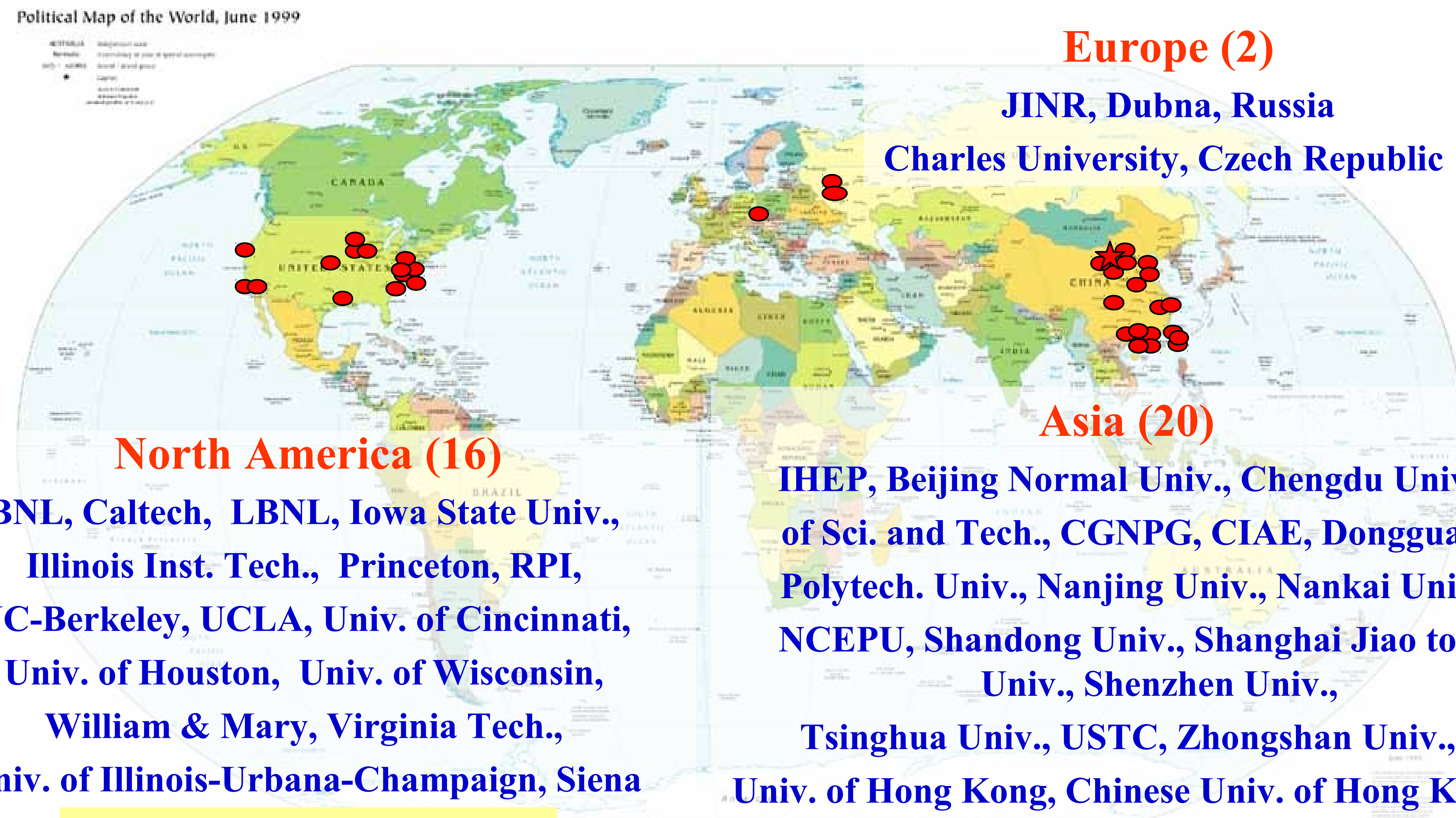
Observation of Electron Anti-neutrino Disappearance in Daya Bay and RENO experiments

The Daya Bay Collaboration



Europe (2)

JINR, Dubna, 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 & Mary, Virginia Tech., Univ. of Illinois-Urbana-Champaign, Siena

~250 Collaborators

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.

Daya Bay: for a New Type of Oscillation

- **Goal : search for a new oscillation θ_{13}**

θ_{12} solar neutrino oscillation

θ_{23} atmospheric neutrino oscillation

ν_1

ν_2

ν_3

θ_{13} ?

- **Neutrino mixing matrix:**

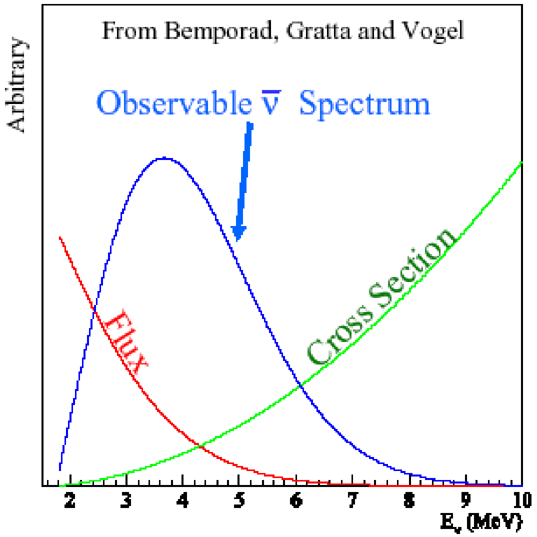
$$\mathbf{V} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13} \\ 0 & e^{-i\delta} & 0 \\ -s_{13} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} e^{i\rho} & 0 & 0 \\ 0 & e^{i\sigma} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

Unknown mixing parameters: θ_{13}, δ + 2 Majorana phases

Need sizable θ_{13} for the δ measurement

Reactor experiments

$$P_{ee} \approx 1 - \sin^2 2\theta_{13} \sin^2(1.27\Delta m^2_{13} L/E) - \cos^4\theta_{13} \sin^2 2\theta_{12} \sin^2(1.27\Delta m^2_{12} L/E)$$



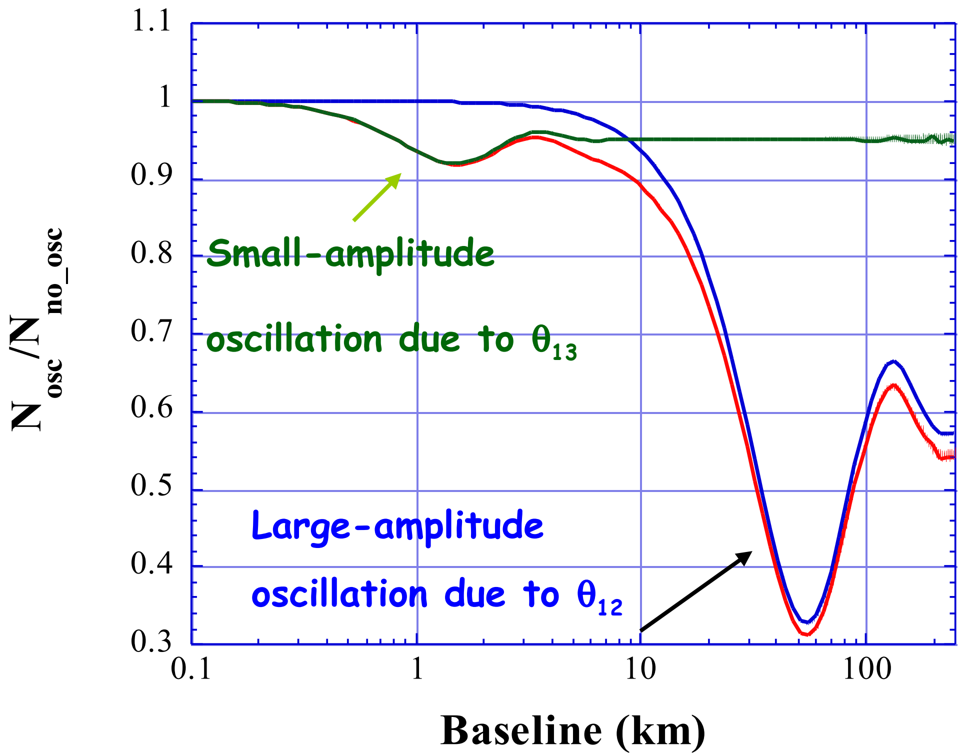
E=4 MeV L = 2.1 km

L $\Delta m^2_{21} = 7.92(1.00 \pm 0.09) \times 10^{-5}\ \mathrm{eV}^2$

Δ

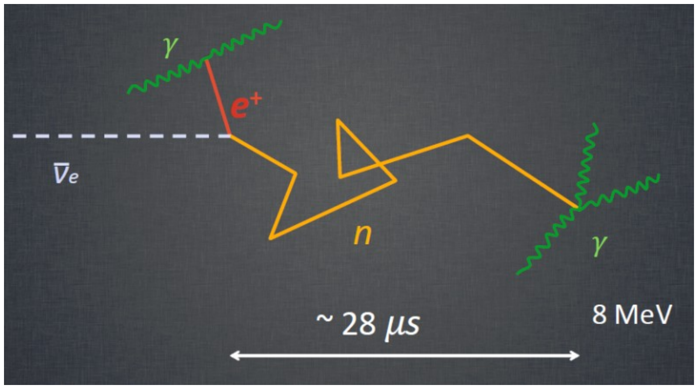
Reactor experiments:

$$P_{ee} \approx 1 - \sin^2 2\theta_{13} \sin^2(1.27\Delta m^2_{13} L/E) - \cos^4\theta_{13} \sin^2 2\theta_{12} \sin^2(1.27\Delta m^2_{12} L/E)$$



Neutrino Detection: Gd-loaded Liquid Scintillator

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

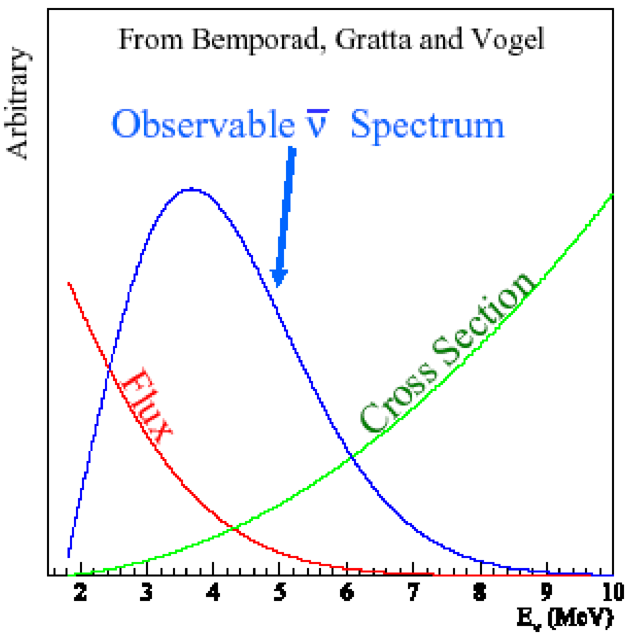


$\tau \approx 28\ \mu s$ (0.1% Gd)

n + p → d + γ (2.2 MeV)

n + Gd → Gd* + γ (8 MeV)

