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# Double Chooz



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for the Double Chooz Collaboration  
Neutrinos and Dark Matter 2009  
September 1, 2009

# Neutrino Mixing

## best fits:

$$\theta_{23} = 45_{-3.4}^{+4}$$

$$|\Delta m_{13}^2| = 2.40 \pm 0.12 \times 10^{-3} \text{ eV}^2$$

SK+K2K+MINOS

Solar+KamLand

$$\theta_{12} = 33.5_{-1.0}^{+1.3}$$

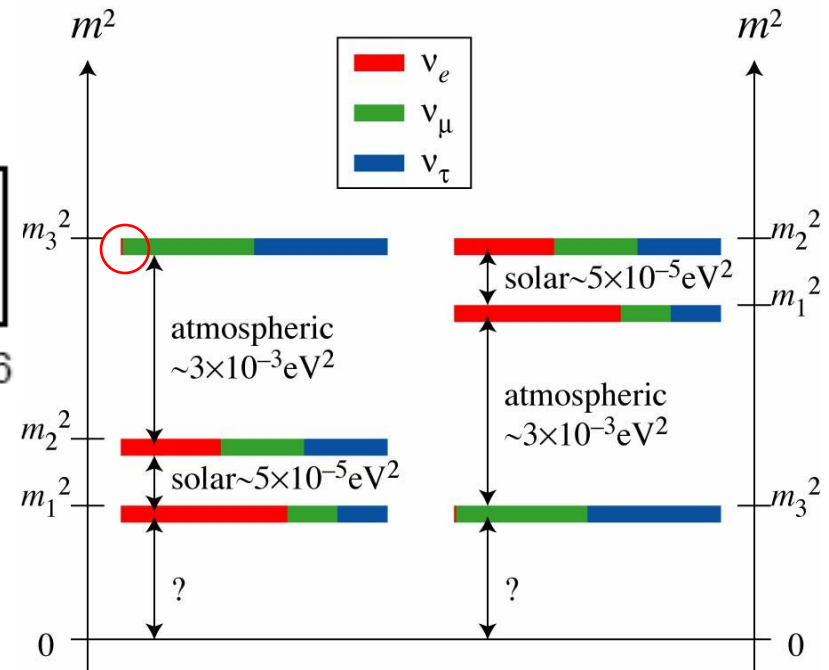
$$\Delta m_{12}^2 = 7.65_{-0.20}^{+0.23} \times 10^{-5} \text{ eV}^2$$

@1 $\sigma$  arXiv:0808.2016

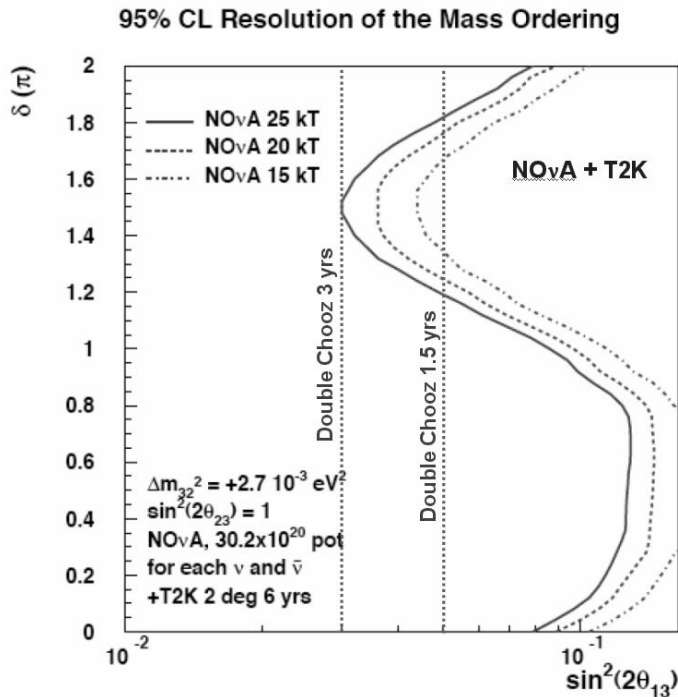
## what is $\nu_e$ component of $\nu_3$ ?

