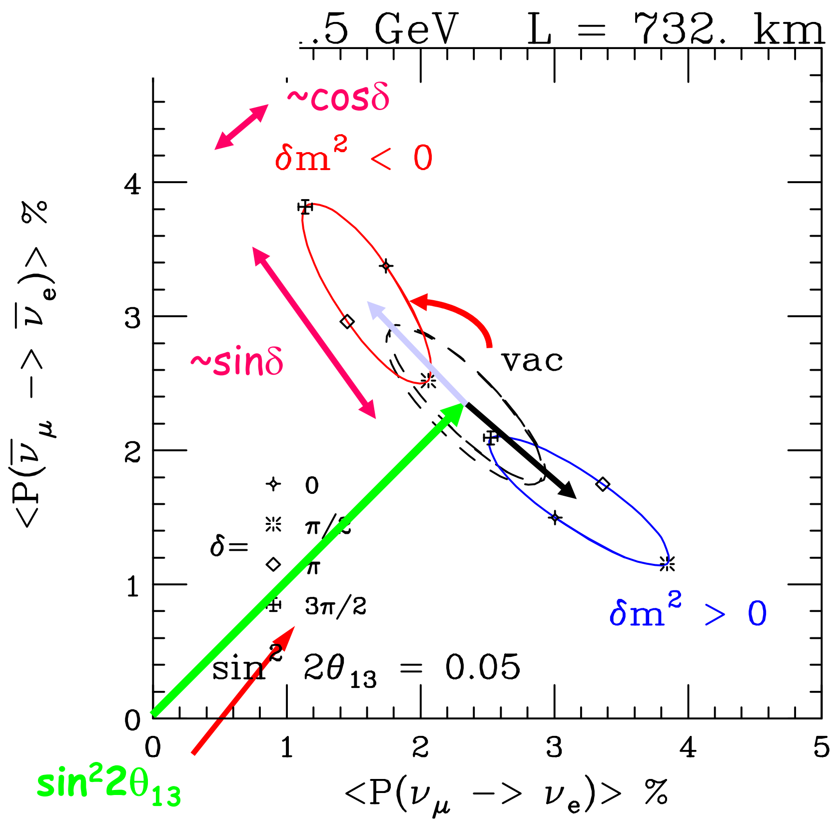
- Need $\sin^2\theta_{23} = \frac{1 \pm \sqrt{1-\sin^2 2\theta_{23}}}{2}$, not $\sin^2 2\theta_{23}$
- Sign of $\Delta m^2_{31} \Rightarrow$ Overall shifts

Correlations:

- CP violation phase $\delta \Rightarrow$ Ellipse Regions
- Interference with subdominant Δm^2_{12} terms

Matter Effects:

$$P_{e\mu} = \sin^2 2\theta_M \sin^2\left(\frac{\Delta_M L}{2}\right)$$
$$\Delta_M = \sqrt{(A - \Delta\cos 2\theta)^2 + \Delta^2 \sin^2 2\theta}$$
$$A = \pm\sqrt{2} G_F N_e \text{ (+ for neutrinos, − for antineutrinos)}$$

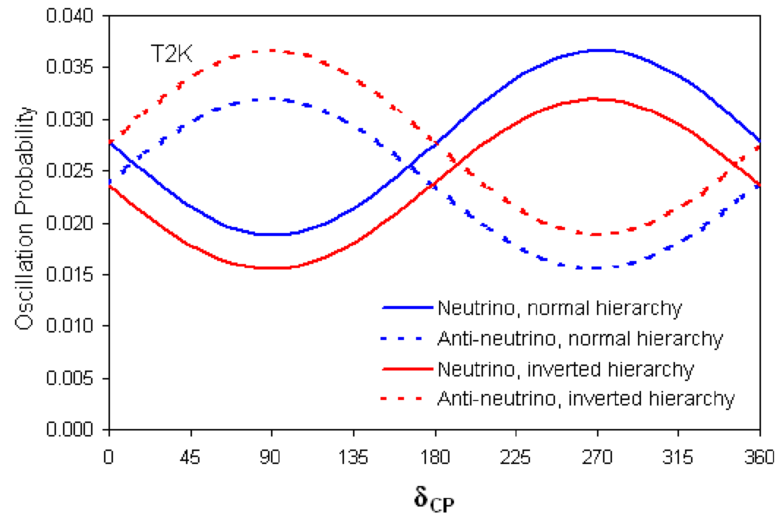


Minakata and Nunokawa, hep-ph/0108085

The "Curse" and the "Blessing"

($\Delta m^2 = 2.5\text{x}10^{-3}$ eV^2 , $\sin^2 2\theta_{13} = 0.05$)

Oscillation probability vs δ_{CP} for T2K and Nova



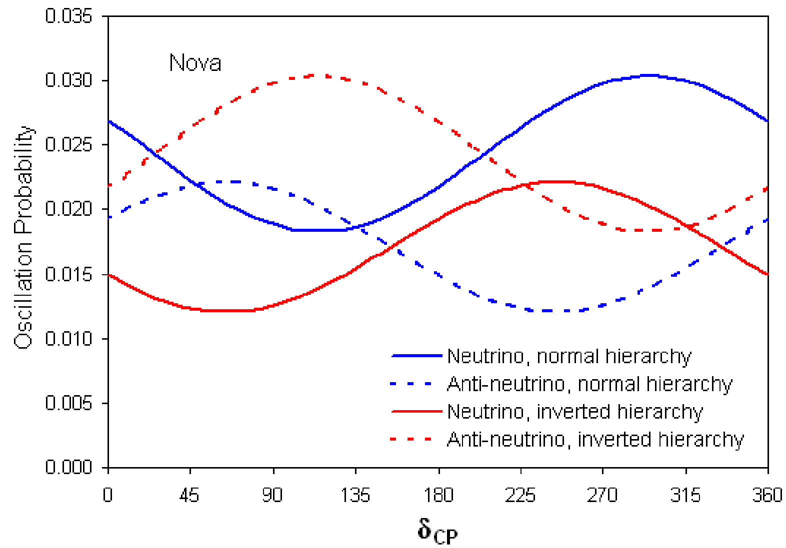
T2K:
Small matter effects

Blue: normal hierarchy

Red: inverted hierarchy

Solid: neutrino

Dashed: antineutrino

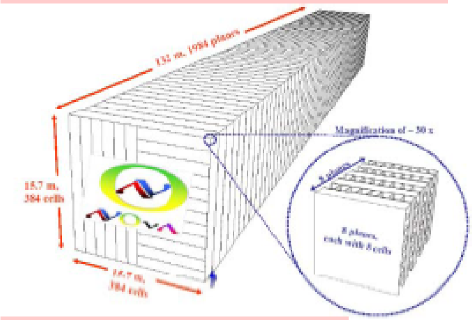


Nova:
Large matter effects

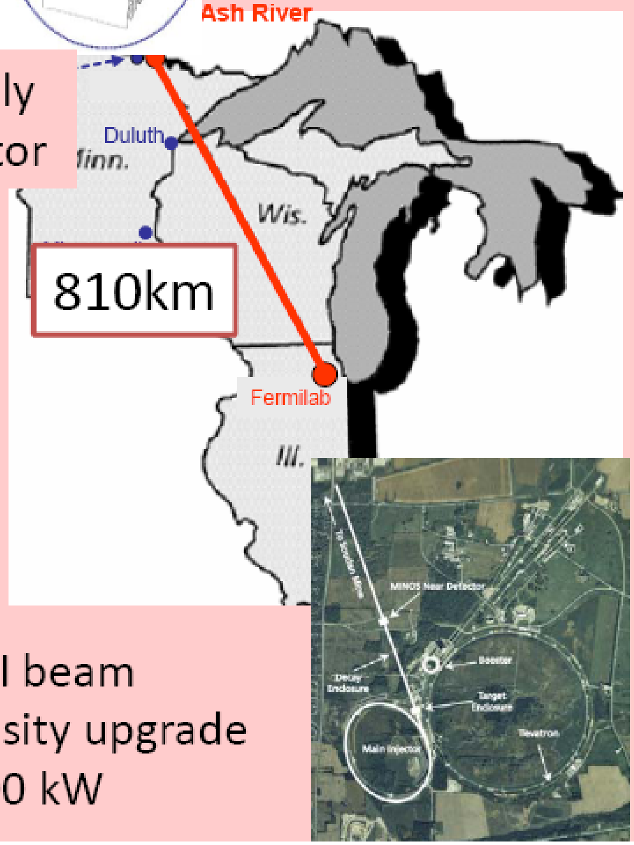
Upcoming Longbaseline Experiment: T2K and Nova

Improved Beams and Near/Far Detectors
Much Higher Intensity

NOνA
(~2013 -)



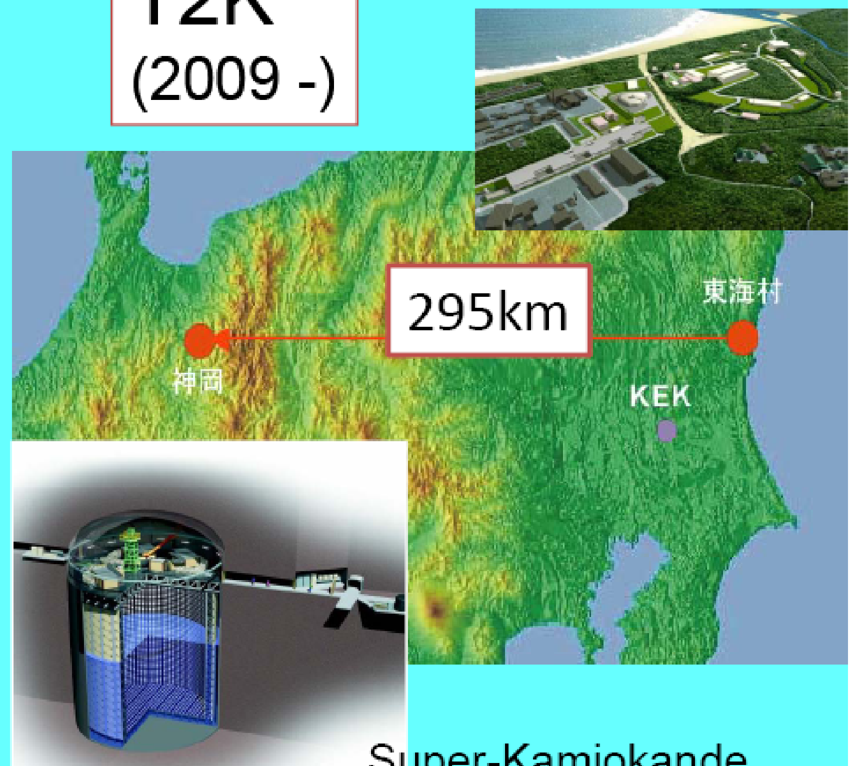
15 kton totally active detector



NuMI beam intensity upgrade to 700 kW

T2K
(2009 -)

