The Experimental Status of ϑ_{13} from the Point of View of the Reactor Neutrino Disappearance Experiments

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Daya Bay collaboration

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References

- Daya Bay
  - **F.P. An et al., Daya Bay Coll., " A side-by-side comparison of Daya Bay anti-neutrino detectors", Nucl. Inst. and Meth. A 685 (2012), pp. 78-97**
  - **F.P. An et al., Daya Bay Coll., "Observation of electron anti-neutrino disappearance at Daya Bay", Phys. Rev. Lett. 108, 171803 (2012)**
  - **D. Dwyer, Talk at Neutrino 2012, Kyoto, June 4, 2012**
- Double Chooz
  - **Y. Abe et al., Double Chooz Collaboration , "Indication for the disappearance of reactor electron antineutrinos in the Double Chooz experiment.", arXiv:1112.6353 [hep-ex], Phys.Rev.Lett. 108 (2012) 131801**
  - **M. Ishitsuka, Talk at Neutrino 2012, Kyoto, June 4, 2012**
- RENO
  - **J.K. Ahn et al., Reno Collaboration, "Observation of Reactor Electron Anti-Neutrino Disappearance in the RENO Experiment",
Phys.Rev.Lett. 108 (2012) 191802**
  - **Soo-Bong Kim, Talk at Neutrino 2012, Kyoto, June 4, 2012**

Neutrino flavor eigenstates $\left|\nu_f\right\rangle,\ f=e/\mu/\tau$ produced in weak Interactions are different from mass eigenstates $\left|\nu_i\right\rangle,\ i=1/2/3$

➔non-diagonal Unitary mixing matrix:

$$U_{fi}\equiv\left\langle\nu_f\middle|\nu_i\right\rangle\Rightarrow\left|\nu_f\right\rangle=\sum_{i=1}^{3}U^*_{fi}\left|\nu_i\right\rangle$$

Canonical representation of Pontecorvo-Magi-Nakagawa-Sakata mixing matrix is done by ordered product of 12, 13 and 23 rotations, one CP phase δ connected to the smallest mixing angle θ_{13} and two Majorana phases $\alpha_{1,2}$.

$\theta_{23}\cong 45^o$

$\theta_{13}\cong 9^o$

$$\begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{pmatrix}=\begin{pmatrix}1&0&0\\0&\cos(\theta_{23})&\sin(\theta_{23})\\0&-\sin(\theta_{23})&\cos(\theta_{23})\end{pmatrix}\cdot\begin{pmatrix}\cos(\theta_{13})&0&\sin(\theta_{13})\cdot e^{-i\delta}\\0&1&0\\-\sin(\theta_{13})\cdot e^{i\delta}&0&\cos(\theta_{13})\end{pmatrix}\cdot$$

$$\begin{pmatrix}\cos(\theta_{12})&\sin(\theta_{12})&0\\-\sin(\theta_{12})&\cos(\theta_{12})&0\\0&0&1\end{pmatrix}\begin{pmatrix}e^{i\alpha_1/2}&0&0\\0&e^{i\alpha_2/2}&0\\0&0&1\end{pmatrix}\cdot\begin{pmatrix}\nu_1\\ \nu_2\\ \nu_3\end{pmatrix}$$

$\theta_{12}\cong 34^o$

Majorana phases α are irrelevant for oscillations.

If masses of mass eigenstates are different then probabilities oscillate:

$$P_{\nu_f \to \nu_g}(L) = \delta_{fg}$$

$$-4\sum_{i<j} \Re\left(U_{gi}U^*_{fi}U_{fj}U^*_{gj}\right)\sin^2\left(\frac{m_j^2 - m_i^2}{4\hbar c}\frac{L}{E}\right)$$

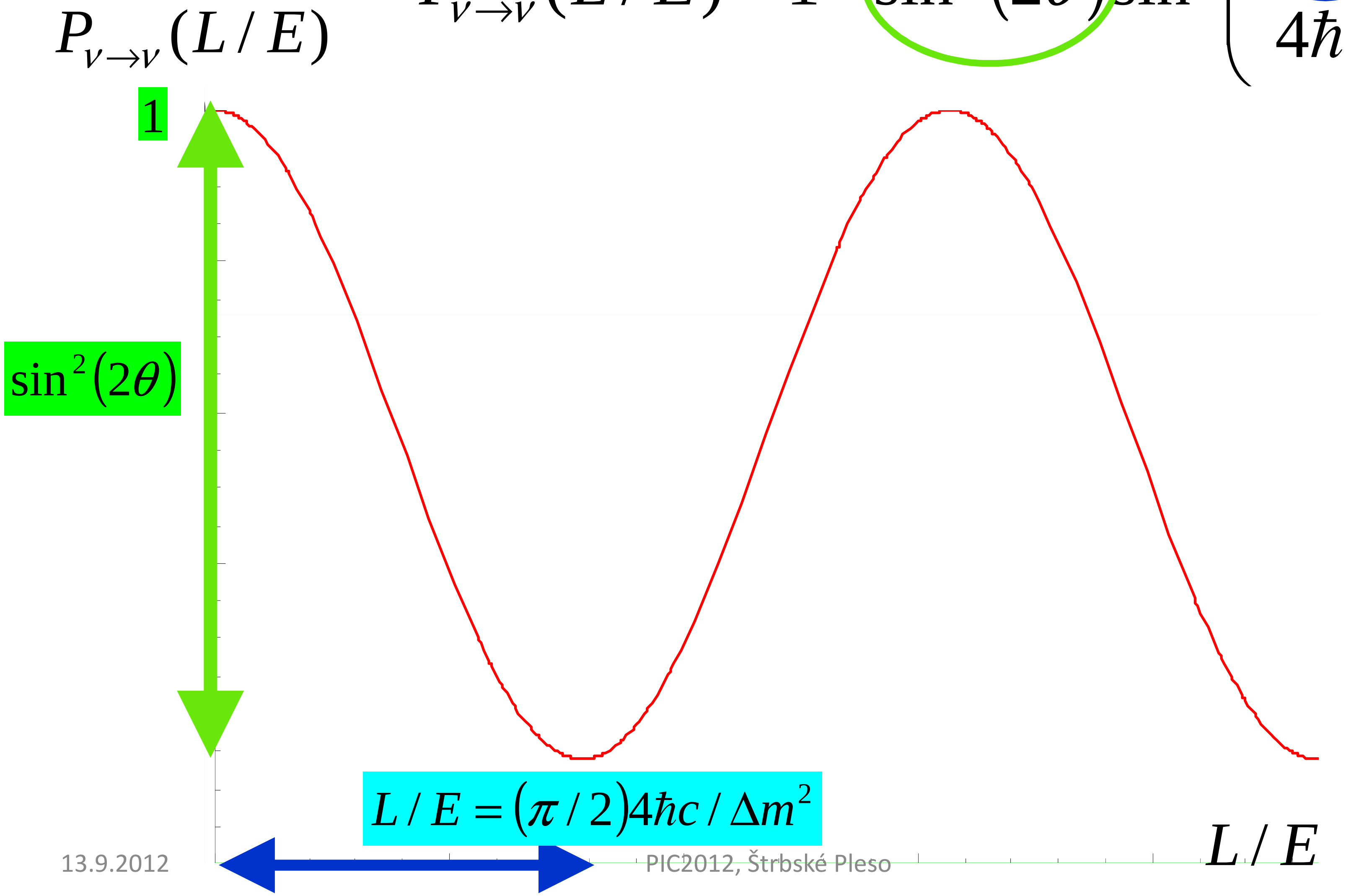
$$+2\sum_{i<j} \Im\left(U_{gi}U^*_{fi}U_{fj}U^*_{gj}\right)\sin\left(\frac{m_j^2 - m_i^2}{2\hbar c}\frac{L}{E}\right)$$

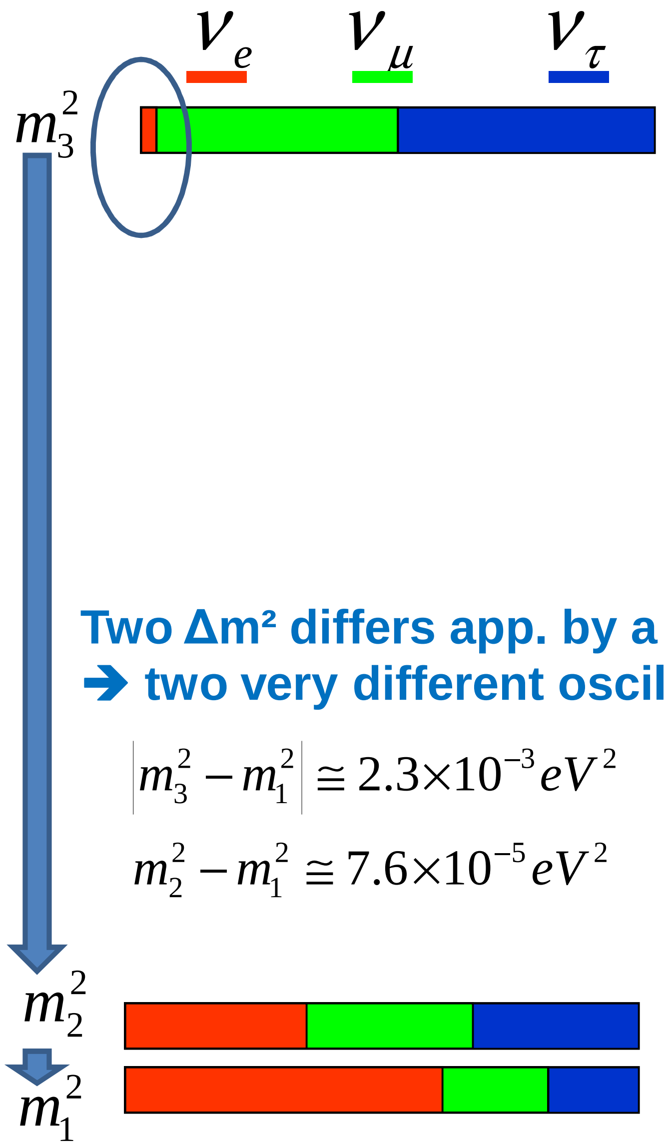
Last term is CP and T odd and it is ≠0 only if:

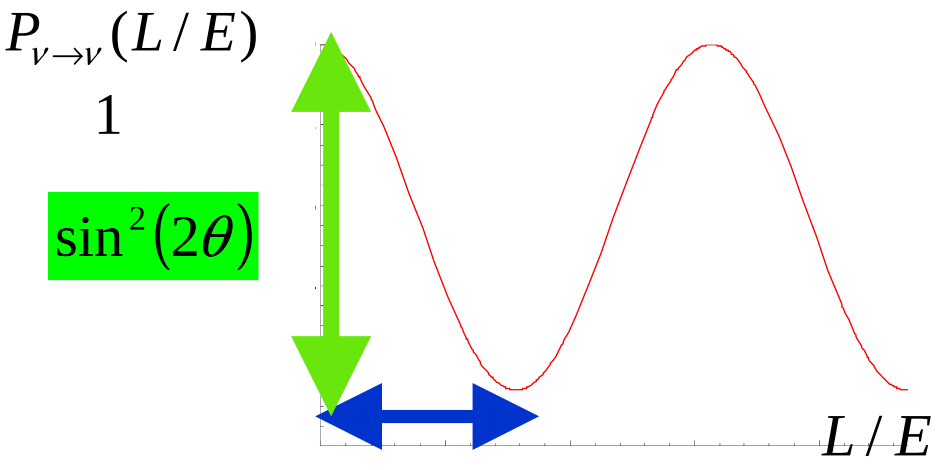
- f≠g
- all three mixing angles ≠0 and
- imaginary part of exp(i δ)=Sin(δ) ≠0

Amplitude of oscillations = sin²(2θ), oscillation length is inversely proportional to Δm²

$$P_{\nu\to\nu}(L/E) = 1 - \boxed{\sin^2(2\theta)}\sin^2\left(\frac{\boxed{\Delta m^2}}{4\hbar c}\frac{L}{E}\right)$$







$$(L/E)_{1stMINIMUM} = (\pi/2)4\hbar c/\Delta m^2$$

$$\approx 0.5\,km/MeV = 500\,km/GeV$$

$$\approx 15\,km/MeV = 15000\,km/GeV$$

Two Δm² differs app. by a factor of 30
➔ two very different oscillation lengths

$$\left|m_3^2 - m_1^2\right| \cong 2.3\times10^{-3}eV^2$$

$$m_2^2 - m_1^2 \cong 7.6\times10^{-5}eV^2$$

	0.5 km/MeV **500 km/GeV**	**15 km/MeV** **15000 km/GeV**
$\nu_e \to \nu_e$	**Daya Bay** **Double Chooz/RENO**	**reactor KAMLAND** **Sun ν_e (+matter efffect)**
$\nu_\mu \to \nu_\mu$	**atm.** **acc.**	

Disappearance probabilty

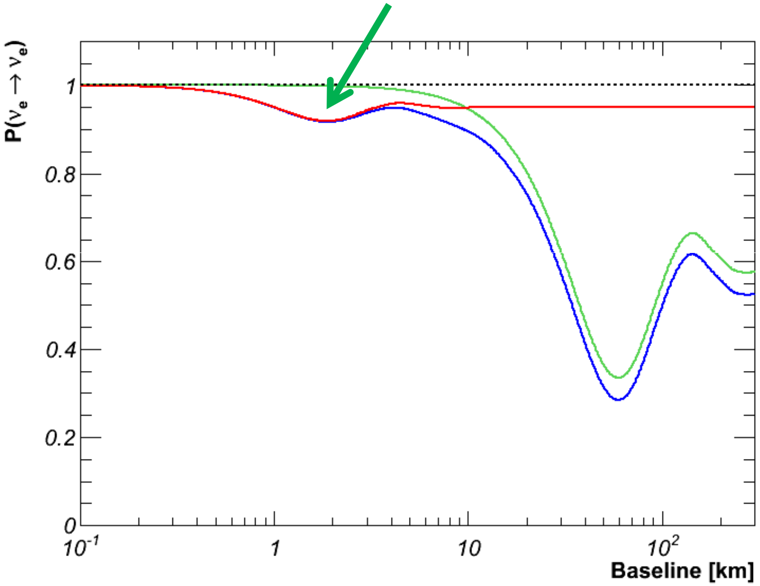
$$P_{\nu_f \to \nu_f}(x) = 1 - \sum_{i<j} 4\left|U_{fi}\right|^2 \left|U_{fj}\right|^2 \sin^2\left(1.267\Delta m_{ij}^2\left[eV^2\right]\frac{x[m]}{E[MeV]}\right)$$

Disappearance probabilty for electron (anti)neutrinos:

$$P_{\nu_e \to \nu_e}(x) \xrightarrow[\Delta m_{31}^2 \cong \Delta m_{32}^2]{}$$

$$1 - \sin^2(2\theta_{13})\sin^2\left(1.267\Delta m_{31}^2\left[eV^2\right]\frac{x[m]}{E[MeV]}\right)$$

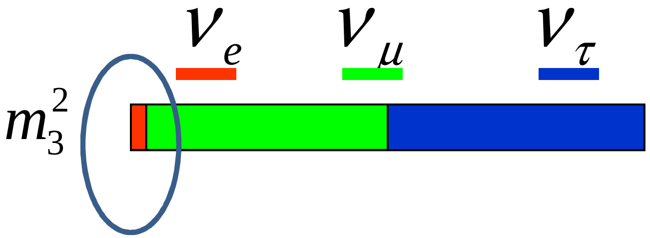
$$-\cos^4(\theta_{13})\sin^2(2\theta_{12})\sin^2\left(1.267\Delta m_{21}^2\left[eV^2\right]\frac{x[m]}{E[MeV]}\right)$$



For E=4 MeV the first minimum is at ~2 km

$$\boxed{P_{\nu_e \to \nu_e}(x) \cong 1 - \sin^2(2\theta_{13})\sin^2\left(1.267\Delta m_{31}^2\left[eV^2\right]\frac{x[m]}{E[MeV]}\right)}$$

