The Daya Bay Reactor Neutrino Experiment

DPF 2006, Honolulu, Hawaii 10/30/2006

Mary Bishai (for the Daya Bay Collaboration)

`mbishai@bnl.gov`

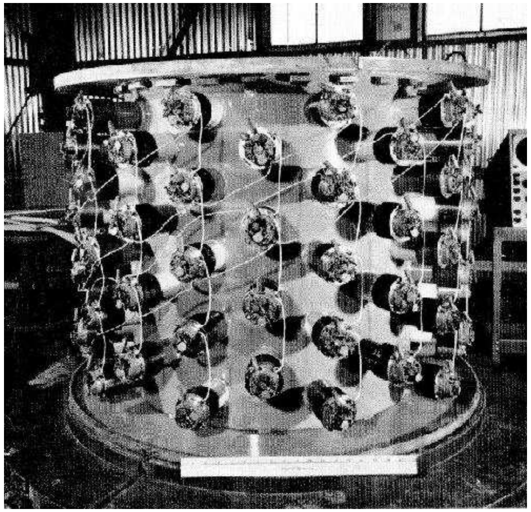
Brookhaven National Lab.

PHYSICS POTENTIAL OF REACTOR NEUTRINO EXPERIMENTS

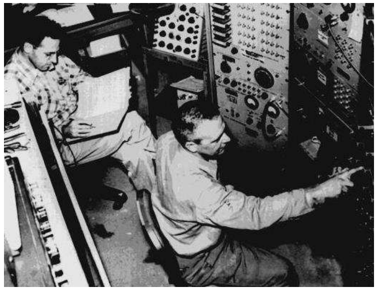
Detecting Neutrinos - History

1950's: **Fred Reines at Los Alamos and Clyde Cowan** mounted an experiment at the Hanford nuclear reactor in 1953 and in 1955 at the new Savannah River nuclear reactor. A detector filled with **water with $CdCl_2$ in solution** was located 11 meters from the reactor center and 12 meters underground.

The detection sequence was as follows:



1. $\bar{\nu}_e + p \longrightarrow n + e^+$
2. $e^+ + e^- \longrightarrow \gamma\gamma$ (2X 0.511 MeV)
3. $n +^{108} Cd \longrightarrow^{109} Cd* \longrightarrow^{109} Cd + \gamma$ ($\tau = 5\mu s$).

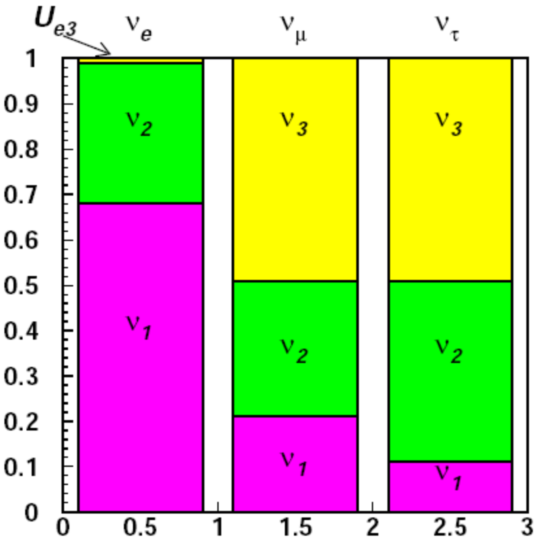


Neutrinos first detected from a reactor!

Neutrino mixing

In 1962 Maki, Nakagawa, Sakata proposed a 2 flavor mixing matrix. The 3-flavor form now used (attributed to MNS and Pontecorvo) is:

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



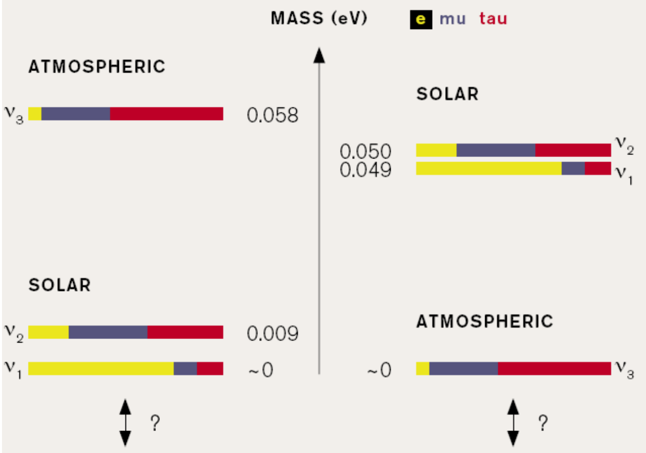
$$U_{PMNS} \sim \begin{pmatrix} 0.8 & 0.5 & ? \\ 0.4 & 0.6 & 0.7 \\ 0.4 & 0.6 & 0.7 \end{pmatrix} \qquad V_{CKM} \sim \begin{pmatrix} 1 & 0.2 & 0.005 \\ 0.2 & 1 & 0.04 \\ 0.005 & 0.04 & 1 \end{pmatrix}$$

Compared to CKM matrix : v. large off diagonal terms, U_{e3} unknown

Neutrino Matrix Parameterization

$$U = \underbrace{\begin{pmatrix}1 & 0 & 0\\ 0 & c_{23} & s_{23}\\ 0 & -s_{23} & c_{23}\end{pmatrix}}_{\text{Atmospheric } \nu' s}\underbrace{\begin{pmatrix}c_{13} & 0 & e^{i\delta_{\rm CP}}s_{13}\\ 0 & 1 & 0\\ -e^{i\delta_{\rm CP}}s_{13} & 0 & c_{13}\end{pmatrix}}_{\text{Reactor } \nu' s}\underbrace{\begin{pmatrix}c_{12} & s_{12} & 0\\ -s_{12} & c_{12} & 0\\ 0 & 0 & 1\end{pmatrix}}_{\text{Reactor,Solar } \nu' s}$$

where $c_{\alpha\beta} = \cos\theta_{\alpha\beta}$ and $s_{\alpha\beta} = \sin\theta_{\alpha\beta}$ and $\delta_{\rm CP}$ is the CP phase.



Normal **Inverted**

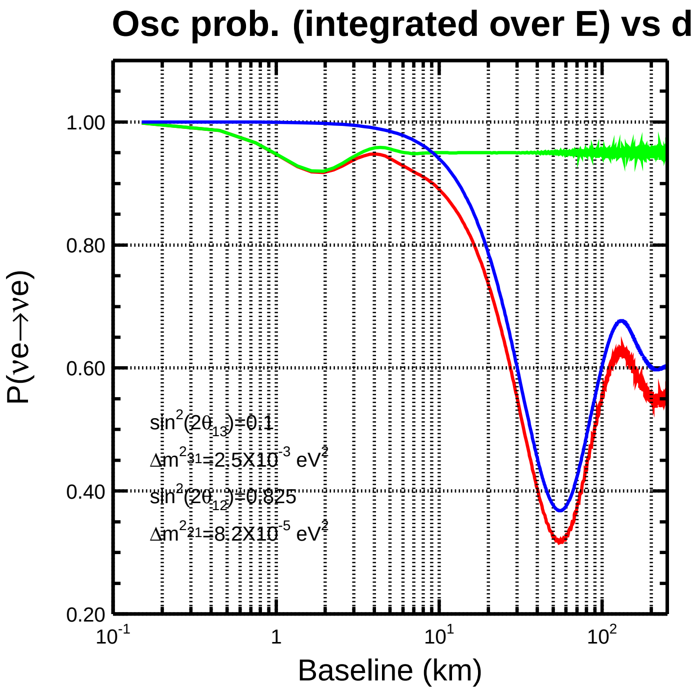
$\sin^2\theta_{13}$: **Amount of ν_e in ν_3** **UNKNOWN !!**

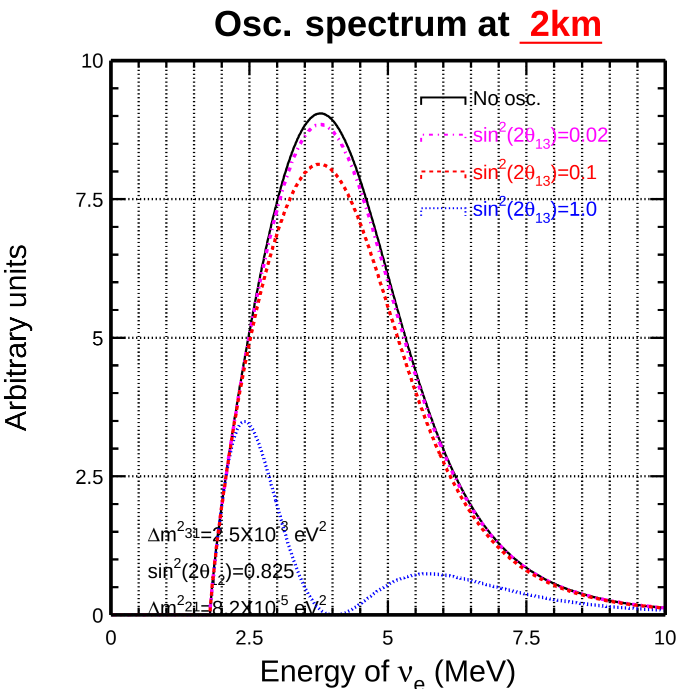
$\tan^2\theta_{23}$: **Ratio of $\frac{\nu_\mu}{\nu_\tau}$ in ν_3**

