Daya Bay Reactor Neutrino Experiment

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Neutrino Oscillation

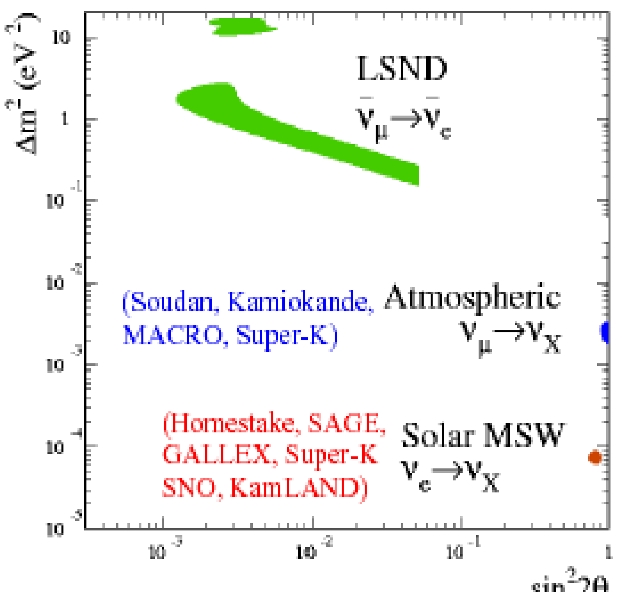
Neutrino Mixing: PMNS Matrix

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

Atmospheric,
K2K, MINOS, T2K, etc.
$\theta_{23} \sim 45^{o}$

Reactor
Accelerator
$\theta_{13} < 12^{o}$

Solar
KamLAND
$\theta_{12} \sim 30^{o}$



Known: $|\Delta m^2_{32}|$, $\sin^2 2\theta_{23}$, Δm^2_{21}, $\sin^2 2\theta_{12}$

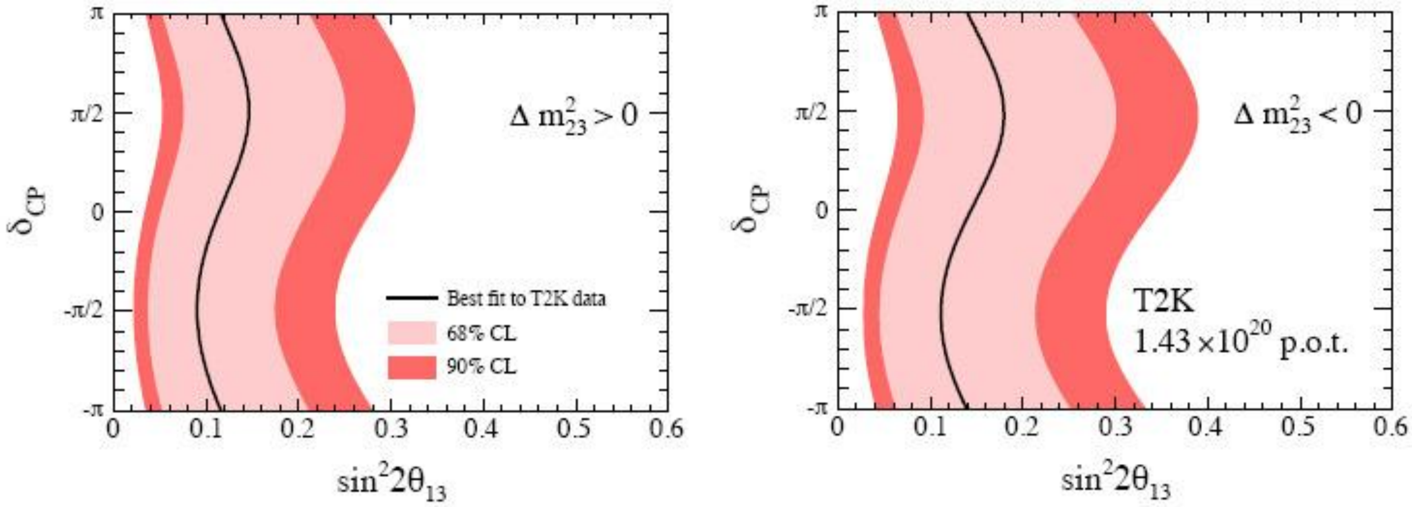
Unknown: $\sin^2 2\theta_{13}$, δ_{CP}, Sign of Δm^2_{32}

Daya Bay Experiment will measure $\sin^2 2\theta_{13}$ to 0.01 or better at 90% C.L. in a three-year run.

T2K Indication

- **6 ν_e events, 1.5±0.3 bkg expected. (1.43×10^{20} POT)**
  - ⇨ **θ_{13} non-zero probability 99.3% (2.5 σ significance)**

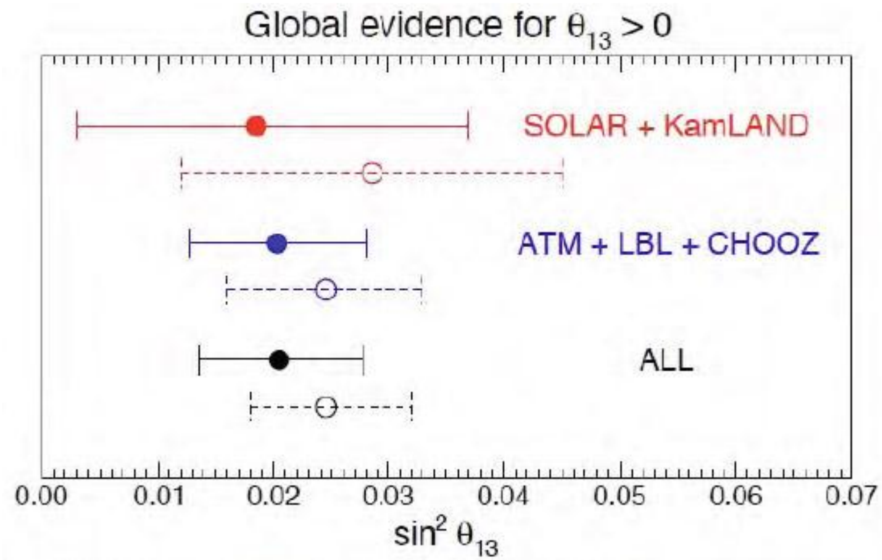
(assuming $\Delta m^2_{23}=2.4 \times 10^{-3}$ eV^2, $\sin^2 2\theta_{23}=1$)



90% C.L. interval & Best fit point (assuming $\Delta m^2_{23}=2.4 \times 10^{-3}$ eV^2, $\sin^2 2\theta_{23}=1$, $\delta_{CP}=0$)

$0.03 < \sin^2 2\theta_{13} < 0.28$	$0.04 < \sin^2 2\theta_{13} < 0.34$
$\sin^2 2\theta_{13} = 0.11$	$\sin^2 2\theta_{13} = 0.14$

Global Fit



Fogli et al. arXiv:1106.6028

Solid line=old flux
dotted line=re-analyzed flux

arXiv:1108.1376v1

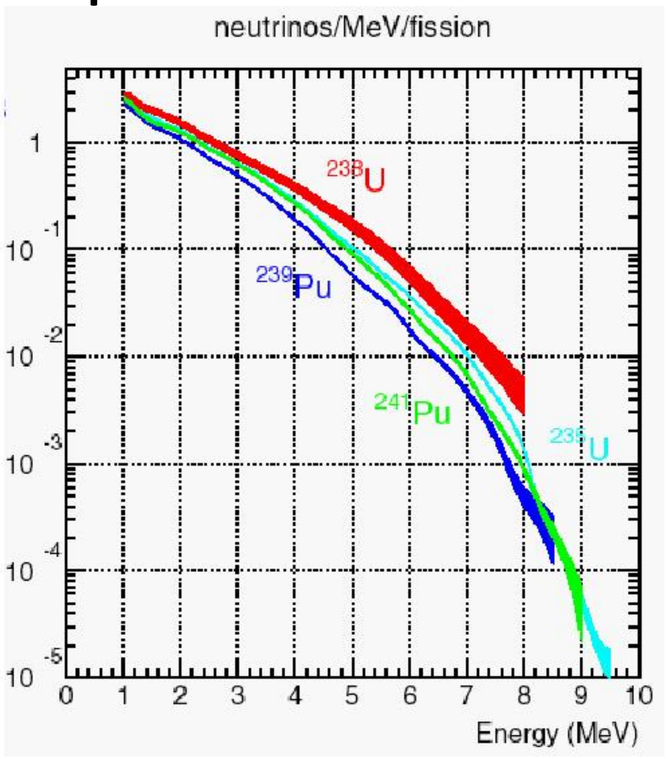
Where we are on θ_{13}: addendum to "Global neutrino data and recent reactor fluxes: status of three-flavour oscillation parameters"

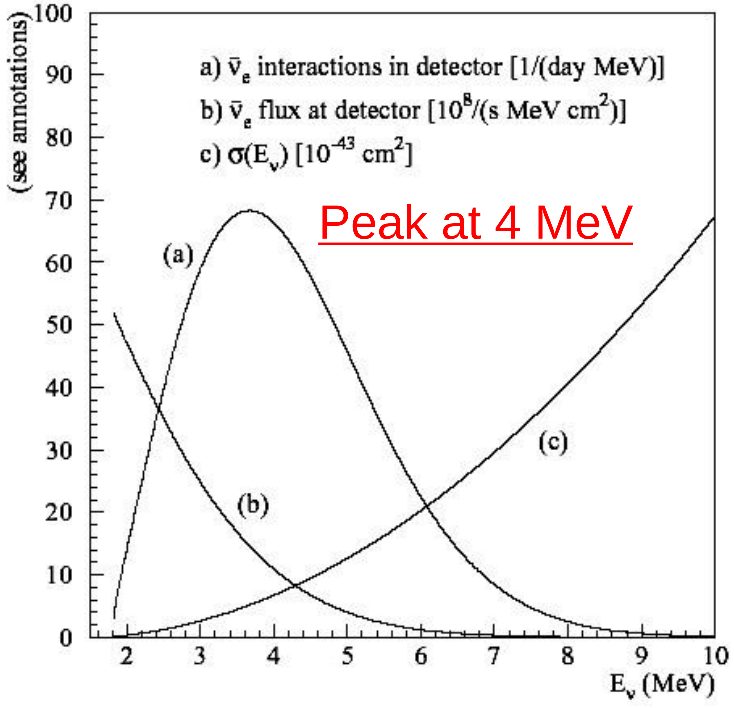
Thomas Schwetz†, Mariam Tórtola§ and J. W. F. Valle§

$$\sin^2\theta_{13} = 0.013^{+0.007}_{-0.005}\,, \quad \Delta\chi^2 = 10.1\,(3.2\sigma) \qquad \text{(normal)},$$
$$\sin^2\theta_{13} = 0.016^{+0.008}_{-0.006}\,, \quad \Delta\chi^2 = 10.1\,(3.2\sigma) \qquad \text{(inverted)}.$$

Reactor Neutrino

- Electron antineutrino from beta decay.
- ^{235}U, ^{239}Pu, ^{241}Pu beta spectra were measured at ILL. ^{238}U spectrum is calculated theoretically.
- Counting rate and spectra were verified by Bugey and Bugey-3
- Power fluctuation <1%, counting rate precision ~2% with burn-up evolution. Spectra precision ~2%
- Rate and spectra precision are less important for next theta13 experiments.

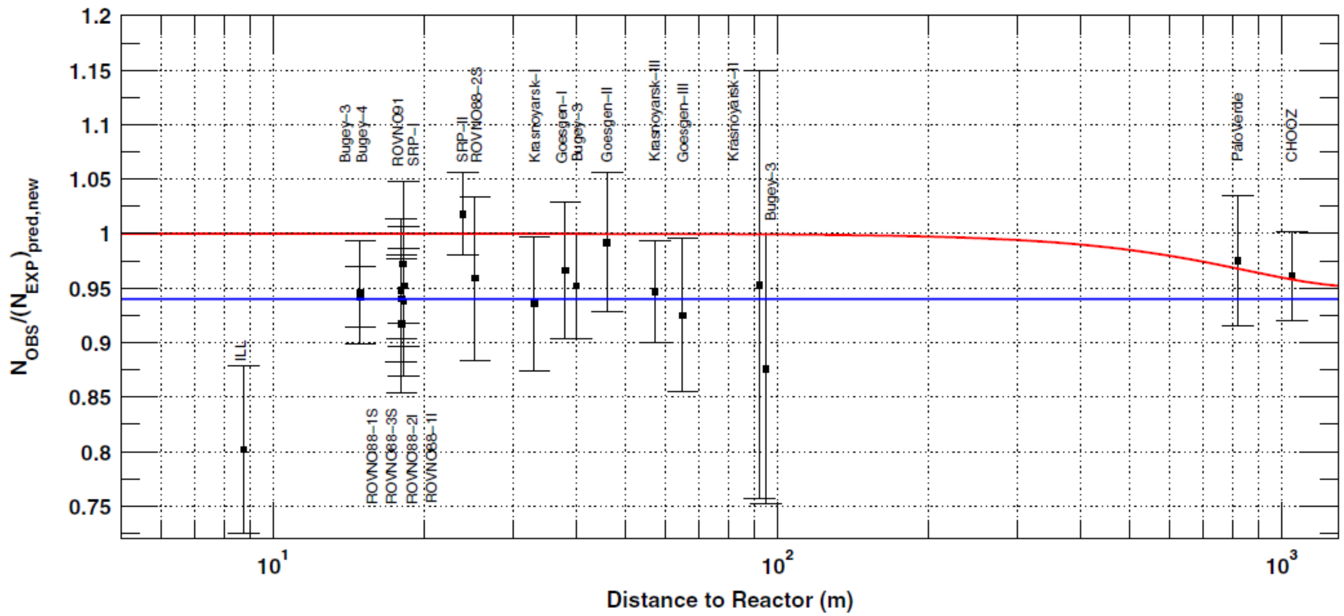




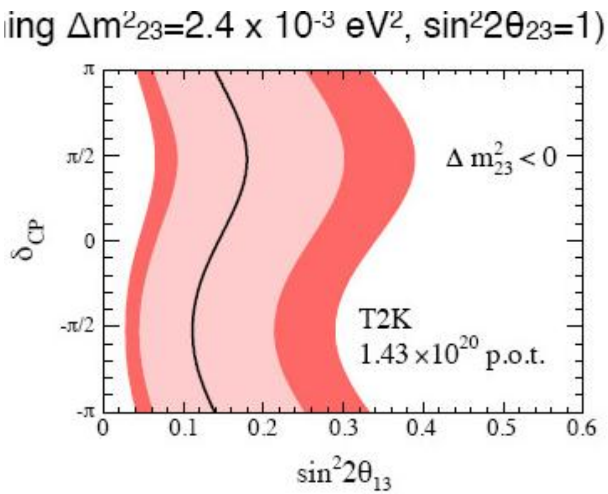
Peak at 4 MeV

Reactor antineutrino anomaly

- Recent calculated reactor flux is larger than ILL by 3%. (T. A. Mueller *et al., Phys. Rev. C 83, 054615, P.Huber, arXiv:1106.0687v3*)
- The reactor antineutrino anomaly is an effect at 98.6% C.L. (G. Mention et al., Phys. Rev. D 83, 073006)
- A large correlated uncertainty has no impact on the Daya Bay sensitivity.
- Using new reactor flux or the old ILL spectra also has no impact on the Daya Bay $\sin^2 2\theta_{13}$ sensitivity.



Measuring θ_{13} at reactors

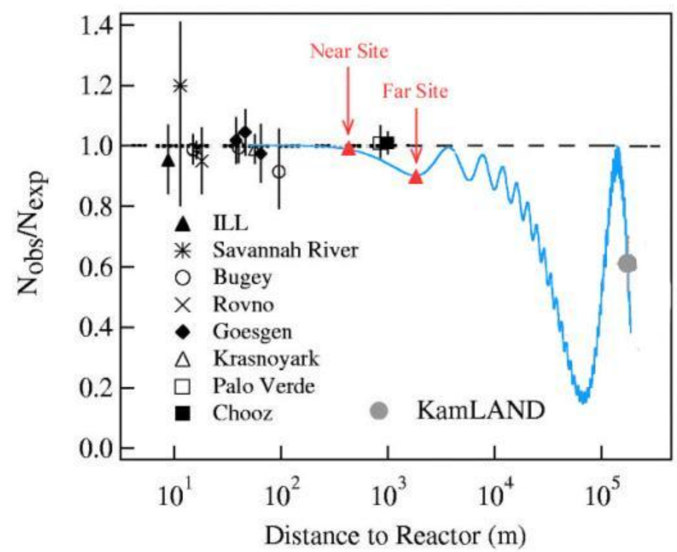


Accelerator (ν_e appearance)

Related to CP phase, θ_{13}, and mass hierarchy

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

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



Reactor ($\bar{\nu}_e$ disappearance)

Clean in physics, only related to θ_{13}

Large statistics, cheaper and faster

How to measure $\sin^2 2\theta_{13}$ to 0.01

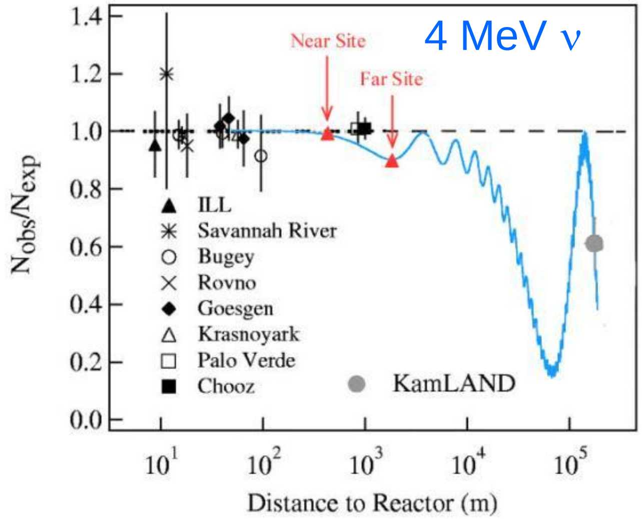
CHOOZ: R=1.01 ± 2.8%(stat) ± 2.7%(syst), $\sin^2 2\theta_{13} < 0.17$

Higher statistics

- 40 ton-GW → 1400 ton-GW at Daya Bay
- Statistical error 0.2% in 3 years.

