# Status of The Daya Bay Reactor Neutrino Experiment

***Neutrino Frontiers 2008, 10/23/2008***

Mary Bishai (for the Daya Bay Collaboration)

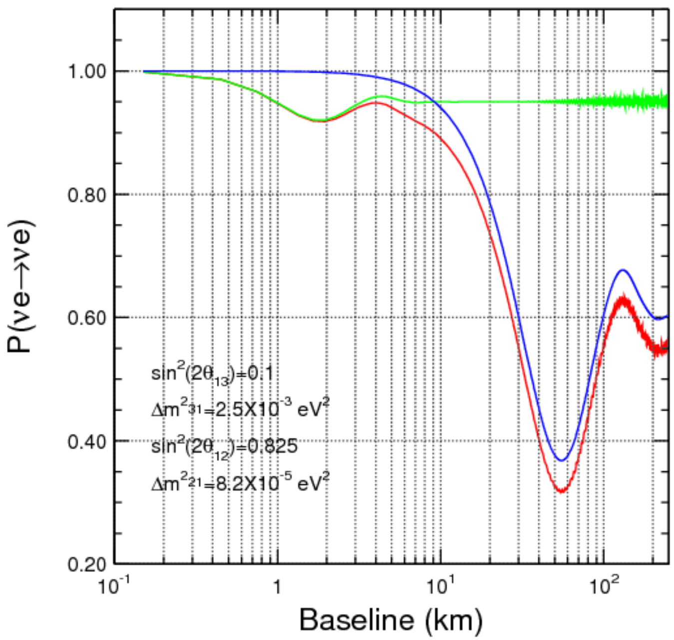
mbishai@bnl.gov

Brookhaven National Lab.

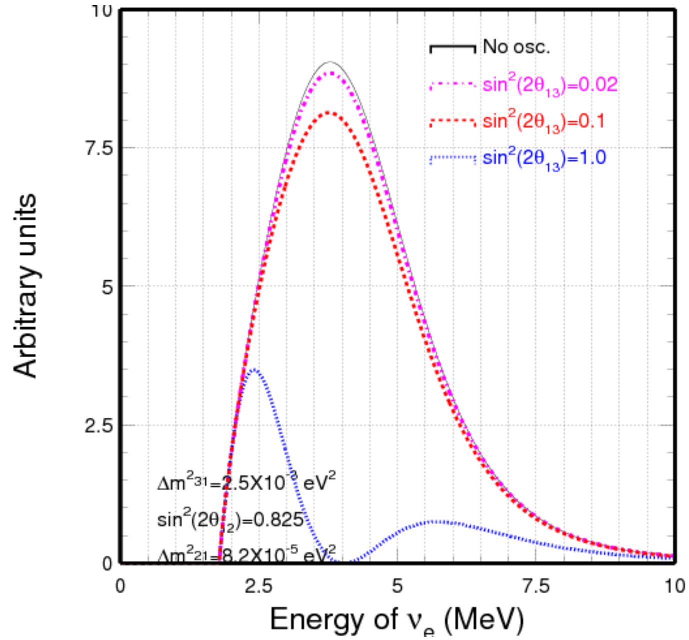
# Reactor $\bar{\nu}_e$ oscillations

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

**Osc prob. (integrated over E) vs distance**




**Osc. spectrum at 2km**



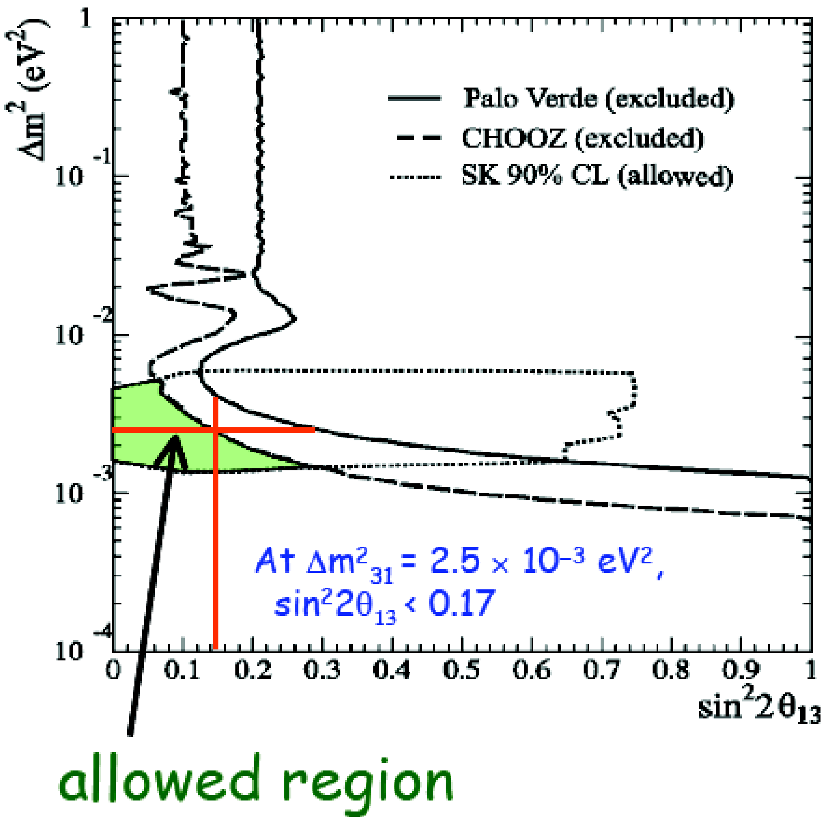

**Reactor $\nu_e$ disappearance = *unambiguous* measurement of $\sin^2 2\theta_{13}$**

# 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:**

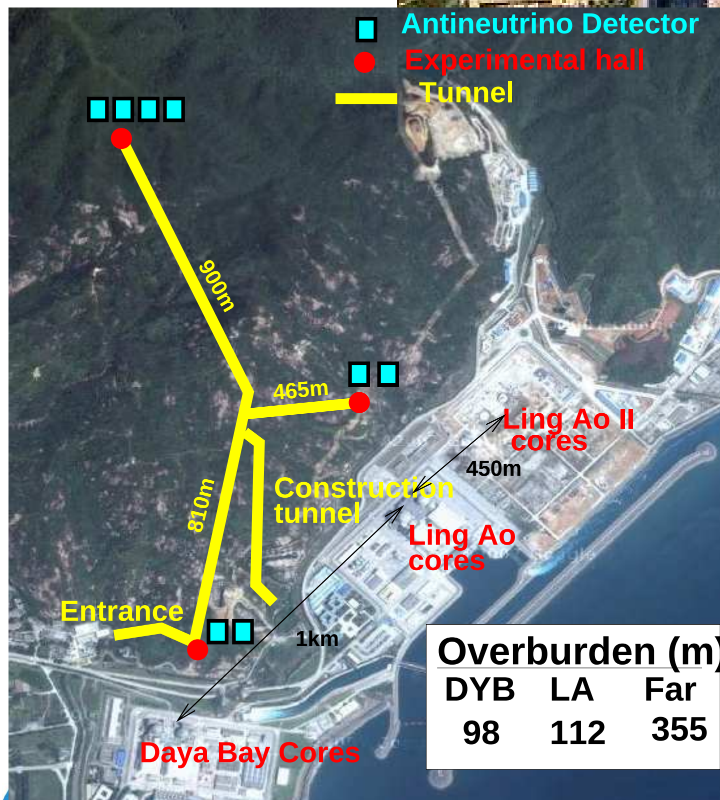
**-Deploy near detectors as close as possible to reactor to minimize reactor flux uncertainties.**