$\tan^2\theta_{12}$: $\frac{\text{Amount of } \nu_e \text{ in } \nu_2}{\text{Amount of } \nu_e \text{ in } \nu_1}$

Reactor $\bar{\nu}_e$ oscillations

$$\begin{aligned} P(\nu_e \to \nu_e) = 1 &- \sin^2 2\theta_{13} \sin^2(1.27 \Delta m^2_{31} L/E) \\ &- \cos^4 \theta_{13} \sin^2 2\theta_{12} \sin^2(1.27 \Delta m^2_{21} L/E) \end{aligned}$$


Osc prob. (integrated over E) vs distance


Osc. spectrum at 2km

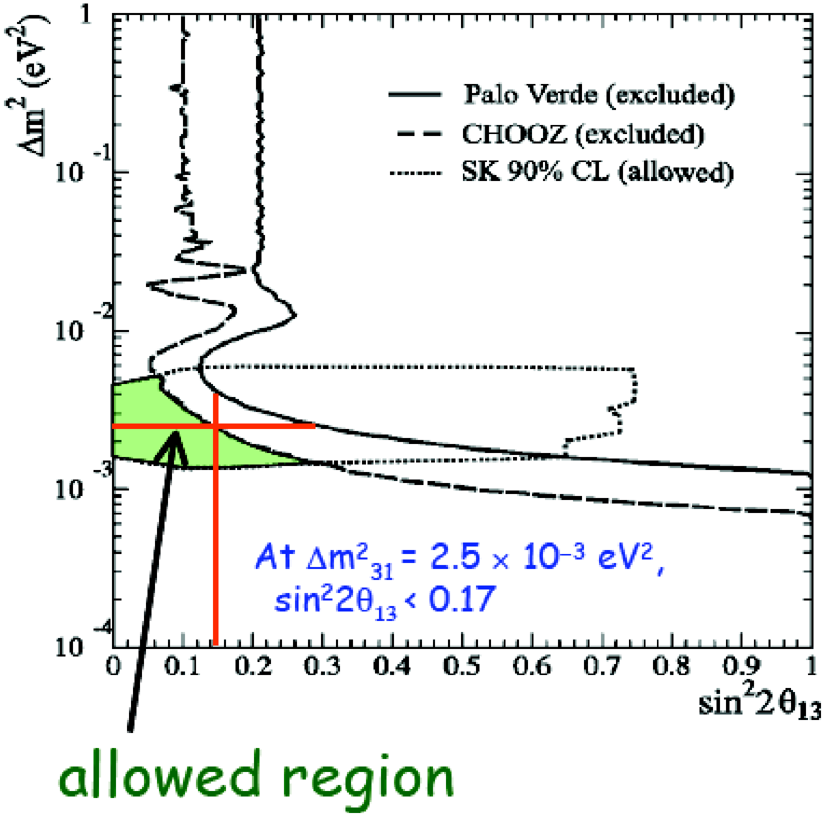
Reactor ν_e disappearance = *unambiguous* **measurement of $\sin^2 2\theta_{13}$**

Getting to $\sin^2 2\theta_{13} < 0.01$

Current knowledge of $\sin^2 2\theta_{13}$:

Global fit: $\sin^2 2\theta_{13} < 0.11$

(90% C.L.)



Lots of statistics: **-Powerful nuclear reactors + more massive detectors**

Supress cosmic backgrounds:

-Increase overburden = go deeper underground.

Reduce systematic uncertainties:

-Optimize baseline for best S:B - Deploy near detectors as close as possible to reactor to minimize reactor flux uncertainties.

-Use multiple, “identical”, and interchangeable detectors to reduce near/far detector uncertainties.

- Calibration, calibration, calibration...

OVERVIEW OF THE DAYA BAY EXPERIMENT

The Daya Bay Reactor Complex

Daya Bay NPP
(2X2.9 GWth)

Ling AO NPP
(2X2.9 GWth)

Ling Ao II NPP (2011)
(2X2.9 GWth)

Reactor Specs:

Located 55km north-east of Hong Kong.

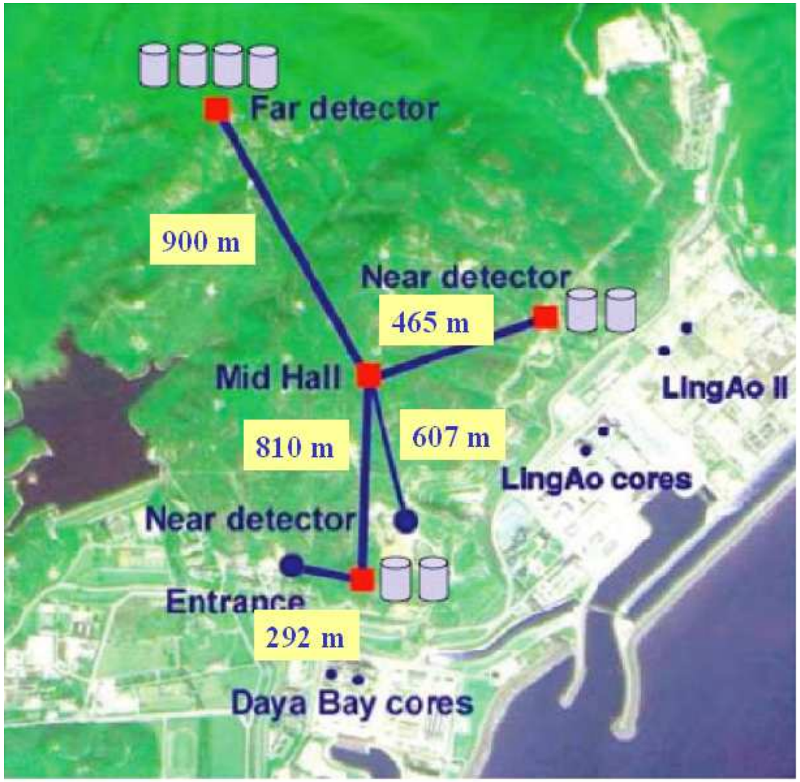
Current: 2 cores at Daya Bay site + 2 cores at Ling Ao site = 11.6 GW_{th}

By 2011: 2 more cores at Ling Ao II site = 17.4 $\mathrm{GW}_{th} \Rightarrow$ 5th most powerful in the world

1 $\mathrm{GW}_{th} = 10^{20}\bar{\nu}_e/$second

Powerful reactors with mountains close by!

Daya Bay Experimental Layout

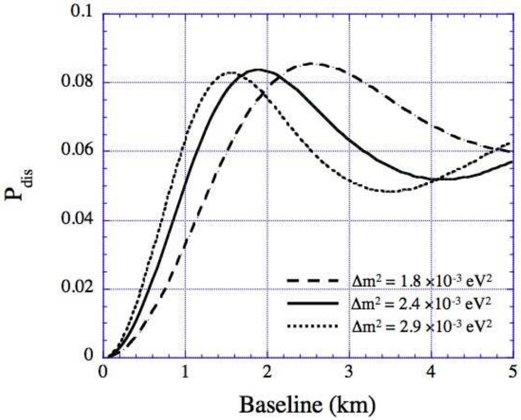


Multiple "identical" detector modules deployed at 2 near sites and 1 far site

2 detector modules at each near site for cross-check and 4 detector modules at far site = 8 total

A midsite hall is planned where 2 detector modules could be deployed while civil construction of the far site is ongoing

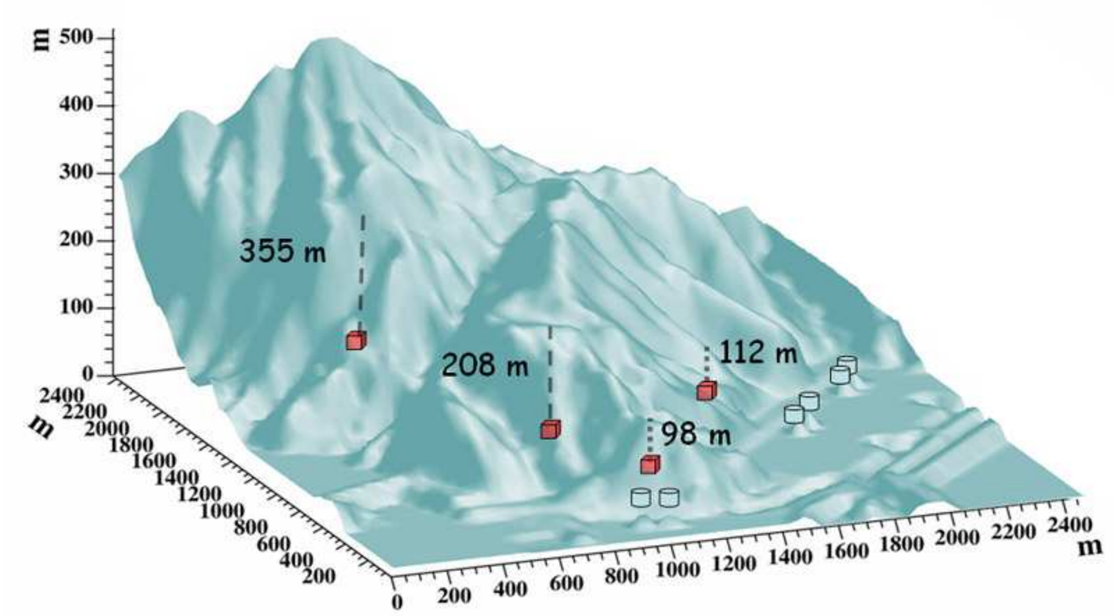
Site locations chosen to optimize overburden and osc. baseline. ⟶



