Measurements of Reactor Neutrinos at Short Distances

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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
- New calculation of reactor neutrino flux and "reactor neutrino anomoly"
- Summary

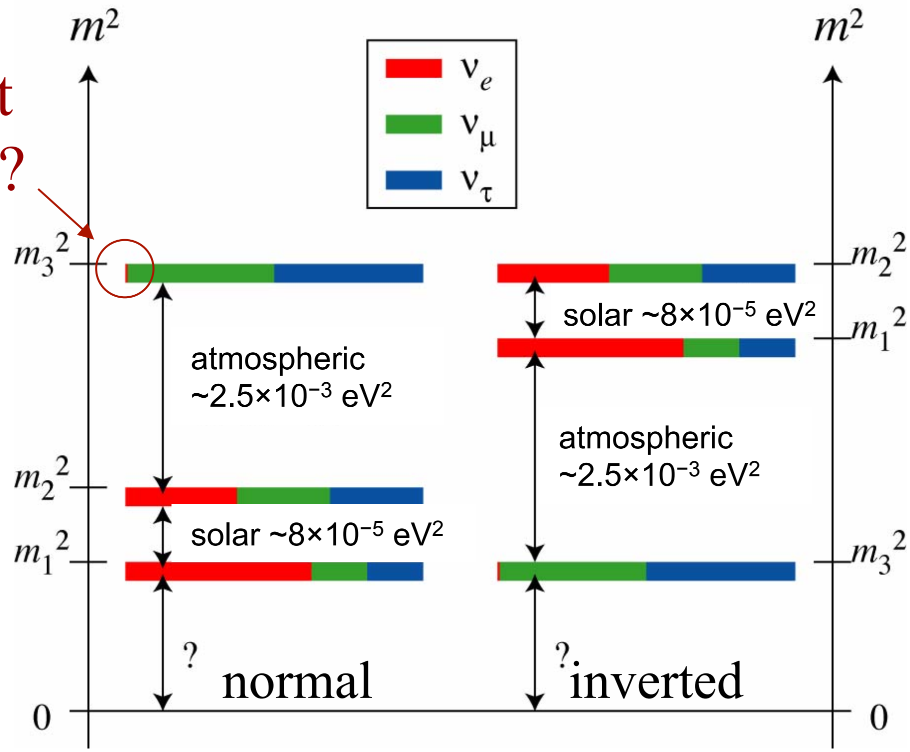
Neutrino mixing and masses

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

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

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

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 $\Delta m^2 \sim 2.5\times 10^{-3}$ 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 $\Delta m^2 \sim 2.5\times 10^{-3}$ eV^2

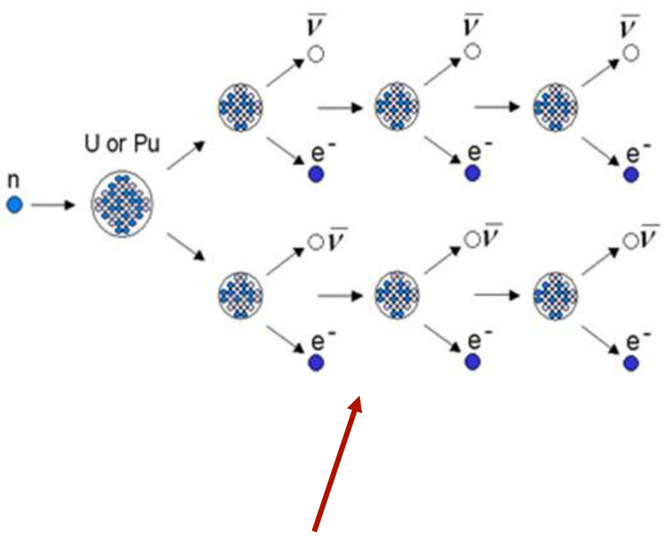
$$P(\bar{\nu}_e \rightarrow \bar{\nu}_e) = 1 - \sin^2 2\theta_{13}\sin^2\frac{\Delta m_{13}^2 L}{4E} + \text{ very small terms}$$

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

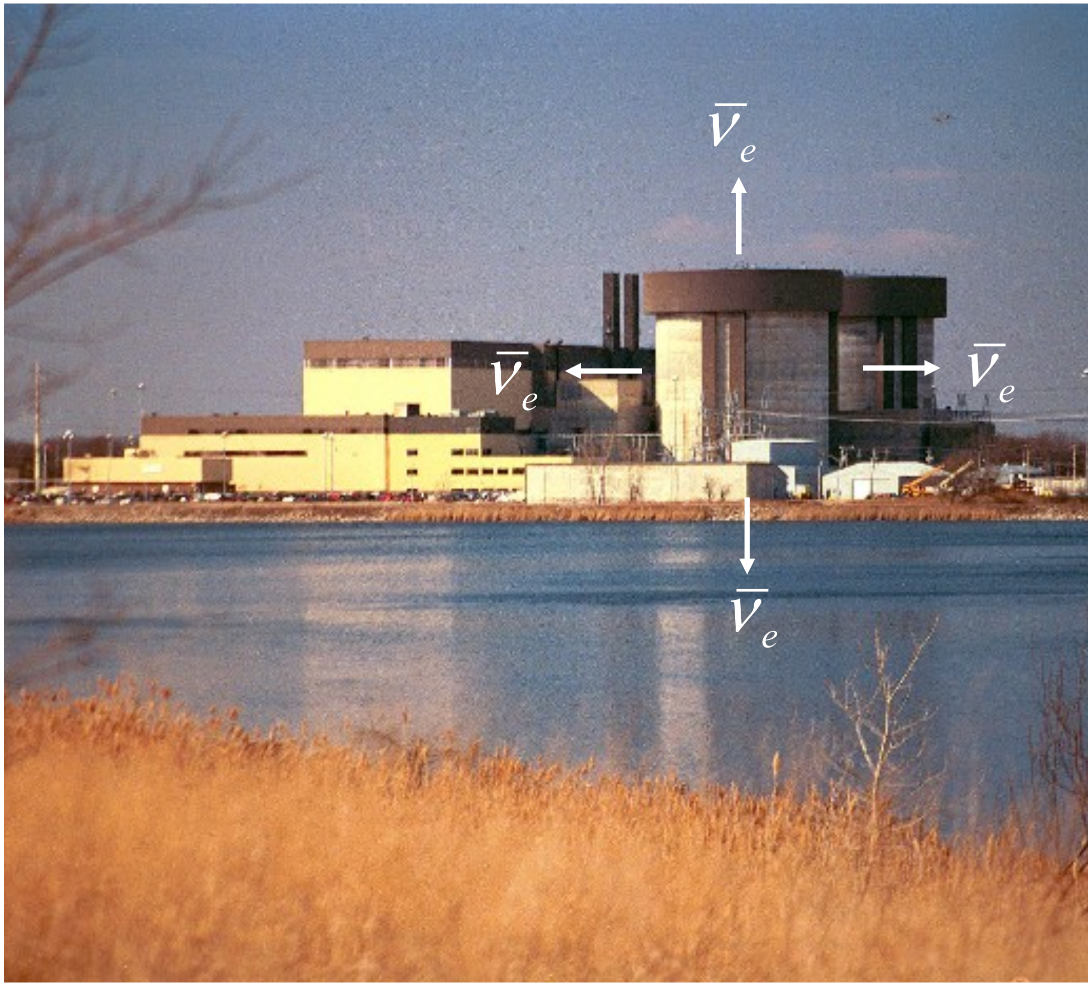
➡ Reactor experiments provide the only clean measurement of $\sin^2 2\theta_{13}$:
no matter effects, no CP violation, almost no correlation with other parameters.

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

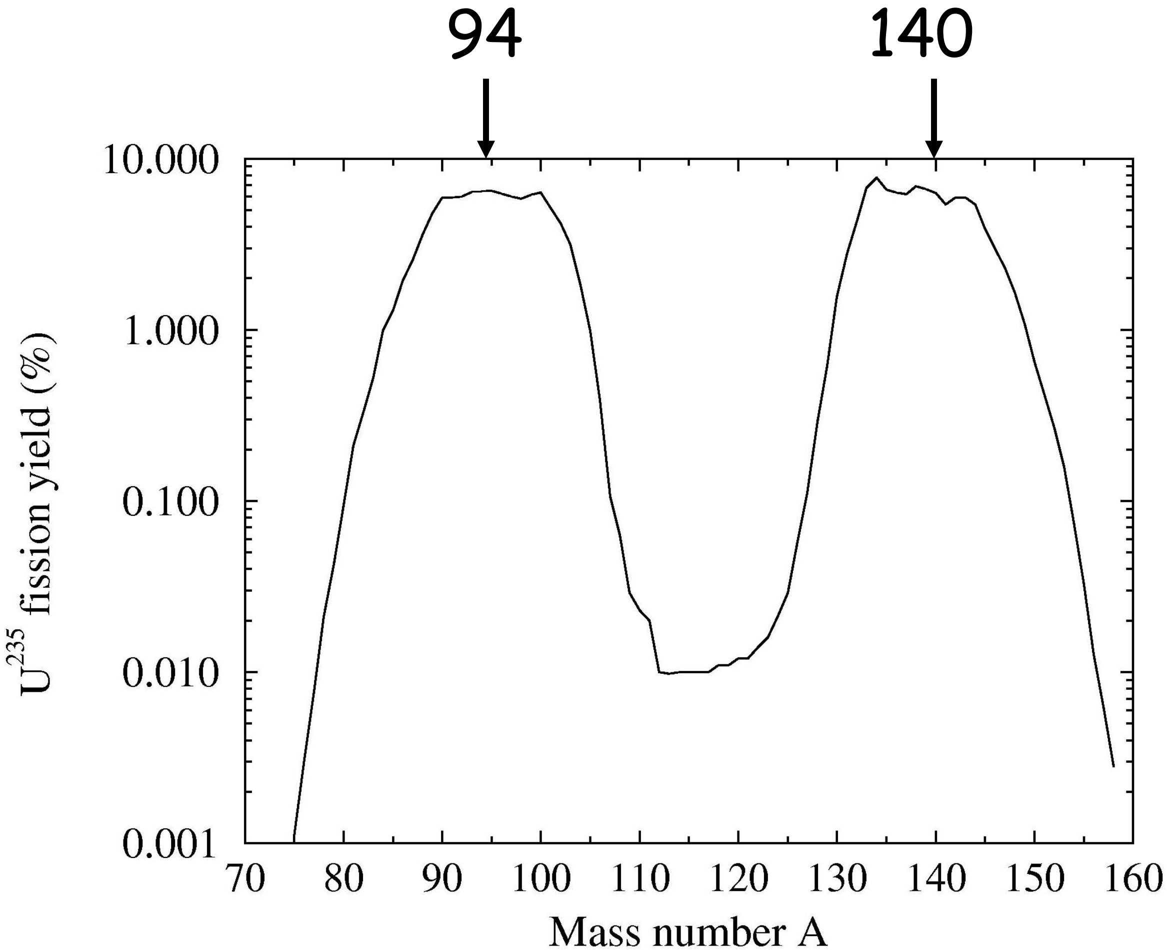
$$^{235}_{92}U + n \rightarrow X_1 + X_2 + 2n$$

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

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

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

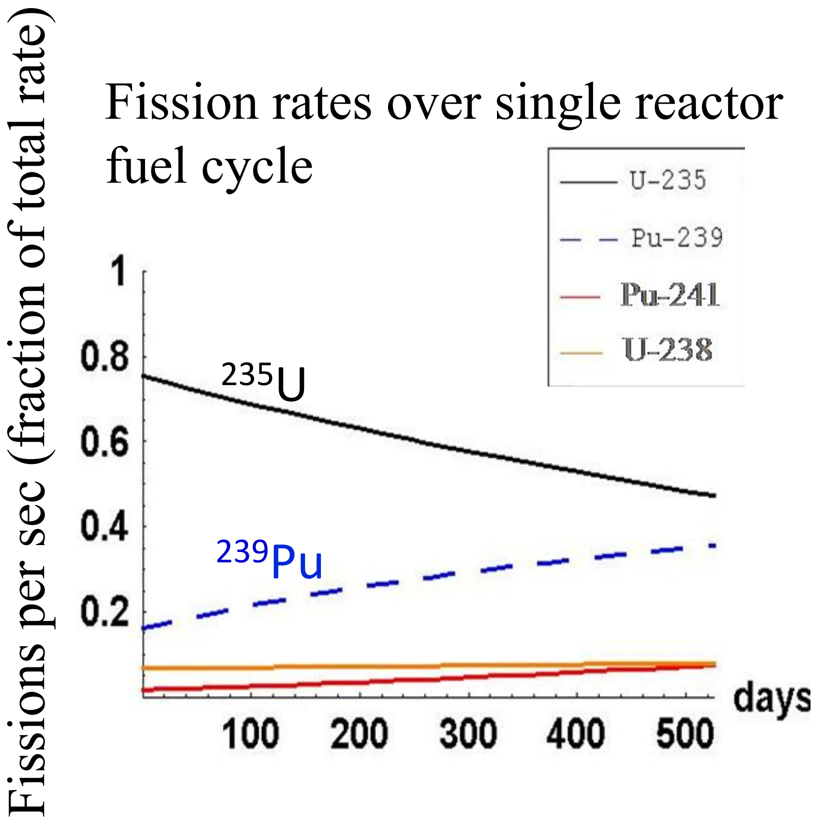
On average, 6 n have to decay to 6 p to reach stable matter

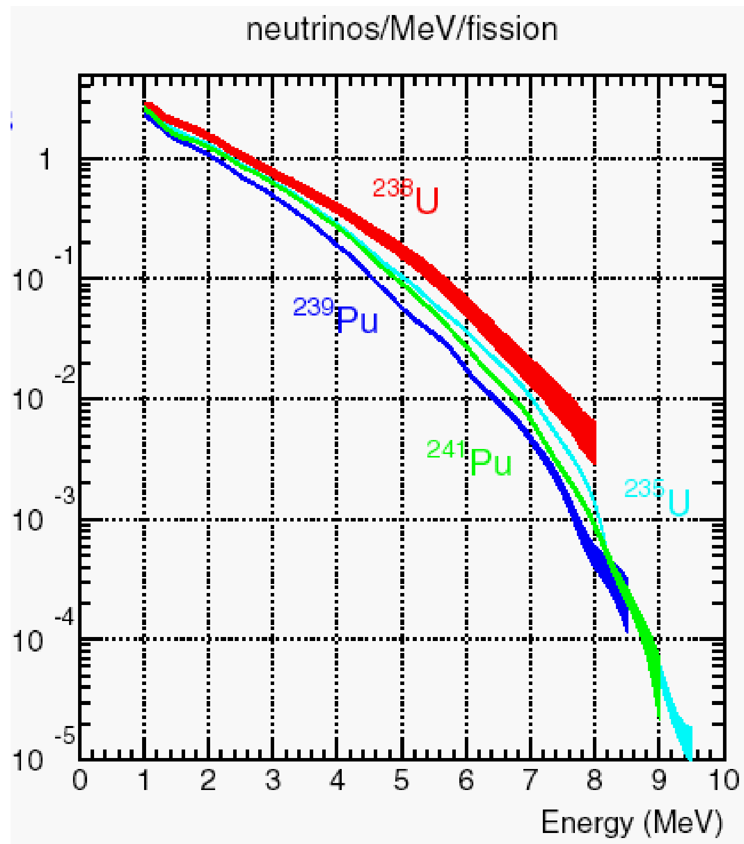


$\Rightarrow$ $\sim$ 200 MeV/fission and ~6 $\bar{\nu}_e$ / fission implies that 3GW$_{th}$ reactor produces $\sim 6\times10^{20}$ $\bar{\nu}_e$ / sec.

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.

