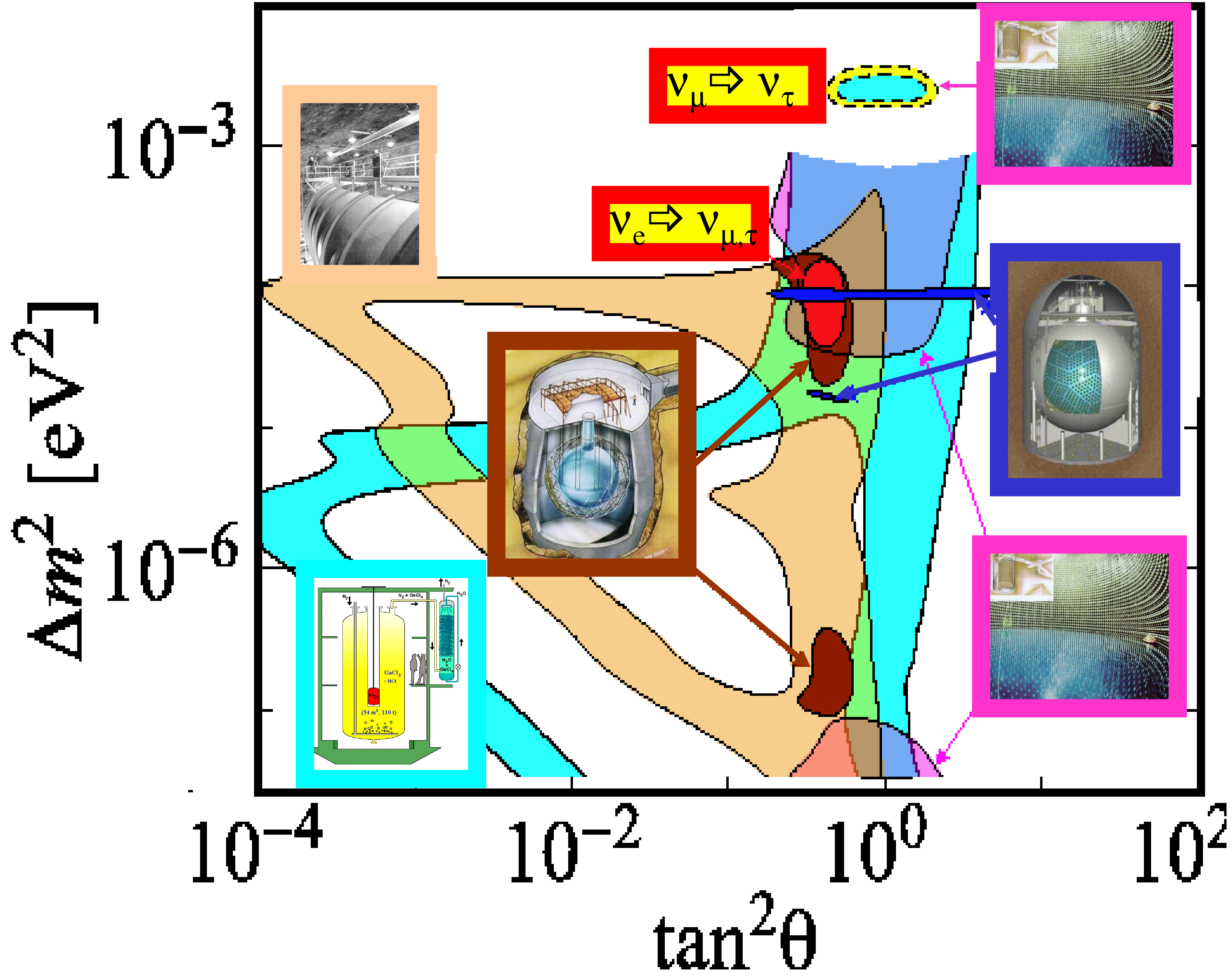
A 'ν' Angle on Oscillations


$\nu_\mu \Rightarrow \nu_\tau$
$\nu_e \Rightarrow \nu_{\mu,\tau}$
10^{-3}
10^{-6}
Δm^2 [eV^2]
10^{-4}
10^{-2}
10^{0}
10^{2}
$\tan^2\theta$
N$_2$
N$_2$ + GeCl$_4$
H$_2$O
GaCl$_3$ + HCl
(54 m^3, 110 t)
H$_2$O + GeCl$_4$

PMNS Neutrino Mixing Matrix

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

CKM Quark Mixing Matrix

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

PMNS Neutrino Mixing Matrix

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

$$\begin{pmatrix} 0.7 & 0.7 & \boxed{< 0.2 e^{i\delta}\,?} \\ -0.5 & 0.5 & 0.7 \\ 0.5 & -0.5 & 0.7 \end{pmatrix}$$

$$\begin{pmatrix} big & big & small? \\ big & big & big \\ big & big & big \end{pmatrix}$$

GUTs? See-Saw?

IF $\theta_{13} > 0.05$

($\sin^2 2\theta_{13} > 0.01$)

Otherwise ⟹ New symmetry?

CKM Quark Mixing Matrix

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

$$\begin{pmatrix} 0.97 & 0.22 & 0.003 e^{i\delta} \\ -0.22 & 0.97 & 0.04 \\ 0.01 & -0.04 & 0.999 \end{pmatrix}$$

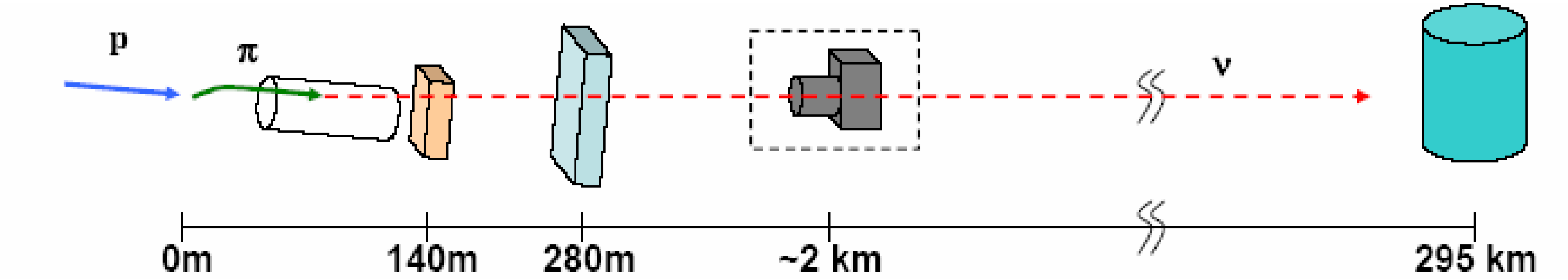
$$\begin{pmatrix} big & small & very\ tiny \\ small & big & tiny \\ tiny & tiny & big \end{pmatrix}$$

The relationship between neutrinos and quarks in GUTs may be the source of the matter-antimatter asymmetry in the Universe

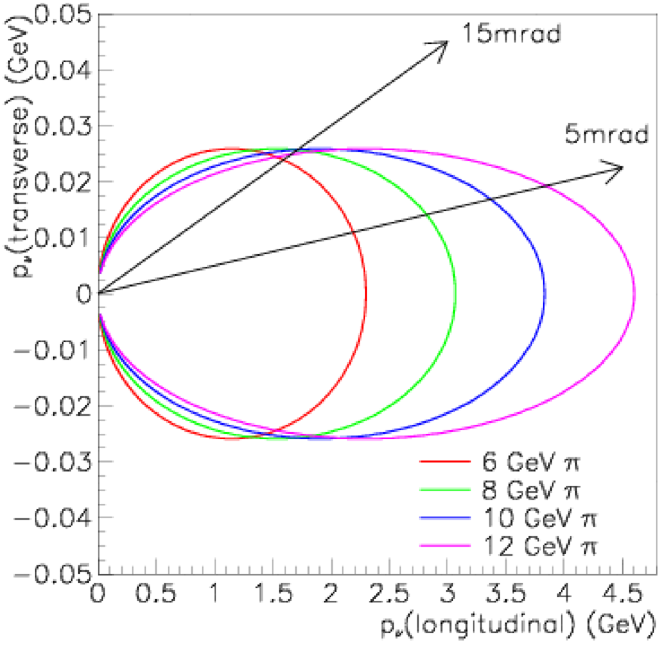
Leptogenesis

Knowing the size of $\sin\theta_{13}$ is the next step and will set the roadmap for how to proceed

Approach #1: “Off Axis” ν Beams



- Take advantage of Lorentz Boost and 2-body decays
- Concentrate ν_μ flux at one energy
- Lower NC and ν_e backgrounds at that energy (3-body decays)