Cosmic Ray Backgrounds

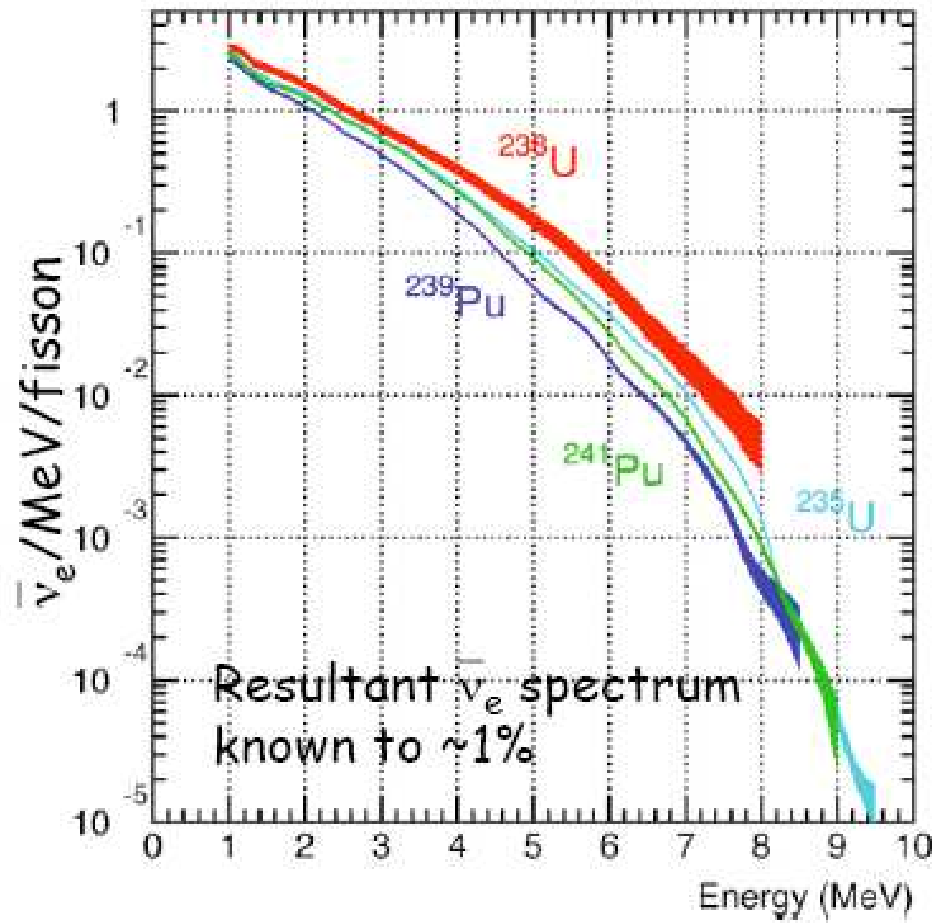
-Used a modified Gaisser parametrization for cosmic-ray flux at surface

-Apply MUSIC and mountain profile to estimate muon intensity and energy

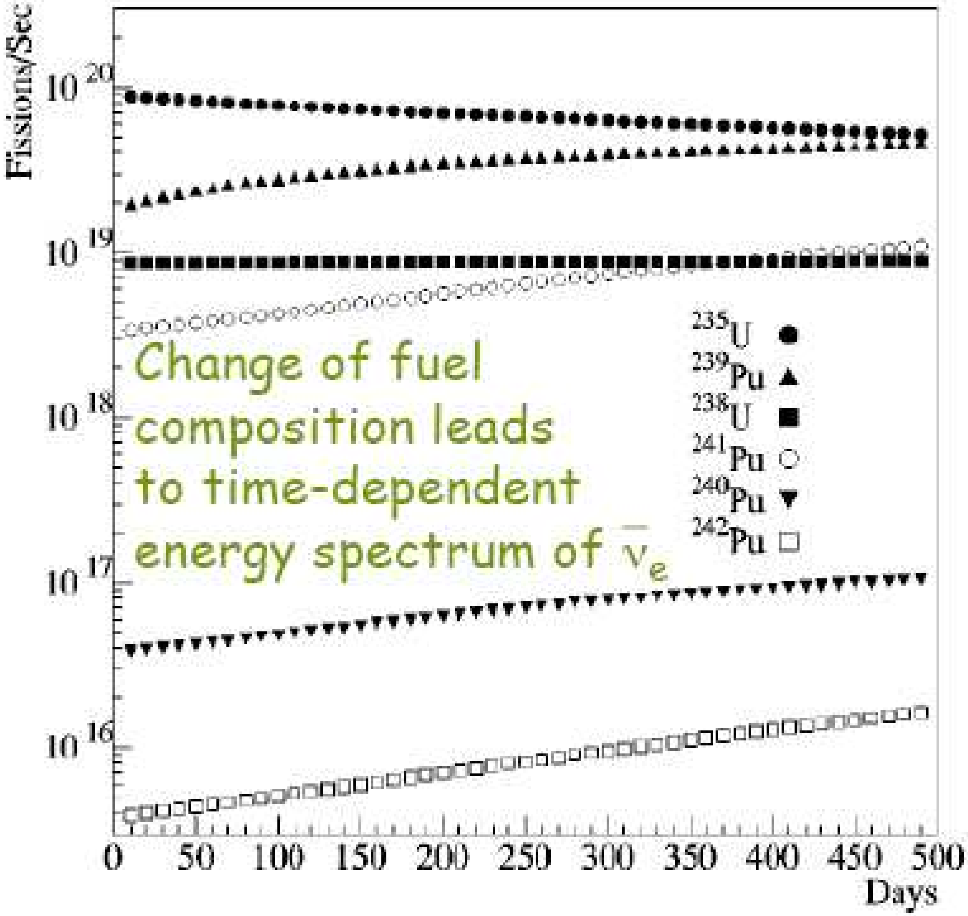


	DYB	LA	Mid	Far
Overburden (m)	**98**	**112**	**208**	**355**
Muon intensity (Hz/m^2)	**1.16**	**0.73**	**0.17**	**0.041**
Mean Energy (GeV)	**55**	**60**	**97**	**138**

Neutrino flux from Reactors



Resultant $\bar{\nu}_e$ spectrum known to ~1%



Change of fuel composition leads to time-dependent energy spectrum of $\bar{\nu}_e$

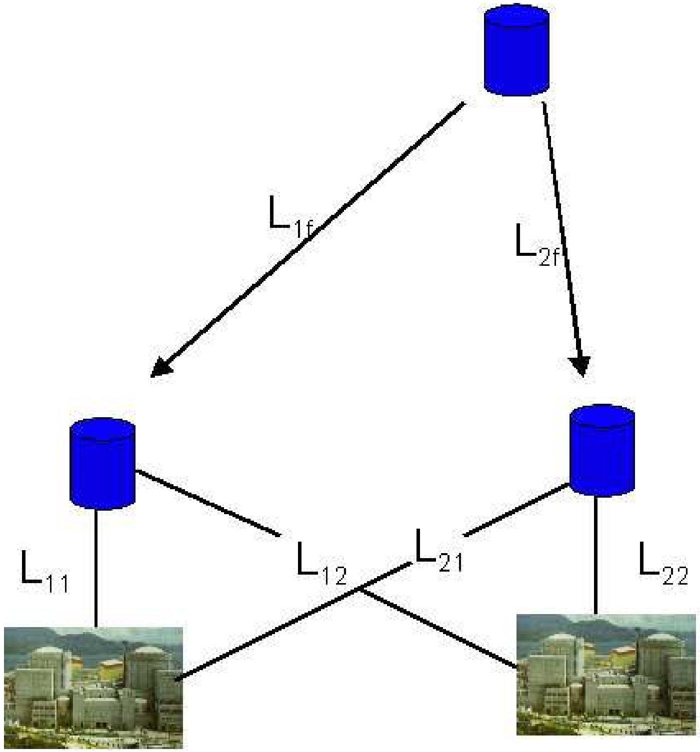
Reactor power is known to at least 2%

(CHOOZ states 0.6% uncertainty)

Near/Far cancellation

FAQ: How does the extended distribution of near cores compromise the near/far cancellation?

