Overview of Reactor Neutrino Measurements

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- With the recent confirmation by Kamland and isolation of the Δm_{solar}^2 in the LMA region, the field of neutrino oscillations is turning to:
  - Measuring the last mixing angle θ_{13}
  - Obtaining better precision on θ_{23}, θ_{12}, Δm_{solar}^2 and Δm_{atm}^2 (along with checking LSND)

  $\Rightarrow$ **Road to measuring ν-mass hierarchy and ν-CP violation**

- Reactor oscillation measurements unique for:
  - Measuring θ_{13}
  - Constraining θ_{23}

- Other reactor neutrino physics
  - Measurement of the weak mixing angle in pure leptonic process
  - Very sensitive probe for neutrino magnetic moment

Thanks to Jon Link and Janet Conrad for many of the slides.

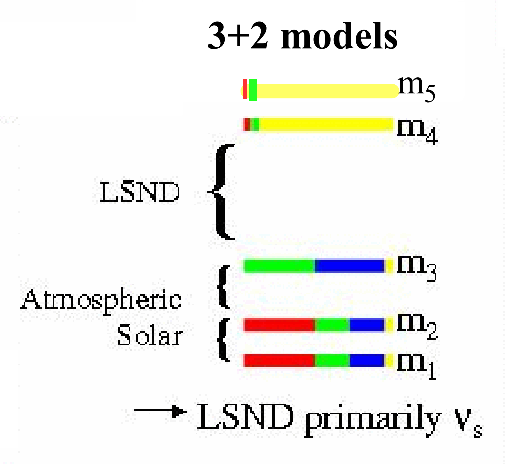
Outline

- Reactor neutrino oscillation measurements
  - Reactor neutrino primer
  - Physics capabilities
  - Experimental method:
    - How to measure a small disappearance signal
  - Possible experimental sites
  - Sensitivity studies
    - Comparisons and combinations with offaxis experiments

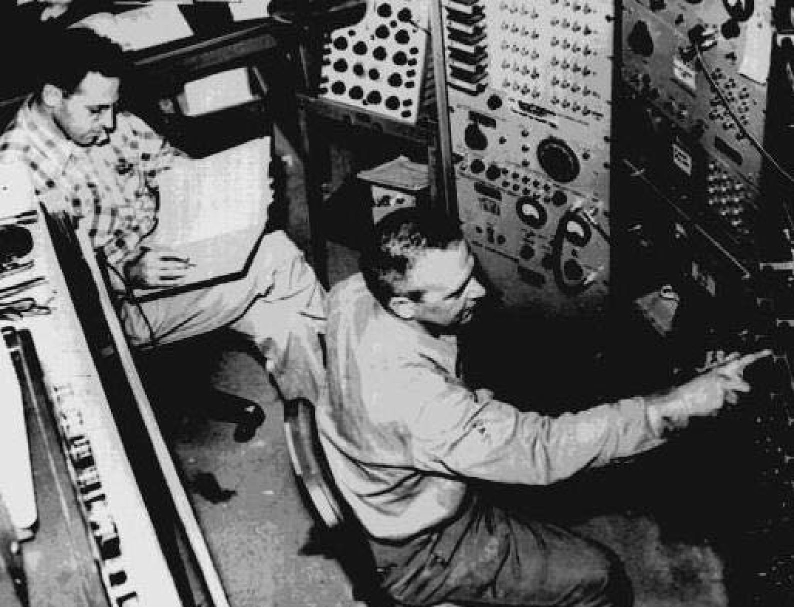
- Reactor neutrino elastic scattering measurements
  - Weak mixing angle sensitivity
  - Sensitivity to neutrino magnetic moments

Key Questions for Neutrino Osc. Phenomenology

- Neutrino mixing matrix is much different from quarks
  $\Rightarrow$ Window for understanding models of neutrino mass
  - Solar and atmospheric angles are very large
    - $\theta_{12} = 32 \pm 3°$
    - $\theta_{23} = 45 \pm 9°$ $\Leftarrow$ Is θ_{23} really maximal?
  - How large is θ_{13}?
    - If very small, may indicate some special symmetry
    - Key to developing future program to measure CP violation and mass hierarchy
- Is there CP violation in the neutrino sector?
  - May give hints about possible "Leptogenesis"
- Are there more than three types of neutrinos?
  - Sterile neutrinos
  - MiniBooNE and LSND signal



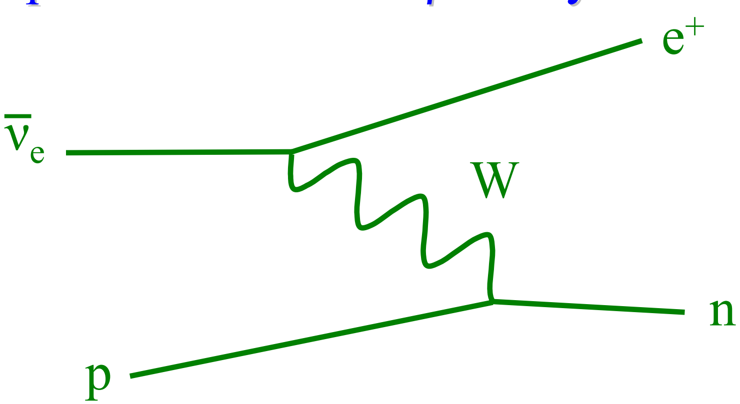
Doing Physics With Reactors Neutrinos



Reines and Cowan at the Savannah River Reactor

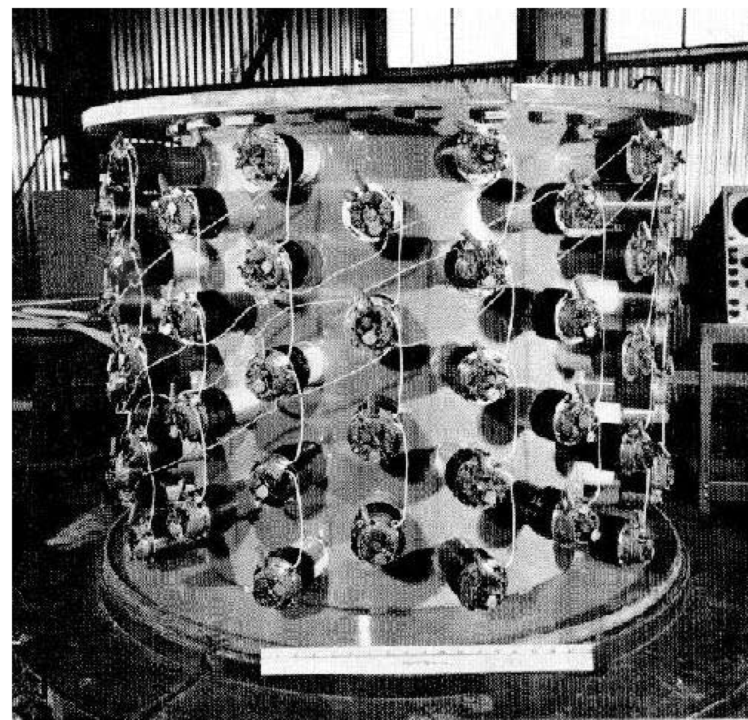
The original neutrino discovery experiment, by Reines and Cowan, used reactor neutrinos…

…actually anti-neutrinos. The $\bar{\nu}_e$ interacts with a free proton via inverse β-decay:



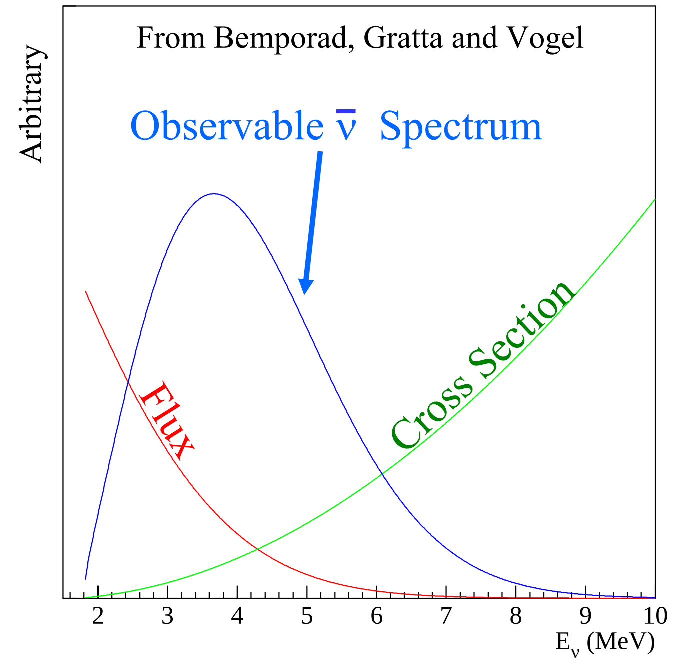
Later the neutron captures giving a coincidence signal. Reines and Cowan used cadmium to capture the neutrons.

The first successful neutrino detector

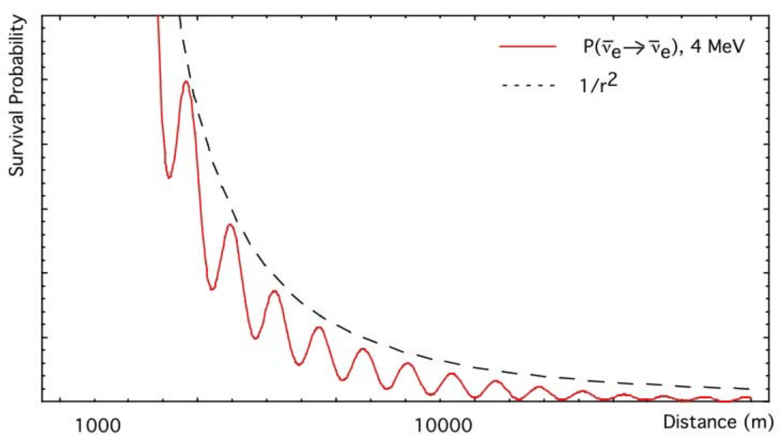


Reactor Measurements of $\sin^2 2\theta_{13}$

- Nuclear reactors are a very intense sources of $\bar{\nu}_e$ with a well understood spectrum
  - 3 GW ≈ 2×10^{21} MeV/s → 6×10^{20} $\bar{\nu}_e$/s
  - Reactor spectrum peaks at ~3.7 MeV
  - Oscillation Max. for $\Delta m^2=2.5\times10^{-3}$ eV^2 at L = 1.7 km



- Look for small rate deviation from $1/r^2$ measured at a 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 Neutrino Event Signature

- The reaction process is inverse β-decay followed by neutron capture
  - Two part coincidence signal is crucial for background reduction.

$$\bar{\nu}_e p \rightarrow e^+ n$$
$$\hookrightarrow n\ capture$$

- Positron energy spectrum implies the neutrino spectrum

$$E_\nu = E_{vis} + 1.8\ \mathrm{MeV} - 2m_e$$

- In undoped scintillator the neutron will capture on hydrogen

$$n\,H \rightarrow D\,\gamma\ \ (2.2\ \mathrm{MeV})$$

- More likely the scintillator will be doped with gadolinium to enhance capture

$$n\,{}^{m}\mathrm{Gd} \rightarrow {}^{m+1}\mathrm{Gd}\ \gamma\text{'s}\ (8\ \mathrm{MeV})$$

Physics of θ_{13} at Reactors

- The reactor experiment is the only one that can make an unambiguous measurement of the mixing parameter $\sin^2 2\theta_{13}$.

Chooz and Palo Verde Reactor Experiments

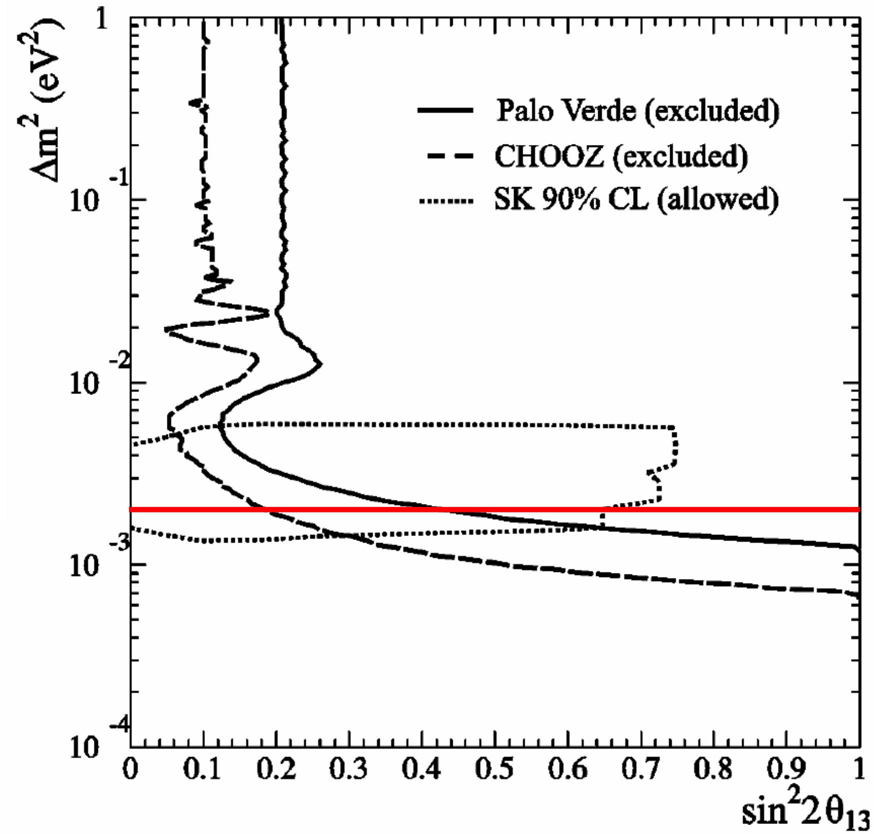
• Neither experiments found evidence for $\bar{\nu}_e$ oscillation.

• This null result eliminated $\nu_\mu \rightarrow \nu_e$ as the primary mechanism for the Super-K atmospheric deficit.

• $\sin^2 2\theta_{13} < 0.18$ at 90% CL (at $\Delta m^2 = 2.0\times10^{-3}$)

• Future experiments should try to improve on these limits by *at least* an order of magnitude.

Down to $\sin^2 2\theta_{13} < 0.01$



Chooz Systematic Uncertainties

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

Physics of θ_{13} at Reactors

- The reactor experiment is the only one that can make an unambiguous measurement of the mixing parameter $\sin^2 2\theta_{13}$.

- Sensitivity should reach $\sin^2 2\theta_{13} \leq 0.01$ at 90% CL in three years of running. Better sensitivity is possible.

The θ_{23} Degeneracy Problem

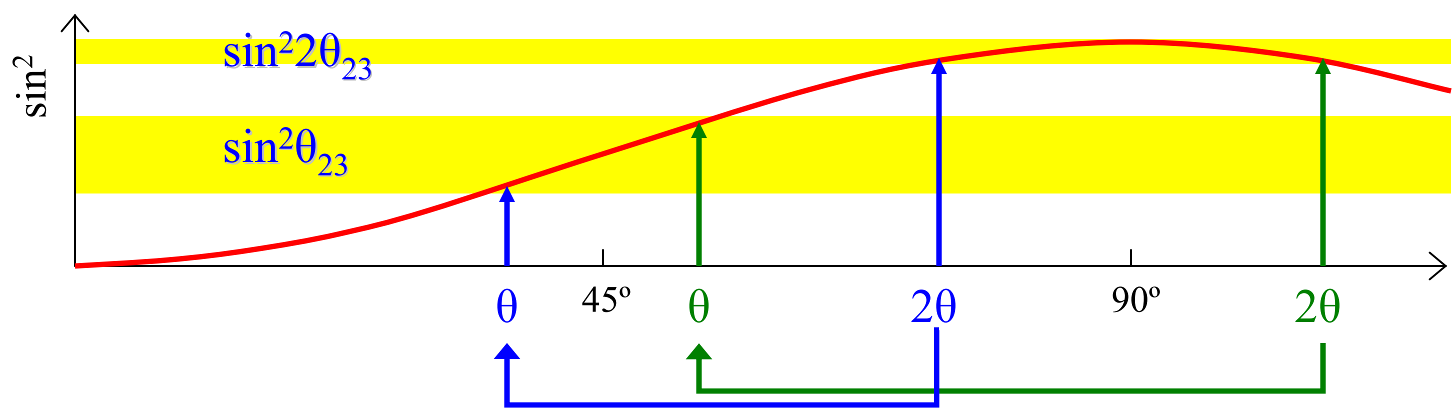
Atmospheric neutrino measurements are sensitive to $\sin^2 2\theta_{23}$

Super-K Measures ⟶ $$P(\nu_\mu \to \nu_x) = \sin^2 2\theta_{23} \sin^2\left(\frac{1.27\Delta m_{23}^2 L}{E_\nu}\right)$$

But the leading order term in offaxis $\nu_\mu \to \nu_e$ oscillations is

Offaxis θ_{13} Measures ⟶ $$P(\nu_\mu \to \nu_e) = \sin^2 \theta_{23} \sin^2 2\theta_{13} \sin^2\left(\frac{1.27\Delta m_{13}^2 L}{E_\nu}\right)$$

If the atmospheric oscillation is not exactly maximal ($\sin^2 2\theta_{23} < 1.0$) then $\sin^2\theta_{23}$ has a twofold degeneracy



Physics of θ_{13} at Reactors

• The reactor experiment is the only one that can make an unambiguous measurement of the mixing parameter $\sin^2 2\theta_{13}$.