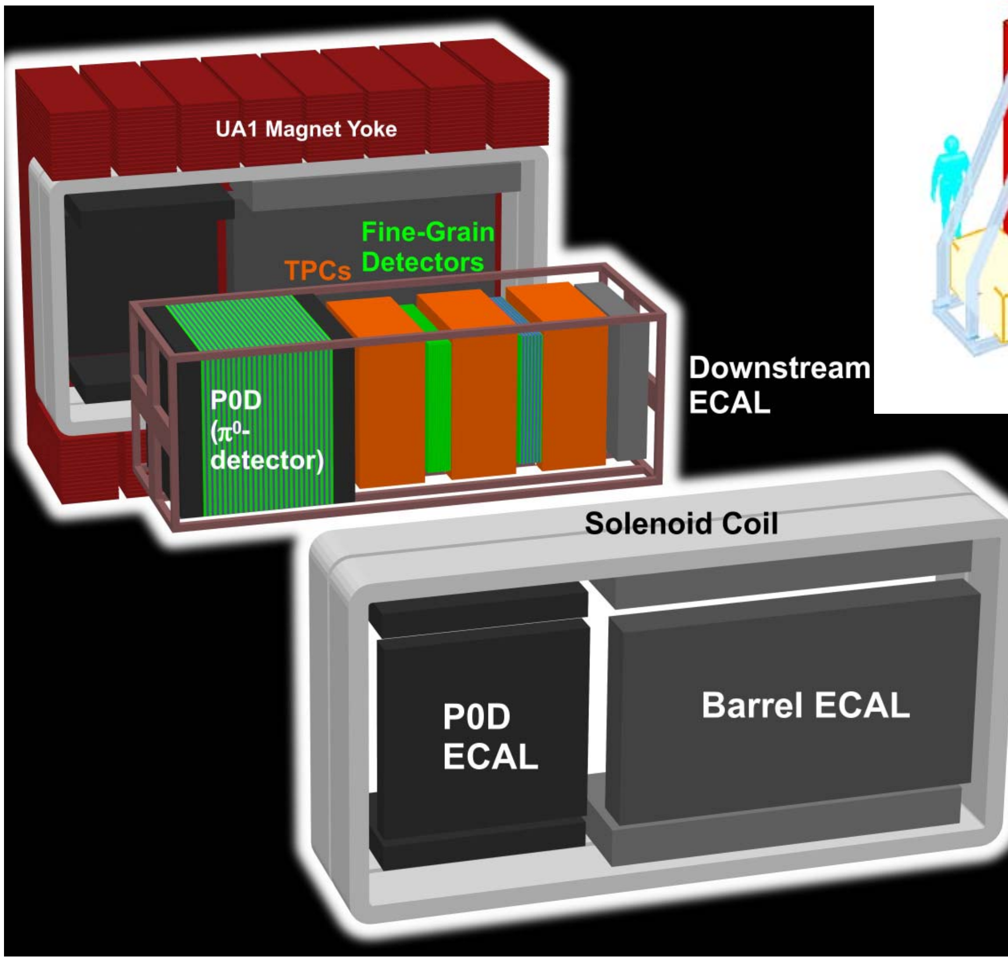
J-PARC
(750kW design)

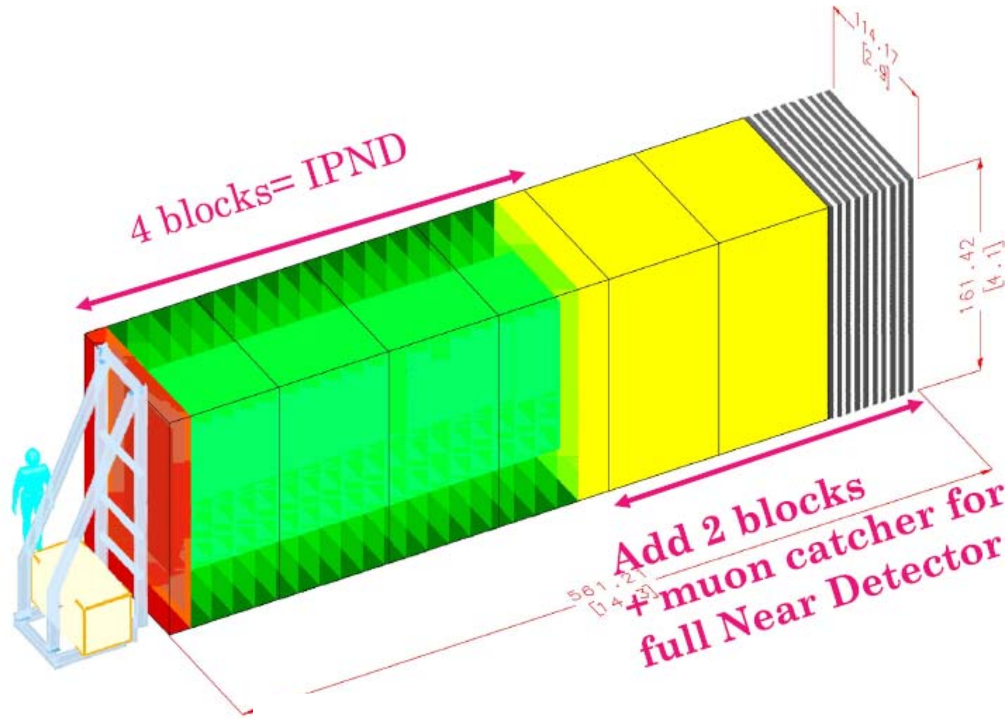


Super-Kamiokande
(22.5 kton fid. vol)

Use Near Detectors to Measure Beam Flux and Backgrounds

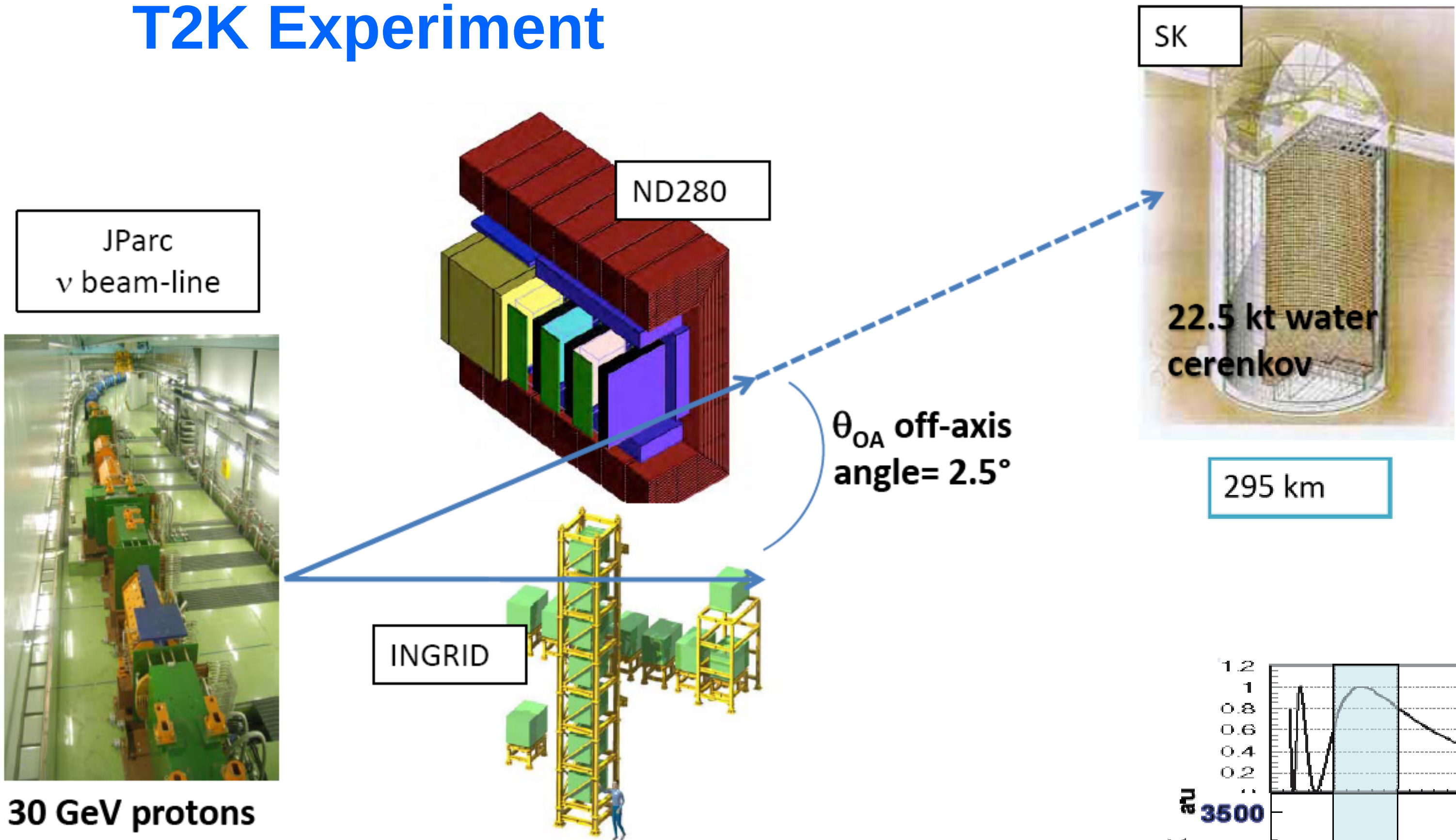
T2K Near Detector





NOνA Near Detector

T2K Experiment



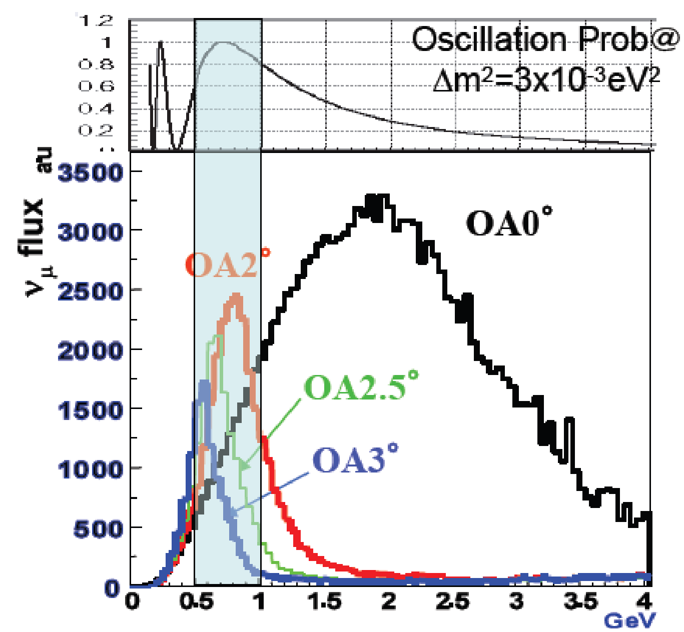
Statistics at SK

(OAB 2.5 deg, 1 yr, 22.5 kt)

