Reactor Neutrino Experiments

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- Motivation for current short-baseline reactor experiments: θ_{13}
- Production and detection of reactor neutrinos
- Experiments to search for θ_{13}: Double Chooz, RENO, Daya Bay
- Summary

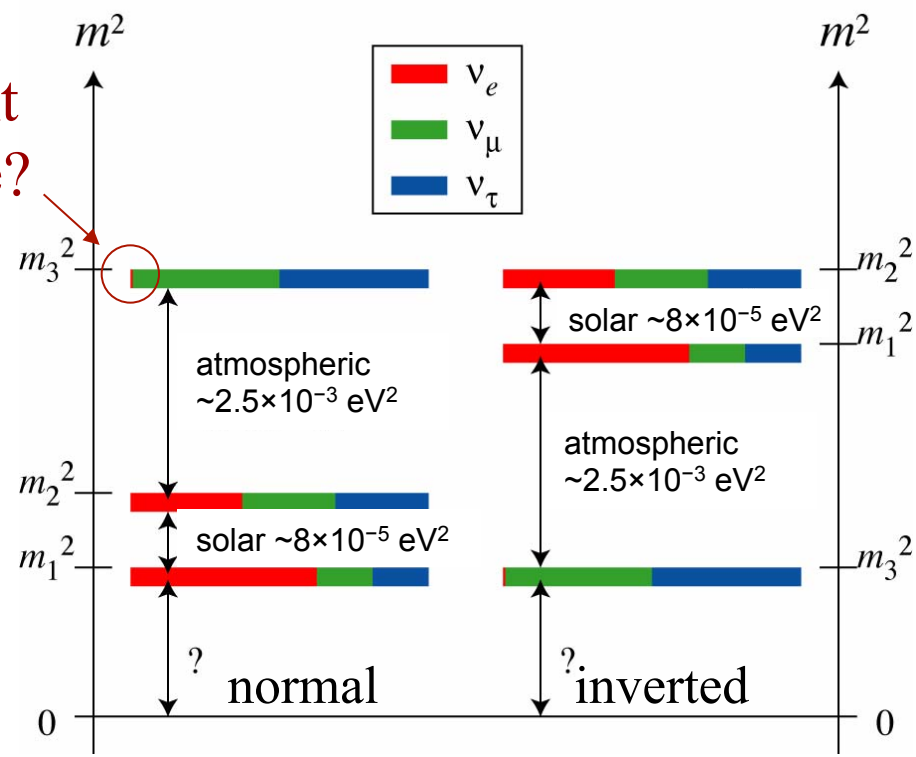
Neutrino mixing and masses

$$U = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} = \begin{pmatrix} Big & Big & Small\,? \\ Big & Big & Big \\ Big & Big & Big \end{pmatrix}$$

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

$\theta_{12} \sim 30°$ $\qquad$ $\sin^2 2\theta_{13} < 0.15$ at 90% CL $\qquad$ $\theta_{23} \sim 45°$

What is ν_e component of ν_3 mass eigenstate?



Key questions in neutrino mixing

- What is value of θ_{13}?

- What is mass hierarchy?

- Do neutrino oscillations violate CP symmetry?

$$P(\nu_\mu \to \nu_e) - P(\bar{\nu}_\mu \to \bar{\nu}_e) = -16 s_{12} c_{12} s_{13} c_{13}^2 s_{23} c_{23} \sin\delta \sin\left(\frac{\Delta m_{12}^2}{4E} L\right) \sin\left(\frac{\Delta m_{13}^2}{4E} L\right) \sin\left(\frac{\Delta m_{23}^2}{4E} L\right)$$

- Why are quark and neutrino mixing matrices so different?

$$U_{MNSP} \sim \begin{pmatrix} Big & Big & Small? \\ Big & Big & Big \\ Big & Big & Big \end{pmatrix} \quad \text{vs.} \quad V_{CKM} \sim \begin{pmatrix} 1 & Small & Small \\ Small & 1 & Small \\ Small & Small & 1 \end{pmatrix}$$

→ Value of θ_{13} central to these questions; it sets the scale for experiments needed to resolve mass hierarchy and search for CP violation.

Methods to measure $\sin^2 2\theta_{13}$

- Accelerators: Appearance ($\nu_\mu \rightarrow \nu_e$) at $\Delta m^2 \sim 2.5\times10^{-3}$ eV^2

$$P(\nu_\mu \rightarrow \nu_e) = \sin^2\theta_{23}\sin^2 2\theta_{13}\sin^2\frac{\Delta m_{13}^2 L}{4E} + \text{not small terms } (\delta_{CP},\ sign(\Delta m_{13}^2))$$

NOνA: $\langle E_\nu \rangle$ = 2.3 GeV, L = 810 km

T2K: $\langle E_\nu \rangle$ = 0.7 GeV, L = 295 km

- Reactors: Disappearance ($\bar{\nu}_e \rightarrow \bar{\nu}_e$) at $\Delta m^2 \sim 2.5\times10^{-3}$ eV^2

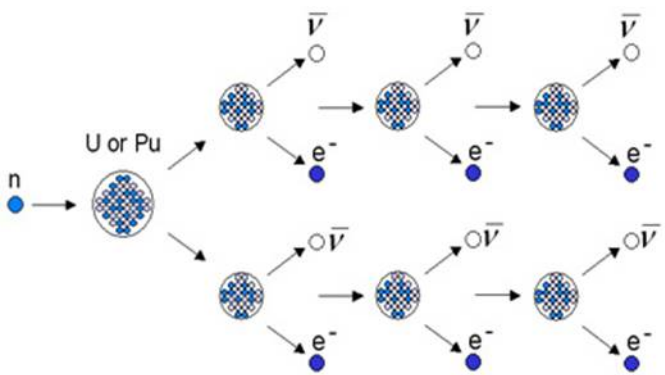
$$P(\bar{\nu}_e \rightarrow \bar{\nu}_e) = 1 - \sin^2 2\theta_{13}\sin^2\frac{\Delta m_{13}^2 L}{4E} + \text{ very small terms}$$

Use reactors as a source of $\bar{\nu}_e$ ($\langle E_\nu \rangle \sim 3.5$ MeV) with a detector 1-2 kms away and look for non-$1/r^2$ behavior of the $\bar{\nu}_e$ rate

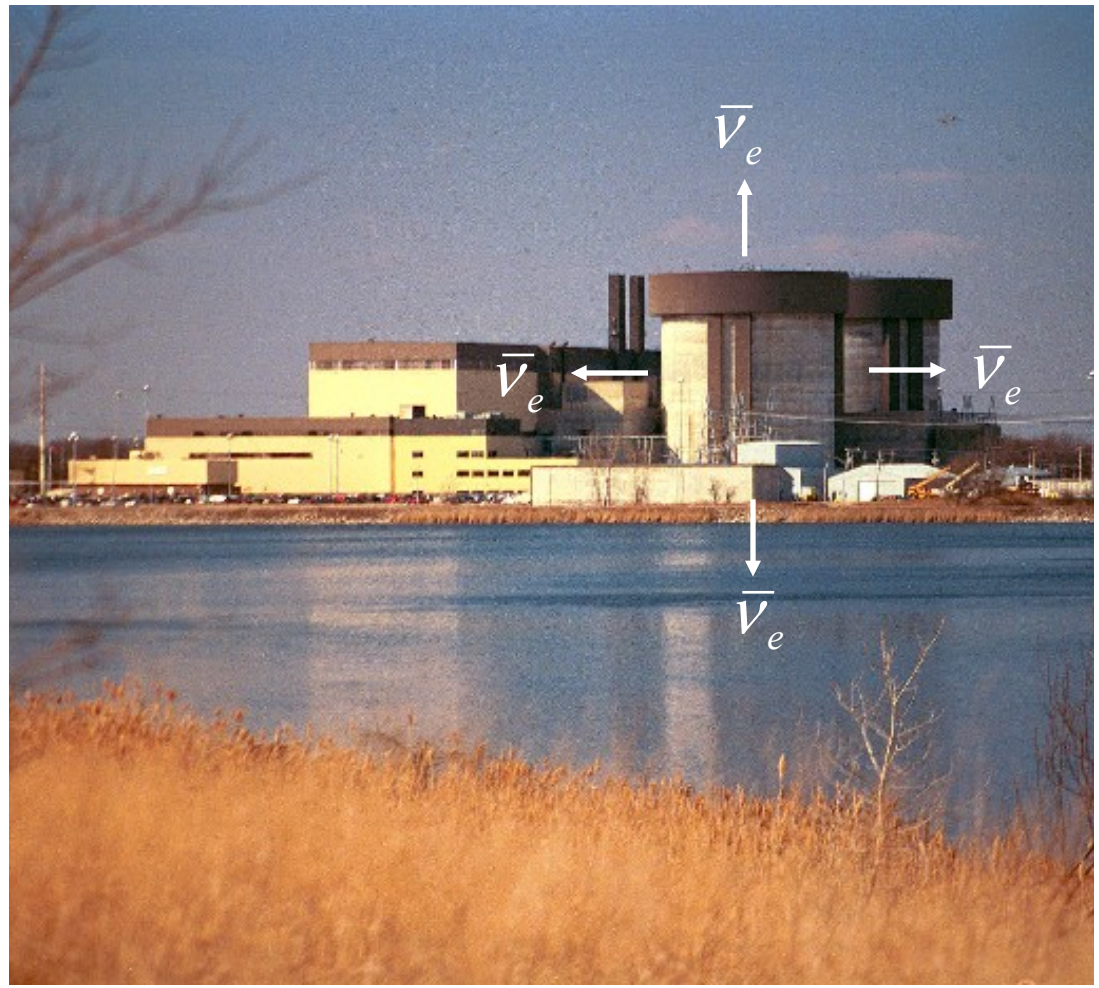
Reactor experiments provide the only clean measurement of $\sin^2 2\theta_{13}$:
no matter effects, no CP violation, almost no correlation with other parameters.

Reactors as Antineutrino Sources

Reactors are copious, isotropic sources of $\bar{\nu}_e$.



β⁻ decay of neutron rich fission fragments of U and Pu



Example: ^{235}U fission

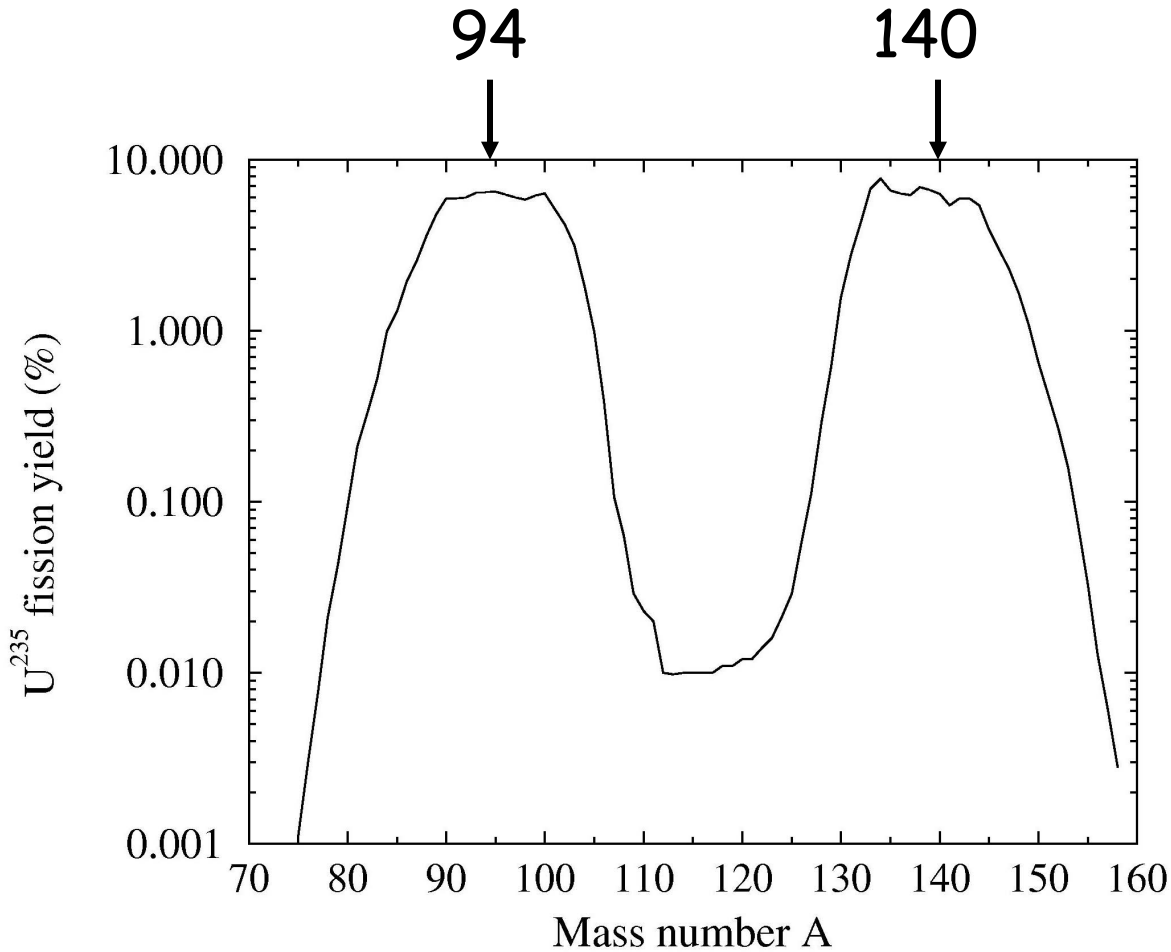
$$^{235}_{92}U + n \rightarrow X_1 + X_2 + 2n$$

Stable nuclei with most likely A from ^{235}U fission:

$^{94}_{40}Zr$ $^{140}_{58}Ce$

Together, these have 98 p and 136 n, while fission fragments (X_1+X_2) have 92 p and 142 n

On average, 6 n have to decay to 6 p to reach stable matter

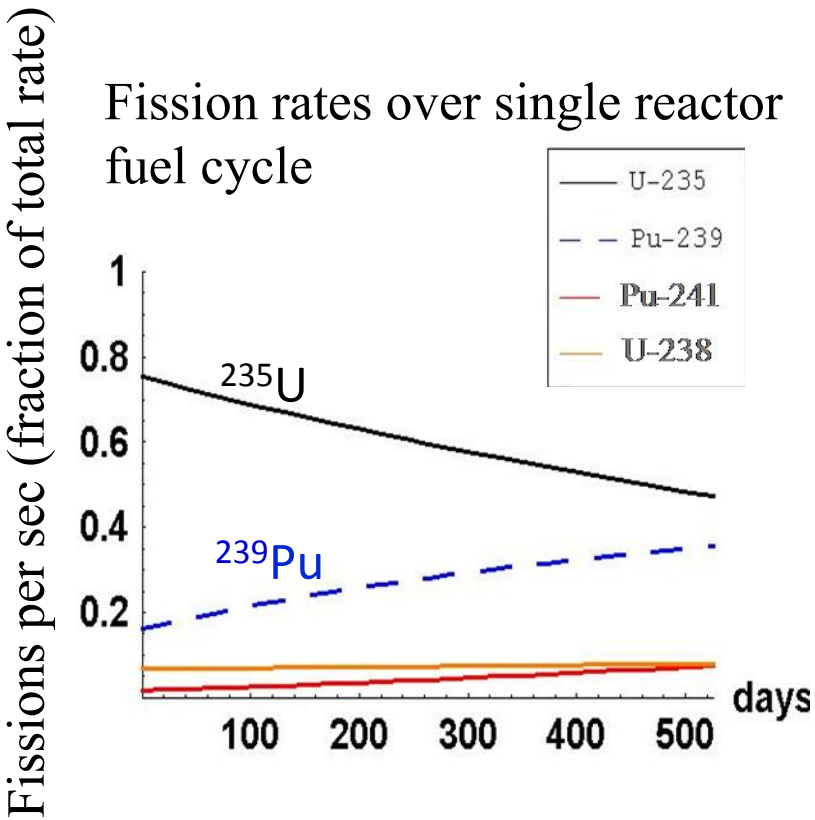


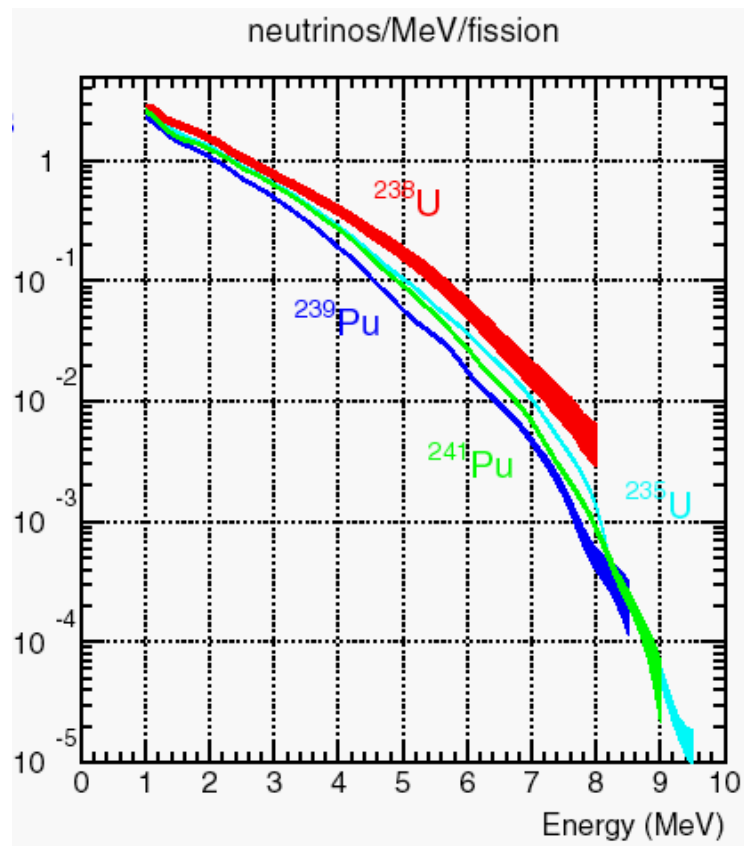
$\sim$ 200 MeV/fission and ~6 $\bar{\nu}_e$ / fission implies that 3GW$_{th}$ reactor produces $\sim 6\times10^{20}$ $\bar{\nu}_e$ / sec.