• Sensitivity should reach $\sin^2 2\theta_{13} \leq 0.01$ at 90% CL in three years of running. Better sensitivity is possible.

• In conjunction with the off-axis (beam experiments) the reactor experiment determines the value of $\sin^2\theta_{23}$.

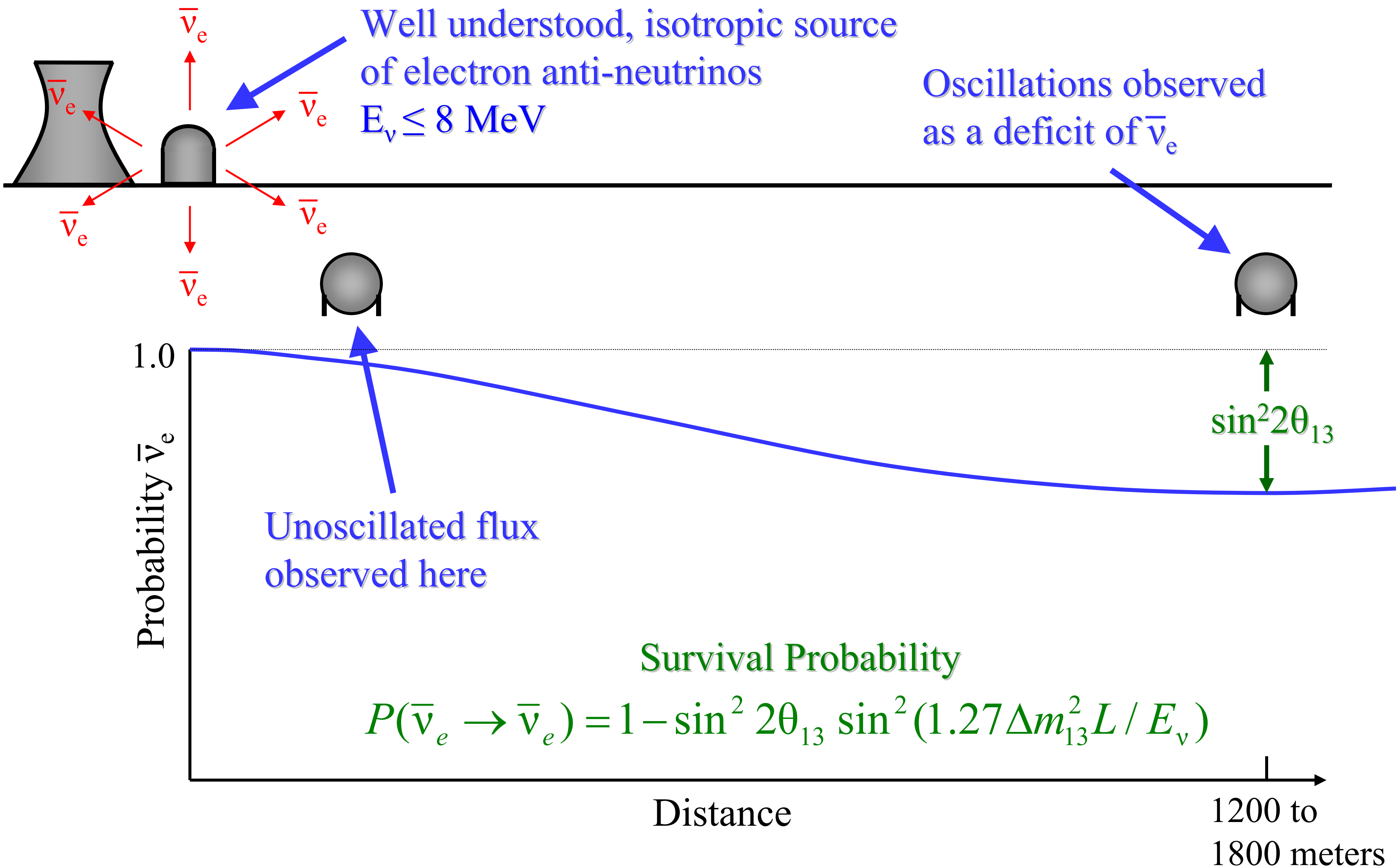
• Direct knowledge of the mixing angles is important in its own right! Could be crucial to constructing a theory of flavor.

• The reactor measurement determines the feasibility of CP violation and mass hierarchy studies in off-axis.

How Do You Measure a Small Disappearance?

- Use identical near and far detectors to cancel many sources of systematics.

$\sin^2 2\theta_{13}$ Reactor Experiment Basics

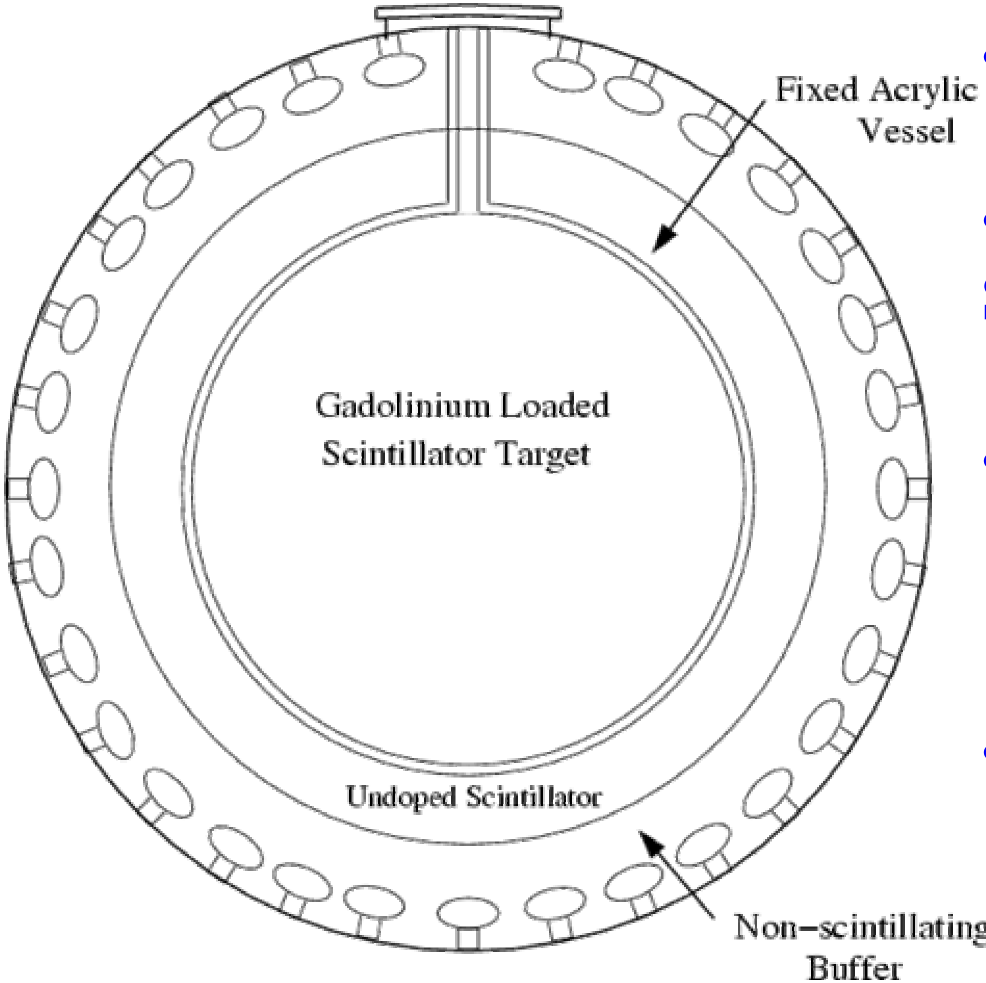


How Do You Measure a Small Disappearance?

- Use identical near and far detectors to cancel many sources of systematics.

- Design detectors to eliminate the need for analysis cuts that may introduce systematic error.

Detector Design Basics



- Homogenous Volume
- Viewed by PMT's
  - Coverage of 20% or better
- Gadolinium Loaded, Liquid Scintillator Target
  - Enhances neutron capture
- Unloaded Scintillator Region
  - To capture energy from gamma rays. *Eliminates need for fiducial volume cut.*
- Pure Mineral Oil Buffer
  - To shield the scintillator from radioactivity in the PMT glass. *Allows you to set an energy cut well below the 1 MeV e^+e^- annihilation energy.*

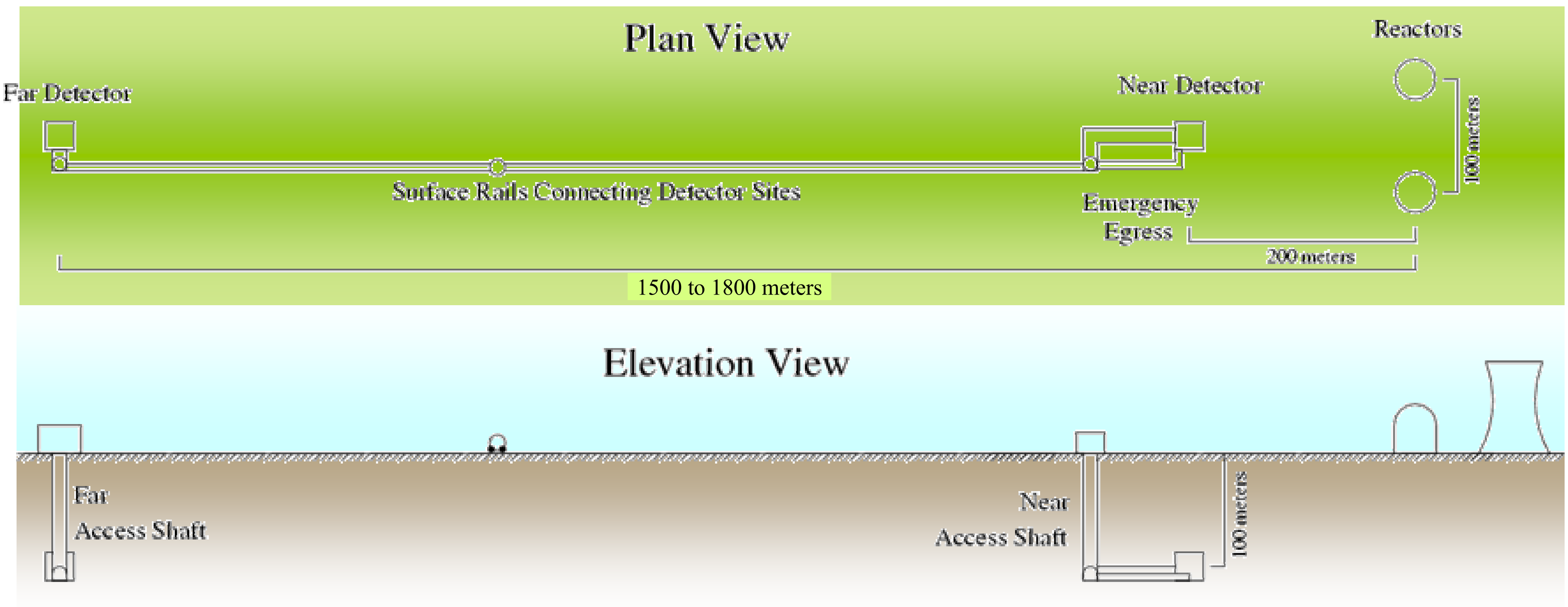
How Do You Measure a Small Disappearance?

- Use identical near and far detectors to cancel many sources of systematics.
- Design detectors to eliminate the need for analysis cuts that may introduce systematic error.
- Detector cross calibration may be used to further reduce the near/far normalization systematic error.

Movable Detectors for Cross Calibration

The far detector spends about 10% of the run at the near site where the relative normalization of the two detectors is measured head-to-head.

Build in all the calibration tools needed for a fixed detector system and verify them against the head-to-head calibration.



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- Reduce background rate and uncertainty

Backgrounds

There are two types of background…

1. Uncorrelated – Two random events that occur close together in space and time and mimic the parts of the coincidence.

   This BG rate can be estimated by measuring the singles rates, or by switching the order of the coincidence events.

2. Correlated – One event that mimics both parts of the coincidence signal.

   These may be caused by fast neutrons (from cosmic μ's) that strike a proton in the scintillator. The recoiling proton mimics the e^+ and the neutron captures.

   Or they may be cause by muon produced isotopes like ^{9}Li and ^{8}He which sometimes decay to $\beta + n$.

Estimating the correlated rate is much more difficult!

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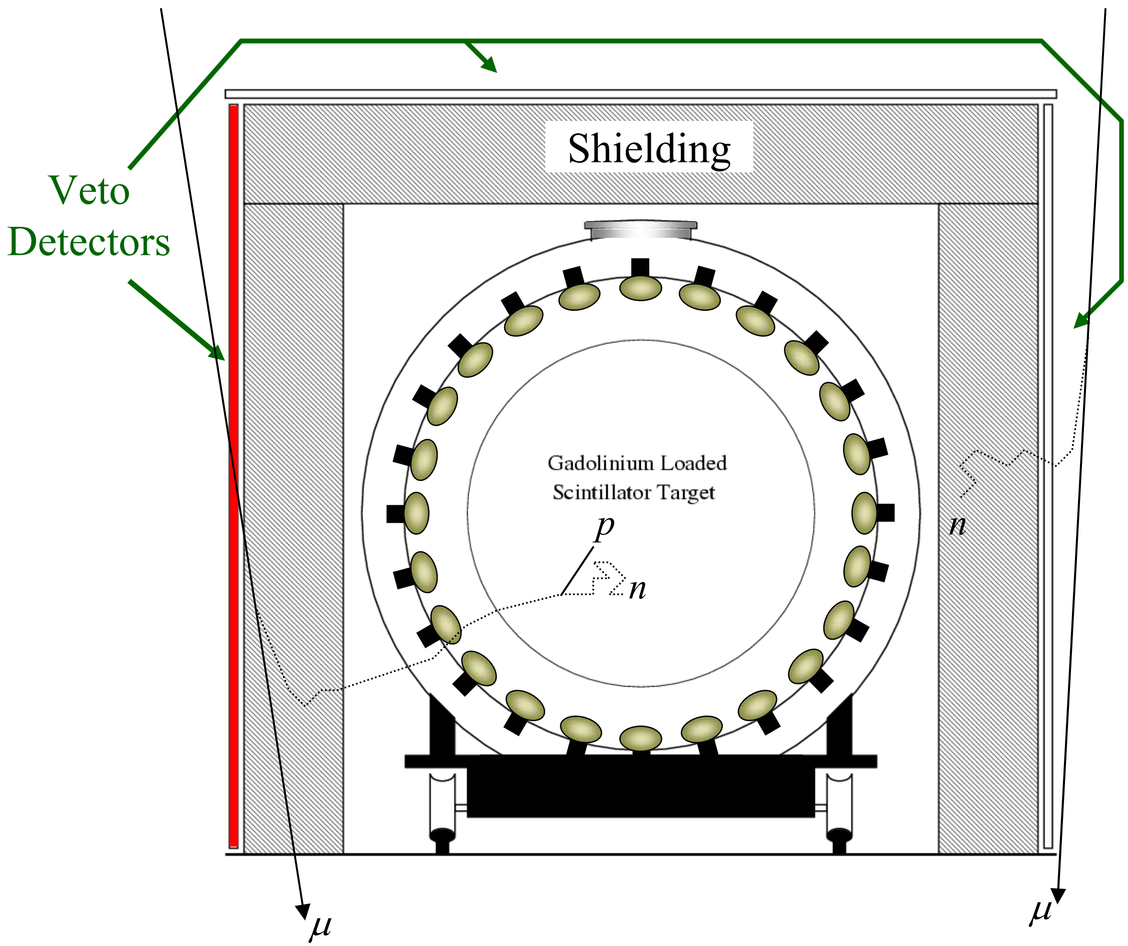
Veto Background Events

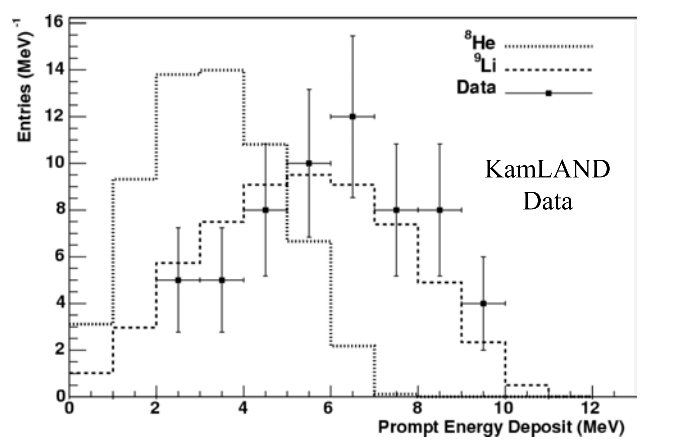
Fast neutrons

Veto μ's and shield neutrons



^{9}Li and ^{8}He

$E \leq 10.6$ MeV
$\tau_{1/2} = 0.18$ to 0.12 s
0.075 produced/ton/day (450 mwe)
50% to 16% correlated β+n



A ½ second veto after every muon that deposits more that 2 GeV in the detector should eliminate 70 to 80% of all correlated decays.