**-Use multiple, "identical" detector pairs to reduce near/far detector uncertainties.**

**-Calibration, calibration, calibration...**

# OVERVIEW OF THE DAYA BAY REACTOR EXPERIMENT

# The Daya Bay Reactor Complex


**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$_{th}$

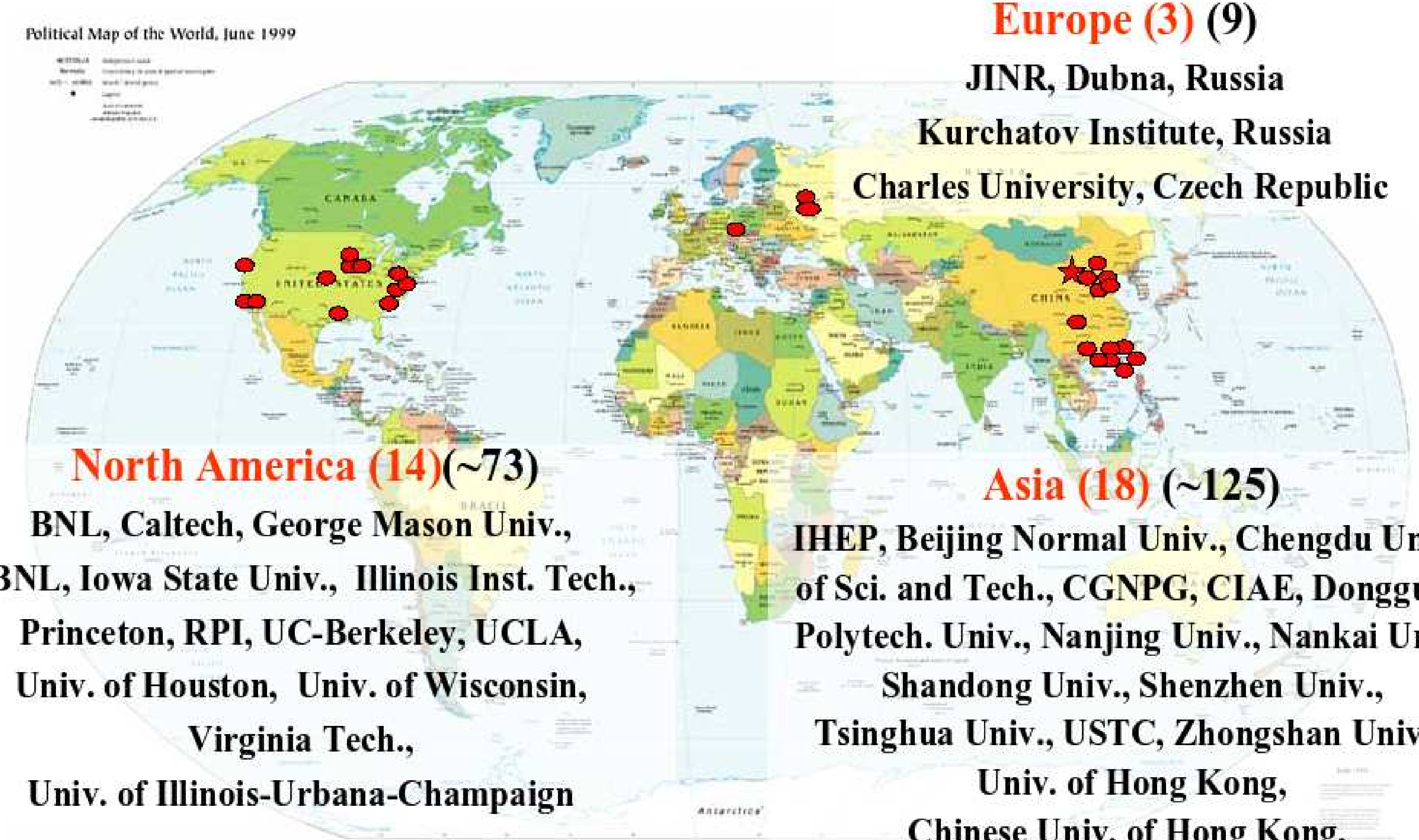
By 2011: 2 more cores at Ling Ao II site = 17.4 GW$_{th}$ $\Rightarrow$ top five worldwide

1 GW$_{th}$ = $2 \times 10^{20} \bar{\nu_e}$/second

**Deploy multiple near and far detectors $\Rightarrow$**

**Reactor power uncertainties cancel to $< 0.1\%$**

# The Daya Bay Collaboration




**Europe (3) (9)**

JINR, Dubna, Russia
Kurchatov Institute, Russia
Charles University, Czech Republic

**North America (14)(~73)**

BNL, Caltech, George Mason Univ., LBNL, Iowa State Univ., Illinois Inst. Tech., Princeton, RPI, UC-Berkeley, UCLA, Univ. of Houston, Univ. of Wisconsin, Virginia Tech., Univ. of Illinois-Urbana-Champaign

**Asia (18) (~125)**

IHEP, Beijing Normal Univ., Chengdu Univ. of Sci. and Tech., CGNPG, CIAE, Dongguan Polytech. Univ., Nanjing Univ., Nankai Univ., Shandong Univ., Shenzhen Univ., Tsinghua Univ., USTC, Zhongshan Univ., Univ. of Hong Kong, Chinese Univ. of Hong Kong, National Taiwan Univ., National Chiao Tung Univ., National United Univ.

**≈ 207 collaborators**

# The Daya Bay Experiment Timeline

**Oct 13, 2007:** Ground breaking

**Aug. '08:** DOE CD3b approval

**Winter '09:** Daya Bay near hall physics ready

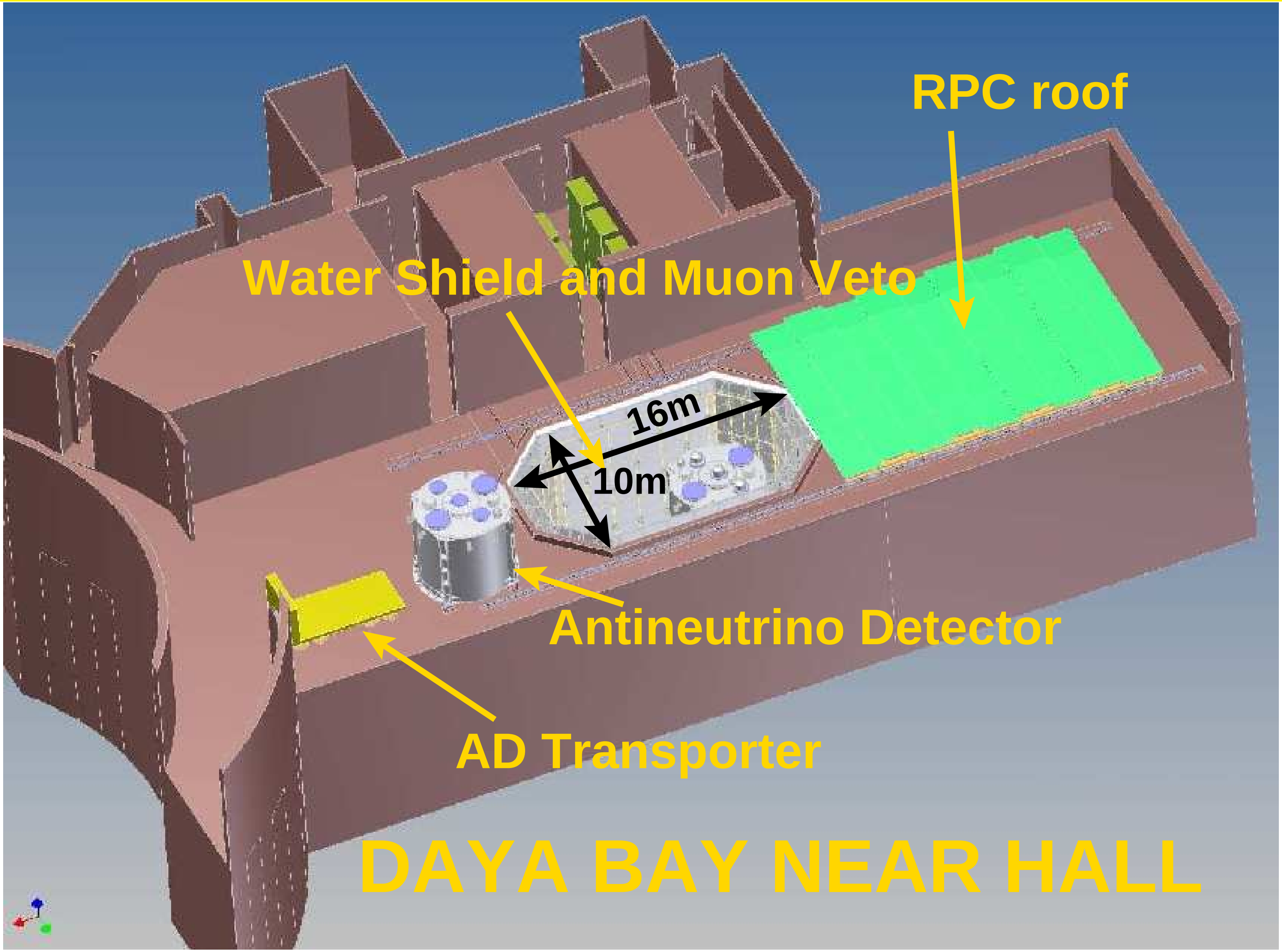
**Winter '10:** Data taking with all detectors

