Introduction to
The Braidwood Reactor Experiment

Neutrino Oscillations: Key Questions

- What is value of θ_{13}?

- What is mass hierarchy?

- Do neutrino oscillations violate CP symmetry?
  - –May give hints about possible "Leptogenesis"

CP violating phase δ
$\sin\delta \neq 0 \Rightarrow$ CP Violation

$$P(\nu_\mu \to \nu_e) - P(\bar{\nu}_\mu \to \bar{\nu}_e) = -16\, s_{12} c_{12} \underset{\substack{\uparrow \\ \sin\theta_{13}}}{\boxed{s_{13}}} c_{13}^2 s_{23} c_{23} \boxed{\sin\delta} \sin\left(\frac{\Delta m_{12}^2}{4E}L\right) \sin\left(\frac{\Delta m_{13}^2}{4E}L\right) \sin\left(\frac{\Delta m_{23}^2}{4E}L\right)$$

- Why are quark and neutrino mixing matrices so different?

$$U_{Neutrinos} \sim \begin{pmatrix} Big & Big & Small\,? \\ Big & Big & Big \\ Big & Big & Big \end{pmatrix} \text{ compared to } V_{Quarks} \sim \begin{pmatrix} 1 & Small & Small \\ Small & 1 & Small \\ Small & Small & 1 \end{pmatrix}$$

⇨ Value of θ_{13} central to these questions; it sets the scale for experiments needed to resolve mass hierarchy and search for CP violation.

Methods to measure $\sin^2 2\theta_{13}$

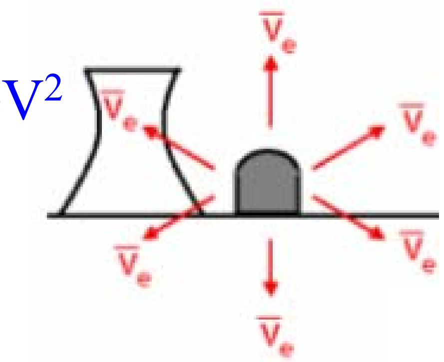
- Accelerators: Appearance ($\nu_\mu \to \nu_e$) at $\Delta m^2 \approx 2.5\times10^{-3}$ eV^2

$$P(\nu_\mu \to \nu_e) = \sin^2\theta_{23}\sin^2 2\theta_{13}\sin^2\frac{\Delta m^2_{13}L}{4E} + \text{not small terms } (\delta_{CP},\ sign(\Delta m^2_{13}))$$

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

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

- Reactors: Disappearance ($\bar{\nu}_e \to \bar{\nu}_e$) at $\Delta m^2 \approx 2.5\times10^{-3}$ eV^2



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

⇨ Reactor experiments allow direct measurement of $\sin^2 2\theta_{13}$:
no matter effects, no CP violation, almost no correlation with other parameters.

Reactor Sensitivity Studies

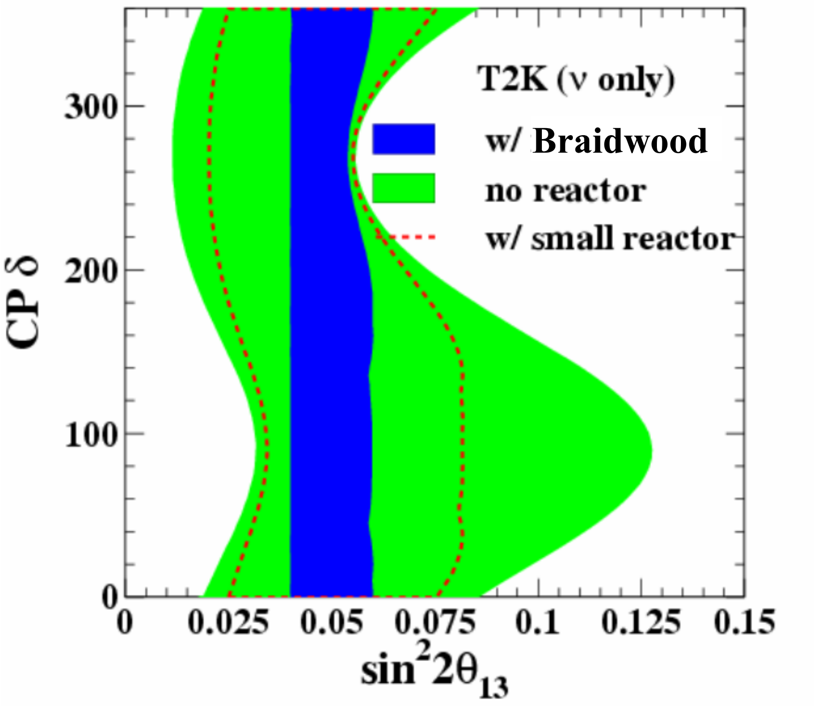
(Comparing and Combining Reactor and Accelerator Measurements)

(Kendall McConnel and M. Shaevitz – hep-ex/0409028)

Try to do estimate, including all exp. and theory effects,

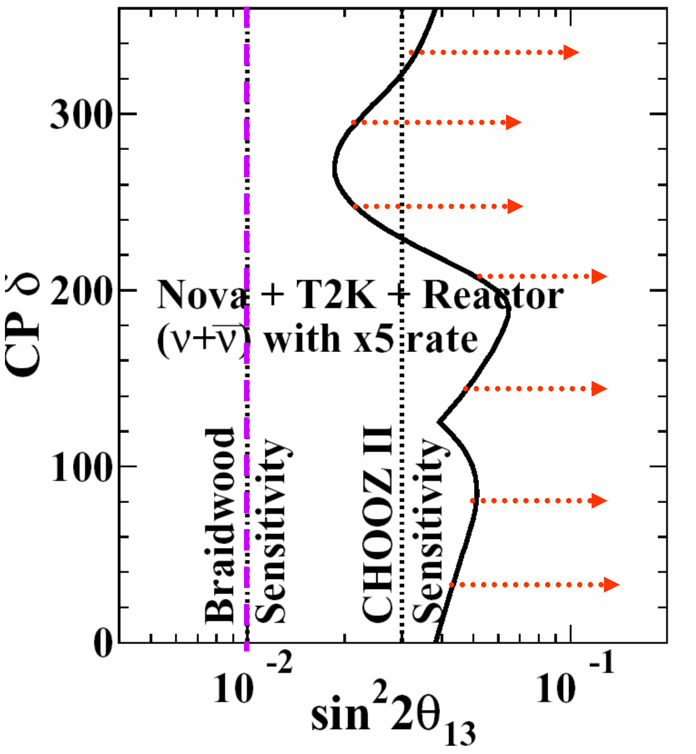
⇒ How well can you measure mixing angle θ_{13} , CP violation (δ_{CP}), and mass hierarchy ?