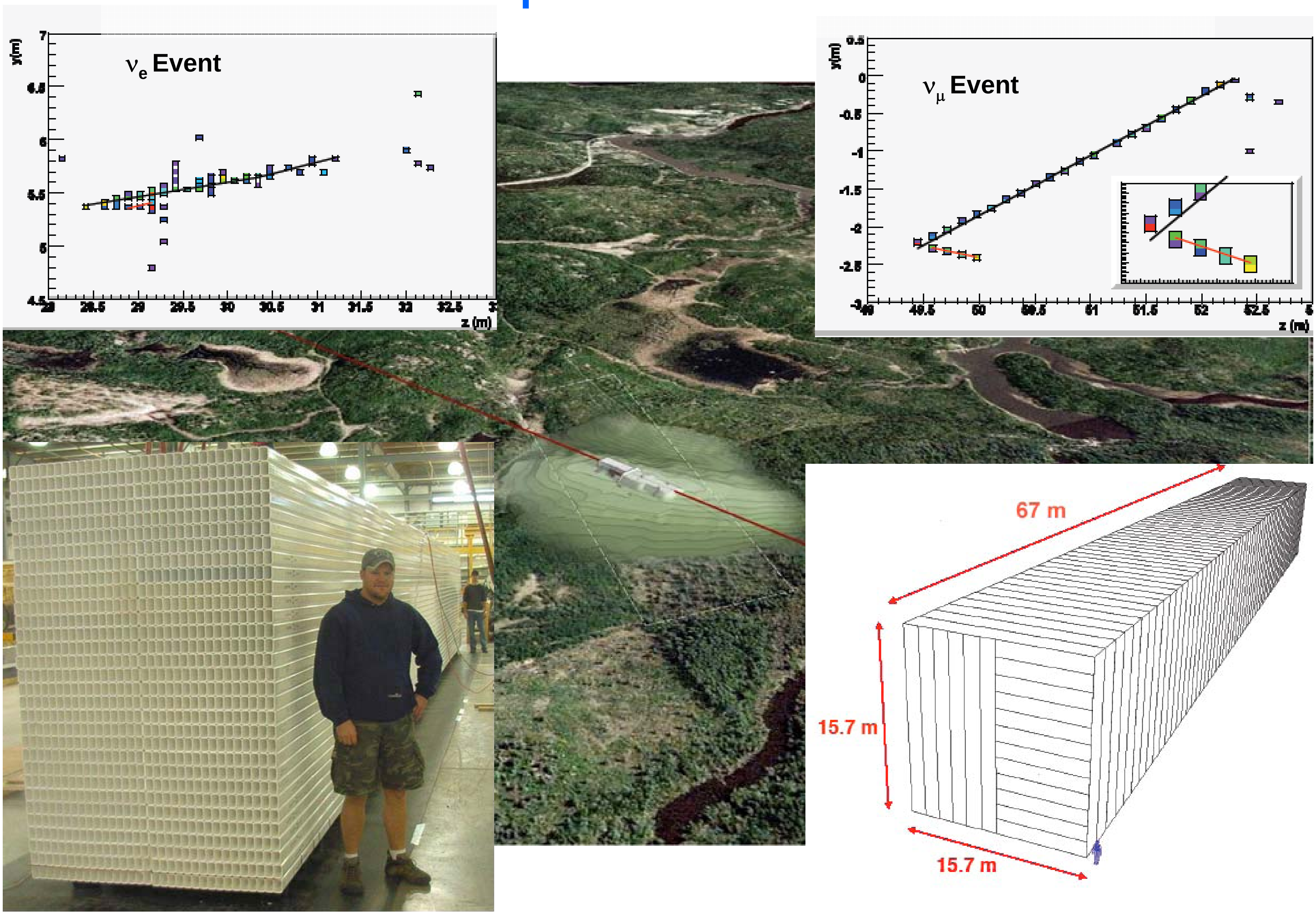
$\sim 2200\ \nu_\mu$ tot

$\sim 1600\ \nu_\mu$ CC

ν_e ~0.4% at ν_μ peak



NOvA Experiment in Minnesota



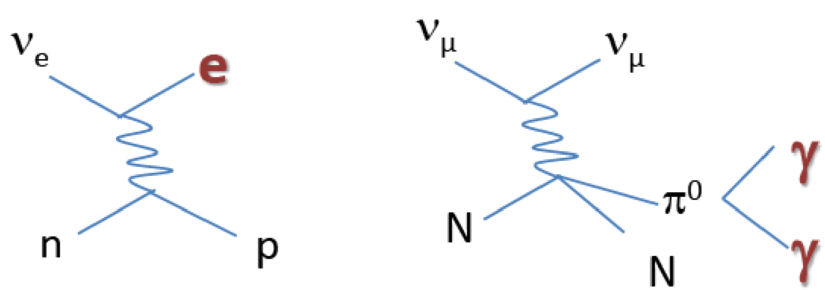
Main Backgrounds For Appearance Experiments

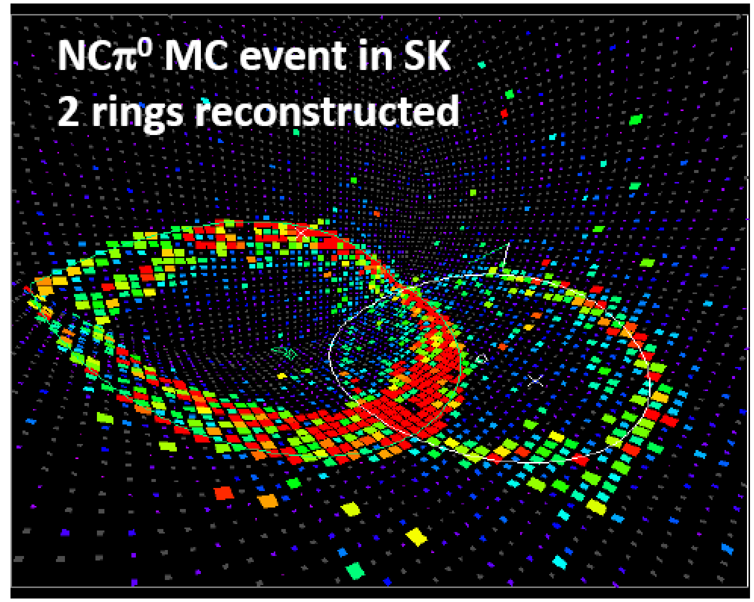
•for ν_e appearance

Measure θ_{13}

-beam ν_e

-NCπ^0 events

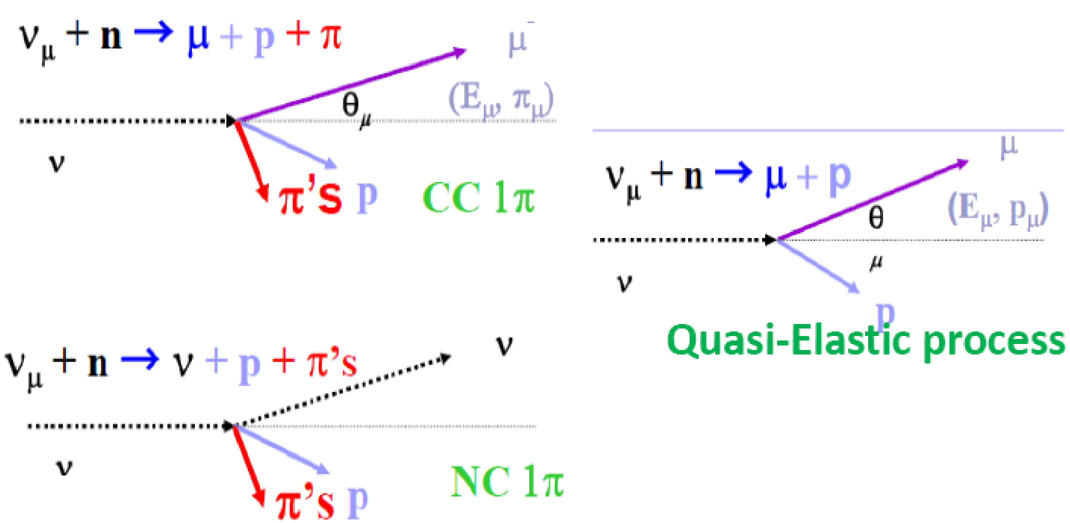


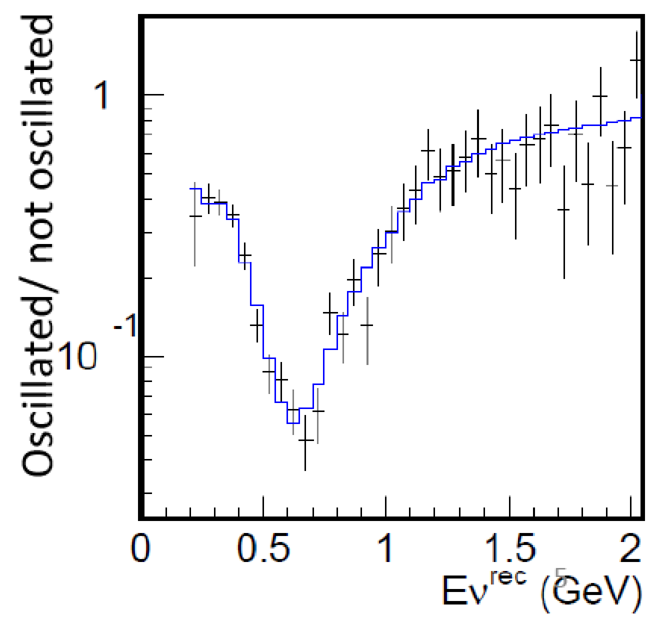


•for ν_μ disappearance (muon energy measurement)

