

# Physics Reach of Reactor Neutrino Oscillations Experiments

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Director's Review of Initiatives in Neutrino Physics

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# Outline

1. Reactor Neutrino Primer
2. Physics of the  $\theta_{13}$  Sector at Reactors
3. Experimental Method: How to measure a small disappearance
4. Possible Experiment Sites
5. Sensitivity and the Big Picture
6. Experiment Timeline
7. Conclusions

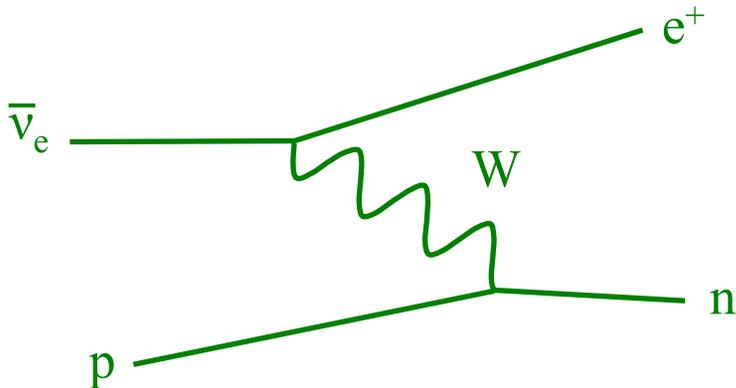
# Doing Physics With Reactors Neutrinos

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



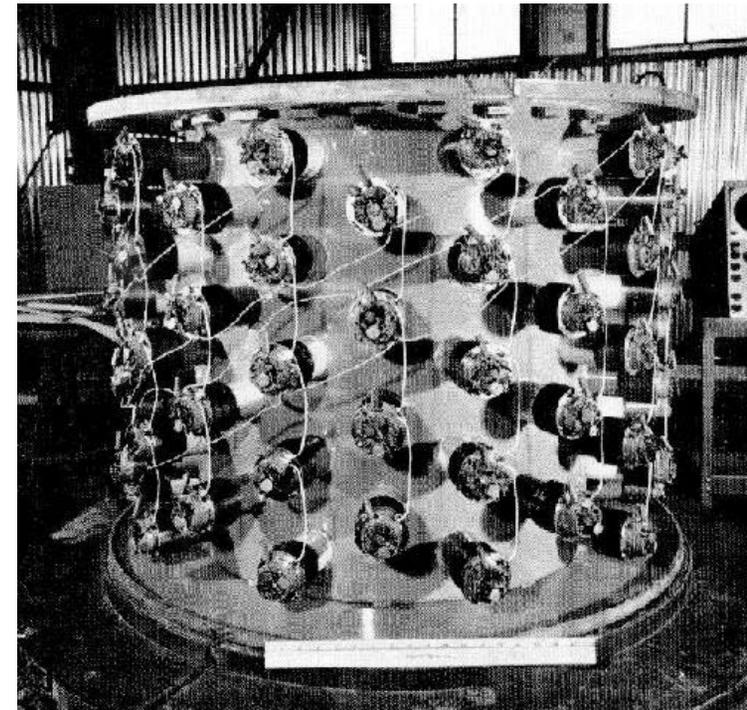
Reines and Cowan at the Savannah River Reactor

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



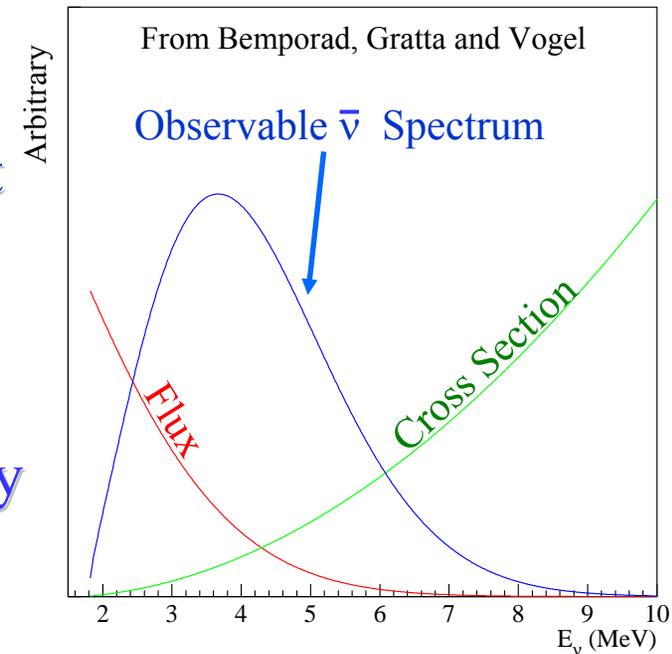
Later the neutron captures giving a coincidence signal. Reines and Cowan used cadmium to capture the neutrons.

The first successful neutrino detector



# Nuclear Reactors as a Neutrino Source

- Nuclear reactors are a very intense sources of  $\bar{\nu}_e$  deriving from the  $\beta$ -decay of the neutron-rich fission fragments.
- A typical commercial reactor, with 3 GW thermal power, produces  $6 \times 10^{20} \bar{\nu}_e/s$
- The observable  $\bar{\nu}_e$  spectrum is the product of the **flux** and the **cross section**.
- The spectrum peaks around  $\sim 3.6$  MeV.
- Visible “positron” energy implies  $\nu$  energy
$$E_\nu = E_e + 0.8 \text{ MeV} \quad (=m_n - m_p + m_e - 1.022)$$
- Minimum energy for the primary signal is 1.022 MeV from  $e^+e^-$  annihilation at process threshold.
- Two part coincidence signal is crucial for background reduction.



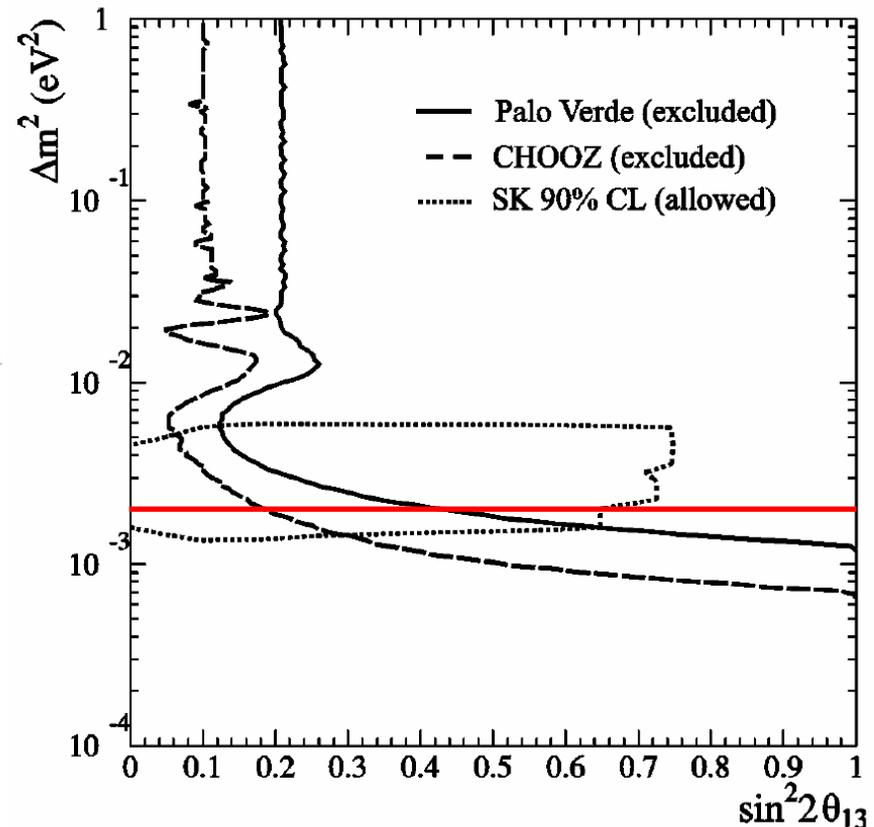
# Physics of $\theta_{13}$ at Reactors

- 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  $\Delta m^2 = 2.0 \times 10^{-3}$ )
- Future experiments should try to improve on these limits by *at least* an order of magnitude.

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



# Physics of $\theta_{13}$ 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 $\theta_{23}$ Degeneracy Problem

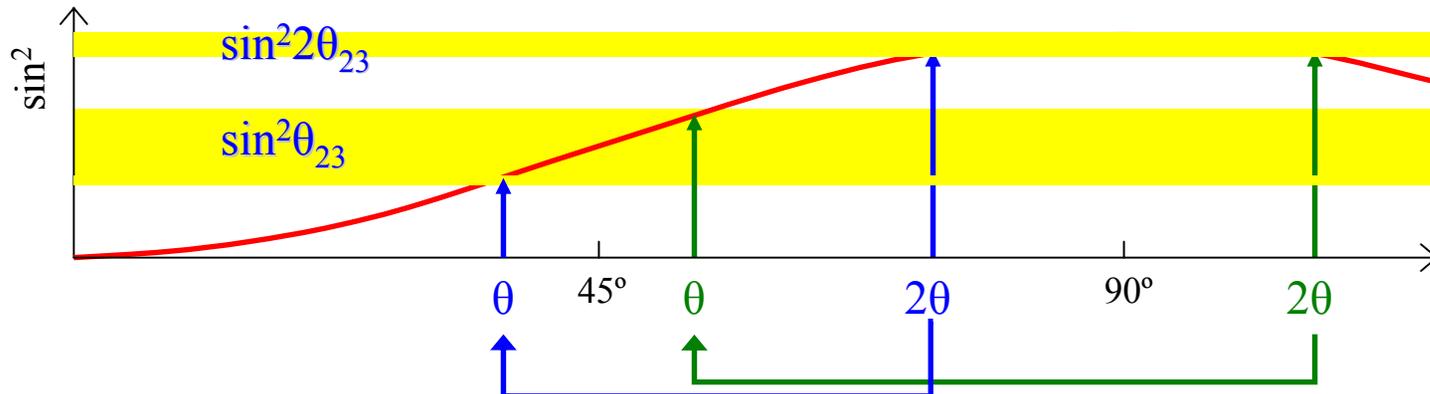
Atmospheric neutrino measurements are sensitive to  $\sin^2 2\theta_{23}$

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

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

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

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



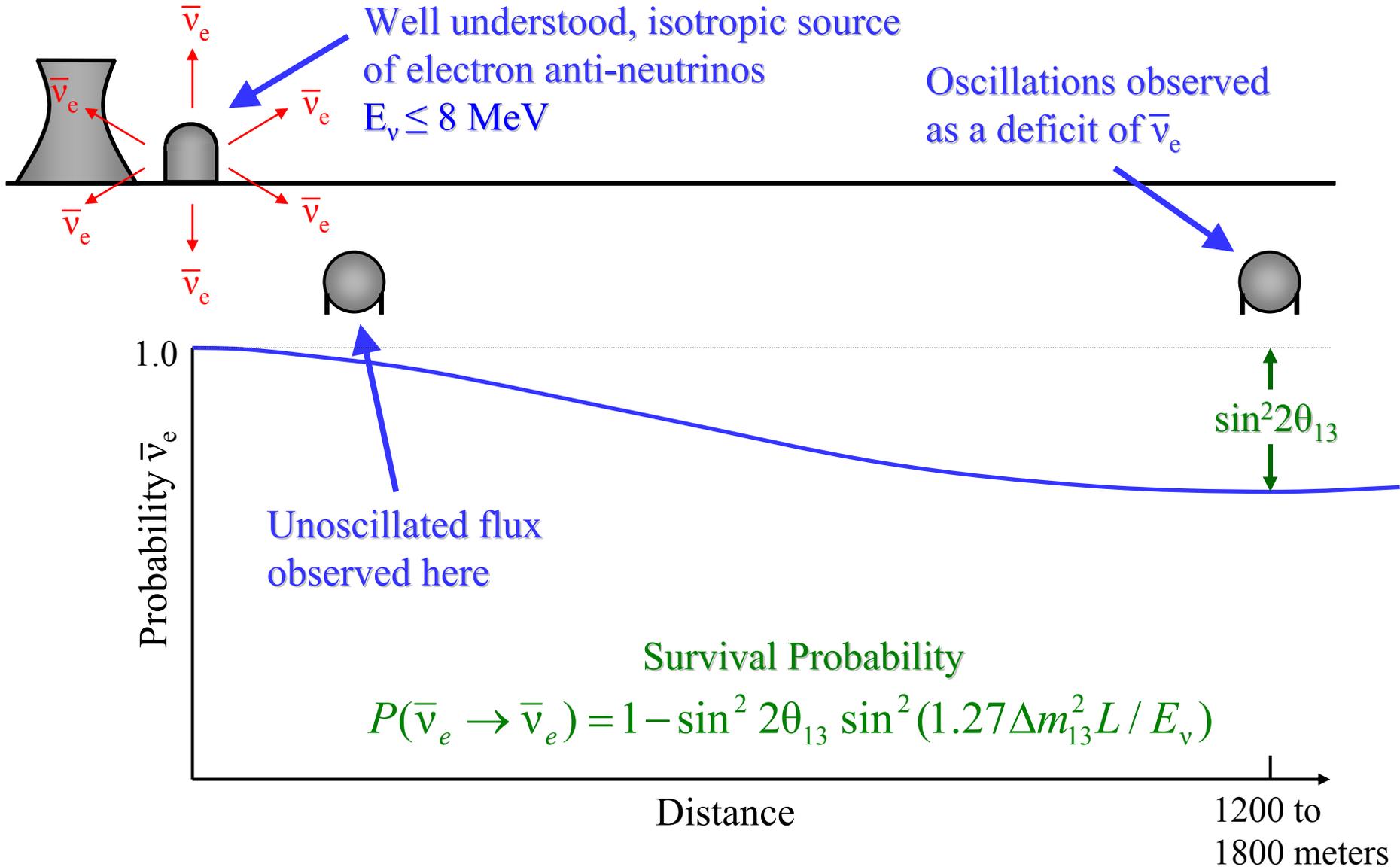
# Physics of $\theta_{13}$ at Reactors

- 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.