Mixing angle θ13



$\sin^2(\theta_{13})$ is the fraction of electron neutrino in mass eigenstate m3

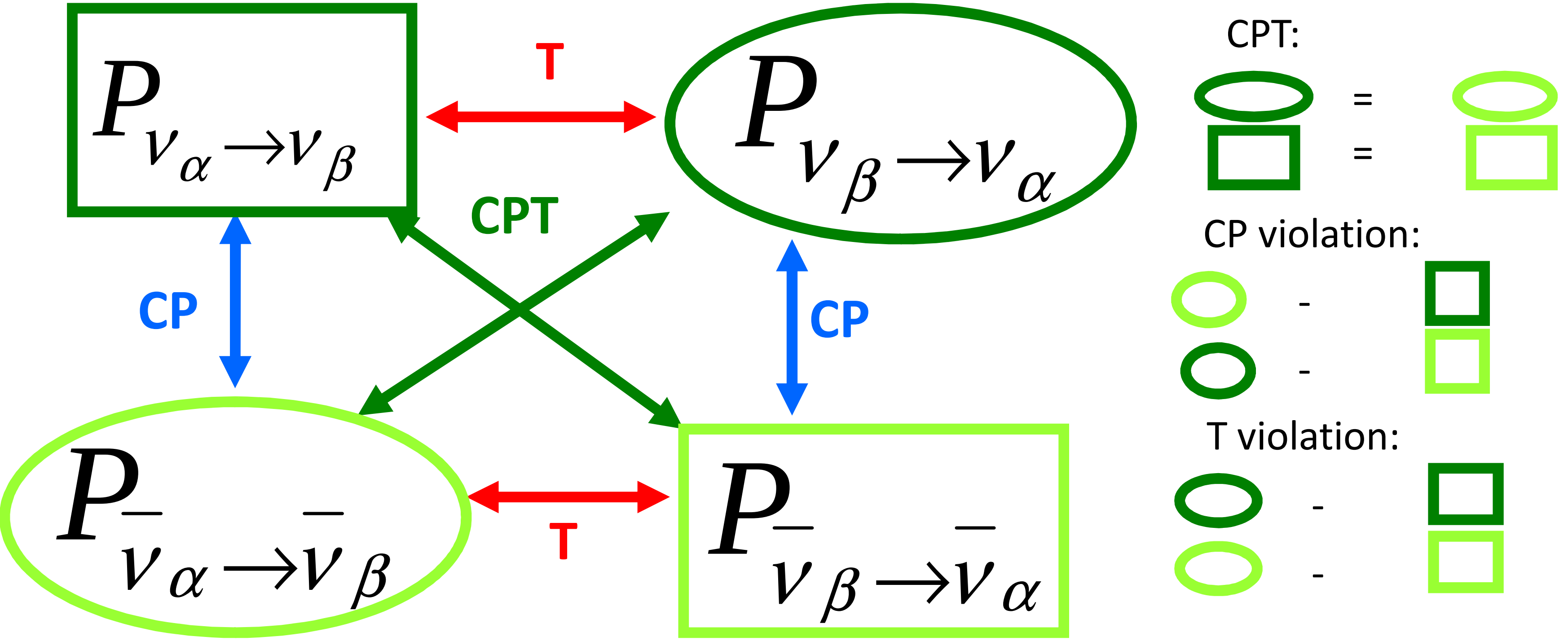
Two ways to measure θ13

-To measure electron (anti)neutrino disappearance

-To measure electron (anti)neutrino appearance in muon (anti)neutrino beam

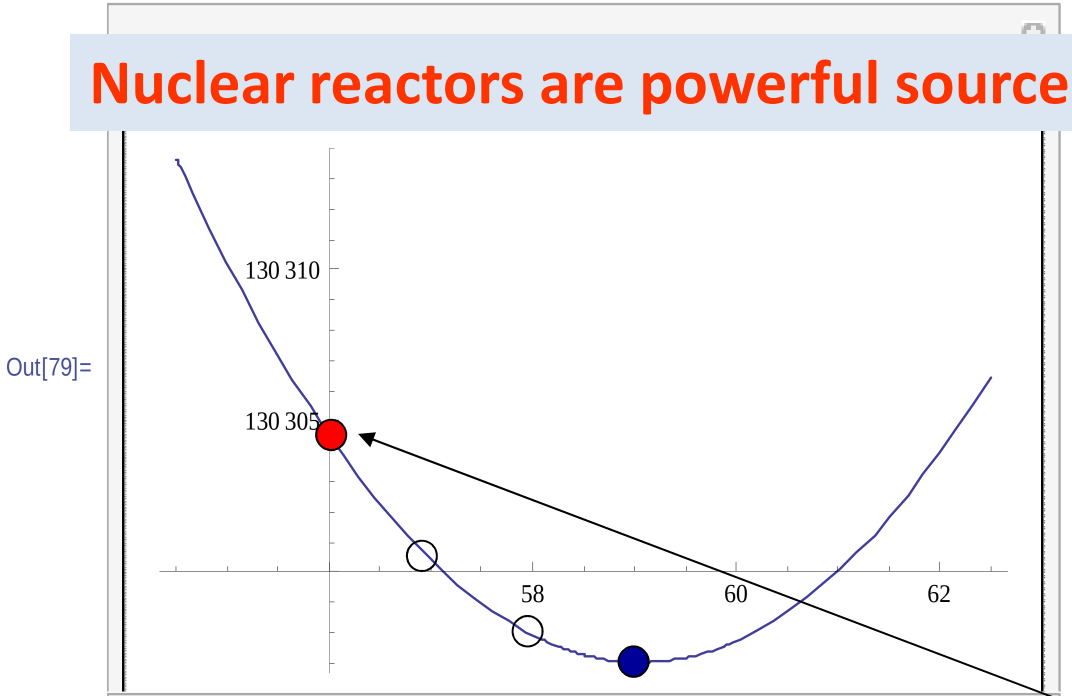
measurements has to be done at small values of L/E~0.5km/MeV = 500 km/GeV:

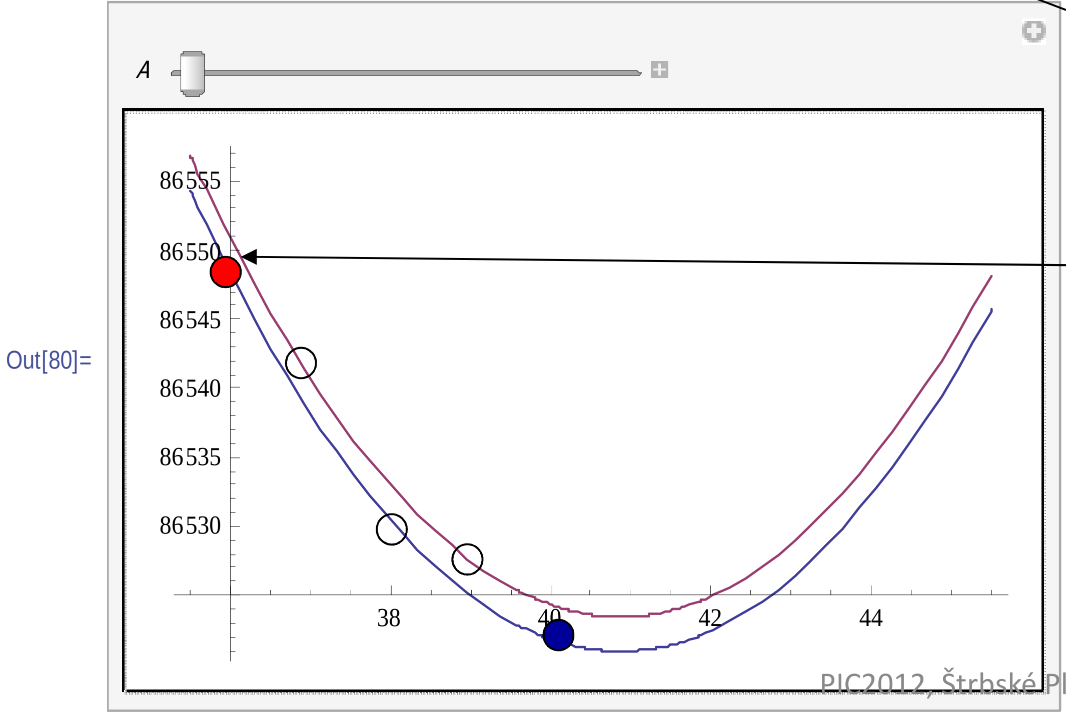
If $\theta_{13} \neq 0$ then CP and T violation in lepton sector could be investigated with neutrino oscillations



$$P_{\nu_\mu \to \nu_e} - P_{\bar{\nu}_\mu \to \bar{\nu}_e} = -2\sin(\delta)\cos(\theta_{13})\sin(2\theta_{13})\sin(2\theta_{12})\sin(2\theta_{23}) \times \sin\left(\frac{\Delta m_{12}^2}{4\hbar c}\frac{L}{E}\right)\sin\left(\frac{\Delta m_{31}^2}{4\hbar c}\frac{L}{E}\right)\sin\left(\frac{\Delta m_{23}^2}{4\hbar c}\frac{L}{E}\right)$$

Nuclear reactors are powerful sources of electron antineutrinos





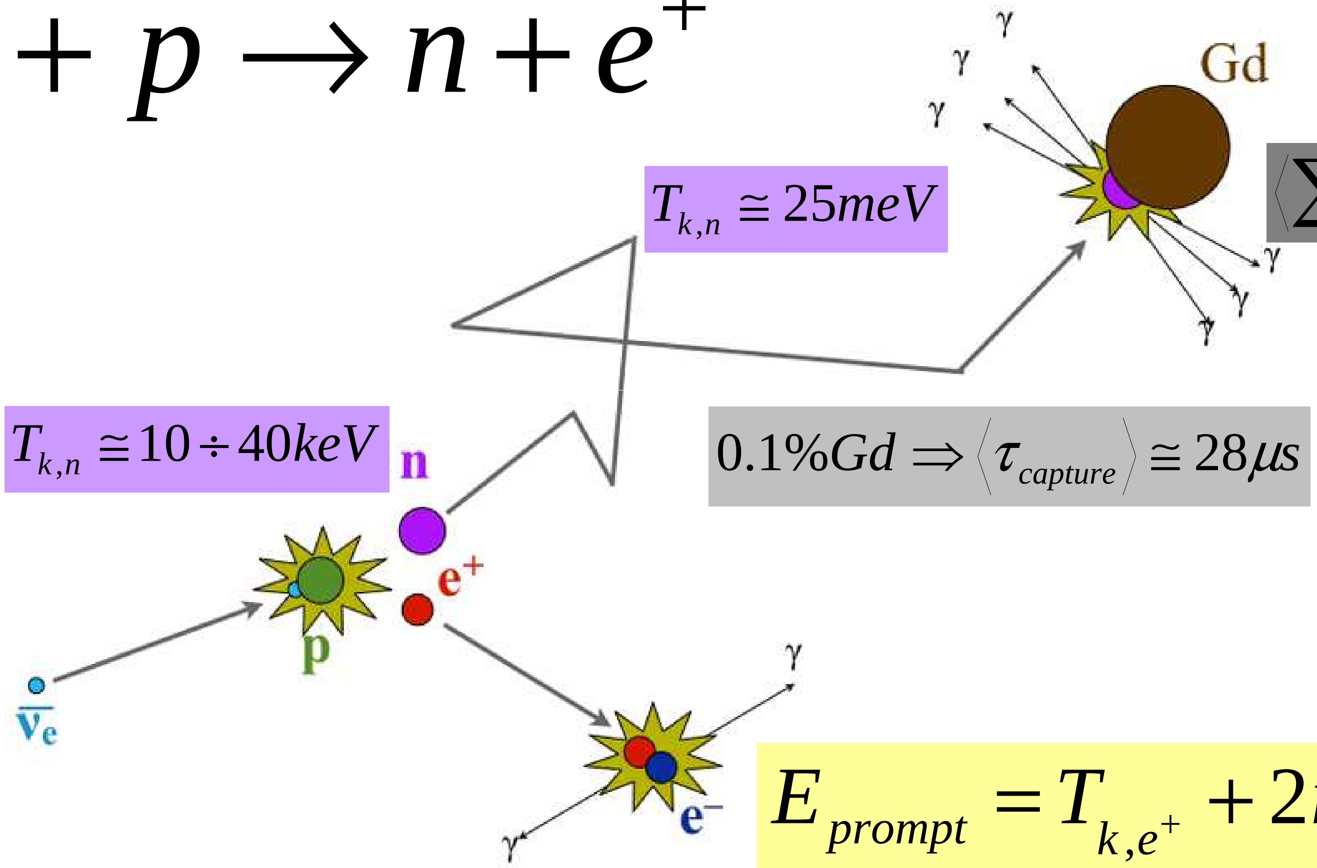
Fission products are neutron rich.
The valley of stability is reached by series of beta- decays.
In average app. **6 electron antineutrinos** are produced per fission.

$${}^{1}_{0}n+{}^{235}_{92}U\rightarrow{}^{139}_{56}Ba+{}^{94}_{36}Kr+3\,{}^{1}_{0}n$$

$$2\cdot 10^{20}\,\overline{\nu}_{e}/s/GW_{th}$$

Detection of antineutrinos via Inverse Beta Decay (IBD). Coincidence of prompt signal from positron and delayed signal of neutron capture on Gd.

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



$T_{k,n} \cong 25 meV$

$\left\langle \sum E_\gamma \right\rangle = 8.05 MeV$

$T_{k,n} \cong 10 \div 40 keV$

$0.1\% Gd \Rightarrow \left\langle \tau_{capture} \right\rangle \cong 28 \mu s$

$$E_{prompt} = T_{k,e^+} + 2m_e$$

$$E_\nu \cong E_{prompt} + 0.8 MeV$$

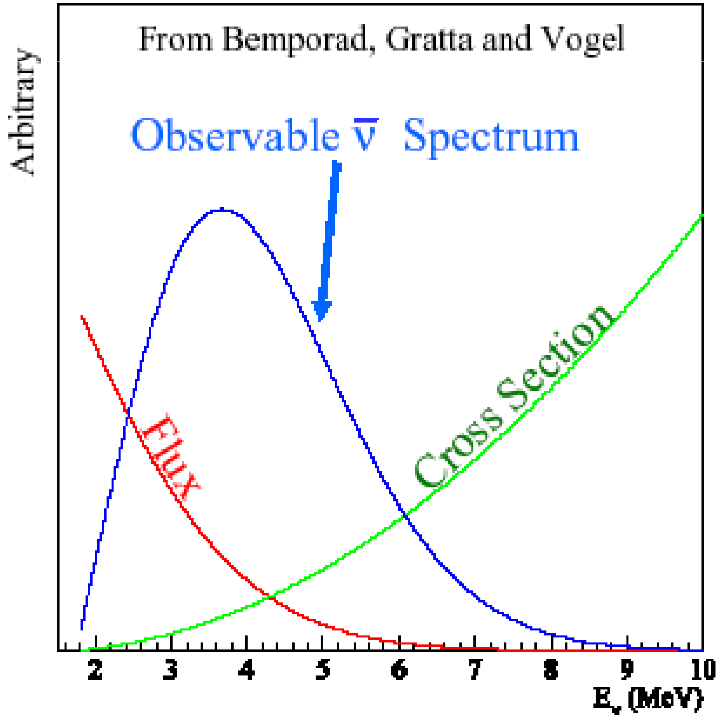
Detection of antineutrinos: Inverse Beta Decay (IBD)

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

$$E_{\nu,THR} = \frac{(m_n + m_e)^2 - m_p^2}{2m_p} = \frac{m_n + m_p + m_e}{2m_p}(m_n - m_p + m_e)$$
$$= 1.00096(m_n - m_p + m_e) = 1.83 MeV$$

Only antineutrinos with energies larger than 1.8 MeV interact.

Detected energy spectrum is the product of reactor neutrino spectrum and IBD cross section and it reaches the maximum around 4 MeV → the first oscillation minimum is at 0.5 km/MeV→2 km for 4MeV



Neutron capture on Gadollinium

$$n + {}^{A}_{64}Gd \to {}^{A+1}_{64}Gd^{*} \to {}^{A+1}_{64}Gd + E_{\gamma}$$

${}^{A}_{64}$Gd	$\sigma_{n+{}^{A}_{64}Gd \to {}^{A+1}_{64}Gd^{*}}$ [b]	**Abund.[%]**	**B[MeV/A]**
$A = 152\ \left(\xrightarrow{\alpha} {}^{148}_{62}Sm\right)$	735	0.20	8.233399
$A = 154$	85	2.18	8.224794
$A = 155$	60900	14.80	8.213248
$A = 156$	1.8	20.47	8.215320
$A = 157$	254000	15.65	8.203501
$A = 158$	2.2	24.84	8.201817
$A = 160\ \left(\xrightarrow{2\beta} {}^{160}_{66}Dy\right)$	1.4	21.86	8.183010

$$\sum E_{\gamma}\left(n + {}^{155}_{64}Gd\right) = 8.536 MeV$$

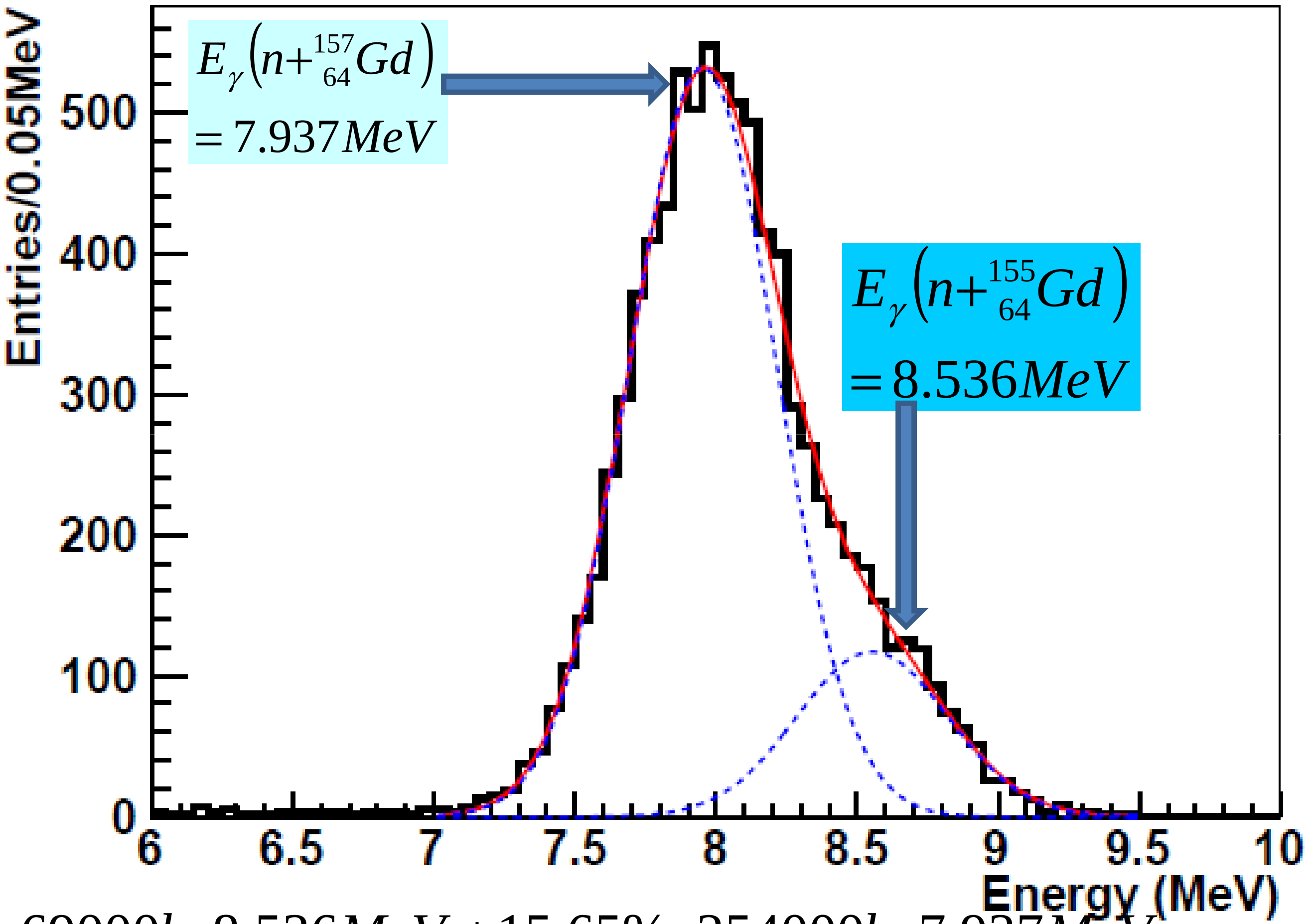
$$\sum E_{\gamma}\left(n + {}^{157}_{64}Gd\right) = 7.937 MeV$$

$$\left\langle E_{\gamma} \right\rangle = 8.048 MeV$$

^{241}Am-^{13}C
Daya Bay

$$^{241}_{95}Am \xrightarrow{432 mil.years} \alpha + ^{237}_{93}Np$$

$$\alpha + ^{13}_{6}C \rightarrow ^{16}_{8}O + n$$



$$\left\langle E_\gamma \right\rangle = \frac{14.80\% \cdot 69000b \cdot 8.536MeV + 15.65\% \cdot 254000b \cdot 7.937MeV}{14.80\% \cdot 69000b + 15.65\% \cdot 254000b} = 8.048 MeV$$

