Measuring $\sin^2 2\theta_{13}$ with Reactor Antineutrinos

- Proposals with US Involvement -

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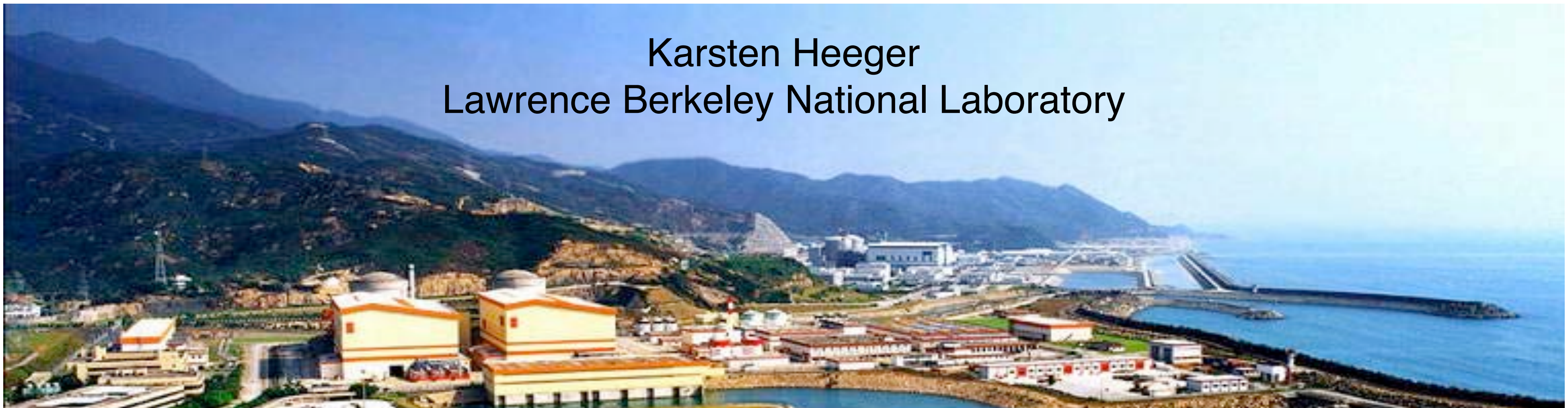
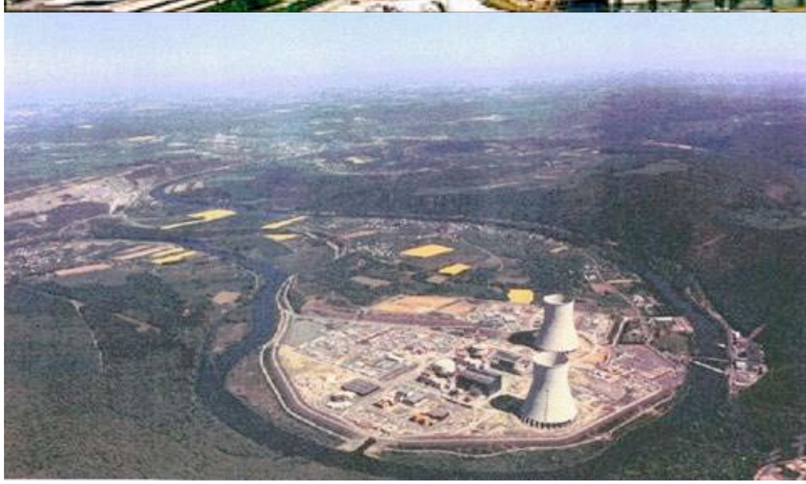
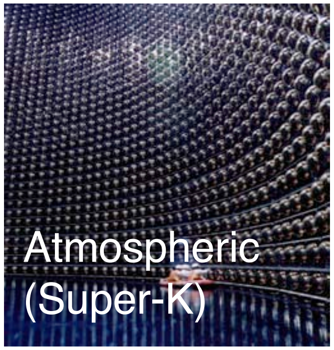
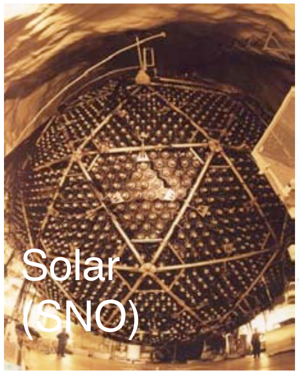
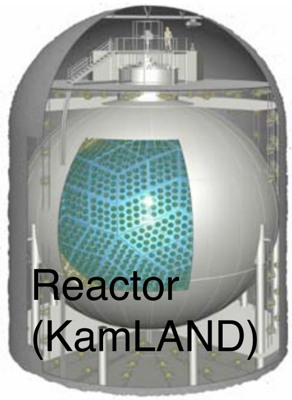


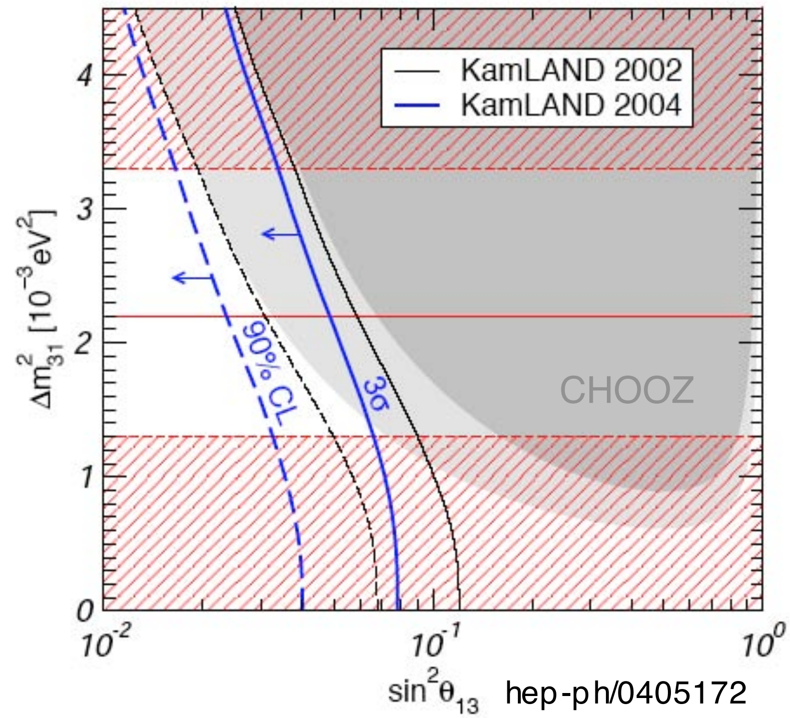


Understanding Neutrino Mixing









$$U = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix}$$

U_{MNSP} Matrix

$$= \underbrace{\begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\theta_{23} & \sin\theta_{23} \\ 0 & -\sin\theta_{23} & \cos\theta_{23} \end{pmatrix}}_{} \times \underbrace{\begin{pmatrix} \cos\theta_{13} & 0 & e^{-i\delta_{CP}}\sin\theta_{13} \\ 0 & 1 & 0 \\ -e^{i\delta_{CP}}\sin\theta_{13} & 0 & \cos\theta_{13} \end{pmatrix}}_{} \times \underbrace{\begin{pmatrix} \cos\theta_{12} & \sin\theta_{12} & 0 \\ -\sin\theta_{12} & \cos\theta_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}}_{} \times \underbrace{\begin{pmatrix} 1 & 0 & 0 \\ 0 & e^{i\alpha/2} & 0 \\ 0 & 0 & e^{i\alpha/2+i\beta} \end{pmatrix}}_{}$$

?

atmospheric, K2K — reactor and accelerator — SNO, solar SK, KamLAND — $0\nu\beta\beta$

$\theta_{23} = \sim 45°$ — $\theta_{13} = ?$ — $\theta_{12} \sim 32°$

θ_{13} from Reactor and Accelerator Experiments

reactor

$$P_{ee} \approx 1 - \sin^2 2\theta_{13} \sin^2\left(\frac{\Delta m_{31}{}^2 L}{4E_\nu}\right) - \cos^4\theta_{13}\sin^2 2\theta_{12}\sin^2\left(\frac{\Delta m_{21}{}^2 L}{4E_\nu}\right)$$

- Clean measurement of θ_{13}
- No matter effects

mass hierarchy

CP violation

matter

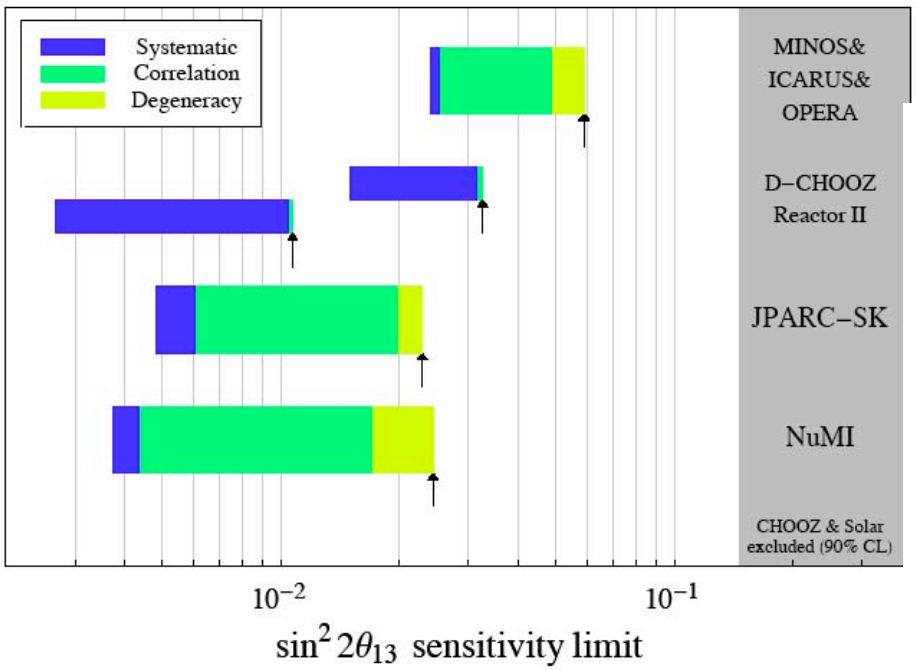
accelerator

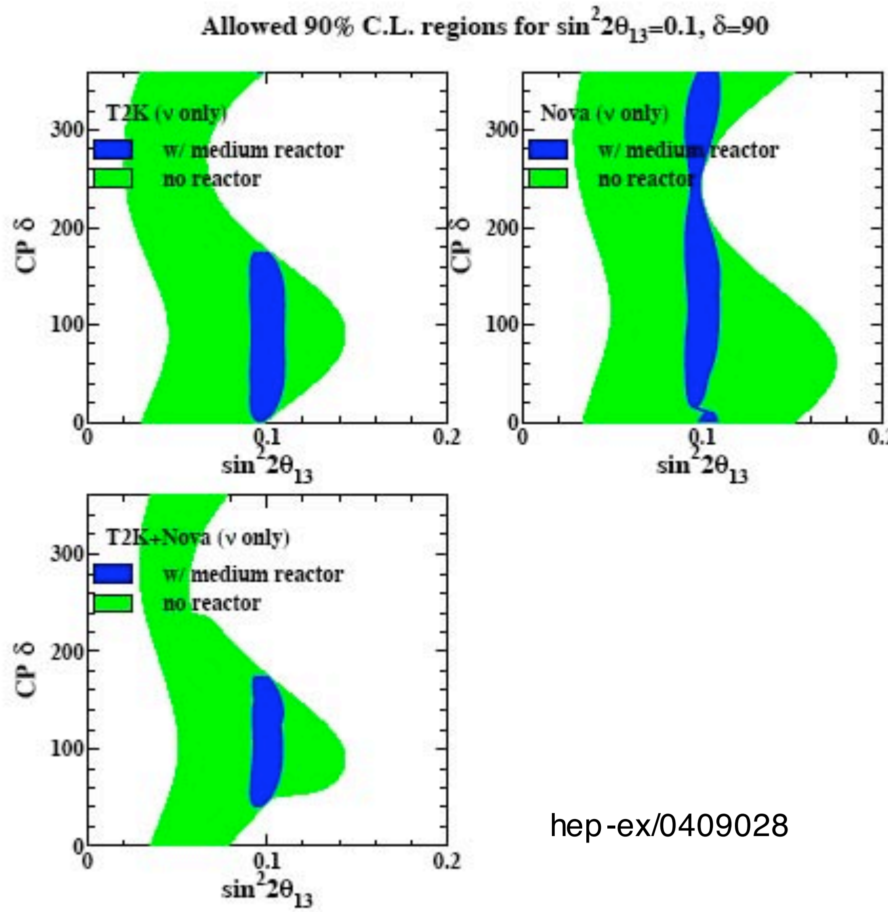
$$\begin{aligned} P(\nu_\mu \to \nu_e) = {} & 4c_{13}^2 s_{13}^2 s_{23}^2 \sin^2\Delta_{31} \\ & + 8c_{13}^2 s_{13} s_{23} c_{23} s_{12} c_{12} \sin\Delta_{31}[\cos\Delta_{32}\cos\delta - \sin\Delta_{32}\sin\delta]\sin\Delta_{21} \\ & - 8c_{13}^2 s_{13}^2 s_{23}^2 s_{12}^2 \cos\Delta_{32}\sin\Delta_{31}\sin\Delta_{21} \\ & + 4c_{13}^2 s_{12}^2[c_{12}^2 c_{23}^2 + s_{12}^2 s_{23}^2 s_{13}^2 - 2c_{12}c_{23}s_{12}s_{23}s_{13}\cos\delta]\sin^2\Delta_{21} \\ & - 8c_{13}^2 s_{13}^2 s_{23}^2(1 - 2s_{13}^2)\frac{aL}{4E_\nu}\sin\Delta_{31}\left[\cos\Delta_{32} - \frac{\sin\Delta_{31}}{\Delta_{31}}\right] . \end{aligned}$$

- $\sin^2 2\theta_{13}$ is missing key parameter for any measurement of δ_{CP}

A Precision Measurement of θ_{13}

Next-generation experiments will not measure CP violation but some values of δ_{CP} could be excluded.