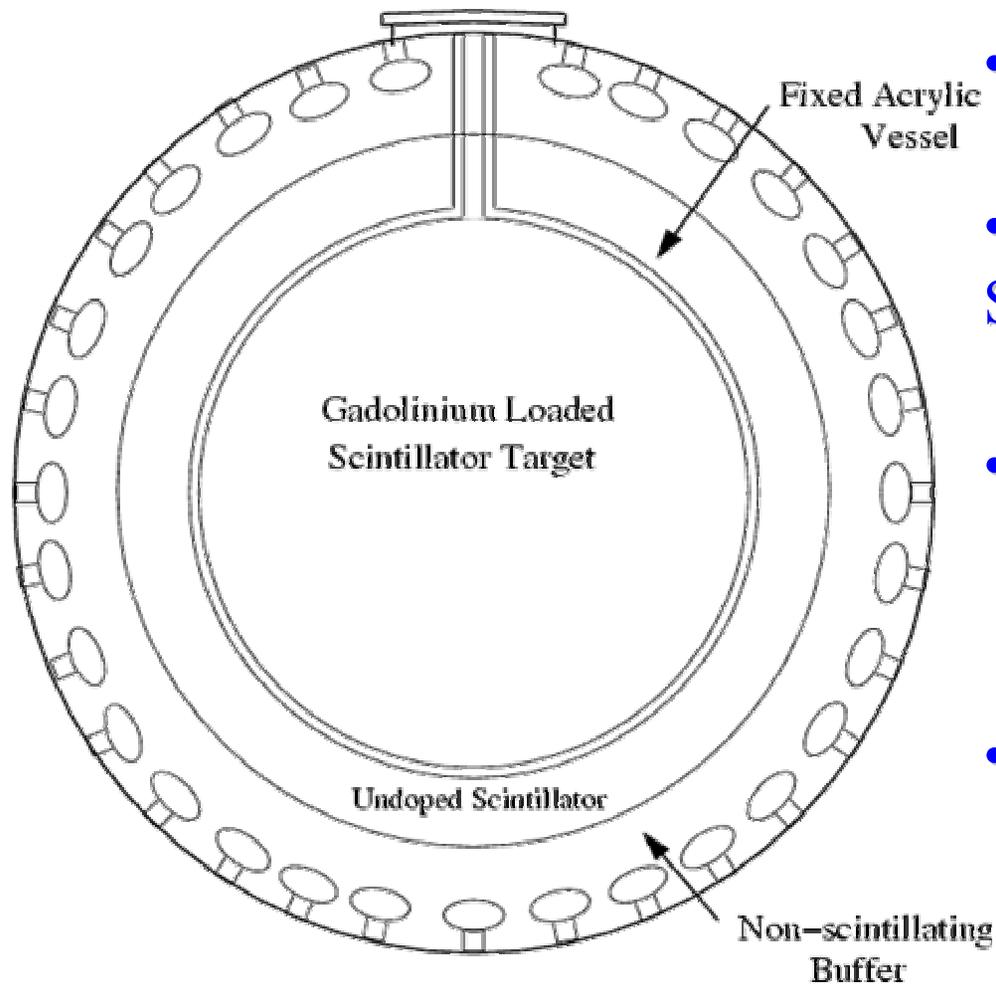
# $\text{Sin}^2 2\theta_{13}$ Reactor Experiment Basics



# 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.*

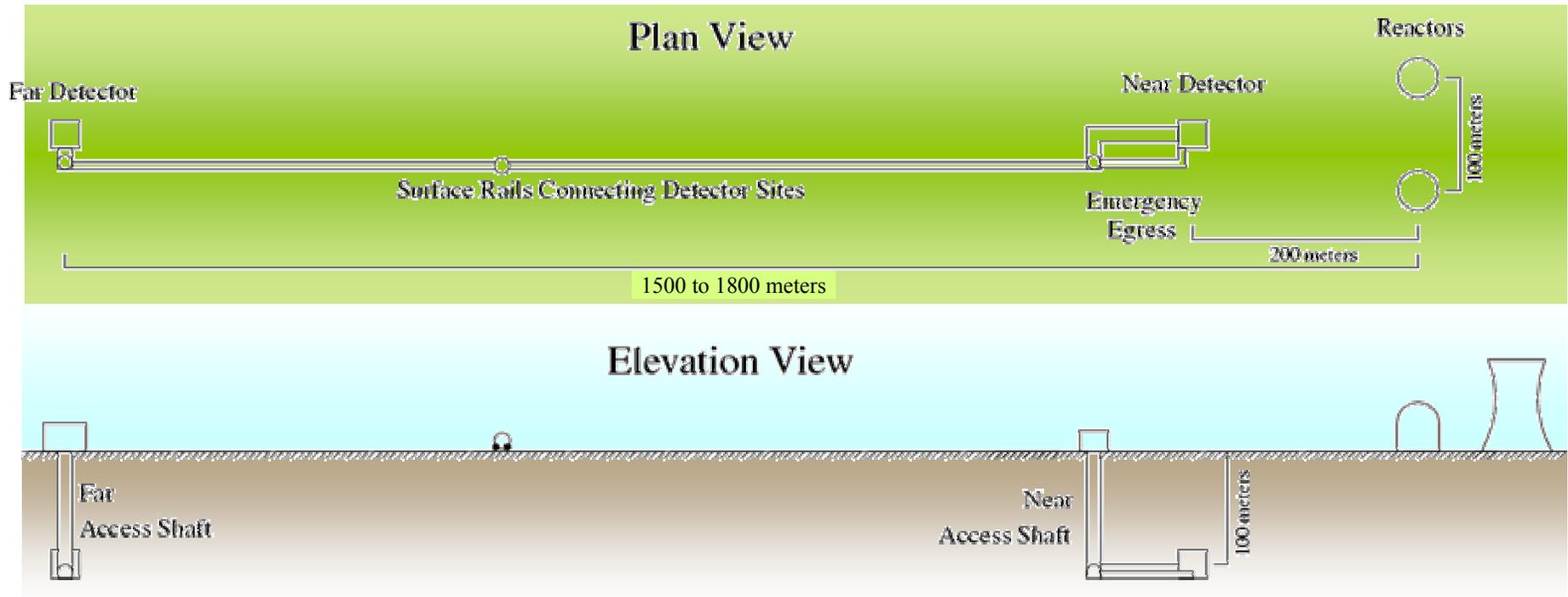
# How Do You Measure a Small Disappearance?

- 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.



# 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

# 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 fast neutrons (from cosmic  $\mu$ 's) that strike a proton in the scintillator. The recoiling proton mimics the  $e^+$  and the neutron captures.

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

**Estimating the correlated rate is much more difficult!**

# How Do You Measure a Small Disappearance?

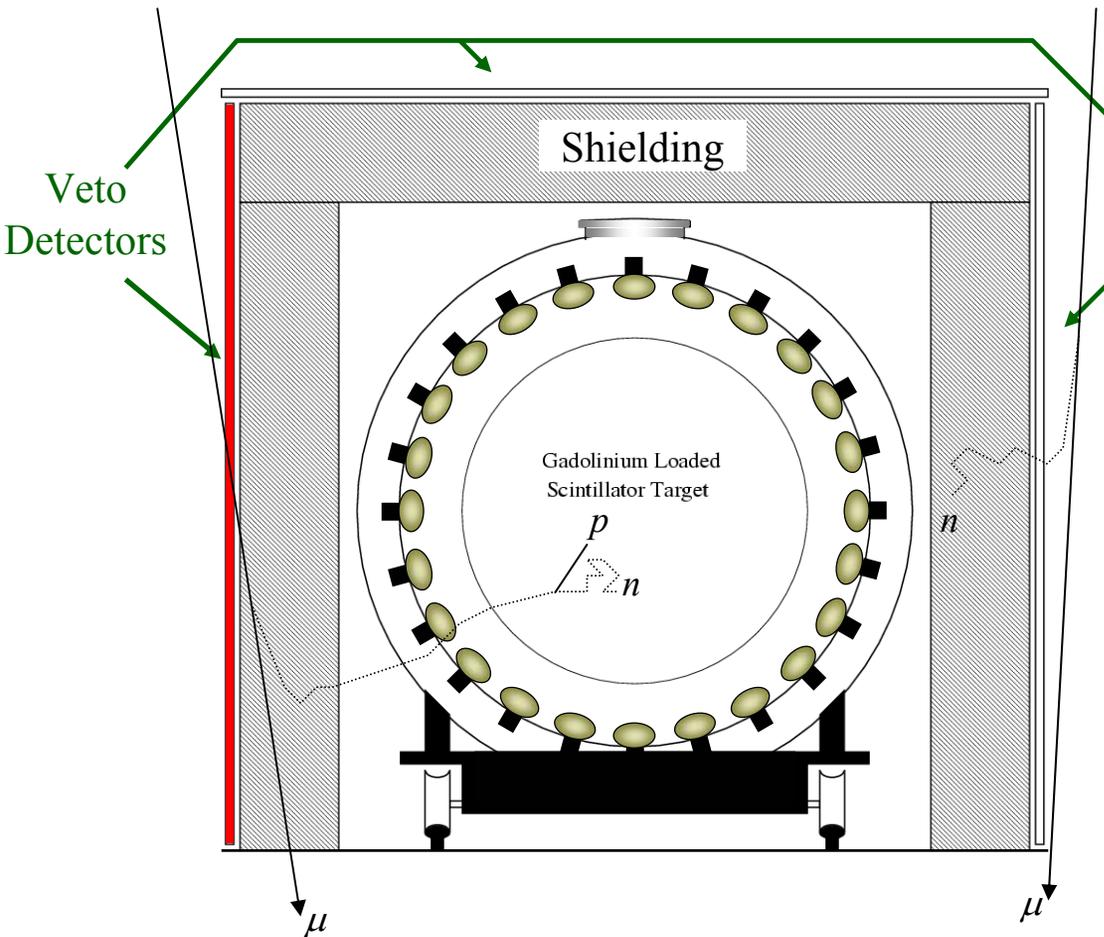
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- Design detectors to eliminate the need for analysis cuts that may introduce systematic error.
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# Veto Background Events

Fast neutrons

${}^9\text{Li}$  and  ${}^8\text{He}$

Veto  $\mu$ 's and shield neutrons

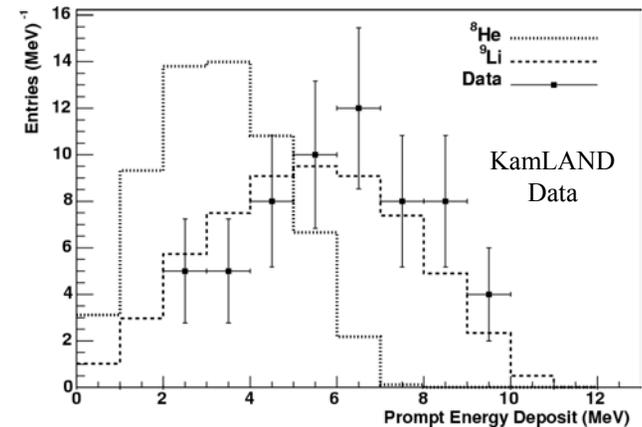


$E \leq 10.6 \text{ MeV}$

$\tau_{1/2} = 0.18 \text{ to } 0.12 \text{ s}$

0.075 produced/ton/day (450 mwe)

50% to 16% correlated  $\beta+n$



A  $\frac{1}{2}$  second veto after every muon that deposits more than 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

# Proposed Sites Around the World

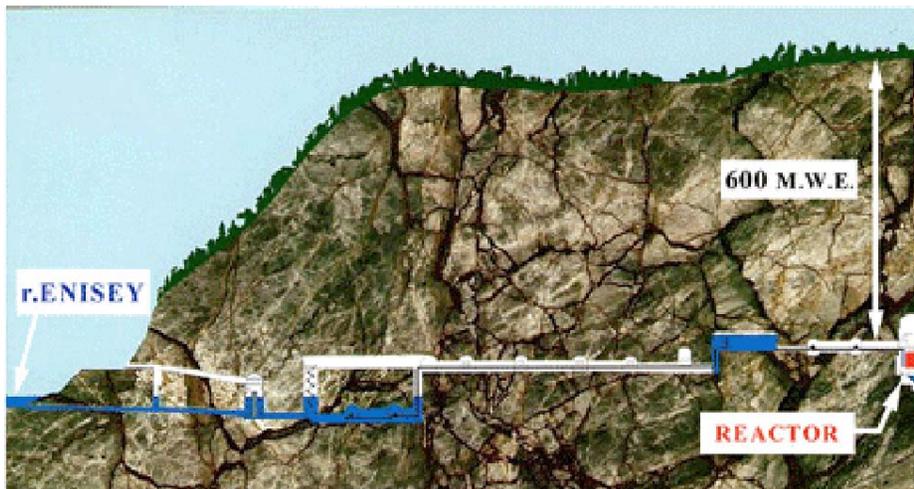
Site	Power (GW <sub>thermal</sub> )	Baseline Near/Far (m)	Shielding Near/Far (mwe)	Sensitivity 90% CL
Krasnoyarsk, Russia	1.6	115/1000	600/600	0.03
Kashiwazaki, Japan	24	300/1300	150/250	0.02
Double Chooz, France	8.4	150/1050	30/300	0.03
Diablo Canyon, CA	6.7	400/1700	50/700	0.01
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Many Sites have been investigated as potential hosts to a reactor neutrino experiment.

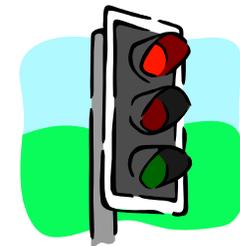
This is appropriate since getting the cooperation of the reactor company is the main challenge.

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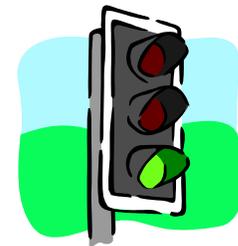


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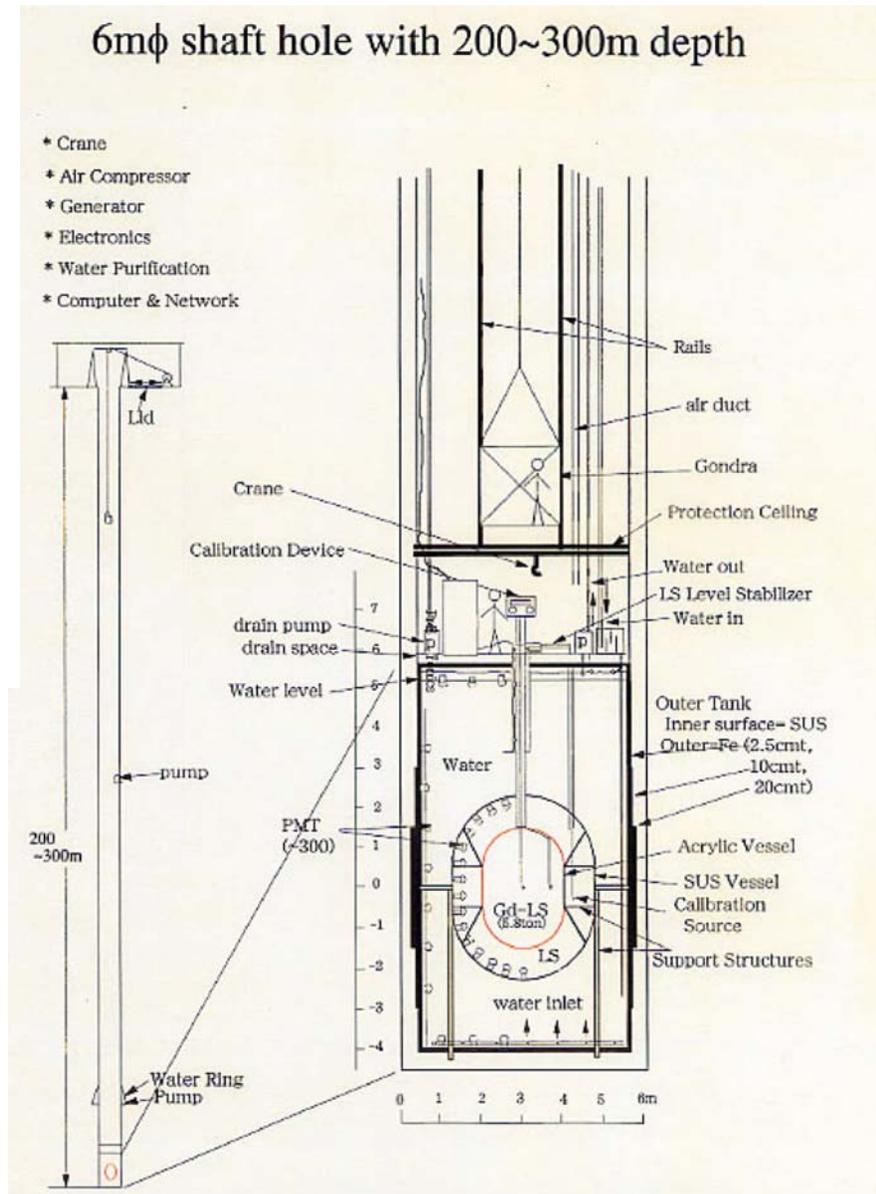
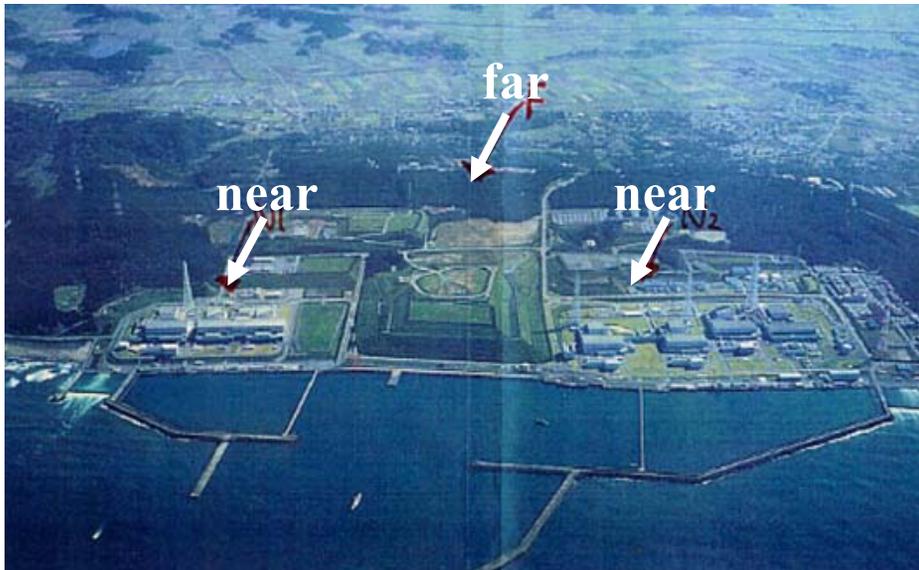