Three runing experiments

Experiment	Power (GW)	Baseline(m) Near/Far	Detector(t) Near/Far	Overburden (MWE) Near/Far	Design sensitivity (90%CL)
Double Chooz	8.5	400/1050	~ /8.2 (8.2/8.2)	120/300	~ 0.03
Daya Bay	17.4	470, 576/1650	40, 20/60 (40, 40/80)	250, 265/860	~ 0.008
RENO	16.5	409/1444	16/16	120/450	~ 0.02

The experiments are constructed following the concept of two identical near/far detecors proposed by:
L.Mikaelyan and V.V.Sinev [Phys.Atom.Nucl.63:1002-1006,2000; Yad.Fiz.63N6:1077-1081,2000]

Daya Bay, China

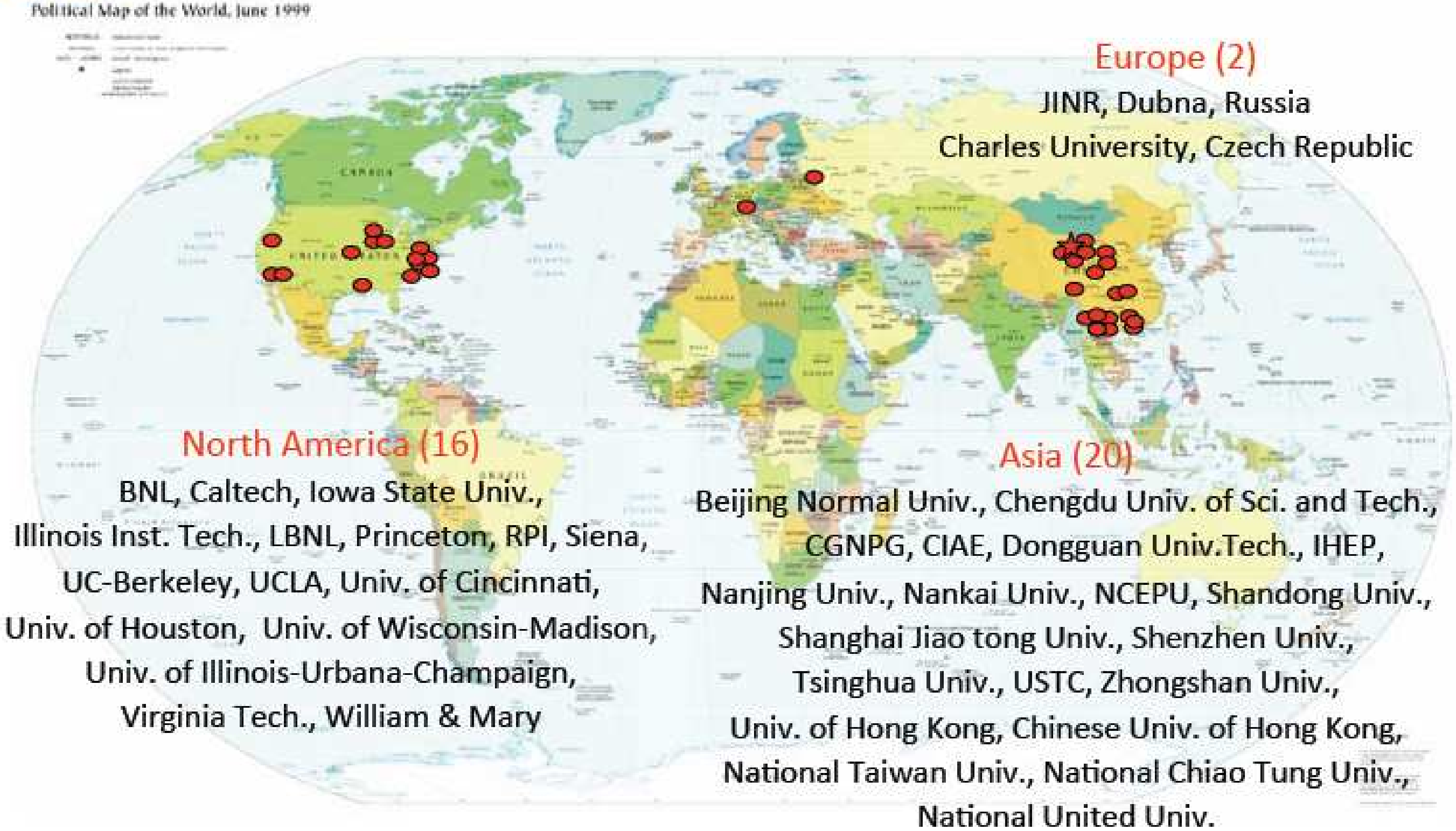
6 reactors:
17.4 GW total
(thermal) power

A total of eight functionally identical and moveable detectors in three detector halls.

6 of the 8 detectors have been taking physics data since Dec. 2012

The remaining two detectors will be installed and commissioned this year.

The Daya Bay Collaboration



Europe (2)

JINR, Dubna, Russia

Charles University, Czech Republic

North America (16)

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

Asia (20)

Beijing Normal Univ., Chengdu Univ. of Sci. and Tech.,
CGNPG, CIAE, Dongguan Univ.Tech., IHEP,
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.

~230 Collaborators

Double Chooz, France

Double Chooz collaboration

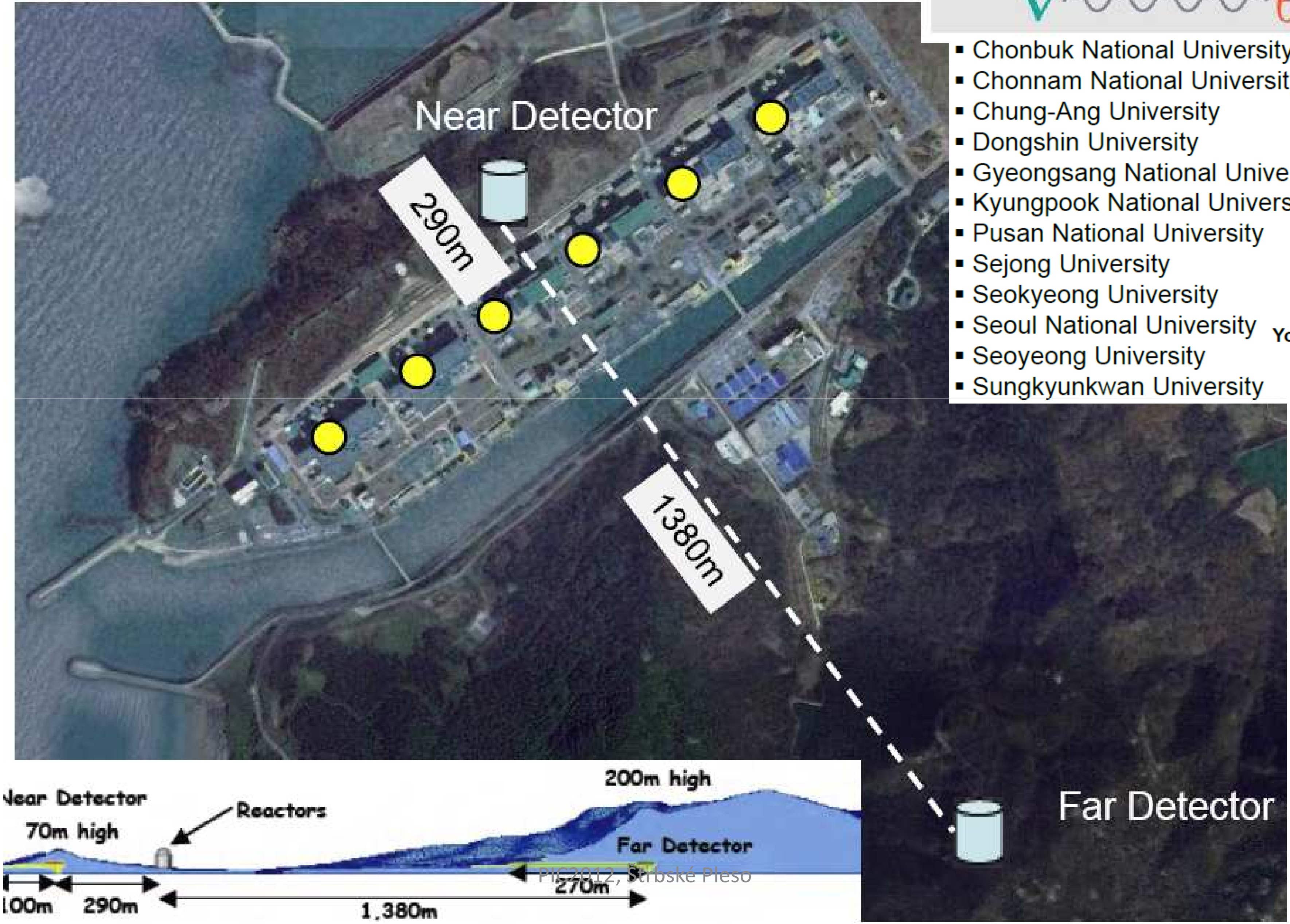
Brazil	France	Germany	Japan	Russia	Spain	USA
CBPF	**APC**	**EKU Tübingen**	**Tohoku U.**	**INR RAS**	**CIEMAT-Madrid**	**U. Alabama**
UNICAMP	**CEA/DSM/IRFU:**	**MPIK Heidelberg**	**Tokyo Inst. Tech.**	**IPC RAS**		**ANL**
UFABC	**SPP**	**RWTH Aachen**	**Tokyo Metro. U.**	**RRC Kurchatov**		**U. Chicago**
	SPhN	**TU München**	**Niigata U.**			**Columbia U.**
	SEDI	**U. Hamburg**	**Kobe U.**			**UCDavis**
	SIS		**Tohoku Gakuin U.**			**Drexel U.**
	SENAC		**Hiroshima Inst. Tech.**			**IIT**
	CNRS/IN2P3:					**KSU**
	Subatech					**LLNL**
	IPHC					**MIT**
						U. Notre Dame
						U. Tennessee

Chooz Reactors
4.27GW$_{th}$ x 2 cores

Near Detector
L = 400m
10m^3 target
120m.w.e.
2013 ~

Far Detector
L = 1050m
10m^3 target
300m.w.e.
April 2011 ~

RENO, South Korea



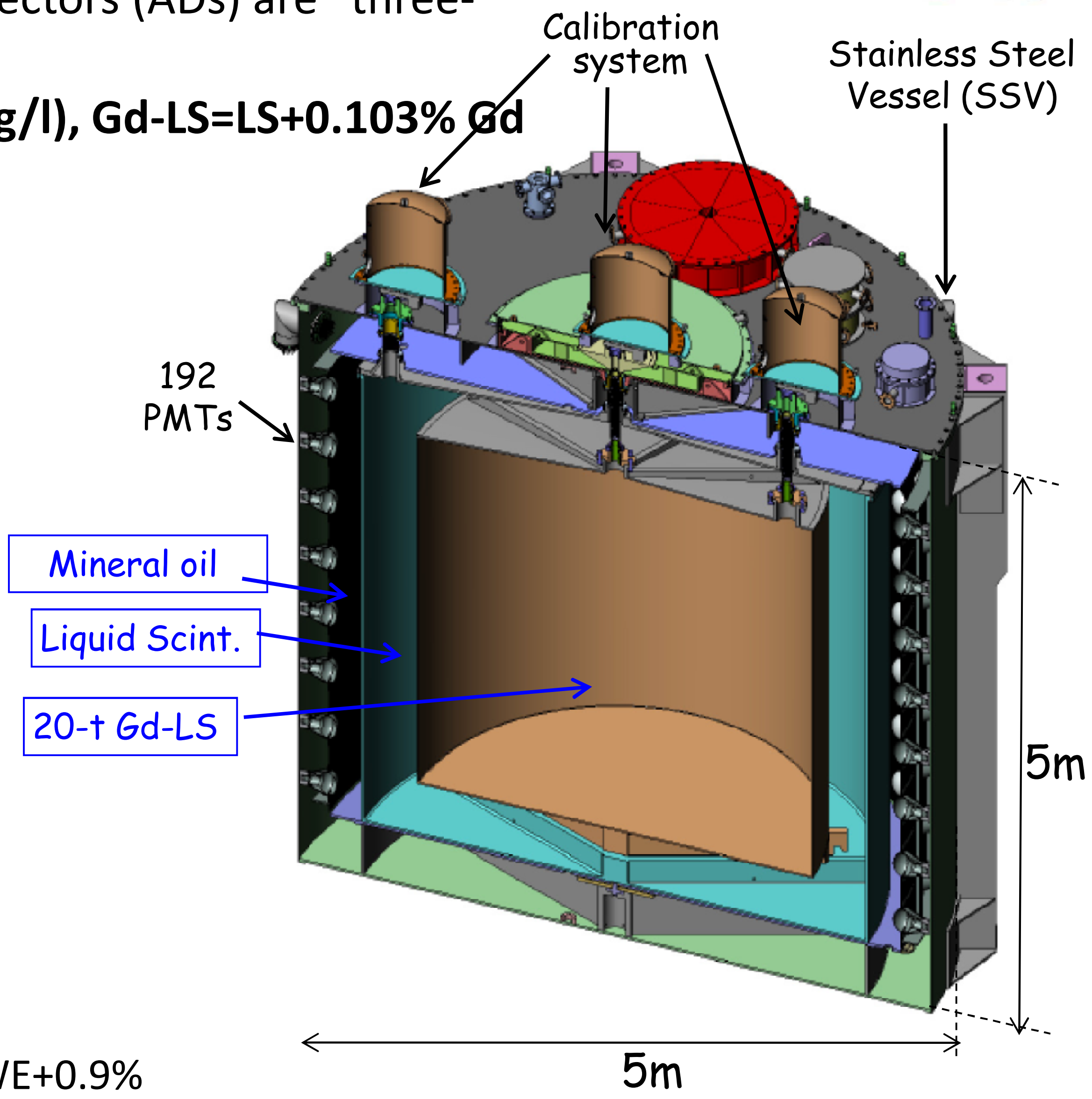
- Chonbuk National University
- Chonnam National University
- Chung-Ang University
- Dongshin University
- Gyeongsang National University
- Kyungpook National University
- Pusan National University
- Sejong University
- Seokyeong University
- Seoul National University
- Seoyeong University
- Sungkyunkwan University

Anti-neutrino detectors

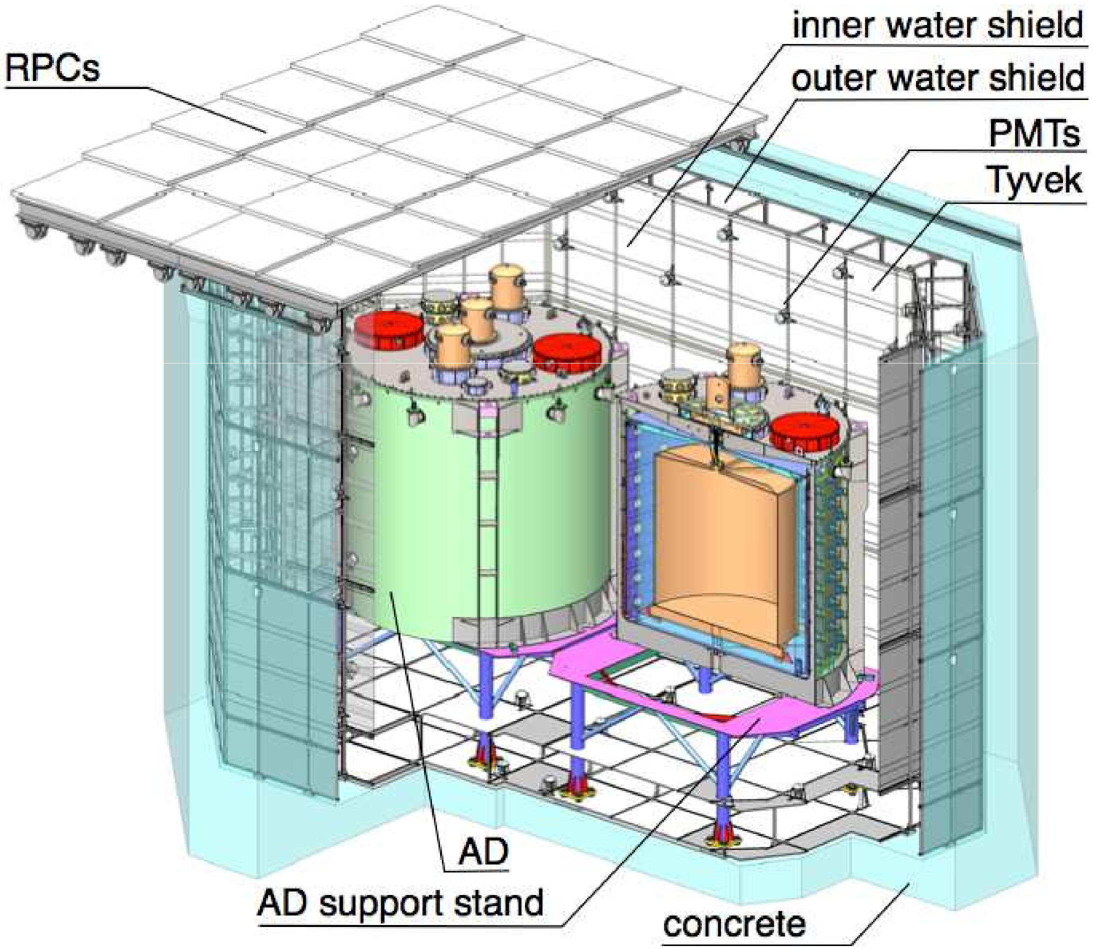
- The Daya Bay anti-neutrino detectors (ADs) are “three-zone” cylindrical modules.
- **LS=LAB+PPO(3 g/l)+MSB(15 mg/l), Gd-LS=LS+0.103% Gd**
  - Zones are separated by acrylic vessels:

Zone	Mass	Liquid	Purpose
Inner acrylic vessel	20 t	Gd-doped liquid scintillator	**Anti-neutrino target**
Outer acrylic vessel	20 t	Liquid scintillator	Gamma catcher (from target zone)
Stainless steel vessel	40 t	Mineral Oil	Radiation shielding