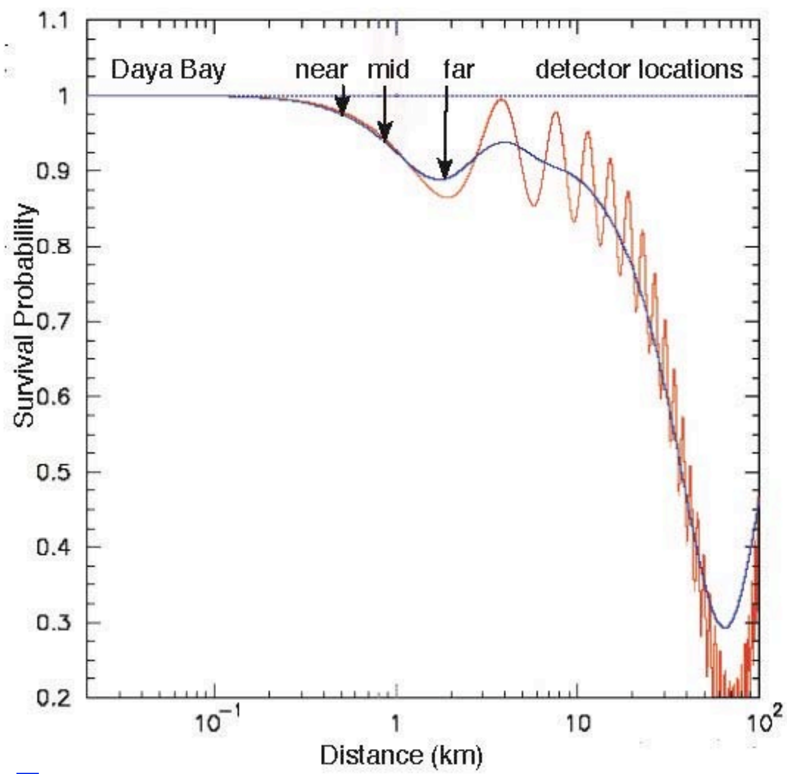
hep-ex/0409028

Measuring θ_{13} with Reactor Antineutrinos

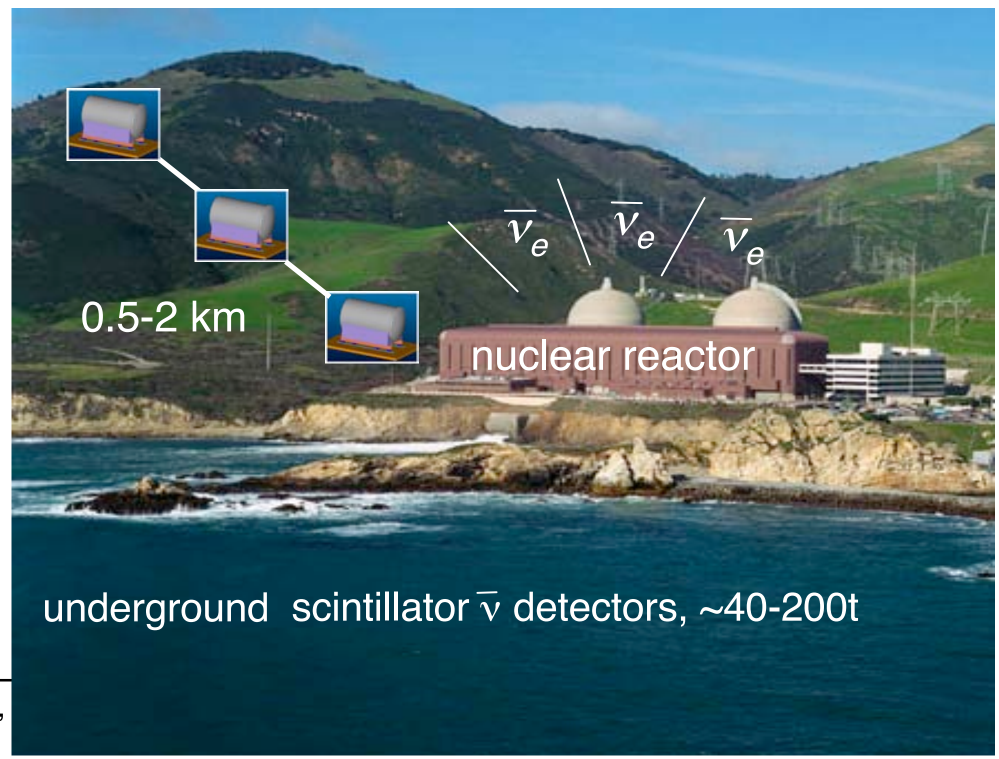
Precision Oscillation Measurement as a Function of Distance from Source

$$P_{ee} \approx 1 - \sin^2 2\theta_{13} \sin^2\left(\frac{\Delta m_{31}{}^2 L}{4E_\nu}\right) - \cos^4\theta_{13} \sin^2 2\theta_{12} \sin^2\left(\frac{\Delta m_{21}{}^2 L}{4E_\nu}\right)$$

$\}\ \theta_{13}$



<u>Relative</u> $\bar{\nu}_e$ flux measurement at different distances.

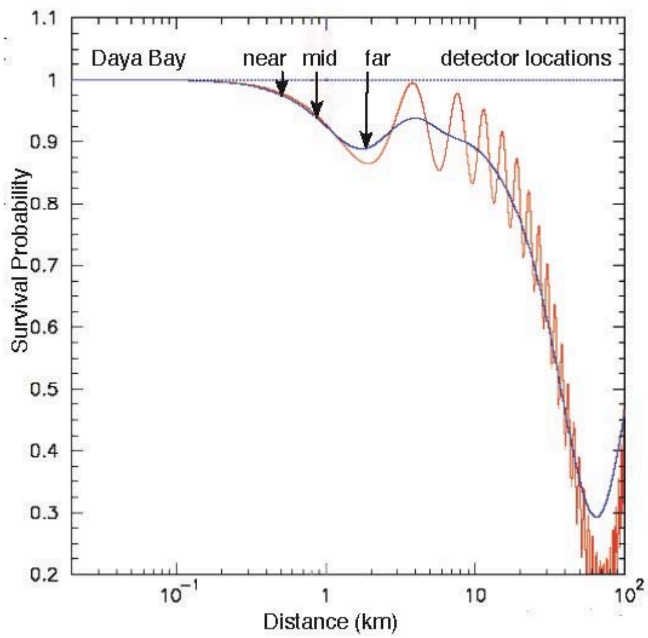


Event rate:

~1 event/GW/ton/day at 1km

Projected sensitivity: $\sin^2 2\theta_{13} \approx 0.01$

Signatures of θ_{13} in a Reactor Experiment



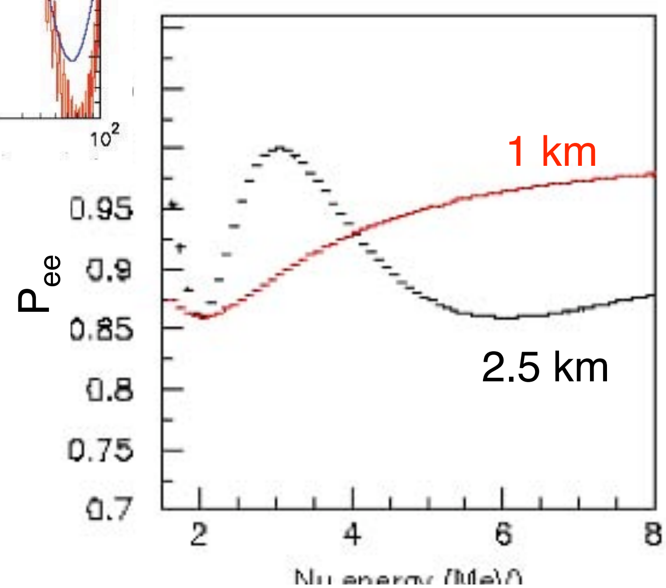
Disappearance of $\overline{\nu}_e$:
Reduction of interaction rate

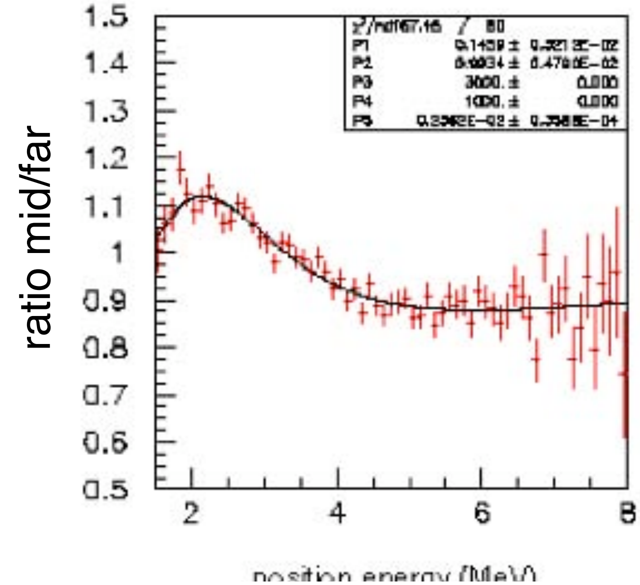
near ↔ far comparison

Rate and shape effects optimize at different baselines

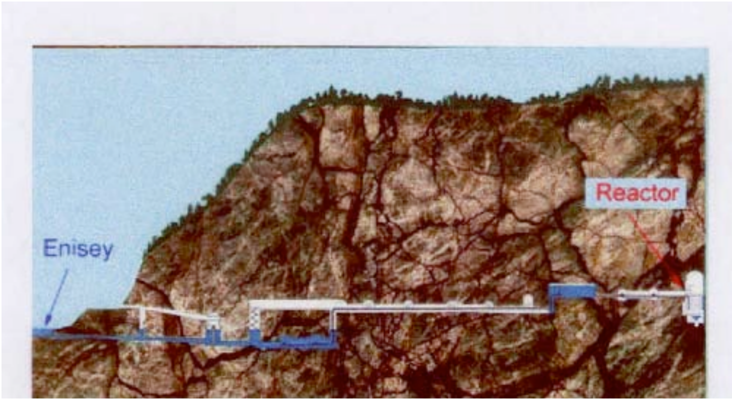
Spectral Distortion

mid ↔ far comparison





→ 3 baselines provide consistency checks and eliminate single point failure of experiment, in particular if the backgrounds are too high in near detector or unaccounted systematics in one of detectors