90% CL allowed regions with osc.signal



$\sin^2 2\theta_{13} = 0.05$, $\delta_{CP}=0$,
$\Delta m^2 = 2.5\times10^{-3}\ eV^2$
(3 yr reactor, 5yr T2K)

Sensitivity regions for resolving the Mass Hierarchy at 2σ (with Proton Driver)



The θ_{23} Degeneracy Problem

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

Super-K / Minos / T2K Measures ⟶

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

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

Offaxis θ_{13} Measures ⟶

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

Example: Measurement with

$\sin^2 2\theta_{23} = 0.95 \pm 0.01$

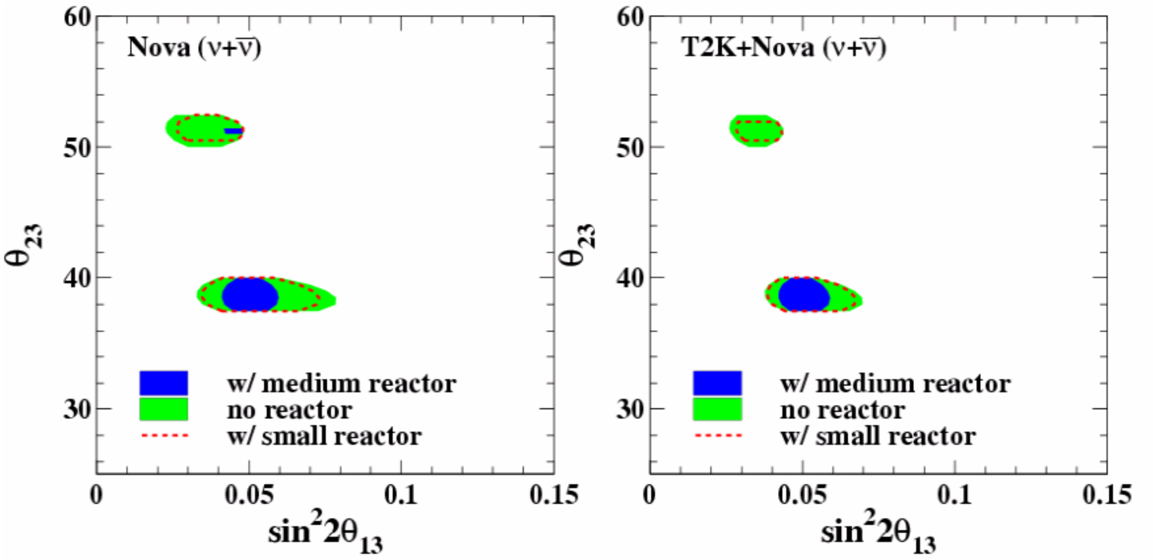
$\Rightarrow \theta_{23} = 38^\circ$ or 52°

Prediction for appearance

rate $\propto \sin^2\theta_{23}$

$\Rightarrow \sin^2\theta_{23} = 0.38$ or 0.62

(x1.6 uncertainty)



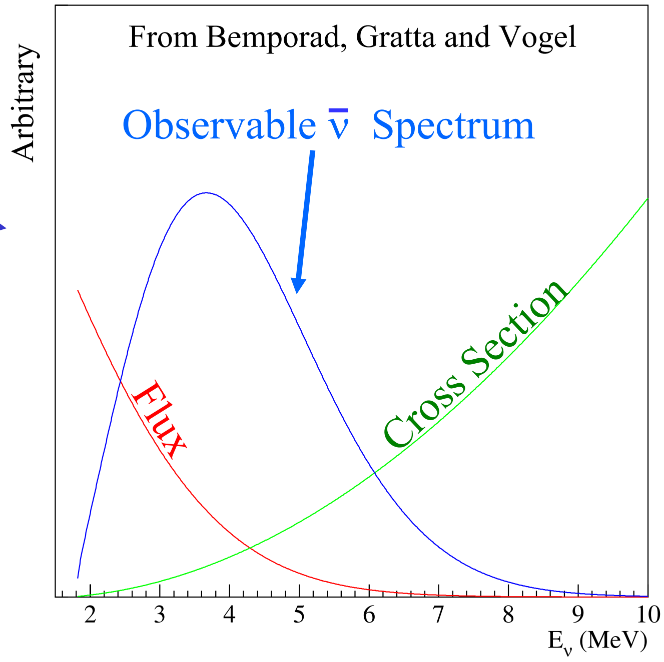
small reactor: Double CHOOZ

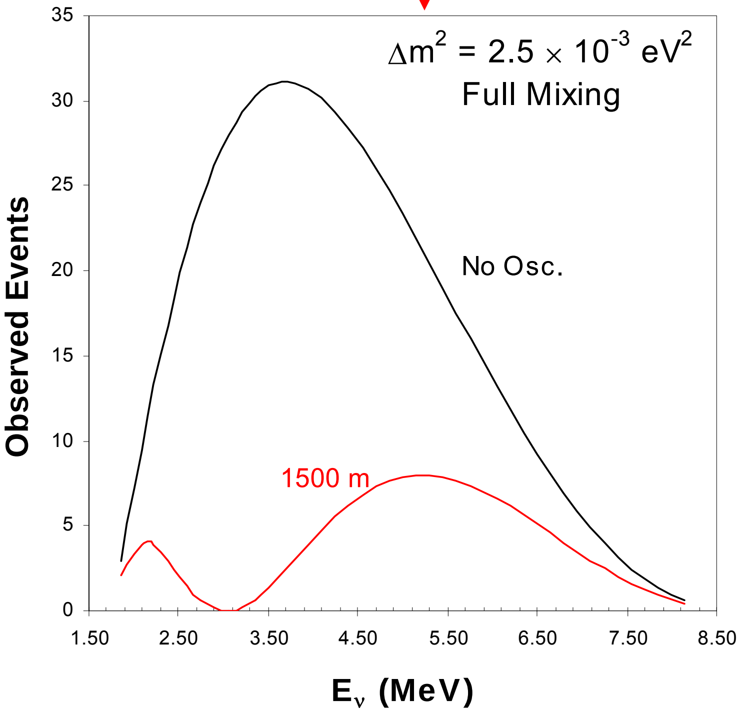
medium reactor: Braidwood

(K. McConnel and M.S. – hep-ex/0409028)

Reactor Measurements of θ_{13}

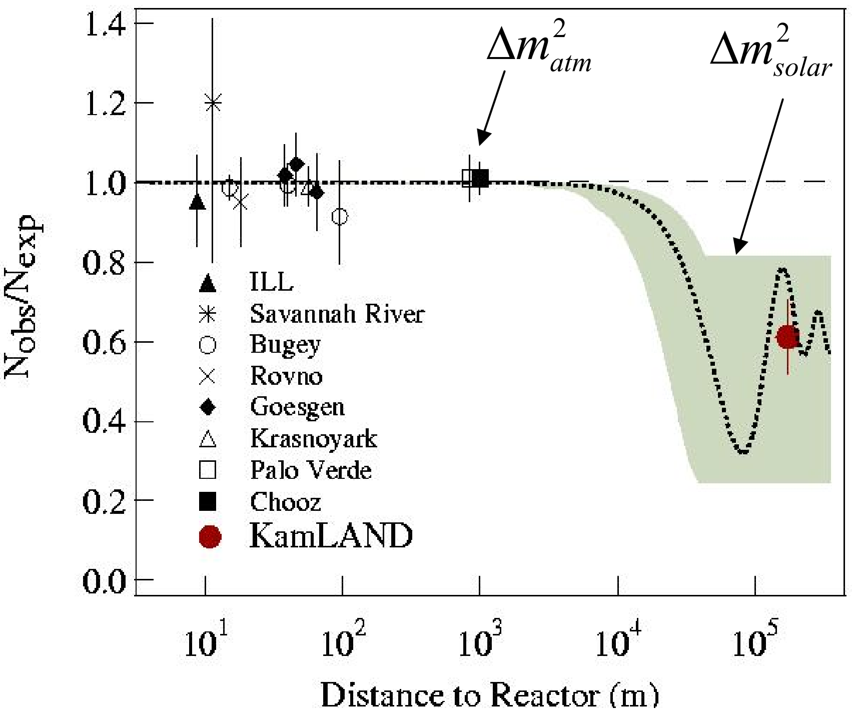
- Nuclear reactors are a very intense sources of $\bar{\nu}_e$ with a well understood spectrum
  - 3 GW → 6×10^{20} $\bar{\nu}_e$/s
    700 events / yr / ton at 1500 m away
  - Reactor spectrum peaks at ~3.7 MeV
  - Oscillation Max. for $\Delta m^2 = 2.5\times10^{-3}$ eV^2 at L near 1500 m


From Bemporad, Gratta and Vogel



- Disappearance Measurement:
  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

Past measurements:



How to do better than previous reactor experiments?