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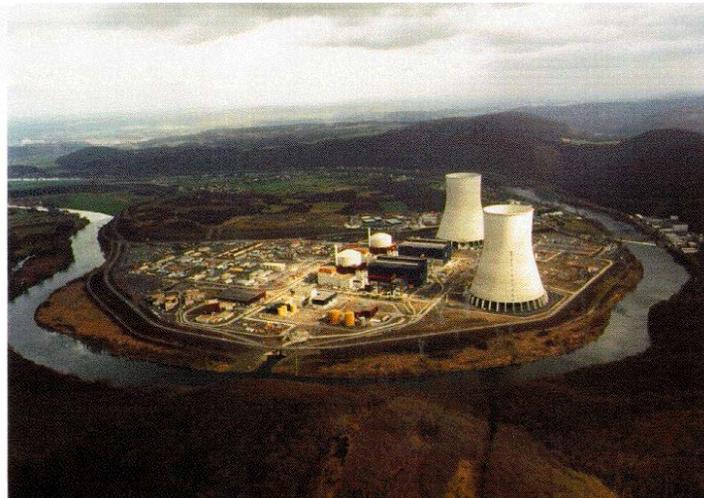
# Kashiwazaki, Japan ( Minakata, Sugiyama, Yasuda, Inoue, and Suekane hep-ph/0211111 )

- 7 Reactors, 24 GW<sub>th</sub>
- 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  $\sin^2 2\theta_{13} \leq 0.02$  in 2 years  
Fast! Reaches systematics limit quickly
- Currently working its way through the Japanese system

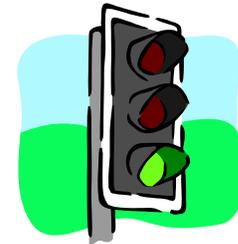


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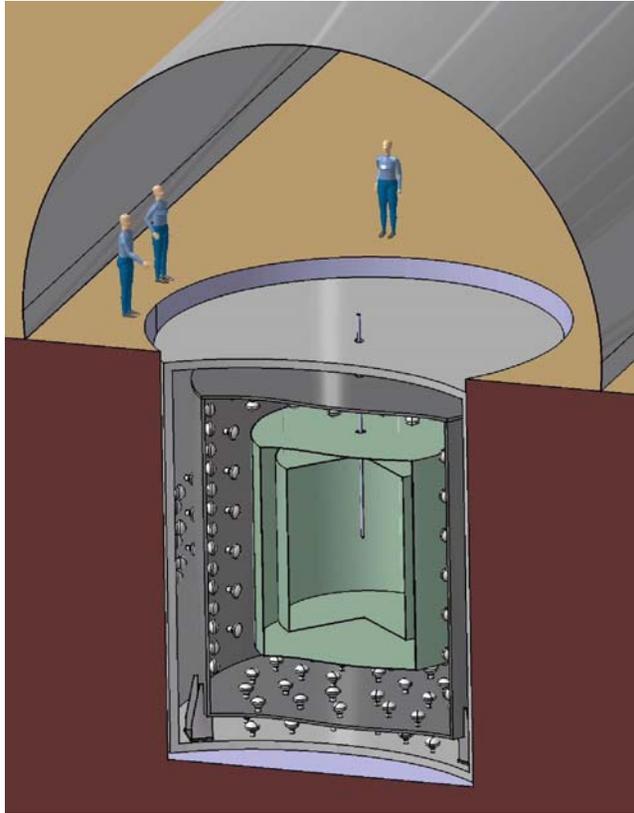


Status



# Double CHOOZ , France

- Use old far detector hall at  $\sim 1050$  meters
- Near detector at 125-250 meters ( $\sim 50$  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)



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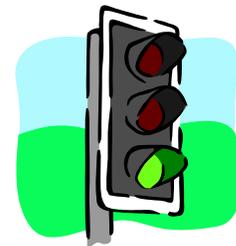


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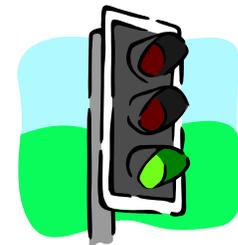


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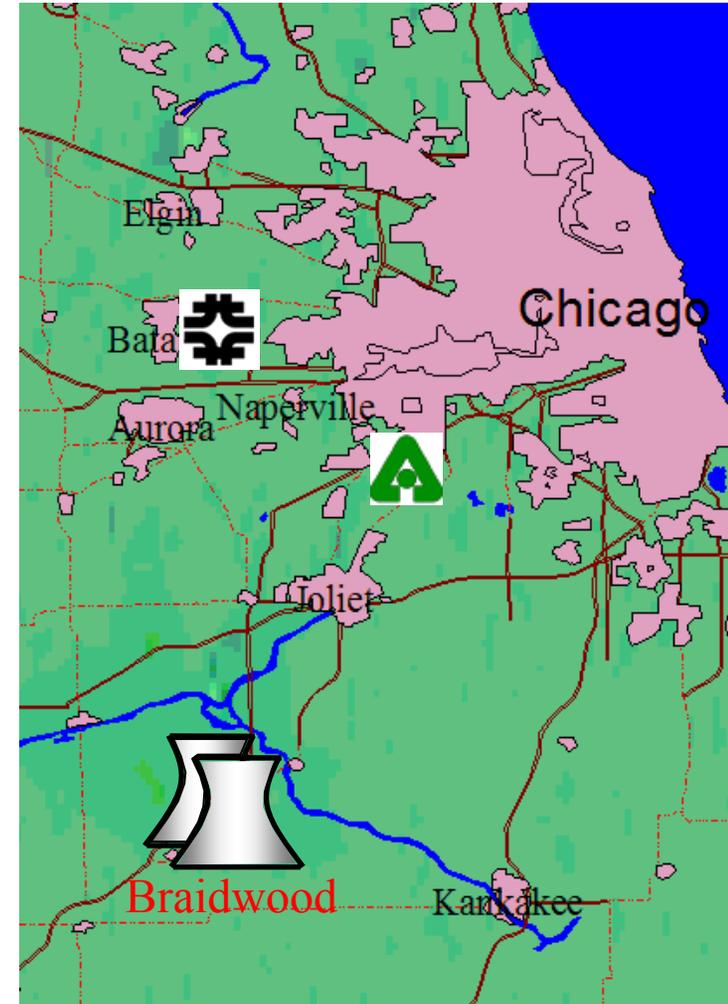


Status



# 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

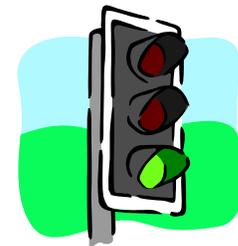


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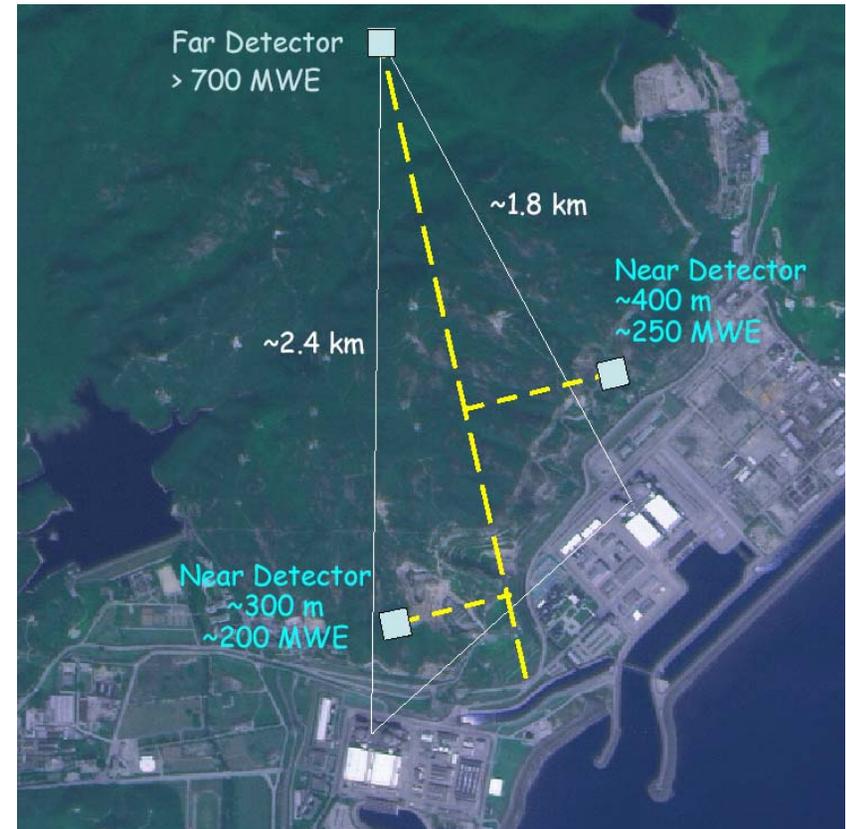


Status



# Daya Bay, China

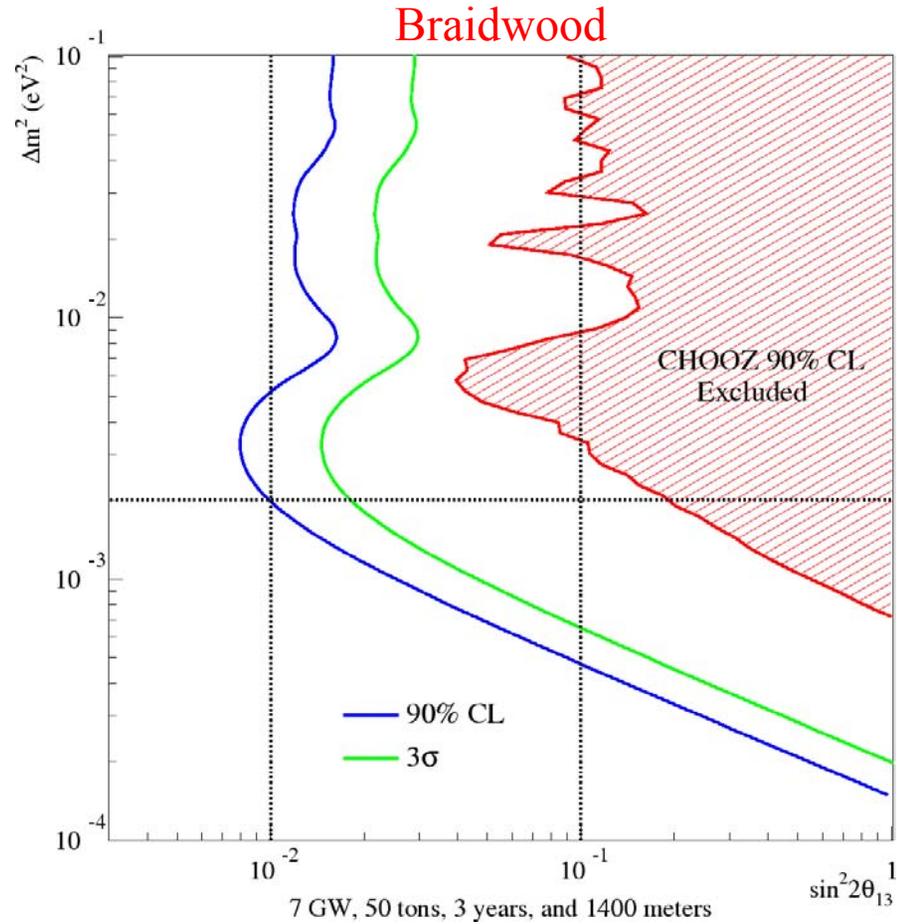
- 4 Reactors, 11.5 GW<sub>th</sub>
- Several ~8 ton detectors
- Near detectors at baseline of 300 and 400 meters, 200 to 250 mwe
- Far detectors at baselines of 1800 and 2400 meters, 1100 mwe
- Sensitivity of  $\sin^2 2\theta_{13} \leq 0.01$  in 3 years



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

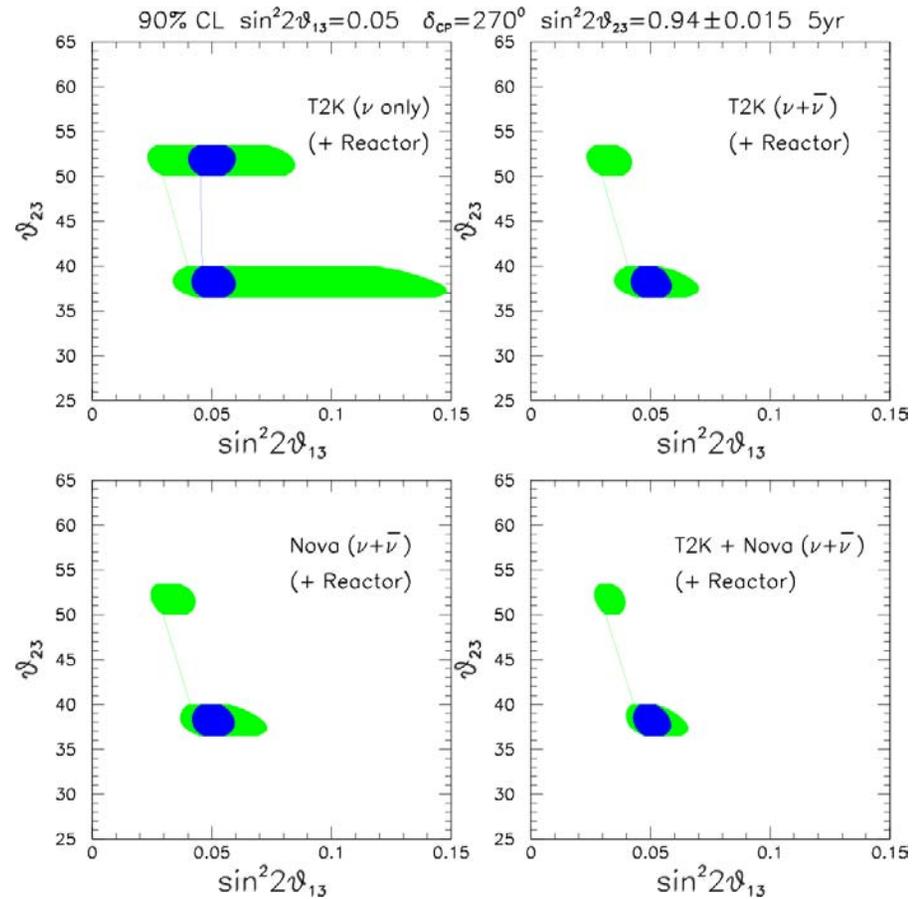
# Reactor Sensitivity

- Sensitivity to  $\sin^2 2\theta_{13} \leq 0.01$  at 90% CL is achievable.