A: Deweigh the oversampled cores by a factor, α, Ratio = $\alpha\frac{\mathbf{Near1}}{\mathbf{far}} + \frac{\mathbf{Near2}}{\mathbf{far}}$



$$\alpha = \frac{1/(L_{22}^2 L_{1f}^2) - 1/(L_{21}^2 L_{2f}^2)}{1/(L_{11}^2 L_{2f}^2) - 1/(L_{12}^2 L_{1f}^2)}$$

For Daya Bay 4 cores, $\alpha = 0.34 \Rightarrow$

factor 50 cancellation: 2% $\longrightarrow$ 0.035%

For Daya Bay 6 cores, $\alpha = 0.39 \Rightarrow$

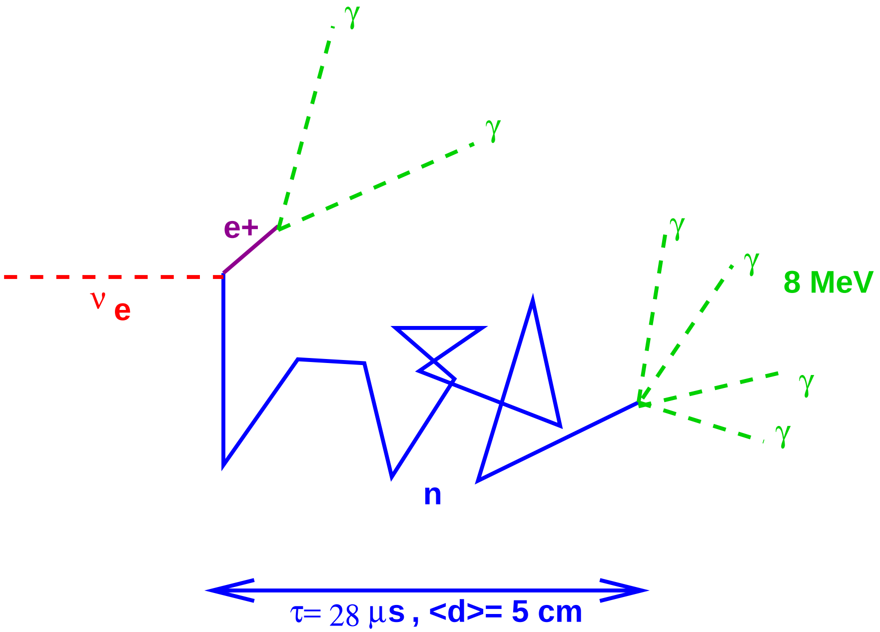
factor 20 cancellation: 2% $\longrightarrow$ 0.1%

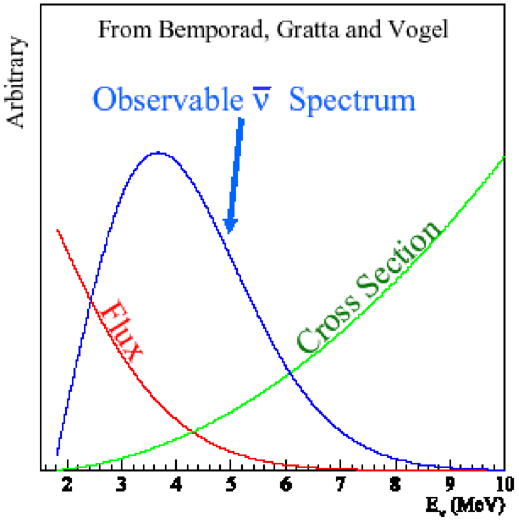
Deweighing $\Rightarrow$ cancellation of reactor power uncertainties to better than 0.1% .

THE DAYA BAY DETECTORS

Detecting $\bar{\nu}_e$ using GD-Liquid Scint.

The active target in each detector module is liquid scintillator loaded with 0.1% Gd





The detection sequence is as follows: $\bar{\nu}_e + p \rightarrow n + e^+$ **THEN**

$e^+ + e^- \rightarrow \gamma\gamma$ **(2X 0.511 MeV, $\underline{\text{prompt}}$)**

$n + Gd \rightarrow Gd* \rightarrow Gd + \gamma$**’s (8 MeV, $\underline{\tau \sim 28\mu s}$, $\sigma = 5 \times 10^4$b). OR**

$n + p^+ \rightarrow D + \gamma$ **(2.2 MeV, $\tau\underline{\sim 180\mu s}$, $\sigma = 0.3$b).**

$\Rightarrow$ delayed co-incidence of e^+ conversion and n-capture

with a specfic energy signature

The Anti Neutrino Detector

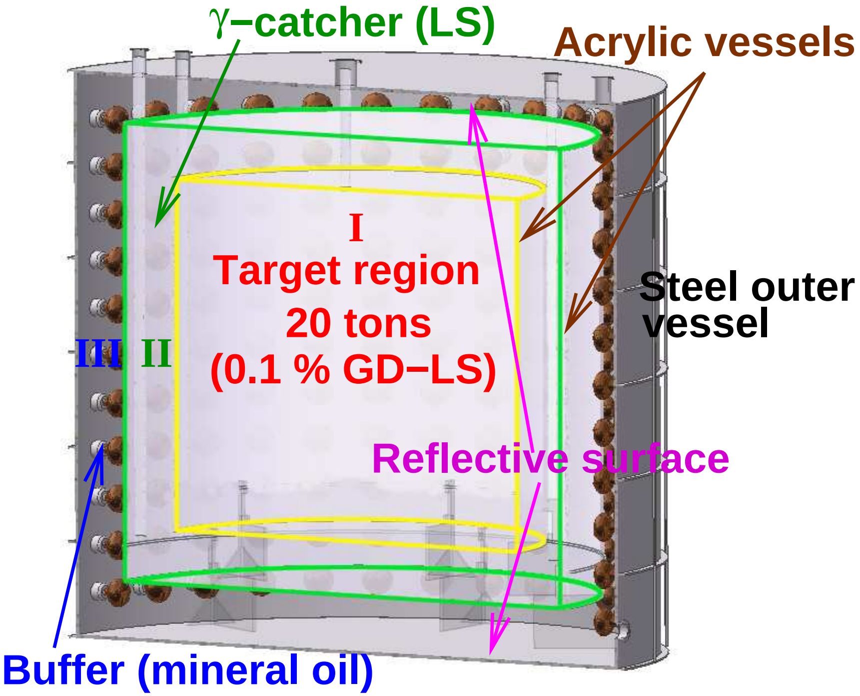
3 zone nested cylindrical structure with the following specifications:

Region	IR (m)	OR (m)	inner height (m)	outer height (m)	vessel thickness (mm)	material
I-target	**0.00**	**1.60**	**0.00**	**3.20**	**10.0**	**Gd-LS**
II-γ-catcher	**1.60**	**2.05**	**3.20**	**4.10**	**15.0**	**LS**
III-buffer	**2.05**	**2.50**	**4.10**	**5.00**	**8.0–10.0**	**Mineral oil**

224 8” PMTS are mounted around the circumference of the outer steel tank with diffuse reflectors on top and bottom:

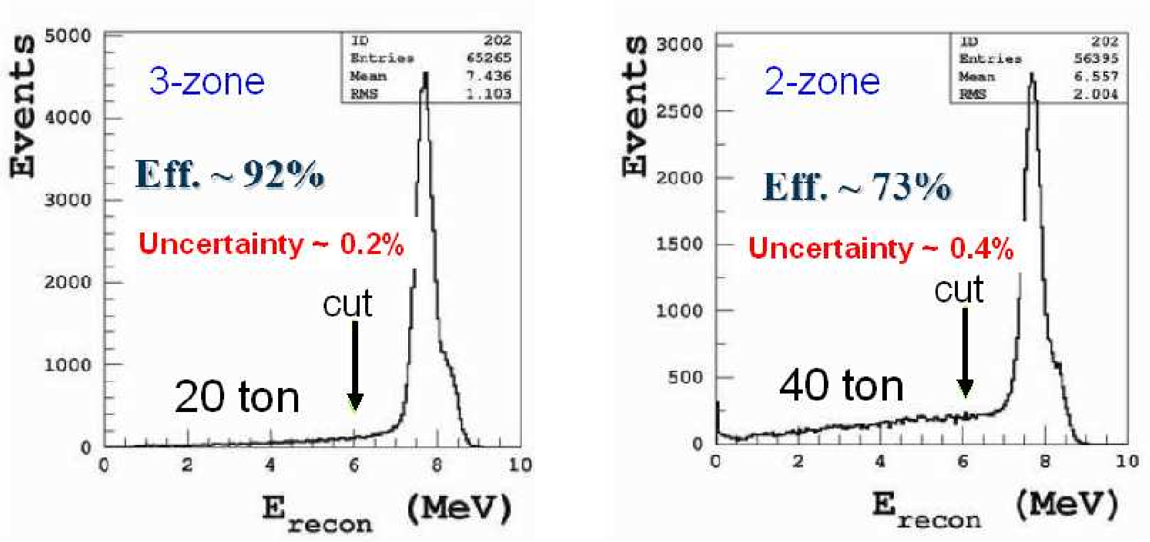
$$\frac{\sigma}{E} \sim \frac{12\%}{\sqrt{E(\mathrm{MeV})}}, \ \sigma_{pos} = 13\,\mathrm{cm}$$

	DYB	LA	Far
Event rates/20T/day	**930**	**760**	**90**



$\bar{\nu}_e$ Detector Design Optimization

3 zone vs 2 zone ⇒ reduced systematic uncertainty in reconstructed energy cut:

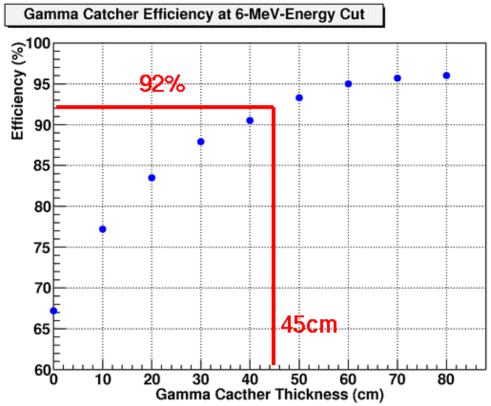


← Selection cut for n capture on Gd only

Separate cut/efficiency for capture on H

n capture on Gd yields 8 MeV with 3-4 γ's

γ catcher efficiency



Buffer oil shielding

		Buffer Oil Thickness (Rates in Hz)			
Isotope	Concentration	20 cm	25 cm	30 cm	40 cm
^{238}U	40 ppb	2.2	1.6	1.1	0.6
^{232}Th	40 ppb	1.0	0.7	0.6	0.3
^{40}K	25 ppb	4.5	3.2	2.2	1.3
Total		7.7	5.5	3.9	2.2

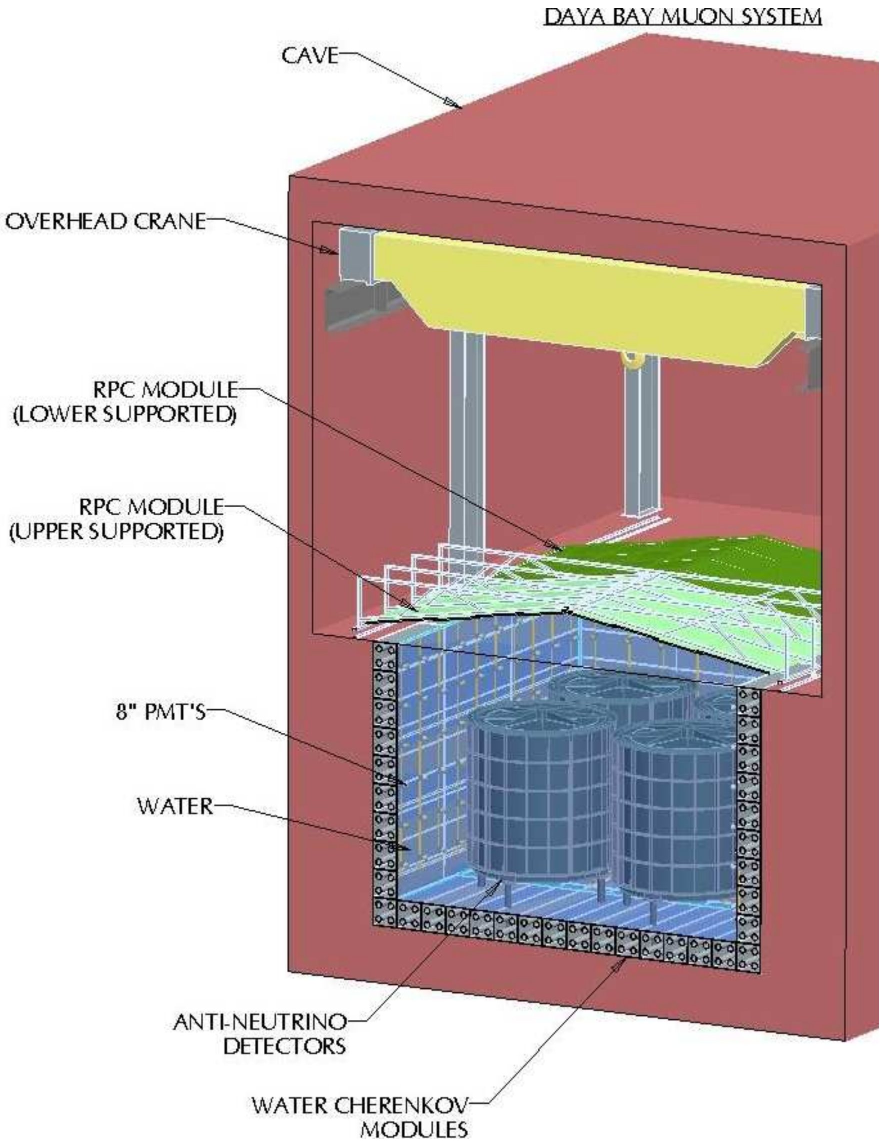
The Daya Bay Detector Hall Layout

Water pool: The $\bar{\nu}_e$ detectors are immersed in a water pool with 2.5m of water on all sides. Shields against fast neutrons, γs from wall.

Inner muon veto: 1m in from the sides and bottom of the pool a single layer of 8" PMTs (3% coverage) acts as a water Cerenkov μ detector.

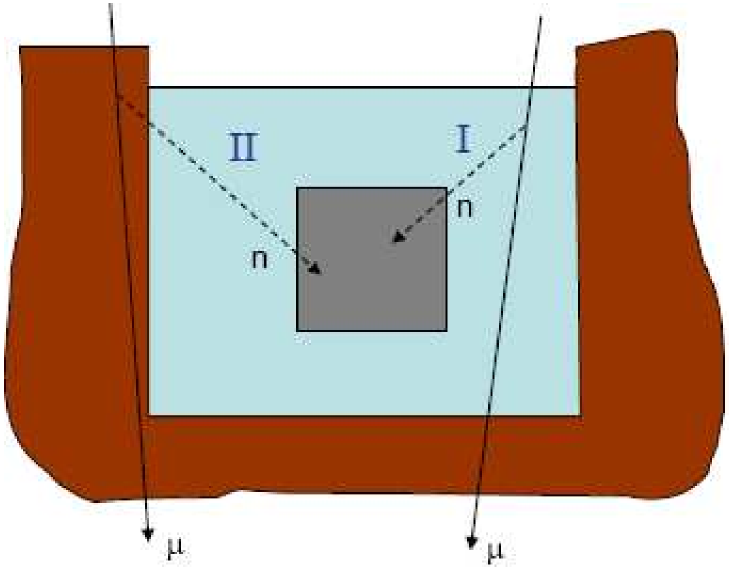
Outer muon veto: The outer 1m of the water pool is instrumented with segmented water Cerenkov detectors.

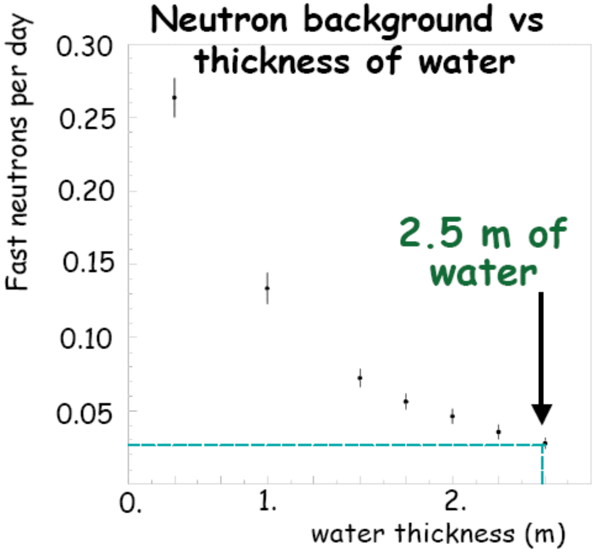
RPC system : On top of pool, multiple layers of resistive plate chambers are mounted on a movable roof.



BACKGROUNDS AND SYSTEMATICS

Fast Neutrons





Fast neutron simulation results: events/day/20T module

	I: Missed veto	II:Rock neutrons	II:Total/Signal
DYB	**0.10**	**0.5**	6×10^{-4}
LA	**0.07**	**0.35**	6×10^{-4}
Far	**0.01**	**0.03**	4×10^{-4}

He^8/Li^9

Generated by showers from cosmic muons:

$$^9Li \rightarrow \underbrace{e^-}_{\text{prompt}} + \bar{\nu}_e + ^9Be^* \rightarrow ^8Be + \underbrace{n}_{\text{delayed n}-\text{capture}}$$

Q= 13 MeV, $\tau = 178$ msec $\Rightarrow$ poor spatial correlation with μ track.