To do this calculation correctly, one must consider ^{235}U, ^{238}U, ^{239}Pu, and ^{241}Pu, account for evolution of the reactor core over the fuel cycle, and consider all of the possible β branches.

Direct measurements of electron spectra from thin layers of ^{235}U, ^{239}Pu, and ^{241}Pu in a beam of thermal neutrons are used as constraints.

Fission rates over single reactor fuel cycle

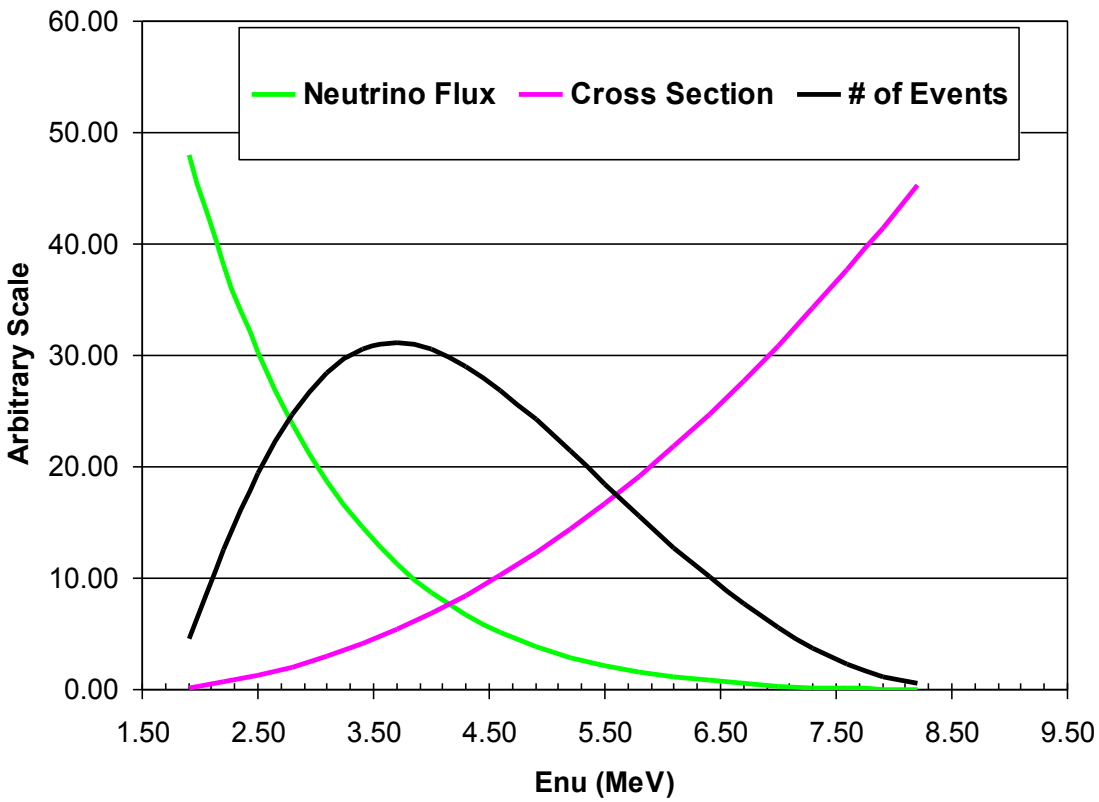




→ Total ν flux uncertainty estimated to be about 2-3%

Detection of $\bar{\nu}_e$

Inverse β Decay: $\bar{\nu}_e + p \rightarrow e^+ + n$



$$\sigma_{\text{tot}}^{(0)} = \frac{2\pi^2/m_e^5}{f_{p.s.}^R \tau_n} E_e^{(0)} p_e^{(0)}$$

$$E_{th} \sim M_n + m_{e+} - M_p$$

$$= 1.804 \text{ MeV},$$

so only ~1.5 $\bar{\nu}_e$ / fission can be detected.

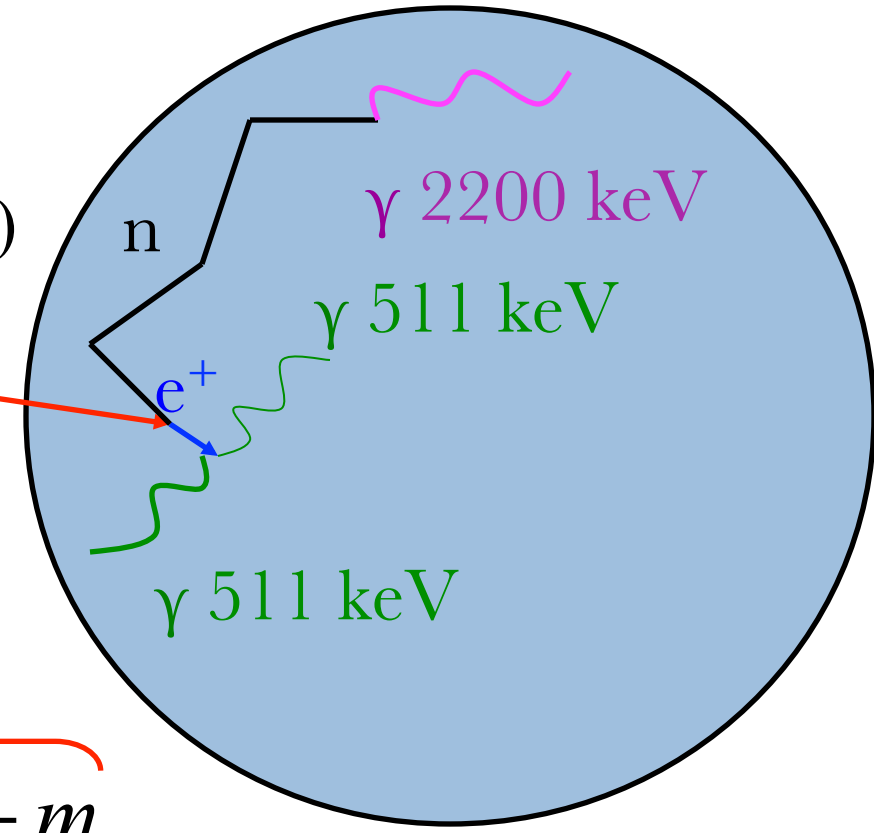
~1 IBD event per day per ton of LS per GW thermal at 1 km

Experiments detect coincidence between prompt e^+ and delayed neutron capture on hydrogen (or Cd, Gd, etc.)

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

$$\tau \approx 200\ \mu s$$

$$p + n \rightarrow d + \gamma(2.2\ MeV)$$



$\bar{\nu}_e$

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

Including E from e^+ annihilation, $E_{prompt} = E_\nu - 0.8$ MeV

Oscillation Experiments with Reactors

Antineutrinos from reactors can be used to study neutrino oscillations with "solar" $\Delta m^2_{12} \sim 8\times10^{-5}$ eV^2 and "atmospheric" $\Delta m^2_{13} \sim 2.5\times10^{-3}$ eV^2

→ Mean antineutrino energy is 3.6 MeV. Therefore, only disappearance experiments are possible.

$$P(\bar{\nu}_e \to \bar{\nu}_e) \approx 1 - \sin^2 2\theta_{13} \sin^2 \frac{\Delta m^2_{13} L}{4E} - \cos^4 \theta_{13} \sin^2 2\theta_{12} \sin^2 \frac{\Delta m^2_{12} L}{4E},$$

where $\Delta m^2_{ij} = m^2_i - m^2_j$.

Experiments look for non-$1/r^2$ behavior of antineutrino rate.

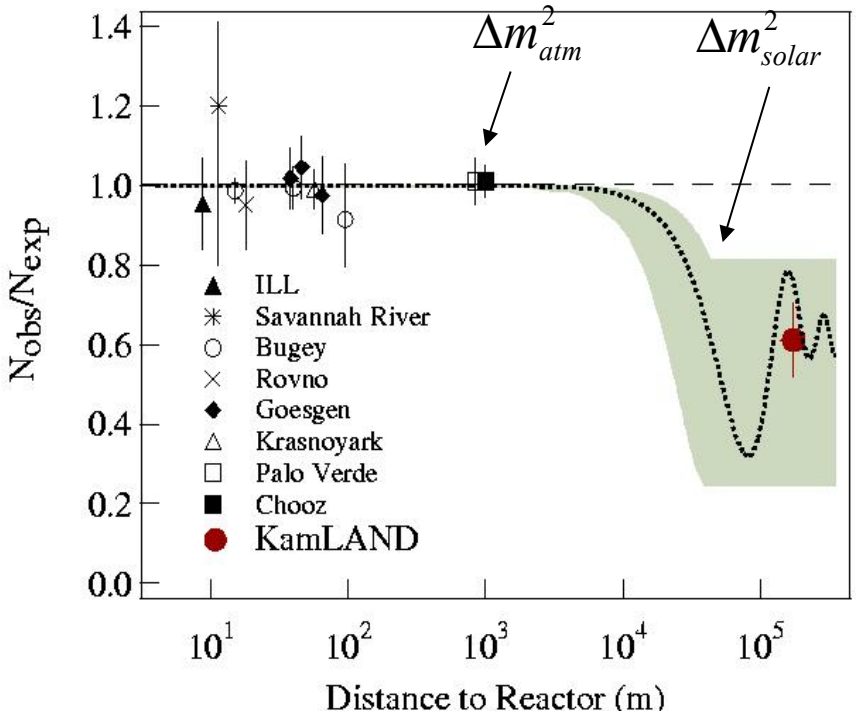
Oscillation maxima for E_ν=3.6 MeV:

$\Delta m^2_{12} \sim 8\times10^{-5}$ eV^2 → L ~ 60 km

$\Delta m^2_{13} \sim 2.5\times10^{-3}$ eV^2 → L ~ 1.8 km

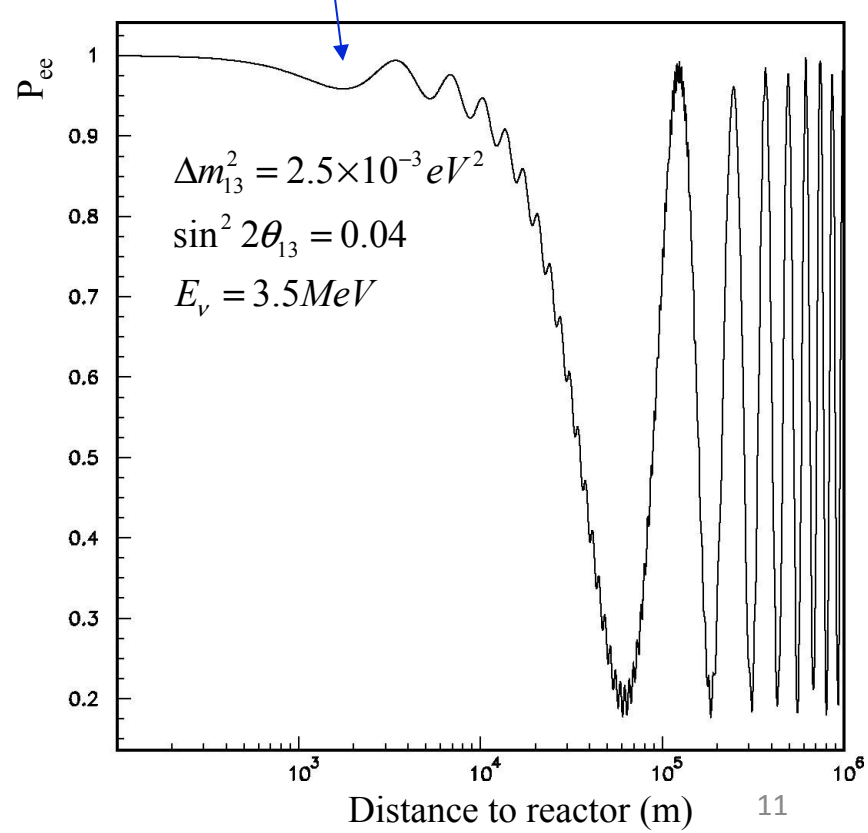
Neutrino Oscillation Searches at Nuclear Reactors

Past measurements:



θ_{13}: Search for small oscillations at 1-2 km distance (corresponding to Δm^2_{atm}).

$$P(\bar{\nu}_e \to \bar{\nu}_e) \approx \underbrace{1 - \sin^2 2\theta_{13} \sin^2 \frac{\Delta m^2_{13} L}{4E}} - c^4_{13} \sin^2 2\theta_{12} \sin^2 \frac{\Delta m^2_{12} L}{4E}$$



Reactor Neutrino Flux and the Reactor Antineutrino Anomoly

Th. A. Mueller et al.``Improved Predictions of Reactor Antineutrino Spectra,'' accepted for publication in Phys. Rev. C, 83 (2011) 054615; arXiv:1101.2663.

G. Mention et al., ``The Reactor Antineutrino Anomoly,'' Phys. Rev. D, 83 (2011) 073006; arXiv:1101.2755.

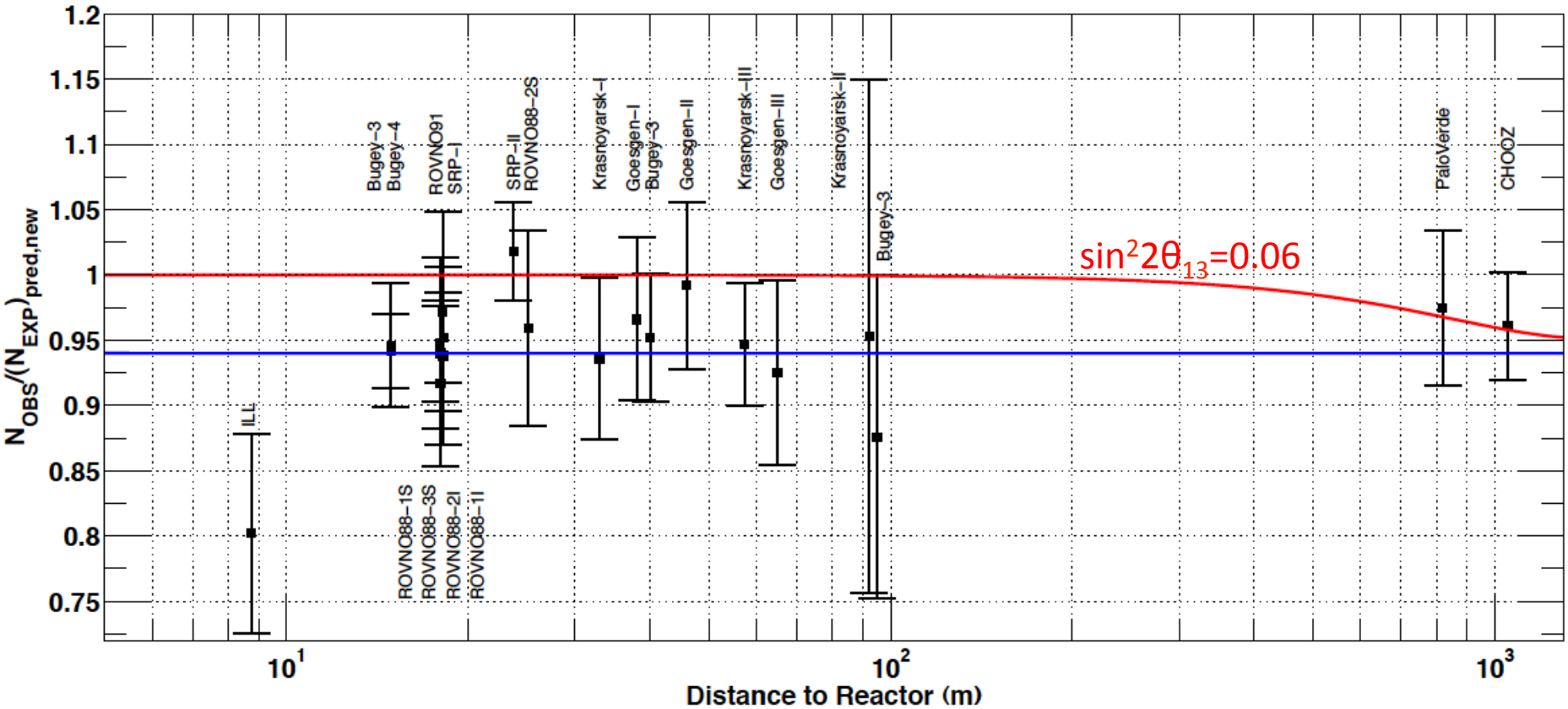
P. Huber, ``On the determination of anti-neutrino spectra from nuclear reactors; arXiv:1106.06874.

