Theta_13 experimental measurements
(reactor neutrinos results)

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

➔non-diagonal Unitary mixing matrix:

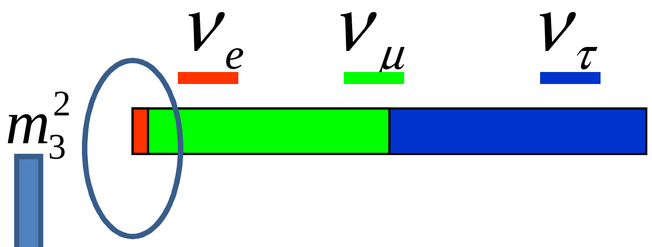
$$U_{fi} \equiv \langle \nu_f | \nu_i \rangle \Rightarrow |\nu_f\rangle = \sum_{i=1}^{3} U^*_{fi} |\nu_i\rangle$$

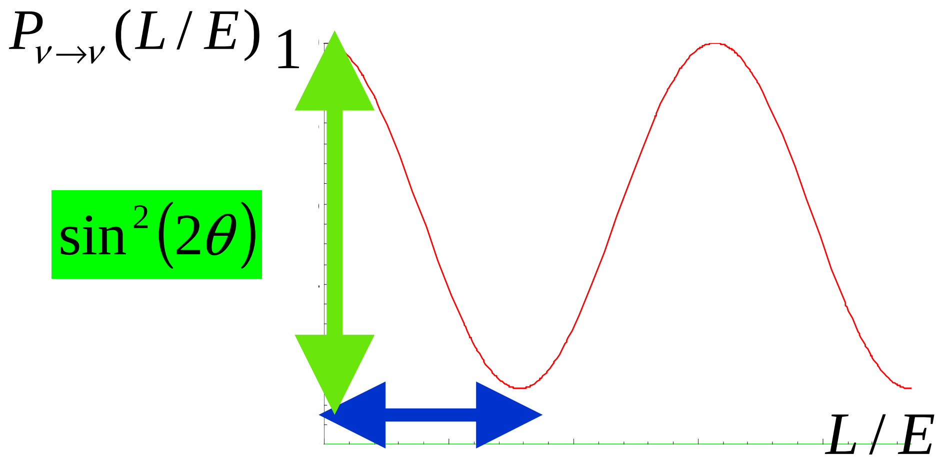
Canonical representation of Pontecorvo-Magi-Nakagawa-Sakata mixing matrix is done by ordered product of 12, 13 and 23 rotations, one CP phase δ connected to the smallest mixing angle θ_{13} and two Majorana phases $\alpha_{1,2}$ (irrelevant for oscillations)

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

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

$\theta_{23} \cong 45^o$, $\theta_{13} \cong 9^o$, $\theta_{12} \cong 34^o$

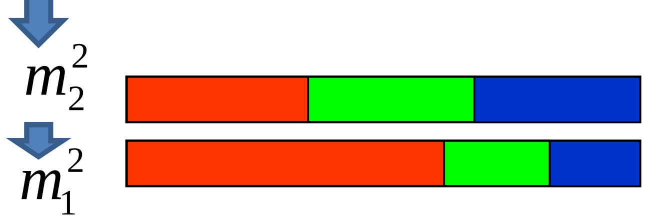




$$(L/E)_{1stMINIMUM} = (\pi/2)4\hbar c/\Delta m^2$$
$$\approx 0.5\,km/MeV = 500\,km/GeV$$
$$\approx 15\,km/MeV = 15000\,km/GeV$$

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

$$|m_3^2 - m_1^2| \cong 2.32\times10^{-3} eV^2$$
$$m_2^2 - m_1^2 \cong 7.59\times10^{-5} eV^2$$



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

Disappearance probabilty

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

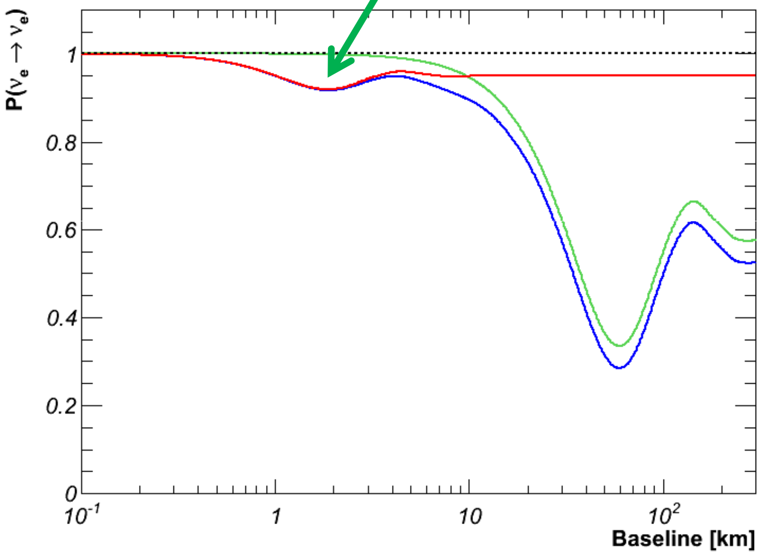
Disappearance probabilty for electron (anti)neutrinos:

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

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

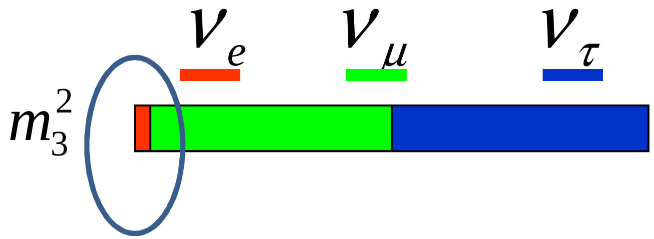
$$1 - \sin^2(2\theta_{13}) \sin^2\left(1.267 \Delta m_{31}^2 [eV^2] \frac{x[m]}{E[MeV]}\right)$$

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



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

Mixing angle θ13



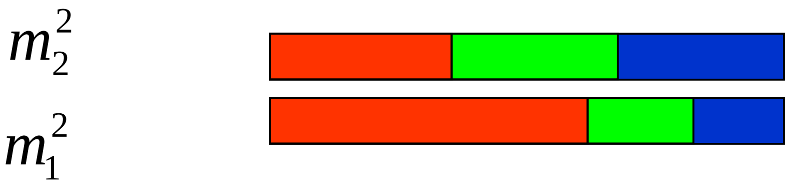
$\sin^2(\theta_{13}) = |U_{e3}|^2$ (~2.3%)

is the fraction of electron neutrino in the mass eigenstate m3

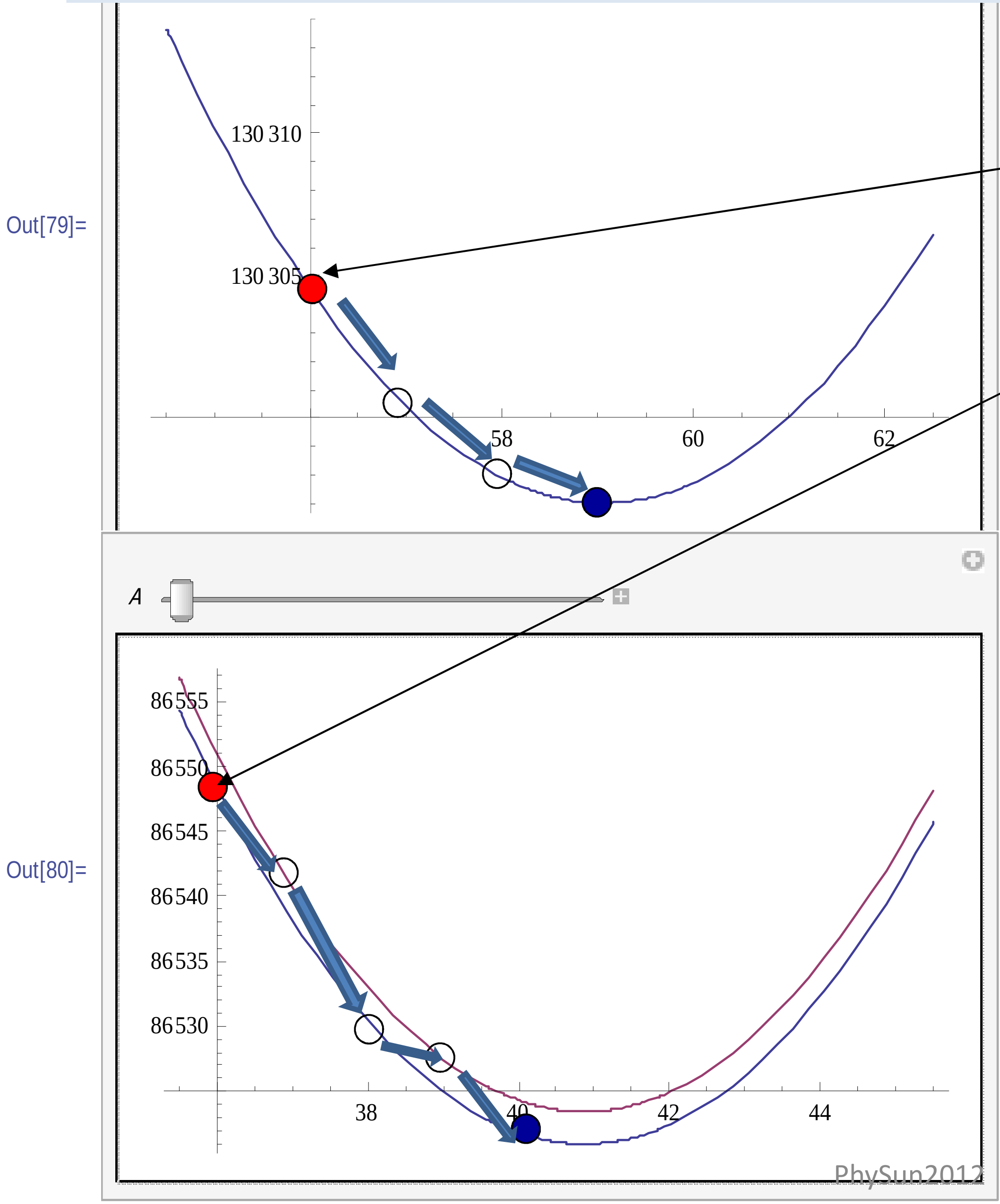
Two ways to measure θ13
(measurements at small values of L/E~0.5km/MeV = 500 km/GeV)

-To measure reactor electron antineutrino disappearance

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



Nuclear reactors are powerful sources of electron antineutrinos



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

~3 neutrons are released in one fission, however fission products are still neutron rich.

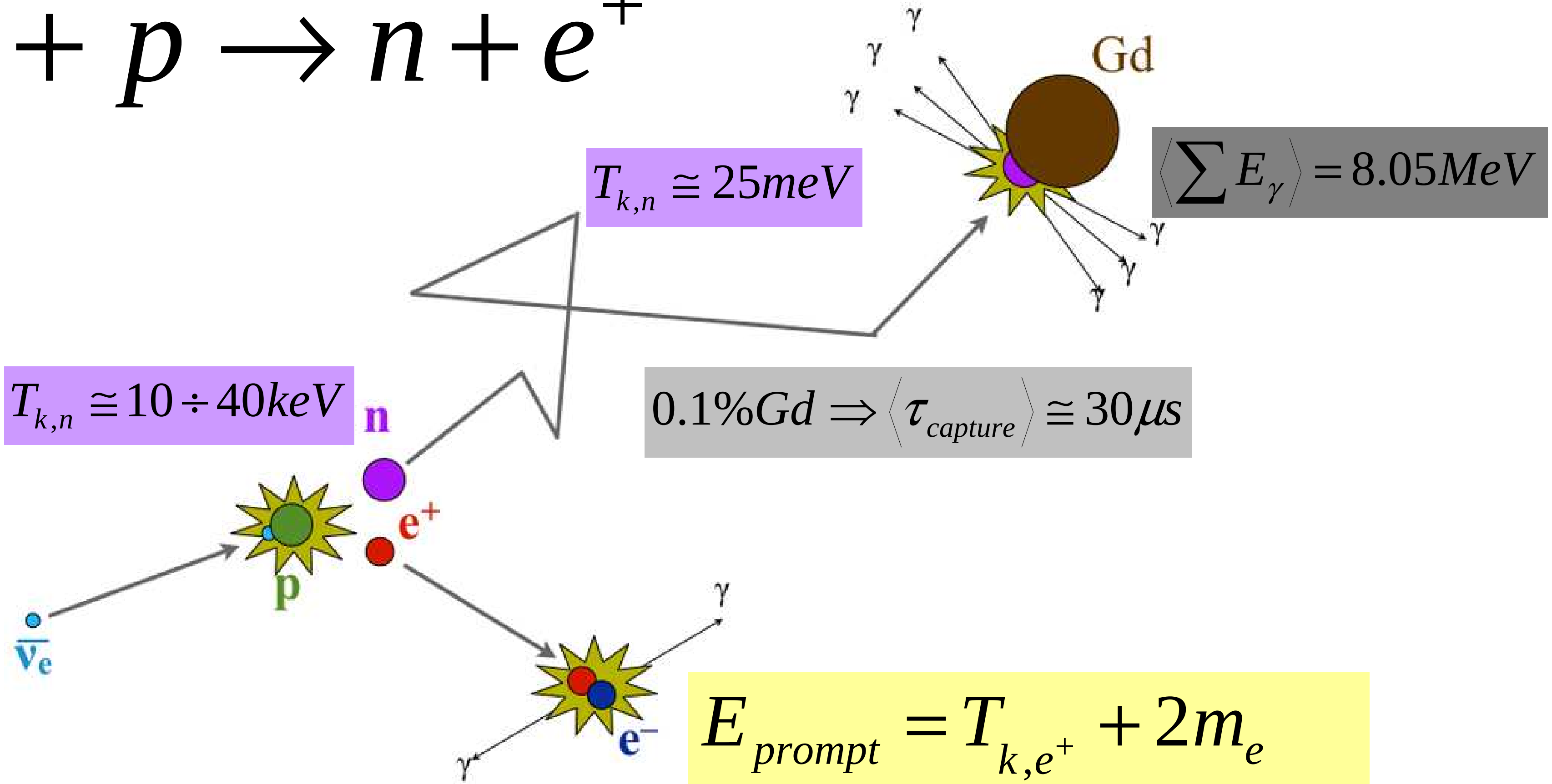
The valley of stability is reached by series of beta- decays.