Lessons from past experience:

- Need near and far detectors
- Chooz: Good Gd-LS
- Palo Verde: Go deeper, good muon system
- KamLAND: No fiducial cut, lower threshold



Parameter	Error	Daya Bay, Relative measurement
Reaction cross section	1.9 %	Cancel out, Near/far
Number of protons	0.8 %	Reduced to <0.3%, filling tank with load cell
Detection efficiency	1.5 %	Reduced to ~0.2%, identical, 3-layer detectors
Reactor power	0.7 %	Reduced to ~0.1%, Near/far
Energy released per fission	0.6 %	Cancel out, Near/far
Chooz Combined	2.7 %	

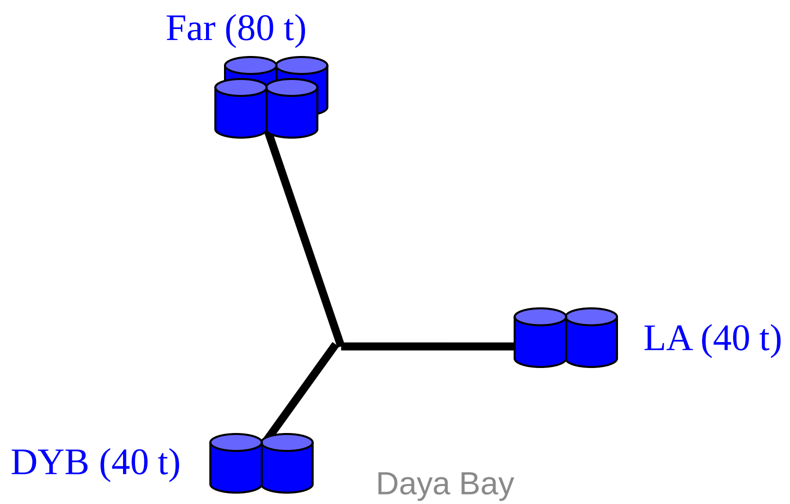
Expected Uncertainties

Source of uncertainty		Chooz (*absolute*)	Daya Bay (*relative*)		
			Baseline	Goal	Goal w/Swapping
# protons		0.8	0.3	0.1	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%

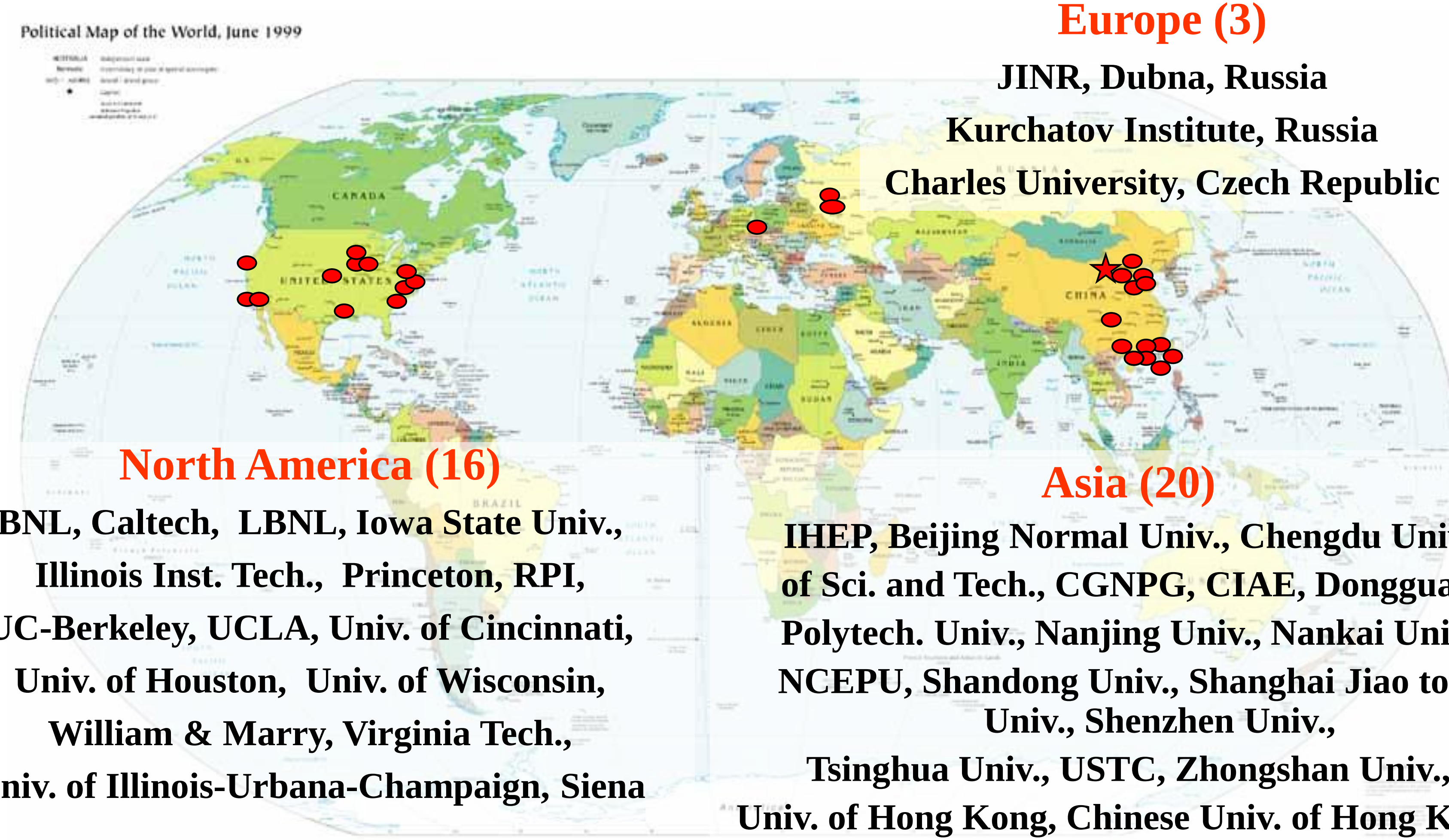
	DYB site	LA site	far site
Antineutrino rate (/day/module)	930	760	90
Natural radiation (Hz)	<50	<50	<50
Single neutron (/day/module)	18	12	1.5
β-emission isotopes	210	141	14.6
Accidental/Signal	$<0.2\%$	$<0.2\%$	$<0.1\%$
Fast neutron/Signal	0.1%	0.1%	0.1%
^{8}He^{9}Li/Signal	0.3%	0.2%	0.2%

Daya Bay Redundancy

- **Measuring $\sin^2 2\theta_{13}$ to 0.01 need to control systematic errors very well.**
- **We believe that the relative (near/far) detector systematic error could be lowered to 0.38%, with near/far cancellation and improved detector design.**
- **Side-by-side calibration: Event rates and spectra in two detectors at the same near site can be compared → How IDENTICAL our detectors are?**
- **Detector swapping: Daya Bay antineutrino detectors are designed to be MOVABLE. All detectors are assembled and filled with liquids at the same place. Detectors at the near sites and the far site can be swapped, although not necessary to reach our designed sensitivity, to cross check the sensitivity and further reduce the systematic errors.**



The Daya Bay Collaboration



Europe (3)

JINR, Dubna, Russia

Kurchatov Institute, Russia

Charles University, Czech Republic

North America (16)

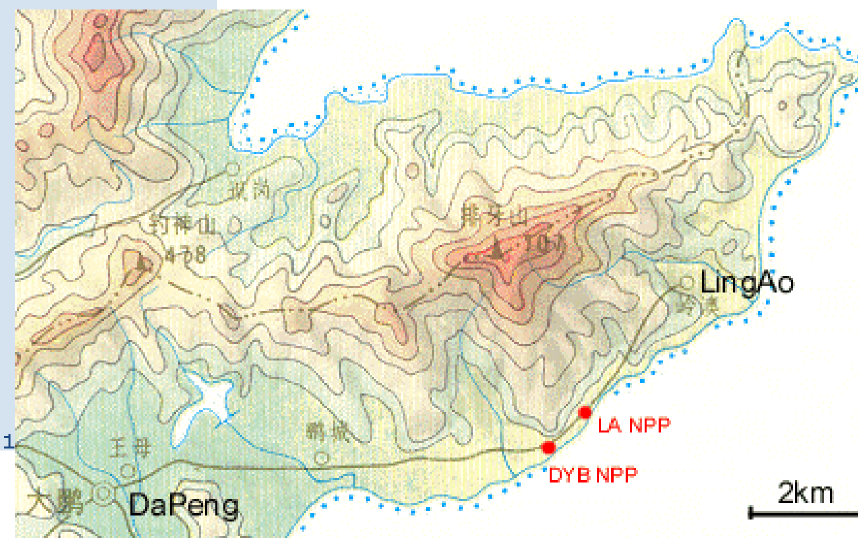
BNL, Caltech, LBNL, Iowa State Univ., Illinois Inst. Tech., Princeton, RPI, UC-Berkeley, UCLA, Univ. of Cincinnati, Univ. of Houston, Univ. of Wisconsin, William & Marry, Virginia Tech., Univ. of Illinois-Urbana-Champaign, Siena

Asia (20)

IHEP, Beijing Normal Univ., Chengdu Univ. of Sci. and Tech., CGNPG, CIAE, Dongguan Polytech. Univ., Nanjing Univ., Nankai Univ., NCEPU, Shandong Univ., Shanghai Jiao tong 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.

~250 Collaborators

Location of Daya Bay



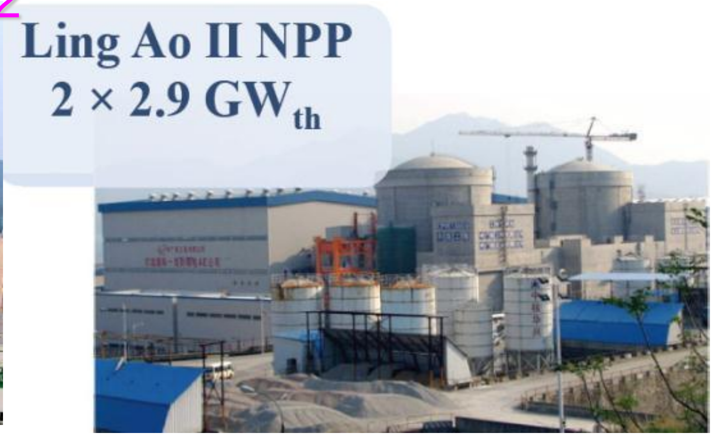
Two metropolises

- Hong Kong 55 km
  θ_{12} maximum
- ShenZhen 45 km

Daya Bay and Ling Ao Nuclear Power Plant

Daya Bay NPP 2.9GW×2

LingAo NPP 2.9GW×2



Daya Bay Layout

Power Plant

6 cores 17.4 GW

Three experimental halls

Multiple detectors at each site

Side-by-side calibration

Horizontal Tunnel

Total length 3200 m

Movable Detector

All detectors filled at the filling hall, w/ the same batch of Gd-LS, w/ a reference tank

Event Rate:

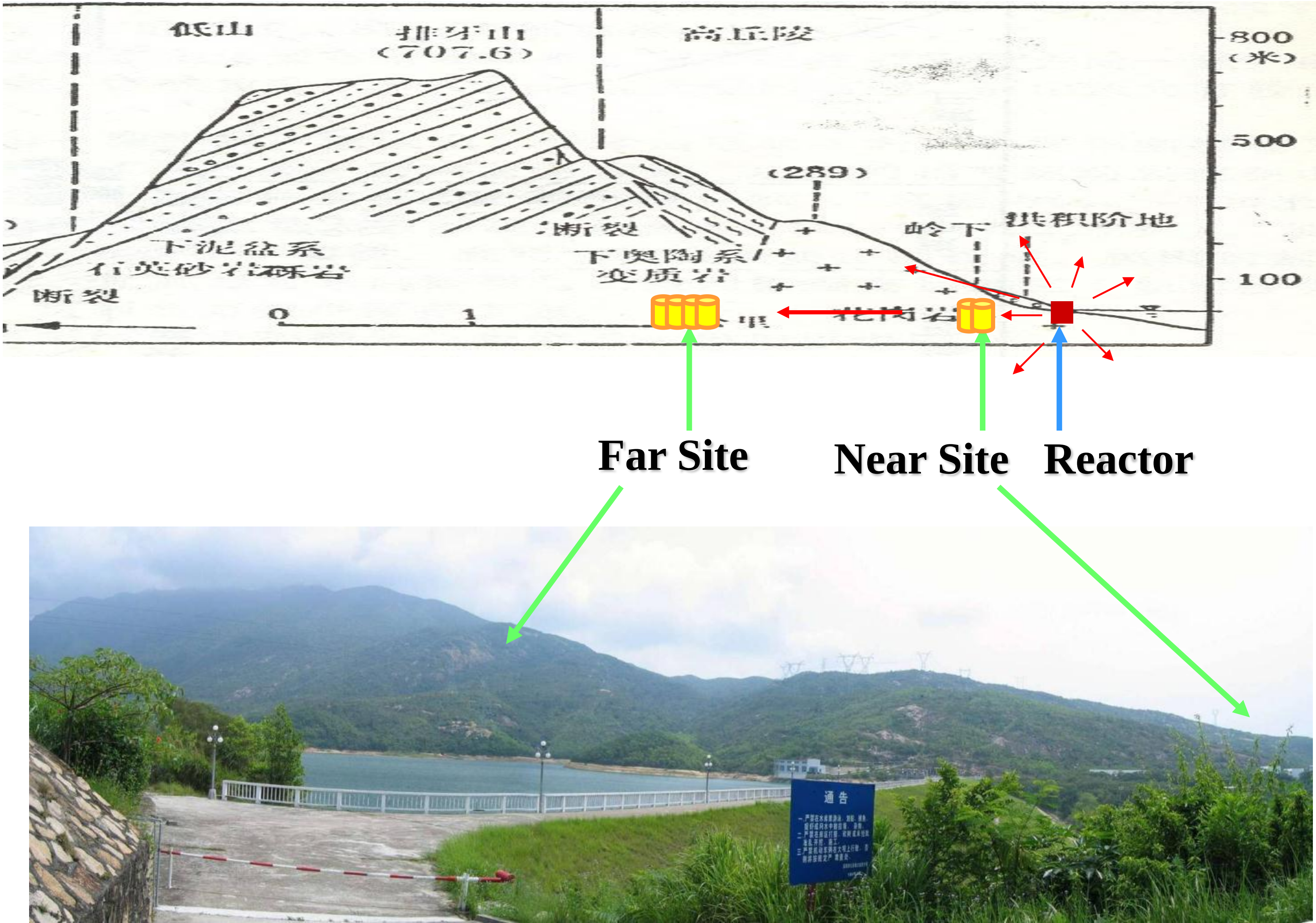
~1200/day Near

~350/day Far

Backgrounds

B/S ~0.4% Near

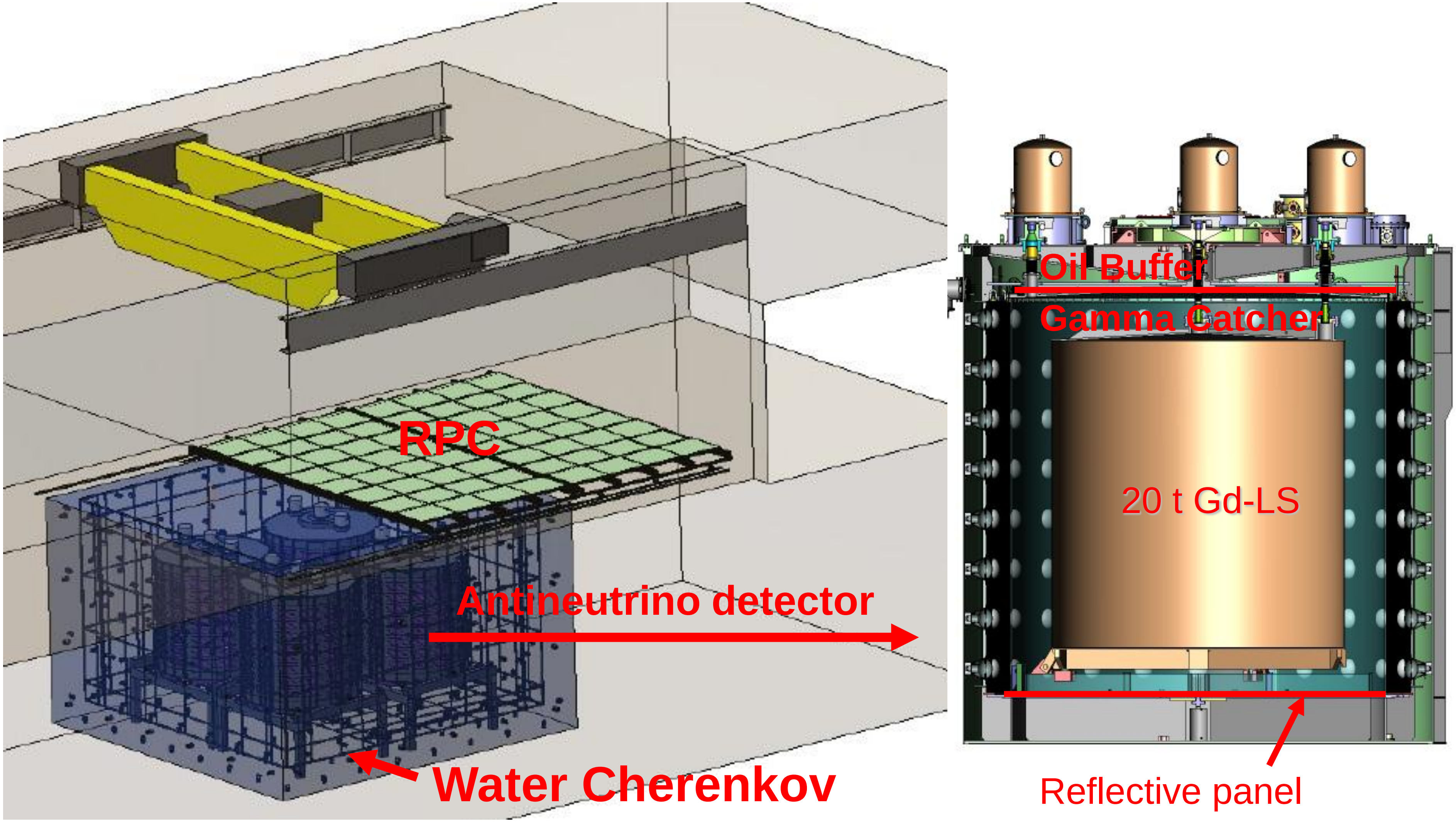
B/S ~0.2% Far


低山
排牙山
(707.6)
高丘陵
800
(米)
500
100
(289)
岭下
洪积阶地
断裂
下泥盆系
石英砂岩砾岩
断裂
下奥陶系
变质岩
花岗岩
0
1
Far Site
Near Site
Reactor
通告