Surface assembly building

Access Tunnel Entrance

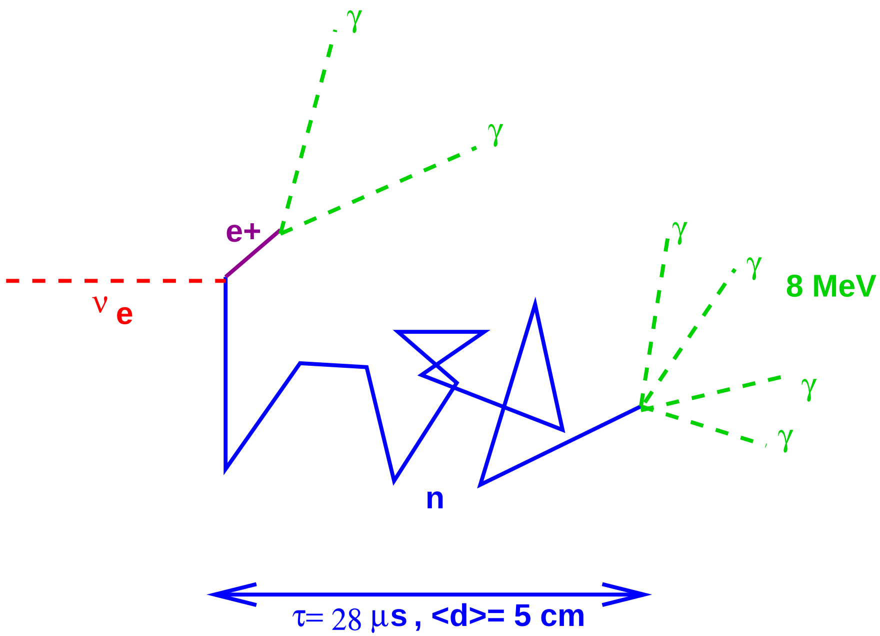
Construction tunnel

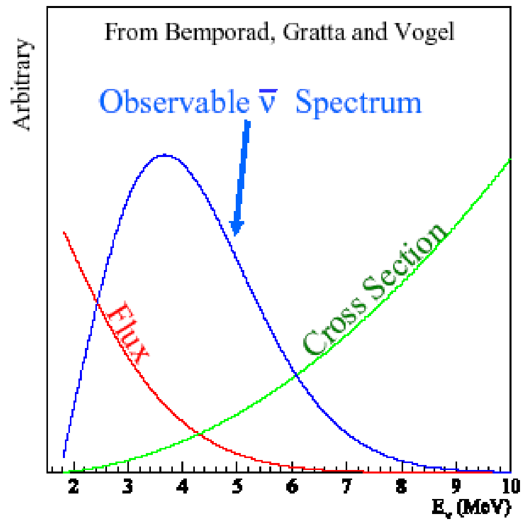
# The Daya Bay Detectors and Detector Systematics



# Detecting $\bar{\nu}_e$ using GD-loaded LS.

*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** $+T_{e^+}$**, prompt)**

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

$n + Gd \rightarrow Gd* \rightarrow Gd + \gamma$**'s (8 MeV,** $\tau \sim 28\mu s$, $\sigma = 5 \times 10^4$**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:*

**Zone I:** **20T GD-liquid scint.**

**Zone II ($\gamma$ catcher):** **20T LS**

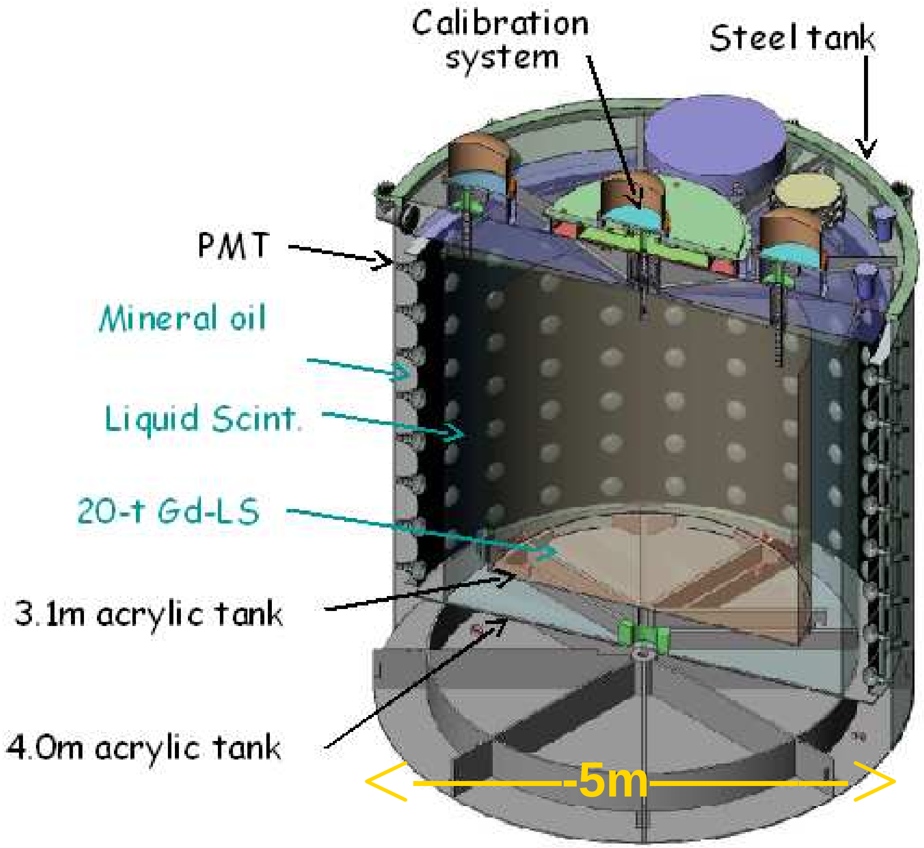
**Zone III (buffer):** **40T mineral oil**

**192 8” PMTS (Hamamatsu R5912) are mounted around the circumference of the outer steel tank**

**Diffuse reflectors on top and bottom: (effective coverage 12%)**

$$\frac{\sigma}{E} \sim \frac{12\%}{\sqrt{E(\mathrm{MeV})}}$$

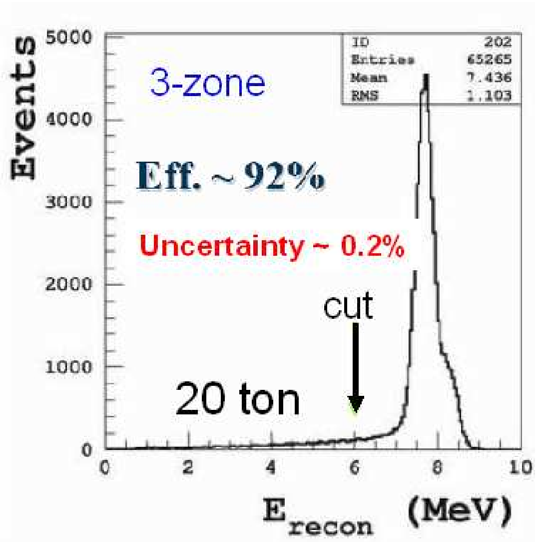
$$\sigma_{pos} = 13\,\mathrm{cm}$$

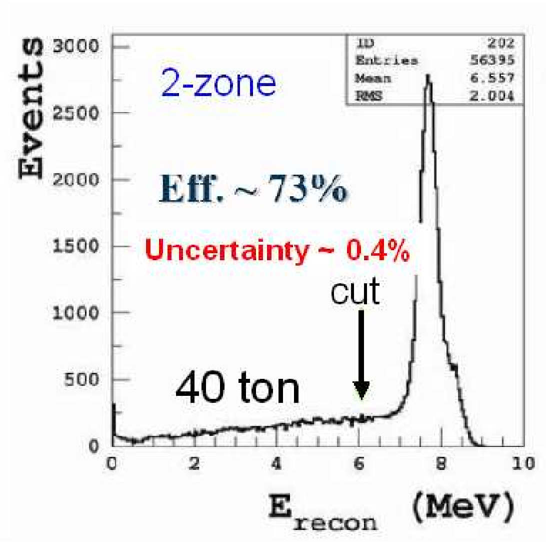



| | DYB | LA | Far |
|---|---|---|---|
| Event rates/20T/day | 840 | 740 | 90 |

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

**3 zone vs 2 zone $\Rightarrow$ reduced systematic uncertainty in reconstructed energy cut:**

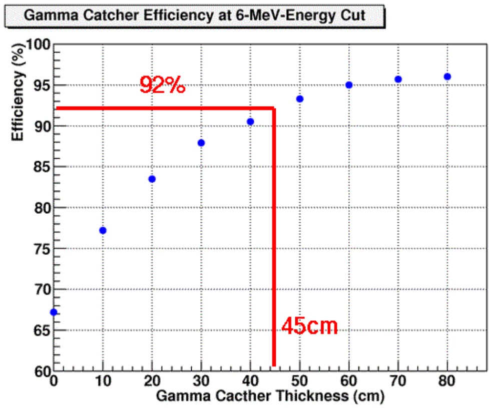



**← Selection cut for n capture on Gd only**

n capture on Gd yields 8 MeV with 3-4 $\gamma$'s

## $\gamma$ catcher efficiency



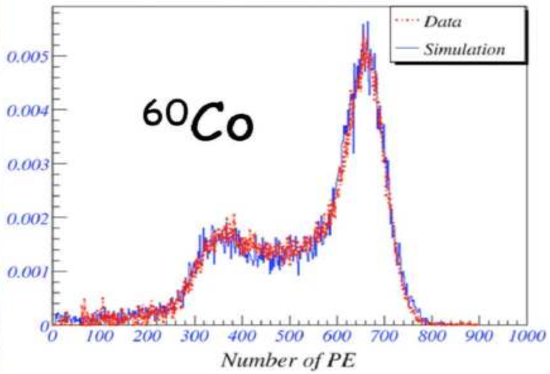

## Buffer oil shielding

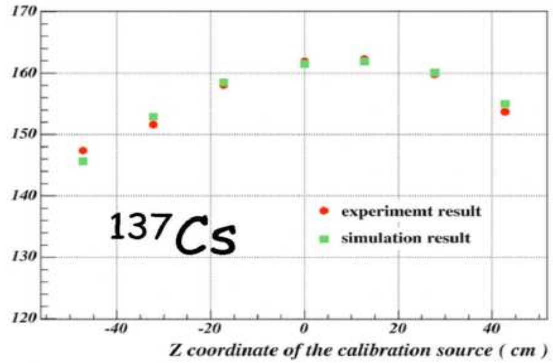
| Isotope | Concentration | Buffer Oil Thickness (Rates in Hz) 20 cm | 25 cm | 30 cm | 40 cm |
|---|---|---|---|---|---|
| $^{238}$U | 100 ppb | 5.5 | 4.0 | 2.8 | 1.5 |
| $^{232}$Th | 150 ppb | 3.8 | 2.6 | 2.3 | 1.1 |
| $^{40}$K | 15 ppb | 2.7 | 1.9 | 1.3 | 0.8 |
| Total | | 12 | 8.3 | 6.4 | 3.4 |