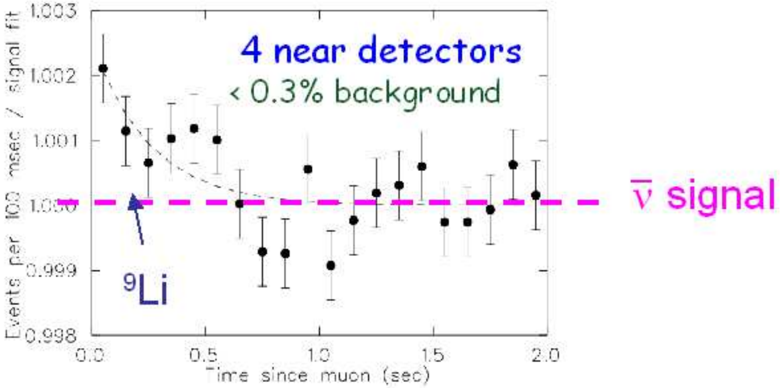
Computed rates (Hagner et. al.) :

	DYB	**LA**	**Far**
$^9Li + ^8He$ **rates/module/day**	**3.7**	**2.5**	**0.26**

But it can be measured ! ⟶

$\sigma(B/S) = 0.3\%$**(near)**

0.1%(far):



Time since muon (sec)

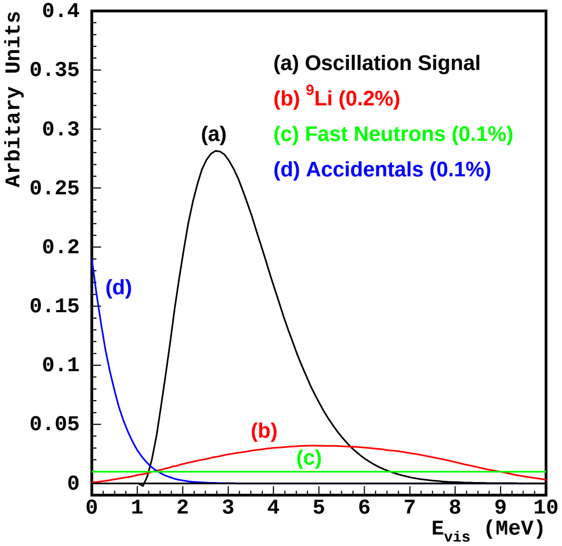
Event rates per Detector Module

Source	Units	DB	LA	far	Use
Antineutrino Signal	**(day^{-1})**	**930**	**760**	**90**	**signal**
Radioactive Backgrounds	(Hz)	30	30	30	e$^+$-thresh.
Rock	(Hz)	4	4	4	
PMT glass	(Hz)	8	8	8	
other materials (steel)	(Hz)	18	18	18	
Gd contamination	(Hz)	1	1	1	
Muons	(Hz)	24	14	1	
Single neutron	(day^{-1})	9000	6000	400	cal.
Tagged single neutron	(day^{-1})	480	320	45	cal./bkg.
Tagged fast neutron	(day^{-1})	20	13	2	Bkg est
β emitters (6-10 MeV)	(day^{-1})	210	140	15	n-thresh.
^{12}B	(day^{-1})	400	270	28	cal.
^{8}He+^{9}Li	(day^{-1})	4	3	0	Bkg

Accidental background rates

Prompt: γ from radioactivity ($\sim$ 50Hz/module)

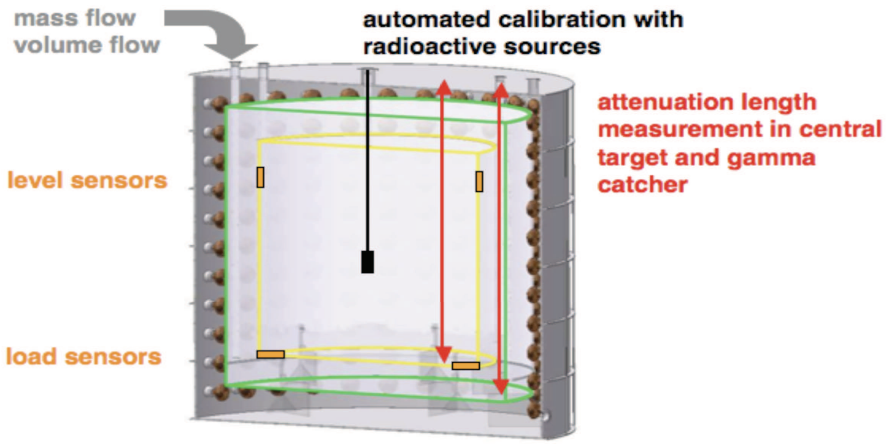
Delayed:: 1) untagged single neutron capture 2) cosmogenic beta emmiters (6-10MeV, mostly ^{10}B) 3)U/Th $\longrightarrow$ O, Si $(\alpha, n, \gamma[6 - 10\,\mathrm{MeV}])$

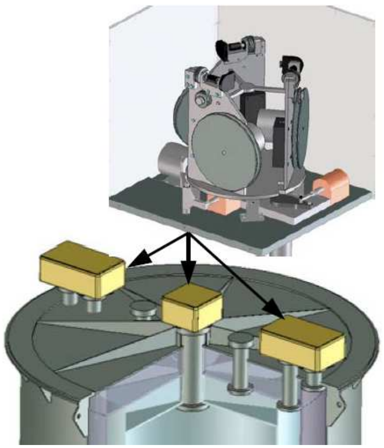


	DYB	LA	Far
Signal rates	930/day	760/day	90/day
1) neutrons	18/day	12/day	1.5/day
2) βs	210/day	141/day	14.6/day
3) $\alpha, n\gamma$	$<$10/day	$<$10/day	$<$10/day
Coinc rate	2.3/day	1.3/day	0.26/day
B/S	$\sim 2 \times 10^{-3}$	$\sim 2 \times 10^{-3}$	$\sim 3 \times 10^{-3}$

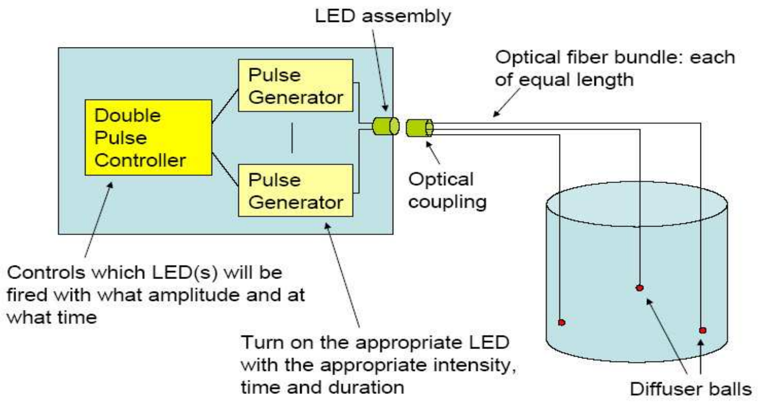
Untagged background rates are tiny and subtractable

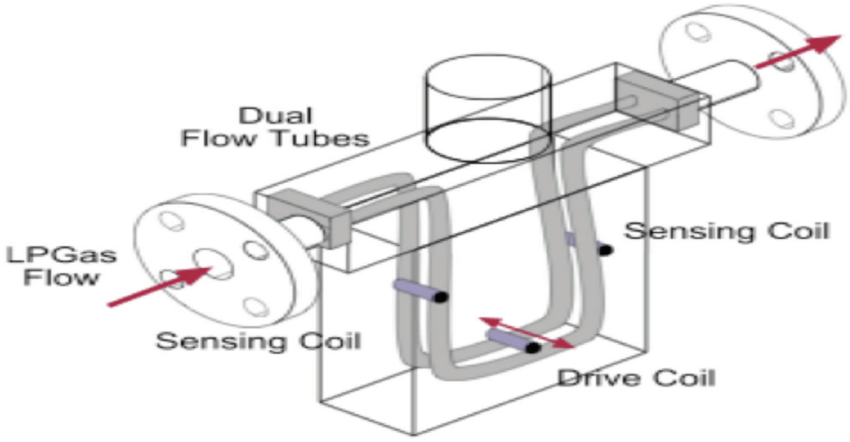
Calibration/Monitoring Systems





3 access ports for calibration at different R Automated system deploys 4 different sources





Pulsed LED system for att. length/PMT response Coriolis mass flowmeters $< 0.2\%$ accuracy

Source Calibrations

Sources	Calibrations
Neutron sources: Am-Be and ^{252}Cf	Neutron response, relative and absolute efficiency, capture time
Positron sources: ^{22}Na, ^{68}Ge	Positron response, energy scale trigger threshold
Gamma sources:	Energy linearity, stability, resolution spatial and temporal variations, quenching effect ^{137}Cs (0.662 MeV), ^{54}Mn (0.835 MeV), ^{65}Zn (1.351 MeV) ^{40}K (1.461 MeV), ^{22}Na (annih + 1.275 MeV), ^{60}Co (1.173 + 1.333 MeV) ^{208}Tl (2.615 MeV), Am-Be (4.43 MeV), ^{238}Pu-^{13}C (6.13 MeV)
H neutron capture	2.223 MeV
Gd neutron capture	$\sim$ 8 MeV

Detector systematics

Source of uncertainty		Chooz (*absolute*)	Daya Bay (*relative*)		
			Baseline	Goal	Goal w/Swapping
# protons	H/C ratio	0.8	0.2	0.1	0
	Mass	-	0.2	0.02	0.006
Detector Efficiency	Energy cuts	0.8	0.2	0.1	0.1
	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	0.1	0.1	0.0
	n multiplicity	0.5	0.05	0.05	0.05
	Trigger	0	0.01	0.01	0.01
	Live time	0	$<$ 0.01	$<$ 0.01	$<$ 0.01
Total detector-related uncertainty		1.7%	0.38%	0.18%	0.12%

