Neutrino Experiments with Reactors

Ed Blucher, Chicago

- Reactors as antineutrino sources
- Antineutrino detection
- Reines-Cowan experiment
- Oscillation Experiments
  - Solar Δm^2 (KAMLAND)
  - Atmospheric Δm^2 -- θ_{13} (CHOOZ, Double-Chooz, Daya Bay)
- Conclusions

Lecture 2

Atmospheric Δm^2: Searching for θ_{13} with Reactors

- Importance of θ_{13}
- Experimental approaches to θ_{13}; motivation for a precise reactor experiment
- Designing an ideal experiment
- Planned experiments
- Conclusions

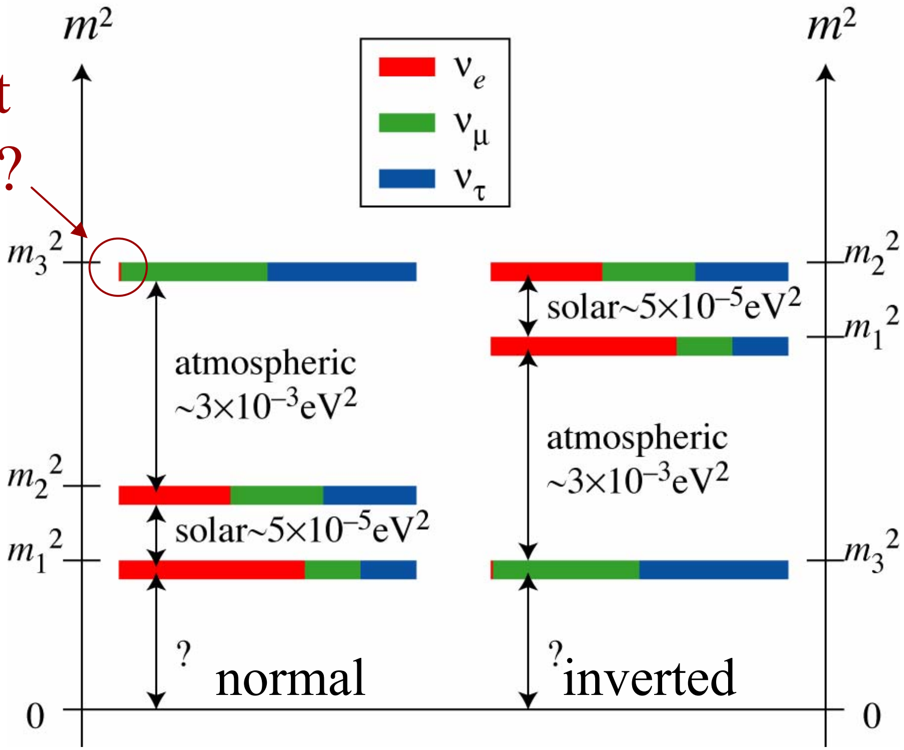
Neutrino mixing and masses

$$U=\begin{pmatrix} U_{e1} & U_{e2} & \boxed{U_{e3}} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix}=\begin{pmatrix} Big & Big & Small\,? \\ Big & Big & Big \\ Big & Big & Big \end{pmatrix}$$

$$=\begin{pmatrix} \cos\theta_{12} & \sin\theta_{12} & 0 \\ -\sin\theta_{12} & \cos\theta_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}\times\begin{pmatrix} \cos\theta_{13} & 0 & e^{-i\delta_{CP}}\sin\theta_{13} \\ 0 & 1 & 0 \\ -e^{i\delta_{CP}}\sin\theta_{13} & 0 & \cos\theta_{13} \end{pmatrix}\times\begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\theta_{23} & \sin\theta_{23} \\ 0 & -\sin\theta_{23} & \cos\theta_{23} \end{pmatrix}$$

$\theta_{12} \sim 30°$ $\sin^2 2\theta_{13} < 0.15$ at 90% CL $\theta_{23} \sim 45°$

What is ν_e component of ν_3 mass eigenstate?



Key questions in neutrino mixing

- What is value of θ_{13}?

- What is mass hierarchy?

- Do neutrino oscillations violate CP symmetry?

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

- Why are quark and neutrino mixing matrices so different?

$$U_{MNSP} \sim \begin{pmatrix} Big & Big & Small? \\ Big & Big & Big \\ Big & Big & Big \end{pmatrix} \quad \text{vs.} \quad V_{CKM} \sim \begin{pmatrix} 1 & Small & Small \\ Small & 1 & Small \\ Small & Small & 1 \end{pmatrix}$$

⇨ 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 ($\nu_\mu \rightarrow \nu_e$) at $\Delta m^2 \approx 2.5\times10^{-3}$ eV^2

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

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

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

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

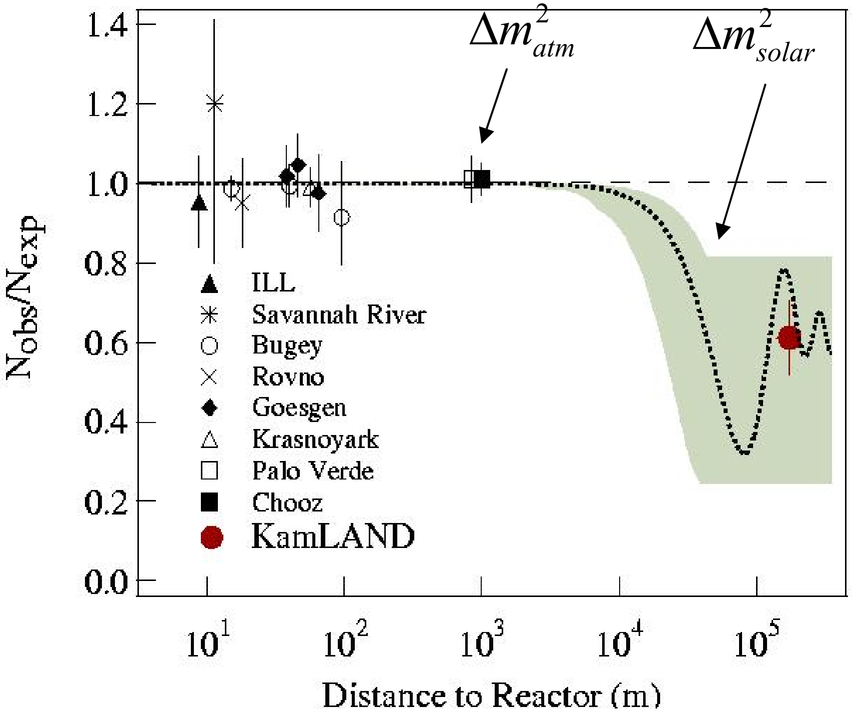
$$P(\bar{\nu}_e \rightarrow \bar{\nu}_e) = 1 - \sin^2 2\theta_{13}\sin^2\frac{\Delta m^2_{13}L}{4E} + \text{ very small terms}$$

Use reactors as a source of ν_e ($\langle E_\nu \rangle \sim 3.5$ MeV) with a detector 1-2 kms away and look for non-$1/r^2$ behavior of the ν_e rate

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

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

Past measurements:



Goals:

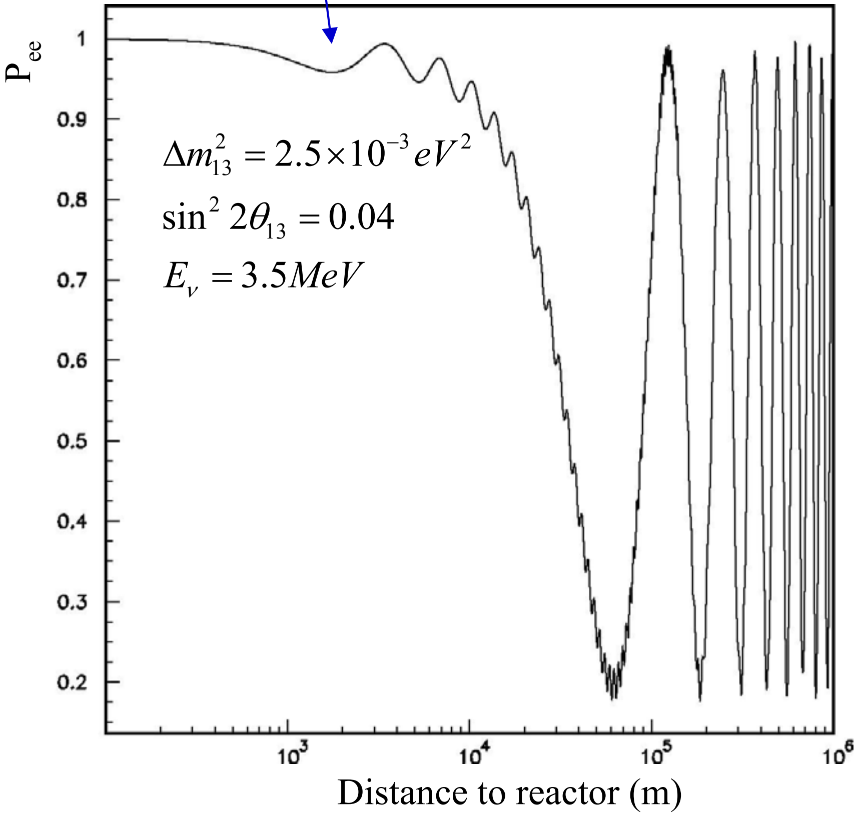
Small: $\sin^2 2\theta_{13} < 0.03$

Medium: $\sin^2 2\theta_{13} < 0.01$

Large: $\sin^2 2\theta_{13} < 0.005$

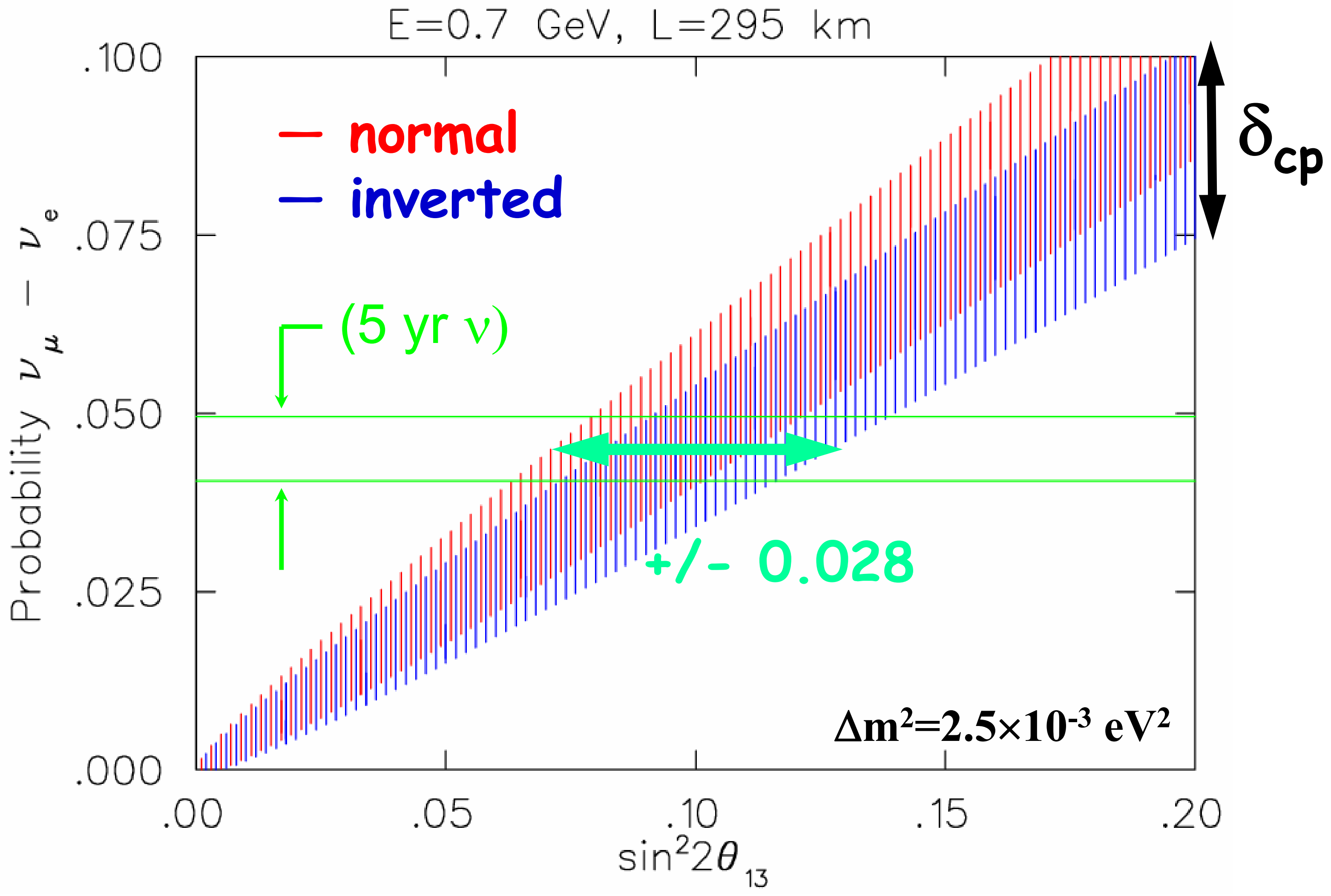
θ_{13}: Search for small oscillations at 1-2 km distance (corresponding to Δm^2_{atm}).

$$P(\bar{\nu}_e \to \bar{\nu}_e) \approx \underbrace{1 - \sin^2 2\theta_{13} \sin^2 \frac{\Delta m^2_{13} L}{4E}}_{} - c^4_{13} \sin^2 2\theta_{12} \sin^2 \frac{\Delta m^2_{12} L}{4E}$$



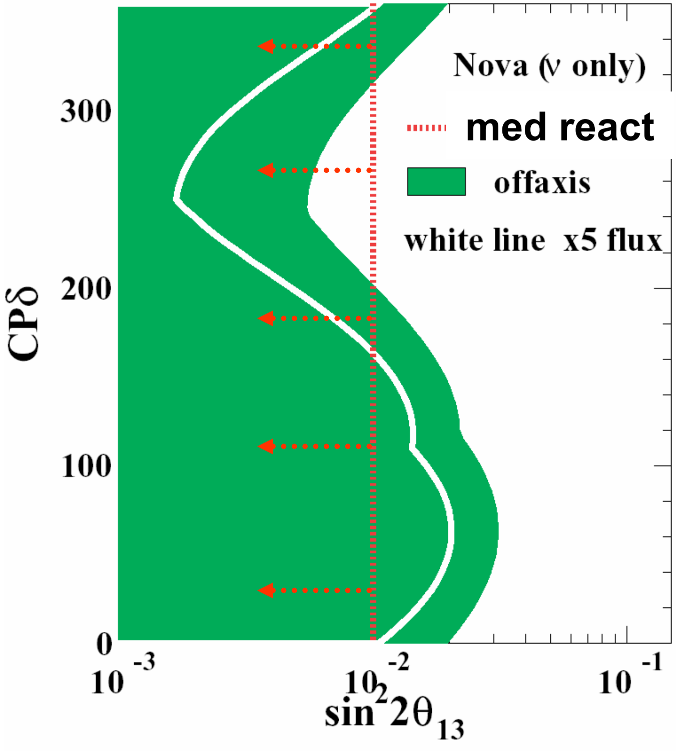
Both reactor and accelerator experiments have sensitivity to $\sin^2 2\theta_{13}$, but accelerator measurements have ambiguities

Example: T2K. $\Delta P(\nu_\mu \rightarrow \nu_e) = 0.0045 \rightarrow \Delta\sin^2 2\theta_{13} = 0.028$



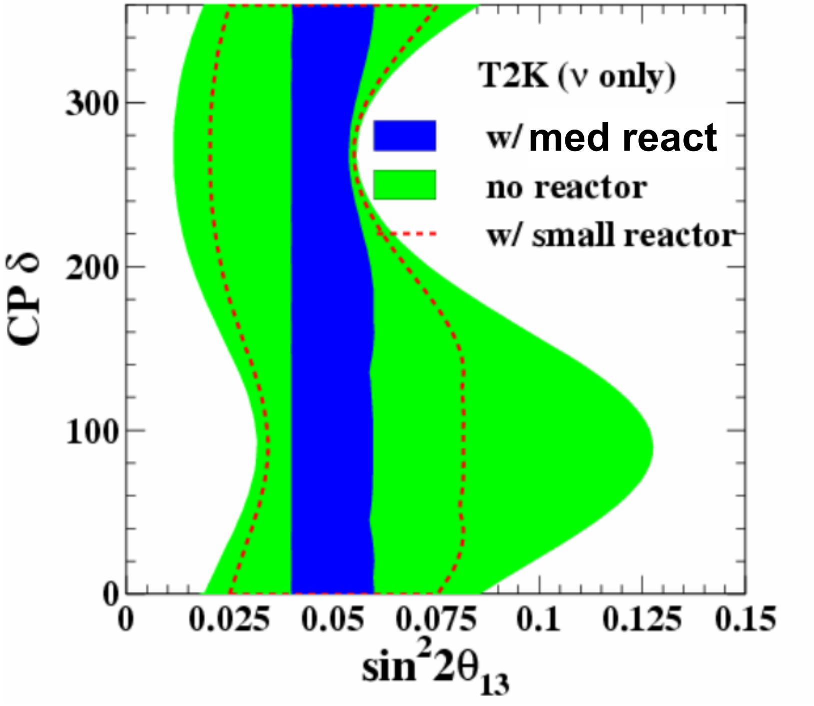
Reactor and accelerator sensitivities to $\sin^2 2\theta_{13}$

90% CL exluded regions with no osc.signal



δ_{CP}=0, $\Delta m^2 = 2.5\times10^{-3}$ eV^2
(3 yr reactor, 5 yr Nova)

90% CL allowed regions with osc.signal



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

Resolving the θ_{23} Degeneracy

ν_μ disappearance experiments measure $\sin^2 2\theta_{23}$, while $P(\nu_\mu \rightarrow \nu_e) \propto \sin^2\theta_{23} \sin^2 2\theta_{13}$.

- If $\theta_{23} \neq 45°$, ν_μ disappearance experiments, leave a 2-fold degeneracy in θ_{23} – it can be resolved by combination of a reactor and $\nu_\mu \rightarrow \nu_e$ appearance experiment.