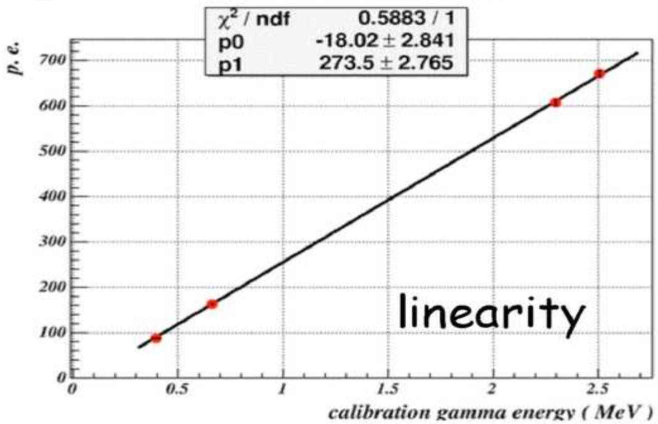
# The Prototype AD at IHEP

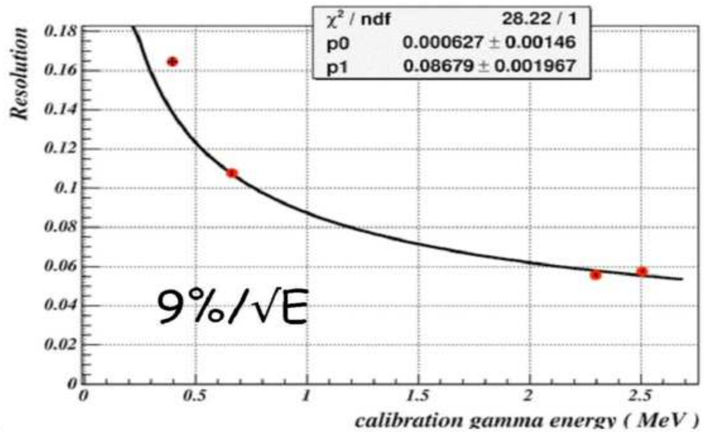
## 2-zone Prototype at IHEP

- 0.5 ton unloaded LS
- 45 8" PMTs with reflecting top and bottom



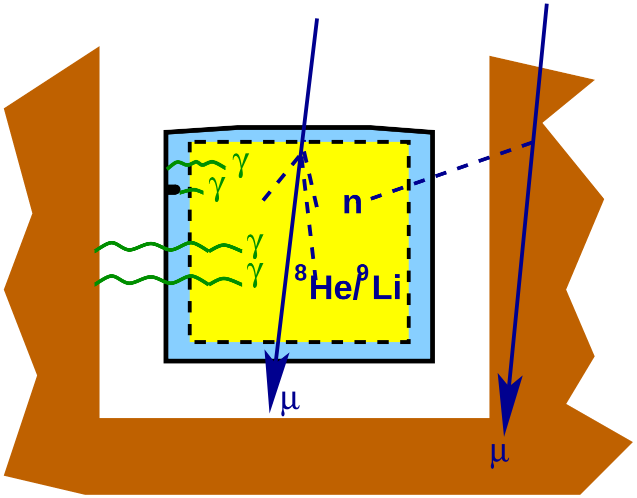




Kam-Biu Luk Daya Bay 22

**Simulation reproduces energy response observed in prototype**

# Background sources in the AD




**Using a modified Gaisser parameterization and the DYB mountain profile the cosmic ray rates are:**

| | DYB | LA | Far |
|---|---|---|---|
| Overburden (m) | 98 | 112 | 355 |
| Muon intensity (Hz/m$^2$) | 1.16 | 0.73 | 0.041 |
| Mean Energy (GeV) | 55 | 60 | 138 |

| Source | Type | Rate/20T module (DYB/LA/FAR) |
|---|---|---|
| Rock | U/Th/K $\gamma > 1$ MeV | $\mathcal{O}$(MHz) w/o shielding! |
| SS vessel and welds | U/Th/K/Co | $\sim$ 20 Hz |
| PMT glass R5912 | U/Th/k | $\sim$ 12 Hz |
| Cosmic muons | $^{12}$B/$^{12}$N $\beta$ only | 396/267/28 |
| Cosmic muons | $^{8}$He/$^{9}$Li $\beta$-n | 3.7/2.5/0.26 |
| Cosmic muons | fast neutrons (2 subevents) | depends on shielding |
| Cosmic muons | neutrons (1 subevent) | depends on shielding |

**Use a thick water shield to reduce neutron and rock $\gamma$ bkgds**

# The He$^8$/Li$^9$ background

*He$^{\mathbf{8}}$/Li$^{\mathbf{9}}$ generated by showers from cosmic muons in the AD LS:*

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

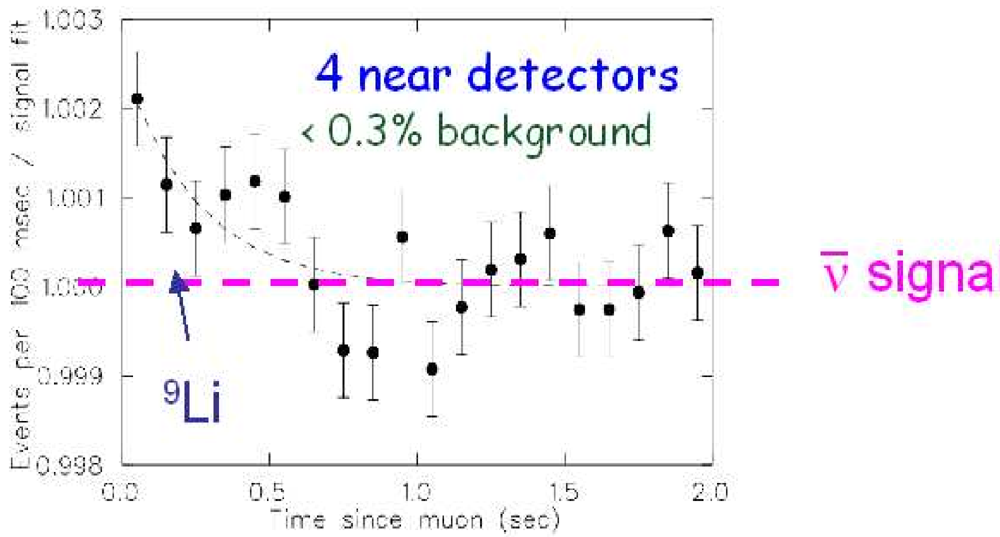
**Q= 13 MeV, $\tau = 178$ msec $\Rightarrow$ poor spatial correlation with $\mu$ track.**

**Computed rates (Hagner et. al.) events/module/day:**

| | DYB | LA | Far |
|---|---|---|---|
| $\bar{\nu}_e$ IBD | 840 | 740 | 90 |
| $^9\mathrm{Li} + ^8\mathrm{He}$ | 3.7 | 2.5 | 0.26 |