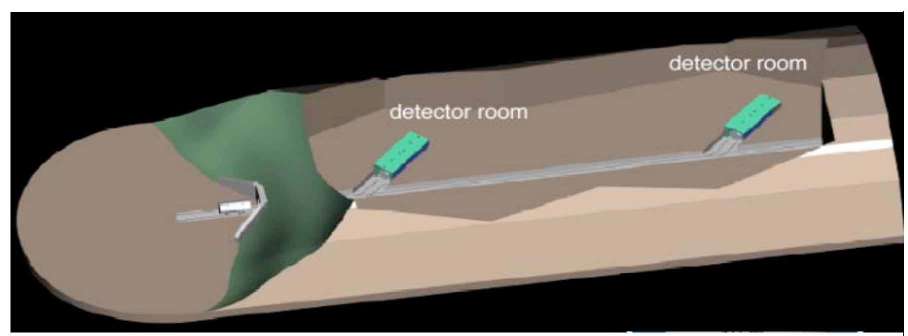


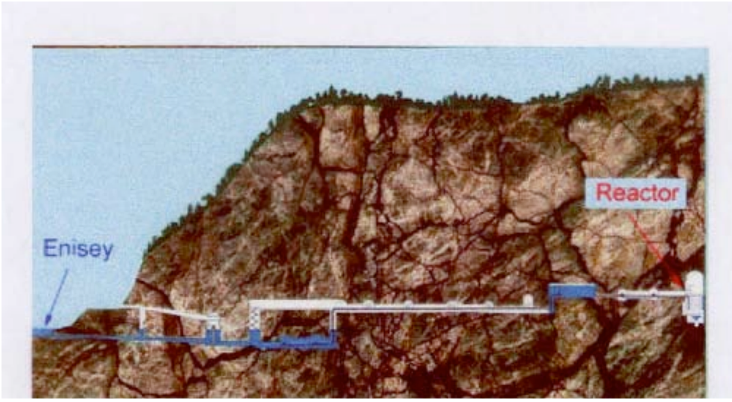

Proposals to Measure θ_{13} with Reactor Neutrinos



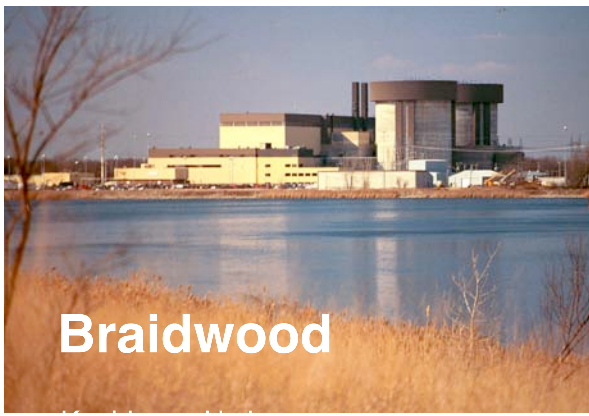
vertical shafts

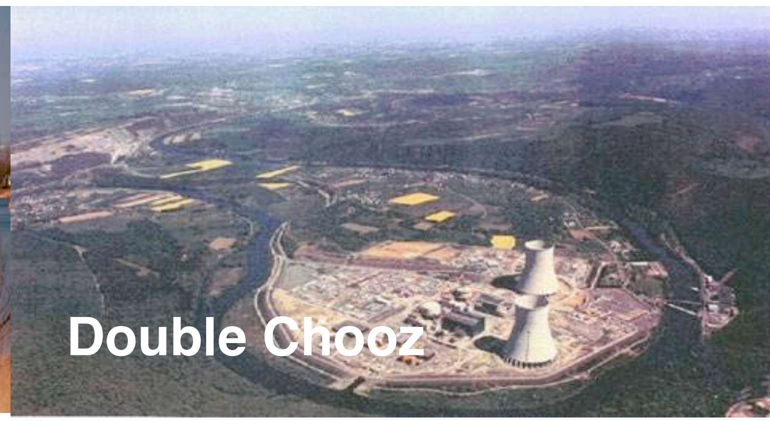
horizontal tunnels



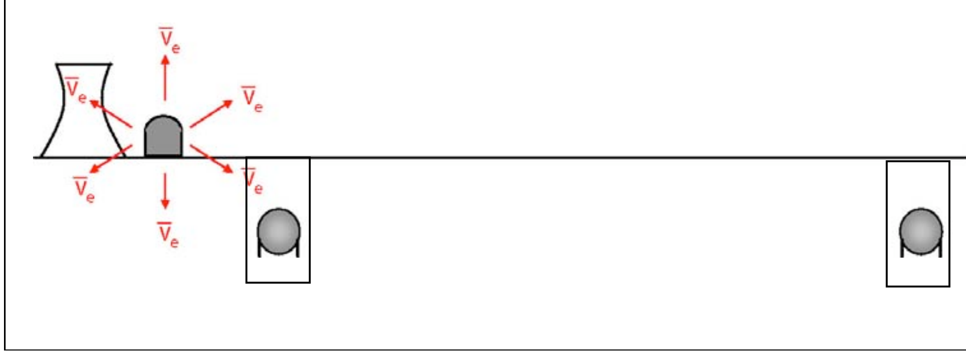



Proposals to Measure θ_{13} with Reactor Neutrinos

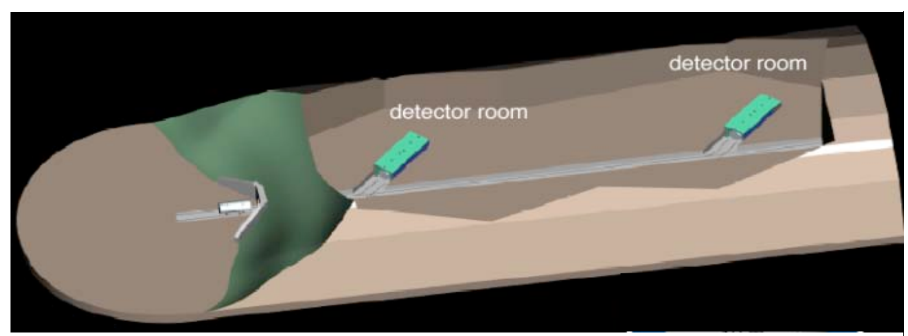




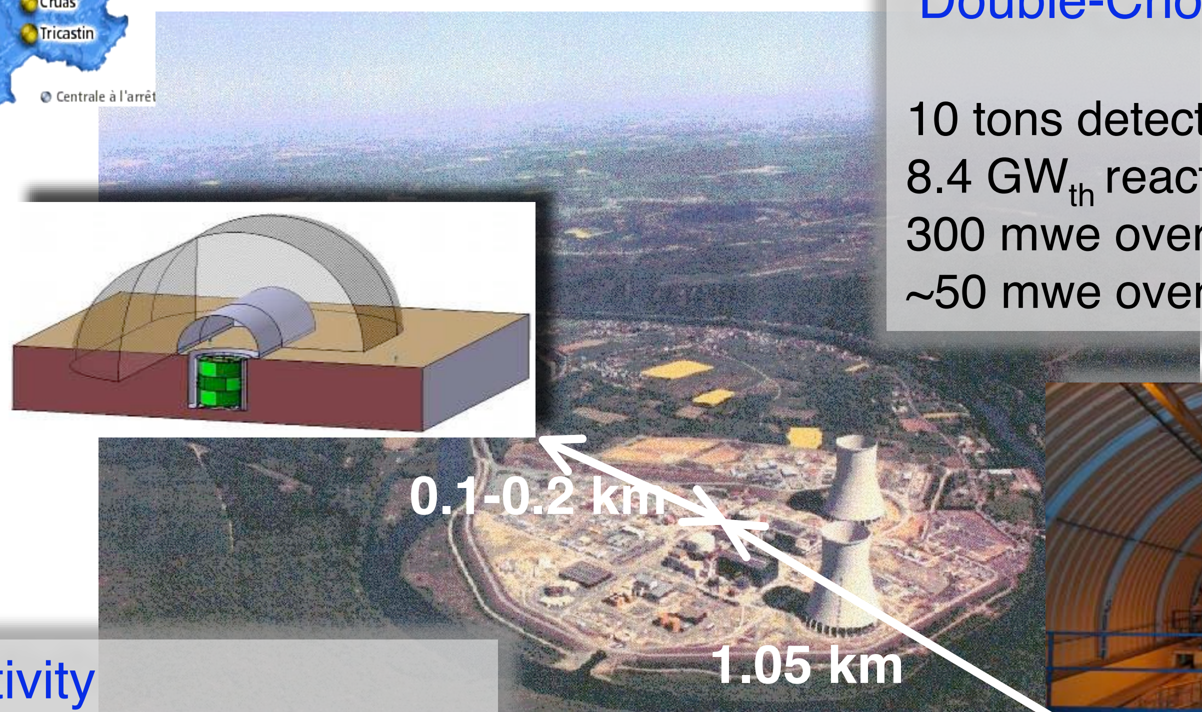
vertical shafts



horizontal tunnels

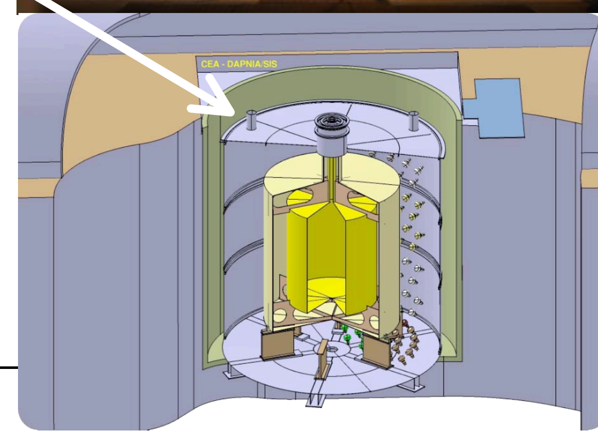


DoubleChooz …Improving on Chooz



‘Double-Chooz’ Project

10 tons detectors
8.4 GW_{th} reactor power
300 mwe overburden at far site
~50 mwe overburden at near site



Sensitivity

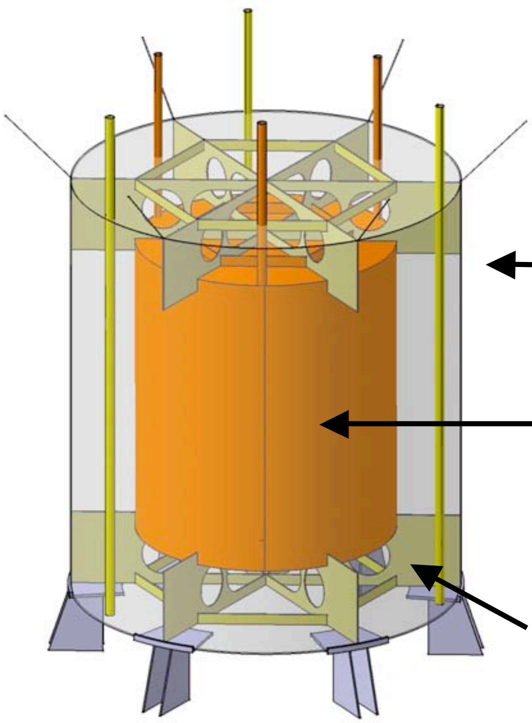
$\sin^2(2\theta_{13}) < 0.03$ at 90% CL

after 3 yrs, $\Delta m_{atm}^2 = 2 \times 10^{-3}$ eV^2

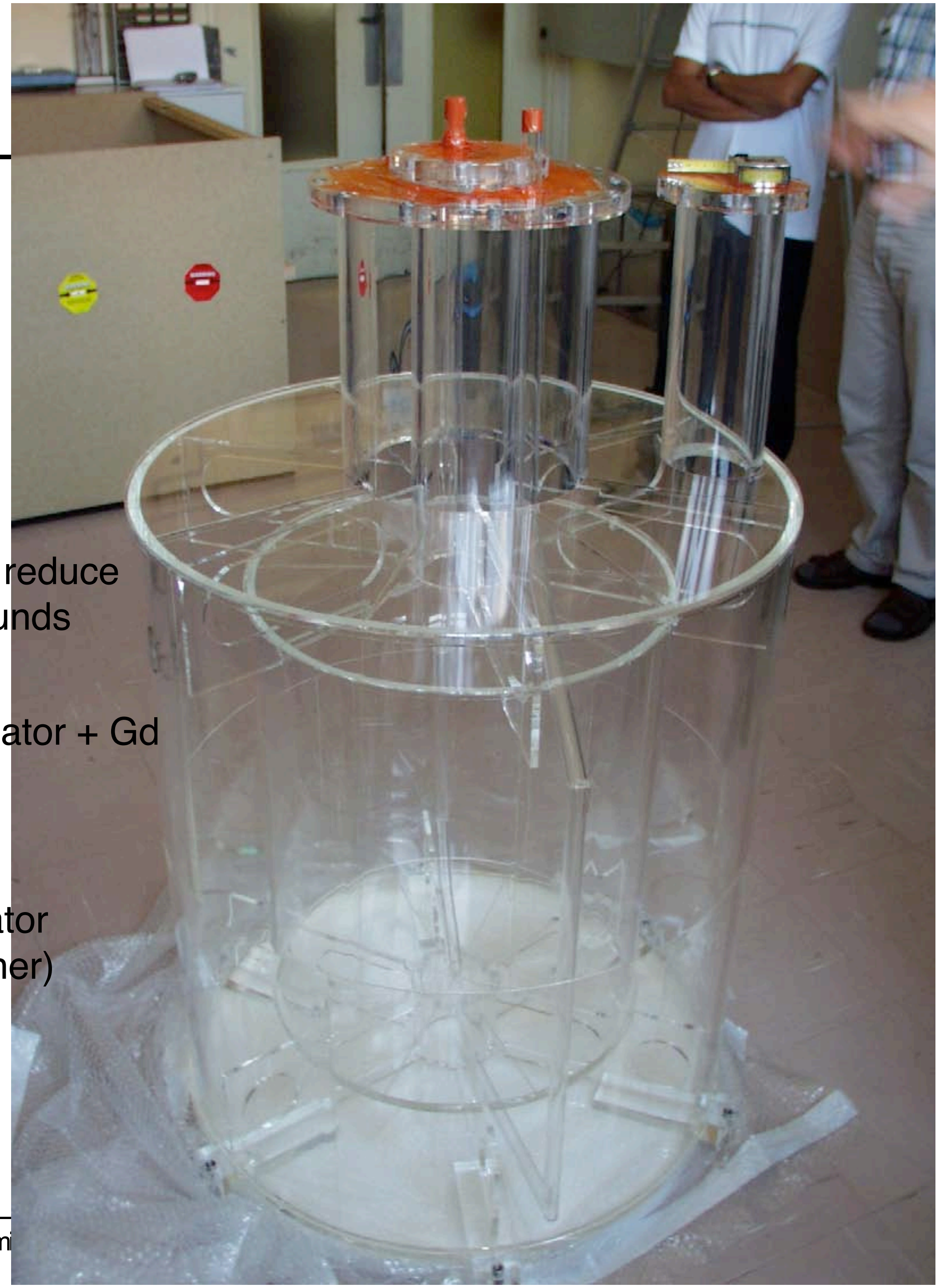
→ Improve the detector concept
→ and backgrounds rejection on Chooz

Prototype Development

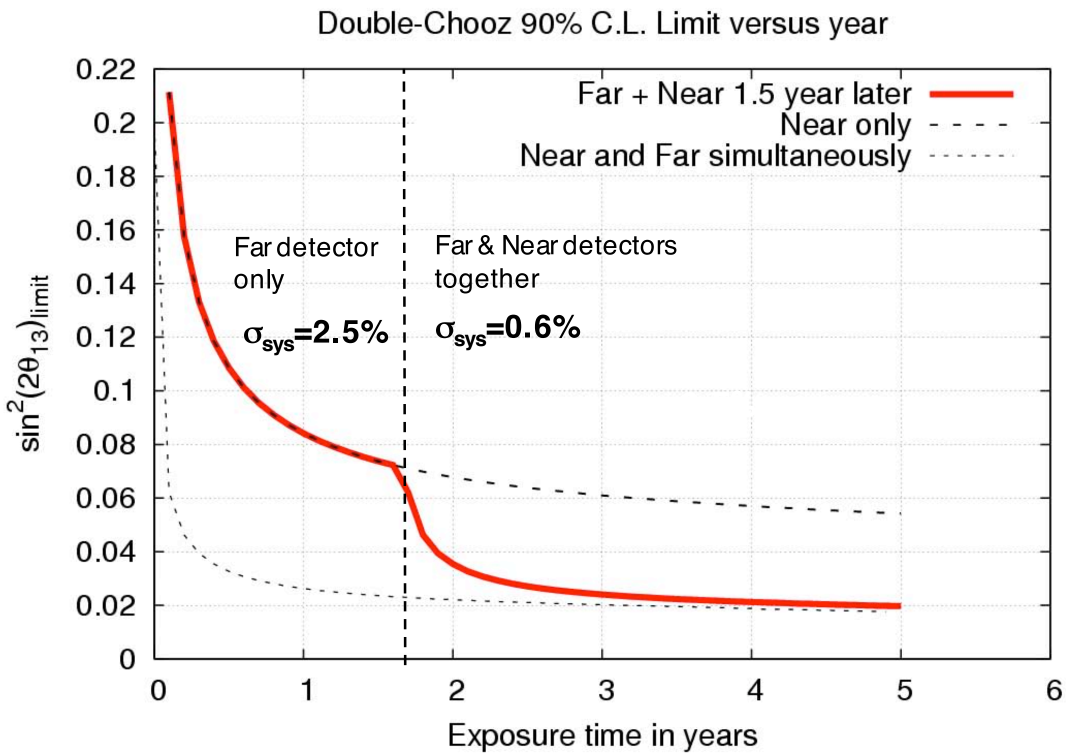
1/5 scale acrylic vessel



3-zone detector



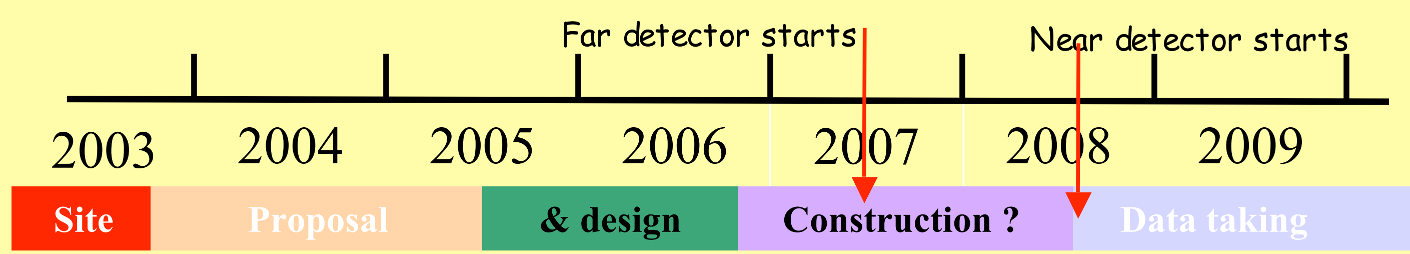
Double Chooz Sensitivity (2007-2012)



Far detector starts in 2007

Near detector 16 months later

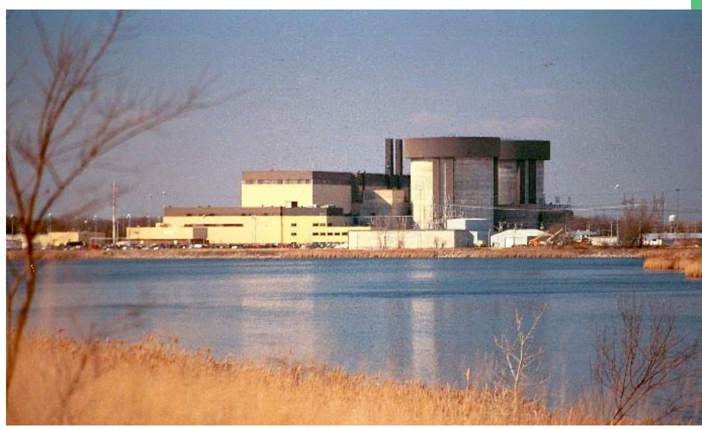
$\Delta m^2_{atm} = 2.8\ 10^{-3}\ eV^2$
Will be known to 20% by MINOS