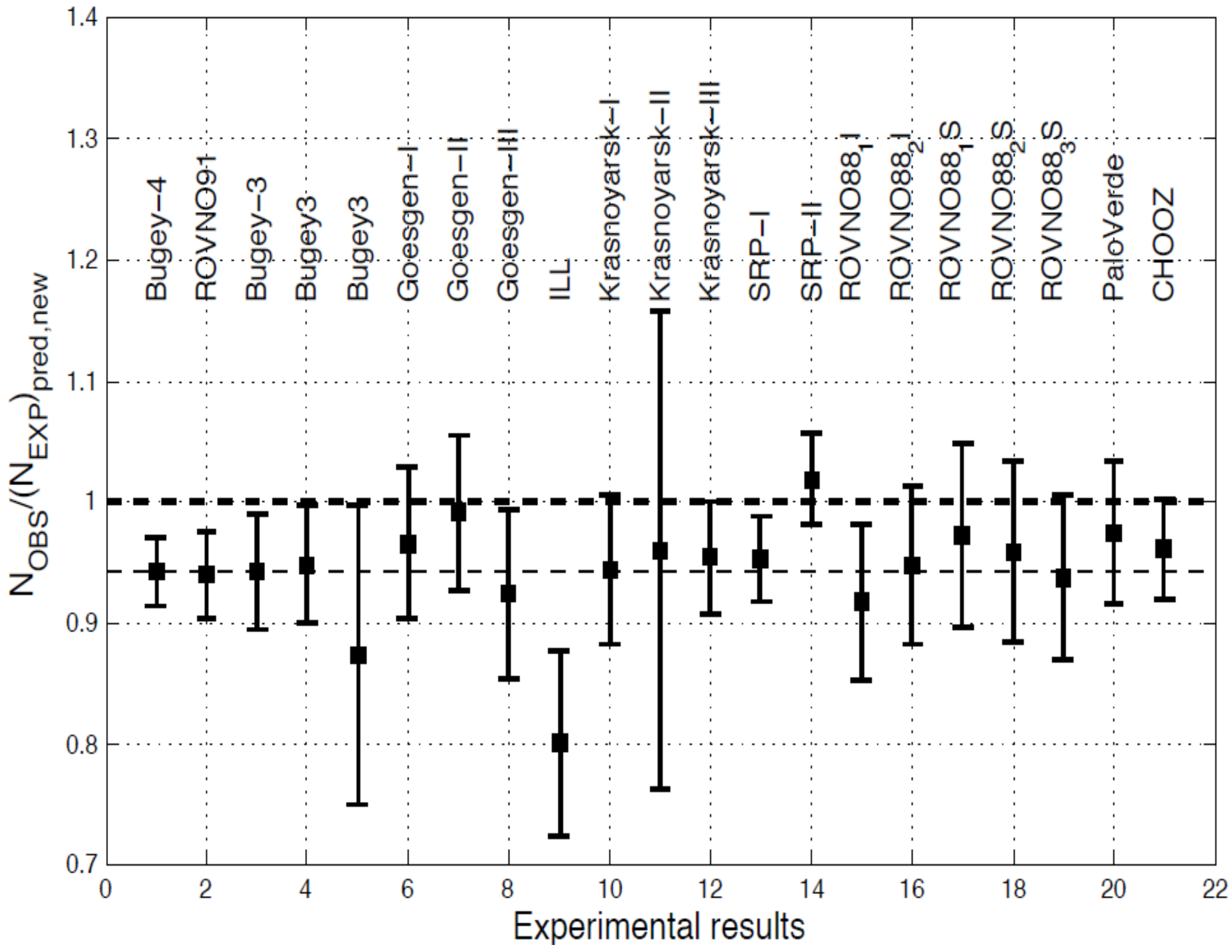
Neutrino Event: coincidence in time, space and energy



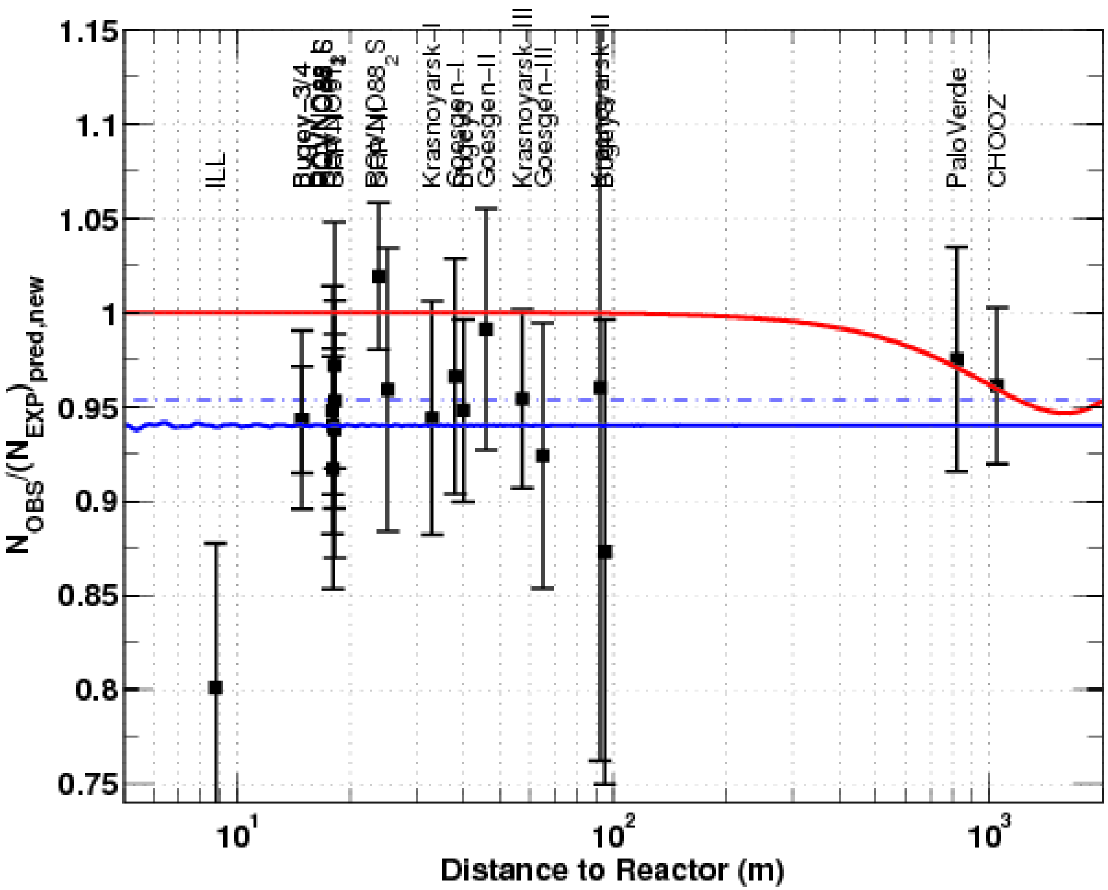
Neutrino energy:

$$E_{\bar{\nu}} \cong T_{e^+} + \underbrace{T_n}_{\text{10-40 keV}} + \underbrace{(M_n - M_p) + m_{e^+}}_{\text{1.8 MeV: Threshold}}$$

Short baseline experiments near reactors

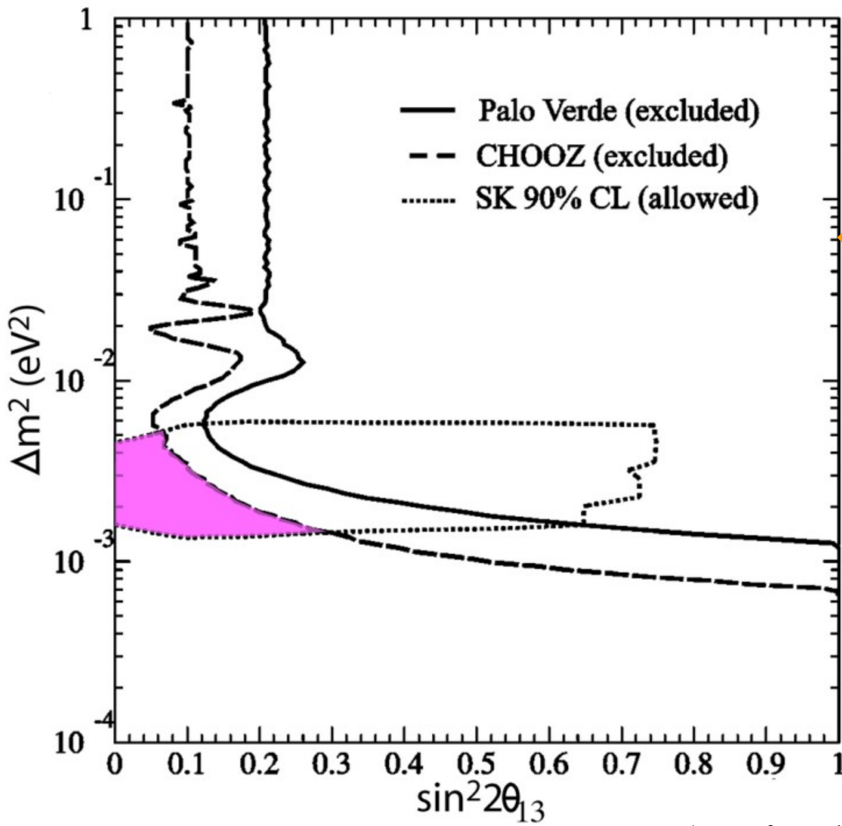


One detector Comparison with calculated neutrino flux



A deficit observed at long baseline can either be caused by θ_{13} or by
new physics closer to the core (oscillation towards a 4th neutrino, qnew)
1
1

Direct Searches in the Past



- **Double Chooz**

L=1050 m

Arxiv:1112.635v1 29 Dec 2011

$$\sin^2 2\theta_{13} = 0.086 \pm 0.041(\text{stat}) \pm 0.030(\text{sys})$$

Reactor Neutrinos

- Reactor neutrino spectrum

$$S(E_\nu) = \frac{W_{th}}{\sum_i (f_i/F)e_i} \sum_i^{istopes} (f_i/F)S_i(E_\nu)$$