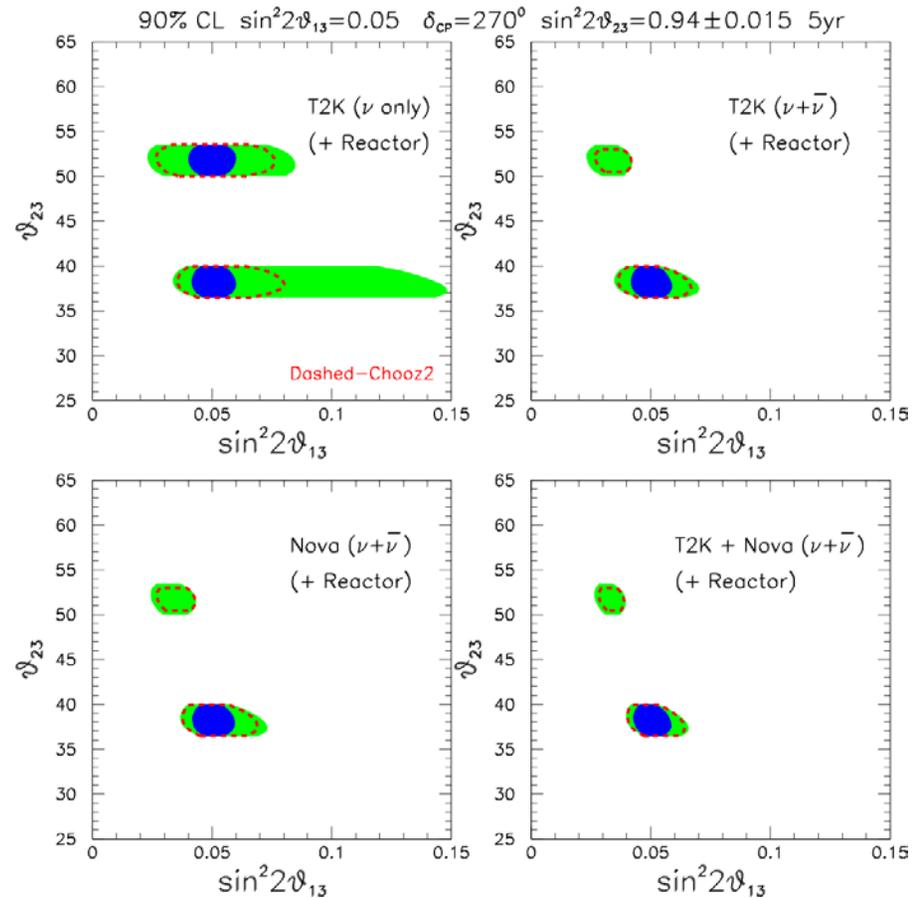
# Reactor Sensitivity

- Sensitivity to  $\sin^2 2\theta_{13} \leq 0.01$  at 90% CL is achievable.
- Combining with off-axis  $\nu$  and  $\bar{\nu}$  running, the  $\theta_{23}$  degeneracy is broken.



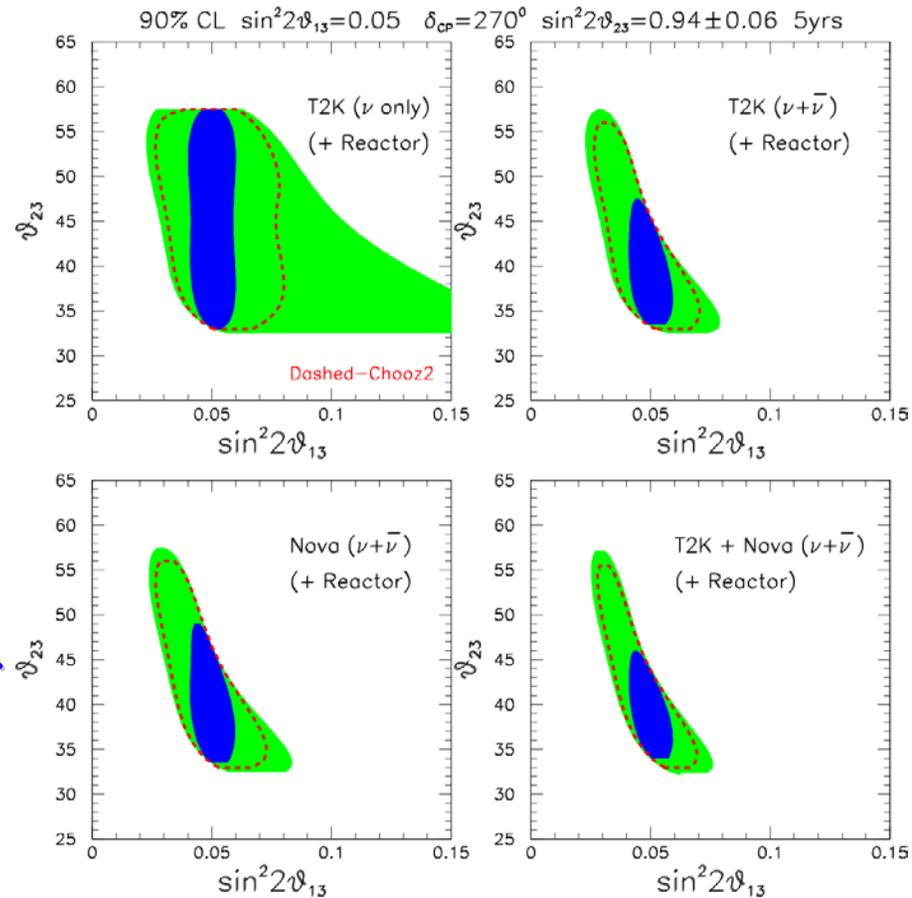
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- The Double Chooz sensitivity of 0.03 is not sufficient to break the degeneracy.



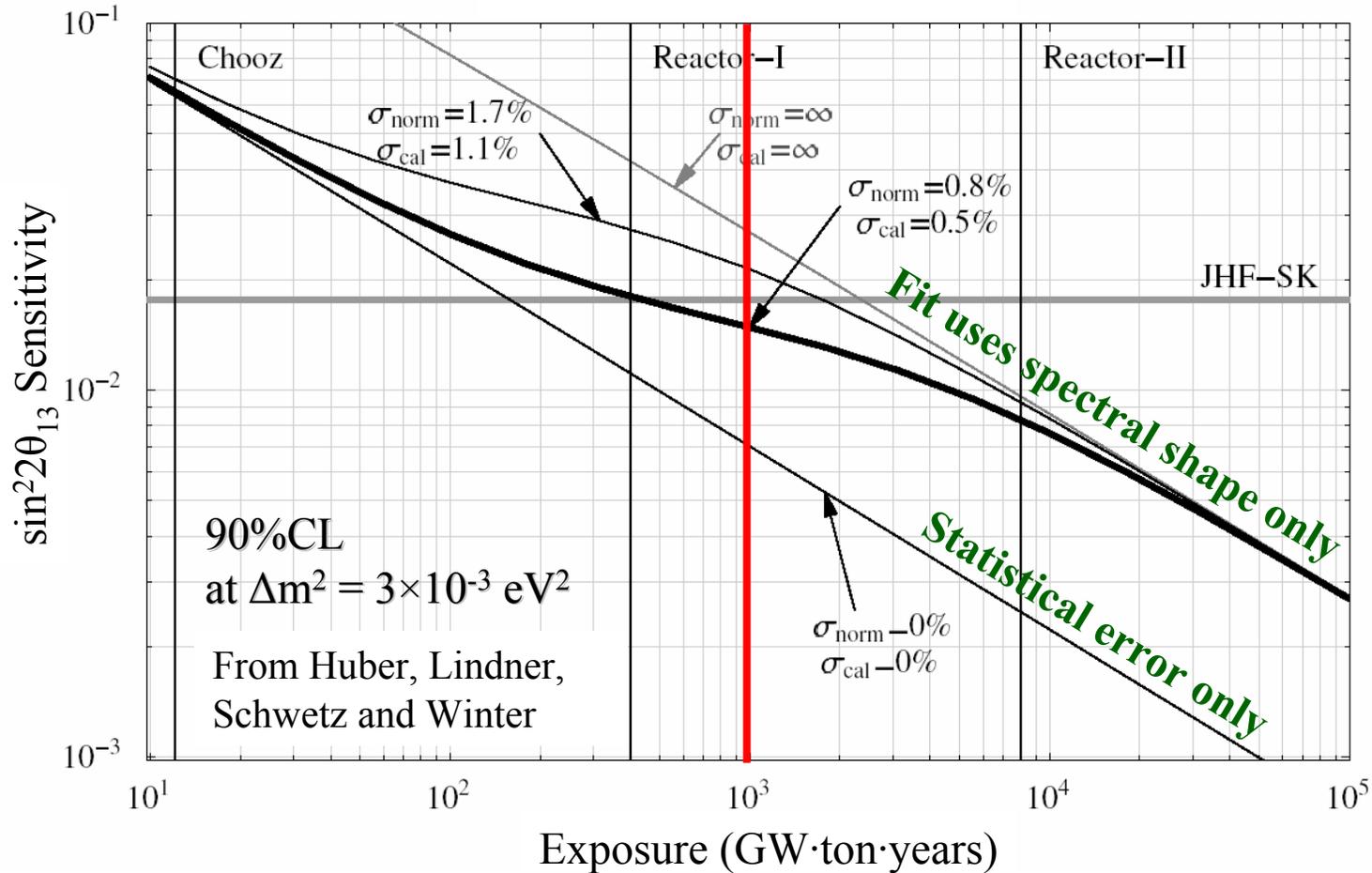
# Reactor Sensitivity

- Sensitivity to  $\sin^2 2\theta_{13} \leq 0.01$  at 90% CL is achievable.
- Combining with off-axis  $\nu$  and  $\bar{\nu}$  running, the  $\theta_{23}$  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  $\theta_{23}$  is not so small.



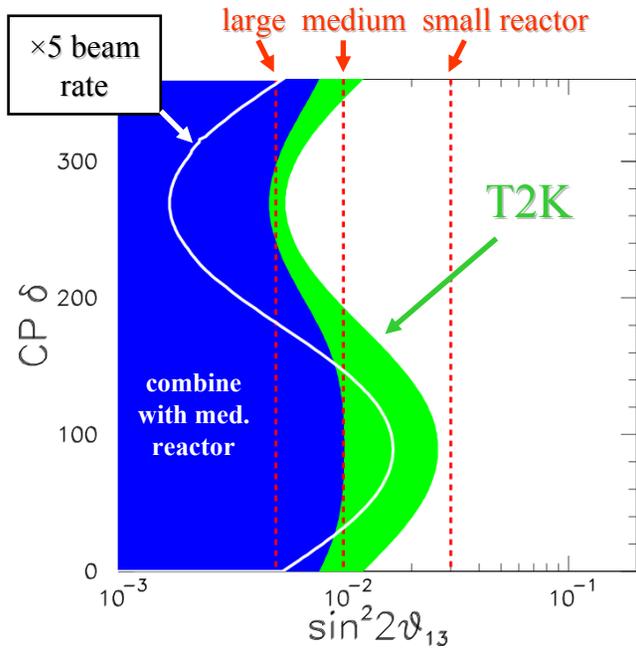
# Reactor Sensitivity

The sensitivity may be pushed lower with large detectors sensitive to a shape deformation.



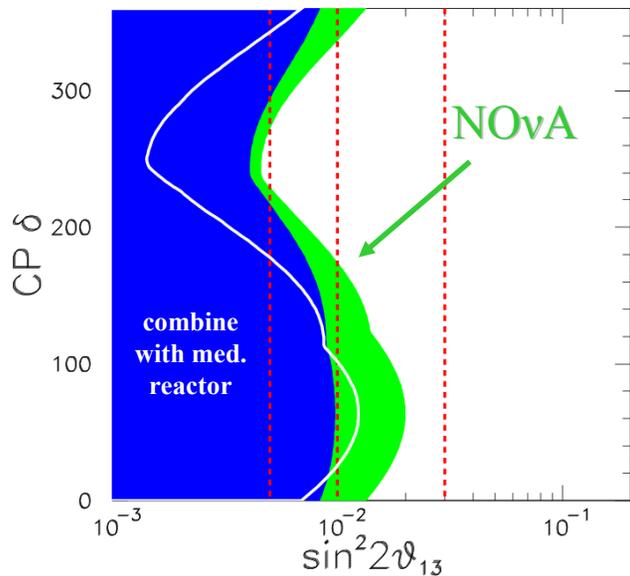
The location of the transition from rate to shape depends on the level of systematic error.

# 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 ( $\times 5$  beam rate).

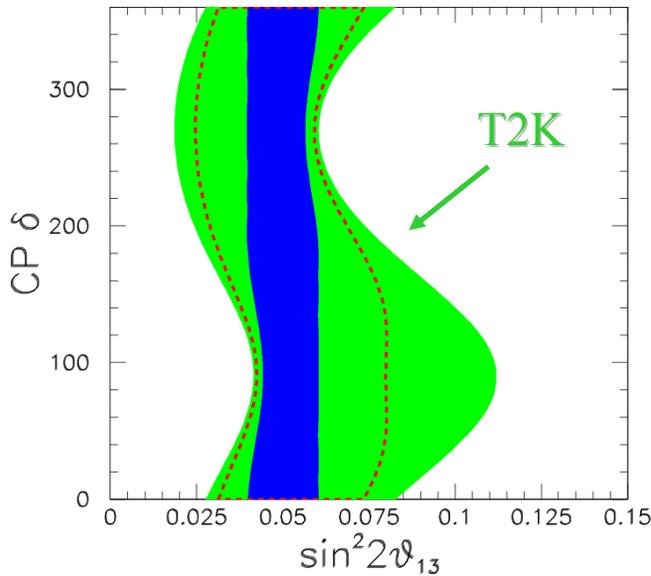


After a reactor limit, only a small window of opportunity exists for an observation of  $\nu_\mu$  to  $\nu_e$  at off-axis.

# Comparison of Reactor to Off-axis

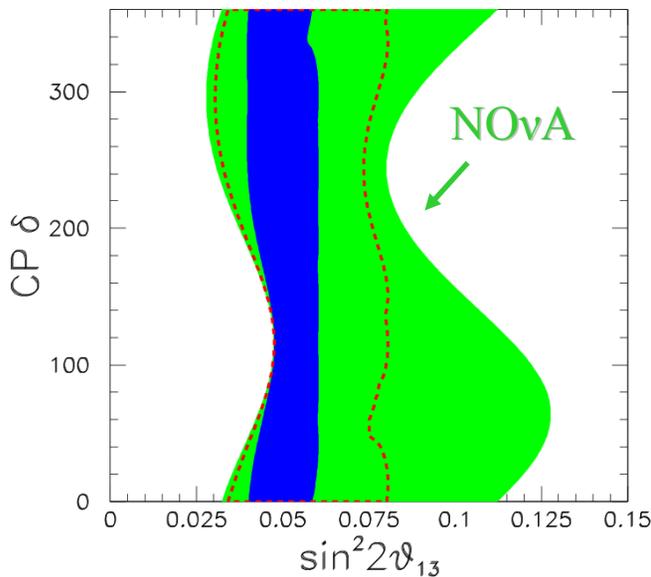
Chooz-like, small scale

Braidwood-like medium scale

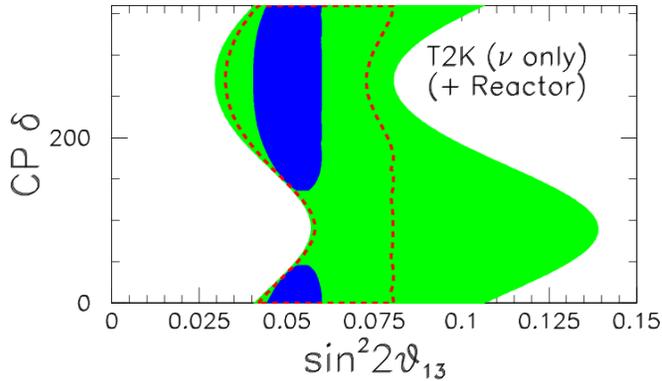


90% CL regions for  $\sin^2 2\theta_{13} = 0.05$ ,  
 $\delta_{CP}=0$  and  $\Delta m^2 = 2.5 \times 10^{-3} \text{ eV}^2$

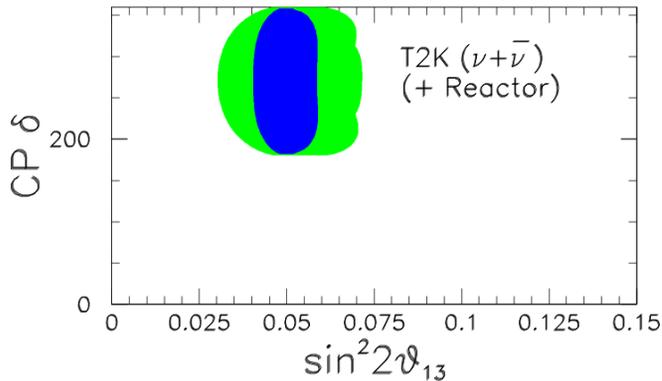
In the case of an observation, even the  
Double Chooz scale measurement makes  
a better determination of  $\sin^2 2\theta_{13}$  than  
off-axis.