Detector systematics could be lowered to 0.18%

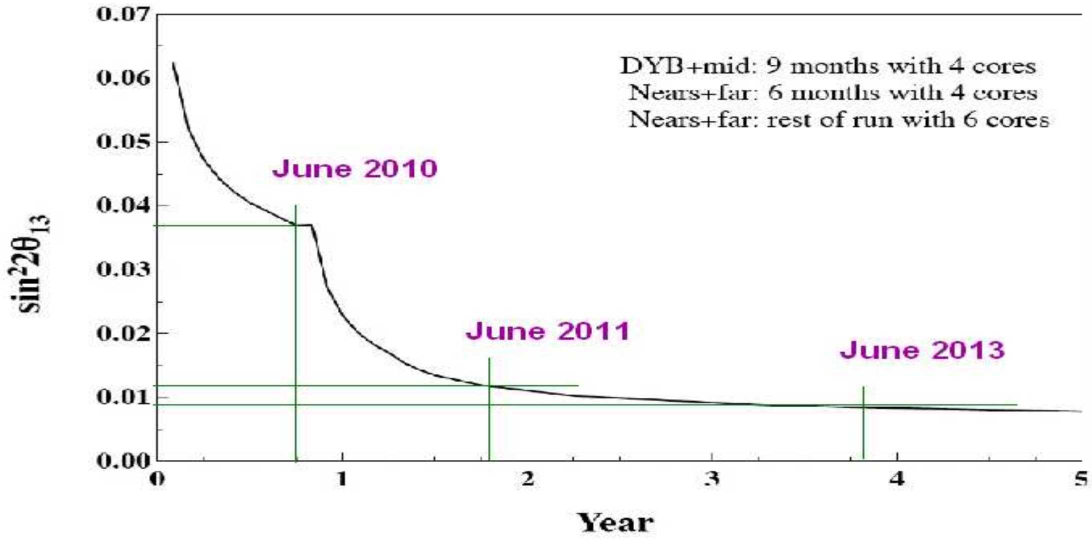
R&D,care in construction, assy, calibration, monitoring

TIMELINE AND SENSITIVITY

Baseline Timeline

Initial Chinese Funding Secured	Apr & Aug 06
US CD-1 approval	Feb 07
Start tunnel construction	Apr 07
PMT Contract Let	Aug 07
US CD-2/3 Approval	Nov 07
Beneficial Occupancy of DB Near Hall	Oct 08
Beneficial Occupancy of Mid Hall	Feb 09
DB near site ready for AD commissioning	Feb 09
Midsite ready to take data	Sept 09
Beneficial occupancy of LA near & far hall	Nov 09
All near and far sites ready to take data	June 10

Sensitivities



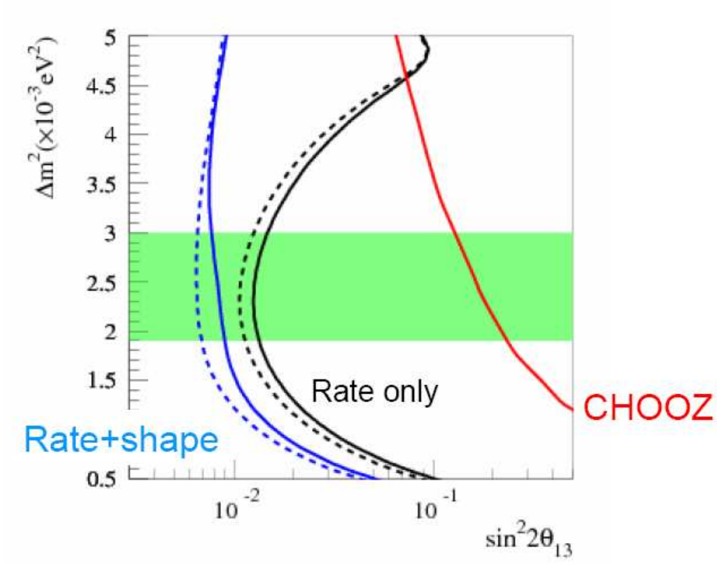
← 90% C.L. limit vs time with baseline detector systematic of 0.38%

2% uncorrelated reactor power uncertainty

After 3 years running ⟶

—— baseline detector systematic 0.38%

- - - - goal detector systematic 0.18%



BACKUP

Neutrino oscillations

Assume 2 flavors only:

$$\begin{pmatrix} \nu_a \\ \nu_b \end{pmatrix} = \begin{pmatrix} \cos(\theta) & \sin(\theta) \\ -\sin(\theta) & \cos(\theta) \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \end{pmatrix}$$

$$\begin{aligned} \nu_a(t) &= \cos(\theta)\nu_1(t) + \sin(\theta)\nu_2(t) \\ P(\nu_a \rightarrow \nu_b) &= | < \nu_b|\nu_a(t) > |^2 \\ &= \sin^2(\theta)\cos^2(\theta)|e^{-iE_2t} - e^{-iE_1t}|^2 \end{aligned}$$

$$P(\nu_a \rightarrow \nu_b) = \sin^2 2\theta \sin^2 \frac{1.27((m_2^2 - m_1^2)/eV^2)(L/km)}{(E/GeV)}$$

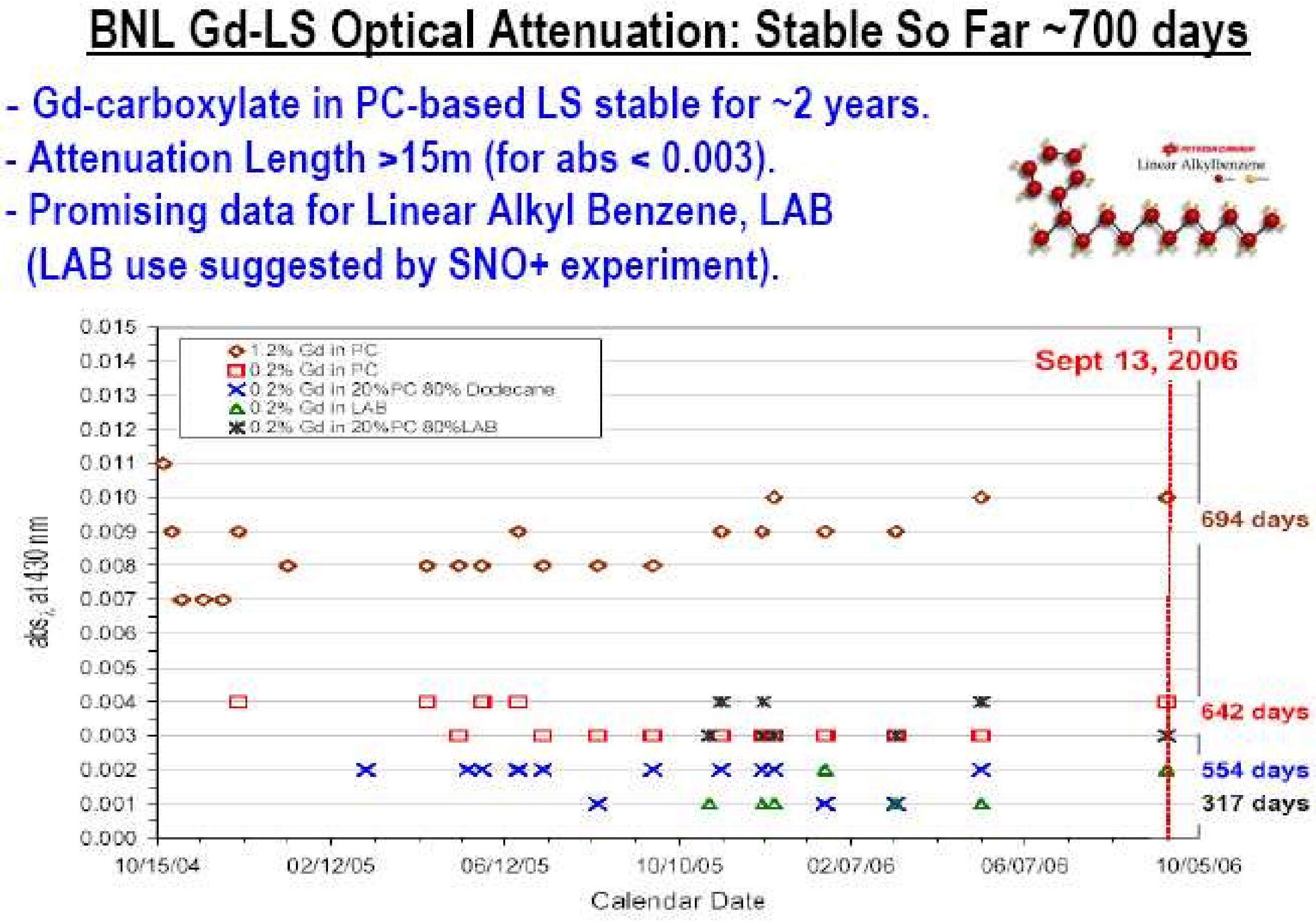
$$P(\nu_a \rightarrow \nu_a) = 1 - \sin^2 2\theta \sin^2 \frac{1.27((m_2^2 - m_1^2)/eV^2)(L/km)}{(E/GeV)}$$

Site Geology

Conceptual design of the tunnel and the Site investigation including bore holes completed