- Thermal power, W_{th}, measured by KIT system, calibrated by KME method
- Fission fraction, f_i, determined by reactor core simulation
- Neutrino spectrum of fission isotopes $S_i(E_\nu)$ from measurements
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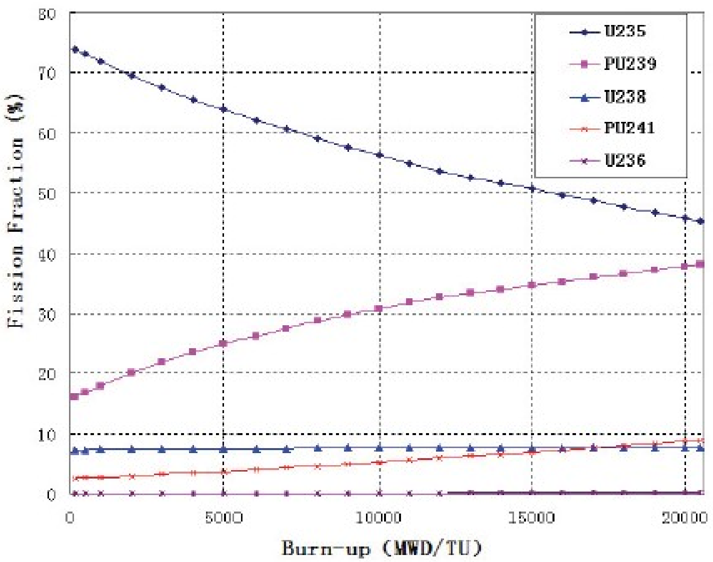


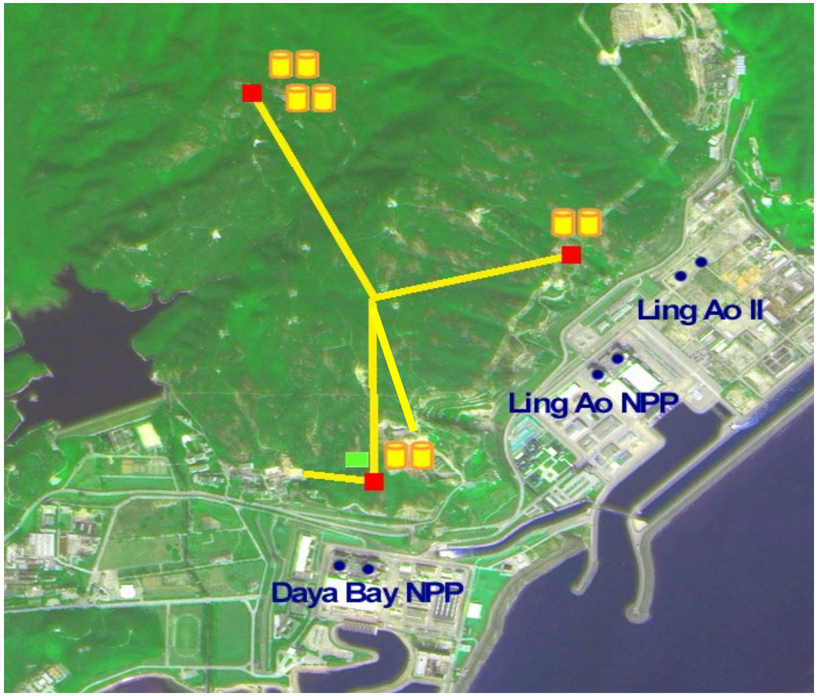
Isotope	E_{fi}, MeV/fission
^{235}U	201.92 ± 0.46
^{238}U	205.52 ± 0.96
^{239}Pu	209.99 ± 0.60
^{241}Pu	213.60 ± 0.65

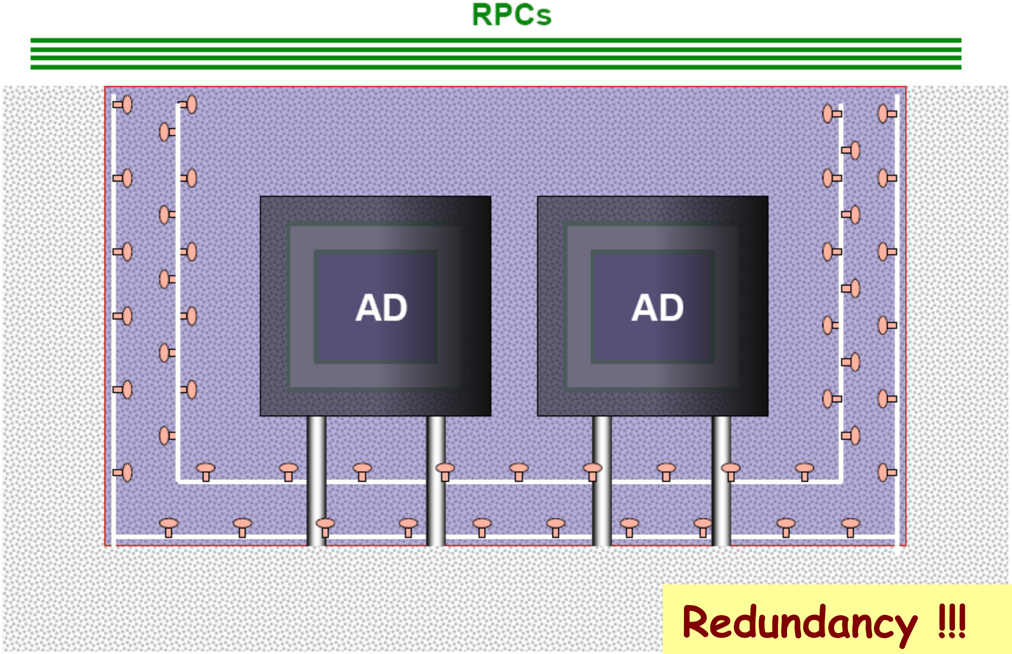
Reactor			
Correlated		Uncorrelated	
Energy/fission	0.2%	Power	0.5%
$\overline{\nu}_e$/fission	3%	Fission fraction	0.6%
		Spent fuel	0.3%
Combined	3%	Combined	0.8%

Kopeikin et al, Physics of Atomic Nuclei, Vol. 67, No. 10, 1892 (2004)

Relative measurement → independent from the neutrino spectrum prediction

Daya Bay Experiment: Layout





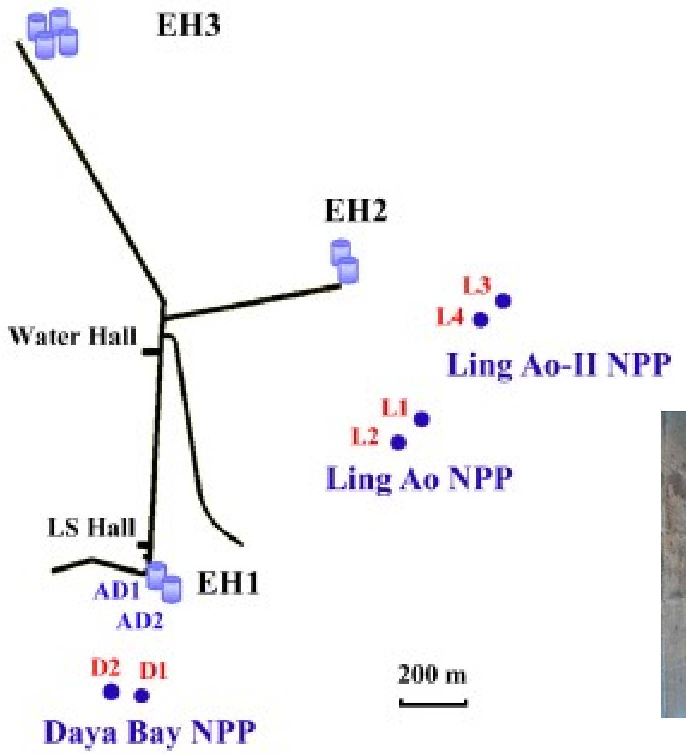
Redundancy !!!

- Relative measurement to cancel Corr. Syst. Err.
  - ⇨ 2 near sites, 1 far site
- Multiple AD modules at each site to reduce Uncorr. Syst. Err.
  - ⇨ Far: 4 modules， near: 2 modules

Cross check; Reduce errors by 1/√N

- Multiple muon detectors to reduce veto eff. uncertainties
  - ⇨ Water Cherenkov： 2 layers
  - ⇨ RPC： 4 layers at the top + telescopes

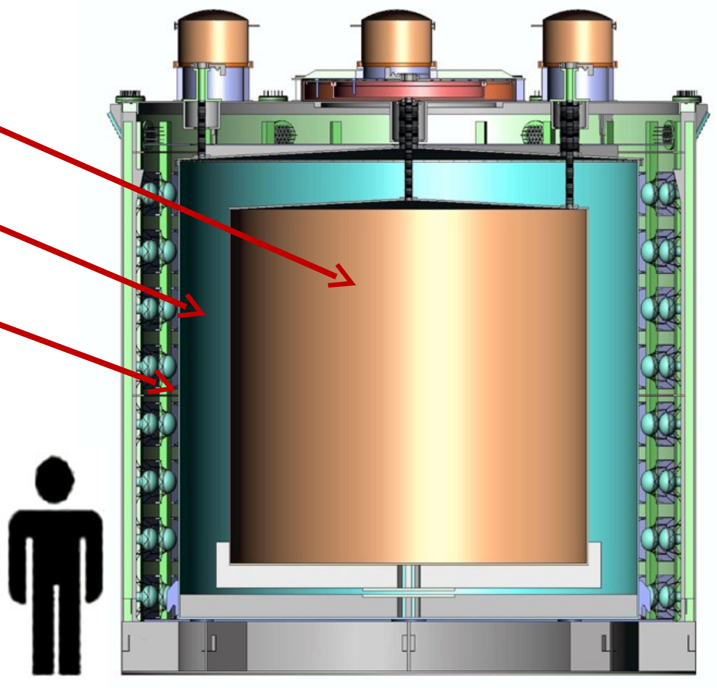
Underground Labs

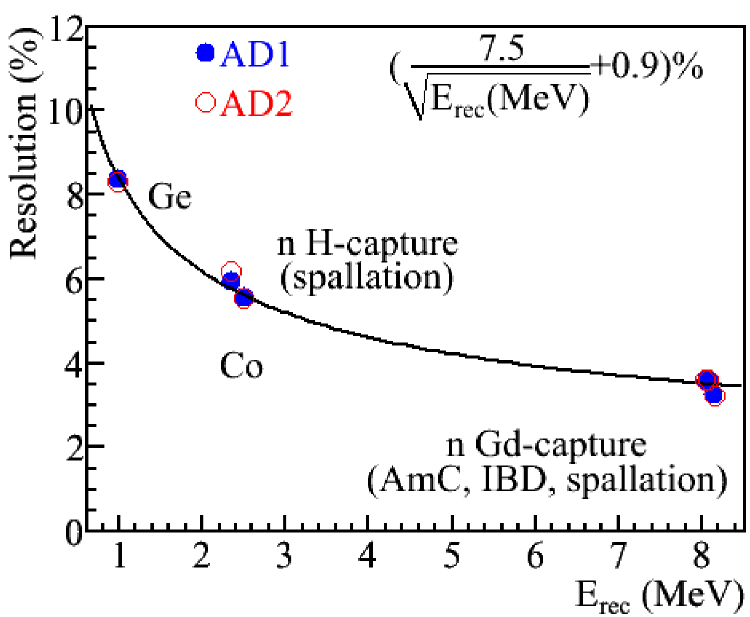


	Overburden（MWE）	R_μ（Hz/m²）	E_μ（GeV）	D1,2 (m)	L1,2 (m)	L3,4 (m)
EH1	250	1.27	57	364	857	1307
EH2	265	0.95	58	1348	480	528
EH3	860	0.056	137	1912	1540	1548

