Review of Present and Future Reactor Neutrino Experiments

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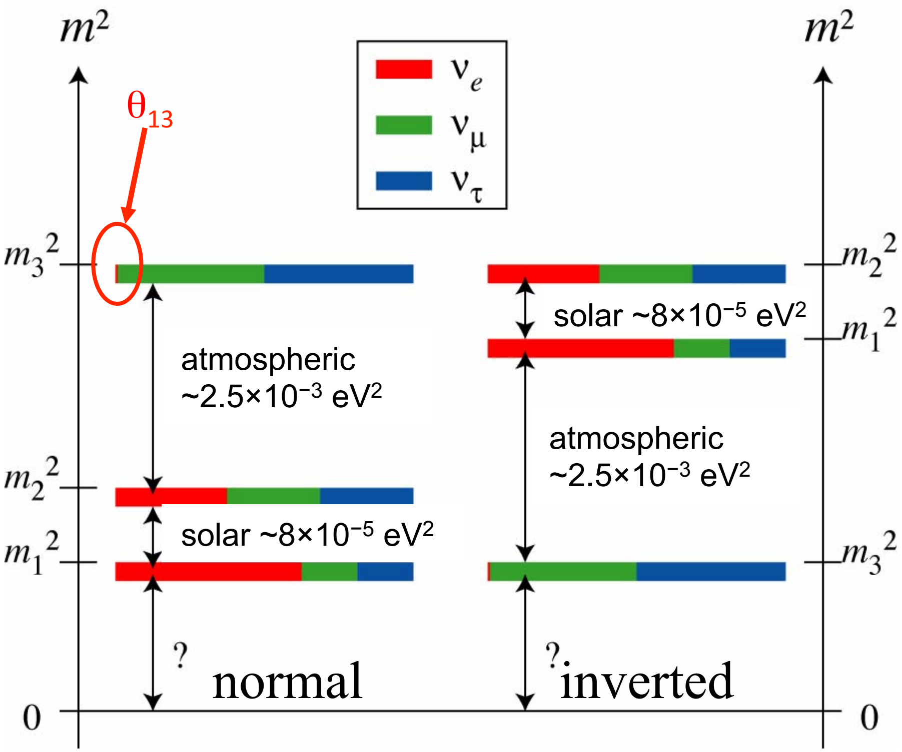
Neutrino Oscillation Results

Missing information in 3x3 ν mixing scheme:

1. What is ν_e component in the ν_3 mass eigenstate, i.e. θ_{13}= ?
   -Only know $\theta_{13} < \sim 11^0$.
2. Is the μ - τ mixing maximal?
   -Only know $\sin^2 2\theta_{23} > 0.90$.
3. What is the mass hierarchy?
   -Normal or inverted?
4. Do neutrinos exhibit CP violation, i.e. is $\delta_{CP} \neq 0$?



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

Discussed by D. Wark

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

$\theta_{12} \sim 30°$ $\quad$ $\sin^2 2\theta_{13} < 0.11$ at 90% CL $\quad$ $\theta_{23} \sim 45°$

Experimental Methods to Measure θ_{13}

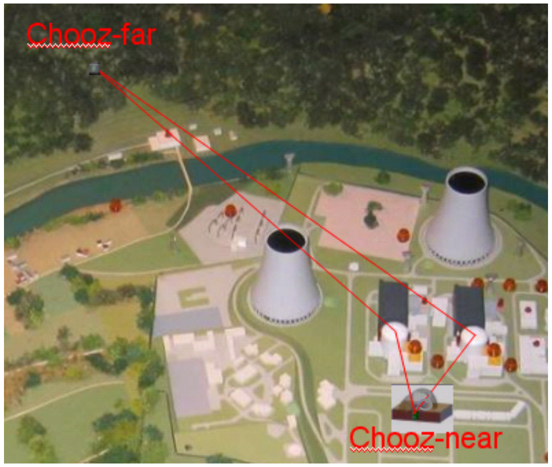
- Long-Baseline Accelerators: Appearance ($\nu_\mu \rightarrow \nu_e$) at $\Delta m^2 \approx 2.5\times10^{-3}$ eV^2
  - Look for appearance of ν_e in a pure ν_μ beam vs. L and E
    - Use near detector to measure background ν_e's (beam and misid)

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 $\Delta m^2 \approx 2.5\times10^{-3}$ eV^2
  - Look for a change in ν_e flux as a function of L and E
    - Look for a non- $1/r^2$ behavior of the $\bar{\nu}_e$ rate
    - Use near detector to measure the un-oscillated flux

Double Chooz:
$\langle E_\nu \rangle = 3.5$ MeV
$L = 1100$ m



Accelerator vs Reactor Experiment

Long-Baseline Accelerator Appearance Experiments

θ_{13} probed by measuring electron neutrino appearance from accelerator produced muon neutrinos.

Need to have an L and E such that interference between solar and atmospheric scales can bee seen

Oscillation probability complicated and dependent not only on θ_{13} but also:

1. CP violation parameter (δ)
2. Mass hierarchy (sign of Δm_{31}^2)
3. Size of $\sin^2\theta_{23}$

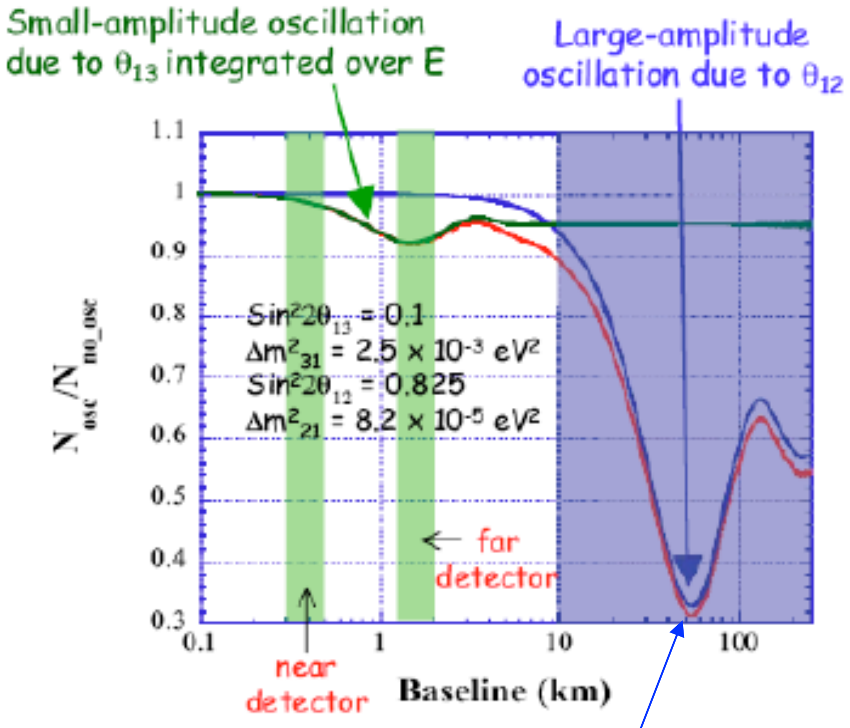
$$\begin{aligned}P(\nu_\mu \to \nu_e) = {} & \sin^2\theta_{23}\sin^2 2\theta_{13}\frac{\sin^2(\Delta_{31}\mp aL)}{(\Delta_{31}\mp aL)^2}\Delta_{31}{}^2 \\ & + \cos^2\theta_{23}\sin^2 2\theta_{12}\frac{\sin^2(aL)}{(aL)^2}\Delta_{21}{}^2 \\ & + \cos\delta\sin 2\theta_{23}\sin 2\theta_{12}\sin 2\theta_{13}\cos\Delta_{32}\left(\frac{\sin(\Delta_{31}\mp aL)}{(\Delta_{31}\mp aL)}\Delta_{31}\right)\left(\frac{\sin(aL)}{(aL)}\Delta_{21}\right) \\ & + \sin\delta\sin 2\theta_{23}\sin 2\theta_{12}\sin 2\theta_{13}\sin\Delta_{32}\left(\frac{\sin(\Delta_{31}\mp aL)}{(\Delta_{31}\mp aL)}\Delta_{31}\right)\left(\frac{\sin(aL)}{(aL)}\Delta_{21}\right)\end{aligned}$$

⇒ These extra dependencies are both a “curse” and a “blessing” since they will let us measure CP violation if θ_{13} is big enough.

Accelerator vs Reactor Experiment

Reactor Disappearance Experiments

θ_{13} probed by measuring the disappearance of reactor produced electron anti-neutrinos.



Another large detector here for precise θ_{12} measurement?

- For θ_{13} need to work at an L/E matched to the atmospheric Δm^2.
- Reactors used in θ_{12} range as well: need to work at an L/E matched to the solar Δm^2 i.e. Kamland measurement at solar Δm^2.

$$P(\bar{\nu}_e \rightarrow \bar{\nu}_e) = 1 - \cos^4\theta_{13}\sin^2 2\theta_{12}\sin^2\Delta_{21} - \sin^2 2\theta_{13}(\cos^2\theta_{12}\sin^2\Delta_{31} + \sin^2\theta_{12}\sin^2\Delta_{32})$$

$$\Delta_{ij} \equiv 1.27\Delta m^2_{ij} L/E$$

L(km), E(MeV), m(10^{-3}eV)

⇒ Reactor disappearance measurements provide a straight forward method to measure θ_{13} with no dependence on matter effects and CP violation

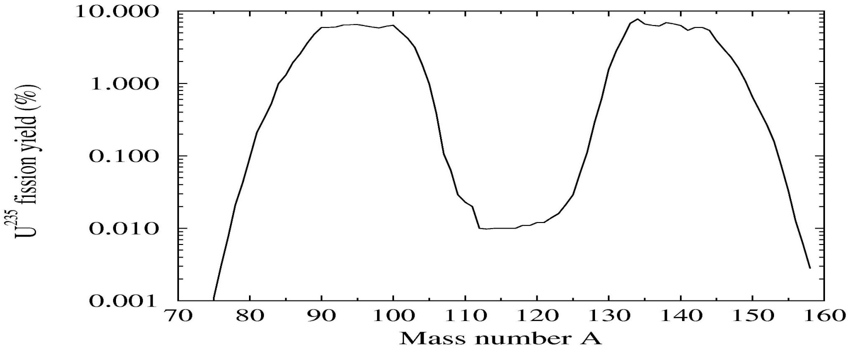
Nuclear Reactors as $\bar{\nu}_e$ Sources

What creates the reactor $\bar{\nu}_e$' s ?

- Typical modern nuclear power reactor has a thermal power of: P_{therm} = 3.8 GW
  - About 200 MeV / fission of energy is released in fission of ^{235}U, ^{239}Pu, ^{238}U, and ^{241}Pu.
  - The resulting fission rate, f, is thus: f = 1.2 $\times 10^{20}$ fissions/s
  - At 6$\bar{\nu}_e$ / fission the resulting yield is: 7.1 $\times 10^{20}$ $\bar{\nu}_e$ / s.

Example: ^{235}U fission

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

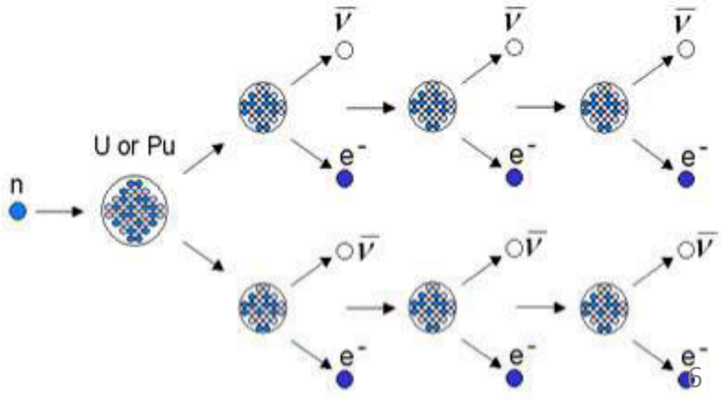


Most likely A from ^{235}U fission ⇒ ^{94}Zr ^{140}Ce

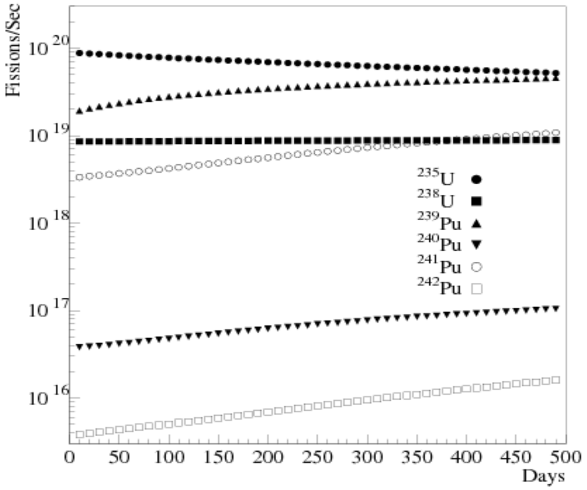
→ on average 6 n have to β-decay to 6 p to reach stable matter: $^{94}_{40}Zr\ ^{140}_{58}Ce$

→ on average 1.5 ν_e are emitted with energy > 1.8 MeV

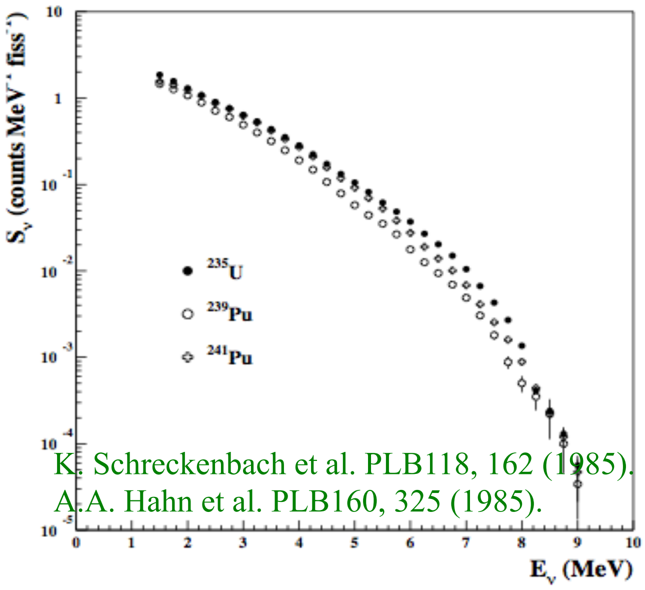
Using e^- spectra measurements for ^{235}U, ^{239}Pu, and ^{241}Pu
Can calculate the ν_e flux to 2-3%.



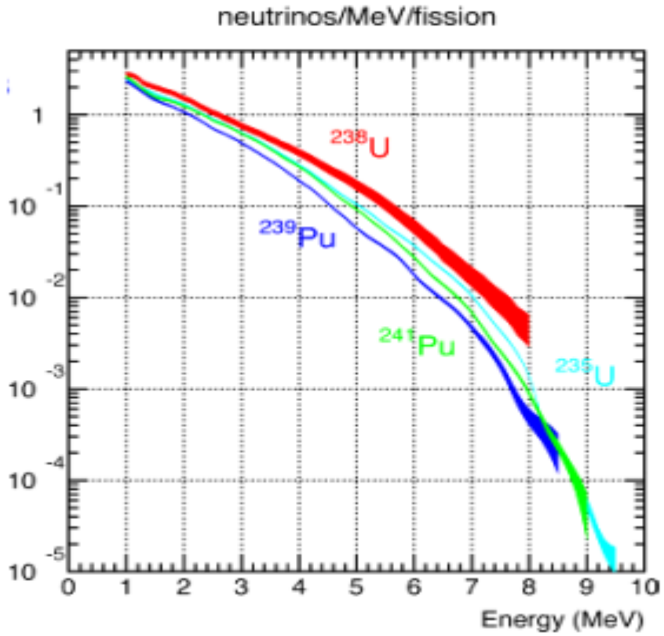
$\overline{\nu}_e$ Flux Calculation



- To perform this calculation correctly one must
  -consider 235U, 238U, 239Pu, and 241Pu
  (> 99.5% $\overline{\nu}_e$ flux) ,
  -account for all possible β branches.
  -correct for evolution of the reactor core over
  the fuel cycle.
- Measurement the β spectra of fission-ing of U-235, Pu-239, and Pu-241 samples by thermal neutrons performed at ILL, and converted to neutrino spectra.
- U-238 relies on theoretical calculation, 10% uncertainty (P. Vogel et al., PRC24, 1543 (1981)). U-238 contributes (7-10)% fissions.