$\nu_\mu \rightarrow \nu_e$ Appearance

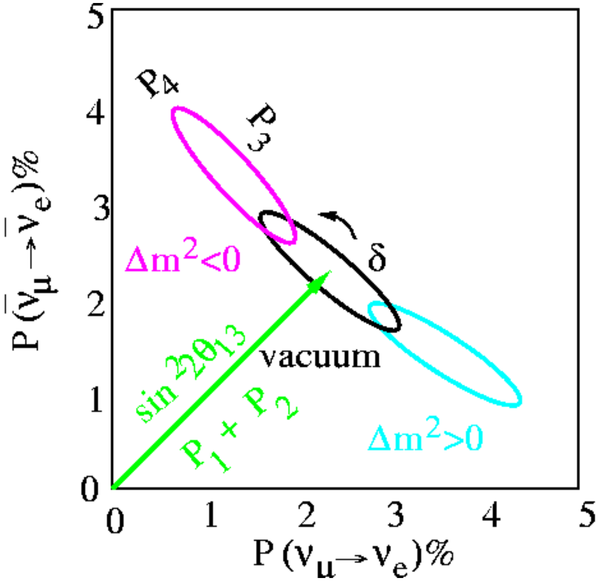
T2K & NOVA

Oscillation Probability: $P(\nu_\mu \rightarrow \nu_e) = P_1 + P_2 + P_3 + P_4$

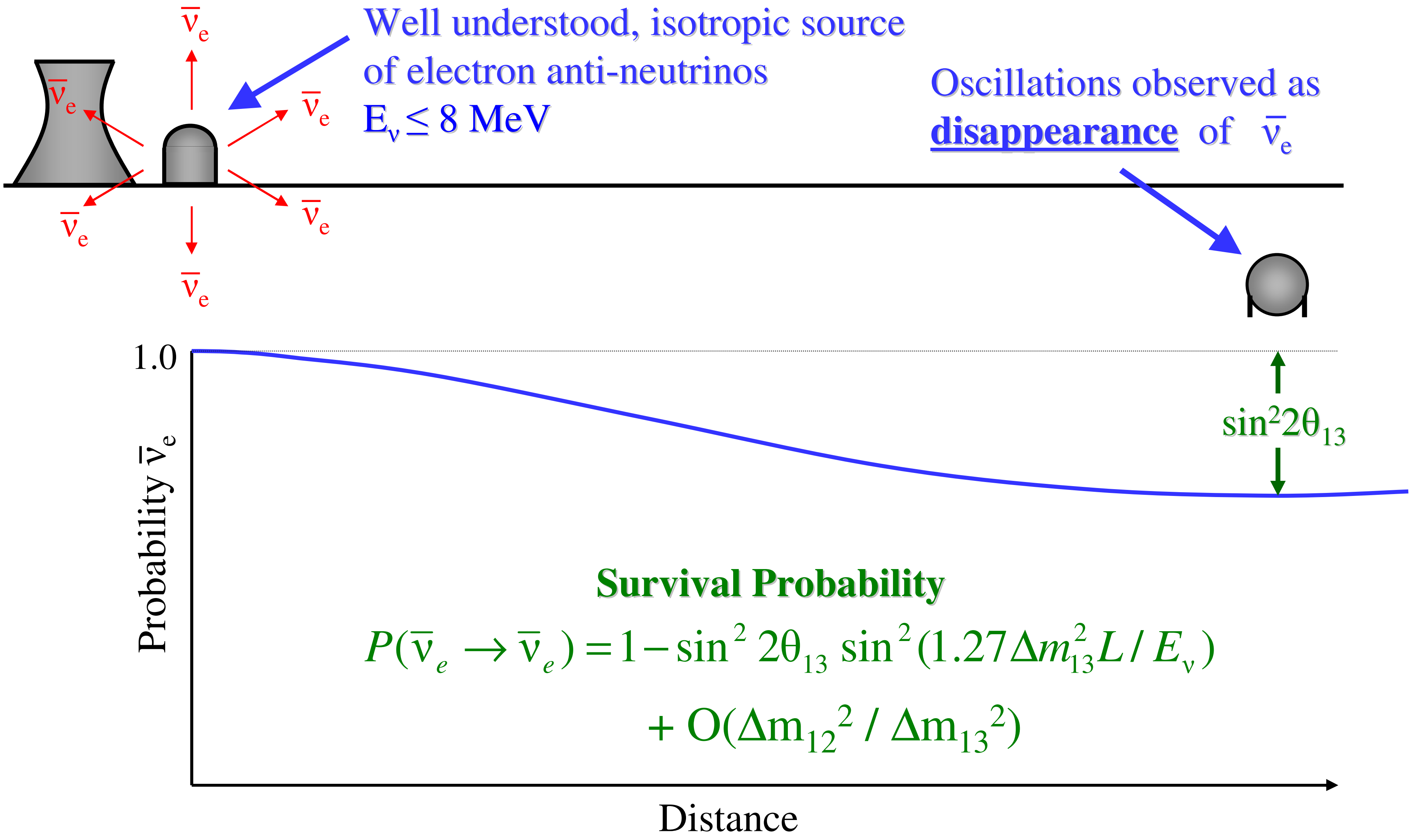
where

$$
\begin{aligned}
P_1 &= \sin^2\theta_{23} \sin^2 2\theta_{13} \left(\frac{\Delta_{13}}{B_\pm}\right)^2 \sin^2 \frac{B_\pm L}{2} \\
P_2 &= \cos^2\theta_{23} \sin^2 2\theta_{12} \left(\frac{\Delta_{12}}{A}\right)^2 \sin^2 \frac{AL}{2} \\
P_3 &= J \cos\delta \left(\frac{\Delta_{12}}{A}\right) \left(\frac{\Delta_{13}}{B_\pm}\right) \cos\frac{\Delta_{13}L}{2} \sin\frac{AL}{2} \sin\frac{B_\pm L}{2} \\
P_4 &= \mp J \sin\delta \left(\frac{\Delta_{12}}{A}\right) \left(\frac{\Delta_{13}}{B_\pm}\right) \sin\frac{\Delta_{13}L}{2} \sin\frac{AL}{2} \sin\frac{B_\pm L}{2}
\end{aligned}
$$

- dependence in $\sin(2\theta_{23})$, $\sin(\theta_{23})$ Ł 2 solutions
- dependence in sign(Δm^2_{31}) Ł 2 solutions
- δ-CP phase ± [0,2π] Ł interval of solutions



Approach #2: Reactor Experiments



Well understood, isotropic source of electron anti-neutrinos

$E_\nu \leq 8$ MeV

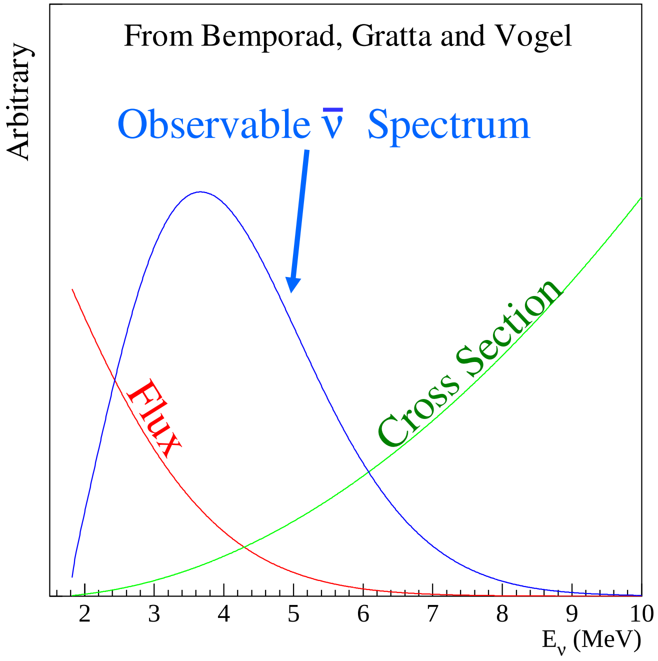
Oscillations observed as **disappearance** of $\bar{\nu}_e$

Survival Probability

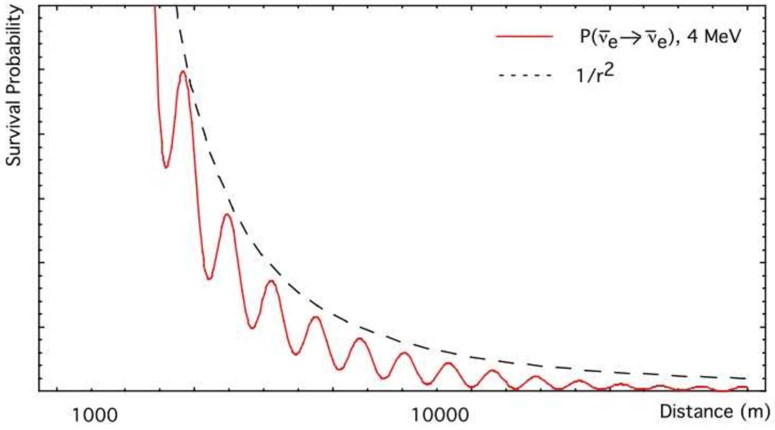
$$P(\bar{\nu}_e \rightarrow \bar{\nu}_e) = 1 - \sin^2 2\theta_{13} \sin^2(1.27 \Delta m_{13}^2 L / E_\nu)$$

$$+ O(\Delta m_{12}^2 / \Delta m_{13}^2)$$

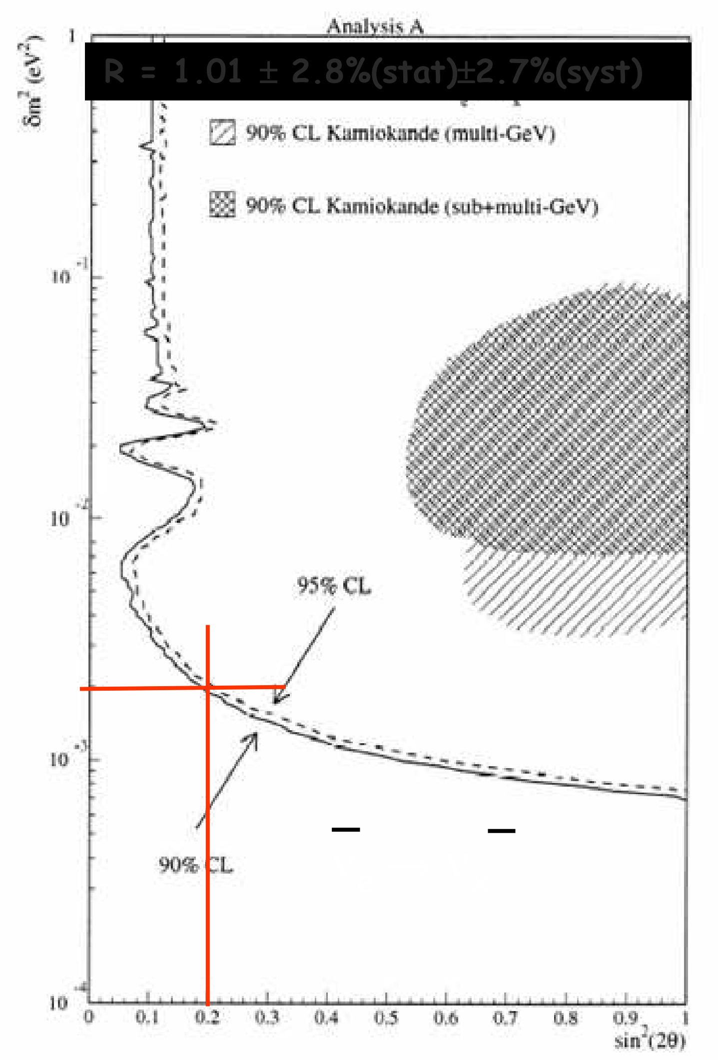
No θ_{13} ambiquity; No δ–CP effects; No matter effects; Minimal dependence on Δm_{12}^2