As part of preparation for Double Chooz analysis with a single far detector, Mueller et al. applied an improved procedure to go from measured ^{235}U, ^{239}Pu, and ^{241}Pu β^- spectra (at ILL) to neutrino spectra.

The result is a +3% increase in neutrino flux, on average.

Huber, using a different method to go from β^- to ν spectra, finds a similar shift.

G. Mention et al.



For L<100m, accounting for correlations, they find

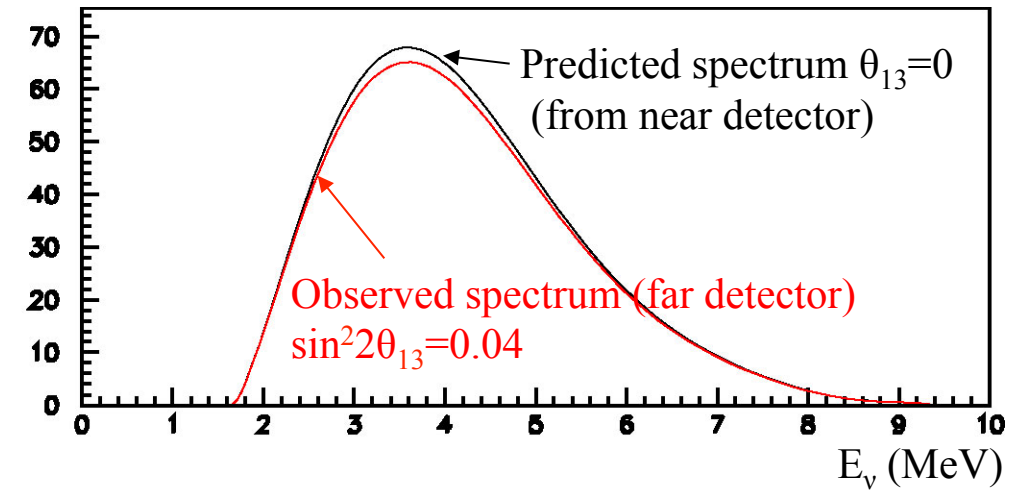
$$N_{OBS}/N_{EXP} = 0.937 \pm 0.027$$

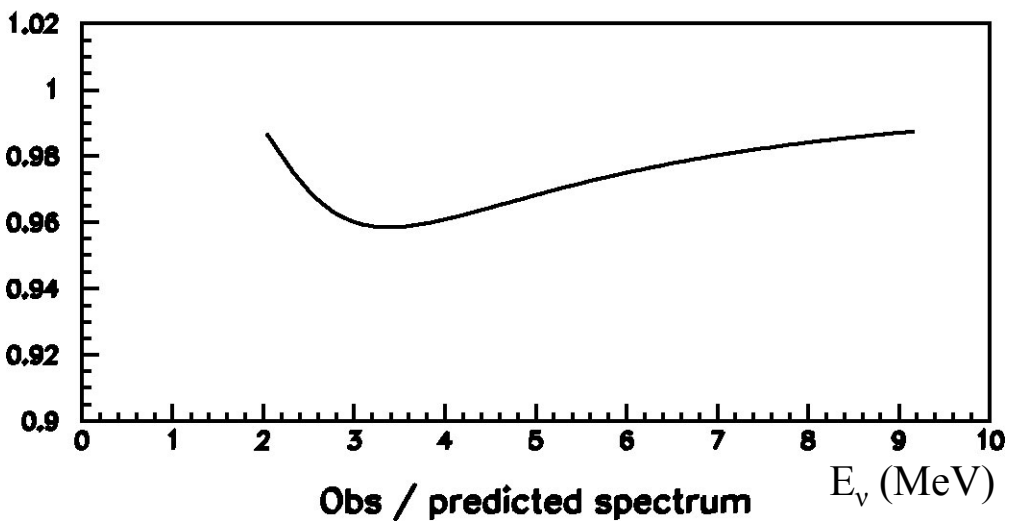
The shift could be a hint of a non-standard neutrino state with $\Delta m^2 > \sim 1\ eV^2$ and $\sin^2 2\theta \sim 0.1$.

Issues affecting oscillation experiments

- Knowledge of antineutrino flux and spectrum
- Detector acceptance
- Understanding of energy reconstruction
- Backgrounds:
  - Uncorrelated backgrounds from random coincidences
    - Reduced by limiting radioactive materials
    - Directly measured from rates and offset time coincidence windows
  - Correlated backgrounds
    - Neutrons that mimic the coincidence signal
    - Cosmogenically produced isotopes that decay to a beta and neutron: ^{9}Li ($\tau_{1/2}$=178 ms) and ^{8}He ($\tau_{1/2}$=119 ms); associated with showering muons.
    - Reduced by shielding (depth) and veto systems

Normalization and spectral information





Counting analysis: Compare number of events in near and far detector

Systematic uncertainties:

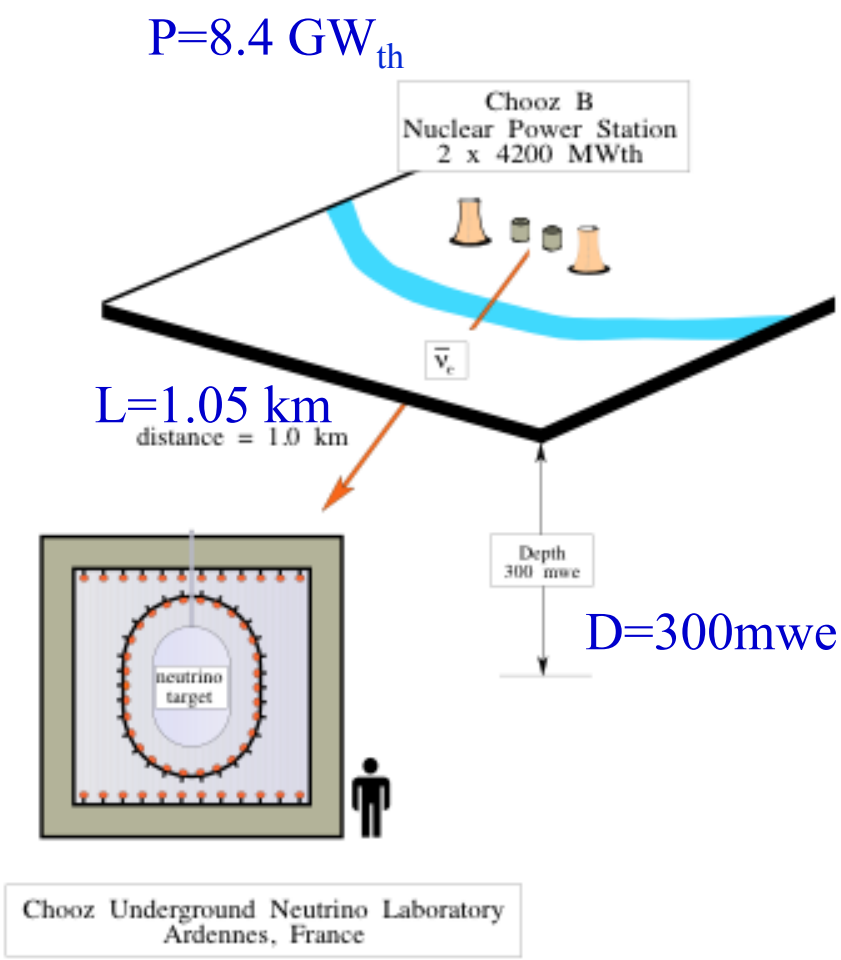
- relative normalization of near and far detectors
- relatively insensitive to energy calibration

Energy spectrum analysis: Compare energy distribution in near and far detectors

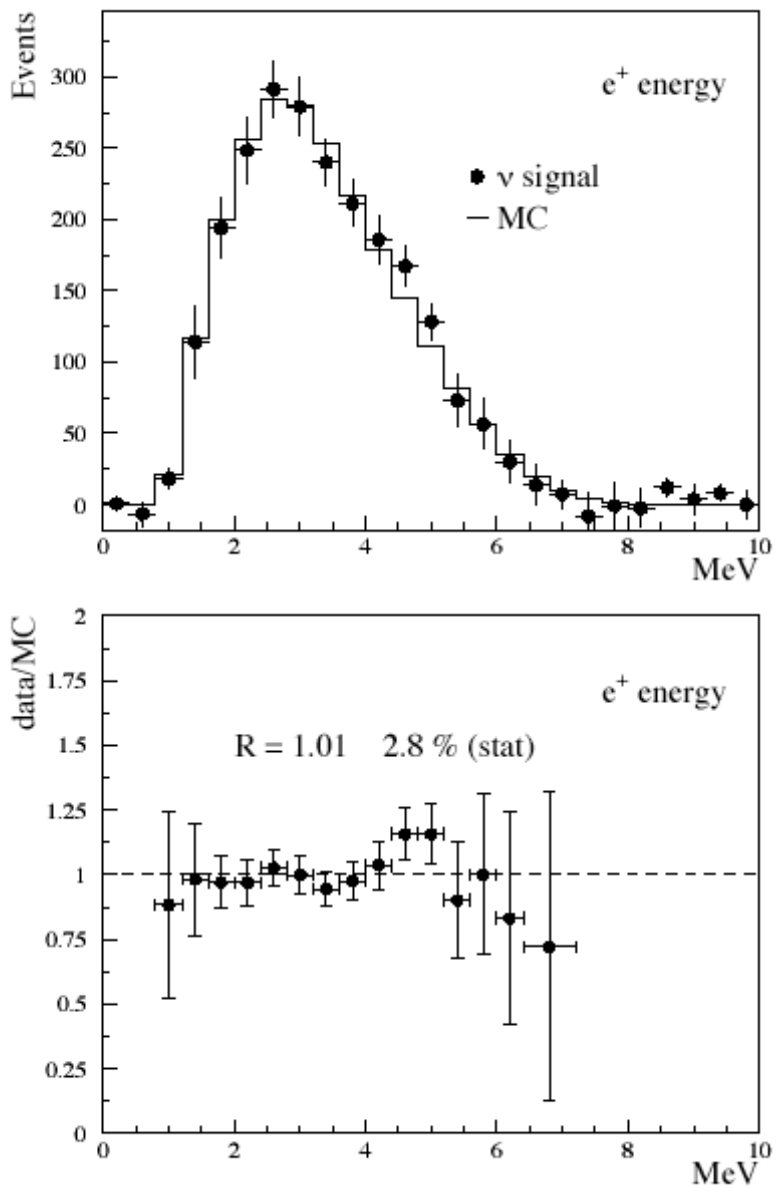
Systematic uncertainties:

- energy scale and linearity
- insensitive to relative efficiency of detectors

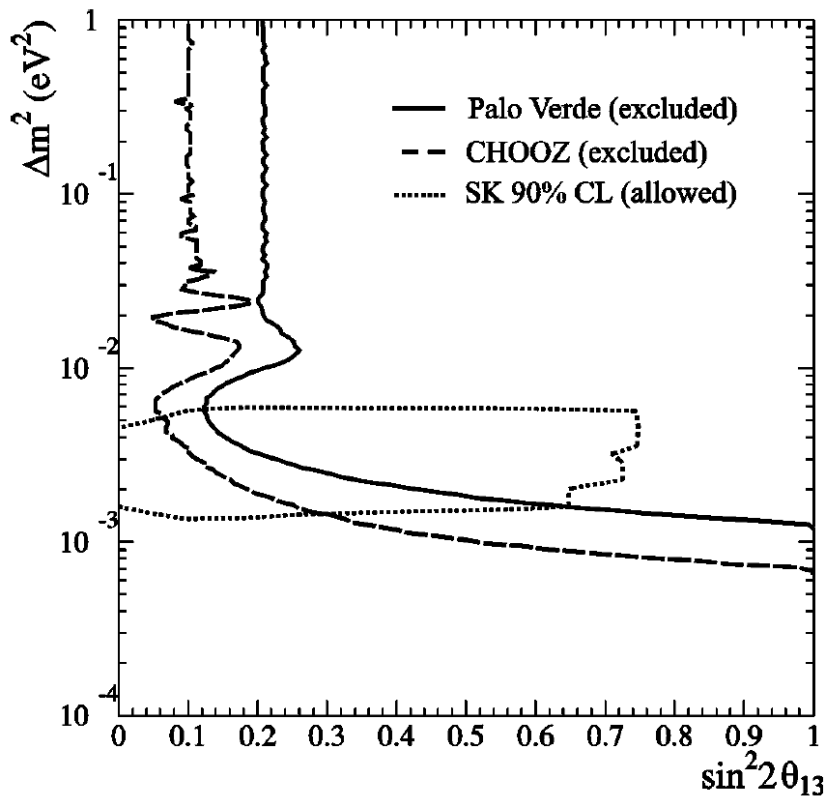
Best θ_{13} Limit: Chooz Experiment



m = 5 tons, Gd-loaded liquid scintillator



CHOOZ Systematic errors	
Reactor ν flux	2%
Detect. Acceptance	1.5%
Total	2.7%



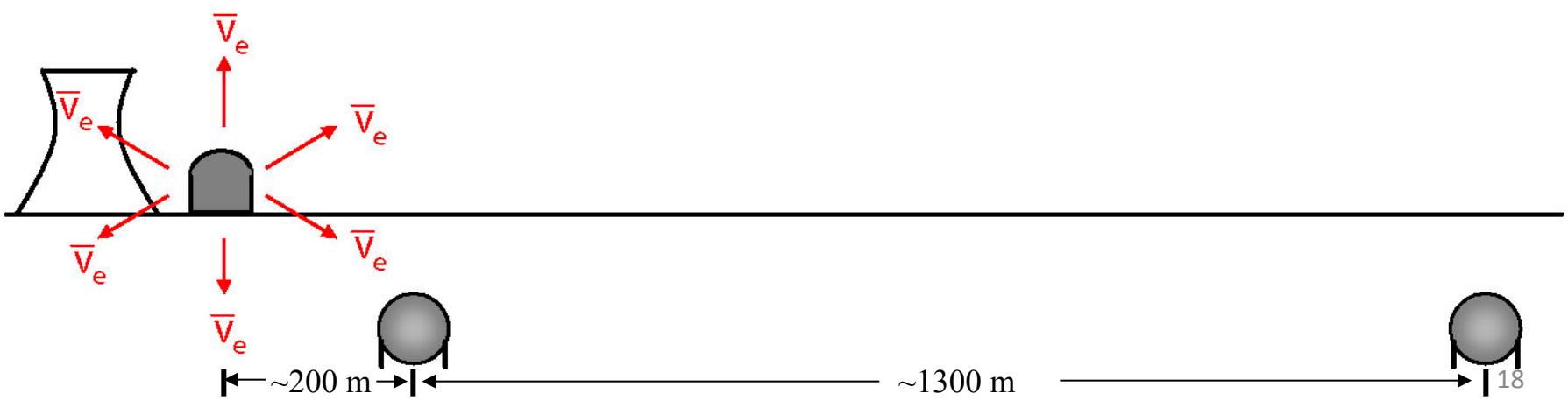
$\sin^2 2\theta_{13} < 0.15$ for $\Delta m^2 = 2.5\times10^{-3}\ eV^2$

How can one improve on Chooz Experiment?