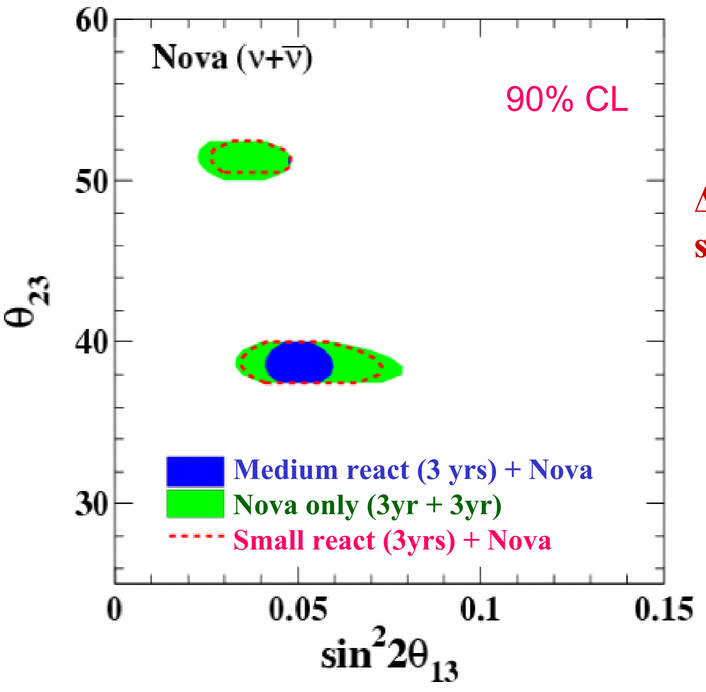
Green: Nova Only

Blue: Medium Reactor plus Nova

Red: Small reactor plus offaxis

Example:

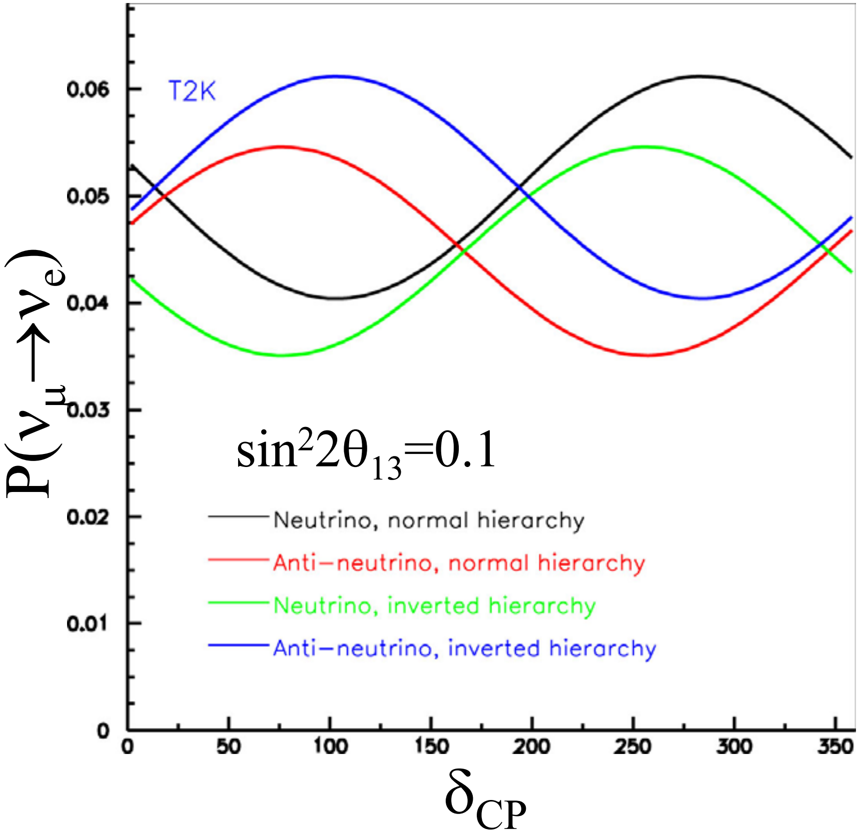
$\sin^2 2\,\theta_{23} = 0.95 \pm 0.01$
$\Delta m^2 = 2.5\times10^{-3}\ \mathrm{eV}^2$
$\sin^2 2\theta_{13} = 0.05$



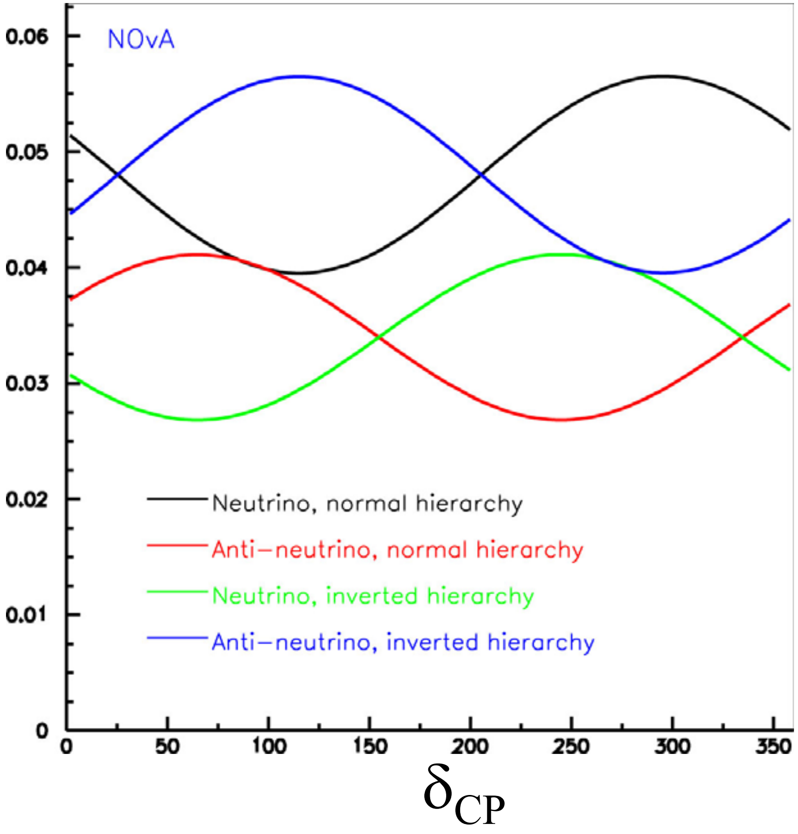
$\Delta m^2 = 2.5\times10^{-3}\ \mathrm{eV}^2$
$\sin^2 2\theta_{13} = 0.05$

CP Violation and the Mass Hierarchy

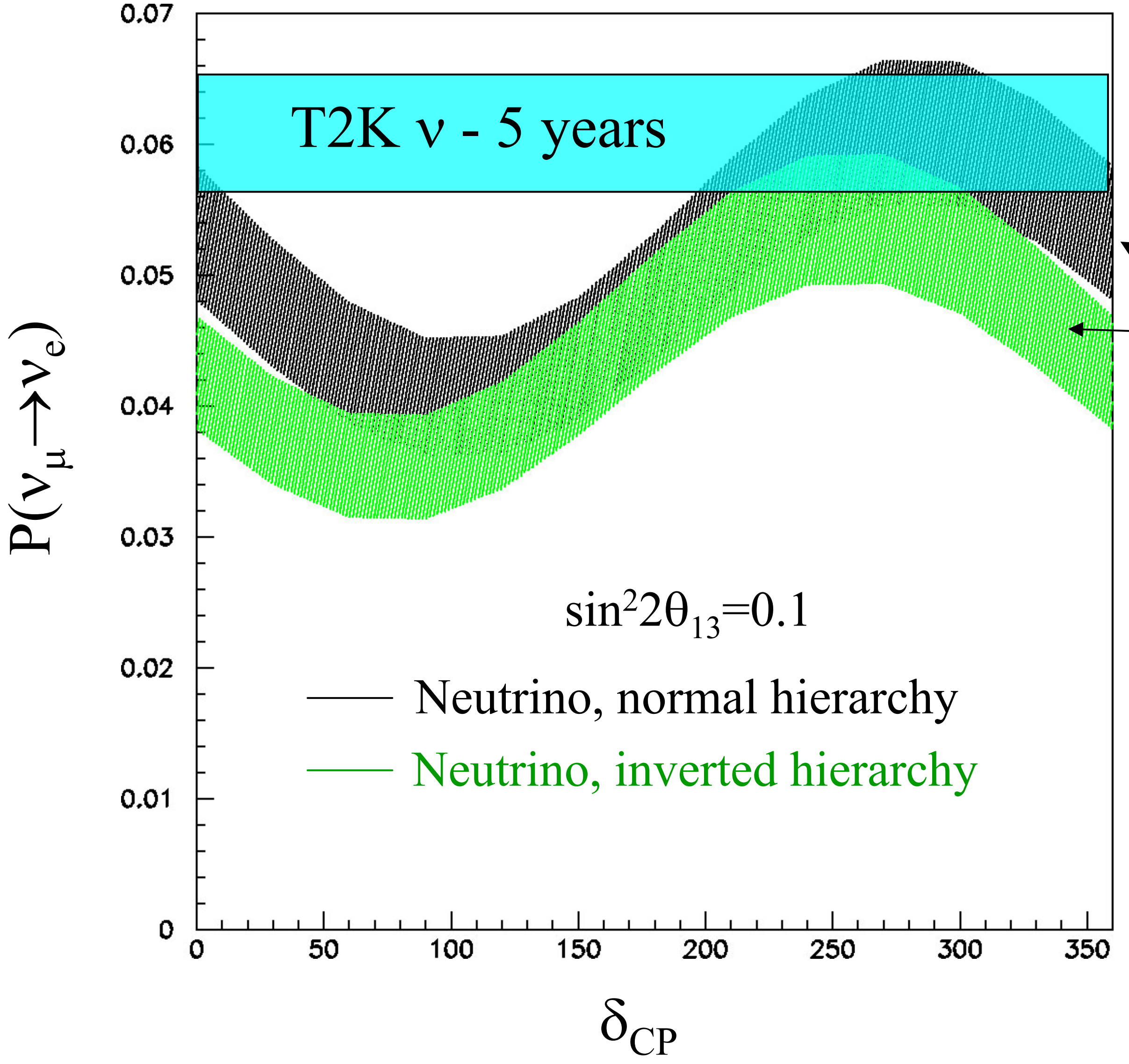
T2K



Nova



Example: Reactor + T2K ν running

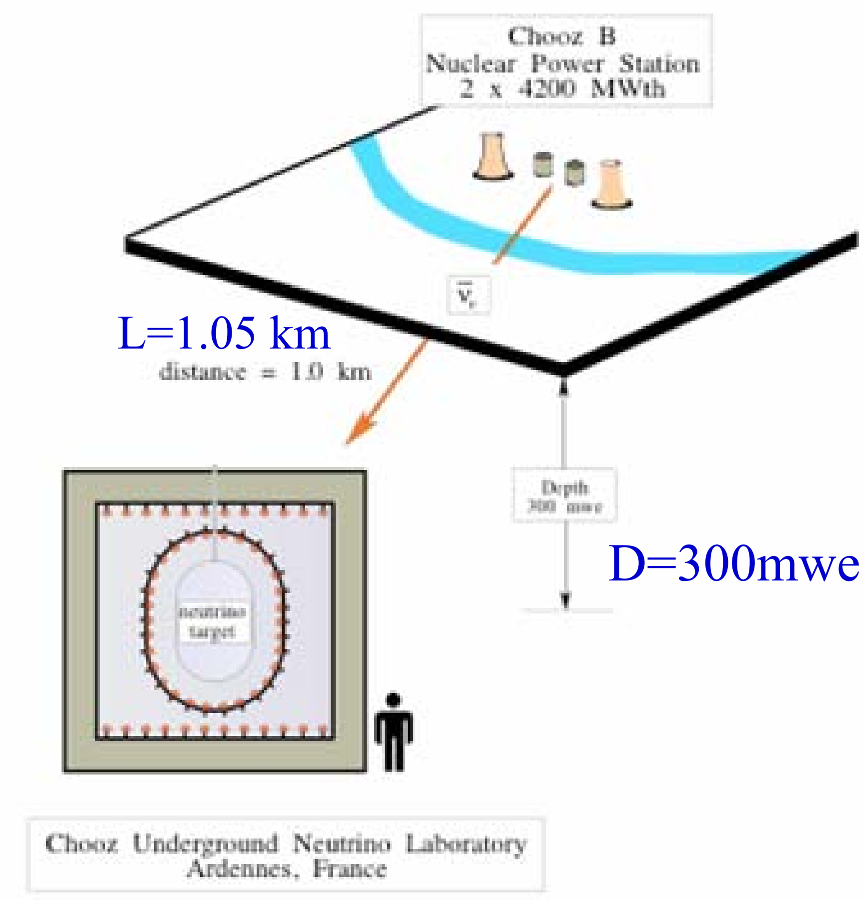


$\Delta\sin^2 2\theta_{13}=\pm0.01$
from reactor

Chooz: Current Best θ_{13} Experiment

Chooz Experiment

P=8.4 GW_{th}

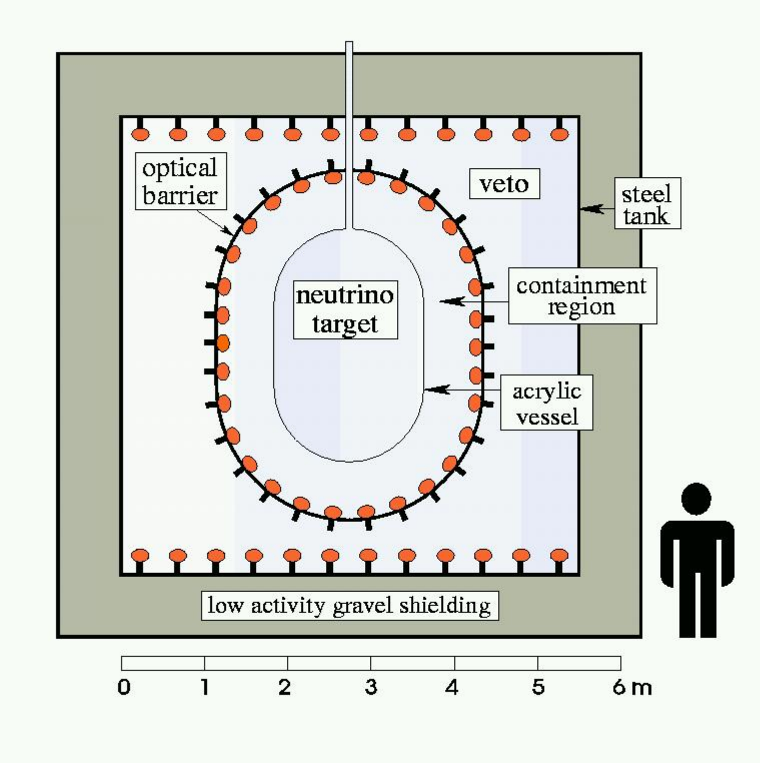


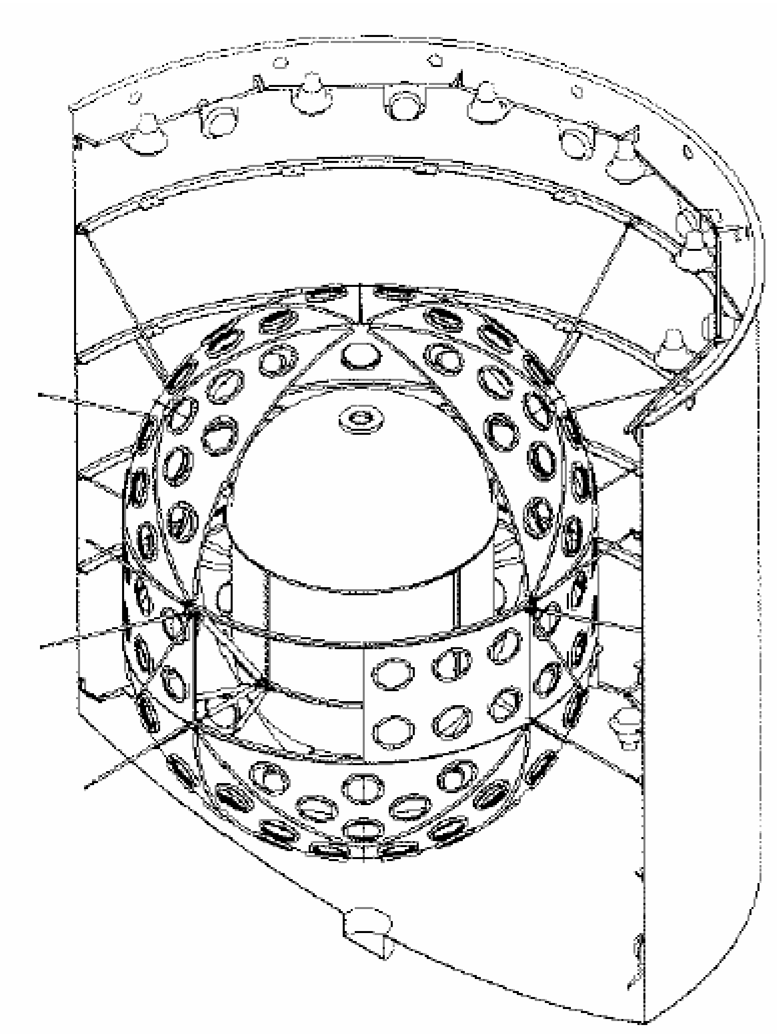
L=1.05 km

D=300mwe

m = 5 tons, Gd-loaded liquid scintillator

CHOOZ


optical barrier
veto
steel tank
neutrino target
containment region
acrylic vessel
low activity gravel shielding
0
1
2
3
4
5
6 m



Gadolinium Loaded Scintillator

Small amount of Gd added to liquid scintillator to improve neutron detection: shorter capture time and higher energy.