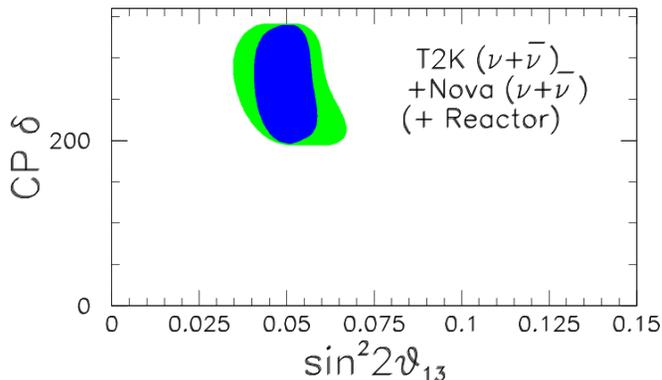
# Reactor Contribution to CP Violation



For  $\delta_{CP} = 270^\circ$  the reactor measurement eliminates some of the range in CP phase when combined with off-axis  $\nu$  only running.



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



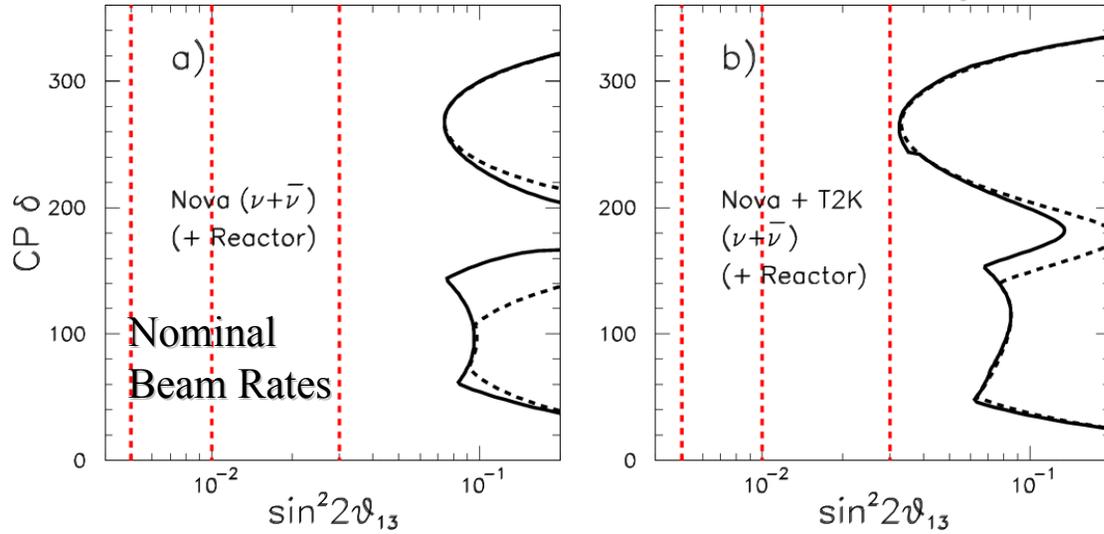
Combining all data sets, the best precision on  $\sin^2 2\theta_{13}$  comes from the reactor experiment.

# Determining Reach in CP Violation

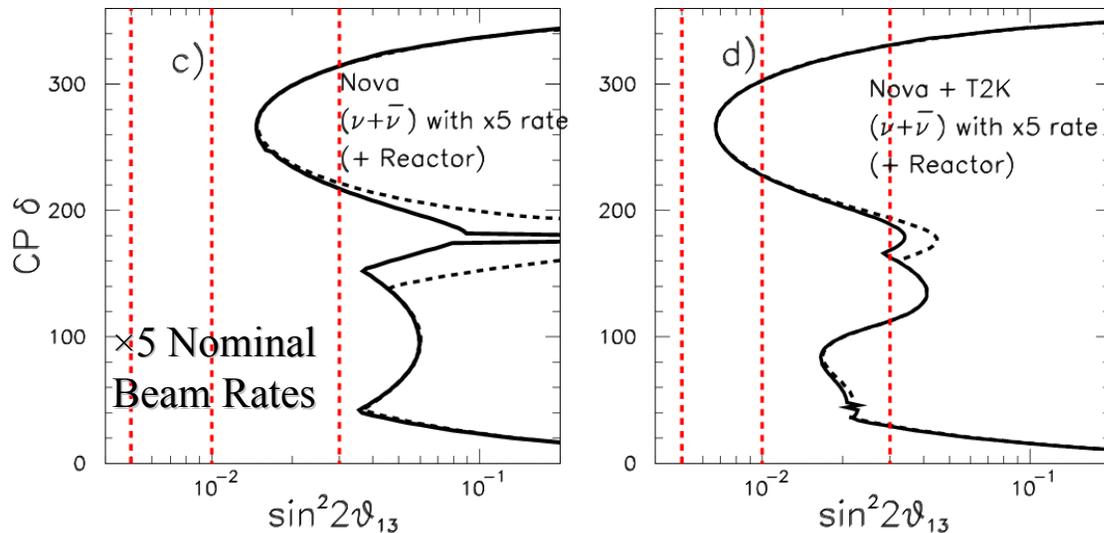
Dashed – without Reactor

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.

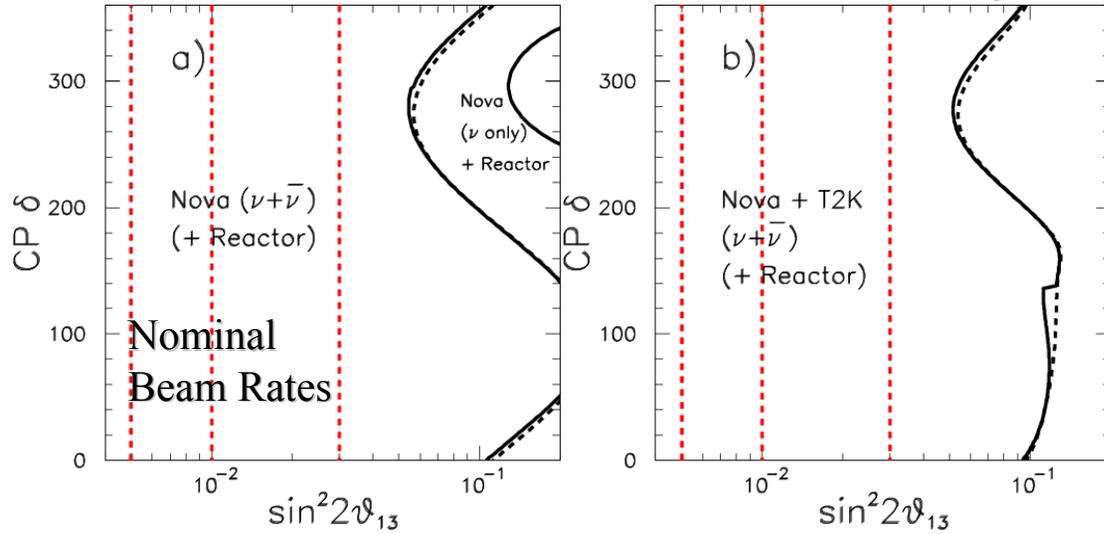
$$\Delta m^2 = 2.5 \times 10^{-3} \text{ eV}^2$$

# Determining Reach in Mass Hierarchy

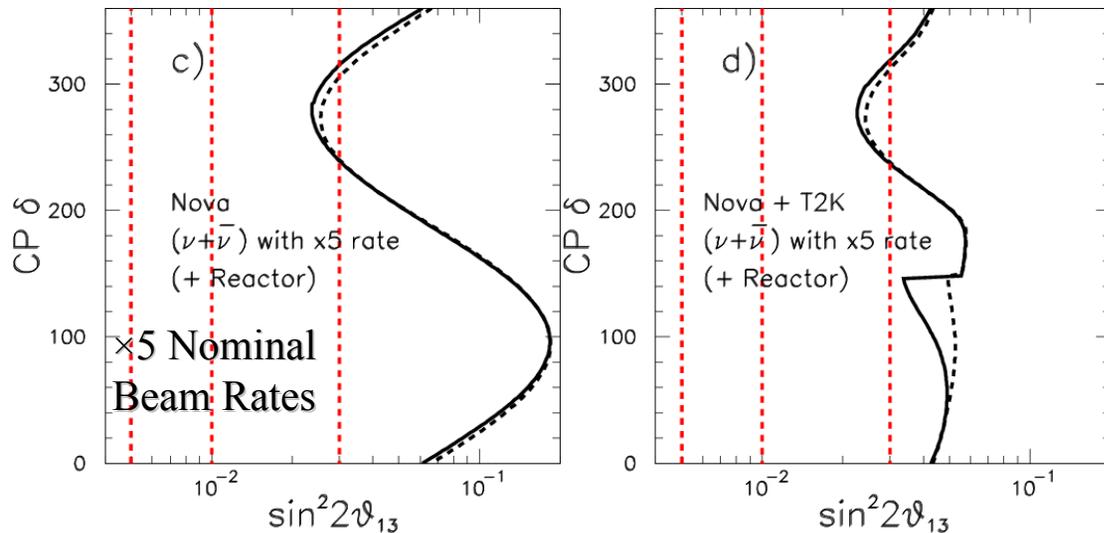
Dashed – without Reactor

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.

$$\Delta m^2 = 2.5 \times 10^{-3} \text{ eV}^2$$

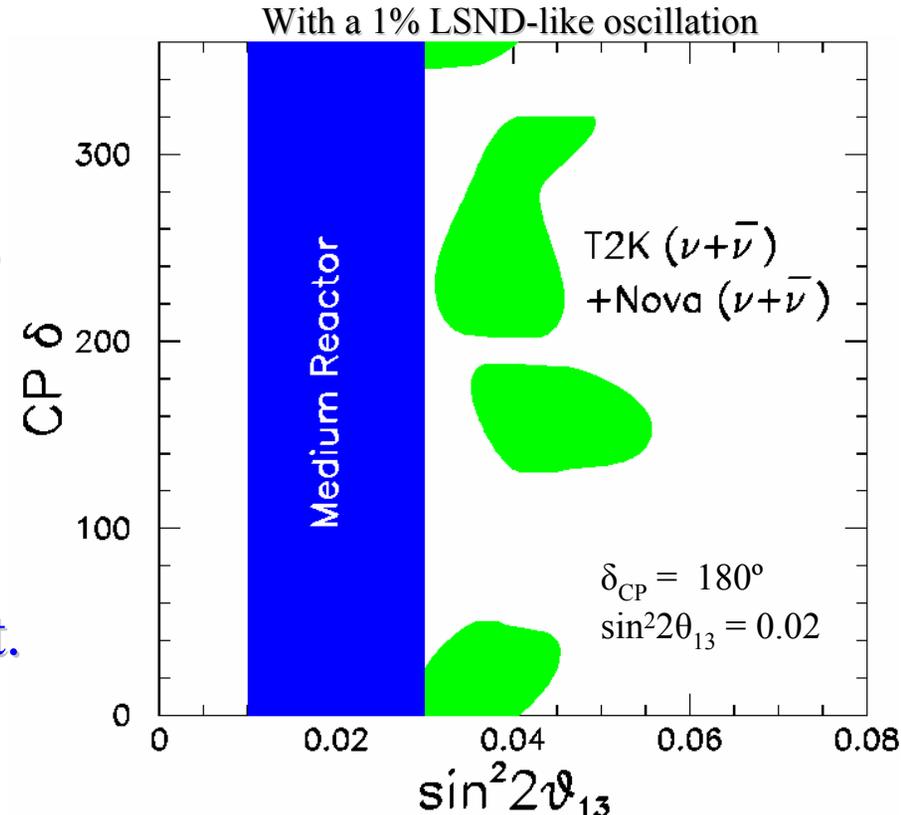
# Combining Off-axis and Reactor

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

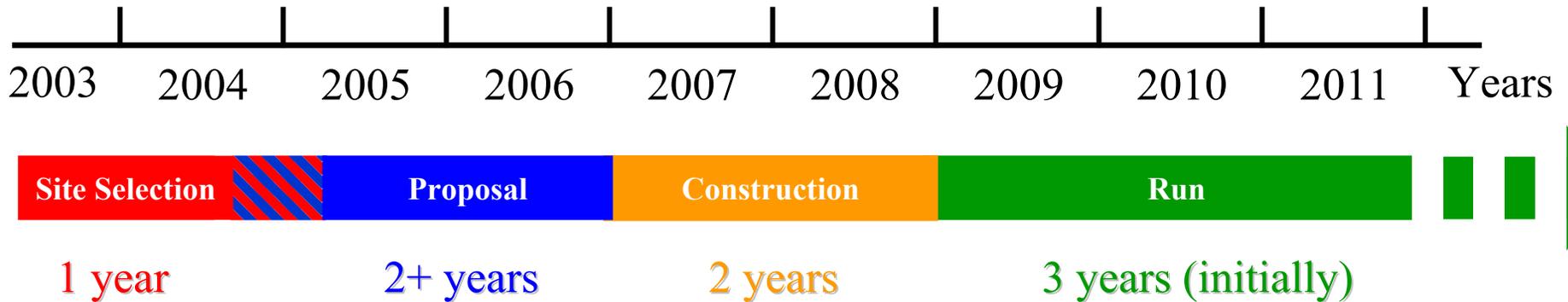
This may indicate new physics.

For example:

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



# Experiment Timeline



Site Selection: Currently underway.

The early work on a proposal is currently underway.

With movable detectors, the detector construction goes in parallel with the civil construction

Run Phase: Initially planned as a three year run. Results or events may motivate a longer run. Should start data taking by 2009.

# Conclusions and Prospects

- Reactor neutrinos experiments make the only direct, unambiguous measurement of  $\sin^2 2\theta_{13}$ .
- The value of  $\sin^2 2\theta_{13}$  determines whether off-axis will be able to measure CP violation or determine the mass hierarchy.
- When combined with off-axis the  $\theta_{23}$  degeneracy can be broken.
- Controlling the systematic errors is the key to making the reactor measurement.
- With a 3+ year run, the sensitivity in  $\sin^2 2\theta_{13}$  should reach 0.01 (90% CL) at  $\Delta m^2 = 2.0 \times 10^{-3}$ .

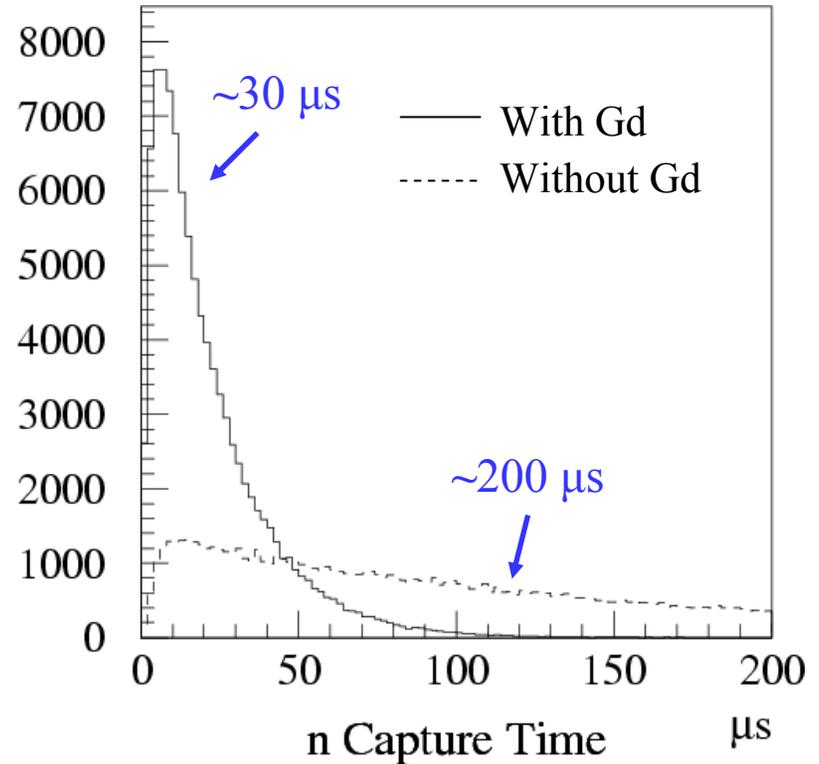
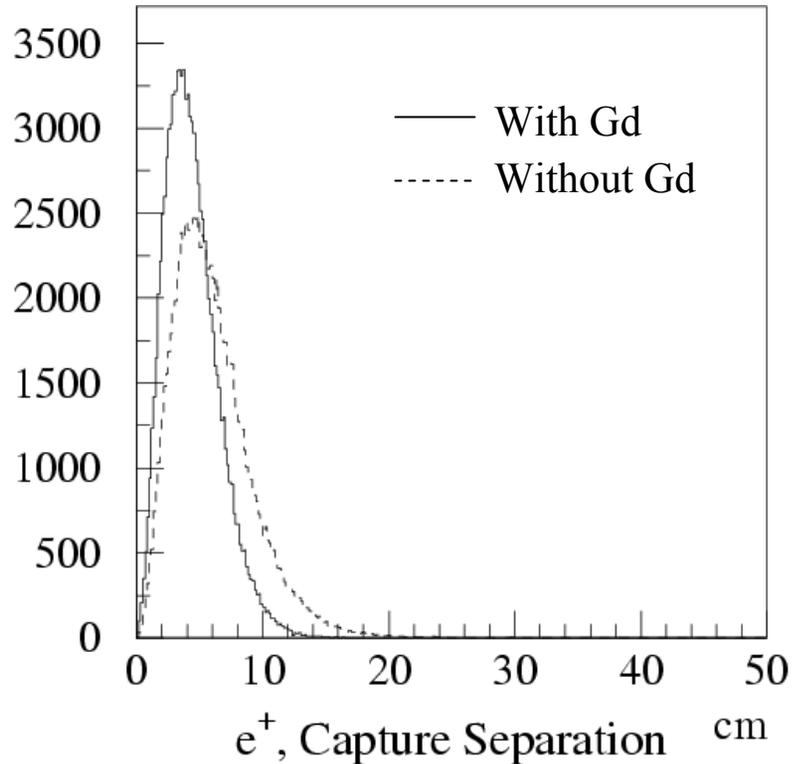
# Conclusions and Prospects

- Reactor sensitivities are similar to off-axis and the two methods are complementary.
- There are many ideas for reactor  $\theta_{13}$  experiments around the world and it is likely that more than one will go forward.
- Reactor neutrinos are an important part of future neutrino oscillation studies.