- Add an identical near detector

  Eliminate dependence on reactor flux; only relative acceptance of detectors needed
- Optimize baseline
- Larger detectors; improved detector design
- Higher power reactor sites
- Reduce backgrounds

  Go deeper and use active veto systems
- Stable scintillator



New Multi-detector θ_{13} Reactor Experiments

Experiment	GW_{th}	Distance Near/Far (m)	Shielding Near/Far (mwe)	Target Mass (tons)	Sensitivity $\sin^2 2\theta_{13}$ (90% c.l.)	Start of data taking
Double Chooz (France)	8.4	390/1050	115/300	8/8	0.03	April 2011 far det only; near in 2013
RENO (Korea)	17.3	290/1380	120/450	16/16	0.02	August 2011 Near+far
Daya Bay (China)	17.4	360(500)/ 1985(1615)	260/910	2×2×20 (N) 4×20 (F)	0.01	Dec 2011 Near (3)+far (3)

- Many similarities in detector design and analysis strategy
- Differences in sensitivity come mainly from statistics (mass, reactor power), baseline optimization, and multiple detectors (for Daya Bay)

Detectors and analysis strategy designed to minimize relative acceptance differences

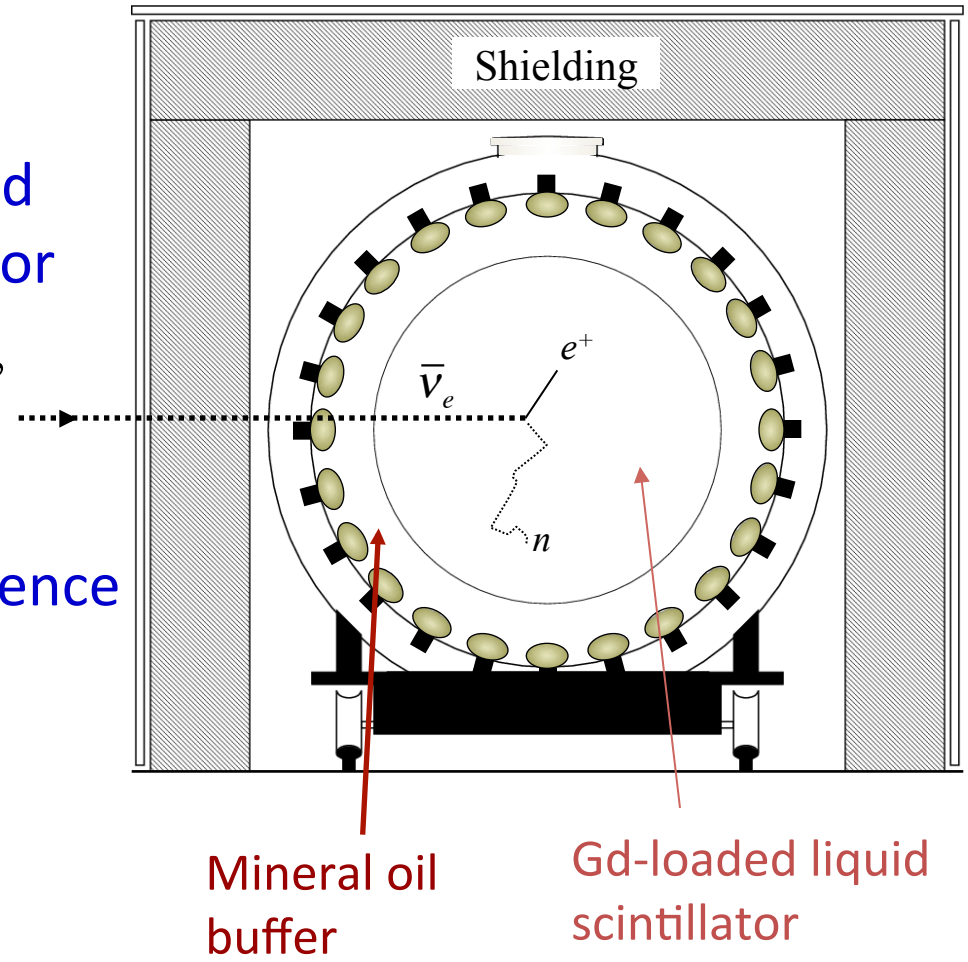
Central zone with Gd-loaded scintillator surrounded by buffer regions; fiducial mass determined by volume of Gd-loaded scintillator

Neutrino detection by $\bar{\nu}_e + p \rightarrow e^+ + n,$

n ^{m}Gd → $^{m+1}$Gd γs (8 MeV); τ=30μsec

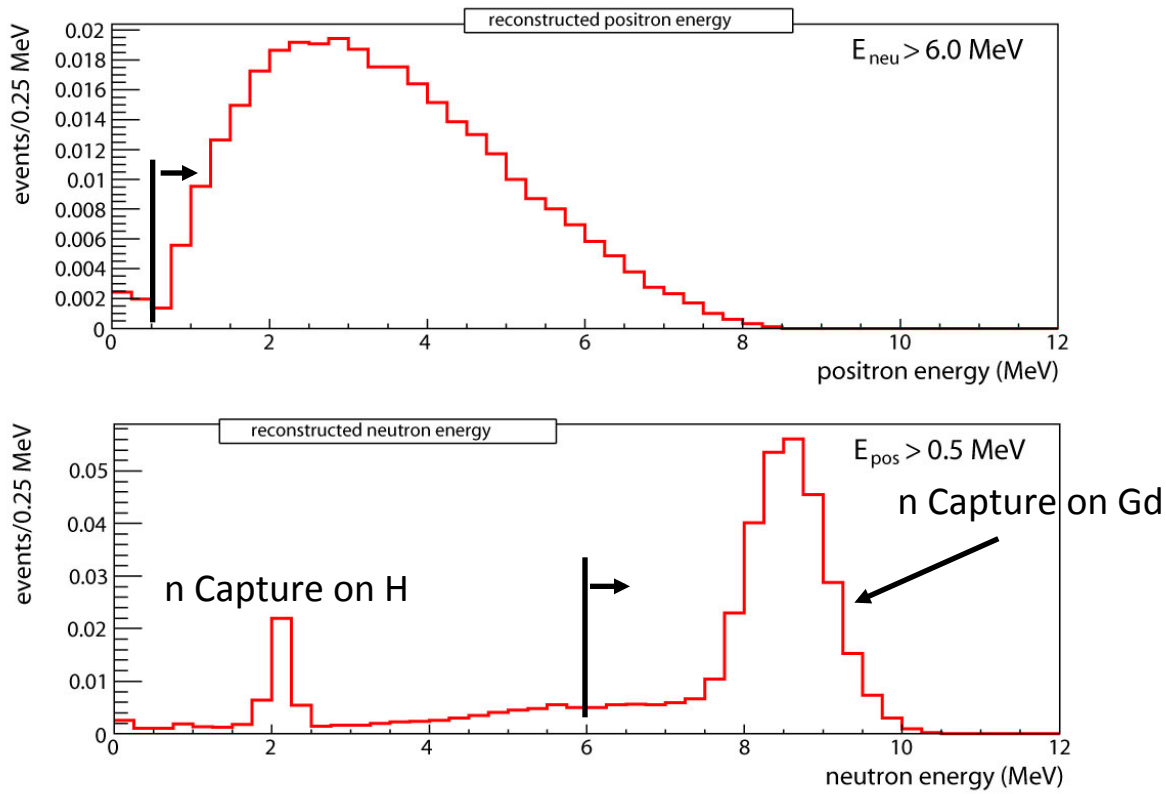
Events selected based on coincidence of e^+ signal (E_{vis}>0.5 MeV) and γs released from n+Gd capture (E_{vis}>6 MeV).

No explicit requirement on reconstructed event position; little sensitivity to E requirements.



Events selected based on coincidence of e^+ signal (E_{vis}>0.5 MeV) and γs released from n+Gd capture (E_{vis}>6 MeV).

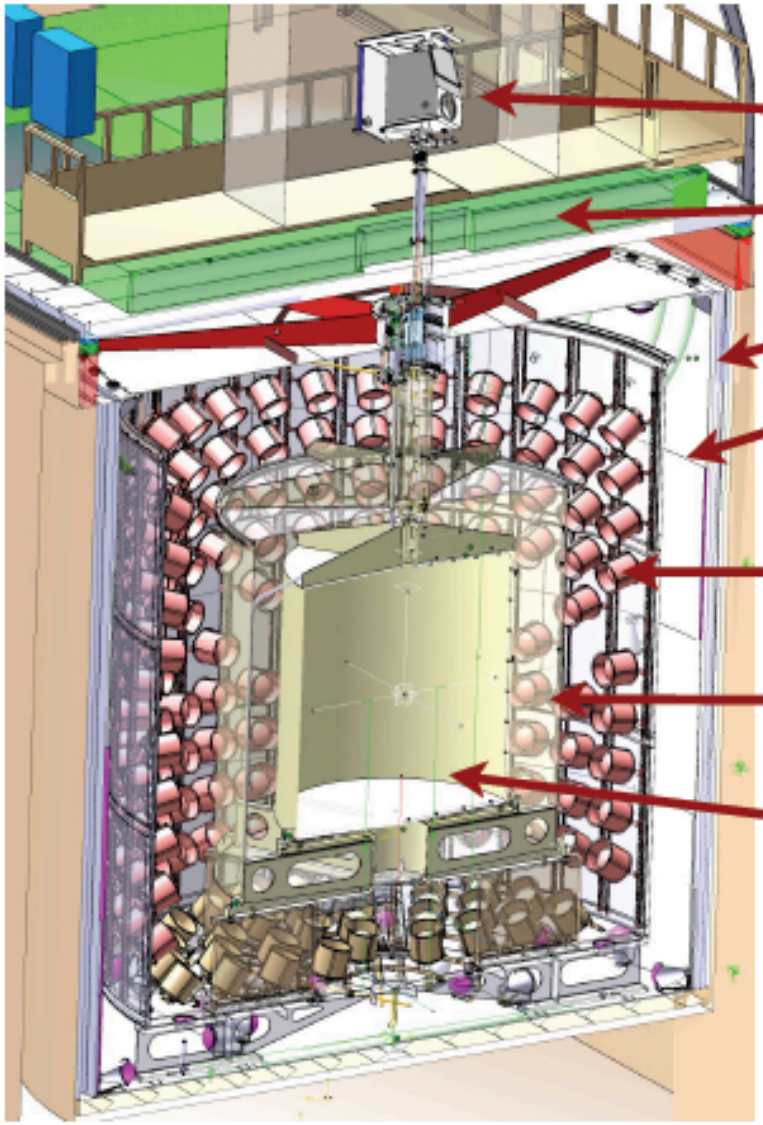
Reconstructed e^+ and n-capture energy



Double Chooz Experiment

Collaboration of ~150 physicists from France, Germany, Spain, Japan, U.K., Russia, Brazil, and U.S.

Double Chooz Detector Design



Calibration glove box

Outer veto: plastic scintillator strips

Shielding: 15 cm steel

Inner veto:

90m^3 of liquid scintillator & 78 8" PMTs

Buffer:

110m^3 of non scintillating mineral oil & 390 10" PMTs

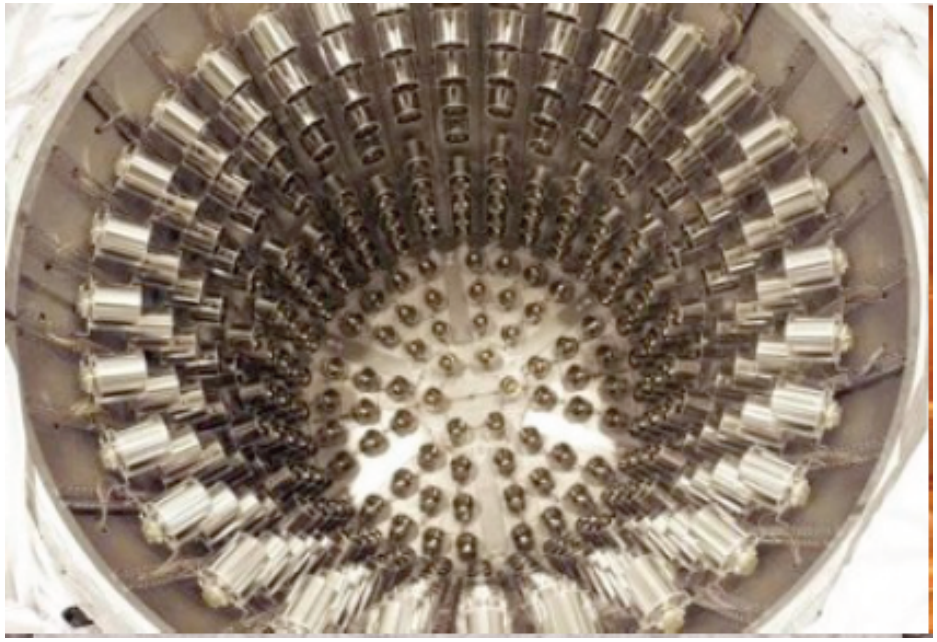
Gamma-catcher:

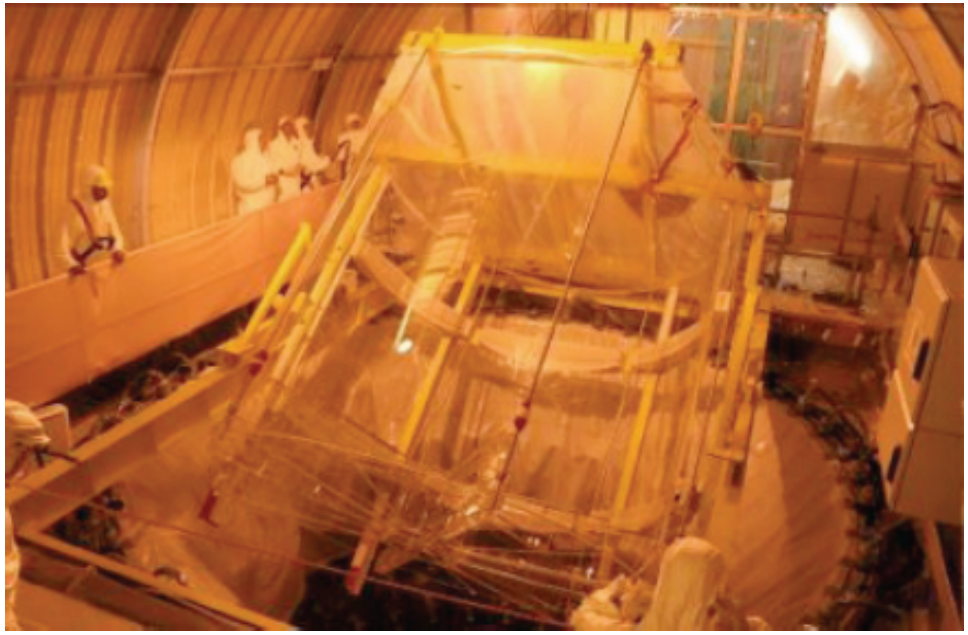
22.3m^3 of liquid scintillator

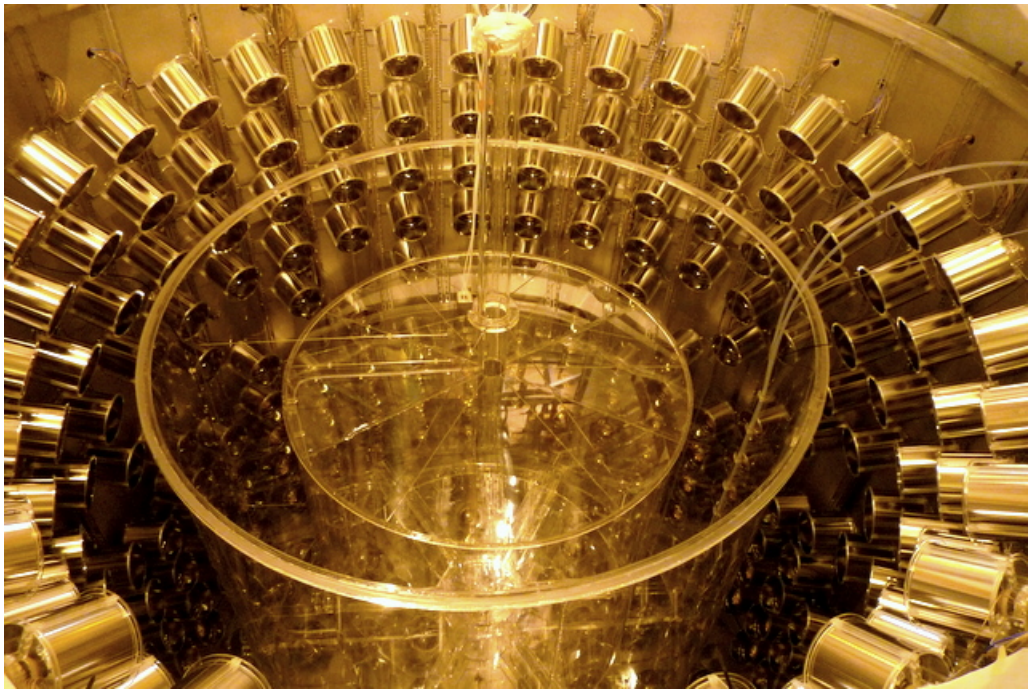
Target:

10.3m^3 of liquid scintillator doped with 1 g/L of Gd

Double Chooz Far Detector Installation

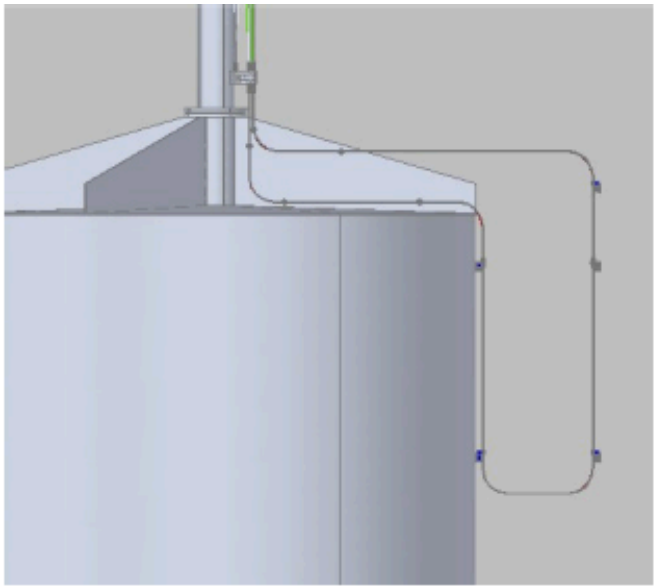


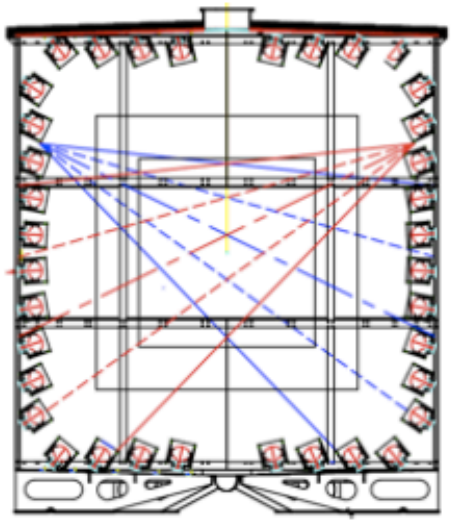


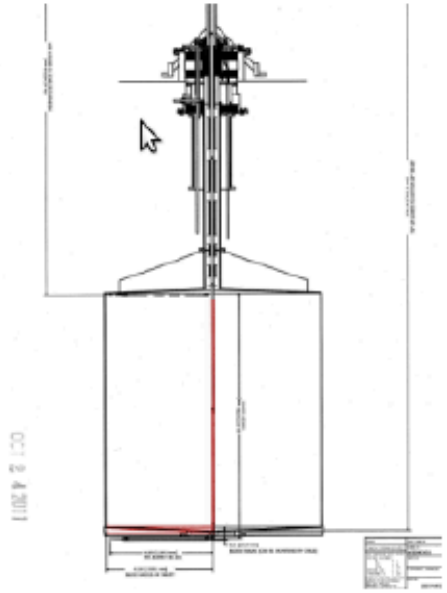


Double Chooz Outer Veto (made in Chicago)