Yifang Want

GD-LS R&D 1

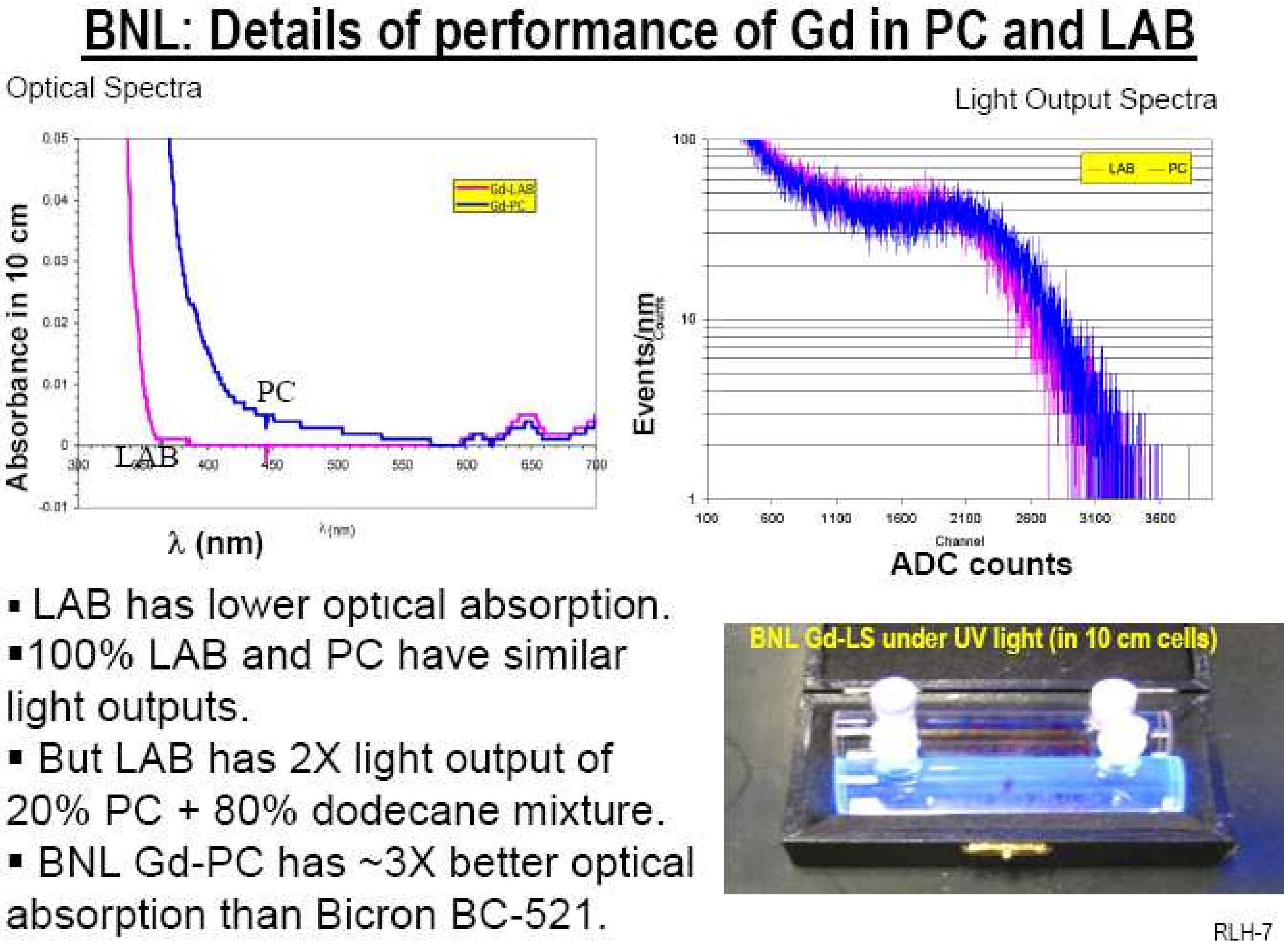


BNL Gd-LS Optical Attenuation: Stable So Far ~700 days

- Gd-carboxylate in PC-based LS stable for ~2 years.
- Attenuation Length >15m (for abs < 0.003).
- Promising data for Linear Alkyl Benzene, LAB
  (LAB use suggested by SNO+ experiment).

Dick Hahn

GD-LS R&D 2



BNL: Details of performance of Gd in PC and LAB

Optical Spectra

Light Output Spectra

- LAB has lower optical absorption.
- 100% LAB and PC have similar light outputs.
- But LAB has 2X light output of 20% PC + 80% dodecane mixture.
- BNL Gd-PC has ~3X better optical absorption than Bicron BC-521.

BNL Gd-LS under UV light (in 10 cm cells)

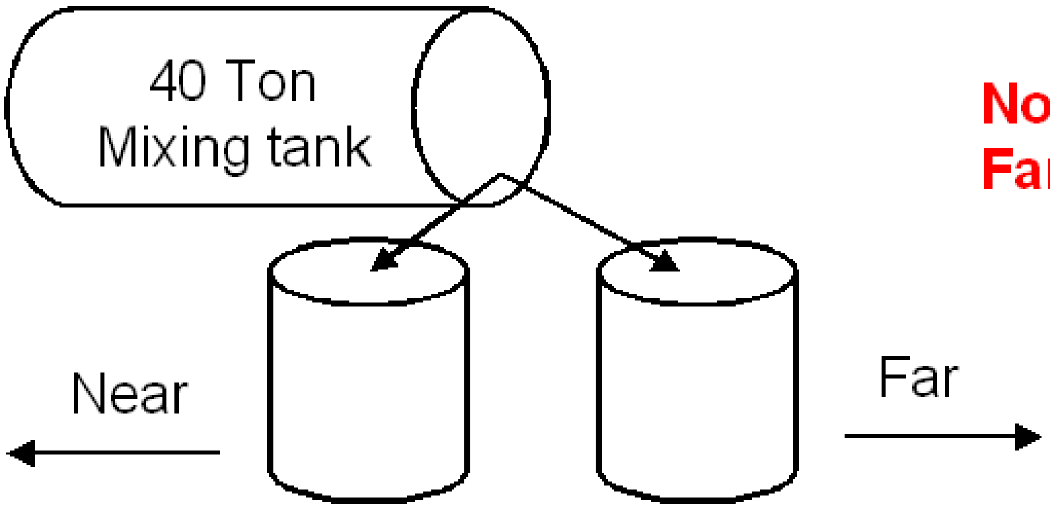
RLH-7

Dick Hahn

H/C Ratio

Bob Mckeown

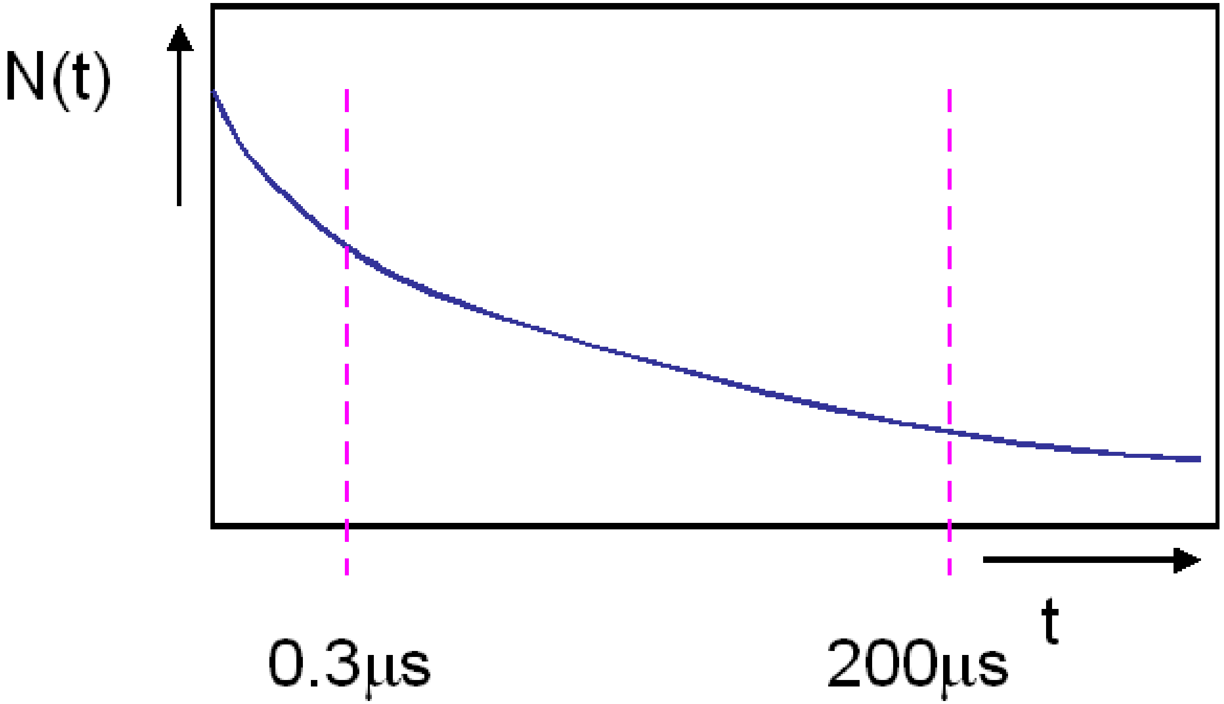
- Combustion analysis (<0.3%?)
- Neutron capture/scattering (R&D)
- Filling detector pairs from common batch



No difference in H/C between Far and Near sites

Neutron Time Cuts

Bob Mckeown



These cut times must be the same to ~10ns for all modules

→ use common clock

→ 0.05% contribution to neutron efficiency

Daya Bay/Chooz comparison

Kam-Biu Luk