Element	σ (barns)	Isotopic abundance (%)
^{155}Gd	61,400	14.8
^{157}Gd	255,000	15.7
Gd (natural)	49,100	--
H	0.328	--

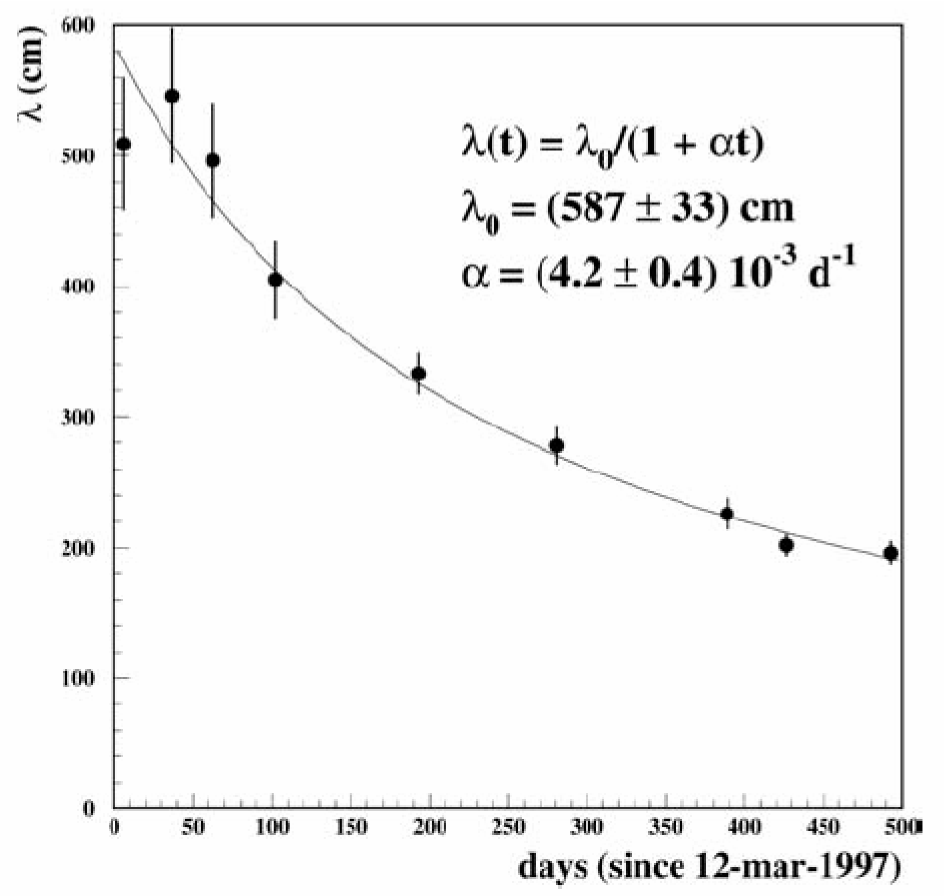
Neutrino detection by $\bar{\nu}_e + p \rightarrow e^+ + n,$

n + ^{m}Gd $\rightarrow$ $^{m+1}$Gd* $\rightarrow$ $^{m+1}$Gd γs (8 MeV); τ=30 μsec

(Compared to $n + p \rightarrow d + \gamma(2.2\ \ MeV);\ \ \tau \sim 200\mu\,\mathrm{sec}$)

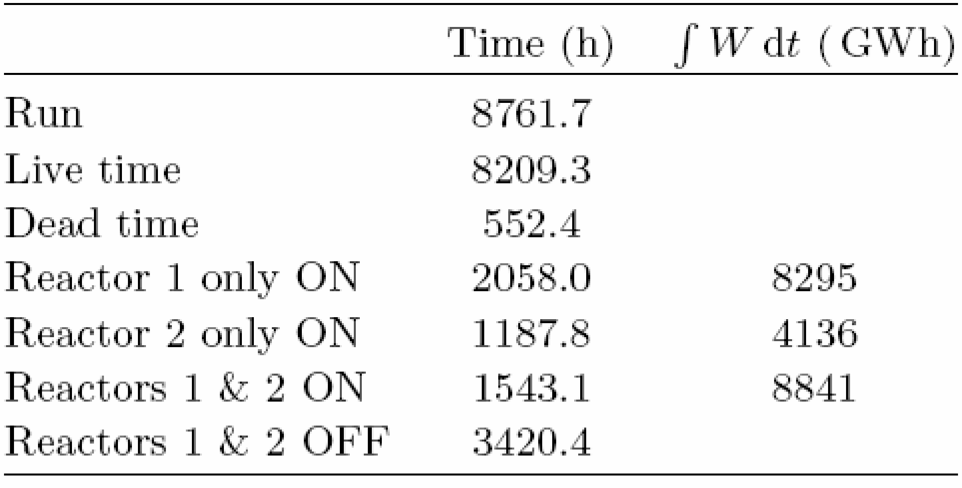
For 0.1% Gd, about 85% of neutrons are captured by Gd

Degradation of Chooz Scintillator



Attenuation degrades by ~0.4% per day.

Summary of Chooz run: 4/97 - 7/98



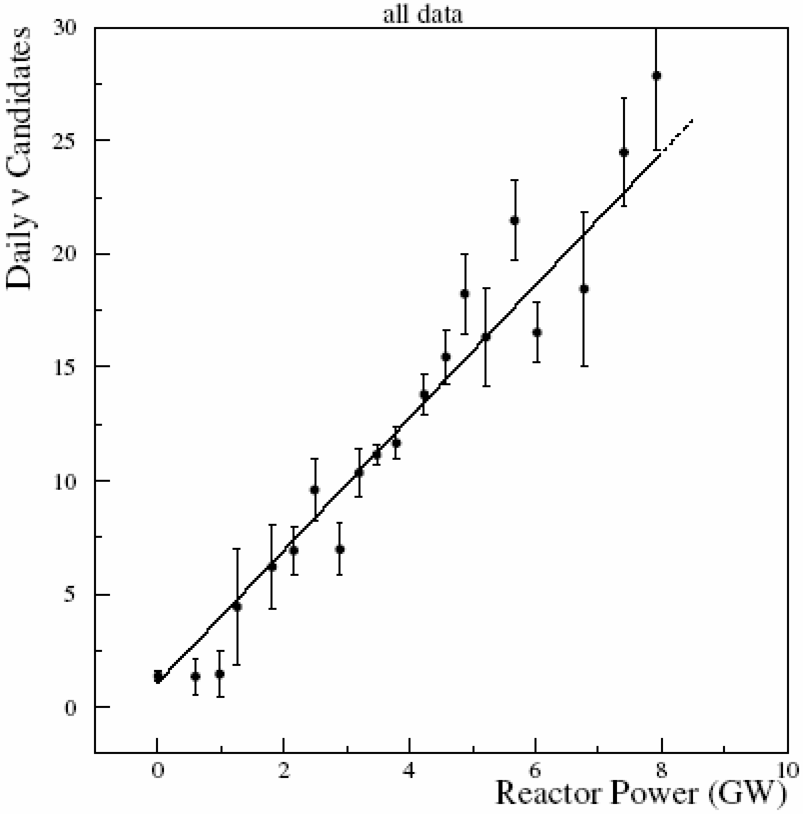
	Time (h)	$\int W\, dt$ (GWh)
Run	8761.7	
Live time	8209.3	
Dead time	552.4	
Reactor 1 only ON	2058.0	8295
Reactor 2 only ON	1187.8	4136
Reactors 1 & 2 ON	1543.1	8841
Reactors 1 & 2 OFF	3420.4	

~2.2 evts/day/ton with 0.2-0.4 bkg evts/day/ton

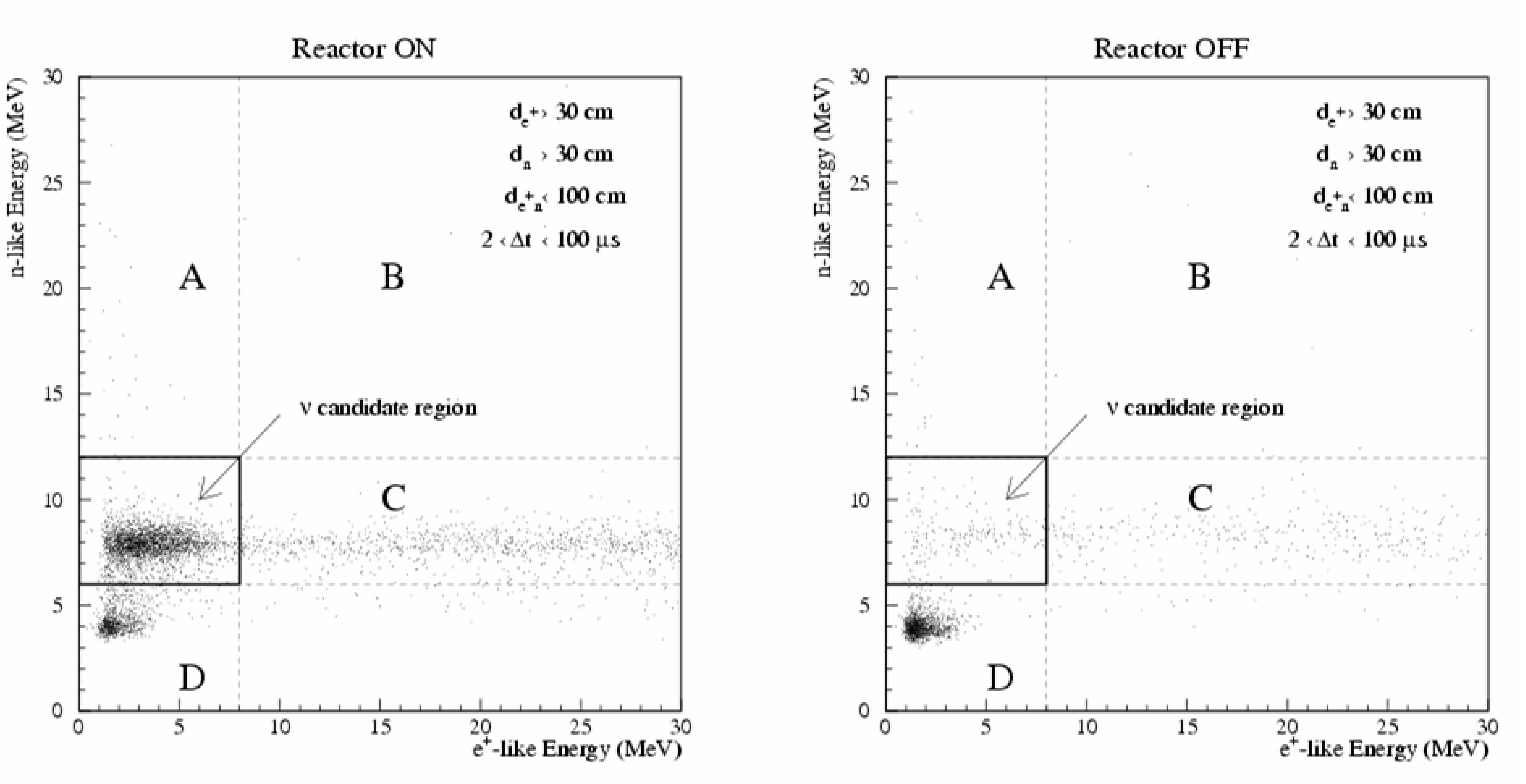
~total sample included 3600 ν events

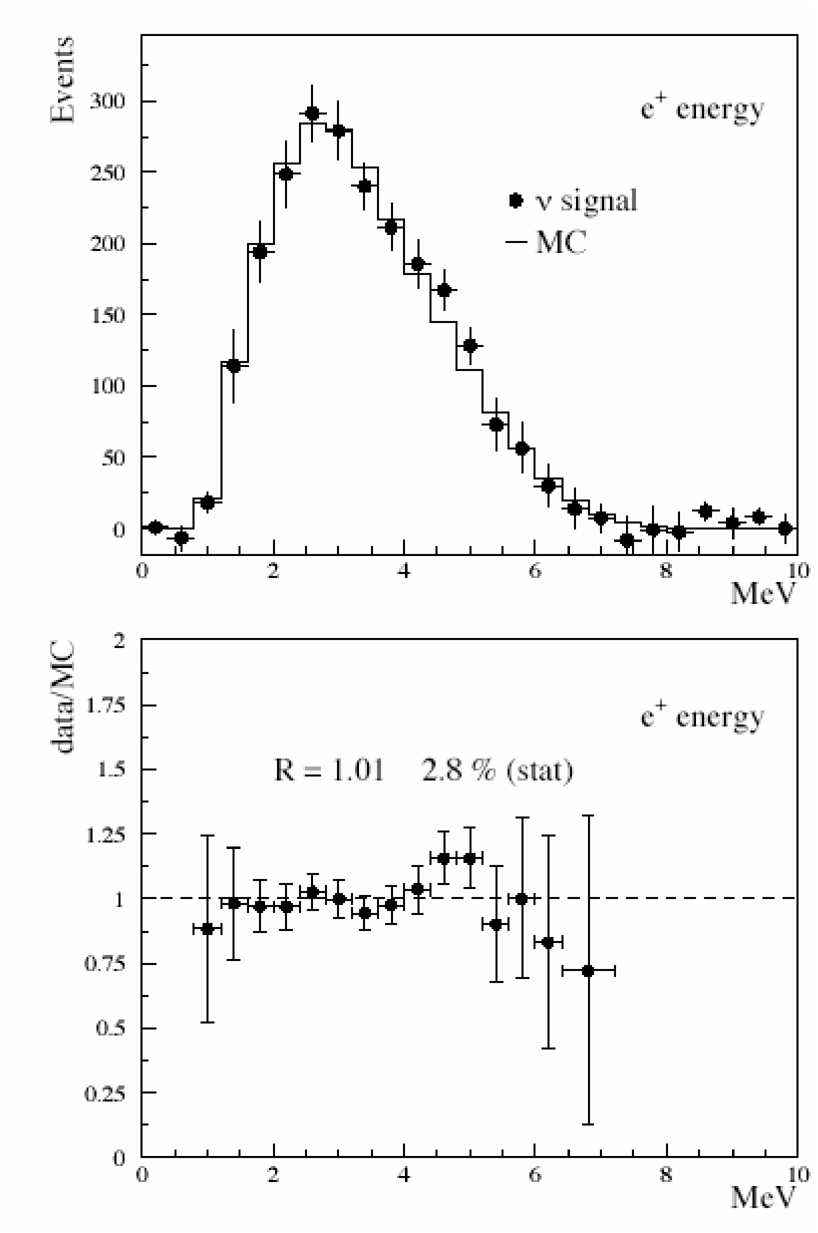
Chooz started data collection before reactor began operating.

UNIQUE possibility to measure backgrounds

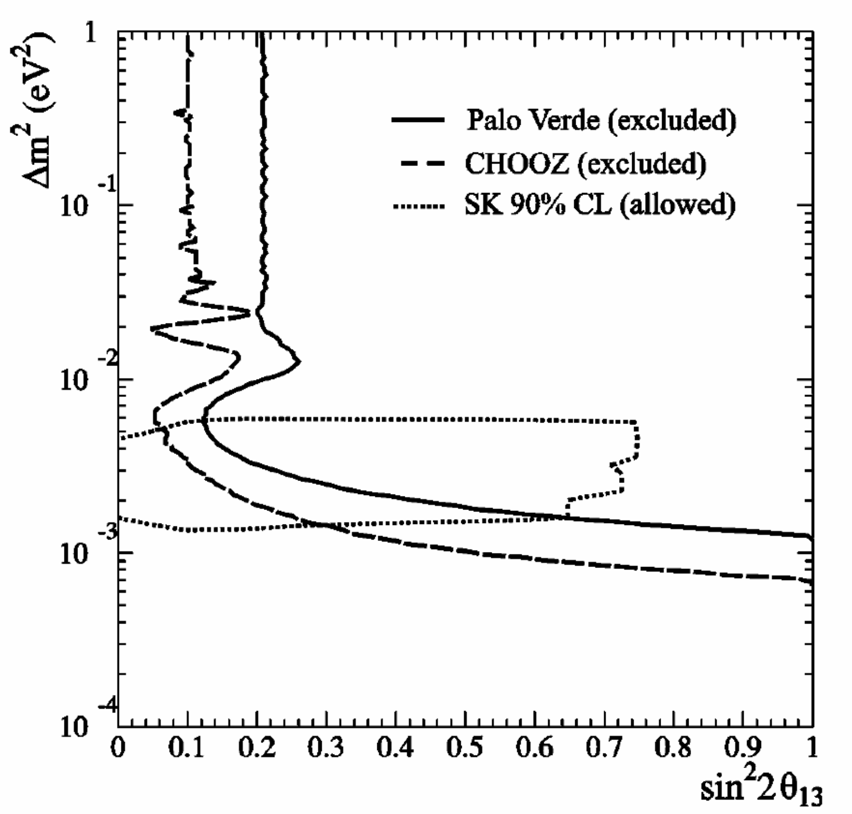


Final Chooz Data Sample





CHOOZ Systematic errors	
Reactor ν flux Detect. Acceptance	2% 1.5%
Total	2.7%



$\sin^2 2\theta_{13} < 0.15$ for $\Delta m^2 = 2.5\times10^{-3}$ eV^2

How can one improve on Chooz Experiment?

⇒Add an identical near detector

Eliminate dependence on reactor flux; only relative acceptance of detectors needed

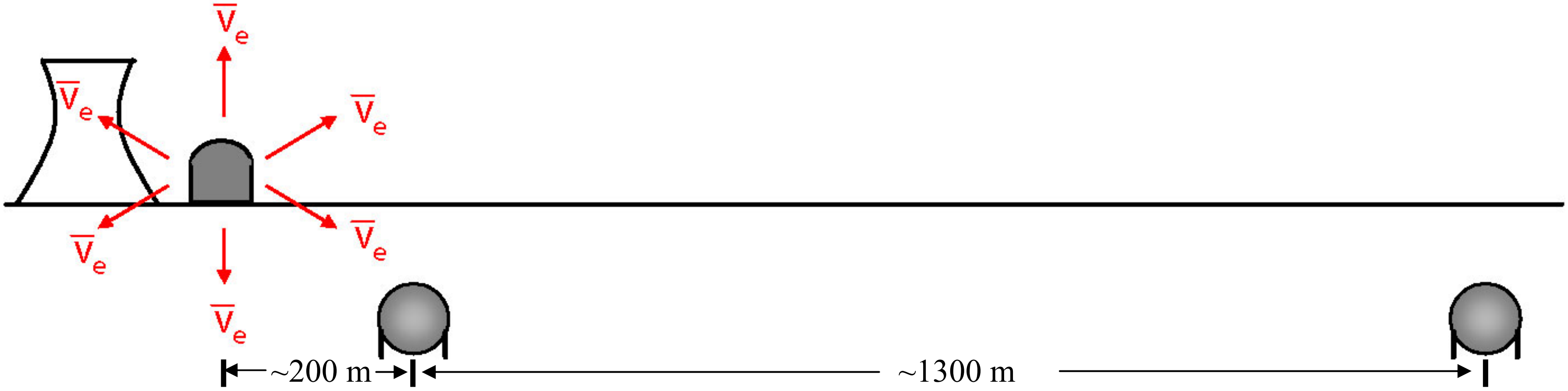
⇒ Optimize baseline

⇒ Larger detectors; improved detector design

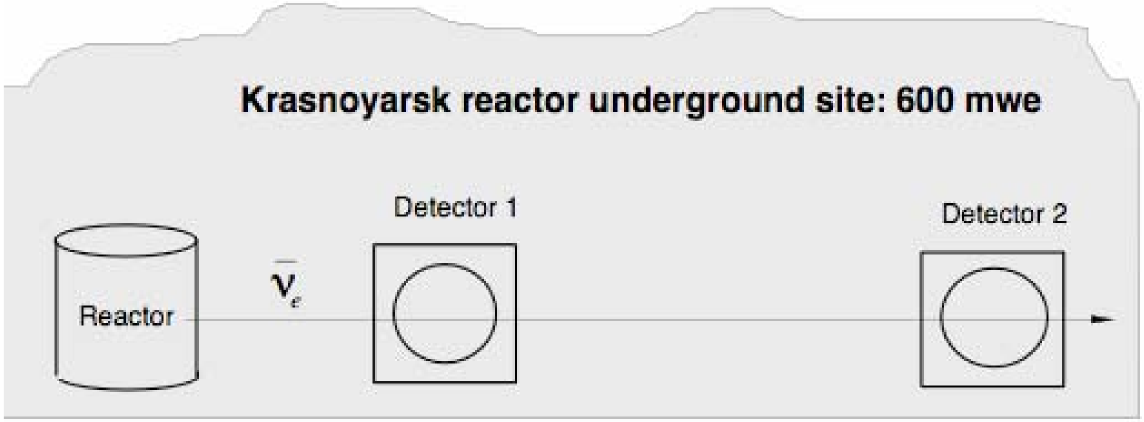
⇒ Reduce backgrounds

(Go deeper and use active veto systems)