In average **~6 electron antineutrinos** are produced per fission.

$$2 \cdot 10^{20} \bar{\nu}_e / s / GW_{th}$$

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

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



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

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

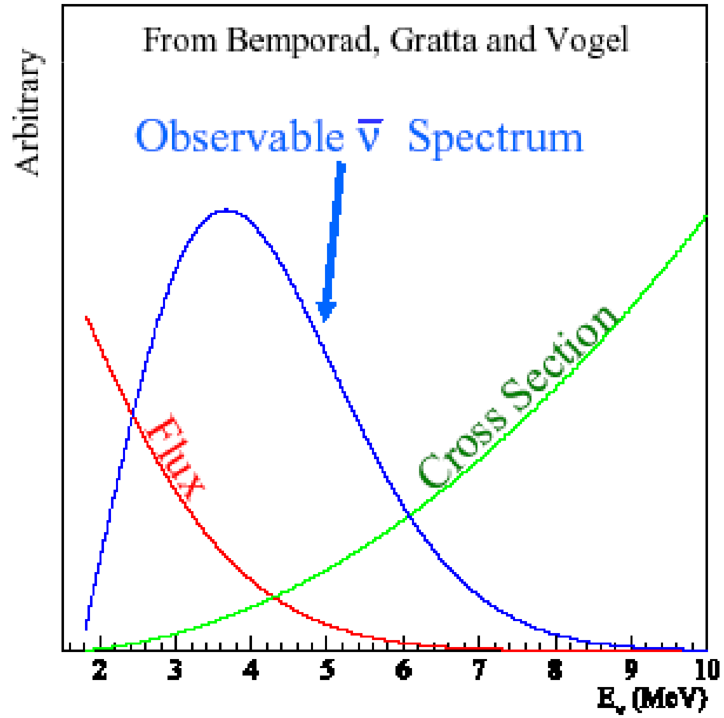
Detection of antineutrinos: Inverse Beta Decay (IBD)

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

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

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

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

${}^{A}_{64}Gd$	$\sigma_{n+{}^{A}_{64}Gd \rightarrow {}^{A+1}_{64}Gd^{*}}$ [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

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

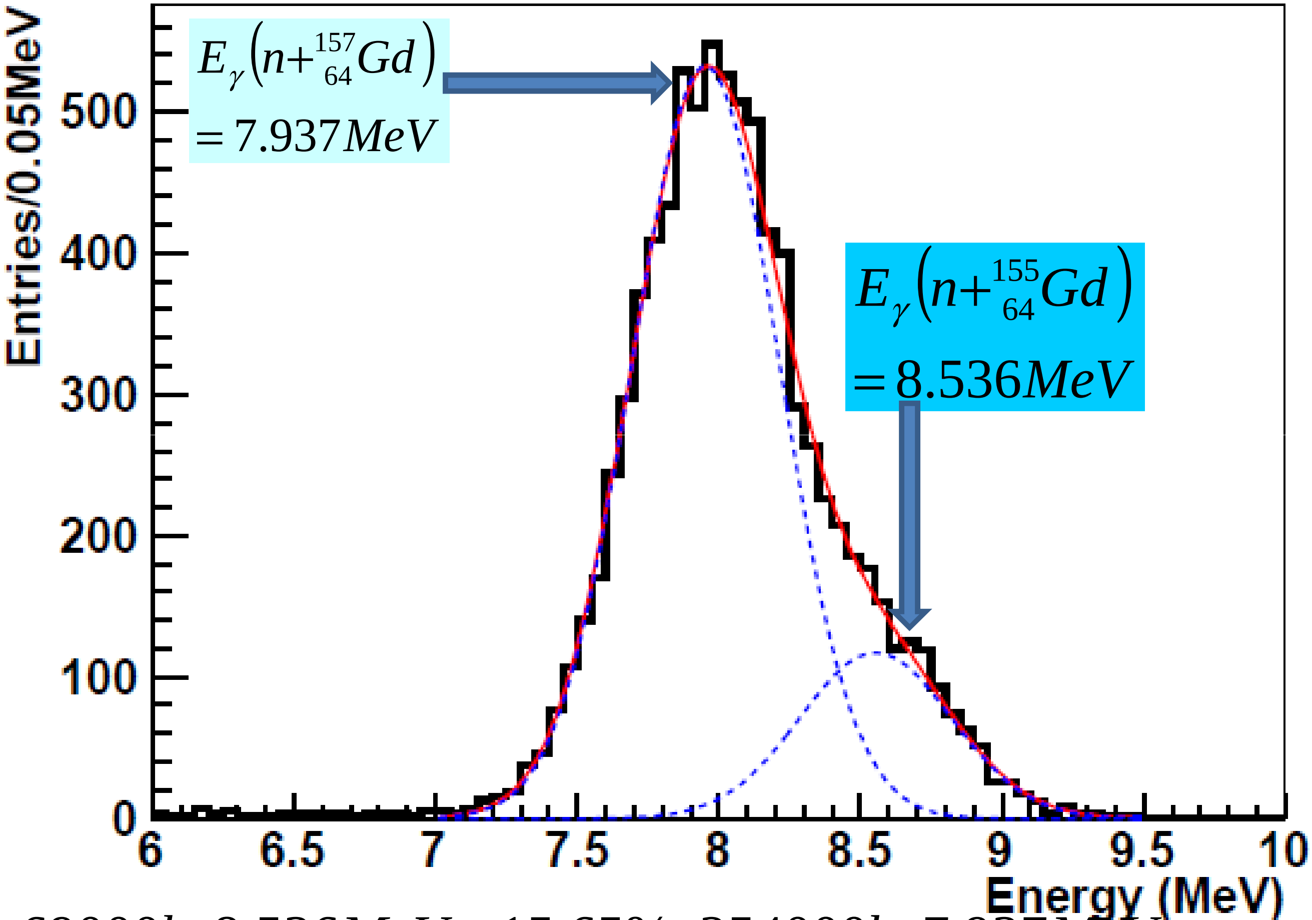
$$\sum E_{\gamma}\left(n + {}^{157}_{64}Gd\right) = 7.937\,MeV$$

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

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

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

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



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

Three running experiments

Daya Bay, China

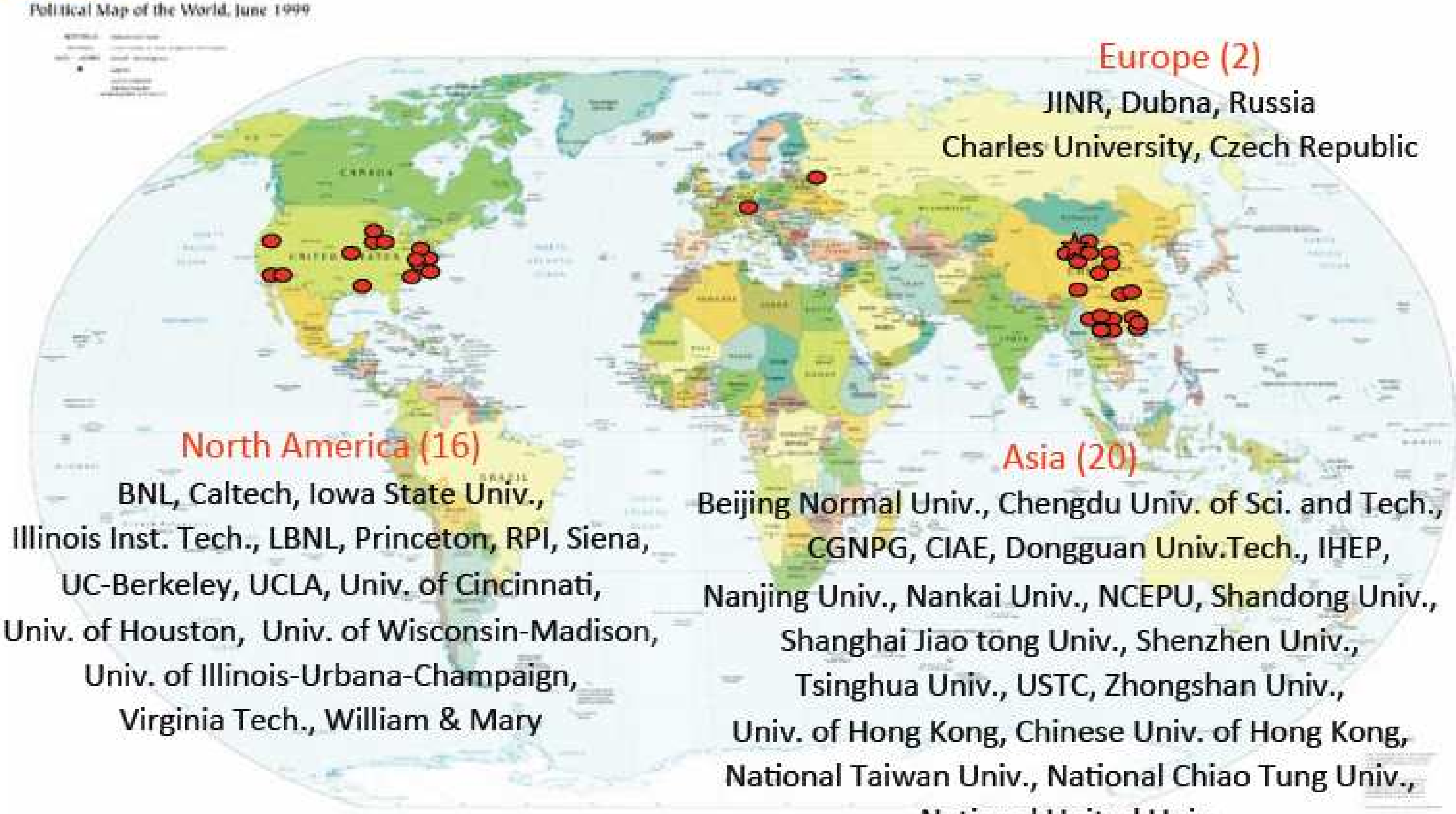
6 reactors:
17.4 GW total
(thermal) power

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 are installed and commissioned this year.

The Daya Bay Collaboration



Europe (2)

JINR, Dubna, Russia
Charles University, Czech Republic

North America (16)

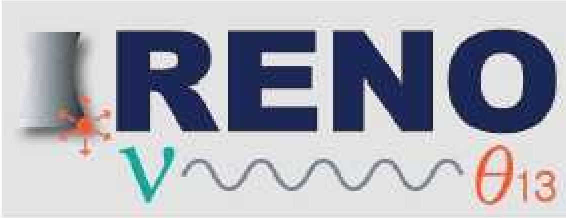
BNL, Caltech, Iowa State Univ., Illinois Inst. Tech., LBNL, Princeton, RPI, Siena, UC-Berkeley, UCLA, Univ. of Cincinnati, Univ. of Houston, Univ. of Wisconsin-Madison, Univ. of Illinois-Urbana-Champaign, Virginia Tech., William & Mary

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

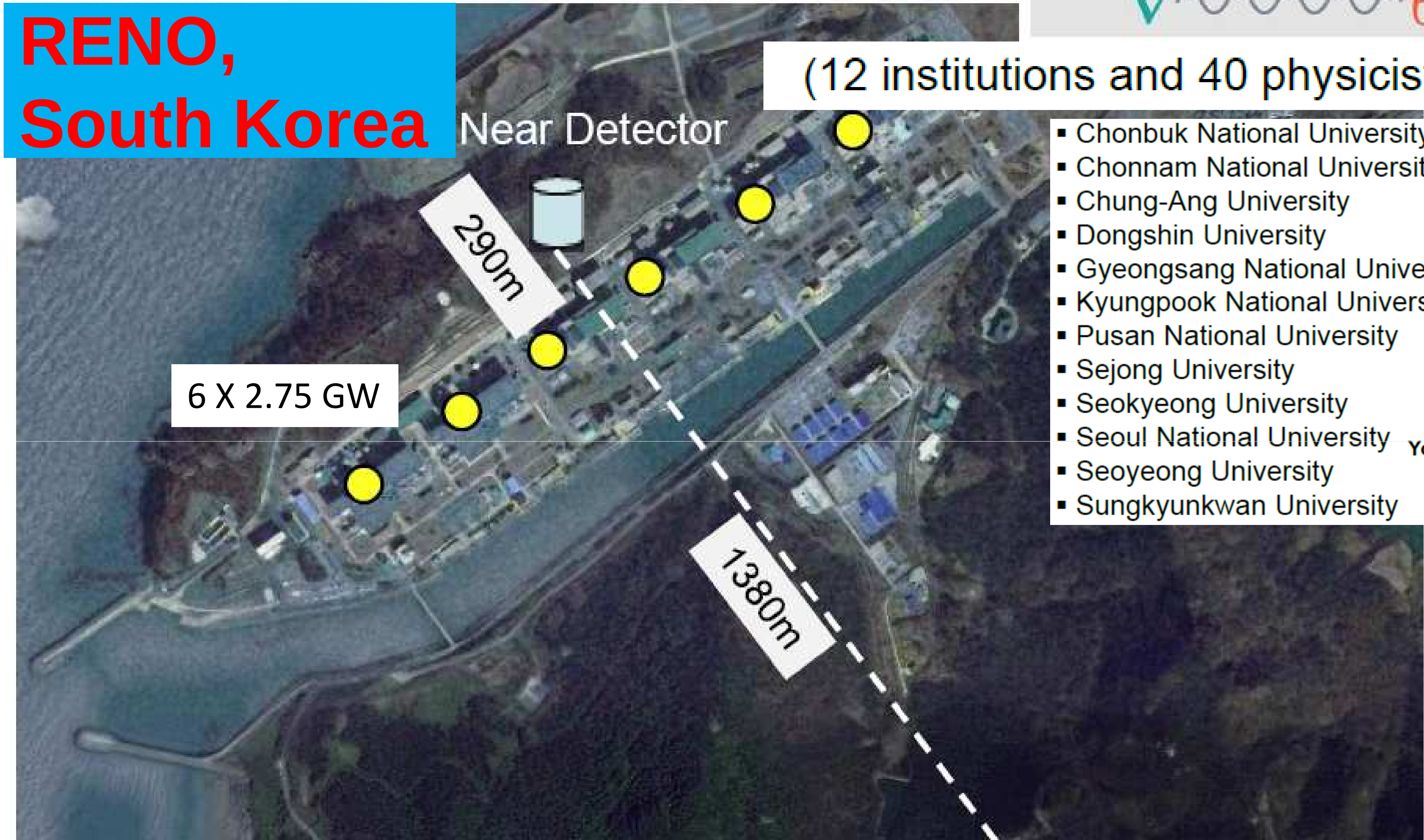
Three running experiments

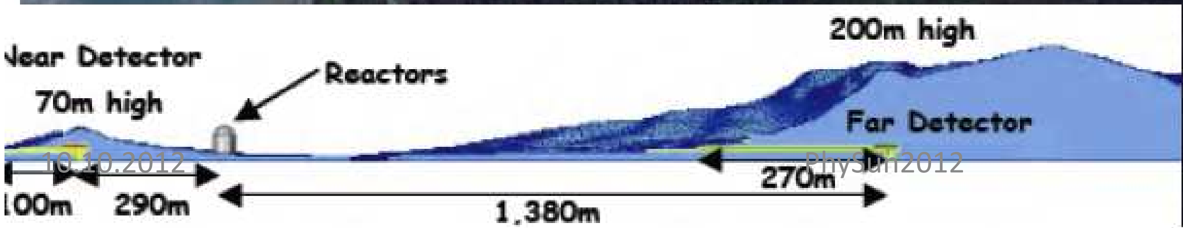


RENO, South Korea

(12 institutions and 40 physicists)