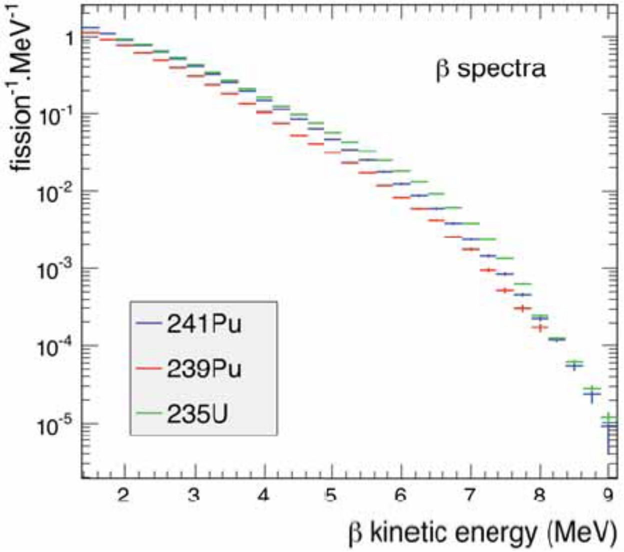


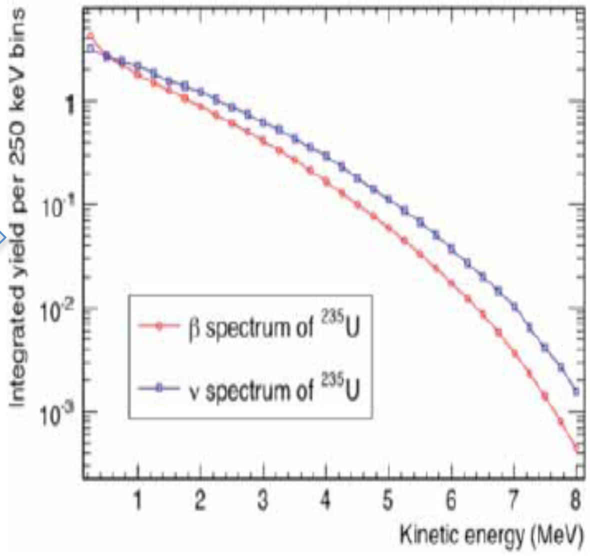
K. Schreckenbach et al. PLB118, 162 (1985).
A.A. Hahn et al. PLB160, 325 (1985).



Conversion from Electron to anti-Neutrino Spectra

- Old method (A. Schreckenbach et al.)
  used 30 effective
  β branches.



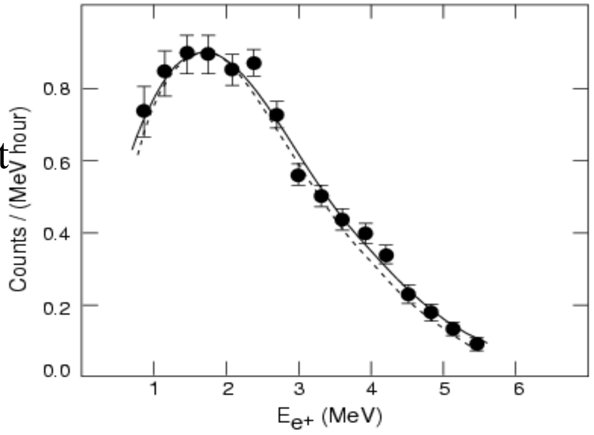


- Comparison of prediction to observation:

Example:

Goesgen Experiment

Solid: Fit to Data
Dashed: Prediction
from β spectrum



Another example

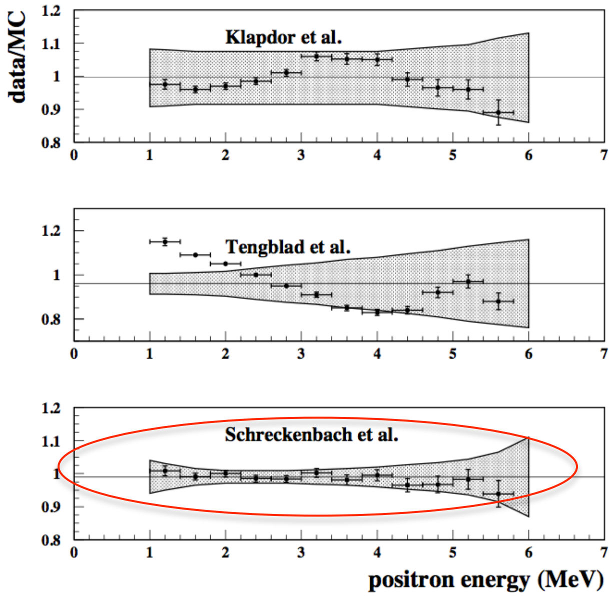
Bugey 3 Exp:

comparison to

three different

reactor spectrum

models.



Normalization error ~1.9%.
Energy dependent (shape) error from
1.34% at 3 MeV to 9.2% at 8 MeV.

Flux and Energy Spectrum known at ~2-3 % level

→Reactors used as "calibrated sources" of ν' s

Reactor $\bar{\nu}$ Flux and “Reactor Anomaly”

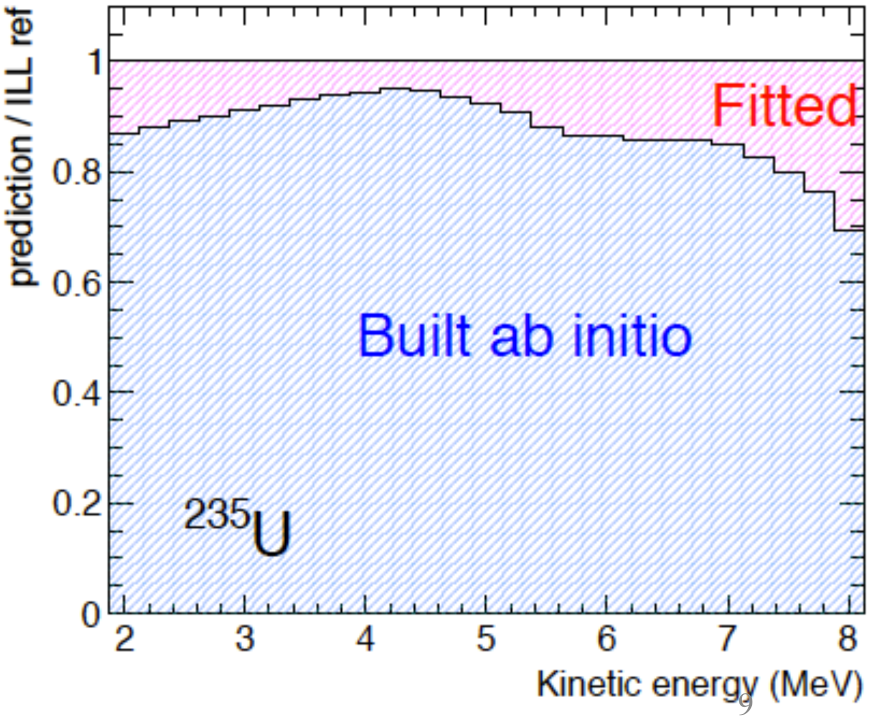
Th. A. Mueller et al.``Improved Predictions of Reactor Antineutrino Spectra,” Phys. Rev. C83, 054615, 2011.

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

New method uses all available information on measured nuclei from nuclear databases (~90% info from data bases, remaining ~10% fitted with 5 effective branches)

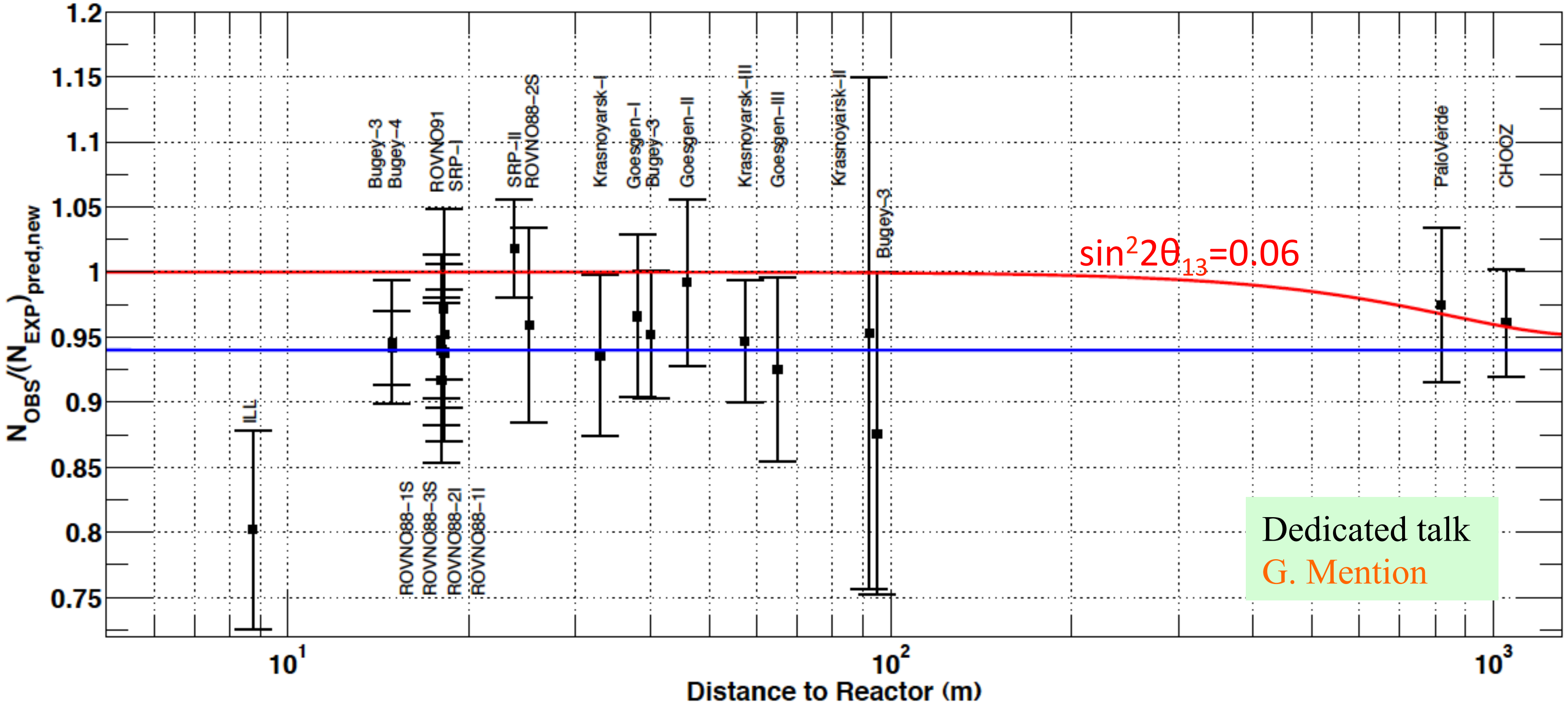
The result is a +3% increase in neutrino flux, on average.

Trend independently confirmed by P. Huber, arXiv:1106.0687.



Reactor $\bar{\nu}$ Flux and "Reactor Anomaly"

G. Mention et al., ``The Reactor Antineutrino Anomaly,'' Phys. Rev. D83, 073006, 2011.



Dedicated talk
G. Mention

For L<100m, accounting for correlations, results is $N_{OBS}/N_{EXP} = 0.937 \pm 0.027$

Possible bias or new physics at short baselines?
Results are compatible with 4th, sterile neutrino state with $\Delta m^2 >\sim 1\ \text{eV}^2$ and $\sin^2 2\theta \sim 0.1$ (i.e. MiniBooNE/LSND, etc).

$\bar{\nu}$ Detection Technique

- The reaction process is inverse β-decay followed by neutron capture
  - Two part coincidence signal is crucial for background reduction.

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

$$\hookrightarrow n\ capture$$

- Positron energy spectrum implies the neutrino spectrum ($e^+e^- \rightarrow \gamma\gamma$)

$$E_\nu = E_{vis} + 1.8\ \text{MeV} - 2m_e$$

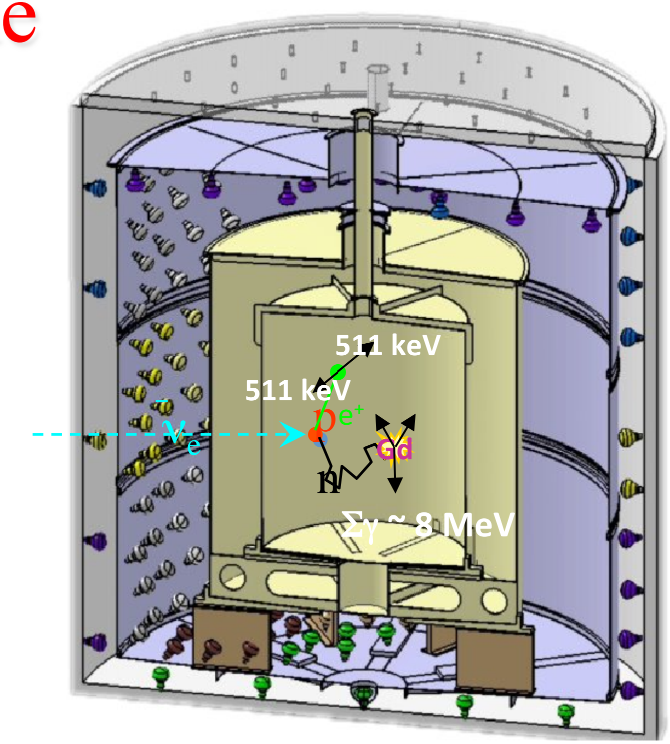
- The scintillator may be doped with gadolinium to enhance capture

$$n\ {}^{m}\text{Gd} \rightarrow {}^{m+1}\text{Gd}\ \gamma\text{'s (8 MeV)}$$

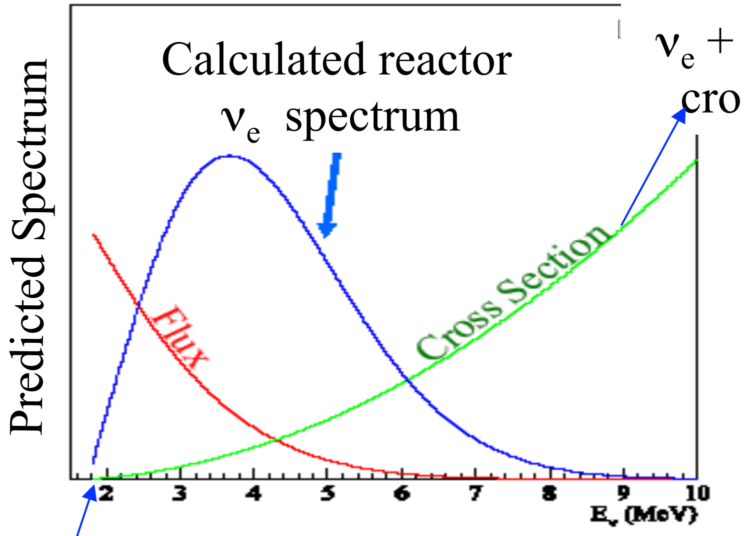
- Cross accurate to 0.2%

P. Vogel and J. Beacom, Phys.Rev.D60:053003,1999

A. Strummia and F. Vissani, Phys.Lett.B564:42-54,2003;



Signal = Positron signal + Neutron Signal (within a few capture times)



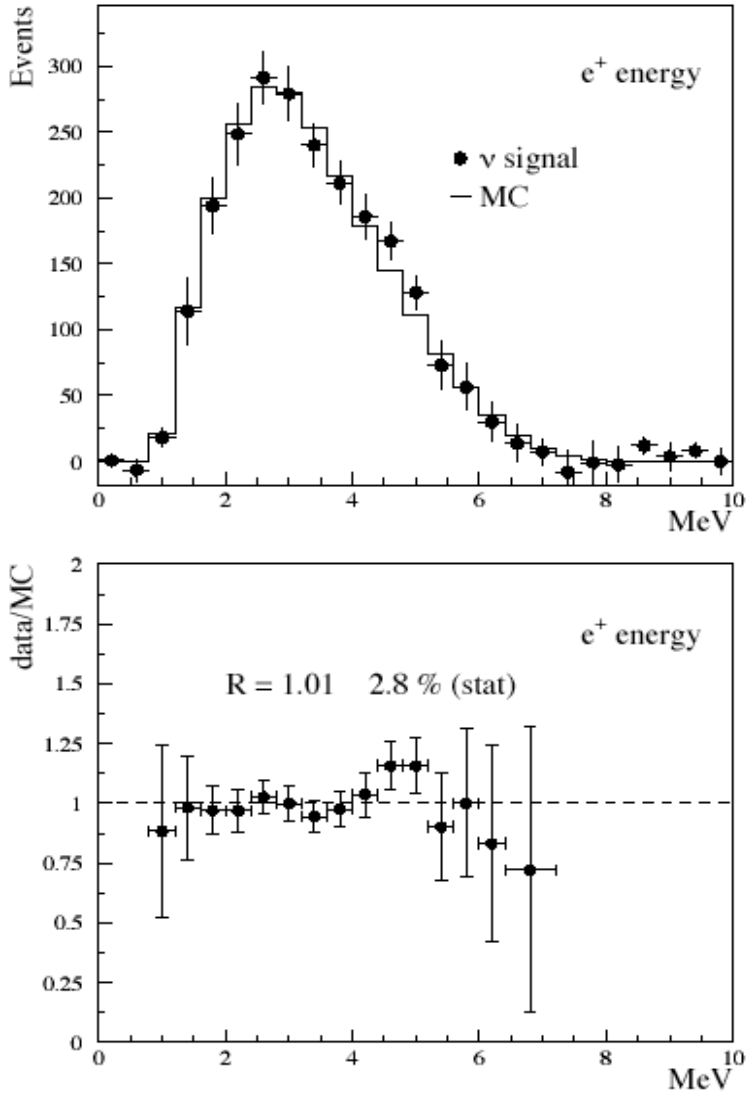
Calculated reactor ν_e spectrum

$\nu_e + p \rightarrow n + e^+$ cross-section

Neutrinos with E<1.8 MeV are not detected.

Best Reactor θ_{13} Limit: CHOOZ Experiment

The current best limit for $\sin^2 2\theta_{13}$ is from the CHOOZ experiment: was built to find out if the atmospheric neutrino deficit was due to θ_{12}, and the measurement of theta-13 was an unexpected by-product.