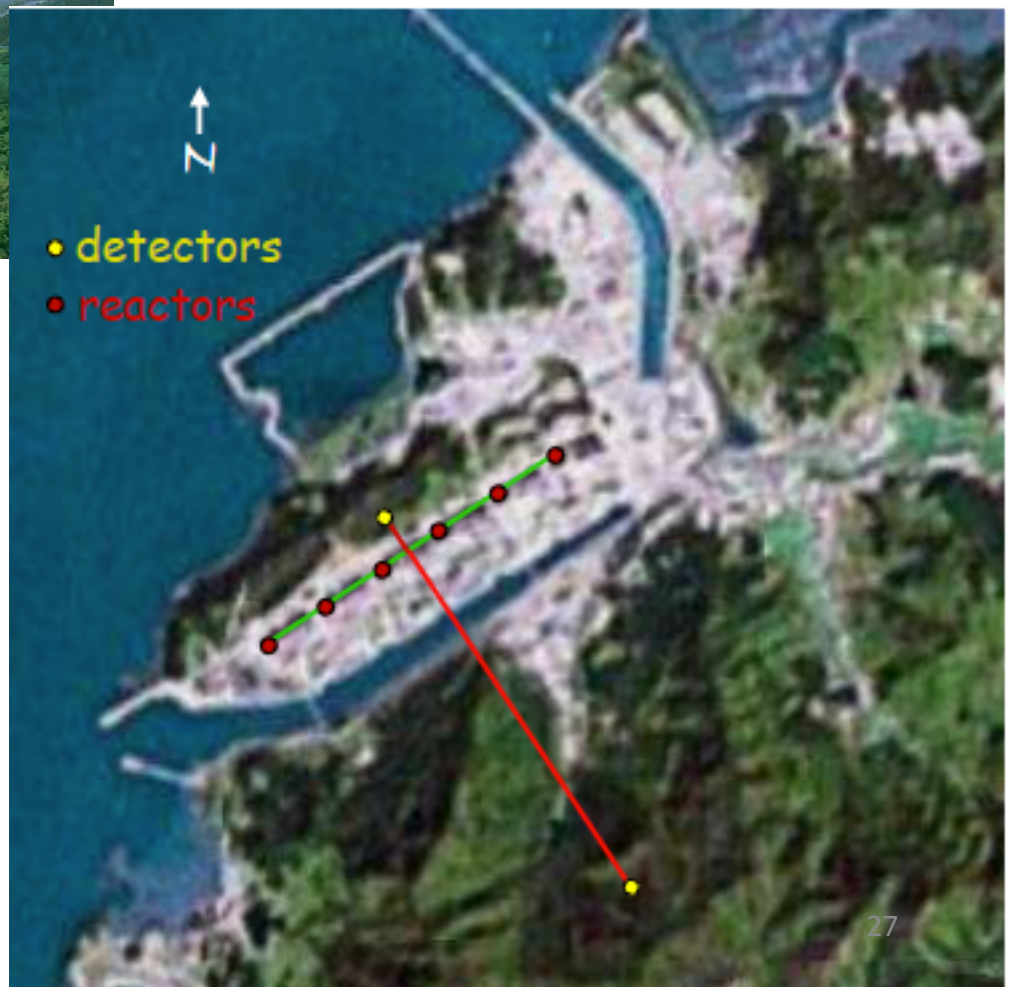
- Gamma sources (^{68}Ge, ^{137}Cs, ^{60}Co) and neutron source (^{252}Cf) deployed along:
  - Vertical axis of target
  - Guide tube in the gamma catcher
- LED light injector (edge of buffer) and laser systems (vertical axis)
  - Speed of light in scintillator
  - PMT gains and time offsets
- Articulated arm in preparation
  - Will allow putting sources or LEDs anywhere in the target







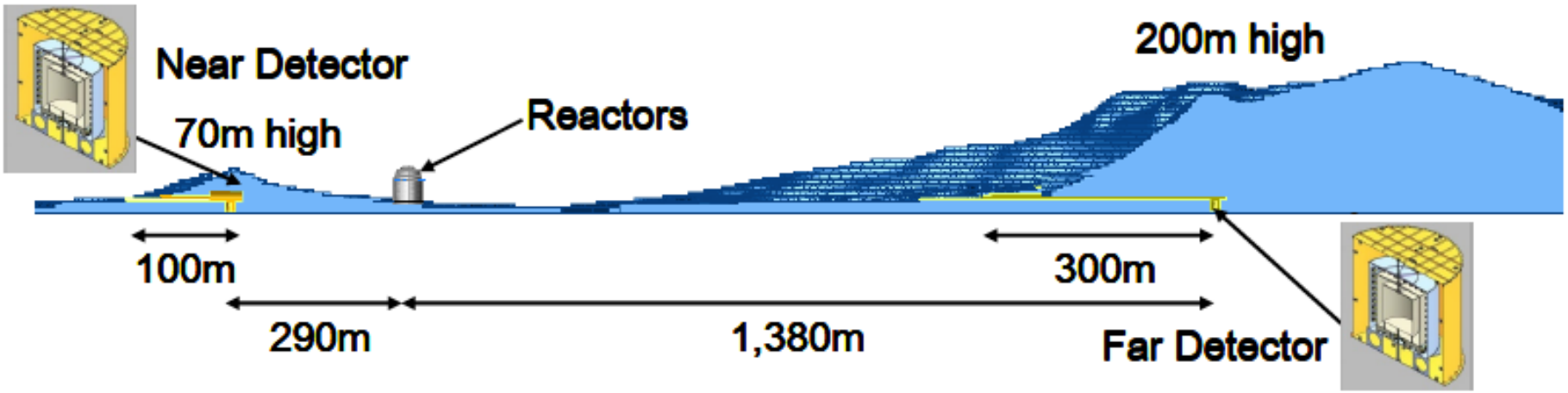
RENO Experiment
South Korea



6 reactors span ~1.3 km
Total average thermal output ~16.4 GW_{th}

40 physicists from 13 South Korean institutions (1 U.S.)

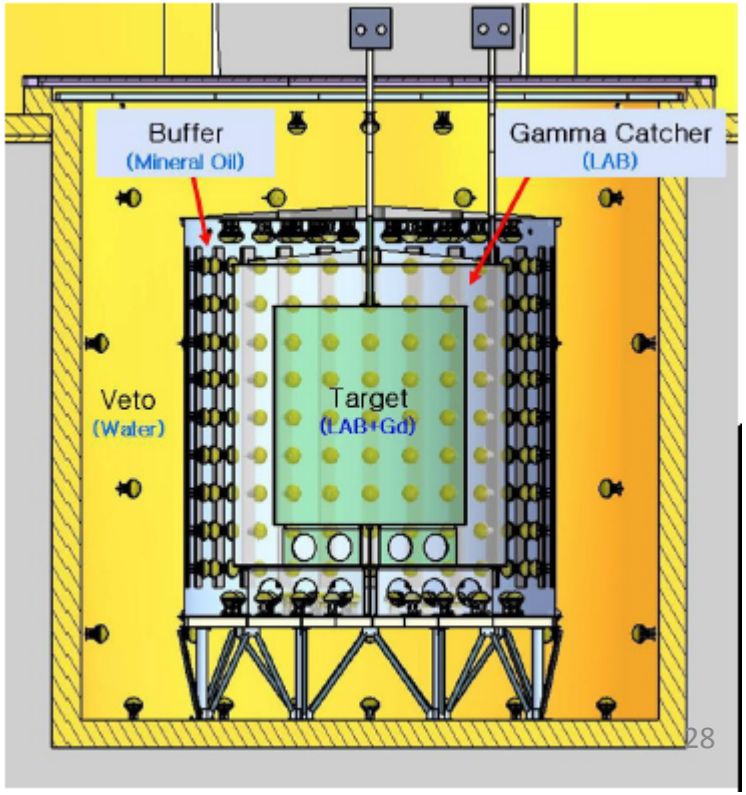
RENO Layout



RENO Detector

- **Inner PMTs: 342 10" PMTs**
  - solid angle coverage = 12.6%
- **Outer PMTs: ~ 60 10" PMTs**

Target: 16 tons

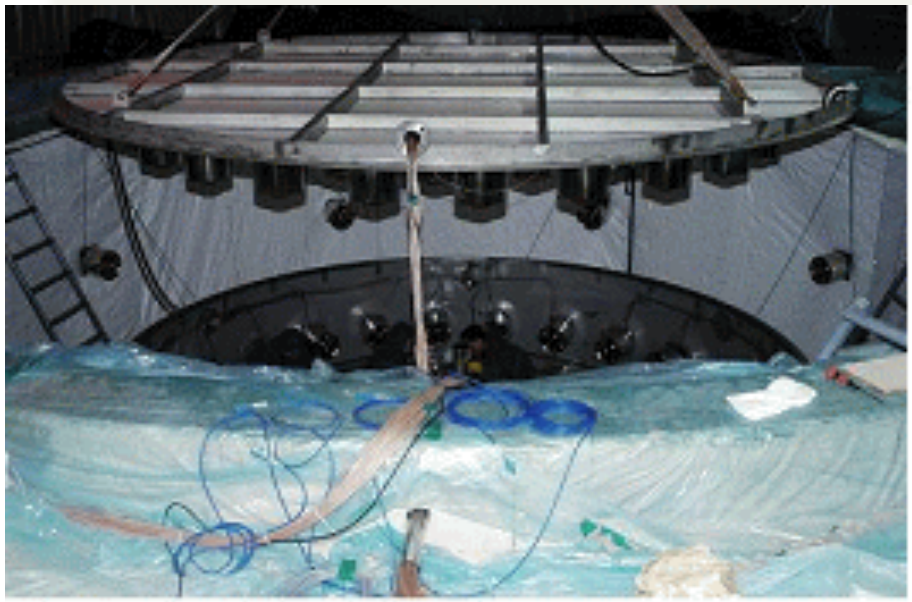


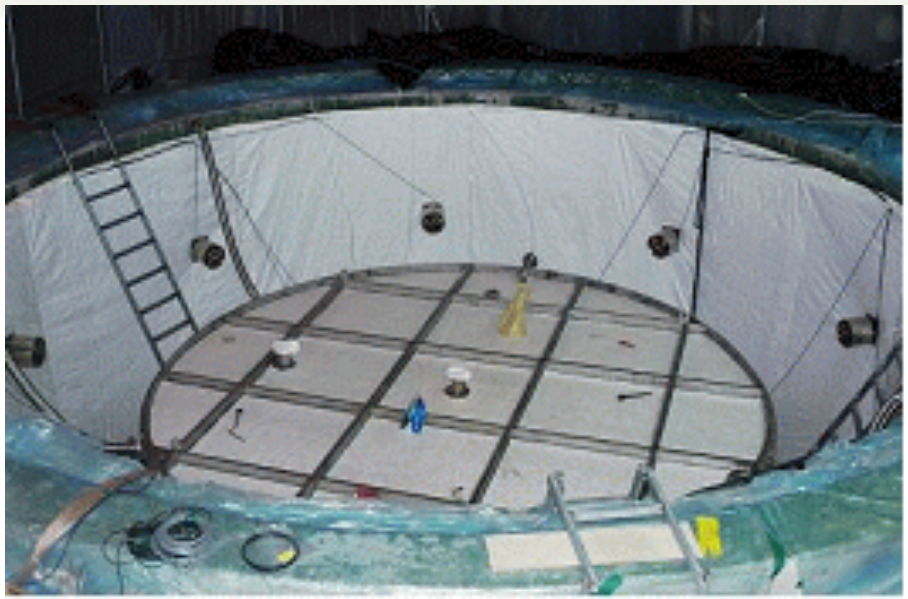
RENO

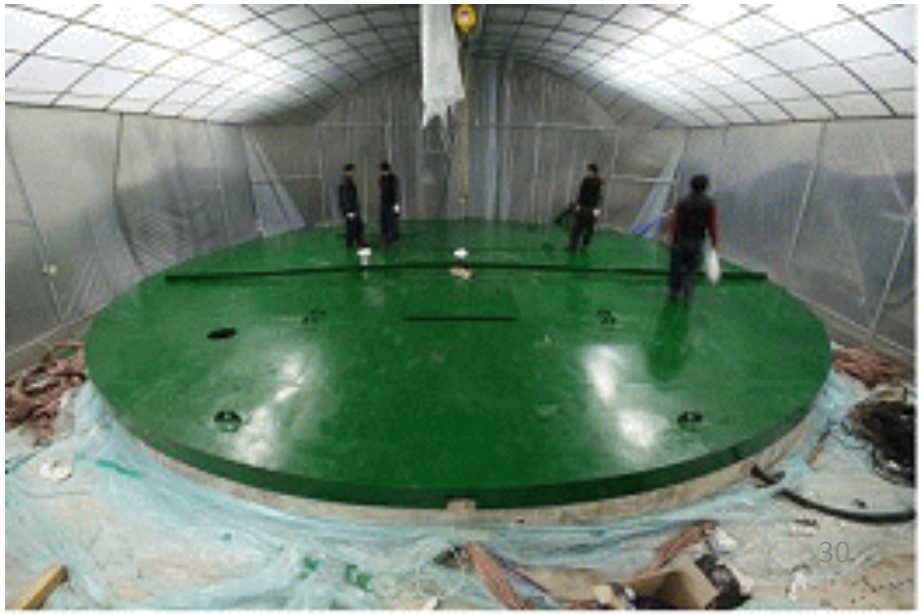
Finishing PMT installation (2011. 1)

RENO

Near and Far Detectors Closed at end of Jan 2011







Daya Bay Reactor Neutrino Experiment

6 reactor cores with 17.4 GW_{th}

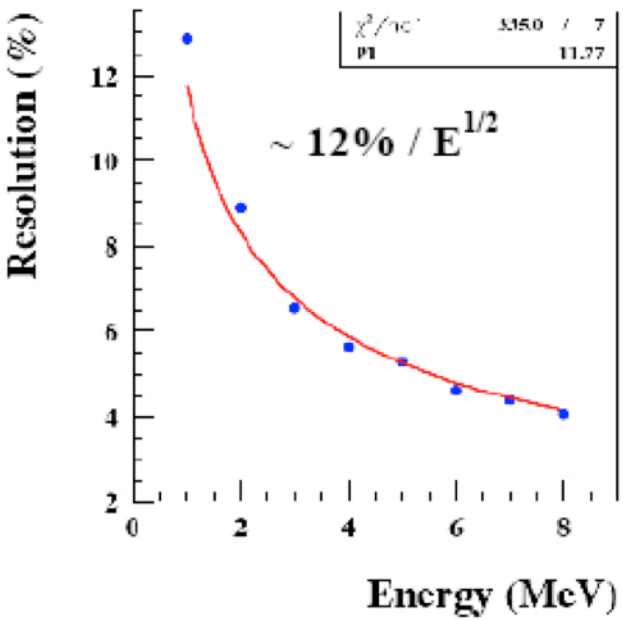
Mountains provide up to 1000 mwe overburden.

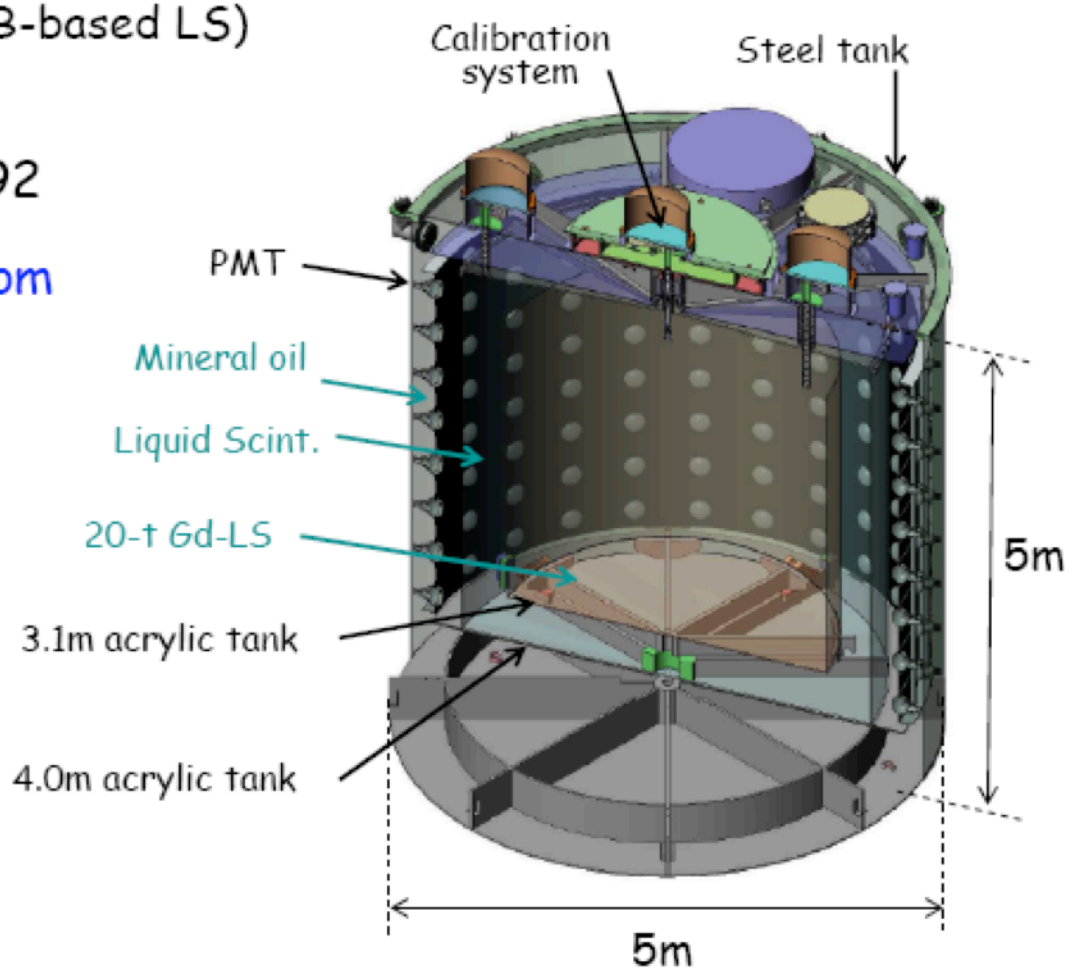
250 physicists from Asia, Europe, and U.S.