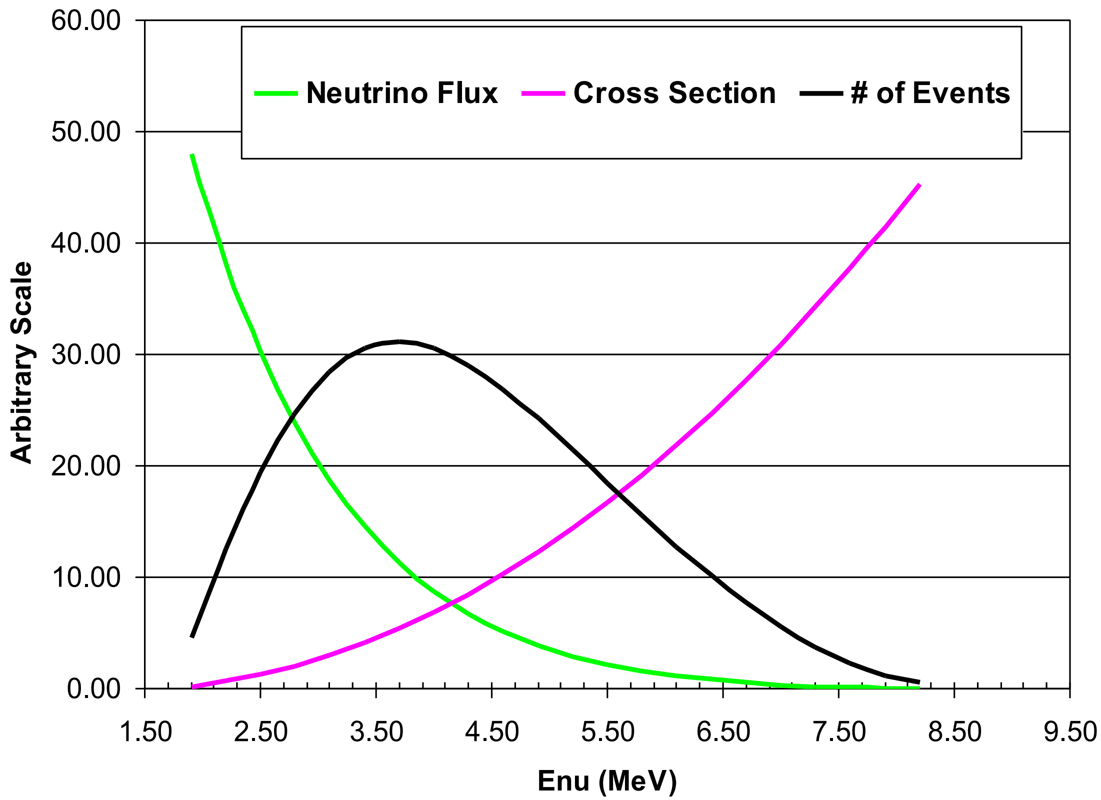




→ Total ν flux uncertainty estimated to be about 2-3%

Detection of $\bar{\nu}_e$

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



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

$$E_{th} \sim M_n + m_{e+} - M_p$$
$$= 1.804 \text{ MeV},$$

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

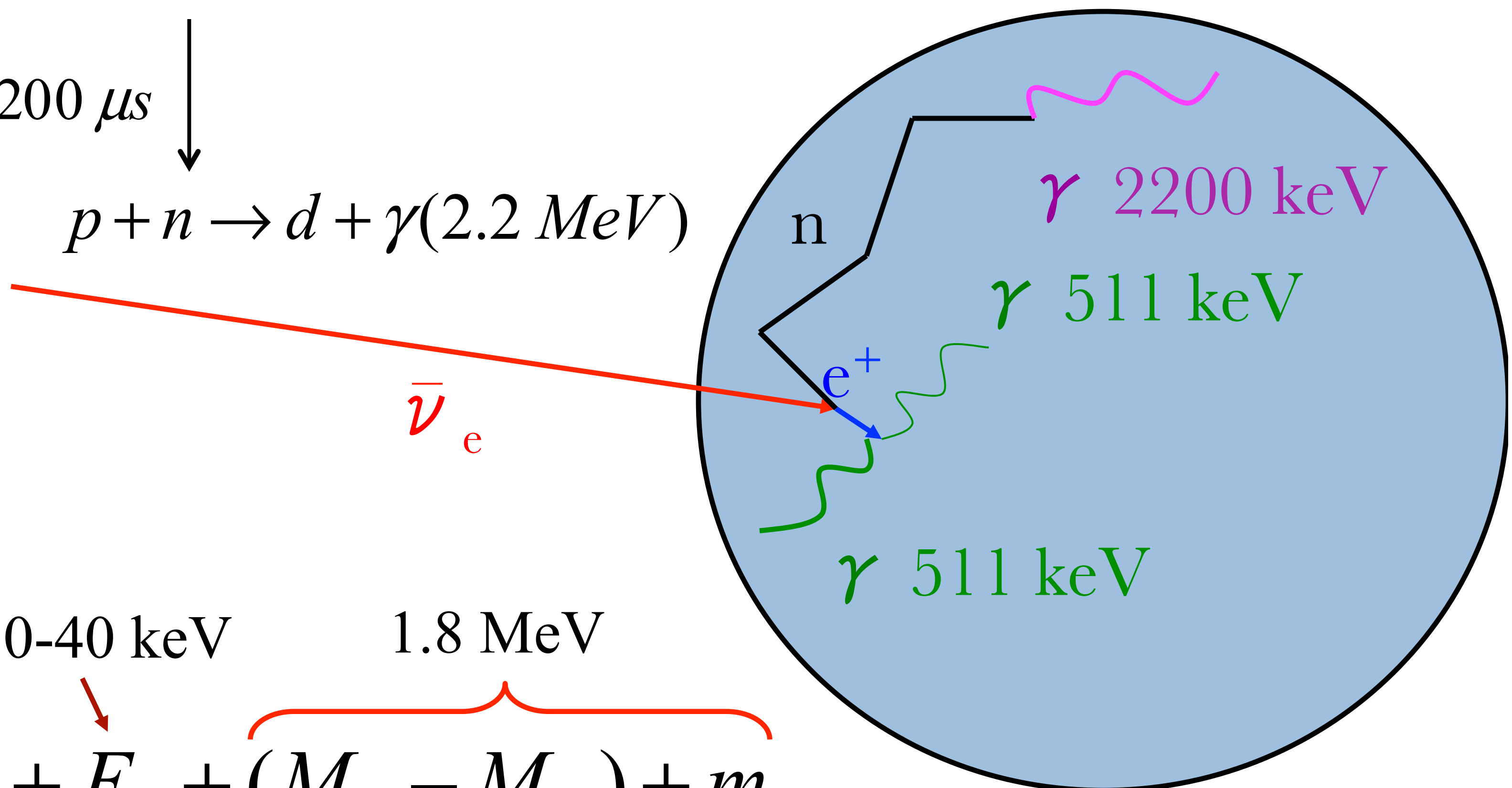
~1 IBD event per day per ton of LS per GW thermal at 1 km

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

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

$$\downarrow \; \tau \approx 200\ \mu s$$

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



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

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.

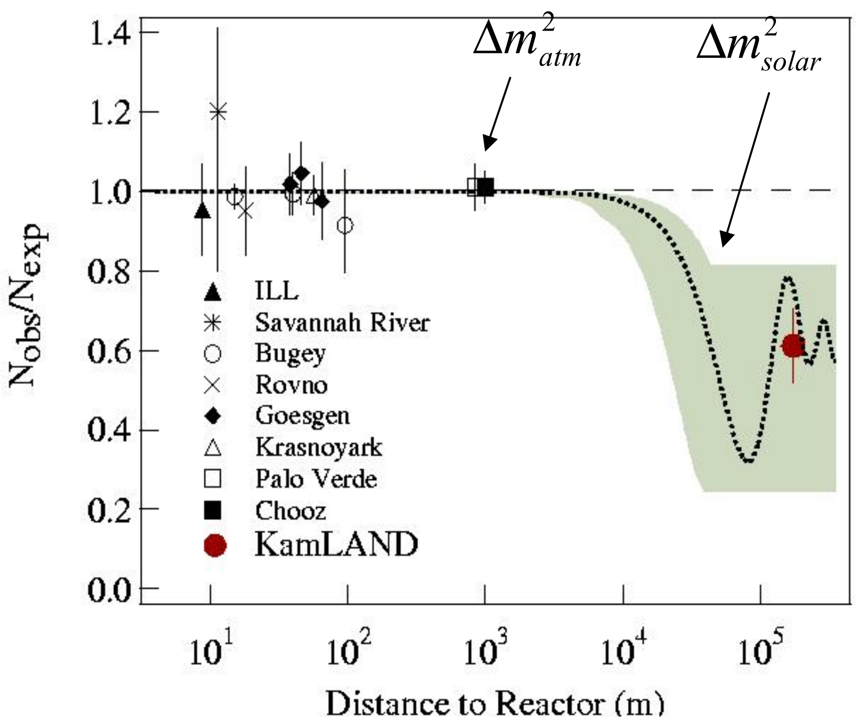
Oscillation maxima for E_ν=3.6 MeV:

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

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

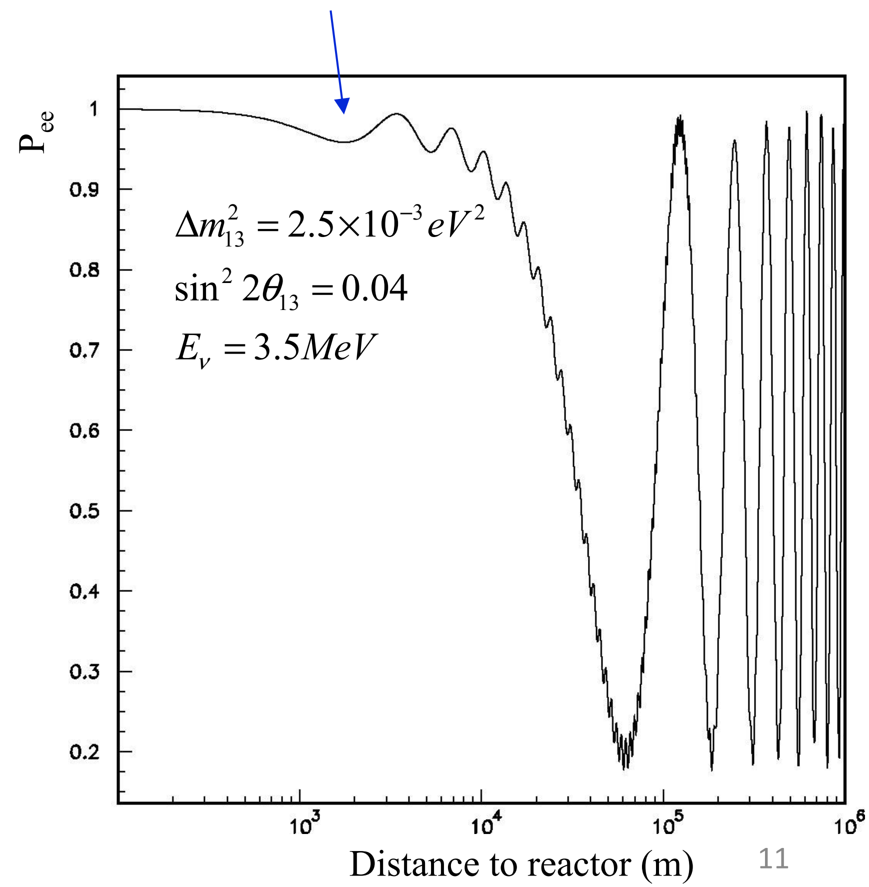
Neutrino Oscillation Searches at Nuclear Reactors

Past measurements:

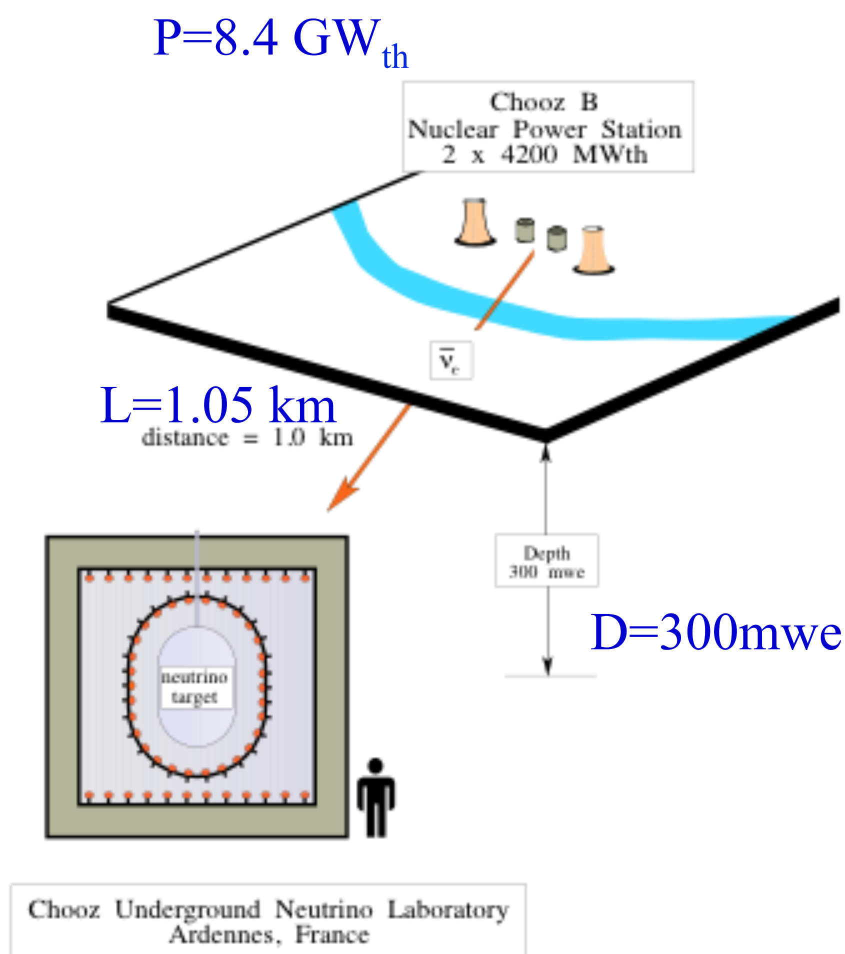


θ_{13}: Search for small oscillations at 1-2 km distance (corresponding to Δm^2_{atm}).