All Civil Works Complete

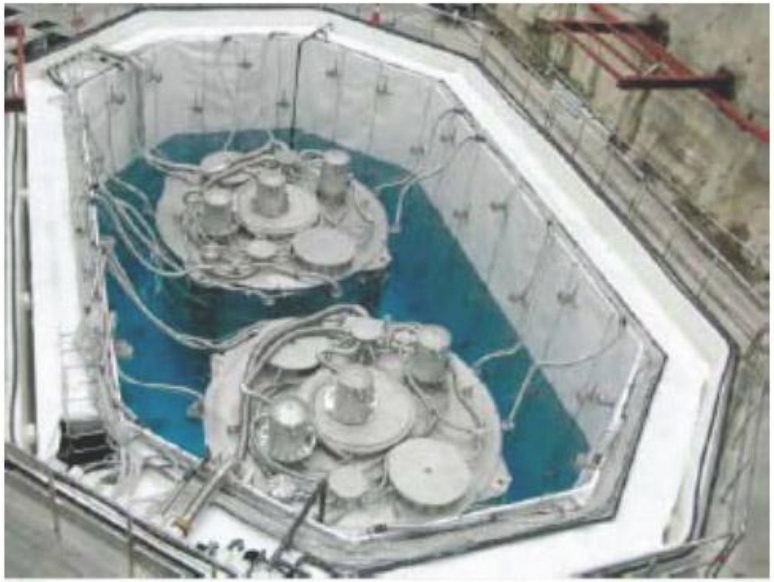
Tunnel, 7m-wide, 7m-high, total 3000m

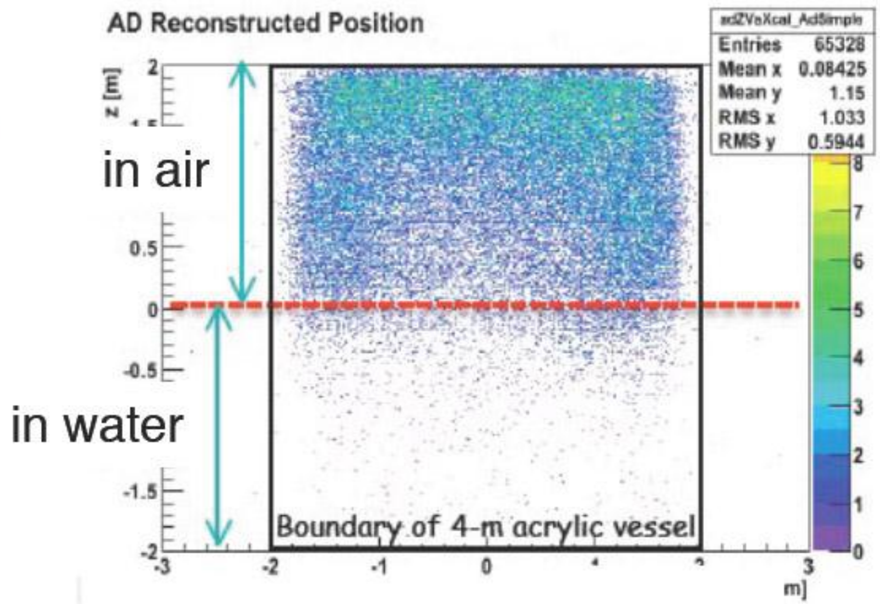
Daya Bay Detectors

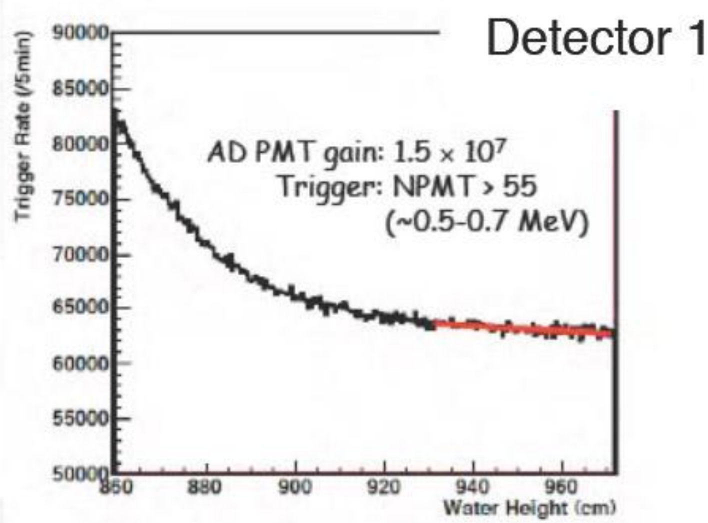


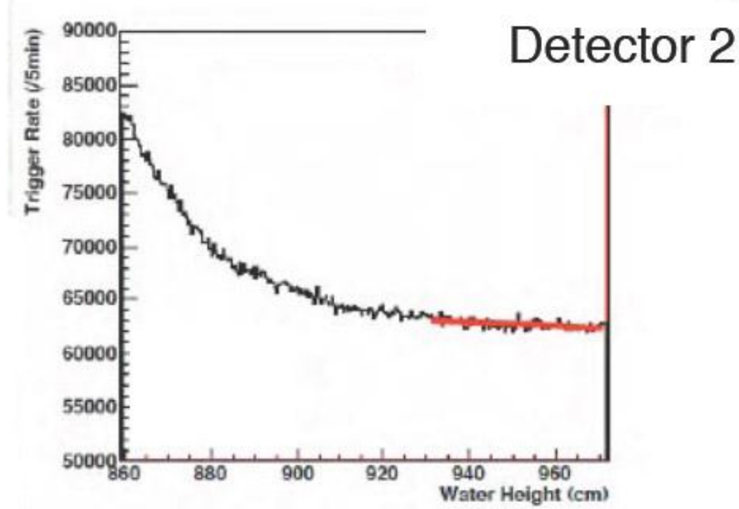
Water Pool: Cherenkov + shielding

Gamma Shielding



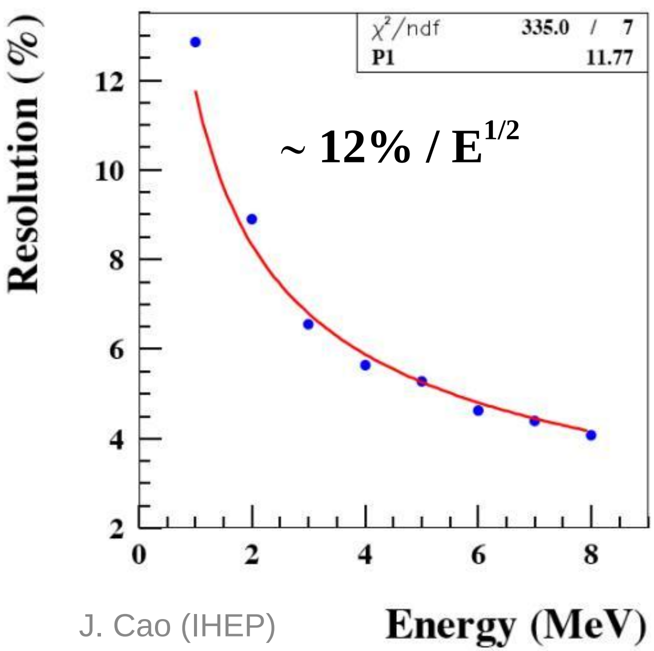


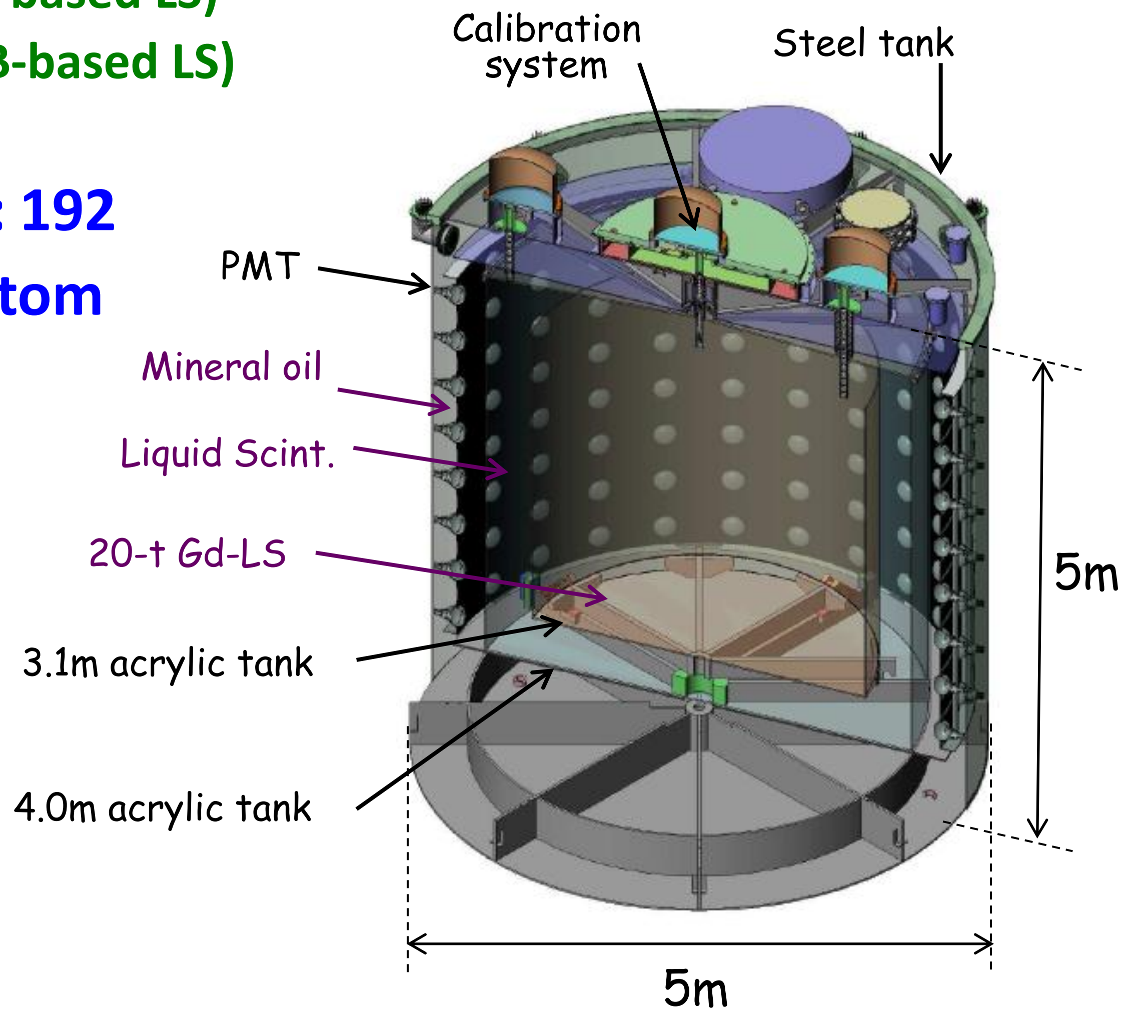




Antineutrino Detectors

- **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**





Signal and Backgrounds in detector

Prompt signal

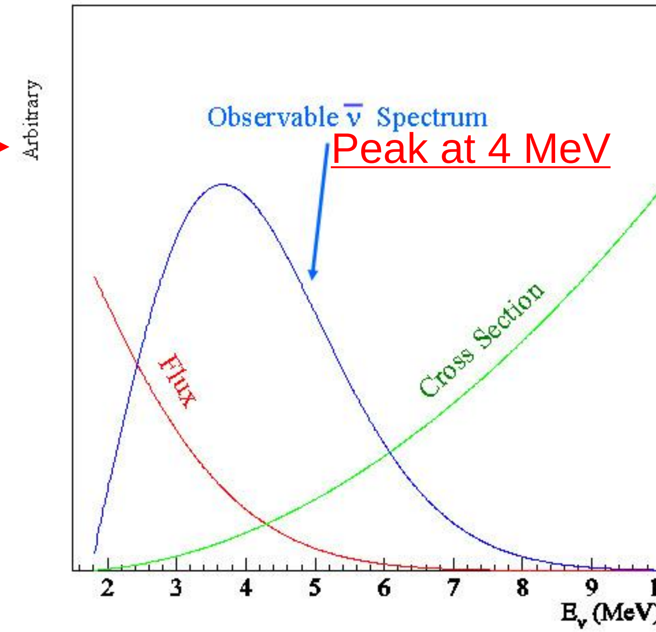
$$e^+ + e^- \rightarrow 2\gamma$$

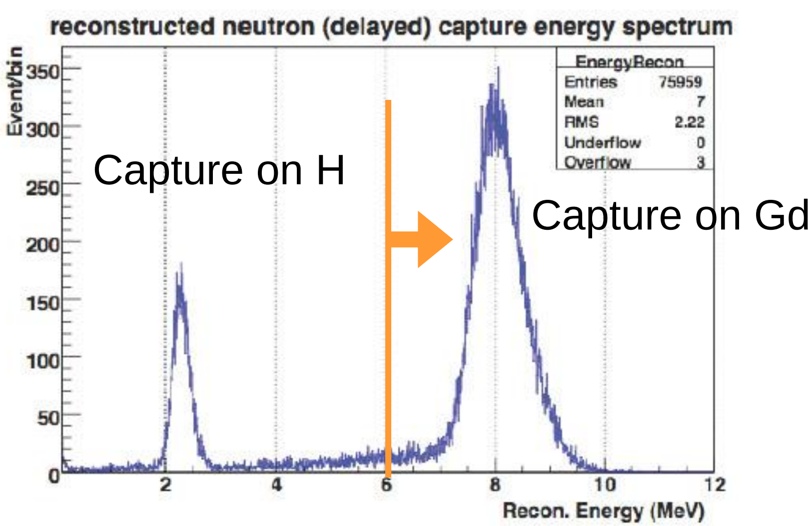
$$\bar{\nu}_e + p \rightarrow e^+ + n$$

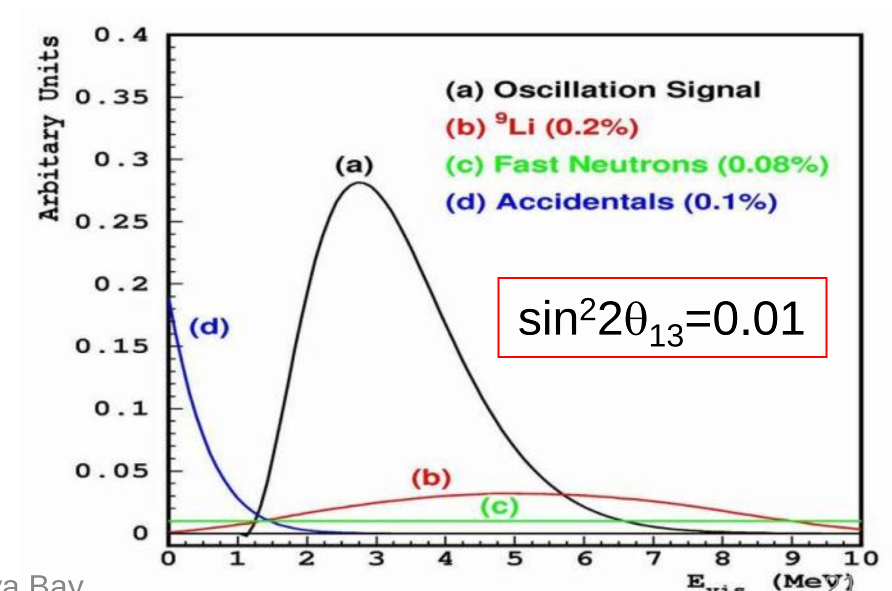
Capture on H or Gd,

Delayed signal, 2.2, 8 MeV

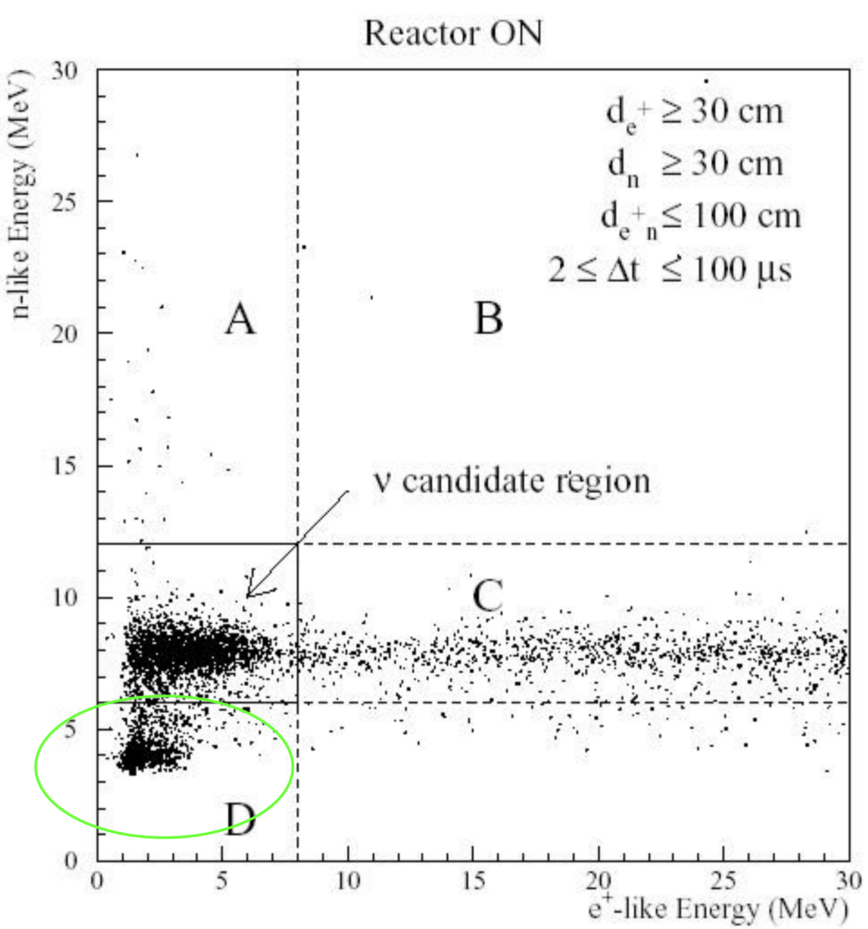
200 μs



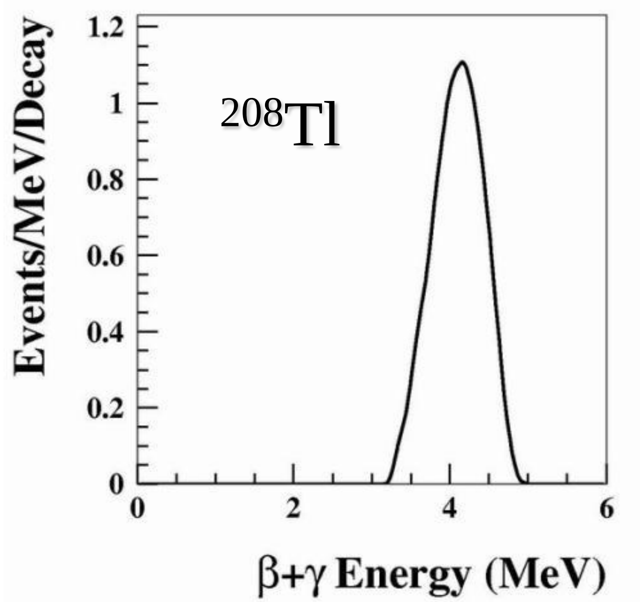




Why 6 MeV



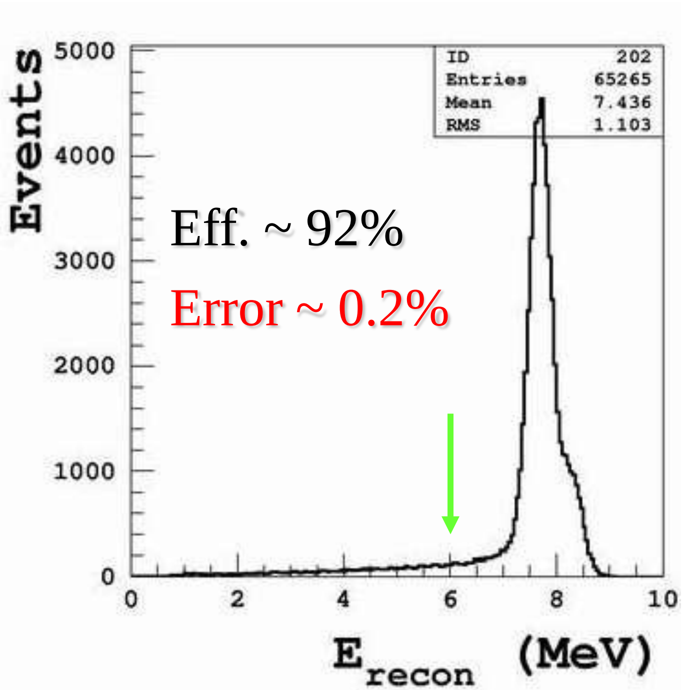
Chooz Event Sample

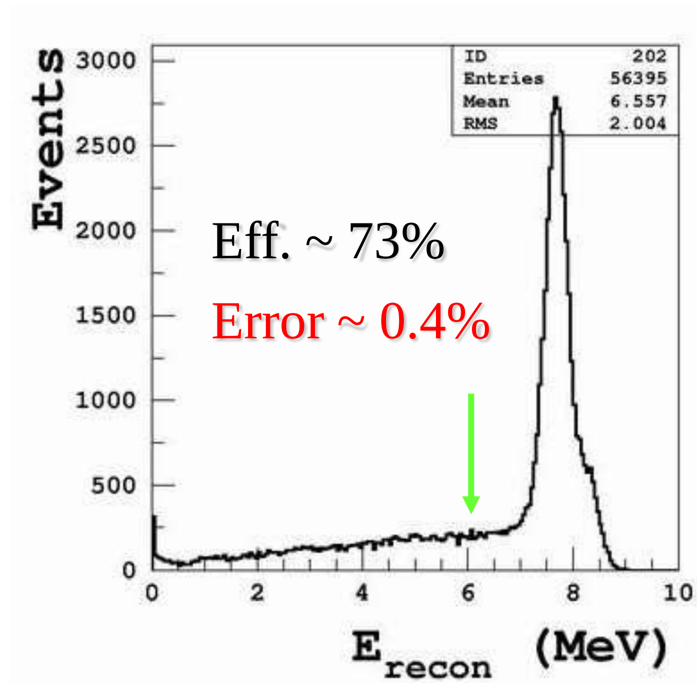


External radiation has only gamma <3MeV