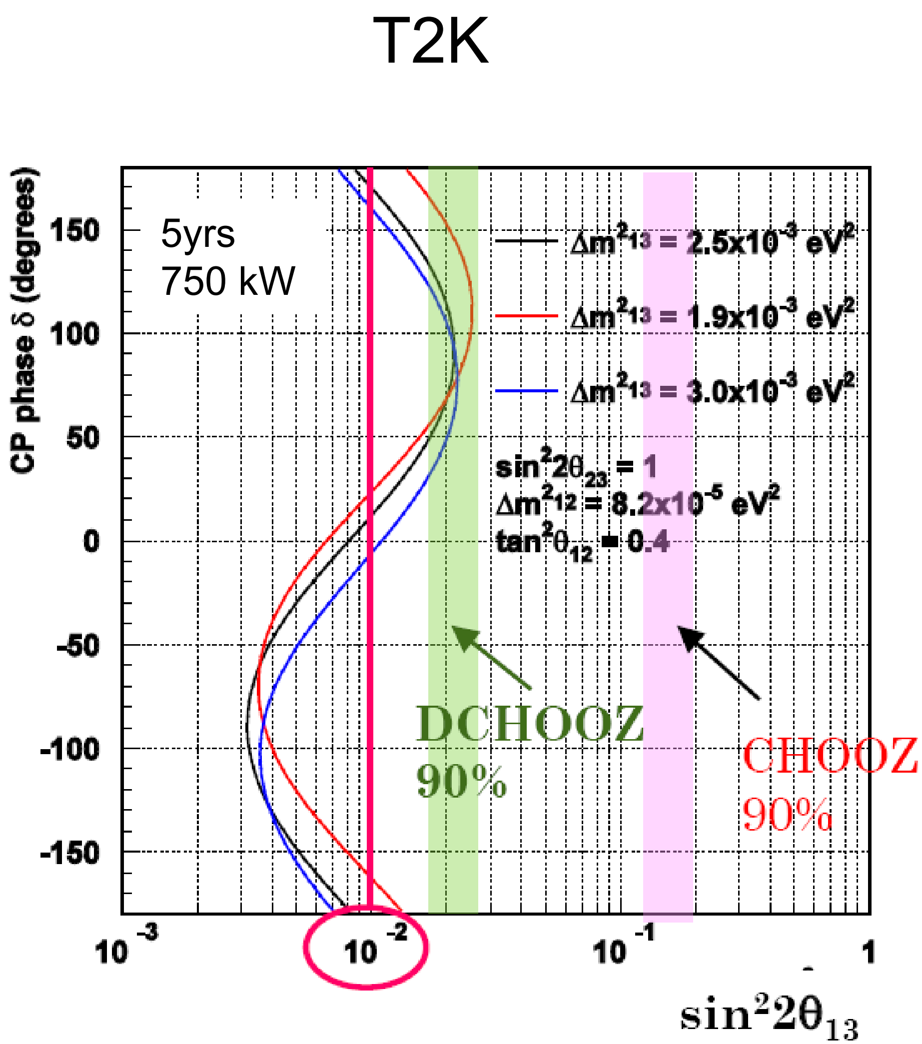
Measure θ_{23}

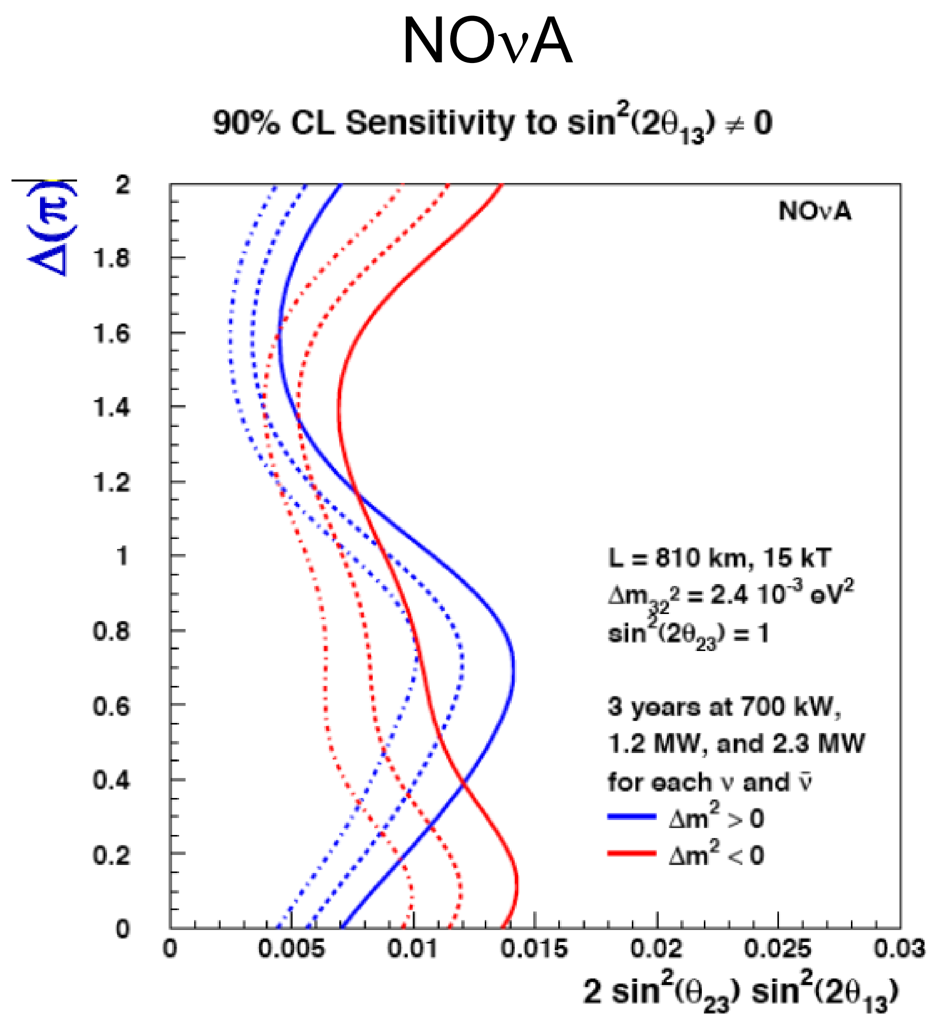
-inelastic processes





Expected Sensitivity to θ_{13}



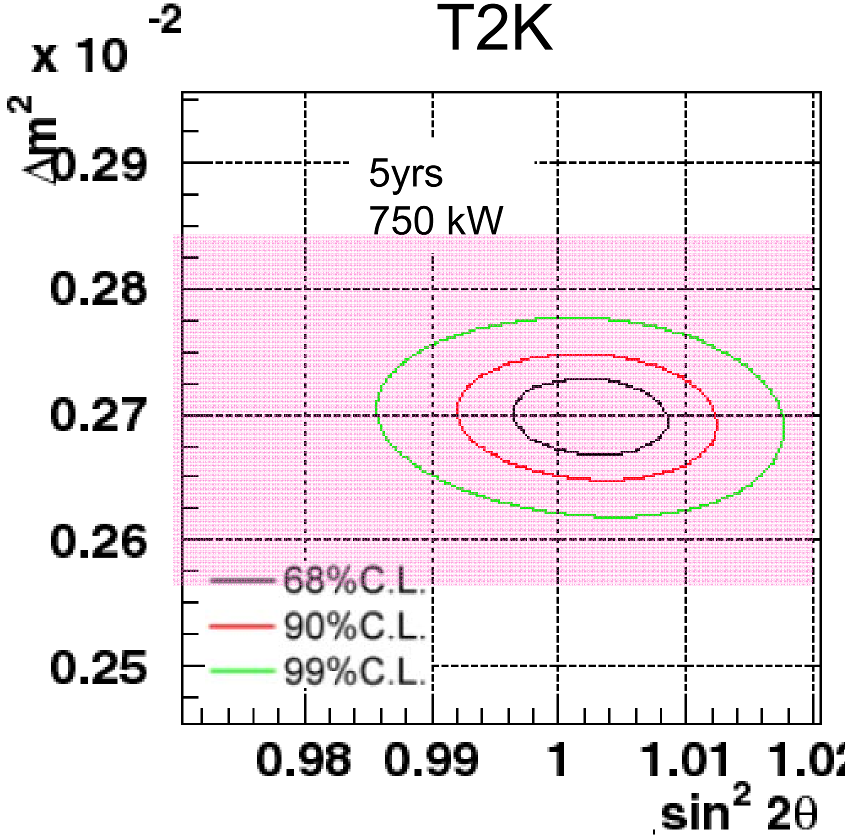


Experiments sensitive to $\sin^2(2\theta_{13}) > 0.008$

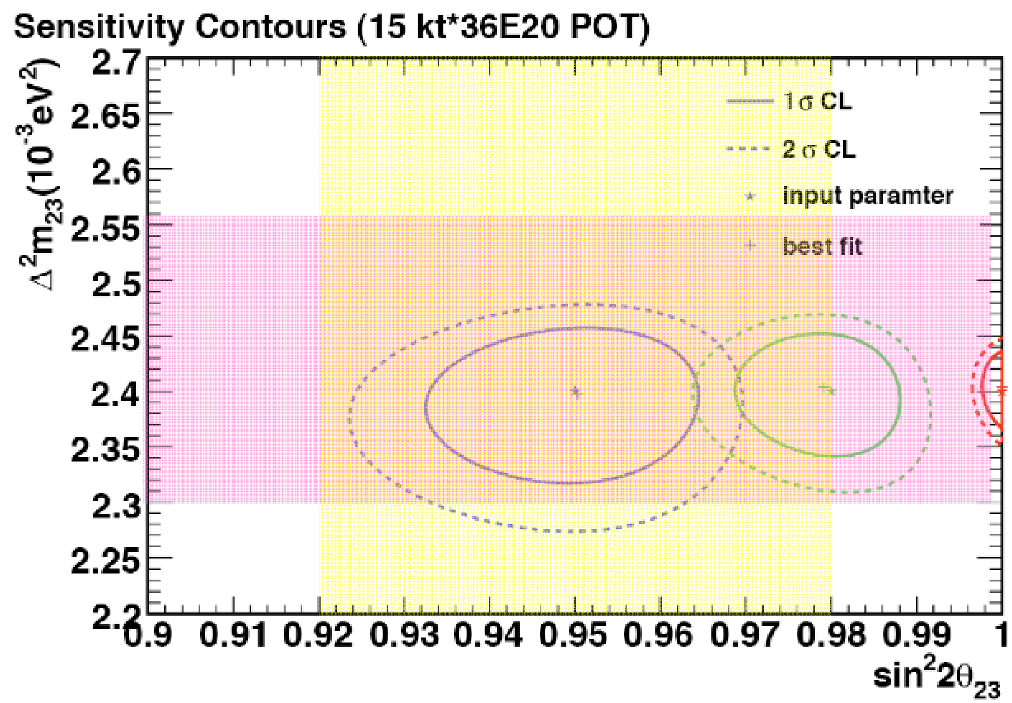
Better Measurements of θ_{23} and Δm^2_{23}

Current Measurements:
$\Delta m^2 = 2.43 \pm 0.13 \times 10^{-3}$ eV^2 → Improvements by x3 to x5
$\sin^2(2\theta_{23}) = 1.00 \pm 0.03$