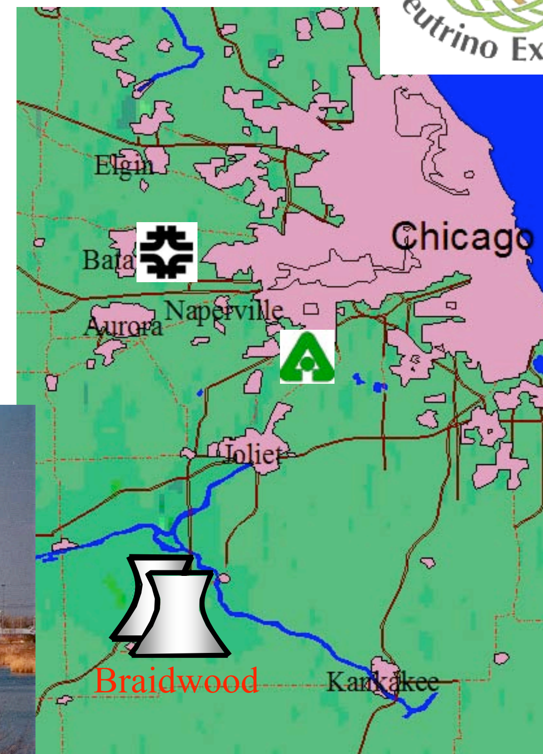


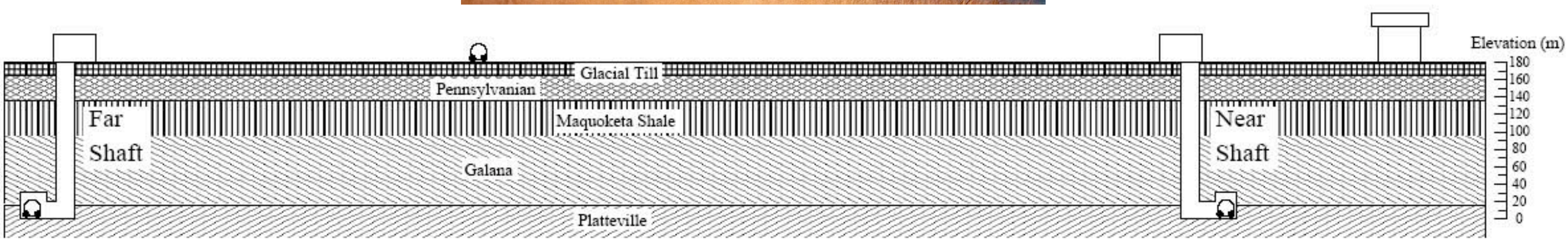
Braidwood Neutrino Experiment

Braidwood Setup

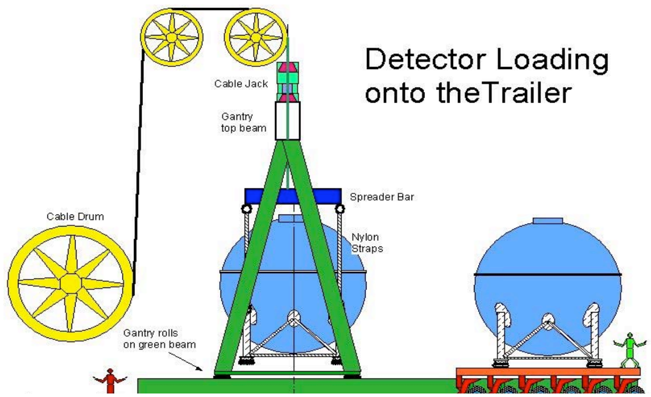
- Two 3.6 GW reactors
- **near:** 2x65 ton (fid vol), 270 m
- **far**: 2x65 ton (fid vol), 1510 m
- 180m shafts and detector halls (450 mwe) depth
- optimized distances



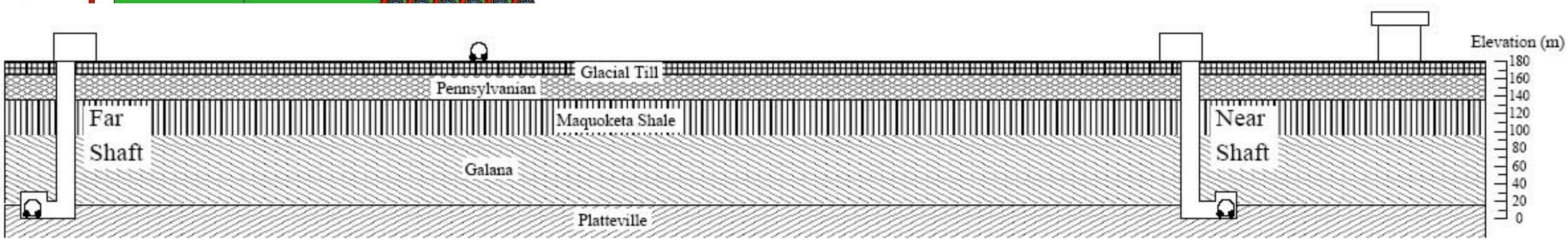


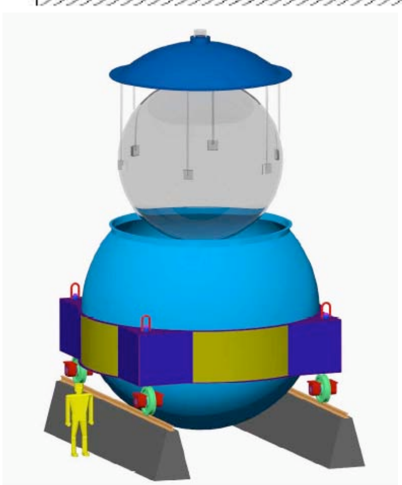


Braidwood Detector Concept



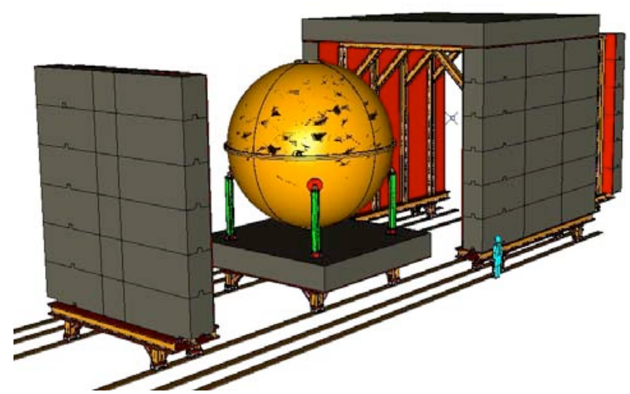
- Transport for moving detectors from construction/filling area to underground halls.
- Moving required for cross checks.





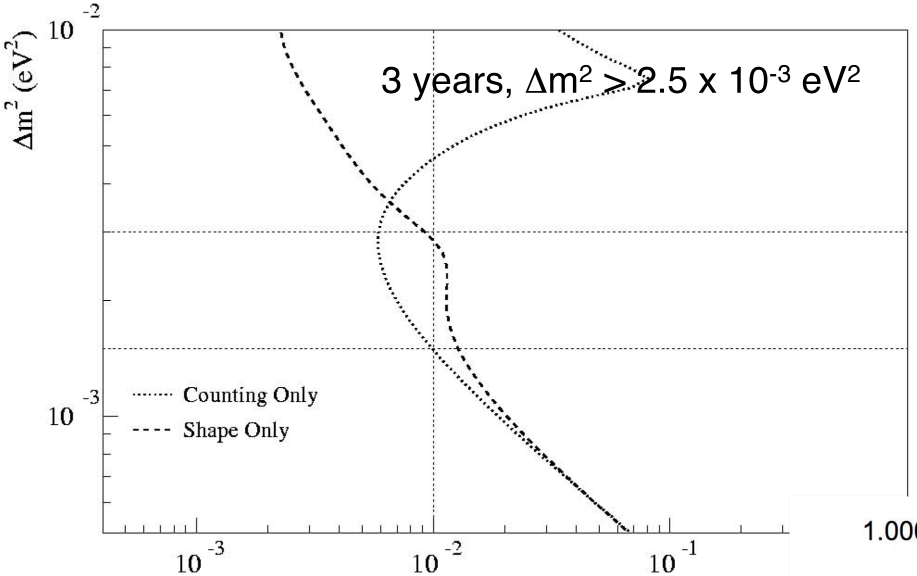
Karsten Heege

- Outer steel buffer oil containment (7m diameter)
- Inner acrylic Gd-Scint containment (5.2m diameter)
- 2-zone detector
- 1000 low activity glass 8” PMTs (25% coverage)



Goal: < 1 neutron background event/day/detector

Braidwood Sensitivity and Discovery Potential



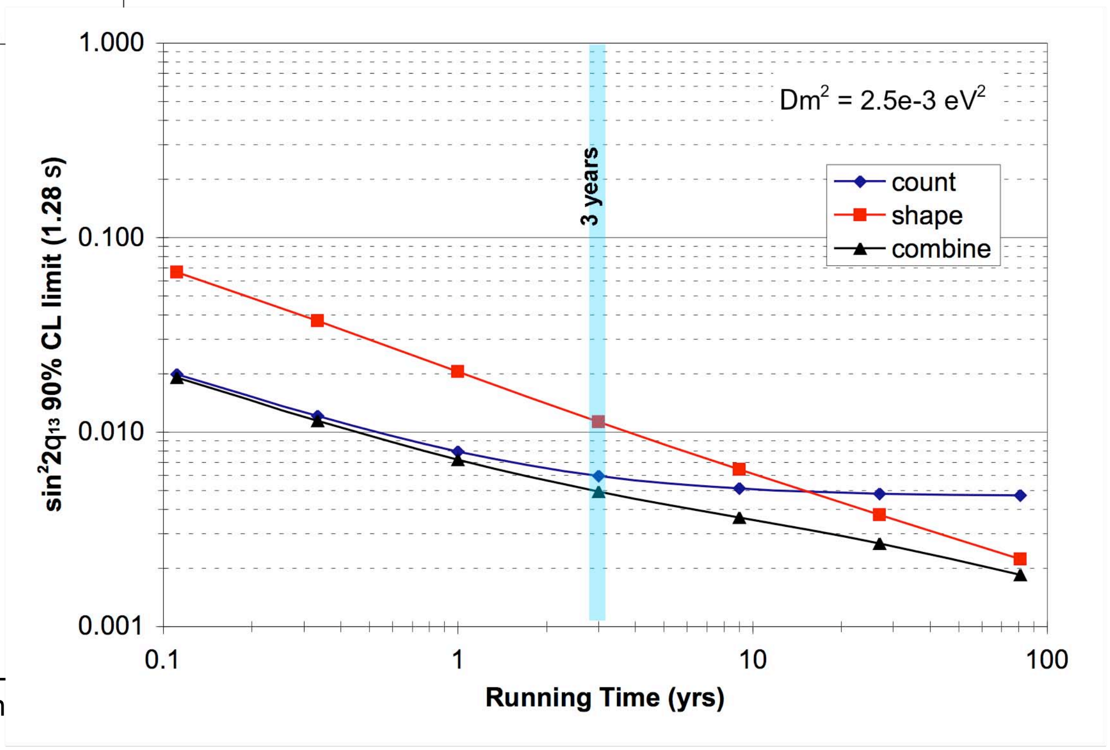
Sensitivity to $\sin^2 2\theta_{13}$ at 90% CL vs. Δm^2

90% CL limit at $\sin^2 2\theta_{13} < 0.005$

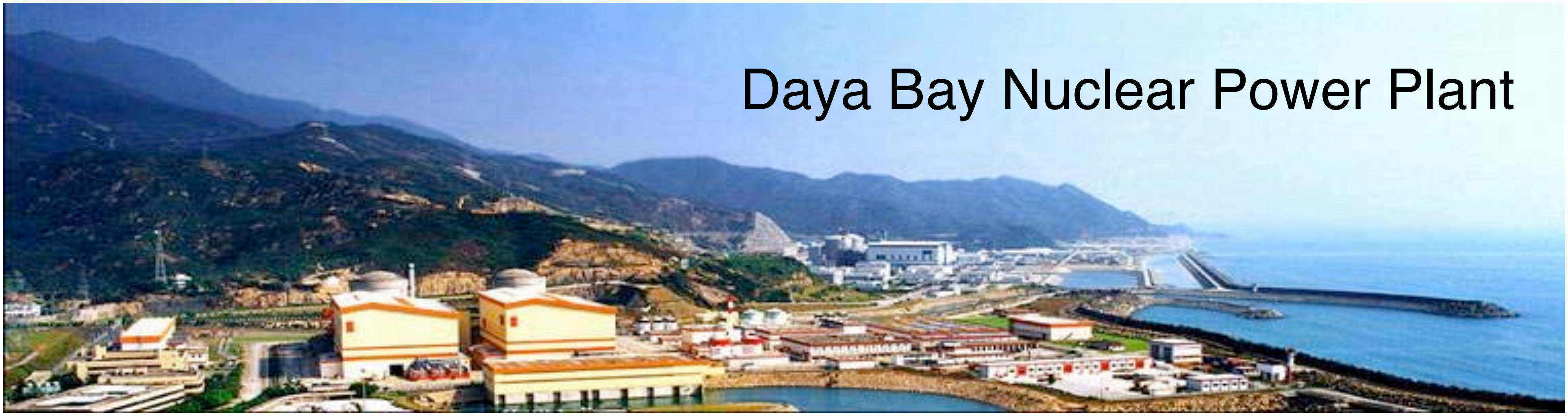
3 σ discovery for $\sin^2 2\theta_{13} > 0.013$

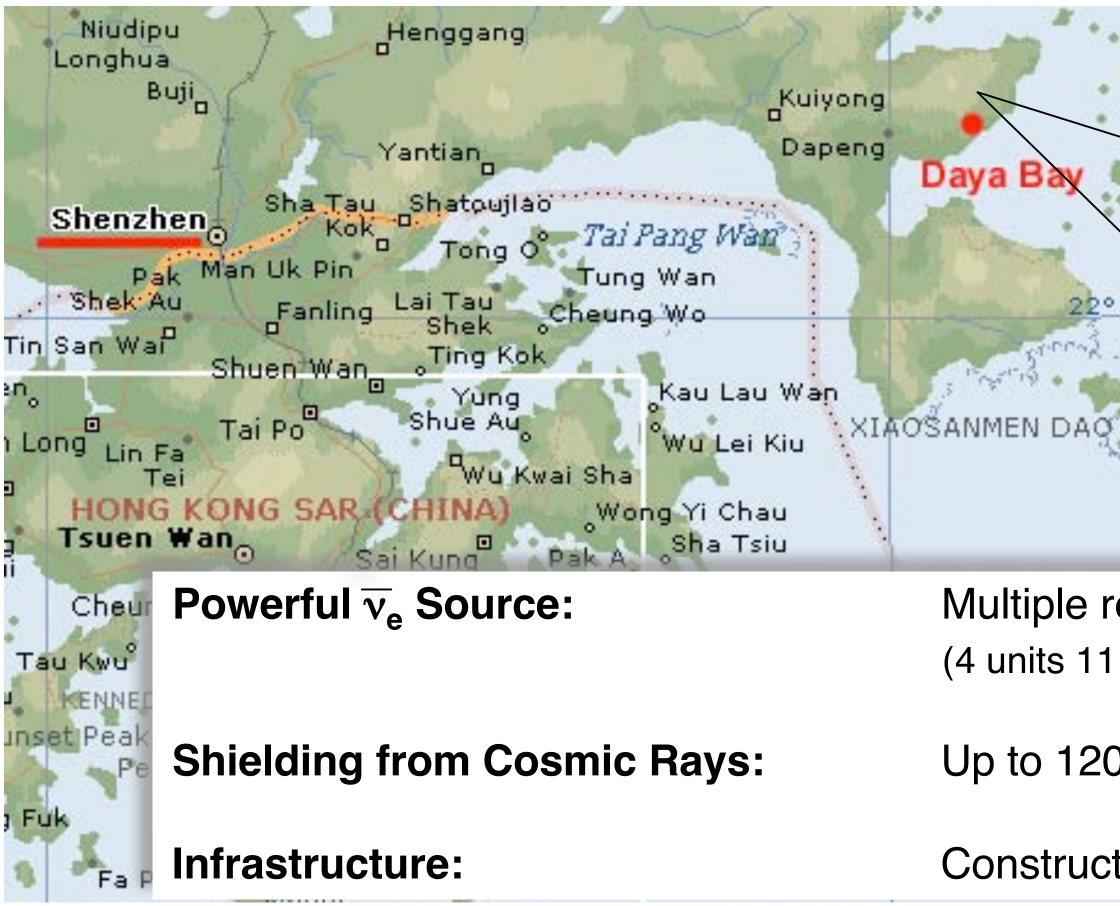
Uncertainties for 3 yr Data

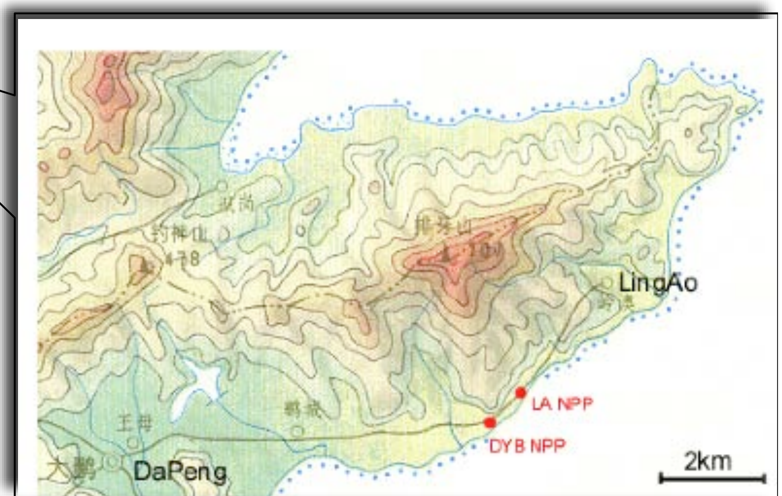
Source of Uncertainty	%
Relative Normalization for each Near/Far Detector Pair	0.3
Far Detector Statistics	0.2
Near Detector Statistics	0.04
Backgrounds	0.15