# Question Slides

# Why Use Gadolinium?

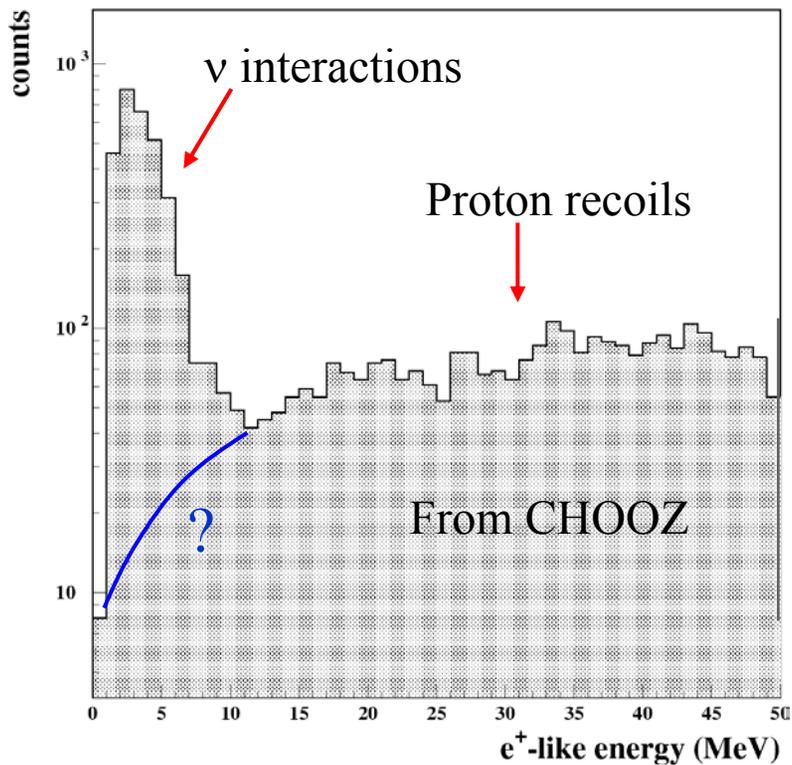
Gd has a huge neutron capture cross section. So you get faster capture times and smaller spatial separation. (Helps to reduce random coincidence backgrounds)



Also the 8 MeV capture energy (compared to 2.2 MeV on H) is distinct from primary interaction energy.

# Characterizing BG with Vetoed Events

Matching distributions from vetoed events outside the signal region to the non-veto events will provide an estimate of correlated backgrounds that evade the veto.



Other Useful Distributions:

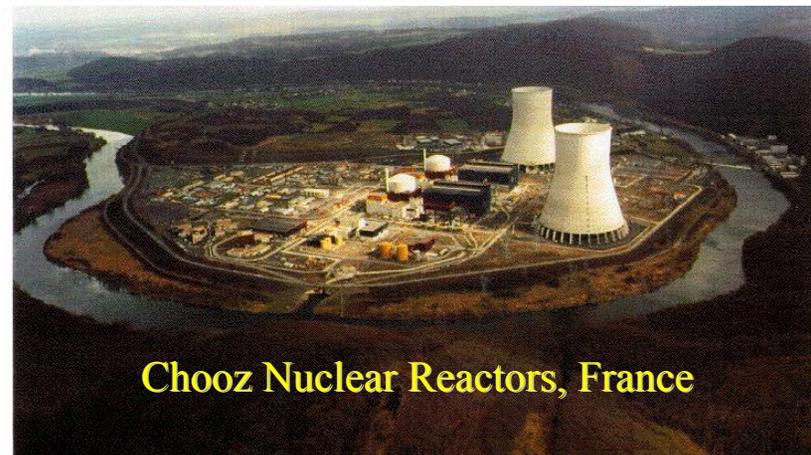
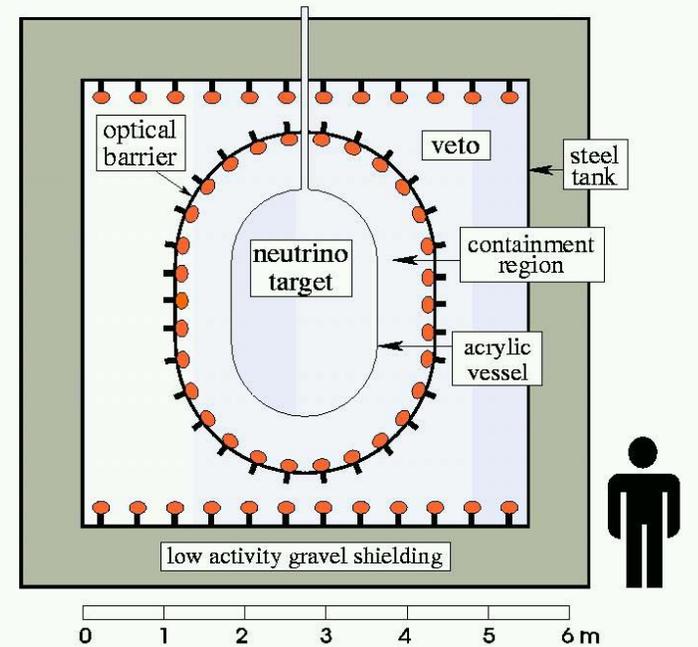
- Spatial separation prompt and delayed events
  - Faster neutrons go farther
- Radial distribution of events
  - BGs accumulate on the outside of the detector.

# Isotope Production by Muons

Source	300 mwe (/ton/day)	450 mwe (/ton/day)	Comments:
${}^9\text{Li}+{}^8\text{He}$	$0.17 \pm 0.03$	$0.075 \pm 0.014$	$E \leq 13.6 \text{ MeV}$ , $\tau_{1/2} = 0.12 \text{ to } 0.18 \text{ s}$ <b>16% to 50% correlated <math>\beta+n</math></b>
${}^8\text{Li}$	$0.28 \pm 0.11$	$0.13 \pm 0.05$	$E \leq 16 \text{ MeV}$ , $\tau_{1/2} = 0.84 \text{ s}$
${}^6\text{He}$	$1.1 \pm 0.2$	$0.50 \pm 0.07$	$E \leq 3.5 \text{ MeV}$ , $\tau_{1/2} = 0.81 \text{ s}$
${}^{11}\text{C}$	$63 \pm 9$	$28 \pm 4$	$E \leq 0.96 \text{ MeV}$ , $\tau_{1/2} = 20 \text{ m}$
${}^{10}\text{C}$	$8.0 \pm 1.5$	$3.6 \pm 0.6$	$E \leq 1.98 \text{ MeV}$ , $\tau_{1/2} = 19 \text{ s}$
${}^9\text{C}$	$0.34 \pm 0.11$	$0.15 \pm 0.05$	$E \leq 16 \text{ MeV}$ , $\tau_{1/2} = 0.13 \text{ s}$
${}^8\text{B}$	$0.50 \pm 0.12$	$0.22 \pm 0.05$	$E \leq 13.7 \text{ MeV}$ , $\tau_{1/2} = 0.77 \text{ s}$
${}^7\text{Be}$	$16.0 \pm 2.6$	$7.2 \pm 1.1$	$E \leq 478 \text{ keV}$ , $\tau_{1/2} = 0.53 \text{ d}$
${}^{12}\text{B}$	11	3	$E \leq 13.4 \text{ MeV}$ , $\tau_{1/2} = 0.02 \text{ s}$

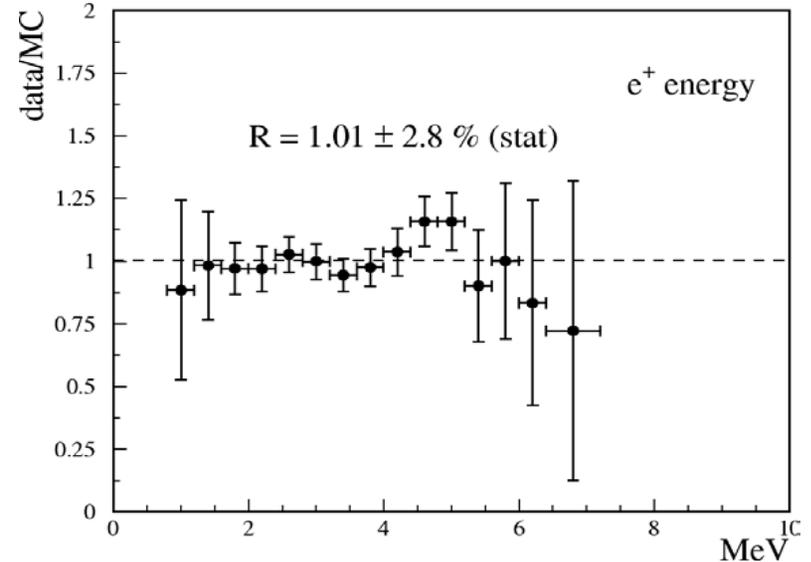
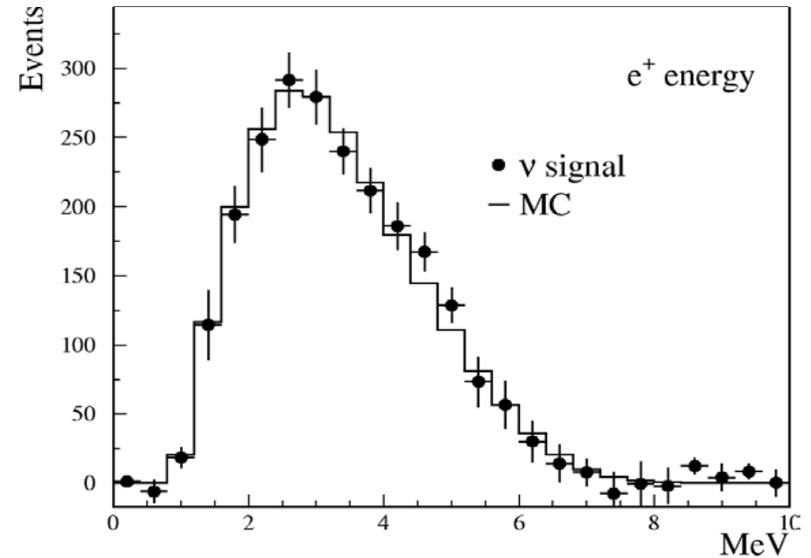
# Medium Baseline Oscillation Searches

- Homogeneous detector
- 5 ton, Gd loaded, scintillating target
- 300 meters water equiv. shielding
- 2 reactors:  $8.9 \text{ GW}_{\text{thermal}}$
- Baselines 1115 m and 998 m
- Used new reactors  $\rightarrow$  reactor off data for background measurement



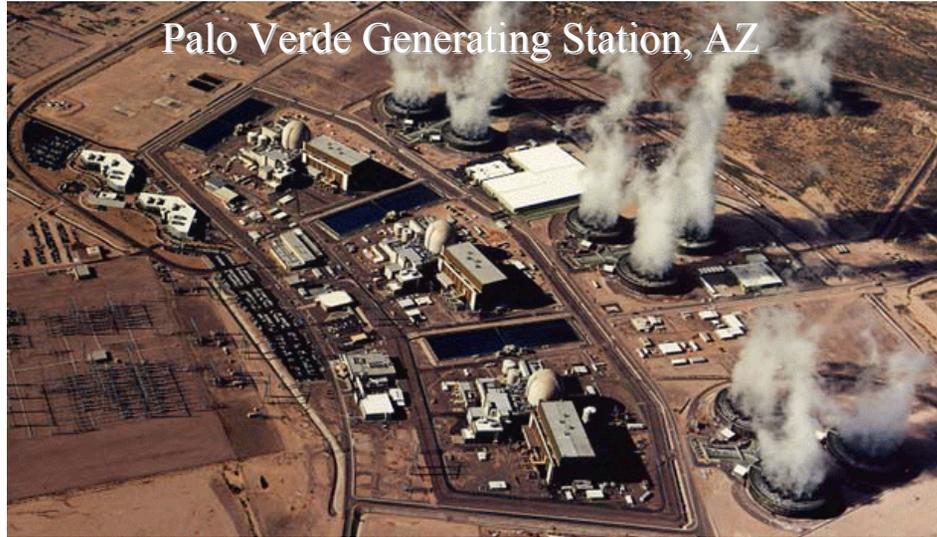
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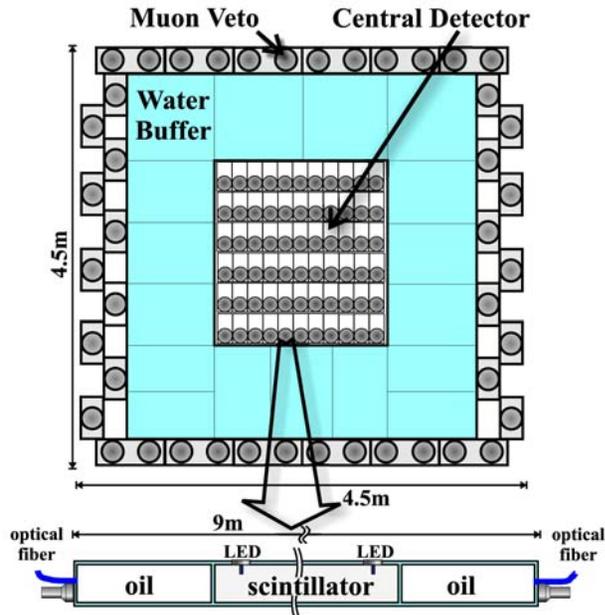