Anti-neutrino Detector (AD)

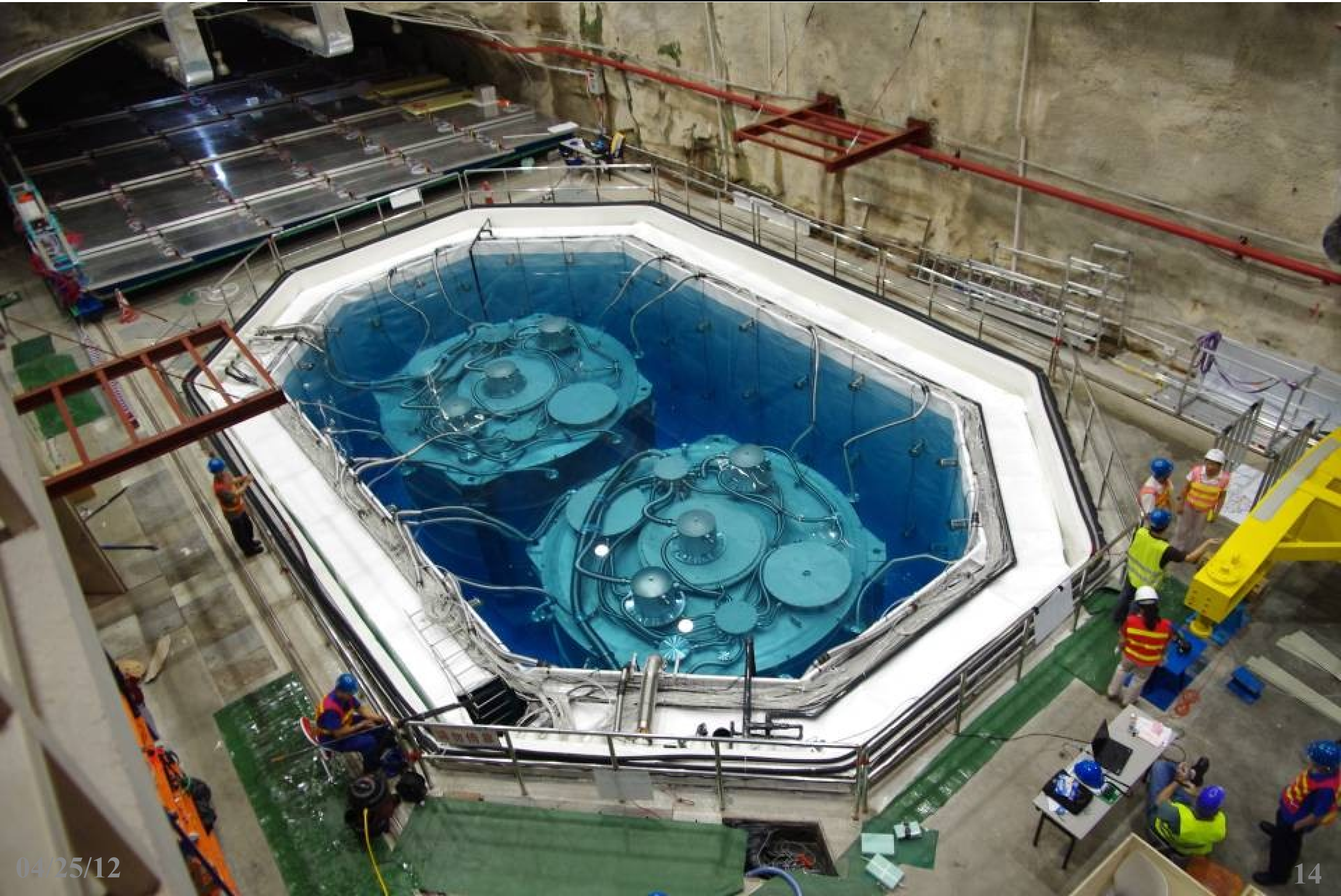
- **Three zones modular structure:**
  - I. target: Gd-loaded scintillator
  - II. γ-catcher: normal scintillator
  - III. buffer shielding: oil
- **192 8" PMTs/module**
- **Two optical reflectors at the top and the bottom,** Photocathode coverage increased from 5.6% to 12%