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

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



# Motivation



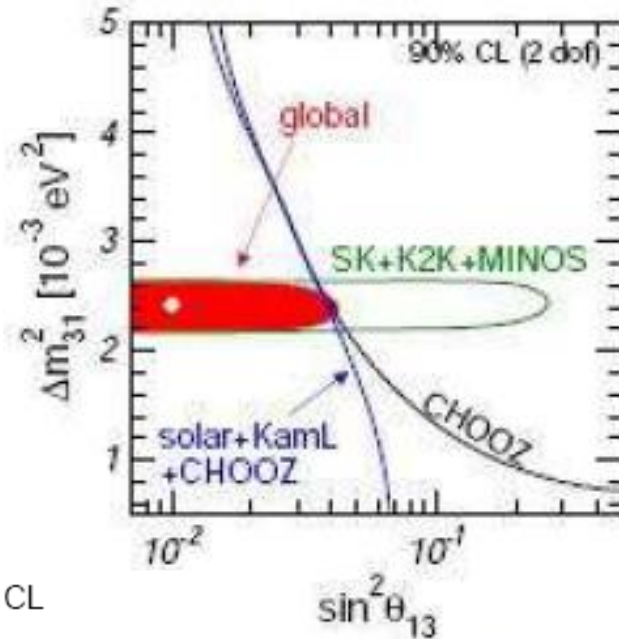
- Value of  $\theta_{13}$  :

- Mass hierarchy and scale
- CP violation

- CHOOZ 1997  $\rightarrow$   $\theta_{13} < 9.5 \text{ deg}$  @ 90% CL

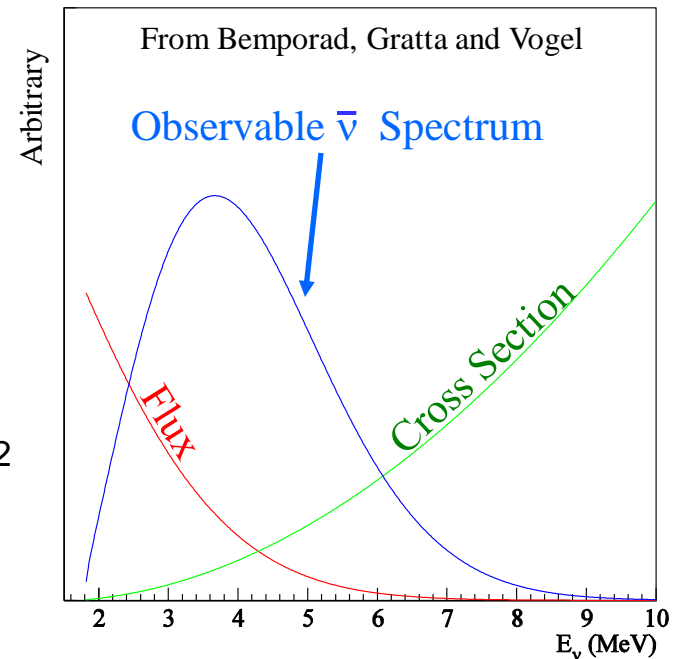
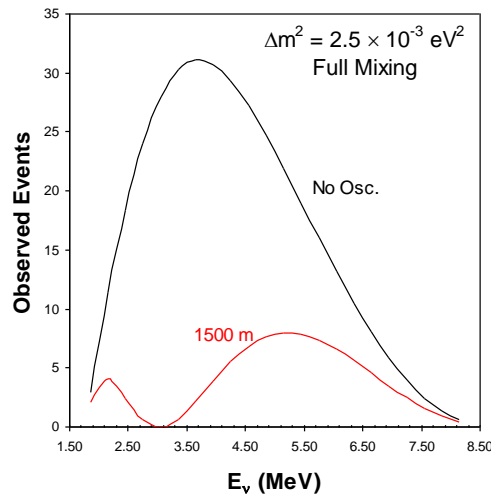
- Reactor experiment provides clean measurement of  $\theta_{13}$ :

$$P(\bar{\nu}_e \rightarrow \bar{\nu}_e) \simeq 1 - \sin^2 2\theta_{13} \sin^2 \left( \frac{1.27 \Delta m_{13}^2 L}{E_\nu} \right)$$