⇒ **Add an identical near detector**

Eliminate dependence on reactor flux and many detector effects

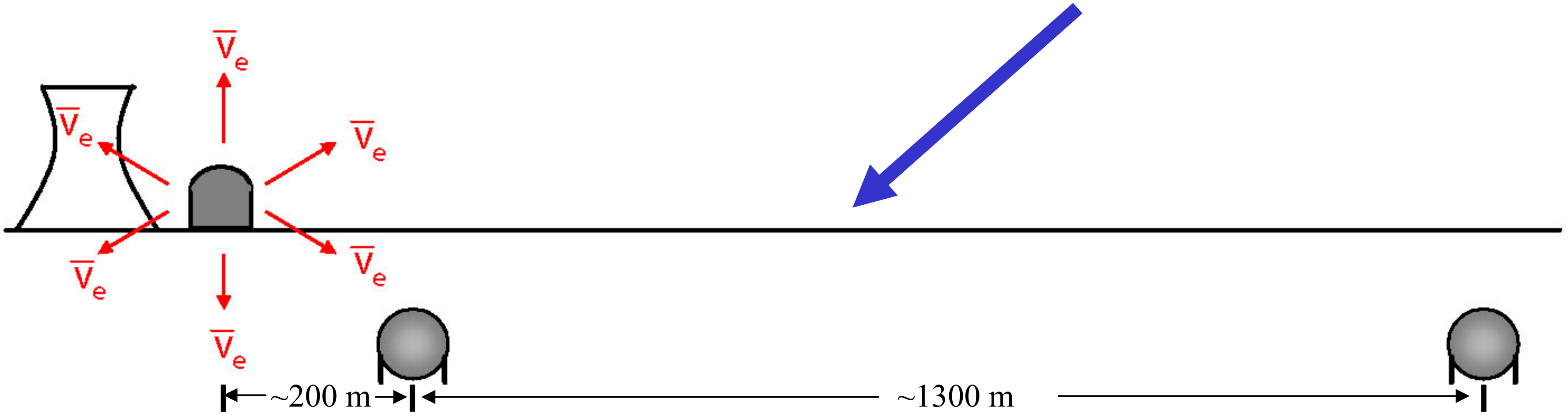
⇒ **Optimize baseline(1500 m)**

⇒ **Larger detectors**

5 ton → 65 tons

⇒ **Reduce backgrounds**

- Go deeper
- Add improved veto system



Experimental Setup

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

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

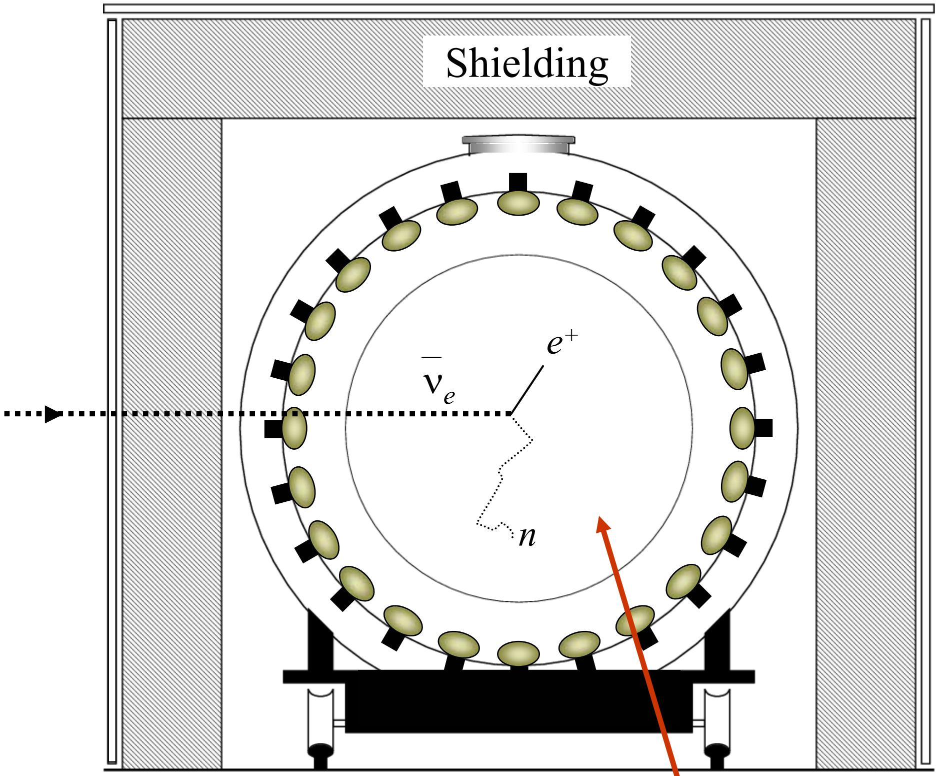
$$\hookrightarrow n\ capture$$

- Positron energy spectrum implies the neutrino spectrum

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

- The scintillator will be doped with gadolinium to enhance capture

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



Liquid Scintillator with Gadolinium

= Photomultiplier Tube

Types of Measurements

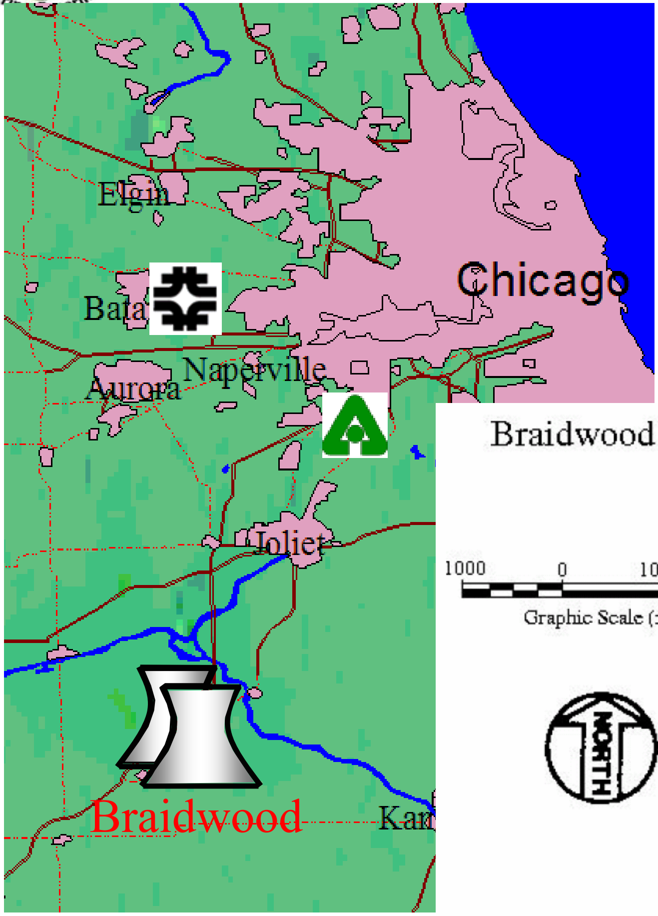
- Counting (Rate) Measurement
  - Compare total number of observed events in near and far detector
  - Systematic uncertainty
    - Relative near/far efficiency and normalization
    - Fairly insensitive to relative energy calibrations
  - Only method available for small detector exp's (> 300 ton-GW-yrs)