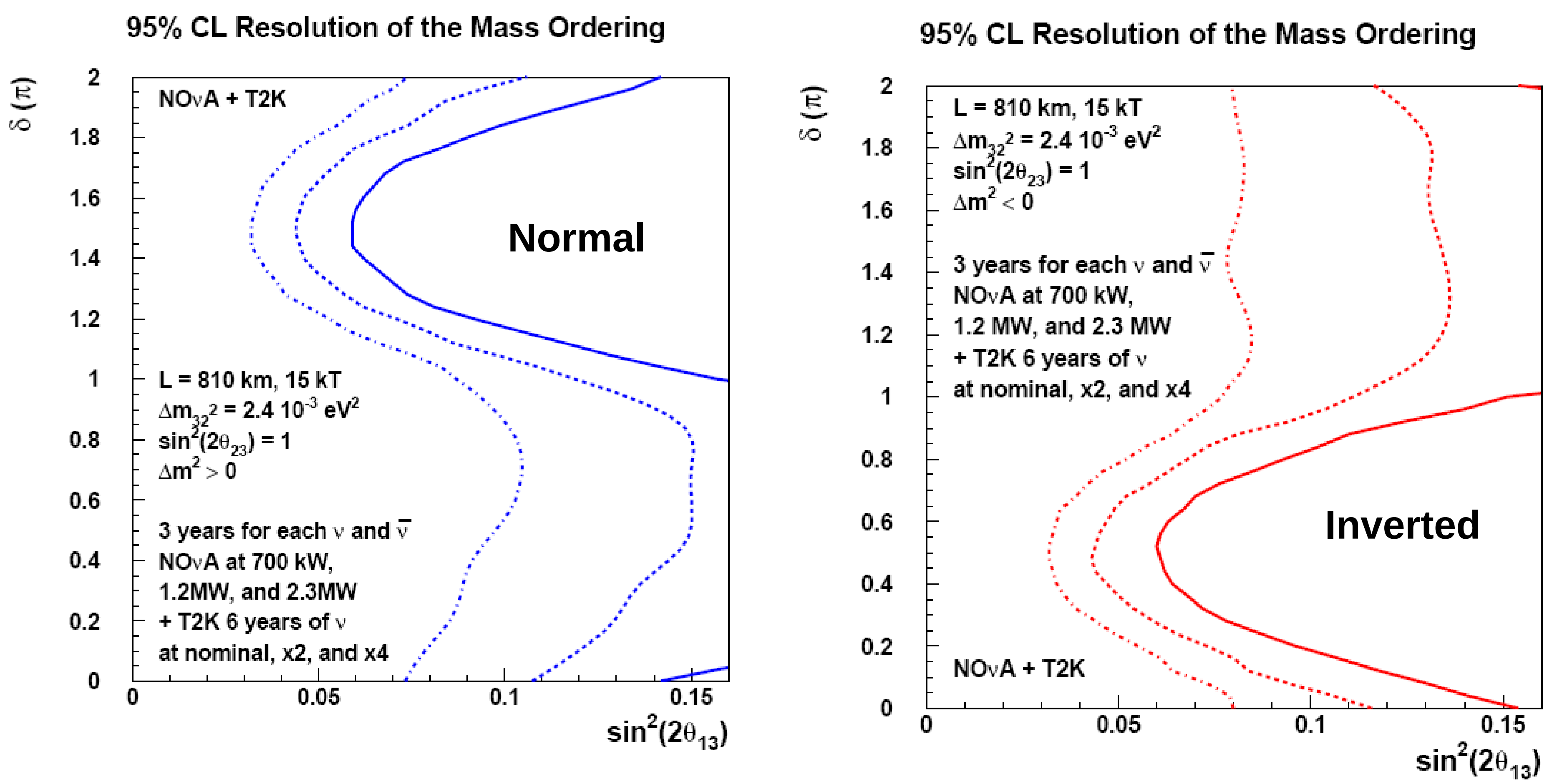
T2K



NOνA



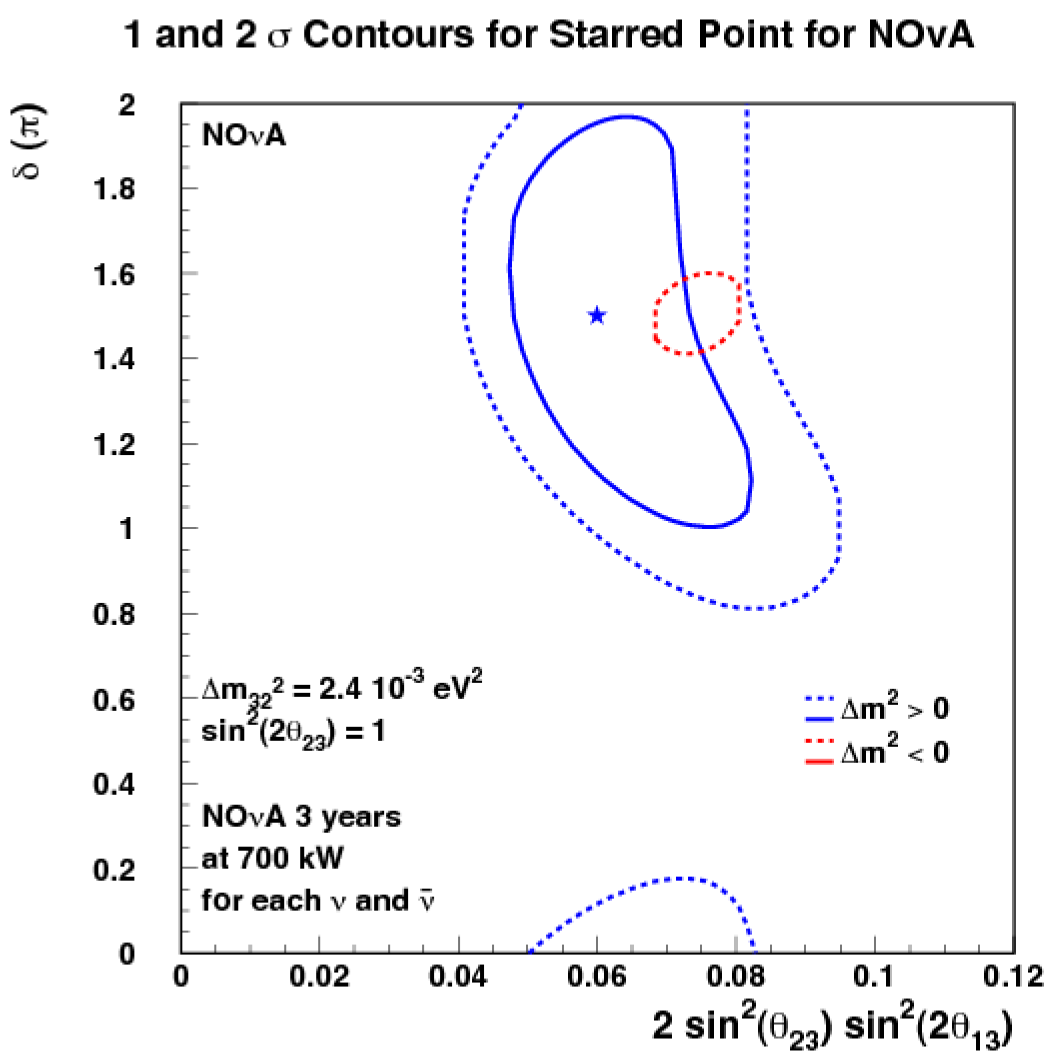
NOvA + T2K Has Some Sensitivity to Mass Hierarchy (sign Δm^2_{23})



And If One Is Lucky ….

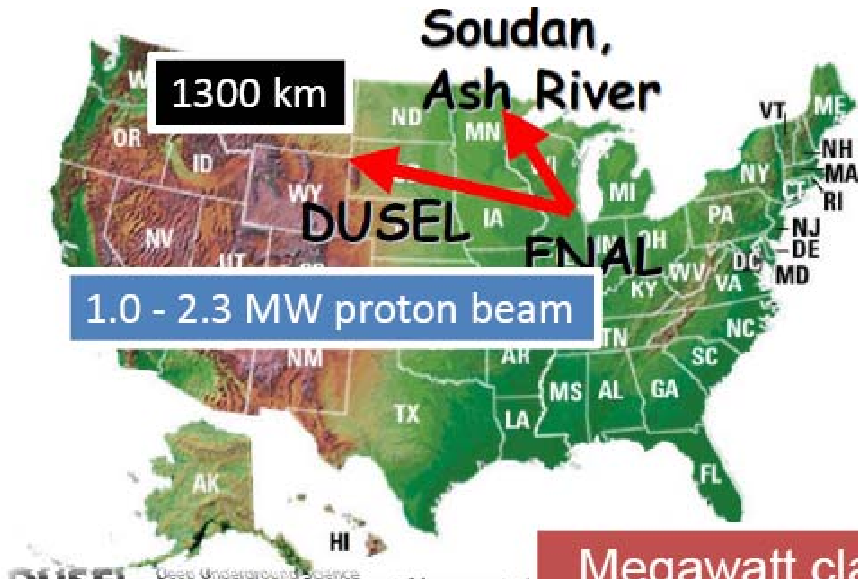
- There are some values of the CP parameter δ that are easier to isolate and measure, i.e.
  If ⇒
  – θ_{13} is big enough
  – Mass hierarchy is normal ($\Delta m^2 > 0$)
  – δ around $3\pi/2$

  Then ⇒
  – Can observe a hint of CP violation at the 1 sigma level.

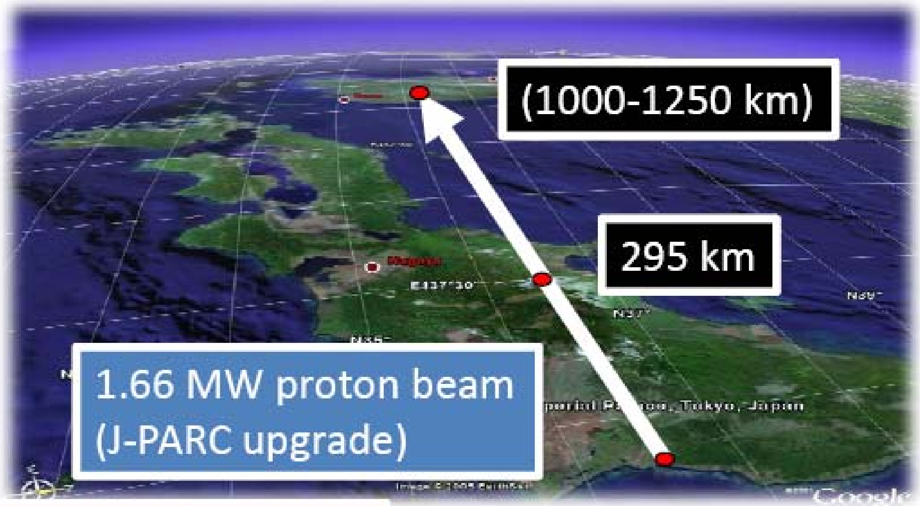


Need Much Larger Experiments For Measuring CP Violation ⇒ Super-Beam Exps

Future Longbaseline Experiments

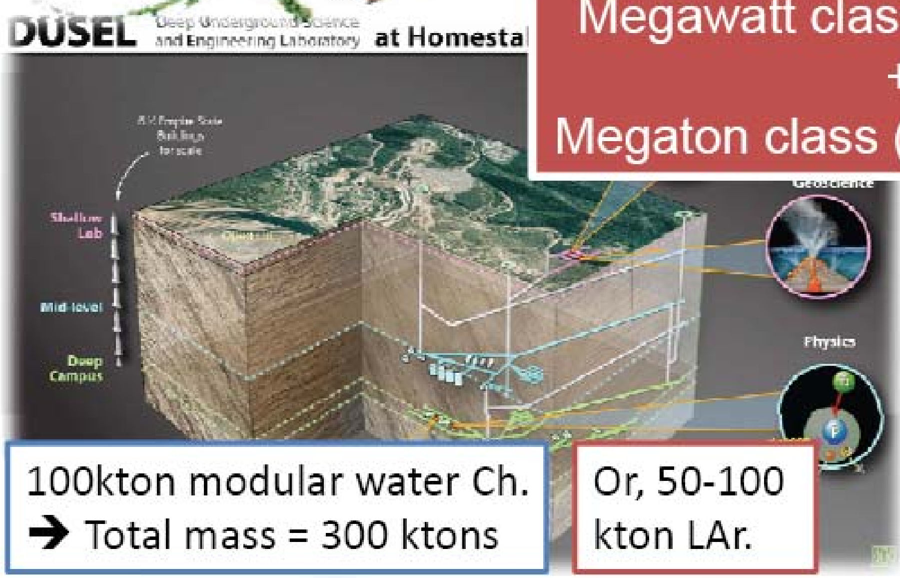


1.0 - 2.3 MW proton beam



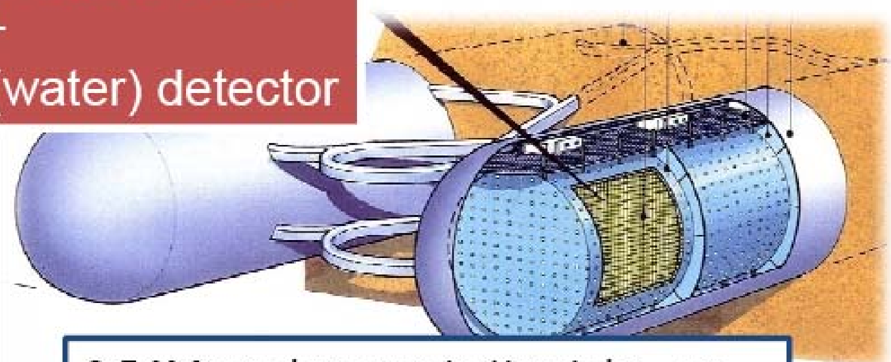
1.66 MW proton beam
(J-PARC upgrade)

Megawatt class super-beam
+
Megaton class (water) detector



100kton modular water Ch.
➔ Total mass = 300 ktons

Or, 50-100
kton LAr.



0.54Mton detector in Kamioka, or
0.27 Mton water Cherenkov detector
in Kamioka and Korea.