- 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

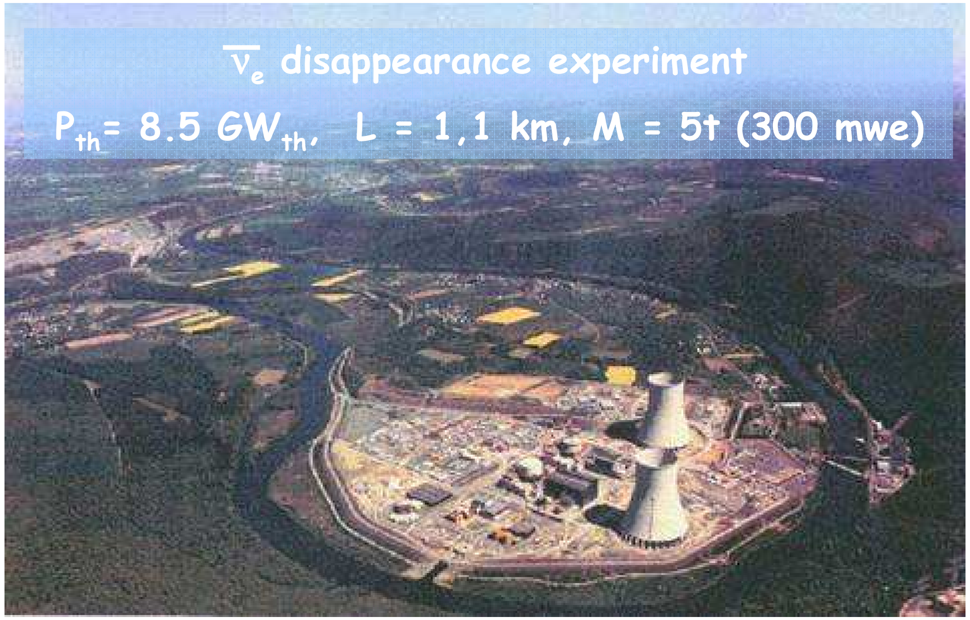


Best current constraint: CHOOZ



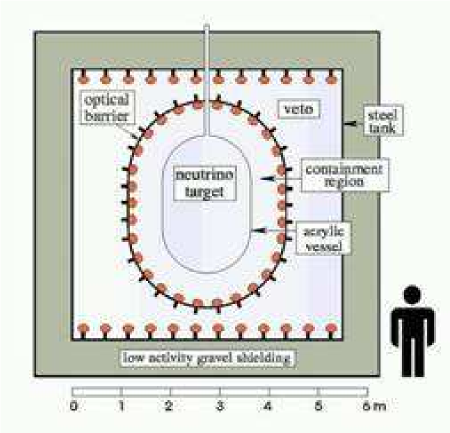
R = 1.01 ± 2.8%(stat)±2.7%(syst)

M. Apollonio et. al., Eur.Phys.J. C27 (2003) 331-374



$\overline{\nu}_e$ disappearance experiment

P_{th}= 8.5 GW_{th}, L = 1,1 km, M = 5t (300 mwe)



World best constraint !

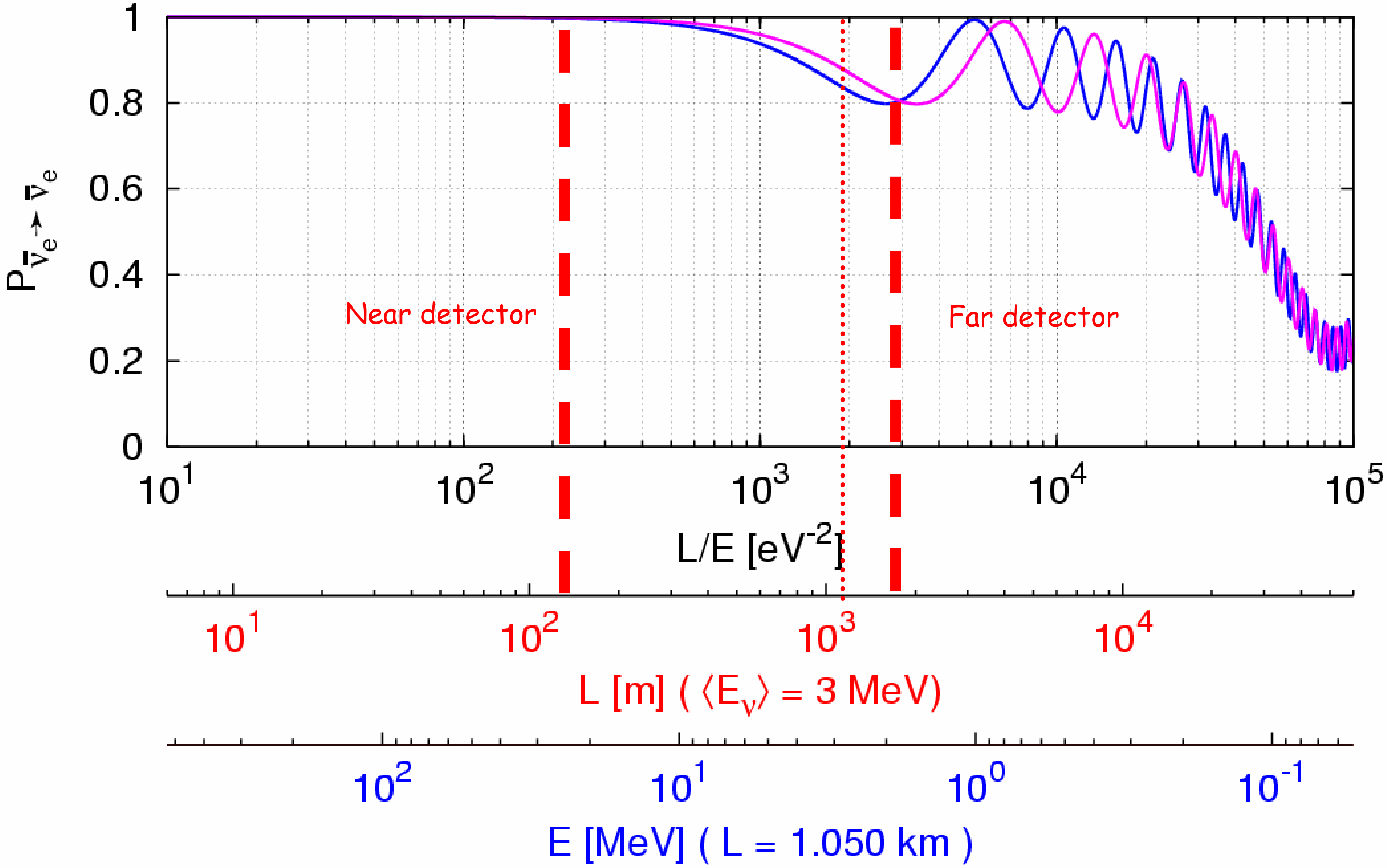
@Δm^2_{atm}=2 10^{-3} eV^2

$\sin^2(2\theta_{13})<0.2$

(90% C.L)

$\Delta m^2_{12} = 7.2\ 10^{-5}\ \mathrm{eV}^2$; $\cos\theta_{12} = 0.8$; $\sin\theta_{13} = 0.23$

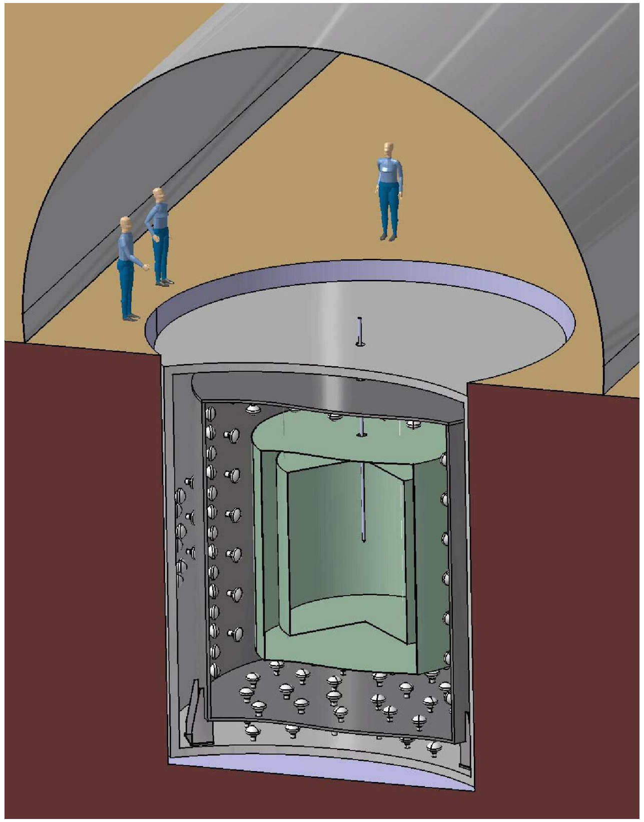
$\Delta m^2_{23} = 2.5\ 10^{-3}\ \mathrm{eV}^2$; $\Delta m^2_{23} = 2.0\ 10^{-3}\ \mathrm{eV}^2$