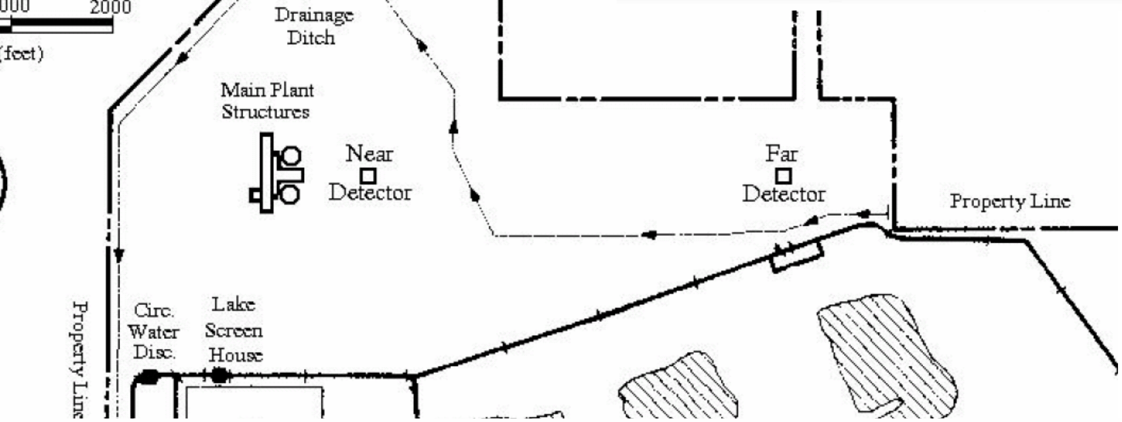
- Energy (Spectral) Shape Analysis
  - Compare the energy distribution in the near and far detectors
  - Systematic uncertainty
    - Largest due to the energy calibration, offsets and scale
    - Insensitive to relative normalization and efficiency
  - Need large detectors in order to obtain required statistics (> 2000 ton-GW-yrs)
  - Need single baseline
    - Multiple baselines can wash out energy variation

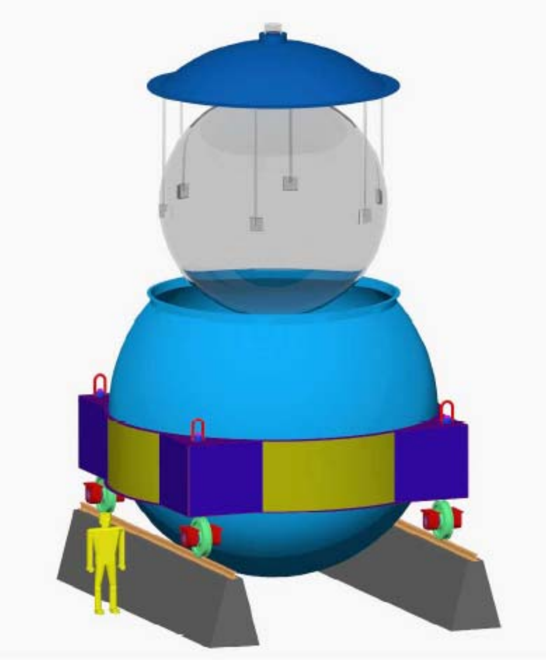
Double-CHOOZ
("rate" only)

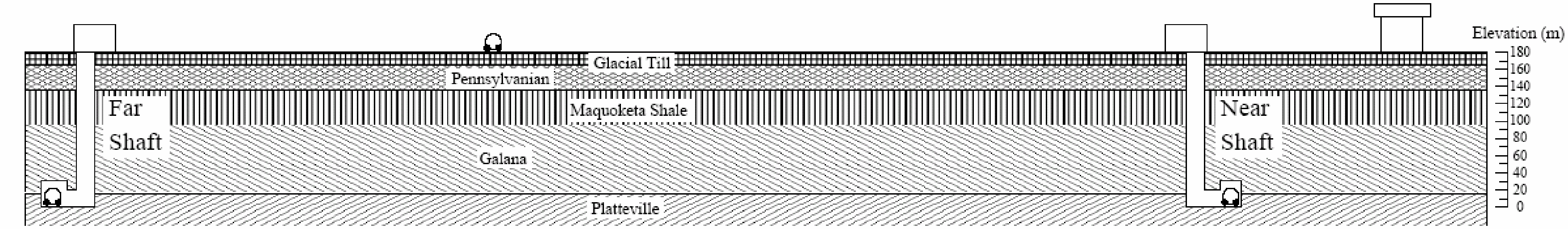
Braidwood will use both "rate" and "shape"
(Gives redundancy and better sensitivity)

Braidwood Reactor Experiment









Braidwood Reactor Collaboration

- **Argonne Nat. Lab.:** M. Goodman, V. Guarino, L. Price, D. Reyna
- **Brookhaven Nat. Lab.:** R. Hahn, M. Yeh, A Garnov, Z. Chang, C. Musikas
- **U. of Chicago:** E. Abouzaid, K. Anderson, E. Blucher, M. Hurowitz, A. Kaboth, D. McKeen, J. Pilcher, J. Seger, M. Worcester
- **Columbia:** J. Conrad, Z. Djurcic, J. Link, K. McConnel, M. Shaevitz, G. Zeller
- **Fermilab:** L. Bartoszek, D. Finley, H. Jostlein, C. Laughton, R. Stefanski
- **Kansas State:** T. Bolton, C. Borjas, J. Foster, G. Horton-Smith, N. Kinzie, J. Kondikas, D. Onoprienko, N. Stanton, D. Thompson
- **U. of Michigan:** M. Longo, B. Roe
- **MIT:** P. Fisher, R. Cowan, L. Osborne, G. Sciolla, S. Sekula, F. Taylor, T. Walker, R. Yamamoto
- **Oxford:** G. Barr, S. Biller, N. Jelley, G. Orebi-Gann, S. Peeters, N. Tagg
- **U. of Pittsburgh:** D. Dhar, N. Madison, D. Naples, V. Paolone, C. Pankow
- **St. Mary's University:** P. Nienaber
- **Sussex:** L. Harris
- **U. of Texas:** A. Anthony, M. Huang, J. Jerz, J. Klein, A. Rahman, S. Seibert
- **U. of Washington:** J. Formaggio

Braidwood Baseline

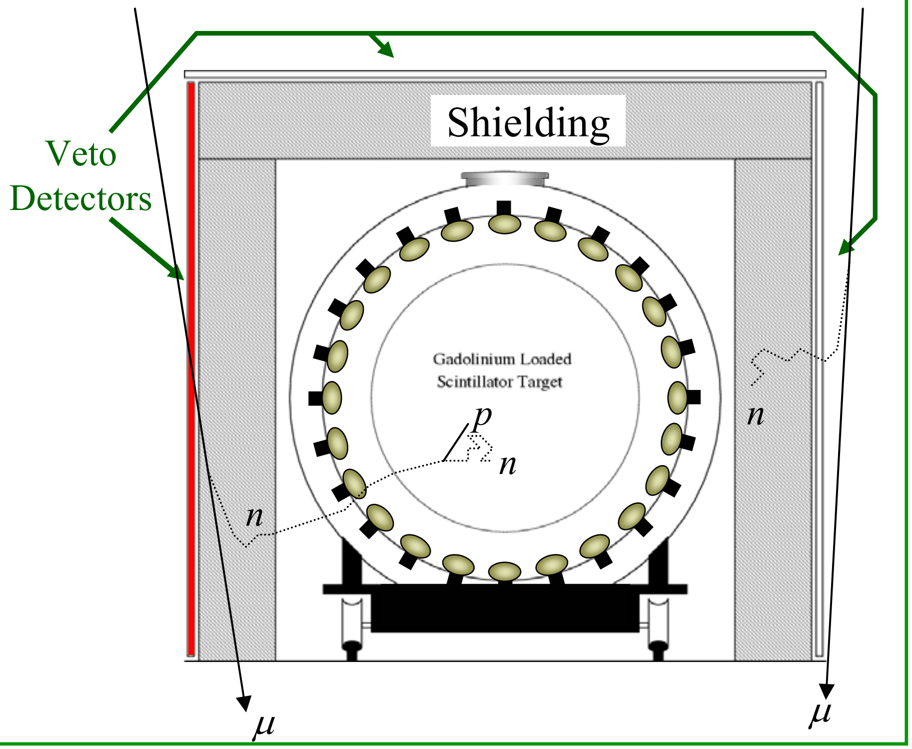
Design Goals: Flexibility, Redundancy, and Cross Checks