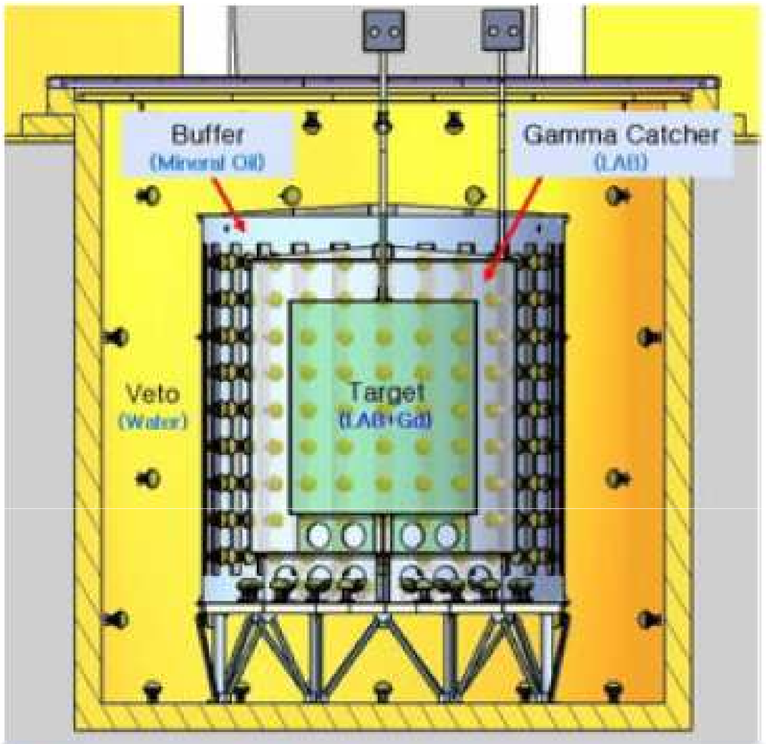
  - Top and bottom reflectors are used to increase light yield
  - Energy resolution: $\sigma_E/E = 7.5\%/\sqrt{E}+0.9\%$



- Outer layer of water Čerenkov detector (on sides and bottom) is 1m thick, inner layer >1.5m. Water extends 2.5m above ADs
    - 288 8” PMTs in each near hall
    - 384 8” PMTs in Far Hall
- 4-layer RPC modules above pool
    - 54 modules in each near hall
    - 81 modules in Far Hall

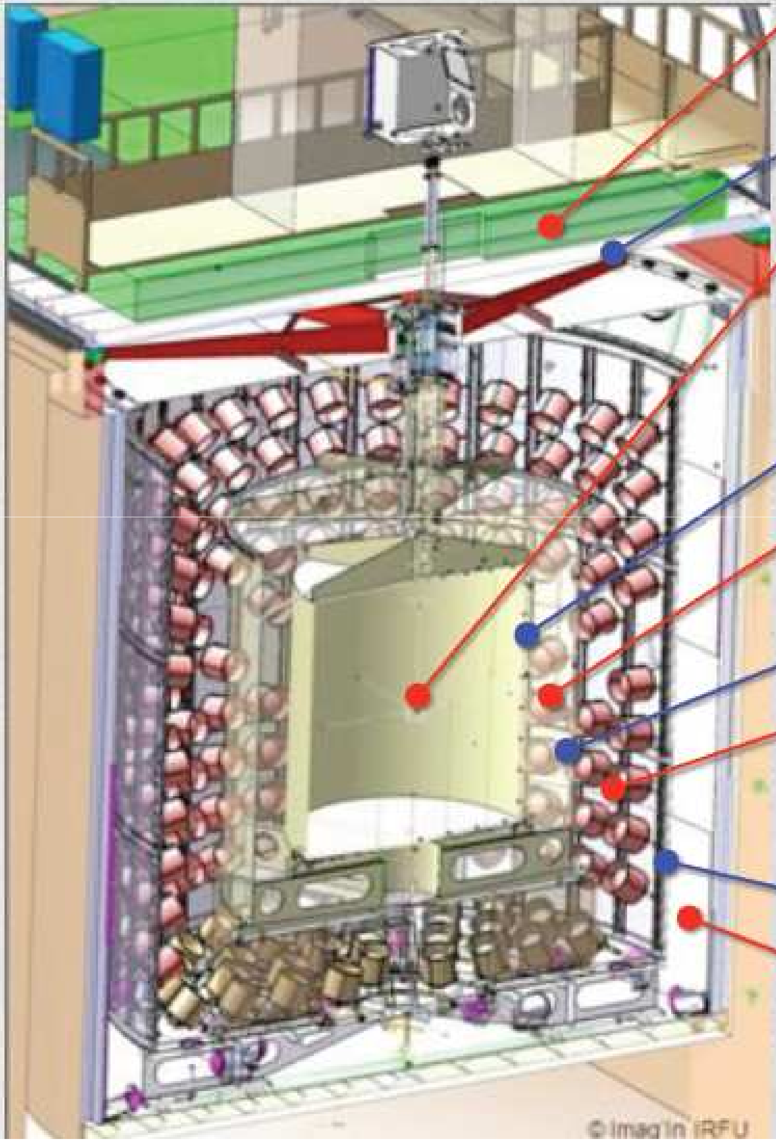


RENO Detector



- 354 ID +67 OD 10” PMTs
- Target : 16.5 ton Gd-LS, R=1.4m, H=3.2m
- Gamma Catcher : 30 ton LS, R=2.0m, H=4.4m
- Buffer : 65 ton mineral oil, R=2.7m, H=5.8m
- Veto : 350 ton water, R=4.2m, H=8.8m

Double Chooz detector



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Outer Veto: Plastic scintillator strips

Identify cosmic μ

Steel shield (15cm thick)

ν-target:

Gd loaded (1g/l) liquid scint. ($10m^3$)

Target of neutrino interaction

Neutrons captured on Gd

Acrylic vessel

γ-catcher: Liquid scintillator ($22m^3$)

Measure γ's escaped from ν-target

Acrylic vessel

Buffer:

Mineral oil ($110m^3$) & 390 10-inch PMT

Reduction of environmental γ's

Steel tank

Inner Veto:

Liquid scintillator ($90m^3$) & 78 8-inch PMT

Identify cosmic μ &reduction neutrons

Detector calibration

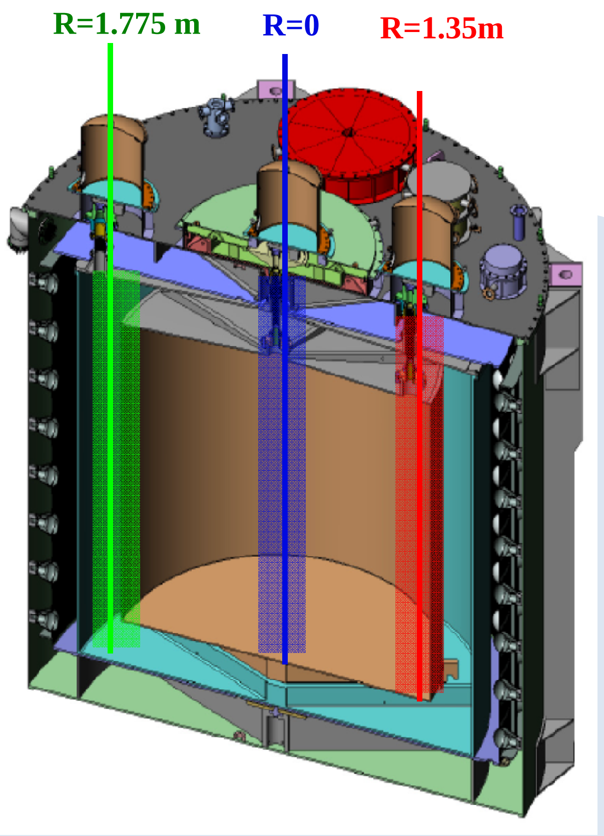
Daya Bay	Double Chooz	RENO
		Cs, 662 keV
Ge, 2x511 keV		Ge, 2x511 keV
Co60 2.5 MeV	Co60 2.5 MeV	Co60 2.5 MeV
	Cf252	Cf252
Am241-C13		
LED	LED	
		Laser

- Three sources + LED in each calibration unit, on a turn-table:
  - ^{68}Ge (1.02MeV)
  - ^{60}Co (2.5MeV)
  - ^{241}Am-^{13}C (8MeV)
  - LED

Energy calibration (linearity, detector response… etc)

Timing, gain and relative QE

- Can also use spallation neutrons (uniformity, stability, calibration, … etc).

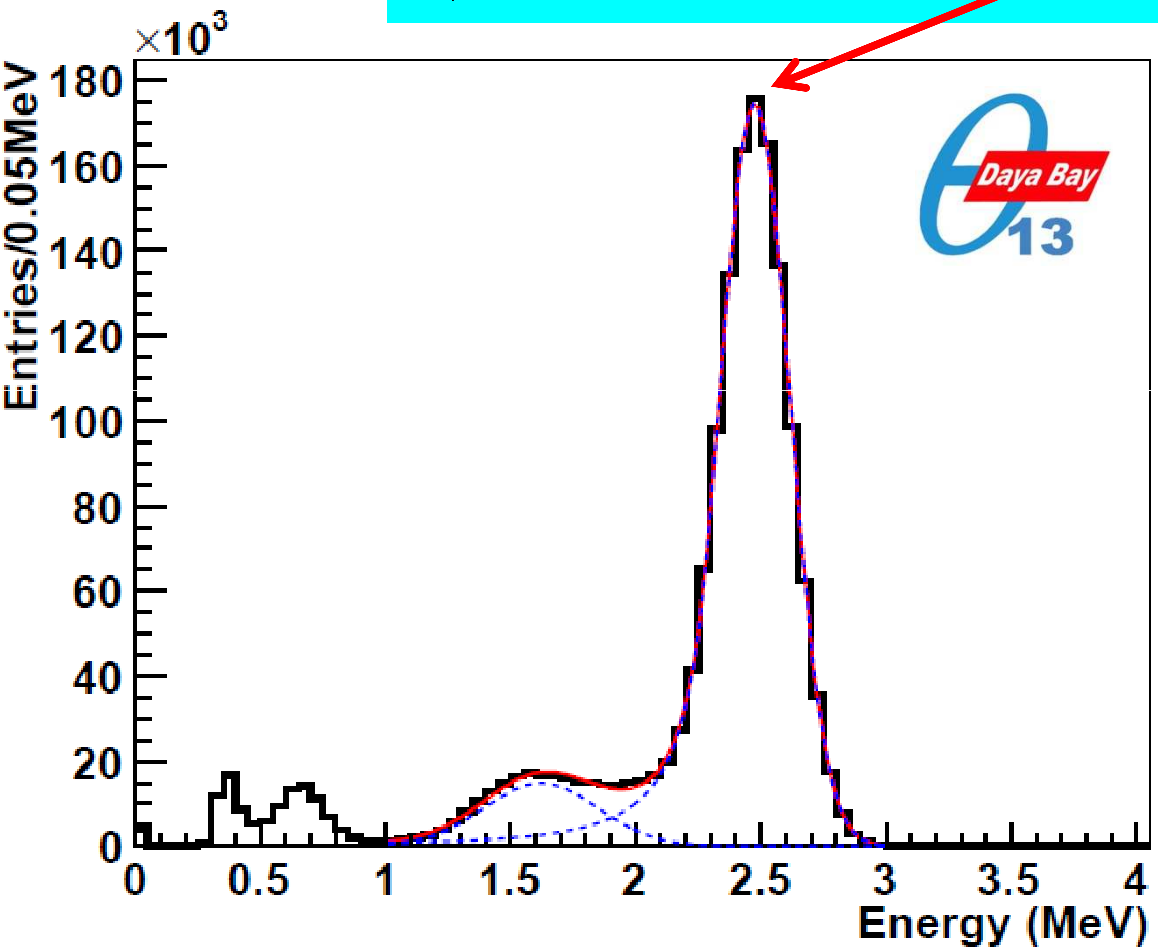


Automated Calibration Units (Daya Bay)

Three calibration units per detector that deploy sources along z-axis

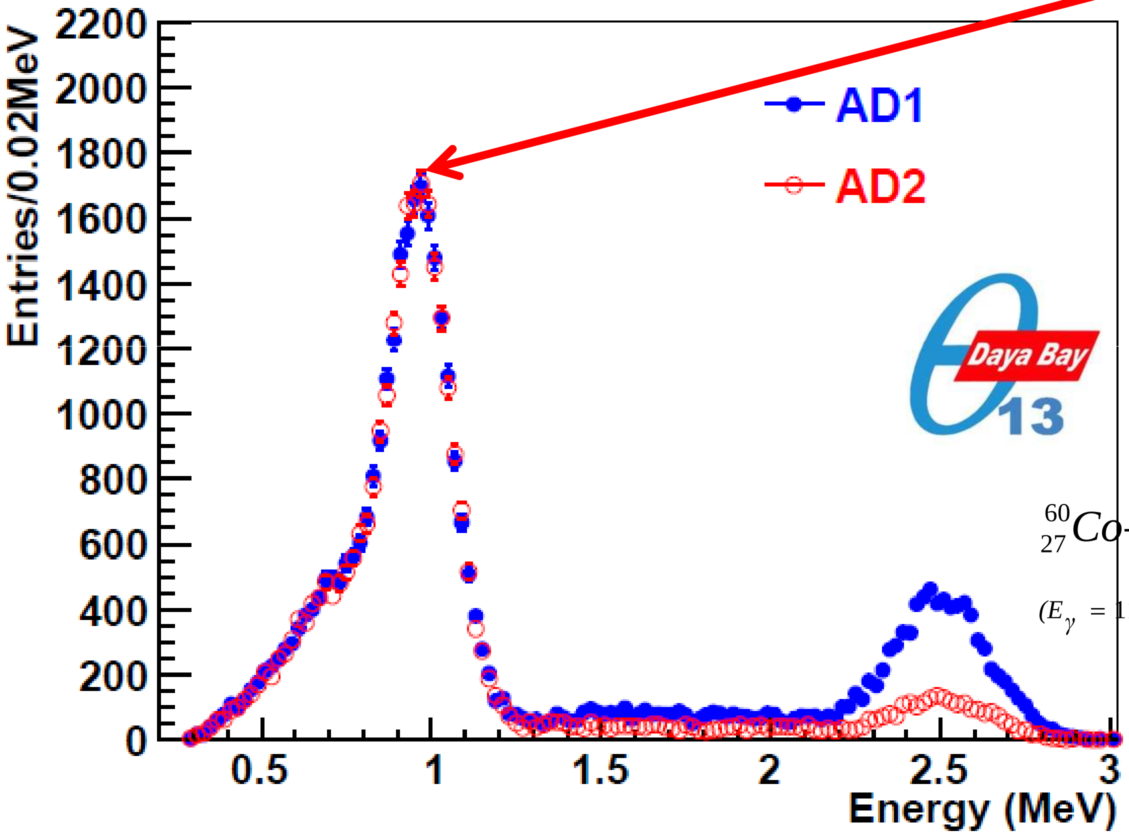
$$ {}^{60}_{27}Co \xrightarrow[\beta-1925d]{} {}^{60}_{28}Ni^{*} \longrightarrow {}^{60}_{28}Ni $$

$$ (E_{\gamma} = 1173.2 + 1332.5 = 2505.7\,MeV) $$



$$^{68}_{32}Ge \xrightarrow[E.C.\,276d]{} {}^{68}_{31}Ga \xrightarrow[\beta+\,68m]{} {}^{68}_{30}Zn$$

$$e^{+} + e^{-} \rightarrow 2\times 511keV\ \gamma$$



$$^{60}_{27}Co \xrightarrow[\beta-1925d]{} {}^{60}_{28}Ni^{*} \longrightarrow {}^{60}_{28}Ni$$

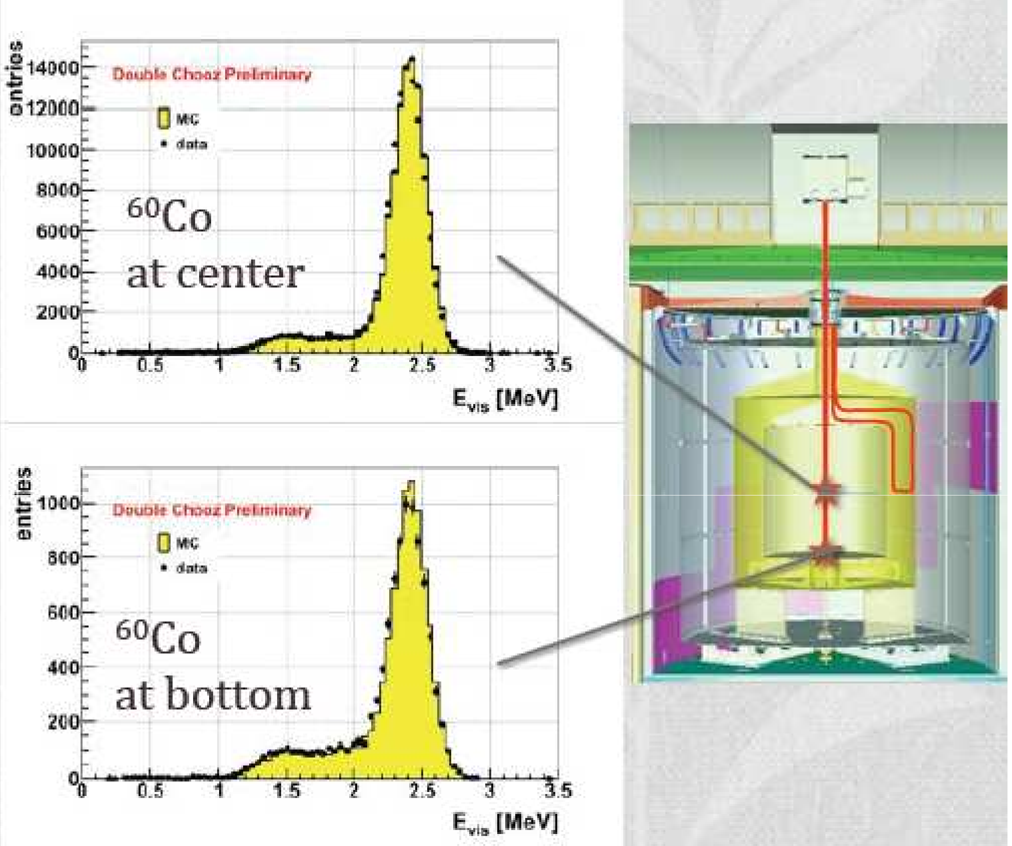
$$(E_{\gamma} = 1173.2 + 1332.5 = 2505.7\,MeV)$$

Figure 15: The energy spectrum of the ^{68}Ge source.