Daya Bay Site
Far
Overburden: ~860 mwe
Weighted baseline: ~1650 m
Tunnel
Overburden: ~265 mwe
Weighted baseline: ~500 m
Ling Ao near
Ling Ao II reactors
Control Building
Surface Assembly Building (SAB)
Water Hall
Construction tunnel
Ling Ao reactors
LS Hall
Entrance
Daya Bay near
Overburden: ~250 mwe
Weighted baseline: ~360 m
Daya Bay reactors

Antineutrino Detectors

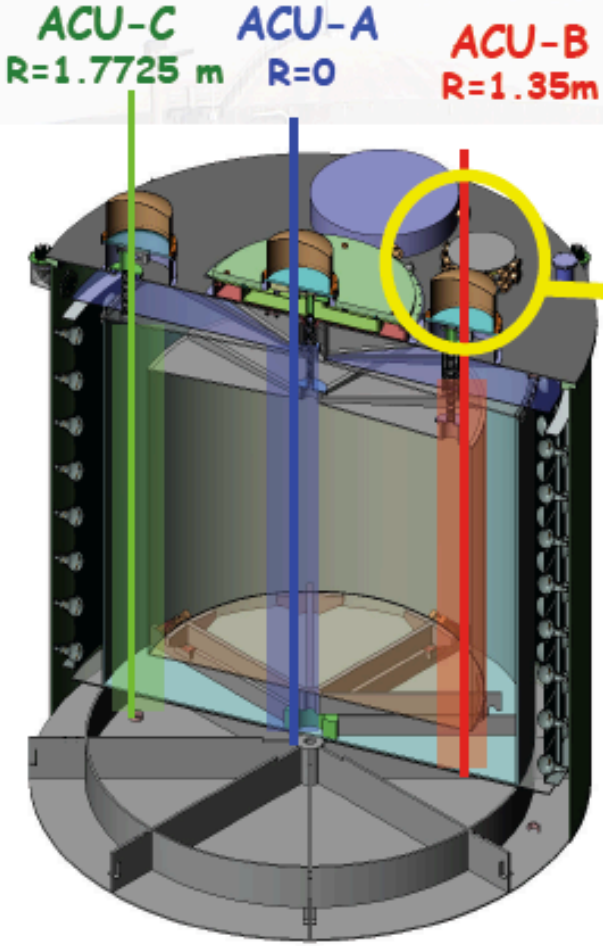
- Three-zone cylindrical detector design
  - Target: 20 t (0.1% Gd LAB-based LS)
  - Gamma catcher: 20 t (LAB-based LS)
  - Buffer : 40 t (mineral oil)
- Low-background 8" PMT: 192
- Reflectors at top and bottom

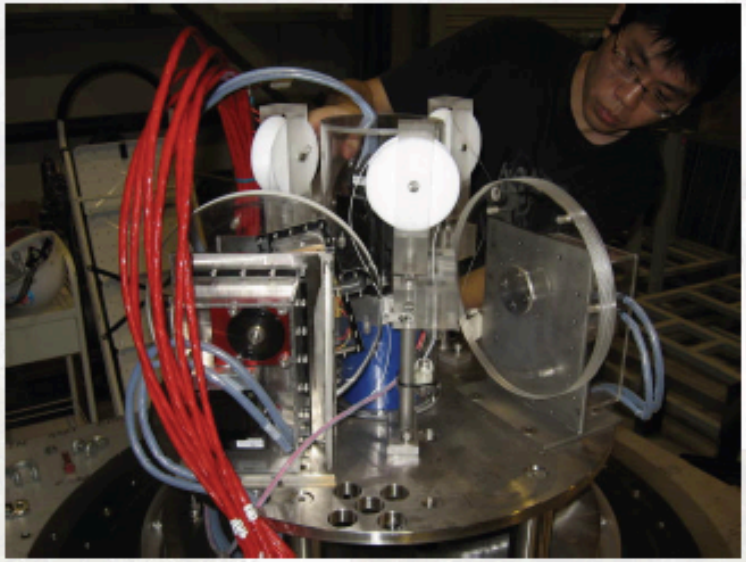




Calibration System of Antineutrino Detectors

3 Automatic calibration 'robots' (ACUs) on each detector



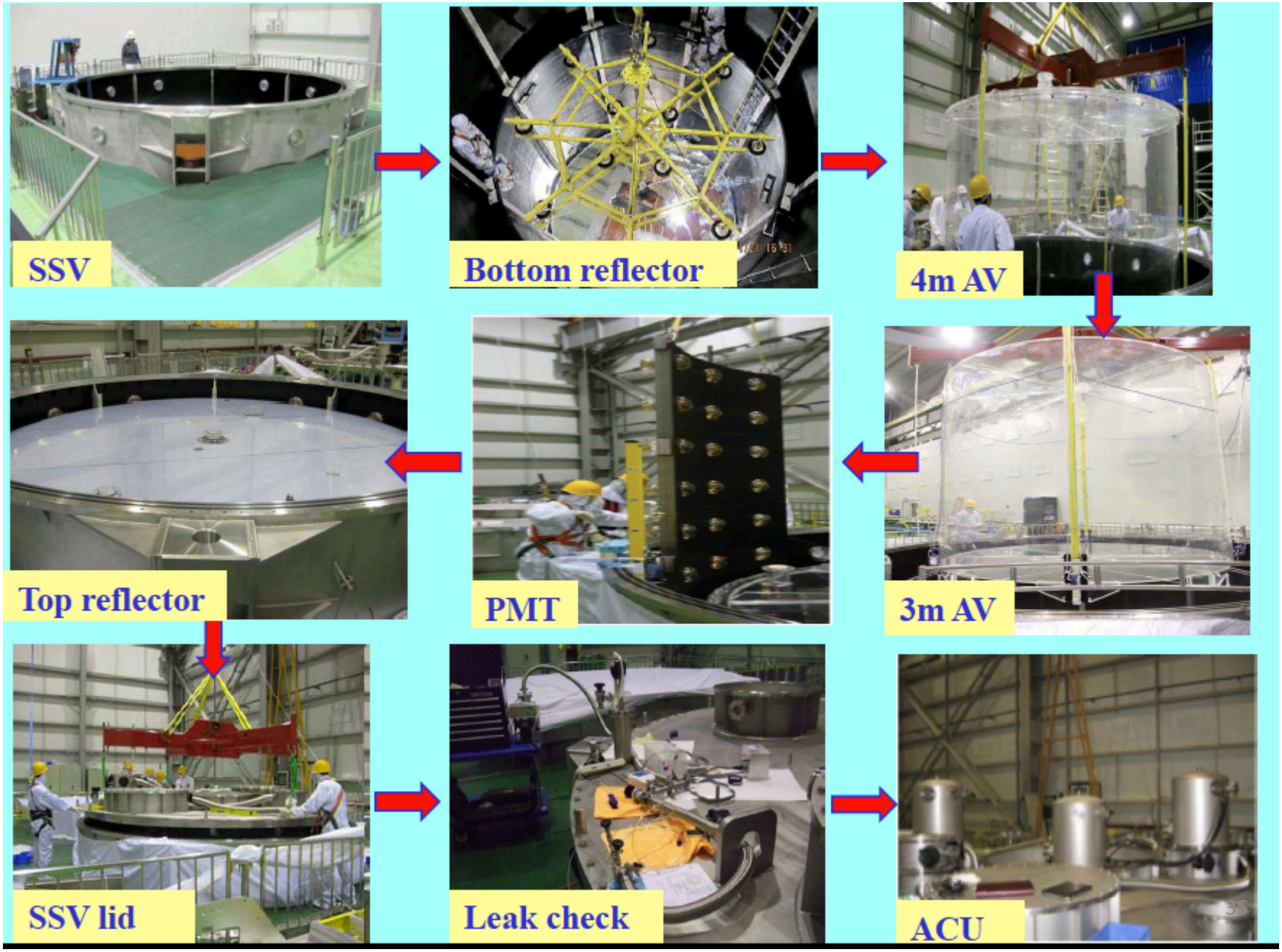


Three axes: center, edge of target, middle of gamma catcher

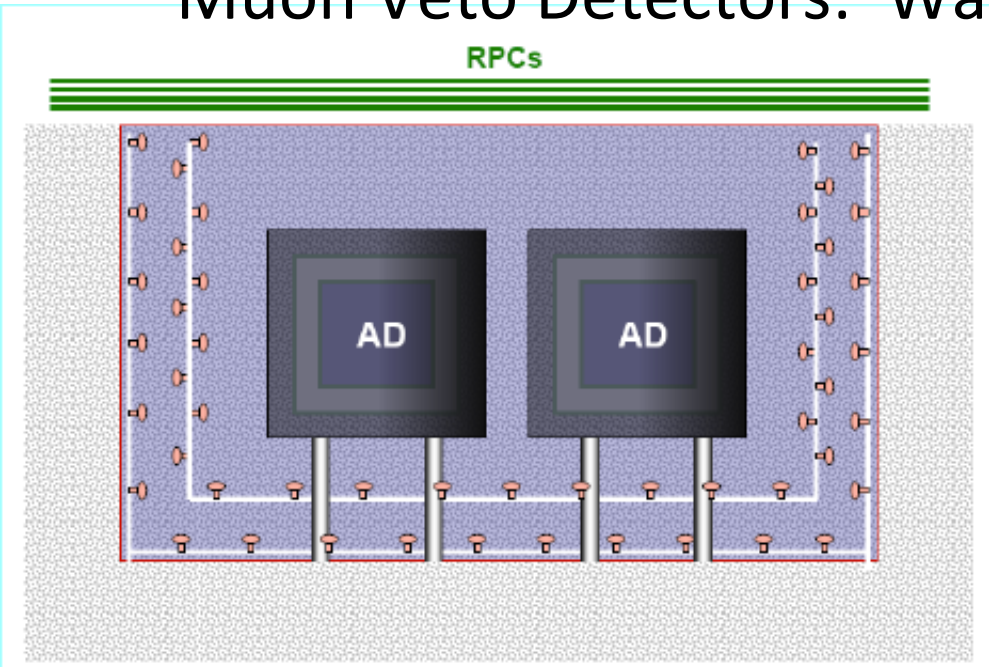
3 sources for each z axis on a turntable (position accuracy < 5 mm):

- 10 Hz ^{68}Ge (2×0.511 MeV γ's)
- 0.5 Hz ^{241}Am-^{13}C neutron source (3.5 MeV n without γ) + 100 Hz ^{60}Co gamma source (1.173+1.332 MeV γ)
- LED diffuser ball (500 Hz) for PMT gain and timing

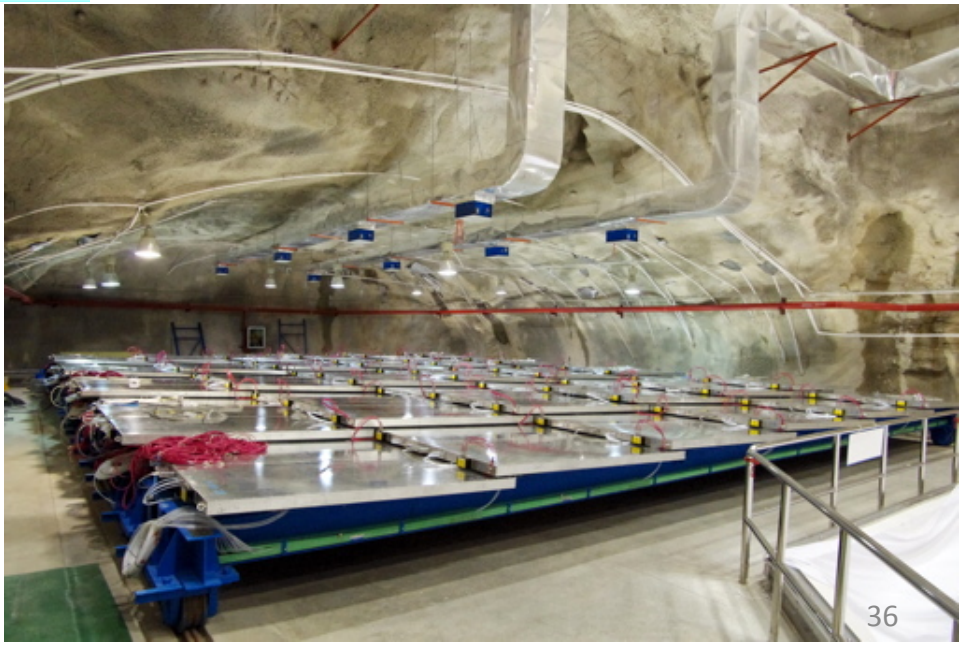
Daya Bay Anti-neutrino Detector Assembly



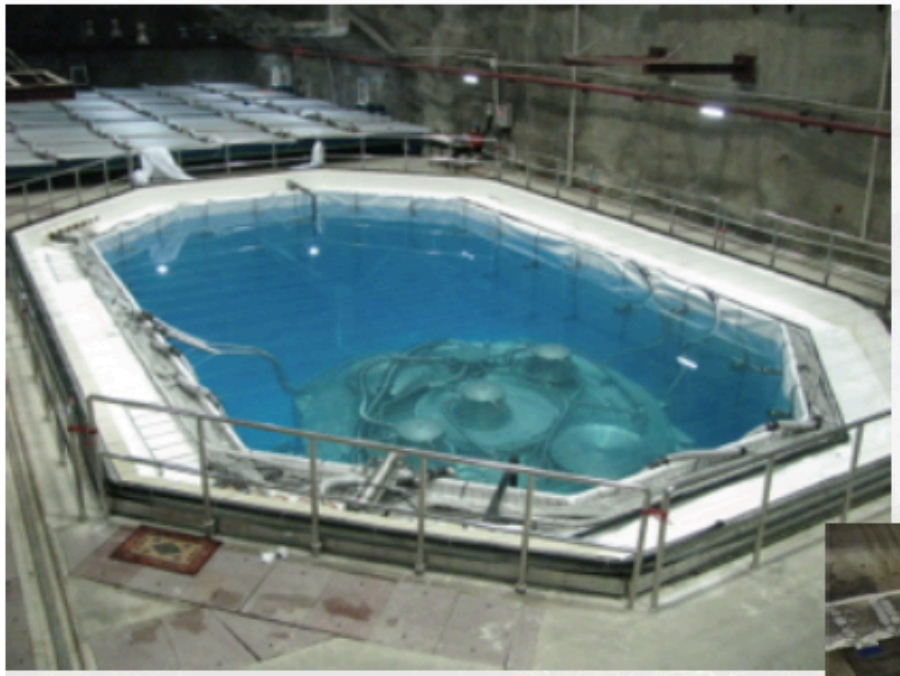
Muon Veto Detectors: Water Cerenkov and RPCs