# Reactor Neutrinos

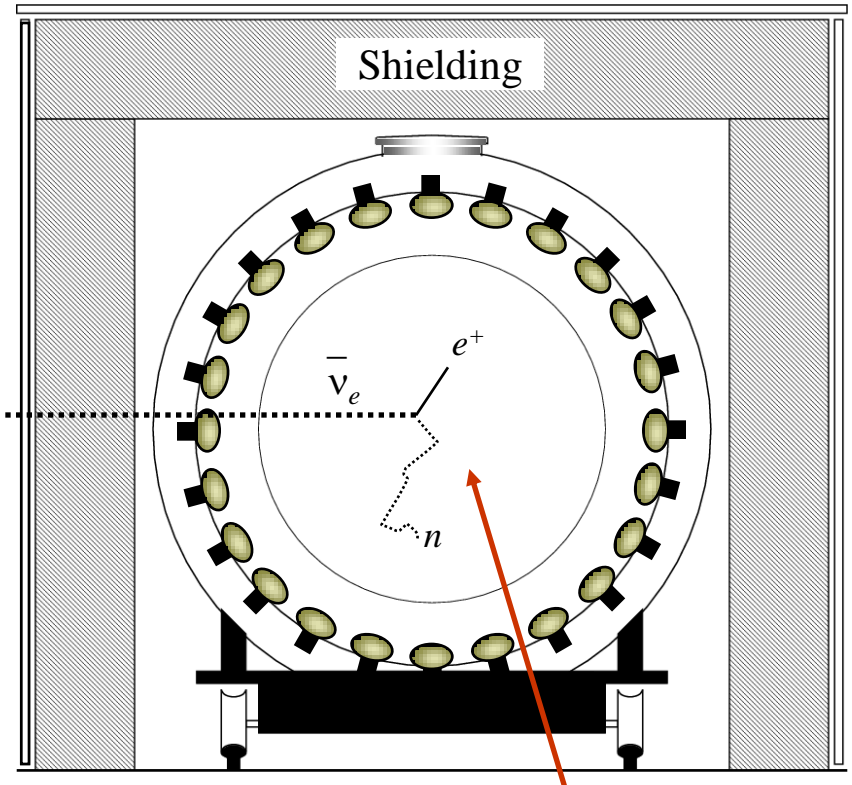
- Nuclear reactors are intense  $\bar{\nu}_e$  sources with a **well-measured flux** and spectrum
  - 3 GW  $\rightarrow 6 \times 10^{20}$   $\bar{\nu}_e$ /sec  
700 events /year/ton at 1500 m
  - **visible spectrum peak at  $\sim 3.7$  MeV**
  - oscillation max. for  $\Delta m^2 = 2.5 \times 10^{-3}$  eV<sup>2</sup> at L  $\sim 1500$  m



- Disappearance measurement:
  - look for small deviation between near ( $\sim 200$ m) and far ( $\sim 1500$ m) detectors:
    - **counting = number of events**
    - **shape = energy spectra**

# Detection

- Inverse  $\beta$ -decay:
  - $\bar{\nu}_e + p \rightarrow e^+ + n$
- $^{155}\text{Gd}, ^{157}\text{Gd}$  capture:
  - $n + \text{Gd} \rightarrow 8 \text{ MeV of } \gamma\text{s}$
  - $\tau \sim 30 \mu\text{sec}$   
(0.1% Gd concentration)
- Events selected by coincidence
- $\nu$  energy spectrum given by visible  $e^+$  energy:
  - $E_\nu = E_{\text{vis}} + 1.8 \text{ MeV} - 2m_e$