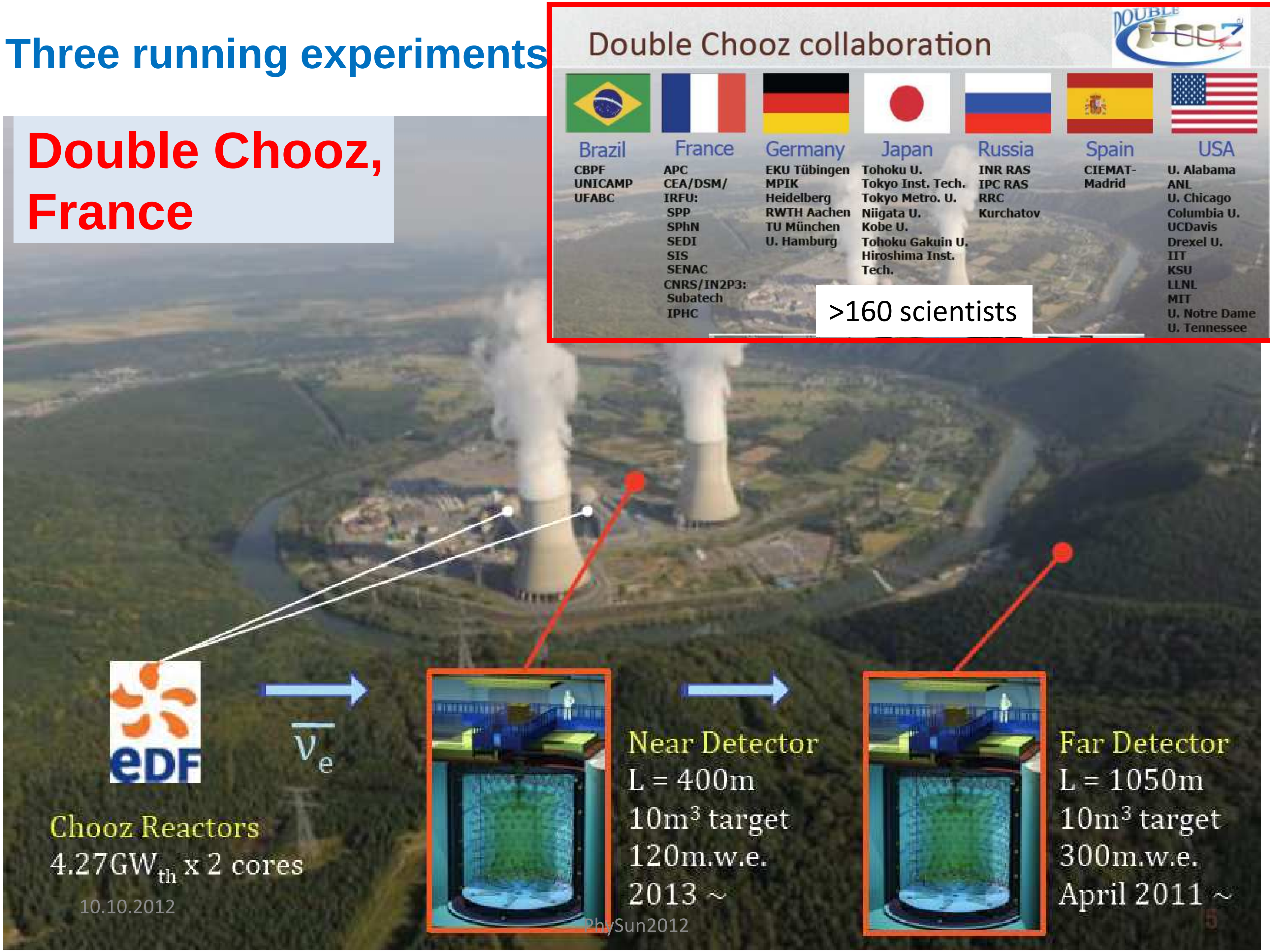
- Chonbuk National University
- Chonnam National University
- Chung-Ang University
- Dongshin University
- Gyeongsang National University
- Kyungpook National University
- Pusan National University
- Sejong University
- Seokyeong University
- Seoul National University
- Seoyeong University
- Sungkyunkwan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





Three running experiments

Double Chooz, France



Three running experiments

	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	2x20, 20 / 3x20 *(2x20, 2x20/4x20)*	250, 265/860	~ 0.008
RENO	16.5	409/1444	16 / 16	120/450	~ 0.02

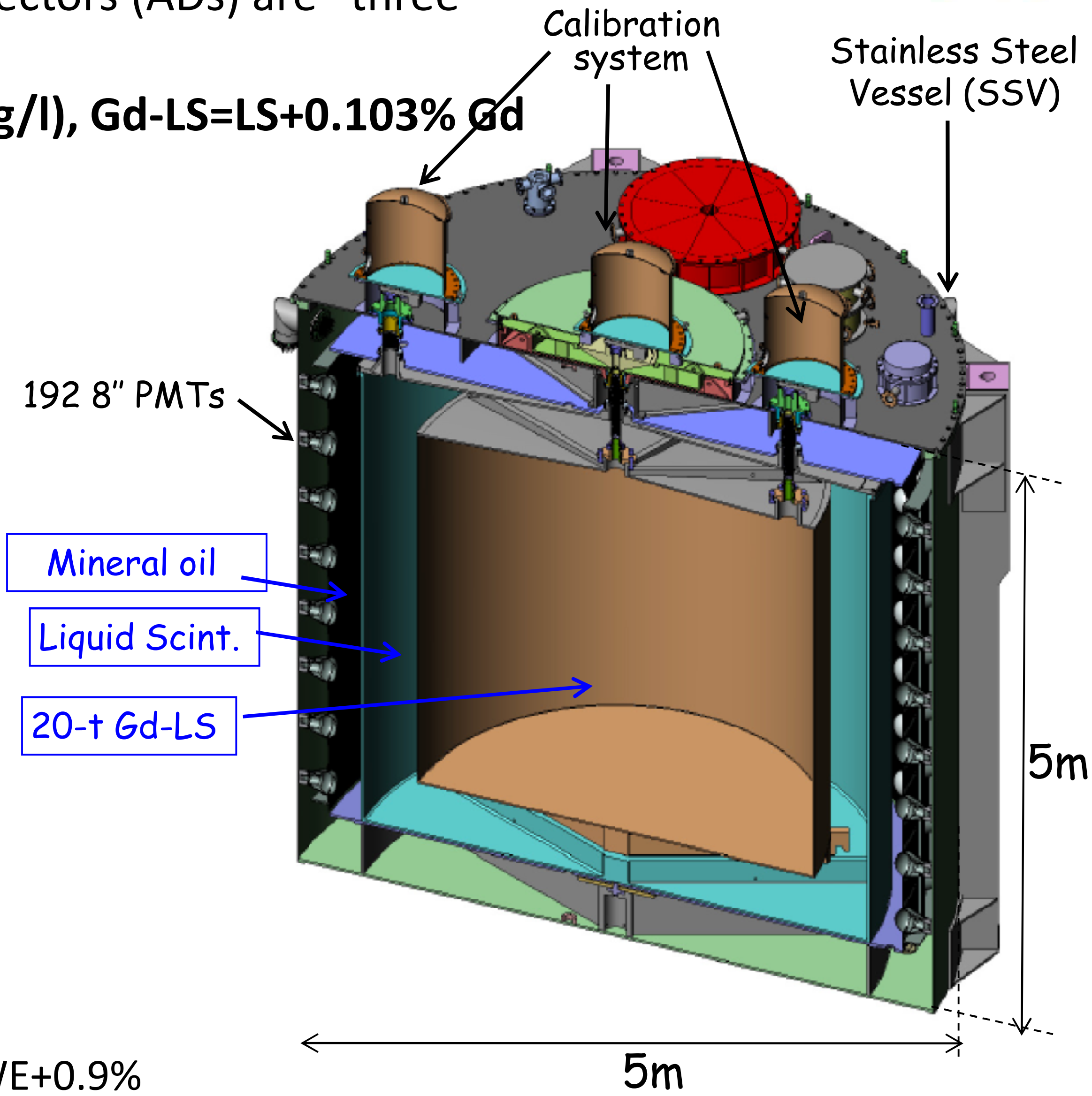
The experiments are constructed following the concept of two identical near/far detecors proposed by:
L.Mikaelyan and V.V.Sinev [Phys.Atom.Nucl.63:1002-1006,2000; Yad.Fiz.63N6:1077-1081,2000]

Anti-neutrino detectors

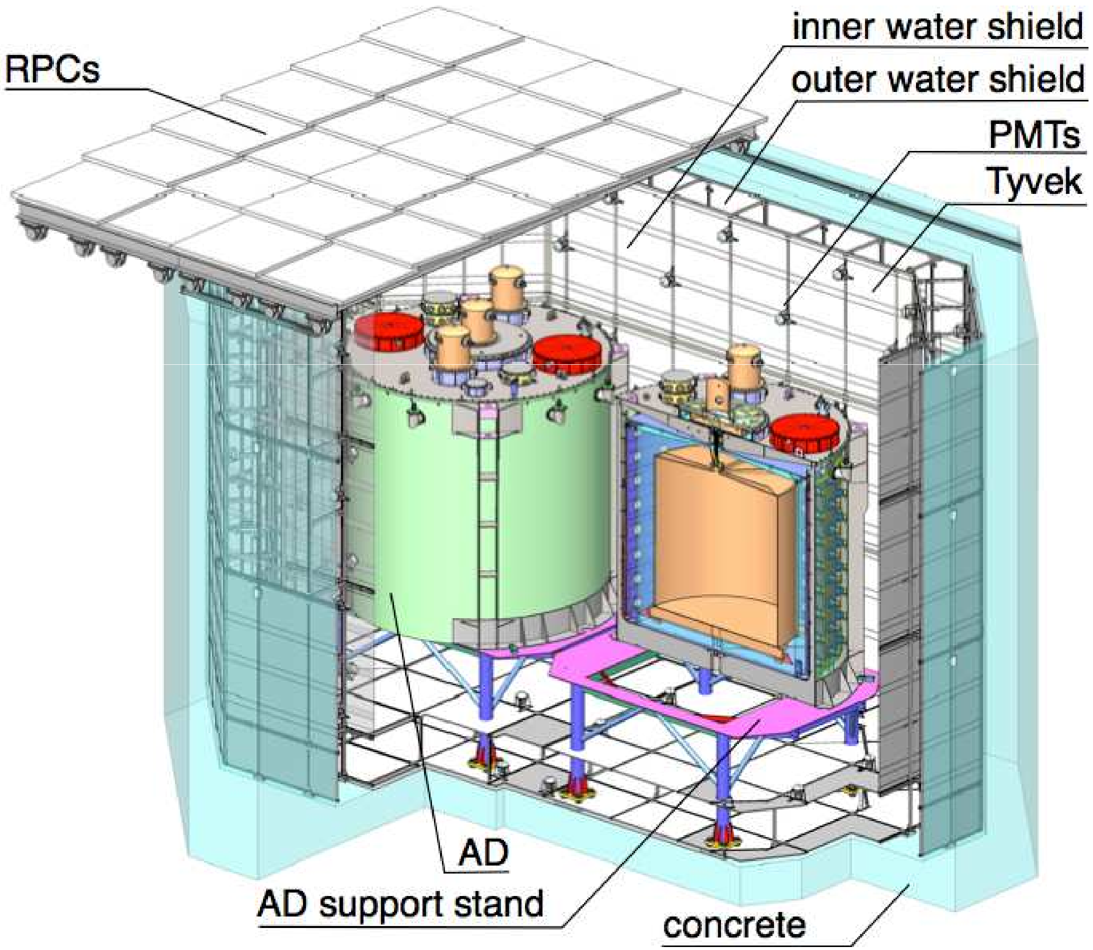
- The Daya Bay anti-neutrino detectors (ADs) are "three-zone" cylindrical modules.
- **LS=LAB+PPO(3 g/l)+MSB(15 mg/l), Gd-LS=LS+0.103% Gd**
  - Zones are separated by acrylic vessels:

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	37 t	Mineral Oil	Radiation shielding

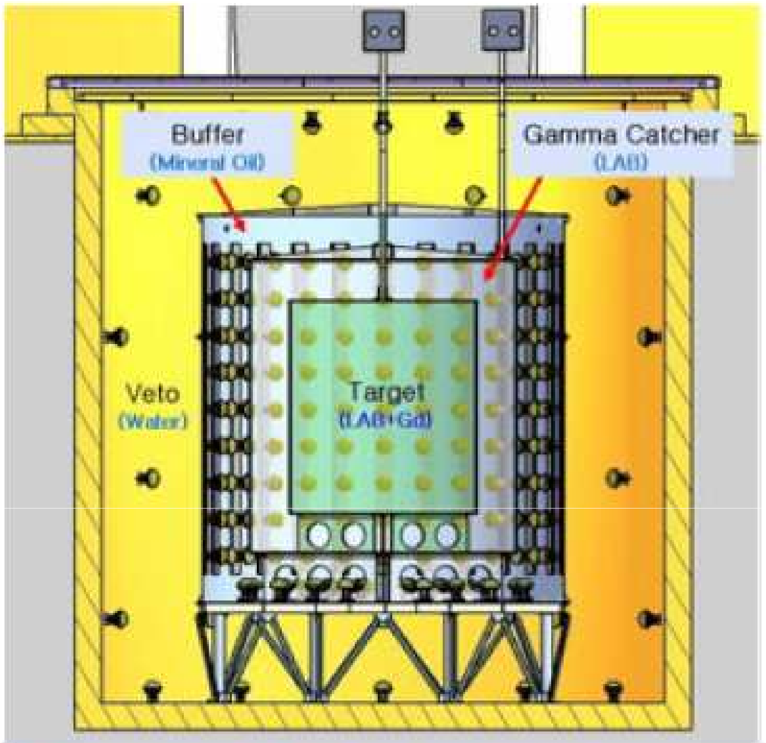
  - Top and bottom reflectors are used to increase light yield
  - Energy resolution: $\sigma_E/E = 7.5\%/\sqrt{E}+0.9\%$