Calibration

Energy calibration

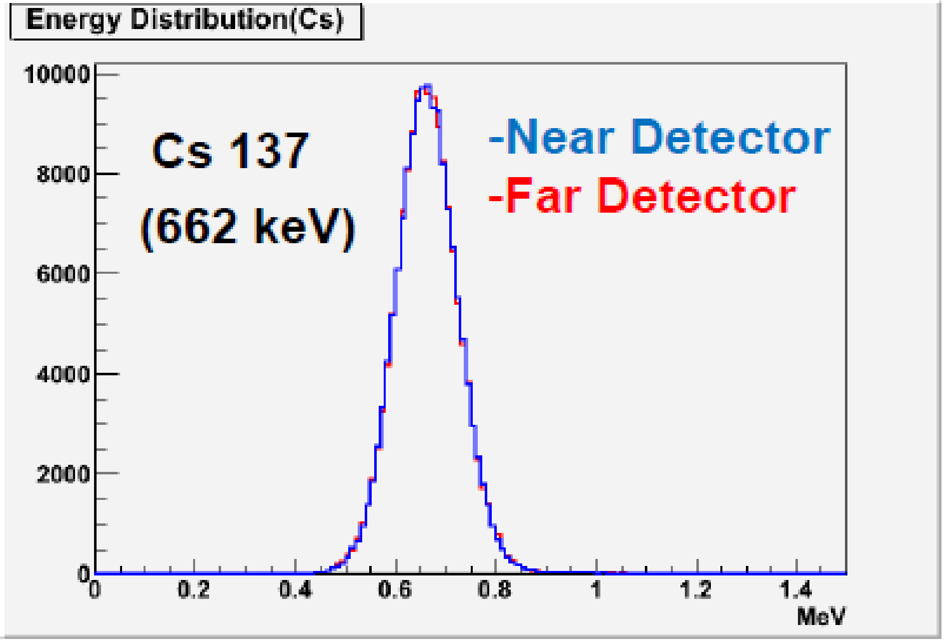
1. PMT and electronics gain non-linearity calibration
   - LED light injection system
2. Correction for position dependence & stability
   - Spallation neutron captures on H and Gd
3. Energy scale
   - Radioactive sources deployed into ν-target and γ-catcher

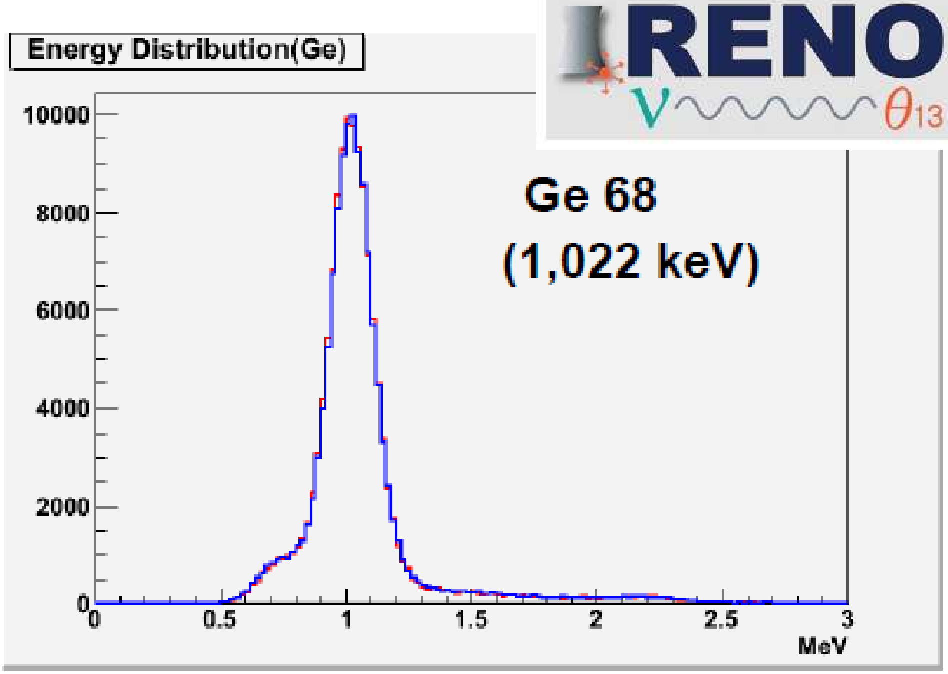


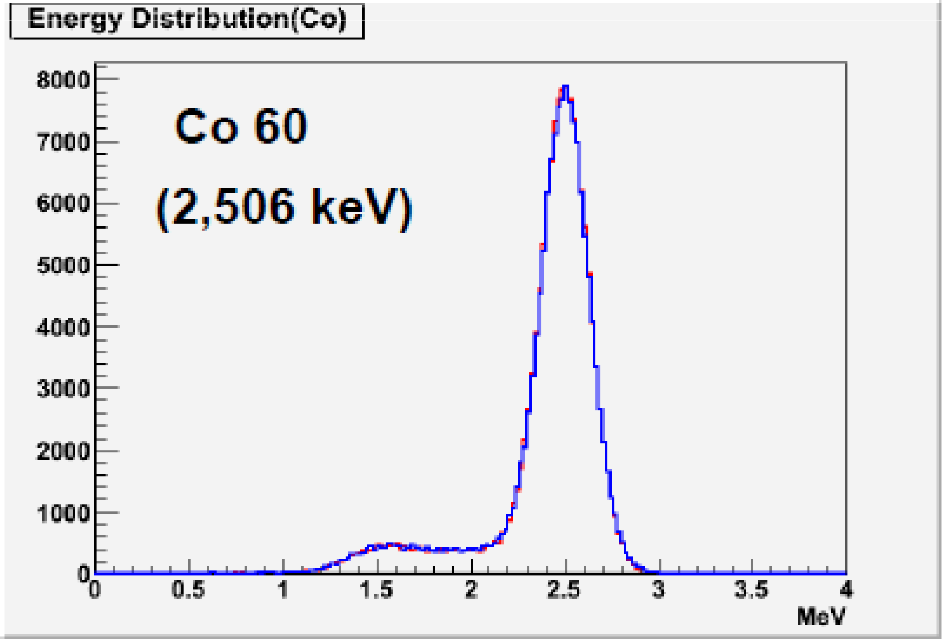
Neutron detection efficiency

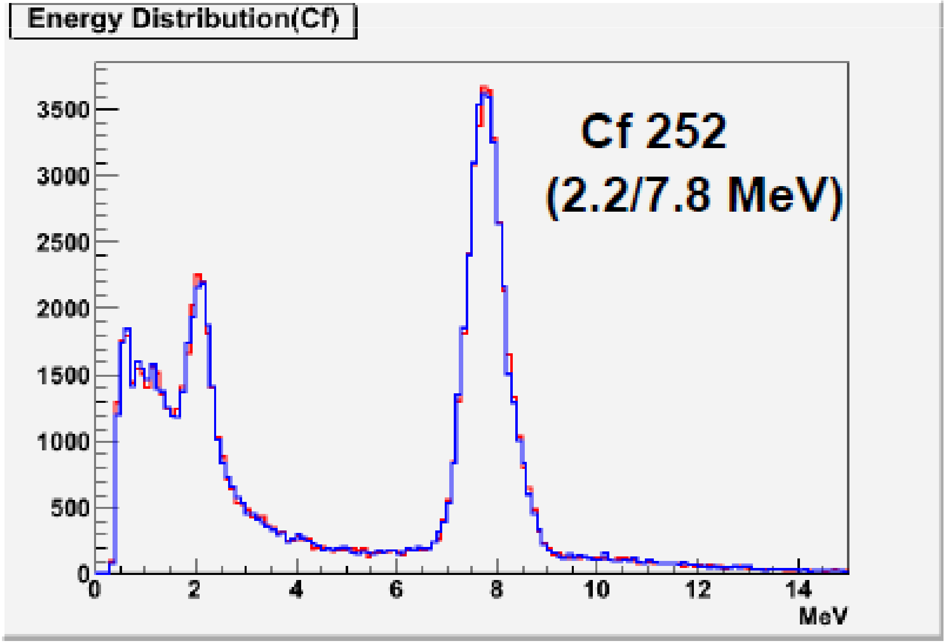
Energy & time window, Gd fraction, spill in/out effects

- ^{252}Cf source deployed into ν-target and γ-catcher

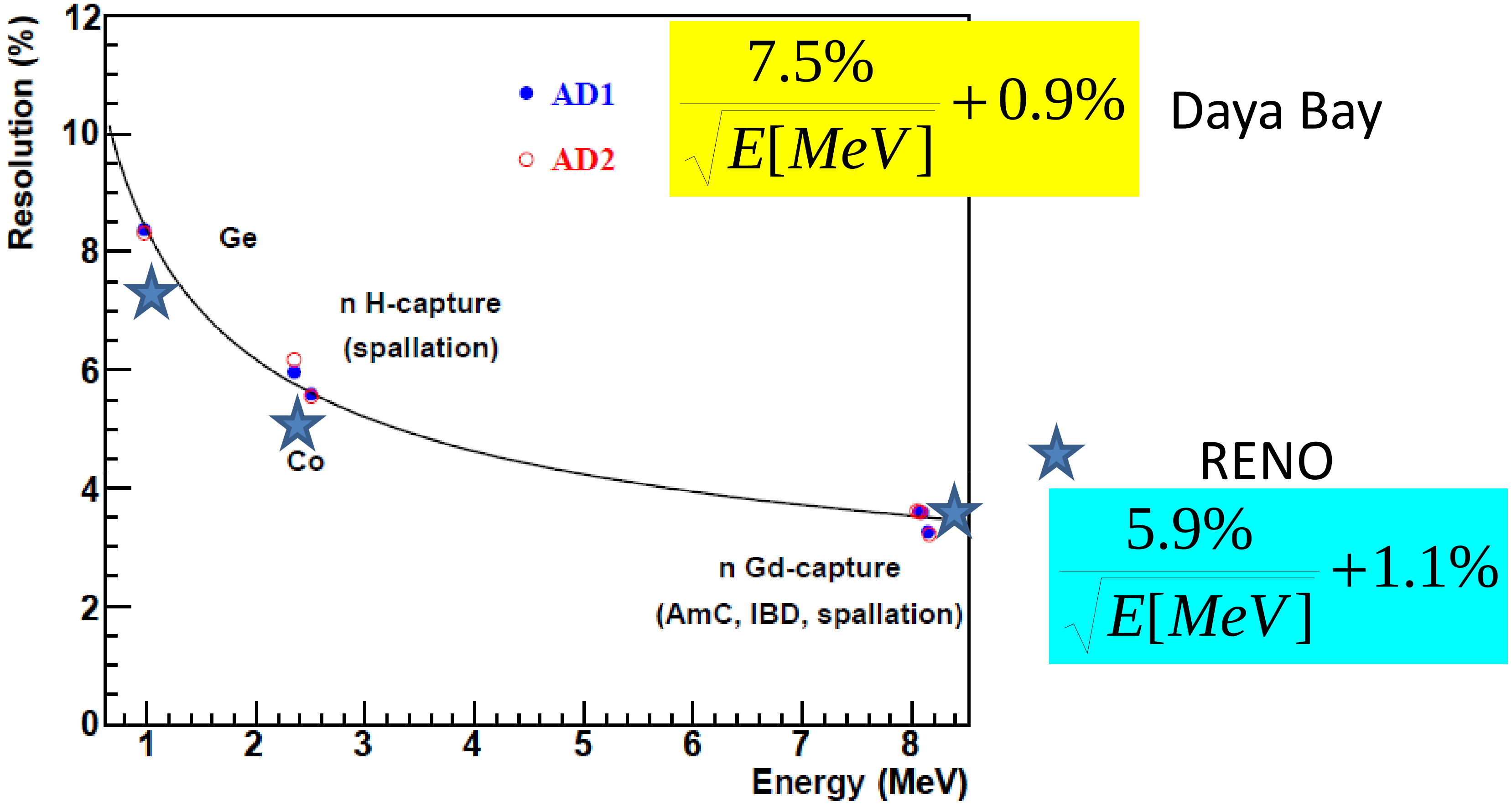

Energy Distribution(Cs)
Cs 137
(662 keV)
-Near Detector
-Far Detector
10000
8000
6000
4000
2000
0
0
0.2
0.4
0.6
0.8
1
1.2
1.4
MeV


Energy Distribution(Ge)
Ge 68
(1,022 keV)
10000
8000
6000
4000
2000
0
0
0.5
1
1.5
2
2.5
3
MeV


Energy Distribution(Co)
Co 60
(2,506 keV)
8000
7000
6000
5000
4000
3000
2000
1000
0
0
0.5
1
1.5
2
2.5
3
3.5
4
MeV


Energy Distribution(Cf)
Cf 252
(2.2/7.8 MeV)
3500
3000
2500
2000
1500
1000
500
0
0
2
4
6
8
10
12
14
MeV

ENERGY RESOLUTION



$$\frac{7.5\%}{\sqrt{E[MeV]}}+0.9\%$$

Daya Bay

★ RENO

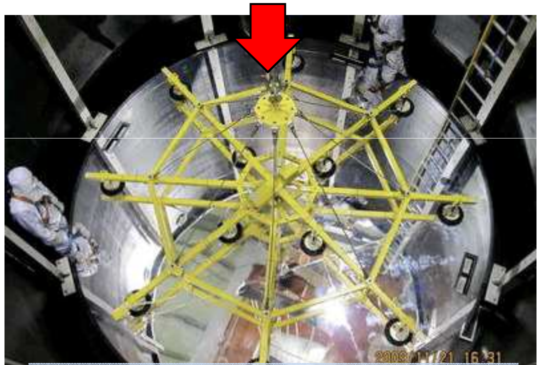
$$\frac{5.9\%}{\sqrt{E[MeV]}}+1.1\%$$

Figure 25: Resolution of reconstructed energy.

Assembly of Anti-neutrino detectors

ADs are assembled in clean-room

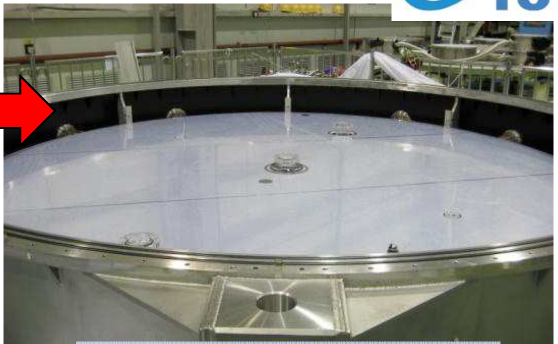
Stainless Steel Vessel (SSV) in assembly pit