-One detector experiment

→Major systematic was reactor flux

-Large singles rate due to radioactivity of PMTs

→problem was scintillator reaching out to tubes

-Detector stability issues with scintillator

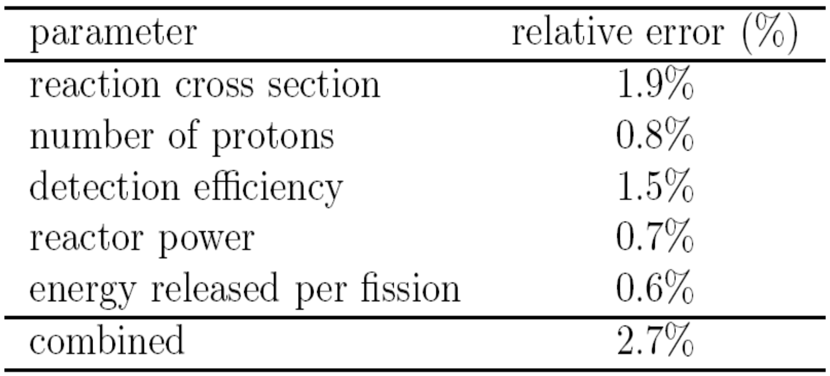
→light output decreasing with τ=720 days

-Small fiducial mass:

→CHOOZ: 5 tons @ 1km, 5.7 GW

~2.2 events/day/ton with 0.2-0.4 bkgd events/day/ton

~3600 ν events total

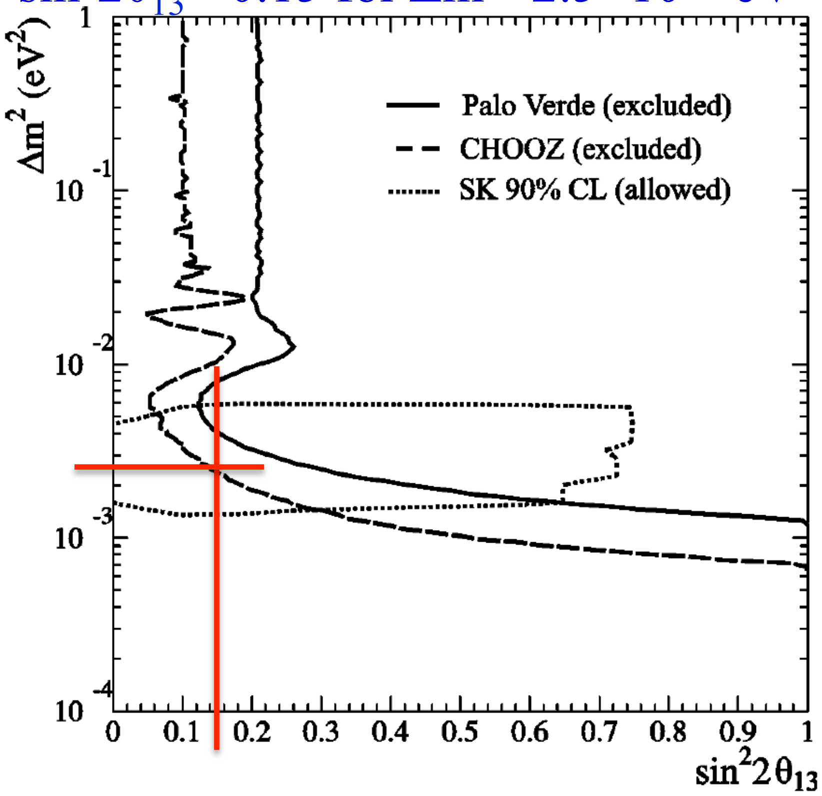


parameter	relative error (%)
reaction cross section	1.9%
number of protons	0.8%
detection efficiency	1.5%
reactor power	0.7%
energy released per fission	0.6%
combined	2.7%

CHOOZ : R_{osc} = 1.01 ± 2.8% (stat) ± 2.7% (syst)

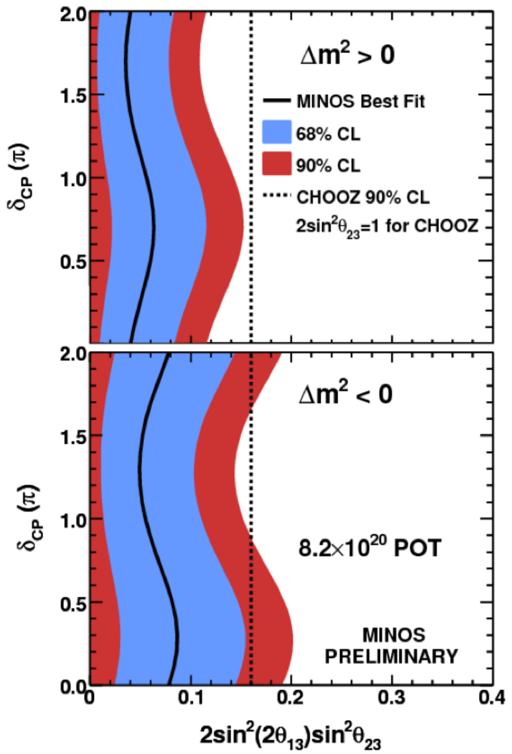
Best Reactor θ_{13} Limit and New Results

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

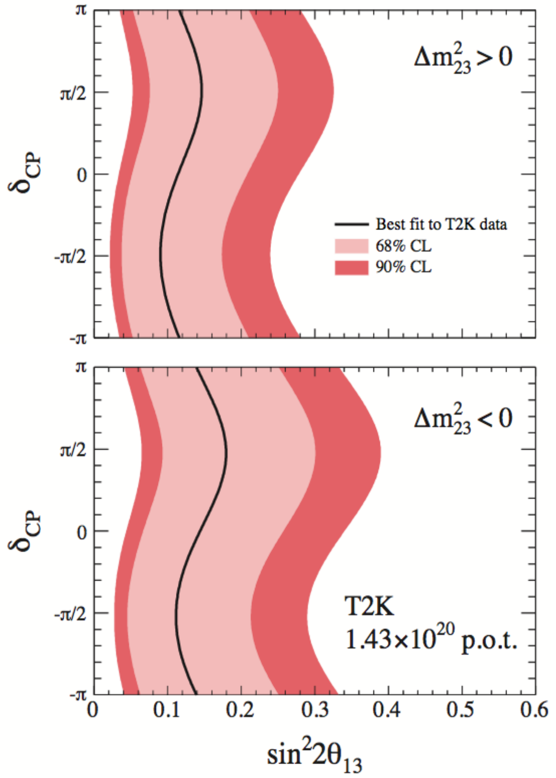


Recent Accelerator Results

MINOS



T2K



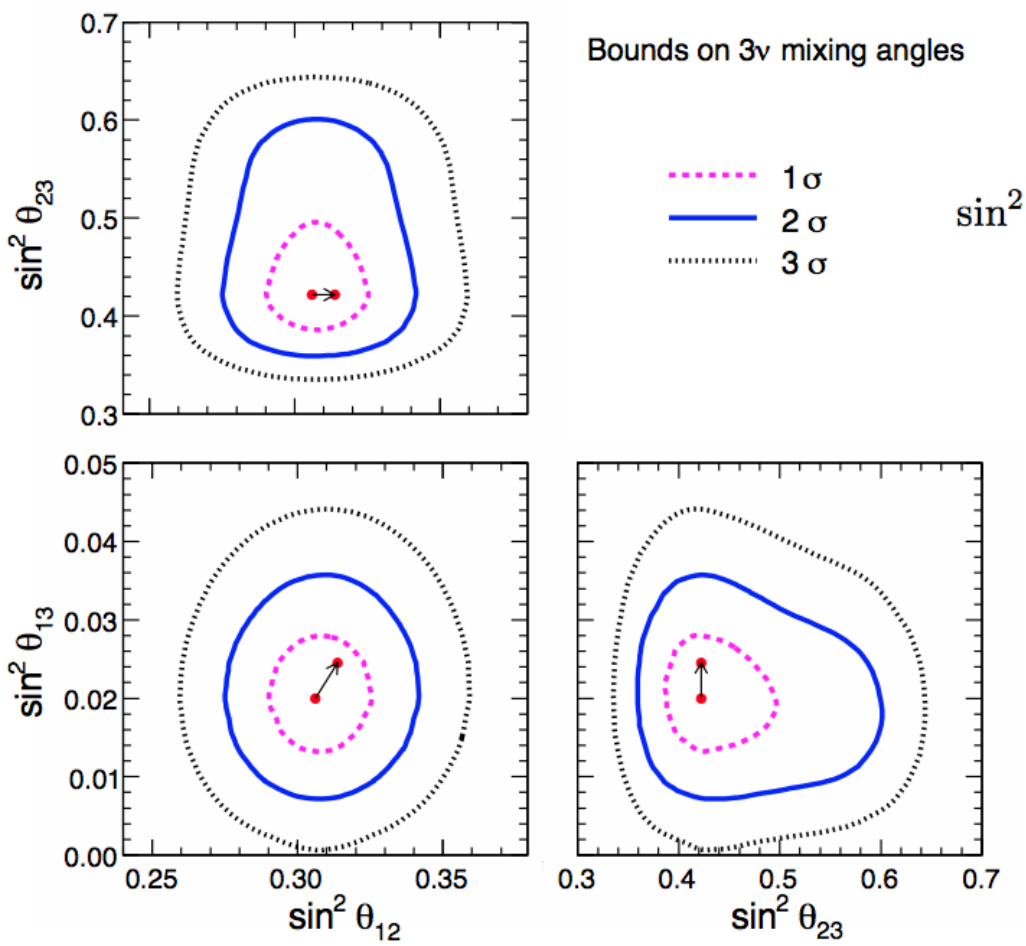
MINOS: For $\delta_{CP} = 0$, the allowed values $2\sin^2(2\theta_{13})\sin^2(\theta_{23})$ at 90%CL:
Normal: 0 to 0.12, central value: 0.04
Inverted: 0 to 0.19, central value: 0.08

T2K: For $\delta_{CP} = 0$, $\Delta m_{23}{}^2 = 2.4\text{x}10^{-3}$eV^2, $\sin^2 2\theta_{23} = 1$, allowed values $\sin^2 2\theta_{13}$ at 90% CL
Normal: 0.03 to 0.28, central value: 0.11
Inverted: 0.04 to 0.34, central value: 0.14

See dedicated talks:
MINOS by J. Nelson
T2K by F. Di Lodovico

Non-zero θ_{13} Evidence

Recent global analysis fit for $\sin^2\theta_{13}$ vs $\sin^2\theta_{12}$: Fogli et al. arXiv: 1106.6028[hep-ph]



$$\sin^2\theta_{13} = \begin{cases} 0.021 \pm 0.007\,, & \text{old reactor fluxes} \\ 0.025 \pm 0.007\,, & \text{new reactor fluxes} \end{cases} \quad (1\sigma)$$

$$\sin^2 2\theta_{13} = \begin{cases} 0.082 \pm 0.028 \\ 0.098 \pm 0.028 \end{cases}$$

Is θ_{13} non-zero and within a reach?
→Need new sensitive experiments to confirm!

How can one improve on CHOOZ Experiment and possibly measure θ_{13}?

Add an identical near detector →eliminate dependence on reactor flux.

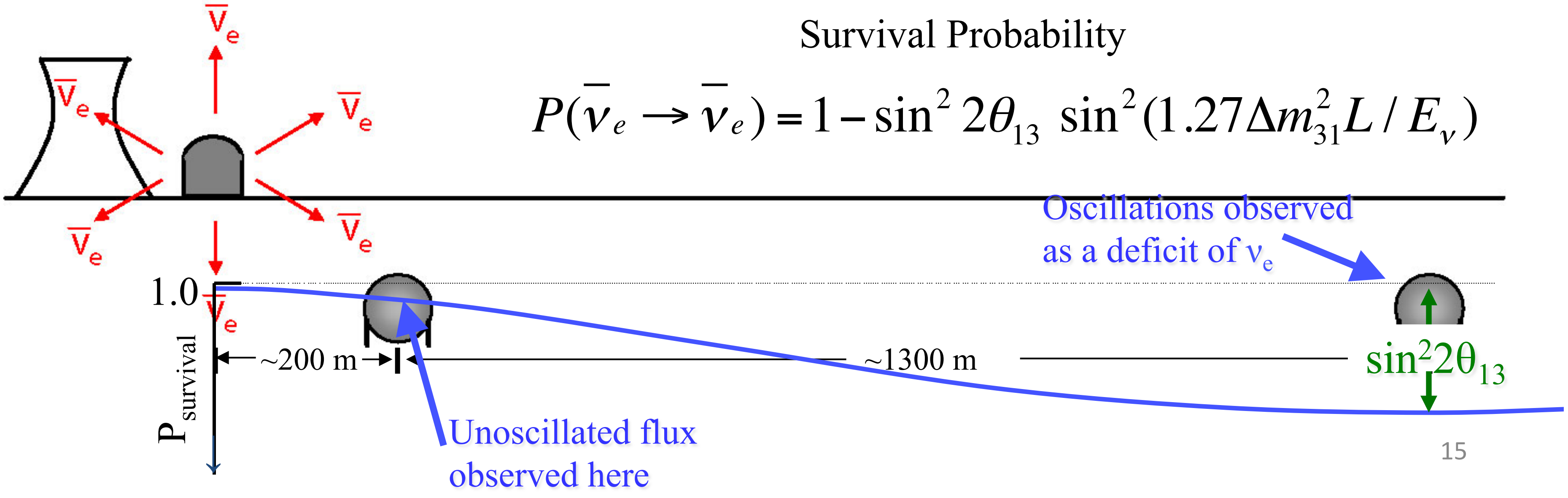
Optimize baseline →near detector close to reactors, far detector at oscillation maximum.

Use larger detectors with reduced systematics uncertainties →improved statistics, minimize systematics.

High power reactor sites →improved statistics.

Reduce backgrounds →go deeper and use active veto systems.

Stable scintillator →eliminate aging effects.



Survival Probability

$$P(\bar{\nu}_e \rightarrow \bar{\nu}_e) = 1 - \sin^2 2\theta_{13}\ \sin^2(1.27\Delta m^2_{31} L / E_\nu)$$

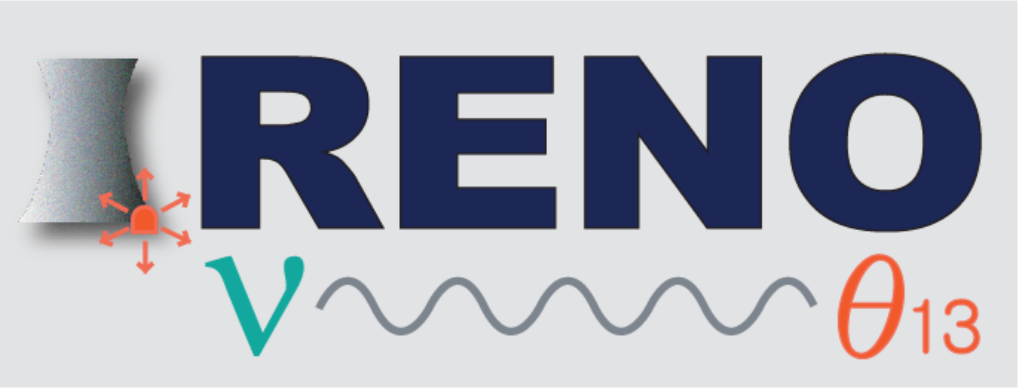
Oscillations observed as a deficit of ν_e

Unoscillated flux observed here

New Multi-detector θ_{13} Reactor Experiments

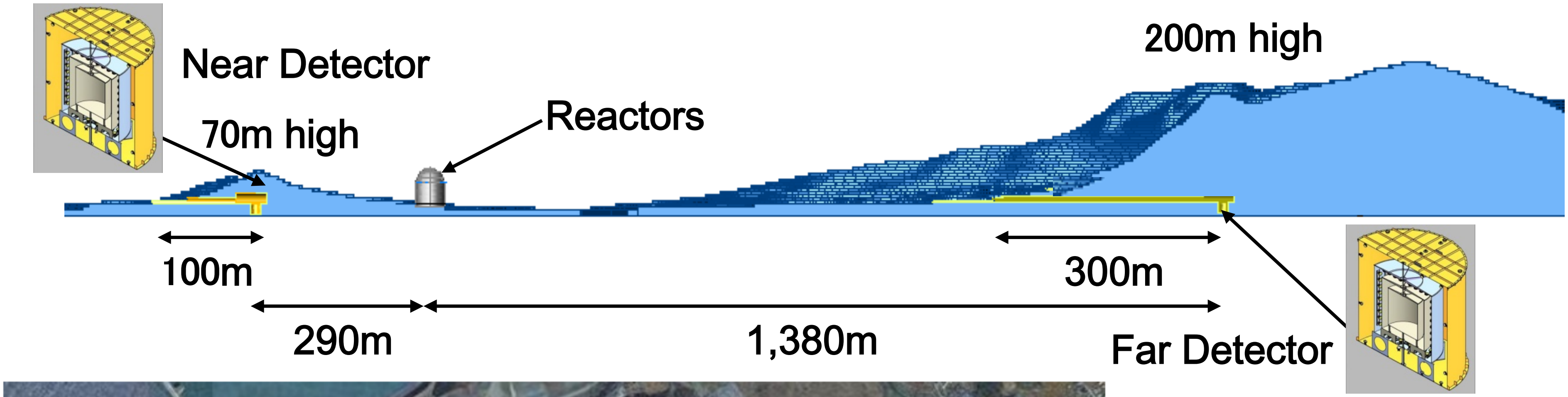
Experiment	GW_{th}	Distance Near/Far (m)	Shielding Near/Far (mwe)	Target Mass (tons)	Sensitivity $\sin^2 2\theta_{13}$ (90% c.l.)	Status
Double Chooz (France)	8.4	390/1050	115/300	8/8	0.03	Data taking with far; near in 2012
RENO (Korea)	17.3	290/1380	120/450	16/16	0.02	Start mid-2011
Daya Bay (China)	17.4	360(500)/ 1985(1615)	260/910	2×2×20 (N) 4×20 (F)	0.01	Start mid-2012