**But it can be measured ! $\longrightarrow$**

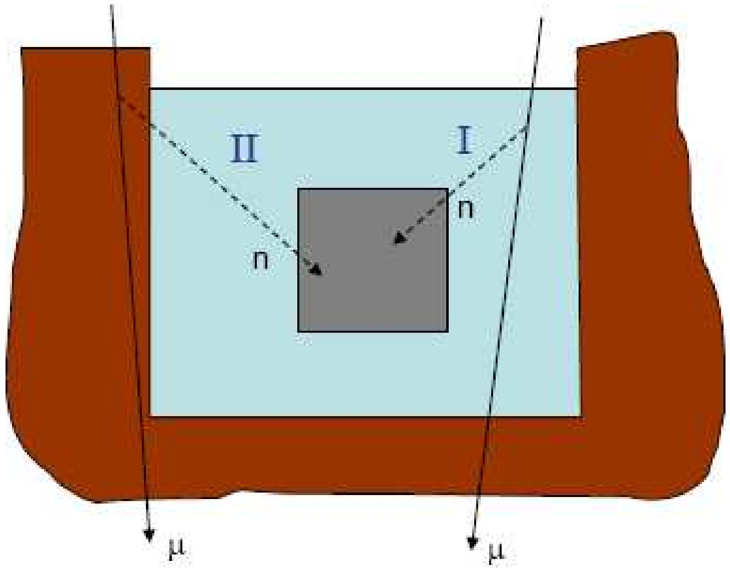
$B/S \approx 0.3\%$

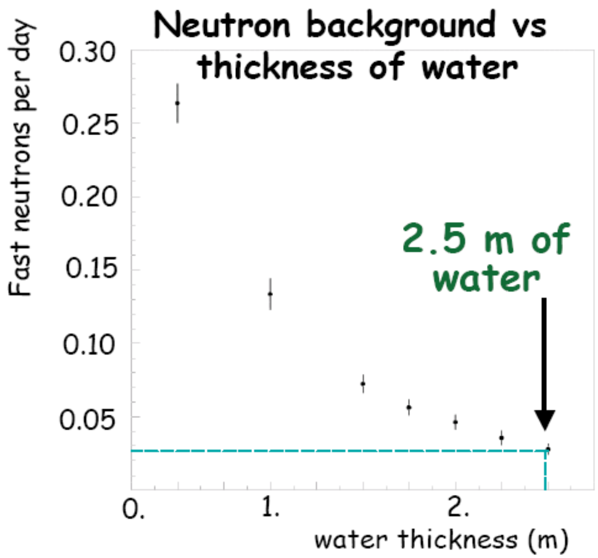



**Time since muon (sec)**

# Fast Neutron Background

$$n_{\text{fast}} + p/n \rightarrow \underbrace{p/n}_{prompt} + \underbrace{n^*}_{delayed}$$

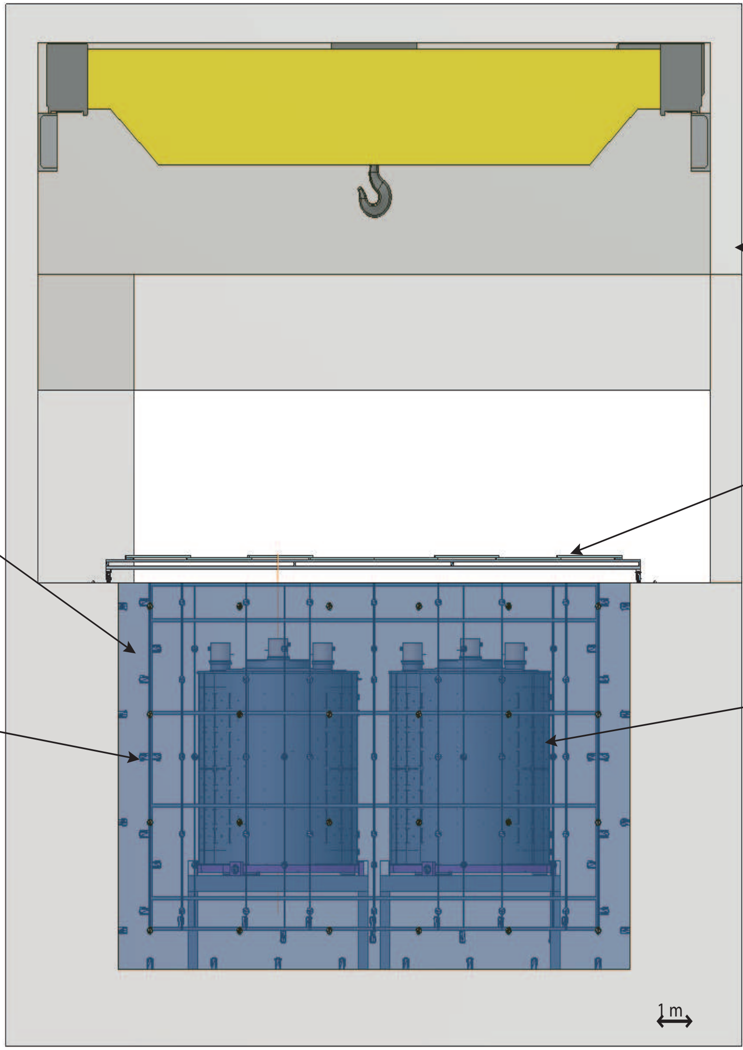



**Fast neutron simulation results assuming active water shield with 99.5% muon tagging eff ( events/day/20T module) :**

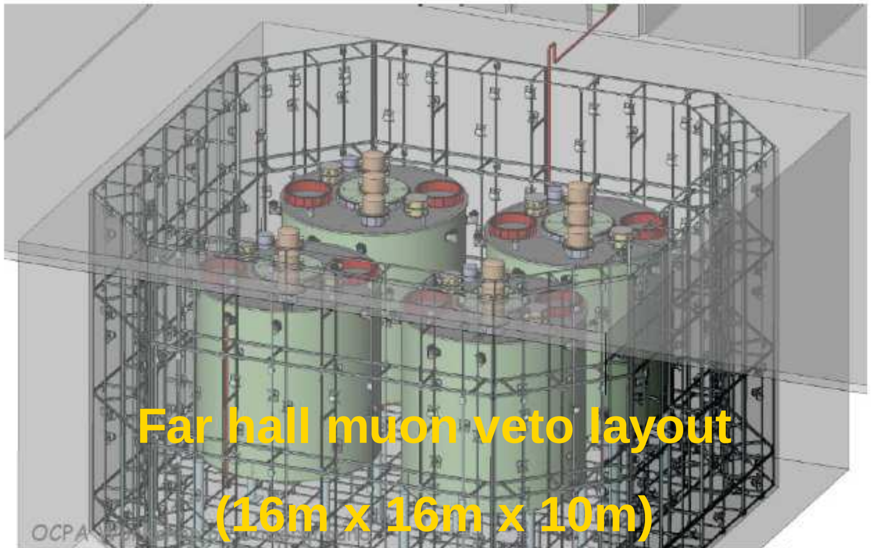
| | I: From untagged $\mu$ | II:Rock neutrons | II:Total/Signal |
|---|---|---|---|
| DYB | 0.10 | 0.5 | $6 \times 10^{-4}$ |
| LA | 0.07 | 0.35 | $6 \times 10^{-4}$ |
| Far | 0.01 | 0.03 | $4 \times 10^{-4}$ |