Beta (and alpha) in LS and acrylic tank can contribute, besides gamma

Two-layer vs Three-layer



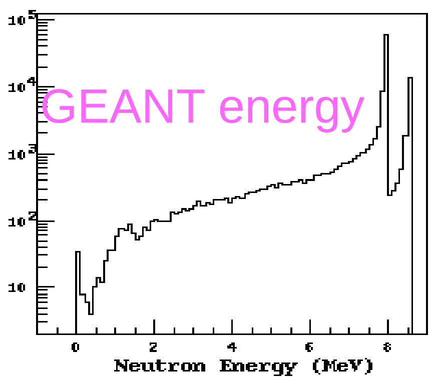


The most important error!

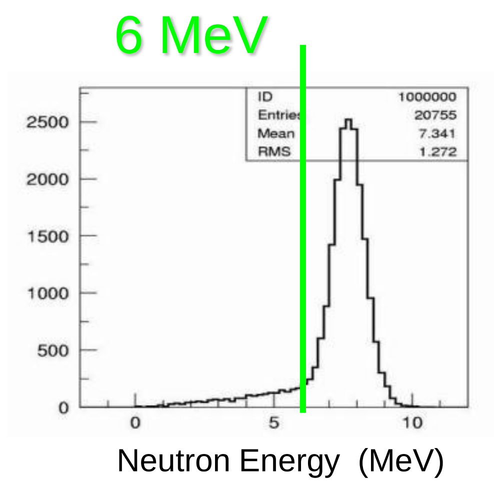
Fill gamma catcher with Gd-LS, it becomes a two-layer detector (60% more events but larger error)

Spectrum distortion (may not critical)

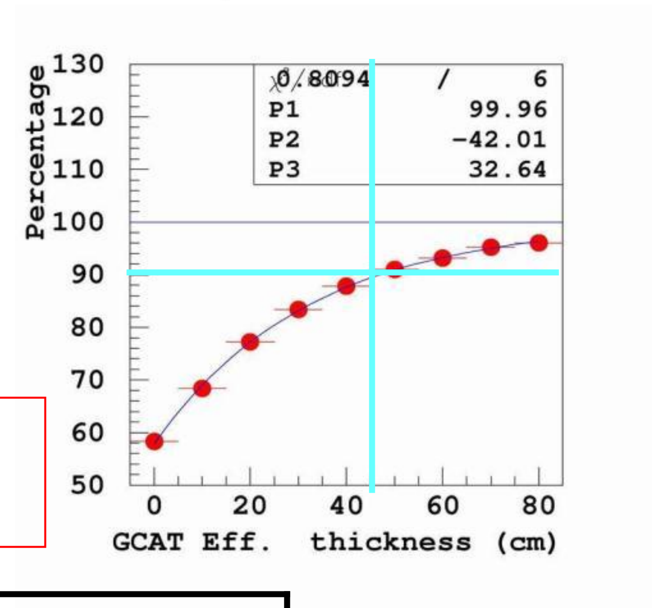
Gamma Catcher



Recon.



45cm gamma catcher



Neutron energy cut eff. 92%
Error ~0.2% (Suppose 1% energy scale error)

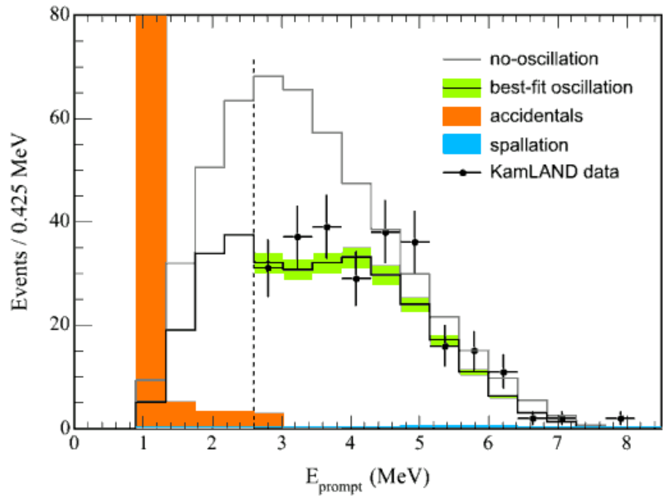
Energy Resolution	10%/sqrt(E)	7%/sqrt(E)	Geant E
6MeV	92.03%	92.05%	92.08%
5.94MeV	92.23%	92.23%	92.25%
6.06MeV	91.79%	91.85%	91.89%
δEff.	-0.24%	-0.20%	-0.19%
	+0.20%	+0.18%	+0.17%

±0.2%

Positron Eff.

Chooz 1.3MeV, error 0.8% （bad LS)

KamLAND 2.6MeV, error 0.26%



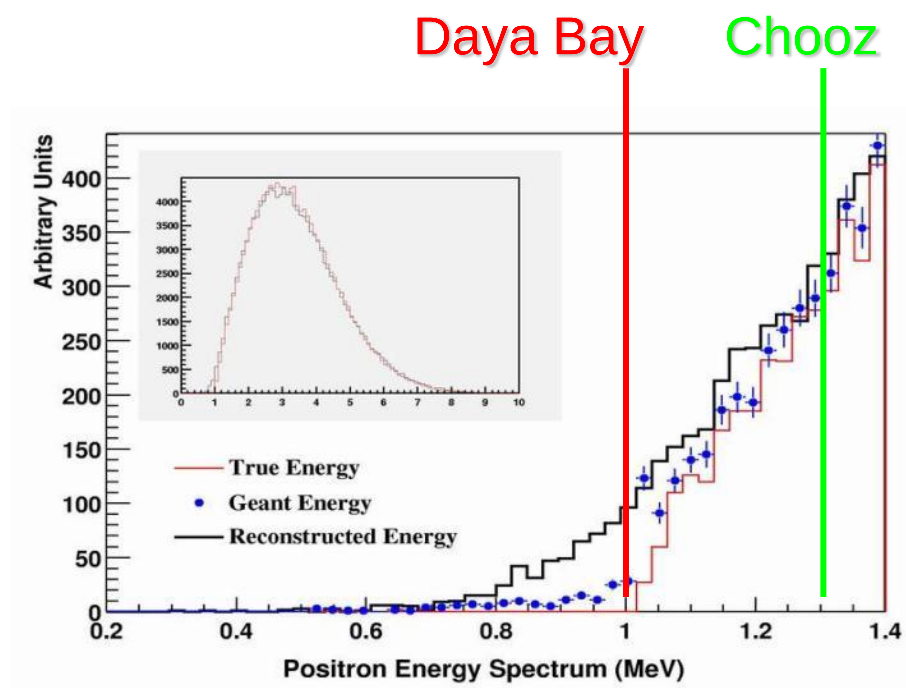
Actual AD1/2:

Better than expected resolution.

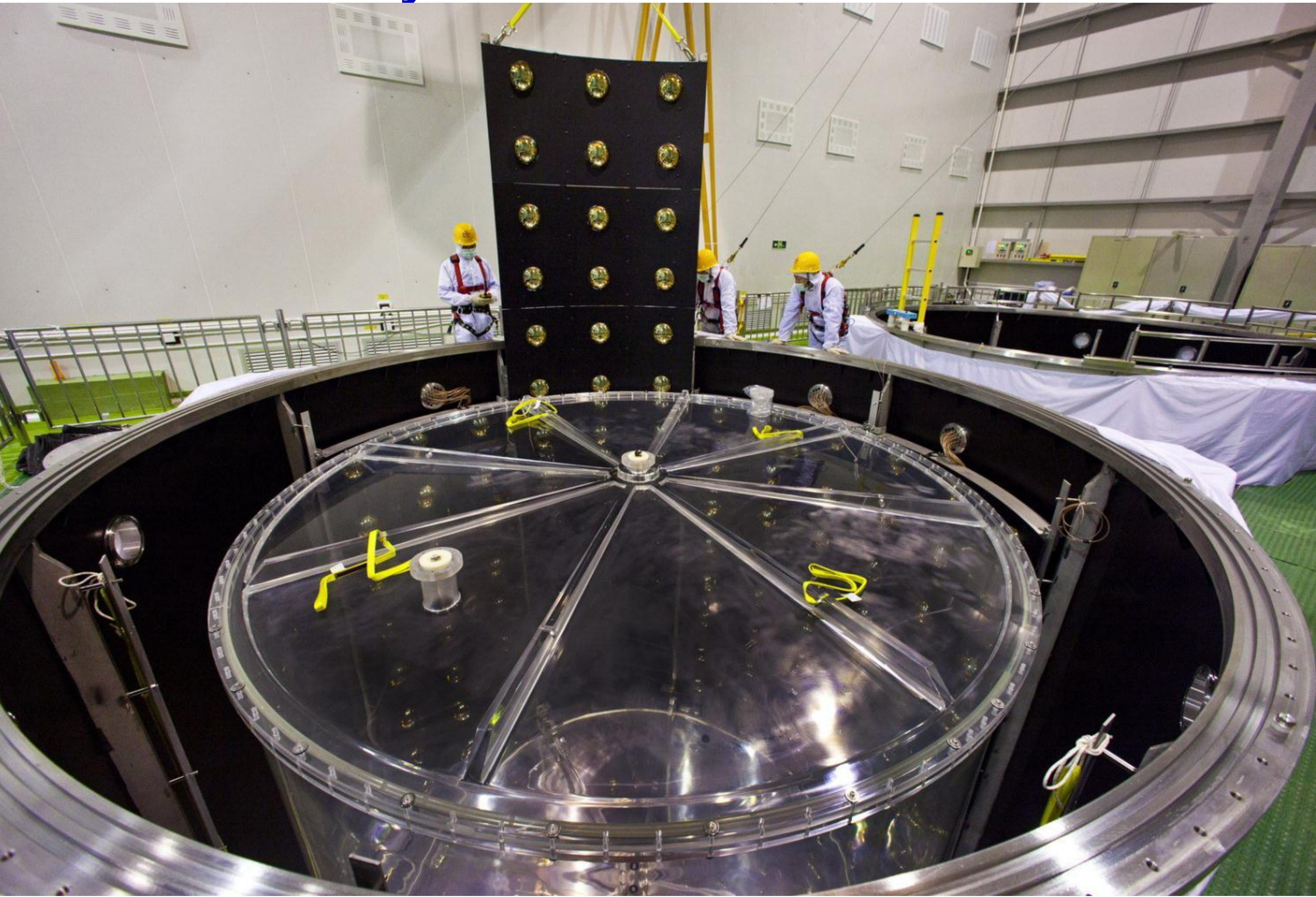
Now > 99.9% trigger eff.

Positron Eff. 99.6%

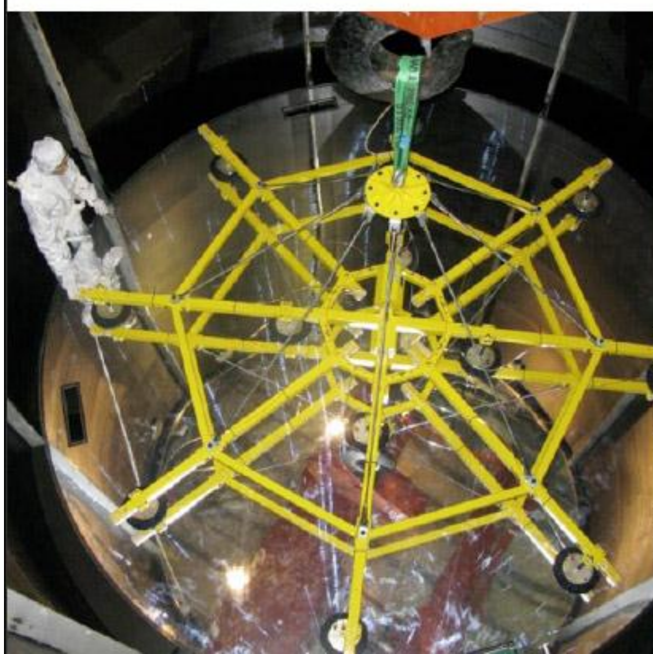
Error ~ 0.05% (suppose 2% energy scale error）