# Palo Verde

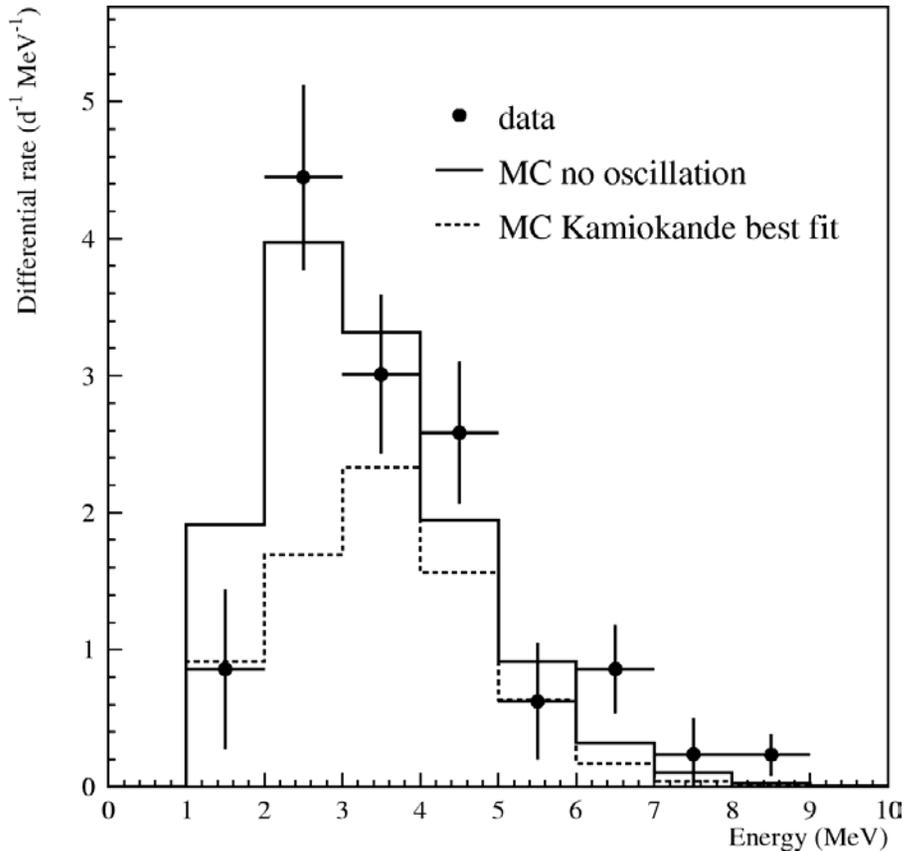
Palo Verde Generating Station, AZ



- 32 mwe shielding (Shallow!)
- Segmented detector:
  - Better at handling the cosmic rate of a shallow site
- 12 ton, Gd loaded, scintillating target
- 3 reactors: 11.6 GW<sub>thermal</sub>
- Baselines 890 m and 750 m
- No full reactor off running



# Palo Verde



- 32 mwe shielding (Shallow!)
- Segmented detector:  
Better at handling the cosmic rate of a shallow site
- 12 ton, Gd loaded, scintillating target
- 3 reactors: 11.6 GW<sub>thermal</sub>
- Baselines 890 m and 750 m
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Exelon Generation  
4300 Winfield Road  
Warrenville, IL 60555

www.exeloncorp.com

RS-03-218

November 14, 2003

Mr. Gerald C. Brown  
Associate Director for Operations and Support  
Fermi National Accelerator Laboratory  
P.O. Box 500  
Batavia, IL 60510-0500

Subject: Authorization to Study the Feasibility of Using Exelon Nuclear Reactors to Perform  
a Precision Measurement of Neutrino Properties

Dear Mr. Brown,

In response to your letter of September 12, 2003, Exelon Nuclear is pleased to grant authorization to scientists and engineers associated with Fermi National Accelerator Laboratory and Argonne National Laboratory to study the feasibility of using Exelon nuclear reactors to perform a precision measurement of neutrino properties. We are excited about the possibility of participating in a scientific endeavor of this nature. Our point of contact for this project will be our Director – Licensing and Regulatory Affairs, Mr. Keith R. Jury, (630) 657-2831.

While Exelon is pleased to agree to this feasibility study, before our final approval is obtained, several business and regulatory issues such as liability, security, and emergency preparedness must be addressed. Any scientific experiment planned must be entirely outside the security perimeter of the host reactor facility. Exelon also requires that the scientific project team pay all costs associated with planning, construction, operation, and decommissioning of all experimental facilities.

We understand the feasibility study will require documents and information such as site maps showing the security perimeter and property boundaries, geological data, and relevant license issues. We will provide these documents to you with the understanding that Exelon reserves the right to control how this information is used. We anticipate entering into a formal memorandum of understanding or other agreement with you in regard to all of these issues.

At this time we see no insurmountable problems that would preclude going forward with this project, and it is our sincere hope that such issues can be resolved to the satisfaction of all parties.

Sincerely,

A handwritten signature in black ink, appearing to read "John L. Skolds".

John L. Skolds  
President and Chief Nuclear Officer  
Exelon Nuclear

Exelon has agreed to work with us to determine the feasibility of using their reactors to perform the experiment.

*“We are excited about the possibility of participating in a scientific endeavor of this nature”*

*“At this time we see no insurmountable problems that would preclude going forward with this project.”*

They have given us reams of geological data which we are currently digesting.

# Limestone Layer

Limestone layer starts at a depth of 272 ft (~200 mwe) and extends to 640 ft (~480 mwe)

We are considering two scenarios: 300 mwe and 450 mwe.

New shaft site bore holes will determine if 450 mwe is practical (groundwater).

Bore holes will also allow us to measure the rock density.

DEPTH TO TOP OF UNIT	SYSTEM	GROUP	FORMATION	LITHOLOGY	ELEVATION AT TOP OF UNIT
0	QUATERNARY			LACUSTRINE SANDS AND GLACIAL TILLS	577
45	PERMIAN		CARBONDALE-SPOON	SILTSTONE, SHALE, COAL, AND SANDSTONE	532
145	ORDEVICIAN	MAQUOKETA SHALE	FORT ATKINSON	LIMESTONE AND DOLOMITE, WHITE, LIGHT GRAY, BROWN, PINK, FINE- TO COARSE- GRAINED, INTERBEDDED SHALE	432
185			SCALES	SHALE, DOLOMITIC, SILTY, BROWN, GRAY; "DEPAUPERATE" FOSSIL ZONES NEAR BASE AND TOP	392
272		GALENA	WISE LAKE-DUNLEITH	DOLOMITE AND SOME LIMESTONE, BUFF TO LIGHT GRAY, ORANGE SPECKLED AT TOP, BLACK SPECKLED AT BASE, FINE- TO MEDIUM- GRAINED	305
			GUTTENBERG	DOLOMITE, RED SPECKLED, RED SHALE PARTINGS	
460		PLATTEVILLE	NACHUSA	DOLOMITE AND LIMESTONE, BUFF, FINE- TO MEDIUM- GRAINED	117
515			GRAND DETOUR	LIMESTONE AND DOLOMITE, LIGHT GRAY, MOTTLED DARK GRAY, VERY FINE- GRAINED; SOME DOLOMITE, PSEUDO-DOLITIC	62
565			MIFFLIN	LIMESTONE AND DOLOMITE, LIGHT GRAY, ORANGE SPECKLED, VERY FINE- GRAINED, SHALE PARTINGS	12
595			PECATONICA	DOLOMITE AND LIMESTONE, BROWN, VERY FINE- TO FINE- GRAINED, SANDY AT BASE	-18
640		ANCELL	GLENHODD-ST. PETER	SANDY DOLOMITE AND DOLOMITIC SANDSTONE, FINE- TO MEDIUM- GRAINED, GREEN SHALE PARTINGS AT TOP	-63
				SANDSTONE, WHITE, FINE- TO MEDIUM- GRAINED, FRIABLE	
860	PRAIRIE DU CHIEN	SHAKOPEE	DOLOMITE, SANDY, LIGHT GRAY, LIGHT BROWN, FINE- GRAINED; CHERT, PARTLY DOLITIC	-283	
960		NEW RICHMOND	SANDSTONE, MEDIUM- GRAINED; SOME LITHOGRAPHIC DOLOMITE & DOLITIC CHERT	-383	
995		ONEOTA-GUNTER	DOLOMITE, SANDY AT TOP, CHERTY AT BASE, LIGHT GRAY, PINK, FINE- TO COARSE- GRAINED	-418	
	SANDSTONE, MEDIUM- GRAINED, A LITTLE DOLOMITE AND GREEN SHALE				
1190	CAMBRIAN	EMINENCE	DOLOMITE, SANDY, LIGHT GRAY, FINE- TO MEDIUM- GRAINED, THIN BEDS OF SANDSTONE; CHERT, PARTLY DOLITIC; DOLOMITIC SANDSTONE AT BASE	-613	
1280			POTOSI	DOLOMITE, LIGHT GRAY TO LIGHT BROWN, FINE- GRAINED, SOME DRUSY QUARTZ; SANDY AT BASE	-703
1405			FRANCONIA	SANDSTONE, SHALE, AND DOLOMITE, GLAUCONITIC, MICACEOUS, SILTY, RED, GREEN	-828
1548			IRONTON	SANDSTONE, DOLOMITIC, MEDIUM- TO COARSE- GRAINED	-971

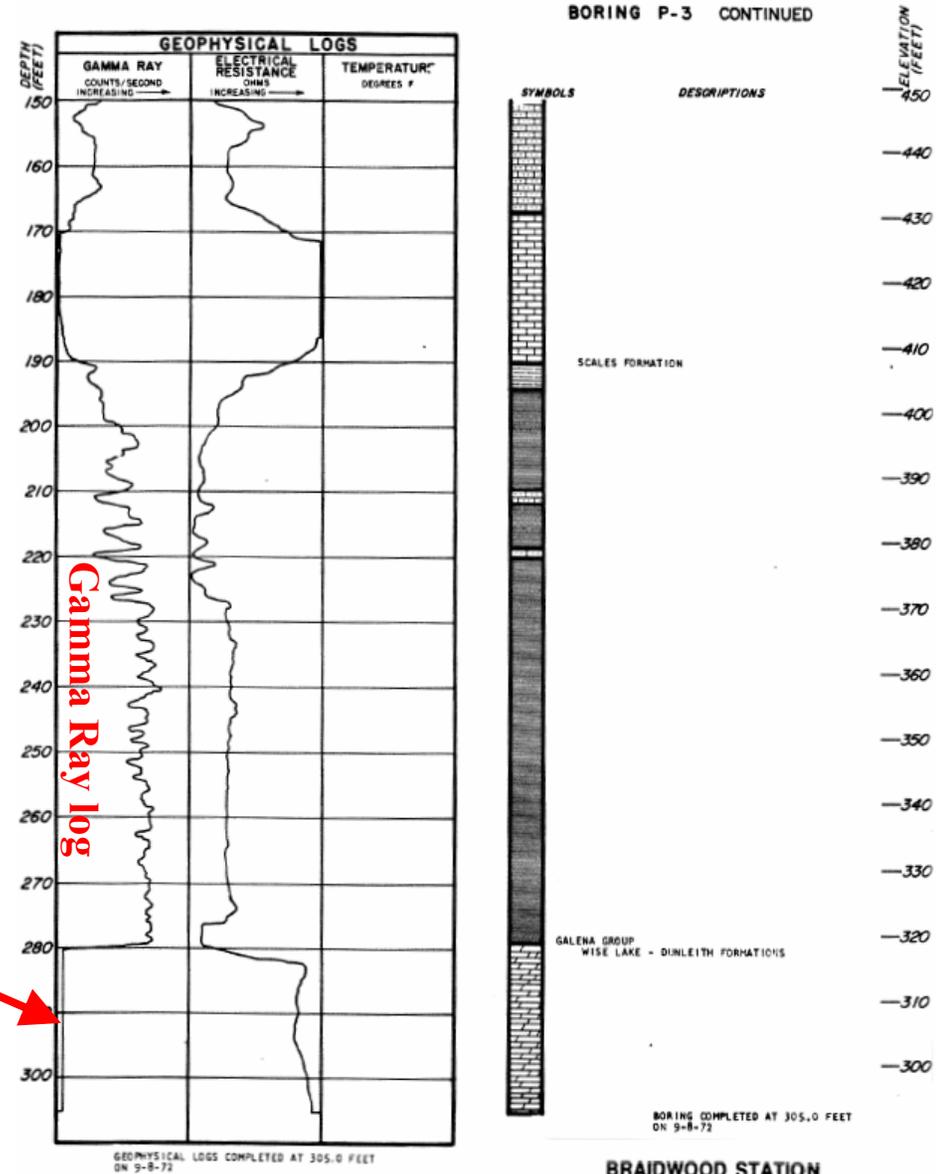
NOTE:

# Natural Radioactivity in Limestone

$^{238}\text{U}$  and  $^{232}\text{Th}$  in different rock types

Type of Rock	U (ppm)	Th (ppm)	U( $\alpha, n$ )	Th( $\alpha, n$ )	Fission	Total
Granite	5	11	7.85	7.755	2.33	17.9
Limestone	1	1	0.64	0.285	0.467	1.4
Sandstone	1	1	0.837	0.38	0.467	1.7
Granite A	1.32	7.79	2.24	5.92	0.62	8.8
Granite B	6.25	4.59	10.62	3.49	2.92	17.0
Granite C	1.83	4.38	3.11	3.33	0.85	7.3
Salt I	0.30	2.06	1.60	4.77	0.14	6.5
Salt II	0.13	1.80	4.17	0.69	0.06	4.9

Natural radioactivity is very low in the dolomitic limestone layer

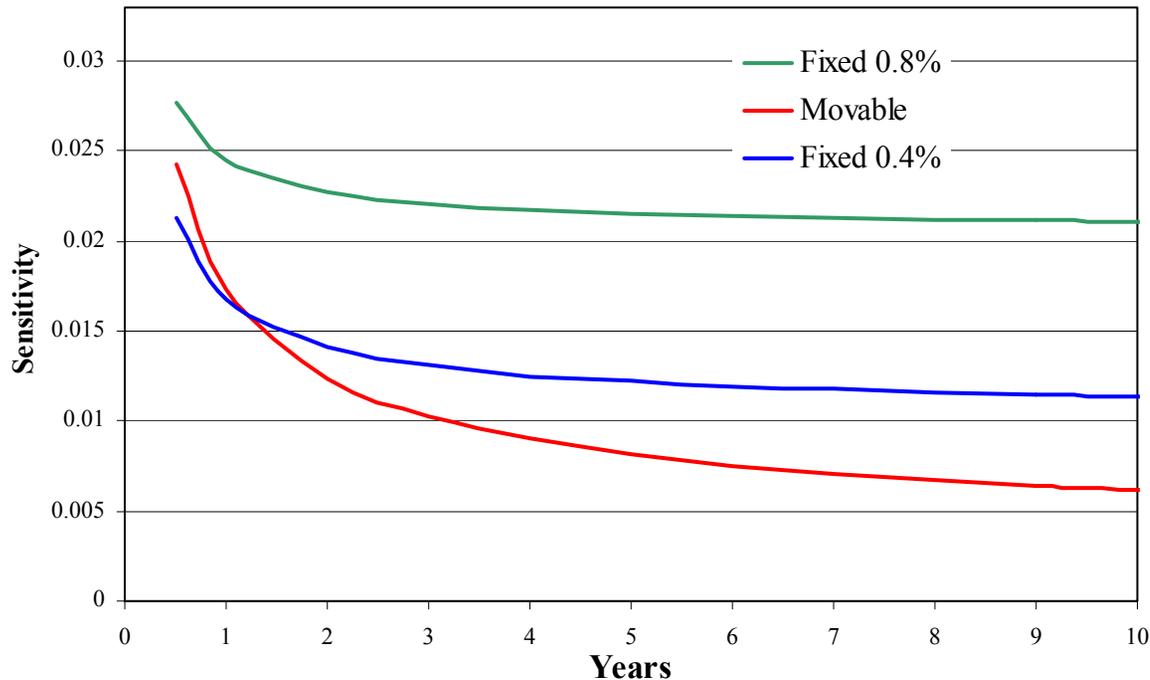


# Quantitative Analysis of Movable vs. Fixed Detectors

Both the Kashiwazaki and Krasnoyarsk proposals assume that they can get the relative normalization systematic down to 0.8% with fixed detectors.

Double Chooz believes that 0.6% is achievable.