Liquid Scintillator  
with Gadolinium

 = Photomultiplier Tube

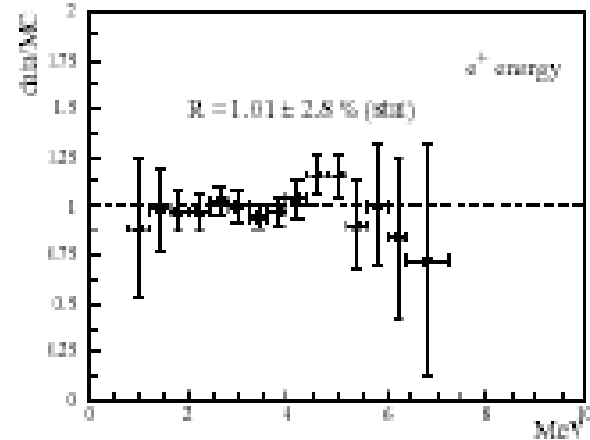
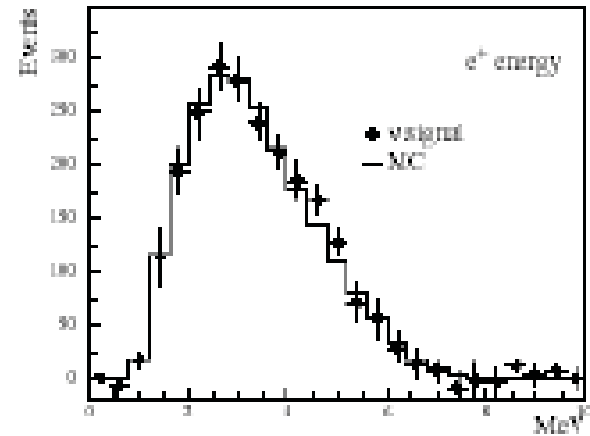
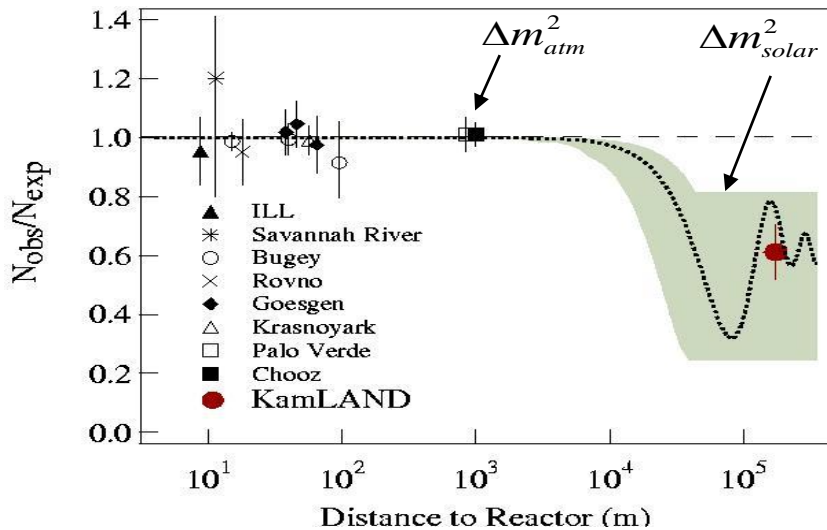
# $\theta_{13}$ Limits

CHOOZ:  $R = N_{\text{meas}}/N_{\text{exp}} = 1.01 \pm 2.8\% \text{ (stat)} \pm 2.7\% \text{ (sys)}$

CHOOZ:

$\theta_{13} < 9.5 \text{ deg}$  @ 90% CL

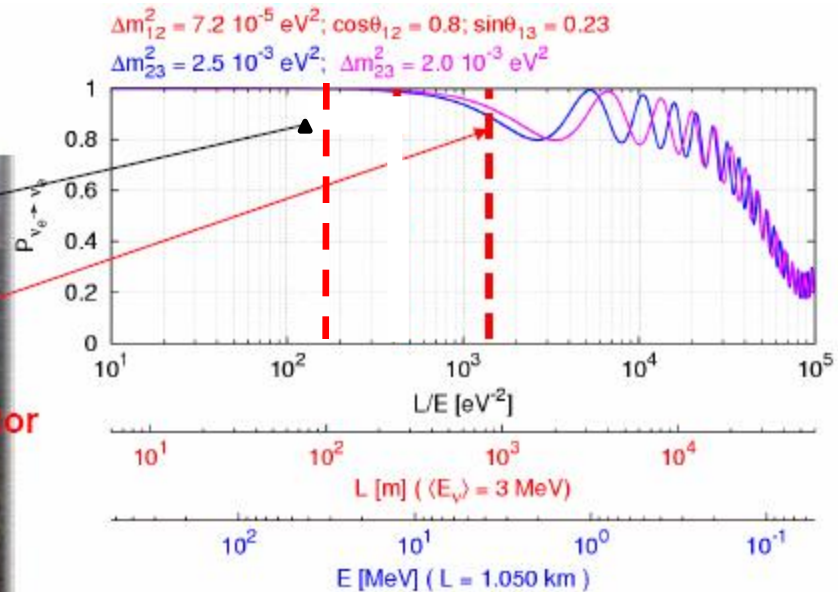
- 5.55 m<sup>3</sup> doped target in single detector @ 1050m
- ~3 months data-taking
- 2% systematic on reactor flux