⇒ Stable scintillator



Kr2Det: Reactor θ_{13} Experiment at Krasnoyarsk

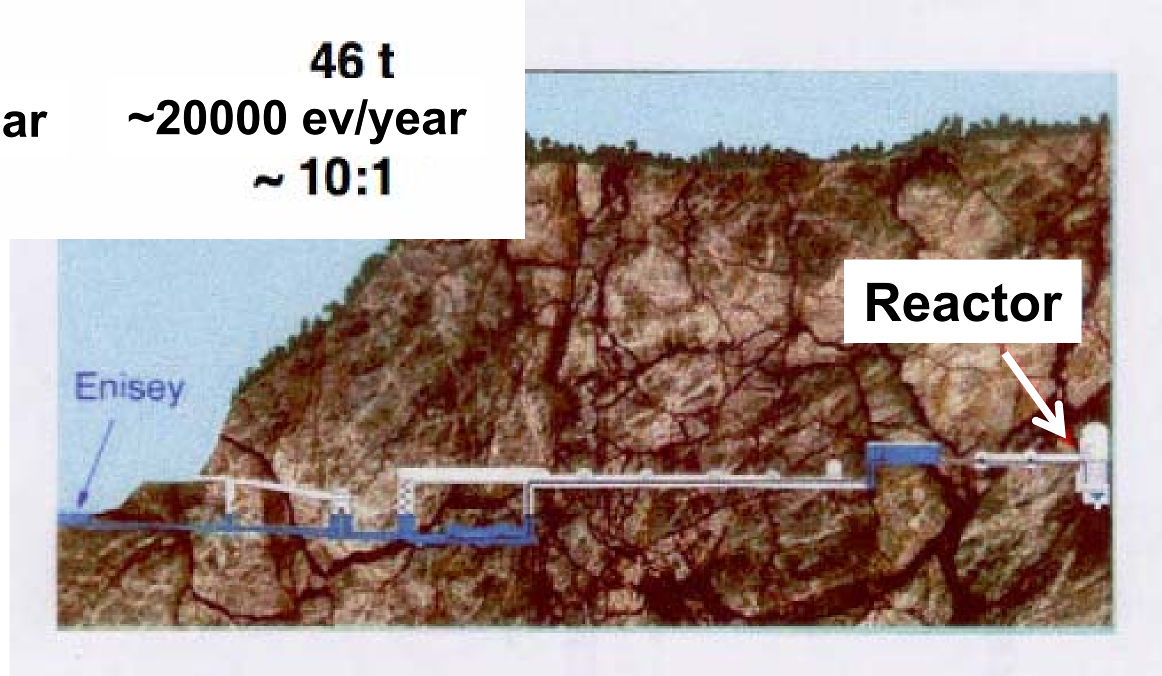


	115 m	1000 m
Target:	46 t	46 t
Rate:	~1.5 x 10^6 ev/year	~20000 ev/year
S:B	>>1	~ 10:1

Features

- underground reactor
- existing infrastructure

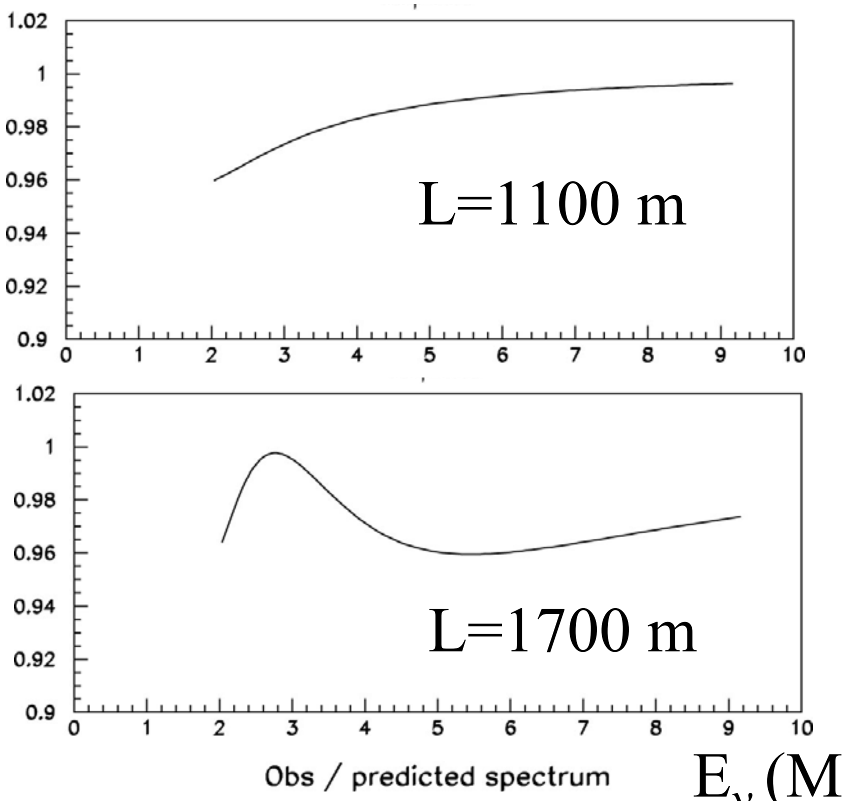
Detector locations constrained by existing infrastructure



Ref: Marteyamov et al, hep-ex/0211070

What is the best baseline? It depends …

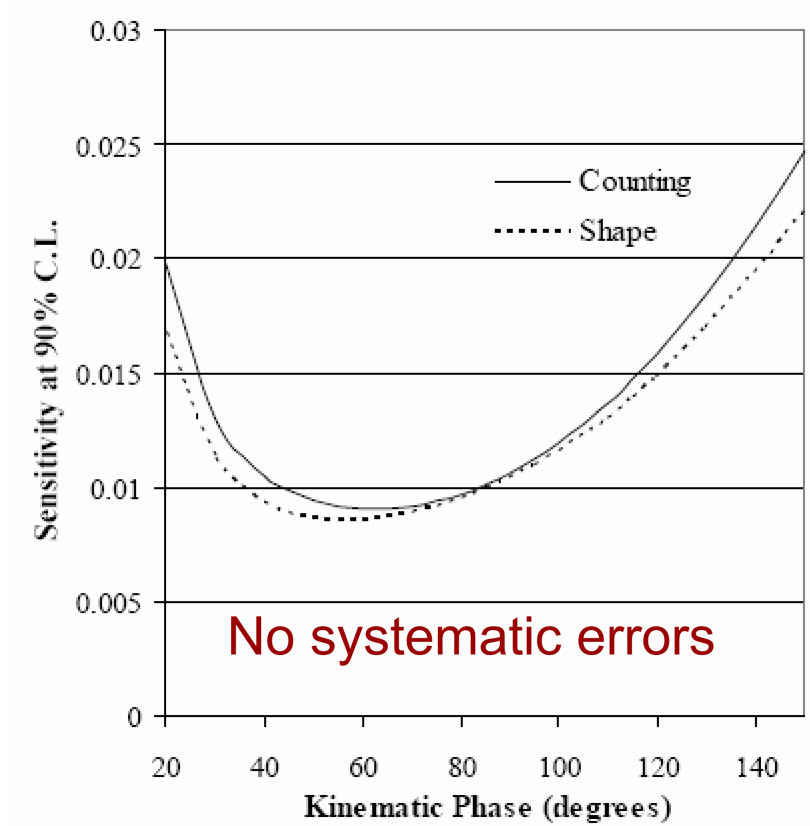
- What is Δm^2?
- For rate measurement, you must consider competition between $1/R^2$ and sinusoidal term.
- For shape measurement, distortion is different at different baselines:



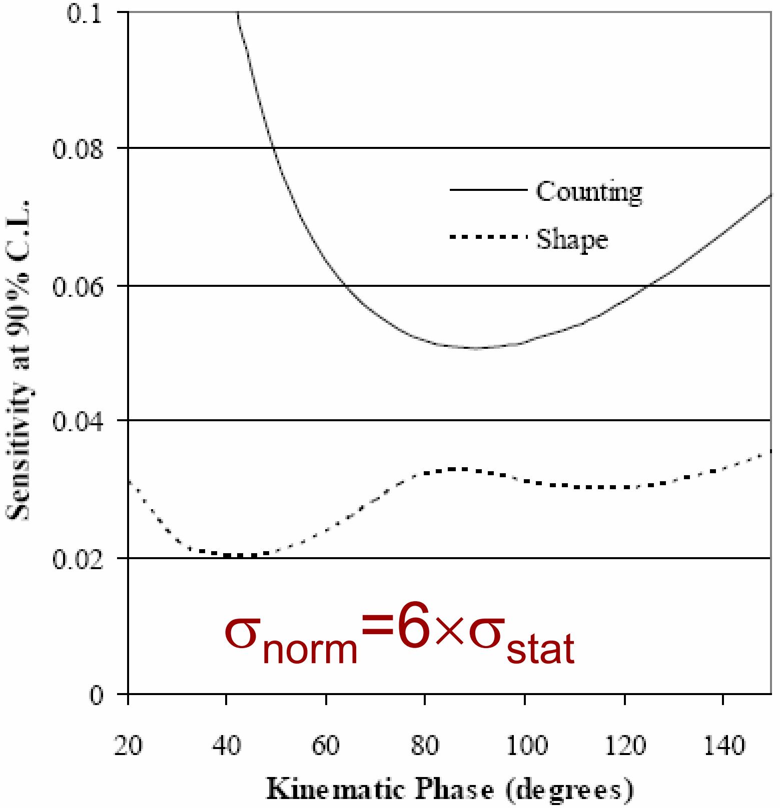
E_ν (MeV)

Best baseline also depends on relative size of statistical and systematic errors.

(From J. Link)



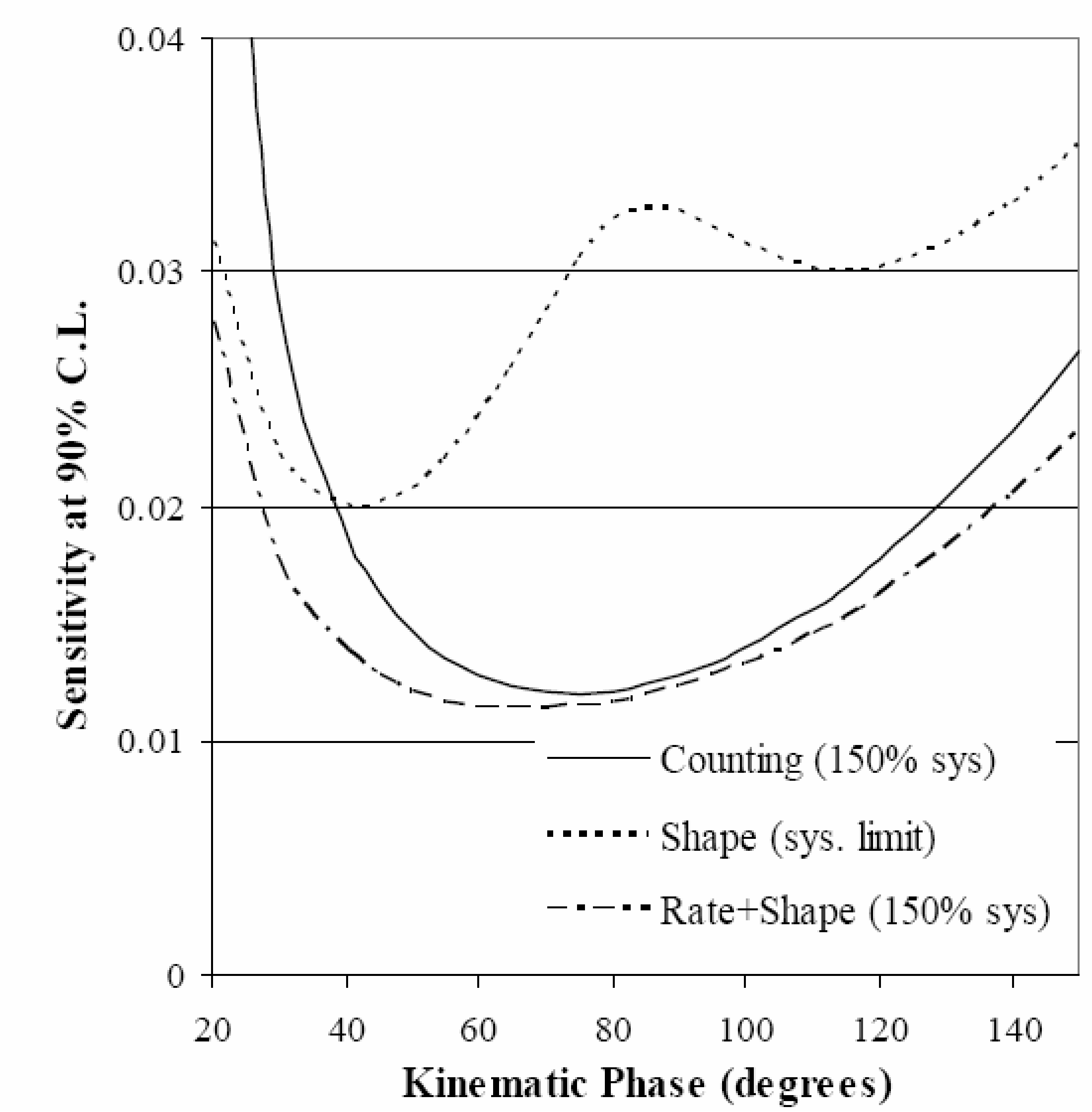
No systematic errors



$\sigma_{norm} = 6 \times \sigma_{stat}$

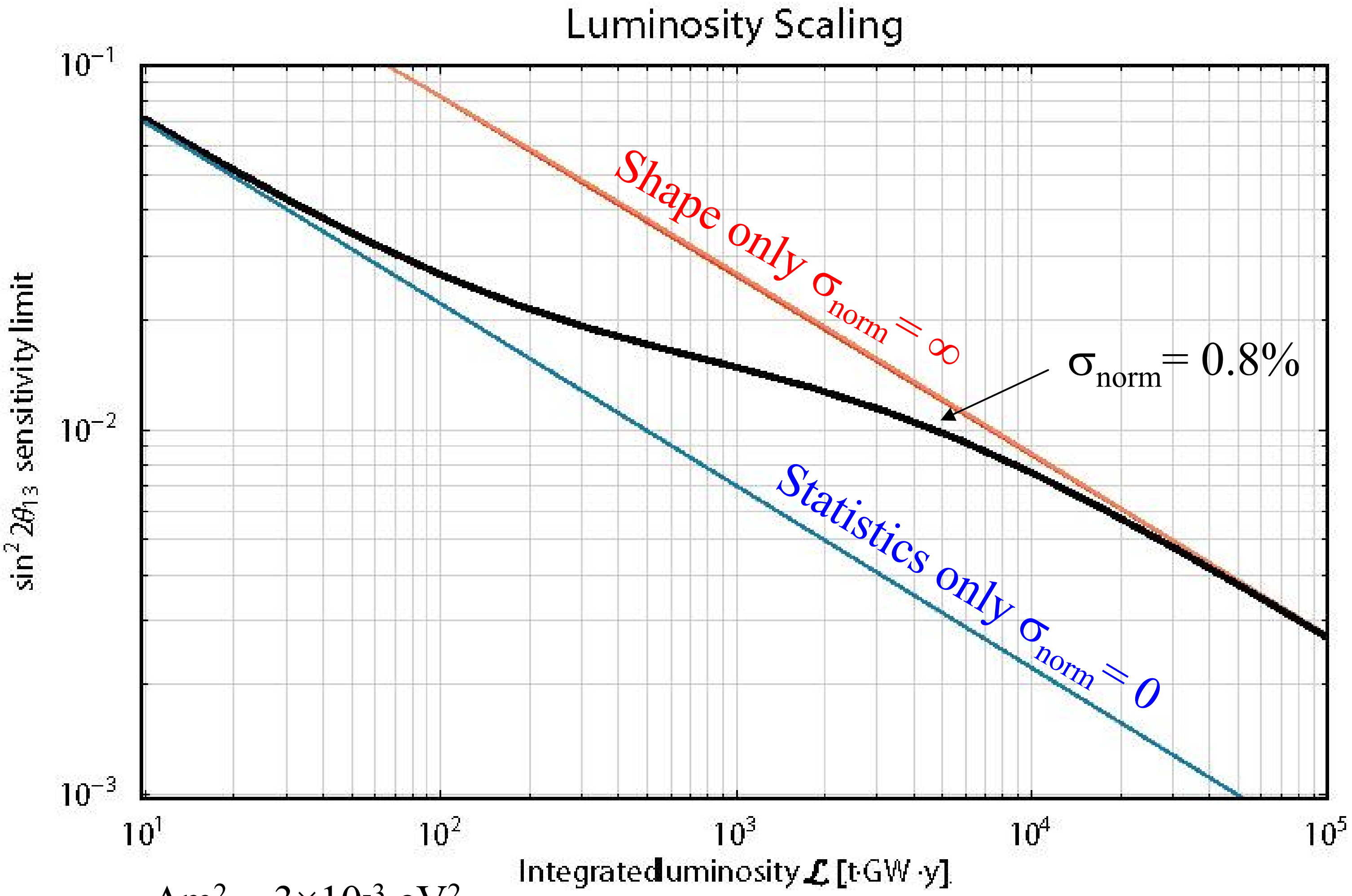
$$P(\overline{\nu}_e \to \overline{\nu}_e) \approx 1 - \sin^2 2\theta_{13} \sin^2 \frac{1.27 \Delta m_{13}^2 L}{E}; \quad \text{Kinematic Phase} \equiv \frac{1.27 \Delta m_{13}^2 L}{3.6\ \text{MeV}} \frac{180}{\pi}$$