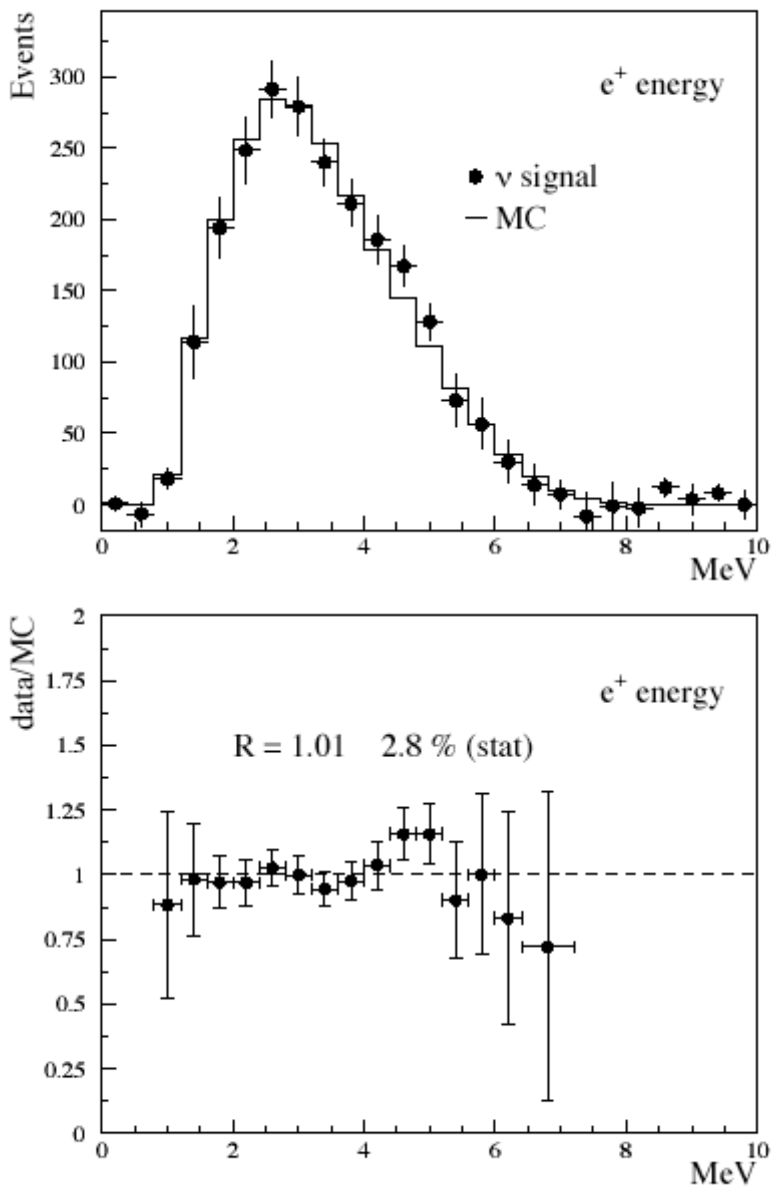
$$P(\bar{\nu}_e \to \bar{\nu}_e) \approx 1 - \sin^2 2\theta_{13} \sin^2 \frac{\Delta m^2_{13} L}{4E} - c^4_{13} \sin^2 2\theta_{12} \sin^2 \frac{\Delta m^2_{12} L}{4E}$$



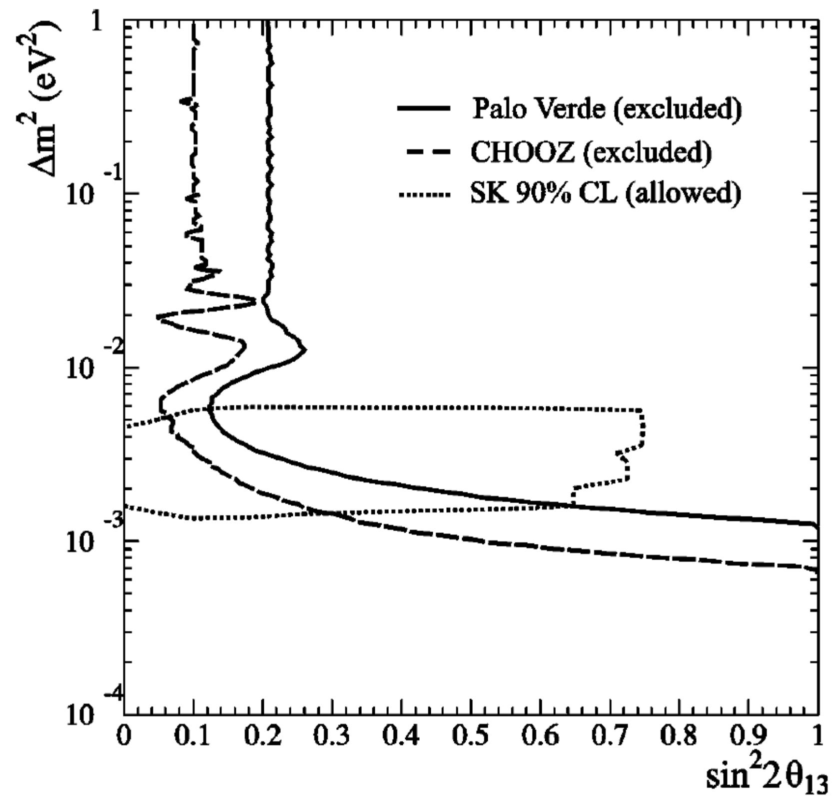
Best θ_{13} Limit: Chooz Experiment



m = 5 tons, Gd-loaded liquid scintillator



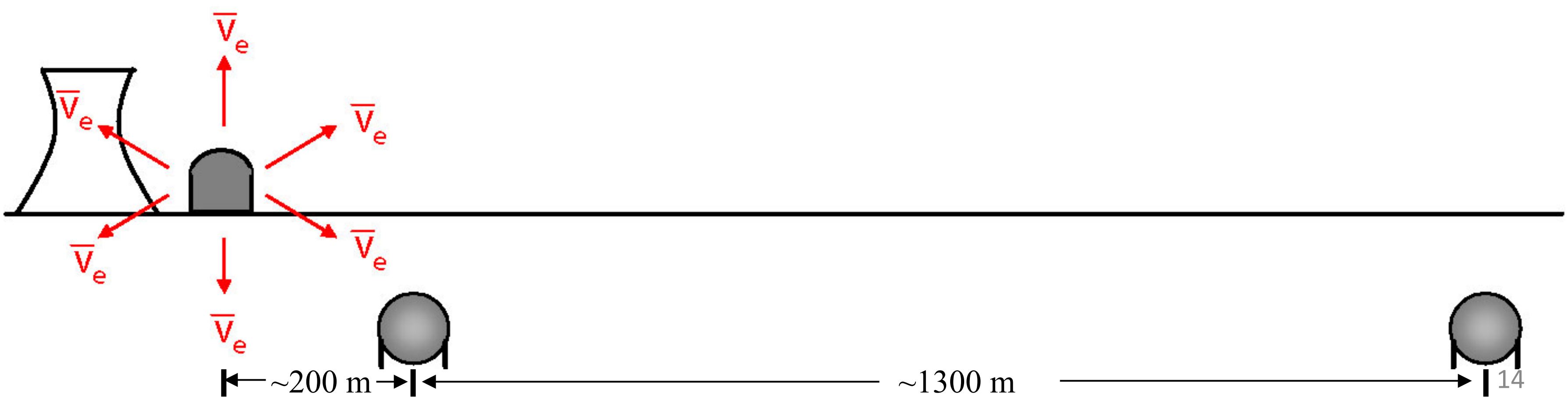
CHOOZ Systematic errors	
Reactor ν flux	2%
Detect. Acceptance	1.5%
Total	2.7%



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

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.)	Status
Double Chooz (France)	8.4	390/1050	115/300	8/8	0.03	Datataking with far; near in 2012
RENO (Korea)	17.3	290/1380	120/450	16/16	0.02	Start mid-2011
Daya Bay (China)	17.4	360(500)/ 1985(1615)	260/910	2×2×20 (N) 4×20 (F)	0.01	Start mid-2012

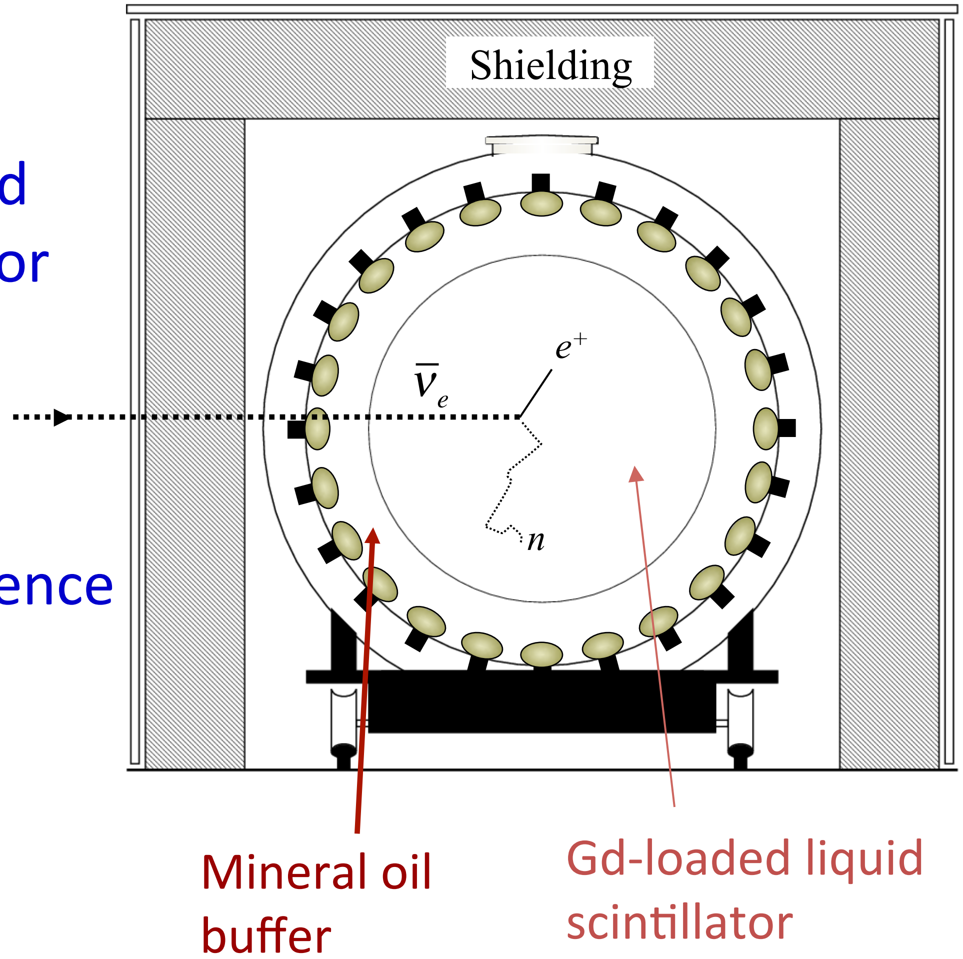
- Many similarities in detector design and analysis strategy
- Differences in sensitivity come mainly from statistics (mass, reactor power), baseline optimization, and multiple detectors (for Daya Bay)

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

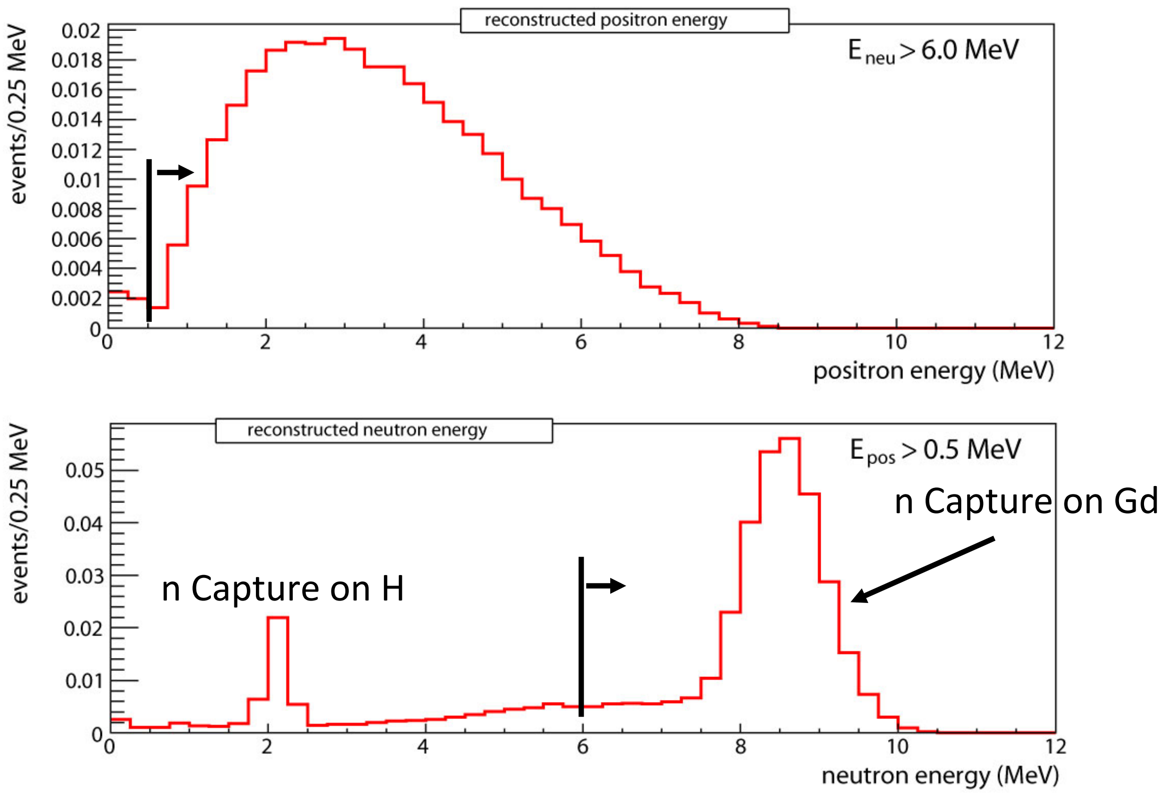


Events selected based on coincidence of e$^+$ signal (E_{vis}>0.5 MeV) and γs released from n+Gd capture (E_{vis}>6 MeV).

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).

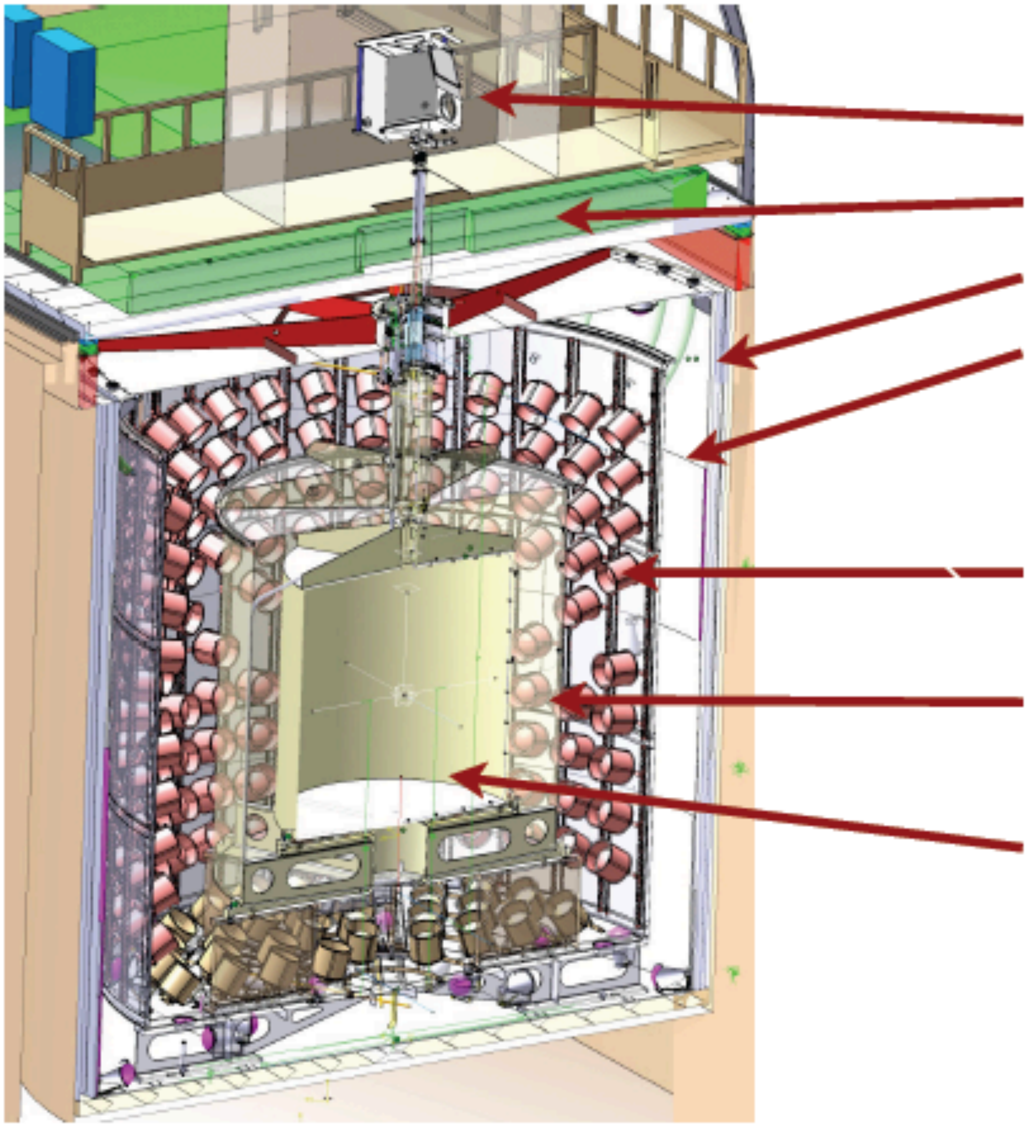
Reconstructed e^+ and n-capture energy



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:

90m³ of liquid scintillator & 78 8" PMTs

Buffer:

110m³ of non scintillating mineral oil & 390 10" PMTs

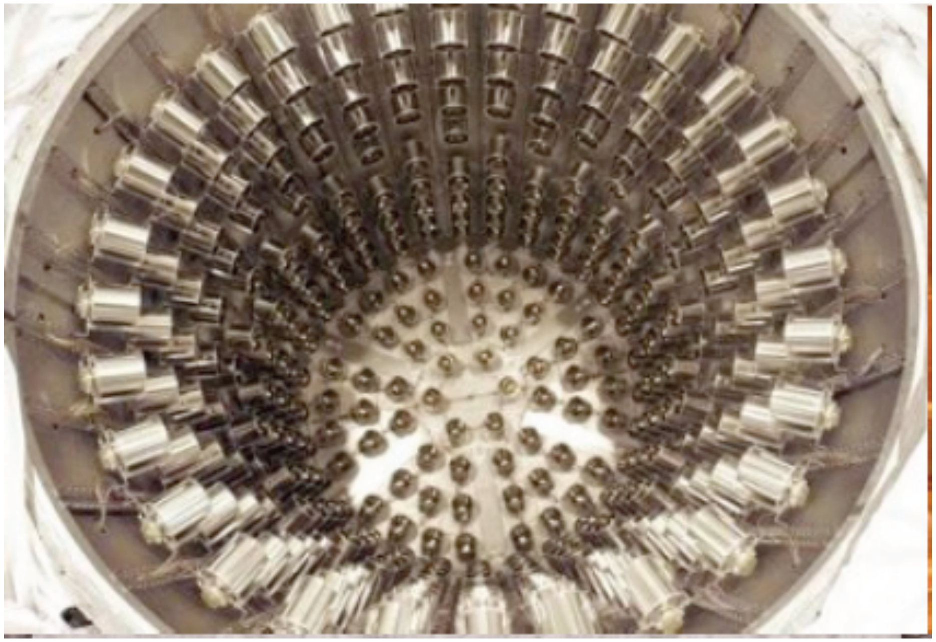
Gamma-catcher:

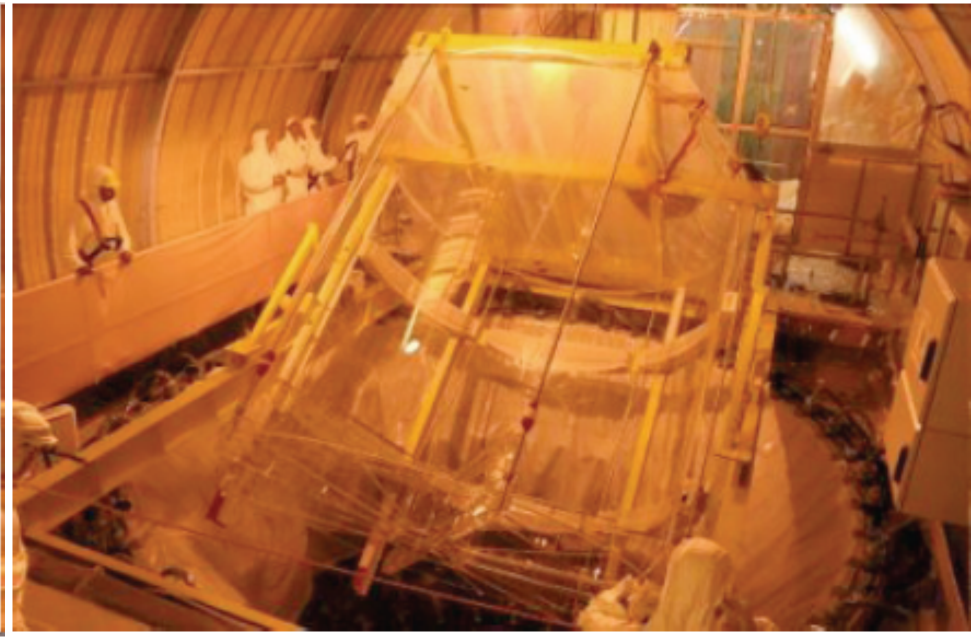
22.3m³ of liquid scintillator

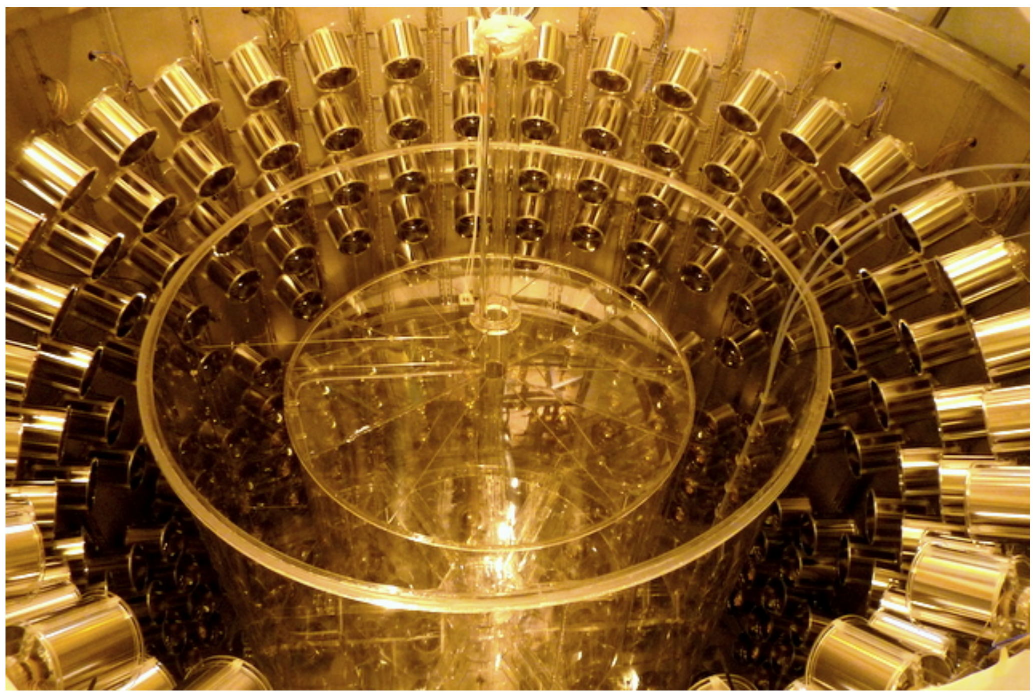
Target:

10.3m³ of liquid scintillator doped with 1 g/L of Gd

Double Chooz Far Detector Installation

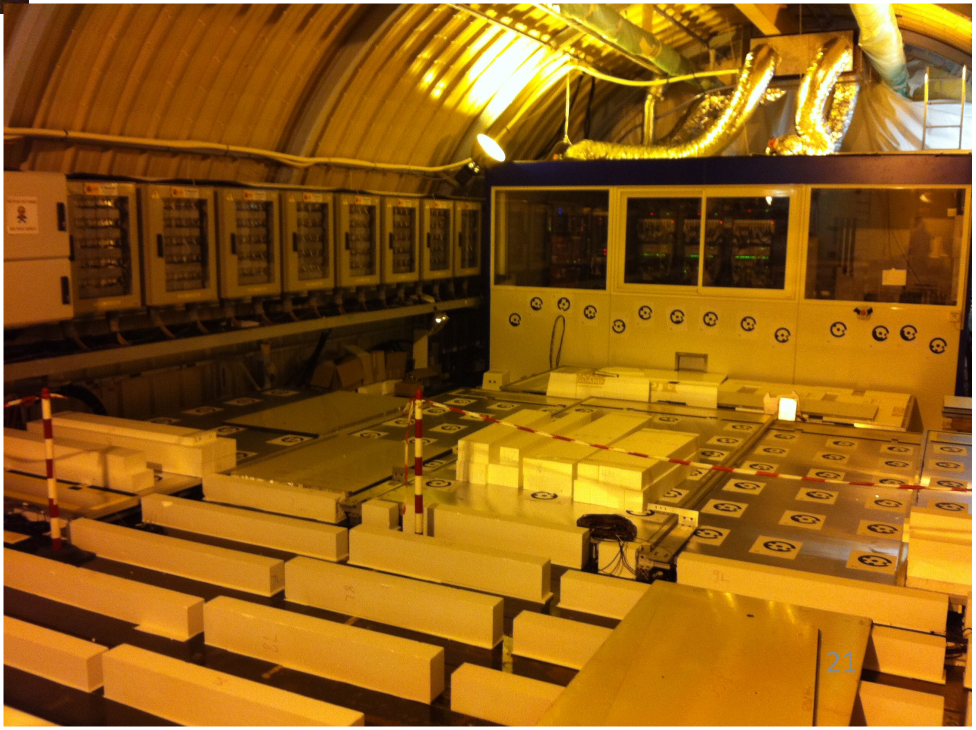




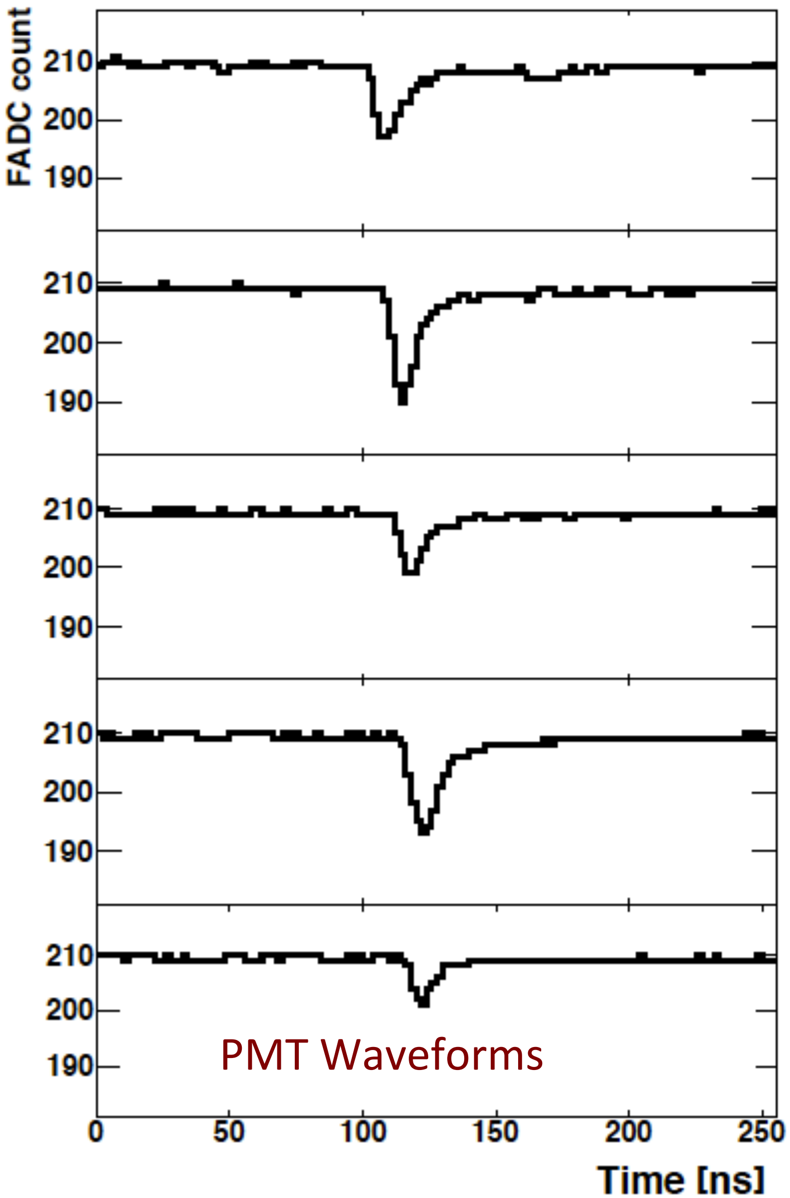


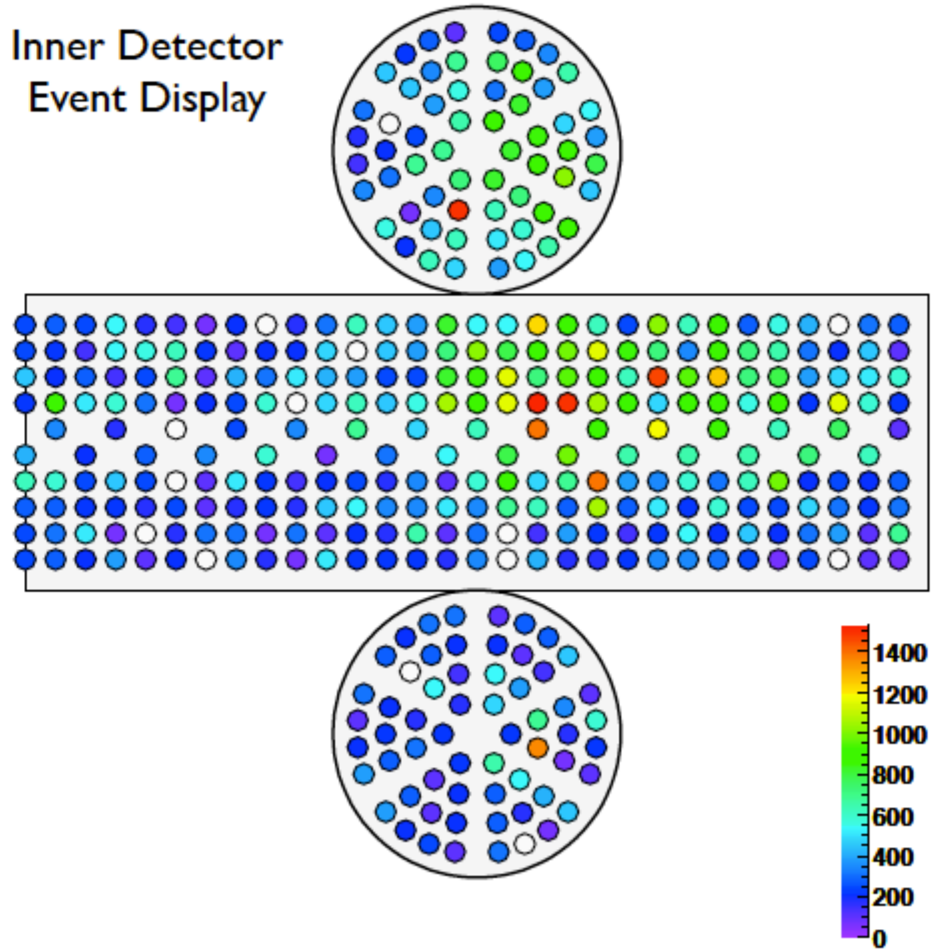
December 2010: Detector filled, shielding complete, commissioning started

April 2011: Steady data taking; installation of outer veto muon system underway.