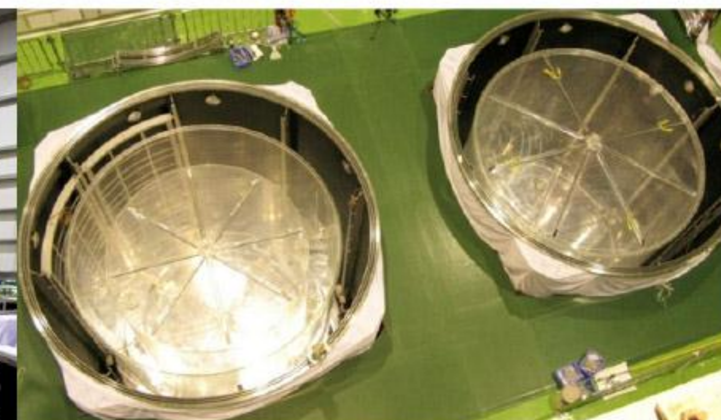


Assembly of Antineutrino Detector



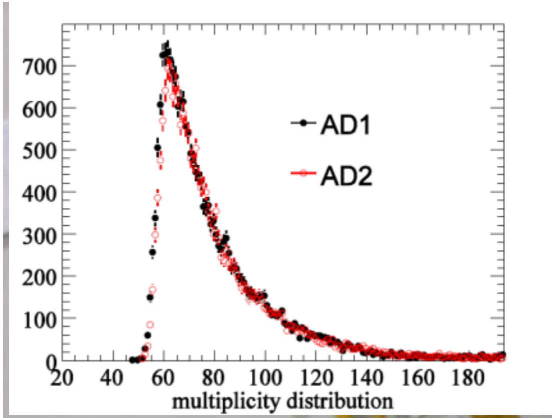
Antineutrino Detector Assembly



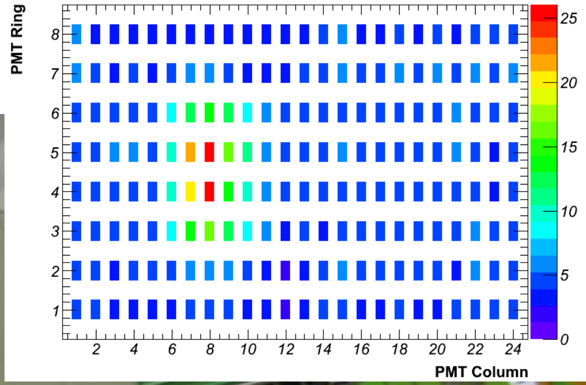


detector assembly in pairs
AD1-4 assembled and filled
AD5,6 assembly in progress

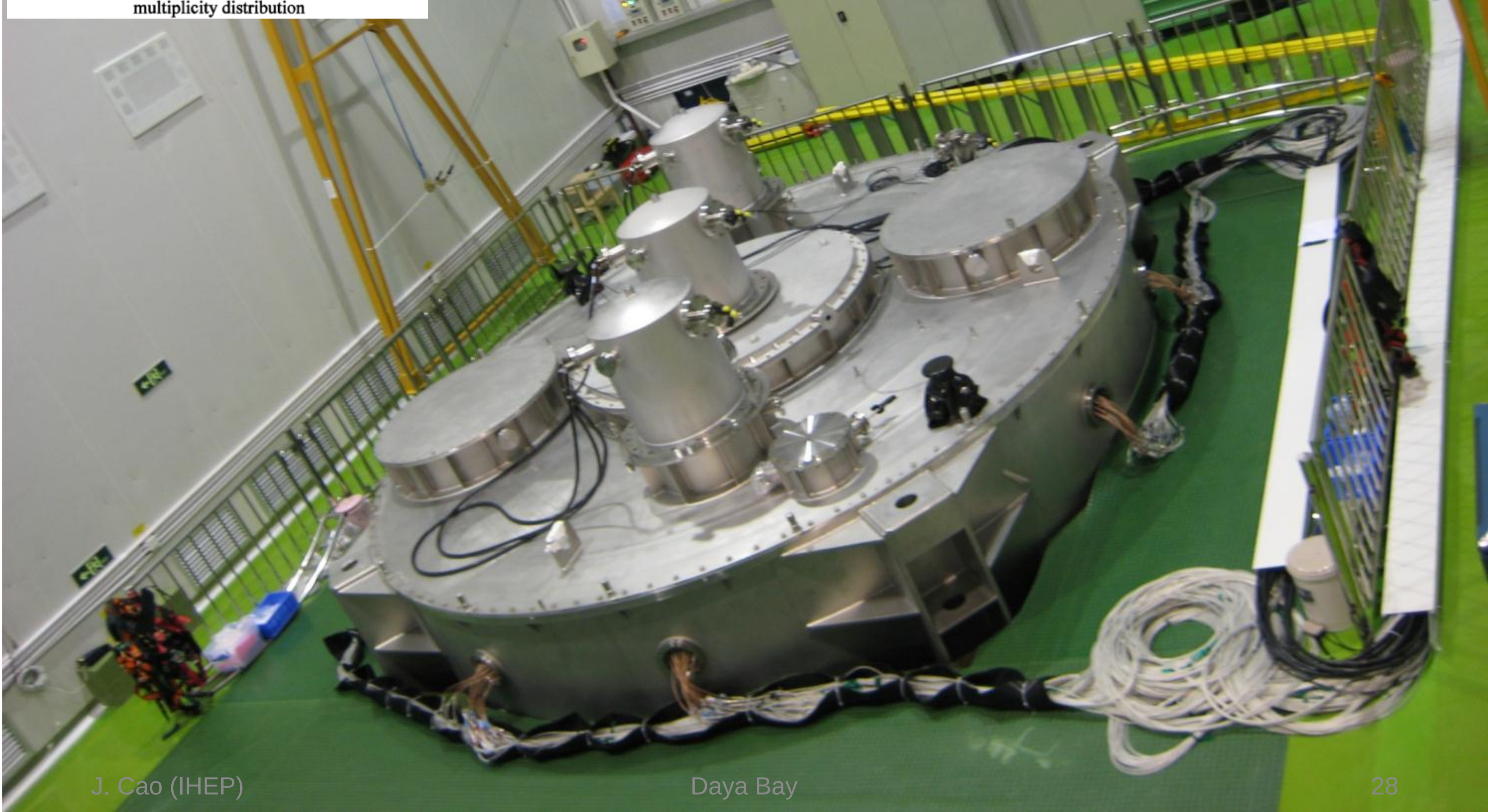
Lid of AD



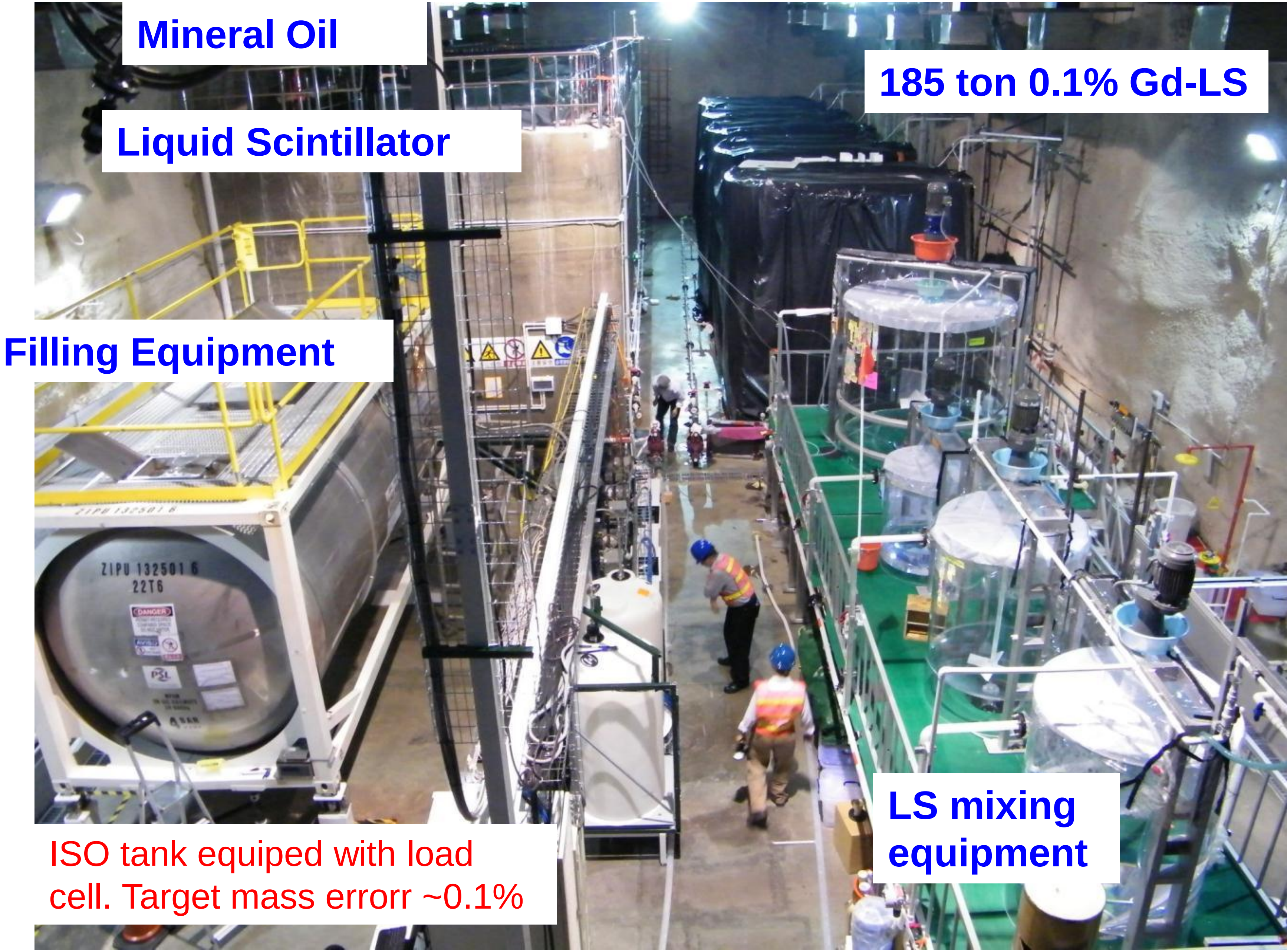
700
600
500
400
300
200
100
0
20 40 60 80 100 120 140 160 180
multiplicity distribution
AD1
AD2



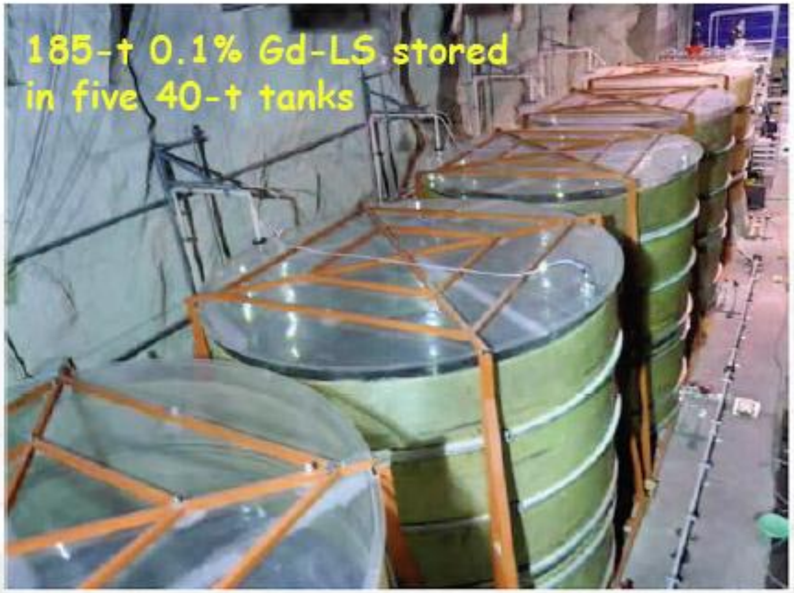
PMT Ring
8
7
6
5
4
3
2
1
2 4 6 8 10 12 14 16 18 20 22 24
PMT Column
25
20
15
10
5
0

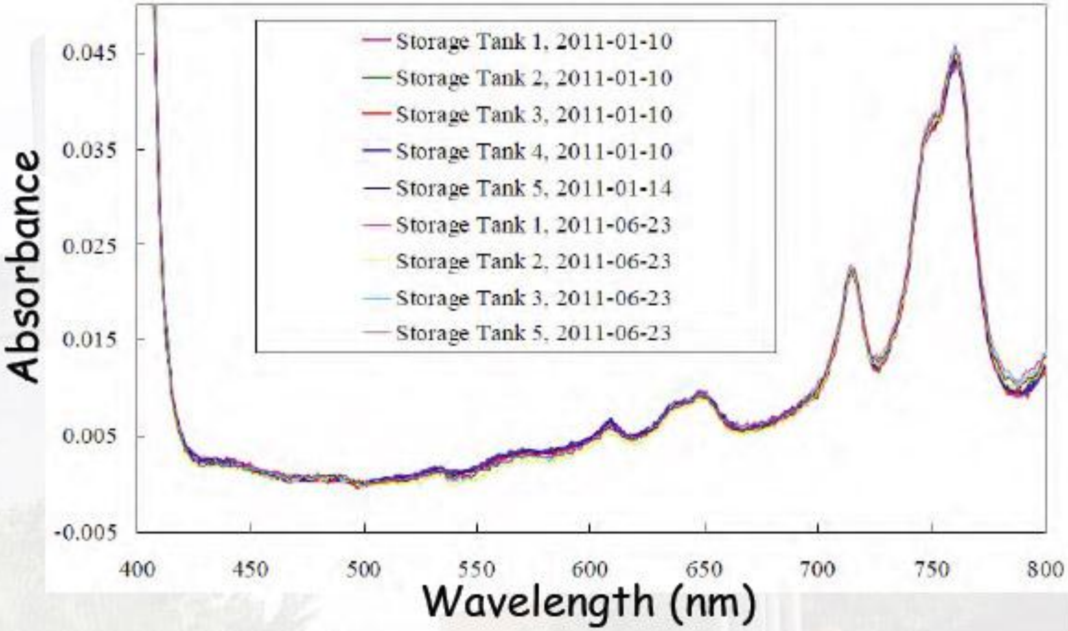


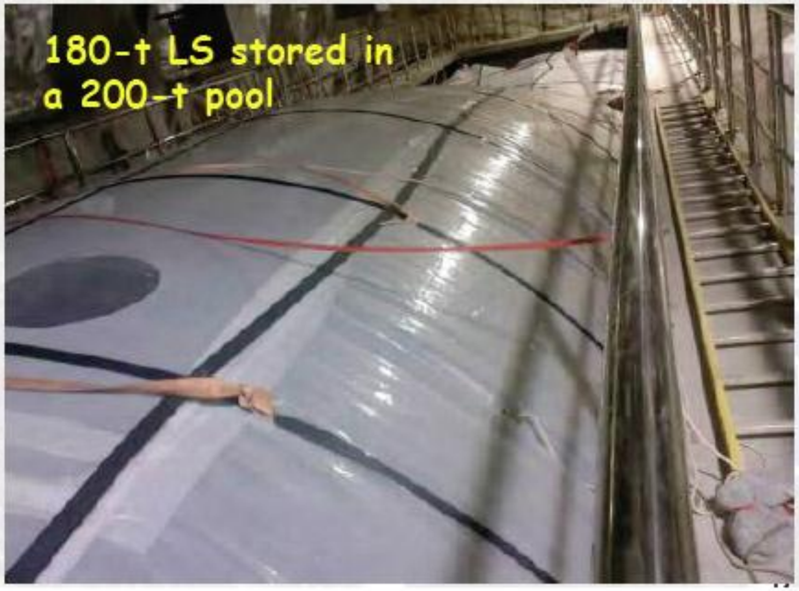
Liquid Scintillator Hall



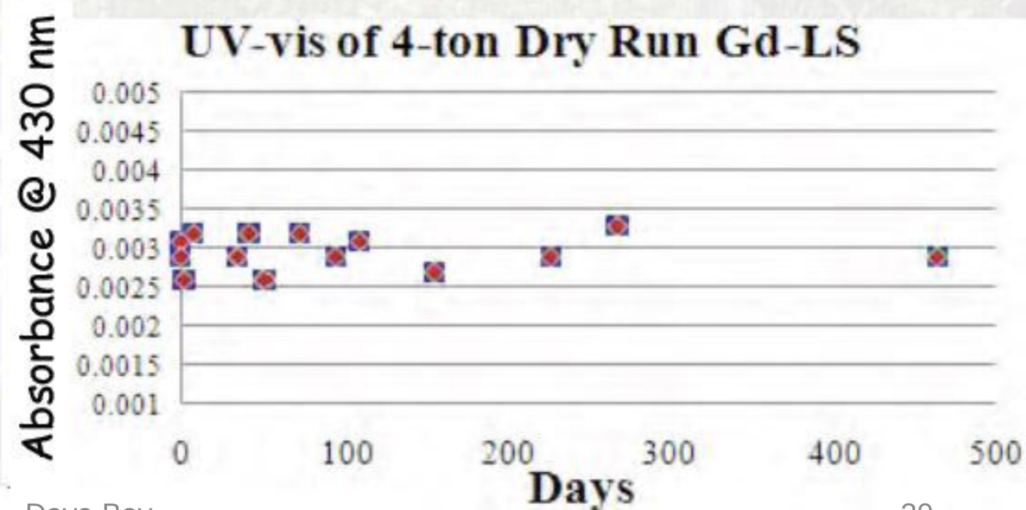
Liquid Scintillator







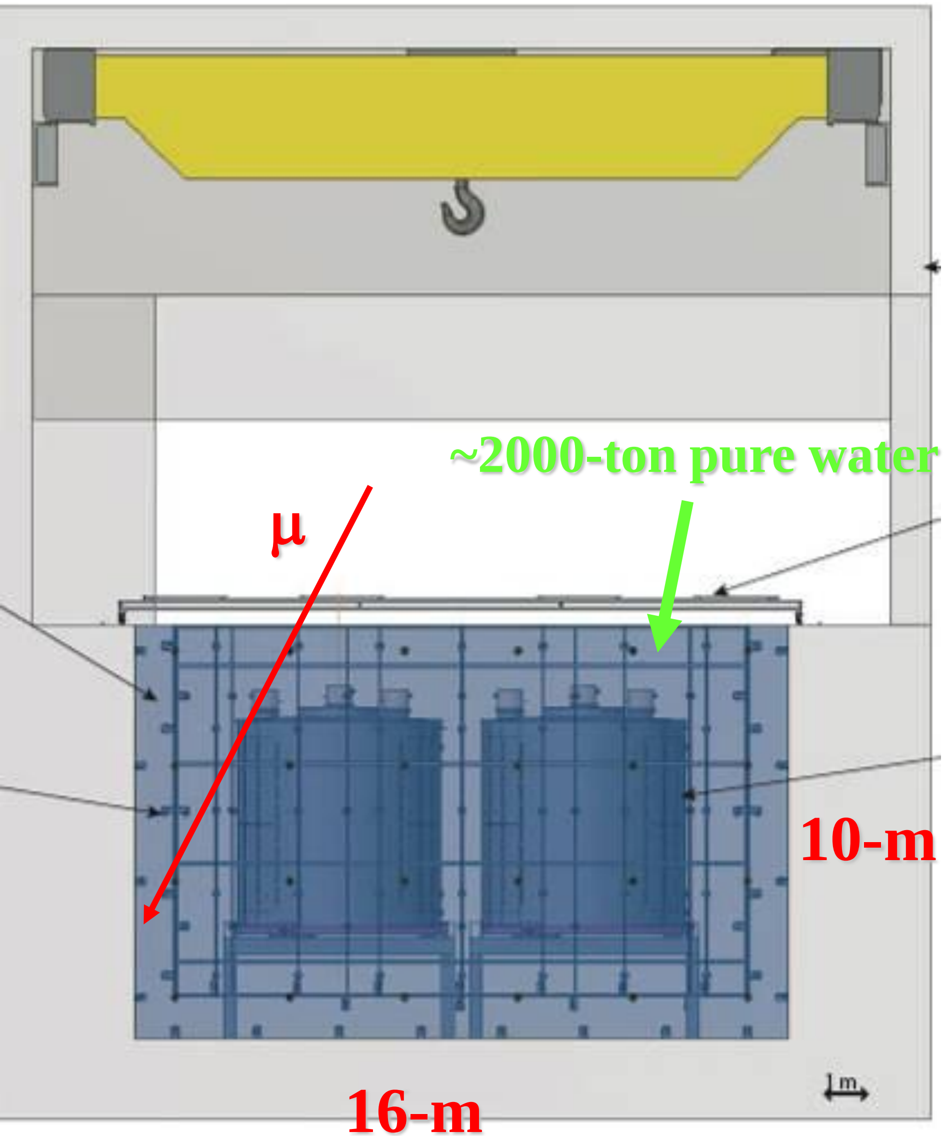
A 1-m apparatus yielded attenuation length of ~15 m @ 430 nm.