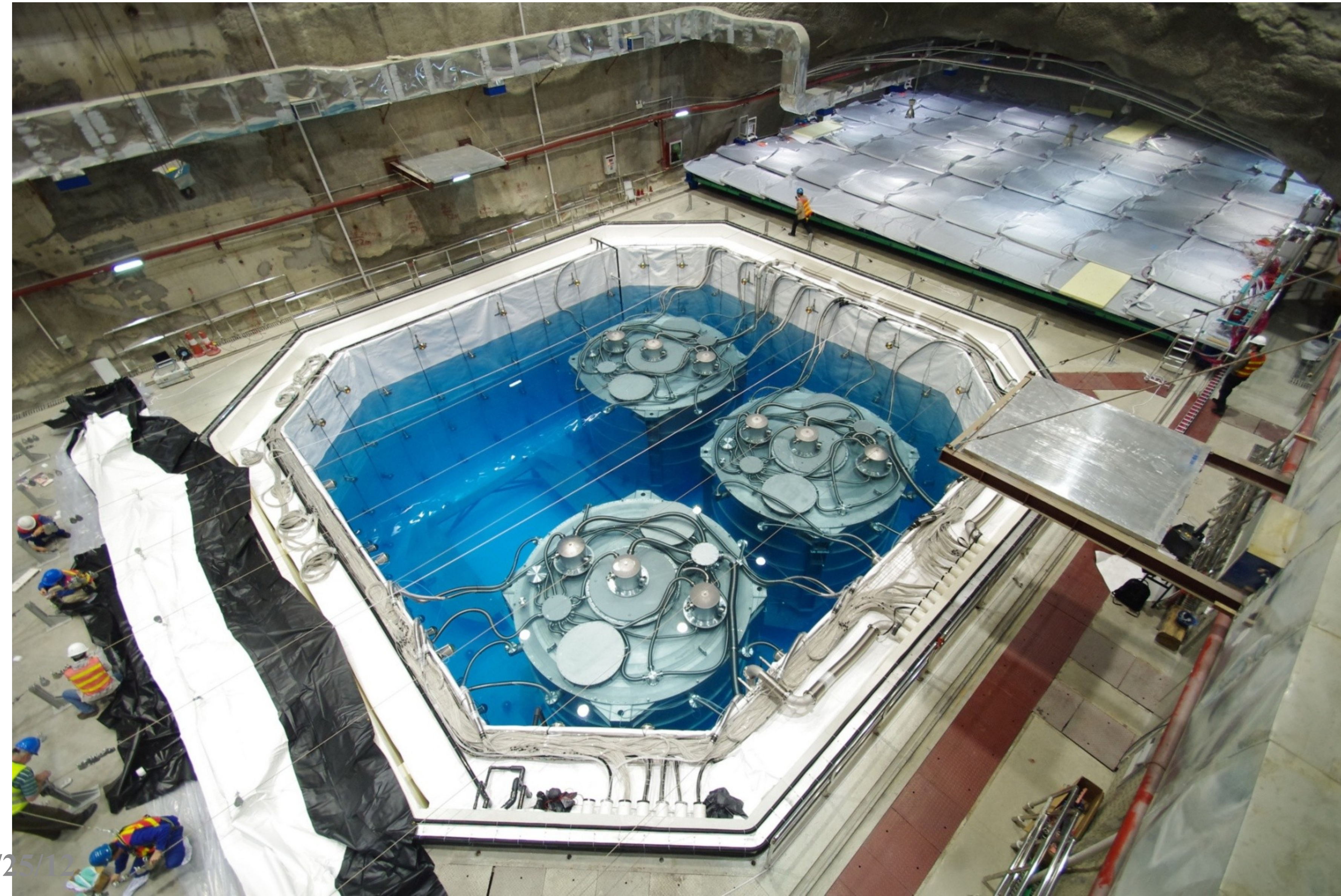


Target: 20 t, 1.6m
γ-catcher: 20t, 45cm
Buffer: 40t, 45cm
Total weight: ~110 t

Two ADs Installed in Hall 1

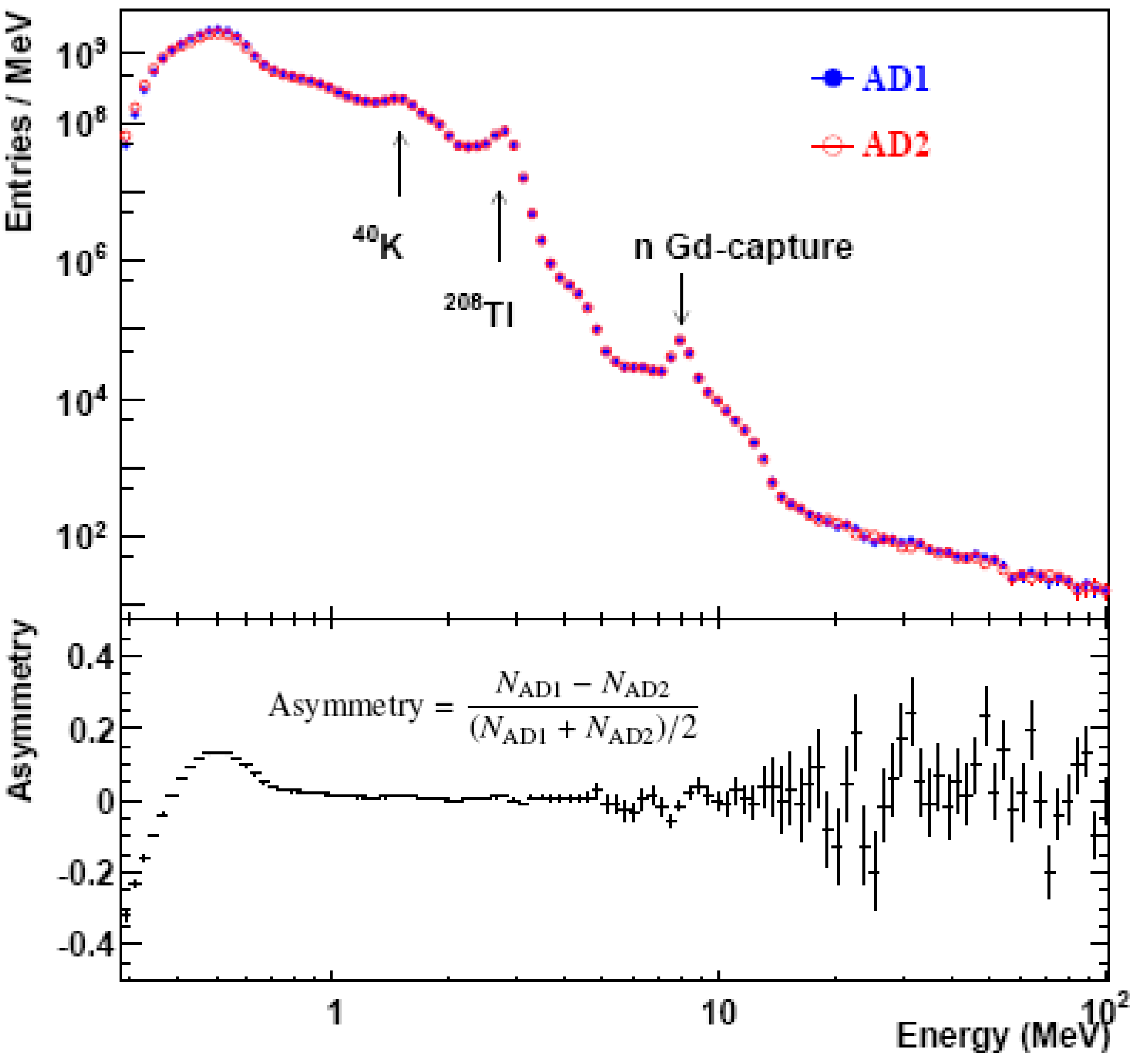


Three ADs insalled in Hall 3
Physics Data Taking Started on Dec.24, 2011



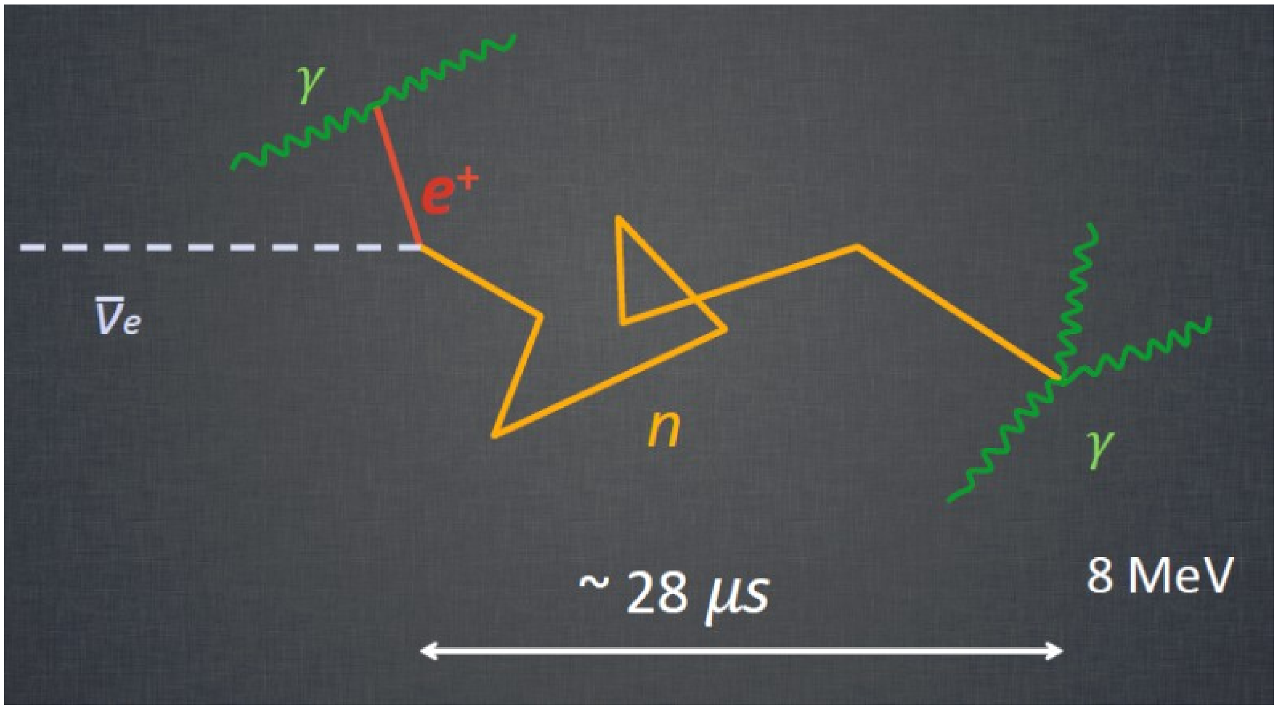
Single Rate: Understood

- Design: ~50Hz above 1 MeV
- Data: ~60Hz above 0.7 MeV, ~40Hz above 1 MeV
- From sample purity and MC simulation, each of the following component contribute to singles
  - ~ 5 Hz from SSV
  - ~ 10 Hz from LS
  - ~ 25 Hz from PMT
  - ~ 5 Hz from rock
- All numbers are consistent



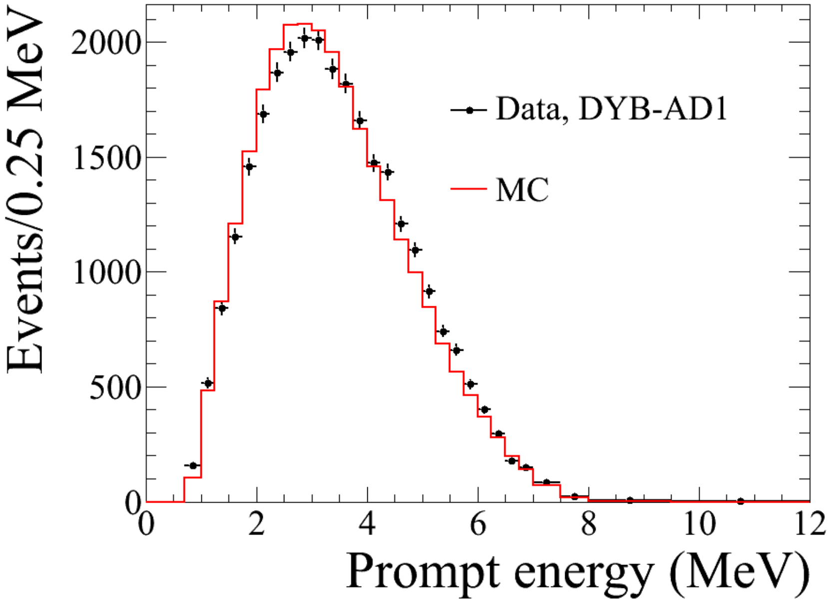
Neutrino Detection: Gd-loaded Liquid Scintillator

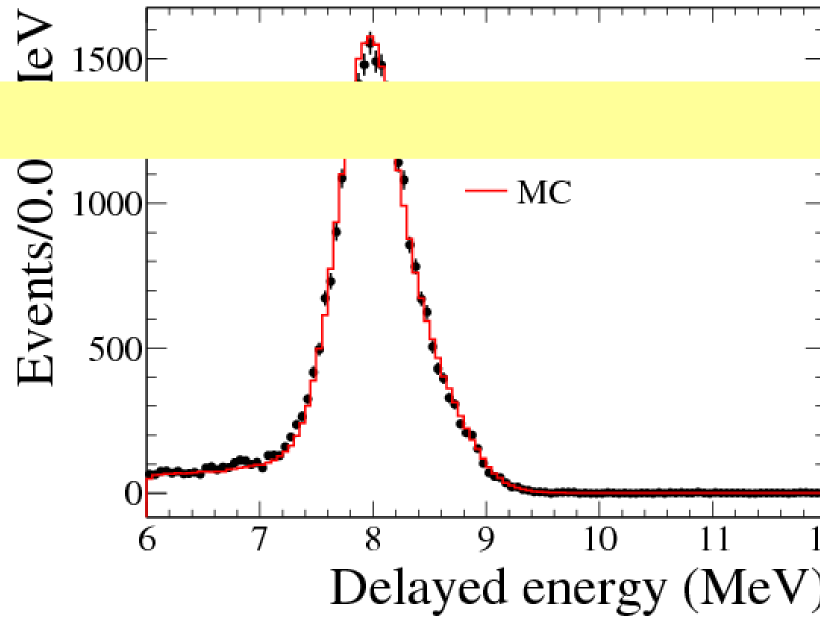
$$\bar{\nu}_e + p \rightarrow e^+ + n \longrightarrow \begin{array}{l} n + p \rightarrow d + \gamma\,(2.2\ \text{MeV}) \\ n + Gd \rightarrow Gd^* + \gamma\,(8\ \text{MeV}) \end{array}$$

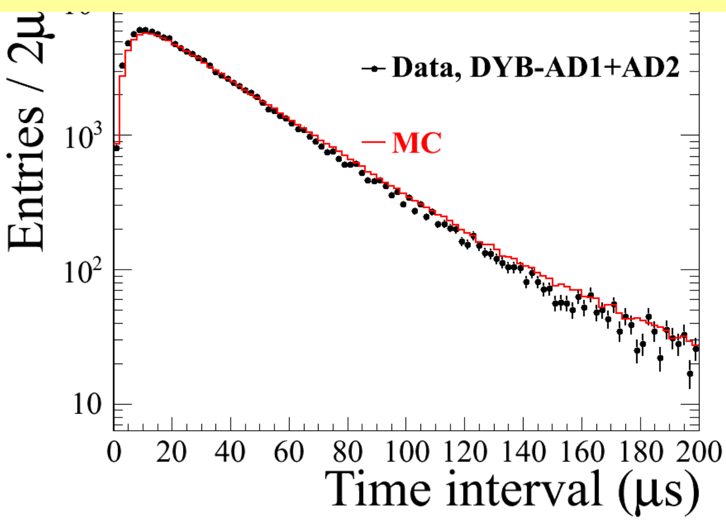


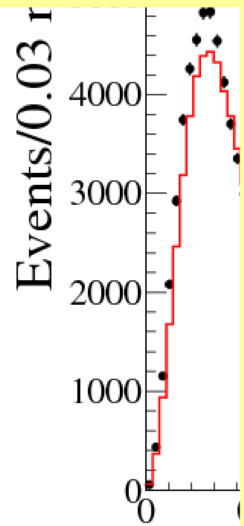
Neutrino Event: coincidence in time, space and energy