- 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

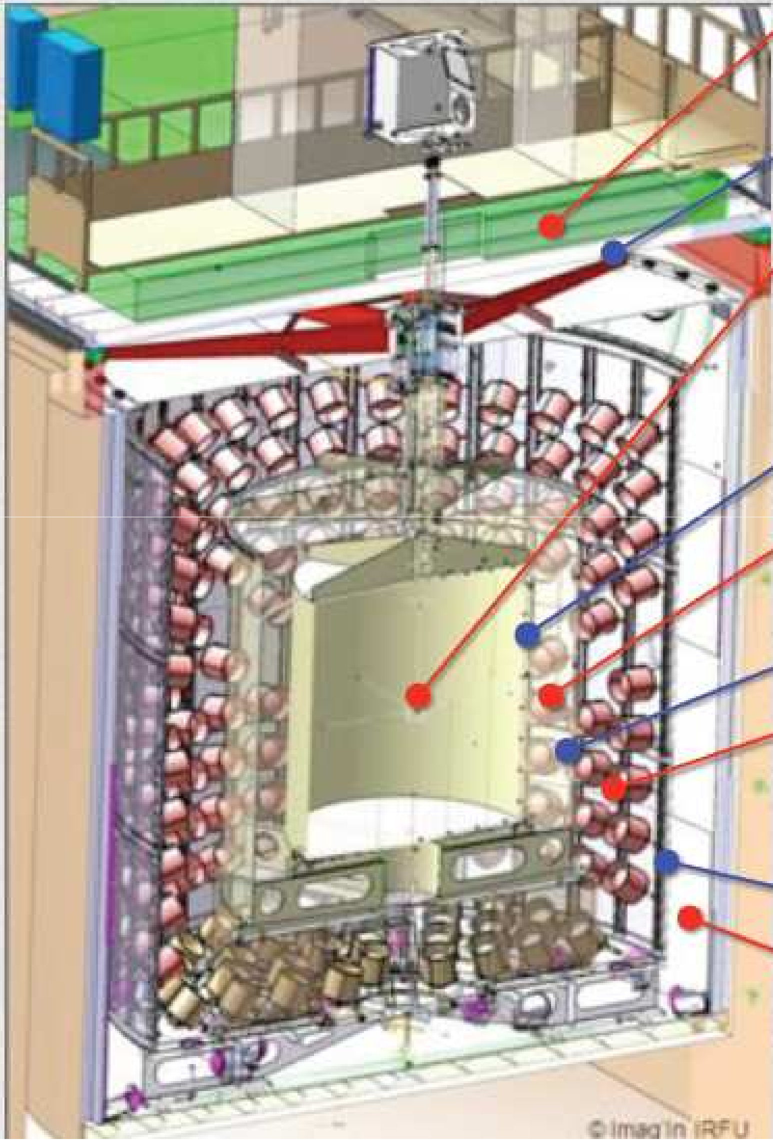


RENO Detector



- 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



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

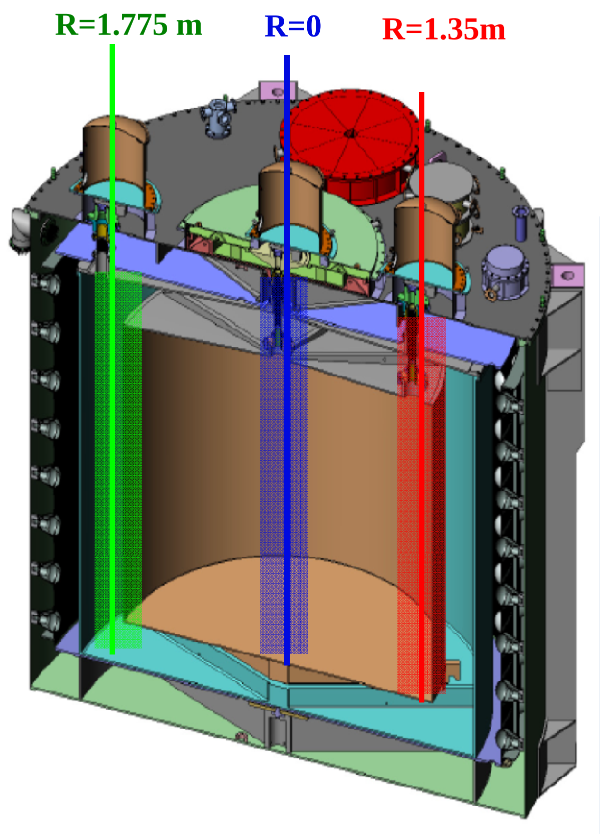
Detector calibration

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 → Timing, gain and relative QE

  (Energy calibration (linearity, detector response… etc) for the first three sources)

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



Automated Calibration Units (Daya Bay)

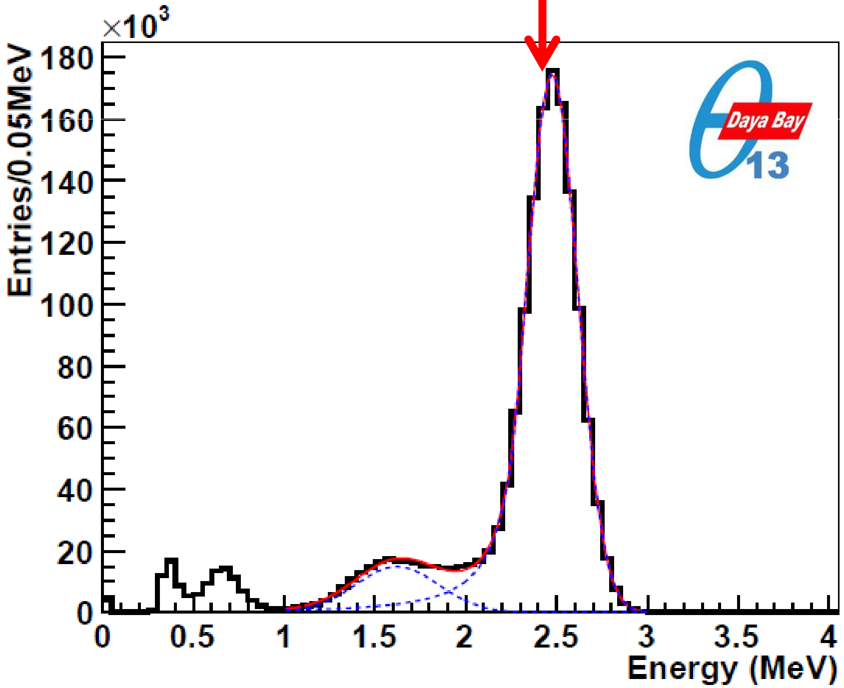
Three calibration units per detector that deploy sources along z-axis

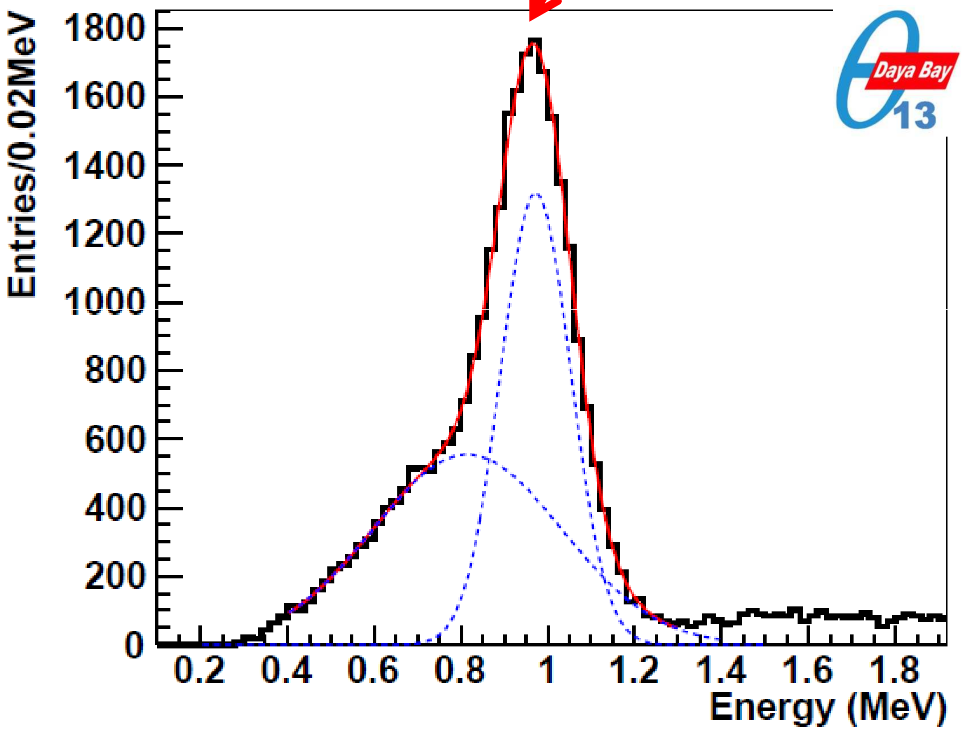
$$^{68}_{32}Ge \xrightarrow[E.C.\,276d]{} {}^{68}_{31}Ga \xrightarrow[\beta+\,68m]{} {}^{68}_{30}Zn$$

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

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

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





ENERGY RESOLUTION

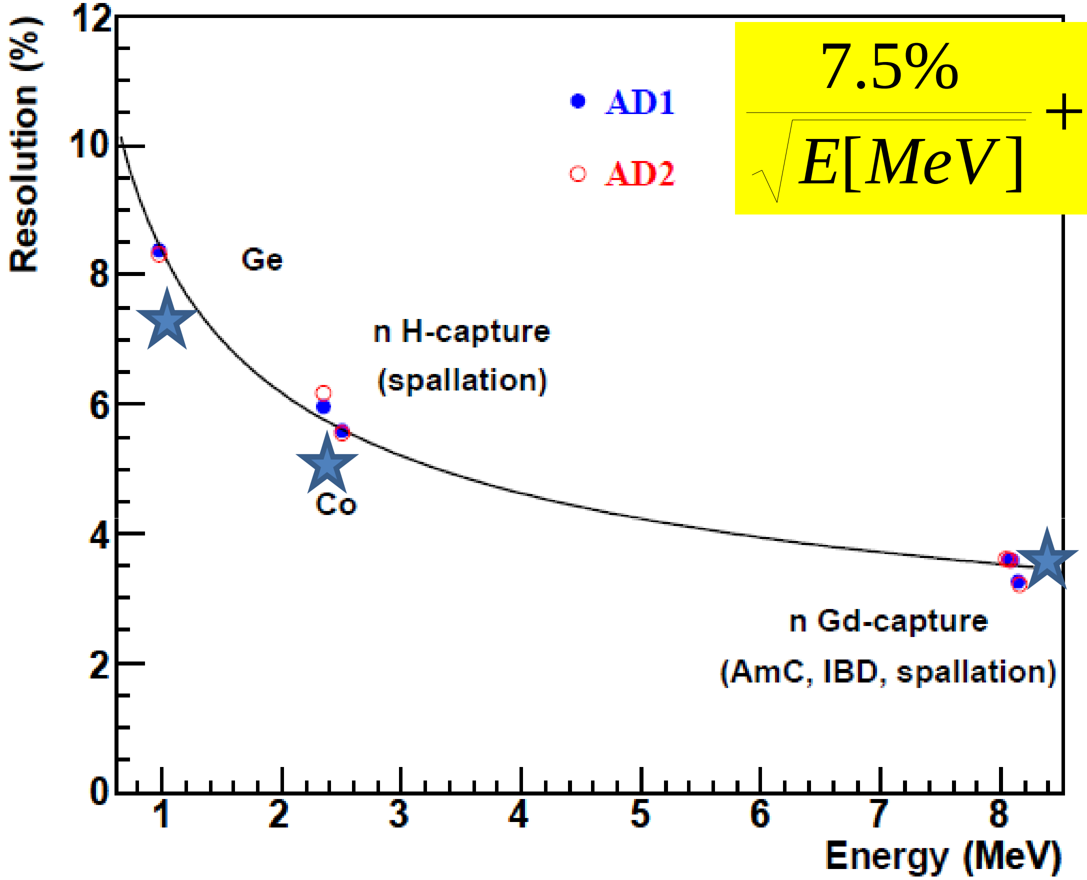


Figure 25: Resolution of reconstructed energy.