Combined Rate and Shape Analysis



Sensitivity Using Rate and Energy Spectrum

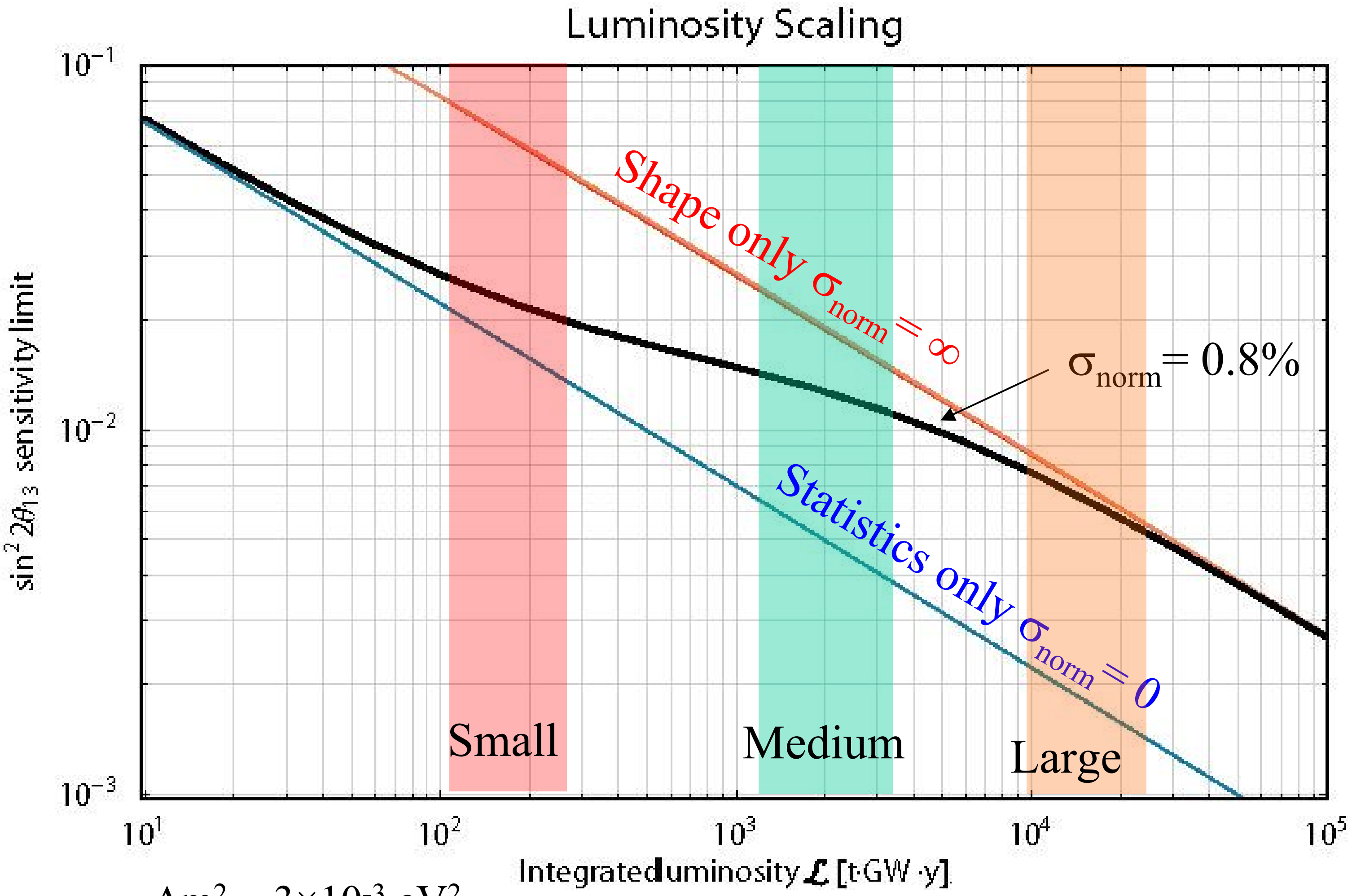
(Huber *et al.* hep-ph/0303232)



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

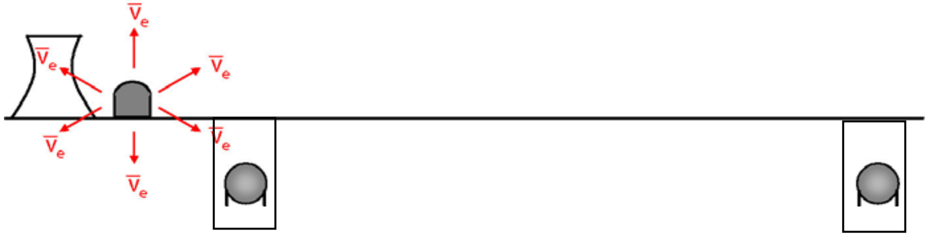
Sensitivity Using Rate and Energy Spectrum

(Huber *et al.* hep-ph/0303232)



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

Different Scales of Experiments



Small: $\sin^2 2\theta_{13} \sim 0.03$ (e.g., Double-Chooz, KASKA,Reno)

Double-Chooz: 10 ton detector at L-1.05 km.

Mostly rate information, fixed detectors, non-optimal baseline

Medium: $\sin^2 2\theta_{13} \sim 0.01$ (e.g., Braidwood, Daya Bay)

50-100 ton detectors, optimized baseline, optimized depths, rate and shape info, perhaps movable detectors to check calibration, multiple far detector modules for additional cross checks

Large: $\sin^2 2\theta_{13} \sim 0.005$ (e.g., Angra)

~500 ton fiducial mass; sensitivity mainly through E spectrum distortion

Acceptance Issues

Must know:

(relative) number of protons in fiducial region
(relative) efficiency for detecting IBD events

Known volume of stable, identical Gd-loaded liquid scintillator in each detector

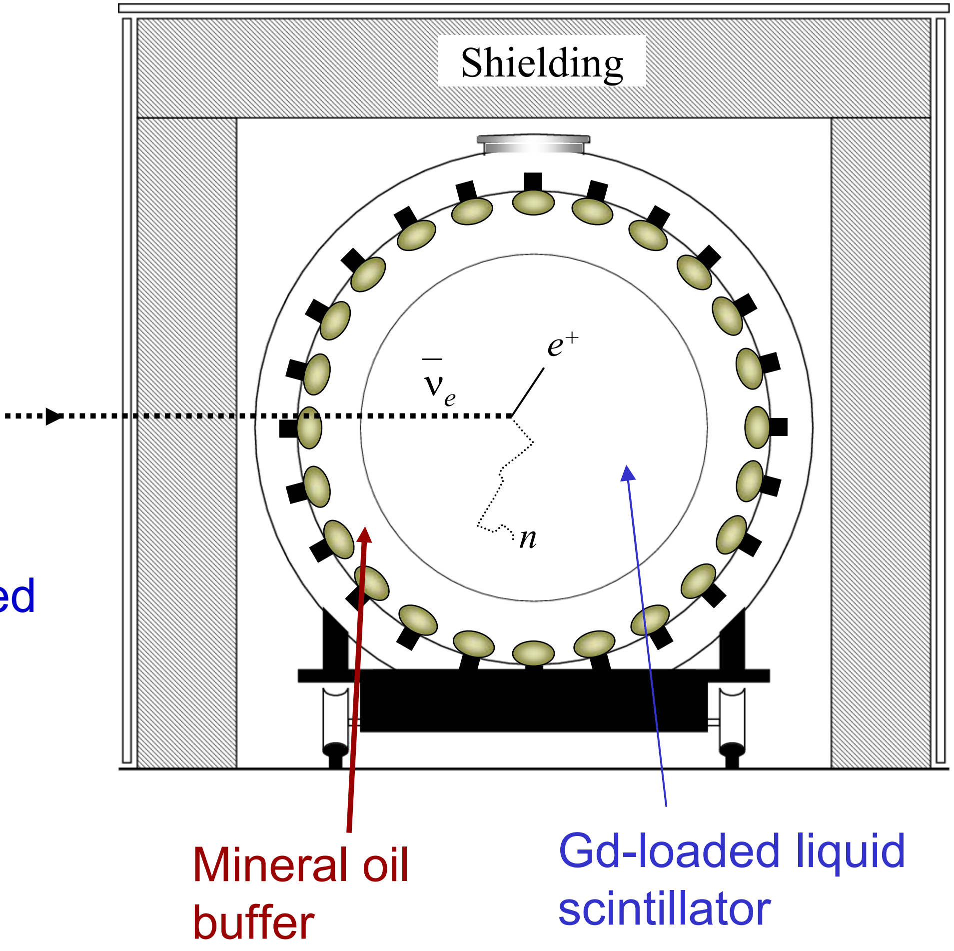
Well understood efficiency of positron and neutron energy requirements

Detectors and analysis strategy designed to minimize relative acceptance differences

Central zone with Gd-loaded scintillator surrounded by buffer regions; fiducial mass determined by volume of Gd-loaded scintillator

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

n ^{m}Gd → $^{m+1}$Gd γs (8 MeV); τ=30μsec



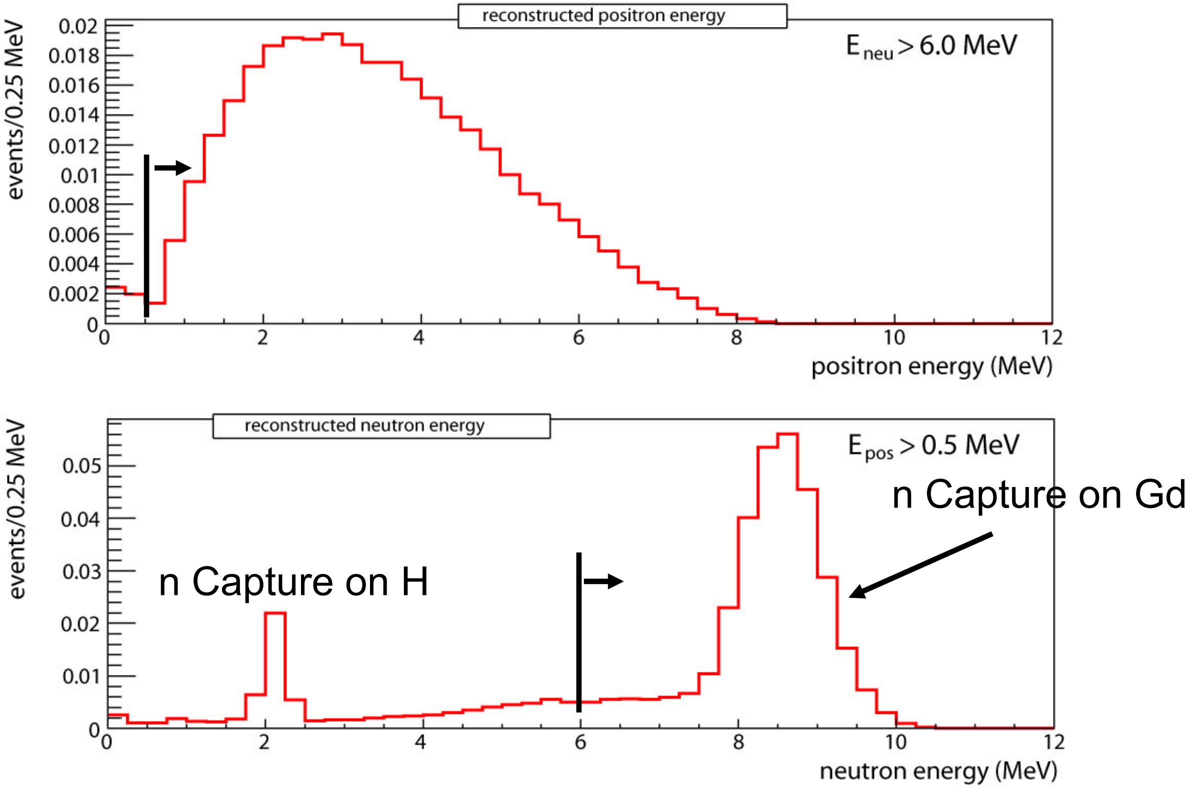
Events selected based on coincidence of e^+ signal (E_{vis}>0.5 MeV) and γs released from n+Gd capture (E_{vis}>6 MeV).

No explicit requirement on reconstructed event position; little sensitivity to E requirements.

To reduce backgrounds: depth + active and passive shielding

Events selected based on coincidence of e^+ signal (E_{vis}>0.5 MeV) and γs released from n+Gd capture (E_{vis}>6 MeV).