- Four identical 65 ton detectors
  - Outside Radius = 3.5 m
  - Fid. Radius = 2.6 m
- Two zones
  (Inner: Gd Scint, Outer: Pure oil)
  - Good access for calibrations
  - Increased fiducial mass
- Redundant detectors at each site
  - Cross checks and flexibility
- Moveable detectors
  - Allows direct cross calibration at near site
- Flat overburden at 450 mwe depth
  - Equivalent to 580 mwe mountain
  - 5 Hz muon rate in 6.5 m radius
  - Deep near detector allows access to unique additional physics (Janet's talk)
- Optimized to use both rate and shape analysis

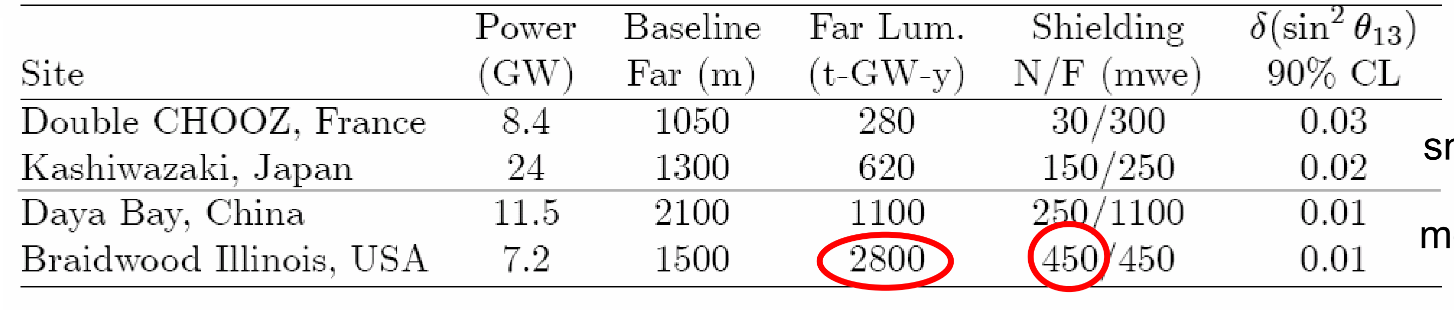
- Mitigate Correlated Background with extensive, active veto system
  - Fast neutrons from muons
  - ^{9}Li and ^{8}He produced from muon

Braidwood Strategy:

Identify and veto the few shower producing muons which produce the neutrons and spallation products



Comparisons to Other Reactor Oscillation Experiments



Site	Power (GW)	Baseline Far (m)	Far Lum. (t-GW-y)	Shielding N/F (mwe)	$\delta(\sin^2\theta_{13})$ 90% CL
Double CHOOZ, France	8.4	1050	280	30/300	0.03
Kashiwazaki, Japan	24	1300	620	150/250	0.02
Daya Bay, China	11.5	2100	1100	250/1100	0.01
Braidwood Illinois, USA	7.2	1500	2800	450/450	0.01

small

medium

Criteria:

	Chooz II	Daya Bay	Braidwood
Adequate Overburden for Far Detector for Near Detector	? X	✓ ✓	✓ ✓
Optimized Baseline/Detector for Rate Measurement for Shape Measurement	X X	? X	✓ ✓
Single Baseline as needed for Shape Measurement		X	✓
Capability to do Near Detector Physics ($\sin^2\theta_W$)	X	X	✓
Improved Veto System	X	✓	✓
Multiple Moveable Detectors for Cross Checks	X	✓	✓
Two Zone Detectors: Better Calibration and Fid. Volume	X	X	✓
Facility Flexibility - Move All Detectors to Far Site - Capability to Expand to a Large Detector	 X X	 ✓ X	 ✓ ✓

Baseline Cost and Schedule Estimates

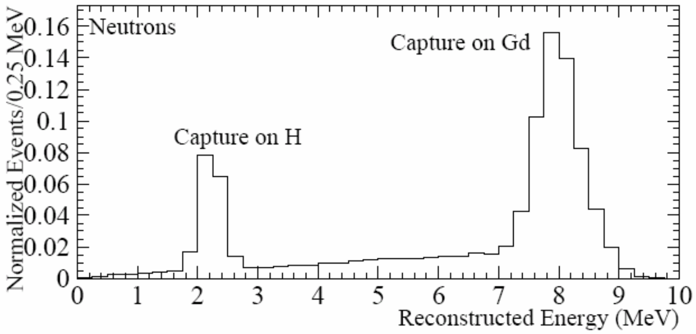
- Baseline Cost Estimate:
  - Civil Costs: (From Hilton and Assoc. consulting firm)
    - Const.+EDIA $34M
    - Contingency $8.5M
  - Detector and Veto System (From Bartoszek Eng. and Argonne)
    - Four Detectors with Veto systems $17M
    - Contingency $5M
    - Other with cont. $1M
- Schedule:
  - 2004: R&D proposal submission.
  - 2005: Full proposal submission
  - 2007: Project approval; start const.
  - 2009: Start data collection

- There has been little value engineering applied to these cost estimates.
  - Likely cost savings in developing an integrated plan for shafts, detectors, and access.
- Results of bore holes and geology studies reduces the needed contingency
- Project also lends itself to operational phasing with near and far shafts and multiple detectors

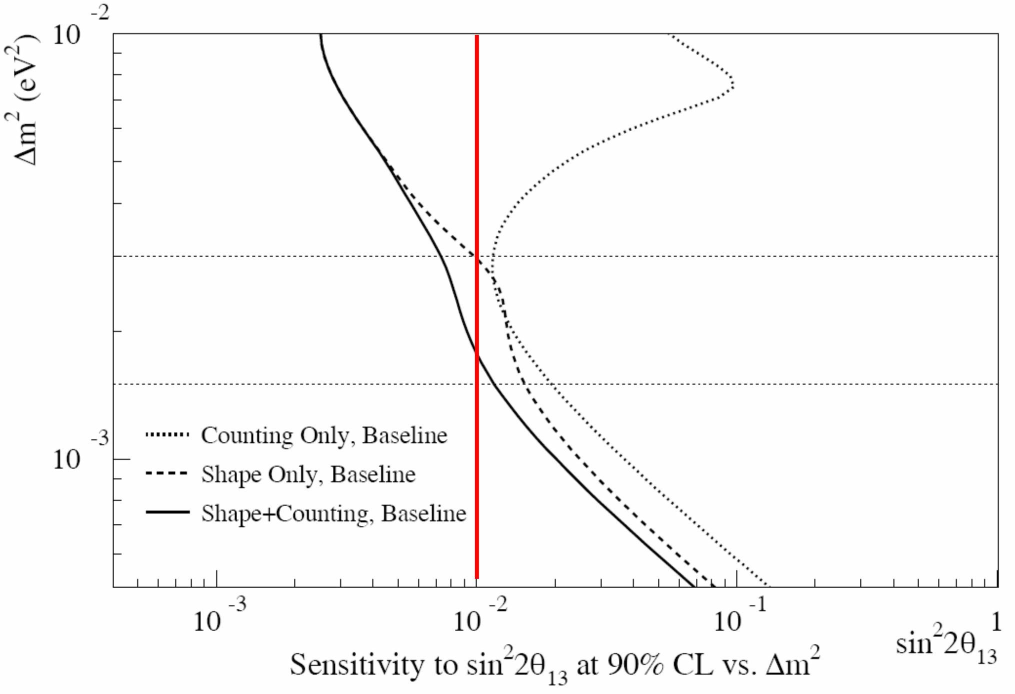
Uncertainties and Sensitivity Estimates

Control of relative systematic uncertainties

- Relative near/far eff., fid.vol., etc.
  - Calibrated filling of detectors
  - Radioactive sources
  - Direct cross calibration at near site
- Calibrations
  - In-situ n capture peaks, ^{12}B, …
  - Flashers, LEDs, sources
- Backgrounds
  - Large overburden
  - Reduce intrinsic radioactivity in PMTs, Gd, material
  - Multi-layer veto system
    - various muon-activity vetos
    - tag and measure background



Source of Uncertainty	%
Near to Far Detector Relative Normalization	0.6
Far Detector Statistics	0.2
Near Detector Statistics	0.04
Backgrounds	0.5