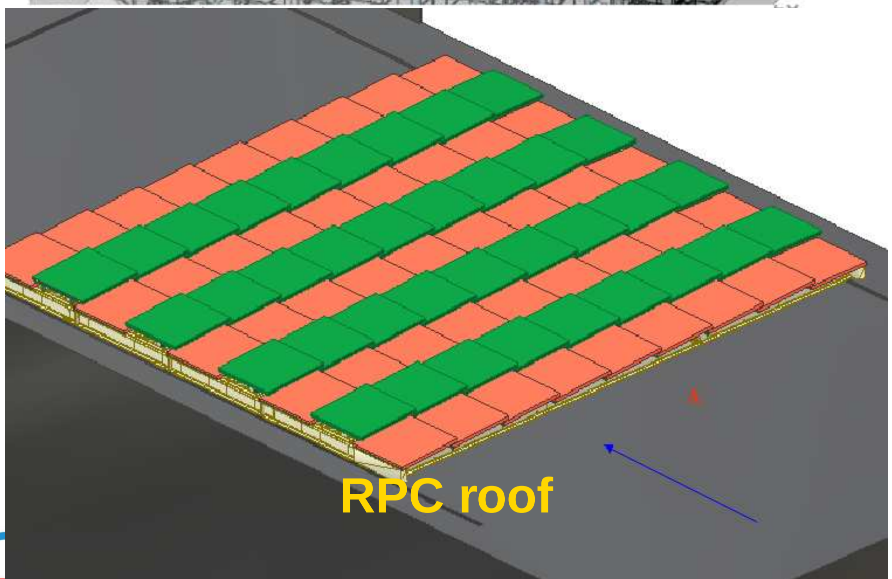
# The Water Shield and Muon Veto



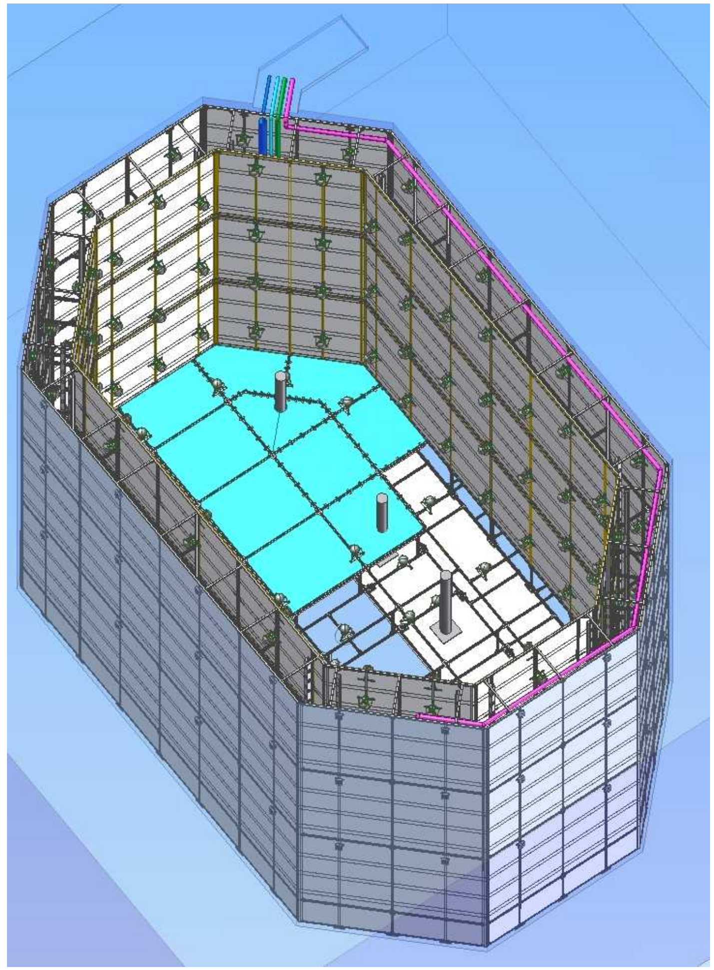

- **Water pool:** **The $\bar{\nu}_e$ detectors are immersed in a water pool with 2.5m of water on all sides.**
  - **Inner muon veto:** **1m in from the sides and bottom of the pool a single layer of 8" PMTs (1/8m$^2$) acts as a water Cherenkov $\mu$ detector.**
  - **Outer muon veto:** **The outer 1m of the water pool is instrumented with 8" PMTs (1/6-7m$^2$). Separated by Tyvek reflectors from inner veto.**
- **RPC system :** **On top of pool, 4 layers of resistive plate chambers (2.1m x 2.1m modules).**

# Muon Veto Details




**Tyvek panels line outer wall and separate inner and outer veto regions. Near Hall layout (16x10x10m):**



# Muon Veto Efficiency Simulation

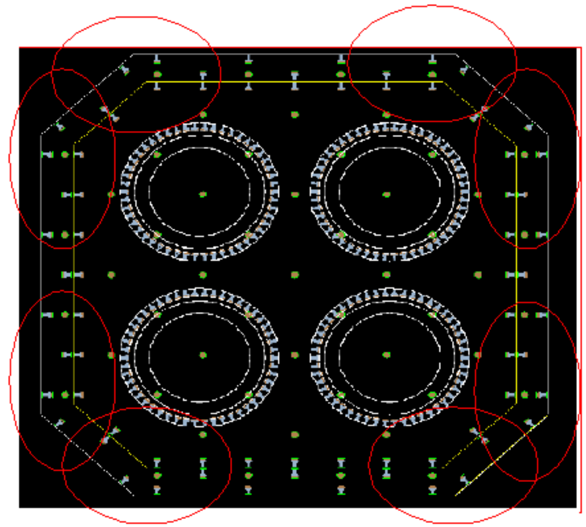
Kevin Zhang, BNL

**Events in AD that occur within 200 $\mu$ s of a muon trigger are vetoed to suppress cosmogenic bkgds. Muon veto trigger:**

**1) $> 12$ PMTs fired in inner water shield OR**

**2) localized triggers in 8 sections of outer shield (8 PMTs fired/section) OR**

**3) 3/4 layers of RPC.**

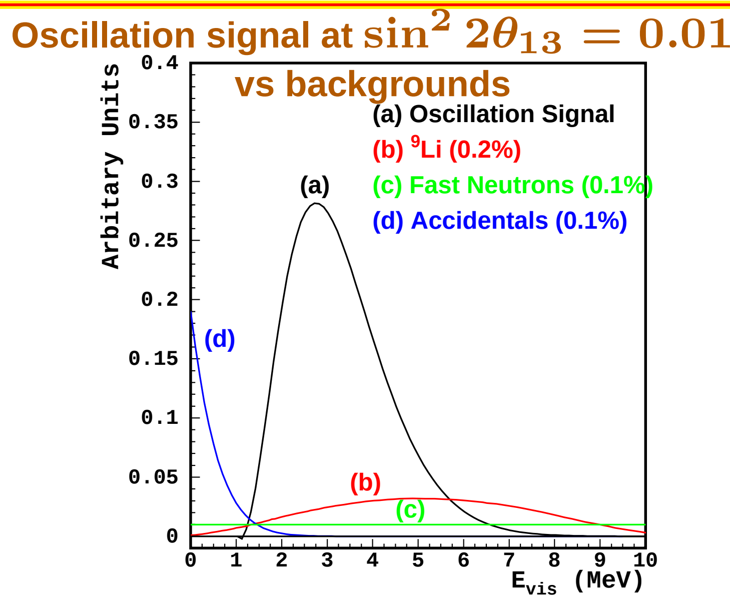


| | Inner veto only | Inner + outer veto only | Water+RPC |
|---|---|---|---|
| Near | $97.62 \pm 0.2\%$ | $98.93 \pm 0.12$% | $99.54 \pm 0.07$ % |
| Far | $98.02 \pm 0.16\%$ | $99.22 \pm 0.09$ % | $99.61 \pm 0.07$ % |

# Accidental background rates

**Prompt:** $\gamma > $ 1MeV from radioactivity $\sim$ 40Hz/AD module with shielding

**Delayed:**: 1) untagged single neutron capture 2) cosmogenic beta emmiters (6-10MeV, mostly $^{12}$B/$^{12}$N) 3)U/Th $\longrightarrow$ O, Si $(\alpha, n, \gamma[6 - 10\,\mathrm{MeV}])$

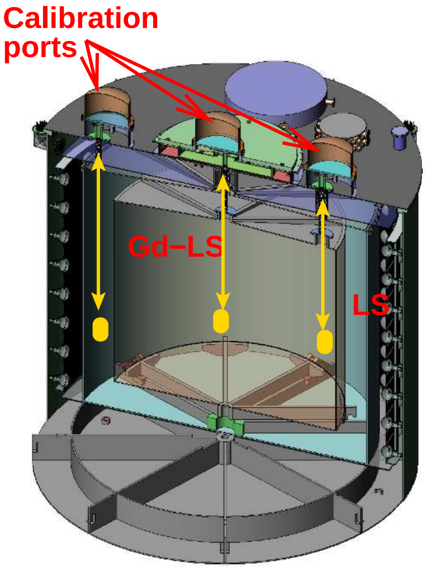



| | DYB | LA | Far |
|---|---|---|---|
| Signal rates | 840/day | 740/day | 90/day |
| 1) neutrons (singles) | 18/day | 12/day | 1.5/day |
| 2) $\beta$s (singles) | 210/day | 141/day | 14.6/day |
| 3) $\alpha, n\gamma$ (singles) | $<$10/day | $<$10/day | $<$10/day |
| Coinc bkgd rate | 2.3/day | 1.3/day | 0.26/day |
| B/S | $\sim 3 \times 10^{-3}$ | $\sim 2 \times 10^{-3}$ | $\sim 3 \times 10^{-3}$ |

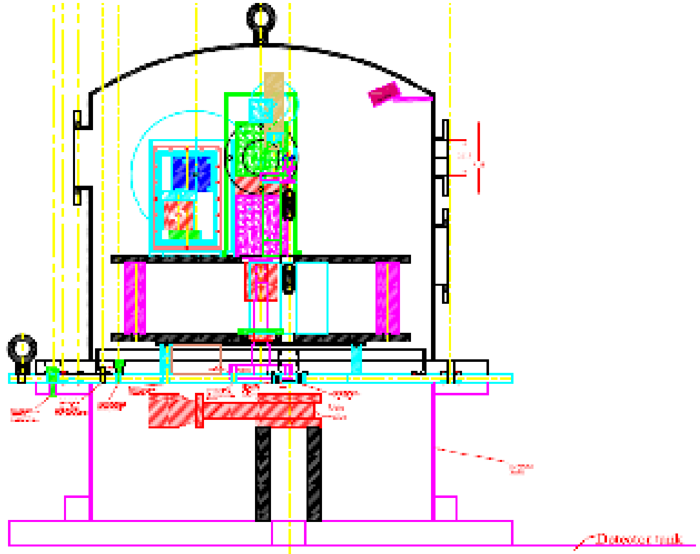
**Untagged background rates are tiny and subtractable**