Install lower reflector

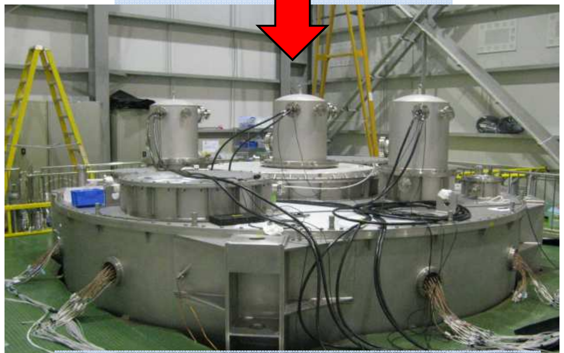
Install Acrylic Vessels

Install PMT ladders



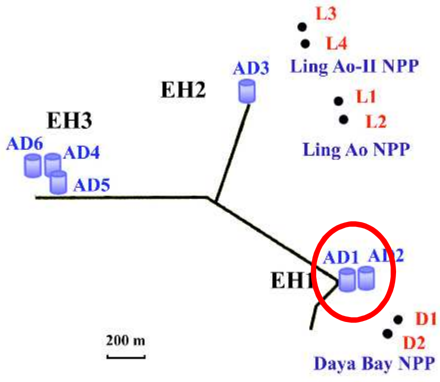
Install top reflector

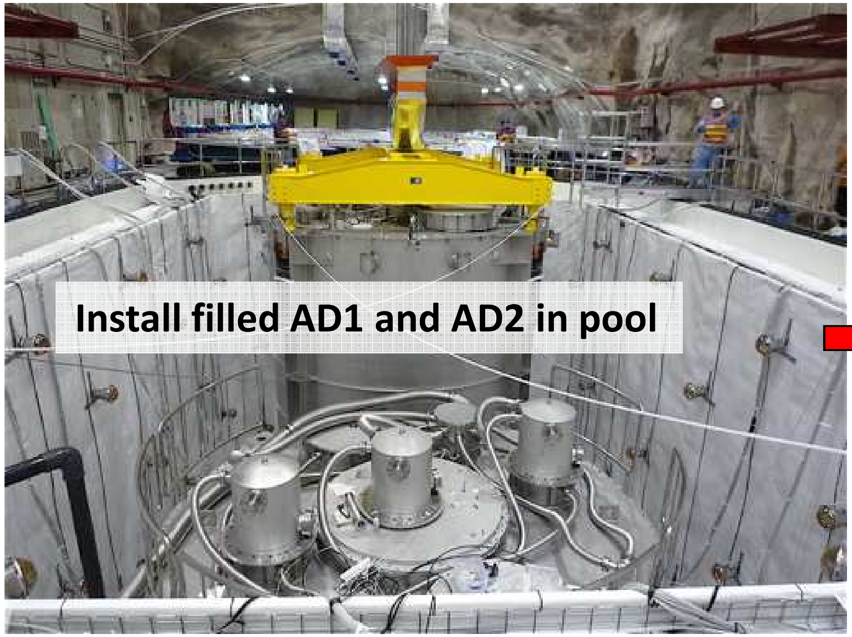
Close SSV lid



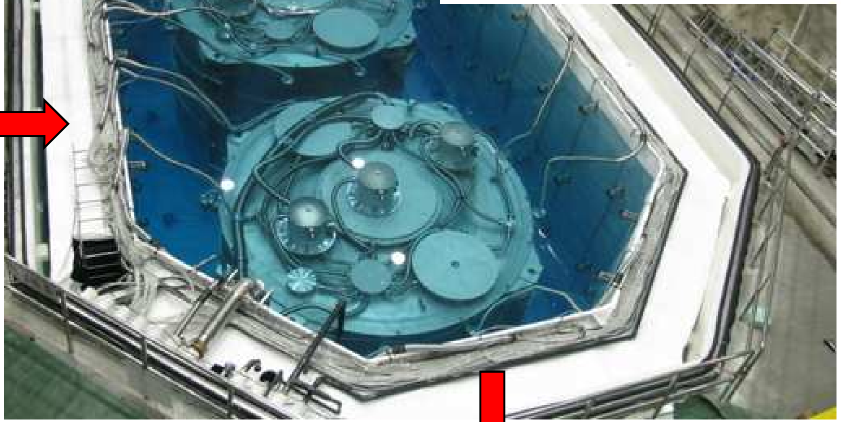
Install calibration units

Near Hall (EH1) Installation





Install filled AD1 and AD2 in pool



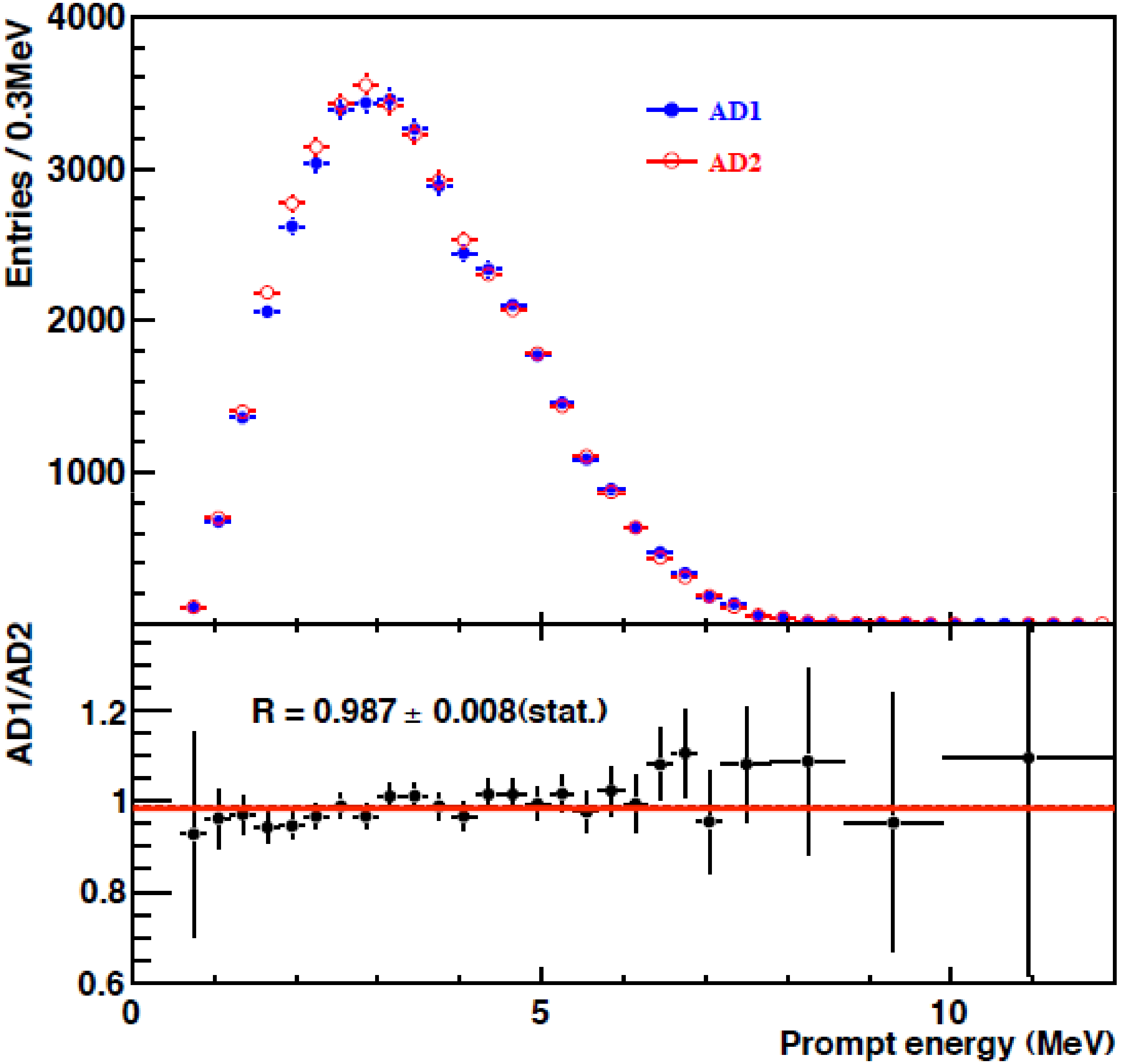
Fill pool with purified water (~1 wk)

Place cover over pool

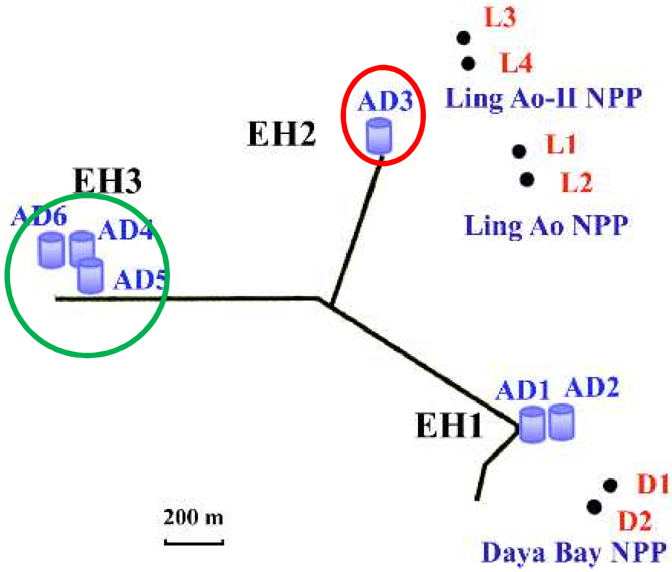
Roll RPC over cover

Data taking started on 15 Aug 2011

Detailed comparison of AD1 and AD2



Ling Ao (EH2) and Far (EH3) Halls

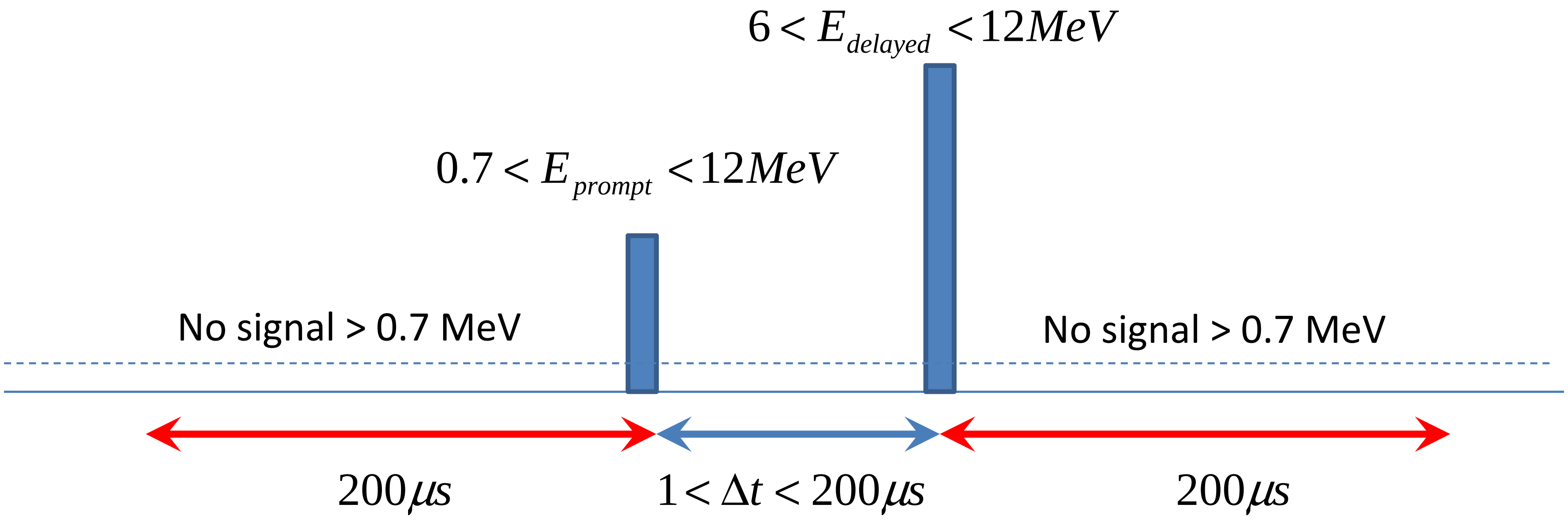


EH2 (Ling Ao Near Hall):
Began operation on 5 Nov 2011

EH3 (Far Hall):
Started data-taking on 24 Dec 2011

- Remaining two ADs will be installed in 2012

Inverse Beta Decay Selection



$6 < E_{delayed} < 12 MeV$

$0.7 < E_{prompt} < 12 MeV$

No signal > 0.7 MeV

No signal > 0.7 MeV

$200 \mu s$

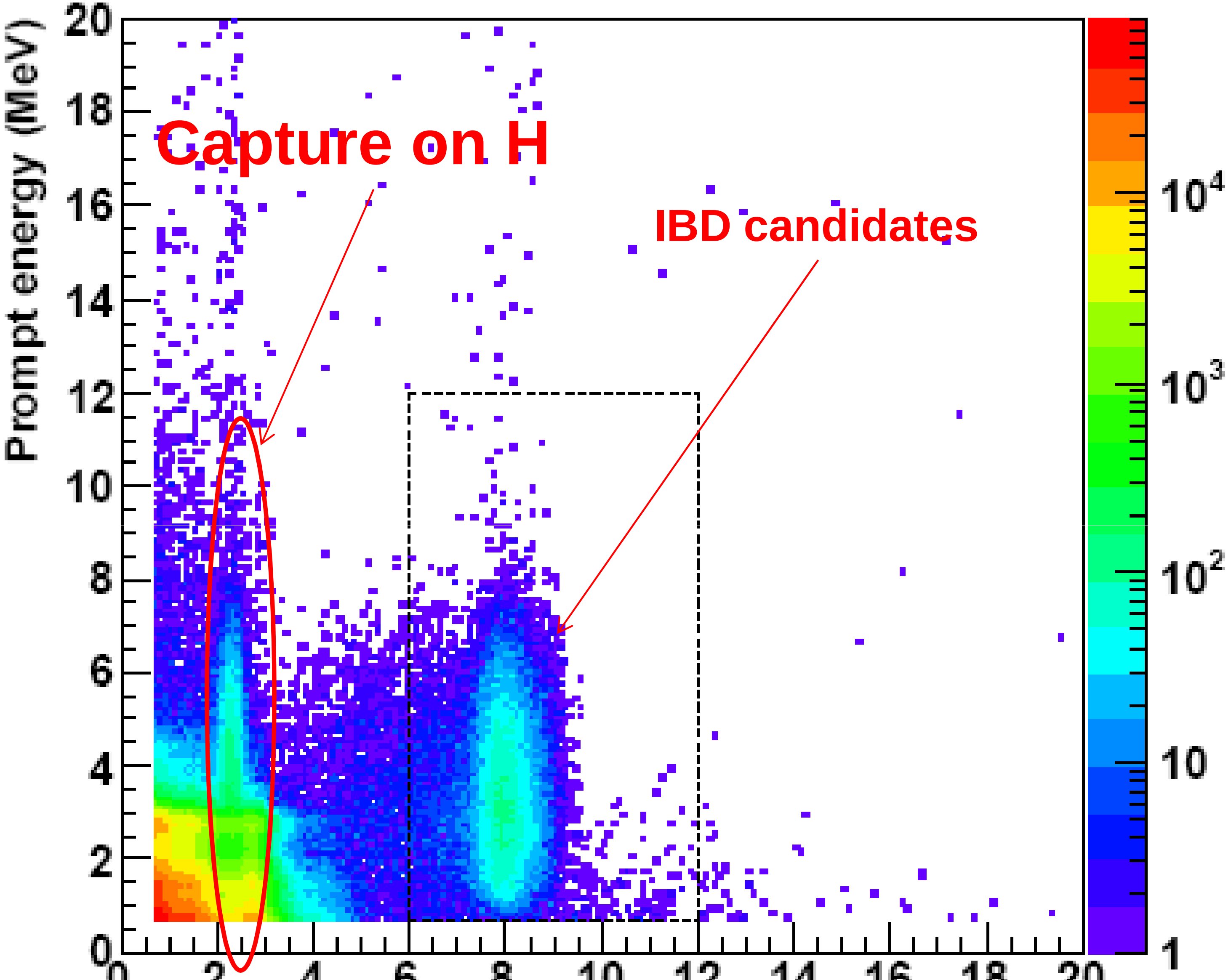
$1 < \Delta t < 200 \mu s$

$200 \mu s$

- **Prompt-delayed coincidence:**
  - Prompt positron: 0.7 MeV < E_p < 12 MeV (DYB, RENO), 12.2 MeV (Double Chooz)
  - Delayed neutron: 6.0 MeV < E_d < 12 MeV (DYB, RENO, Double Chooz)
  - Capture Time: 1 µs < Δt< 200 µs (DYB), 2 µs < Δt< 100 µs (Double Chooz,RENO)
- **Multiplicity:**
  - No signal 200 µs (Daya Bay), 100 µs (Double Chooz, RENO) around IBD

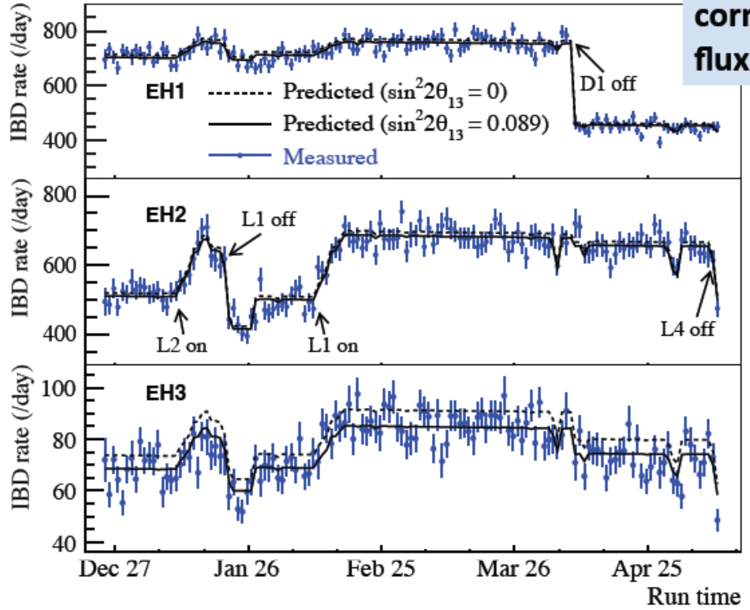
- Muon Veto
  - Pool muon: veto following 0.6 ms
  - AD muon (> 20 MeV): veto following 1 ms
  - AD shower muon (>2.5 GeV): veto following 1 s that is >5 T1/2 of Li9/He8 isotopes

  - Muon>600 MeV veto 0.5 s (Double Chooz)
  - Muon>1.5GeV veto 0.01 s (RENO)

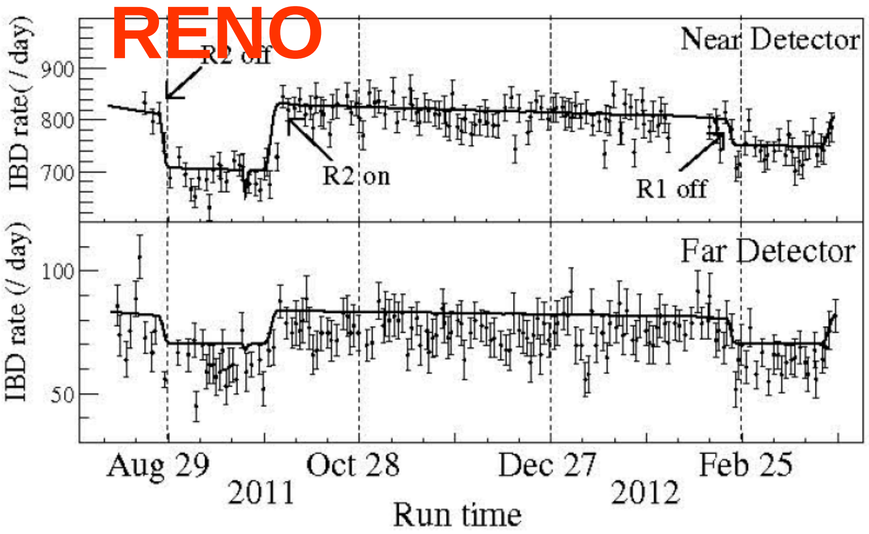

Capture on H
IBD candidates
Prompt energy (MeV)
Delayed energy (MeV)
0
2
4
6
8
10
12
14
16
18
20
1
10
10^2
10^3
10^4

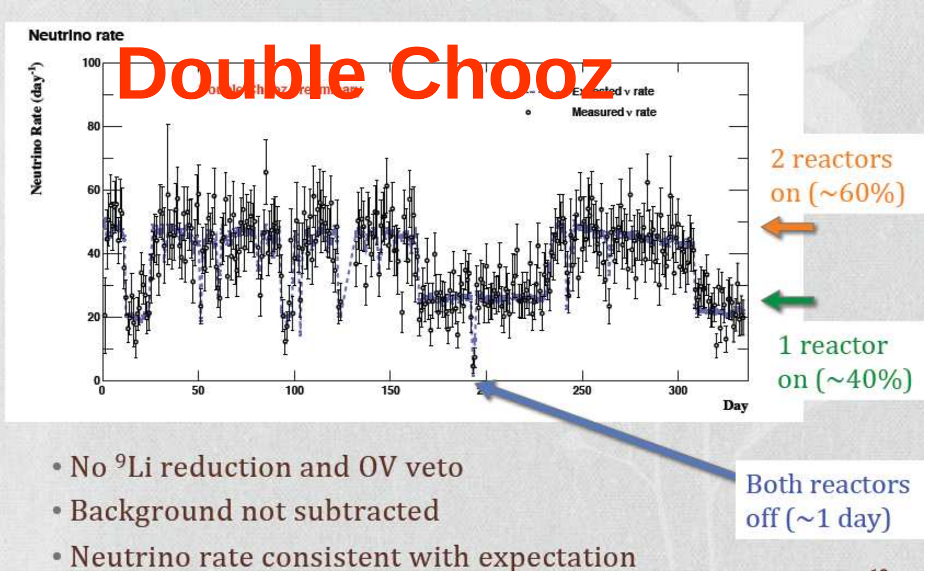
Antineutrino Rate vs. Time

Detected rate strongly correlated with reactor flux expectations.