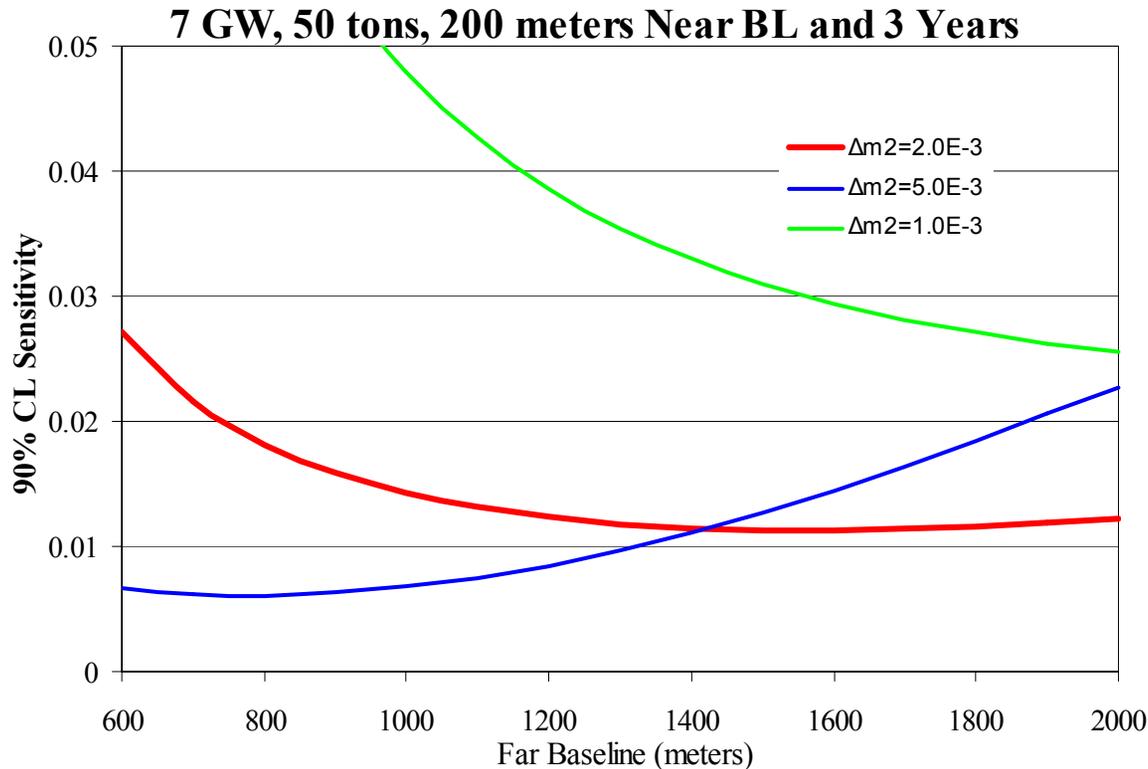
6 GW, 50 tons and 1200 meters Baseline



Even if you halve the relative normalization, fixed detector are not as sensitive for a two year (or longer) run.

All fixed detector scenario quickly become systematics limited.

# Optimal Far Baseline

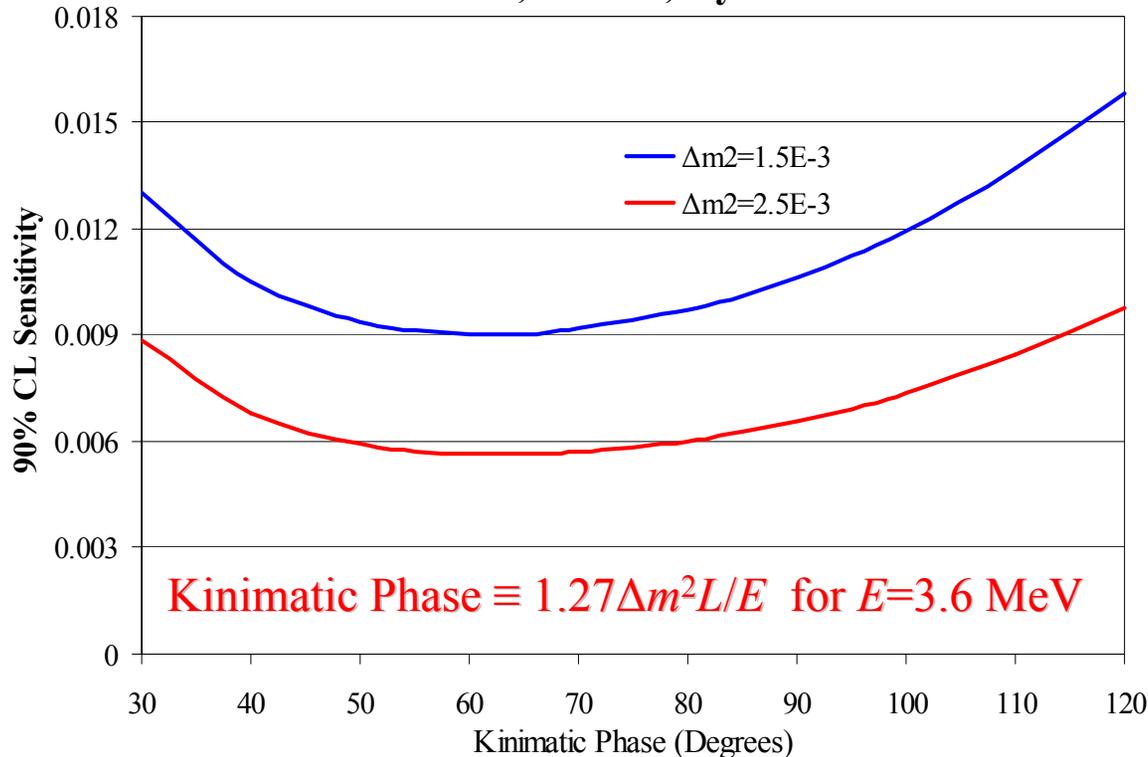


One must consider both the location of the oscillation maximum ( $\sim 2200$  m at  $\Delta m^2 = 2 \times 10^{-3}$ ) and statistics loss due to  $1/r^2$  flux.

At the preferred  $\Delta m^2$  the optimal region is quite wide. In a configuration with a tunnel connecting the two detector sites, one should choose a far baseline that gives the shortest tunnel (1200 to 1400 meters).

# Optimal Far Baseline

7 GW, 50 tons, 5 years

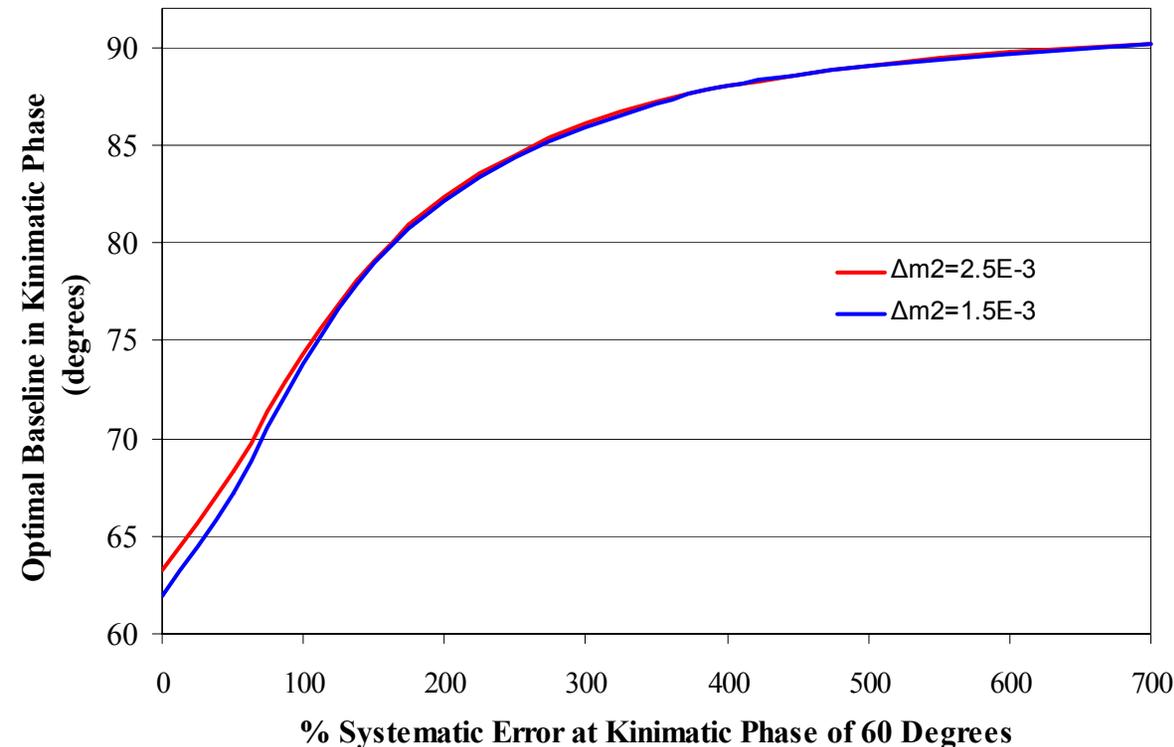


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# Sensitivity Scaling with Systematic Error

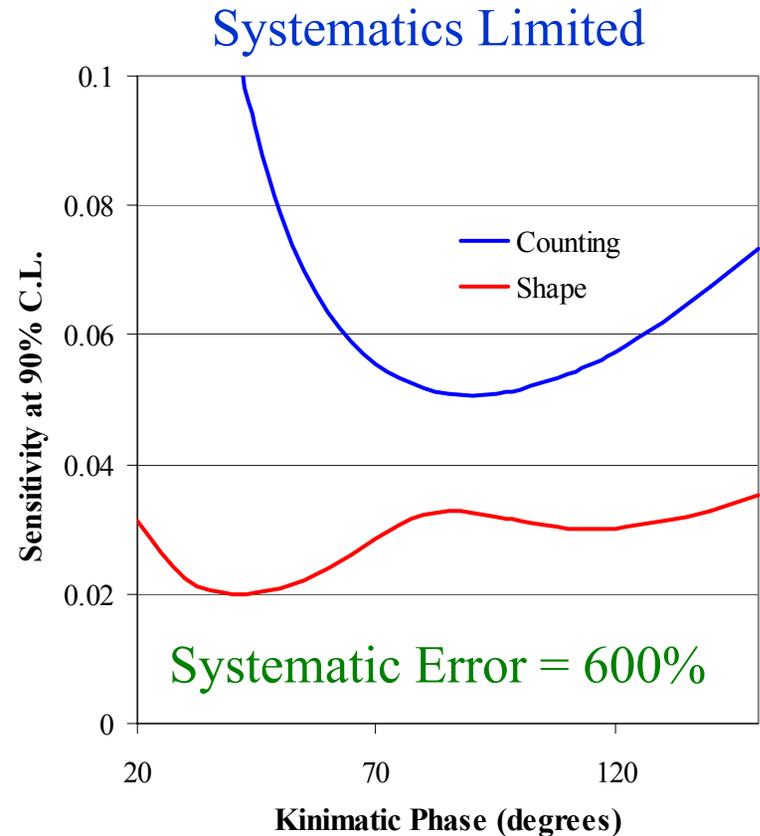
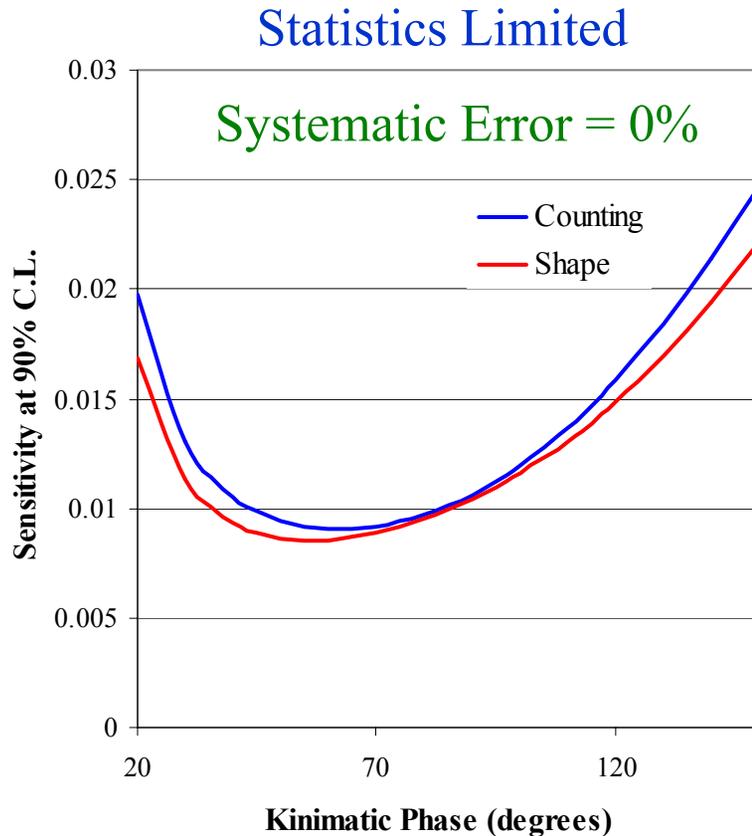
For a rate only analysis



The optimal baseline is very sensitive to the level of systematic error.

The standard assumption of 0.8% relative efficiency error for fixed detectors is  $\sim 250\%$  of the statistical error after 3 years at Braidwood.

# Comparison of Shape & Rate



The optimal Baseline for the systematics limited shape analysis is  $\sim 40^\circ$ .

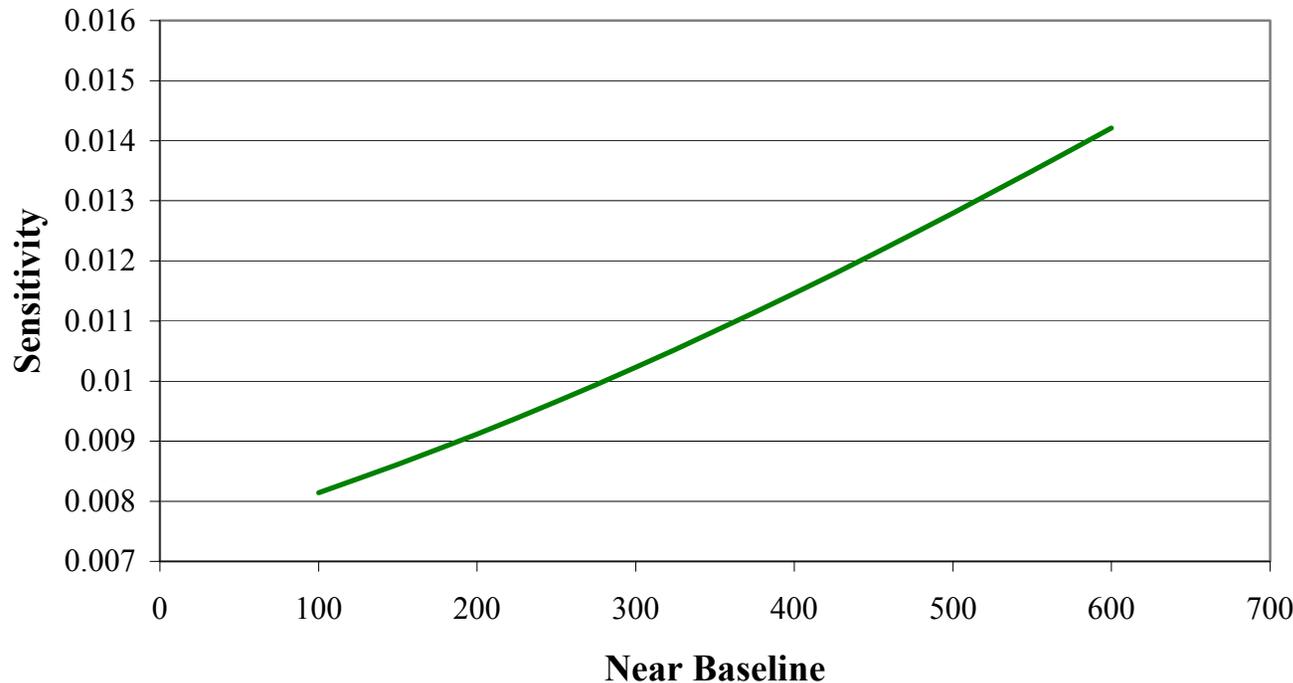
The optimal baseline for the systematics limited counting experiment is at the least optimal spot for a shape analysis!

You better know what regime your working in.

# Sensitivity wrt Near Baseline

Ultimately the location of the near detector will be determined by the reactor owners. The main question here is what can we live with?

**7 GW, 50 tons, 1200 meters Far Baseline and 3 years**



There is a  $1/r^2$  dependence in statistics (a small effect) and increasing oscillation probability with distance.

Sensitivity degrades with increasing near baseline.

When  $L_{near} = L_{far}$  the sensitivity is about the same as CHOOZ.