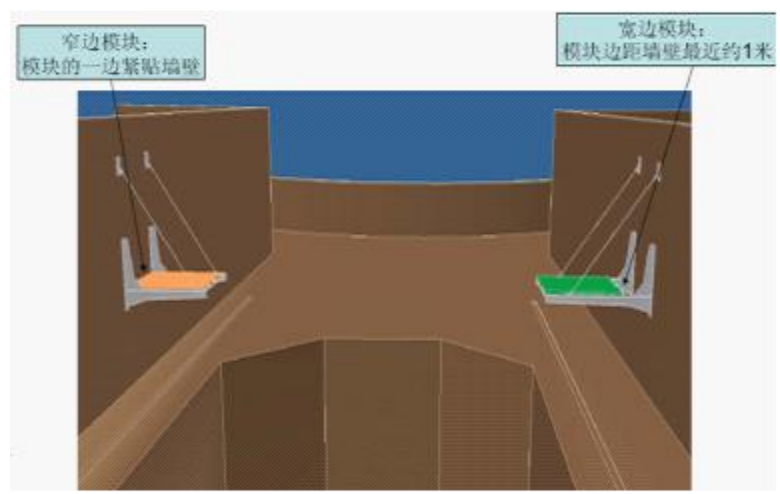
Filling AD

AD1/2/3/4 filled

Muon System



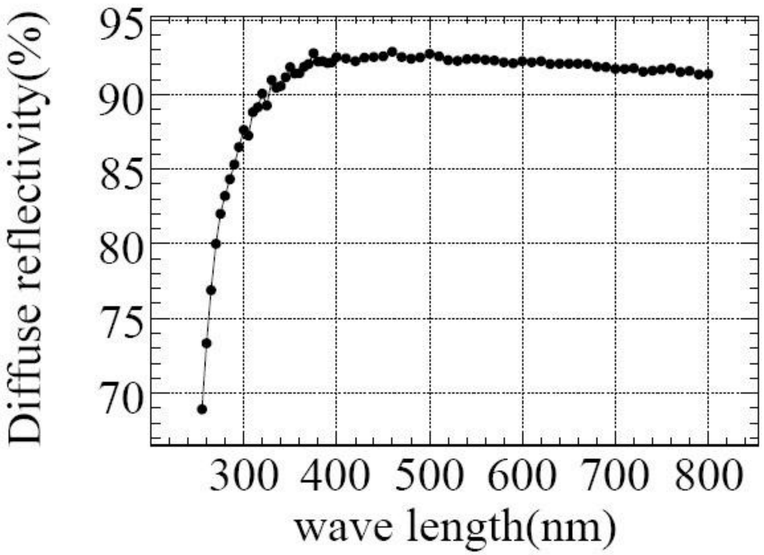
- 2.5m thick water shielding to AD in all directions.
- Two-layer water cherenkov
  - Cross check
  - Measuring fast-neutron backgrounds
- Covered w/ 4-layer RPC on top.
- The combined muon efficiency ~ 99.5%.

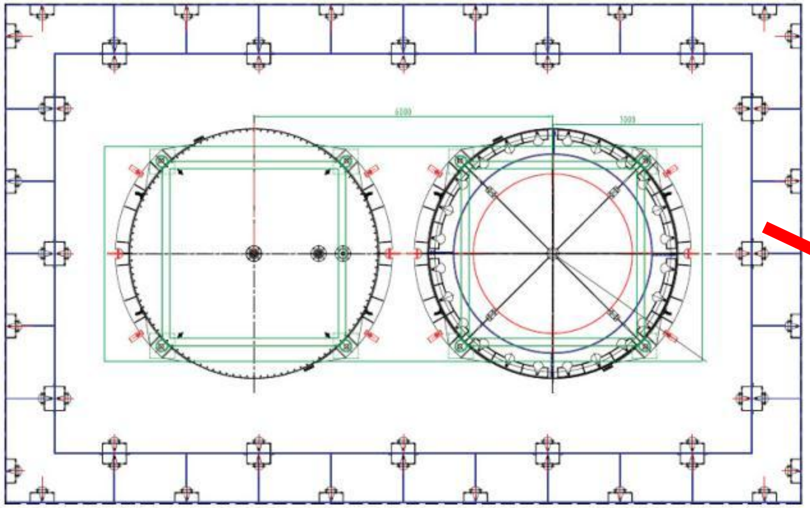


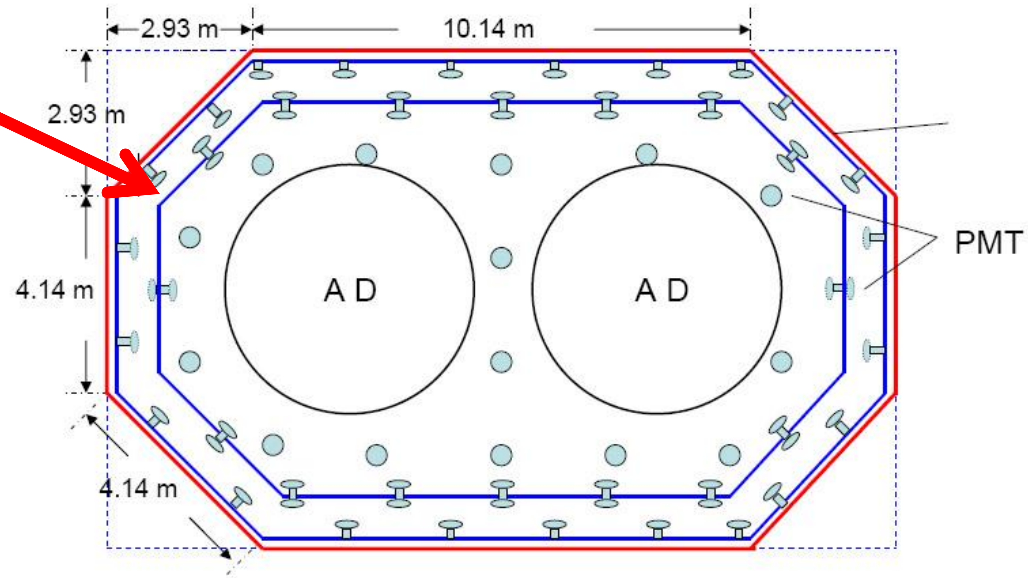
Telescope RPC

Two-Layer Water Cherenkov

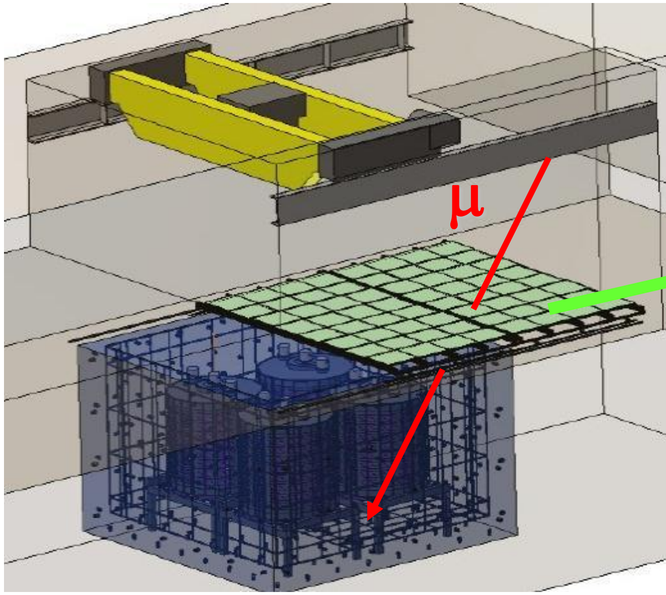
- **High reflective Tyvek, improve the light collection 5 times.**
- **Rectangle --> Octagon, improve water circulation**

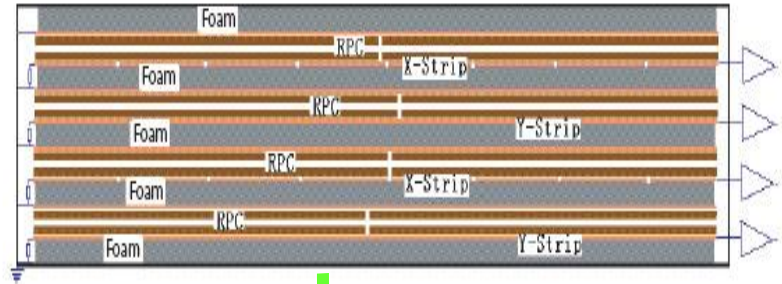


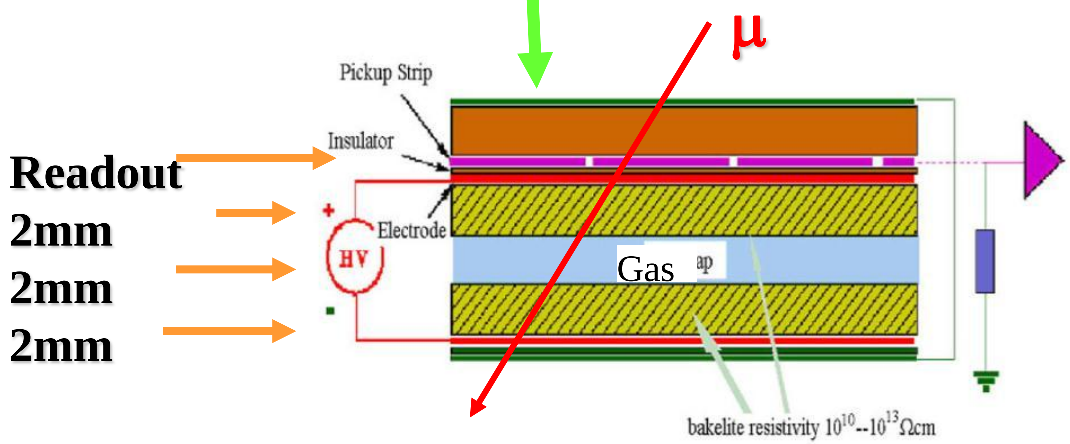


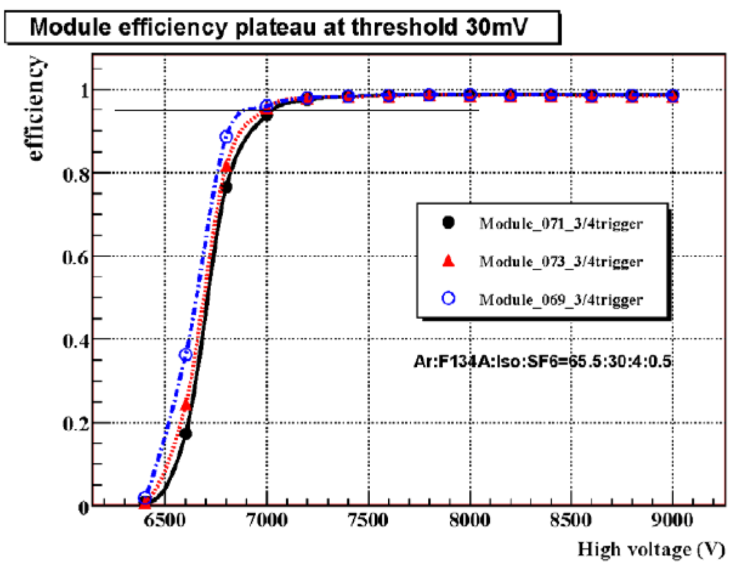


Resistive Plate Chamber





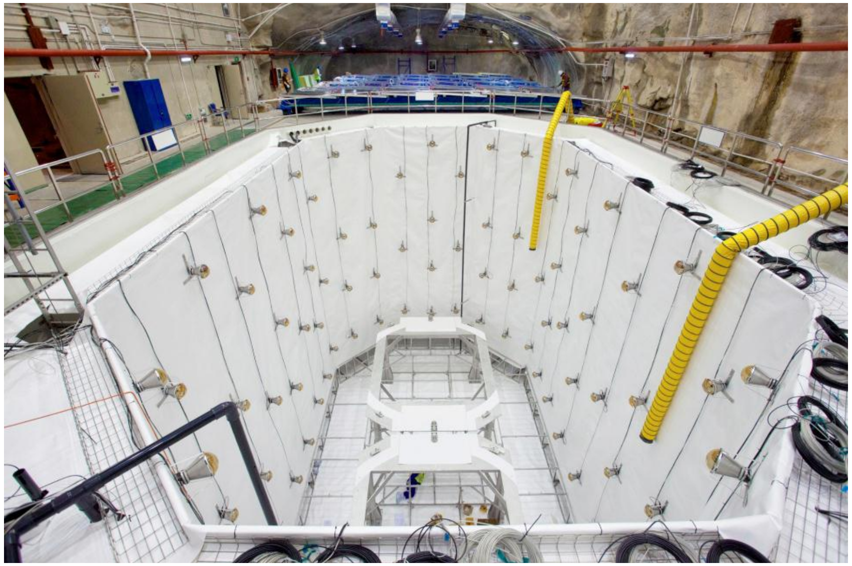




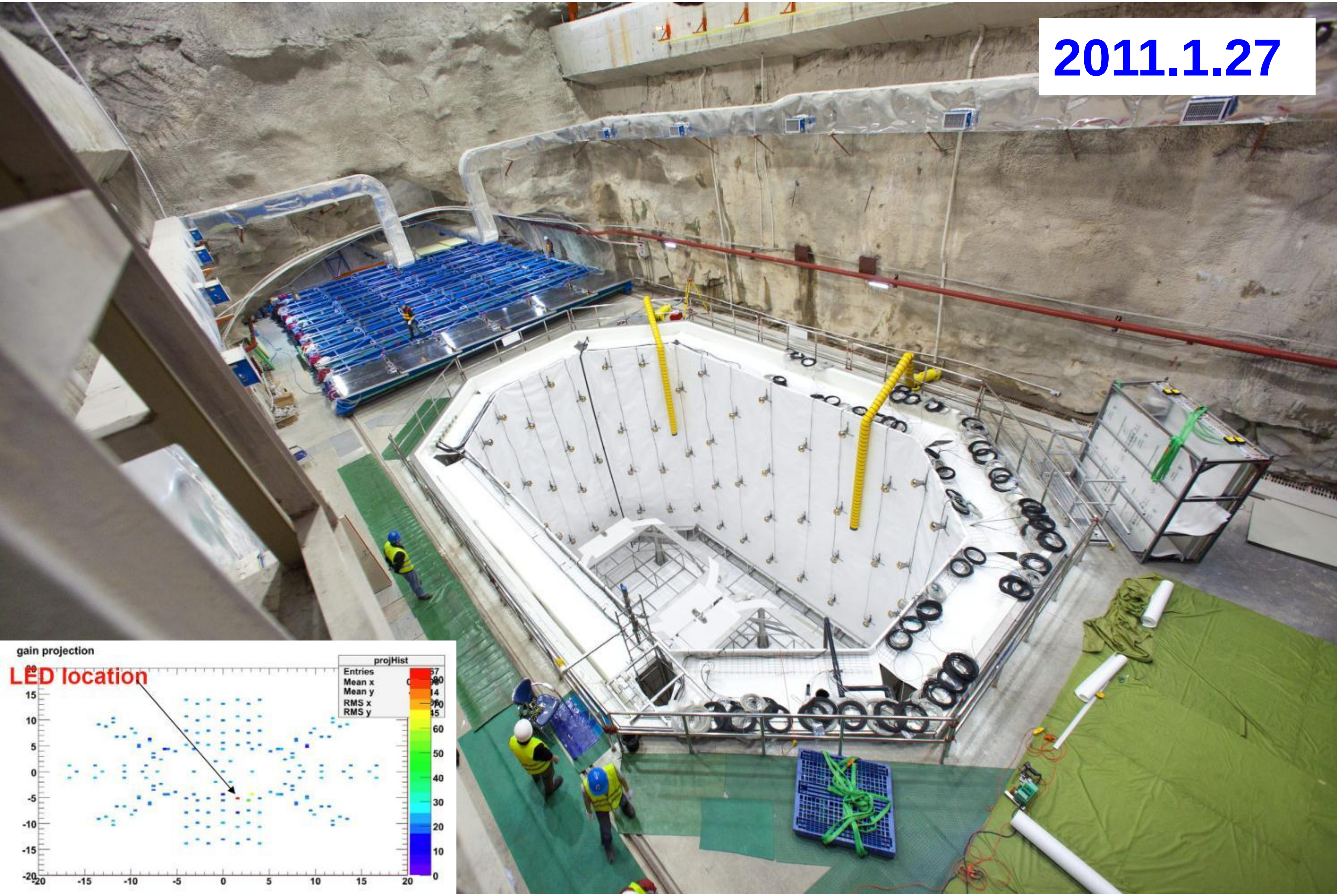
Cross check w/ water cherekov to determine muon eff.