IBD candidates/day	Near	Far
Daya Bay	662+671(EH1) 613 (EH2)	78+75+77
Double Chooz		~40
RENO	779	73


RENO


Double Chooz

2 reactors on (~60%)

1 reactor on (~40%)

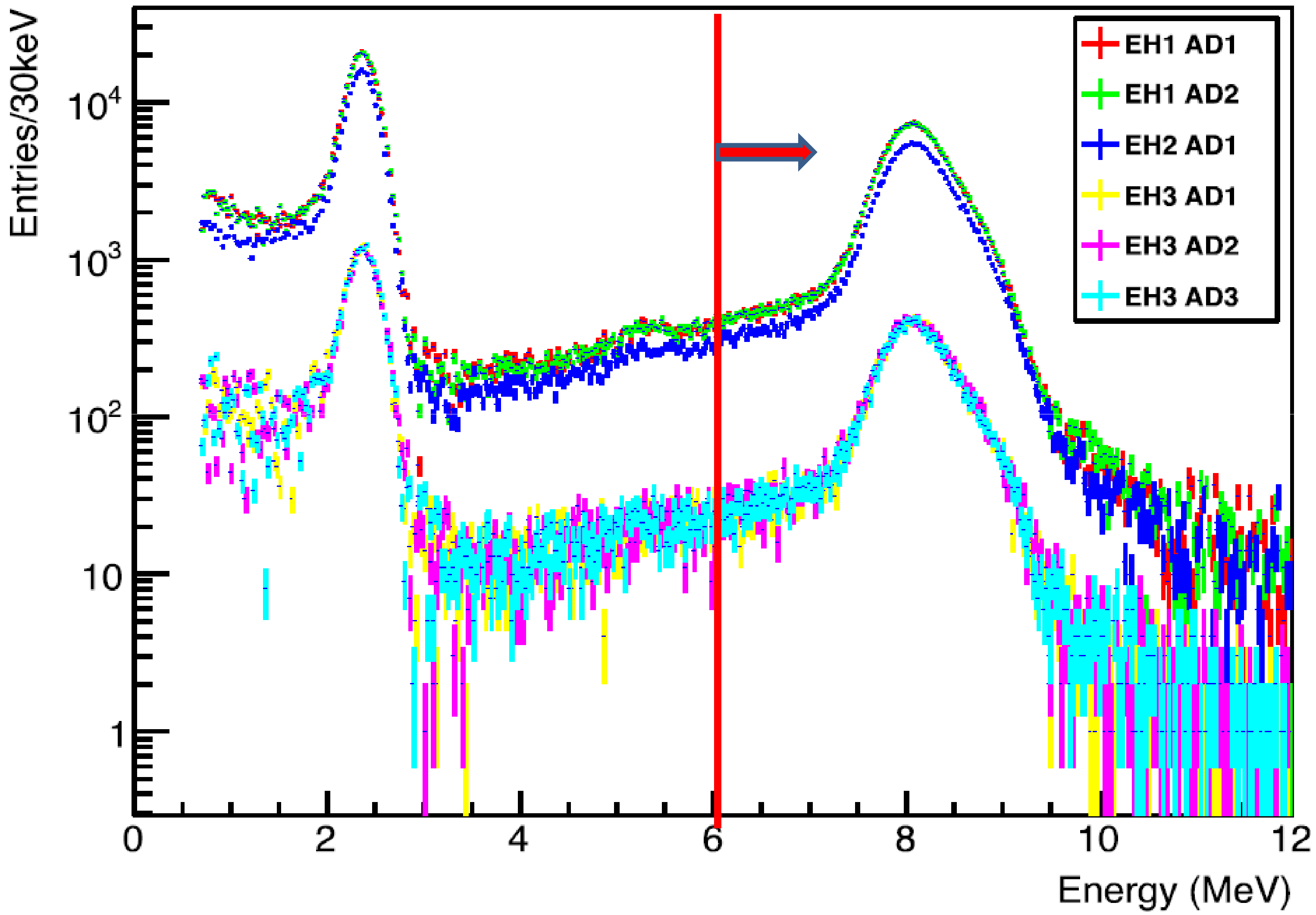
Both reactors off (~1 day)

- No ^{9}Li reduction and OV veto
- Background not subtracted
- Neutrino rate consistent with expectation

Systematics

	Daya Bay		Reno		Double Chooz
	Corr.	Uncorr.	Corr.	Uncorr.	Corr/Uncorr.
Target proton	0.47%	0.03%	0.5%	0.1%	0.3%
Flasher cut	0.01%	0.01%	0.1%	0.01%	-
Delayed energy cut	0.6%	0.12%	0.5%	0.1%	0.7%
Prompt energy cut	0.1%	0.01%	0.1%	0.01%	-
Energy response	-	-	-	-	0.3%
Trigger efficiency					<0.1%
Multiplicity cut	0.02%	<0.01%	0.06%	0.04%	-
Capture time cut	0.12%	0.01%	0.5%	0.01%	0.5%
Gd capture ratio	0.8%	<0.1%	0.7%	0.1%	0.3%
Spill-in	1.5%	0.02%	1.0%	0.03%	0.3%
livetime	0.002%	<0.01%			-
Muon veto cut	-	-	0.06%	0.04%	-
Total	**1.9%**	**0.2%**	**1.5%**	**0.2%**	**1.0%**

DELAYED ENERGY CUT



Gd content is monitored by measurement of the time of neutron capture on Gd

$$\langle \tau \rangle = \frac{1}{\langle v_n \cdot \sigma \rangle \cdot N_{Gd}}$$

Very simplified estimation using Maxwell Boltzmann distribution of neutron velocities, app. cross section and Gd concentration gives:

$$\frac{dP}{dv} = \sqrt{\frac{2}{\pi}\left(\frac{m}{kT}\right)^3}\, v^2 e^{-\frac{mv^2}{2kT}} \Rightarrow m.p.\quad v = \sqrt{\frac{2kT}{m_n}} \xrightarrow[T=20^o C]{} 2200 m/s$$

$$N_{Gd} = 0.103\% \cdot \rho \cdot \frac{N_A}{\langle A_{Gd} \rangle} = 0.00103 \cdot 0.86 g/cm^3 \cdot \frac{6.022/mol}{157.25 g/mol} = 3.29 \cdot 10^{18}/cm^3$$

$$\langle \sigma \rangle = (0.148 \cdot 60900 + 0.1565 \cdot 254000) \cdot 10^{-24} cm^2 = 4.876 \cdot 10^{-20} cm^2$$

$$\langle \tau \rangle = \frac{1}{v \cdot \langle \sigma \rangle \cdot N_{Gd}} = 28.3 \mu s$$

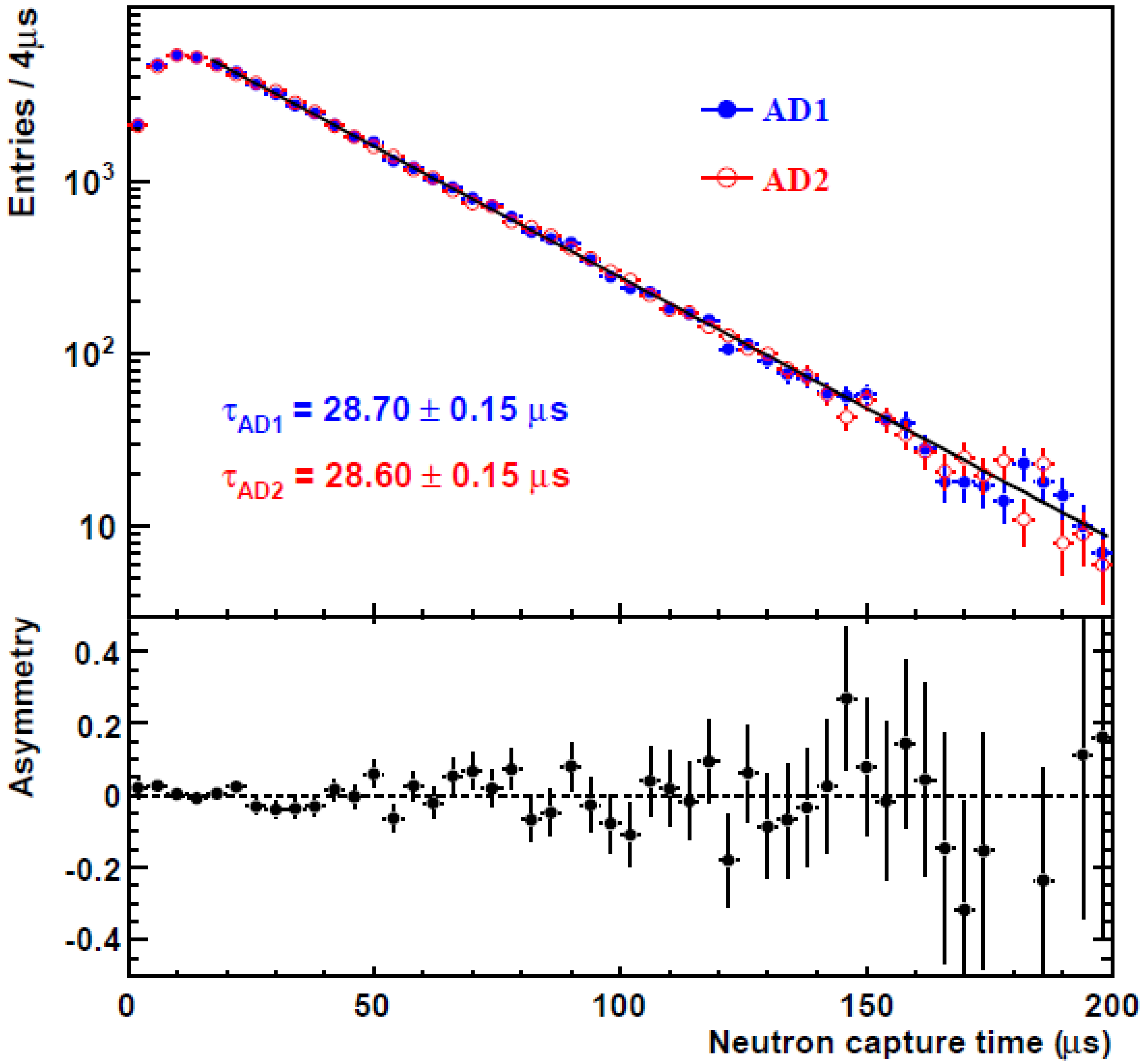


Figure 14: The neutron capture time on Gd from the Am-^{13}C source at the detector center.

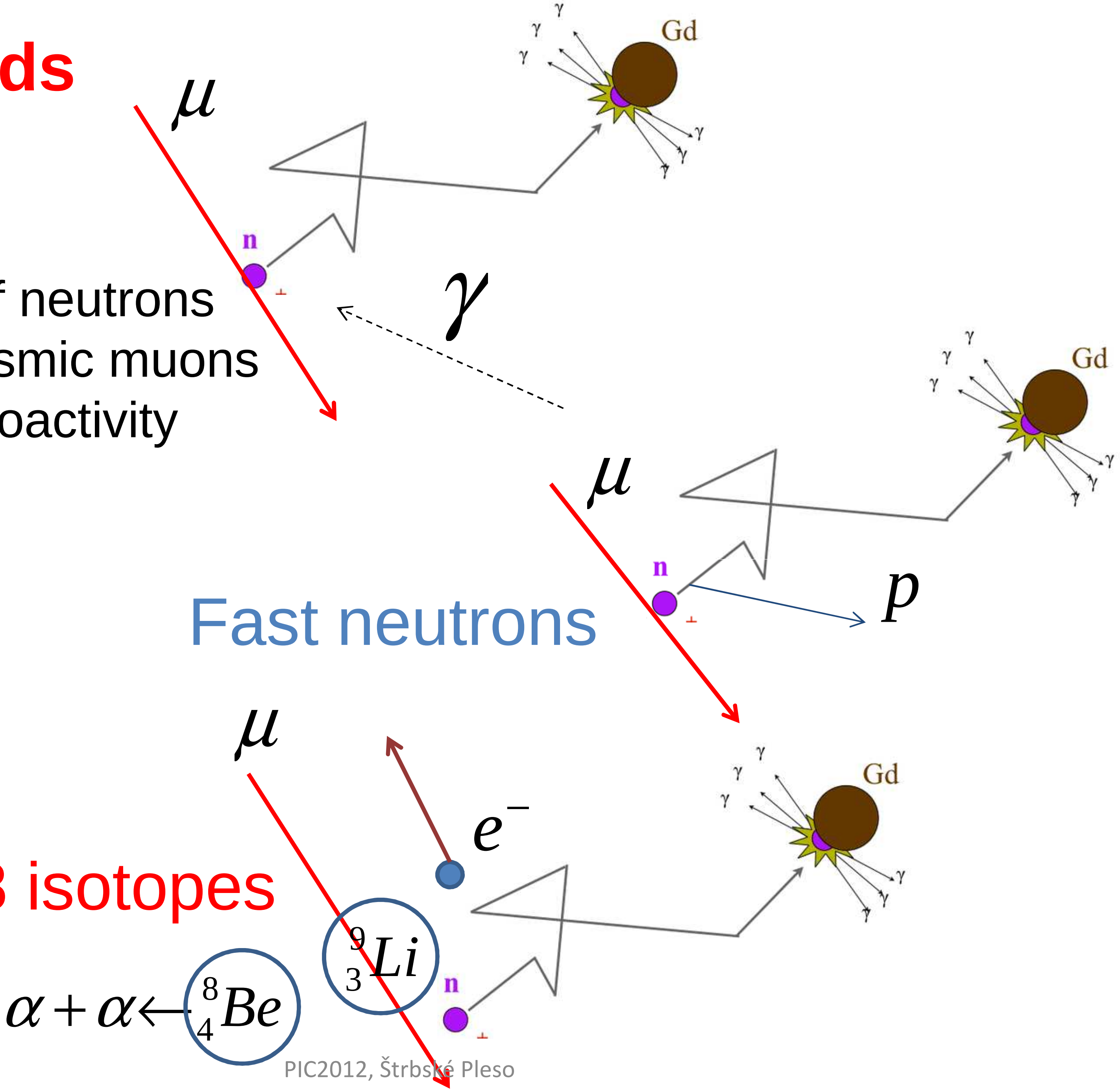
Reactor flux estimate

	Daya Bay		Reno		Double Chooz
	Corr.	Uncorr.	Corr.	Uncorr.	Corr./Uncorr.
Thermal power		0.5%		0.5%	0.5%
Fission fraction/Fuel composition		0.6%		0.7%	0.9%
Fission cross section /Bugey 4 measurement	3%		1.9%		1.4%
Reference spectra			0.5%		0.5%
IBD cross section			0.2%		0.2%
Energy per fission	0.2%		0.2%		0.2%
Baseline	0.02%		-		0.2%
Spent fuel		0.3%			
Total	**3%**	**0.8%**	**2.0%**	**0.9%**	**1.8%**

Backgrounds

-Accidental

coincidencies of neutrons produced by cosmic muons and natural radioactivity



Fast neutrons

Li9 and He8 isotopes

Li9 and He8 background

These isotopes are products of photonuclear interactions of cosmic muons on C

$$ {}^{8}_{2}He \xrightarrow{119ms\ 16\%} {}^{7}_{3}Li + \enclose{circle}{e^-} + \bar{\nu}_e + \enclose{circle}{n} $$

$$ {}^{8}_{2}He \xrightarrow{84\%} {}^{8}_{3}Li^* + e^- + \bar{\nu}_e $$

$$ {}^{8}_{3}Li^* \rightarrow {}^{8}_{3}Li + 0.98MeV\gamma $$

$$ {}^{8}_{3}Li \xrightarrow{840ms} {}^{8}_{4}Be + e^- + \bar{\nu}_e $$

$$ {}^{8}_{4}Be \rightarrow \alpha + \alpha $$

$$ {}^{9}_{3}Li \xrightarrow{178ms\ 50\%} {}^{8}_{4}Be + \enclose{circle}{e^-} + \bar{\nu}_e + \enclose{circle}{n} $$

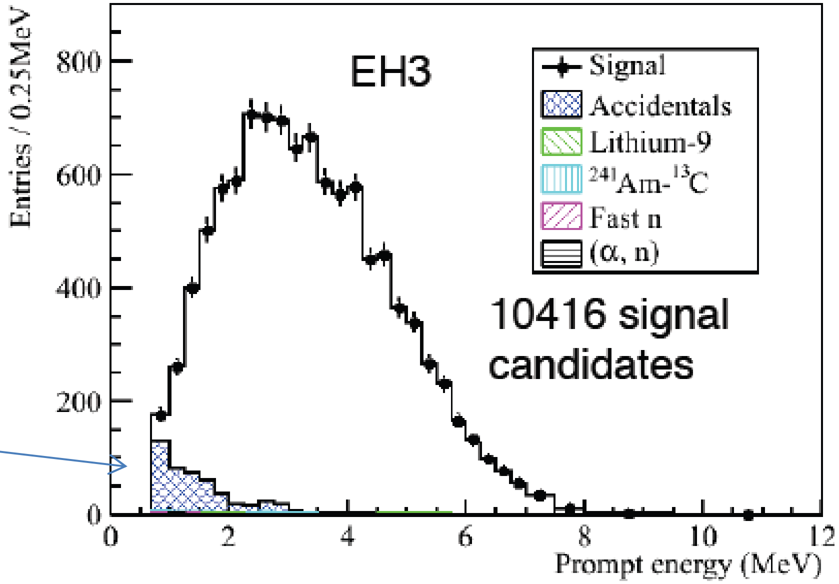
$$ {}^{8}_{4}Be \rightarrow \alpha + \alpha $$

$$ {}^{9}_{3}Li \xrightarrow{178ms\ 50\%} {}^{9}_{4}Be + e^- + \bar{\nu}_e $$

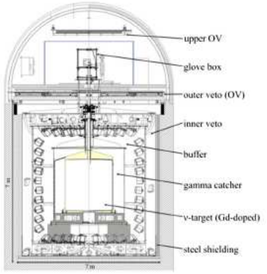
Backgrounds & uncertainties

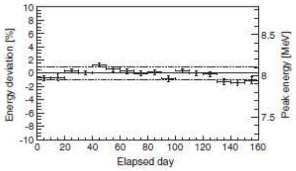
	Daya Bay		Reno		Double Chooz
	Near	Far	Near	Far	Far
Accidentals (B/S)	1.4%	4.0%	0.56%	0.93%	0.6%
Uncertainty(ΔB/B)	1.0%	1.4%	1.4%	4.4%	0.8%
Fast neutrons(B/S)	0.1%	0.06%	0.64%	1.3%	1.6%
Uncertainty(ΔB/B)	31%	40%	2.6%	6.2%	30%
^{8}He/^{9}Li (B/S)	0.4%	0.3%	1.6%	3.6%	2.8%
Uncertainty (ΔB/B)	52%	55%	48%	29%	50%
α-n(B/S)	0.01%	0.05%	-	-	-
Uncertainty(ΔB/B)	50%	50%	-	-	-
Am-C(B/S)	0.03%	0.3%	-	-	-
Uncertainty (ΔB/B)	100%	100%	-	-	-
Total backgrounds(B/S)	1.9%	4.7%	2.8%	5.8%	5.0%
Total Uncertainties (Δ(B/S))	0.2%	0.35%	0.8%	1.1%	1.5%

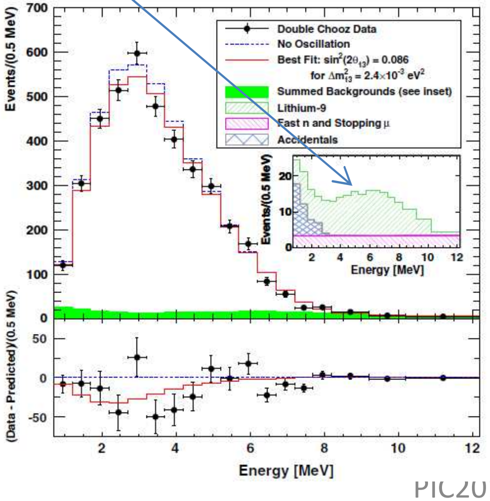
Due to large overburden and strict showering muons veto cut Daya Bay Li/He background is suppressed and the background is dominated by accidental coincidencies which are concentrated at low neutrino energies.