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

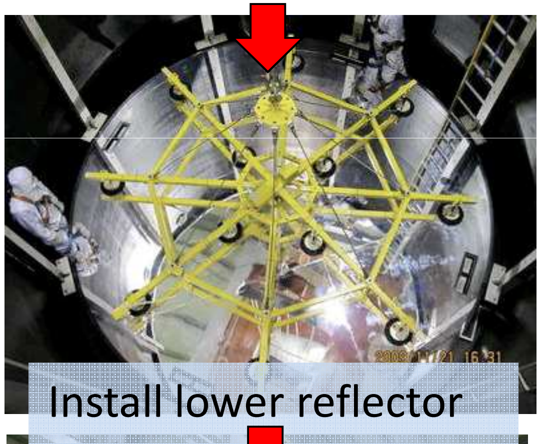
RENO ★

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

Assembly of Anti-neutrino detectors

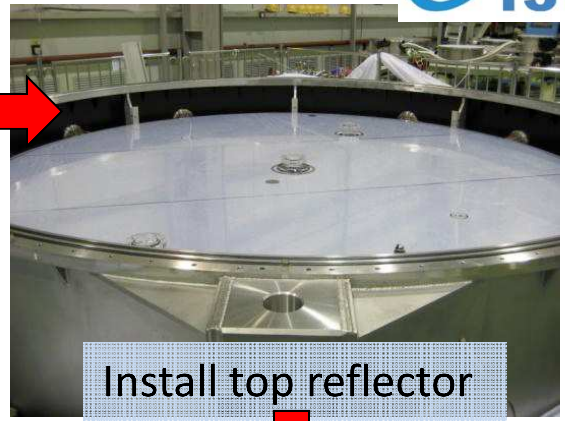
ADs are assembled in clean-room


Stainless Steel Vessel (SSV) in assembly pit


Install lower reflector


Install Acrylic Vessels

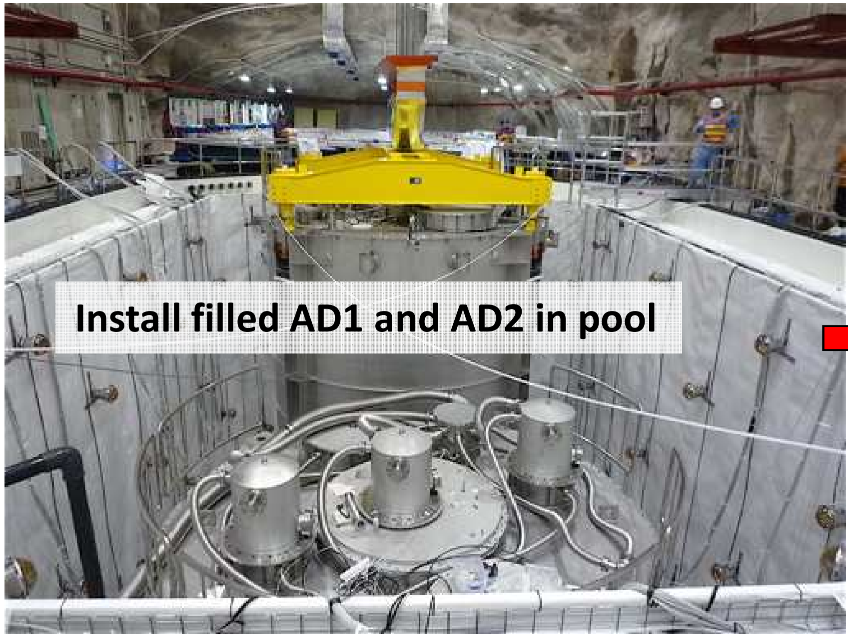

Install PMT ladders

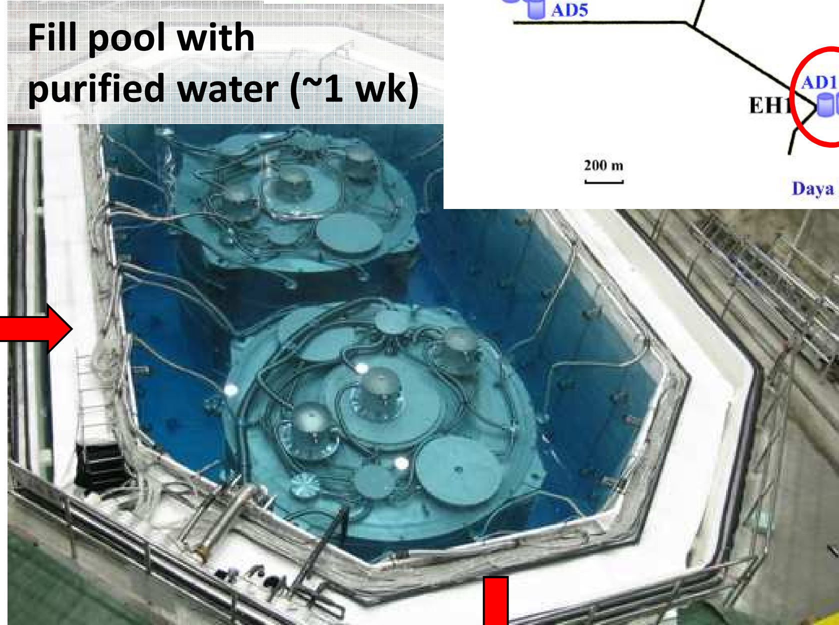

Install top reflector

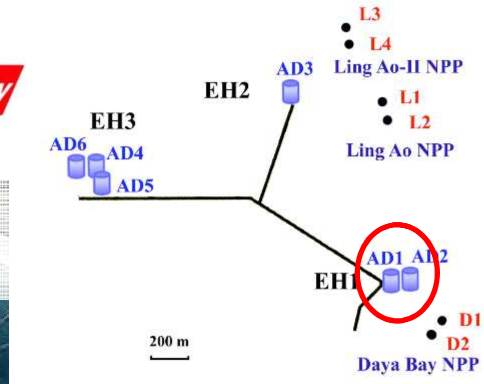

Close SSV lid


Install calibration units

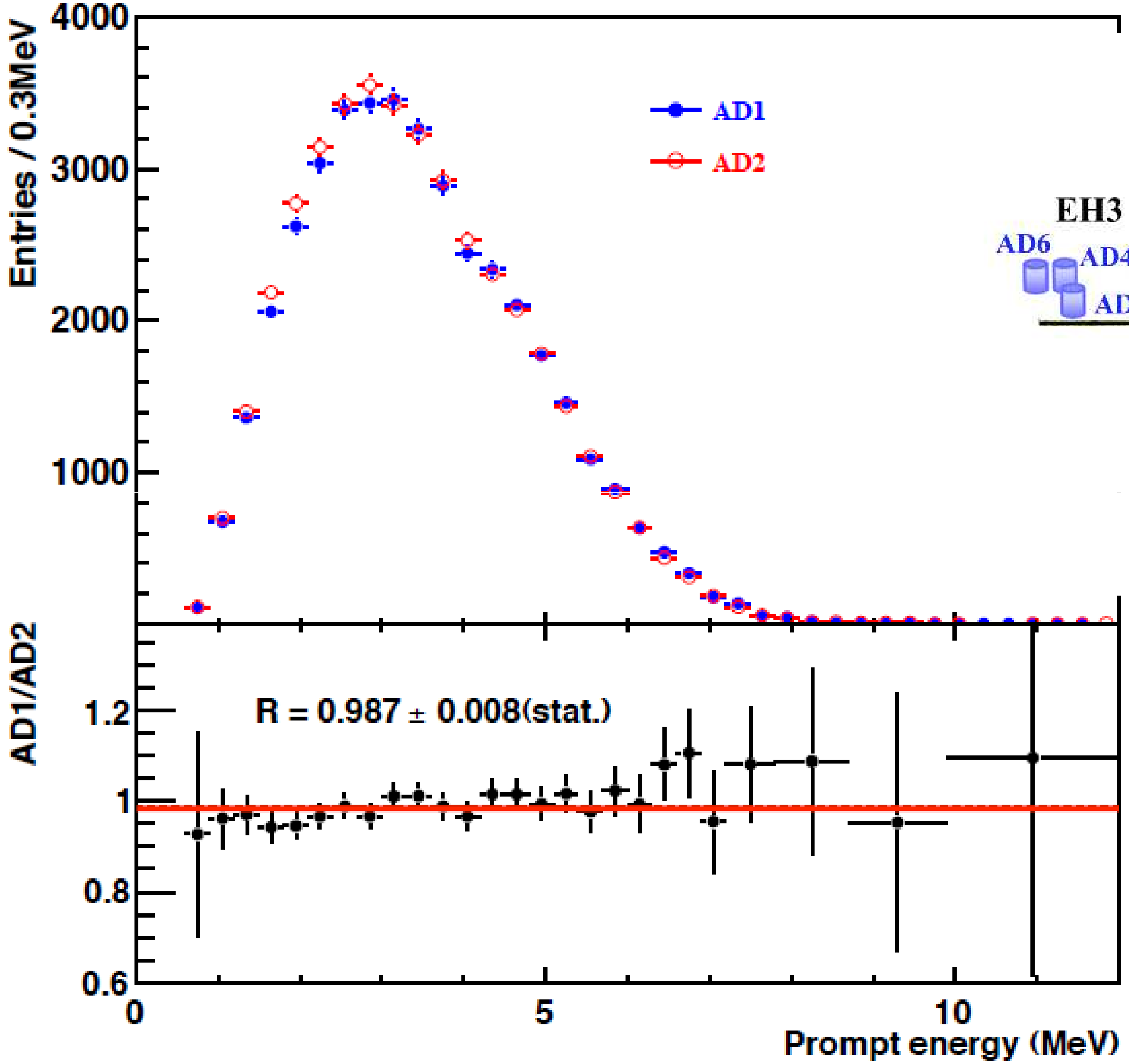
Near Hall (EH1) Installation

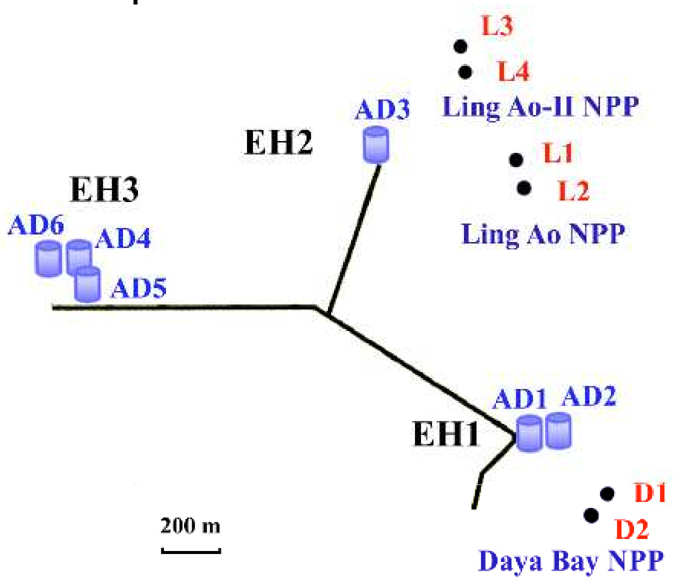






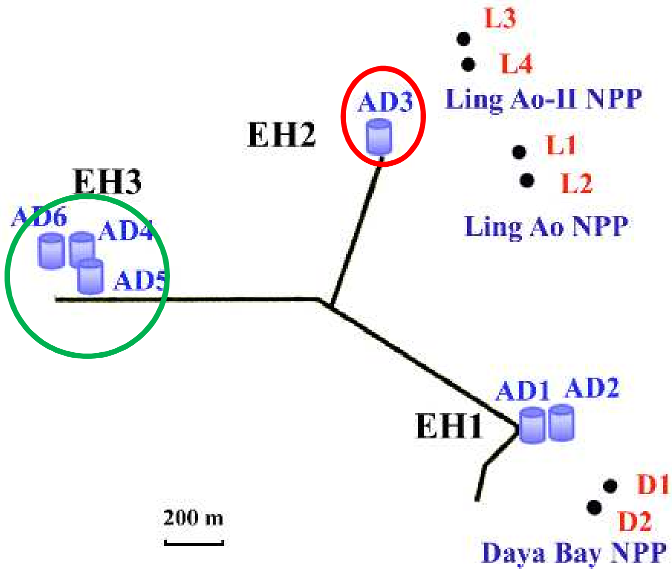
Detailed comparison of AD1 and AD2





R=0.982 expected
AD1 is few m farther from power plant than AD2

Ling Ao (EH2) and Far (EH3) Halls

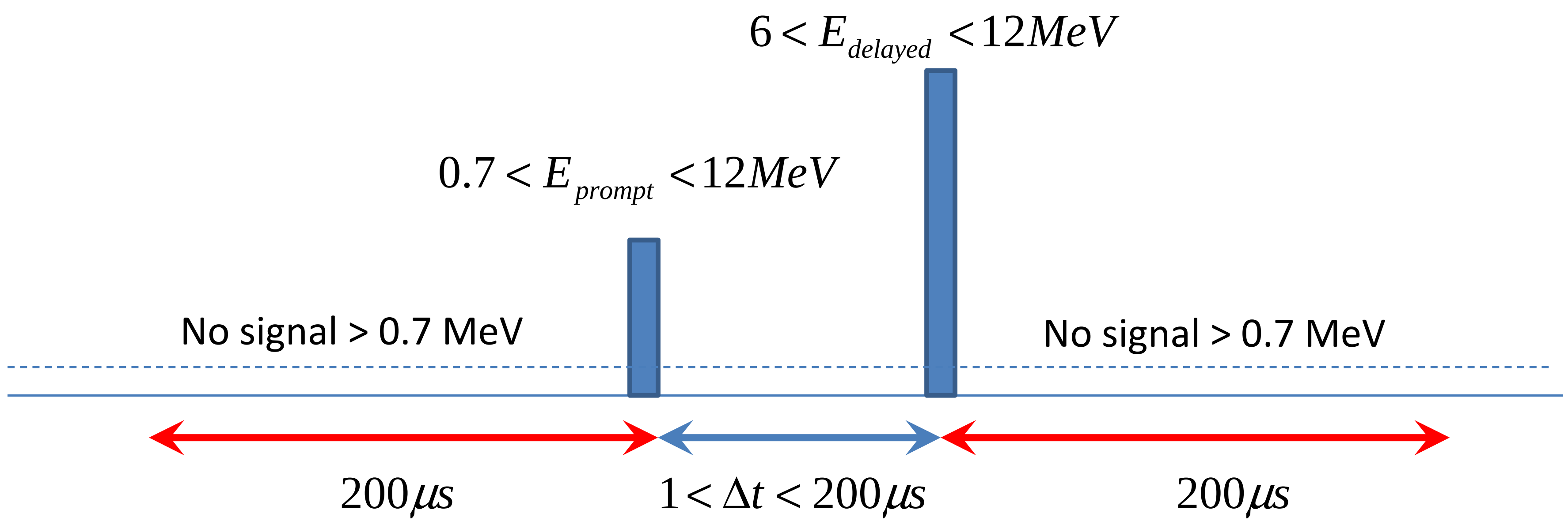


➢ **Remaining two ADs are now installed**

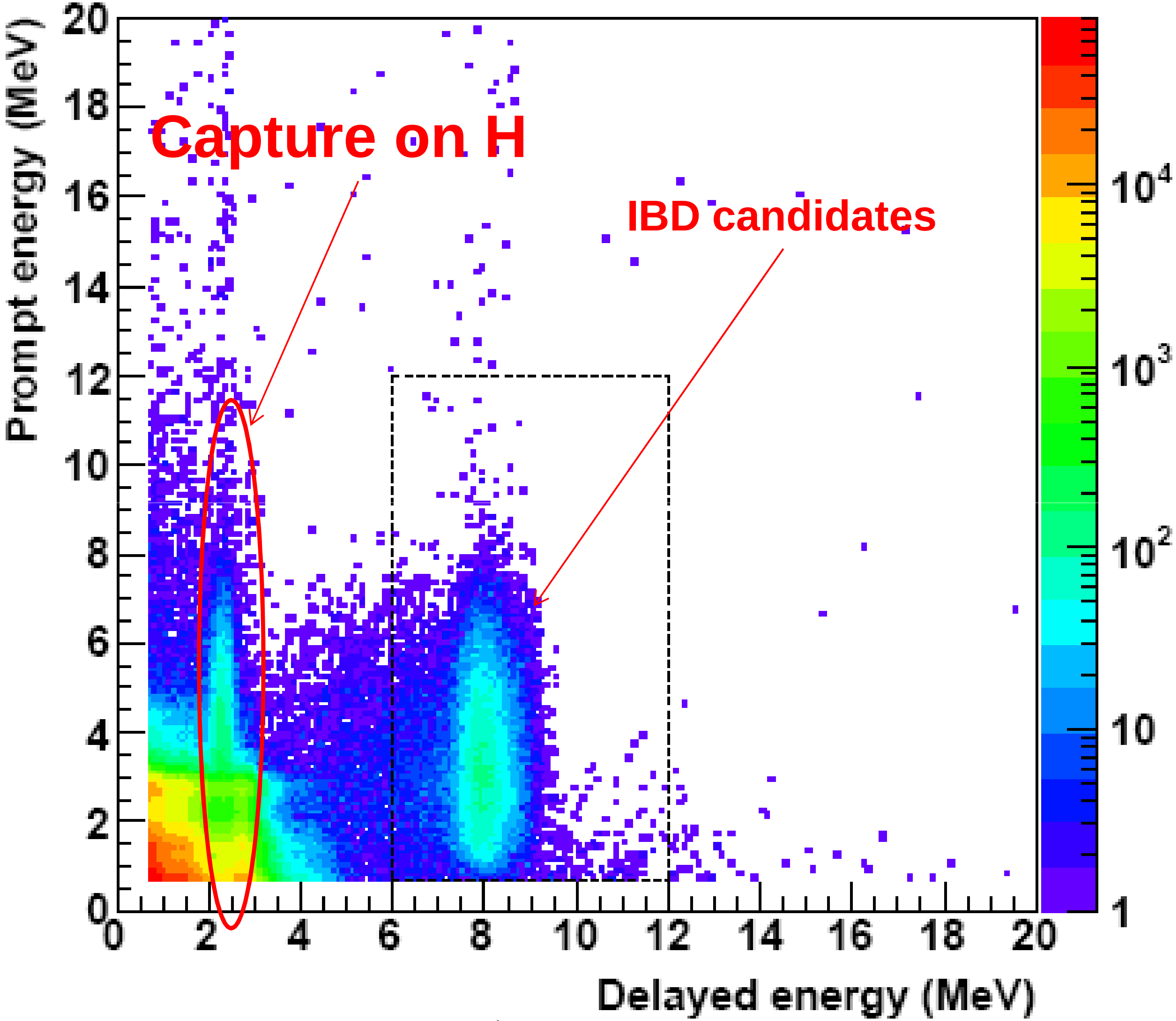
EH2 (Ling Ao Near Hall):
Began operation on 5 Nov 2011