Proposed Sites Around the World

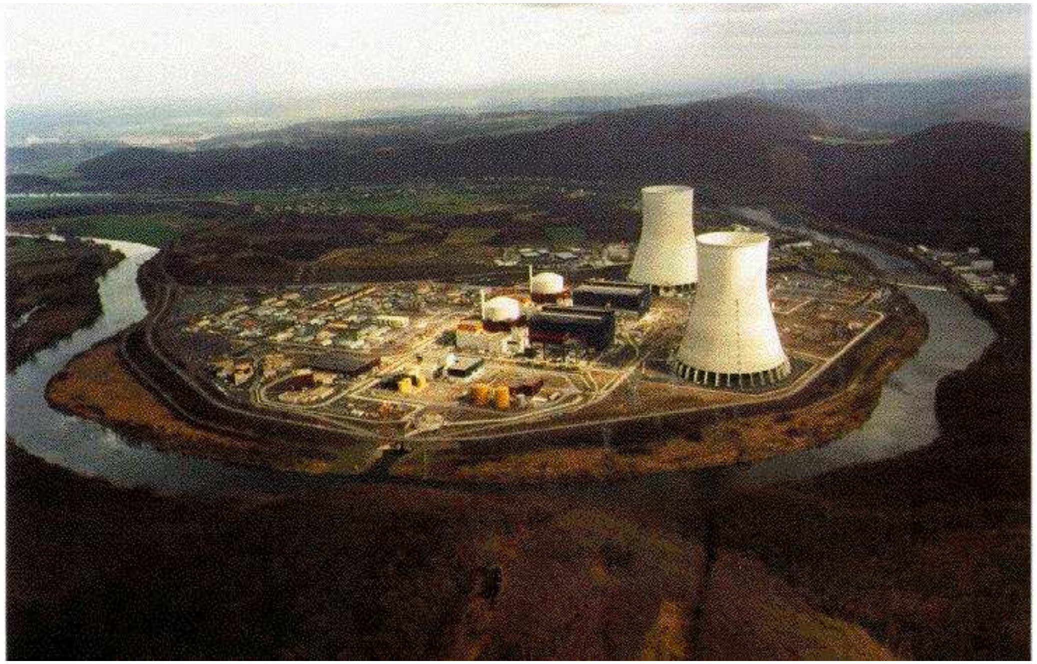
Site	Power ($GW_{thermal}$)	Baseline Near/Far (m)	Shielding Near/Far (mwe)	Sensitivity 90% CL
Krasnoyarsk, Russia	1.6	115/1000	600/600	0.03
Kashiwazaki, Japan	24	300/1300	150/250	0.02
Double Chooz, France	8.4	150/1050	30/300	0.03
Diablo Canyon, CA	6.7	400/1700	50/700	0.01
Angra, Brazil	5.9	500/1350	50/500	0.02
Braidwood, IL	7.2	200/1500	450/450	0.01
Daya Bay, China	11.5	250/2100	250/1100	0.01

Double CHOOZ , France



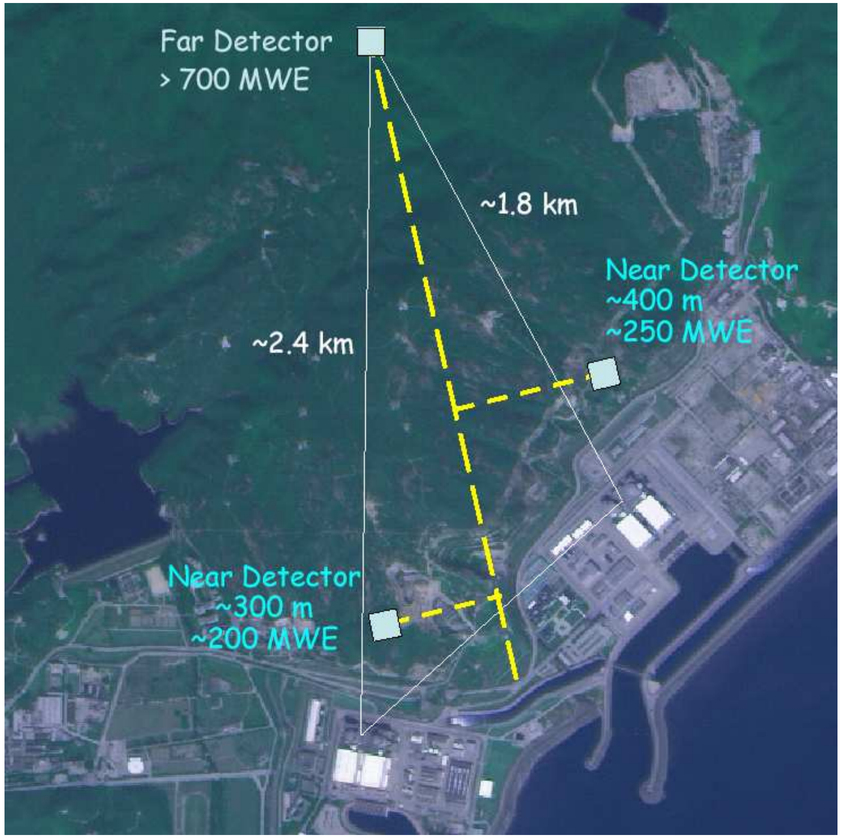
- Use old far detector hall at ~1050 meters
- Near detector at 125-250 meters (~50 mwe)
- 11 ton Gd loaded detectors.
- Sensitivity of $\sin^2 2\theta_{13} \sim 0.03$ in 3 years

  Fast (?) and Inexpensive
- Has scientific approval



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 $\sin^2 2\theta_{13} \sim 0.01$ in 3 years



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

Braidwood Neutrino Experiment

Braidwood Setup:

- Two 3.6 GW reactors
- Two 65 ton (fid vol) near detectors at 270 m
- Two 65 ton (fid vol) far detectors at 1510 m
- 180m shafts and detector halls at 450 mwe depth

- Sensitivity of $\sin^2 2\theta_{13} \leq 0.01$ in 3 years
- High level of cooperation with utility

Argonne National Laboratory

M. Goodman, D. Reyna, L. Price

Brookhaven National Laboratory

R. Hahn, M. Yeh, A. Garnov, Z. Chang

University of Chicago

E. Blucher, J. Pilcher, K. Anderson, M. Worcester,
E. Abouzaid, M. Hurowitz, D. McKeen

Columbia University

J. Conrad, M. Shaevitz, Z. Djurcic, J. Link, G. Zeller,
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H. Jostlein, C. Laughton, D. Finley, R. Stefanski

Kansas State University

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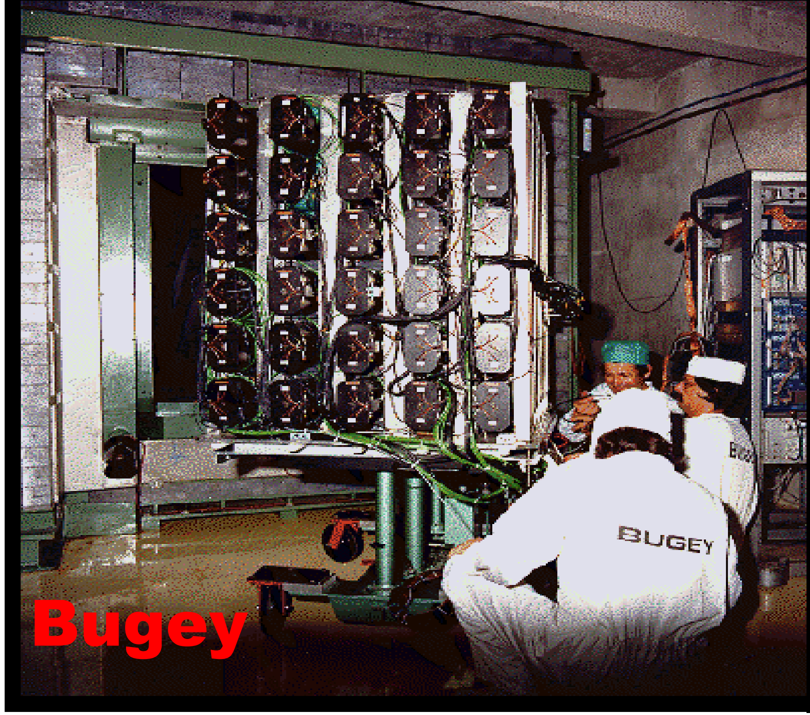
E. Falk-Harris

University of Texas

J. Klein, M. Huang, S. Seibert, A. Anthony


E-776


Savannah River



Bugey


E-816

“No one ever lost money betting that a neutrino experiment was wrong!”

D. Perkins

What’s changed?

SNO (solar): Redundant NC + CC + ES
SuperK (atmospheric): Flux + E/L dependance
KamLAND (reactor): Flux + Spectrum

The Two Golden Rules of Neutrino Physics:

1) Redundancy

2) Redundancy

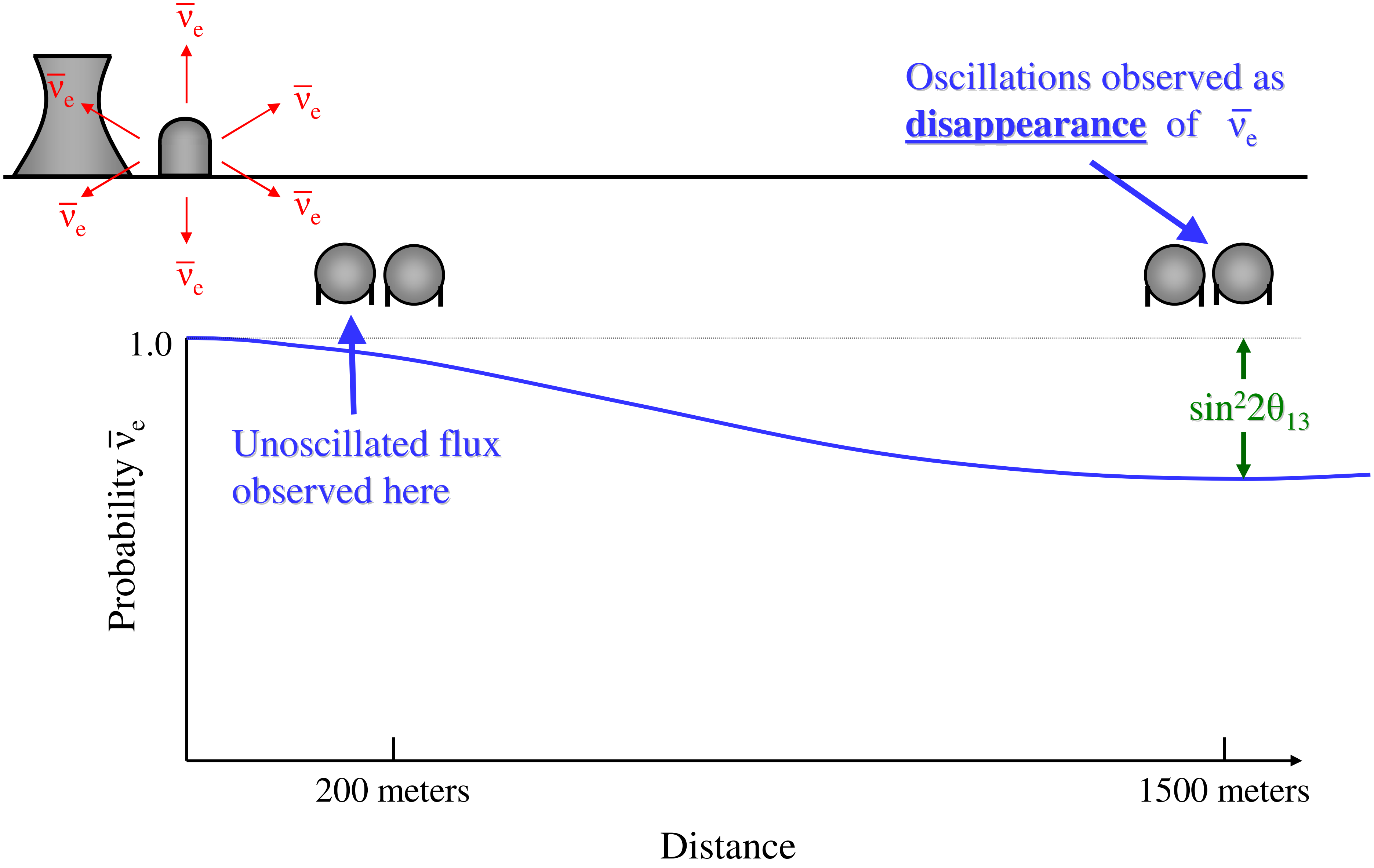
Braidwood Design Principles

Compare rate/shape in identical, large, spherical, on-axis detectors at two distances that have equal overburden shielding
(Multiple detectors at each site: two near and two far)

RELATIVE measurement ⇒ Removes uncertainty in generated spectrum, plus systematic uncertainties cancel to first order and only have uncertainties for second order effects

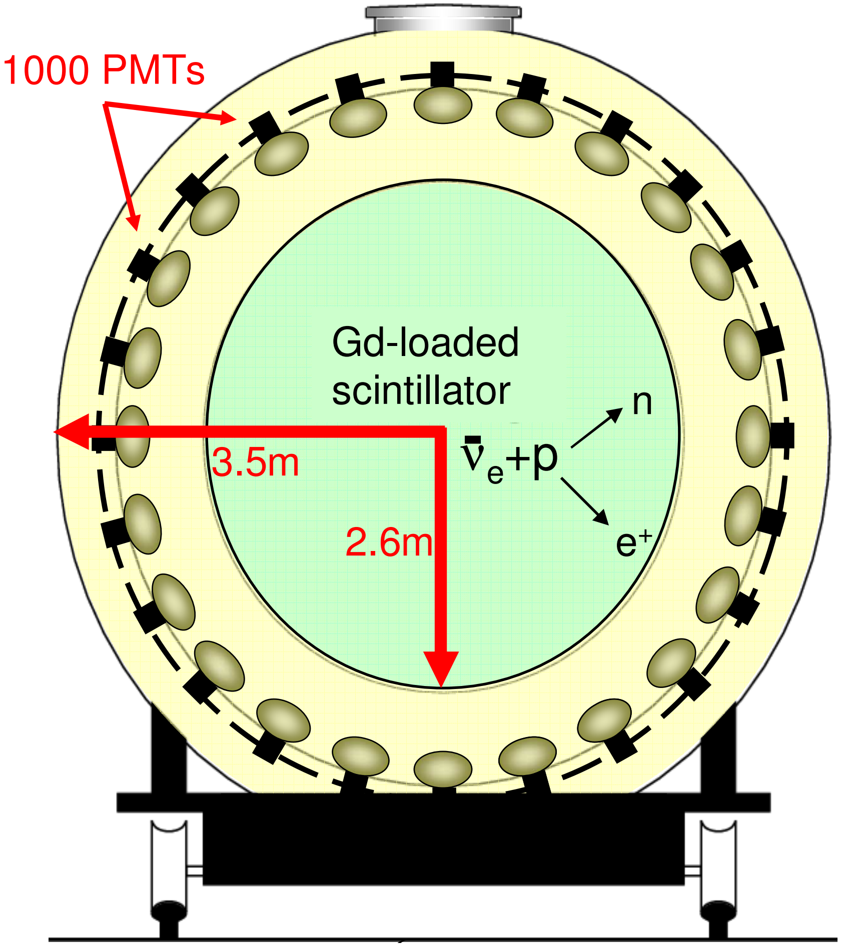
- Detectors **filled simultaneously** with common scintillator on surface
- Large (65 ton fiducial) detectors give **large data samples**
- Spherical detectors **reduce any geometrical effects** from neutrino direction and reconstruction
- On-axis detectors **eliminate any dependence on reactor power** variations in a multi-reactor setup.
- Equal overburden shielding gives **equal spallation rates** in near and far that can be exploited for detector and background checks

- See signal in both total **rate and energy shape** measurements
- **Directly verify detector calibration systems** at high-rate near site
- Cross **calibrate near/far detectors using spallation isotopes** like ^{12}B (since detectors at same deep depth)
- **Multiple near and far detectors give direct cross checks** on detector systematics at 0.05% for the near set and 0.3% for far
- Large detectors allow **studies of the radial dependence** of the IBD signal and backgrounds.



Oscillations observed as **disappearance** of $\bar{\nu}_e$

Unoscillated flux observed here



~65 tonne fiducial volume

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.

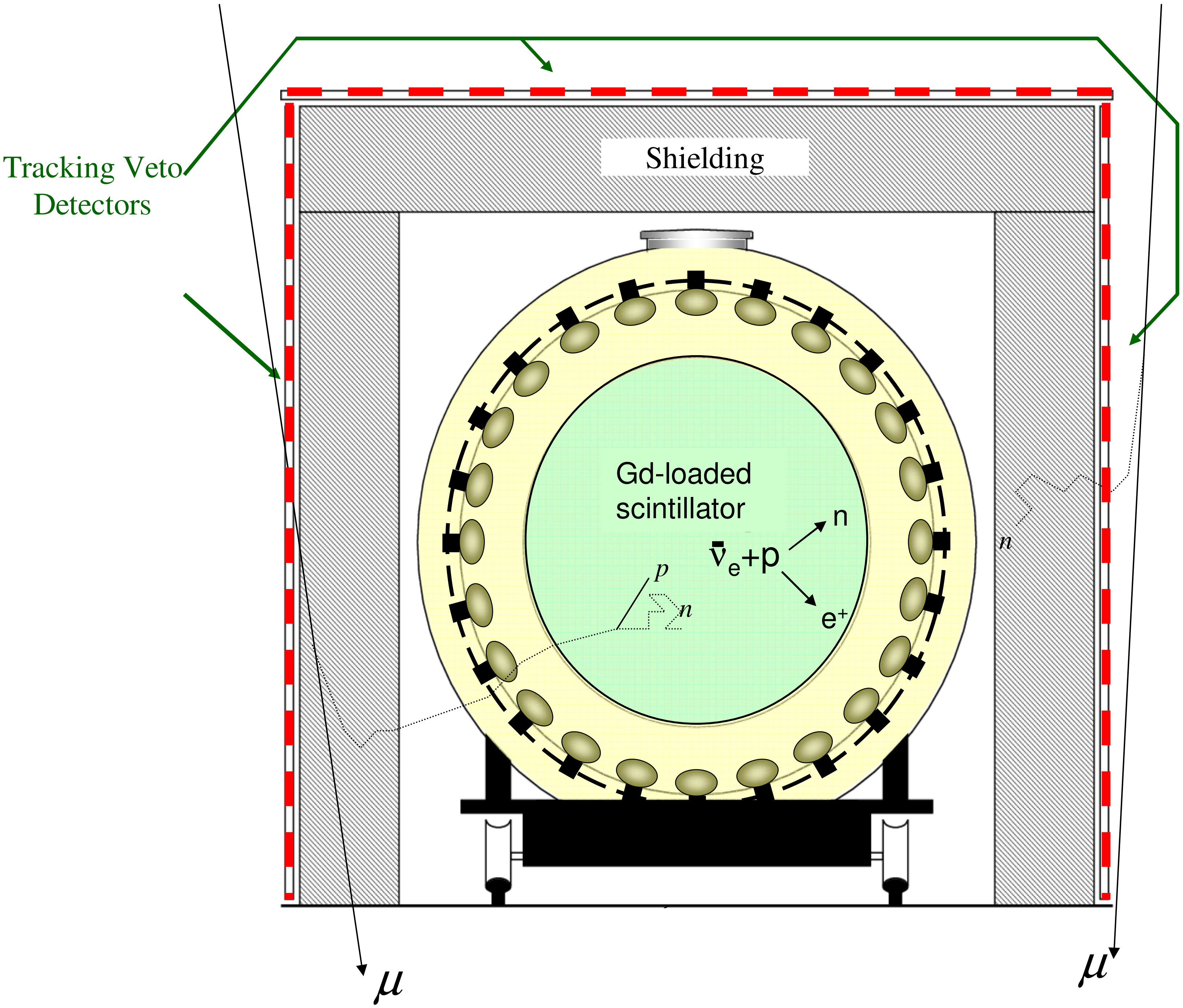
   This BG rate can be estimated by measuring the singles rates, or by switching the order of the coincidence events.

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.

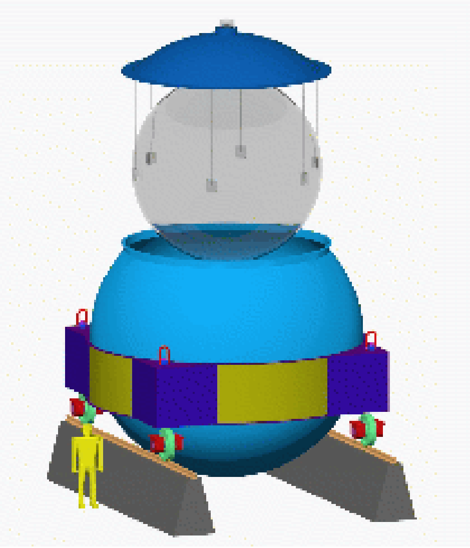
   Or they may be cause by muon produced isotopes like ^{9}Li and ^{8}He which sometimes decay to $\beta + n$.