How Do You Measure a Small Disappearance?

- Use identical near and far detectors to cancel many sources of systematics.
- Design detectors to eliminate the need for analysis cuts that may introduce systematic error.
- Detector cross calibration may be used to further reduce the near/far normalization systematic error.
- Reduce background rate and uncertainty
  - Go as deep as you can
  - Veto
  - Use vetoed events to make a subtraction or in an energy fit

Scales of Experiments and Sensitivities

small: $\sin^2 2\theta_{13}$~0.03

- Goal: fast experiment to explore region just below Chooz limit.
- Sensitivity through rate only
- Example: "Double-Chooz" experiment

medium: $\sin^2 2\theta_{13}$~0.01

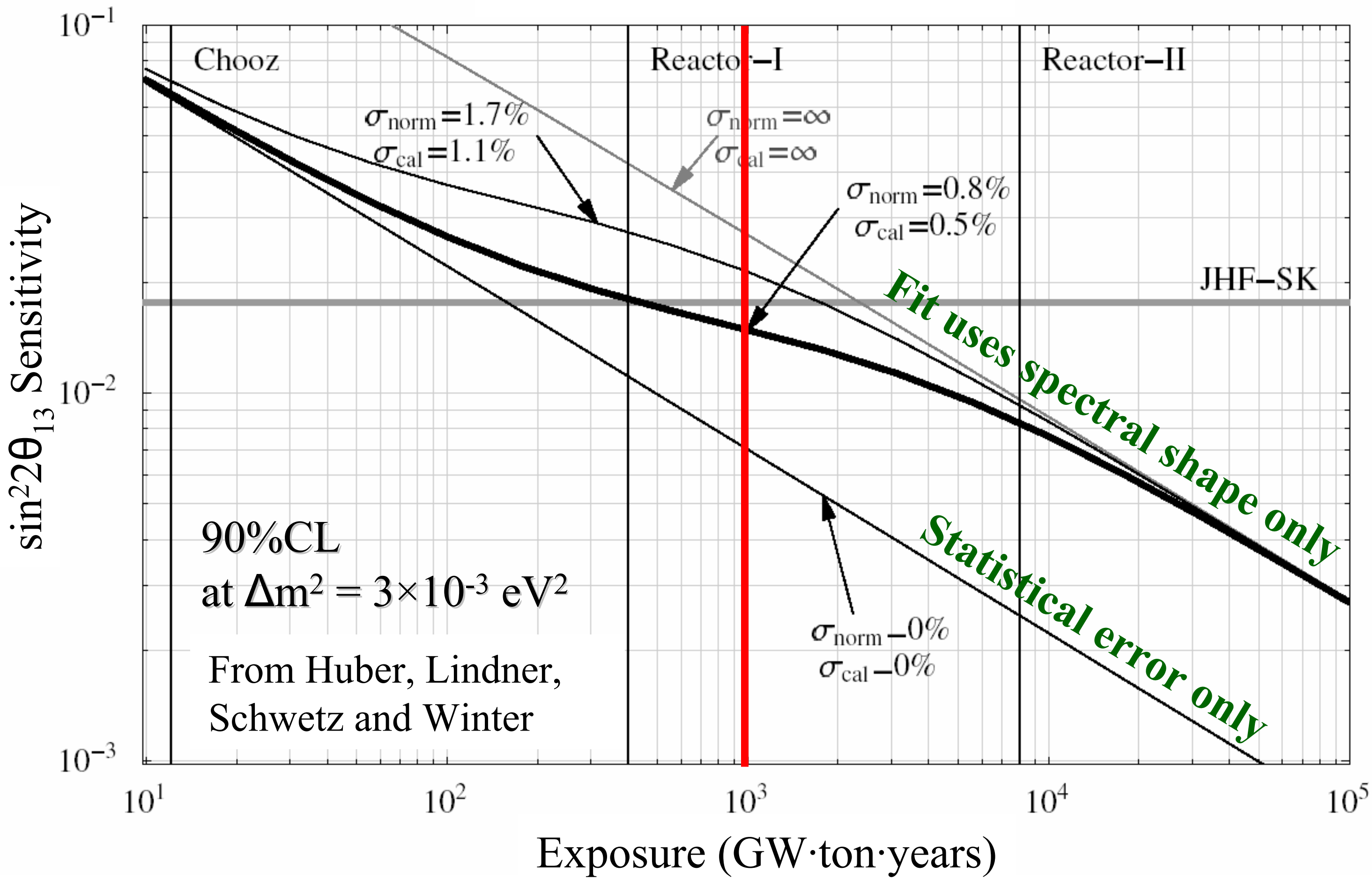
- Make a discovery of θ_{13} in region of interest for the next 10 year program
- Sensitivity enough to augment the physics of offaxis measurements
- Sensitivity mainly rate but also some energy shape

large: $\sin^2 2\theta_{13}$~0.002-0.004??

- Measurement capability comparable to second generation offaxis experiments
- Sensitivity mainly through energy shape distortions

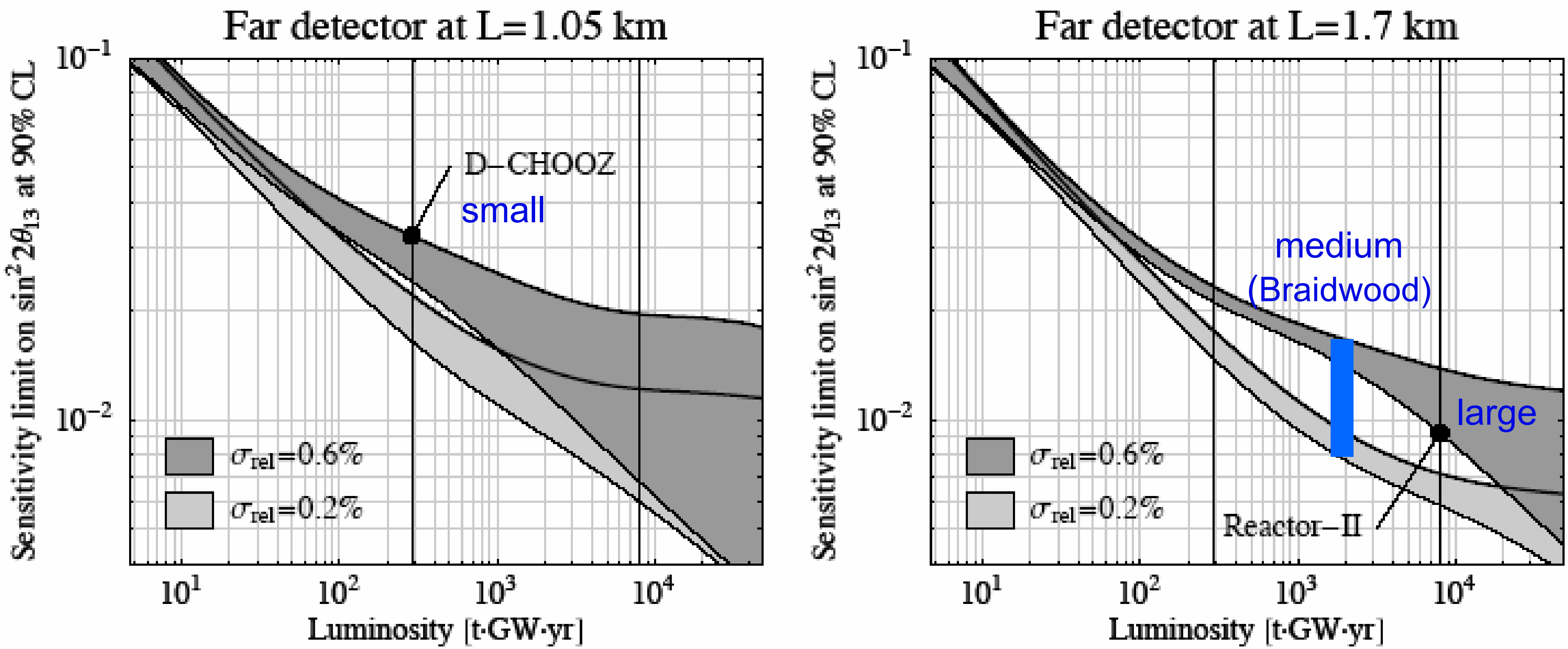
Counting (Rate) vs Energy Shape Measurement

Small detectors give a rate comparison near to far
Large detectors can show a energy shape distortion near to far



The location of the transition from rate to shape depends on the level of systematic error.

Sensitivity Estimates



$\Delta m^2 = 2\times10^{-3}$ eV^2

Ref: hep-ph/0403068

Proposed Sites Around the World

Site	Power ($GW_{thermal}$)	Baseline Near/Far (m)	Shielding Near/Far (mwe)	Sensitivity 90% CL
Krasnoyarsk, Russia	1.6	115/1000	600/600	0.03
Kashiwazaki, Japan	24	300/1300	150/250	0.02
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Diablo Canyon, CA	6.7	400/1700	50/700	0.01
Angra, Brazil	5.9	500/1350	50/500	0.02
Braidwood, IL	7.2	200/1700	450/450	0.01
Daya Bay, China	11.5	250/2100	250/1100	0.01

Many Sites have been investigated as potential hosts to a reactor neutrino experiment.

This is appropriate since getting the cooperation of the reactor company is a main challenge.

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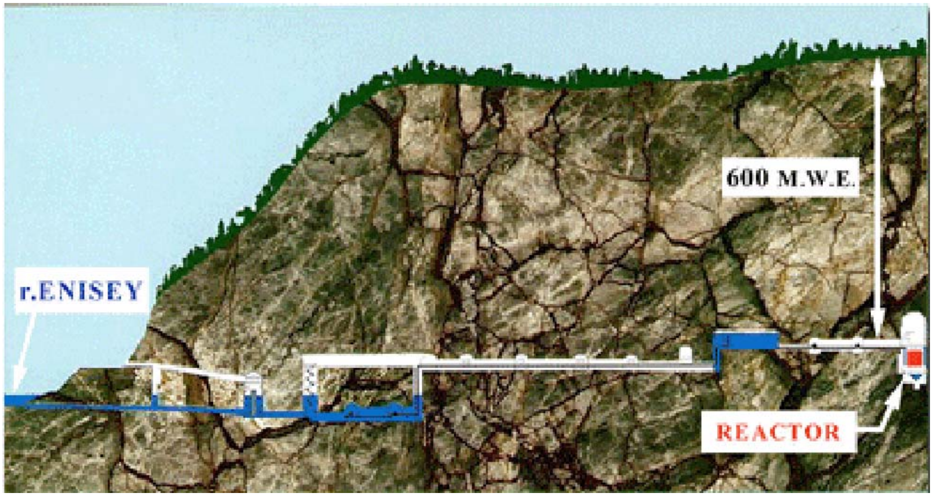

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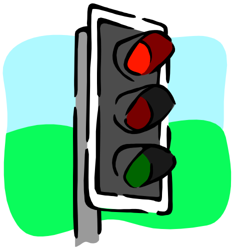

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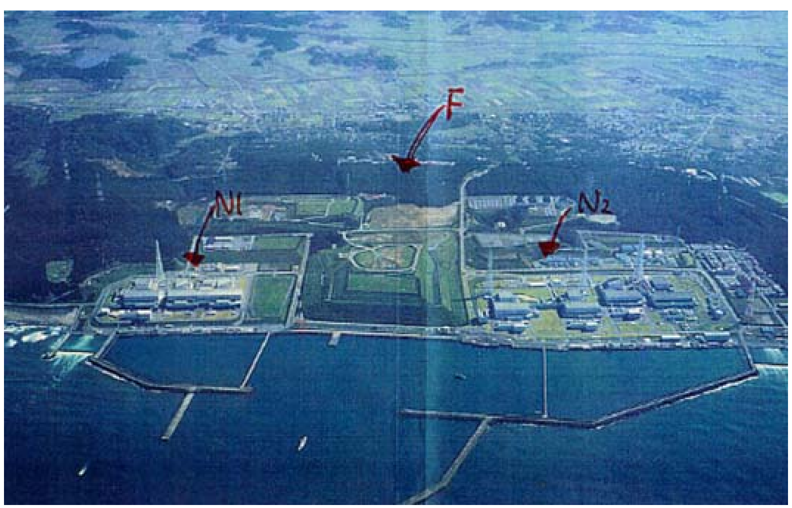

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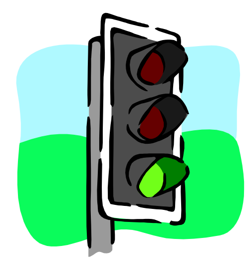
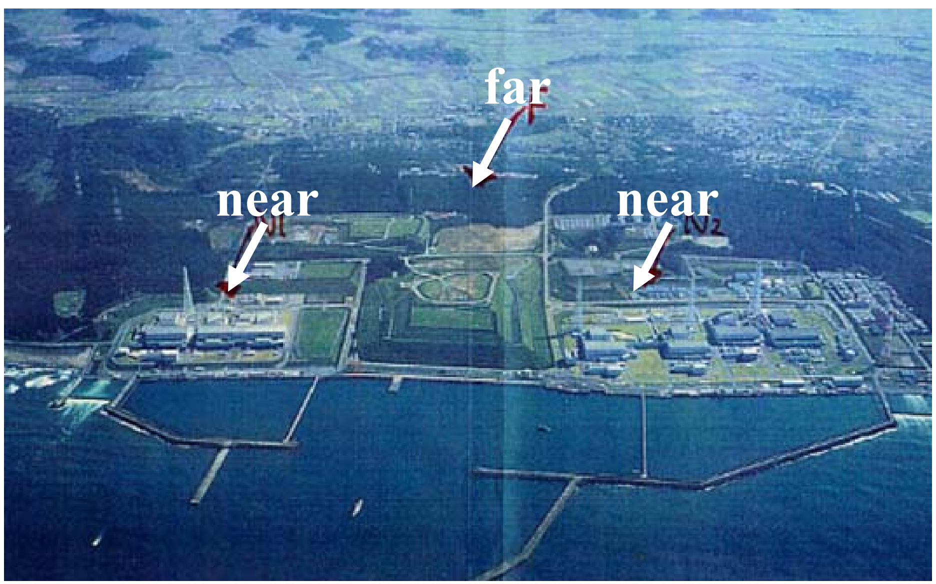
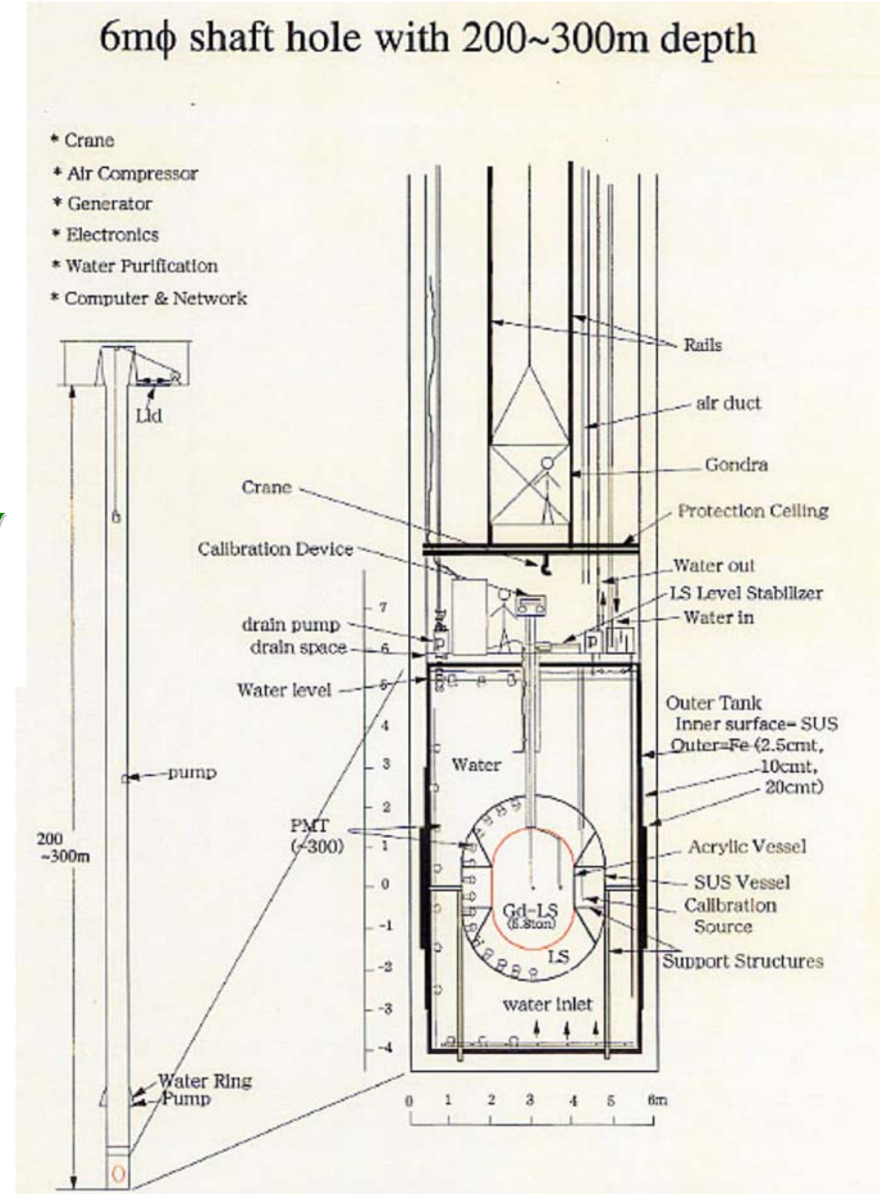