Selected Signal Events： Good Agreement with MC









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Signals and Backgrounds

	AD1	AD2	AD3	AD4	AD5	AD6
Neutrino candidates	28935	28975	22466	3528	3436	3452

	B/S @EH1/2	B/S @EH3
Accidentals	**~1.4%**	**~4.5%**
Fast neutrons	**~0.1%**	**~0.06%**
^{8}He/^{9}Li	**~0.4%**	**~0.2%**
Am-C	**~0.03%**	**~0.3%**
α-n	**~0.01%**	**~0.04%**
Sum	**1.5%**	**4.7%**

Predictions

- Baseline ±35 mm
- Target mass dm/m = 0.47%
- Reactor neutrino flux ±0.8%

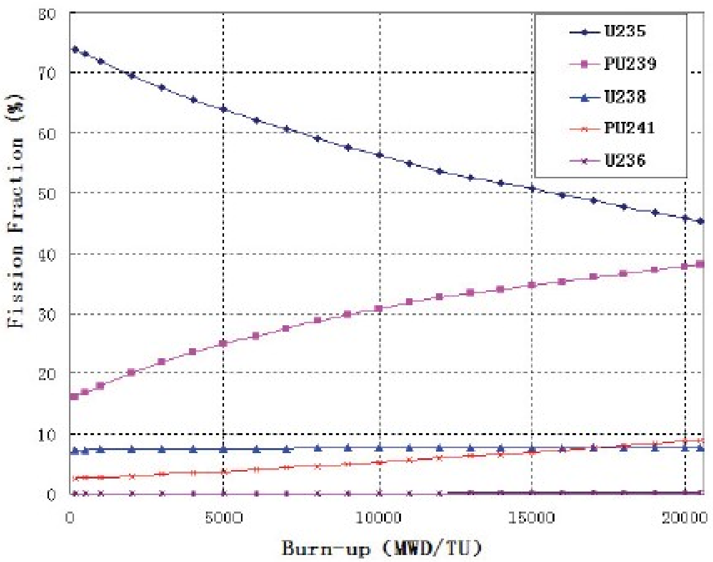
- These three predictions are **blinded** before we fix our analysis cuts and procedures
- They are opened on Feb. 29, 2012
- The physics paper is submitted to PRL on March 7, 2012

Reactor Neutrinos

- **Reactor neutrino spectrum**

$$S(E_\nu) = \frac{W_{th}}{\sum_i (f_i/F) e_i} \sum_i^{istopes} (f_i/F) S_i(E_\nu)$$

- **Thermal power, W_{th}, measured by KIT system, calibrated by KME method**
- **Fission fraction, f_i, determined by reactor core simulation**
- **Neutrino spectrum of fission isotopes $S_i(E_\nu)$ from measurements**
- **Energy released per fission e_i**



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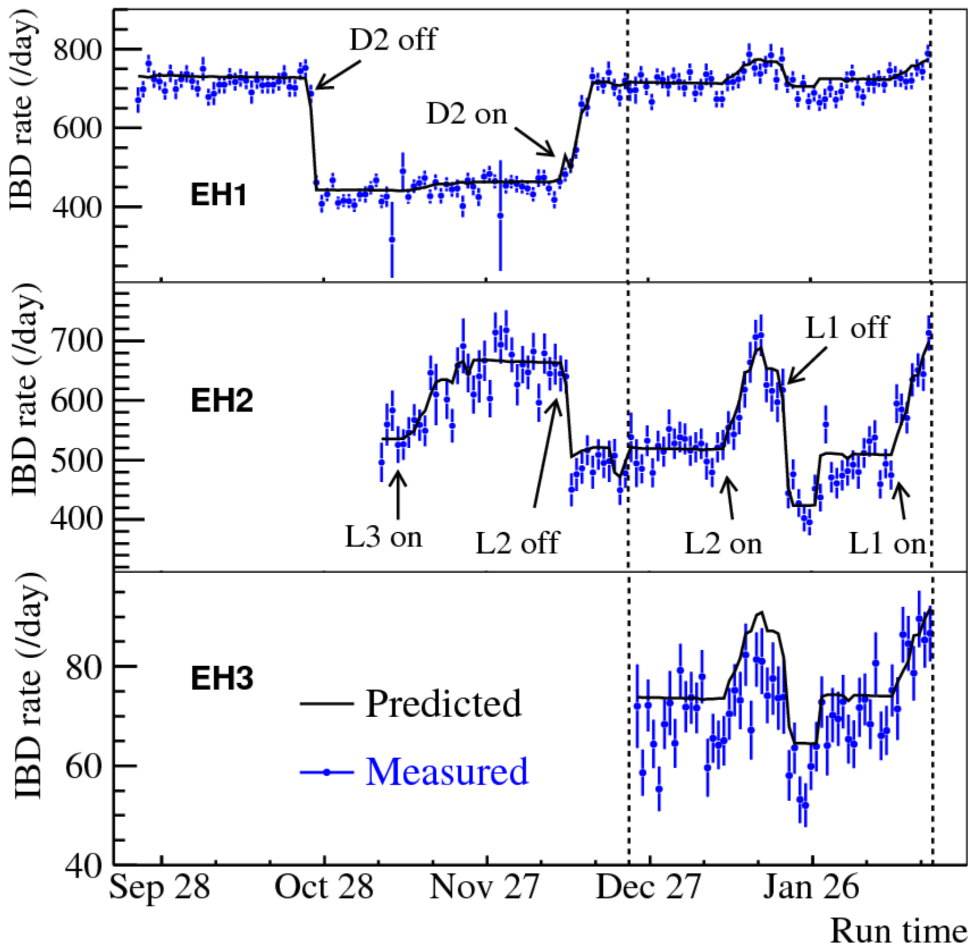
Combined	3%	Combined	0.8%

Kopeikin et al, Physics of Atomic Nuclei, Vol. 67, No. 10, 1892 (2004)

Relative measurement ➔ independent from the neutrino spectrum prediction

Daily Rate

- Three halls taking data synchronously allows near-far cancellation of reactor related uncertainties
- Rate changes reflect the reactor on/off.



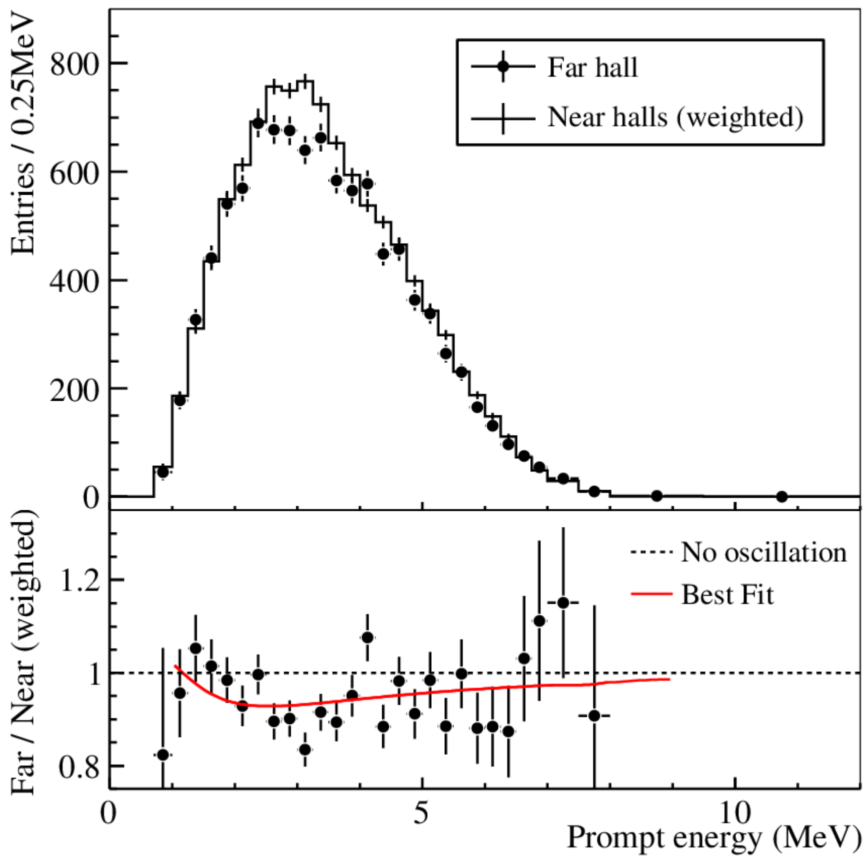
Predictions are absolute, multiplied by a normalization factor from the fitting

Electron Anti-neutrino Disappearence

Using near to predict far:

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

$$M_i = \frac{IBD_i - B_i^{Acc} - B_i^{FNeutron} - B_i^{9Li/8He} - B_i^{AmC} - B_i^{\alpha-n}}{\epsilon_i^{muon}\epsilon_i^{multi} T Mass_i}$$



Determination of α, β:

1) Set R=1 if no oscillation

2) Minimize the residual reactor uncertainty

Observed : 9901 neutrinos at far site,
Prediction : 10530 neutrinos if no oscillation

Spectral distortion
Consistent with oscillation

R = 0.940 ±0.011 (stat) ±0.004 (syst)