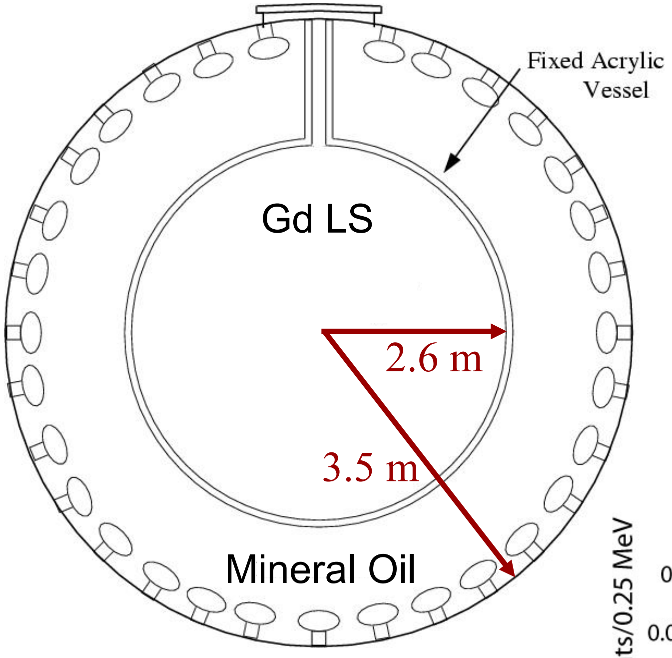
Reconstructed e^+ and n-capture energy

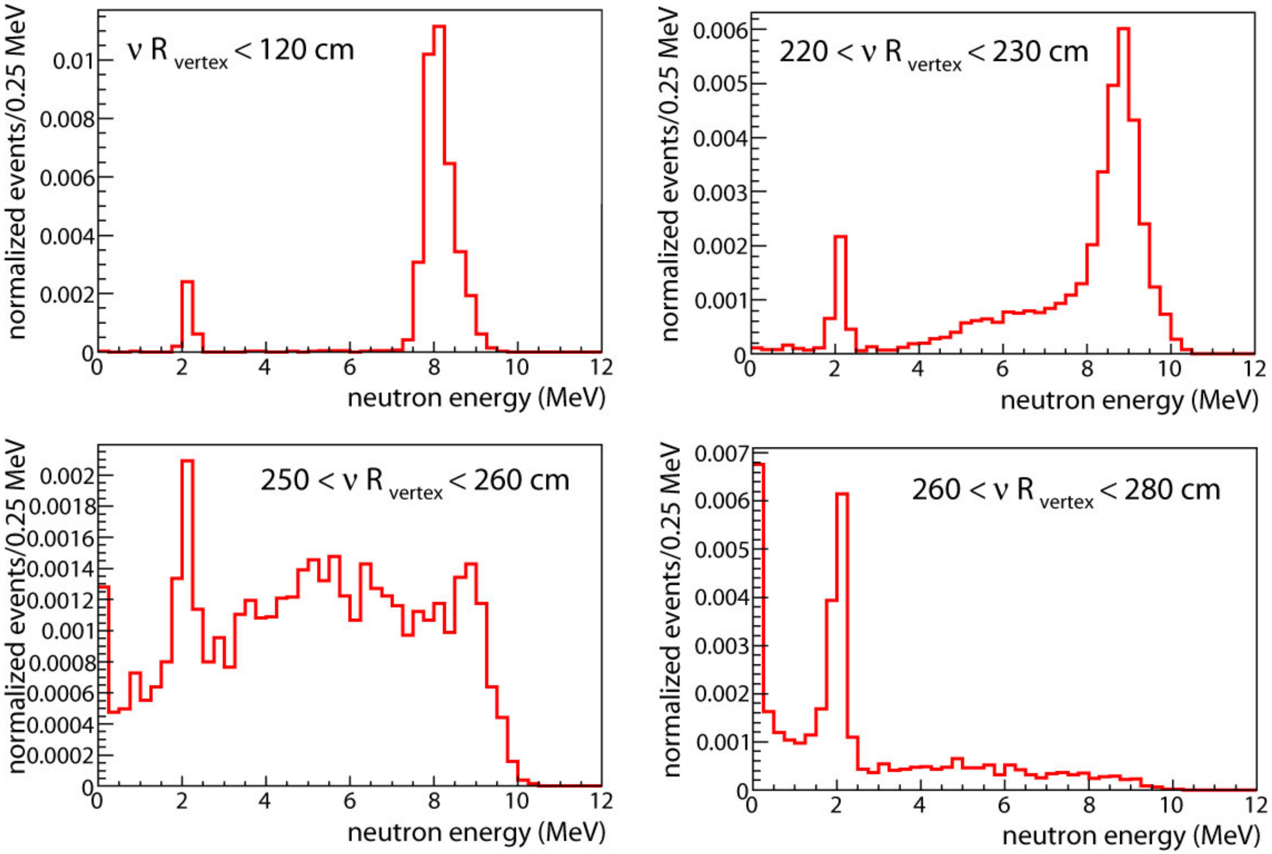


n Capture on Gd

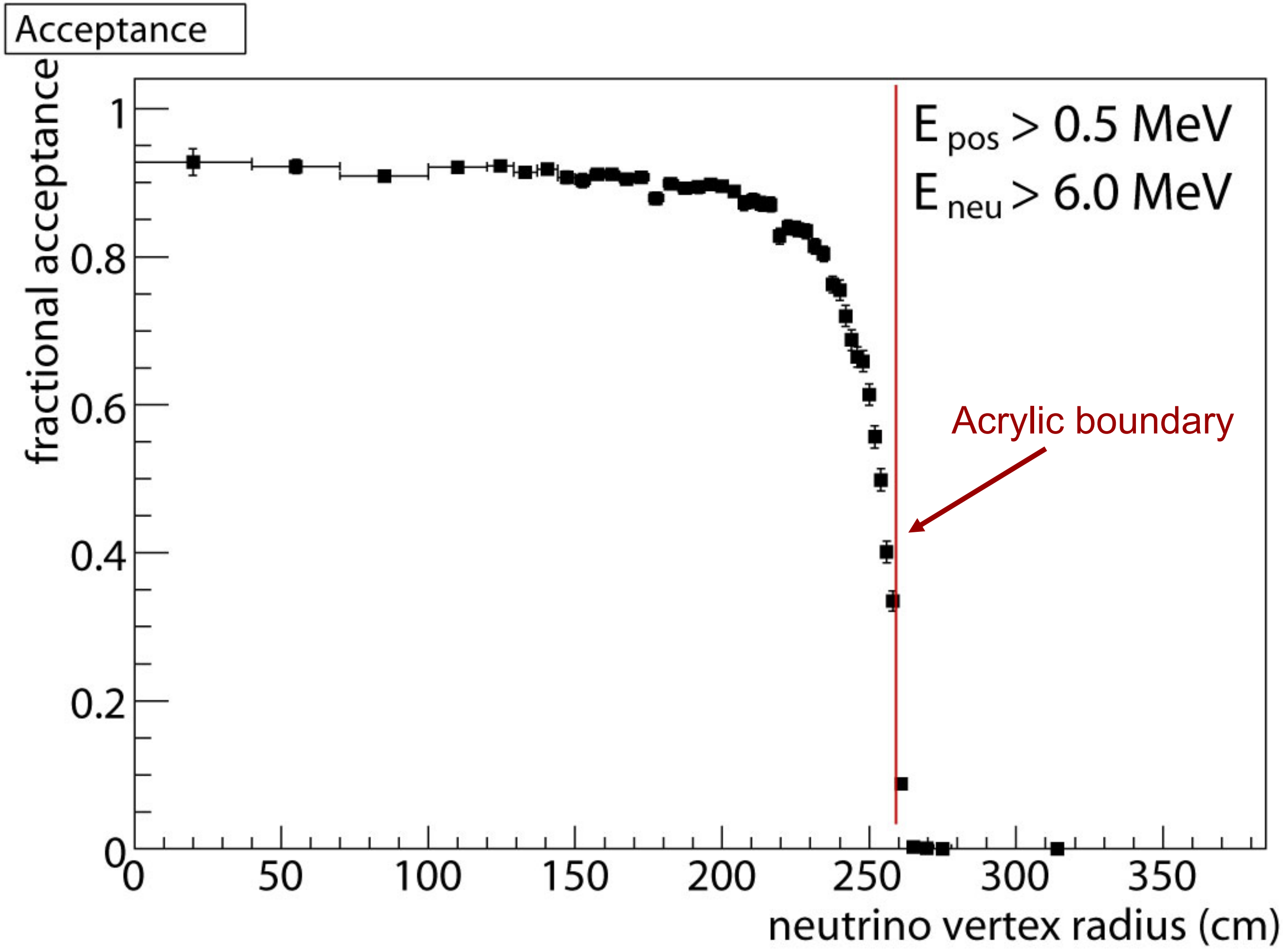
n Capture on H

Neutron Capture Energy as a Function of R





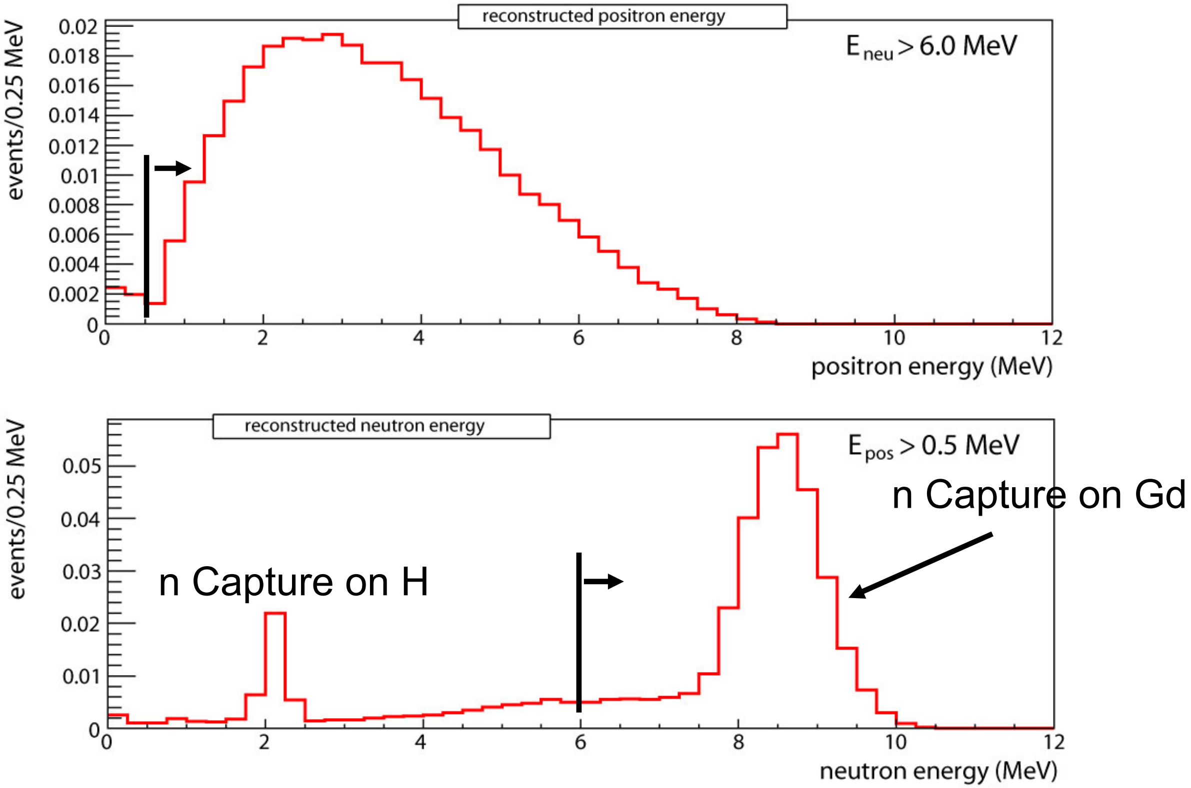
Acceptance as a function of R



Acrylic boundary

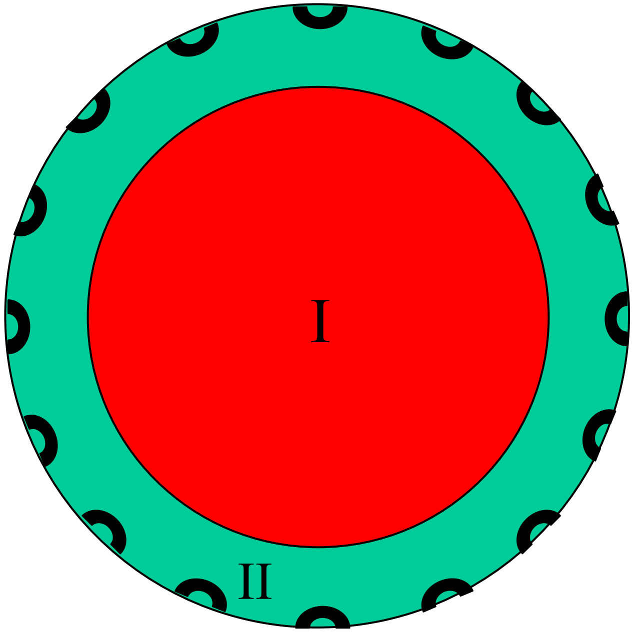
Events selected based on coincidence of e^+ signal (E_{vis}>0.5 MeV) and γs released from n+Gd capture (E_{vis}>6 MeV).

Reconstructed e^+ and n-capture energy

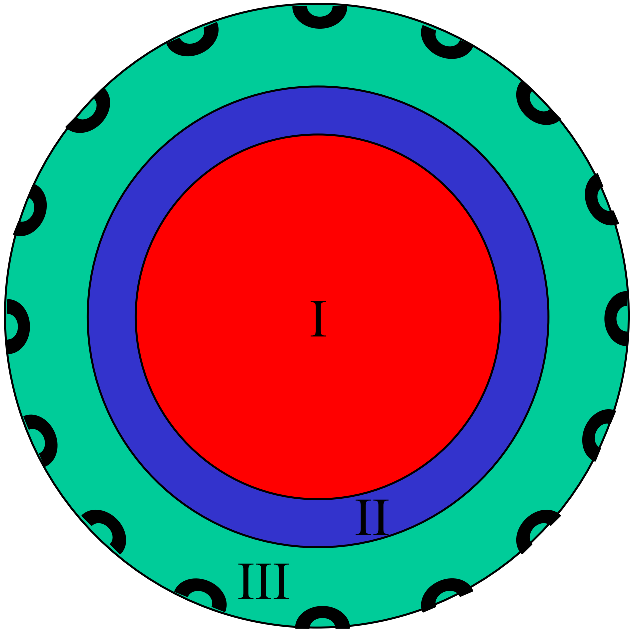


2-zone versus 3-zone detectors

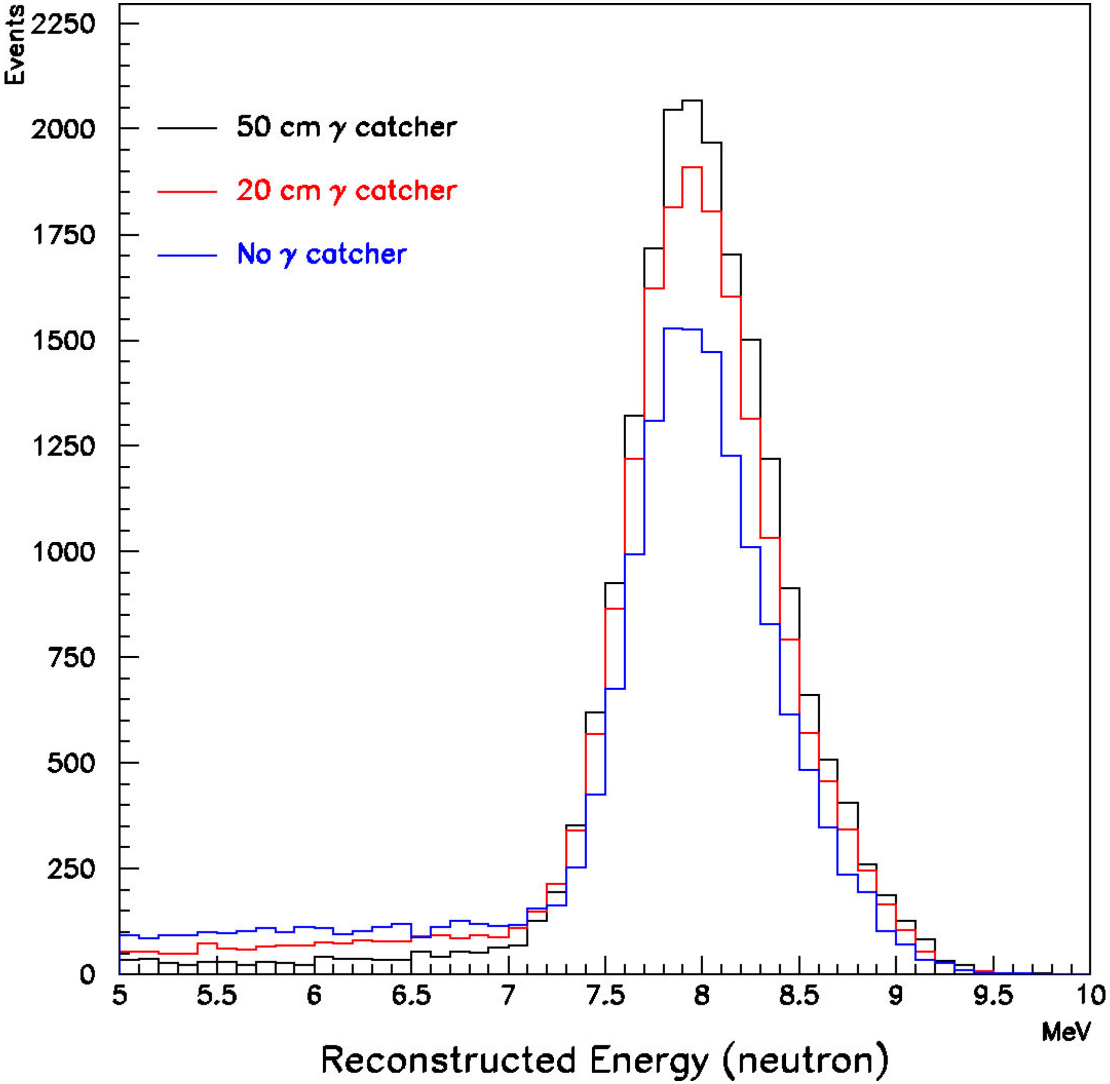
I. Gd-loaded liquid scintillator
II. Non-scintillating buffer



I. Gd-loaded liquid scintillator
II. γ catcher: liquid scintillator (no Gd)
III. Non-scintillating buffer



3-zone versus 2-zone detectors



I. Gd-loaded liquid scintillator
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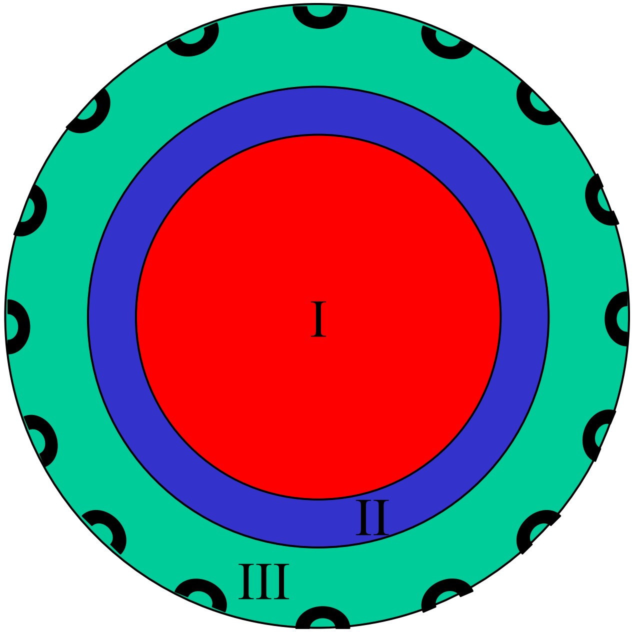

Questions

What should the detectors look like?

To achieve a certain detector mass, is it better to have lots of small detectors or fewer big detectors?

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To achieve a certain detector mass, is it better to have lots of small detectors or fewer big detectors?

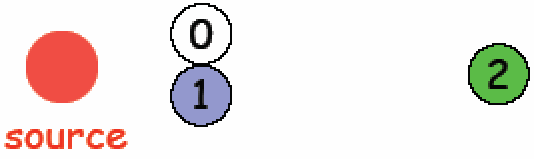
Larger, spherical detectors minimize surface area to volume ratio, simplify reconstruction, and make it possible to study radial dependence of signal and background.

Multiple detectors allow additional cross checks, and systematic errors could be reduced by $\sqrt{N_{det}}$ if sys errors are independent.

Acceptance cross checks: Movable Detectors

Take data with Near and Far detectors simultaneously at near site.
High flux a near site allows precise check of acceptance in ~1 month.

Taken to extreme: swap near and far detectors (Daya Bay)



$$\frac{N_1}{F_2} = \frac{N}{F}\cdot\frac{\varepsilon_1}{\varepsilon_2}$$

N = number of $\bar{\nu}$ at near site
ε_1 = efficiency of detector 1
F = number of $\bar{\nu}$ at far site
ε_2 = efficiency of detector 2

Detector 0 is used to cross check detectors before and after swapping

$$\frac{N_2}{F_1} = \frac{N}{F}\cdot\frac{\varepsilon_2}{\varepsilon_1} = \frac{N}{F}\left(1+\frac{\delta}{\varepsilon_1}\right)$$

$$\frac{N_1}{F_2}+\frac{N_2}{F_1} \approx 2\frac{N}{F}\left[1+\frac{1}{2}\left(\frac{\delta}{\varepsilon_1}\right)^2\right] = 2\frac{N}{F}(1+\eta)$$

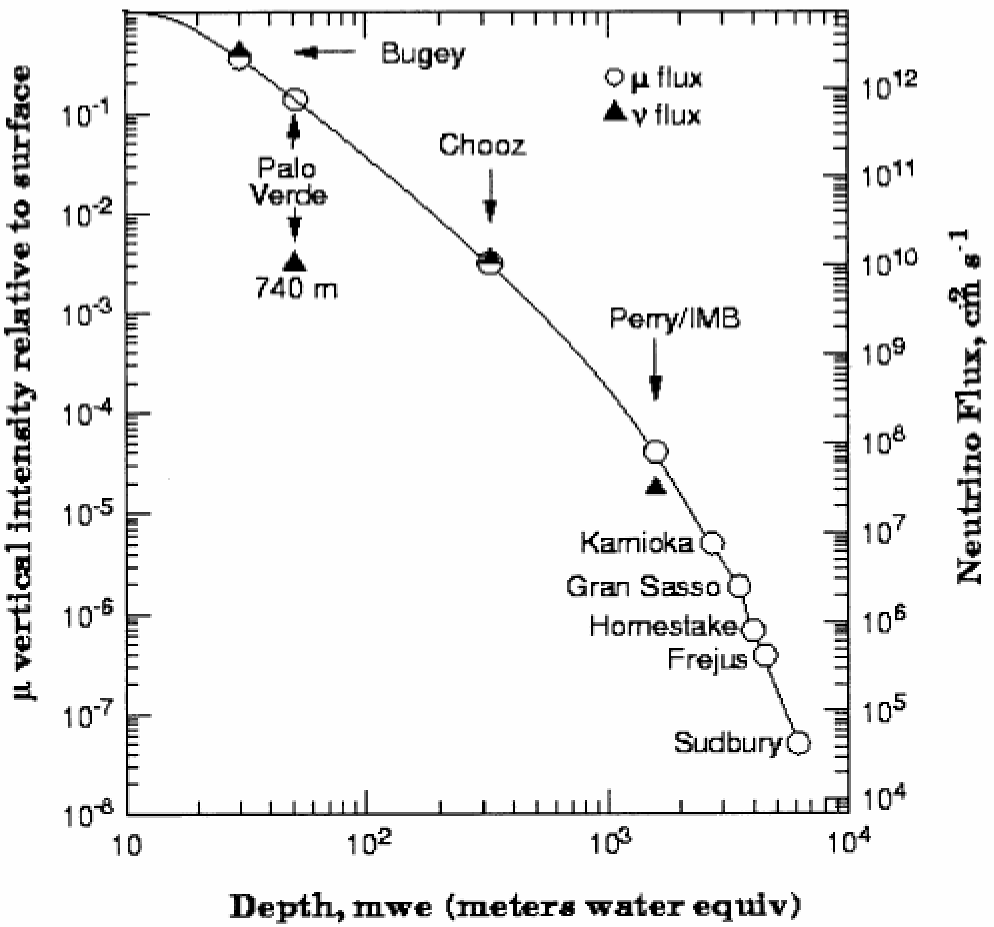
For example,
$\varepsilon_1 \approx 0.8$ (KamLAND)
$\delta = 0.02$
$\Rightarrow \eta = 3\times10^{-4}$

Backgrounds

- Uncorrelated backgrounds from random coincidences
  - Reduced by limiting radioactive materials
  - Directly measured from rates and random trigger setups

- Correlated backgrounds
  - Neutrons that mimic the coincidence signal
  - Cosmogenically produced isotopes that decay to a beta and neutron: ^{9}Li ($\tau_{1/2}$=178 ms) and ^{8}He ($\tau_{1/2}$=119 ms); associated with showering muons.
  - Reduced by shielding (depth) and veto systems

How deep should detector be?