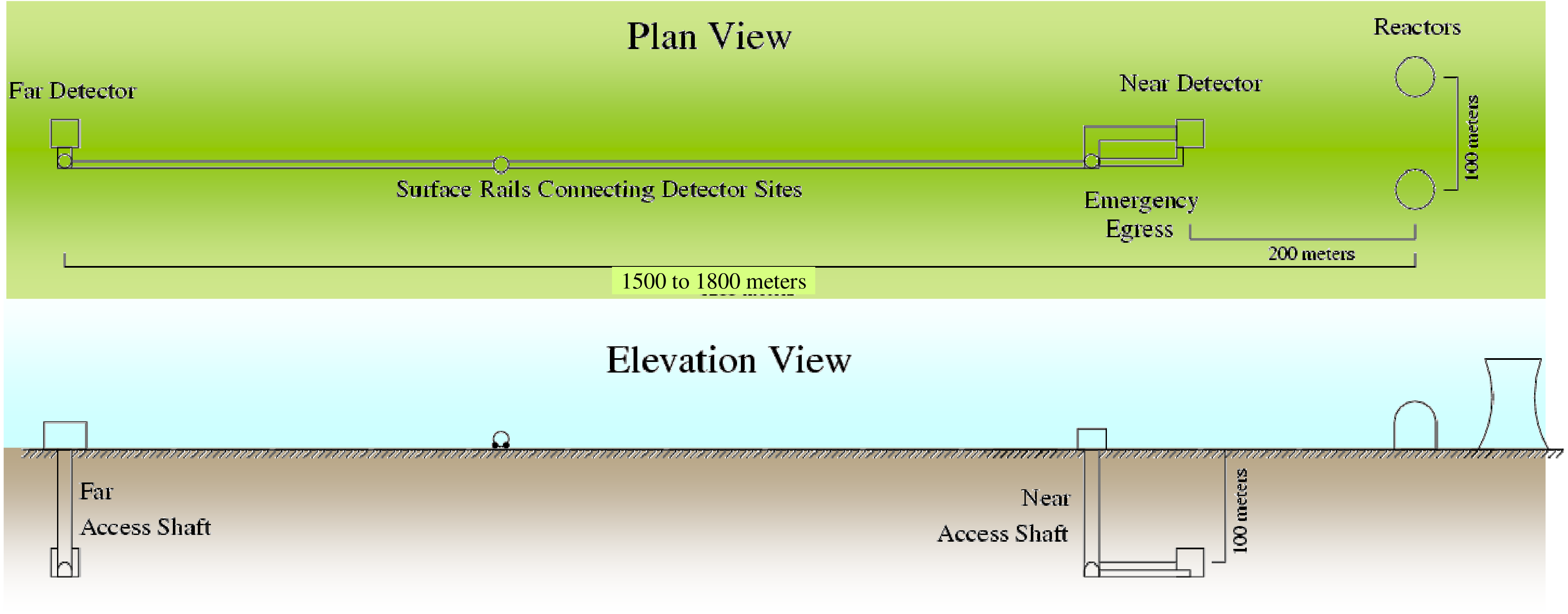
Estimating the correlated rate is much more difficult!

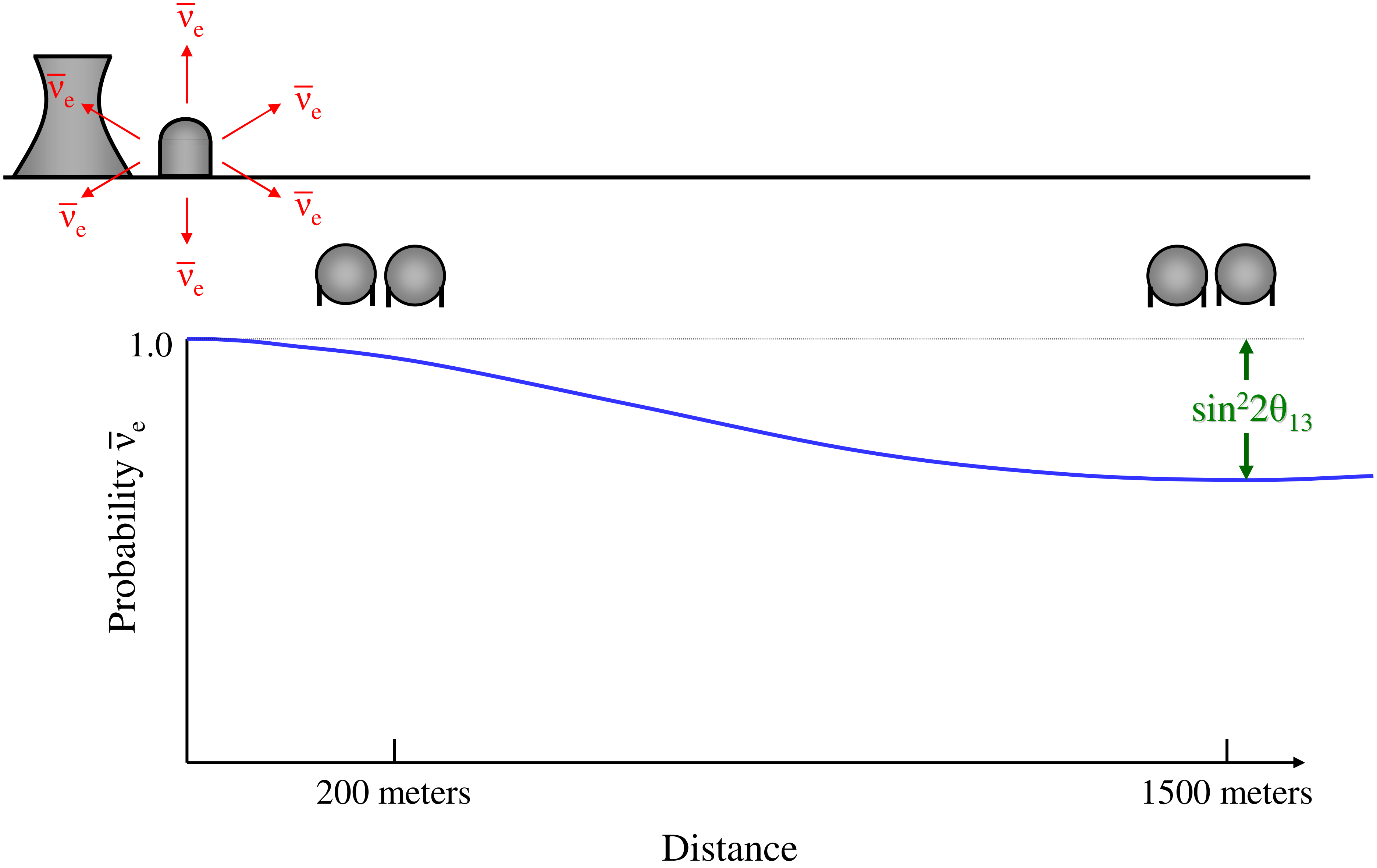

Tracking Veto
Detectors
Shielding
Gd-loaded
scintillator
n
$\bar{\nu}_e$+p
e+
p
n
n
μ
μ

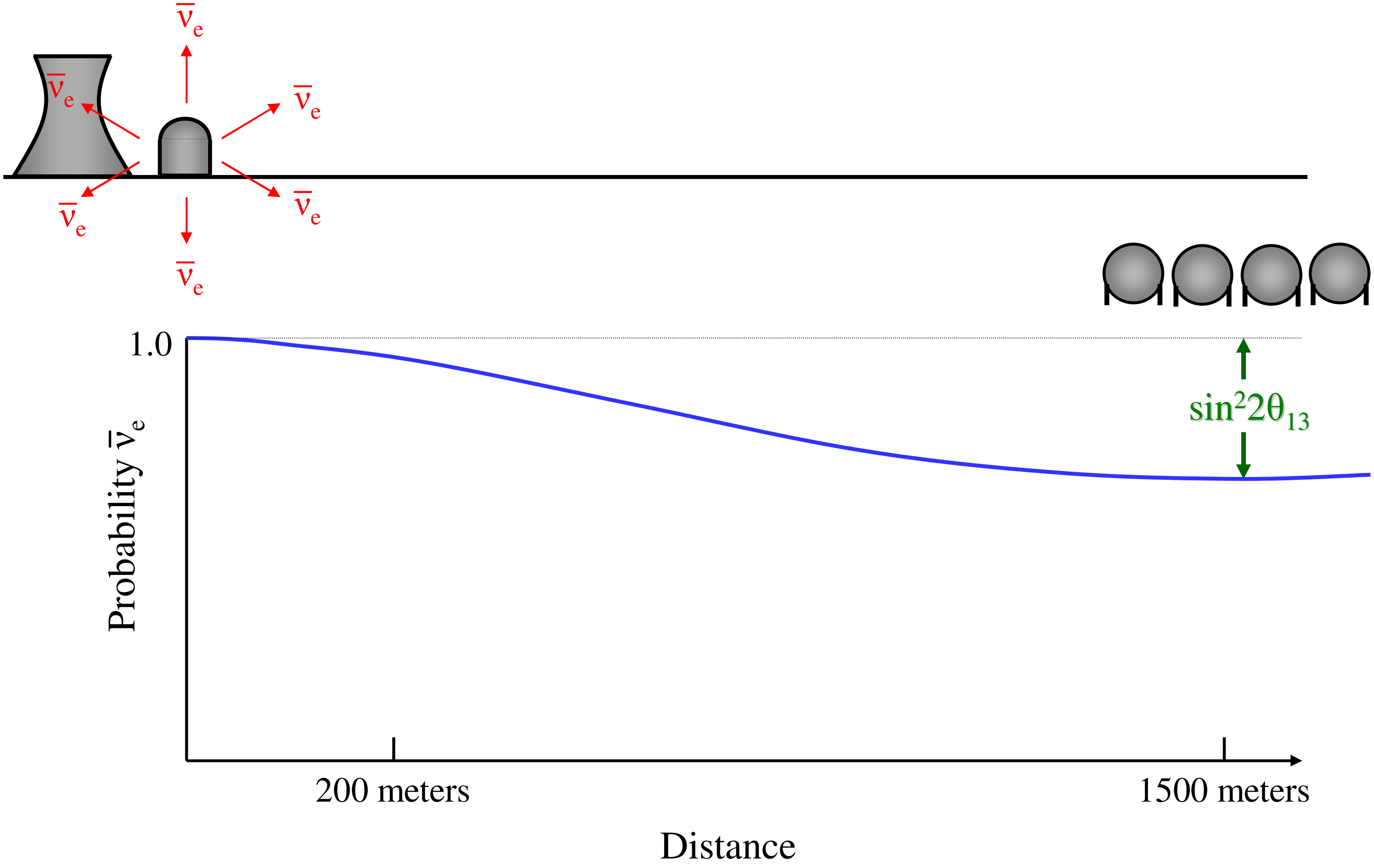
Movable Detectors to Verify Calibration Systems