Kashiwazaki, Japan (Minakata, Sugiyama, Yasuda, Inoue, and Suekane hep-ph/0211111)

- 7 Reactors, 24 GW_{th}
- Three ~8.5 ton detectors
- Two near detectors at baselines of 300 to 350 meters
- One far detector at ~1300 meters
  21 different baselines!
- Sensitivity of $\sin^2 2\theta_{13} \leq 0.025$ in 2 years
  Fast! Reaches systematics limit quickly
- Currently working its way through the Japanese system (R&D budget approved)





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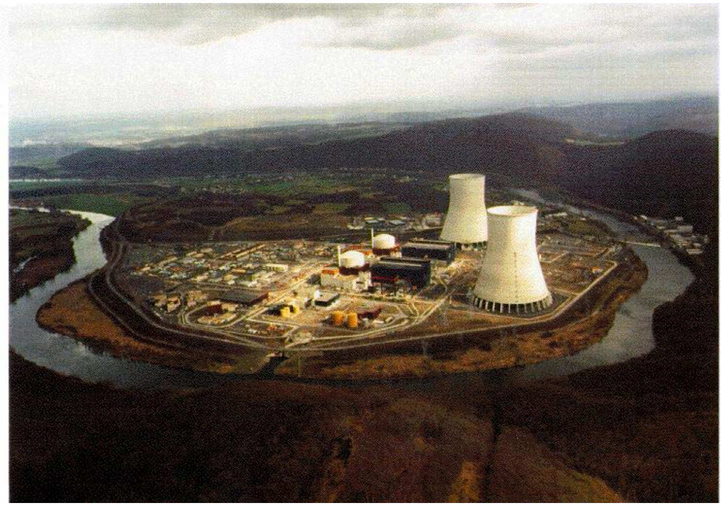

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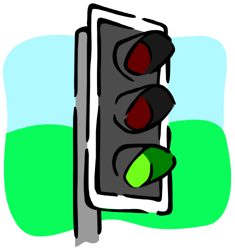
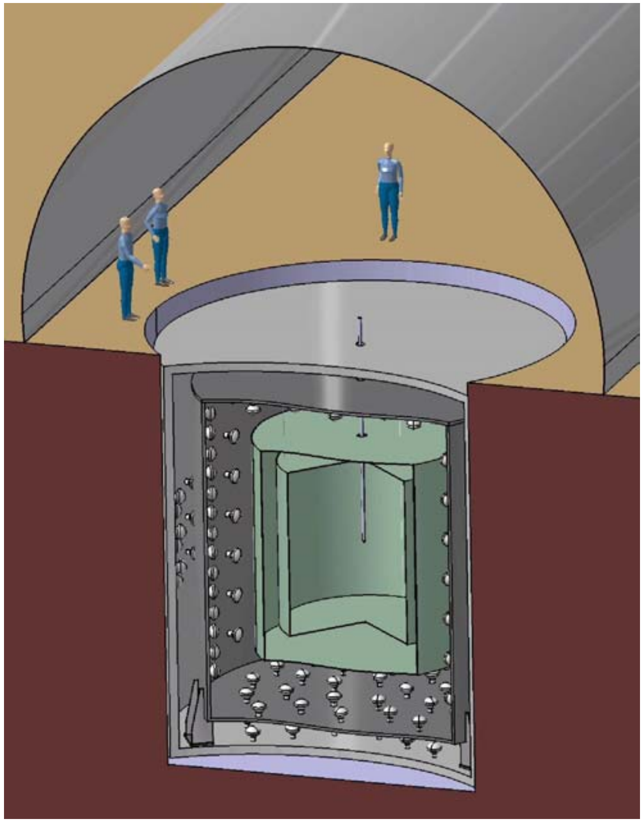
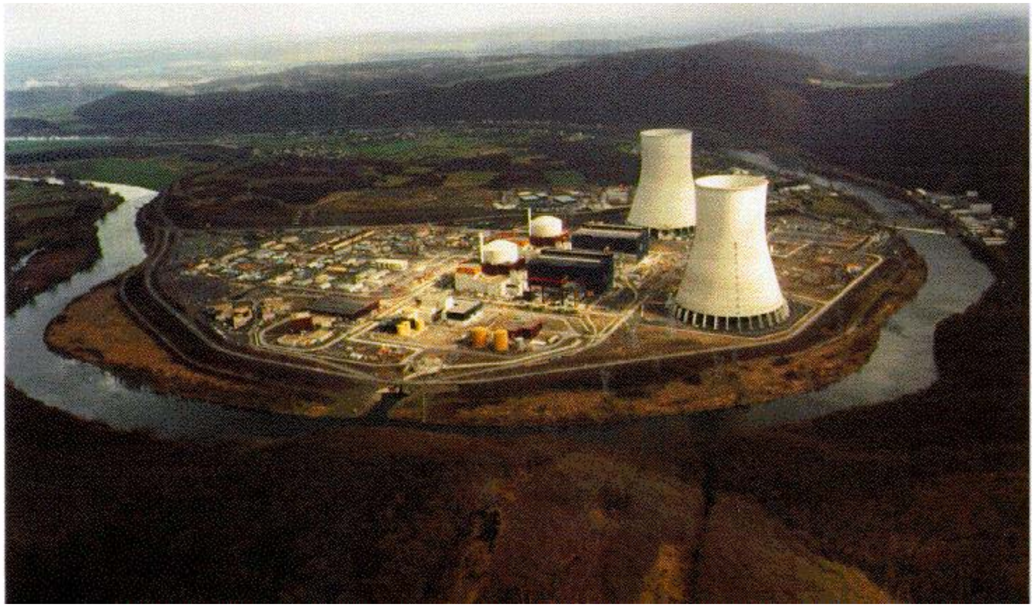


Double CHOOZ , France



- Use old far detector hall at ~1050 meters
- Near detector at 125-250 meters (~50 mwe)
- 11 ton Gd loaded detectors.
- Sensitivity of $\sin^2 2\theta_{13} \leq 0.03$ in 3 years

  Fast and Inexpensive
- Has scientific approval
- Recently released an LOI (hep-ex/0405032)



Double-CHOOZ Experimental Group

I. Barbanov[10], J.C. Barrière [6], L. Bezroukov[10], C. Buck[11], C. Cattadori [8,9], M. Cribier [1,3], F. Dalnoki-Veress [11], N. Danilov[2], H. de Kerret [1,12], F. Ardellier [5], A. Di Vacri [8,15], A. Etenko [13], C. Grieb [14], M. Goeger [14], C. Jeanney [5], Y.S. Krilov[2], D. Kryn [1,12], W. Hampel [11], F.X. Hartmann [11], P. Huber [14], J. Jochum [7], T. Lachenmaier [14], Th. Lasserre [*,1,3], C. Lendvai [14], M. Lindner [14], F. Marie [4], G. Mention [1,12], A. Milsztajn [3], J.P. Meyer [3], D. Motta [11], L. Oberauer [14], M. Obolensky [1,12], L. Pandola [8,15], W. Potzel [14], S. Schönert [11], U. Schwan [11], T. Schwetz [14], L. Scola [6], M. Skorokhvatov [13], S. Sukhotin [12,13], A. Letourneau [4], D. Vignaud [1,12], F. von Feilitzsch [14], W. Winter [14], E. Yanovich[10]

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[5] DSM/DAPNIA/SEDI, CEA/Saclay, 91191 Gif-sur-Yvette, France

[6] DSM/DAPNIA/SIS, CEA/Saclay, 91191 Gif-sur-Yvette, France

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[8] INFN, LGNS, I-67010 Assergi (AQ), Italy

[9] INFN Milano, Via Celoria 16, 20133 Milano, Italy

[10] INR, 7a, 60th October Anniversary prospect, Moscow 117312, Russia

[11] MPI für Kernphysik, Saupfercheckweg 1, D-69117 Heidelberg, Germany

[12] PCC Collège de France, 11 place Marcelin Berthelot, 75005 Paris, France

[13] RRC Kurchatov Institute, 123182 Moscow, Kurchatov sq. 1, Russia

[14] TU Muenchen. James-Franck-Str. 1, D-85747 Garching, Germany

Double – CHOOZ Experiment

- Experimental Goals:
  - Statistical error = 0.4%
  - Background error = 1%
  - Relative detector error = 0.6%

- Advantages:
  - Infrastructure exists for far site
  - Reactor company would build near site if approved

- Disadvantages:
  - Shallow near detector site (50-100 mwe)
    - Deadtime = 500 μs / muon $\Rightarrow$ 50% Deadtime
    - Higher cosmogenic bkgnd.
  - Far baseline only 1km which limits sensitivity especially for low Δm^2

- Cost estimate:
  - Detectors: ~ $7M
  - Civil Construction: ~ $10M

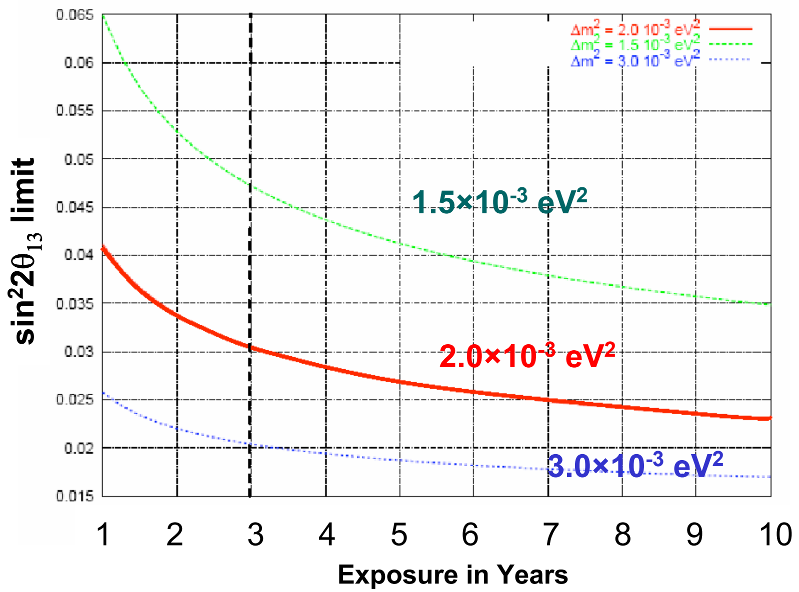
- Schedule:

  Now : Securing approvals from agencies and company

  Feb. 05: If approved, complete design and put out bids

  May 07: Complete far detector

  Early 08: Complete near detector



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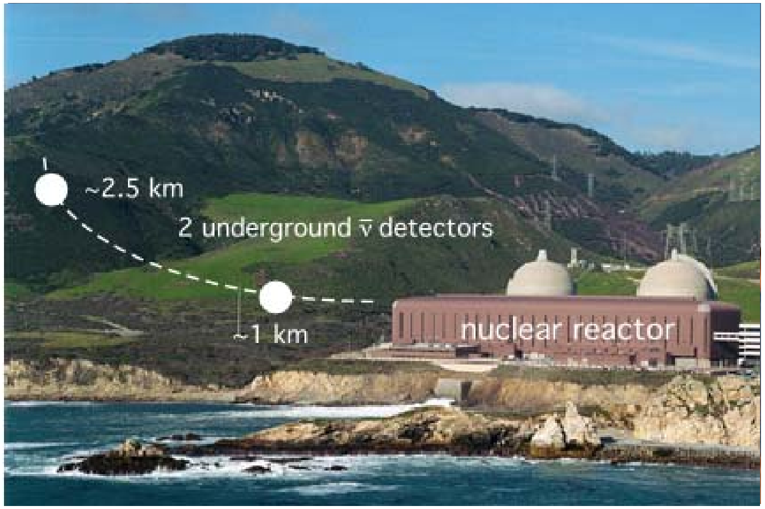

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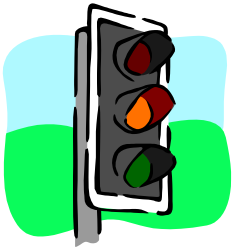

Proposed Sites Around the World

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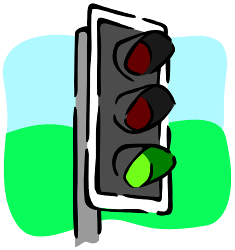
Krasnoyarsk, Russia	1.6	115/1000	600/600	0.03
Kashiwazaki, Japan	24	300/1300	150/250	0.02
Double Chooz, France	8.4	150/1050	30/300	0.03
Diablo Canyon, CA	6.7	400/1700	50/700	0.01
Angra, Brazil	5.9	500/1350	50/500	0.02
Braidwood, IL	7.2	200/1700	450/450	0.01
Daya Bay, China	11.5	250/2100	250/1100	0.01

Status



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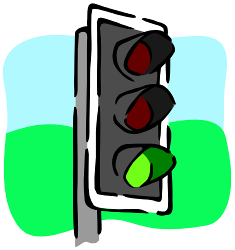
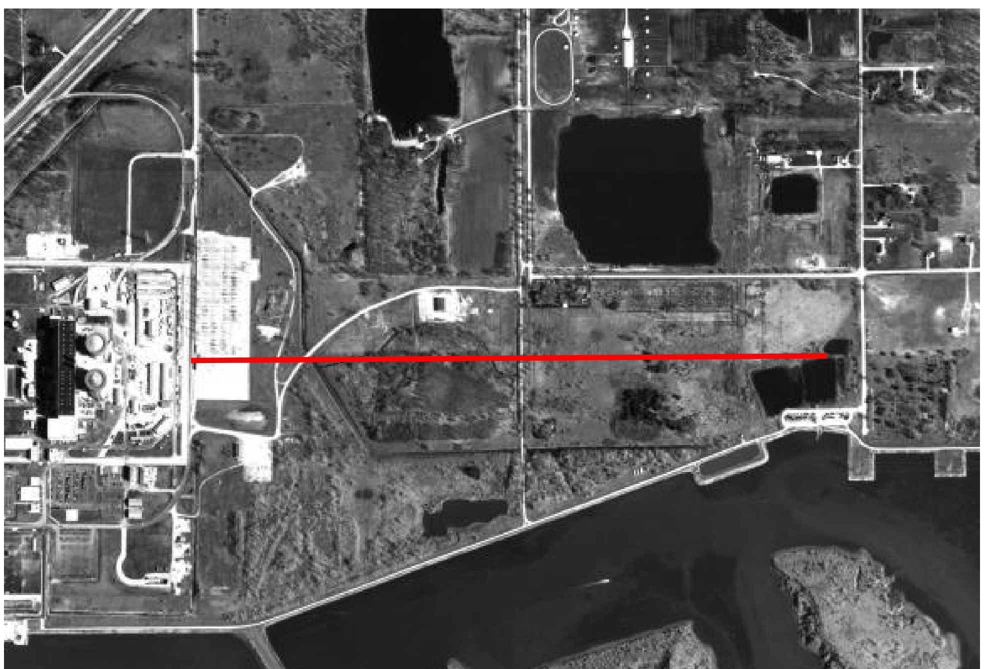
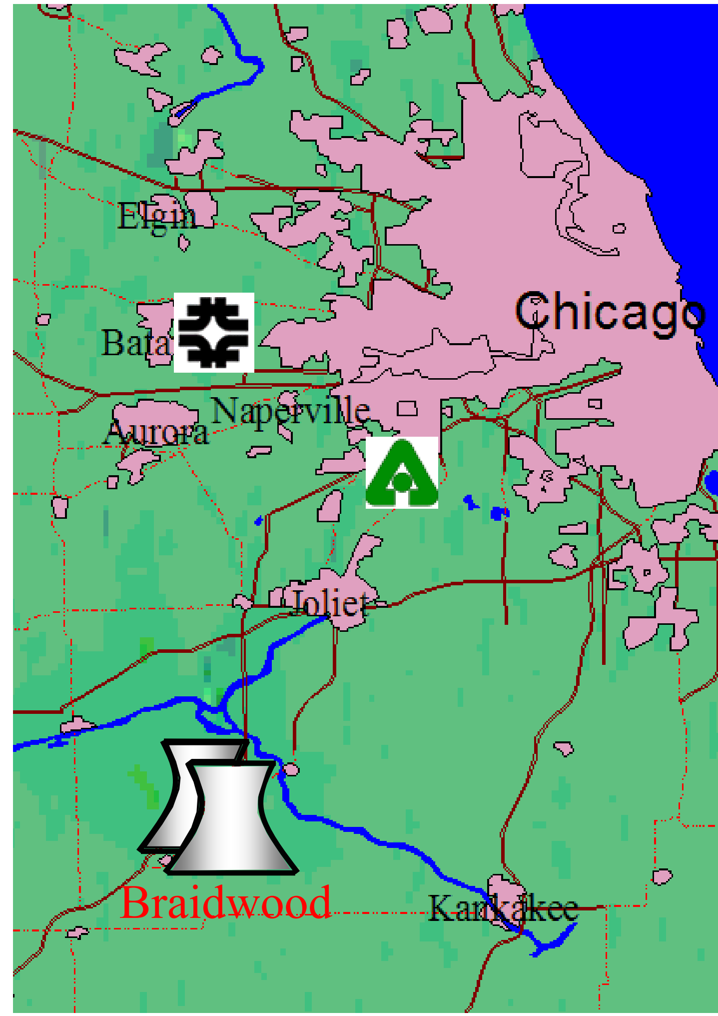