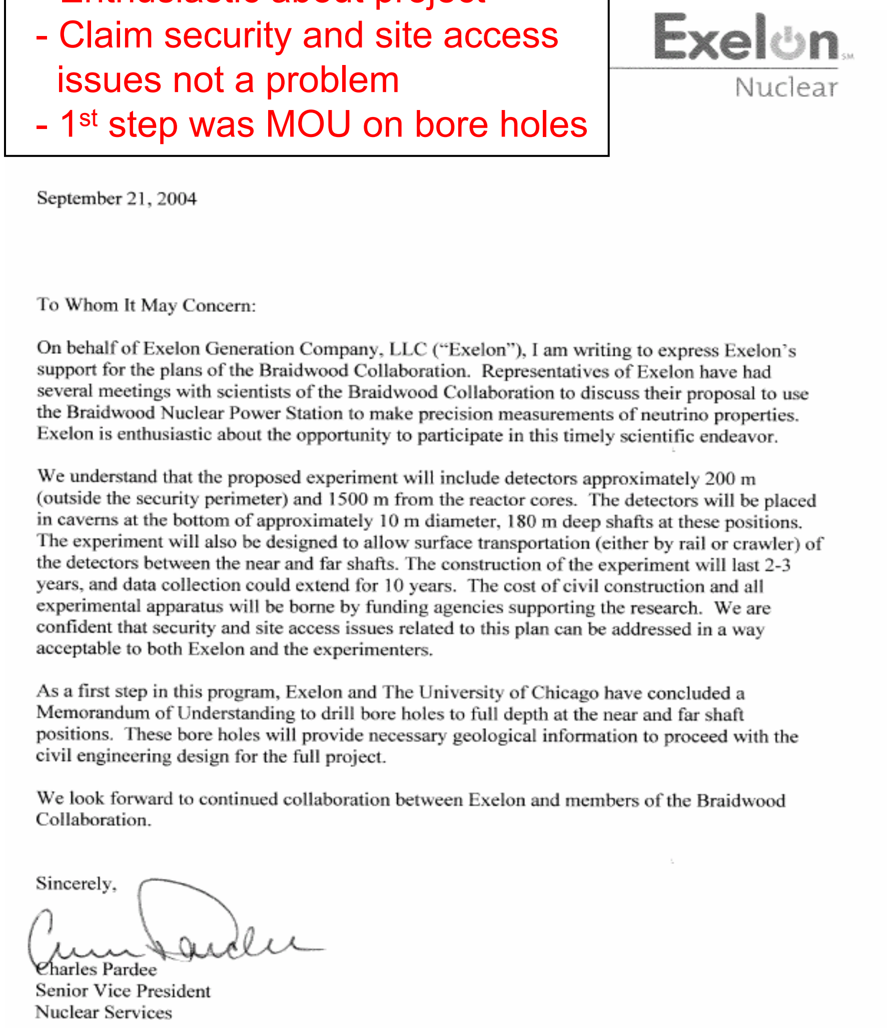
J. Link calculation for 3 yr data run

Engineering/R&D Proposal
(Submitted to NSF and DOE)

- Requests funding to complete the design and engineering of the baseline project.
  - Civil engineering design leading to RFP for a “Design and Build”
  - Detector engineering leading to full “Design Report”
  - Final development of stable Gd loaded scintillator
- Amount requested

– Civil Engineering	$525k
– Detector Engineering	$408k
– Liquid Scint.	$28k
– Edu. and Outreach	$78k

Exelon Letter of support:
- Enthusiastic about project
- Claim security and site access issues not a problem
- 1st step was MOU on bore holes



Exelon Nuclear

September 21, 2004

To Whom It May Concern:

On behalf of Exelon Generation Company, LLC (“Exelon”), I am writing to express Exelon’s support for the plans of the Braidwood Collaboration. Representatives of Exelon have had several meetings with scientists of the Braidwood Collaboration to discuss their proposal to use the Braidwood Nuclear Power Station to make precision measurements of neutrino properties. Exelon is enthusiastic about the opportunity to participate in this timely scientific endeavor.

We understand that the proposed experiment will include detectors approximately 200 m (outside the security perimeter) and 1500 m from the reactor cores. The detectors will be placed in caverns at the bottom of approximately 10 m diameter, 180 m deep shafts at these positions. The experiment will also be designed to allow surface transportation (either by rail or crawler) of the detectors between the near and far shafts. The construction of the experiment will last 2-3 years, and data collection could extend for 10 years. The cost of civil construction and all experimental apparatus will be borne by funding agencies supporting the research. We are confident that security and site access issues related to this plan can be addressed in a way acceptable to both Exelon and the experimenters.

As a first step in this program, Exelon and The University of Chicago have concluded a Memorandum of Understanding to drill bore holes to full depth at the near and far shaft positions. These bore holes will provide necessary geological information to proceed with the civil engineering design for the full project.

We look forward to continued collaboration between Exelon and members of the Braidwood Collaboration.

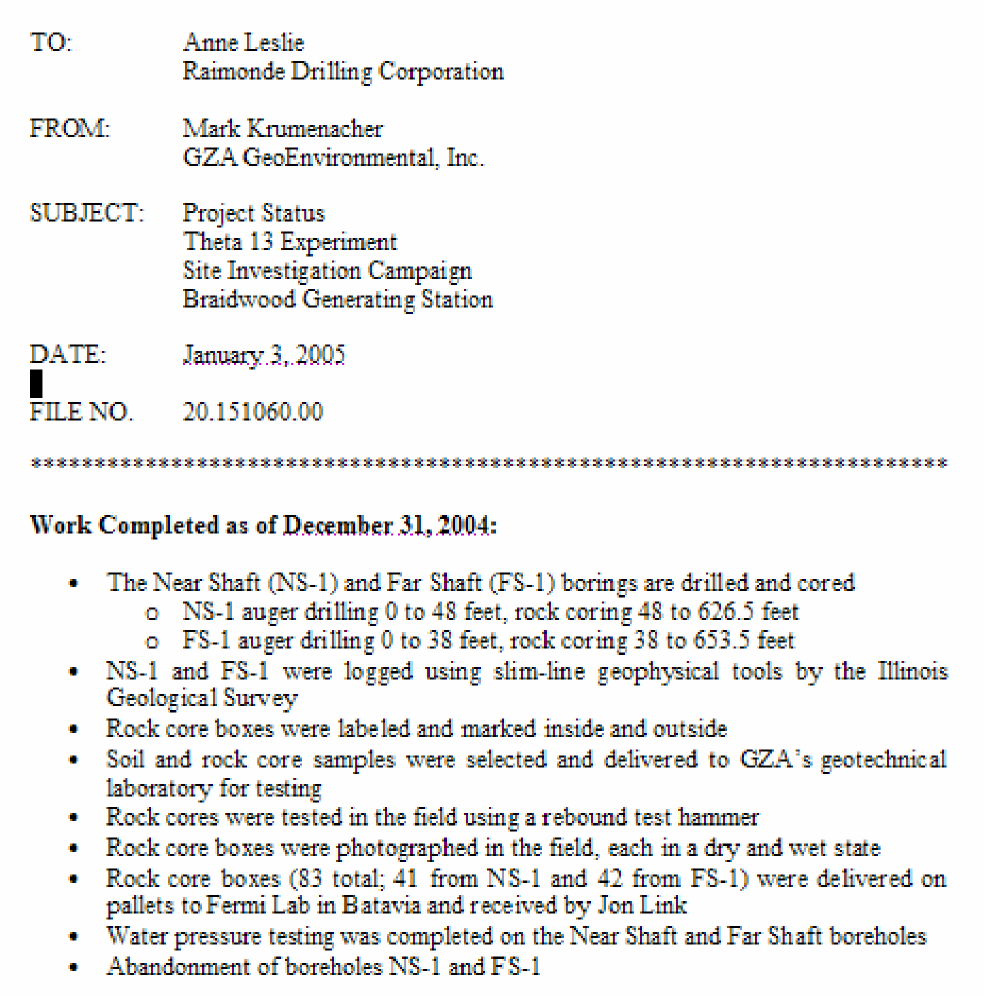
Sincerely,

Charles Pardee
Senior Vice President
Nuclear Services

First Construction at Braidwood Site: Bore Holes to Depth

- First interaction with Exelon very successful (J. Link supervision)
  - MOU developed to do work on site
- The drilling and onsite studies completed
  - Geology and ground water characteristics determined
  - Cores studied and stored
- Found what was expected
  - Brings confidence to baseline and may allow reduced contingency

- Costs from funds provided by Univ. of Chicago ($100K seed money)



TO: Anne Leslie
Raimonde Drilling Corporation

FROM: Mark Krumenacher
GZA GeoEnvironmental, Inc.