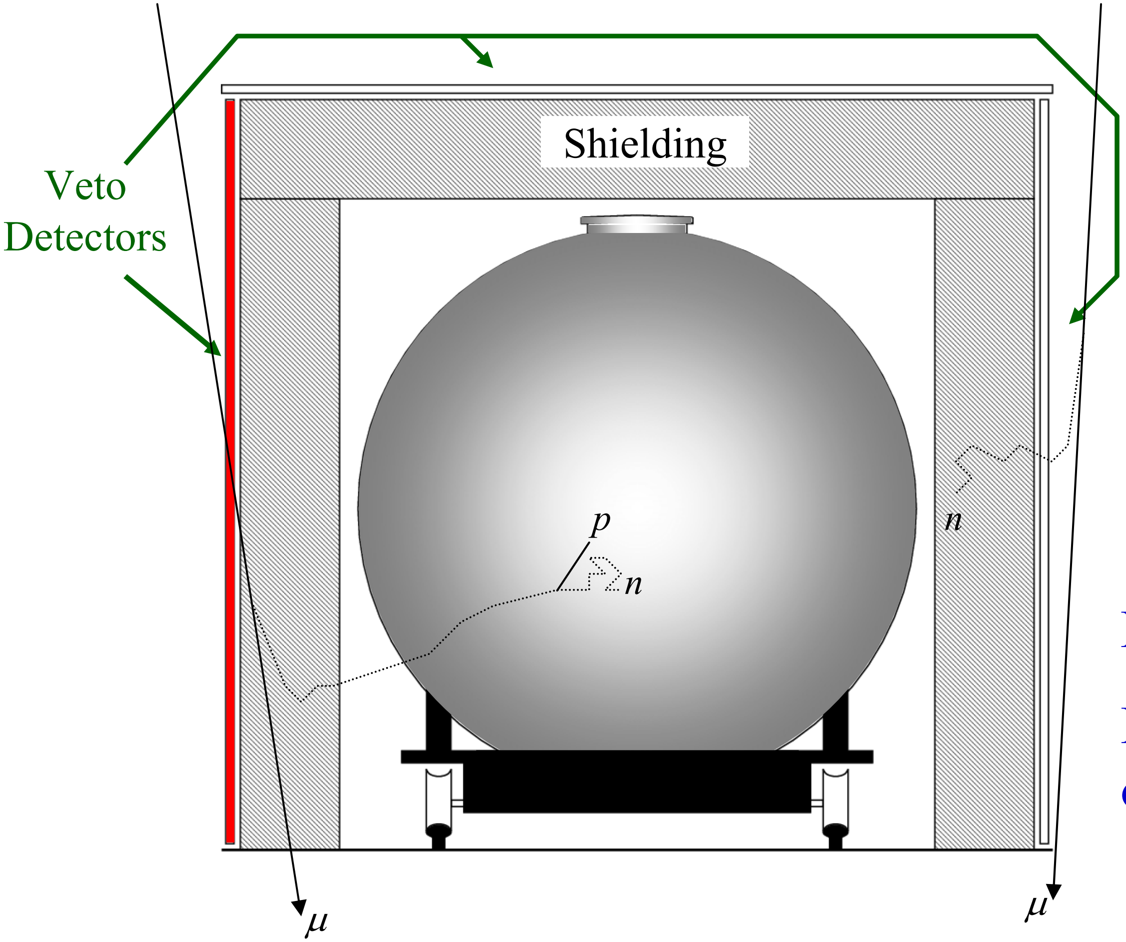


Should the near and far detectors be at the same depth?

Not necessary since signal rates are very different, but same depth offers systematic advantages.

Veto (Tagging) System

Strategy: tag muons that pass near the detector. Use shielding to absorb neutrons produced by muons that miss the veto system.



Residual n background:

1. Veto inefficiency
2. Fast neutron created outside the shielding

Dead time:

E.g., with μ rate in the veto system of 20 Hz and the tag window of 100 μs → 0.2% dead time

Muon identification should allow *in situ* determination of the residual background rate

Features of Ideal Experiment:

- multiple large, spherical detectors that minimize boundary effects
- all detectors protected by an equal and well-understood overburden so cosmic ray backgrounds are similar
- detectors on the reactor symmetry axis to eliminate reactor flux effects
- a robust shielding system to reduce and measure backgrounds in situ

(+ reactor-off time to measure backgrounds)

What do real experiments look like?

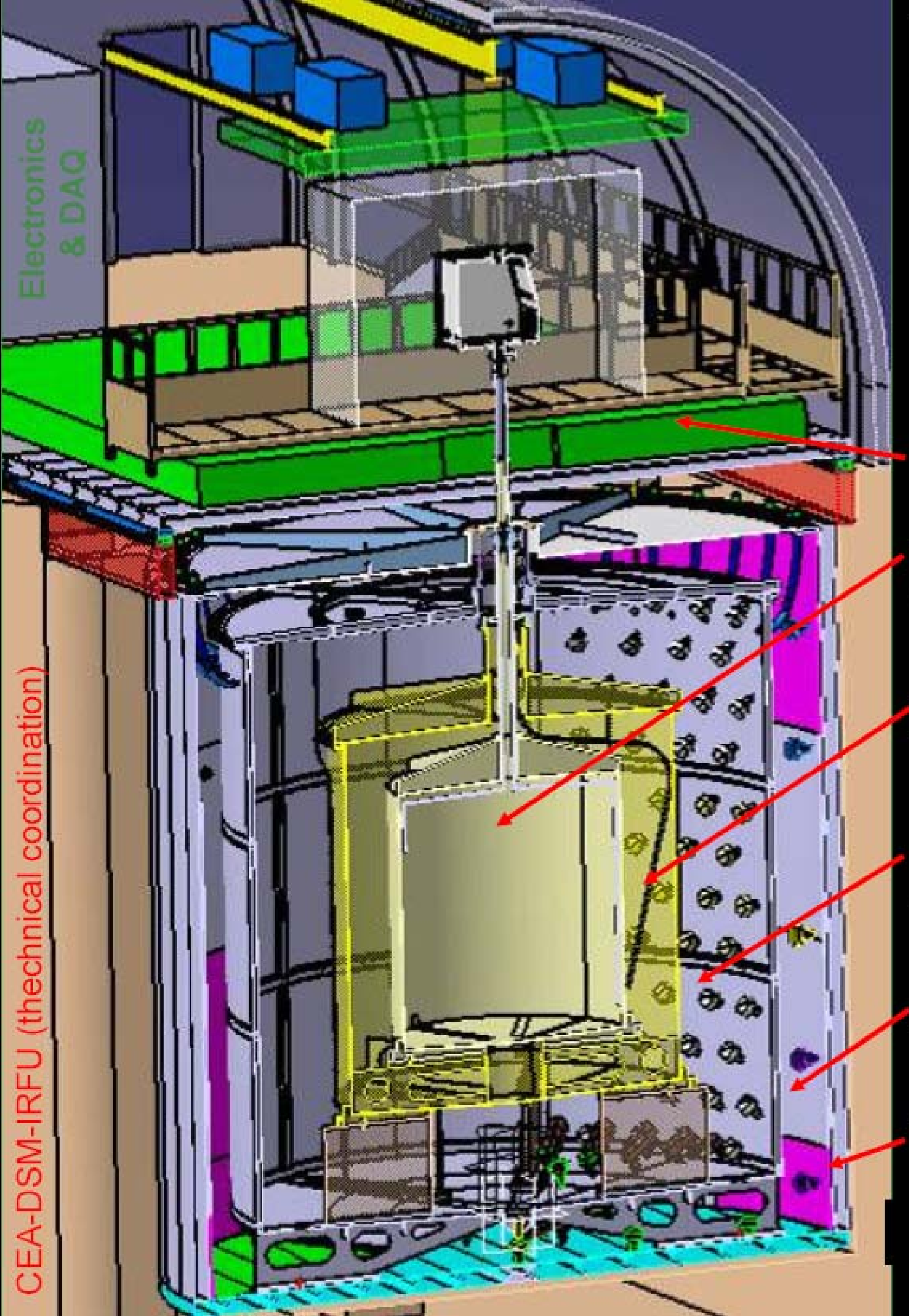
Double Chooz Experiment

Collaboration of ~150 physicists from France, Germany, Spain, Japan, U.K., Russia, Brazil, and U.S.

Chooz Far Detector Hall

300 m.w.e. Shielding

Detector Design



New 4-region large detector concept from Double Chooz Coll. (2003)

http://bama.ua.edu/~busenitz/rnu2003_talks/lasserre1.doc

Outer Veto: plastic scintillator strips (400 mm)

ν-Target: 10,3 m^3 scintillator doped with 0,1g/l of Gd compound in an acryclic vessel (8 mm)

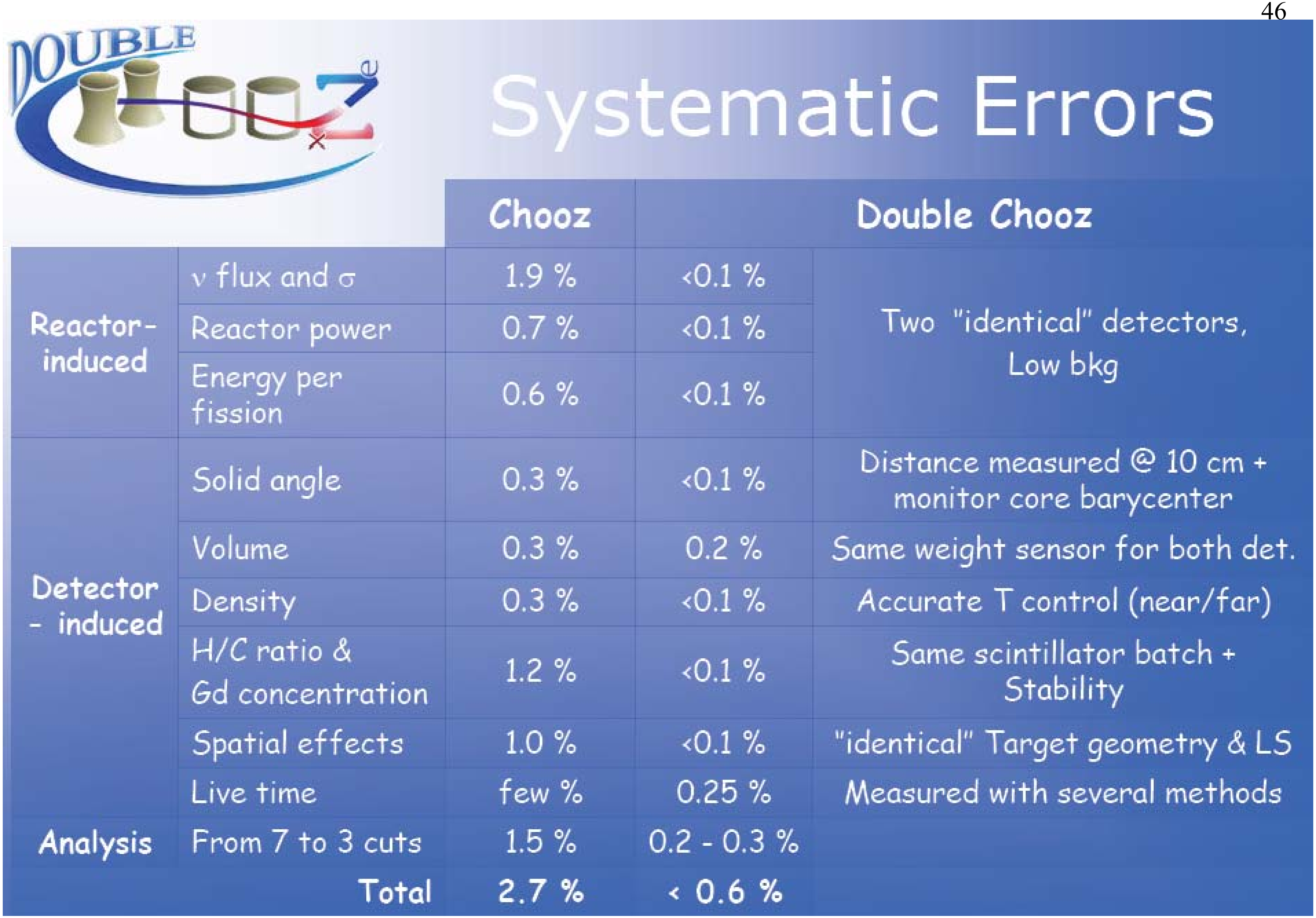
γ-Catcher: 22,3 m^3 scintillator in an acrylic vessel (12 mm)

Buffer: 110 m^3 of mineral oil in a stainless steel vessel (3 mm) viewed by 390 PMTs

Inner Veto: 90m^3 of scintillator in a steel vessel equipped with 78 PMTs

Veto Vessel (10mm) & **Steel Shielding** (150 mm)

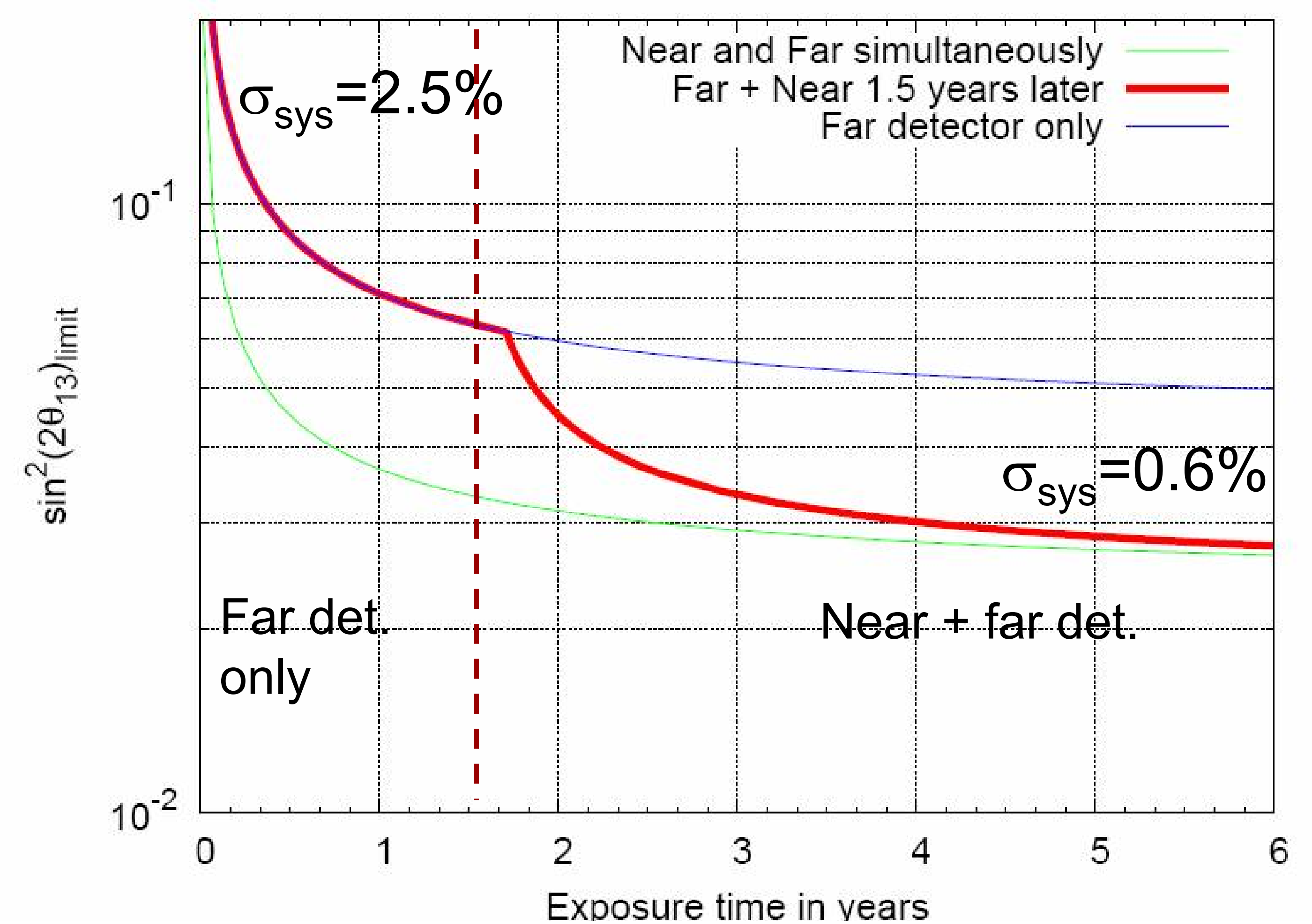
(4 liquid densities adjusted at 0,800±0,005)

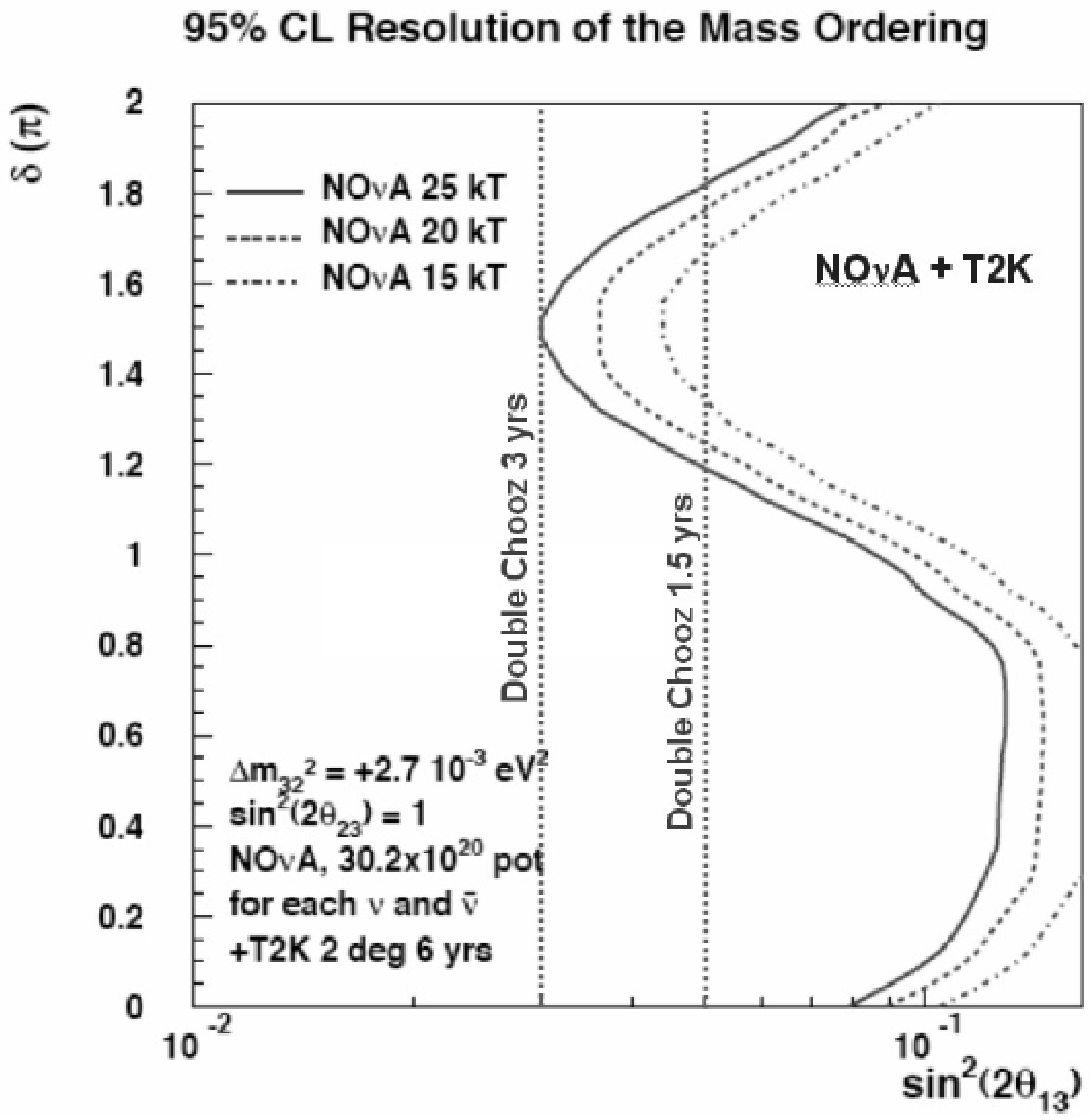


Systematic Errors

		Chooz	Double Chooz	
Reactor-induced	ν flux and σ	1.9 %	<0.1 %	Two "identical" detectors, Low bkg
	Reactor power	0.7 %	<0.1 %	
	Energy per fission	0.6 %	<0.1 %	
Detector-induced	Solid angle	0.3 %	<0.1 %	Distance measured @ 10 cm + monitor core barycenter
	Volume	0.3 %	0.2 %	Same weight sensor for both det.
	Density	0.3 %	<0.1 %	Accurate T control (near/far)
	H/C ratio & Gd concentration	1.2 %	<0.1 %	Same scintillator batch + Stability
	Spatial effects	1.0 %	<0.1 %	"identical" Target geometry & LS
	Live time	few %	0.25 %	Measured with several methods
Analysis	From 7 to 3 cuts	1.5 %	0.2 - 0.3 %	
	Total	**2.7 %**	**< 0.6 %**	