Braidwood, Illinois

- Three (or more) 25 ton detectors
- Near detector at 200 meters & 450 mwe
- Two far detectors located somewhere between 1500 & 1800 meters, 450 mwe
- Sensitivity of $\sin^2 2\theta_{13} \leq 0.01$ in 3 years
- High level of cooperation with utility





Braidwood Experimental Group

Midwest θ_{13} Collaboration

ANL: Maury Goodman, David Reyna

Chicago: Erin Abouzaid, Kelby Anderson, Ed Blucher, Jim Pilcher, Matt Worcester

Columbia: Janet Conrad, Jon Link, Mike Shaevitz

FNAL: Larry Bartoszek, Dave Finley, Hans Jostlein, Chris Laughton, Ray Stefanski

Kansas: Tim Bolton, Noel Stanton

Oxford: Steve Biller, Nick Jelley

Pittsburgh: Donna Naples, Vittorio Paolone

Texas: Josh Klein

Michigan: Byron Roe

Braidwood Experiment

- Experimental Goals:
  - Statistical error = 0.15%
  - Background error = 0.4%
  - Relative detector error = 0.4%
- Advantages:
  - Shaft access
    - Flat overburden gives better shielding
    - Deep near site allows other reactor physics measurements
    - Surface transport of detectors for cross calibration
    - Favorable geology and low bkgnd
- Disadvantages:
  - Infrastructure costs high due to green field site

- Cost estimate:

  Civil: ~ $30M

  Detectors: $15M

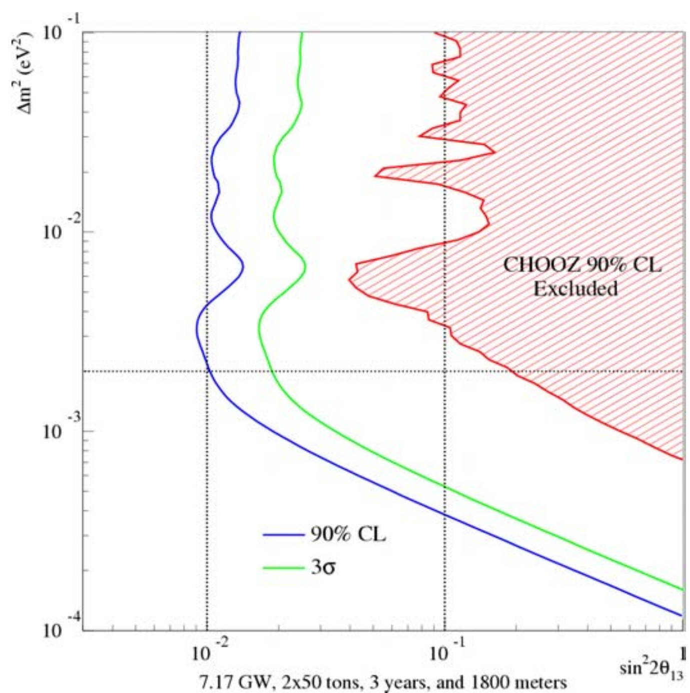
- Schedule:

  2005: R&D and full proposal preparation

  2006: Project approval

  2007: Construction

  2009: Start data collection



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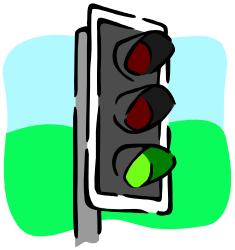
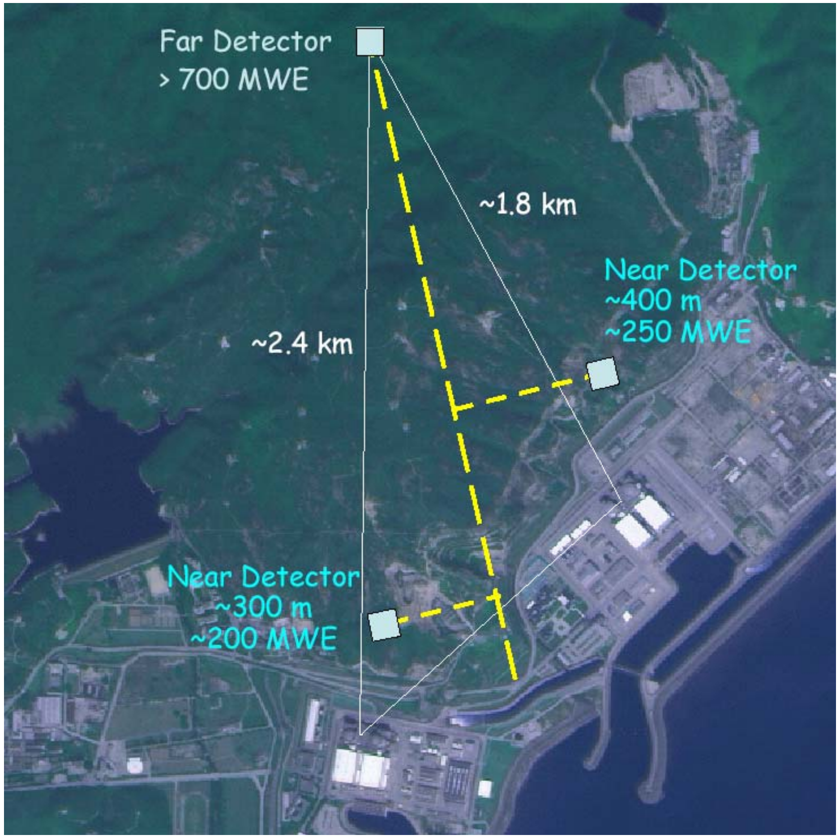


Daya Bay, China

- 4 Reactors, 11.5 GW_{th}
- Several ~8 ton detectors
- Near detectors at baseline of 300 and 400 meters, 200 to 250 mwe
- Far detectors at baselines of 1800 and 2400 meters, 1100 mwe
- Sensitivity of $\sin^2 2\theta_{13} \leq 0.01$ in 3 years



- Utility/government approval is likely
- China would support civil construction, but foreign support is needed for detectors

Daya Bay Experimental Group

- Collaborators in China:
  - Institute of High Energy Physics
  - China institute of atomic energy
  - Tsinghua University
  - Hong Kong University
  - Hong Kong Chinese University
- **People who are involved:**

K.B. Luk, Berkeley;

B.L. Young, K. Whistnat, Iowa State;

J. Peng, Urbana-Champaign;

K. Lau, Houston

- **Collaboration on R&D**

S. Freedman, K.B. Luk, R. Kadel, K. Heeger

----- Berkeley

R. McKeown ------ Caltech

Daya Bay Experiment

- Experimental Goals:
  - Statistical error = 0.2%
  - Background error = 0.3%
  - Relative detector error = 0.4%

- Advantages:
  - Horizontal access tunnel approach
    - Large overburden reduces bkgnd
    - Flexibility to change baseline
    - Easy to service detector
    - Cross calibration by moving detectors to near site
  - Multiple small detectors

- Disadvantages:
  - Chinese politics and approval system
  - Multiple small detectors

- Cost estimate:

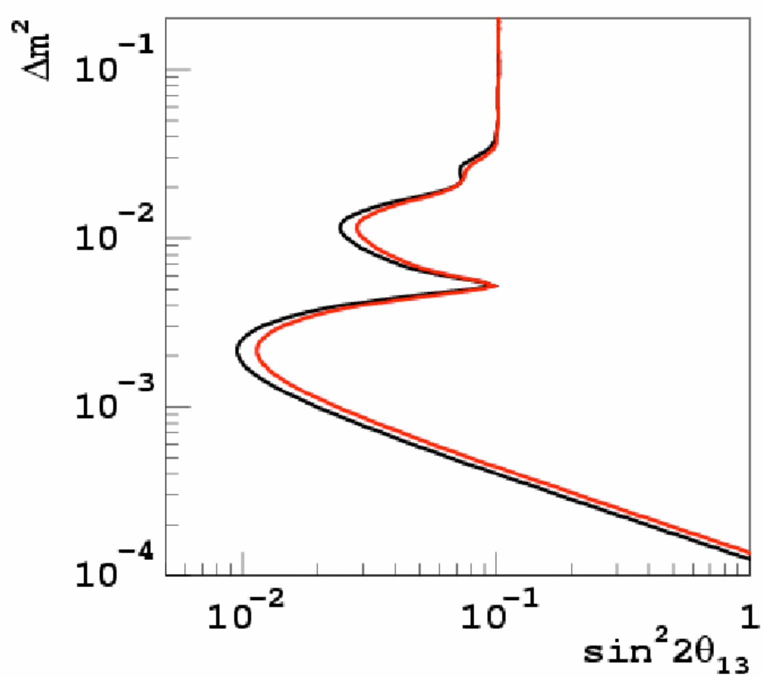
  ~ $25M

- Schedule:

  2005: R&D, engineering design, and secure funding

  2006-2007: Construction

  2008: Start data collection



Reactor Sensitivity Studies
(Comparing and Combining with Offaxis Measurements)

Study that is to become part of the American Physical Society Neutrino Study

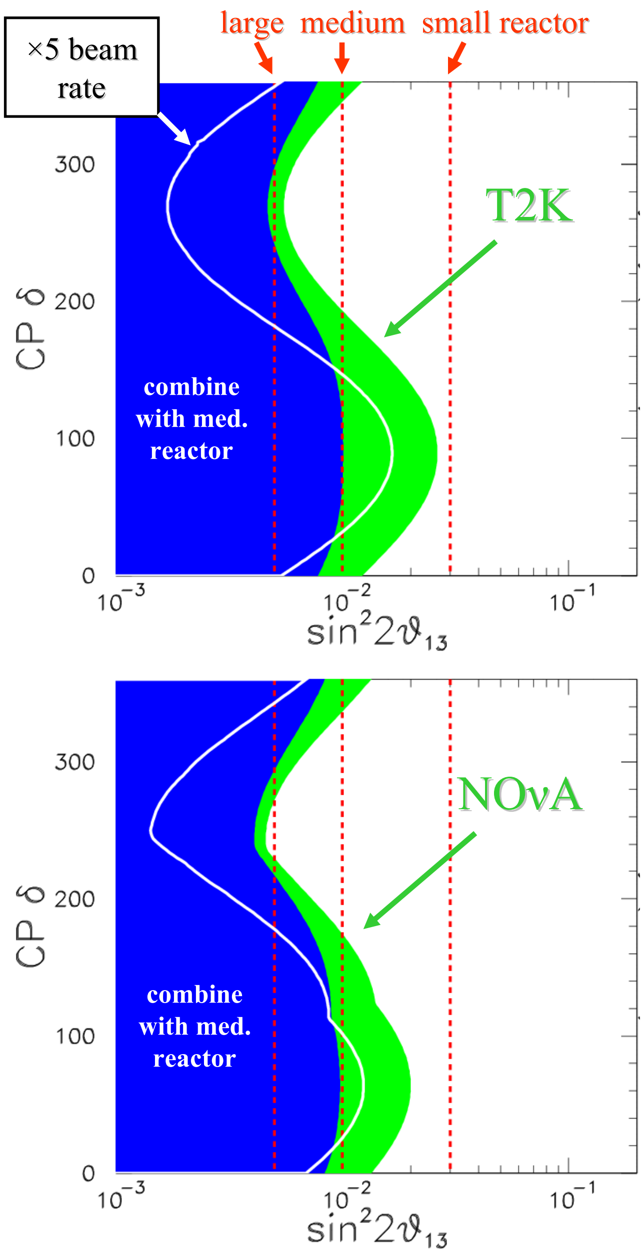
(Plan to augment and release as a preprint and PRD article)

- Experimental Inputs:
  - Medium scale reactor experiment
    - $\delta(\sin^2 2\theta_{13}) = 0.01$
  - JPARC to SuperK (T2K) exp.
    - ν: 102 signal / 25 bkgnd 5 yrs
      $\bar{\nu}$: 39 signal / 14 bkgnd 5 yrs
    - Also upgrade x5 rate
  - Offaxis NuMI (Nova) exp.
    - ν: 175 signal / 38 bkgnd 5 yrs
      $\bar{\nu}$: 66 signal / 22 bkgnd 5 yrs
    - Also Proton Driver upgrade x5 rate

- Oscillation parameters estimates

Parameter	Value	Current σ	Future σ
$\sin^2 2\theta_{23}$	1.0	0.06 (SuperK)	0.01 (T2K)
$\Delta m^2_{23}(\mathrm{eV}^2)$	2.5×10^{-3}	0.33×10^{-3} (SuperK)	0.05×10^{-3} (T2K)
$\theta_{12}(\mathrm{deg})$	30	–	–
$\Delta m^2_{12}(\mathrm{eV}^2)$	7.1×10^{-5}	–	–

Comparison of Reactor to Off-axis



90% CL upper limits for an underlying $\sin^2 2\theta_{13}$ of zero

A medium scale reactor experiment, like Braidwood, makes a more stringent limit on $\sin^2 2\theta_{13}$ than off axis, even with proton driver like statistics (×5 beam rate).

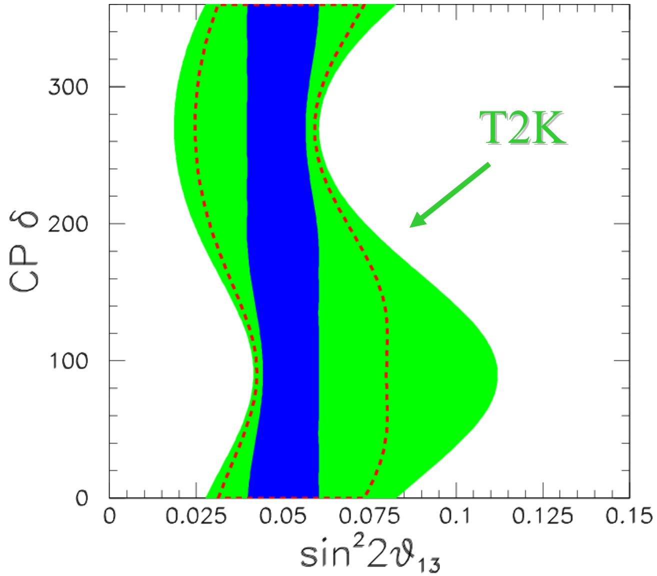
After a reactor limit, only a small window of opportunity exists for an observation of ν_μ to ν_e at off-axis.