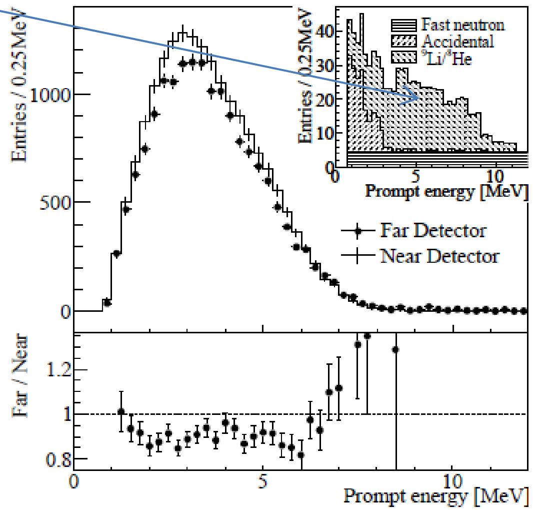


In Double Chooz and RENO the background is still dominated by decays of Li/He isotopes that spans the whole range of neutrino energies.

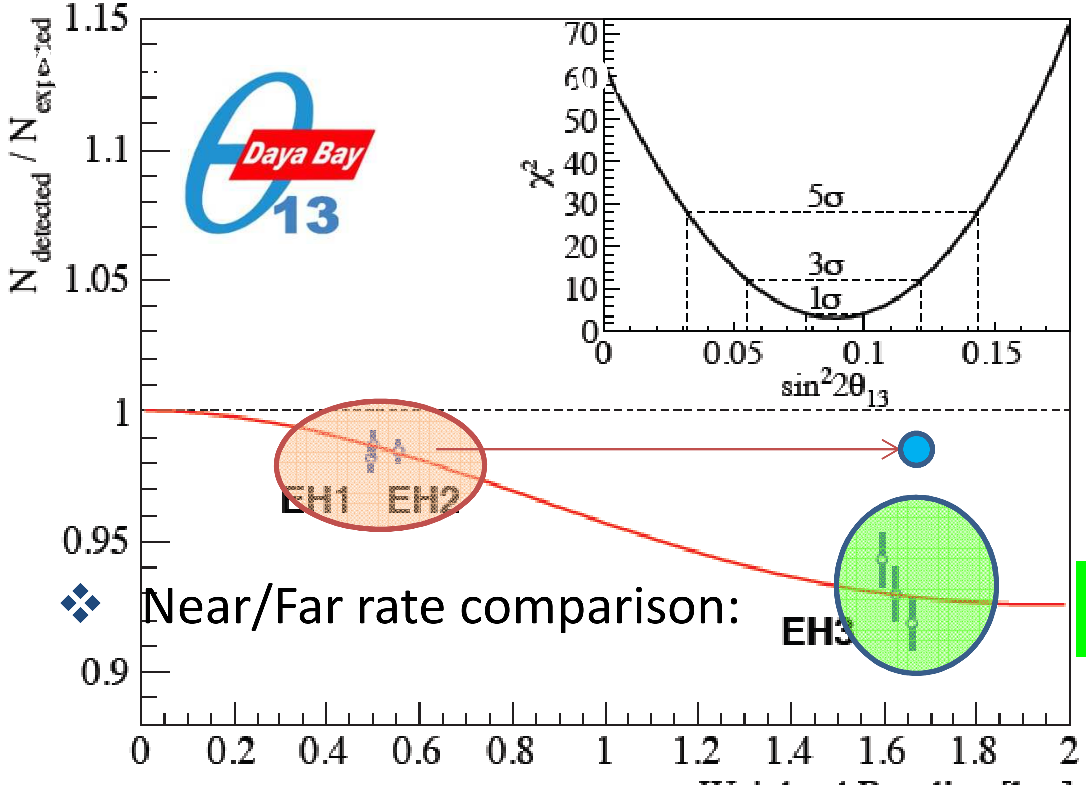






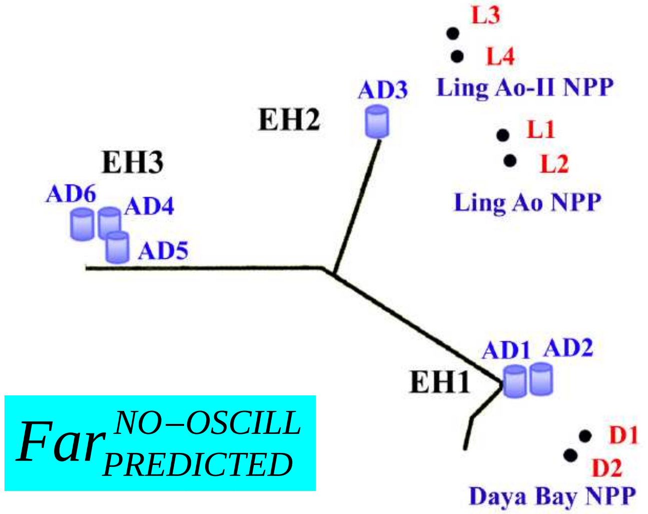


- Near/Far rate comparison:



$Far^{NO-OSCILL}_{PREDICTED}$

$Far_{MEASURED}$



$$R = \frac{Far_{measured}}{Far_{expected}} = \frac{M_4 + M_5 + M_6}{\sum_{i=4}^{6}(\alpha_i(M_1 + M_2) + \beta_i M_3)}$$

M_n : measured rates in each detector.

Weights α_i,β_i : determined from baselines and reactor fluxes, no oscillations assumed.

R = 0.944 ± 0.007 (stat) ± 0.003 (syst)

- Unambiguous observation of antineutrino deficit at the far site!

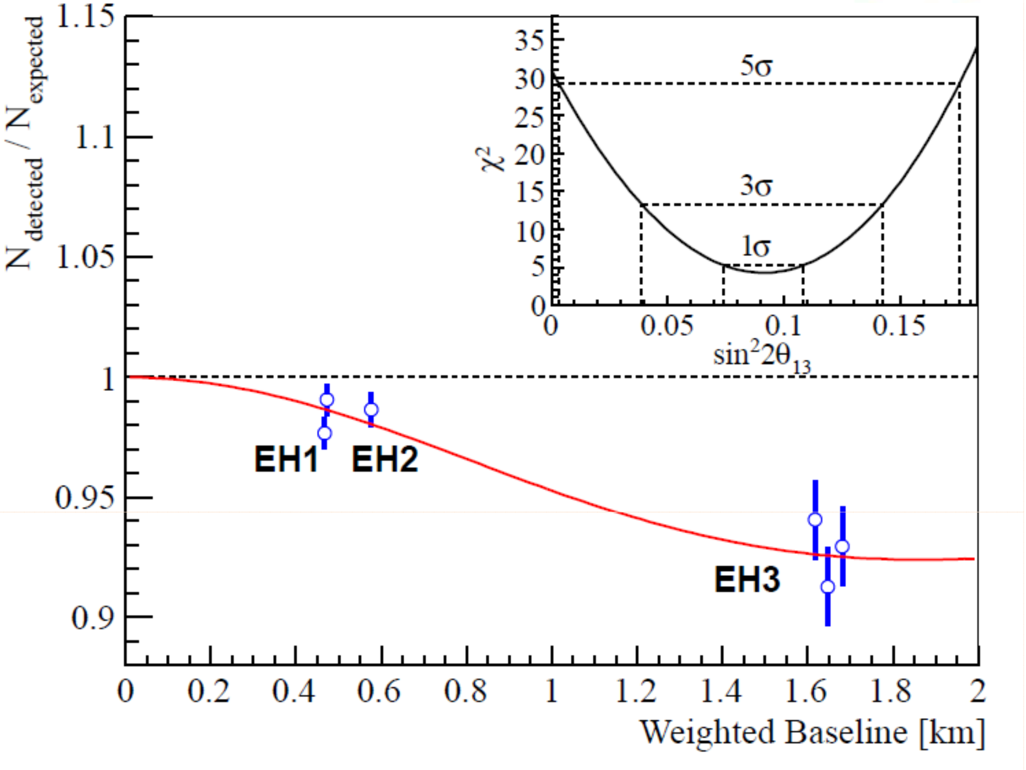
Rate-only analysis

- Determine θ_{13} using measured rates in each detector:

Uses standard χ^2 approach (χ^2/NDF=4.26/4)

$$\chi^2 = \sum_{d=1}^{6} \frac{[M_d - T_d(1 + \varepsilon + \sum_r \omega_r^d \alpha_r + \varepsilon_d) + \eta_d]^2}{M_d + B_d} + \sum_r \frac{\alpha_r^2}{\sigma_r^2} + \sum_{d=1}^{6}\left(\frac{\varepsilon_d^2}{\sigma_d^2} + \frac{\eta_d^2}{\sigma_B^2}\right),$$

[Absolute rate is not constrained.]
Consistent results obtained by independent analyses, different reactor flux models.



$\sin^2 2\theta_{13}$ = 0.089 ± 0.010 (stat) ± 0.005 (syst)
$\sin^2 2\theta_{13}$ = 0 excluded at 7.7σ

$$\theta_{13} \cong 8.7^o$$

The smallest lepton mixing angle is comparable to largest (Cabibbo) quark mixing angle.

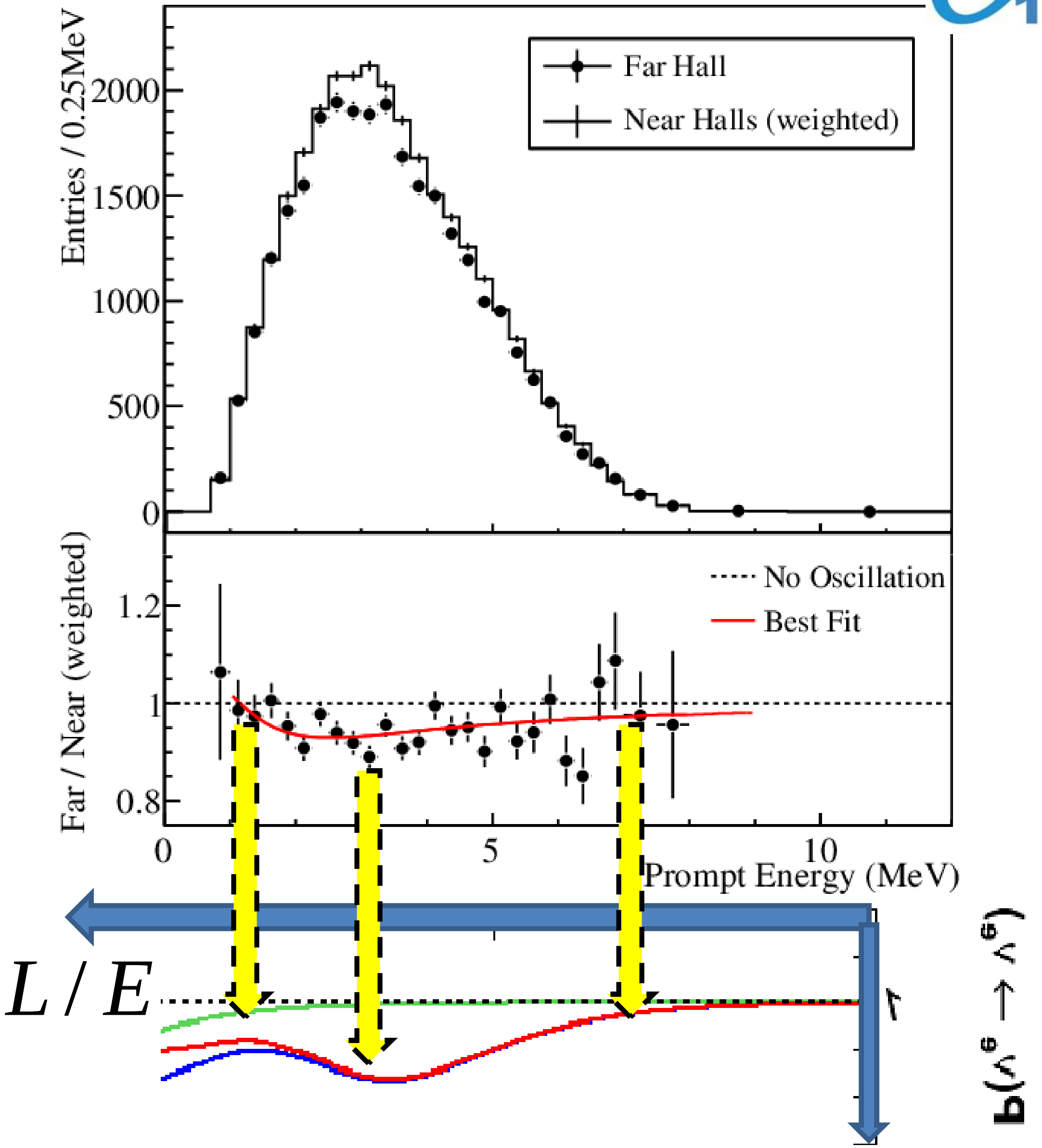
The disagreement of the spectra in far and near hall provides further evidence of neutrino oscillation.

The ratio of the spectra is consistent with the best-fit oscillation solution of

$\sin^2 2\theta_{13} = 0.089$

obtained from the rate-only analysis.

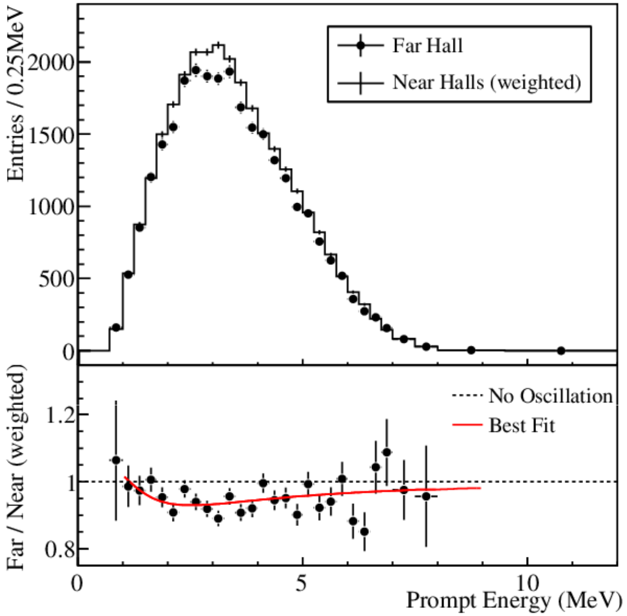
Currently the result is only from rate analysis!



Reactor neutrinos Disappearence:

Latest results from Neutrino 2012

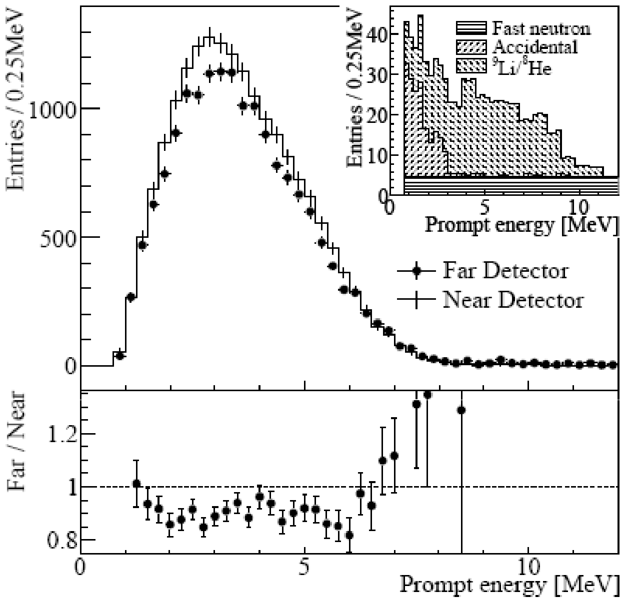
Daya Bay



R=0.944±0.007 ±0.003

$\mathrm{Sin}^2 2\theta_{13}$=0.089±0.010±0.005
7.7 σ for non-zero θ_{13}

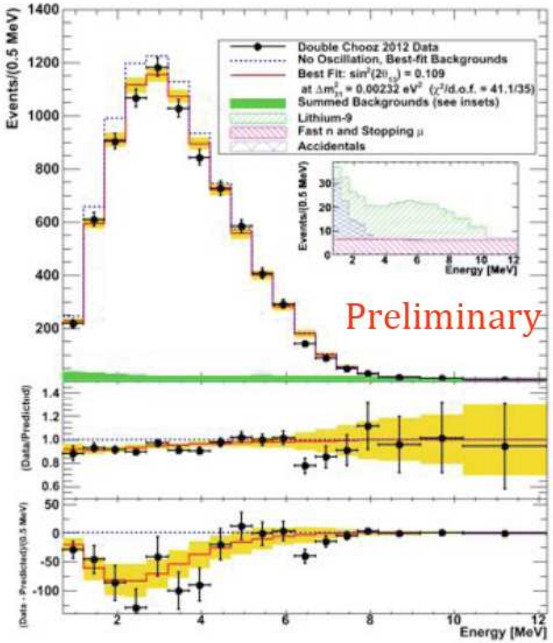
Reno



R= 0.920±0.009±0.014

$\mathrm{Sin}^2 2\theta_{13}$=0.113±0.013±0.019
4. 9σ for non-zero θ_{13}

Double Chooz



$\mathrm{Sin}^2 2\theta_{13}$=0.170±0.035±0.040

$\mathrm{Sin}^2 2\theta_{13}$=0.109±0.030±0.025
2.9 σ for non-zero θ_{13}

CONCLUSIONS

-A non zero, surprisingly large value of the third mixing angle theta 13 has been measured in 2012. The result is important as it opens future searches for violation of CP in lepton sector.

-After 2011 hints for non zero value of theta13 from accelerator experiments, combined data and Double Chooz it is important that today we have:
- convincing results from Daya Bay with the significance of 7.7 sigma reported at Neutrino 2012 (the discovery of non zero value with significance exceeding 5 sigma was announced in March and published)
-observation paper published from RENO (significance close to 5 sigma announced in April and published) and
-latest results from Double Chooz (3 sigma significance reported at Neutrino2012 is now on arXiv).

-One can expect improvements in near future:
- reduction of statistical errors and systematic uncertainties with more data
- shape analyses
- completion of Daya Bay setup (2012)
- near detector at Double Chooz experiment (2013)
….
Already now the three experiments collected several hundred thousands antineutrino interactions and I am convinced that new, interesting analyses will be performed using such unique set of data.