Hyper-K Experiment

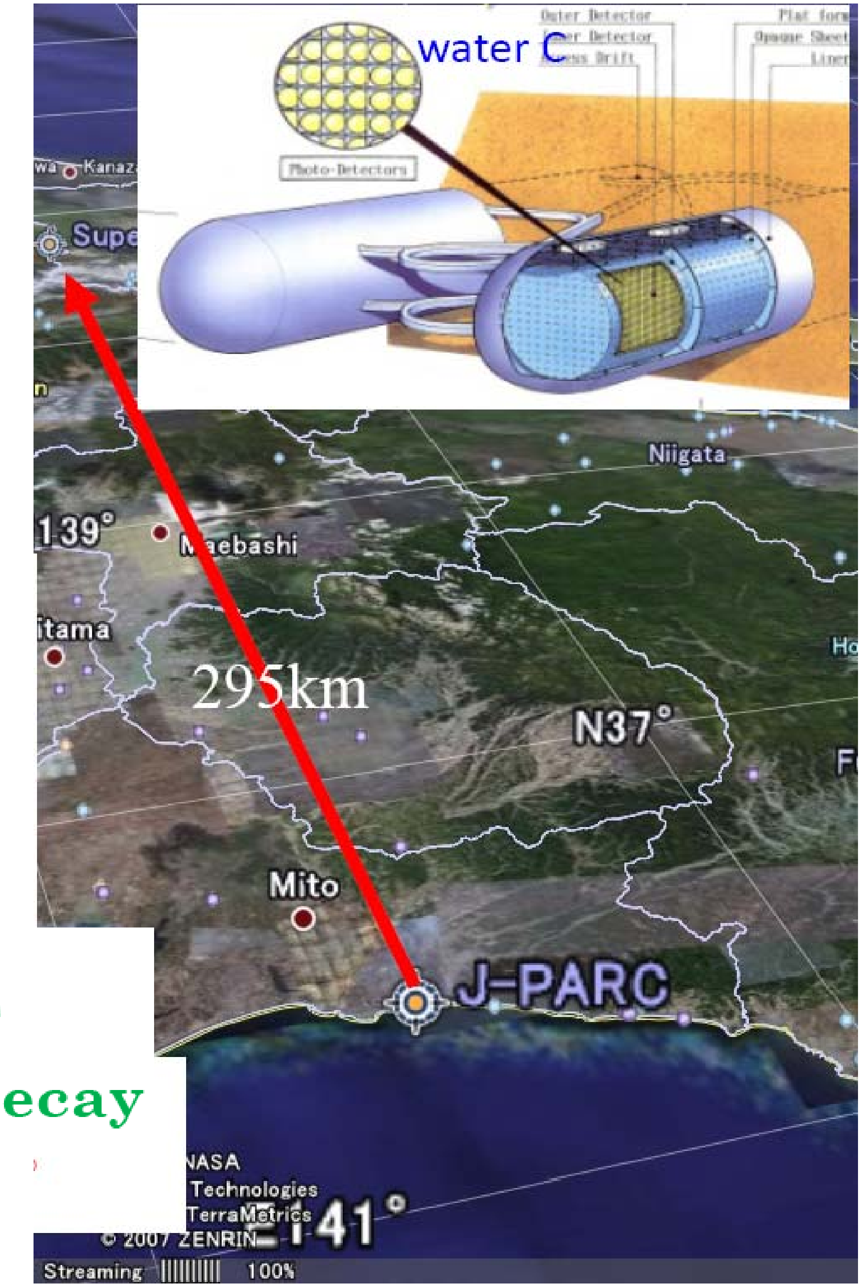
J-PARC Upgrade
KEK Roadmap
→1.7MW

Best Optimization

Huge ν detector
- Water Cherenkov (500 kton)
- Lq. Ar TPC

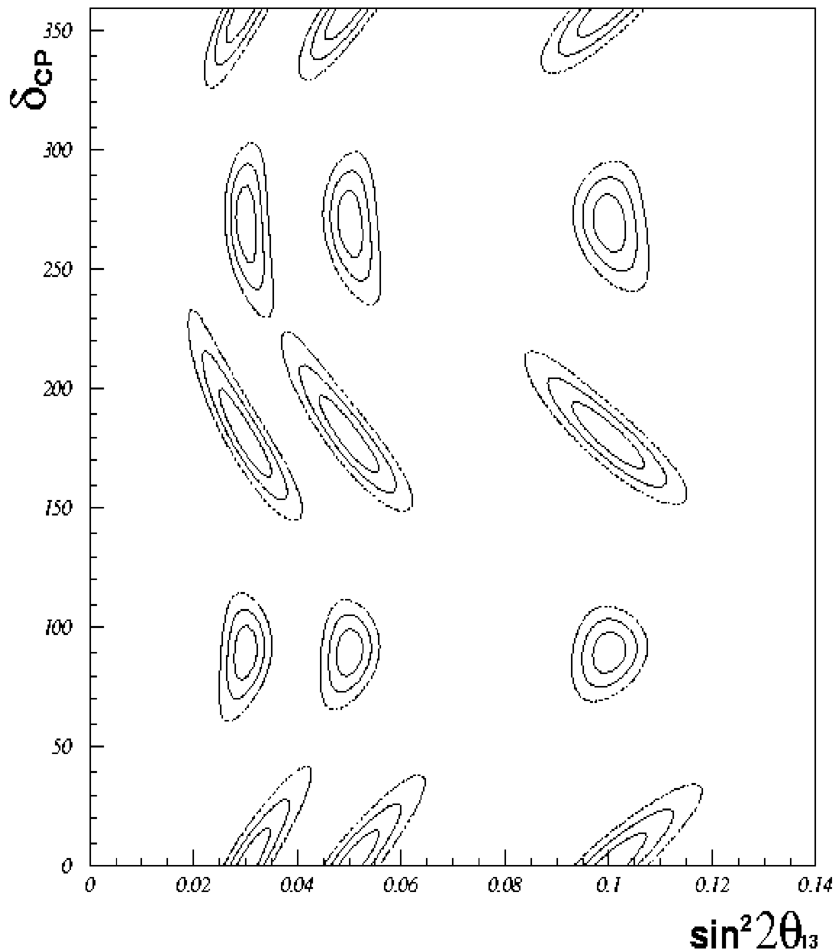
O(~100k)ton

GUT
Proton Decay

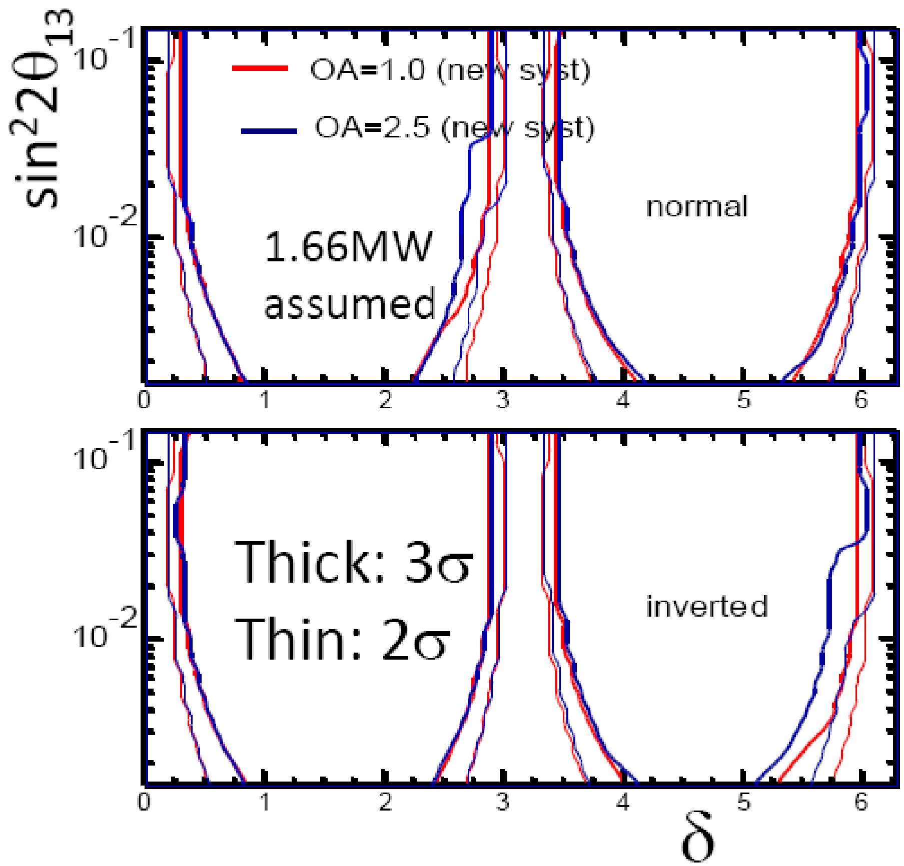


Hyper-K CP Violation Sensitivities

100 kton Liquid Argon Detector

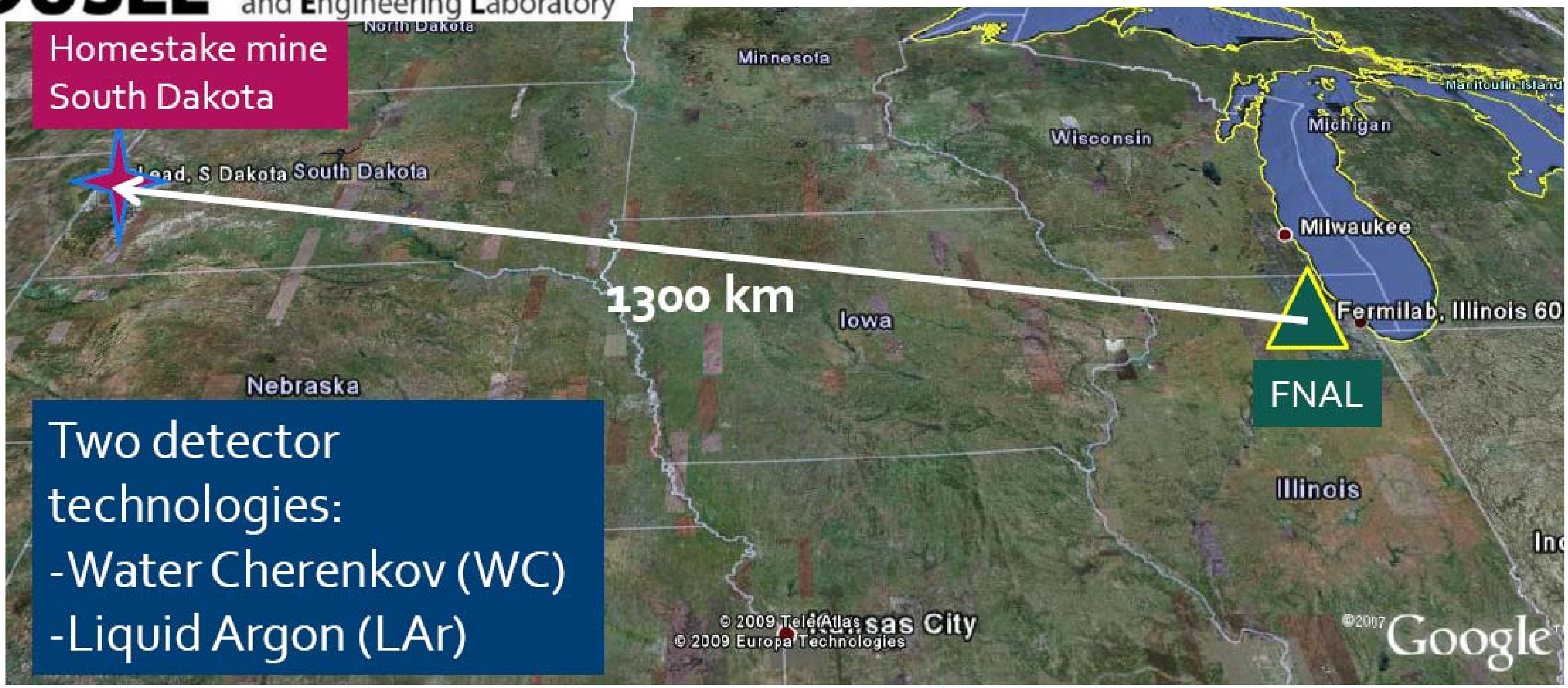


J-PARC to Kamioka + Korea



Long Baseline Neutrino Experiment at DUSEL

DUSEL Deep Underground Science and Engineering Laboratory

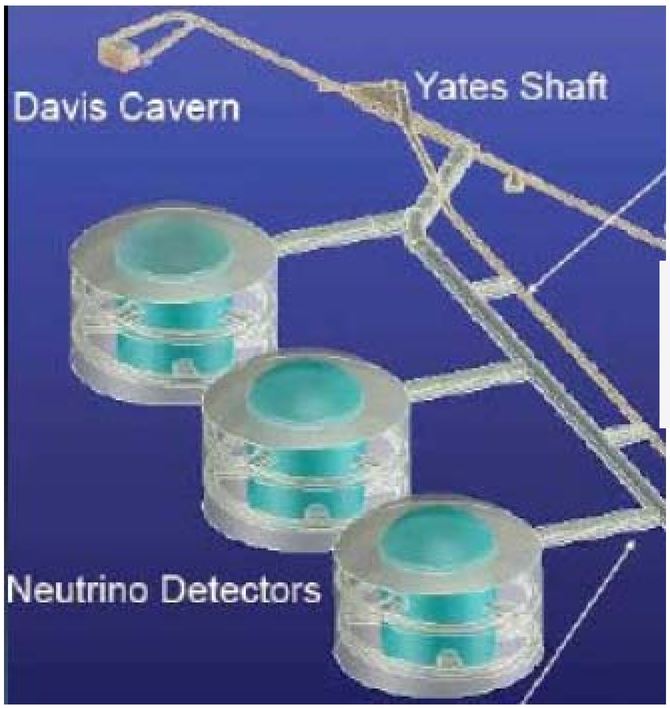


- Beam Requirements:
  - Large neutrino flux covering 1st and 2nd oscillation max points (0.8 and 2.4 GeV)
  - High purity ν_μ flux with little ν_e contamination
  - Minimize flux with energy above 5 GeV that causes background

$\Rightarrow$ Run at reduced energy 90 $\pm$ 30 GeV but then less flux

DUSEL LBNE Experiment and Expectations

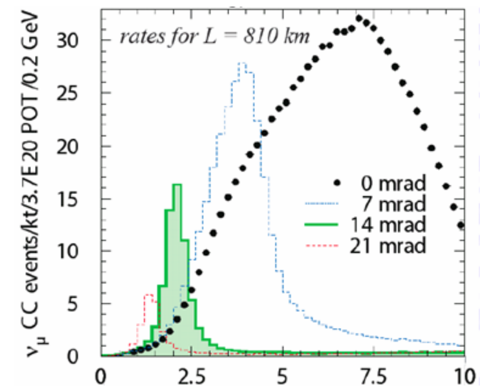
- Baseline experiment:
  - Three 100 kton fiducial “water Cherenkov” detectors (Each 5 times Super-K)
  - 1 MegaWatt (2.3 MW) 120 GeV beam with plug to reduce high E_ν
  - 3 yrs ν + 3 yrs $\bar{\nu}$ of data

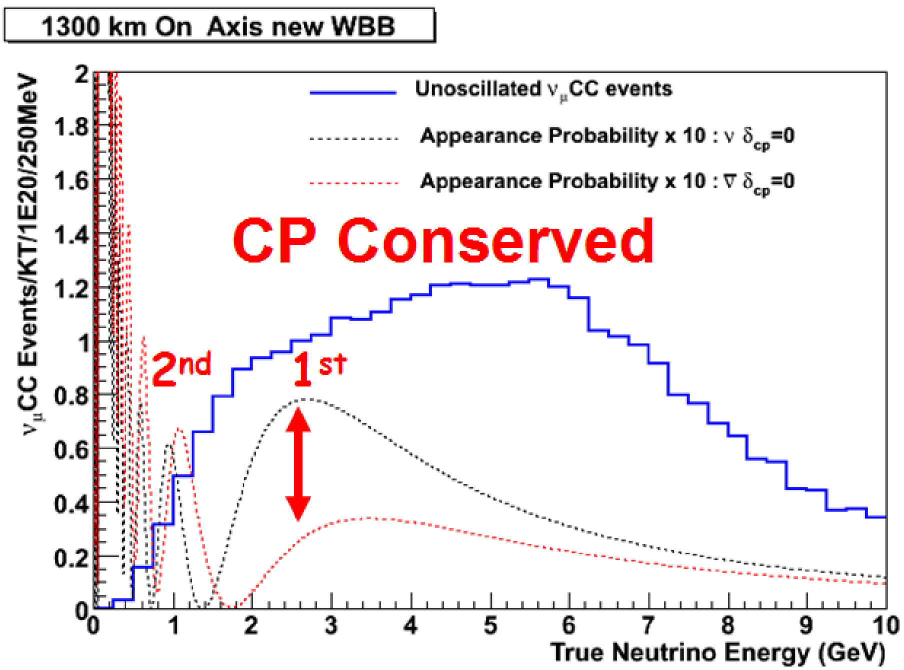