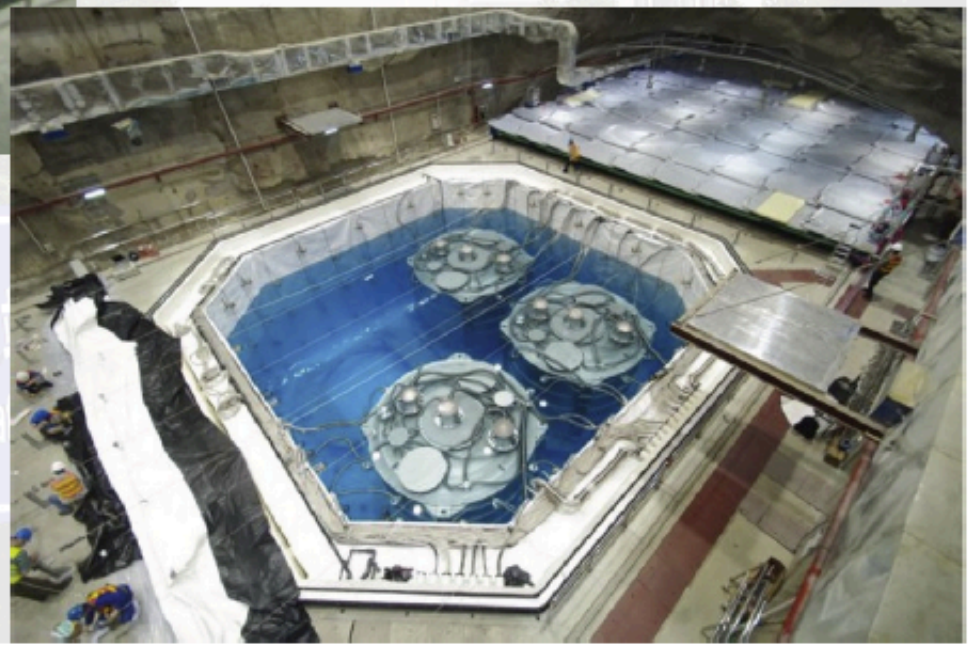
RPCs in Daya Bay Hall



Getting Ling Ao Near and Far Halls Ready



EH 2 (Ling Ao Near Hall):
Began operation on
5 Nov 2011



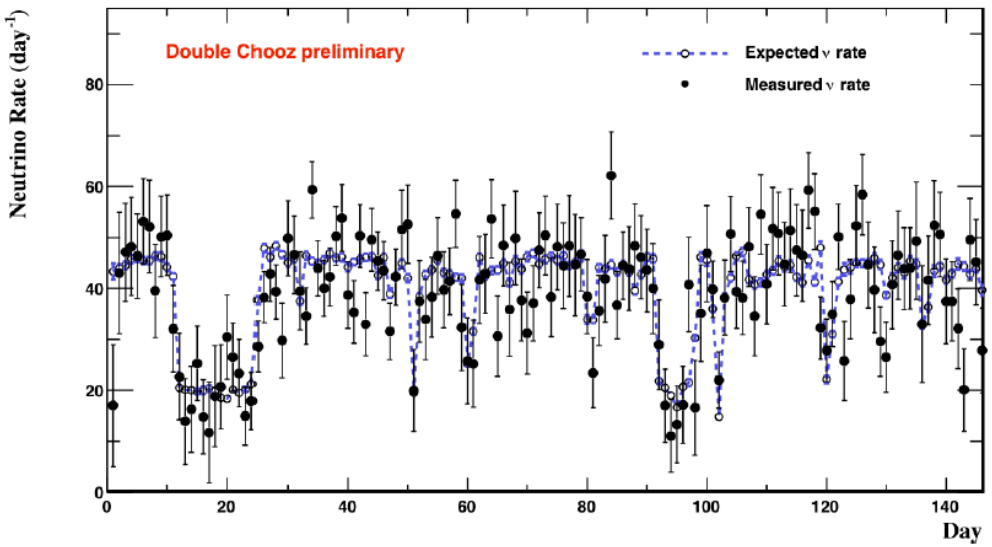
EH 3 (Far Hall):
Started data-taking on
24 Dec 2011

All three experiments announced first results during the last 6 months

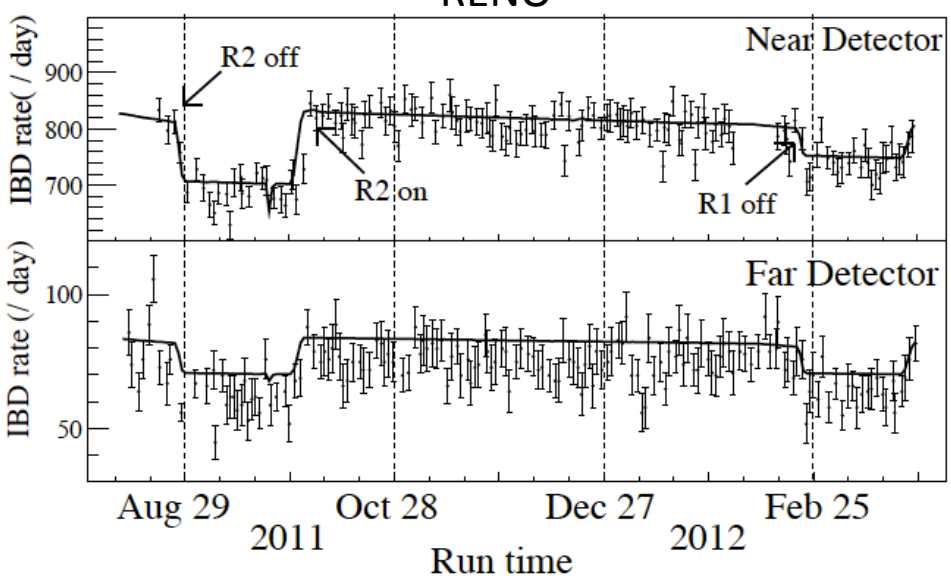
Experiment	Date of 1st Result	Live Days	Far Detector IBD candidates	Signal to background
Double Chooz	Nov 2011	101	4121	11
Daya Bay	March 2012	49	10416	19
RENO	April 2012	222	17102	17

Inverse β Decay Rate History

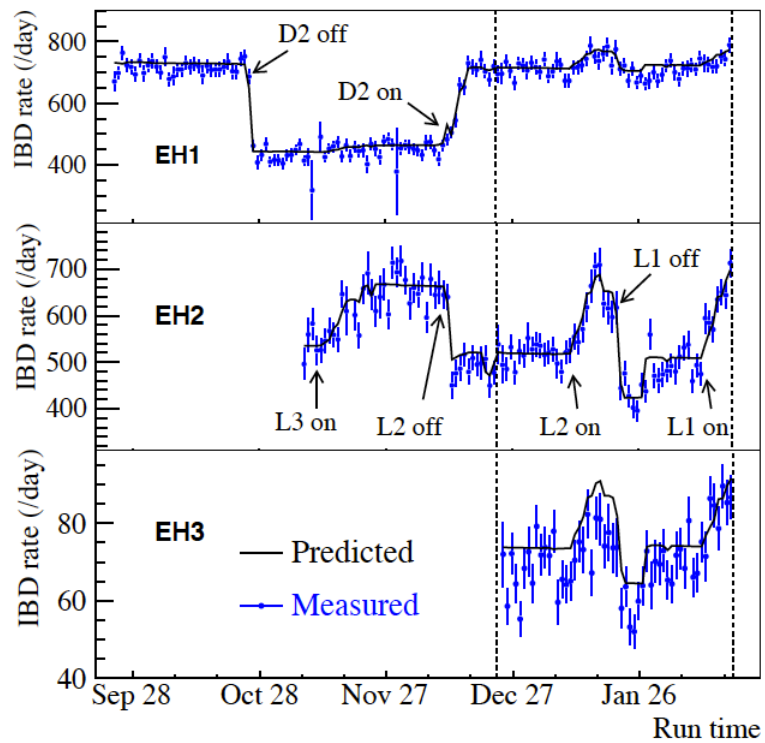
Double Chooz



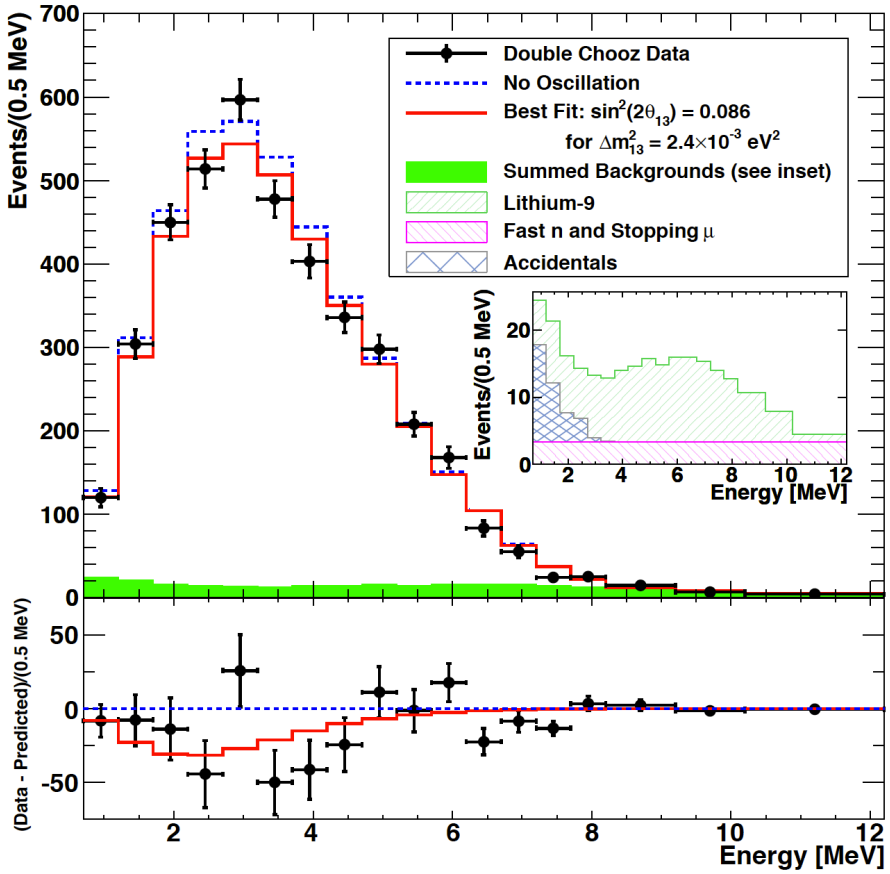
RENO



Daya Bay



Double Chooz Results



From rate+shape analysis: $\sin^2 2\theta_{13} = 0.086 \pm 0.041\ (\text{stat}) \pm 0.030\ (\text{syst})$

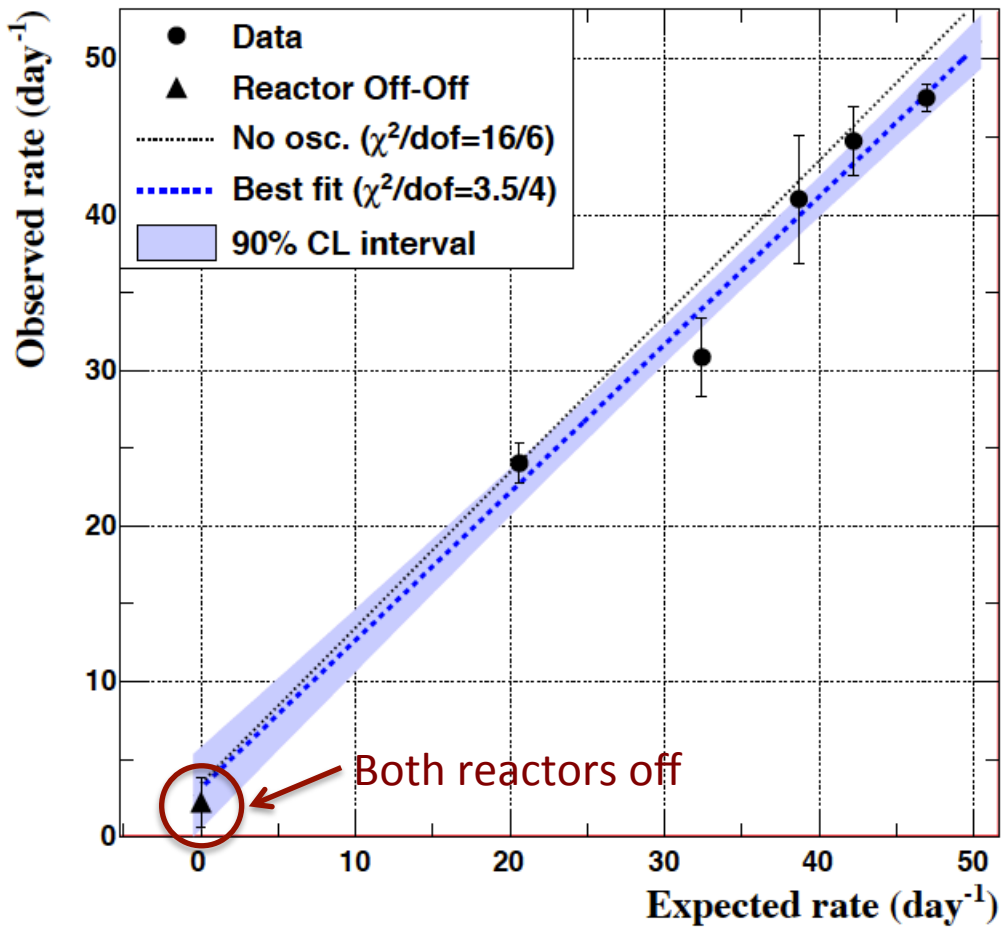
From rate-only analysis: $\sin^2 2\theta_{13} = 0.104 \pm 0.030\ (\text{stat}) \pm 0.076\ (\text{syst})$

Y. Abe et al., Phys. Rev. Lett. **108**, 131801 (2012).

Double Chooz Systematic Errors on Absolute Normalization

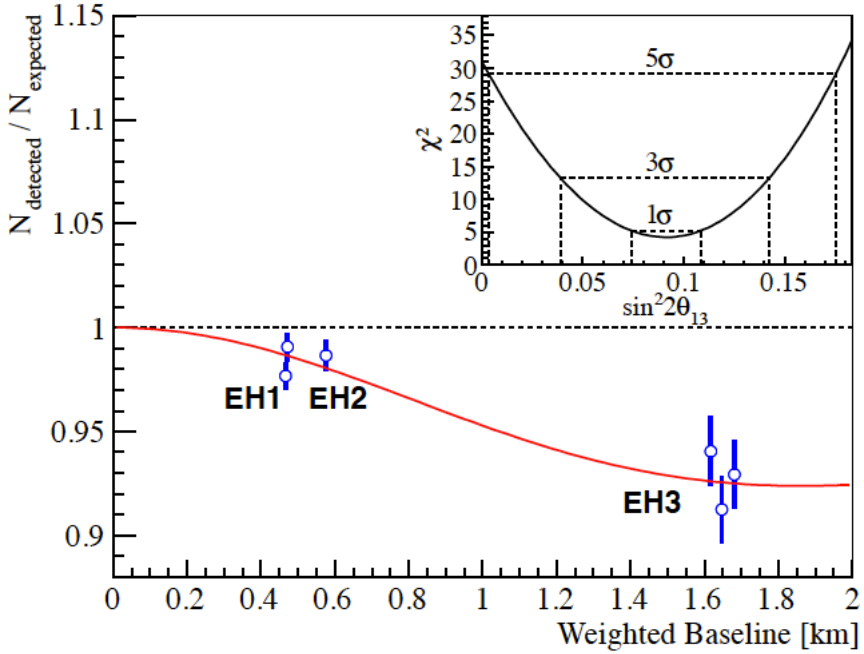
Detector		Reactor	
Energy response	1.7%	Bugey4 measurement	1.4%
E_{delay} Containment	0.6%	Fuel Composition	0.9%
Gd Fraction	0.6%	Thermal Power	0.5%
Δt_{e+n}	0.5%	Reference Spectra	0.5%
Spill in/out	0.4%	Energy per Fission	0.2%
Trigger Efficiency	0.4%	IBD Cross Section	0.2%
Target H	0.3%	Baseline	0.2%
Total	2.1 %	Total	1.8%

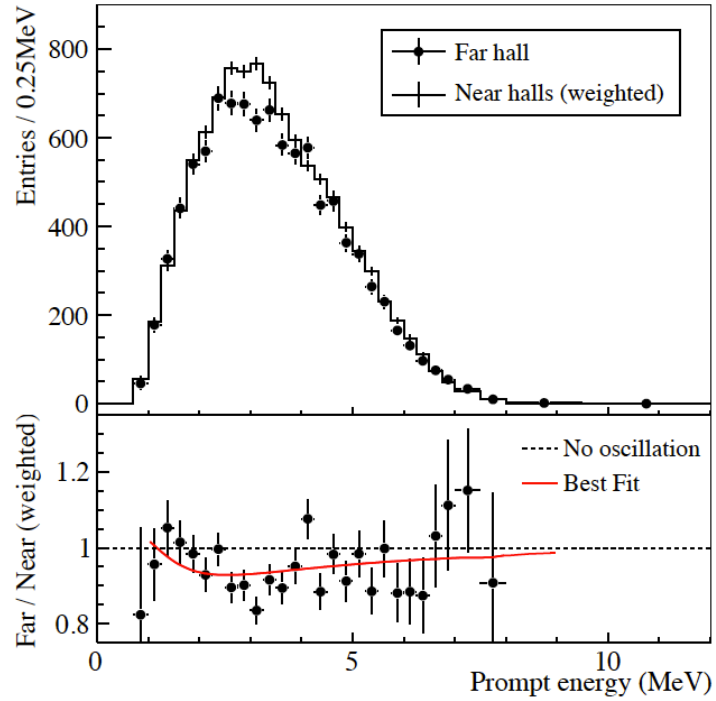
Double Chooz: Cross check of background estimate



- During 21.3 hours with both reactors off, observed 2 events (both consistent with ^{9}Li)
- Background estimate from detailed studies: 3.3 ± 1.3 / day
- Estimate from fit to above plot (blue dashed line): 3.2 ± 1.3 / day

Daya Bay Results





From rate-only analysis: $\sin^2 2\theta_{13} = 0.092 \pm 0.016\ (\text{stat}) \pm 0.005\ (\text{syst})$