Daya Bay Nuclear Power Plant





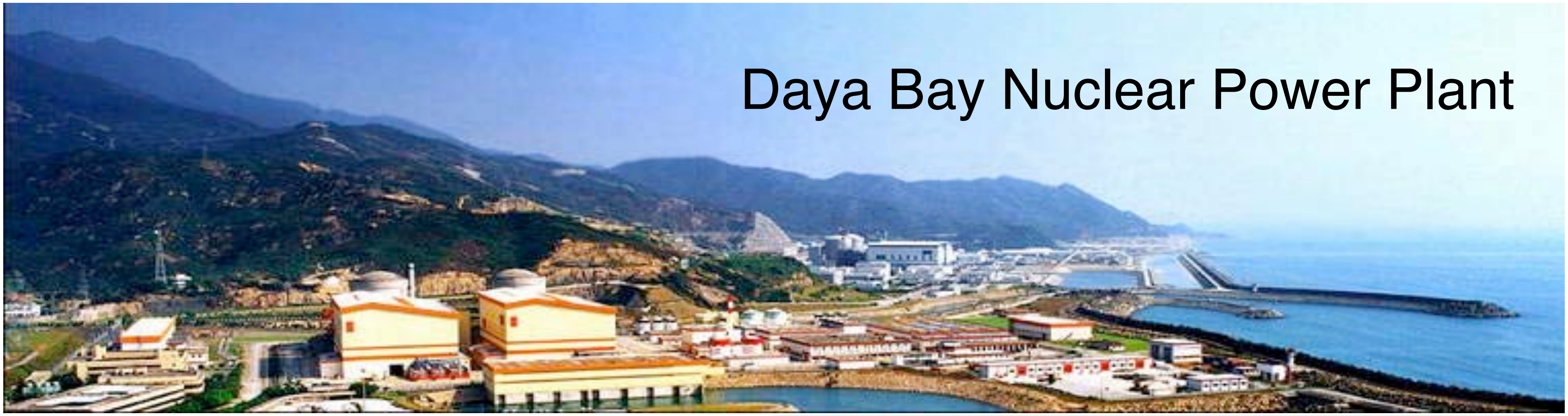


Powerful $\overline{\nu}_e$ Source: Multiple reactor cores.
(4 units 11.6 GW E_{th}, eventually 6 units 17.4 GW E_{th})

Shielding from Cosmic Rays: Up to 1200 mwe overburden nearby.

Infrastructure: Construction roads. Controlled access.

Daya Bay Nuclear Power Plant



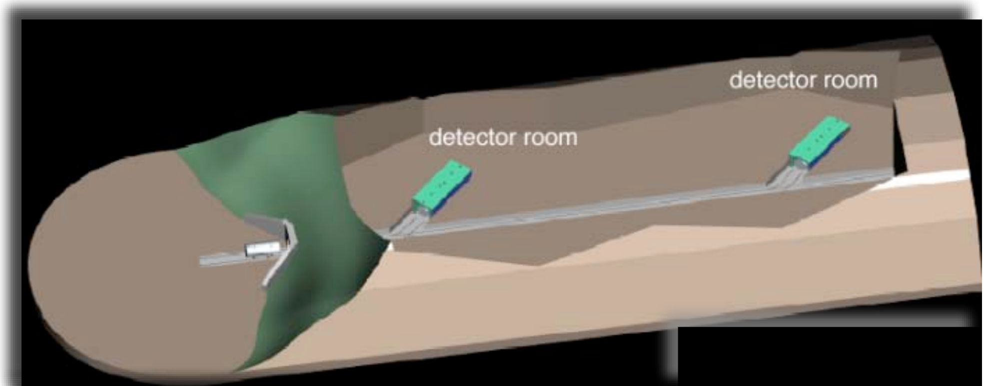
Laboratory with Horizontal Tunnels

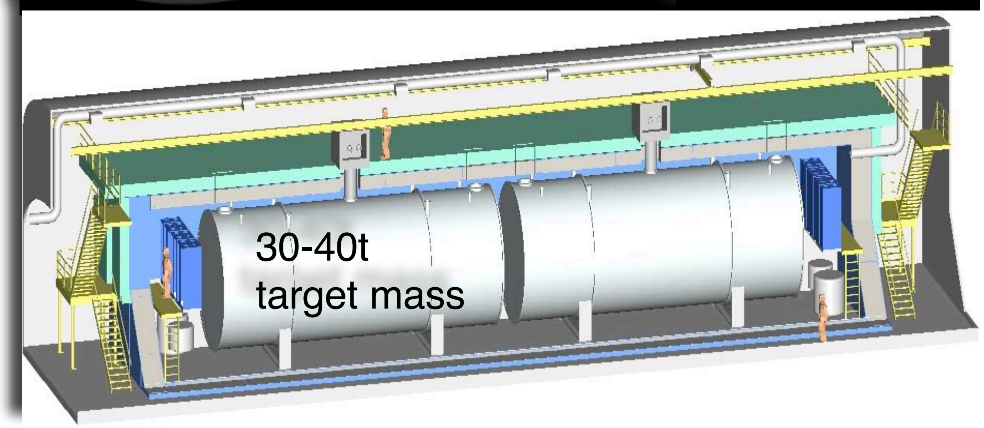
- Simplifying logistics: Build detectors outside before moving into tunnel.

- Swapping detectors: Eliminates most systematic errors. Helps understand backgrounds.

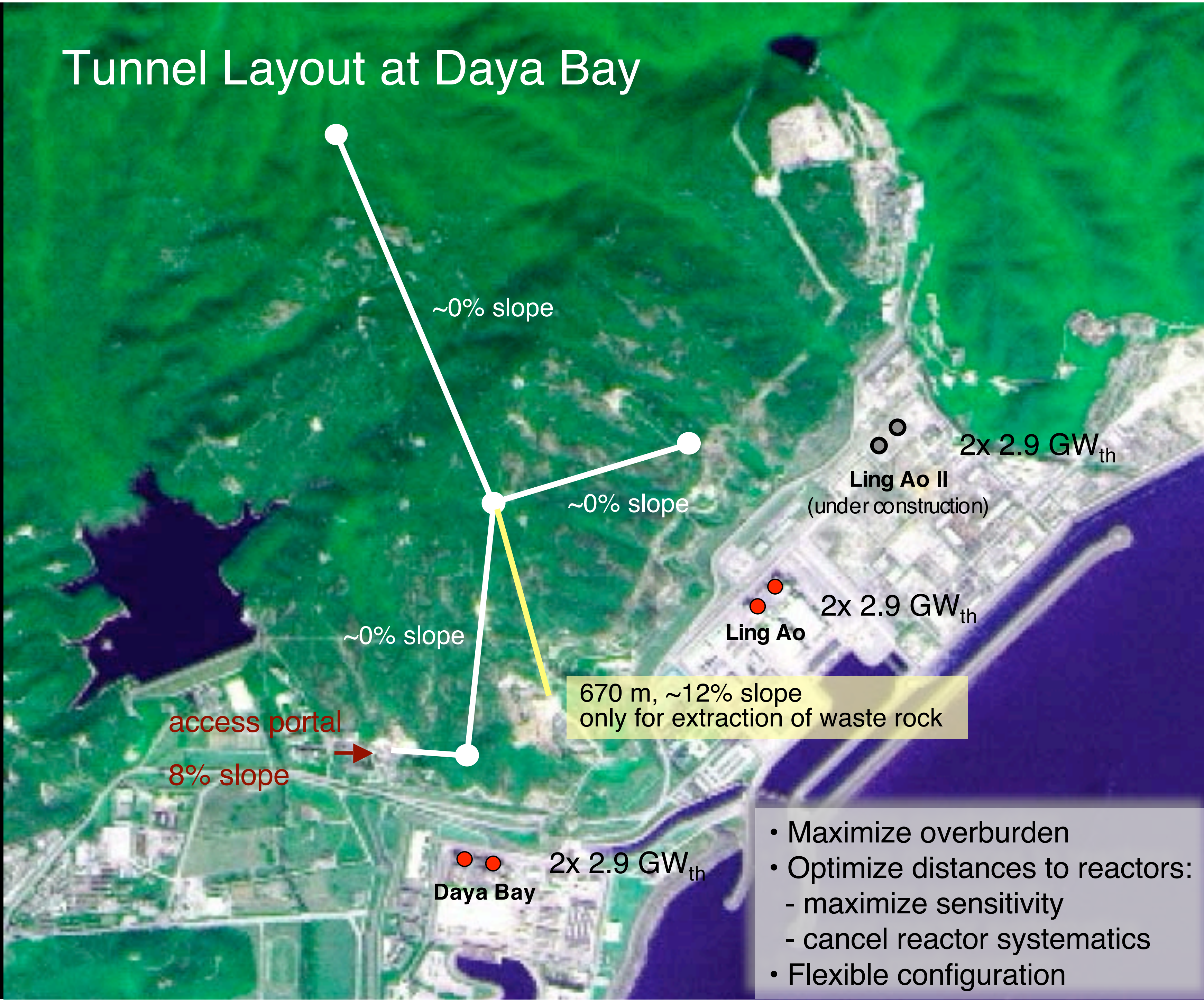
- Modular detectors: Phased approach, allowing rapid deployment, different configurations, and cross-calibration.

-Optimizing distance to reactors



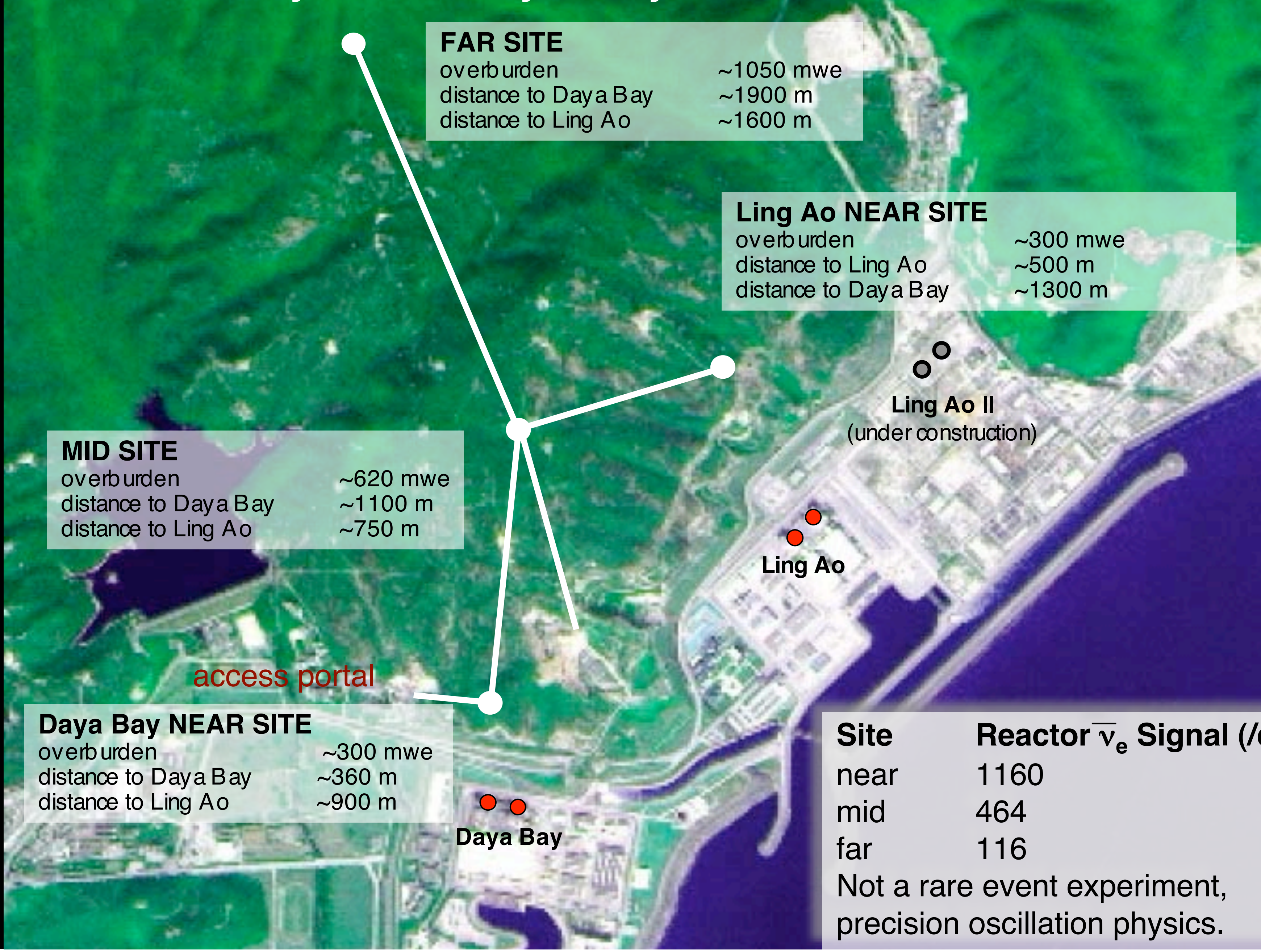


Tunnel Layout at Daya Bay



- Maximize overburden
- Optimize distances to reactors:
  - maximize sensitivity
  - cancel reactor systematics
- Flexible configuration