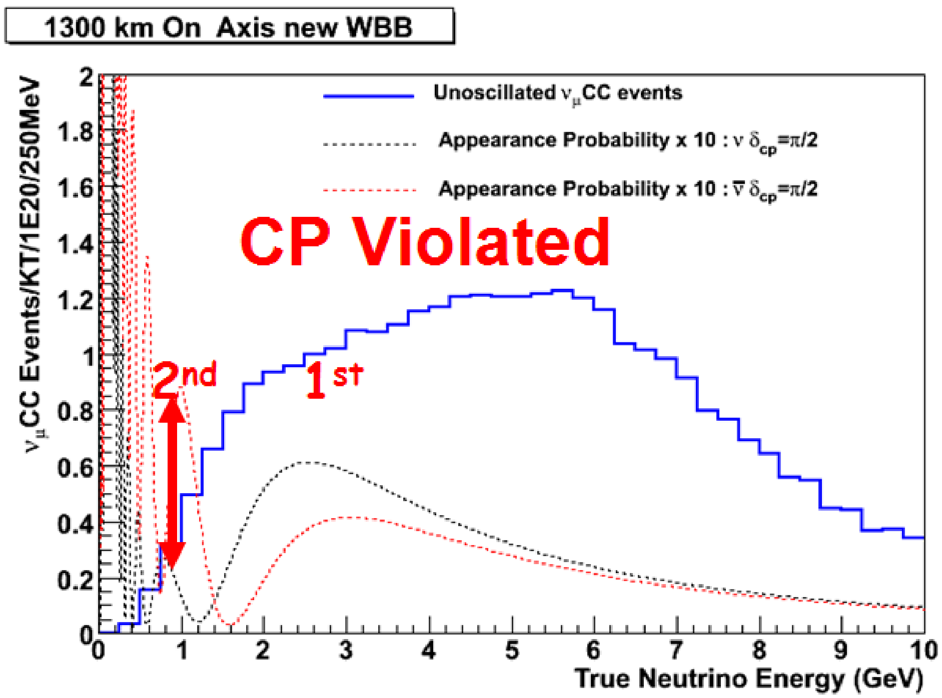
	$\sin^2 2\theta_{13} \neq 0$	$\mathrm{sign}(\Delta m^2_{31})$	CPV
	3σ, all δ_{cp}	3σ, all δ_{cp}	3σ, 50% δ_{cp}
1 MW	0.007	0.021	0.019
2.3 M	0.004	0.014	0.012

On-axis Beam May Be Better for DUSEL Exp

- On-axis beam spans large energy region that allows one to measure the oscillation probability at both the first and second maximum ($\sin^2(1.27\Delta m^2 L/E)$)



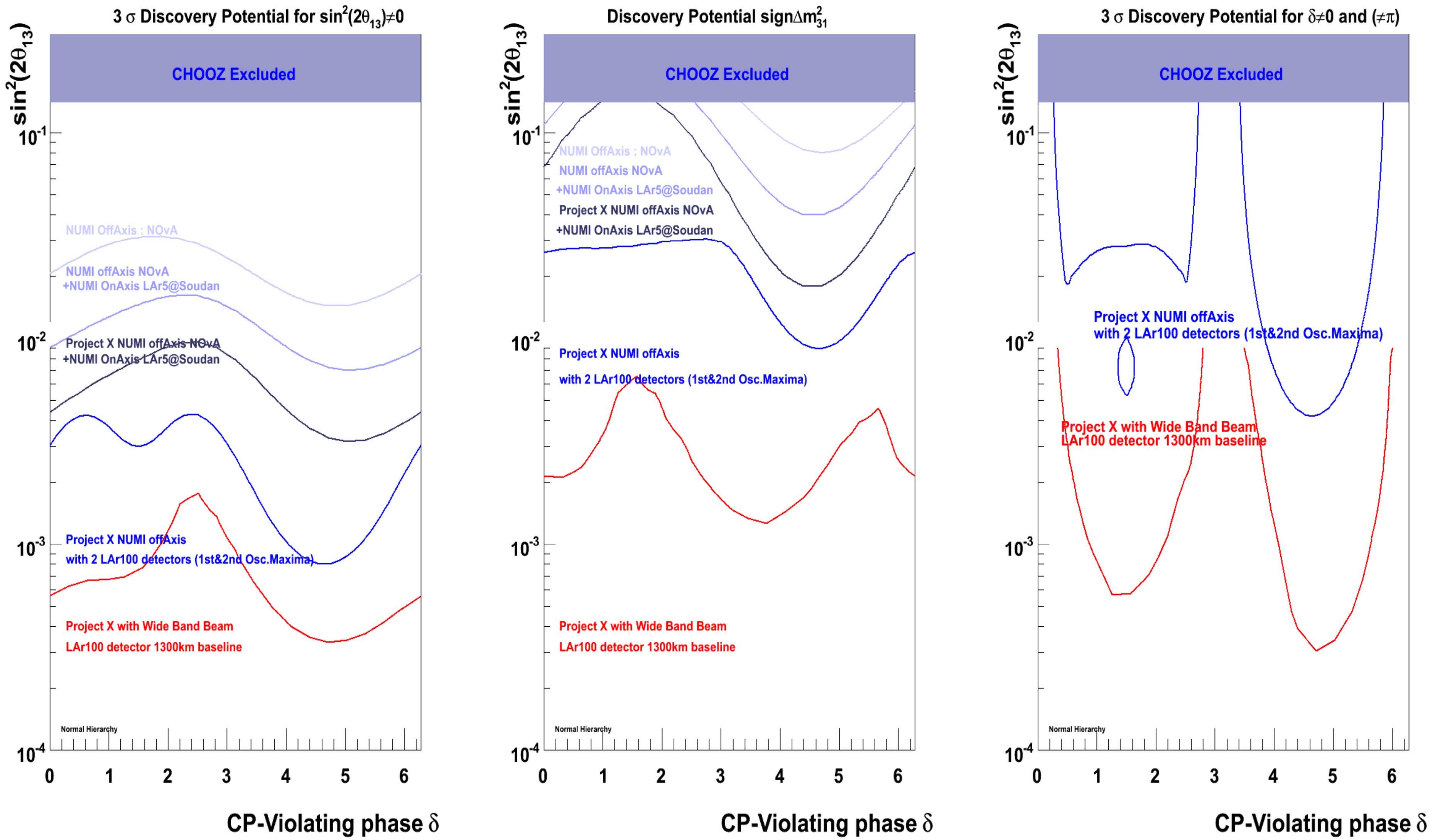




1st Maximum : Gives the neutrino mass hierarchy

2nd Maximum : Sensitive to CP Violation effects

Fermilab to DUSEL Sensitivities



NOvA - NOvA+5ktLAr - NOvA+5ktLAr+PX - NOvA+100kt LAr +PX

100ktLAr (OR 500kt WC) +New WBB+PX at DUSEL

Final Comments

- Reactor and longbaseline experiments will be soon providing new information on θ_{13}
  - θ_{13} is a important physics parameter for modeling ν mixing
  - θ_{13} is key for planning future long-baseline experiments to measure CP violation and the mass hierarchy
    - If $\sin^2 2\theta_{13}$ is > ~0.03, T2K and Nova can make important measurements
    - If $\sin^2 2\theta_{13}$ is < ~0.01, need other techniques to access the physics (1st,2nd max. measurements; Superbeam exps, Neutrino Factory….)