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

Inverse Beta Decay Events Selection

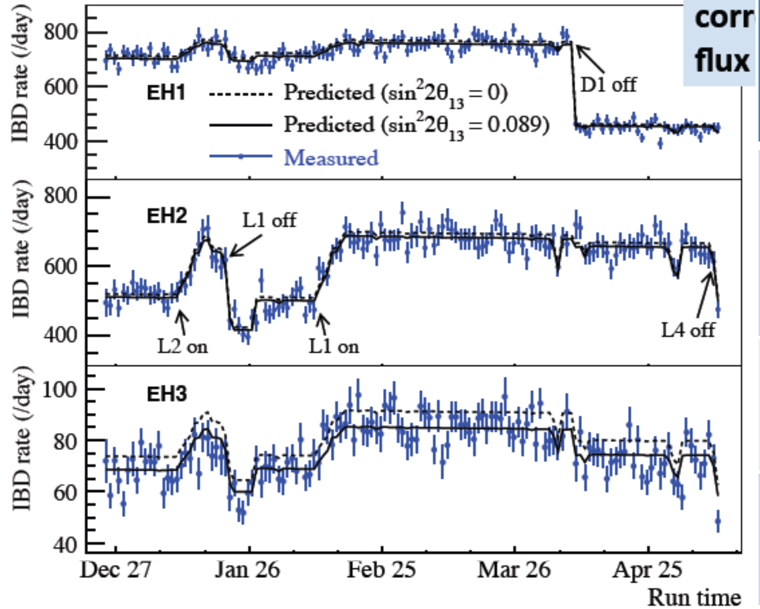


- **Prompt-delayed coincidence:**
  - Prompt positron: 0.7 MeV < E_p < 12 MeV (DYB, RENO), 12.2 MeV (Double Chooz)
  - Delayed neutron: 6.0 MeV < E_d < 12 MeV (DYB, RENO, Double Chooz)
  - Capture Time: 1 μs < Δt< 200 μs (DYB), 2 μs < Δt< 100 μs (Double Chooz,RENO)
- **Multiplicity:**
  - No signal 200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



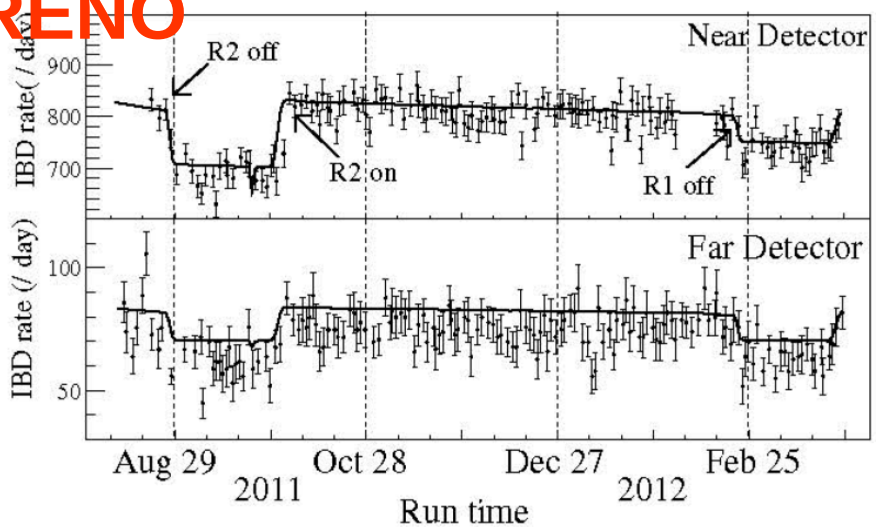
Capture on H
IBD candidates
Prompt energy (MeV)
Delayed energy (MeV)
0
2
4
6
8
10
12
14
16
18
20
1
10
10^2
10^3
10^4

Antineutrino Rate vs. Time

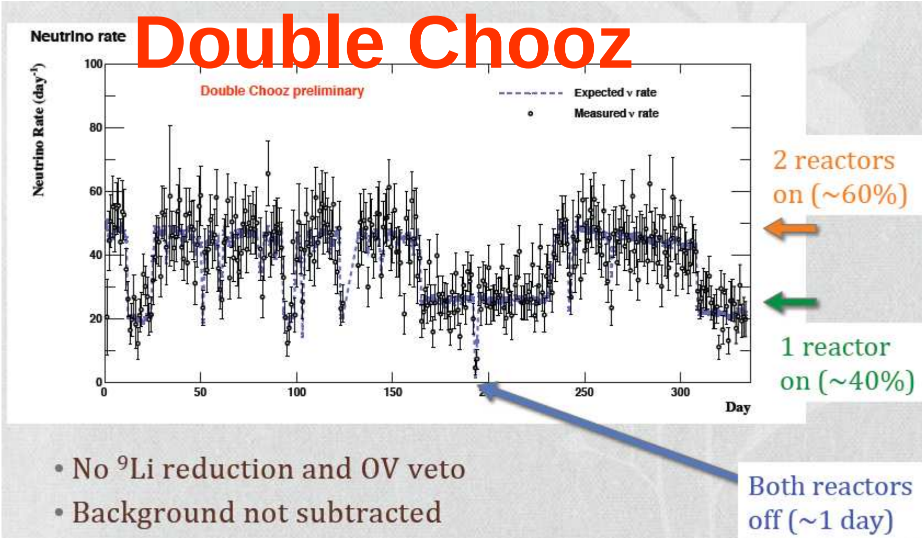


IBD candidates/day and total	Near	Far
Daya Bay	662+671(EH1) 614 (EH2) **Total = 205 308**	78+77+75 **Total = 28 909**
Double Chooz		~40 **Total = 8 249**
RENO	779 **Total = 154 088**	73 **Total = 17 102**

RENO



Double Chooz

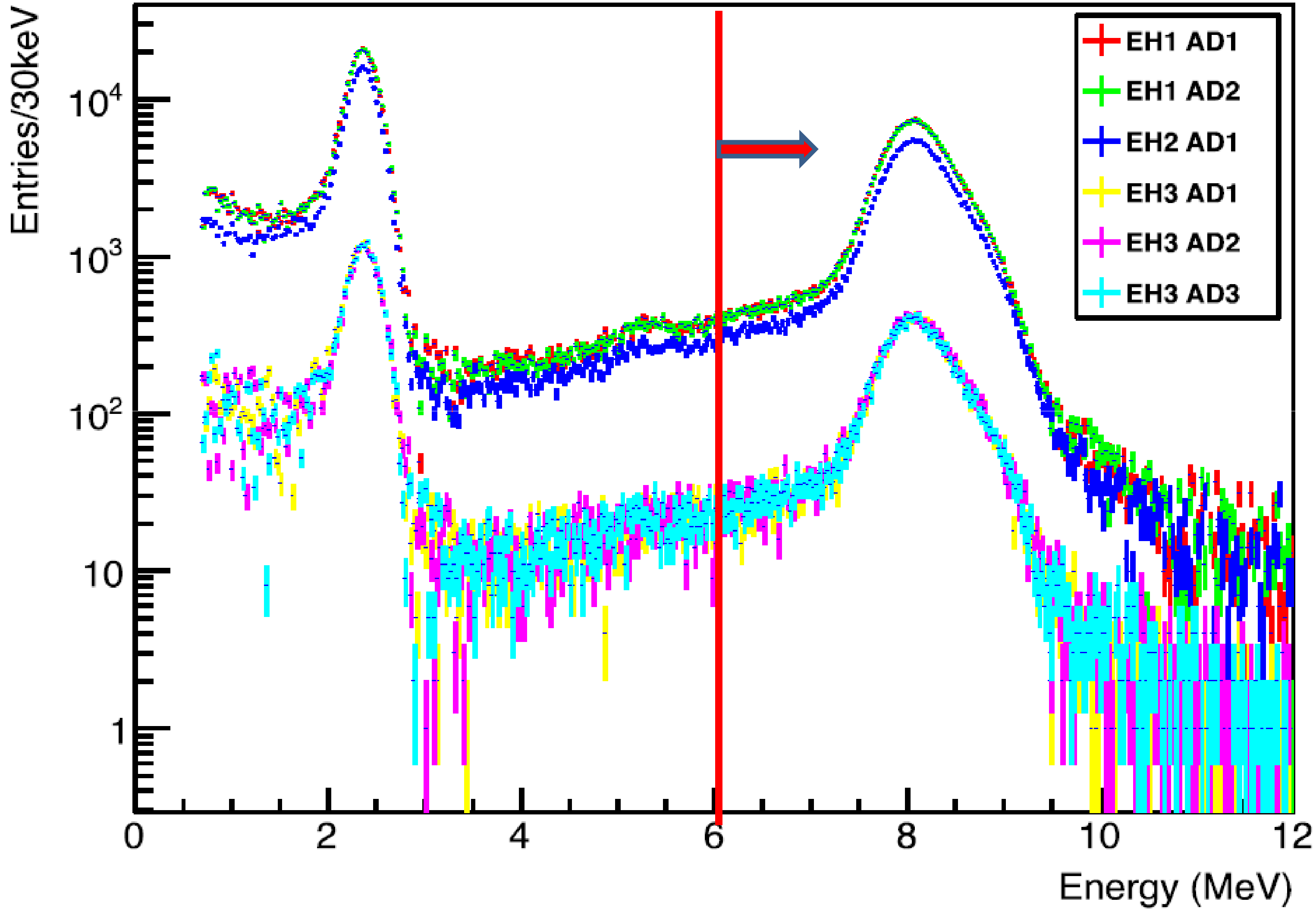


- No ^{9}Li reduction and OV veto
- Background not subtracted
- Neutrino rate consistent with expectation

Detector related 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

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

$$\sim 28\mu s$$

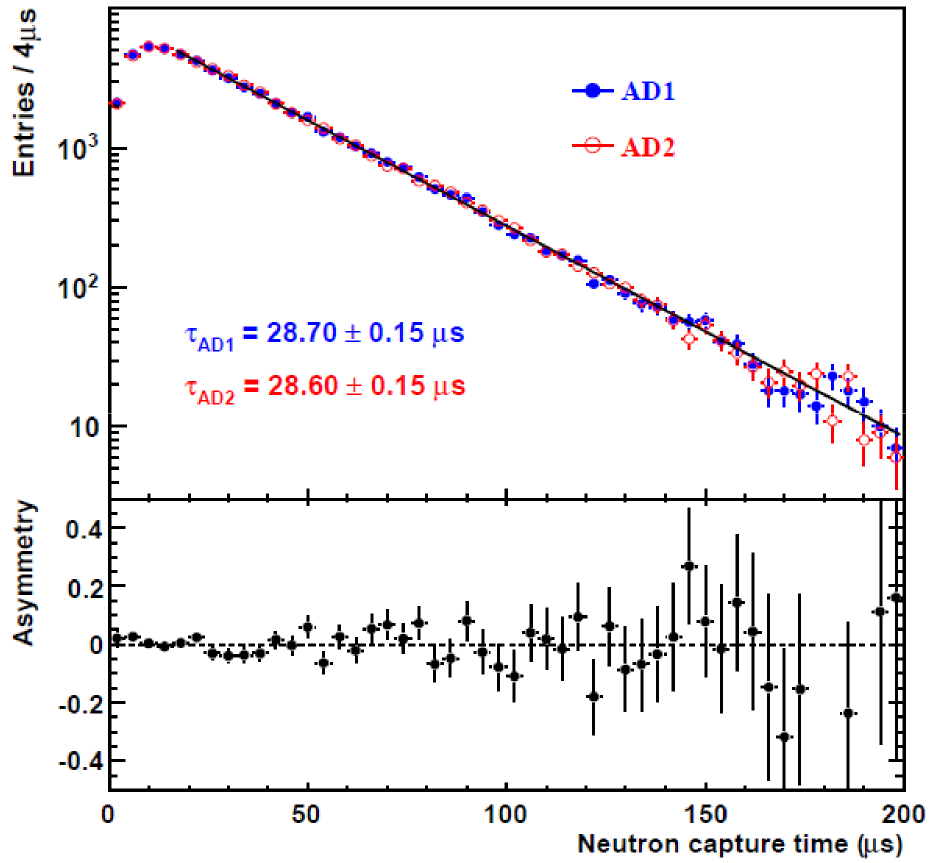


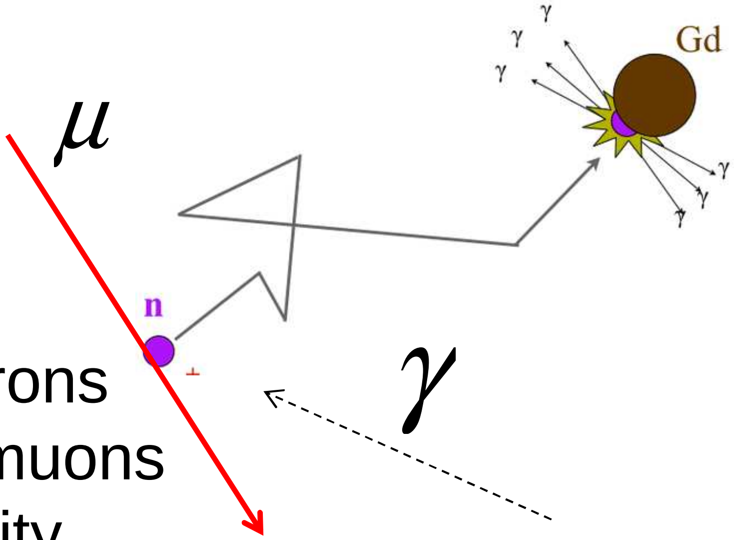
Figure 14: The neutron capture time on Gd from the Am-^{13}C source at the detector center.