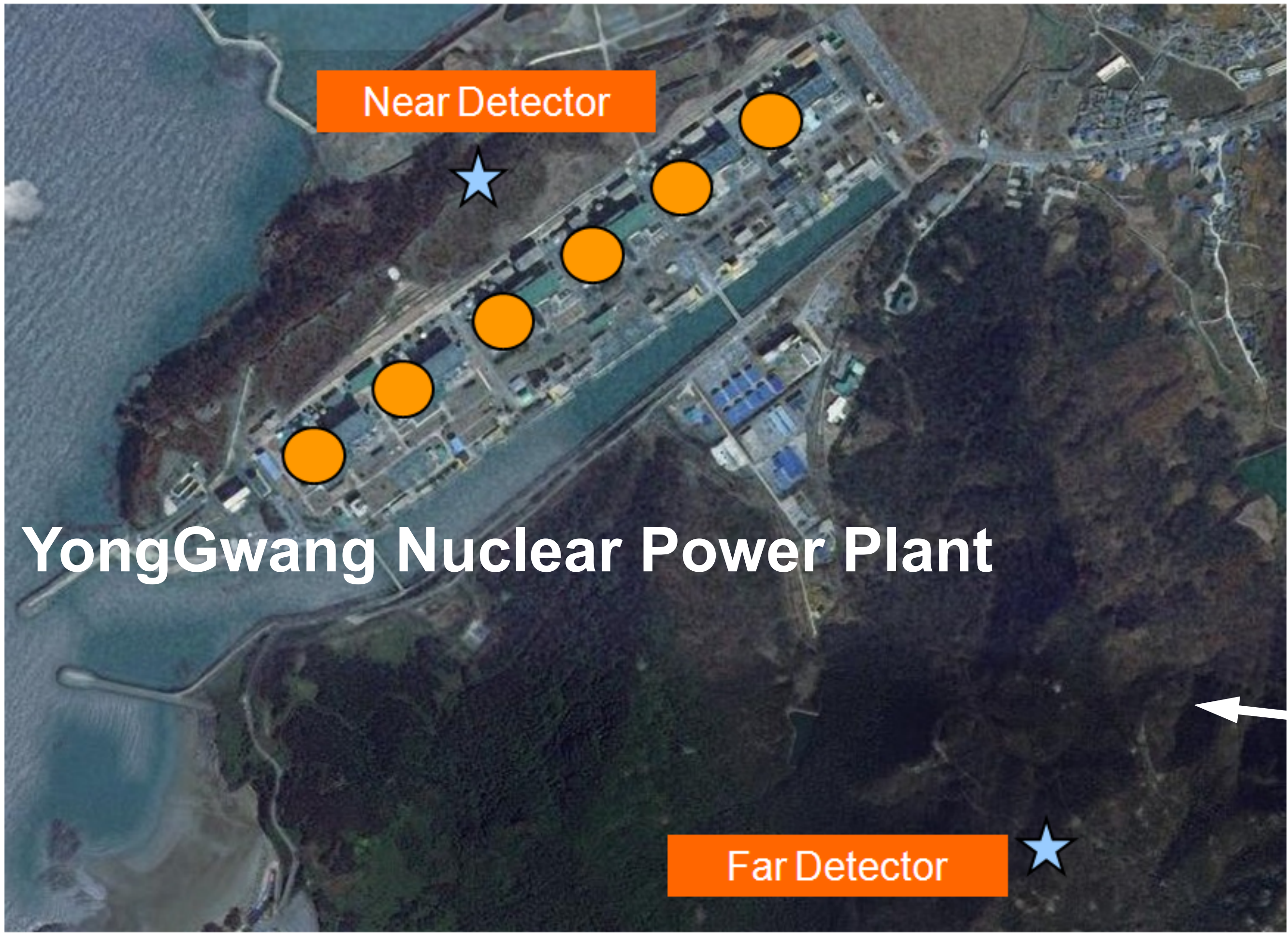
- Many similarities in detector design and analysis strategy
- Differences in sensitivity come mainly from statistics (mass, reactor power), baseline optimization, and multiple detector sites (for Daya Bay)



Reactor Experiment for Neutrino Oscillations at YoungGwang in Korea

Courtesy : S. B. Kim

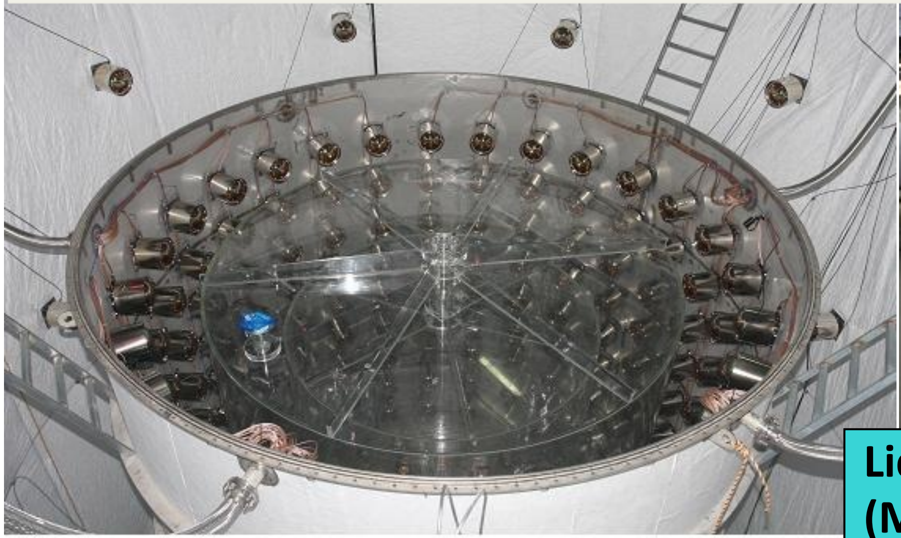




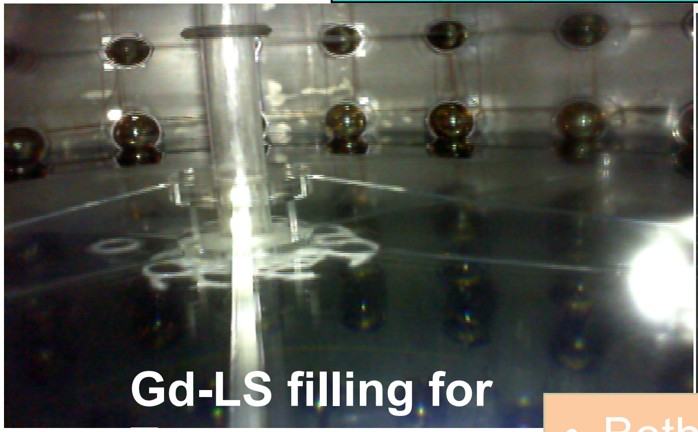
RENO

KNRC
Korea Neutrino Research Center

Completed RENO Detector (Feb. 2011)



Liquid(Gd-LS/LS/MO/Water) Production & Filling (May-July 2011)



- Both near and far detectors are filled with Gd-LS, LS & mineral oil as of July 5, 2011.
- Veto water filling is 90% through, and will be done in the end of July, 2011. Take data August 2011!

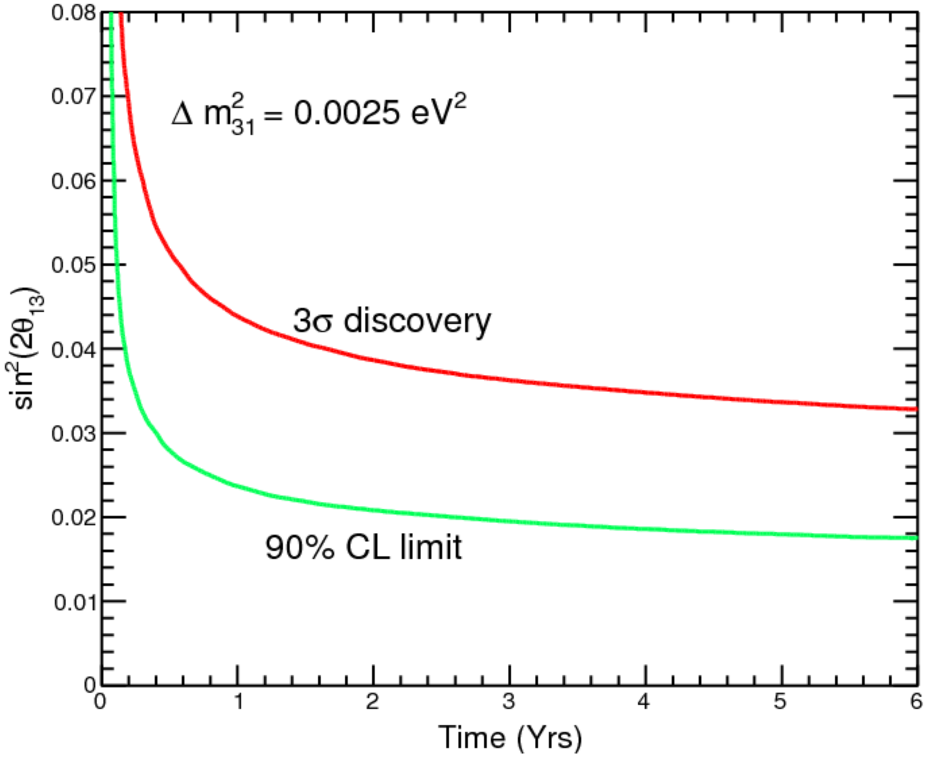
RENO Sensitivity on $\sin^2(2\theta_{13})$

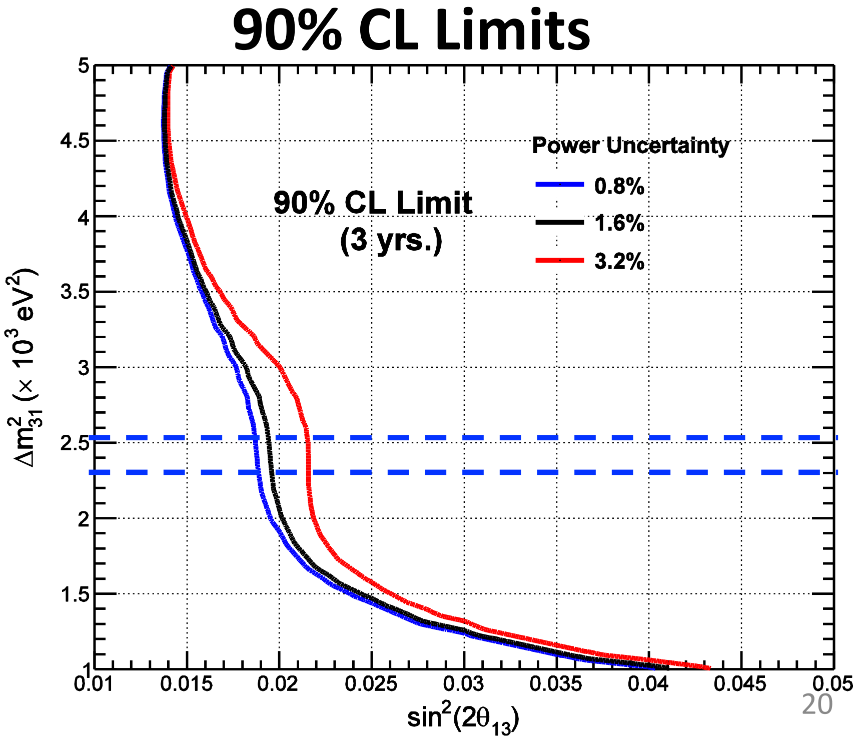
- **Statistical errors (3 years of data taking with 70% efficiency)**

Near : $9.83\times10^5 \approx 10^6$ (0.1% error)
Far : $8.74\times10^4 \approx 10^5$ (0.3% error)

- **Systematic error : <0.5%**

*** Sensitivity : $\sin^2(2\theta_{13}) > 0.02$ at 90% C.L.**

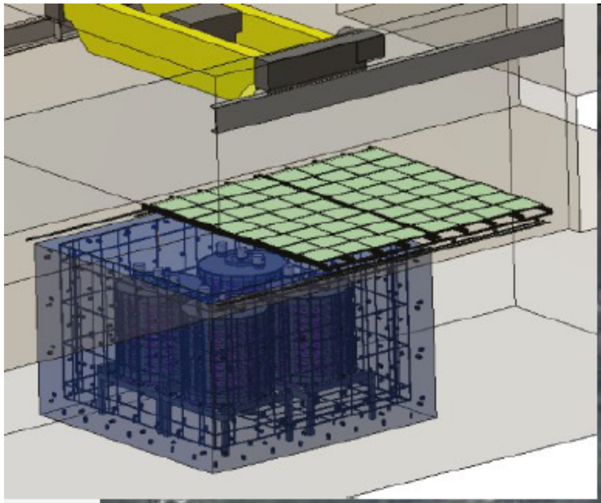


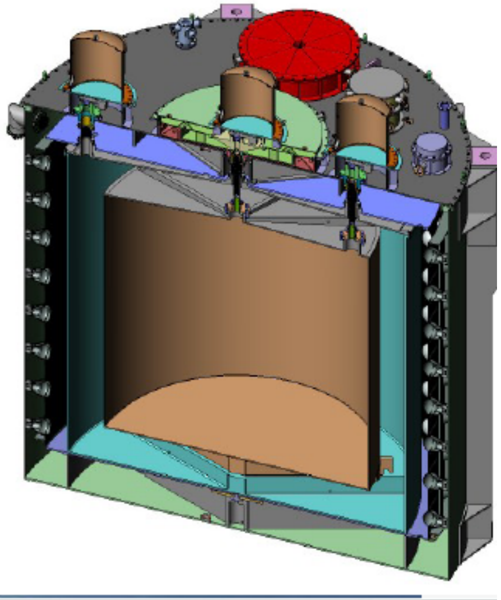


The Daya Bay experiment at the Daya Bay nuclear power complex in Shenzhen, China.

Courtesy : K-B. Luk, Y. Wang
Also see the dedicated talk on “Status of Daya Bay” by Zhimin Wang

Daya Bay Experiment





	DYB Site (m)	LA Site (m)	Far Site (m)
DYB	363	1347	1985
LA	857	481	1618
LA II	1307	526	1613