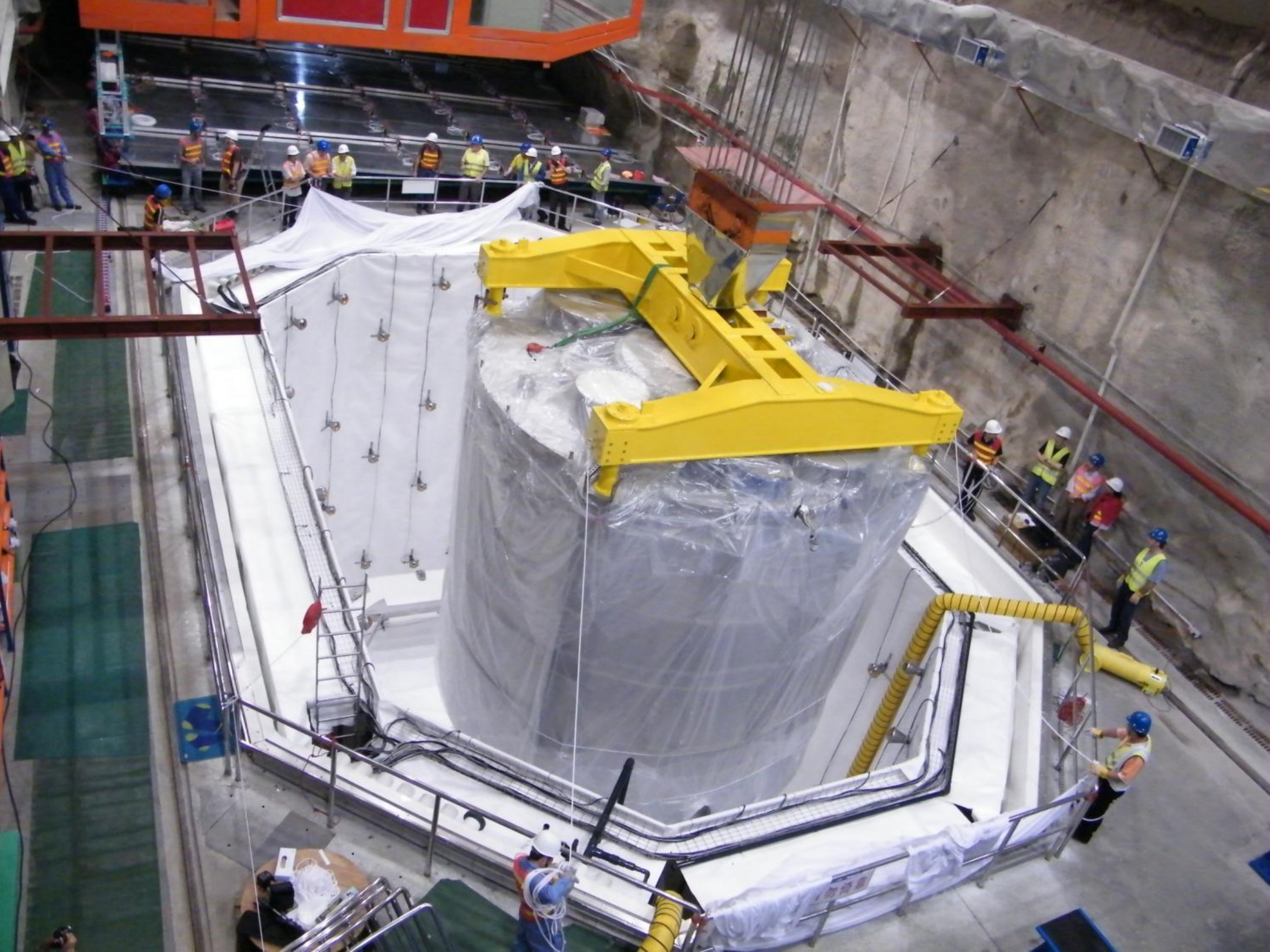
Improve the combined eff. to 99.5%

Muon Installation

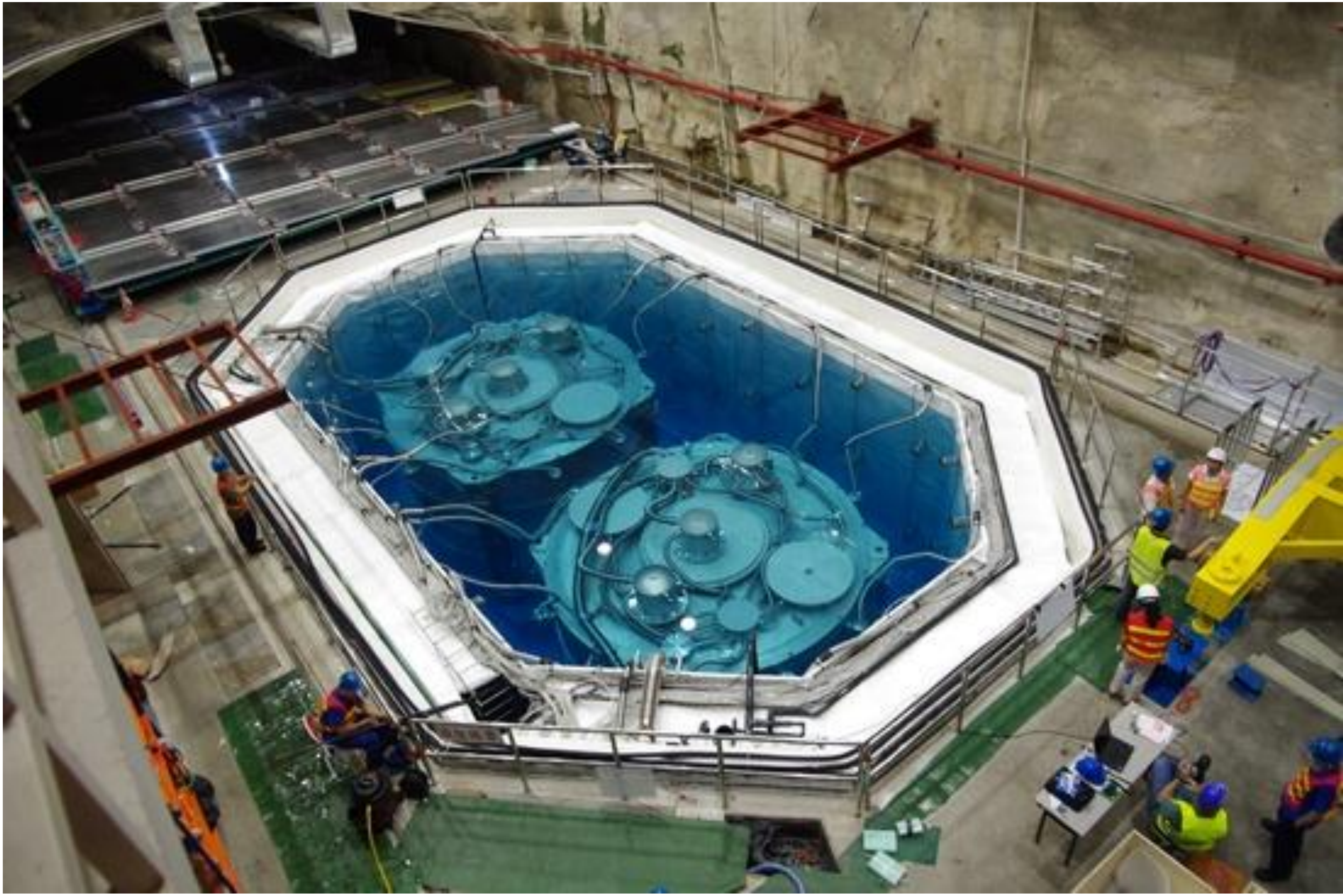


DYB Near Experimetnal Hall

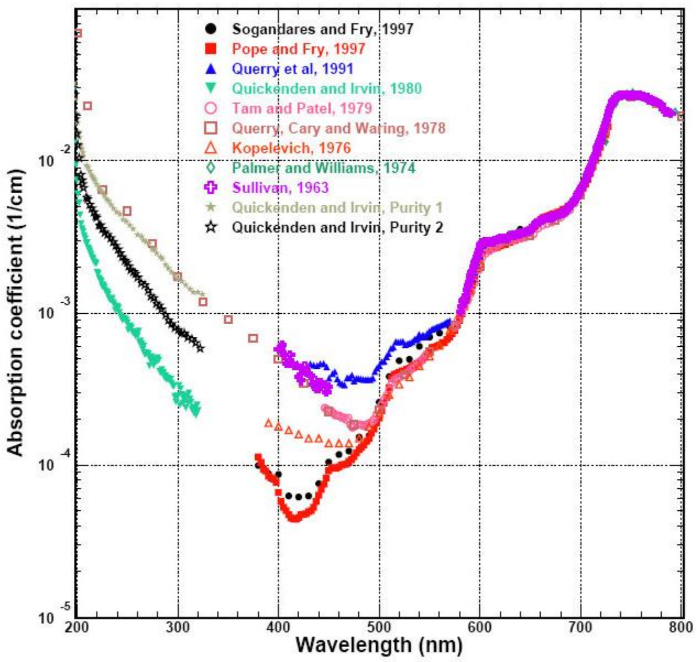




Filled Water Pool



Dark Blue Water



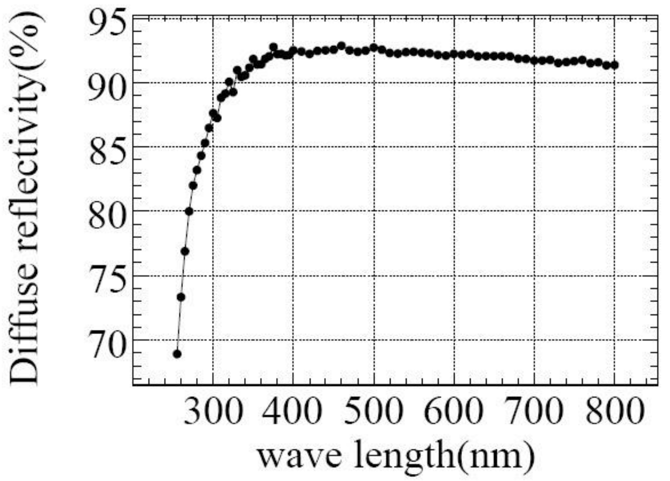
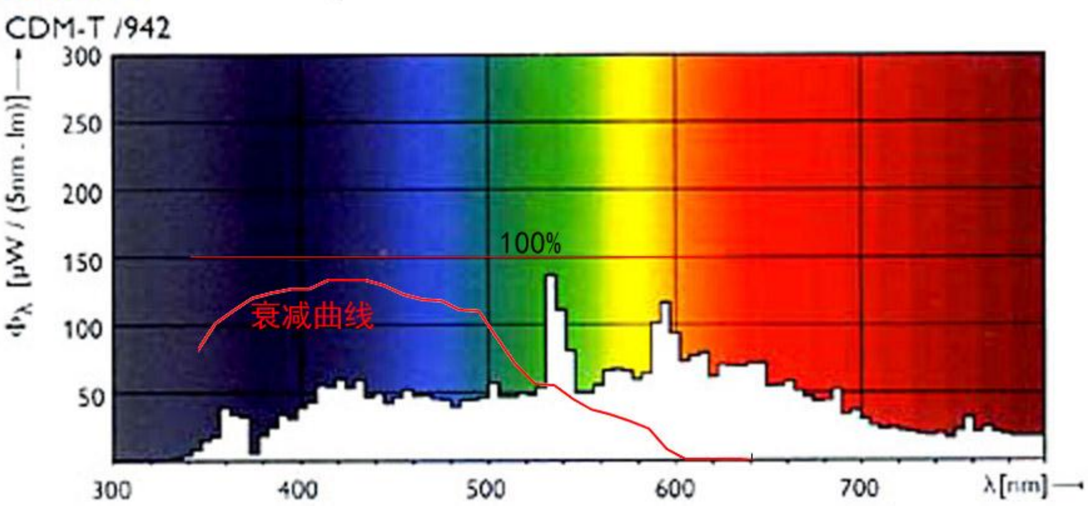


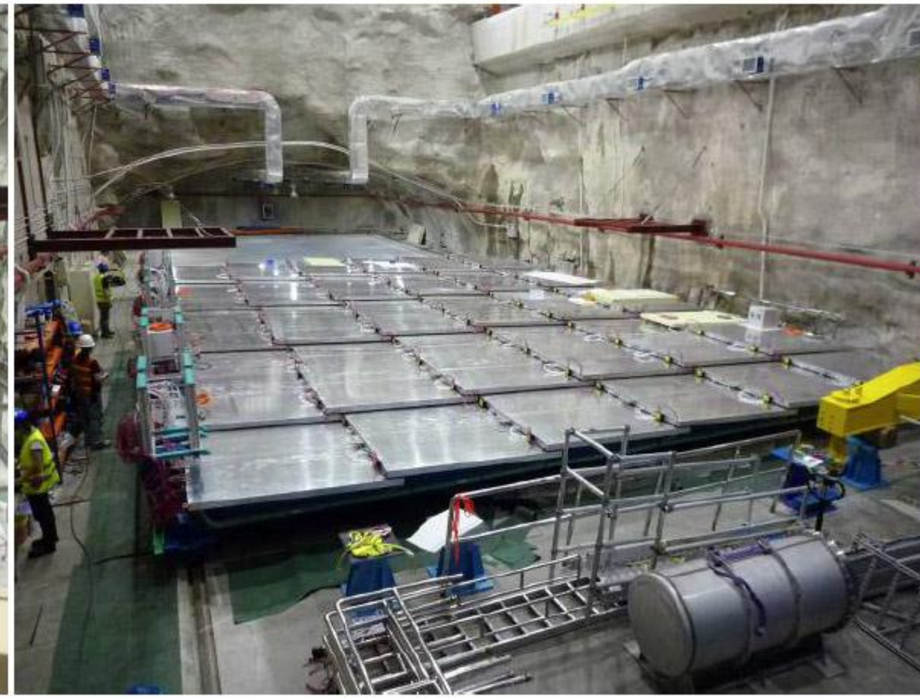
图 3.3: Tyvek反射率与光子波长之间的关系。

光谱功率分



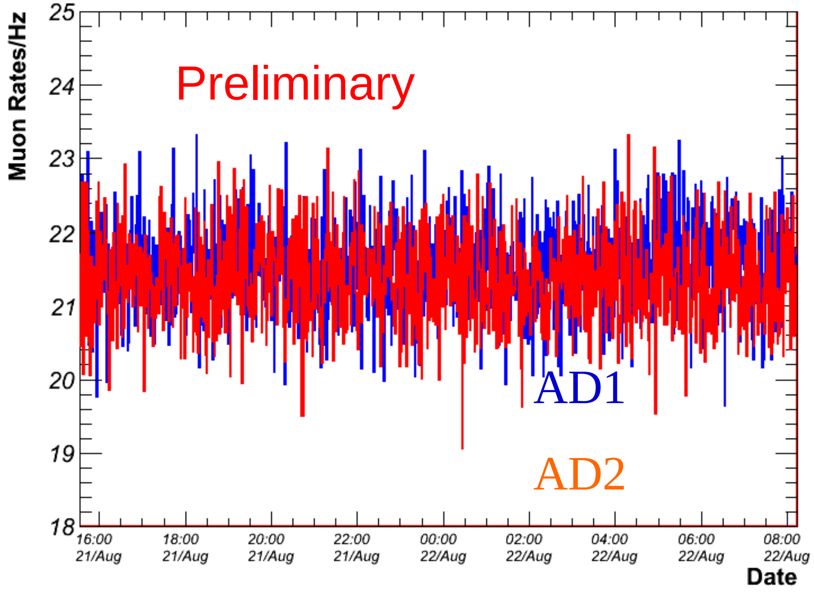
Data Taking on Aug.15, 2011

Filled pool cover on

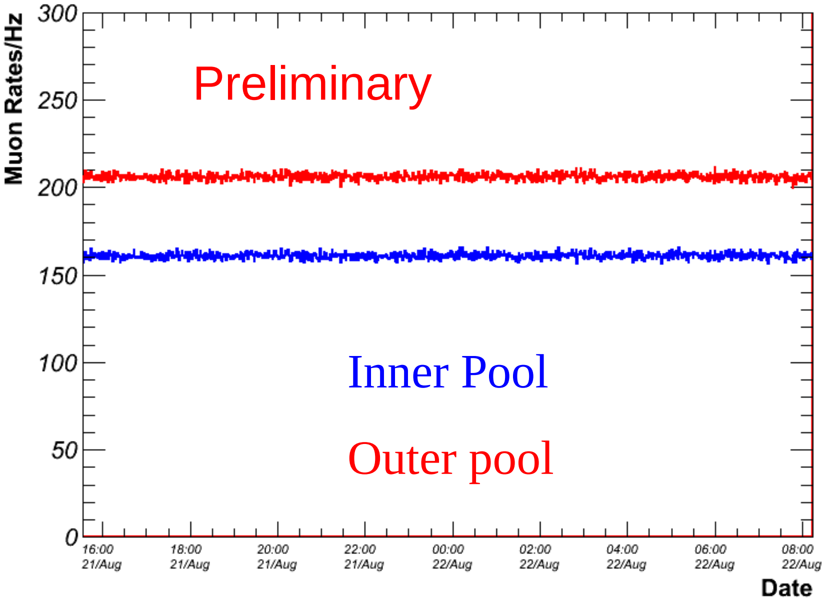


RPC on pool

Muon rates



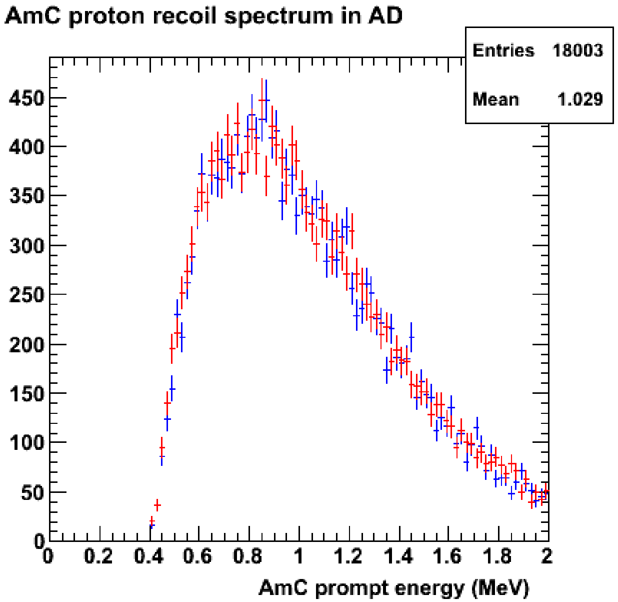
~16hours

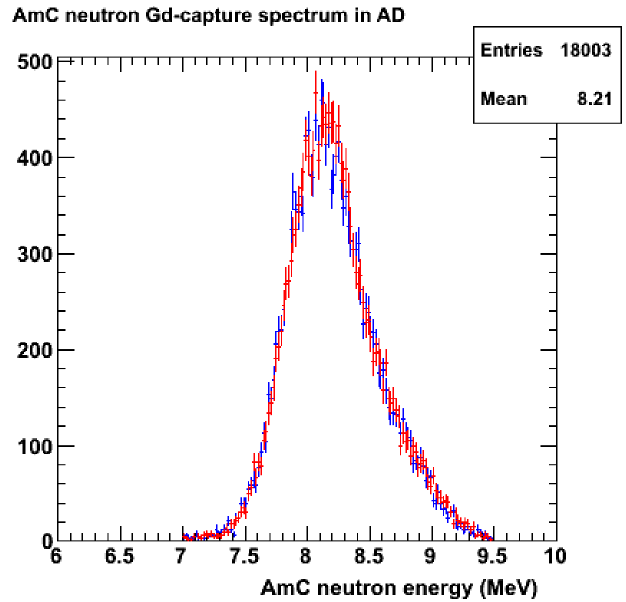


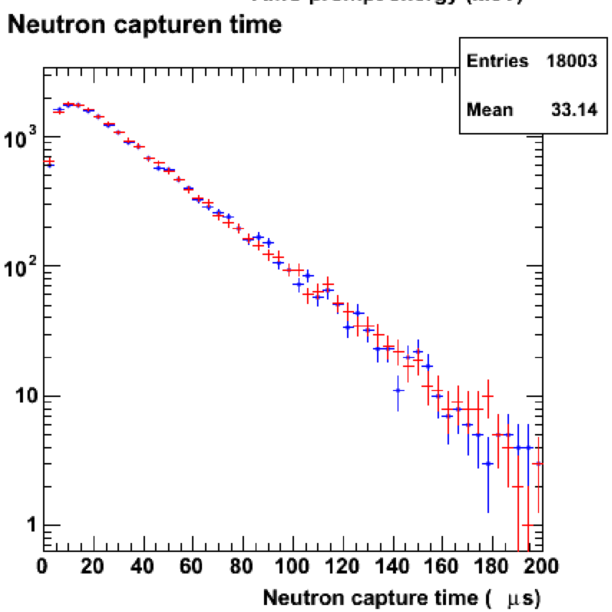
~16hours

They are stable and work as our expectation.