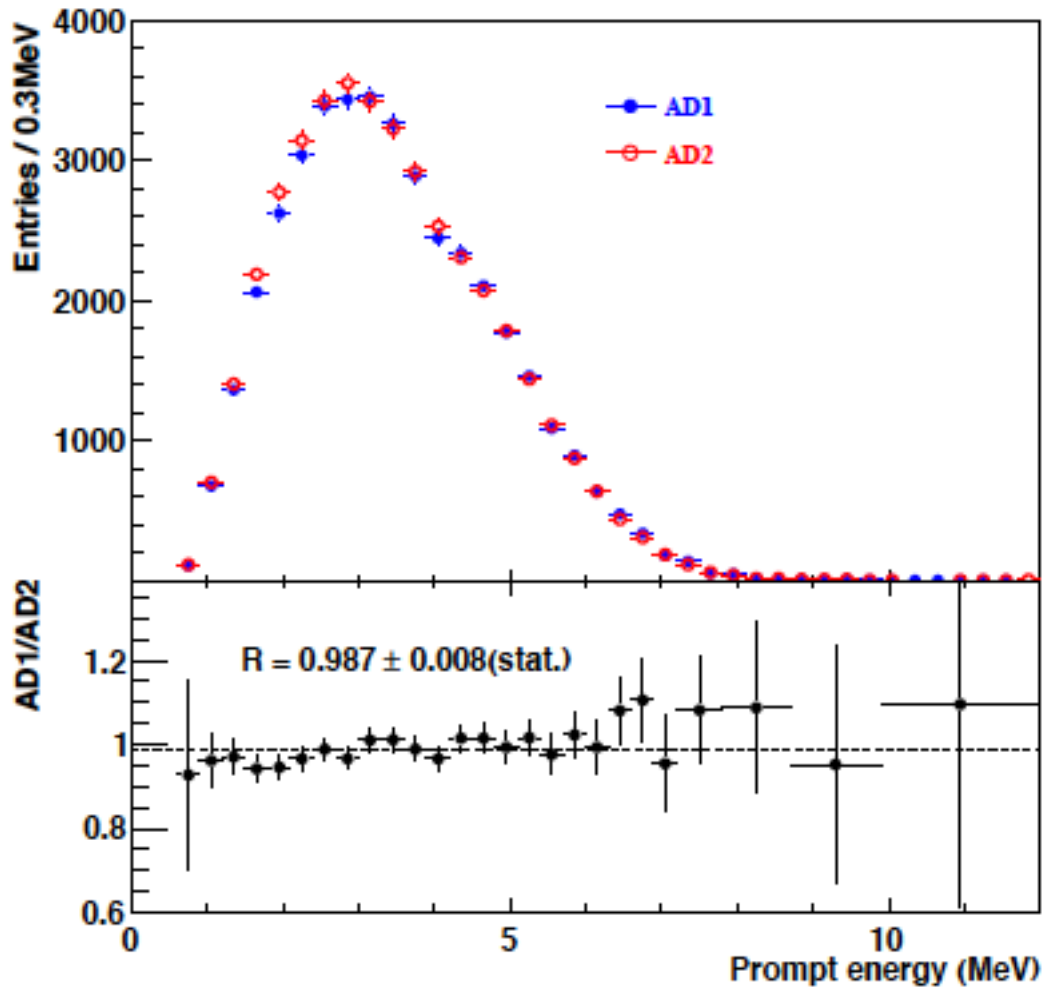
F. P. An et al., Phys. Rev. Lett. **108**, 171803 (2012)

Daya Bay Systematic Errors on Normalization

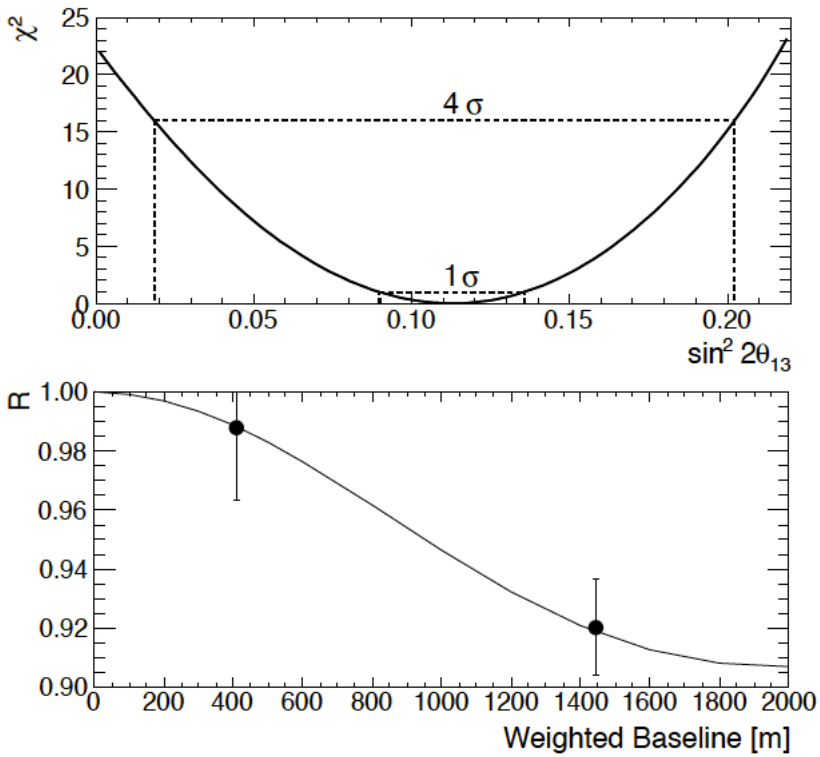
Detector			
	Efficiency	Correlated	Uncorrelated
Target Protons		0.47%	0.03%
Flasher cut	99.98%	0.01%	0.01%
Delayed energy cut	90.9%	0.6%	0.12%
Prompt energy cut	99.88%	0.10%	0.01%
Multiplicity cut		0.02%	<0.01%
Capture time cut	98.6%	0.12%	0.01%
Gd capture ratio	83.8%	0.8%	<0.1%
Spill-in	105.0%	1.5%	0.02%
Livetime	100.0%	0.002%	<0.01%
Combined	78.8%	1.9%	0.2%

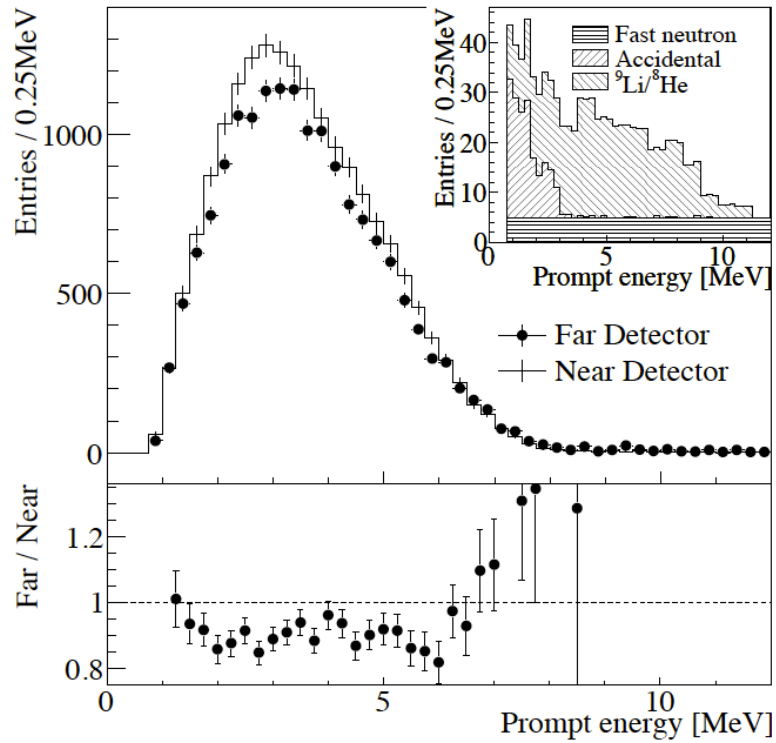
Reactor			
Correlated		Uncorrelated	
Energy/fission	0.2%	Power	0.5%
IBD reaction/fission	3%	Fission fraction	0.6%
		Spent fuel	0.3%
Combined	3%	Combined	0.8%

Daya Bay: Side-by-side comparison of two near detectors



RENO Results





From rate-only analysis: $\sin^2 2\theta_{13} = 0.113 \pm 0.013\ (\text{stat}) \pm 0.019\ (\text{syst})$

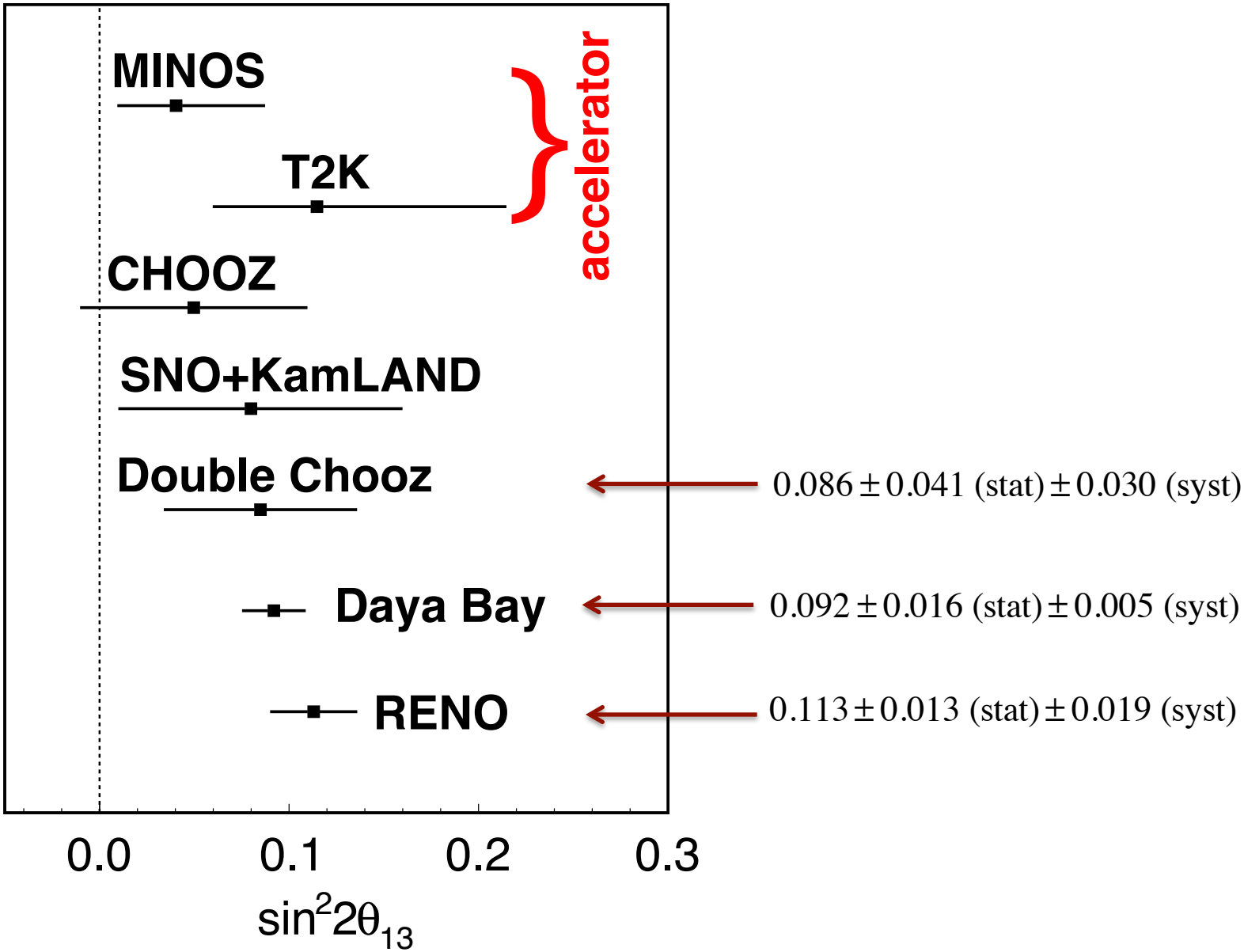
J. K. Ahn et al., Phys. Rev. Lett. **108**, 191802 (2012).

RENO Systematic Errors on Normalization

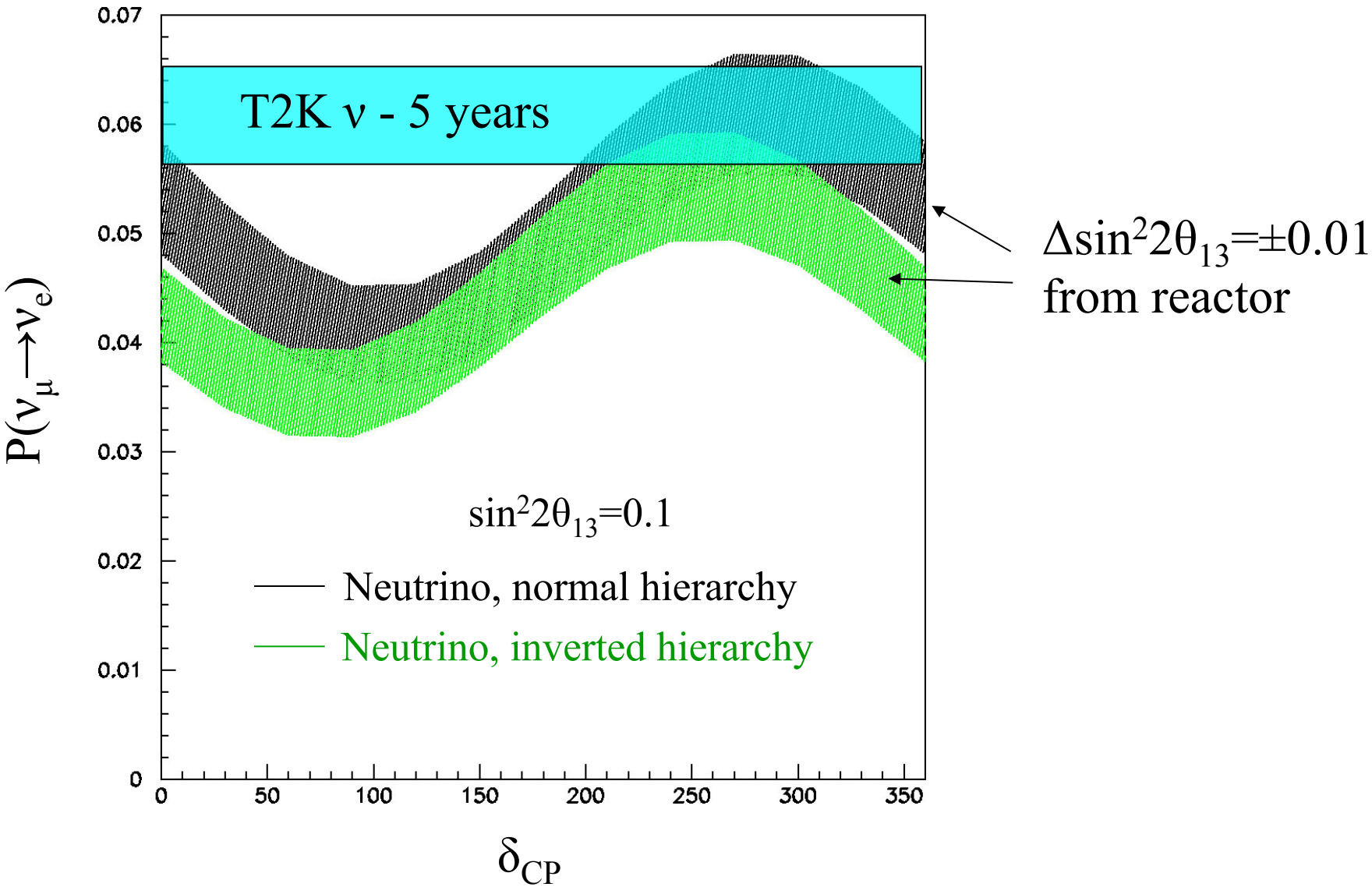
Reactor		
	Uncorrelated	Correlated
Thermal power	0.5%	–
Fission fraction	0.7%	–
Fission reaction cross section	–	1.9%
Reference energy spectra	–	0.5%
Energy per fission	–	0.2%
Combined	0.9%	2.0%

Detection		
	Uncorrelated	Correlated
IBD cross section	–	0.2%
Target protons	0.1%	0.5%
Prompt energy cut	0.01%	0.1%
Flasher cut	0.01%	0.1%
Gd capture ratio	0.1%	0.7%
Delayed energy cut	0.1%	0.5%
Time coincidence cut	0.01%	0.5%
Spill-in	0.03%	1.0%
Muon veto cut	0.02%	0.02%
Multiplicity cut	0.04%	0.06%
Combined (total)	0.2%	1.5%

Summary of $\sin^2 2\theta_{13}$ Results



Combination of precise reactor and accelerator experiments could give glimpse of CP violation



Summary

- Very exciting year for reactor experiments
- θ_{13} is non-zero and is relatively large. New results from all three experiments at Neutrino 2012. Uncertainty on $\sin^2 2\theta_{13}$ will soon be less than 10%.
- Non-zero θ_{13} opens the door to search for CP violation in neutrino oscillations.
- Near detectors of current experiments will provide measurements of reactor spectra with unprecedented precision. These measurements may help clarify reactor "anomoly"
- A measurement of few MeV neutrinos at very short baseline (< 10 m) would be very interesting.
- Ambitious new ideas for reactor experiments to address the mass hierarchy.