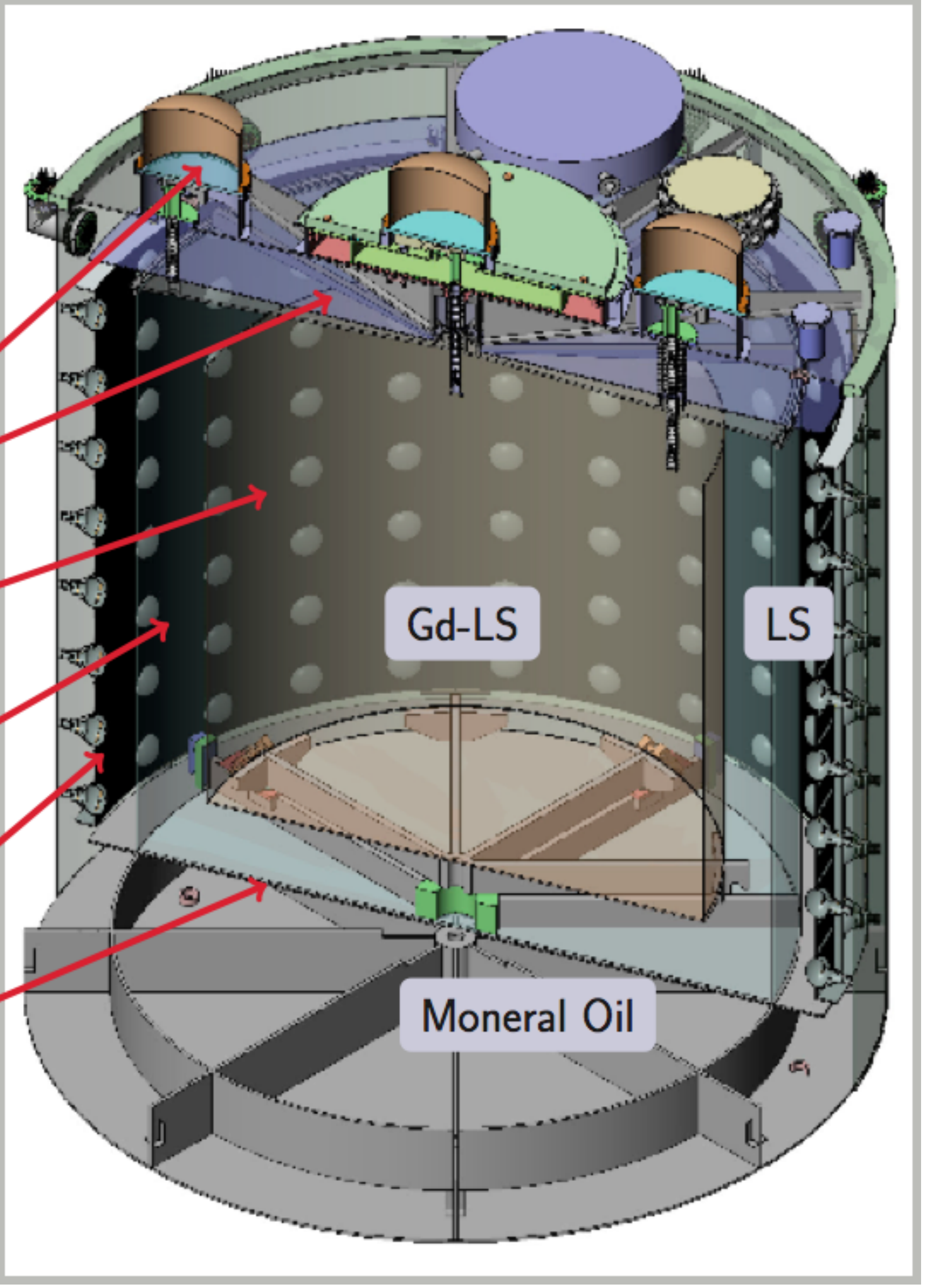
Daya Bay/Ling Ao Power Plant

- 4 cores, 11.6 GW_{th}
- 2011: 6 cores, 17.4 GW_{th}

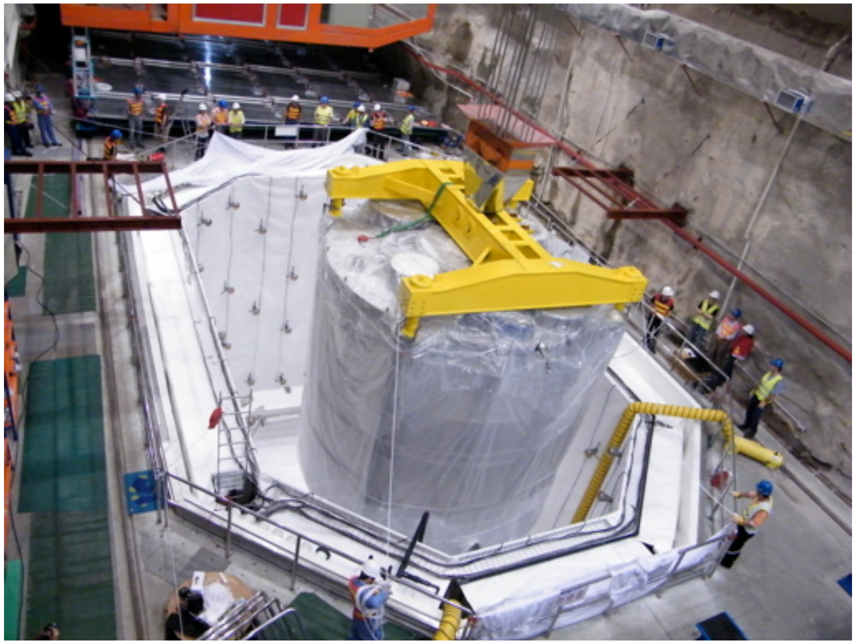
8 identical, 3-zone detectors: 2@Near and 4@Far

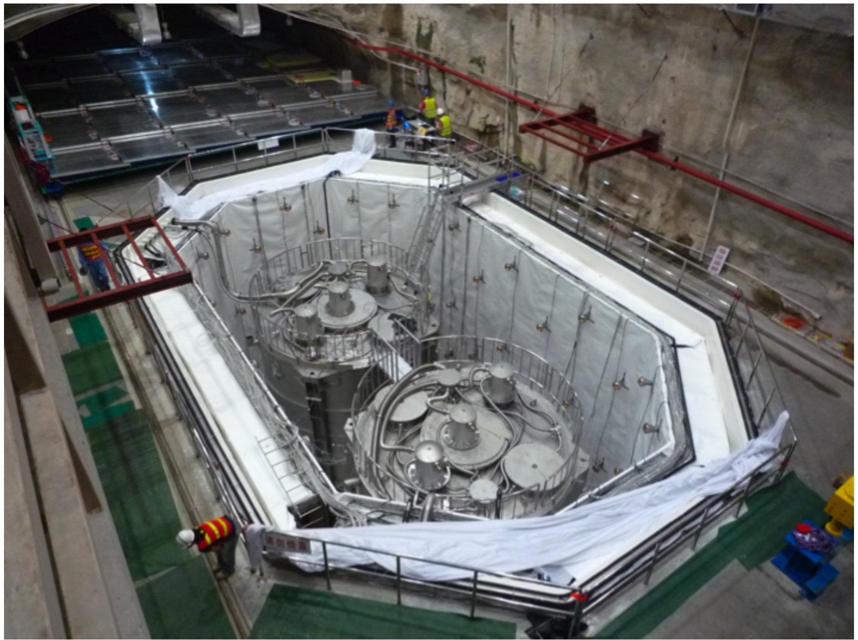
target mass: 20t GdLS
detector mass: ∼ **110**t
photosensors: 192 PMTs

- Calibration system
- Top reflector
- Inner acrylic vessel (3m ØH)
- Outter acrylic vessel (4m ØH)
- Stainless steel vessel (5m ØH)
- Bottom reflector



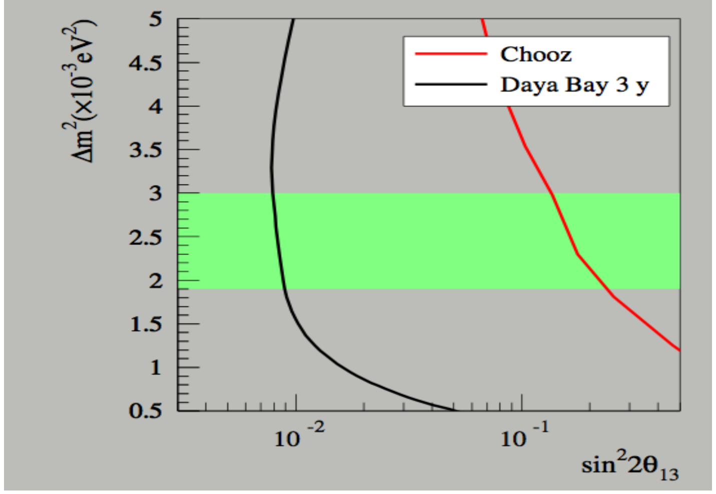
Installation of ADs at Daya Bay Site and Schedule

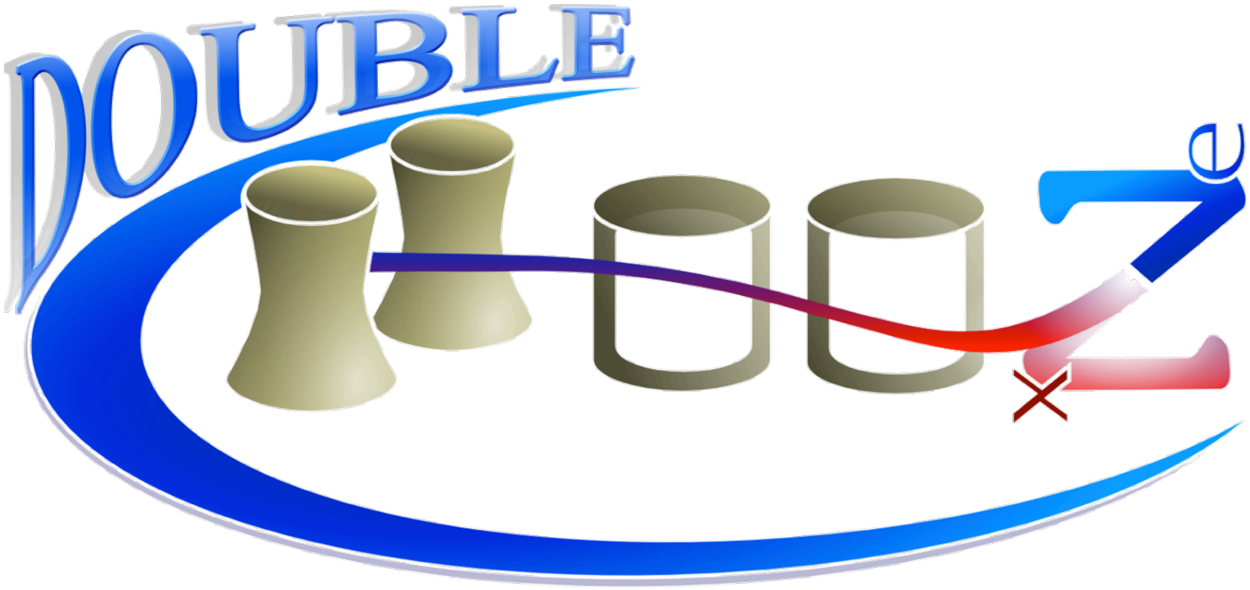




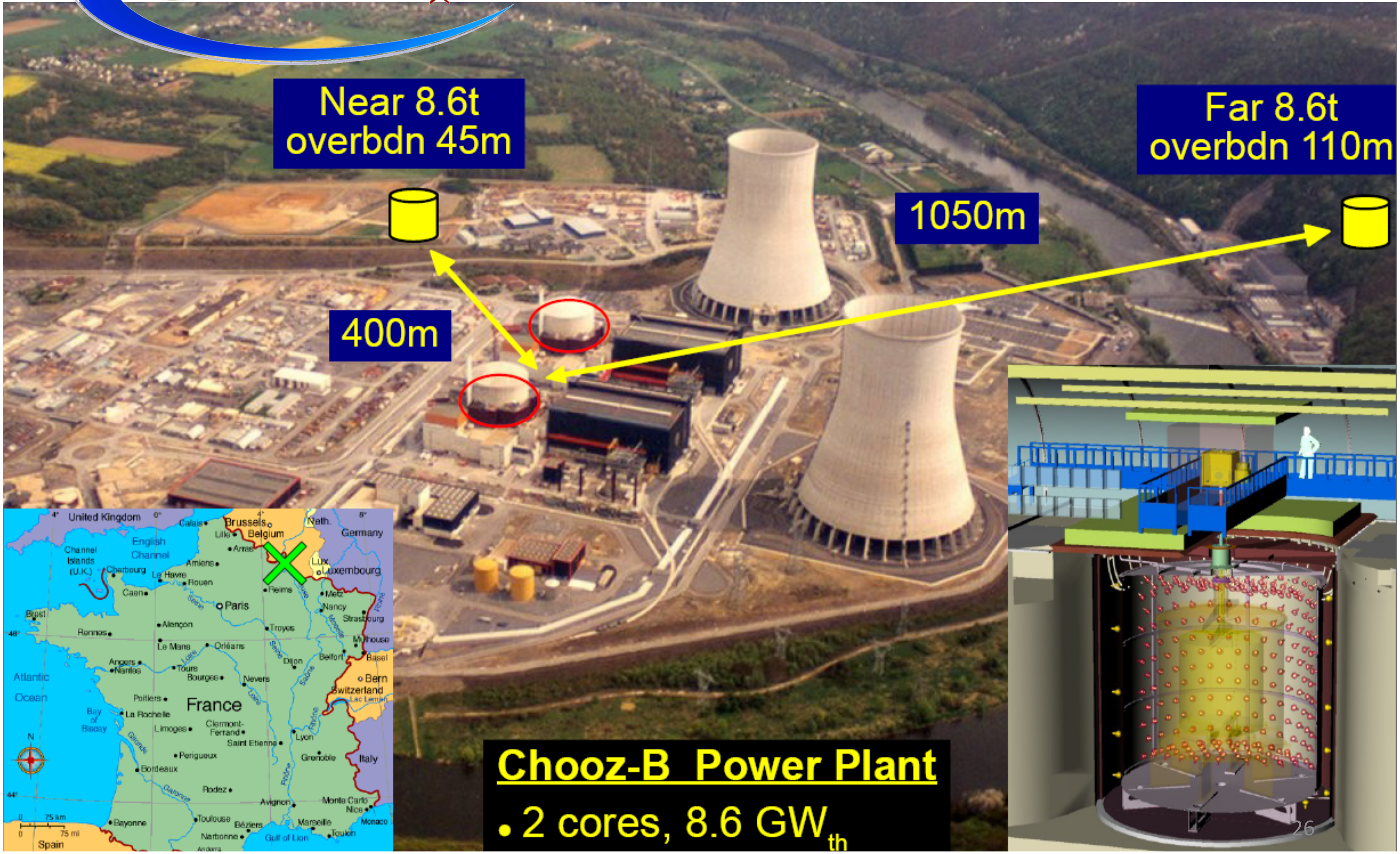
- AD and muon veto systems are installed in Daya Bay Hall, dry run data taken.
- Begin data taking with two ADs in the Daya Bay Hall in the summer of 2011.
- Begin data taking with all eight ADs in three halls in 2012 to reach a design sensitivity of $\sin^2 2\theta_{13}$ of 0.01 or better.

Goal sensitivity:
$\sin^2\theta_{13} < 0.01$ at 90% C.L. in 3 years





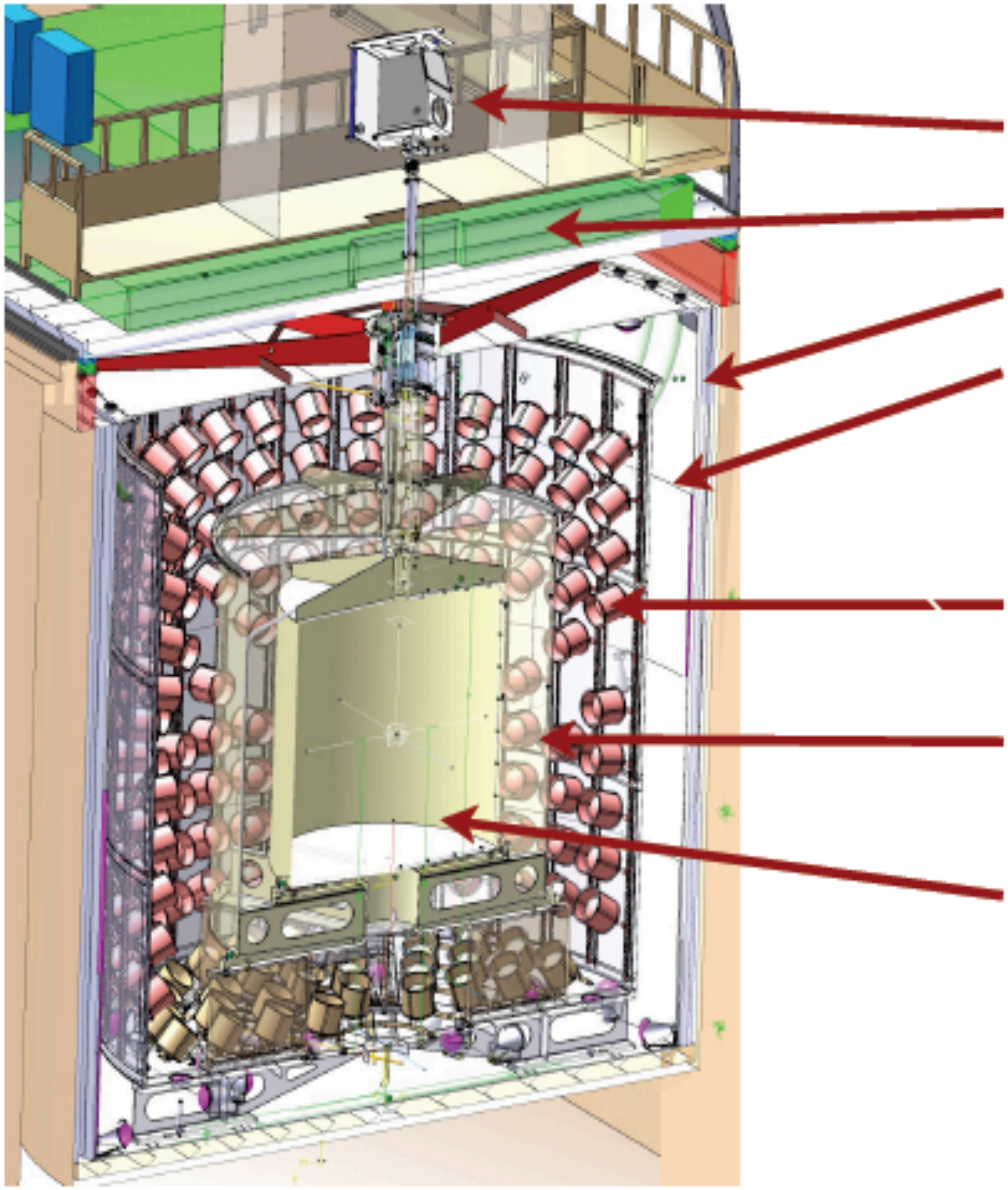
Double Chooz Reactor Experiment in Ardennes, France