- Longbaseline experiments are more complicated but have the promise to give information on the mass hierarchy and CP violation
  - T2K and Nova could give some early hints of these parameters
  - Next generation superbeams will be necessary to make quantitative measurements

- There is a strong ongoing program of oscillation experiments and serious plans for taking the next step to superbeams
  - Bright future for energetic young physicists to make all this happen

Hallelujah !


BROTHERS AND SISTERS, AT THE TIME OF 10^{-33} SECONDS AFTER THE BIG BANG, THE HEAT WAS ENORMOUS.
VERILY, IT WAS OVER 10^{32} DEGREES !
MATTER AND ANTI-MATTER AROSE!
HALLELUJAH- THEY ANNIHILATED EACH OTHER.
AND THE UNIVERSE WAS FILLED WITH PARTICLES...
AMEN! QUARKS
AND GLUONS
YEA, LEPTONS
Maybe it was the ν's !

Changes sign with:
1) Mass Hierarchy
or
2) 1st vs 2nd Max

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

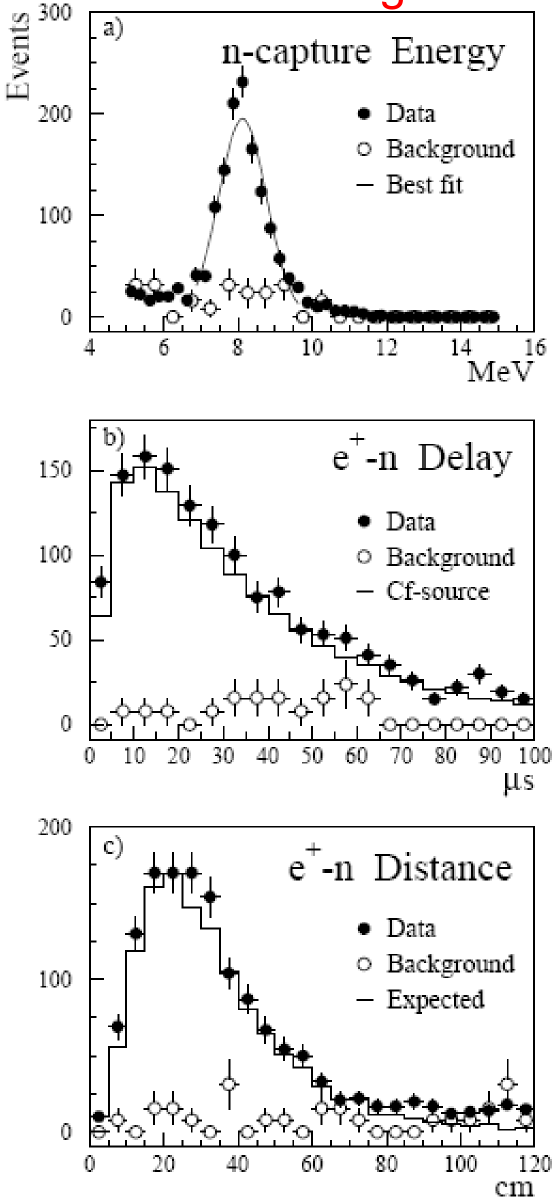
Changes sign with: ν or $\bar{\nu}$

CP Violation

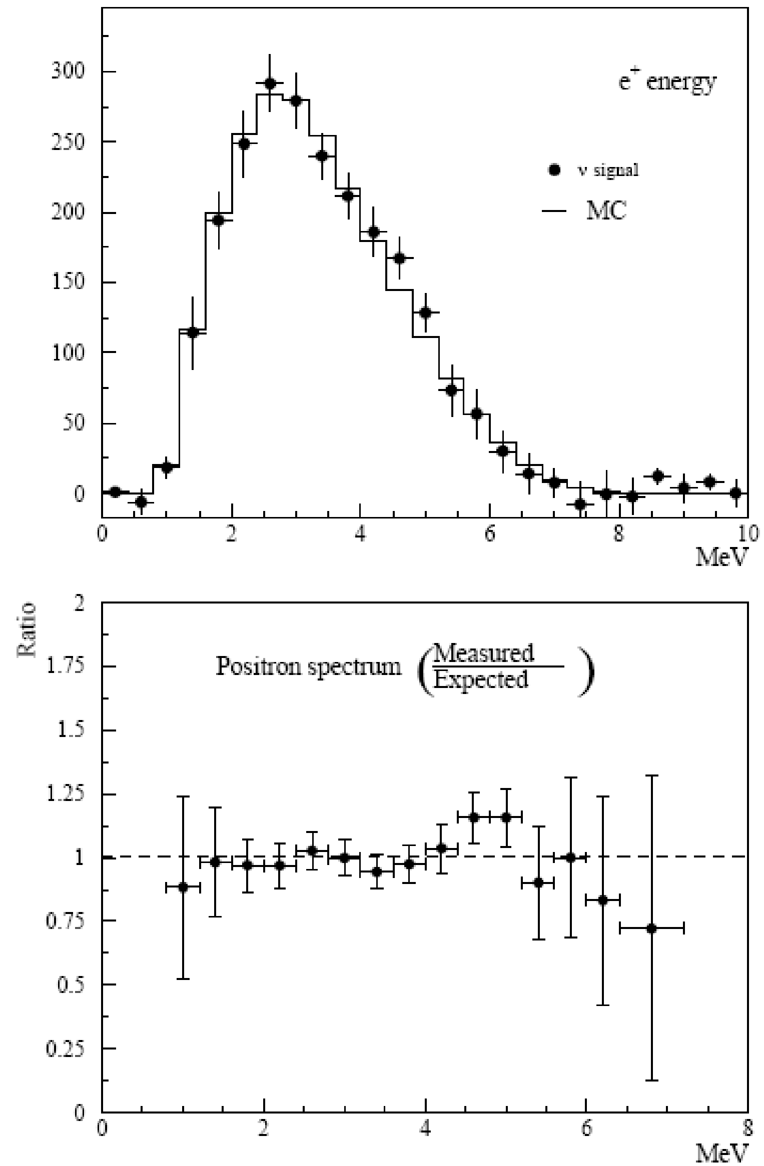
with $\alpha \equiv \Delta m^2_{21}/\Delta m^2_{23}$ and $\Delta \equiv \Delta m^2_{31} L/(4E_\nu)$

CHOOZ Data and Predictions

Experimental Cuts to Isolate IBD Signal



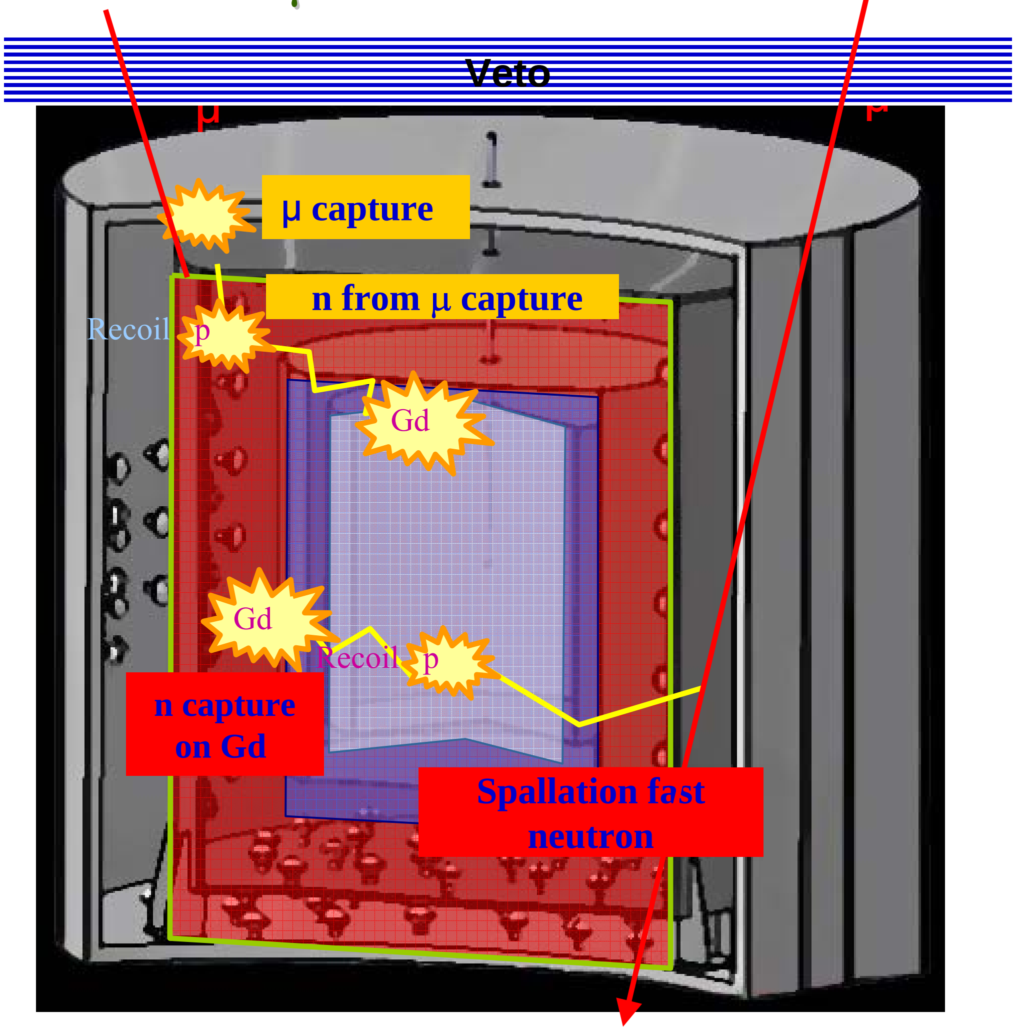
Data Compared to Expectation



Veto Background Events

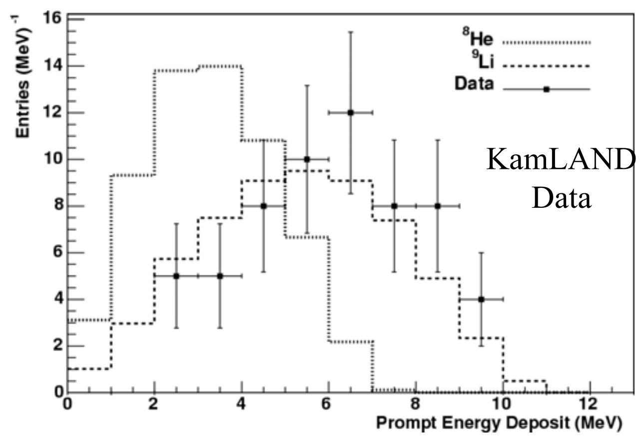
Fast neutrons

Veto μ's and shield neutrons



^{9}Li and ^{8}He

- Produced by a few cosmic ray muons through spallation
- Large fraction decay giving a correlated β+n



A few second veto after every muon that deposits more than 2 GeV in the detector may be able to reduce this rate.