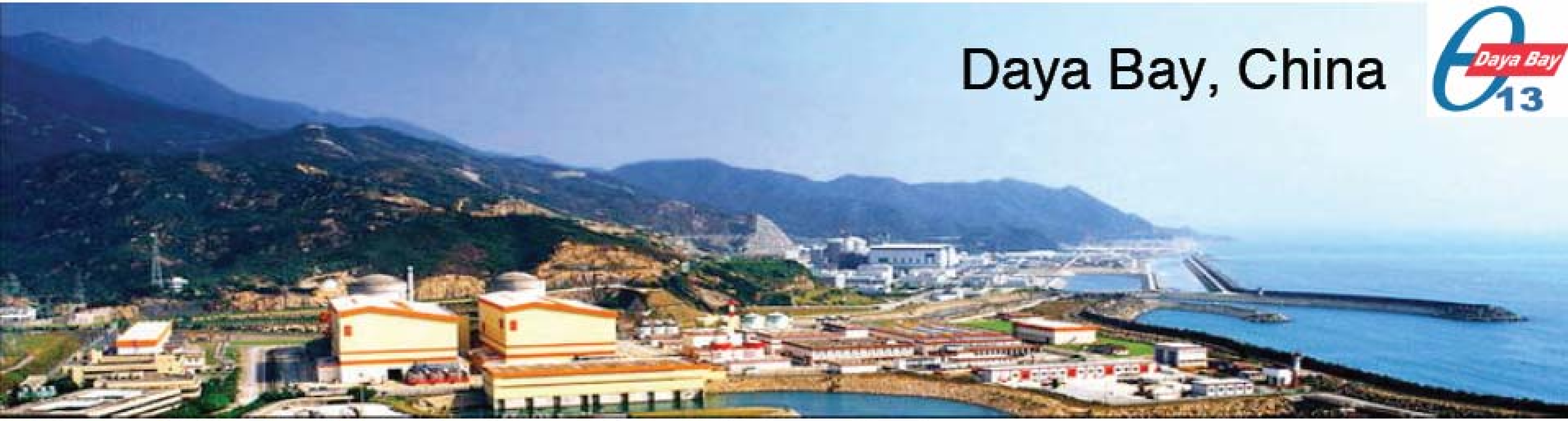
Double Chooz will begin data taking in April 2009 with far detector only. The near detector will be installed 12-18 months later.





95% CL Resolution of the Mass Ordering

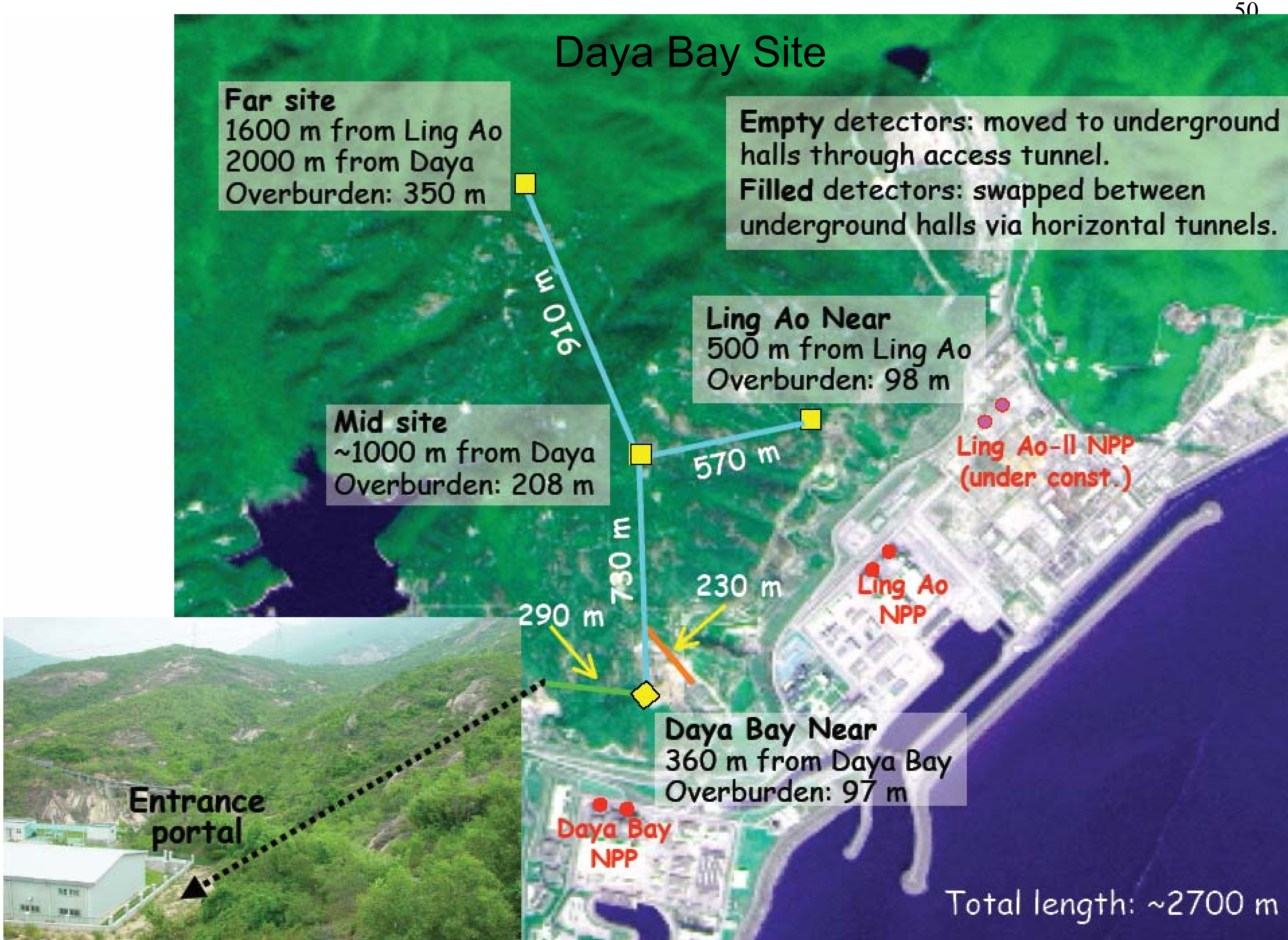
Daya Bay, China



Powerful $\overline{\nu}_e$ Source: Multiple reactor cores.
(at present 4 units 11.6 GW_{th}, in 2011 6 units with 17.4 GW_{th})

Shielding from Cosmic Rays: Up to 1000 mwe overburden nearby. Adjacent to mountain, easy to construct tunnels to reach underground labs with sufficient overburden to suppress cosmic rays

Daya Bay Site



Far site
1600 m from Ling Ao
2000 m from Daya
Overburden: 350 m

Empty detectors: moved to underground halls through access tunnel.
Filled detectors: swapped between underground halls via horizontal tunnels.

Ling Ao Near
500 m from Ling Ao
Overburden: 98 m

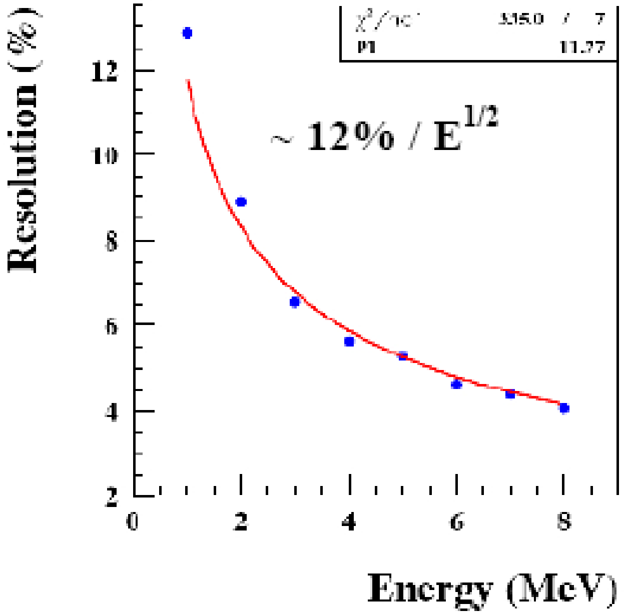
Mid site
~1000 m from Daya
Overburden: 208 m

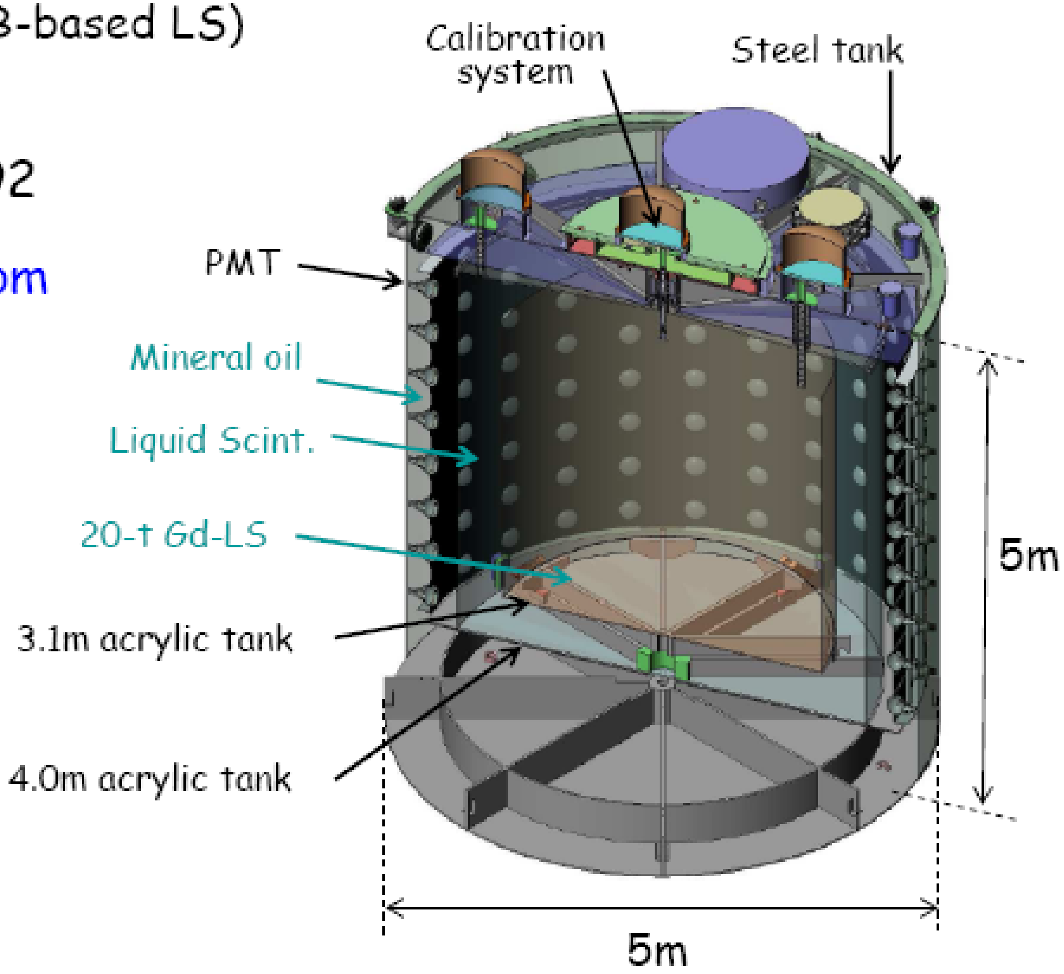
Daya Bay Near
360 m from Daya Bay
Overburden: 97 m

Total length: ~2700 m

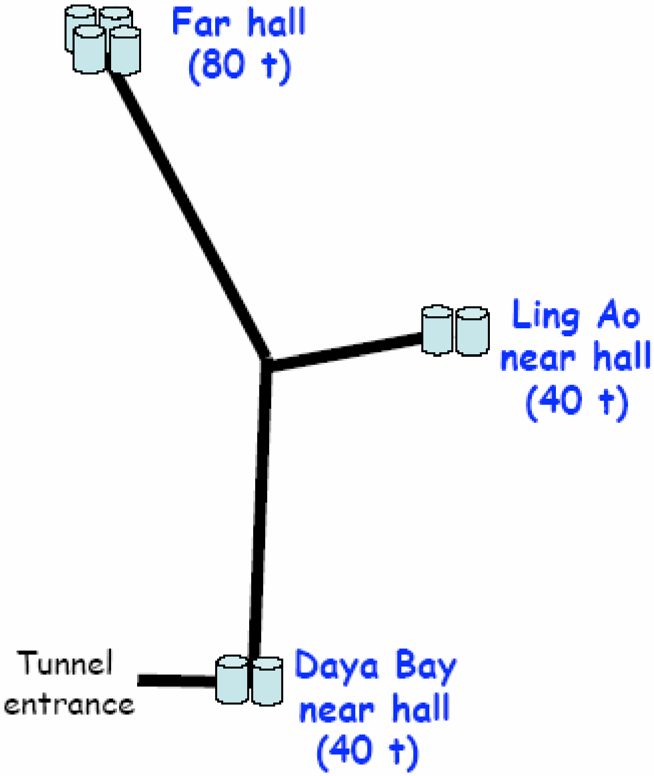
Antineutrino Detectors

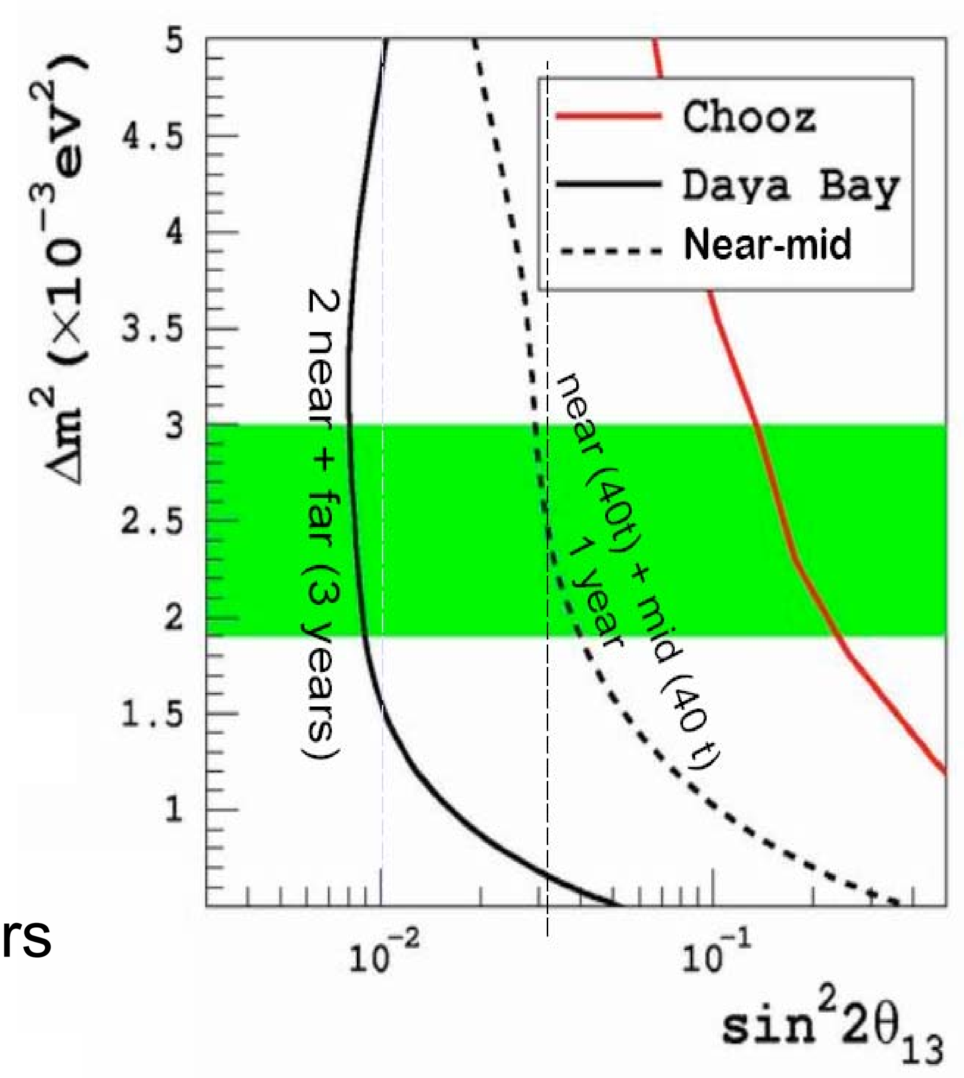
- Three-zone cylindrical detector design
  - Target: 20 t (0.1% Gd LAB-based LS)
  - Gamma catcher: 20 t (LAB-based LS)
  - Buffer : 40 t (mineral oil)
- Low-background 8" PMT: 192
- Reflectors at top and bottom





Daya Bay Projected Sensitivity





90% confidence level

Datataking with all 8 detectors by December 2010.

Conclusions

- Reactor experiments have played an important role in investigating the properties of the neutrino.

- The worldwide program to understand ν oscillations and determine the mixing parameters, CP violating effects, and mass hierarchy will require a broad range of measurements – a reactor experiment to measure θ_{13} is a key part of this program.

- A reactor experiment will provide the most precise measurement of θ_{13} or set the most restrictive limit.

- An observation of θ_{13} will open the door to searching for CP violation in neutrino oscillations.

Many new results to look forward to …