Chooz-B Power Plant

- 2 cores, 8.6 GW_{th}

Improved Detector Design



Calibration glove box

Outer Veto: plastic scintillator strips

Shielding: steel 15 cm thick

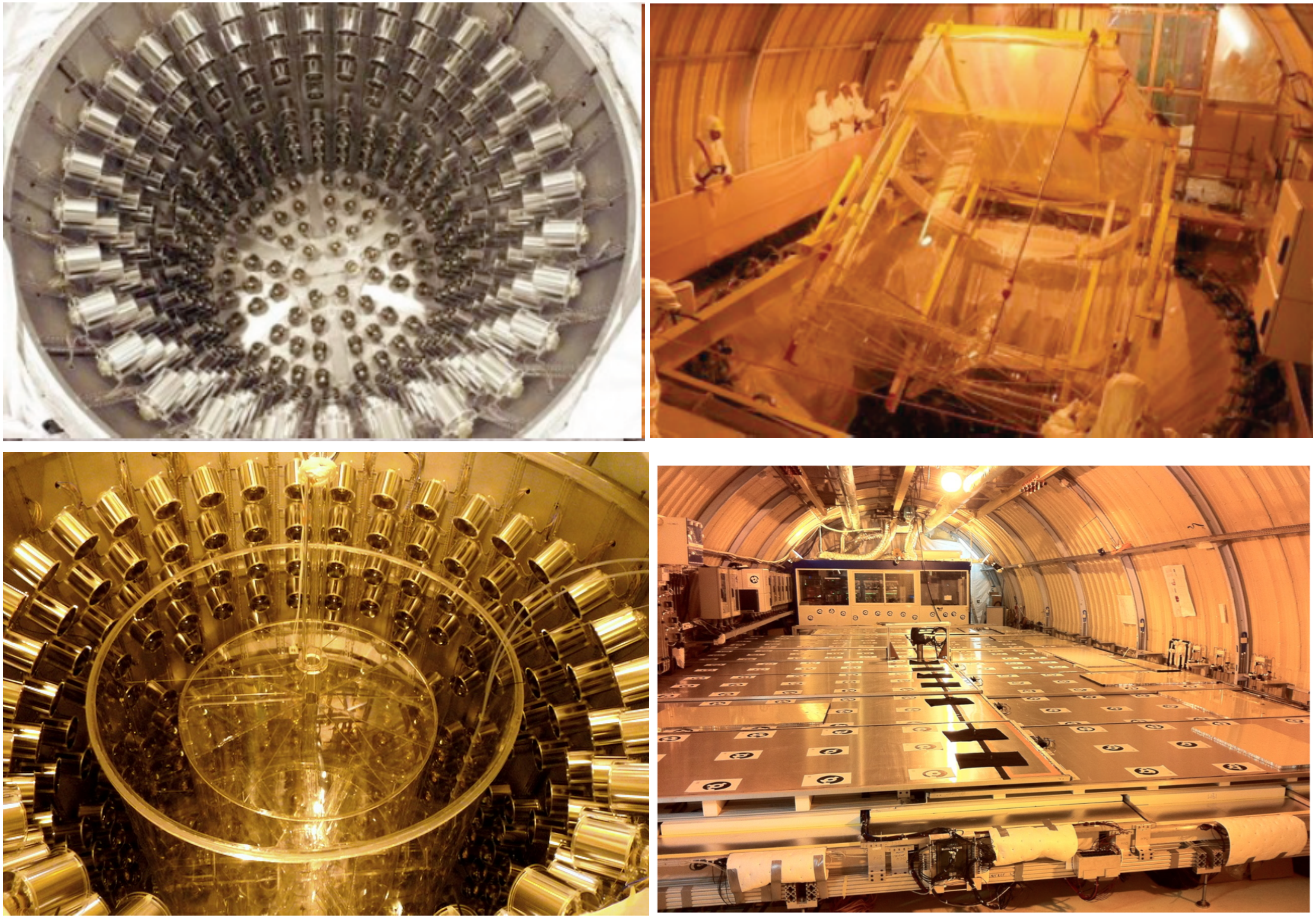
Inner Veto: 90m^3 of liquid scintillator
78 8" PMTs

Buffer: 110m^3 of non-scintillating
mineral oil
390 10" PMTs

Gamma-Catcher: 22.3m^3 of liquid
scintillator

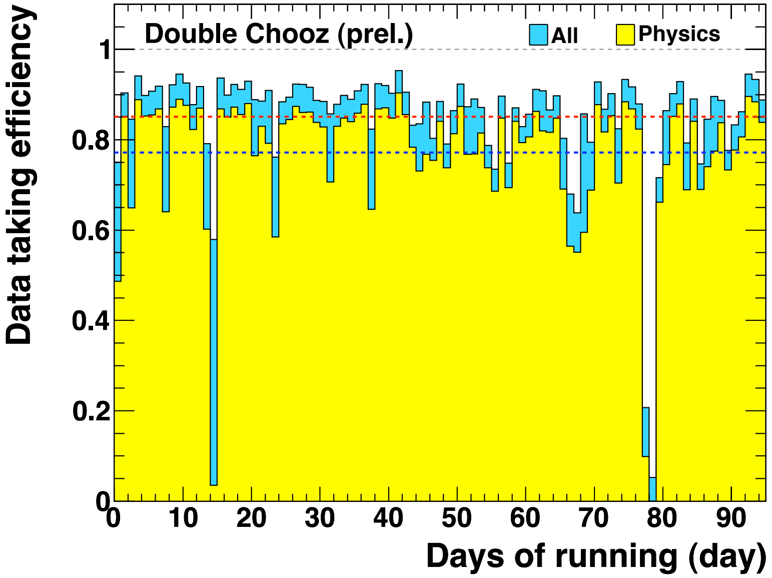
Target: 10.3m3 of liquid scintillator
doped with 1g/L of Gd

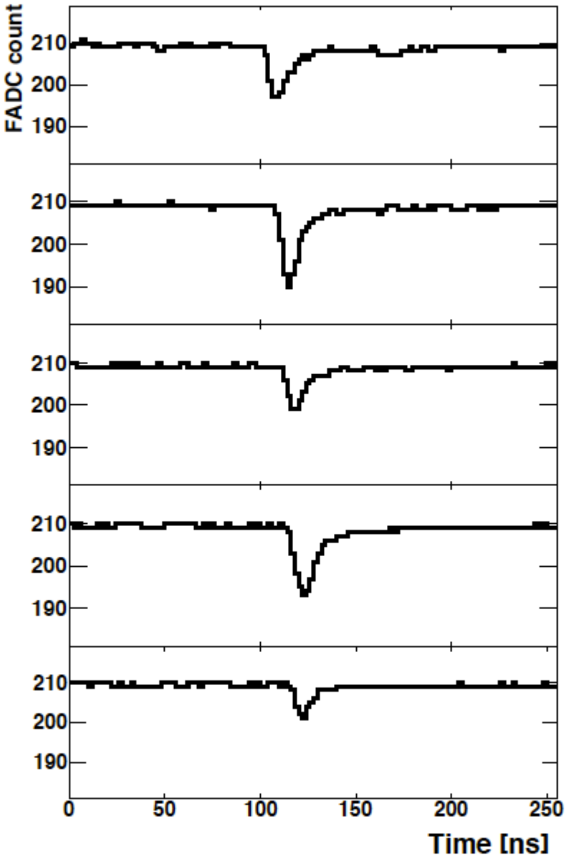
Far Detector Installation

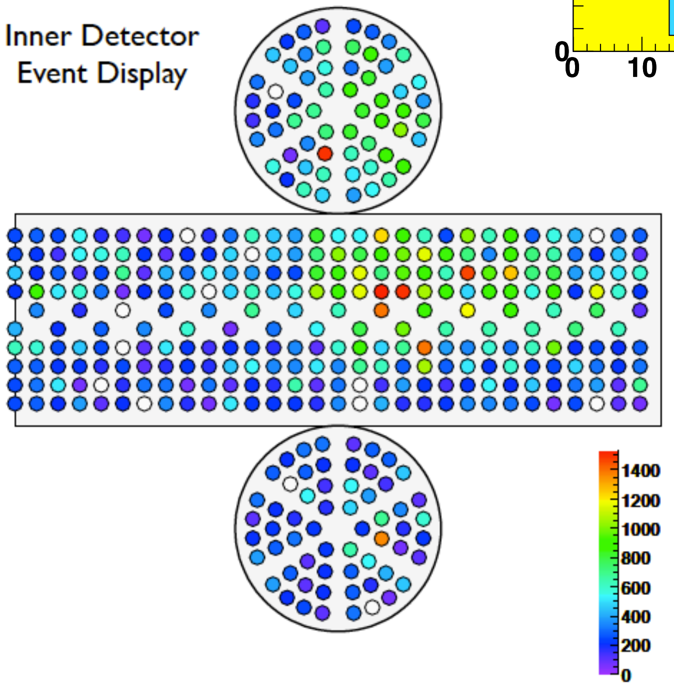


Stable Data Taking since April 13th 2011

- >70 full days of physics (Physics Run Eff. 75%)
- Trigger rate 120 Hz - Trigger threshold < 0.6 MeV
- Calibration runs 10% of the time (light injection through embedded fiber)
- Outer Muon Veto & Source Calibration systems being commissioned

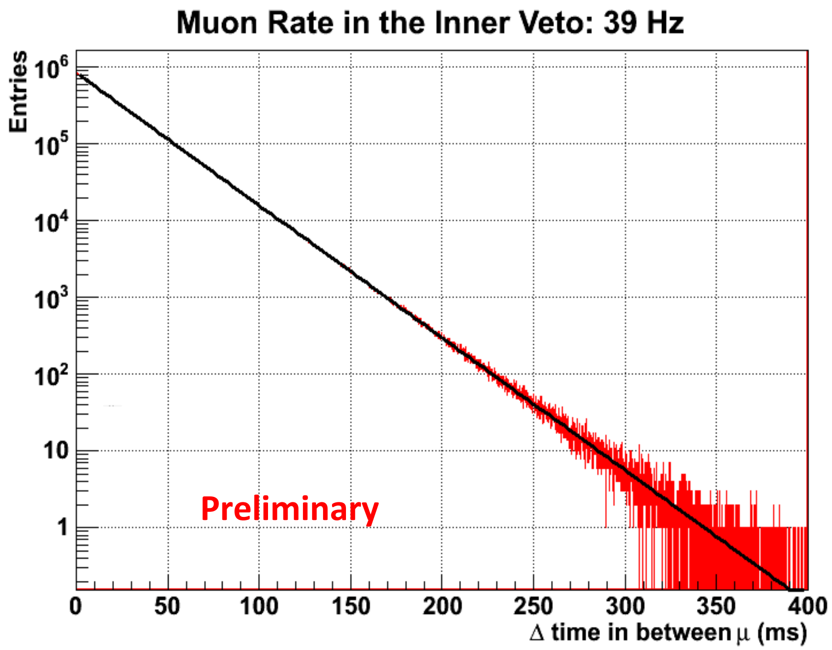


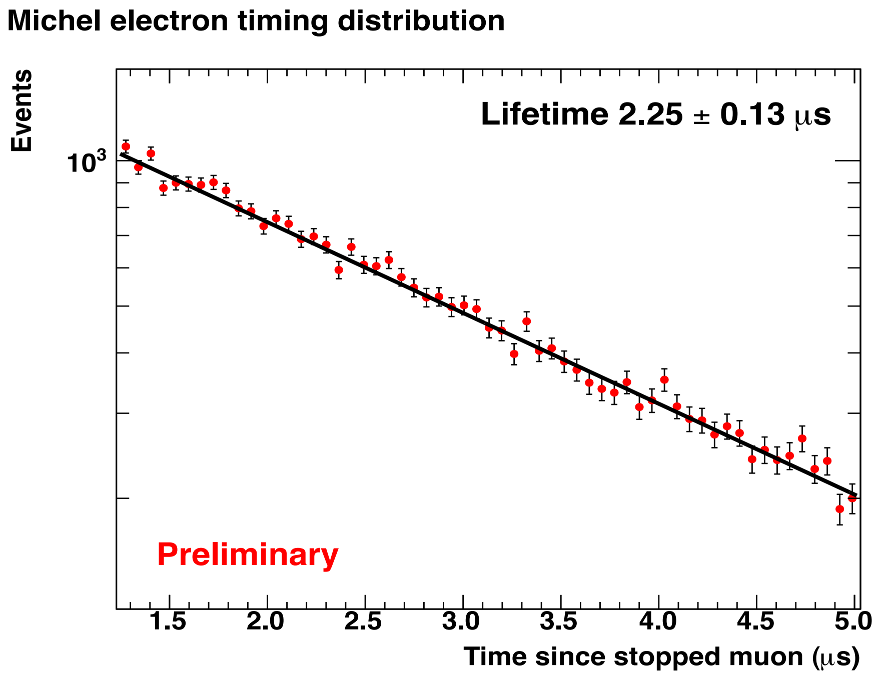




Physics Data: Muons and Michel Electrons

- ~40Hz of muons tagged by Inner Veto.
- ~10Hz of muons tagged by Inner Detector.
- Delayed coincidence method works well and tags Michel electrons: selection Criteria based on time since stopped muon (μs) and energy requirements.
- Only Statistical errors shown here.





Physics Data: Neutrons and Accidental Background Events

-Muon-correlated events in Gd-capture time window (left plot).

-Mostly spallation neutrons: Peaks of neutron capture on:

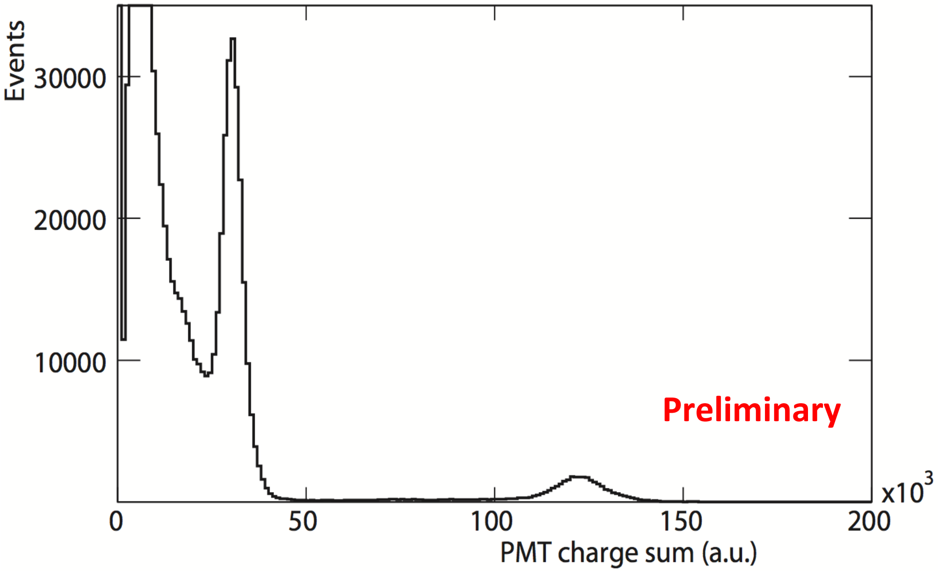
Hydrogen (2.2MeV)

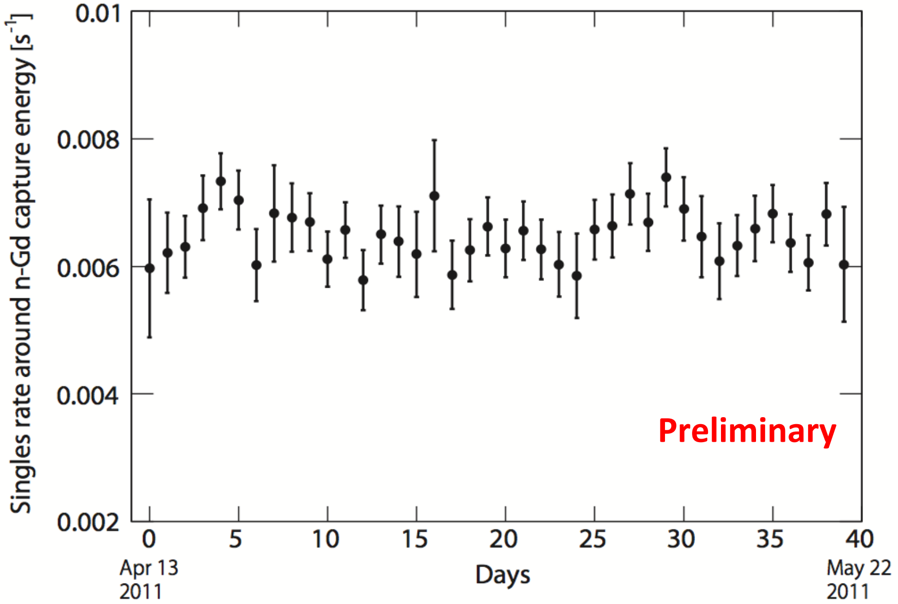
Gadolinium (~8MeV).

-Caveat: un-calibrated data shown.

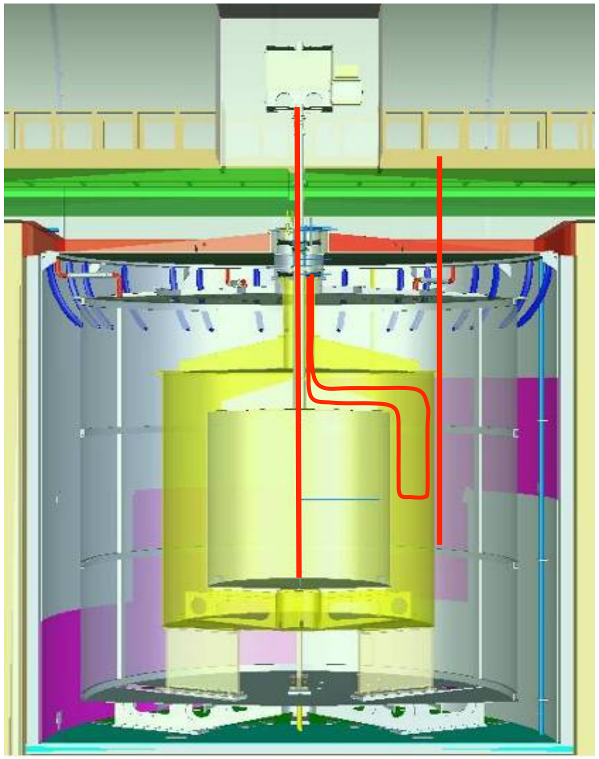
-Stability of the radioactivity background singles rate in the delayed energy window, i.e. under gadolinium peak (right plot):

muon-correlated events vetoed.