# Improve Limits

- Add identical near detector: need only relative acceptance
  - remove systematics from reactor neutrino flux, energy
- New detector design
  - low radioactivity PMTs protected by mineral oil
  - addition of non-doped “gamma-catcher” defines target volume
- New Gd scintillator mixture: instability in CHOOZ scintillator attenuation
- Reduce cosmogenic backgrounds: add outer detectors

Chooz B nuclear power plant  
on France/Belgium border



# Double Chooz

## Near + far detectors

45,600  $\nu_e$  (far detector) in 3 years

0.5% stat. uncertainty

## Far detector only

22,800  $\nu_e$  in 1.5 years

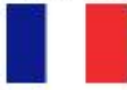
0.7% stat. uncertainty


Features of Double Chooz site:

- 2×4.27 GW<sub>thermal</sub> reactors – 8.54 GW maximum power
- Far site hall reusable from original CHOOZ with 300 mwe mountain overburden at 1050 m baseline
- Near site: ~40 m rock (115 mwe) overburden at 410 m baseline

# Collaboration


Spokesman: Hervé de Kerret (APC)

 **France:** APC Paris, CEA/Dapnia Saclay, Subatech Nantes, Strasbourg

 **Germany:** Aachen, MPIK Heidelberg, TU München, ECU Tübingen, Hamburg


 **Spain:** CIEMAT Madrid

 **UK:** Sussex

 **Japan:** HIT, Kobe, Niigata, TGU, TIT, TMU, Tohoku

 **Russia:** RAS, RRC Kurchatov Institute

 **USA:** Alabama, ANL, Chicago, Columbia, Drexel, Illinois, Kansas, LLNL, LSU, Notre Dame, Sandia, Tennessee, UCD

 **Brazil:** CBPF, UNICAMP



# Phase 1: Far detector only

Systematic	% Error
Reactor Power	1.9
Energy per fission	0.6
$\nu_e$ /fission	0.2
$\nu$ cross section	0.1

## Reactor

- 2.0% total systematic
- based on CHOOZ analysis
- dominates Phase 1 errors

## Detector and data selection

- < 1.3% total systematic (CHOOZ analysis: 1.5% total)

Systematic	% Error
Detector volume	0.2
Scintillator density	0.01
H/C composition	< 0.5
Gd concentration	0.3
Deadtime	0
e+ energy cut	0.1
n loss (spill in/out)	< 1.0
n energy cut	0.1
Time cut	0.4

# Phase 2: Near + Far Detectors

## Systematic errors on the relative normalization

			CHOOZ	Double Chooz
Reactor		Solid Angle	—	0.2%
Detector	H nuclei in Target	Volume	0.3%	0.2%
		Fiducial Volume	0.2%	0
		Density		0.1%
		H/C	0.8%	0
Detector	Electronics	Dead Time	—	0%
Particle Identification	Positron	Escape	0.1%	0
		Capture	0	0
		Identification Cut	0.8%	0.1%
Particle Identification	Neutron	Escape	1.0%	0
		Capture (% Gd)	0.85%	0.3%
		Identification Cut	0.4%	0.1%
Particle Identification	Antineutrino	Time Cut	0.4%	0.1%
		Distance Cut	0.3%	0
		Unicity	0.5%	0
Total			1.5%	0.5%