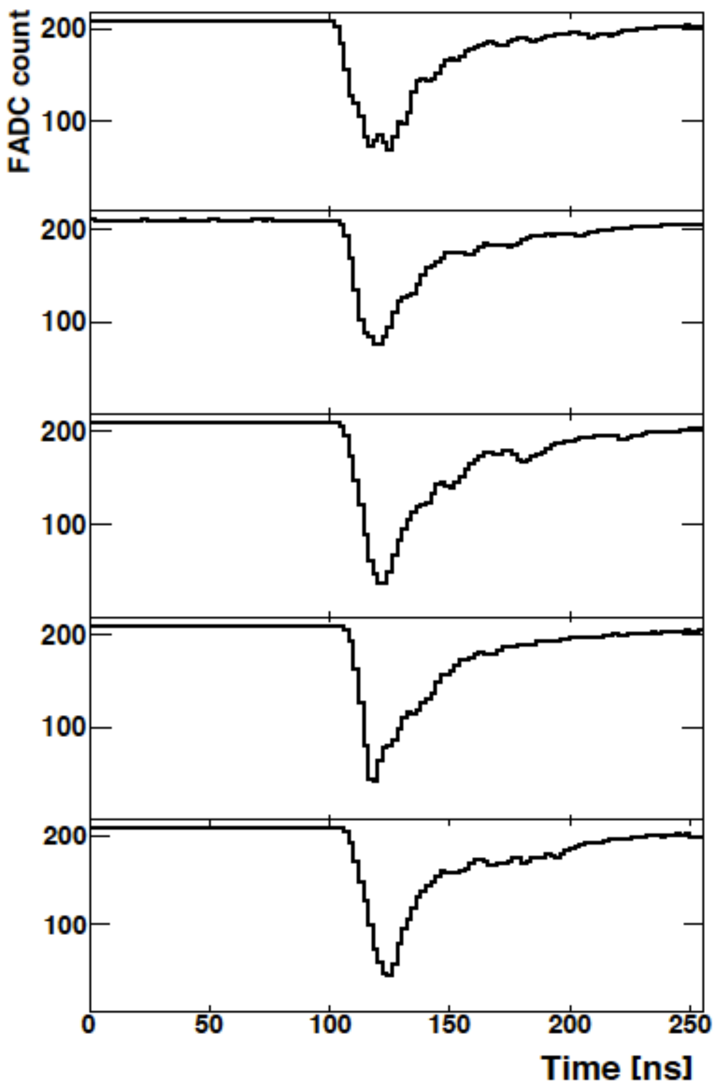
DC Preliminary: Contained Event

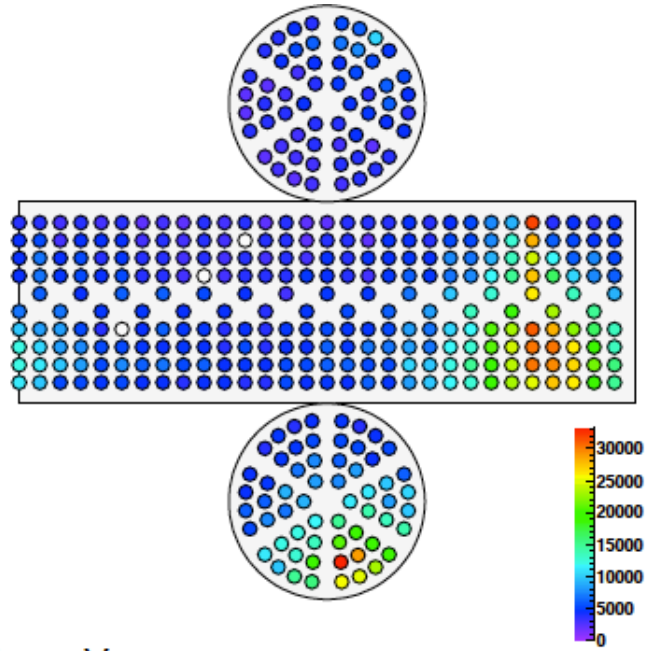




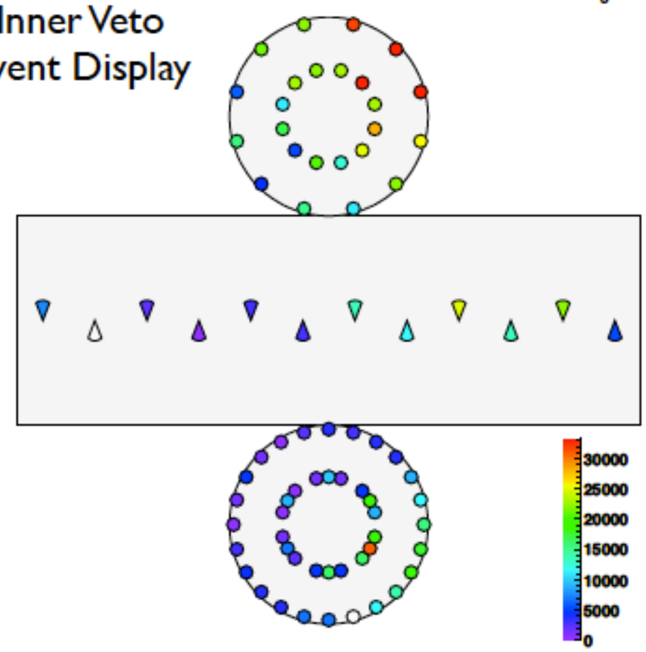
DC Preliminary: Muon Event

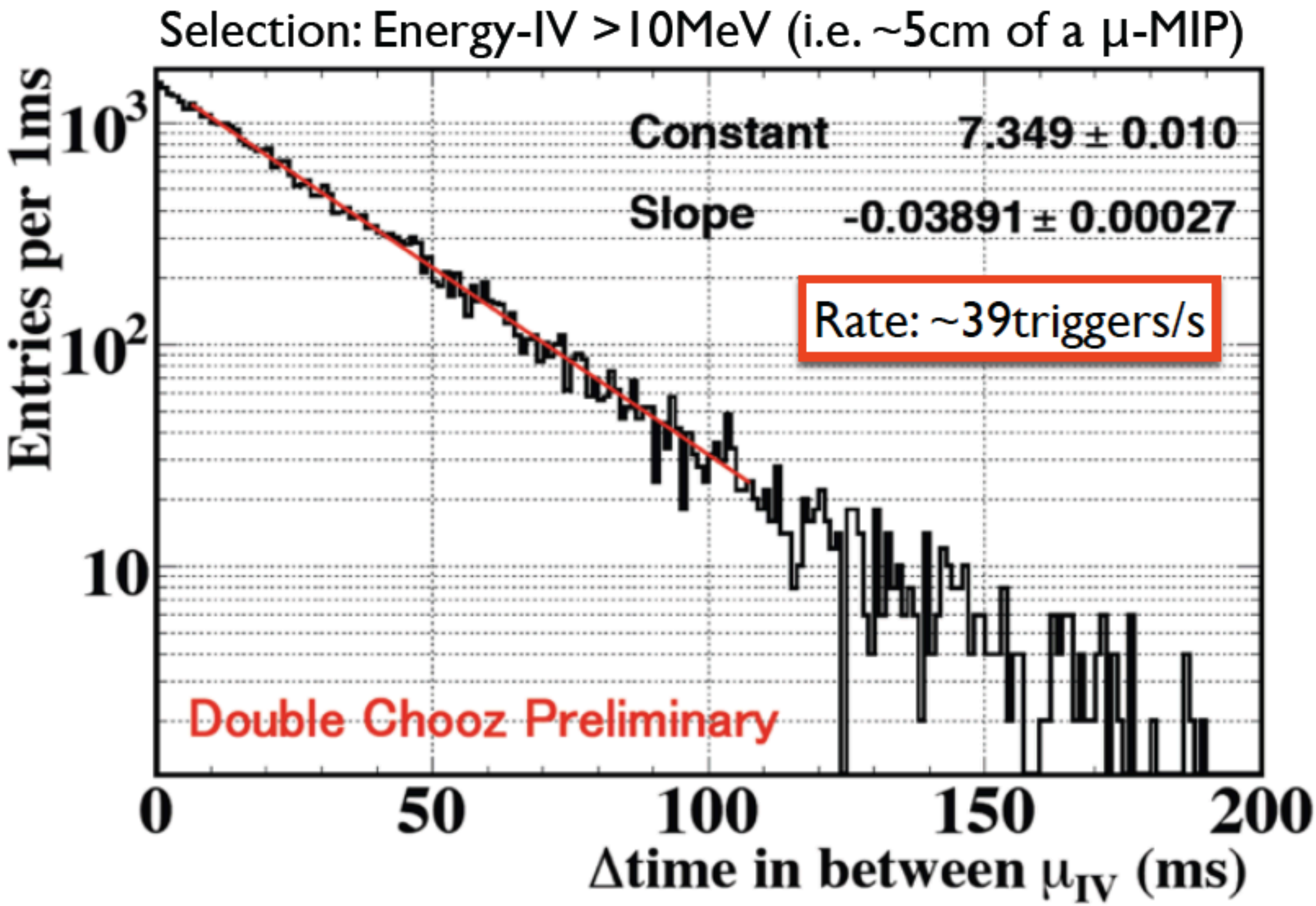
Inner Detector Waveforms





Inner Veto
Event Display



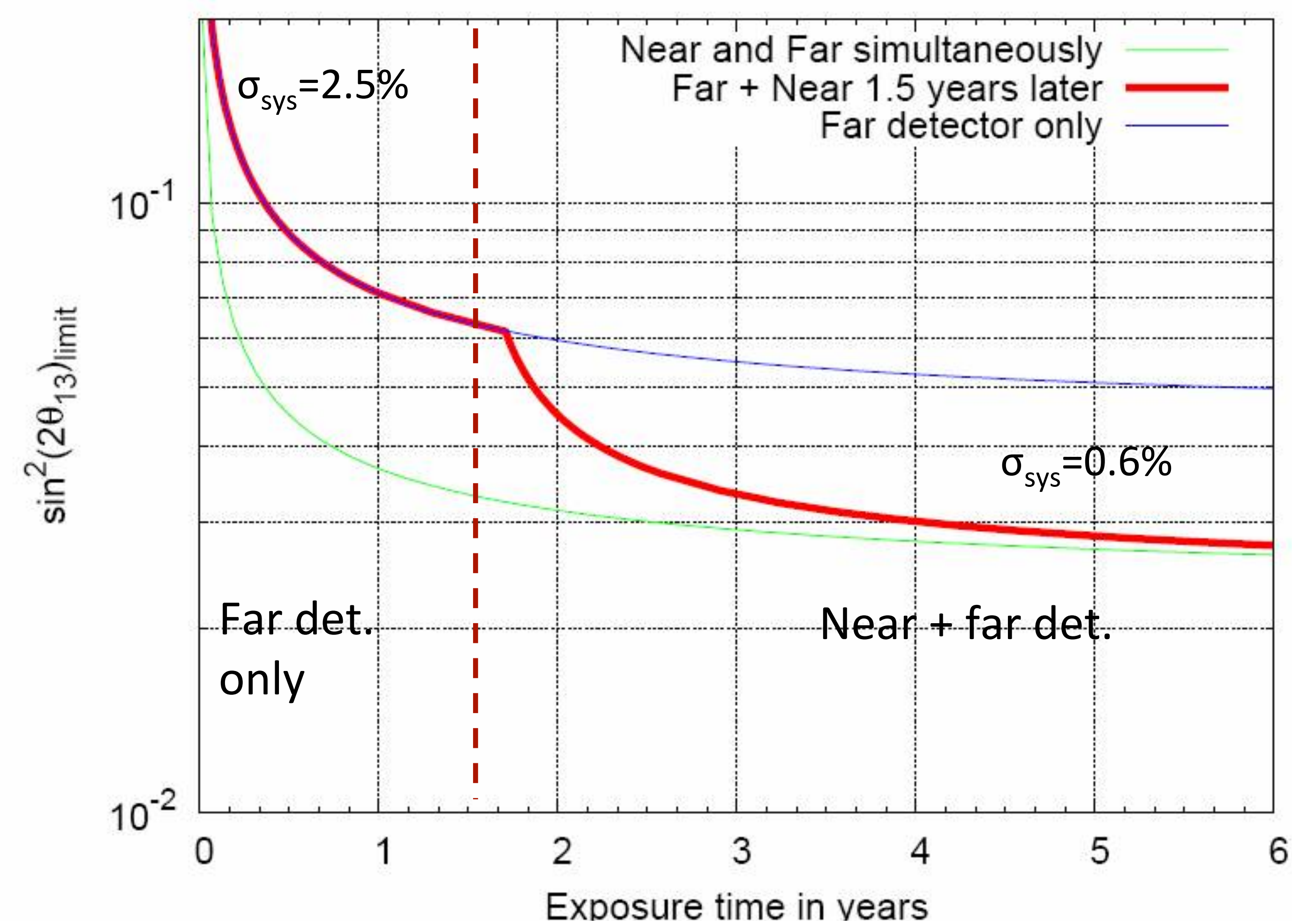

Selection: Energy-IV >10MeV (i.e. ~5cm of a μ-MIP)
Entries per 1ms
Constant 7.349 ± 0.010
Slope -0.03891 ± 0.00027
Rate: ~39triggers/s
Double Chooz Preliminary
Δtime in between μIV (ms)

Systematic Errors

		Chooz	Double Chooz	
Reactor-induced	ν flux and σ	1.9 %	<0.1 %	Two "identical" detectors, Low bkg
	Reactor power	0.7 %	<0.1 %	
	Energy per fission	0.6 %	<0.1 %	
Detector - induced	Solid angle	0.3 %	<0.1 %	Distance measured @ 10 cm + monitor core barycenter
	Volume	0.3 %	0.2 %	Same weight sensor for both det.
	Density	0.3 %	<0.1 %	Accurate T control (near/far)
	H/C ratio & Gd concentration	1.2 %	<0.1 %	Same scintillator batch + Stability
	Spatial effects	1.0 %	<0.1 %	"identical" Target geometry & LS
	Live time	few %	0.25 %	Measured with several methods
Analysis	From 7 to 3 cuts	1.5 %	0.2 - 0.3 %	
	Total	**2.7 %**	**< 0.6 %**	

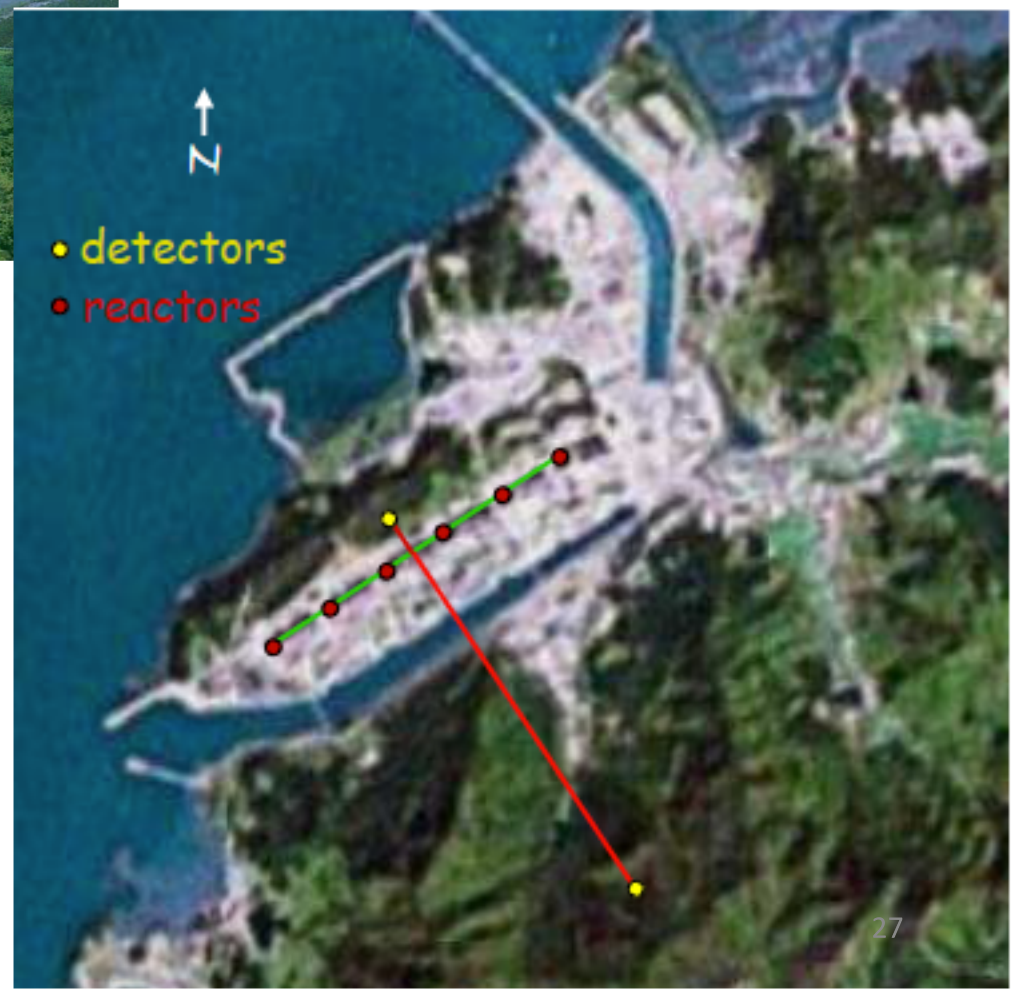
•Double Chooz far detector was filled and began commissioning in December 2010.