SUBJECT: Project Status
Theta 13 Experiment
Site Investigation Campaign
Braidwood Generating Station

DATE: January 3, 2005

FILE NO. 20.151060.00

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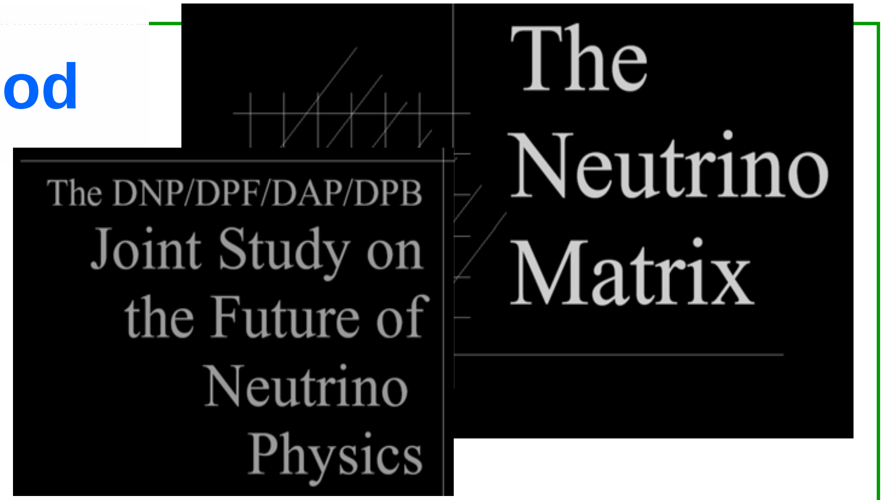
Work Completed as of December 31, 2004:

- The Near Shaft (NS-1) and Far Shaft (FS-1) borings are drilled and cored
  - NS-1 auger drilling 0 to 48 feet, rock coring 48 to 626.5 feet
  - FS-1 auger drilling 0 to 38 feet, rock coring 38 to 653.5 feet
- NS-1 and FS-1 were logged using slim-line geophysical tools by the Illinois Geological Survey
- Rock core boxes were labeled and marked inside and outside
- Soil and rock core samples were selected and delivered to GZA's geotechnical laboratory for testing
- Rock cores were tested in the field using a rebound test hammer
- Rock core boxes were photographed in the field, each in a dry and wet state
- Rock core boxes (83 total; 41 from NS-1 and 42 from FS-1) were delivered on pallets to Fermi Lab in Batavia and received by Jon Link
- Water pressure testing was completed on the Near Shaft and Far Shaft boreholes
- Abandonment of boreholes NS-1 and FS-1

Summary of θ_{13} at Braidwood

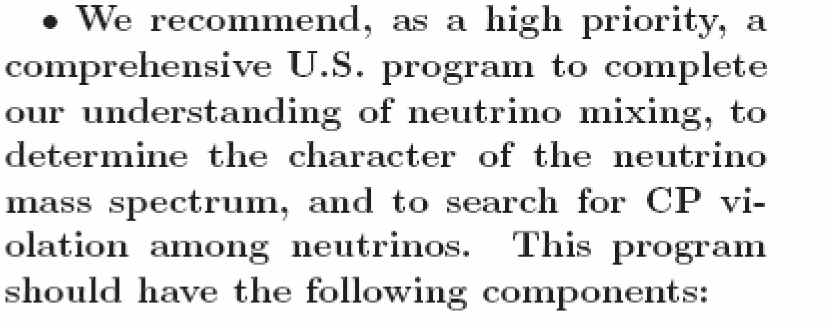
- A reactor experiment is prime and unambiguous technique to measure θ_{13}
  - θ_{13} is an important physics parameter
    - Needed to constrain the models of lepton mixing matrix
    - If very small, probably indicates a new symmetry
  - θ_{13} is key for planning the future long-baseline experiments 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 then may need other techniques to access the physics



The Neutrino Matrix

The DNP/DPF/DAP/DPB Joint Study on the Future of Neutrino Physics

Consensus Recommendation 2 (of 3):



- We recommend, as a high priority, a comprehensive U.S. program to complete our understanding of neutrino mixing, to determine the character of the neutrino mass spectrum, and to search for CP violation among neutrinos. This program should have the following components:

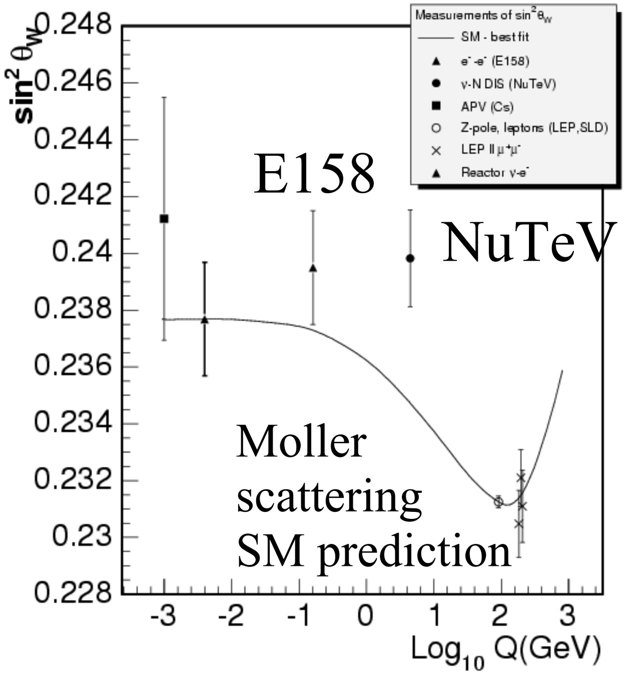
  - An expeditiously deployed multi-detector reactor experiment with sensitivity … $\sin^2 2\theta_{13}=0.01$ …
  - A timely accelerator experiment with comparable … sensitivity …
  - A proton driver … with an appropriate very large detector …

- Funding agencies now working towards implementing the plan

The Weak Mixing Angle at Braidwood

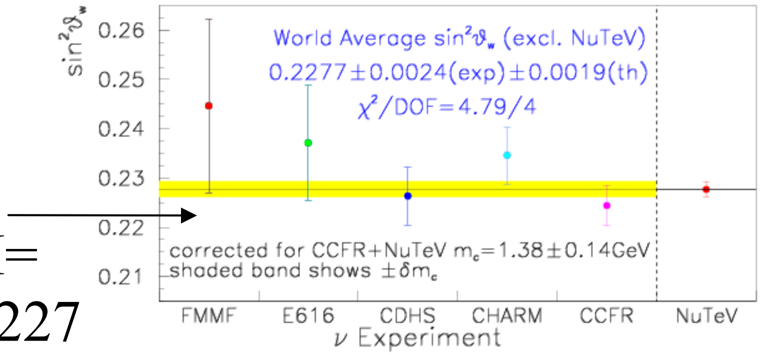
Motivation: To Study the NuTeV Anomaly

a measurement of $\sin^2\theta_W$ which is off from the SM by 3σ

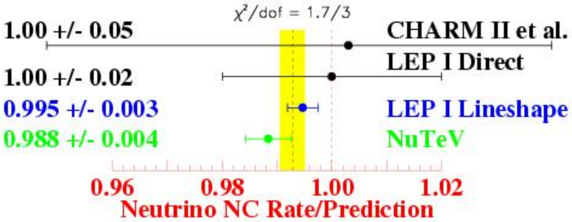


Agrees with other DIS ν measurements, but with much smaller errors...