Calibration Systems



- Embedded LEDs inside inner detector and inner veto
  → routinely used to monitor detector stability and PMT gains.
- Calibration source (γ, n, β) deployment devices:
  - -Z-axis system,
  - -Guide tubes,
  - -Articulated Arm.

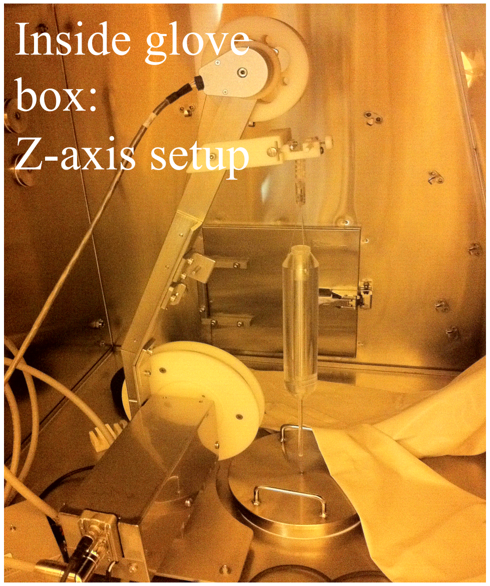
  -Z-axis system and -Guide tubes → being commissioned
- Radioactive sources ready for deployment (Cs-137, Co,-60 Ge-68, Cf-252).

Inside clean tent:
guide tube setup

2011/07/28 04 : 44

Inside clean tent:
glove box setup

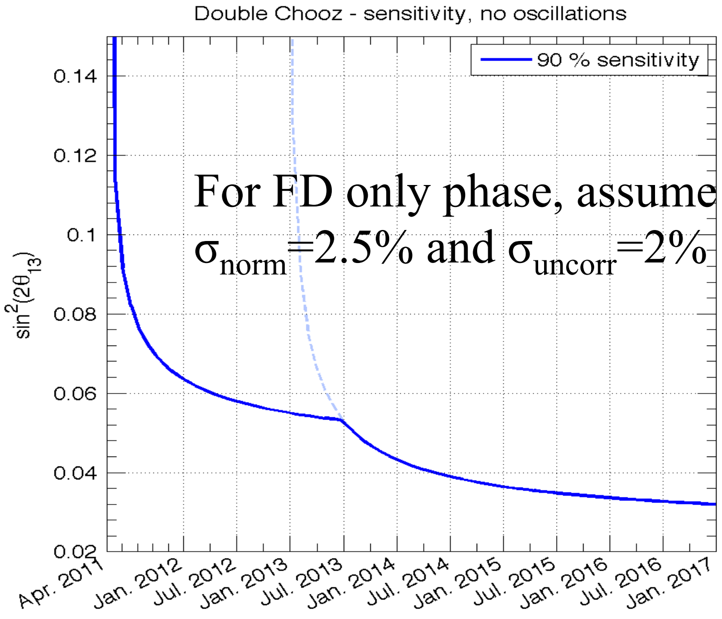
2011/07/28 07 : 49



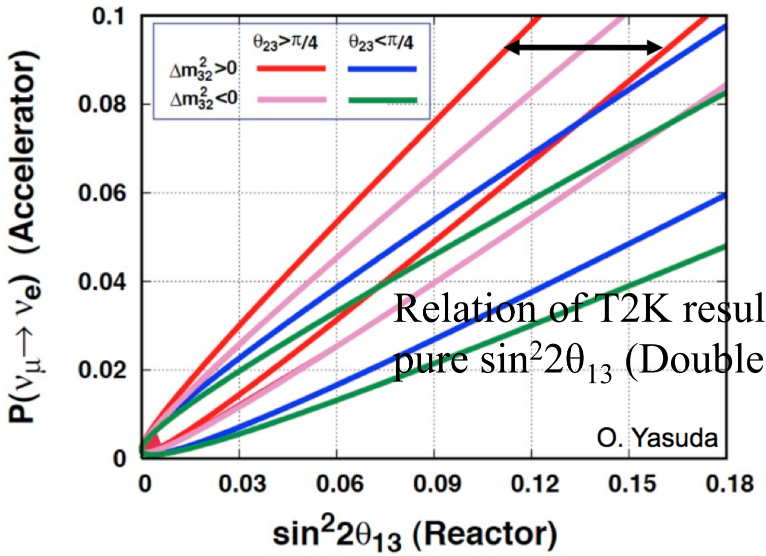
Inside glove box:
Z-axis setup

Current Status and Expected Sensitivity

- More than 70 full days of physics collected.
- Detector stable: singles rates, muon-rates, and neutron-capture rates are as expected.
- Correlated backgrounds being studied.
- Oscillation analysis under way.
- ”Reactor Anomaly” and DC analysis with the far Detector only strategy: use the experimental cross section per fission of Bugey-4 (apply burn-up correction).
- T2K’s central values to be addressed at 99% CL with 2011 data.

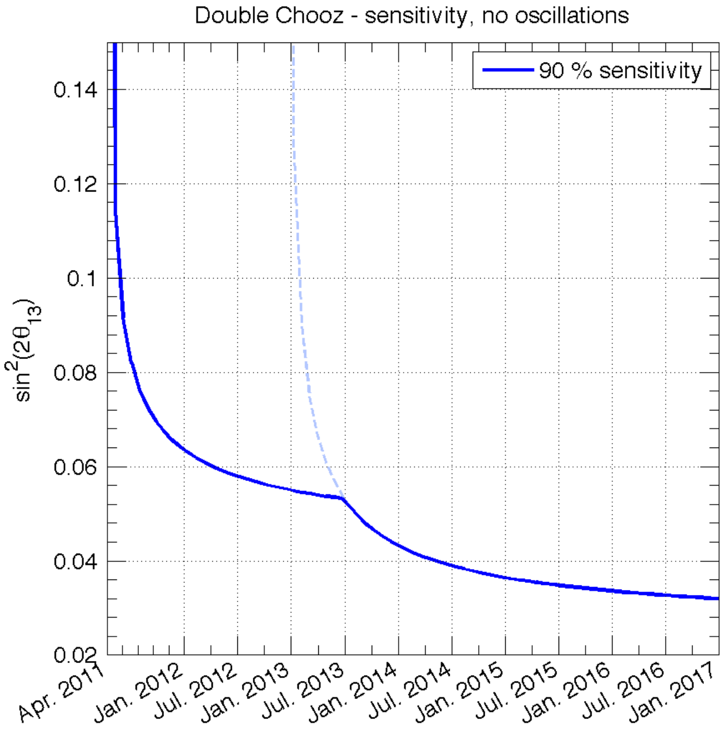


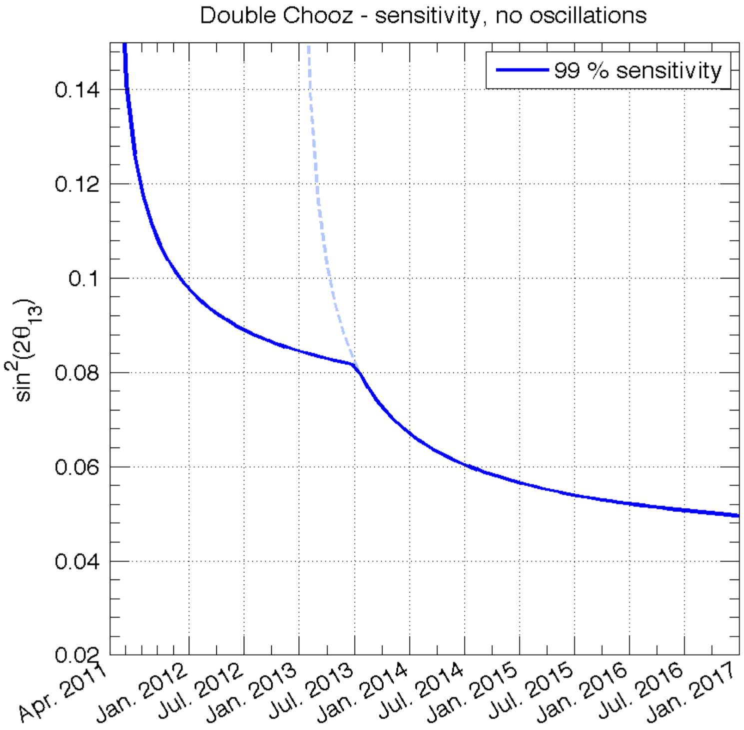
For FD only phase, assume σ_{norm}=2.5% and σ_{uncorr}=2%



Relation of T2K result and pure $\sin^2 2\theta_{13}$ (Double Chooz)

Double Chooz 90 and 99%CL Sensitivity


Double Chooz - sensitivity, no oscillations


Double Chooz - sensitivity, no oscillations

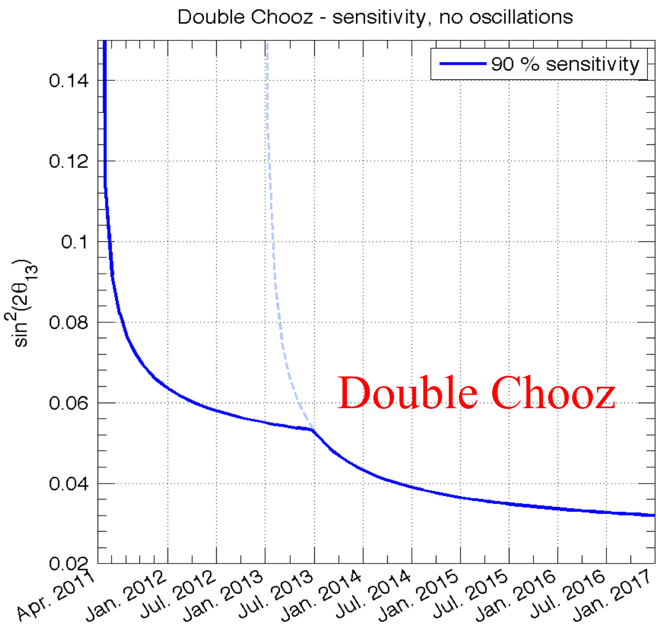
Double Chooz Near Detector Status

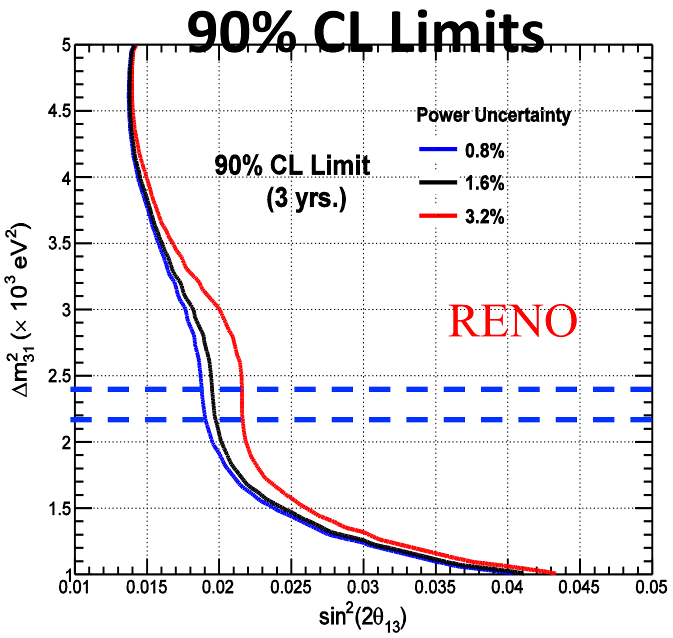
-Near Site/Lab Construction started 29th April 2011.

-Lab expected to be ready for physics April 2012.

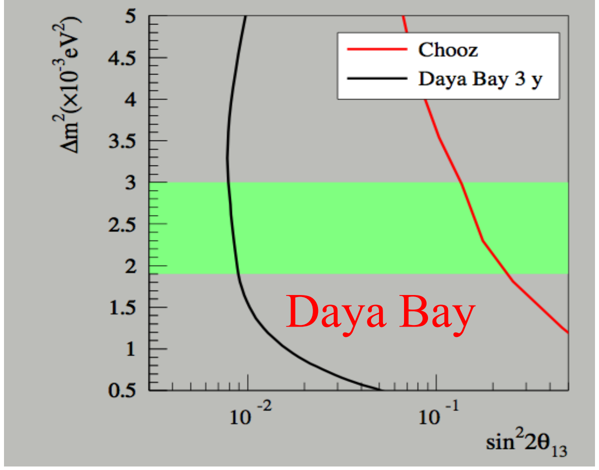
-Near Detector ready at the end of 2012.

Expected Sensitivities of Current Short-baseline Experiments





Goal sensitivity:
$\mathbf{\sin^2\theta_{13} < 0.01}$ at 90%
C.L. in 3 years

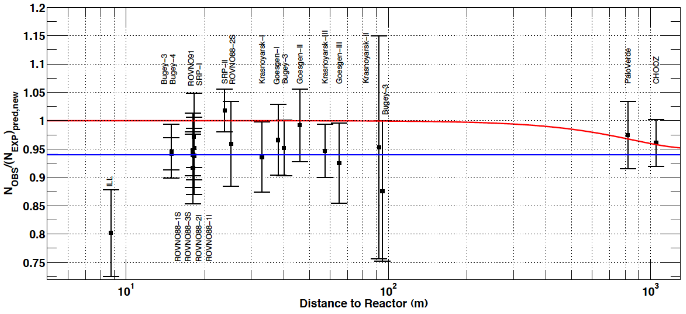


Experiment	σ_{stat}[%]	σ_{syst}(rel.)[%]	$\sin^2 2\theta_{13}$> (90%CL)
Double Chooz	0.5	0.6	~0.03
RENO	0.3	0.5	~0.02
Daya Bay	0.2	0.4	~0.01

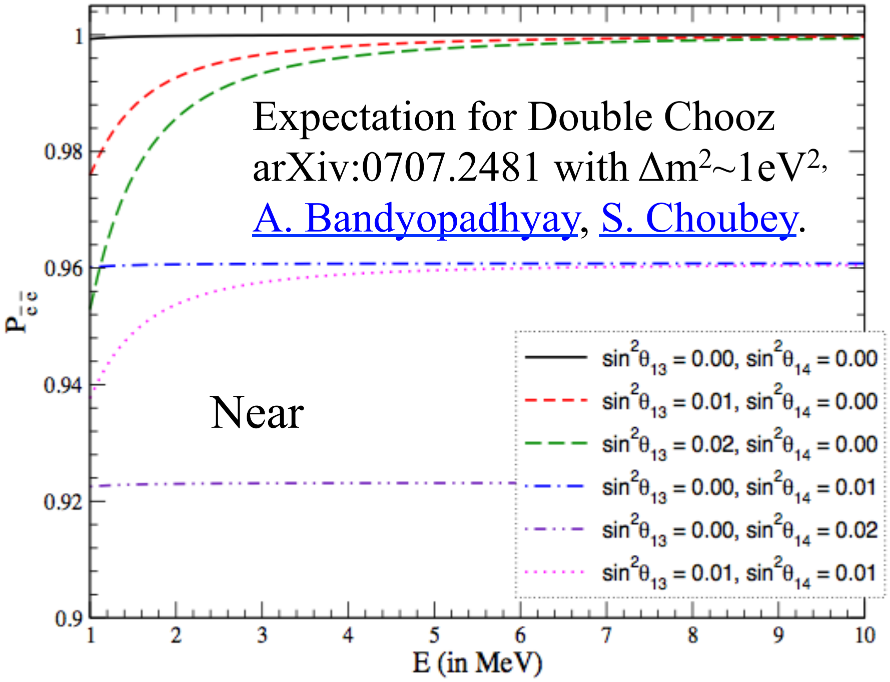
What to do if θ_{13} very small/large? See dedicated talks: S. Garwalla, H. Minakata

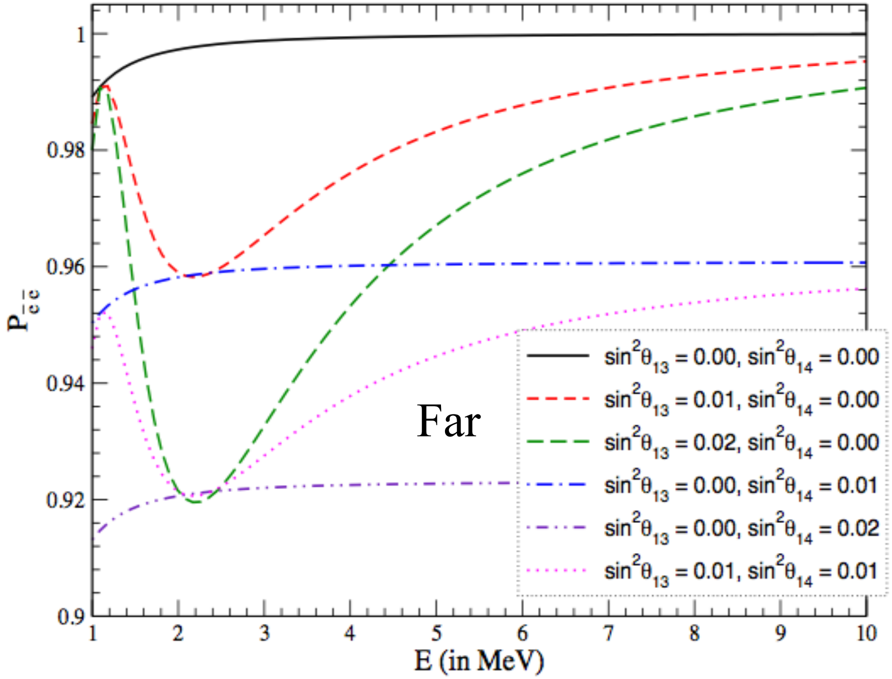
Note on Sterile Neutrinos

- ``The Reactor Antineutrino Anomaly,'' G. Mention et al., Phys. Rev. D83, 073006, 2011: Results are compatible with 4th, sterile neutrino state with $\Delta m^2 >\sim 1$ eV^2 and $\sin^2 2\theta \sim 0.1$.