Tunnel Layout at Daya Bay



Site	Reactor $\overline{\nu}_e$ Signal (/day)
near	1160
mid	464
far	116

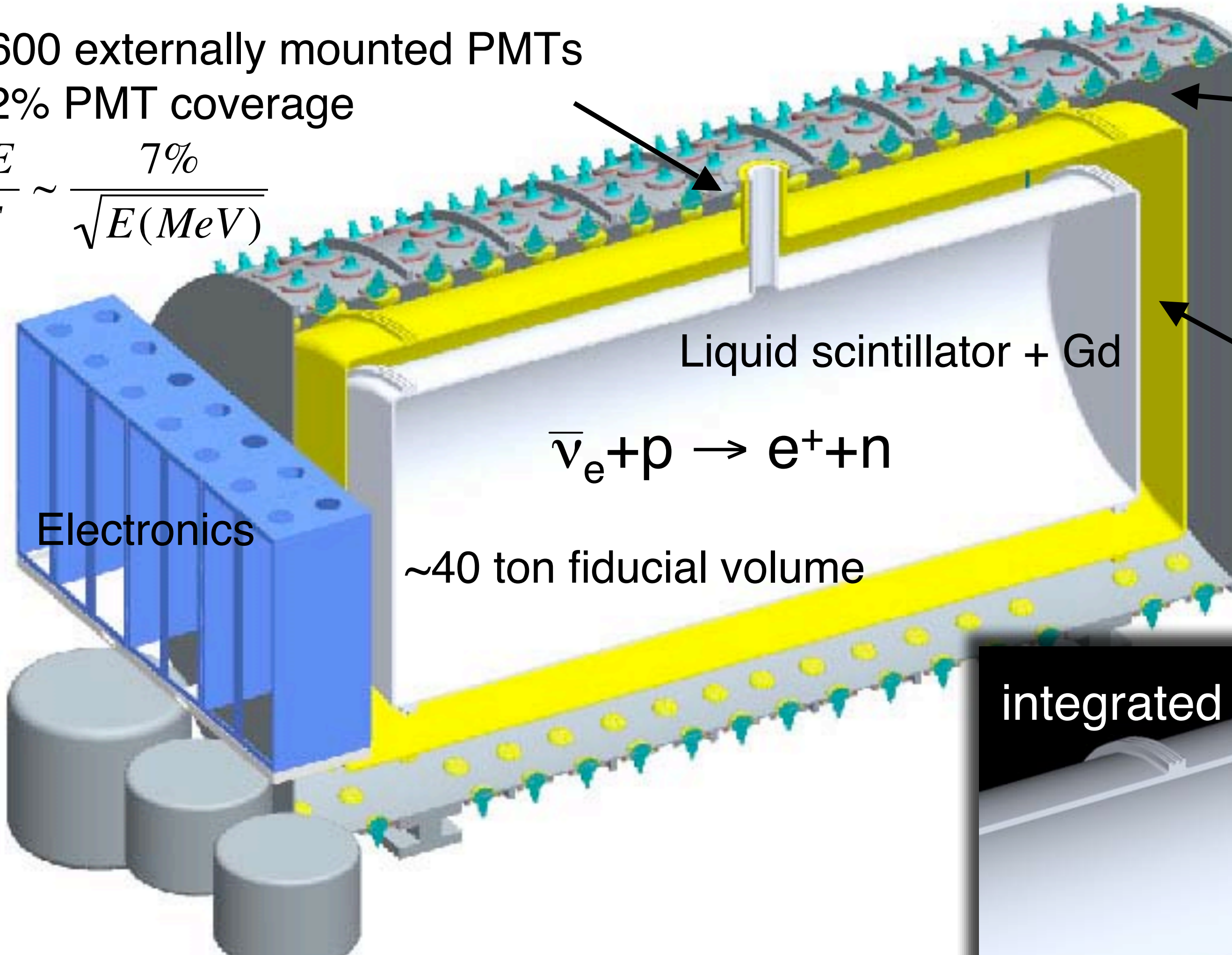
Not a rare event experiment, precision oscillation physics.

Development of Multi-Layer Detector Modules

Option A: horizontal, cylindrical modules

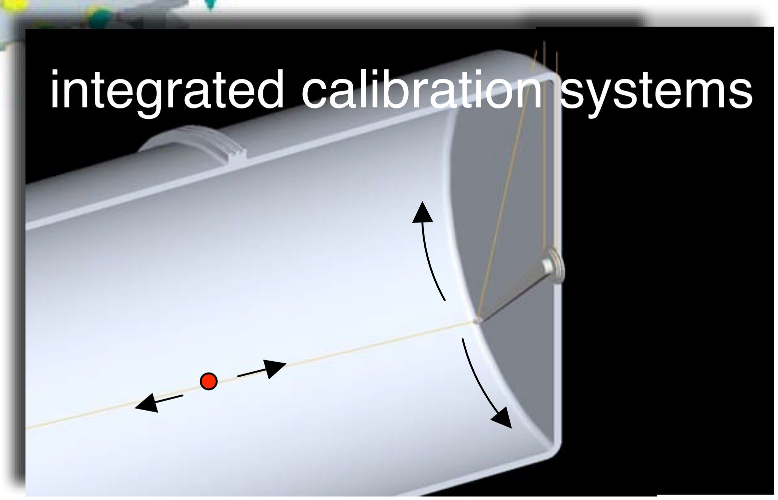
~600 externally mounted PMTs
12% PMT coverage

$$\frac{\Delta E}{E} \sim \frac{7\%}{\sqrt{E(MeV)}}$$



~40cm of mineral oil buffer to reduce backgrounds

Liquid scintillator (gamma catcher)
→ evaluating need for 2 or 3 zones

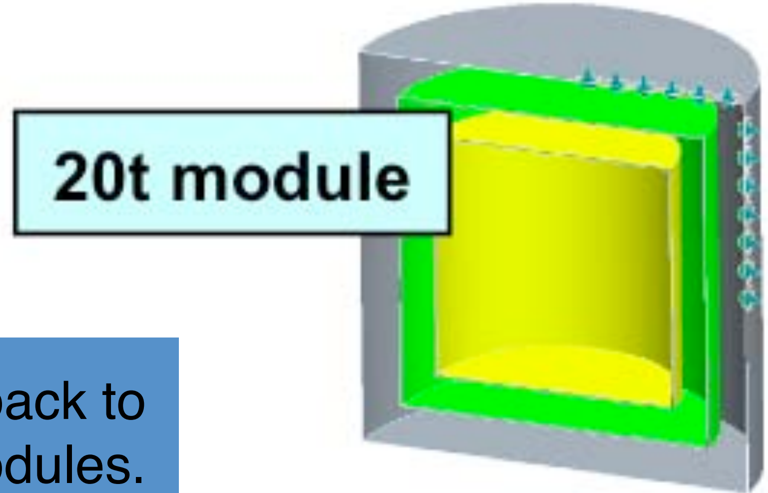


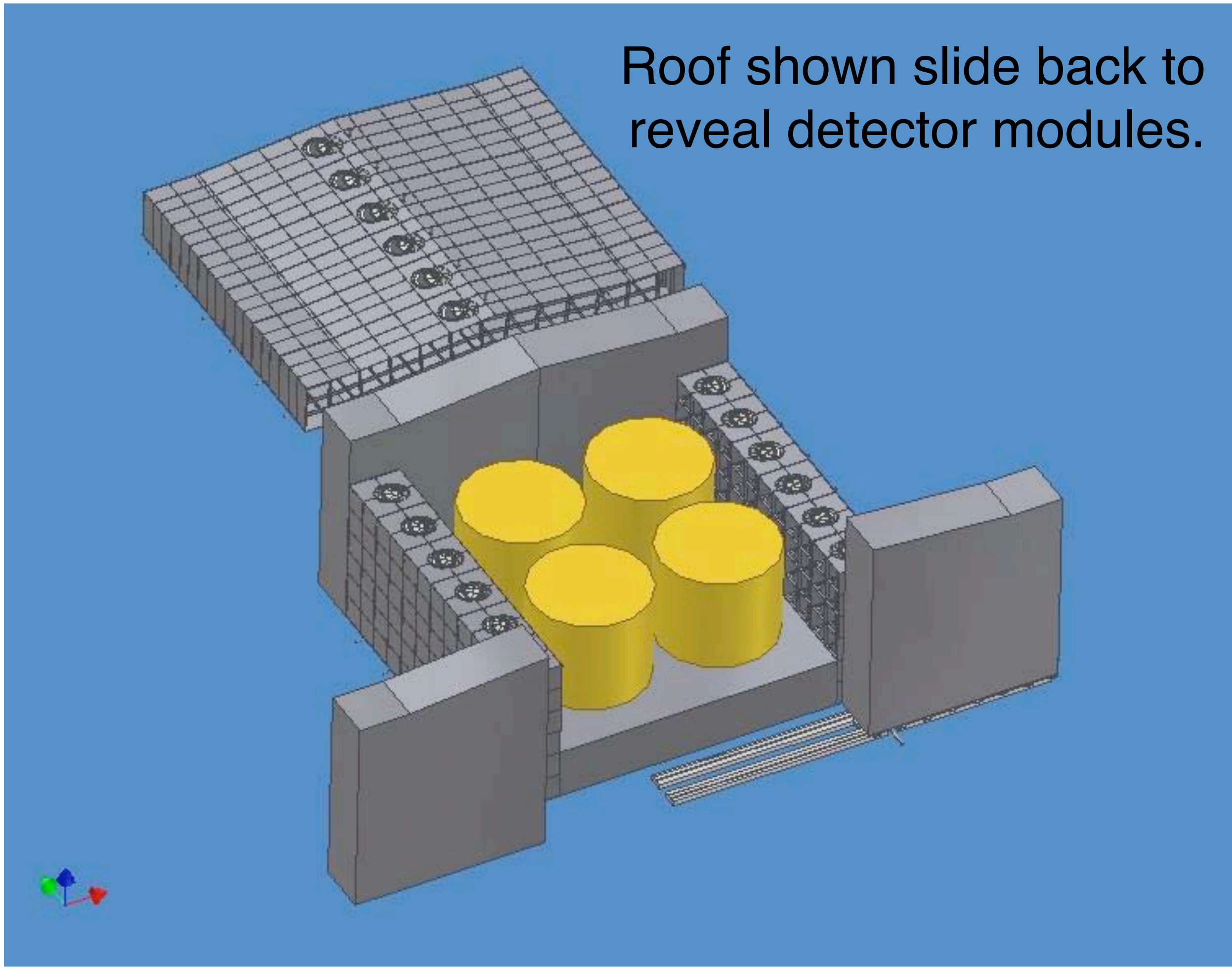
- movable over a distance of ~2km

Detector Design Studies

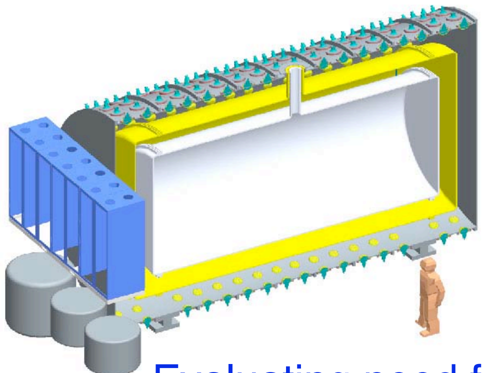
Option B: vertical, upright modules

- multiple modules, easier to fabricate
- modular muon shielding with water tanks





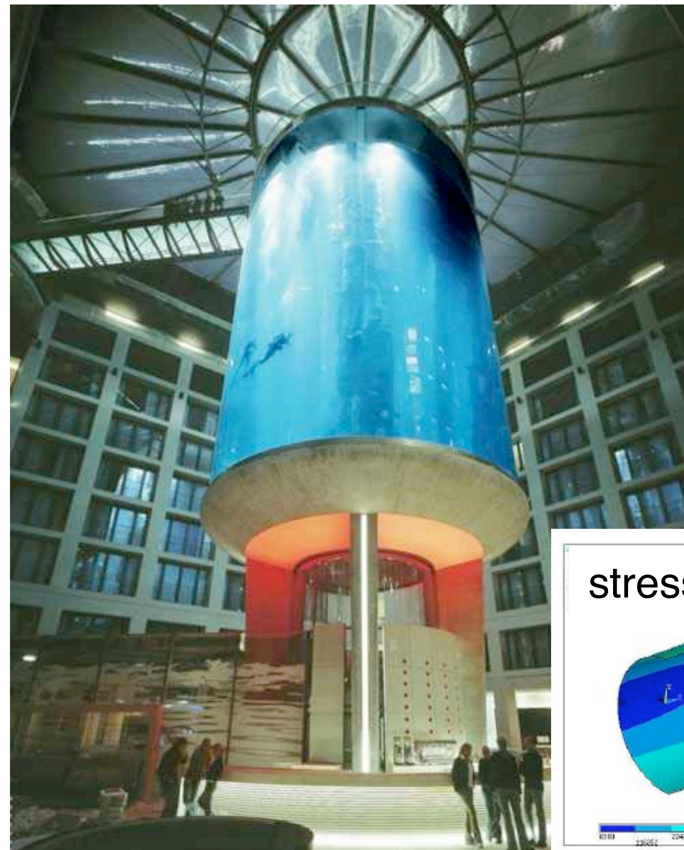
Technical Challenges: Multi-Layer Acrylic Detectors



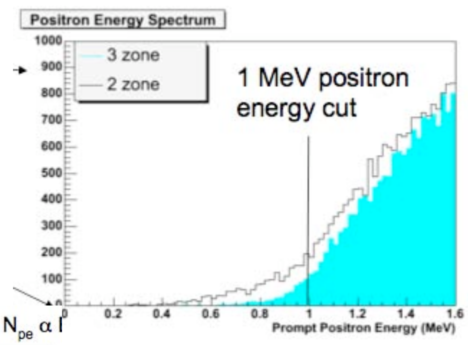
Evaluating need for 2 or 3 zones:

• third layer increases cost, difficulty of construction, complexity

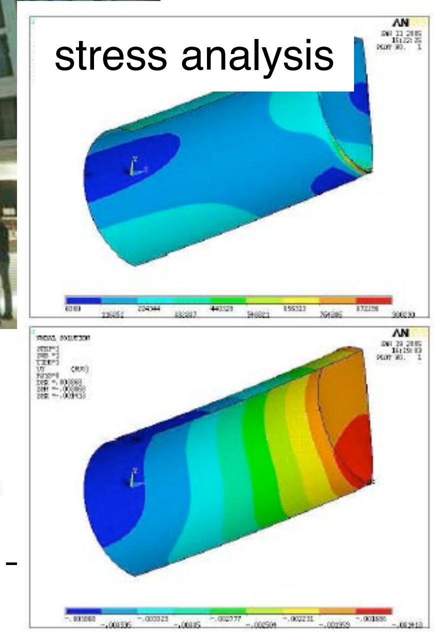
A commercial double-walled acrylic tank



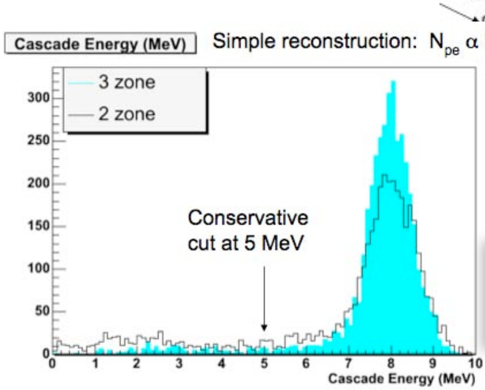
threshold on positron spectrum?



stress analysis



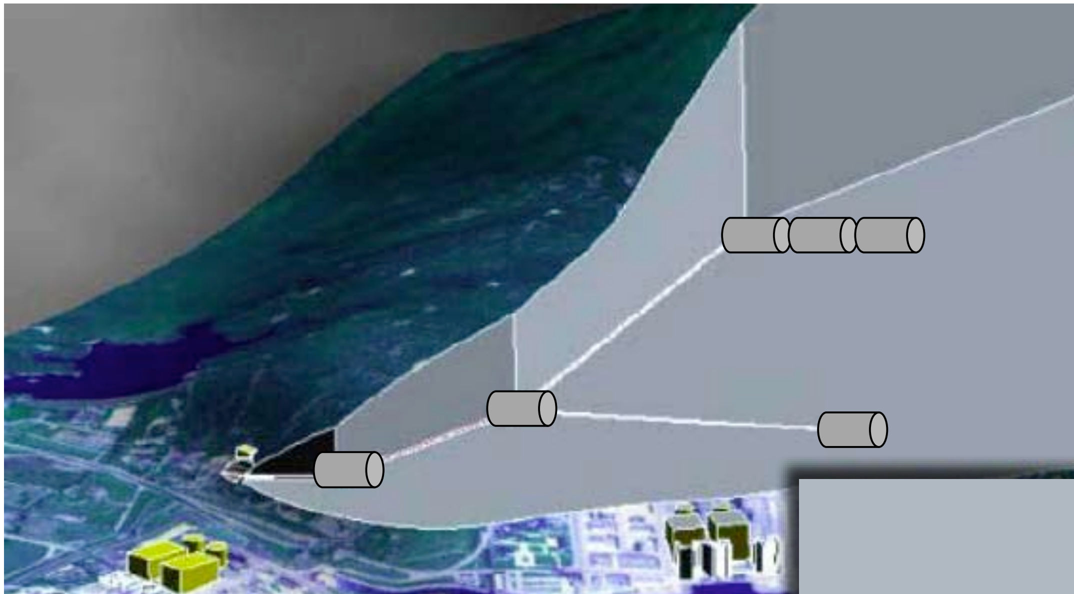
Simple reconstruction: $N_{pe} \propto E$



gamma cascade tail?