SM=
0.2227



Implies $N_\nu<3$, consistent with LEP I lineshape



Complete list of unsuccessful attempts to explain the anomaly:

http://home.fnal.gov/~gzeller

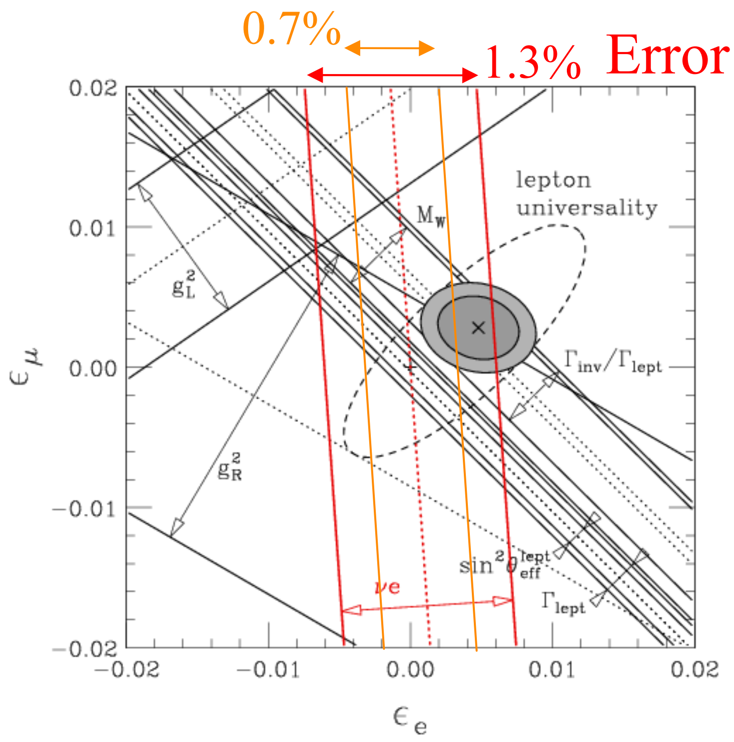
New Physics Possibility:

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

LEP+NuTeV can be fit well if neutrinos are allowed to have non-standard couplings (adjusted by $\varepsilon\sim0.3\%$)

$Z\nu\nu \leftrightarrow (1-\varepsilon)$
$Wl\nu \leftrightarrow (1-\varepsilon/2)$

Idea has now been expanded to consider flavor dependence, with fits to world's data on lepton couplings...



Error on...

Elastic Scattering Measurement at a reactor experiment:

Sensitive to ε_e

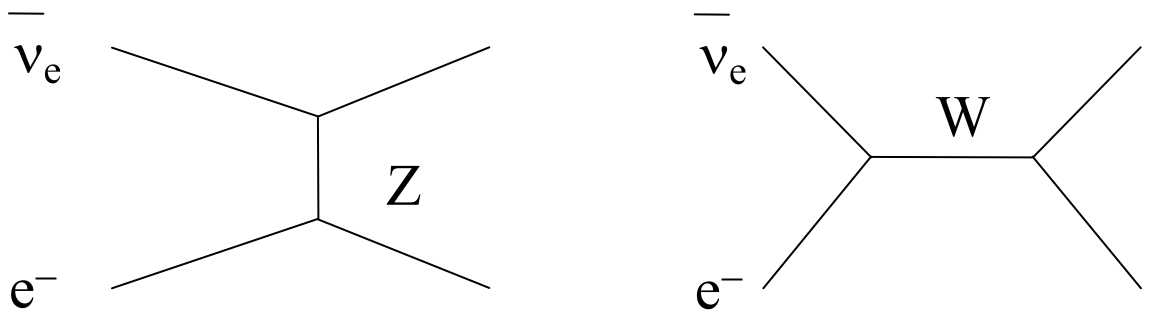
(slight ε_μ sensitivity comes through G_F)

Plot by Loinaz, Fisher & Takeuchi...

(doesn't include SLAC E158)

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

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



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

$C_V = ½ + 2\, \mathbf{\sin^2\theta_W}$

$C_A = ½$

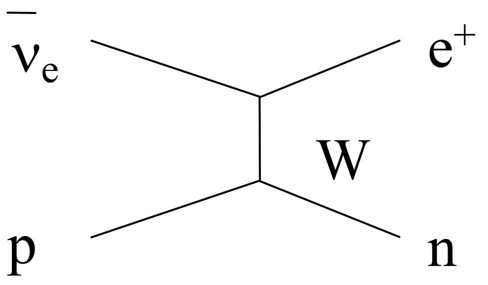
T = electron KE energy
E = neutrino energy
m= mass of electron
This assumes μ_ν=0

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

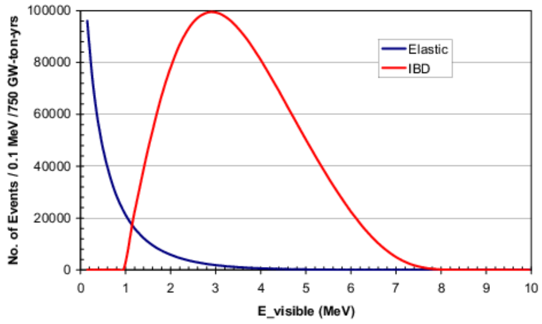
See: Conrad, Link, Shaevitz, hep-ph/0403048 (sub. to PRD, now responding to referee)

Tricks to make a precision measurement possible:

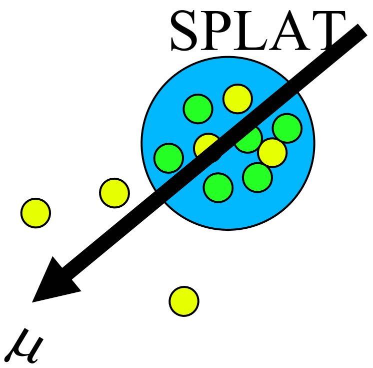
- Normalize to IBD events (addresses flux and fiducial volume issues)

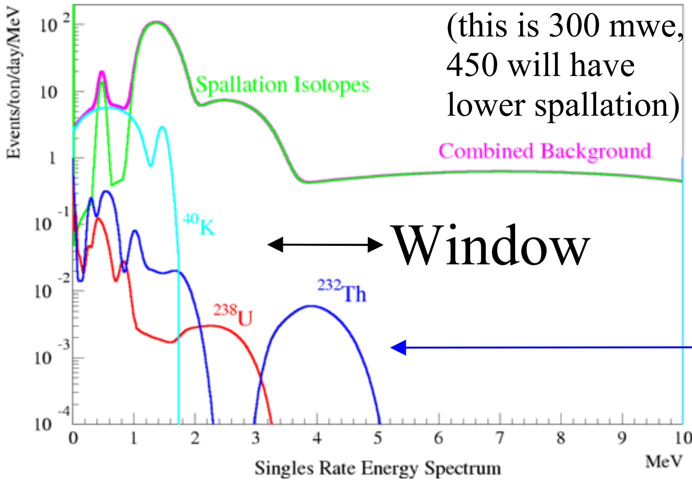


This cross section is known to 0.2%



- Use a 3 to 5 MeV window (reduces issue of contaminants and spallation)





(this is 300 mwe,
450 will have
lower spallation)

Most spallation
product beta
decays can
be tagged by
accompanying
decay particles.

^{208}Tl can be tagged
by accompanying
high energy photons

- Go deep but not too far from reactor (maintain flux but escape spallation)

The reason this can only be done at Braidwood