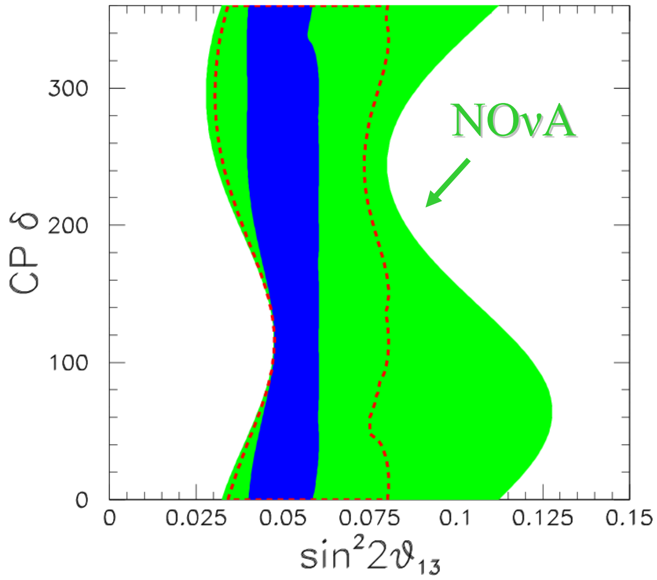
Green: Offaxis exp. Only
Blue: Combined Reactor plus Offaxis
White: Offaxis Only (x5 rate)

Comparison of Reactor to Off-axis

Chooz-like, small scale

Braidwood-like medium scale





90% CL regions for $\sin^2 2\theta_{13} = 0.05$, $\delta_{CP}=0$ and $\Delta m^2 = 2.5\times10^{-3}$ eV^2

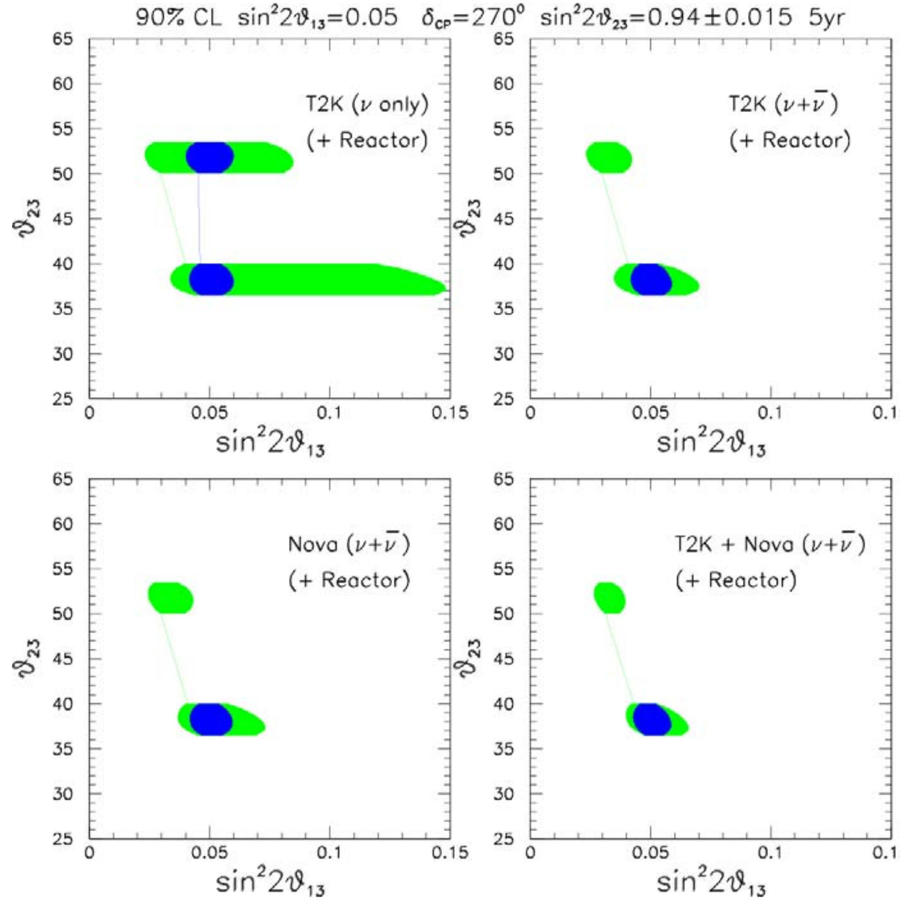
In the case of an observation, even the Double Chooz scale measurement makes a better determination of $\sin^2 2\theta_{13}$ than off-axis.

Green: Offaxis exp. Only
Blue: Combined Medium Reactor plus Offaxis
Red: Combined Small Reactor plus Offaxis

Reactor Sensitivity

- Combining with off-axis ν and $\bar{\nu}$ running, the θ_{23} degeneracy is broken.

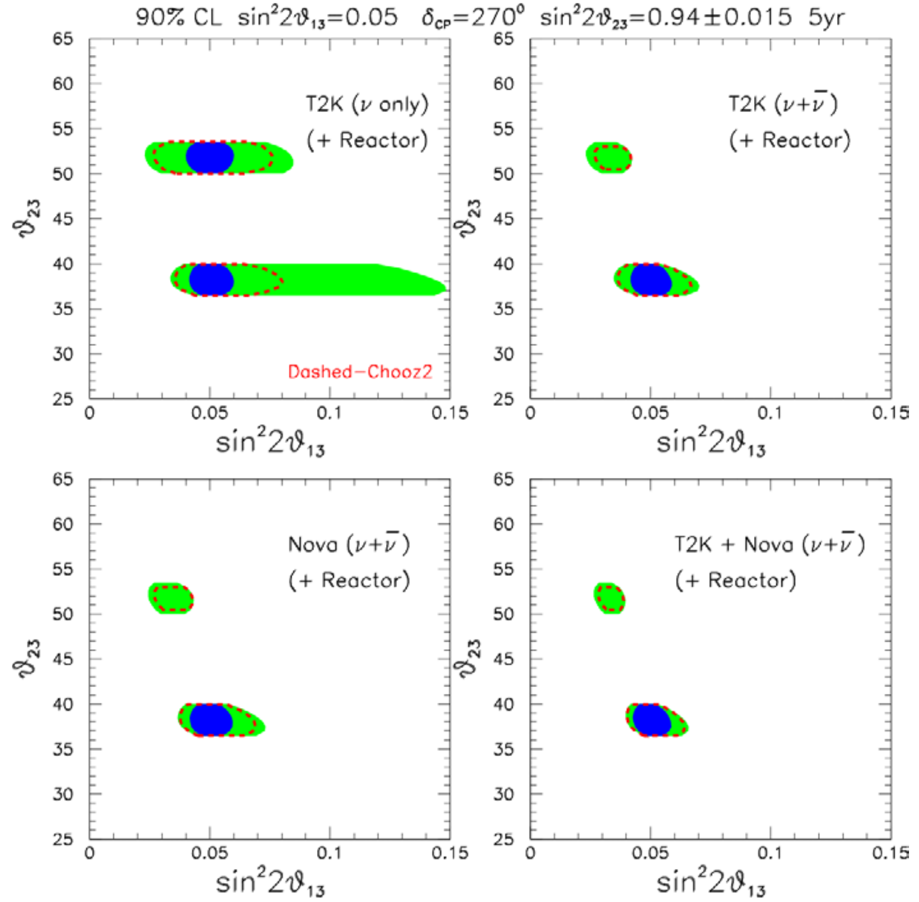
Green: Offaxis exp. Only
Blue: Combined Reactor plus Offaxis



Reactor Sensitivity

- Combining with off-axis ν and $\bar{\nu}$ running, the θ_{23} degeneracy is broken.
- The Double Chooz sensitivity of 0.03 is not sufficient to break the degeneracy.

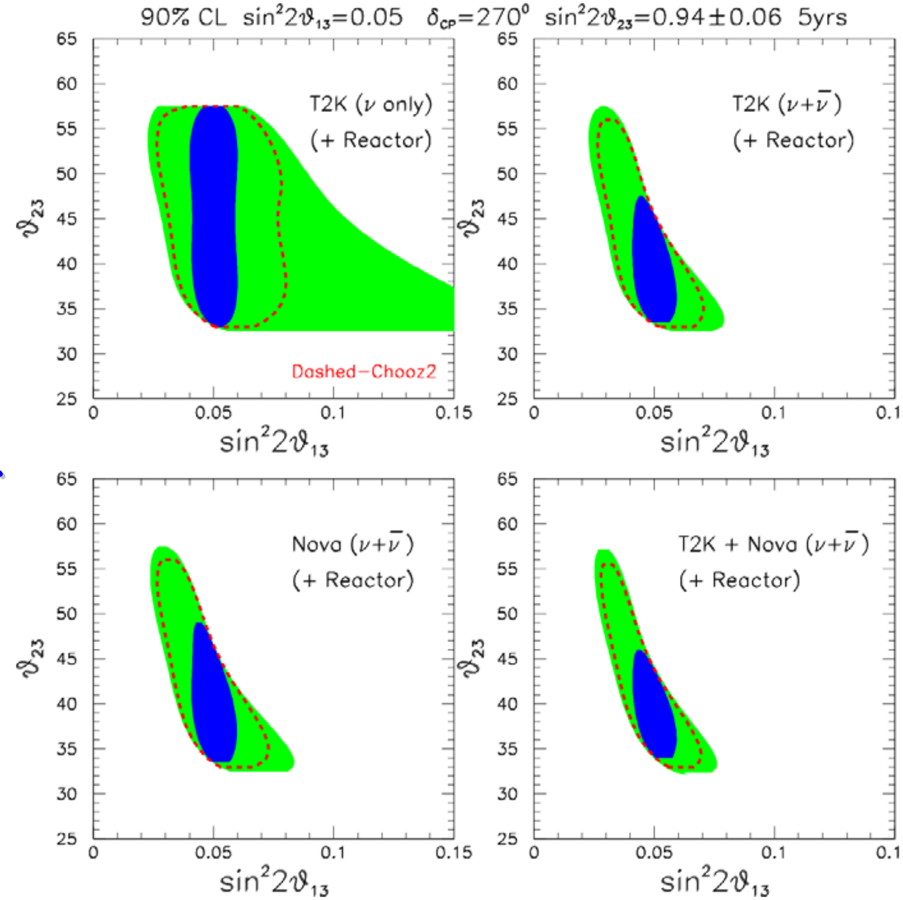
Green: Offaxis exp. Only
Blue: Combined Reactor plus Offaxis



Reactor Sensitivity

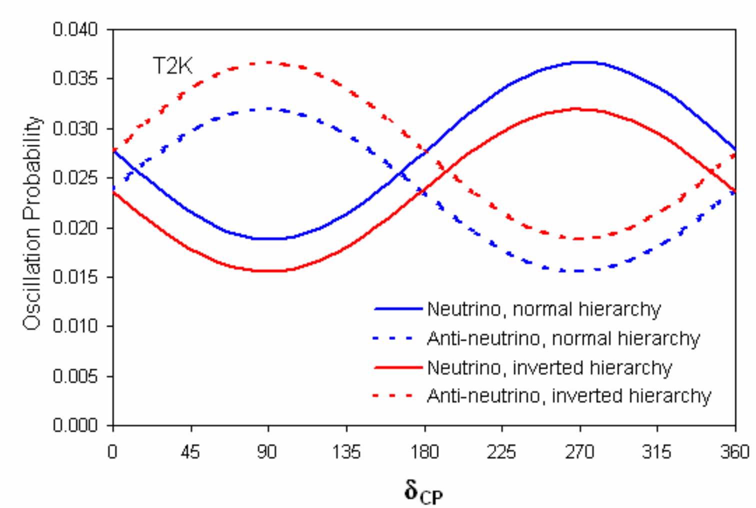
- Combining with off-axis ν and $\bar{\nu}$ running, the θ_{23} degeneracy is broken.
- The Double Chooz sensitivity of 0.03 is not sufficient to break the degeneracy.
- The degeneracy is broken even if the error on θ_{23} is not so small.

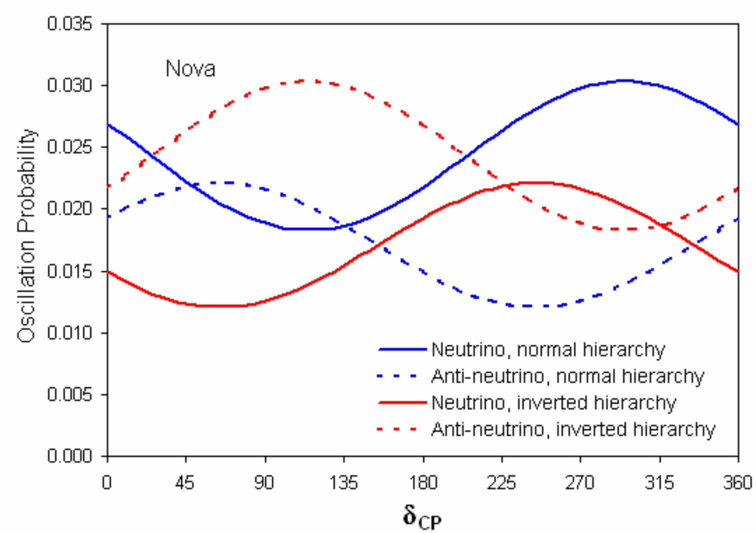
Green: Offaxis exp. Only
Blue: Combined Reactor plus Offaxis



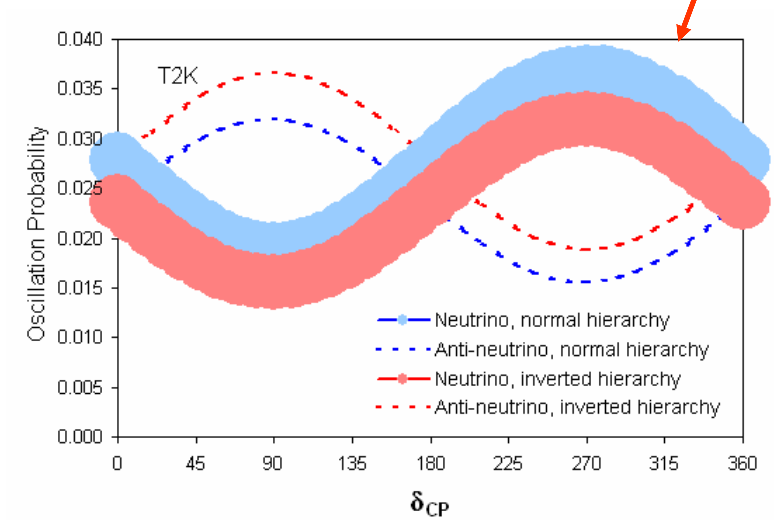
Constraining the CP Violation Parameter, δ_{CP} and Determining the Mass Hierarchy

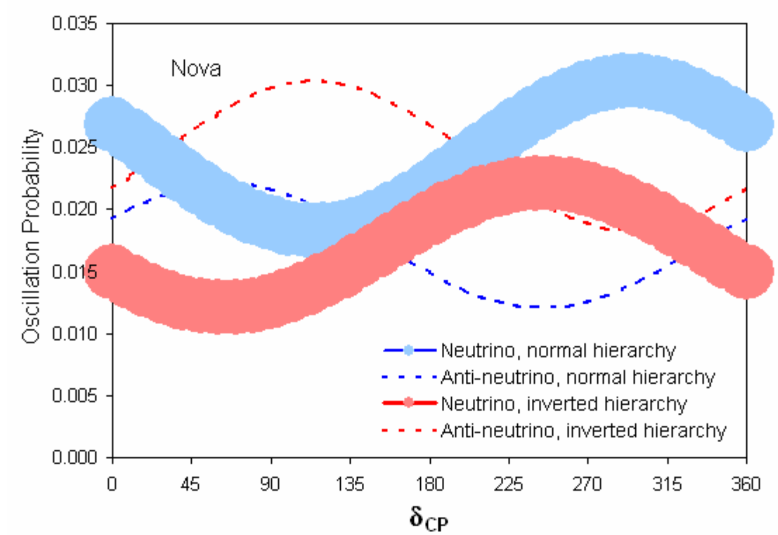
- Oscillation probability vs δ_{CP} ($\Delta m^2 = 2.5\times10^{-3}$ eV^2 , $\sin^2 2\theta_{13} = 0.05$)



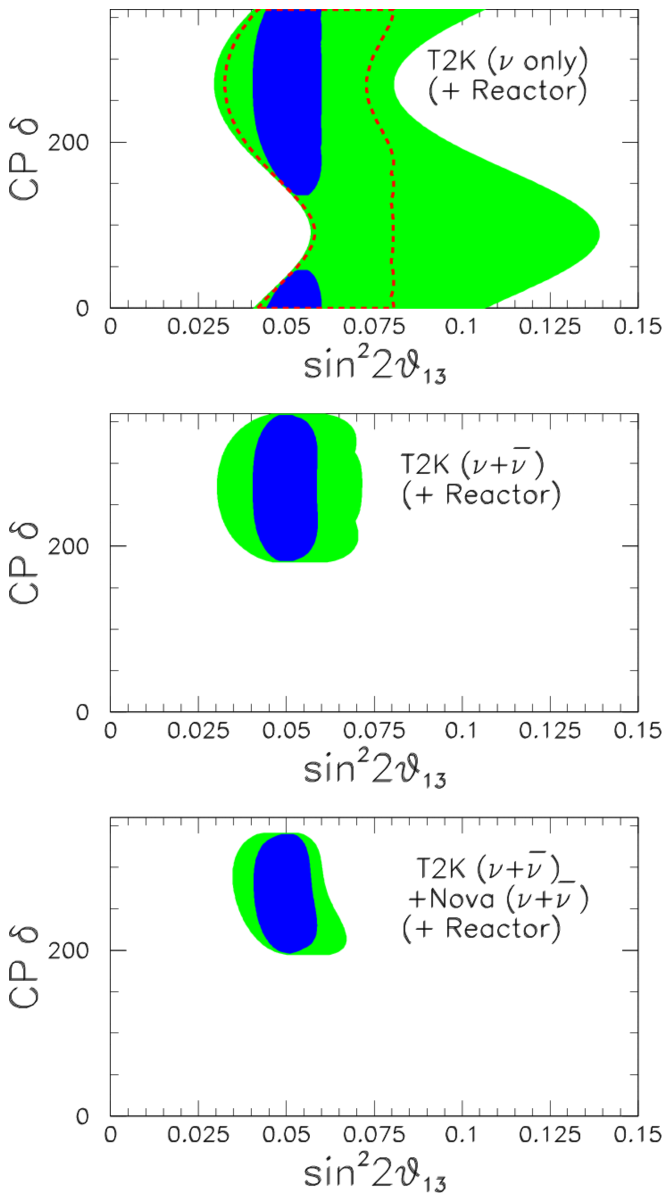


- Use Medium Reactor ($\delta(\sin^2 2\theta_{13}) = 0.01$) can predict the neutrino prob.