# Calibration/Monitoring Systems

**3 <u>automated</u> systems for calibration at different $R$**




**Automated system deploys 2 different sources ($\beta$, $n$) + LED**



**Prototype automated calibration system at Caltech**

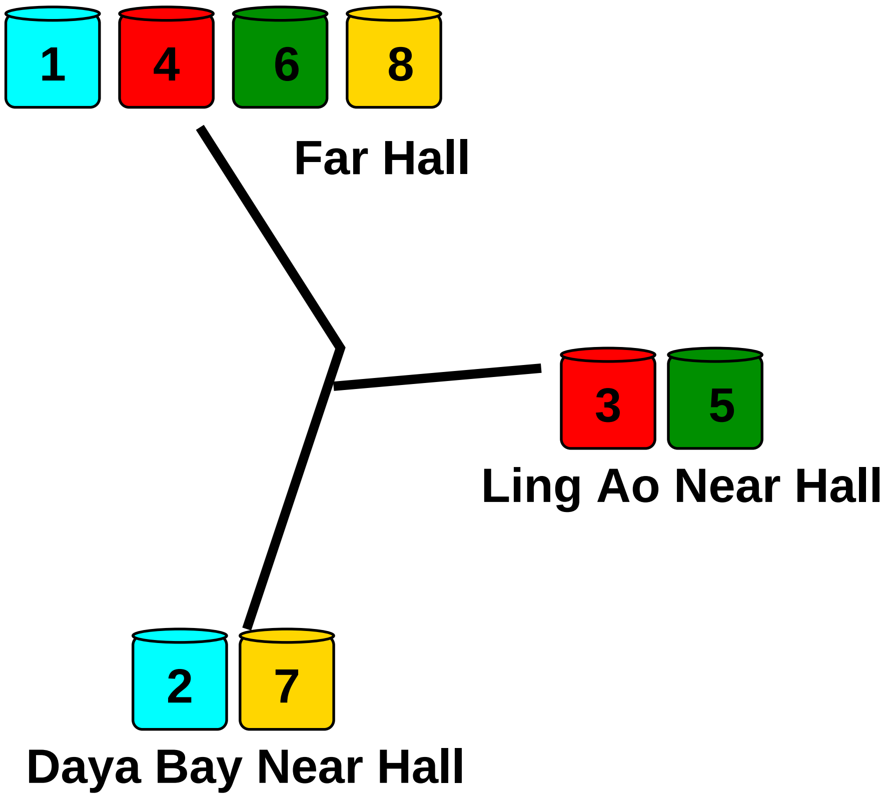
**Initial filling/commisioning** Load cells and high precision mass flowmeters used during filling (accuracy $< 0.1\%$). Calibration using a manual deployment system with sources/LED.

**Routine monitoring:** Weekly/monthly automatically deploys sources and LEDs to monitor response in 3 zones. Supplement with spallation product (e.g. neutron) measurements.

# Detector Deployment Strategy

*To control H/C and H/Gd ratio uncertainties, detectors are filled and commisionned in matched pairs, at least one of each pair stays at the near site and the other is deployed at the far site.*

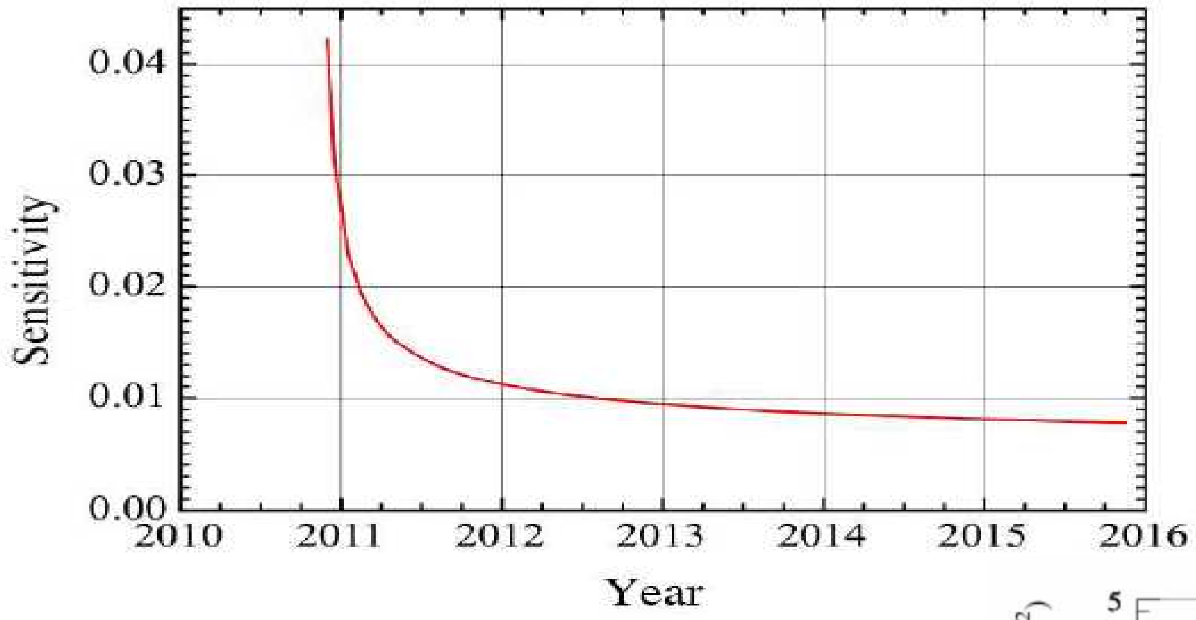
**Deploy matched pairs (same color) at near/far sites:**



# Detector systematics

| Source of uncertainty | | Chooz (*absolute*) | Daya Bay (*relative*) | Strategy |
|---|---|---|---|---|
| # protons | H/C ratio | 0.8 | $<$ 0.1 | Fill in pairs/calib |
| | Mass | - | $<$ 0.3 | Load cells and mass flowmeters |
| Detector Efficiency | Energy cuts | 0.8 | 0.2 | lower threshold/calib |
| | Position cuts | 0.32 | 0.0 | 3-zone |
| | Time cuts | 0.4 | 0.1 | Common clock $\sim$ 10ns |
| | H/Gd ratio | 1.0 | 0.1 | fill in pairs/calib |
| | n multiplicity | 0.5 | 0.05 | Deeper/muon veto |
| | Trigger | 0 | 0.01 | Redundant triggers |
| | Live time | 0 | $<$ 0.01 | Common GPS clock |
| Total detector-related uncertainty | | 1.7% | 0.38% | |

# Sensitivities



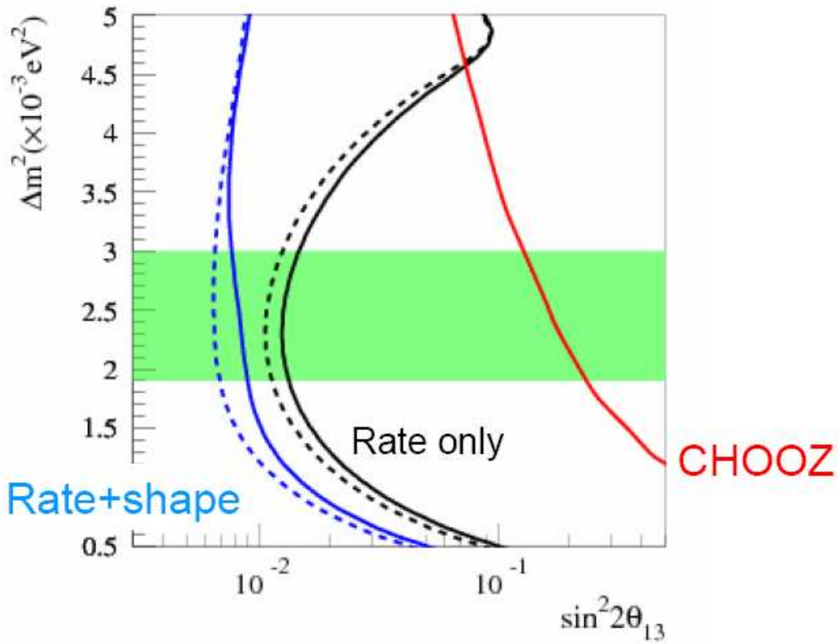

← **90% C.L. limit vs time with <u>baseline</u> detector systematic of <u>0.38%</u>**

**2% uncorrelated reactor power uncertainty**

**After 3 years running ⟶**

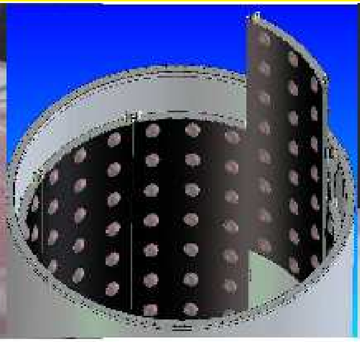
**—— <u>baseline</u> detector systematic <u>0.38%</u>**

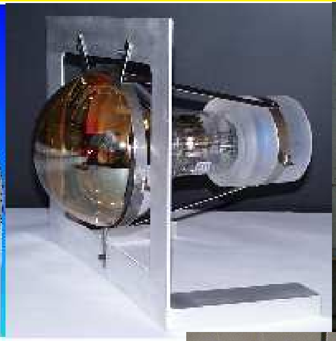
**- - - - <u>goal</u> detector systematic <u>0.18%</u>**