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






$\bar{\nu}_e$
$\bar{\nu}_e$
$\bar{\nu}_e$
$\bar{\nu}_e$
$\bar{\nu}_e$
$\bar{\nu}_e$
1.0
Probability $\bar{\nu}_e$
$\sin^2 2\theta_{13}$
200 meters
1500 meters
Distance

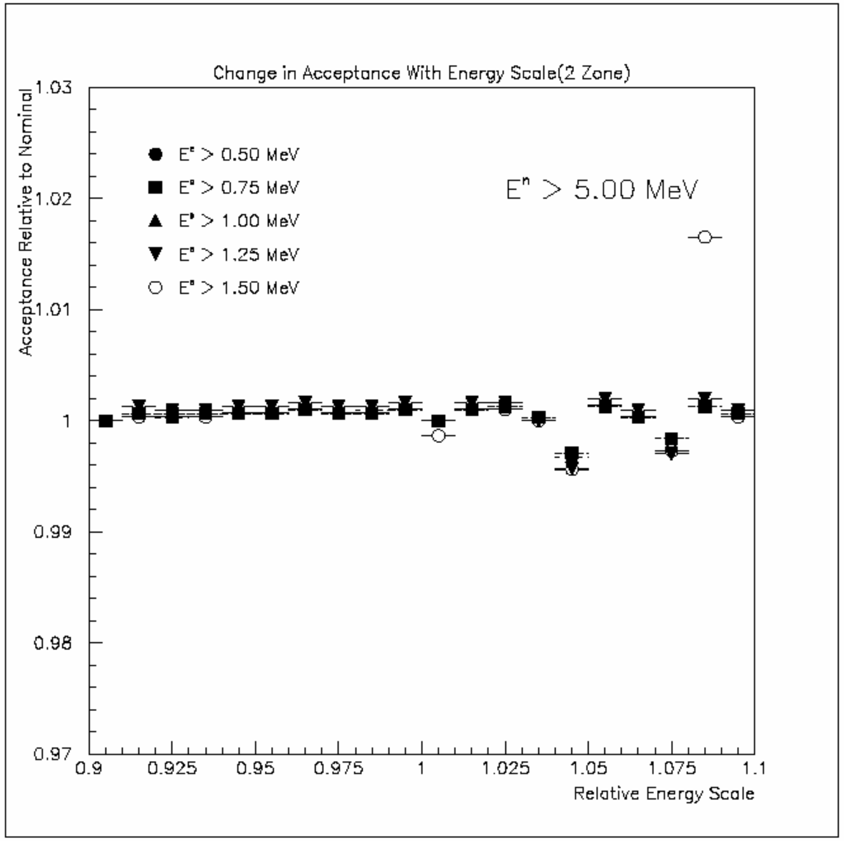

$\bar{\nu}_e$
$\bar{\nu}_e$
$\bar{\nu}_e$
$\bar{\nu}_e$
$\bar{\nu}_e$
$\bar{\nu}_e$
1.0
Probability $\bar{\nu}_e$
$\sin^2 2\theta_{13}$
200 meters
1500 meters
Distance

< 1% ?!!

A Few Tricks:

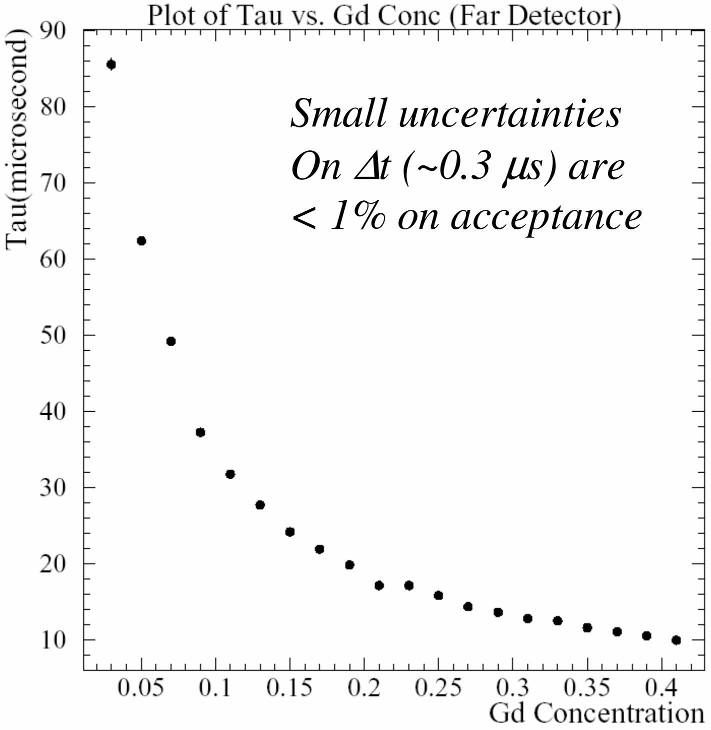
1) Fiducial volume based on neutron signal is independent of neutrino energy.

2) Absolute energy scale is not so important in a relative measurement. Neutron peak continuously "self-calibrates" **relative** energy scale. Event selection/acceptance based on this is **very** stable:



3) Positron always gives annihilation signal (zero threshold possible)

4) Δt distribution for neutron signal relative to positron signal “self-calibrates” neutron capture efficiency:



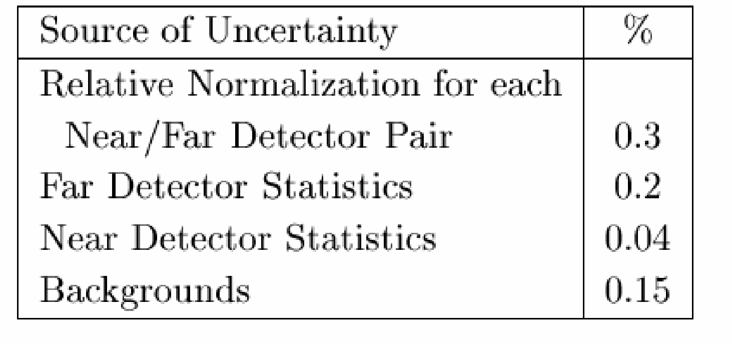
Small uncertainties
On Δt (~0.3 μs) are
< 1% on acceptance

5) ^{12}B events from muon spallation provide a tagged (τ~0.02s) electron calibration source with identical rates at near & far sites.

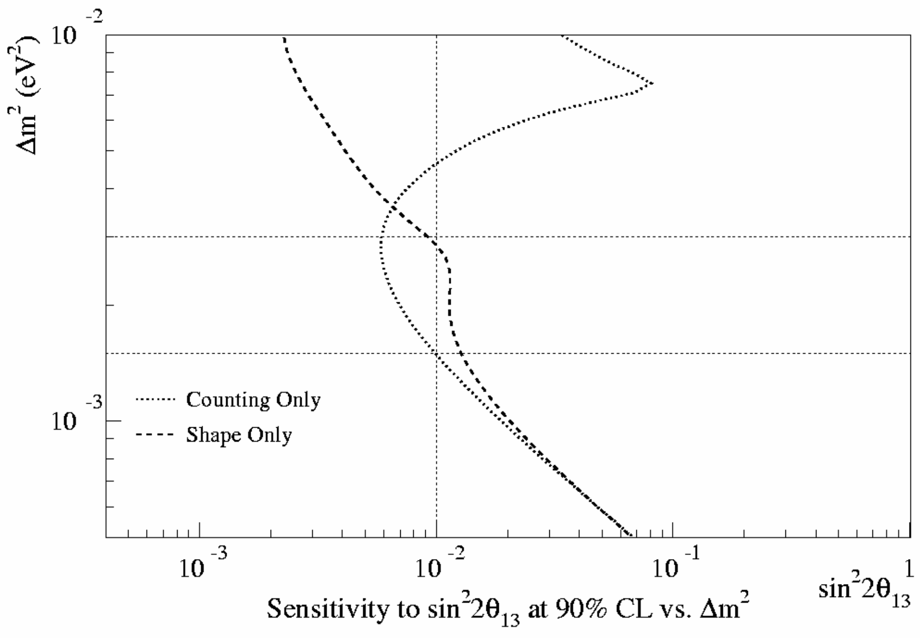
Sensitivity

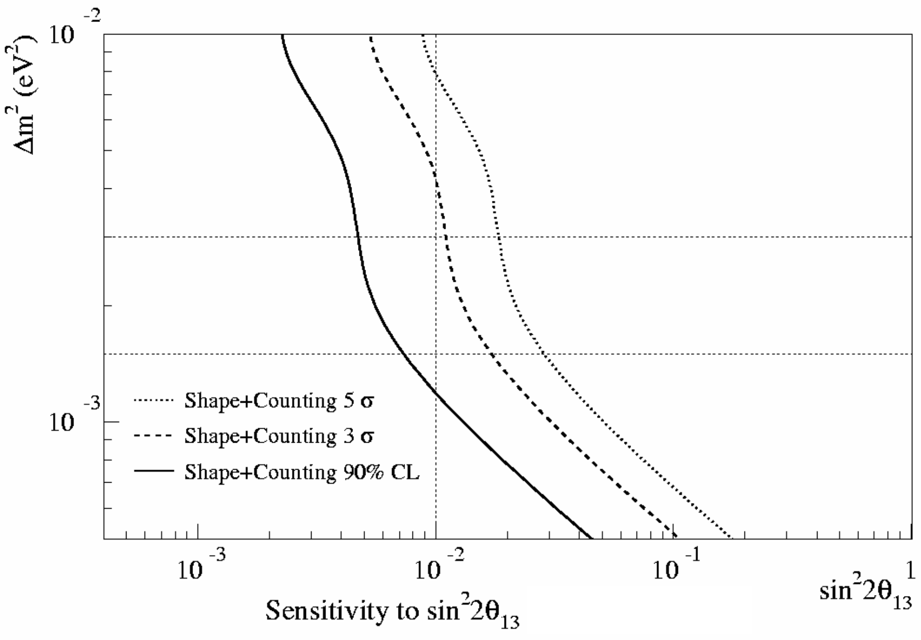
- For three years of Braidwood data and $\Delta m^2 > 2.5 \times 10^{-3}$ eV^2
  - 90% CL limit at $\sin^2 2\theta_{13} < 0.005$
  - 3 σ for $\sin^2 2\theta_{13} > 0.013$