Reactor Contribution to CP Violation



For δ_{CP} = 270º the reactor measurement eliminates some of the range in CP phase when combined with off-axis ν only running.

Off-axis anti-neutrino running resolves the CP problem on its own, after an additional 3 to 5 years.

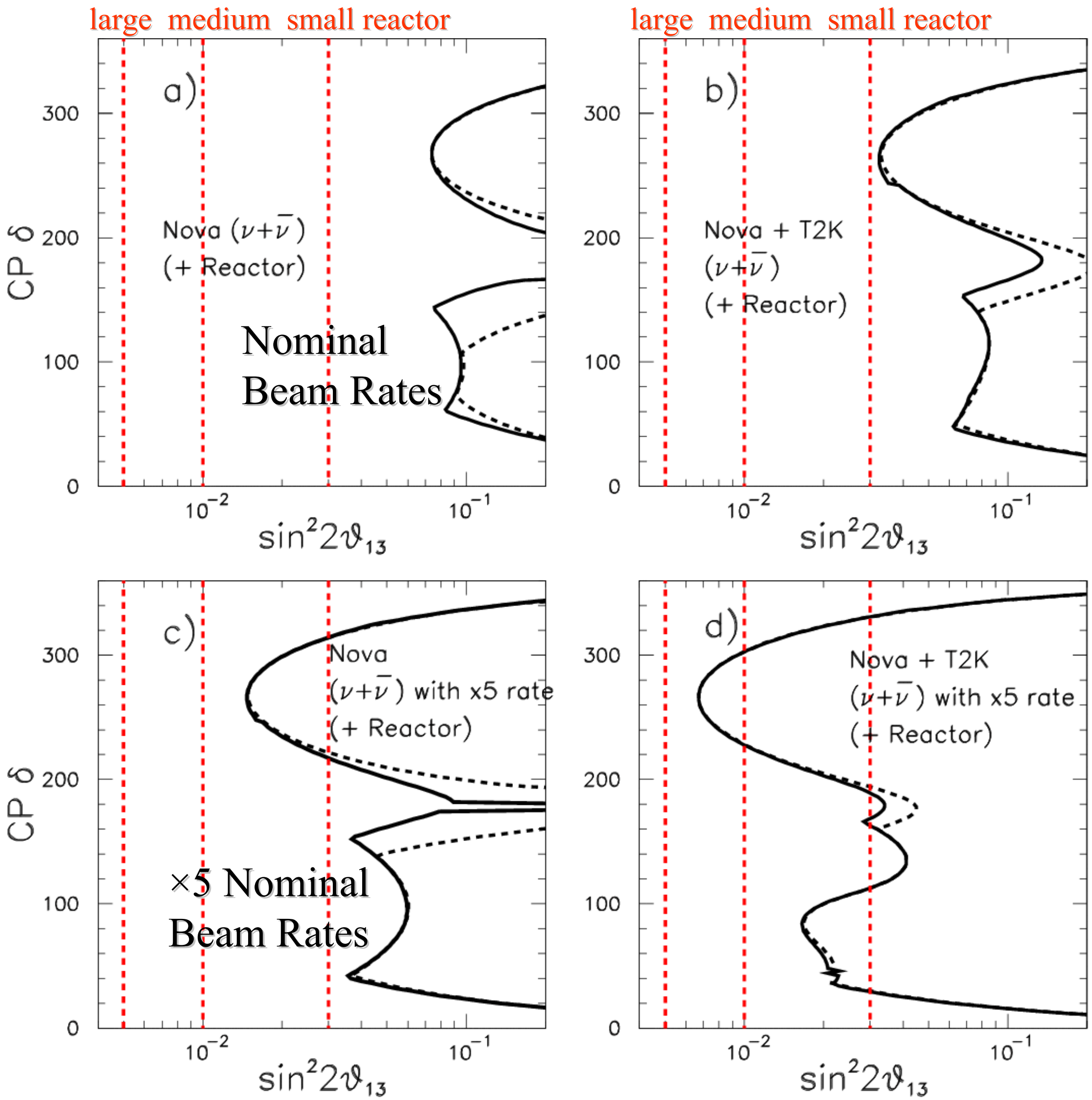
Combining all data sets, the best precision on $\sin^2 2\theta_{13}$ comes from the reactor experiment.

Green: Offaxis exp. Only
Blue: Combined Medium Reactor plus Offaxis
Red: Combined Small Reactor plus Offaxis

Determining Reach in CP Violation

Dashed – without Reactor
Solid – with medium scale Reactor

To the right of the curve, $\delta_{CP}=0$ is excluded by at least two sigma



Reactor measurement does not contribute much to measuring CP violation…

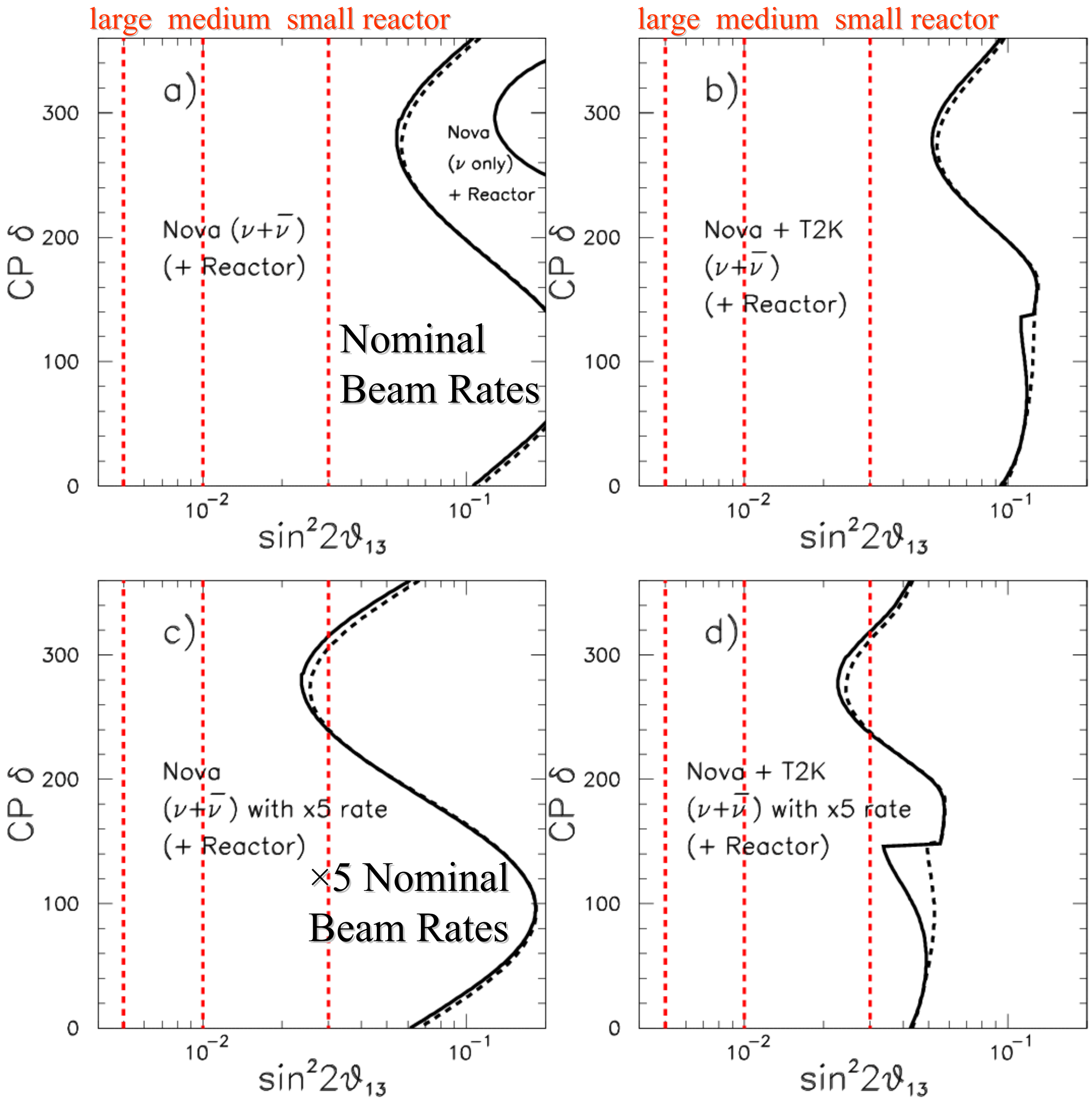
But a null measurement, even at the Double Chooz sensitivity, can mostly rule out the measurement in off-axis.

$\Delta m^2 = 2.5\times10^{-3}$ eV^2

Determining Reach in Mass Hierarchy

Dashed – without Reactor
Solid – with medium scale Reactor

To the right of the curve, mass hierarchy is resolved by at least two sigma



Reactor measurement does not contribute much to resolving the mass hierarchy…

But a null measurement, even at the Double Chooz sensitivity, can mostly rule out the measurement in off-axis.

$\Delta m^2 = 2.5\times10^{-3}$ eV^2

Combining Off-axis and Reactor

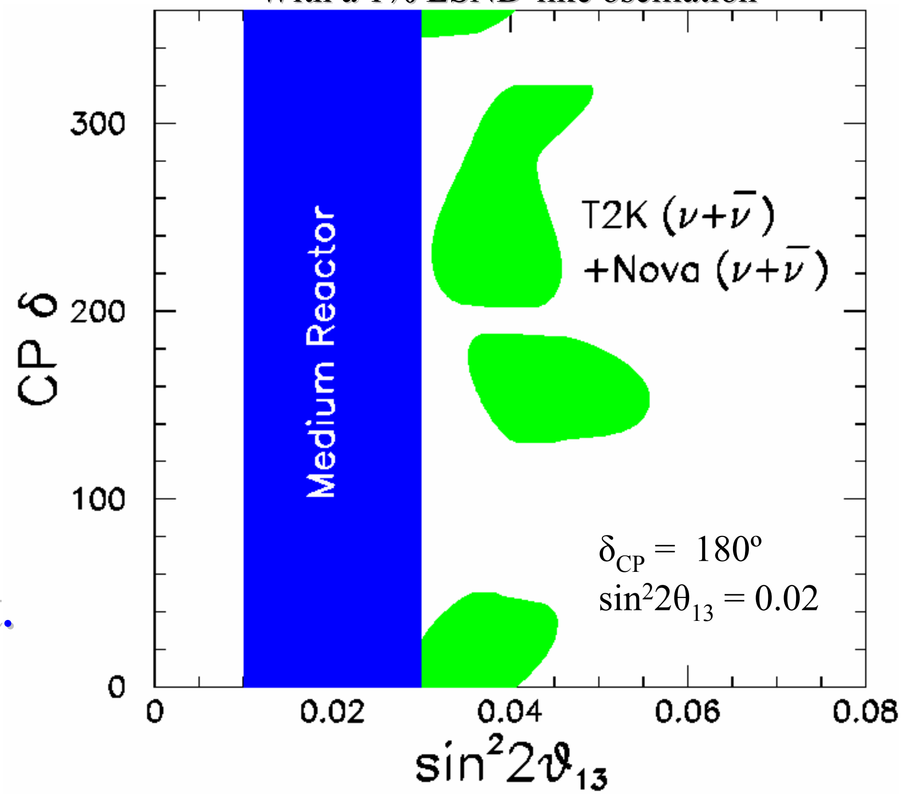
The reactor measurement may not agree with the results of the off-axis experiments.

This may indicate new physics.

For example:

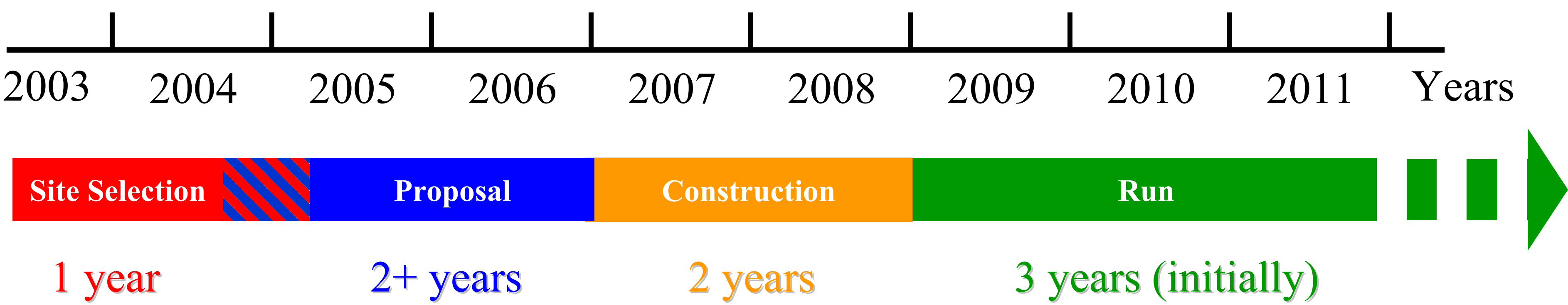
The reactor experiment is blind to an LSND-like oscillation, but it shows up in off-axis as an unexpectedly large ν_e appearance. The combination of the two experiments can resolve the effect.

With a 1% LSND-like oscillation



Cost and Schedule for Medium Reactor

- Cost: Moderate Scale Project (< $50M)
  - Detector scale of MiniBooNE ~$8M / detector
  - Civil construction – Tunnels or Shafts and Halls ~$20 - 30M
  - Need to identify site, do engineering and develop proposal
  - R&D needed especially for Gd-liq.scint. and moveable detector
- Schedule:
  - After site selection, approval process 1? year
  - Construction ~2 years
  - Start in 2008/2009?



Conclusions

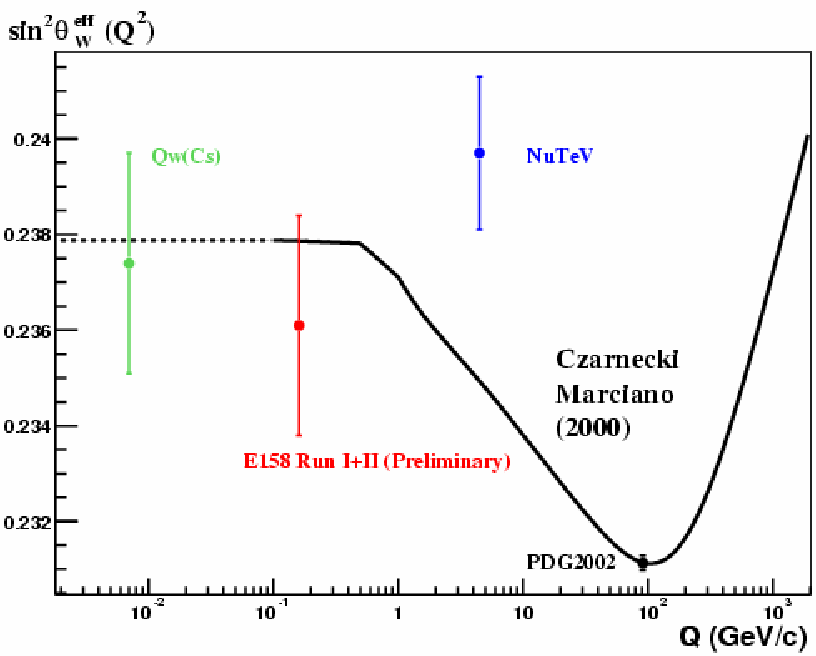
- A reactor experiment is "<u>the</u>" prime and only unambiguous measurement of θ_{13}
  - θ_{13} is a important physics parameter
    - Needed to constrain the models of lepton mixing matrix
    - If very small, probably indicates a new symmetry
  - θ_{13} is key for planning future long-baseline experiments to measure CP violation and the mass hierarchy
    - If $\sin^2 2\theta_{13}$ is > ~0.02, T2K and Nova make a nice program
    - If $\sin^2 2\theta_{13}$ is < ~0.01, need other techniques to access the physics (1^{st},2^{nd} maxima measurements; BNL-Homestake, NuMI-Homestake,….)
- Reactor measurements are important for sorting out the θ_{23} ambiguity (θ_{23} vs 90^0- θ_{23})
  - Again this is an important, fundamental physics parameter (like θ_{13})
- Reactor measurements do not add much to constraining CP violation and mass hierarchy with T2K and Nova type measurements
  - Is this also true for other techniques? (1^{st},2^{nd} maxima i.e. BNL-Homestake)

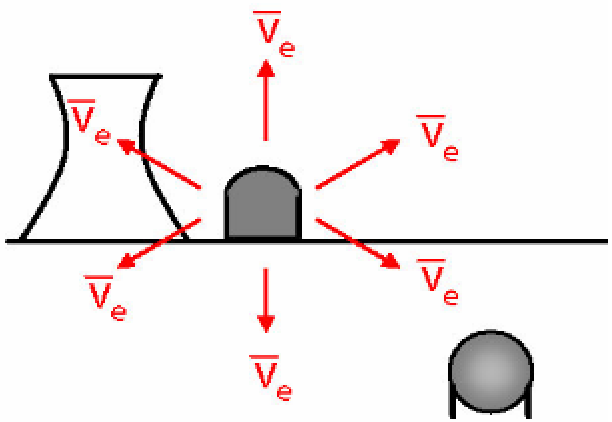
But there is even more ….