•Steady datataking (~90% datataking efficiency) began in April 2011



Sensitivity goal: $\sin^2 2\theta_{13}$~0.03

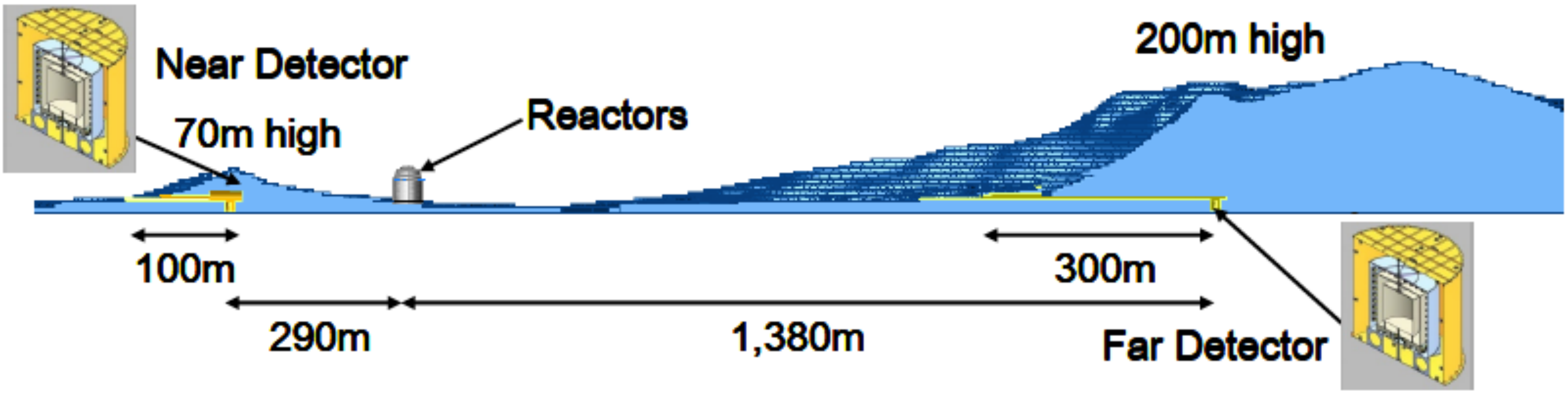
RENO Experiment
South Korea



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

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

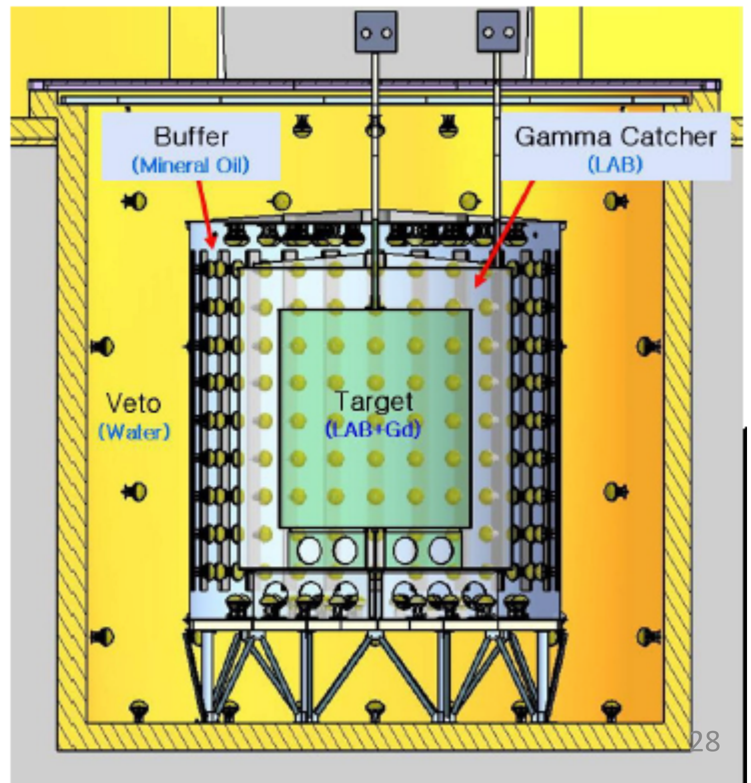
RENO Layout



RENO Detector

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

Target: 16 tons

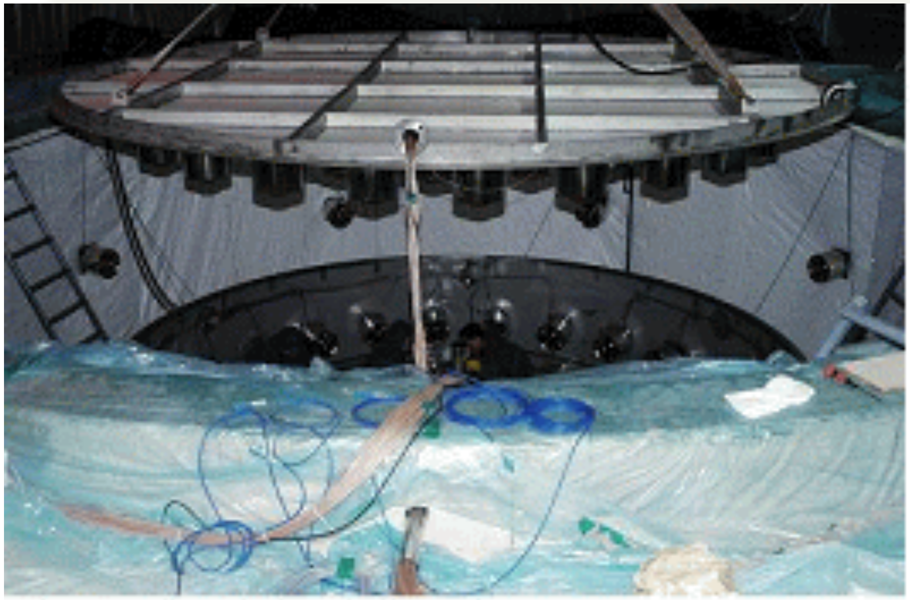
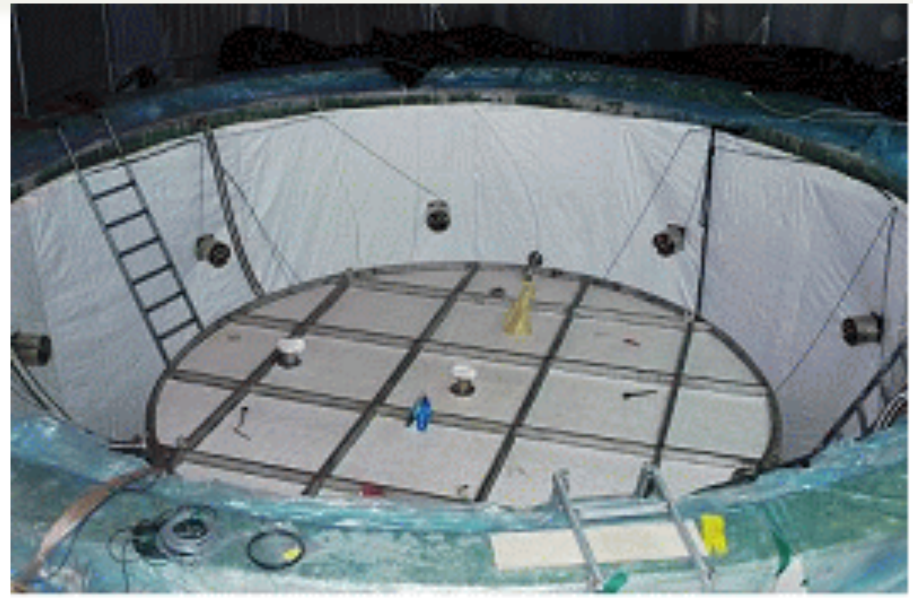
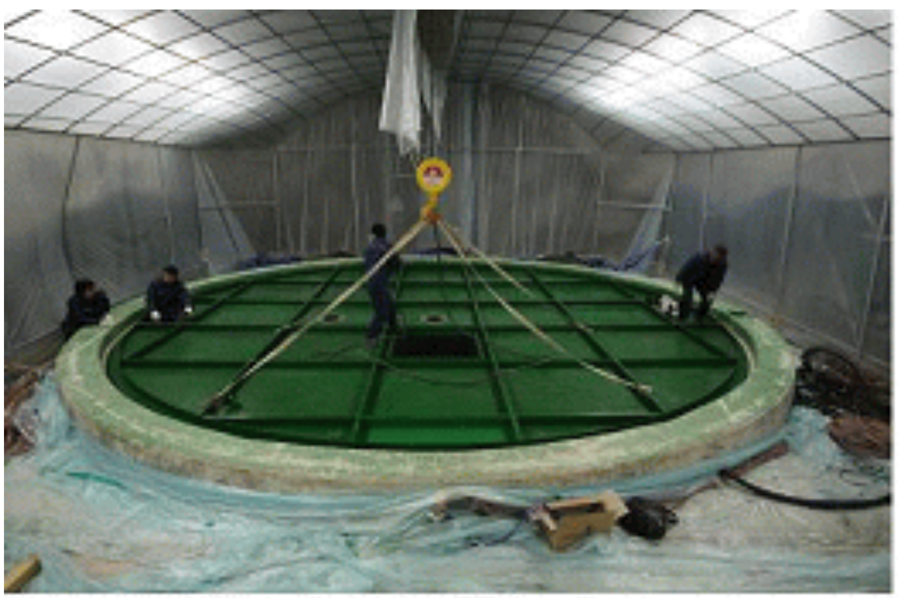
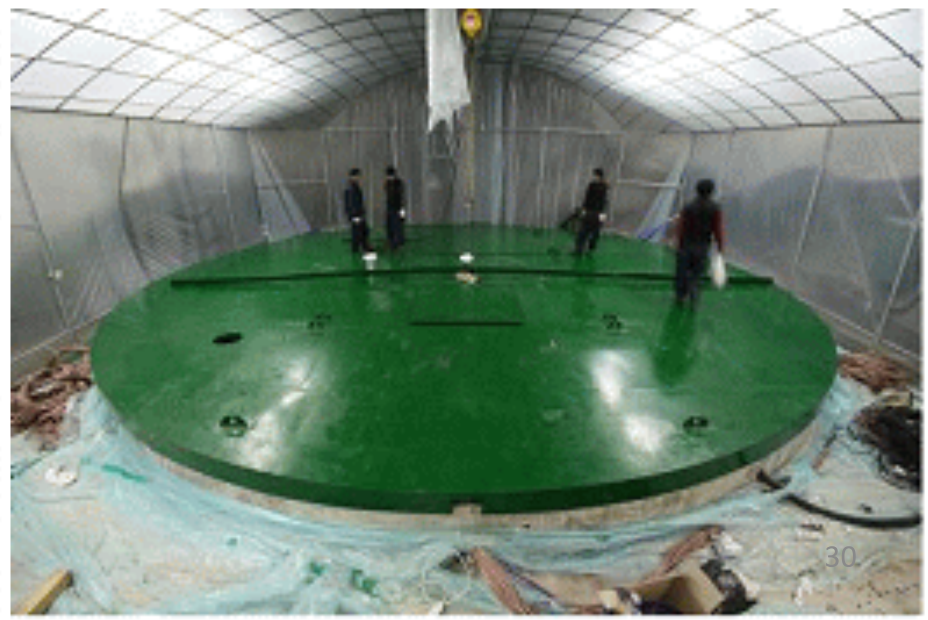


RENO

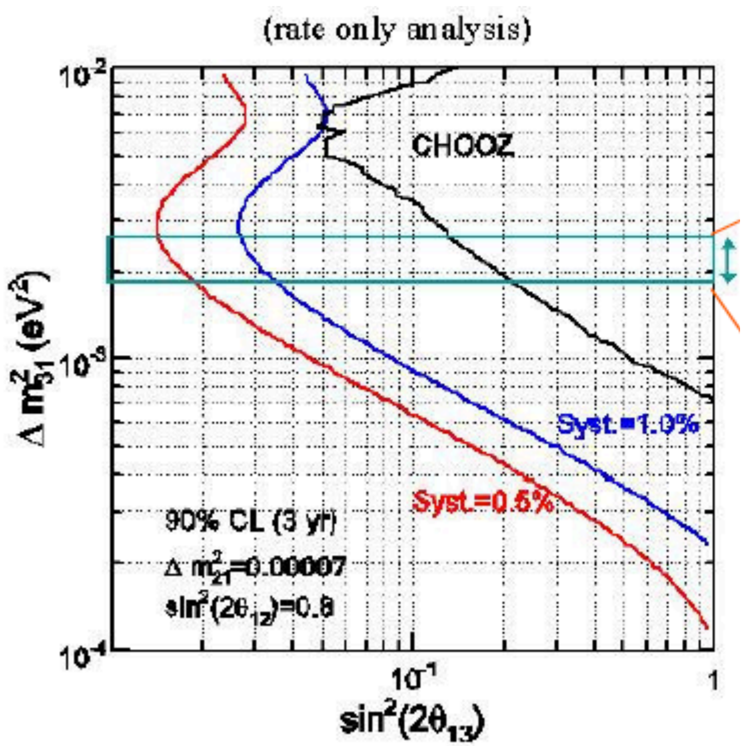
Finishing PMT installation (2011. 1)

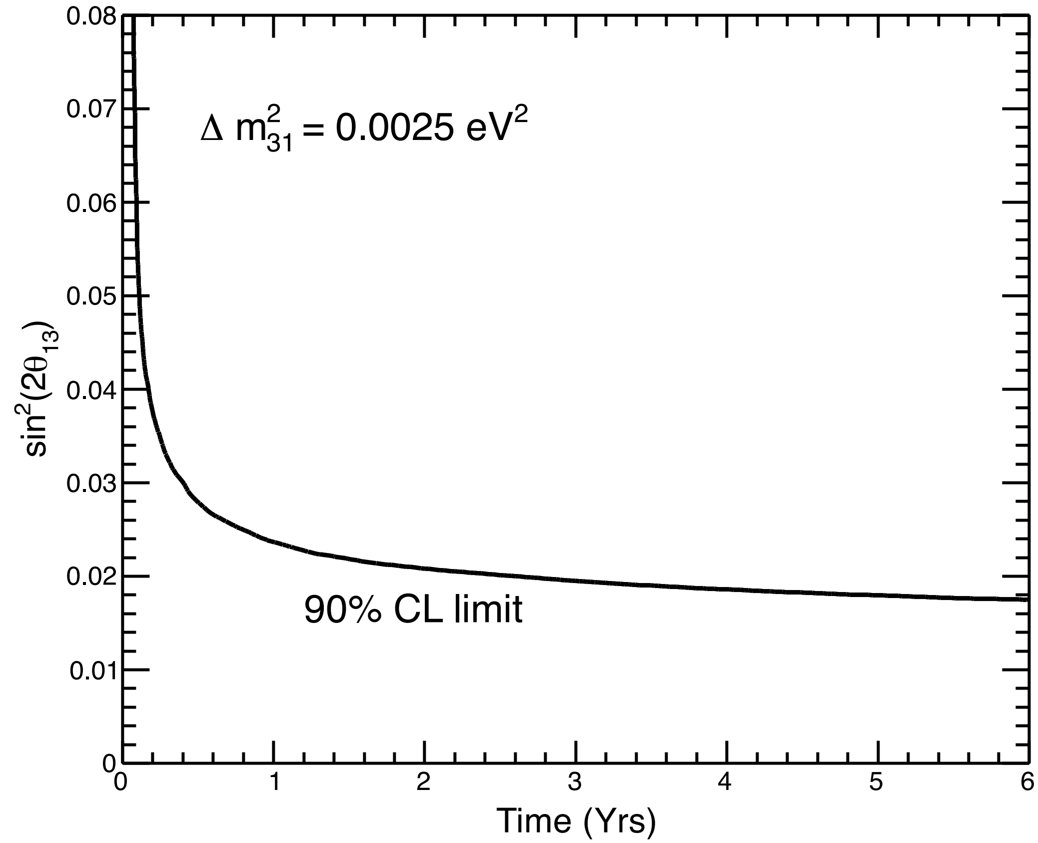
RENO

Near and Far Detectors Closed at end of Jan 2011

RENO Projected Sensitivity





Sensitivity goal: $\sin^2 2\theta_{13}$~0.02

May-June 2011: Production of liquid scintillator and filling

July 2011: Start of data taking

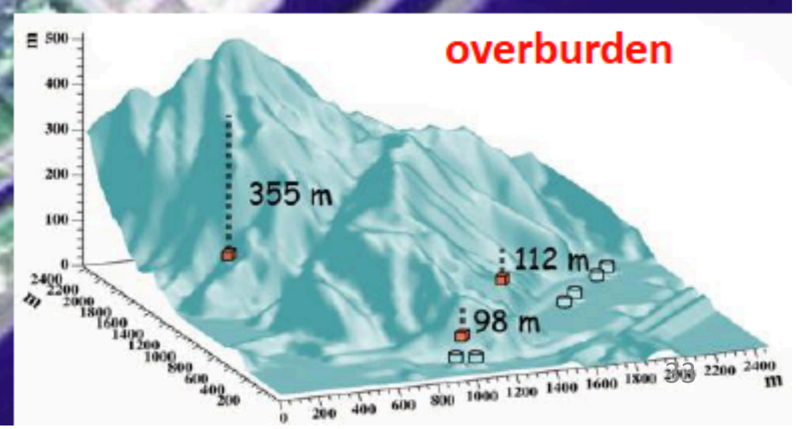
Daya Bay Reactor Neutrino Experiment

Will have 6 reactor cores with 17.4 GW_{th} by the end of this year.