Summary of Uncertainties for 3 yr Data



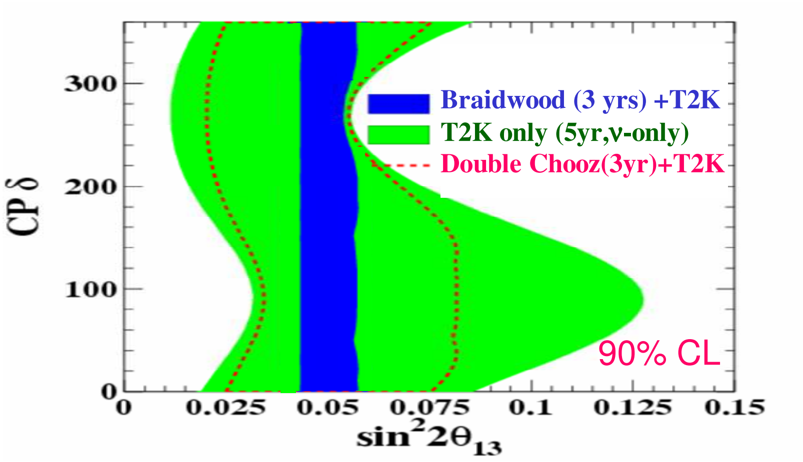
Source of Uncertainty	%
Relative Normalization for each Near/Far Detector Pair	0.3
Far Detector Statistics	0.2
Near Detector Statistics	0.04
Backgrounds	0.15





Motivation

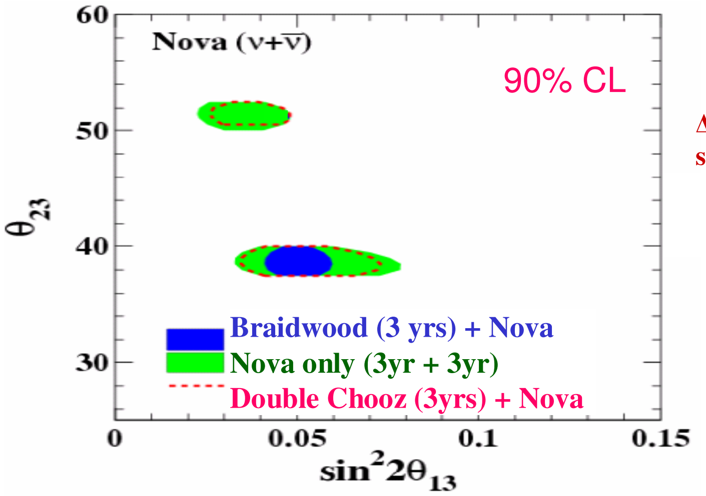
Reactor Exp. Best for **Determining θ_{13}**



$\Delta m^2 = 2.5\times10^{-3}$ eV^2
$\sin^2 2\theta_{13} = 0.05$

Reactor Can **Lift θ_{23} Degeneracy**

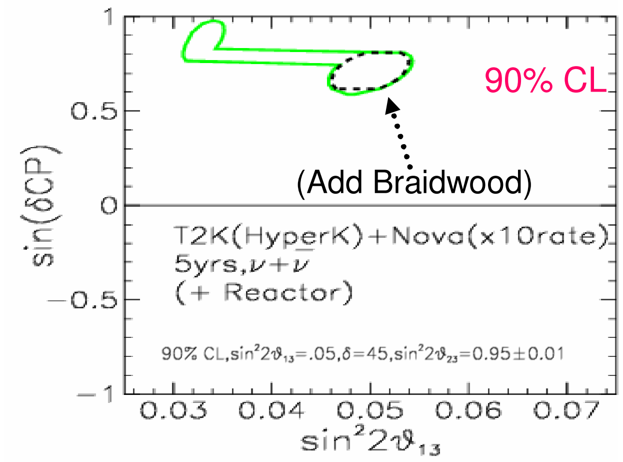
(Example: $\sin^2 2\,\theta_{23} = 0.95 \pm 0.01$)



$\Delta m^2 = 2.5\times10^{-3}$ eV^2
$\sin^2 2\theta_{13} = 0.05$

McConnel / Shaevitz hep-ex/0409028

Far future: **Precision Osc. Parameter Measurements**



Other Guidance

- In many models, **θ_{13} could be very small** ⇒ $\sin^2 2\theta_{13} < 0.01$ seems to be a dividing level for both theory and exp.
  - Such a low level might imply a new underlying symmetry or change in theory paradigm
  - Longer baseline experiments needed
- **Measuring the full set of mixing parameters** (θ_{12}, θ_{13}, θ_{23}, and δ) is needed for addressing quark-lepton unification models.

Braidwood Status and Schedule

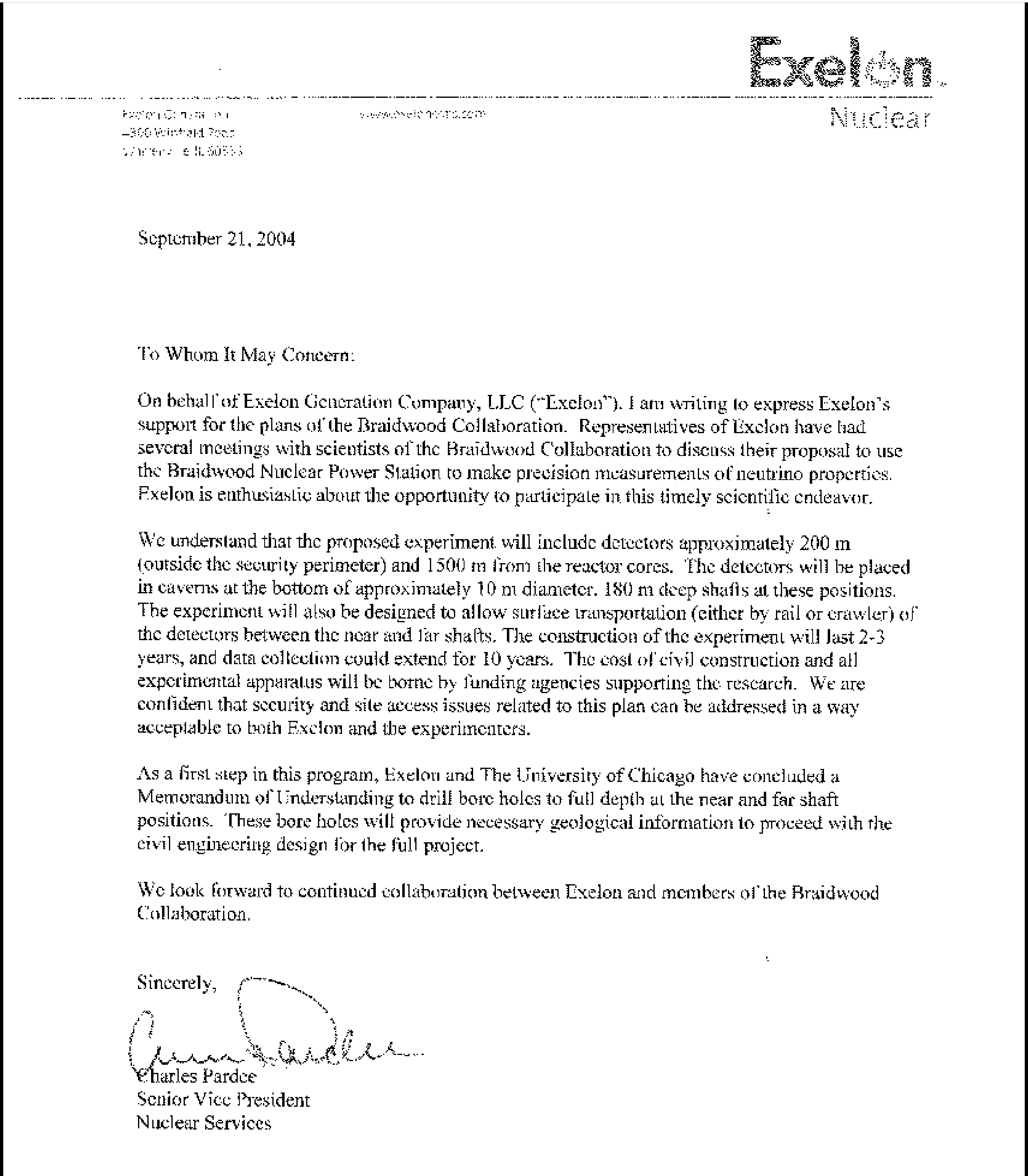
- Engineering / R&D Proposal ($1M) submitted in Nov. 2004
  - Need this funding to complete the engineering for a proposal
    - Develop a "Design and Build" package for civil construction
    - Complete detector design at the bid package level
    - Complete and set up management plan and project oversight
    - Complete the development of the Gd-Scint and provide test batches for prototypes

- Baseline Cost Estimate:
  - Civil Costs: $34M + $8.5M (Cont.)
  - 4 Detectors and Veto Systems:
    $18M + $5M (Cont.)

- Schedule:
  - 2004: R&D proposal submission.
  - 2004: Bore hole project completed on Braidwood site.
  - 2005: First NuSAG review
  - 2006: Full proposal submission
  - 2007: Project approval; start construction
  - 2010: Start data collection

UK Status

Science Committee has encouraged us to seek seedcorn funding from PPAP for R&D work to develop the proposal. We intend to submit a full proposal in concert with the US in 2007, with the main construction expendature scheduled for the next Spending Review period, starting in 2008.



Exelon.
Nuclear

Exelon Generation
4300 Winfield Road
Warrenville IL 60555

www.exeloncorp.com

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

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