- Oscillations driven by the extra sterile neutrinos would produce a constant suppression at both near and far detectors (picture complicated if $\Delta m^2 < 1$eV^2).


Expectation for Double Chooz arXiv:0707.2481 with $\Delta m^2 \sim 1$eV^2, A. Bandyopadhyay, S. Choubey.



- Data from near and far detectors can be used to probe θ_{13} and θ_{14}-driven effects.

See Dedicated Talks on Sterile vs: Bill Louis, C. Giunti

New Reactor Neutrino Experiments?

Atmospheric Range: New ideas might develop after current generation of experiments (Double Chooz, Daya Bay, RENO) is completed.
-One of possible follow-up idea is “Triple Chooz” (P. Huber et. Al., arXiv: hep-ph/0601266).

Solar Range: An experiment with very large detector at oscillation maximum from powerful rector complex would provide a very precise measurement of θ_{12} mixing; see for example H. Minakata et. al., Phys.Rev. D71, 013005 (2005).

Sterile Neutrino Range: all current short-baseline experiments essentially sensitive
-Near/far detector data from upcoming experiments should be studied closely.
-A measurement of few MeV neutrinos at very short baseline (~10 m) would be interesting (→ note overlap with testing plutonium diversion at commercial reactor)
SCRAAM: The Southern California Reactor Antineutrino Anomaly Monitor, USA
Nucifer (France)
DANSS (Detector of the Anti-Neutrinos based on the Solid Scintillator, Russia)
…

Summary

- Exciting time for reactor $\bar{\nu}$ experiments: Upcoming experiments will tell us much about θ_{13} (hopefully measure it!).
- Measurement of $\sin^2 2\theta_{13} > 0.01$ is key to planning leptonic CPV searches in long-baseline ν oscillation experiments.
- New reactor flux calculation and "anomaly":
  - 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.
- Future intermediate/long-baseline reactor antineutrino experiments may be used for a precision measurement of θ_{12} (using baseline from $\Delta m^2_{21} = \Delta m^2_{sol}$).

Backups

Double Chooz systematic uncertainties

		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 %	Precise control of detector filling
	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 detectors and monitoring
	Live time	-----	0.25 %	Special electronic systems and monitoring
Analysis	From 7 to 3 cuts	1.5 %	0.2 - 0.3 %	Simplified cuts due to detector design
	Total	2.7 %	< 0.6 %	

From Detection Cross Section to $\overline{\nu}_e$ Energy Spectrum

$$\sigma_{tot}(E_e) \approx \frac{2\pi^2\hbar^3}{m_e^5 c^7 f\tau_n} \cdot p_e \cdot E_e \approx \frac{p_e \cdot E_e}{1\,MeV^2} \cdot 10^{-43}\ cm^2$$

In lowest order, assuming infinitely heavy neutron.

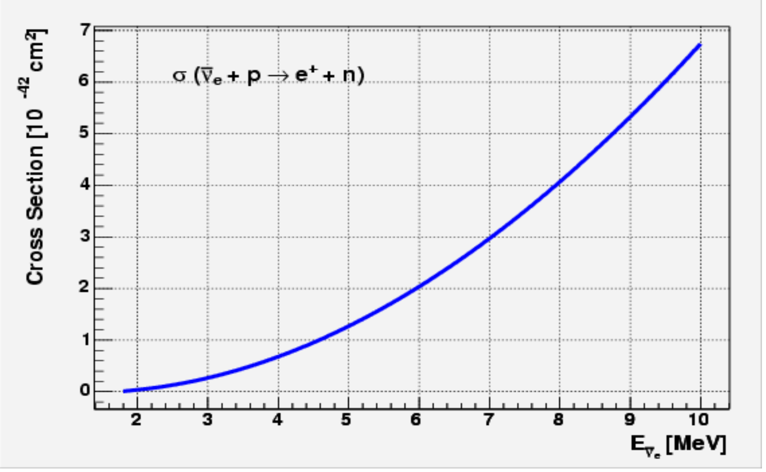
No nuclear matrix element involved.

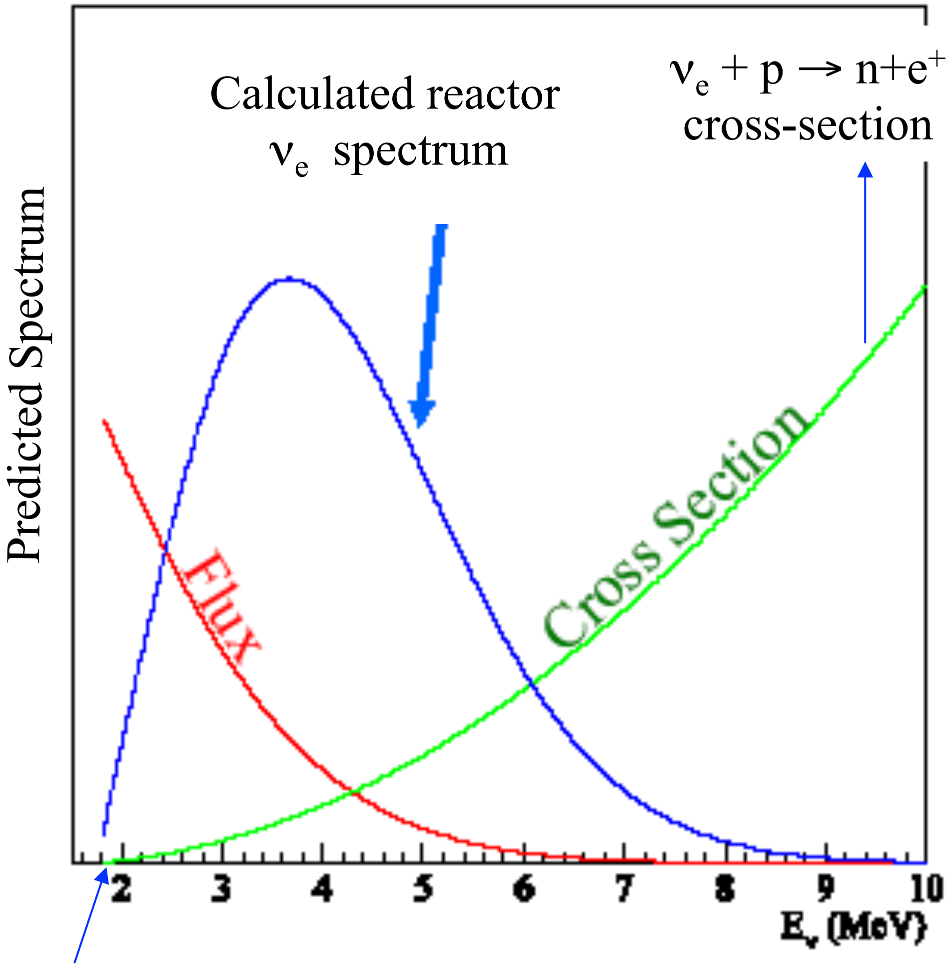
Cross section directly linked to measured neutron life time and phase space.

Use cross section by Vogel & Beacom:

σ to order 1/M, radiative corrections, weak magnetism → few % correction

Cross section accurate to 0.2%





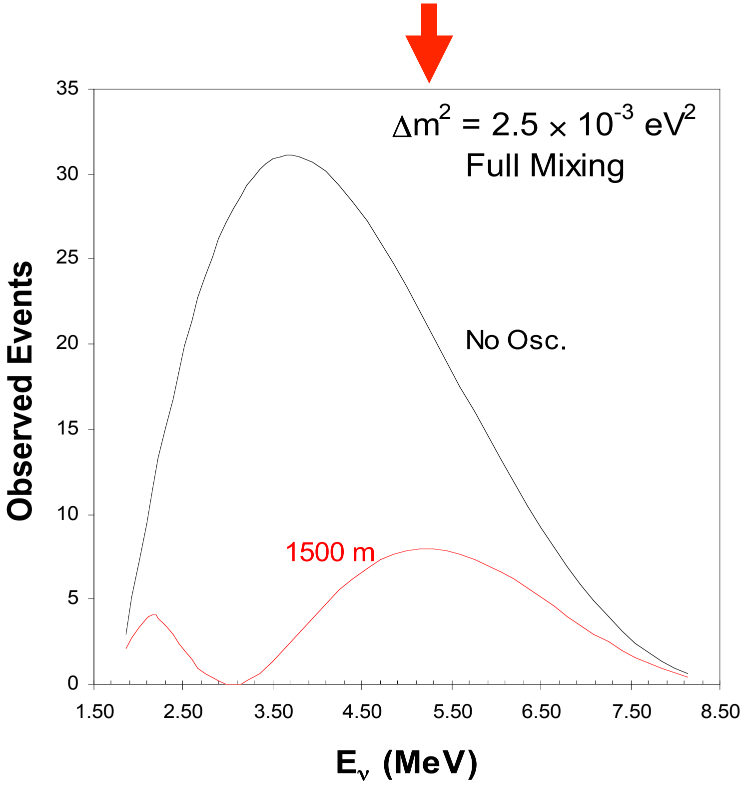
Calculated reactor ν_e spectrum

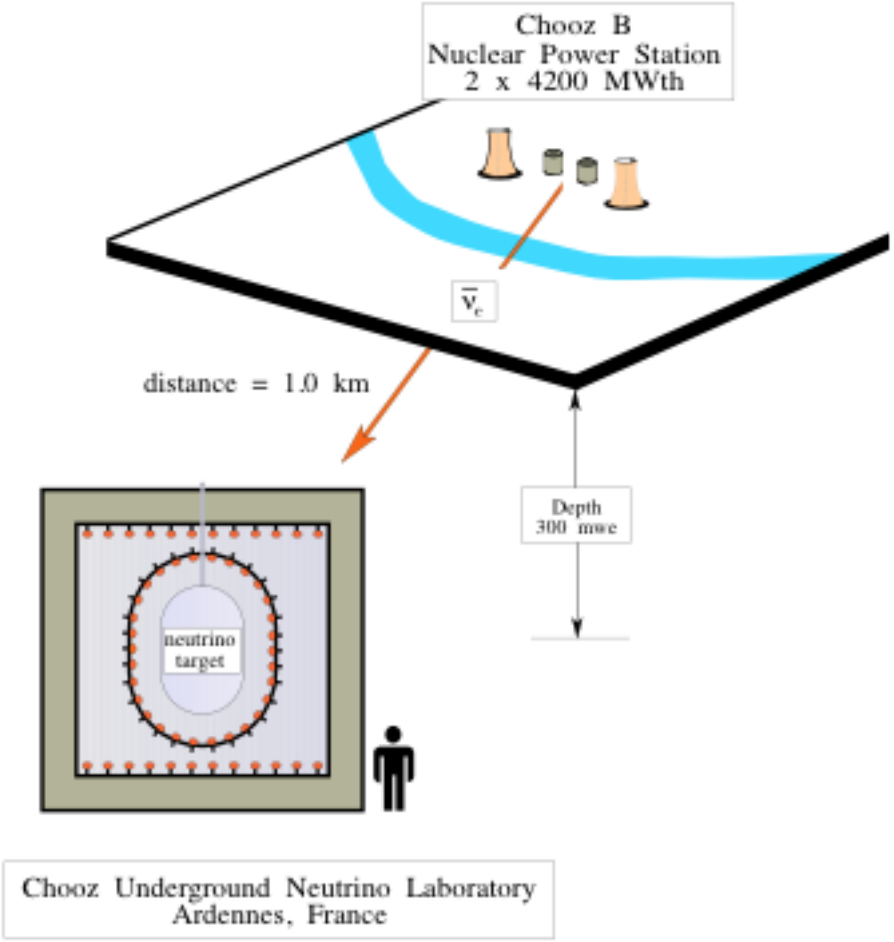
ν_e + p → n+e⁺ cross-section

Neutrinos with E<1.8 MeV are not detected

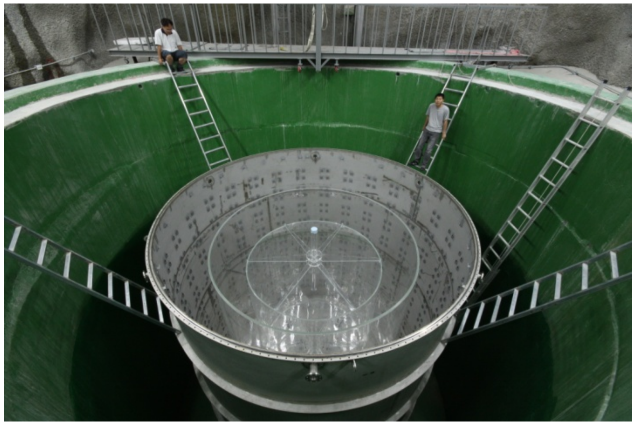
Reactor Measurements of θ_{13}

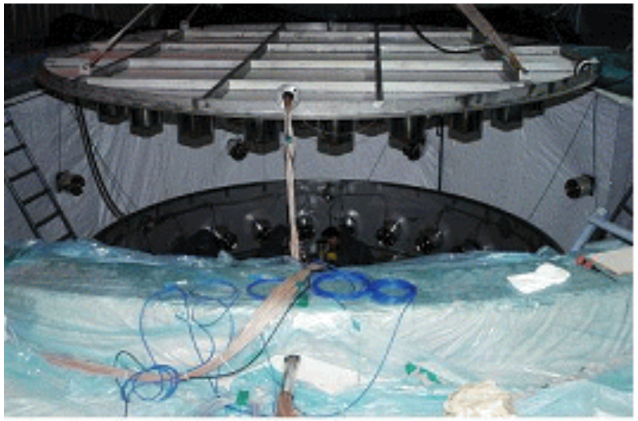
- 3.8 GW → 7×10^{20} ν_e/s
  ~800 events / yr / ton at 1500 m away
- Reactor spectrum peaks at 3 to 4 MeV
- Oscillation Max. for $\Delta m^2=2.5\times10^{-3}$ eV^2
  at L ~ 1000 - 1500 m

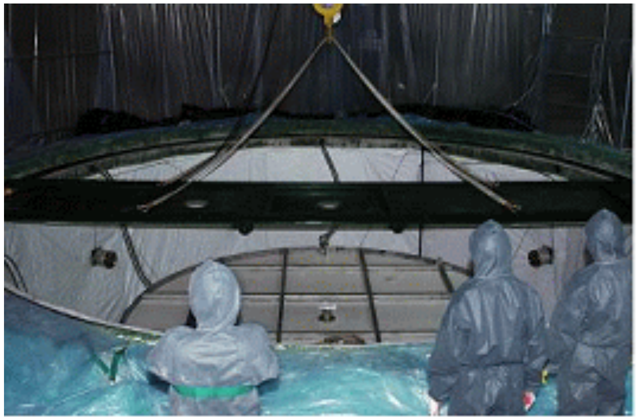


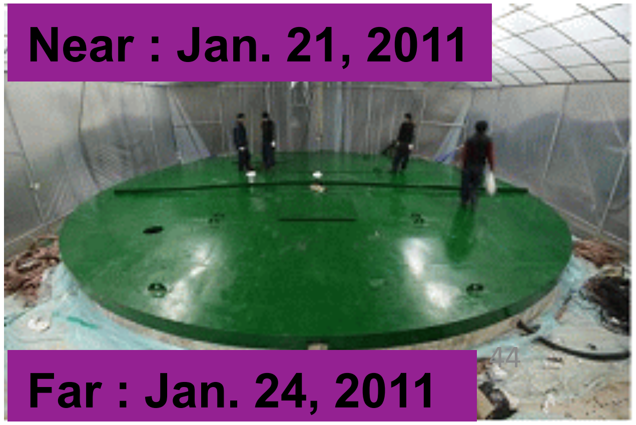


RENO Detector Construction & Closing (Jan. 2011)









Near : Jan. 21, 2011

Far : Jan. 24, 2011

Summary of RENO Status

- Construction of both near and far detectors are completed in Feb. 2011.

- All the liquids including Gd loaded liquid scintillator are produced and filled as of July 5, 2011.

- Dry runs were performed to check PMT and DAQ in March ~ May, 2011.

- Background data-taking has been made since the middle of June, 2011.

- Commissioning shifts and calibration efforts are on progress.

- Regular data-taking is expected to begin from August 1, 2011.

Daya Bay Anti-neutrino Detector Assembly