Reactor flux uncertainties

	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%

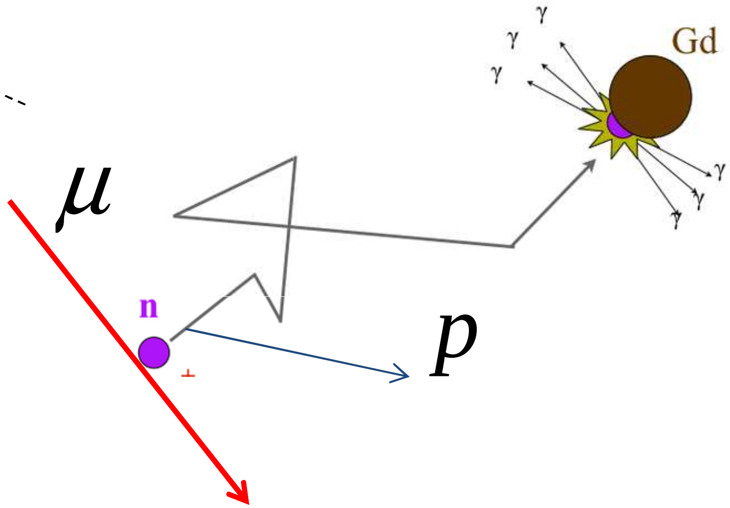
Only 0.04% contribution to the result

Backgrounds



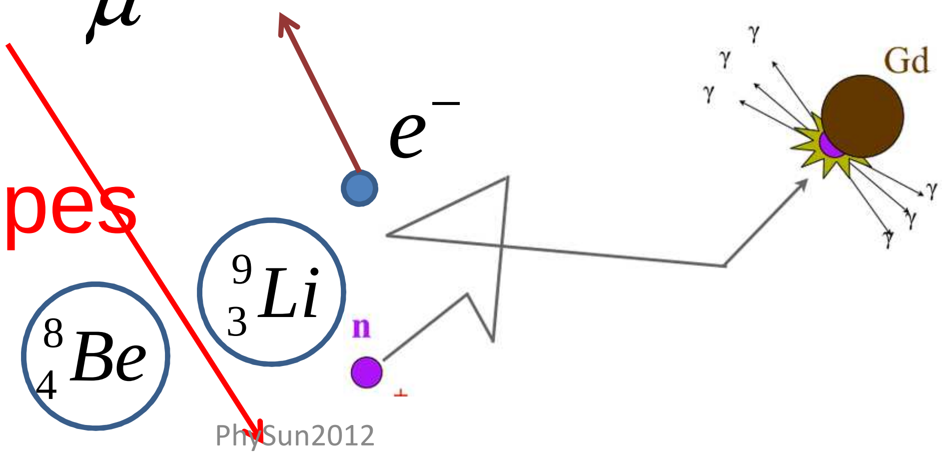
-Accidental

coincidencies of neutrons produced by cosmic muons and natural radioactivity



Fast neutrons

Recoiled protons mimic the prompt signal



Li9 and He8 isotopes

Beta decays with neutron emission

Li9 and He8 background

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

$$^{8}_{2}He \xrightarrow{T_{1/2}=119ms\ 16\%} {}^{7}_{3}Li + e^{-} + \bar{\nu}_e + n \qquad Q = 10.651\,MeV$$

$$^{8}_{2}He \xrightarrow{T_{1/2}=119ms\ 84\%} {}^{8}_{3}Li^{*} + e^{-} + \bar{\nu}_e$$

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

$$^{8}_{3}Li \xrightarrow{T_{1/2}=840ms} {}^{8}_{4}Be + e^{-} + \bar{\nu}_e$$

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

$$^{9}_{3}Li \xrightarrow{T_{1/2}=178ms\ 50\%} {}^{8}_{4}Be + e^{-} + \bar{\nu}_e + n \qquad Q = 13.607\,MeV$$

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

$$^{9}_{3}Li \xrightarrow{T_{1/2}=178ms\ 50\%} {}^{9}_{4}Be + e^{-} + \bar{\nu}_e$$

Muon Veto

Daya Bay

- "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
  (>5 T1/2 of Li9/He8 isotopes)

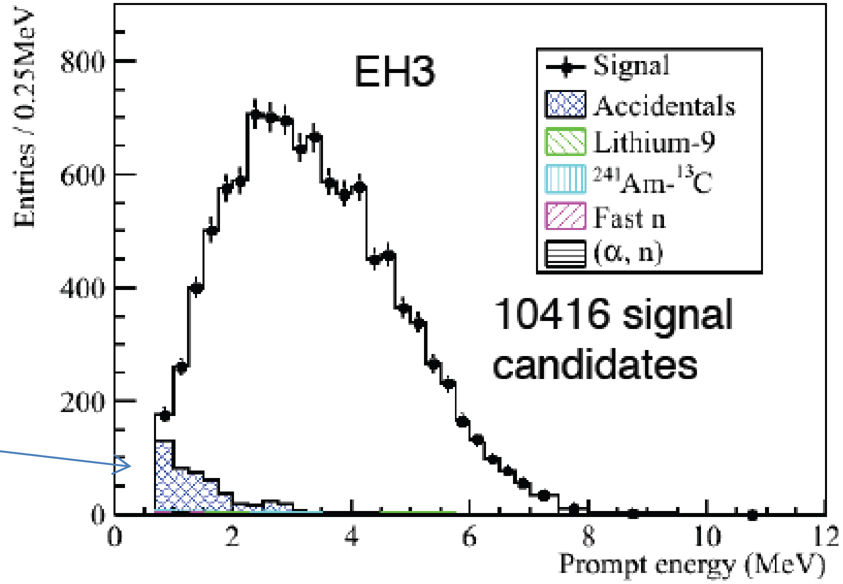
Double Chooz

- Muon>600 MeV veto 0.5 s

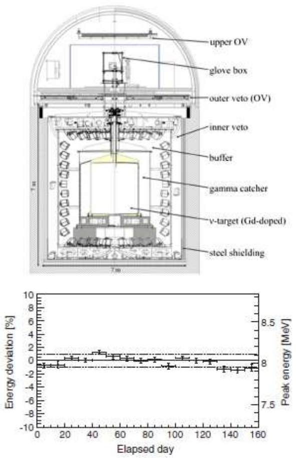
RENO

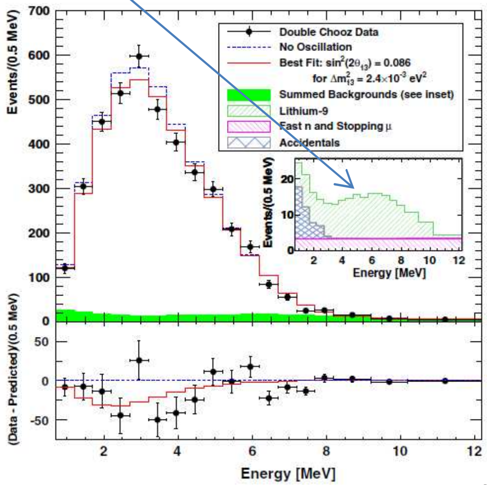
- Muon>1.5GeV veto 0.01 s (RENO)

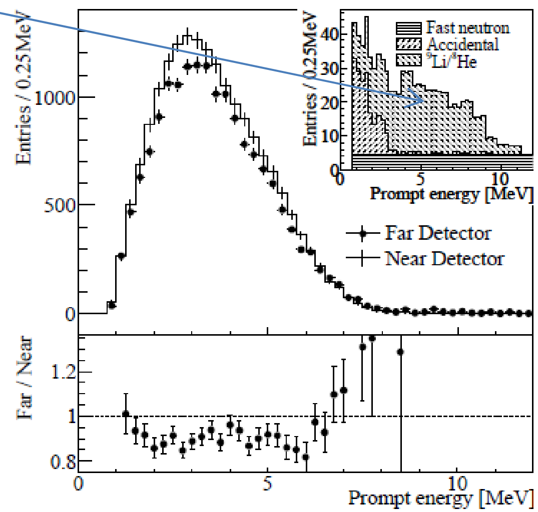
Due to large overburden and strict showering muons veto cut Daya Bay Li/He background is suppressed and the background is dominated by accidental coincidencies which are concentrated at low neutrino energies.



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

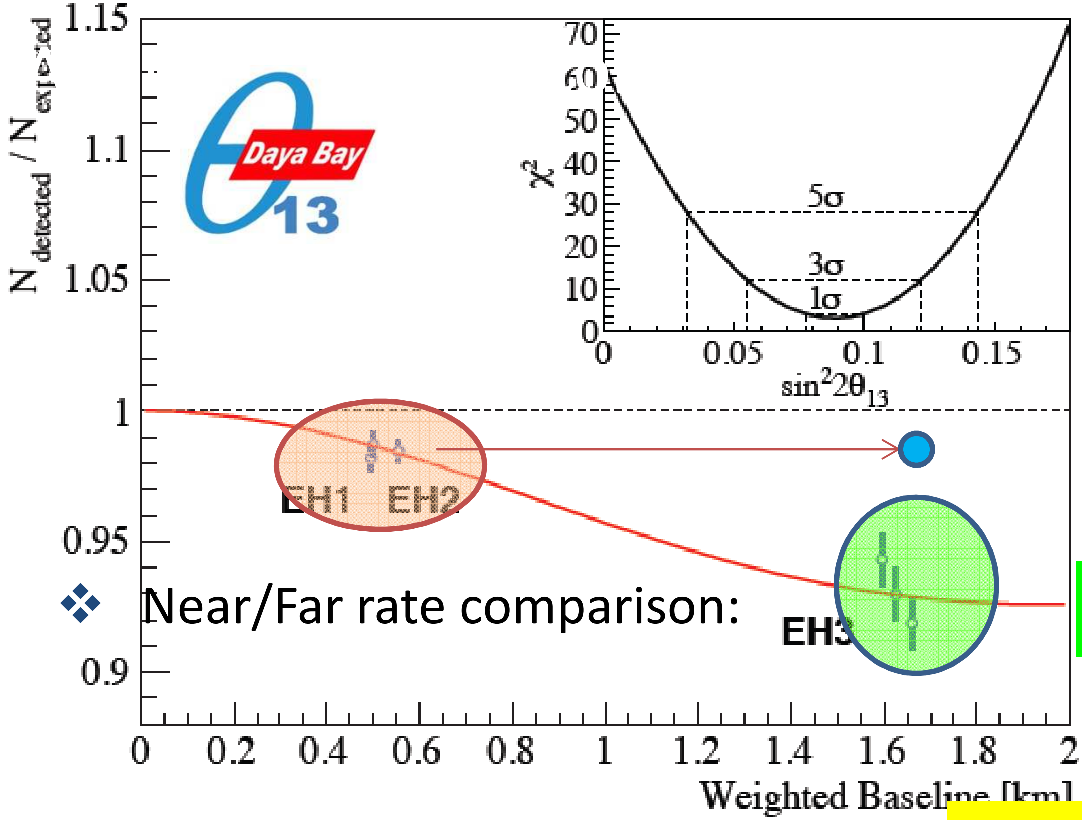




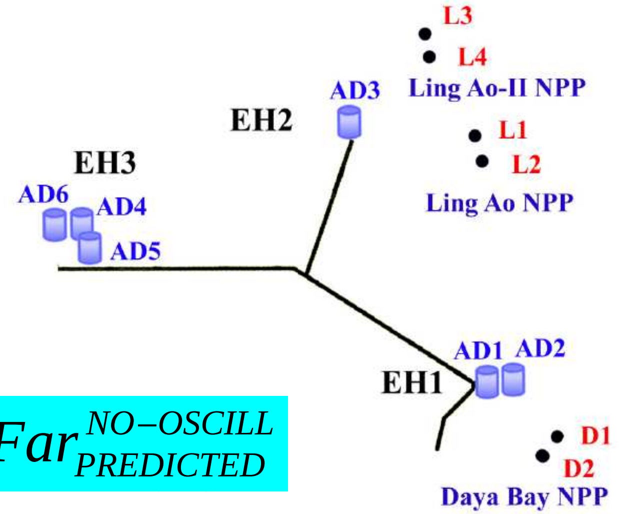


Backgrounds & uncertainties

	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%



- Near/Far rate comparison:



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

$Far_{MEASURED}$

$$R = \frac{Far_{measured}}{Far_{predicted}} = \frac{M_4 + M_5 + M_6}{\alpha \cdot (M_1 + M_2) + \beta \cdot M_3}$$

M_n : measured rate in ADn detector.

Weights α,β : determined from baselines and reactor fluxes, no oscillations assumed.

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

1-R= 5.6% ± 0.7% (stat) ± 0.3% (syst)

- Unambiguous observation of antineutrino deficit at the far site!

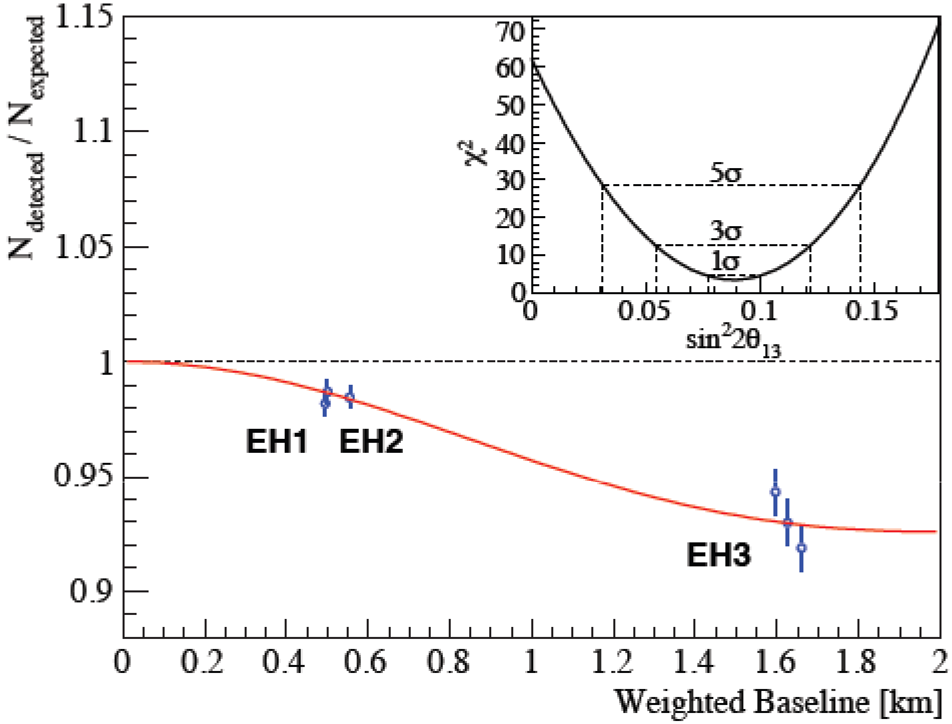
Rate-only analysis

- 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 **ε** 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)

7.7σ significance for $\sin^2 2\theta_{13} > 0$

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

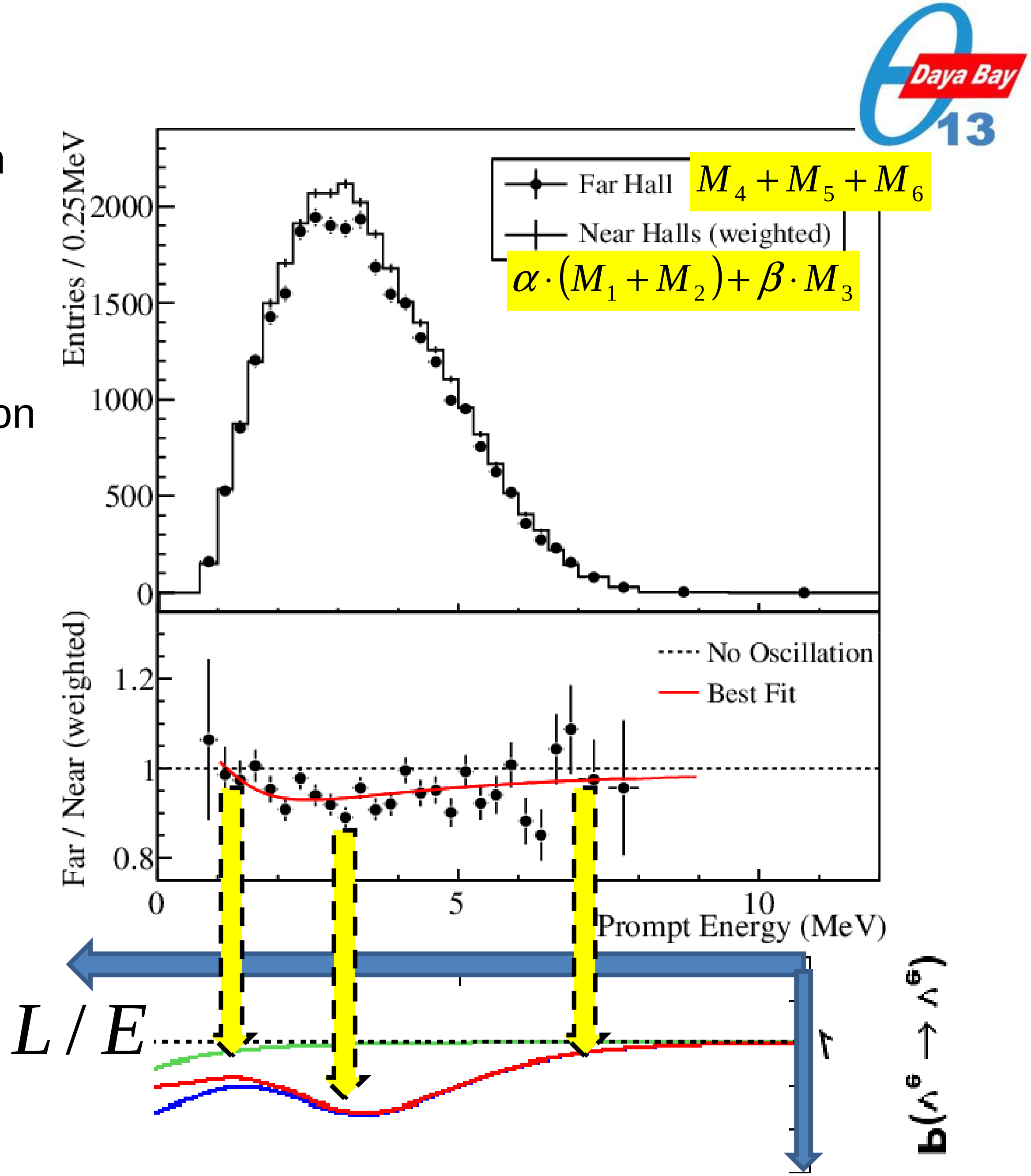
The smallest lepton mixing angle is comparable to the largest (Cabibbo) quark mixing angle.