AD1/2 comparison







Am-C neutron source at AD center

neutron capture time:

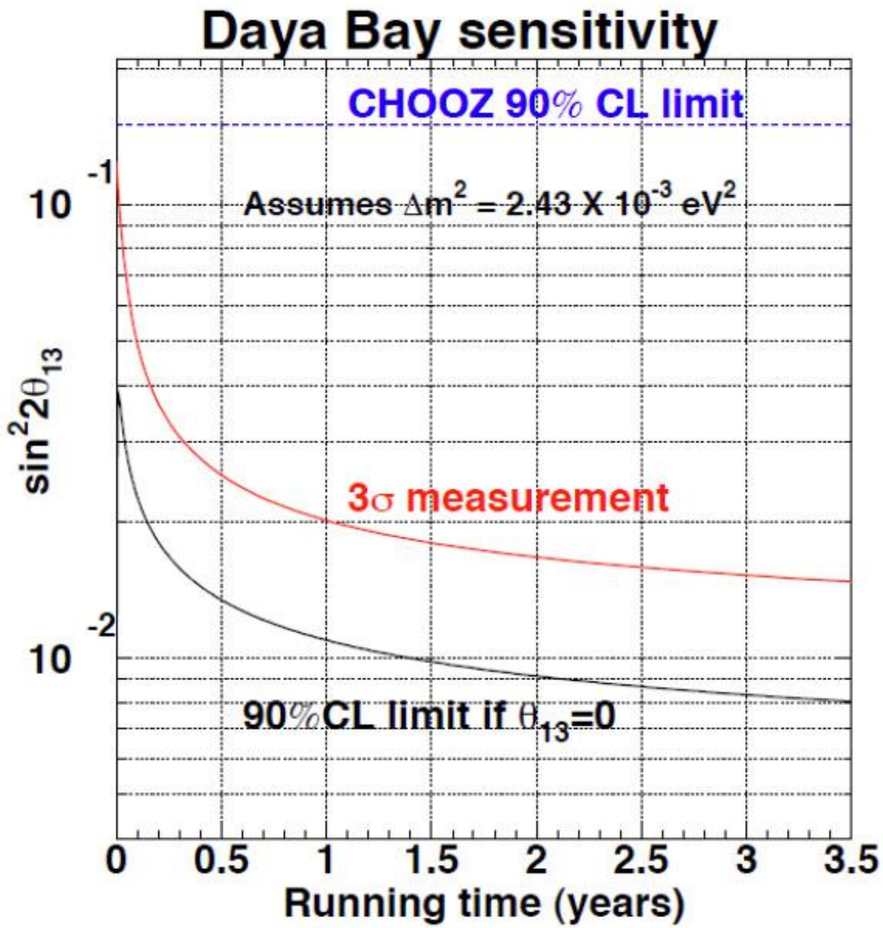
AD1 : 28.40 ±0.40 us

AD2 : 28.21 ±0.35 us

--> Same Gd concentration in 2 ADs

Schedule

- **Aug.15, 2011, Daya Bay Near Hall data taking**
- **Fall 2011, Ling Ao Near Hall ready for data**
- **Summer 2012, Full Operation with 8 ADs**



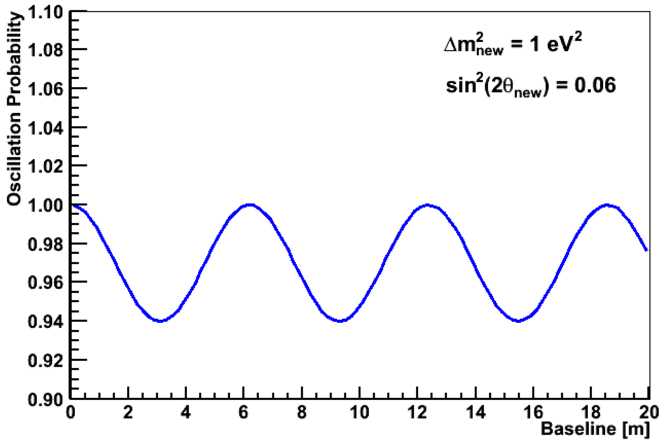
After Daya Bay

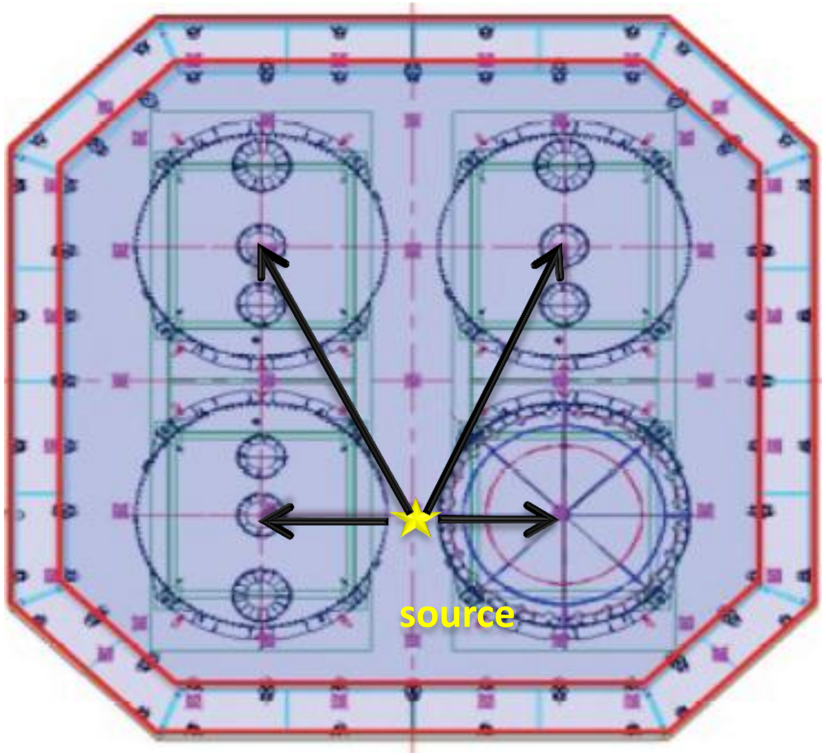
- Sterile ν at Daya Bay
- Daya Bay-II

Sterile Neutrino

- **LSND, MiniBooNE, Reactor Anomaly, Gallex Anomaly**
- **Good Physics Motivation**

- **Movable. Relative measurement.**



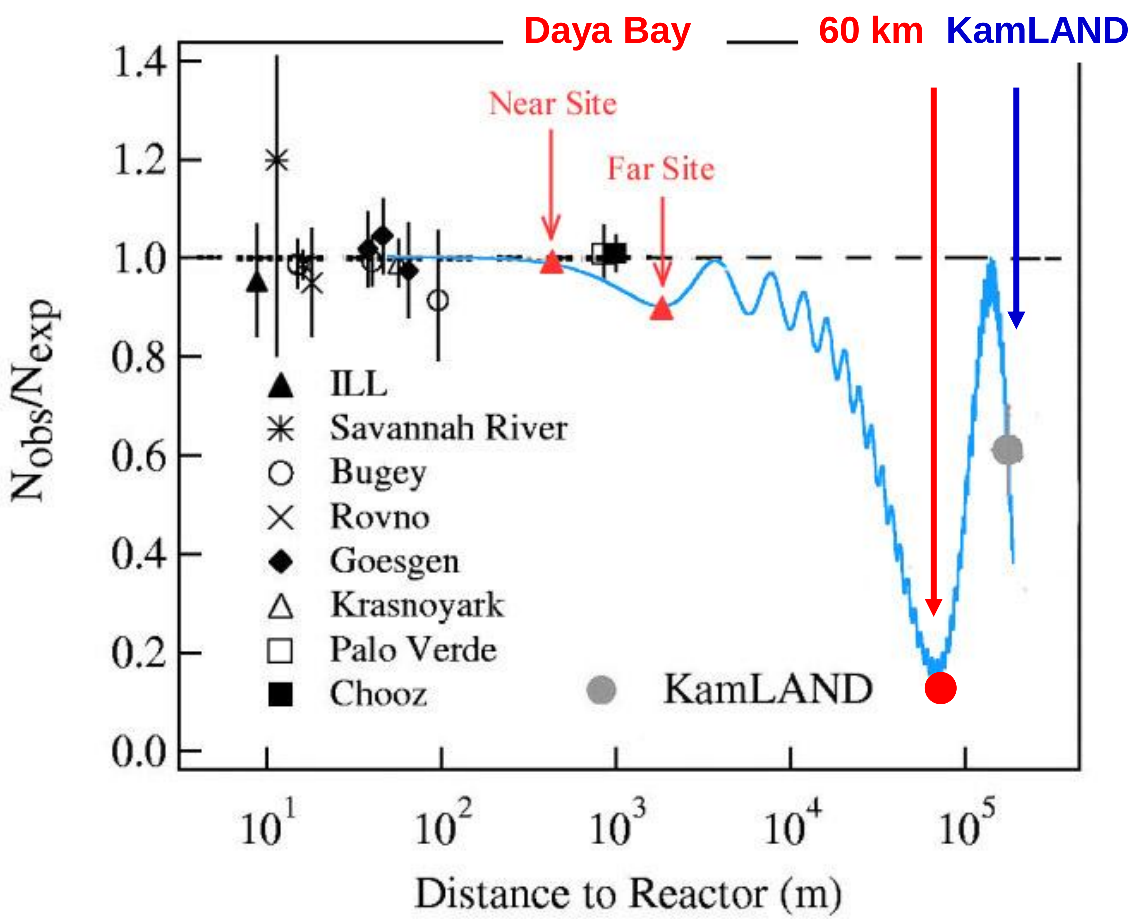


Strong Source

- EC Neutrino source
  - Mono-energetic **but low energy (<1 MeV)**
  - **Known experience. The GALLEX experiment made a 62PBq ^{51}Cr source for test.**
  - **ν-e scattering cross section is smaller than inverse β decay reaction.**
  - **Not easy to reject radioactive background for Daya Bay**
  - **Hundreds of events are expected with a ~100 PBq ^{51}Cr source (half life = 28 days) at Daya Bay far site.**
- Antineutrino source (preferred)
  - **Isotopes produced by spent reactor fuel**
  - **Background rejection is easier.**
  - **Re-use Daya Bay detector/electronics**
  - **100-200 events/day is expected with a ~10 PBq source.**

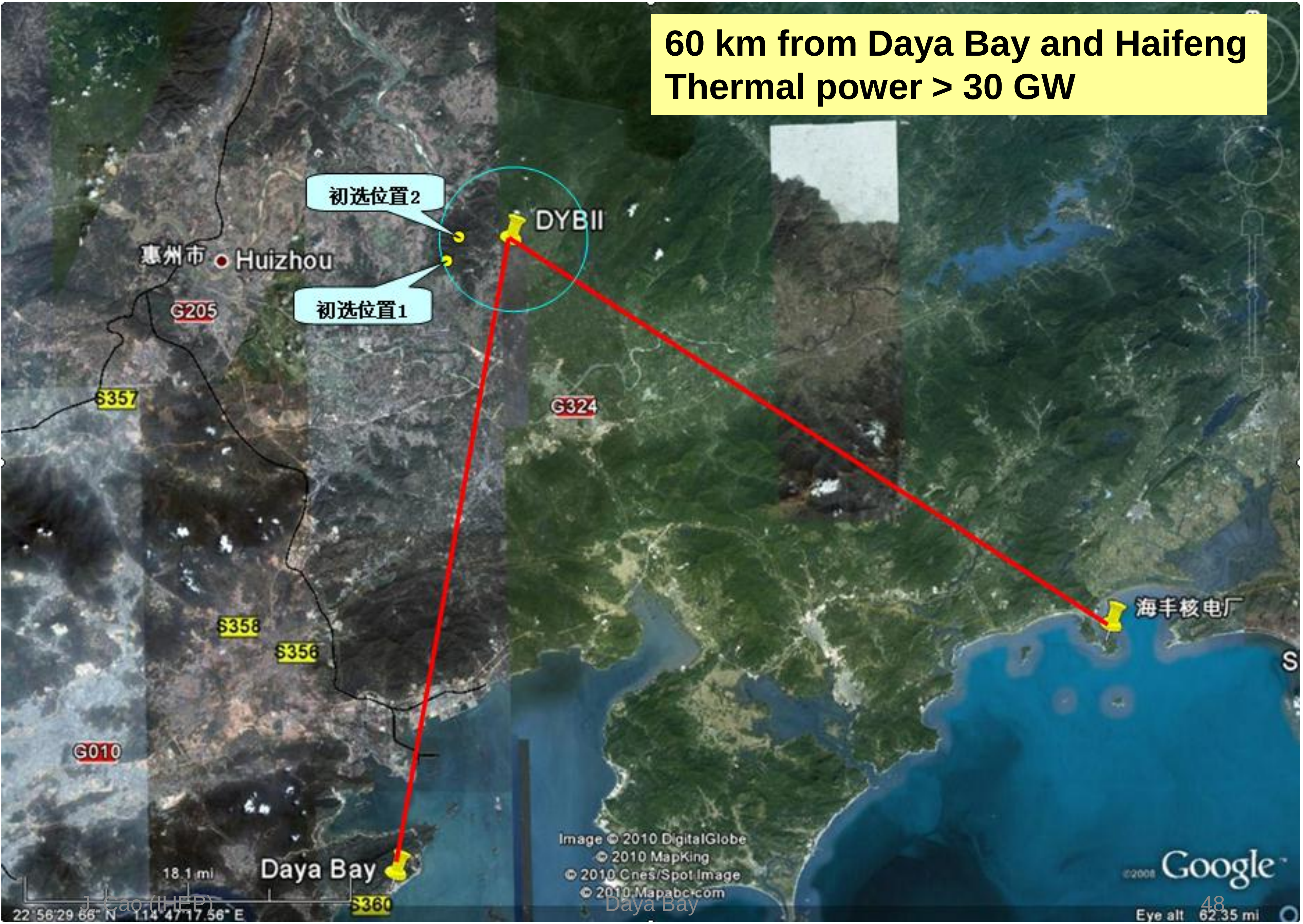
Daya Bay-II Experiment

Giant Detector located at 60 km from Daya Bay reactors, the 1st maximum of θ_{12} oscillation.



- 10-50 kton detector
- 2-3% energy resolution
- Rich physics possibilities
  - ⇨ Mass hierarchy
  - ⇨ Precision measurement of 4 mixing parameters
  - ⇨ Supernovae neutrino
  - ⇨ Geoneutrino
  - ⇨ Sterile neutrino
  - ⇨ Abnormal magnetic moment
  - ⇨ Discoveries with a high precision detector?

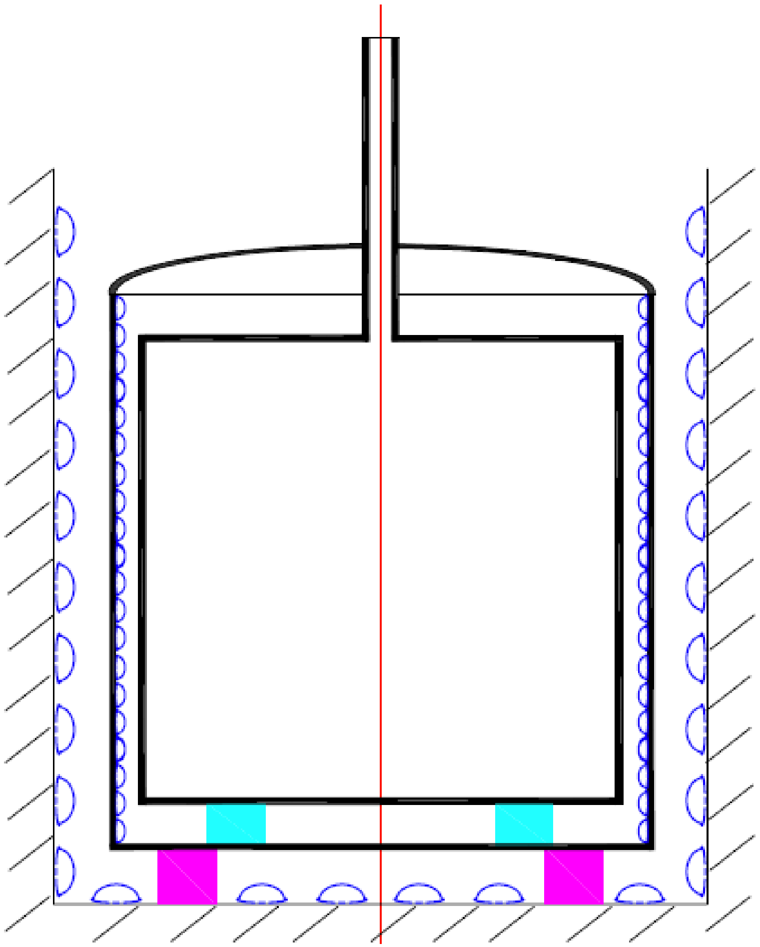
60 km from Daya Bay and Haifeng
Thermal power > 30 GW



Detector concept

- Neutrino target: ~20kt LS, LAB based

  30m(D)×30m(H)
- Oil buffer: 6kt
- Water buffer: 10kt
- PMT: 15000 20”
- Energy resolution: 2%/√E ➔ 2500 p.e./MeV



Thanks!