2-zone: cascade cut at ~4MeV gives an uncertainty of <0.2% for threshold uncertainties <1%

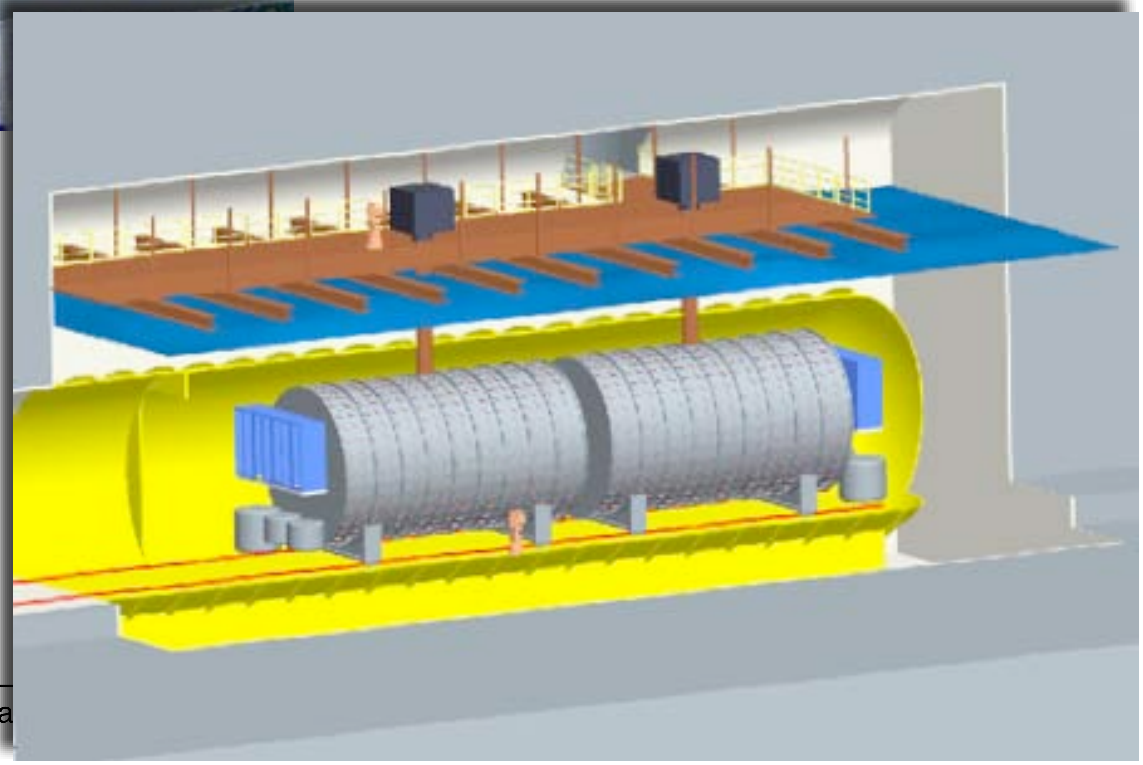
Movable Detector Modules in Underground Halls



Swapping: Cancellation of systematics

Side-by-Side Calibration: Initial side-by-side calibration at near site

Cross-Check of Modules



Mountainous Site With Horizontal Access Tunnel

- reduce systematics by swapping
- access to large overburden
- Daya Bay offers up to 1100 mwe overburden

Antineutrino candidate signal:

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

Muon flux underground

Correlated Backgrounds

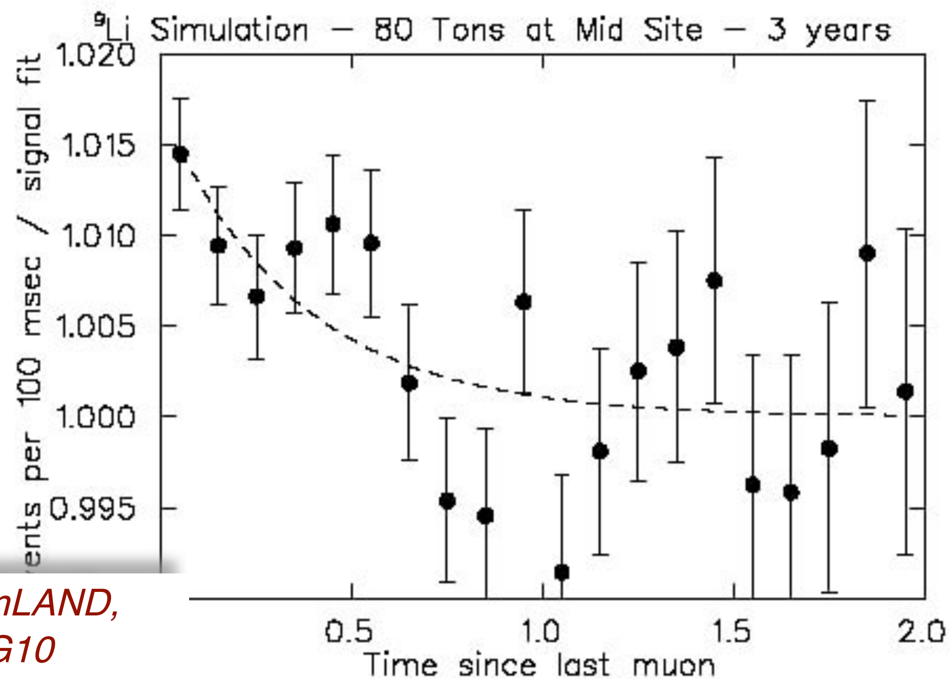
- Muon spallation
- ^{9}Li
- Fast neutrons

Correlated Backgrounds

Measuring ^{9}Li

Muon flux low enough at mid and far sites so that we can measure ^{9}Li production and subtract it.

mid:	depth	560 mwe
	μ	0.176/m^{2}/sec
	^{9}Li	0.32 ± 0.10%
far:	depth	~1100 mwe
	μ	0.016/m^{2}/sec
	^{9}Li	0.17 ± 0.14%



→ ^{9}Li at KamLAND, D. Dwyer, JG10

near: muon flux high, we cannot make sufficiently precise measurement of ^{9}Li background, need calculation based on measurements at mid and far site

Ref: Daya Bay US LOI

Correlated Backgrounds

Fast Neutrons

Neutrons can leave prompt signal due to nuclear reaction in LS, then thermalize and capture on Gd
→ coincidence signature

Past Experience: Chooz

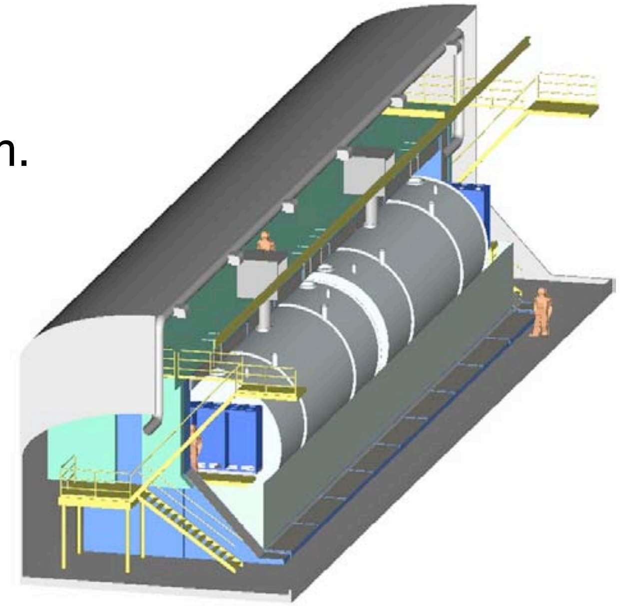
Observed neutron rate: 45+2/hr
Correlated background: ~1/day
→ Reduction of 10^{-3}

Site	Reactor $\bar{\nu}_e$ Signal (/day)	Correlated neutron rate (/day)	$\frac{\text{Neutron background}}{\text{Signal}}$
Near	1160	0.63	0.05%
Mid	464	0.22	0.05%
Far	116	0.03	0.03%

Note: If a substantial fraction of Chooz background is due to ^{9}Li then these calculations are upper limits → needs more MC studies.

Ref: Daya Bay US LOI

Muon System and Passive Shielding



Requirements

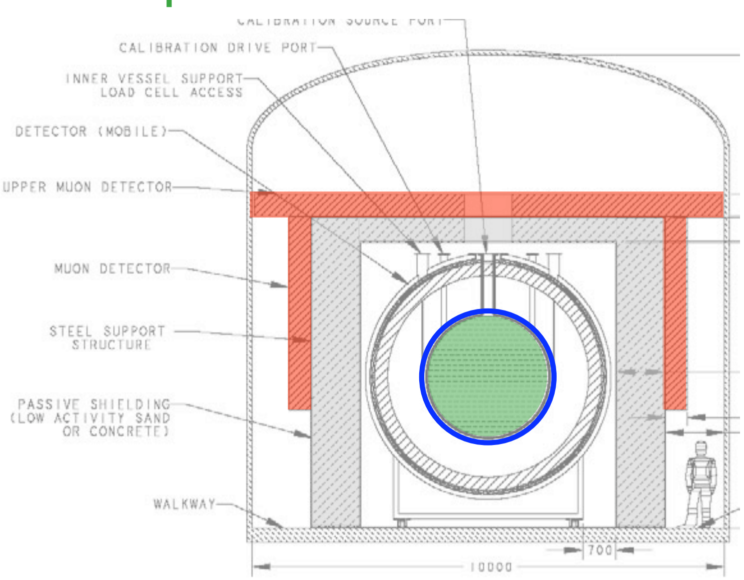
- Excellent muon tagging/tracking
- Low muon rates to <u>measure</u> muon-induced ^{9}Li spectrum.
- >2m water shielding around detector against neutrons.

Example of Passive Shielding: Sand or Water

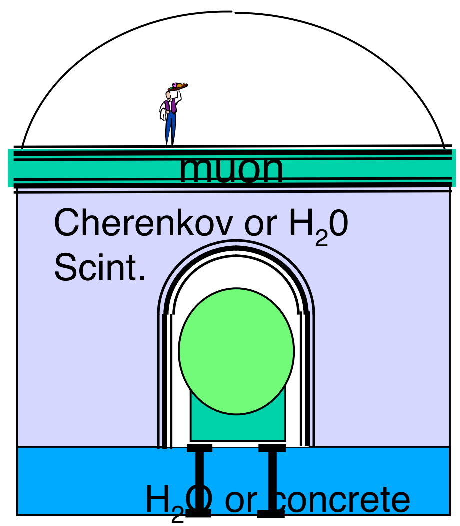
Active muon tracker

+ passive shielding

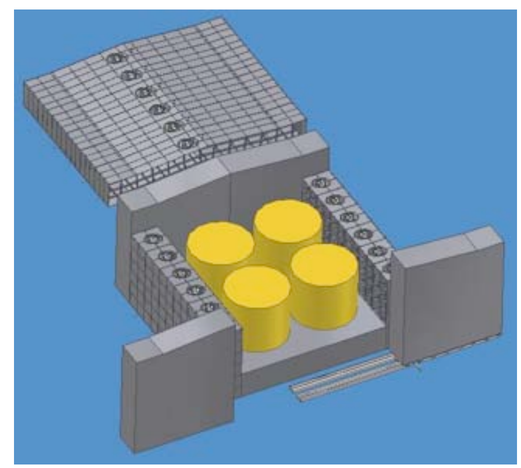
+ inner liquid scintillator detector



option A



option B



option C

Systematic Errors in the Daya Bay θ_{13} Experiment

Reactor Power Uncertainty

2% uncorrelated error per reactor core

Baseline configuration near	far	# cores	Uncertainty Power	Location	Total
500	2000	4	0.08%	0.08%	0.11%
500	2000	6	0.08%	0.06%	0.10%
1000	2000	4	0.20%	0.03%	0.20%
1000	2000	6	0.20%	0.03%	0.20%

Detector Systematics

Source of error		CHOOZ	Daya Bay Baseline	Daya Bay Goal
# protons	H/C ratio	0.8	0.2	0.1
	Mass	-	0.2	0.02
Detector Efficiency	Energy cuts	0.8	0.2	0.05
	Position cuts	0.32	0.0	0.0
	Time cuts	0.4	0.1	0.03
	H/Gd ratio	1.0	0.01	0.01
	n multiplicity	0.5	0.05	0.01
	Trigger	0	0.01	0.01
	Live time	0	< 0.01	< 0.01
Total detector-related uncertainty		1.7%	0.36%	0.12%

Background Uncertainties

Background error	CHOOZ	Daya Bay 500/2000	Daya Bay 1000/2000
correlated	0.6%	0.4%	0.17%
uncorrelated	0.3%	0.05%	0.05%

Projected sensitivity $\sin^2(2\theta_{13}) < 0.01$ at 90% CL

Ref: Daya Bay LOI

Power of Swapping Detectors

Source of error		CHOOZ	Daya Bay		
			Baseline	Goal	Swapping
# protons	H/C ratio	0.8	0.2	0.1	0.0
	Mass	-	0.2	0.02	0.006
Detector Efficiency	Energy cuts	0.8	0.2	0.05	0.05
	Position cuts	0.32	0.0	0.0	0.0
	Time cuts	0.4	0.1	0.03	0.03
	H/Gd ratio	1.0	0.01	0.01	0.0
	n multiplicity	0.5	0.05	0.01	0.01
	Trigger	0	0.01	0.01	0.01
	Live time	0	< 0.01	< 0.01	< 0.01
Total detector-related uncertainty		1.7%	0.36%	0.12%	0.06%