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.

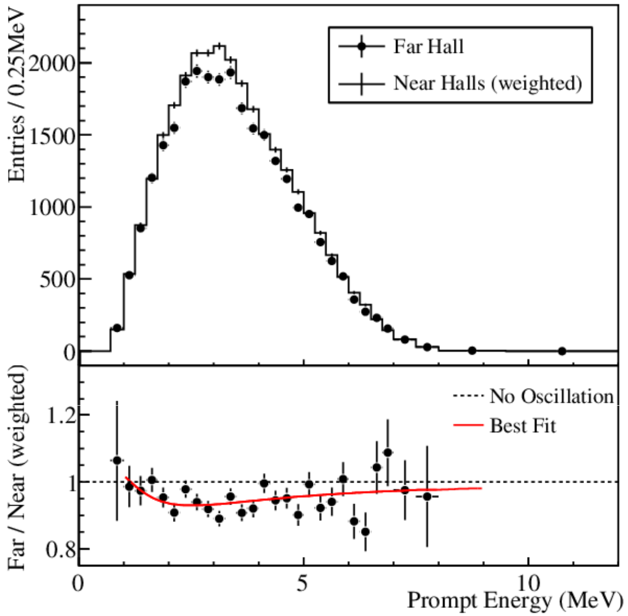
Currently the result is only from rate analysis!



Reactor neutrinos Disappearence:

Latest results from Neutrino 2012

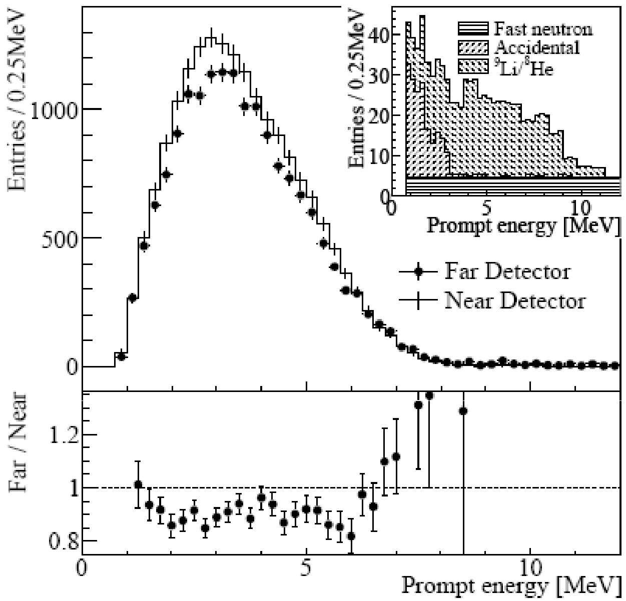
Daya Bay



R=0.944±0.007 ±0.003

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

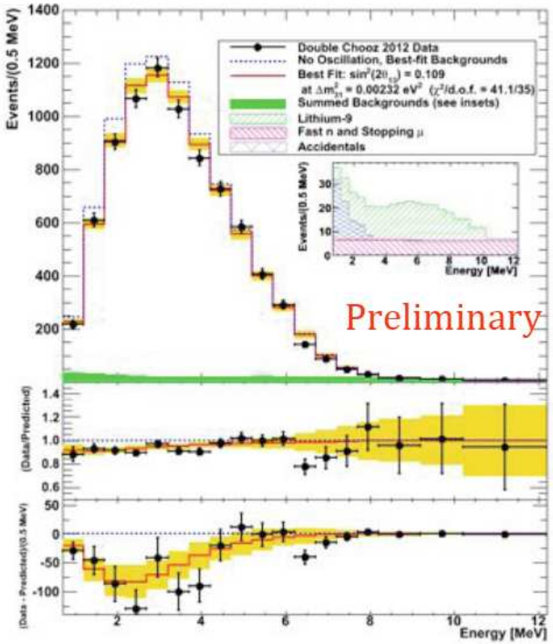
Reno



R= 0.920±0.009±0.014

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

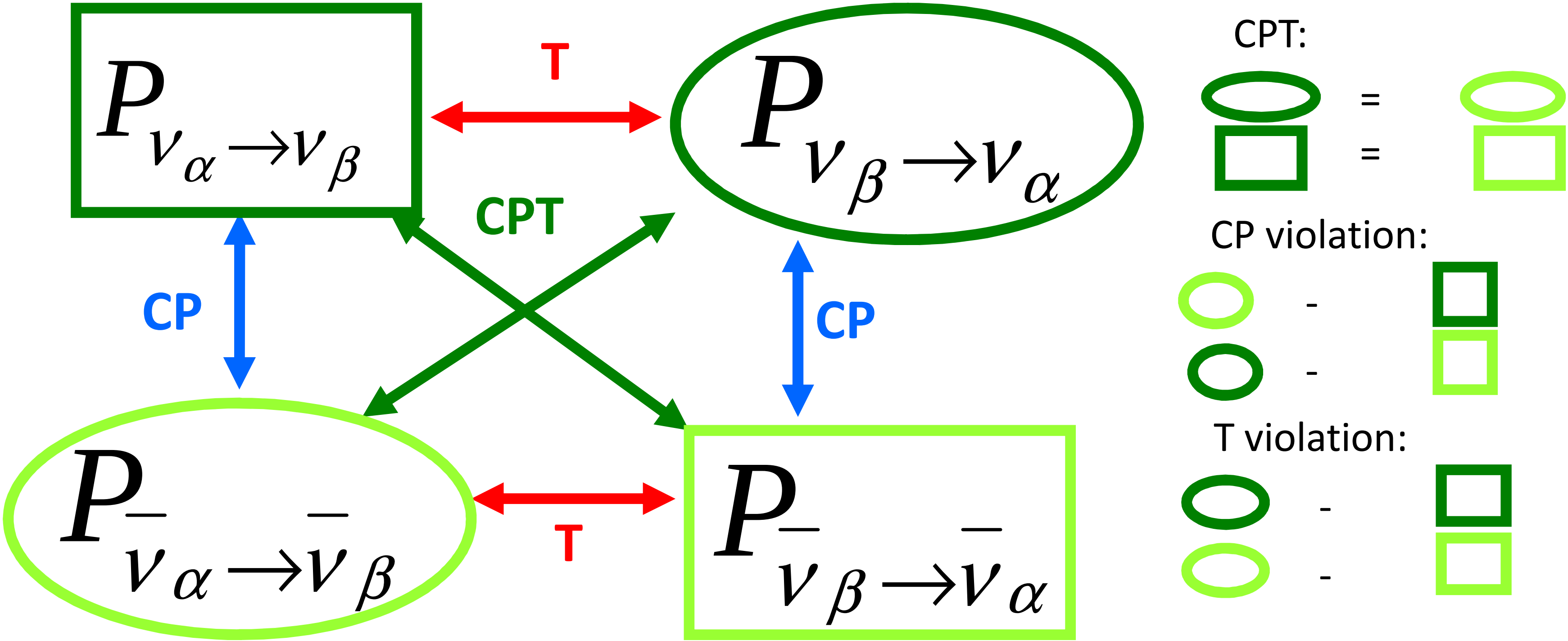
Double Chooz



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

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

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

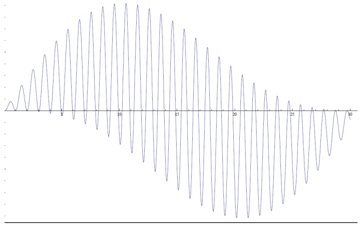


$$P_{\bar{\nu}\mu \to \bar{\nu} e}(L/E) - P_{\nu\mu \to \nu e}(L/E) =$$

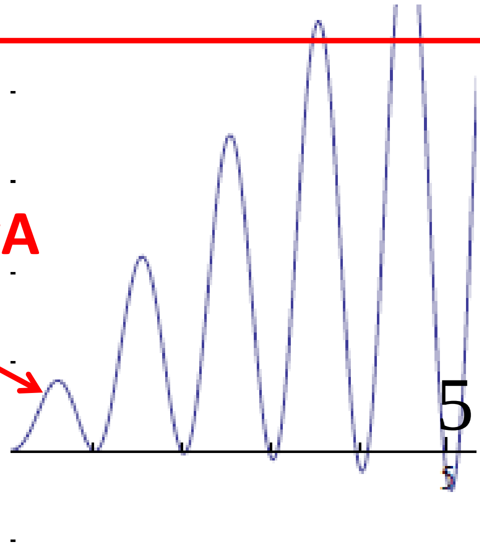
$$2\sin(\delta)\cdot 0.95\cdot 0.30\cdot 0.93\cdot 1.00 = 0.57\sin(\delta)$$

$$2\sin(\delta)\cos(\theta_{13})\sin(2\theta_{13})\sin(2\theta_{12})\sin(2\theta_{23})$$

$$\times\sin\left(\frac{\Delta m_{21}^2}{4\hbar c}\frac{L}{E}\right)\sin\left(\frac{\Delta m_{31}^2}{4\hbar c}\frac{L}{E}\right)\sin\left(\frac{\Delta m_{32}^2}{4\hbar c}\frac{L}{E}\right)$$

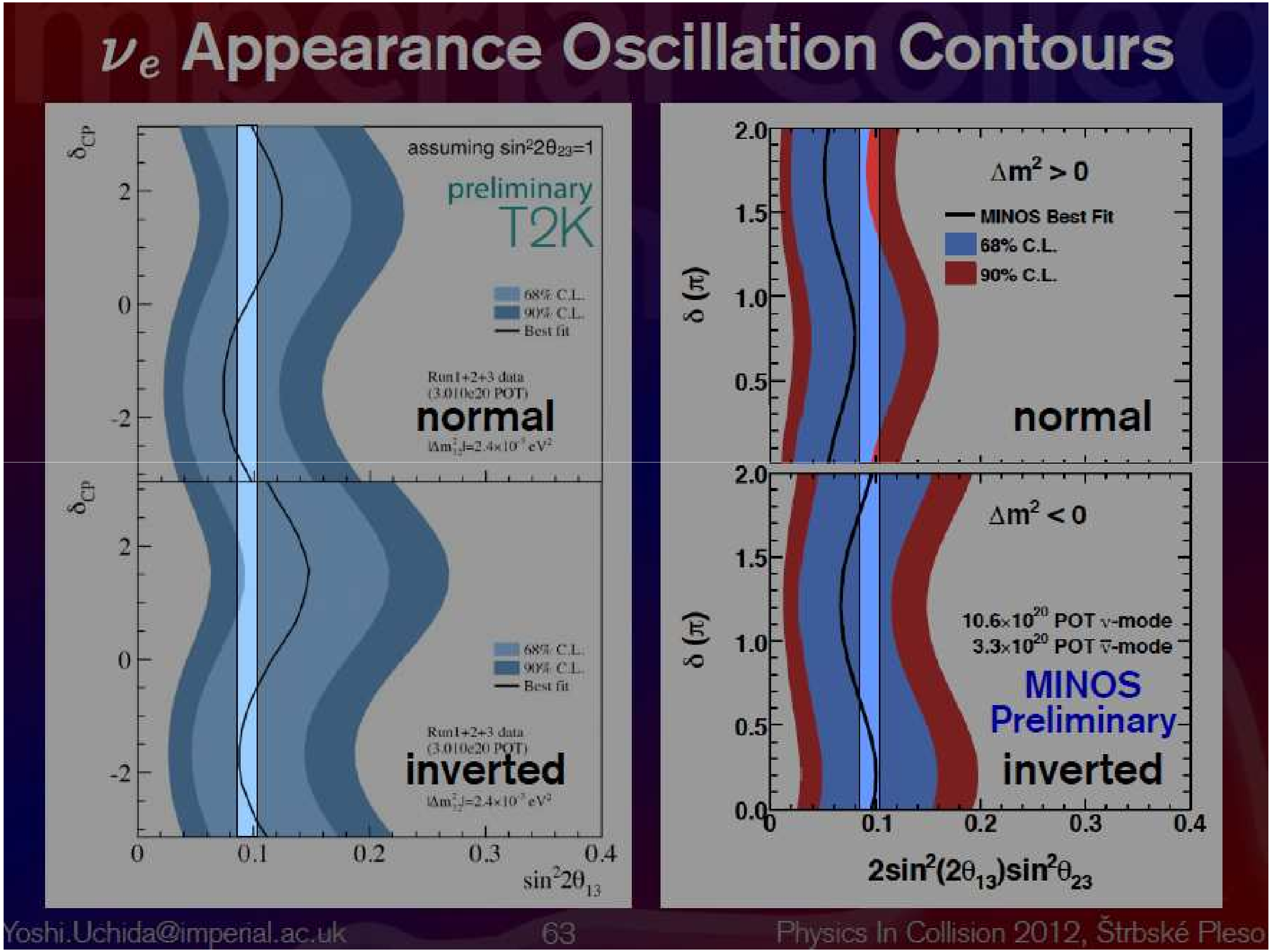


$$= \sin(\delta)\times 0.57\times$$



$$L/E,\ km/MeV$$

Reactor and accelerator θ13 measurements



CONCLUSIONS

-A non zero, surprisingly large value of the third mixing angle theta 13 has been measured in 2012. The result is extremely 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 was 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
- completed Daya Bay detector
- shape analyses
- 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.