# Daya Bay Detectors in Production







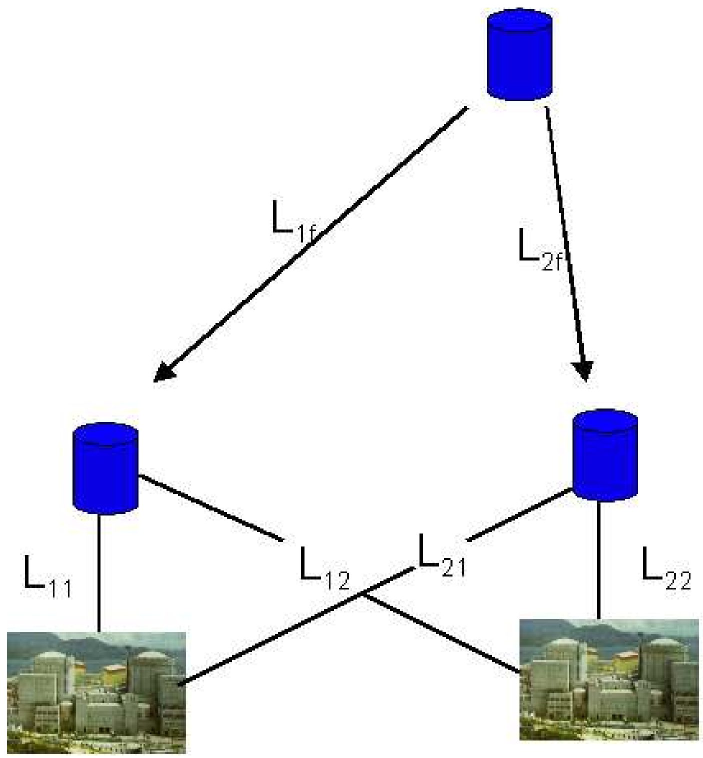

- -All AD prototyping activities completed (China/US)
- -AD design for all subsystems completed (China/US)
- -RPC modules are in production (China)
- -AD PMT production testing in progress (China/US)
- -Stainless steel vessel completed this mo (China)
- -Acrylic vessels in fabrication(Taiwan/US)


**BACKUP**

# Near/Far cancellation

*Q: Near/far cancelation with multiple cores?*

**A: Deweight the oversampled cores by a factor, $\alpha$, Ratio = $\alpha\frac{\textbf{Near1}}{\textbf{far}} + \frac{\textbf{Near2}}{\textbf{far}}$**




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

**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%**

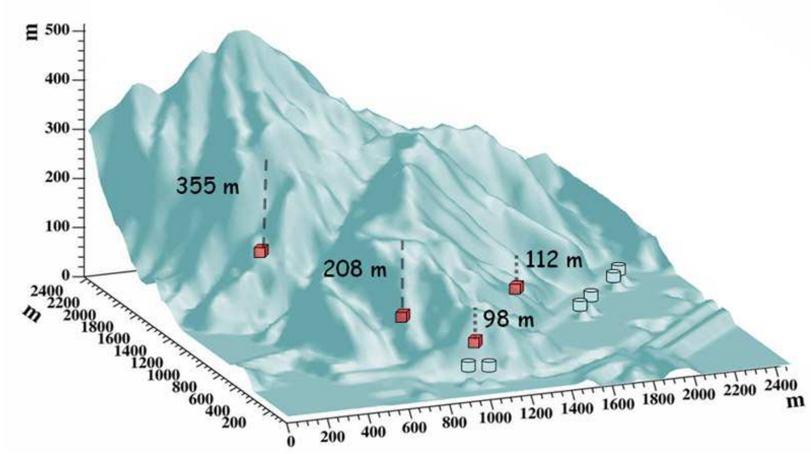
**Deweighting $\Rightarrow$ cancellation of reactor power uncertainties to better than 0.l%**

# Cosmic Ray Rates

**Most backgrounds in the AD are induced by cosmic muons:**

**-Using a modified Gaisser parametrization for cosmic-ray flux at surface**

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

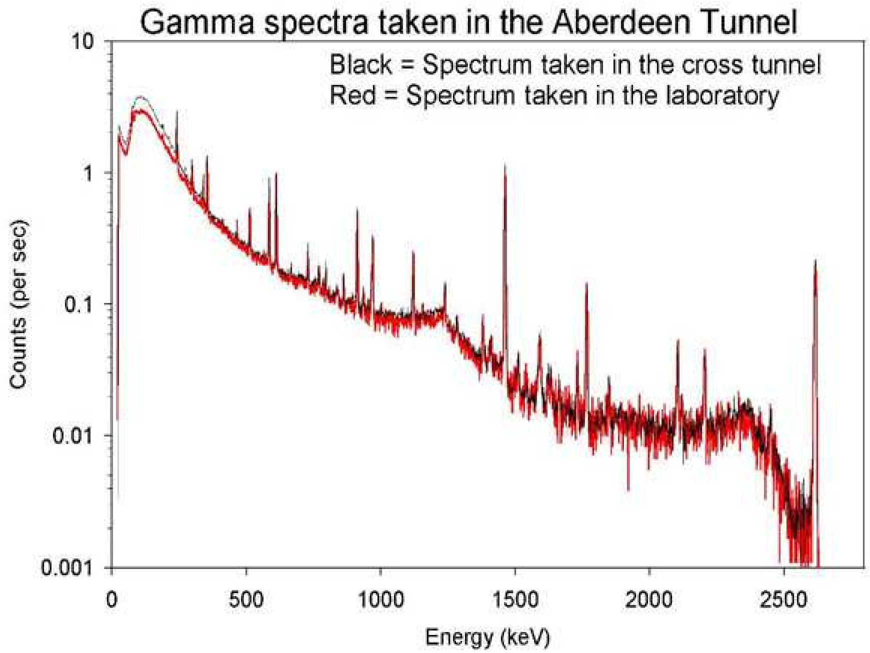



| | DYB | LA | Far |
|---|---|---|---|
| Overburden (m) | 98 | 112 | 355 |
| Muon intensity (Hz/m$^2$) | 1.16 | 0.73 | 0.041 |
| Mean Energy (GeV) | 55 | 60 | 138 |

# Rock Radioactivity

**Daya Bay granitic rock is very radioactive!**

**Measured U/Th/K $\approx$ 10ppm/30ppm/5ppm in samples. Also measured the spectrum from the Aberdeen tunnel in HK (same type of rock):**

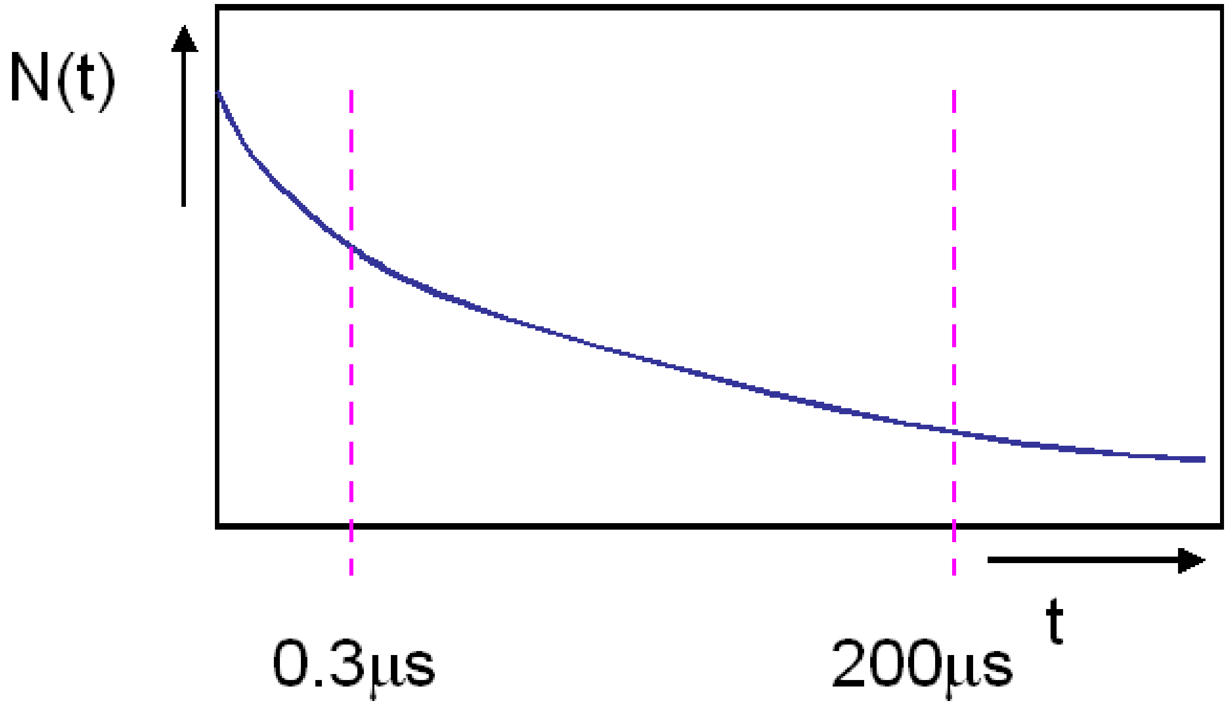



**Low-E $\gamma$ from radioactivity = x10 reduction for every 50 cm H2O.**

**2.5m water and 45cm mineral oil buffer $\sim$ 3.5 Hz/20T module**

# 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