Summary

- **Electron anti-neutrino disappearance is observed at Daya Bay,**

  R = 0.940 ±0.011 (stat) ±0.004 (syst),

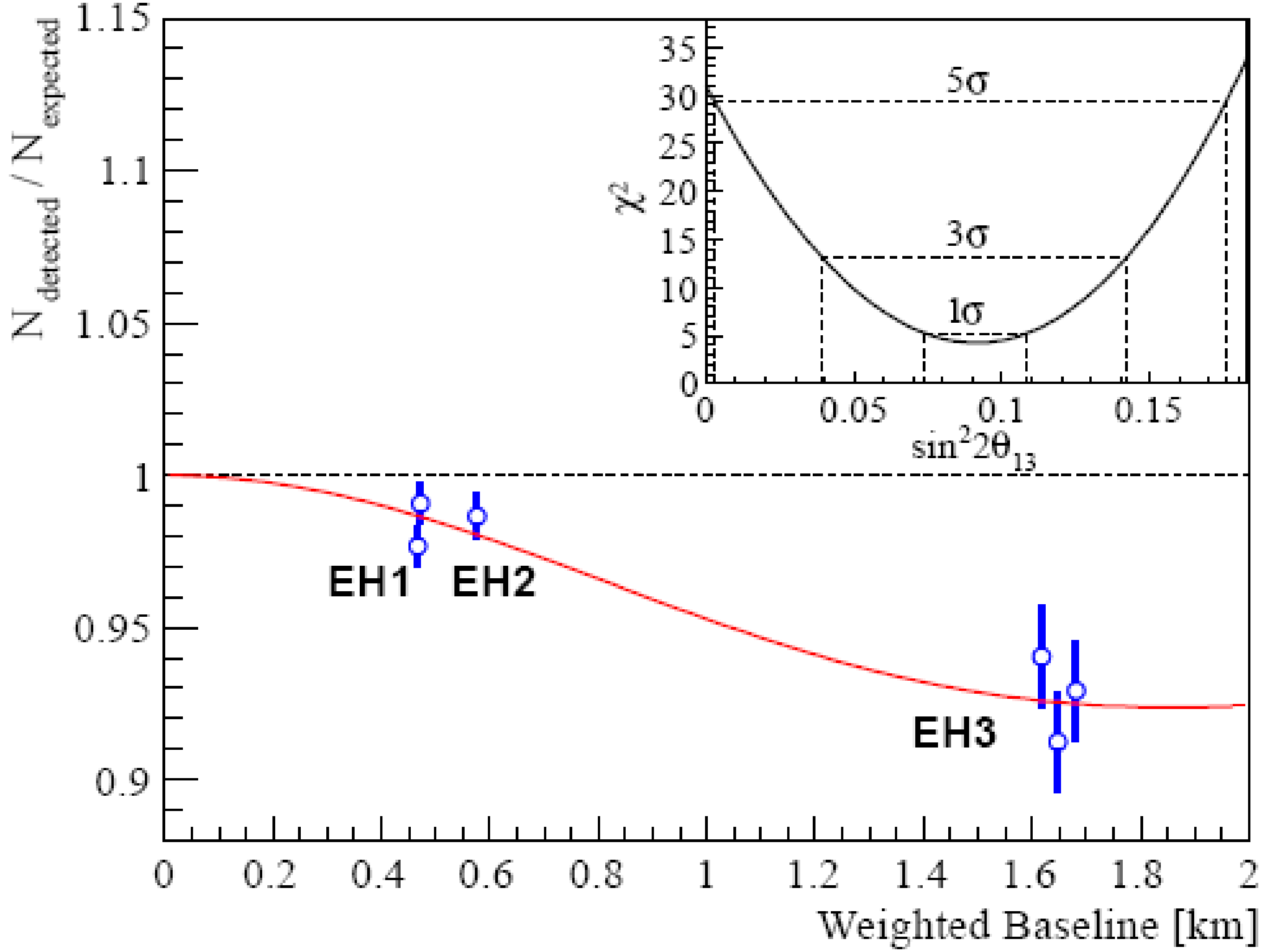
  together with a spectral distortion

- **A new type of neutrino oscillation is thus discovered**

$\sin^2 2\theta_{13}$=0.092± 0.016 (stat)±0.005(syst)

χ^2/NDF = 4.26/4

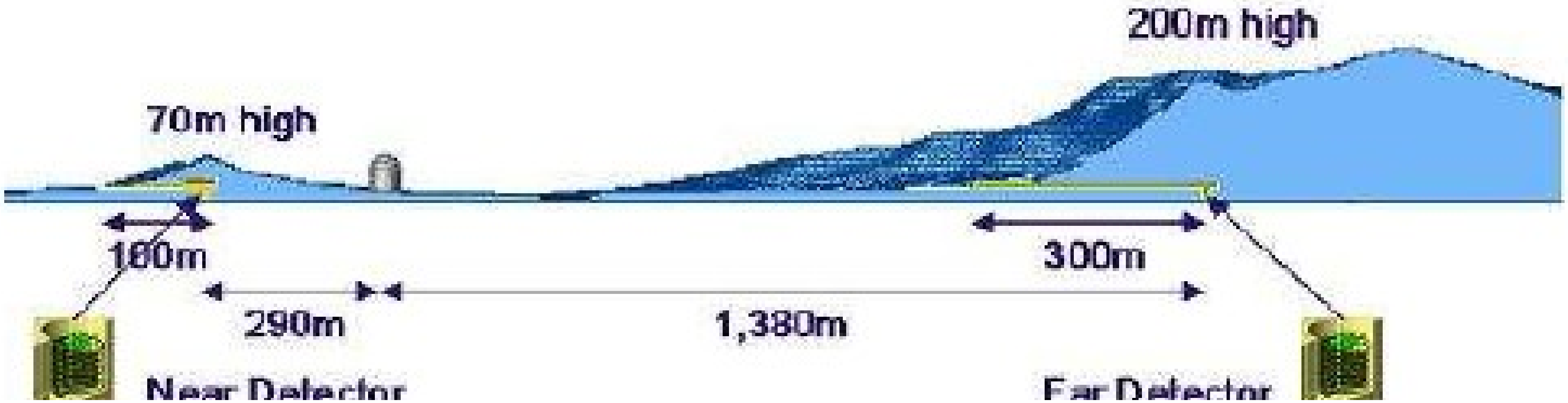
5.2 σ for non-zero θ_{13}



$N_{detected} / N_{expected}$
1.15
1.1
1.05
1
0.95
0.9
0
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6
1.8
2
Weighted Baseline [km]
EH1
EH2
EH3
χ^2
35
30
25
20
15
10
5
0
0.05
0.1
0.15
$\sin^2 2\theta_{13}$
5σ
3σ
1σ


Yellow Sea
Near Detector
Reactors
1 km
Far Detector

RENO experiment



Reno results

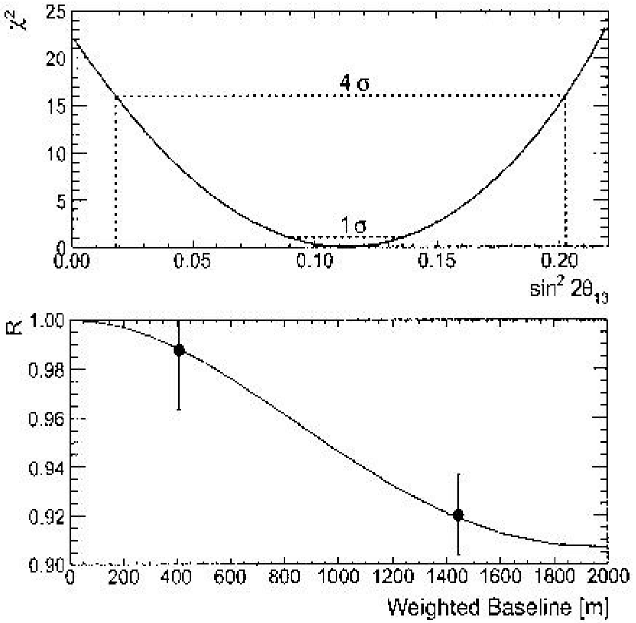


FIG. 3. The χ^2 distribution as a function of $\sin^2 2\theta_{13}$. Bottom: Ratio of the measured reactor neutrino events relative to the expected with no oscillation. The curve represents the oscillation survival probability at the best fit, as a function of the flux-weighted baselines.

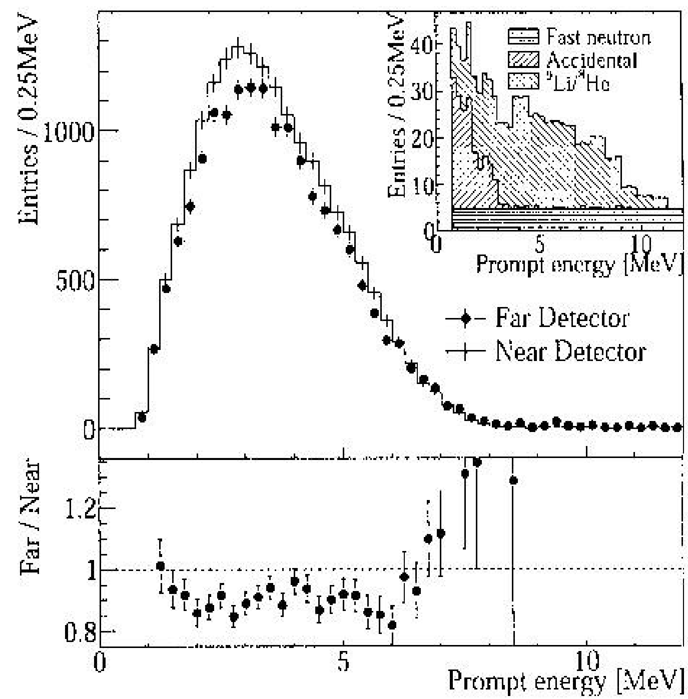


FIG. 4. Observed spectrum of the prompt signals in the far detector compared with the non-oscillation predictions from the measurements in the near detector. The backgrounds shown in the inset are subtracted for the far spectrum. The background fraction is 5.5% (2.7%) for far (near) detector. Errors are statistical uncertainties only. Bottom: The ratio of the measured spectrum of far detector to the non-oscillation prediction.

Gd-loaded liquid scintillator, and a 229 day exposure to

Reno results

R

$$\mathrm{Sin}^2(2\theta_{13}) = \quad 0.113 \pm 0.013(\mathrm{stat}) \pm 0.019(\mathrm{syst})$$

$$
U_{\mathrm{MNSP}} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & C_{23} & S_{23} \\ 0 & -S_{23} & C_{23} \end{pmatrix} \begin{pmatrix} C_{13} & 0 & S_{13}^{*} \\ 0 & 1 & 0 \\ -\hat{S}_{13} & 0 & C_{13} \end{pmatrix} \begin{pmatrix} C_{12} & S_{12} & 0 \\ -S_{12} & C_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} e^{i\phi_1} & & \\ & e^{i\phi_2} & \\ & & 1 \end{pmatrix}
$$

$$
= \begin{pmatrix} C_{12}C_{13} & C_{13}S_{12} & \hat{S}_{13}^{*} \\ -S_{12}C_{23} - C_{12}\hat{S}_{13}S_{23} & C_{12}C_{23} - S_{12}\hat{S}_{13}S_{23} & C_{13}S_{23} \\ S_{12}S_{23} - C_{12}\hat{S}_{13}C_{23} & -C_{12}S_{23} - S_{12}\hat{S}_{13}C_{23} & C_{13}C_{23} \end{pmatrix} \begin{pmatrix} e^{i\phi_1} & & \\ & e^{i\phi_2} & \\ & & 1 \end{pmatrix}
$$

$$\sin^2\theta_{12} = 0.314(1.00^{+0.18}_{\text{[illegible]}})$$

$$\sin^2\theta_{23} = 0.44(1.00^{+0.41}_{-0.22})$$

$$\sin^2\theta_{13} = 0.010(1.00 \pm 0.15)$$

$$\Delta m^2_{13} = \Delta m^2_{23} = (2.32 \pm 0.12/0.08)10^{-3}\ \mathrm{eV}^2$$

$$\Delta m^2_{21} = 7.92(1.00 \pm 0.09) \times 10^{-5}\ \mathrm{eV}^2$$

Следствия

- Ограничение на стерильное нейтрино

$$\mathrm{Sin}^2(2\theta_{14}) < 0.03$$

- Возможность изучать CP в лептонном секторе

$$U_{e3} = \sin\theta_{13} e^{-i\delta_{CP}}.$$

- Возможность установить иерархию нейтринных масс

определить знак Δm^2_{13}

- Возможность улучшить точность Δm^2_{13}

- Не требуется специальная симметрия нейтринной массовой матрицы (anarchy models)