Mountains provide up to 1000 mwe overburden.

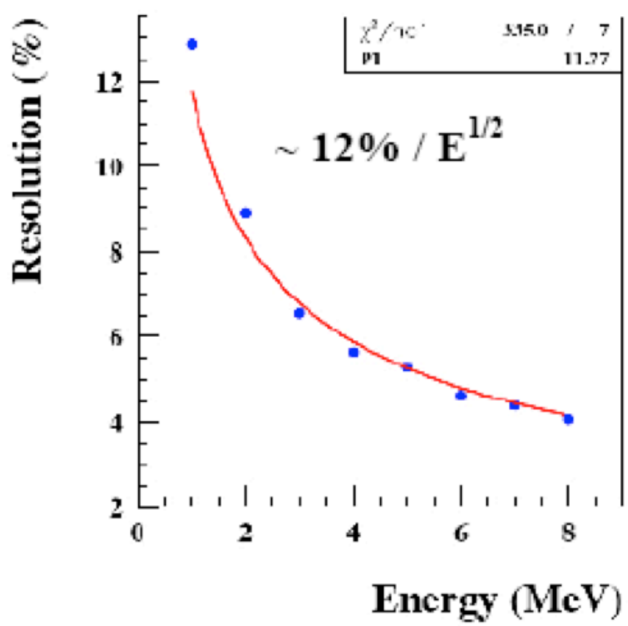
250 physicists from Asia, Europe, and U.S.

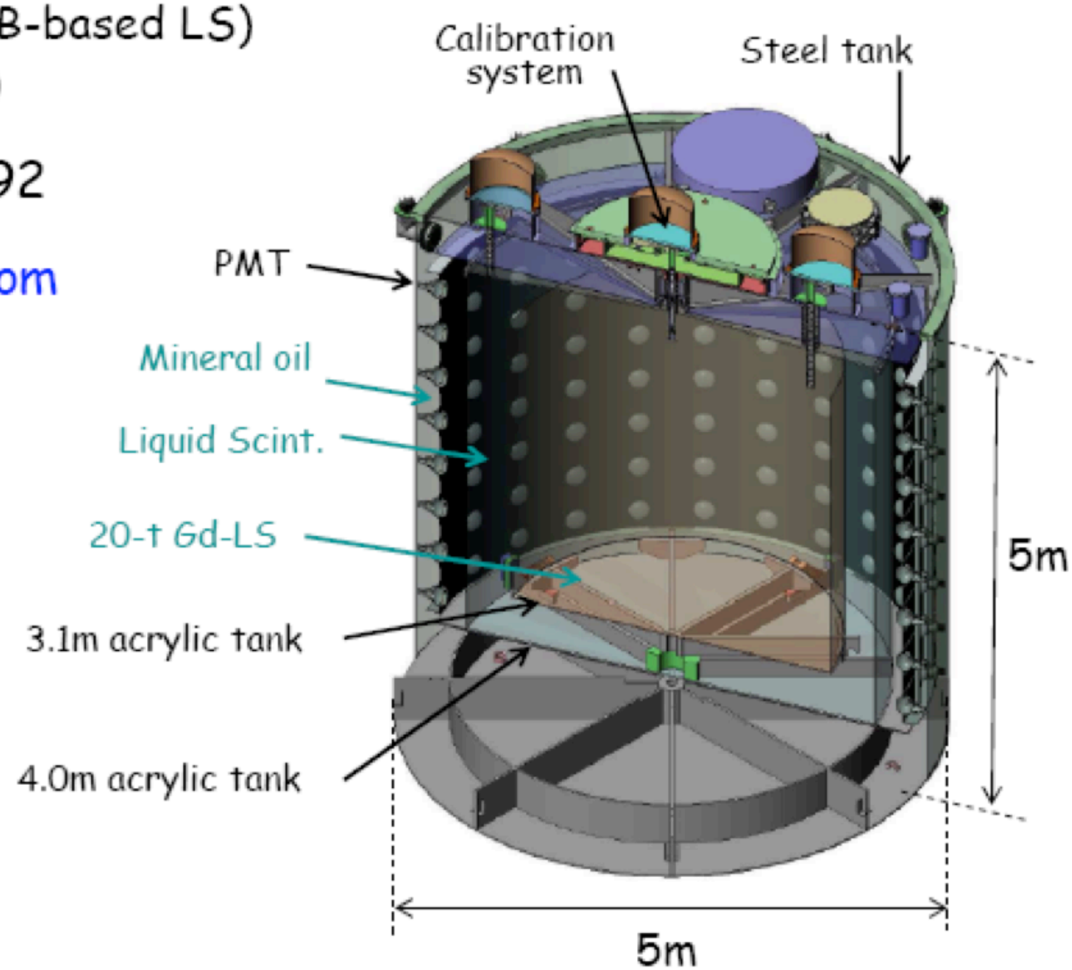
baseline (m)	DYB site	LA site	far site
DYB cores	363	1347	1985
LA cores	857	481	1618
LA-II cores	1307	526	1613