Ref: Daya Bay US LOI

Control of Systematics

Liquid monitoring in chimney: 0.1 l → rel. mass 0.006%

Livetime difference between (day/night at SNO): 5×10^{-7}

Energy response to calibration sources (KamLAND): 0.05% → rel. cut eff. 0.013%

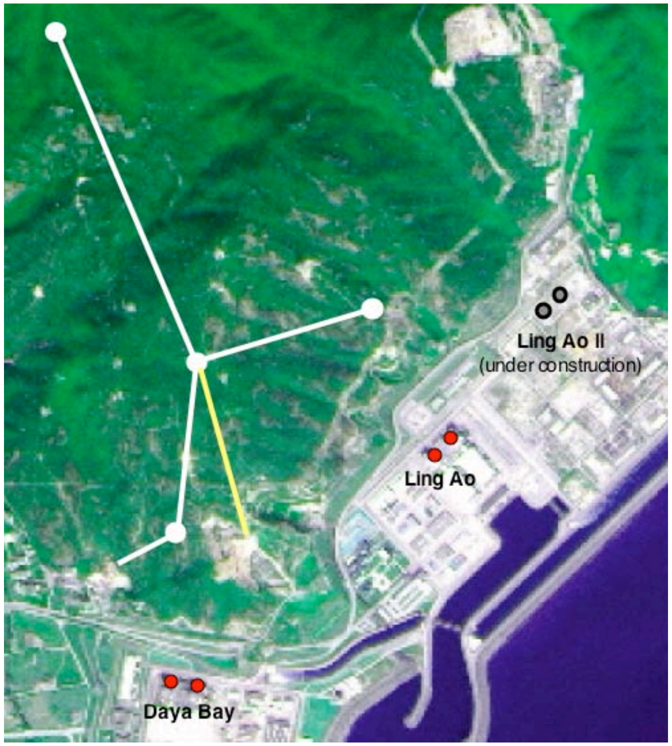
Combining data from 6 detector modules

correlated error (relative mass, n multiplicity) ~0.01%

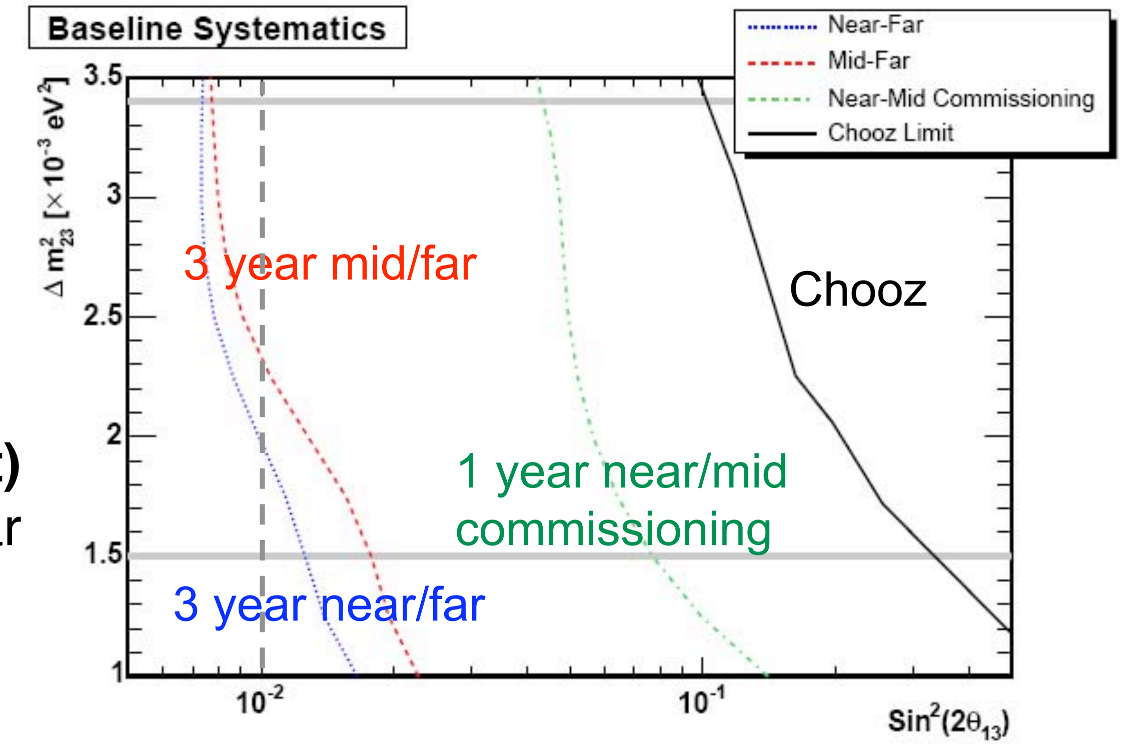
uncorrelated errors (energy scale, live time, time cuts): $0.06\%/\sqrt{6}=0.024\%$

→ combining them in quadrature: 0.026%

→ Reduction in detector-related systematic error by swapping with careful monitoring of detector performance.



Sensitivity in a Phased Experiment at Daya Bay



Scenarios Total Tonnage (t)
near1/near2/mid/far

near/mid 40-0-40-0

mid/far 0-0-80-120

near/far 40-40-0-120

near/mid/far 40-40-40-80

90% CL
$\Delta\chi^2=2.71,\ 1.64\sigma$

Ref: Daya Bay LOI

Sensitivity

Scenario Total Tonnage (t)
near1/near2/mid/far

near/mid 40-0-40-0

mid/far 0-0-80-120

near/far 40-40-0-120

Source of error		CHOOZ	Daya Bay	
			Baseline	Goal
# protons	H/C ratio	0.8	0.2	0.1
	Mass	-	0.2	0.02
Detector Efficiency	Energy cuts	0.8	0.2	0.05
	Position cuts	0.32	0.0	0.0
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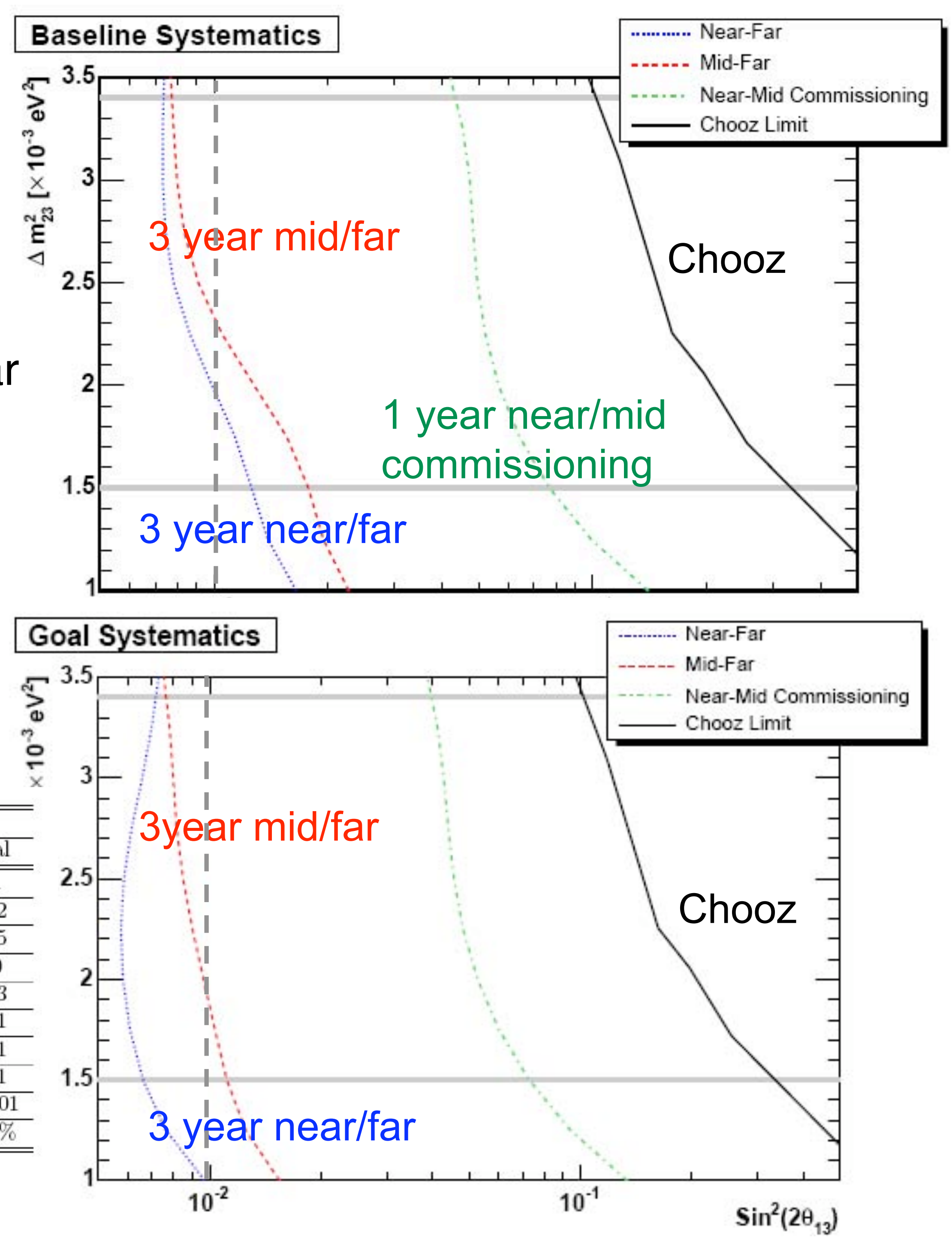
	H/Gd ratio	1.0	0.01	0.01
	n multiplicity	0.5	0.05	0.01
	Trigger	0	0.01	0.01
	Live time	0	< 0.01	< 0.01
Total detector-related uncertainty		1.7%	0.36%	0.12%



Timeline and Sensitivity of the Daya Bay Project

2005

Ongoing: geological studies

Oct-Dec: bore hole drilling

2007/2008

Start of data taking at near and mid sites

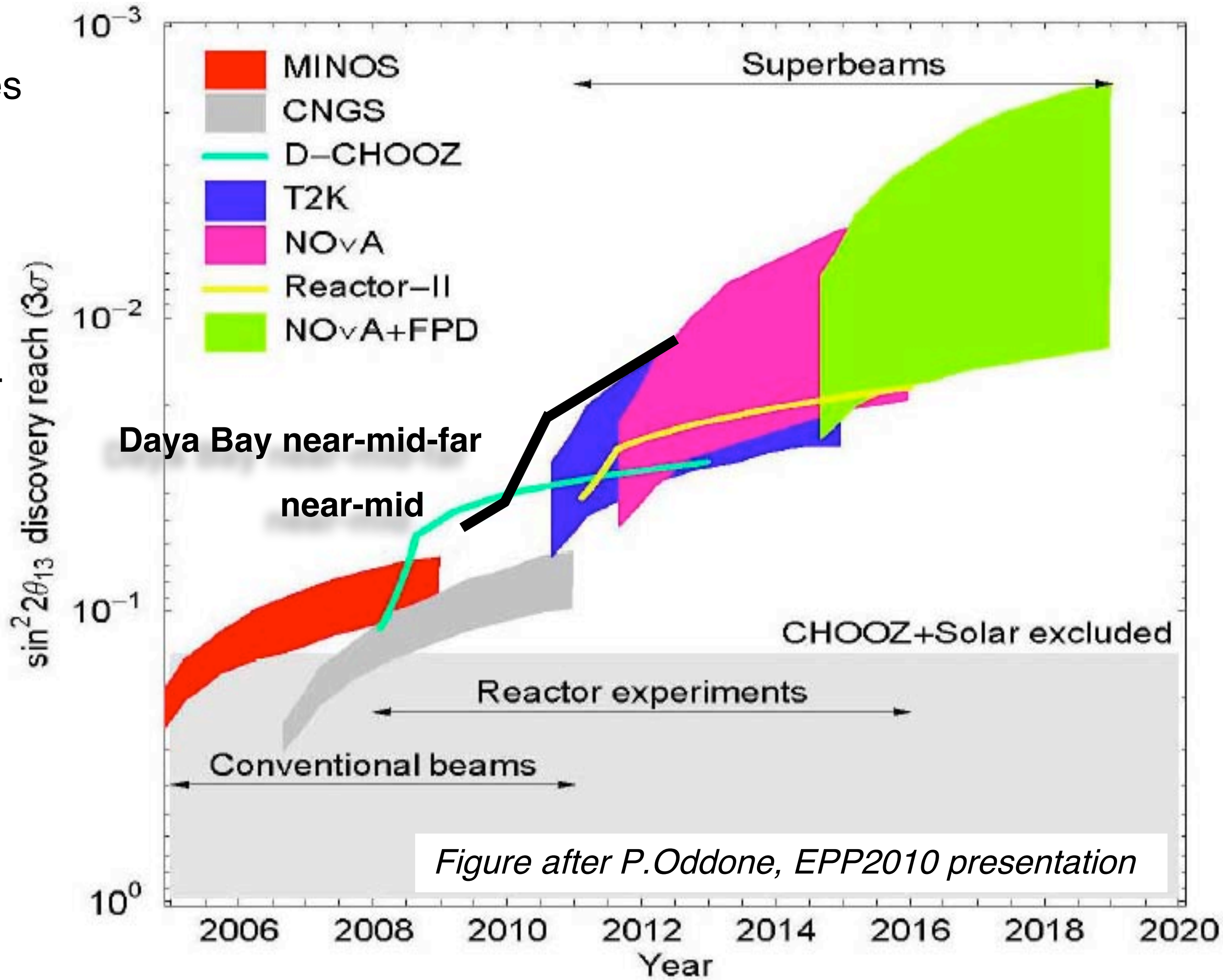
2009

First result based on near and mid sites.

Start of data taking at far site.

2010

First result based on data from far site.



Summary

• Measuring $\sin^2 2\theta_{13}$ with reactor antineutrinos will be challenging. (Ratio of two large numbers. Systematics < 1%)

• For precision oscillation physics we would like to measure $\sin^2 2\theta_{13} < 0.01$ at 90% CL. Greatest impact in long-term. Complementary with long-baseline experiments.

→ Optimize baseline, redundant measurement methods in reactor experiment.

• Three reactor θ_{13} experiments with US involvement have been proposed.

• NuSAG - Neutrino Science Assessment Group - is evaluating new experiments in neutrino physics. We are waiting for assessment of reactor and accelerator-based experiments.

• Phased approach of Daya Bay with different configurations creates program for measuring θ_{13}, with

→ early results (near-mid, few % in $\sin^2 2\theta_{13}$)

→ long-term reach ($\sin^2 2\theta_{13} < 0.01$)

→ cross-check with 3 baselines (near-far, mid-far, near-mid-far)

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Institute of High Energy Physics, Beijing
Iowa State University
Joint Institute for Nuclear Research
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Tsing Hua University
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University of Hong Kong
University of Maryland
University of Illiinois at Urbana-Champaign
University of Science and Technology of China

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