Возможность улучшить точность Δm^2_{13}

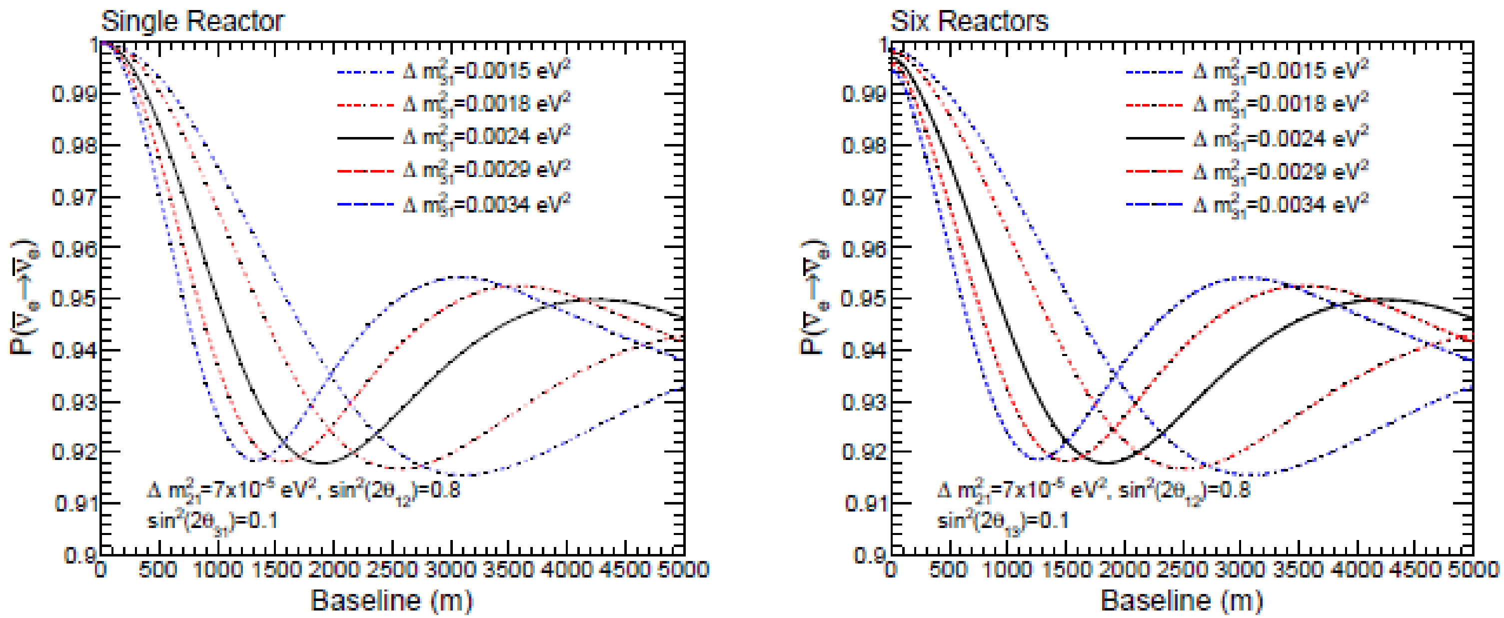


Figure 2.8: Survival probabilities of the reactor neutrinos with $\sin^2(2\theta_{13}) = 0.1$ and various values of Δm^2_{31} as a function of the distance from a single reactor (left) and six reactors arranged as shown in Fig. 1.2 (right). $\Delta m^2_{31} = 0.0024$ eV^2 represents the most probable value and the ranges $0.0018 \sim 0.0029$ eV^2 and $0.0015 \sim 0.0034$ eV^2 represent 63% and 90% CL, respectively. There is little difference between these two cases except at very small distances.

In general, if θ_{13} is not too small i.e., close to the current upper limit of $\sin^2 2\theta_{13} \approx 0.1$ and $\theta_{23} \neq \frac{\pi}{4}$, the neutrino mass matrix does not have to have any special symmetry features, sometimes referred to as anarchy models, and the specific values of the mixing angles can be understood as a numerical accident.

However, if θ_{13} is much smaller than the current limit, special symmetries of the neutrino mass matrix will be required. As a concrete example, the study of Mohapatra [23] shows that for $\theta_{13} < \frac{\Delta m^2_{\rm sol}}{\Delta m^2_{\rm atm}} \approx 0.03$ a μ-τ lepton-flavor-exchange symmetry is required. It disfavors a quark-lepton unification type theory based on $SU_c(4)$ or $SO(10)$ models.

For a larger value of θ_{13}, it leaves open the question of quark-lepton unification.

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

$$\sin^2\theta_{12} = 0.314(1^{+0.18}_{-0.15}) \qquad \Delta m^2_{21} = 7.92(1 \pm 0.09) \times 10^{-5}\ \mathrm{eV}^2$$

$$\sin^2\theta_{23} = 0.44(1^{+0.41}_{-0.22}) \qquad \Delta m^2_{23} = 2.4(1^{+0.21}_{-0.26}) \times 10^{-3}\ \mathrm{eV}^2.$$

$$U \simeq \begin{pmatrix} 0.8 & 0.5 & < 0.2 \\ 0.4 & 0.6 & 0.7 \\ 0.4 & 0.6 & 0.7 \end{pmatrix}$$

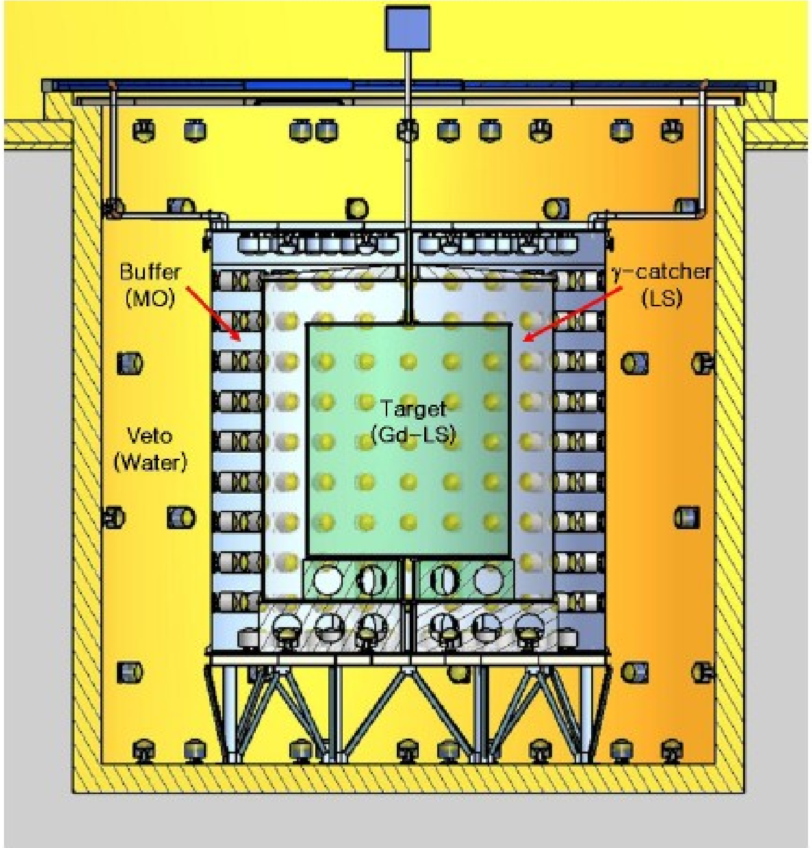
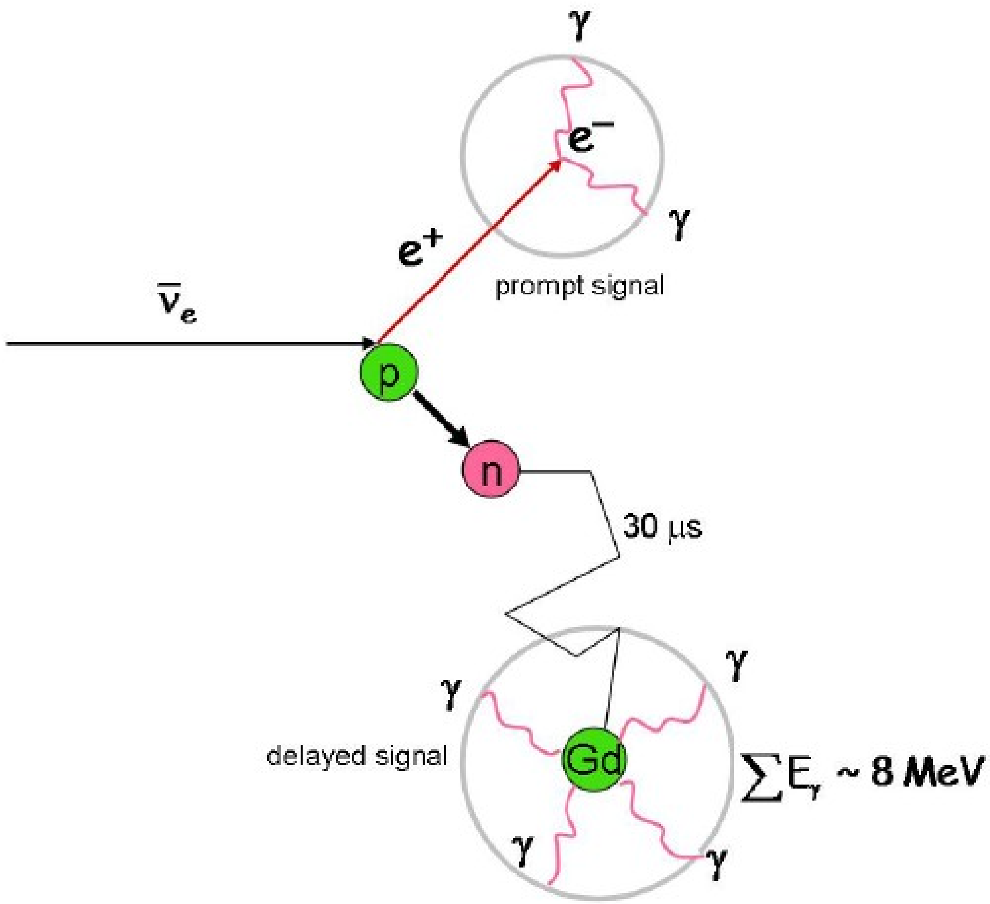


Figure 1.9: A schematic view of RENO detector. A neutrino target of 18.7 m^3 Linear Alkyl Benzene (LAB) based liquid scintillator doped with Gd is contained in a transparent acrylic vessel, and surrounded by 33.2 m^3 unloaded liquid scintillator of gamma catcher and 76.5 m^3 non-scintillating buffer. There are 354 and 67 10-inch PMTs mounted on buffer and veto vessel walls, respectively.



γ
e⁻
γ
e⁺
prompt signal
ν̄e
p
n
30 μs
γ
γ
delayed signal
Gd
ΣEγ ~ 8 MeV
γ
γ