Going beyond θ_{13}: A whole new angle on reactor studies

A reactor-based $\sin^2\theta_W$ measurement:

- Probes new physics in the neutrino sector (like NuTeV)
- Has low $Q^2 \sim 4E\text{-}6\ GeV^2$
- Has different systematics from NuTeV



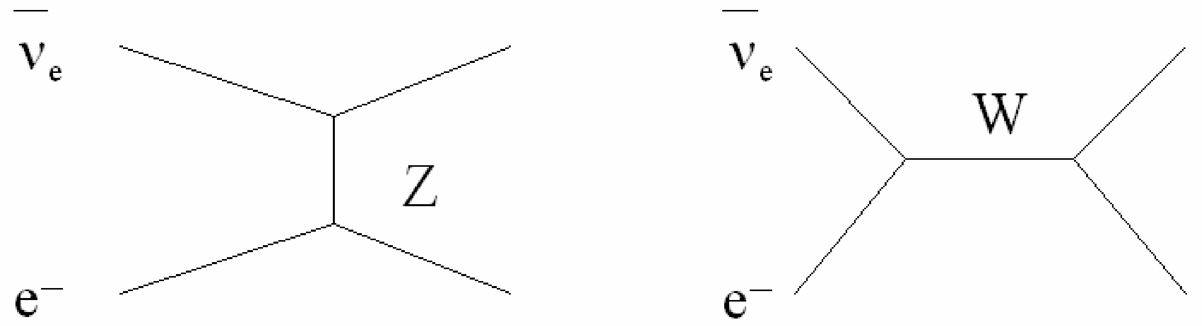


- Use near detector for measurement
- Use far detector to measure background

(See J.Conrad, J.Link, and M.Shaevitz, hep-ex/0403048)

How to measure $\sin^2\theta_W$ at a reactor:

Use the antineutrino-electron **elastic scattering** (ES)



$$\frac{d\sigma}{dT} = \frac{G^2 m}{2\pi}\left\{(C_V+C_A)^2 + (C_V-C_A)^2\left(1-\frac{T}{E}\right)^2 + (C_A{}^2-C_V{}^2)\, m\frac{T}{E^2}\right\}$$

$C_V = ½ + 2 \sin^2\theta_W$

$C_A = -½$

T = electron KE energy
E = neutrino energy
m= mass of electron
This assumes μ_ν=0

The total rate for this process is sensitive to $\sin^2\theta_W$

A sensible range to consider for the measurement is:

dN/N	= 1.3%.......	We can do that
	= 1.0%.......	May be attainable
	= 0.7%......	Hard!

$$\boxed{dN/N=1.3\% \quad \Leftrightarrow \quad d(\sin^2\theta_W)=\pm 0.0019}$$

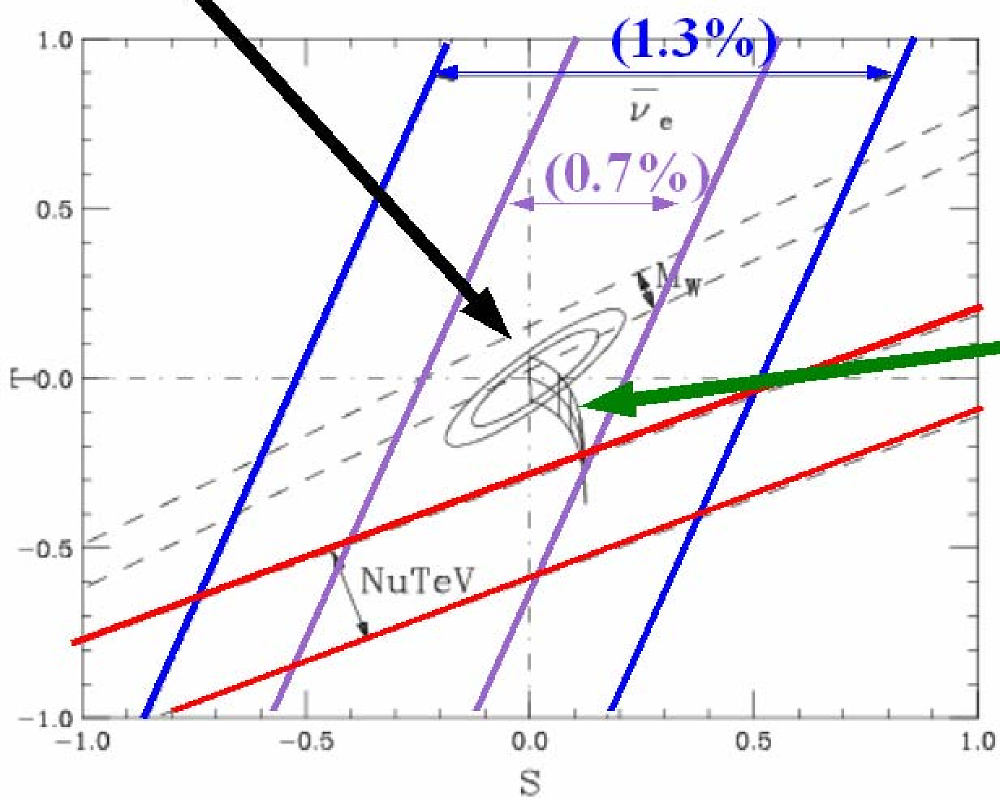
Compare to NuTeV: ±0.0017

Sensitivity to S and T

See Rosner, hep-ph/0404264

Fit which does not include NuTeV and uses a light Higgs...

Unusual in strong S-dependence



indicates Higgs dependence

(see Loinaz et al, hep-ph/0403306)

A better fit is obtained if neutrinos are allowed to have non-standard couplings (adjusted by ε~0.3%)

$Z\nu\nu \leftrightarrow (1\text{-}\varepsilon)$

$W\ell\nu \leftrightarrow (1\text{-}\varepsilon/2)$

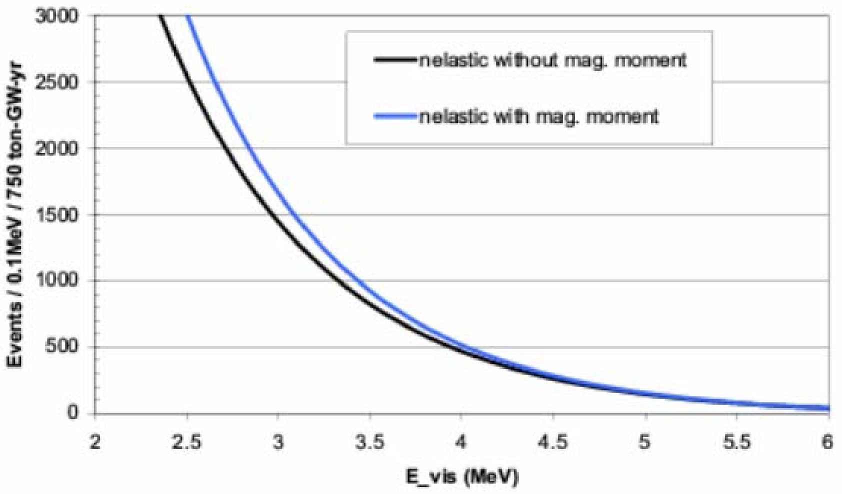
Sensitivity to a neutrino magnetic moment

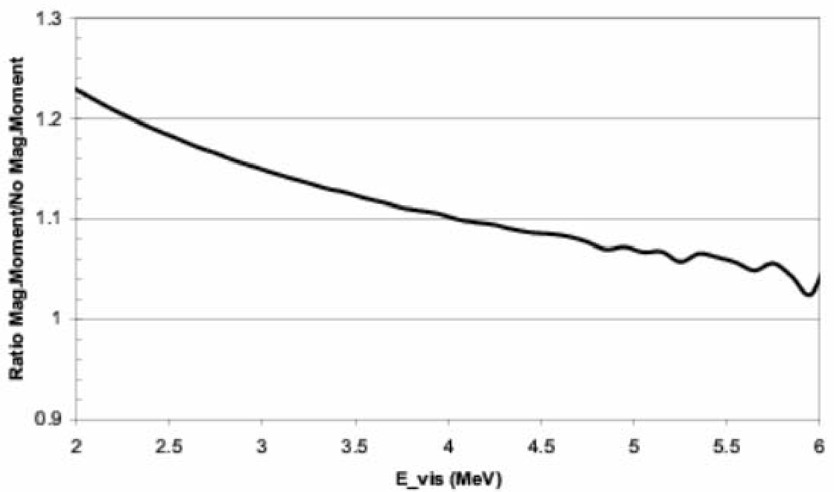
(Not cause of NuTeV anomaly!)

Neutrino magnetic moment:

A dN/N ~ 1% in agreement w/
SM would set a limit
×3 better than present lab limit

A analysis using the Evis
shape will improve this
sensitivity further
(requires good model of backgrounds
as function of Evis ... underway)



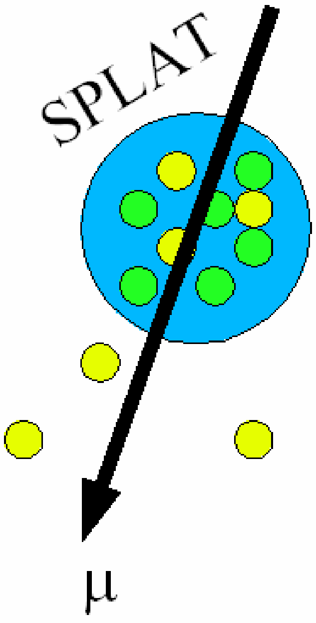


Reality Checks:

How do you measure ES at a reactor-experiment to ~1%   ???

1. The reactor flux is only known to 2%

2. This is a single-electron signal (unlike inverse beta decay)
   Potential backgrounds are:
   beta-decaying contaminants
   spallation-produced isotopes.

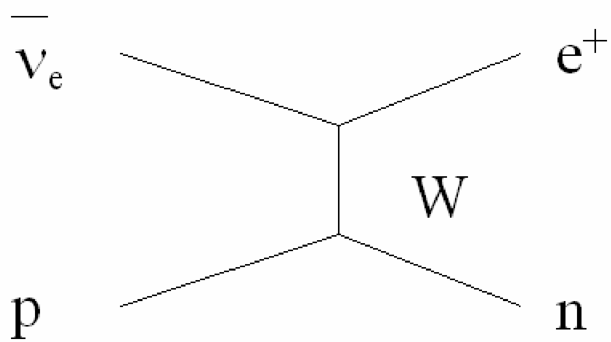


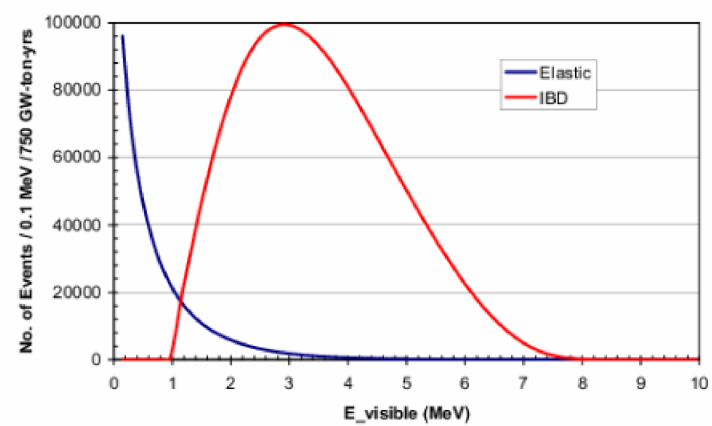
3. The energy scale must be calibrated to 0.5%
   (same level as NuTeV)

How are these going to be solved?

Tricks to make a precision measurement possible:

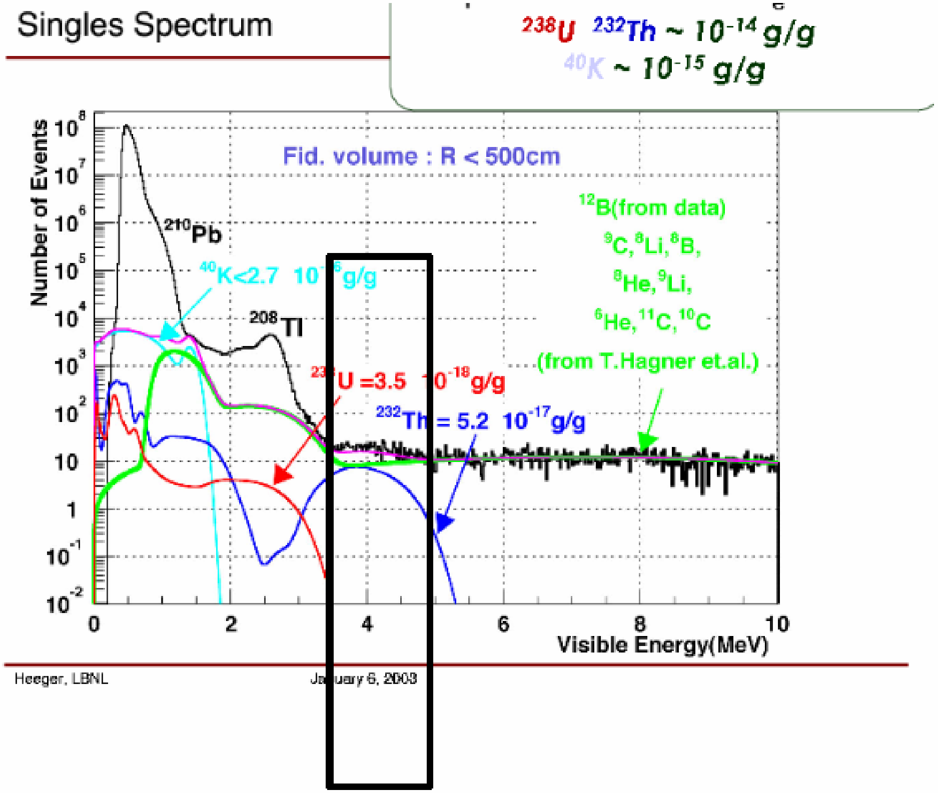
1. Remove the reactor flux uncertainty by normalizing to inverse beta decay (IBD)





This cross section is known to 0.2%

2. Use the window from 3.5-5 MeV to reduce backgrounds



Contamination:

Employ techniques for
Th clean-up from Borexino

Spallation

Go deep!
Measure the rate
w/ the far detector
& w/ small R&D exp.

3. Use many beta sources to calibrate the detector:
cosmic-ray produced: muon decay, ^{12}B
naturally in the oil: ^{14}C
sources introduced into the oil

We have looked at many other potential systematic issues!

Summary

- Elastic scattering at a reactor can open new windows on the NuTeV anomaly and BSM physics

- The experiment needs a close detector (< 200m) with > 300 mwe shielding
  $\Rightarrow$ Braidwood looks like a good possibility

- Detector requirements very similar to oscillation experiment
  $\Rightarrow$ Elastic scattering experiment comes for low cost if location requirements can be satisfied.

- Still many experimental details to work out
  $\Rightarrow$ Plan to bring out a revised version of our preprint hep-ex/0403048

(Also see http://faculty.washington.edu/josephf/beyond_theta13.html)