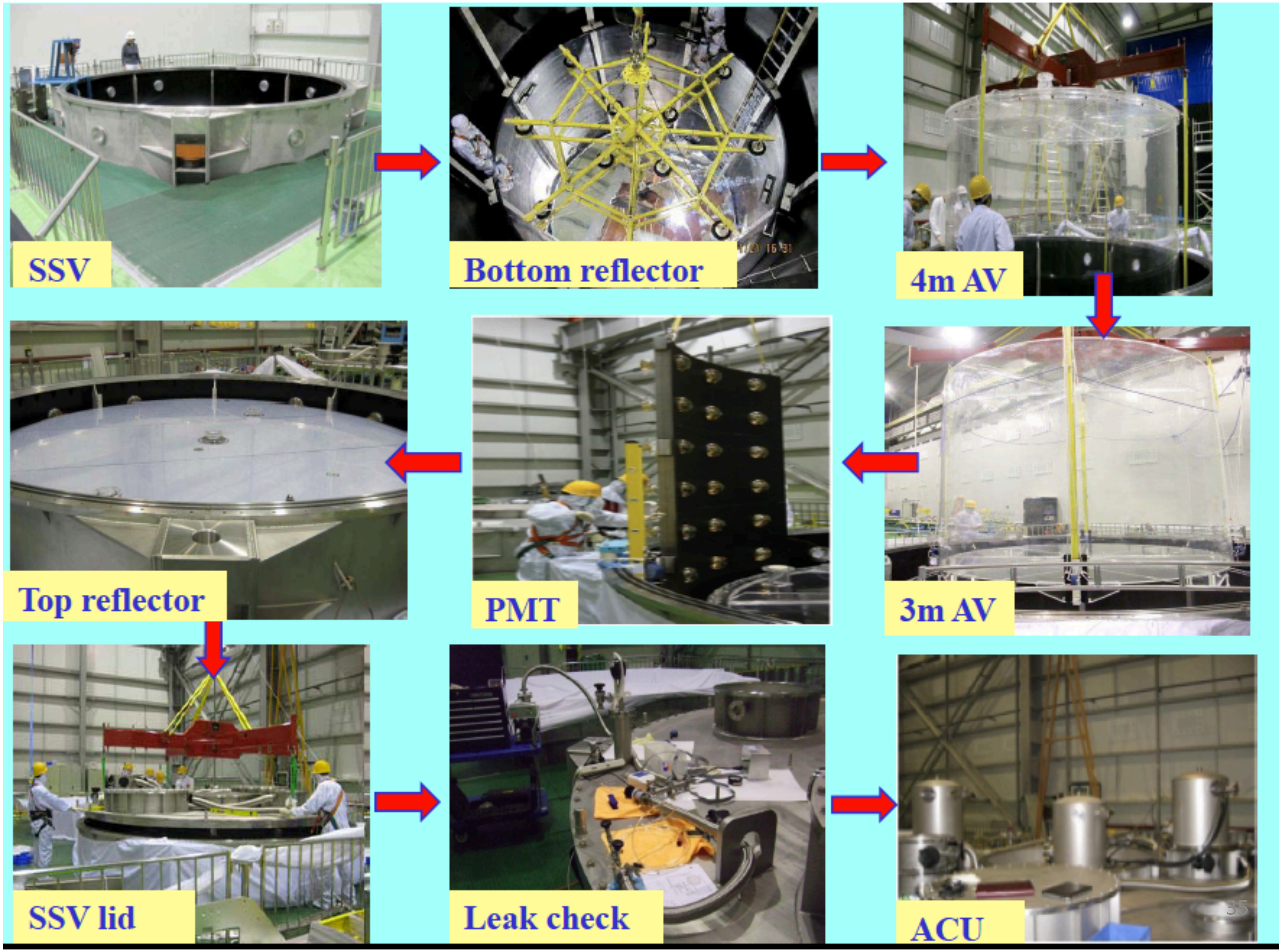
Antineutrino Detectors

- 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

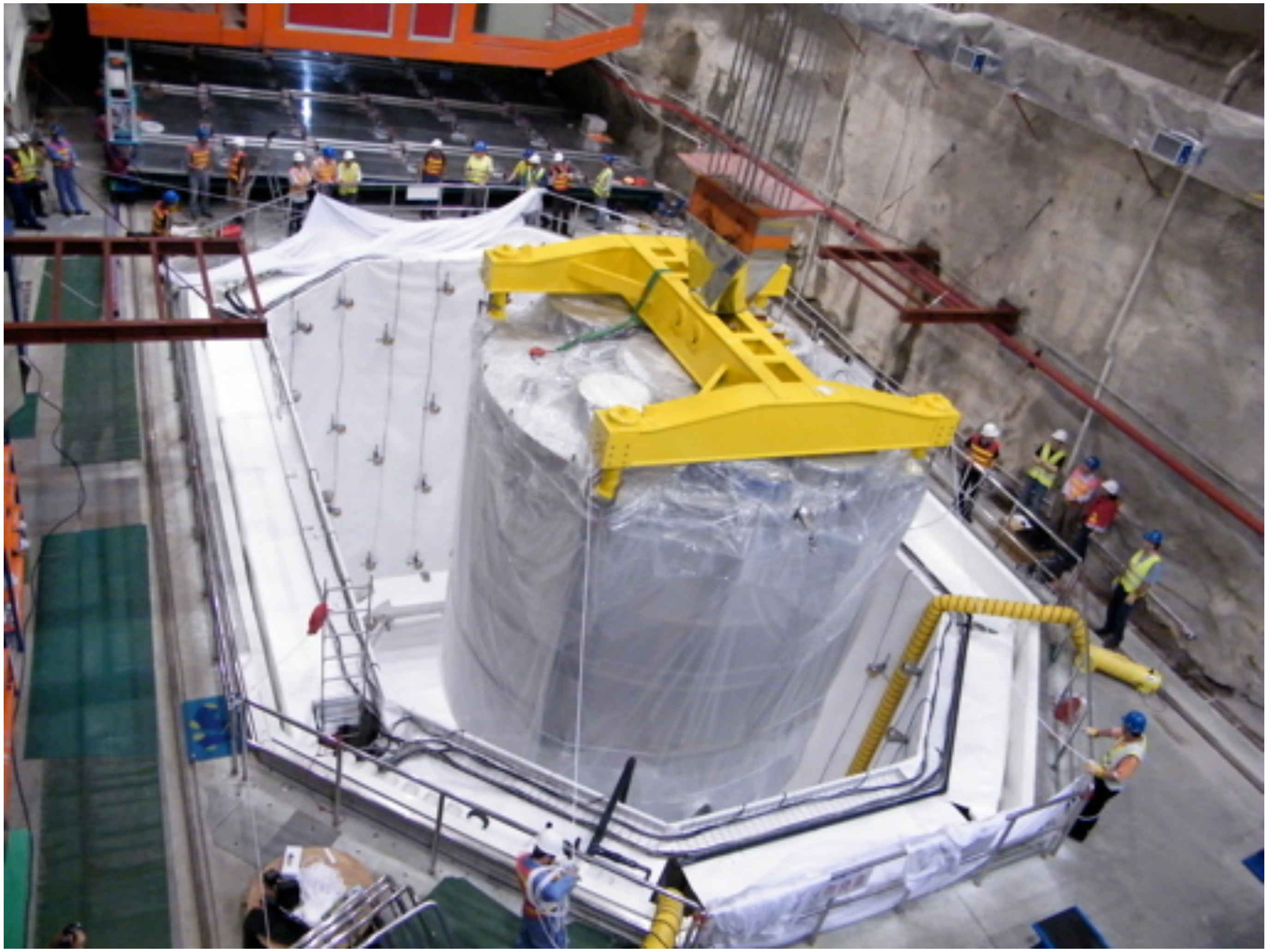




Daya Bay Anti-neutrino Detector Assembly

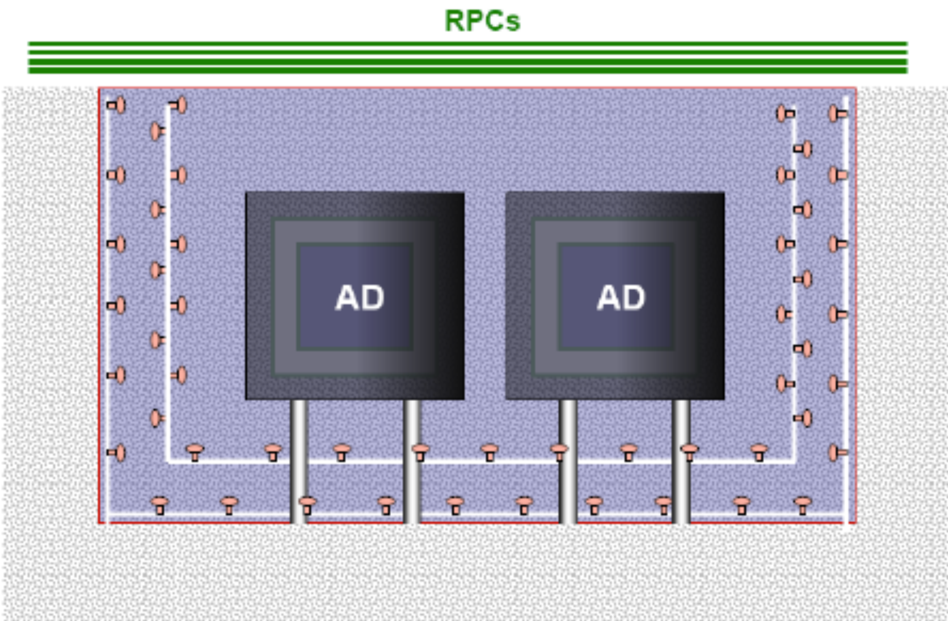


Installation of first AD at Daya Bay Site

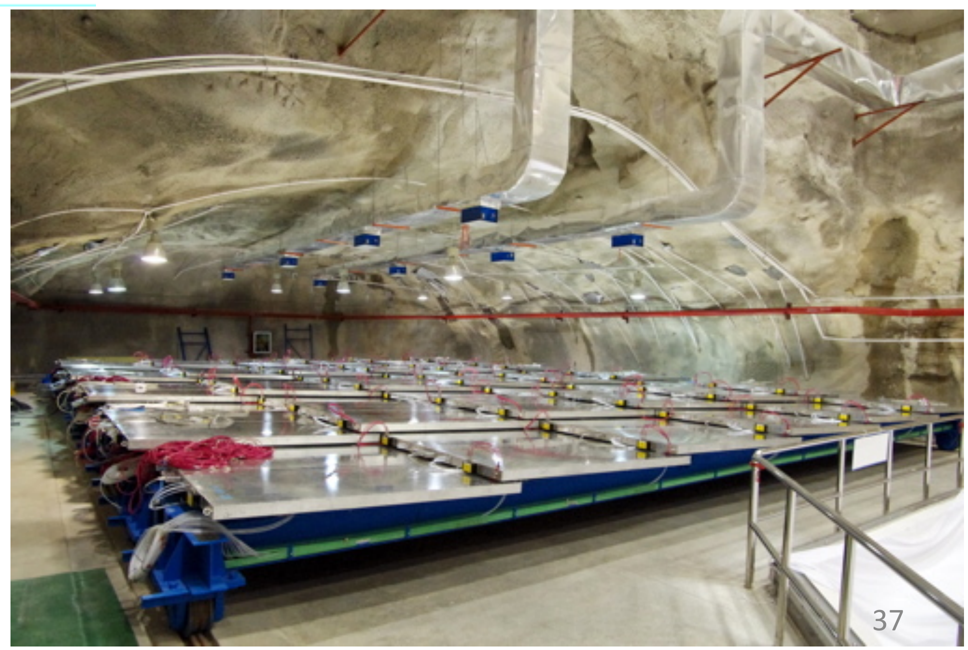


Datataking with first two ADs in Daya Bay Hall this summer

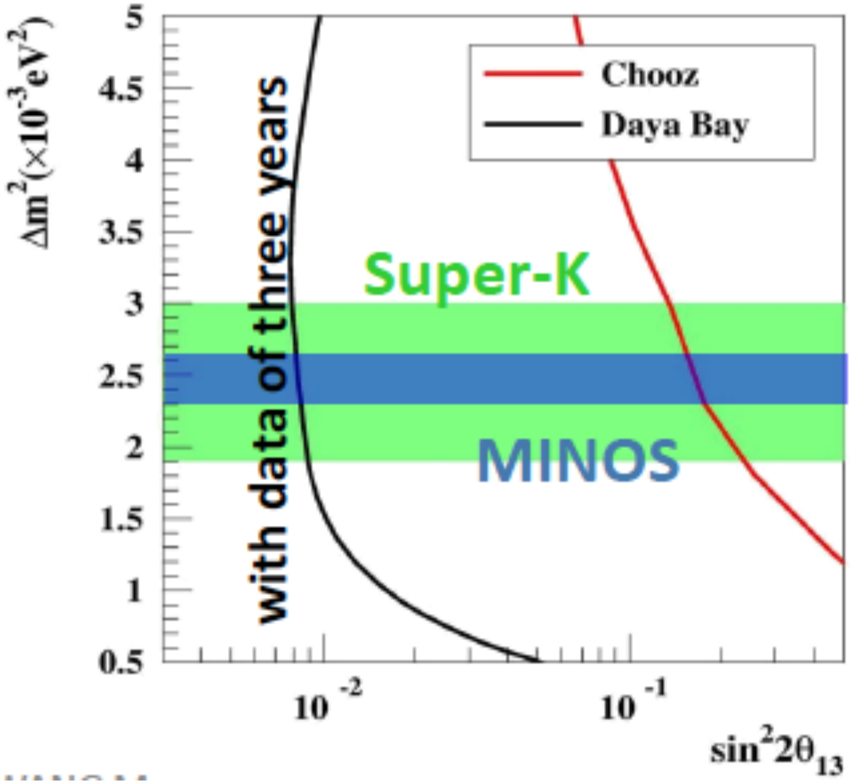
Muon Veto Detectors: Water Cerenkov and RPCs

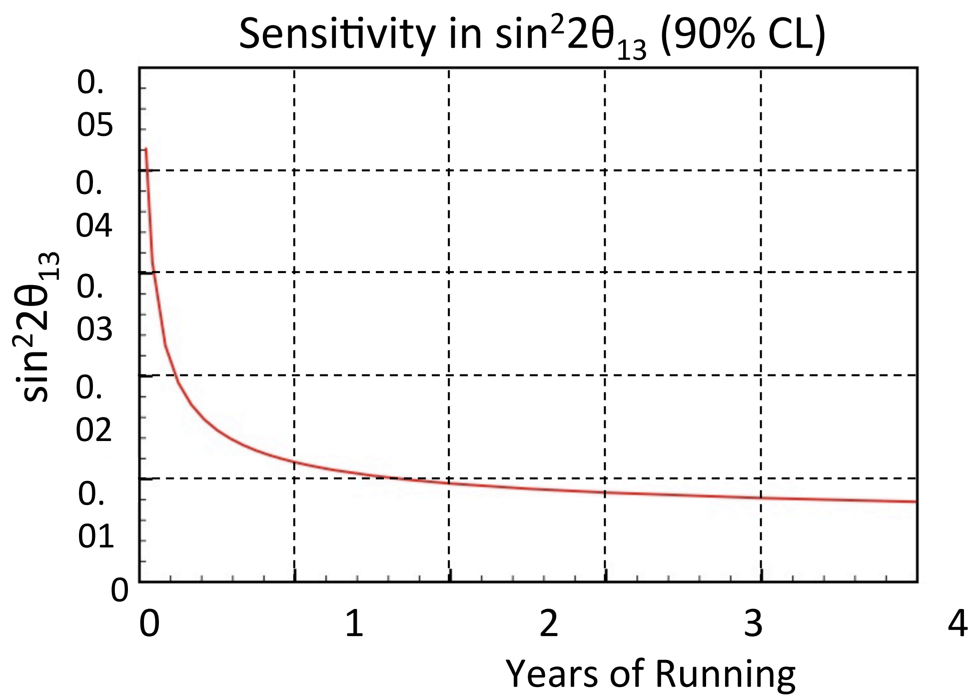


RPCs in Daya Bay Hall



Daya Bay Projected Sensitivity





Sensitivity goal: $\sin^2 2\theta_{13}$~0.01

Datataking with all 8 detectors in mid 2012.

Reactor Neutrino Flux and the Reactor Antineutrino Anomoly

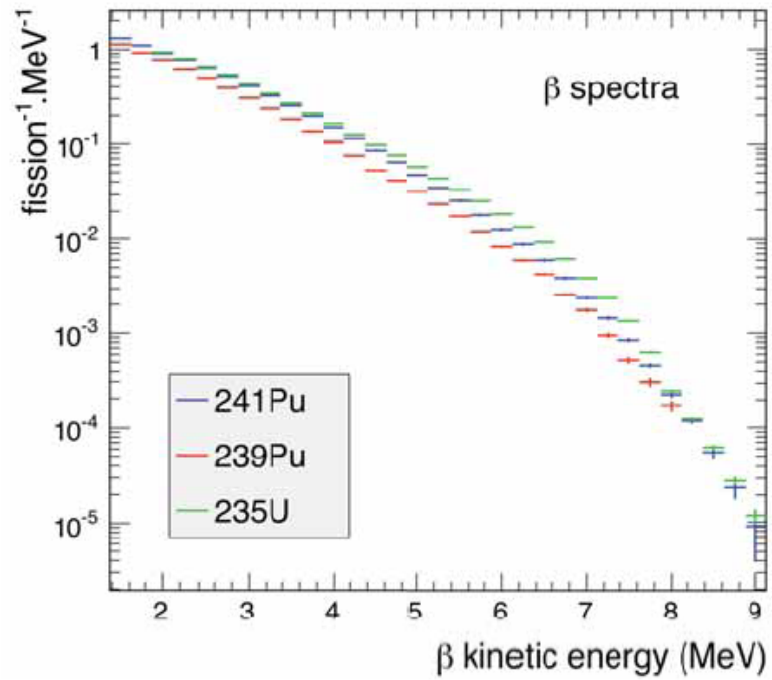
Th. A. Mueller et al.``Improved Predictions of Reactor Antineutrino Spectra,'' accepted for publication in Phys. Rev. C, arXiv:1101.2663.

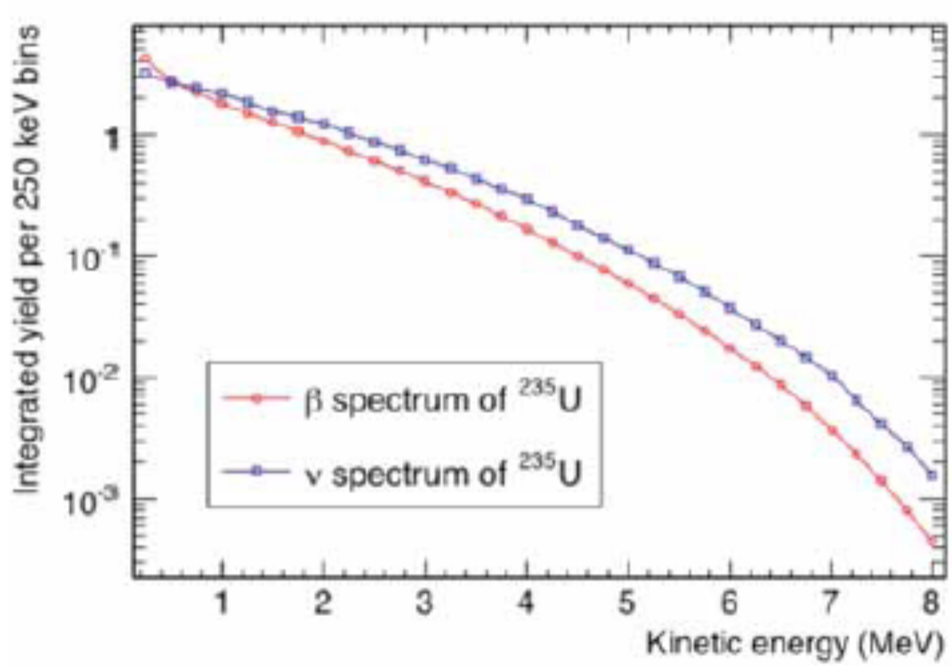
G. Mention et al., ``The Reactor Antineutrino Anomoly,'' accepted for publication in Phys. Rev. D, arXiv:1101.2755.

Mueller et al. have refined method to go from measured ^{235}U, ^{239}Pu, and ^{241}Pu β^{-} spectra (at ILL) to neutrino spectra.

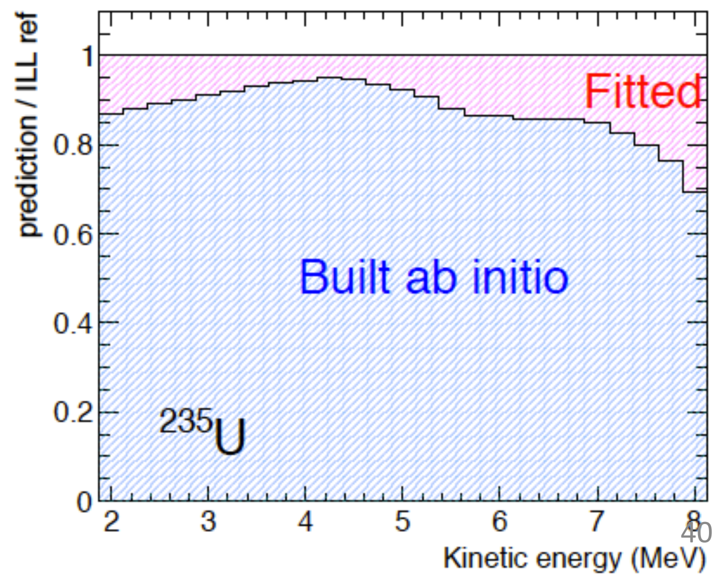
The result is a +3% increase in neutrino flux, on average.

Conversion from Electron to anti-Neutrino Spectra

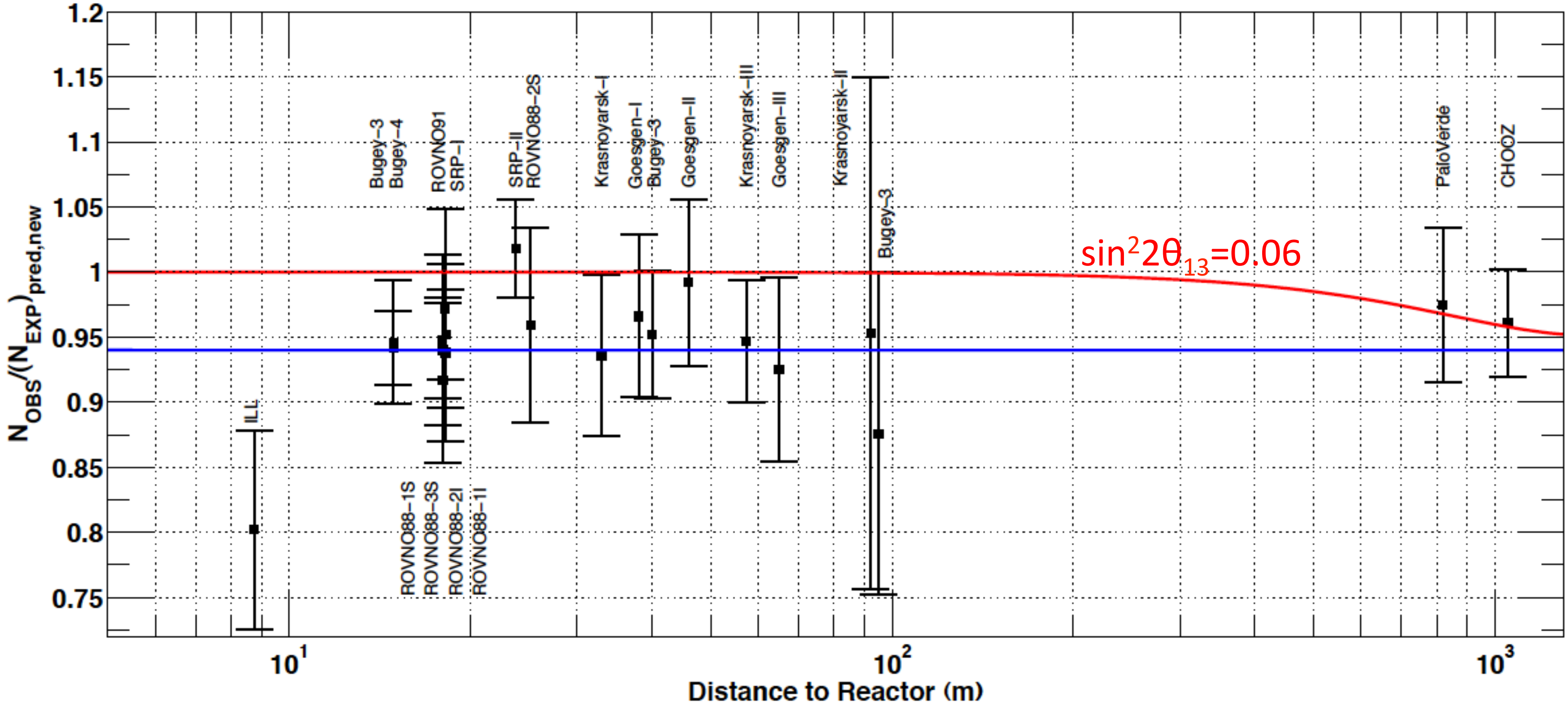




- Old method (A. Schreckenbach et al.) used 30 effective β branches
- New method uses all available information on measured nuclei from nuclear databases (~90% info from data bases, remaining ~10% fitted with 5 effective branches)



G. Mention et al.



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

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

Explanations?

- Statistics
- Mistake in new calculation; perhaps uncertainty in flux calculation is larger than estimated
- Bias in normalization of ILL experiment (uncertainty quoted as 2%)
- Common systematic bias in reactor experiments
- New physics at short baselines. Results are compatible 4^{th}, non-standard neutrino state with Δm^2 >~ 1 eV^2 and $\sin^2 2\theta \sim 0.1$

Summary

- Exciting time for short baseline ν experiments
- In a couple of years, we should know much more about θ_{13} – maybe sooner.
- New reactor flux calculation and "anomoly":
  - Near/far detector experiment is the right way to measure θ_{13}
  - Near detector data from upcoming experiments should be studied closely
  - A measurement of few MeV neutrinos at very short baseline (< 10 m) would be interesting.