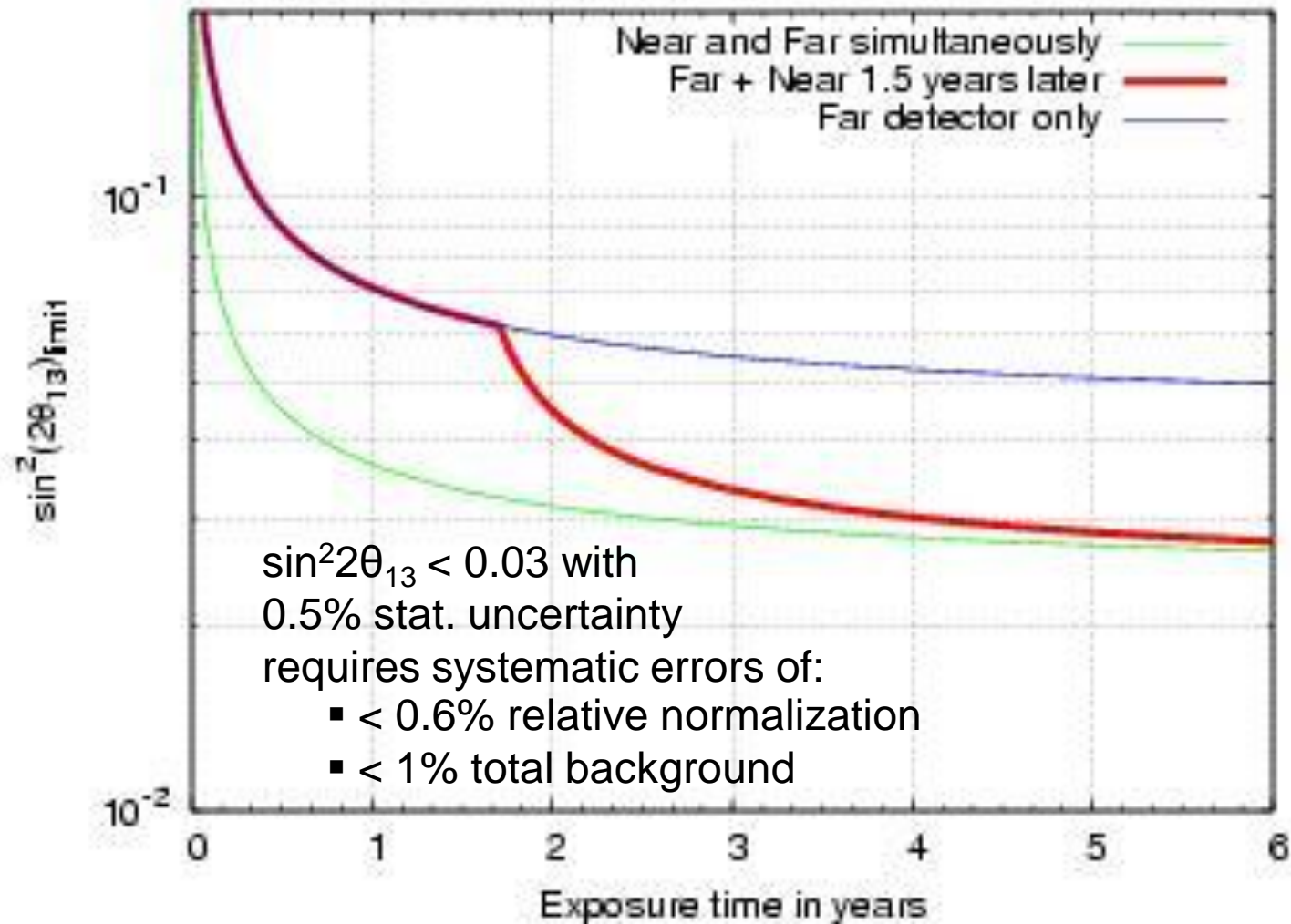
- PMT radioactivity protected by oil buffer (CHOOZ: 60 Hz, DC: 1.5 Hz)
- cosmogenic neutron background reduced by improved vetos
- *in situ* calibrations improve energy scale for selection cuts

# Backgrounds

- Accidental
  - random coincidences between two different events (e.g. radioactive decay plus cosmogenic neutron) together fake IBD signal
- Correlated
  - fast neutron – from muon showers near detector. A single neutron can elastically scatter in the target and subsequently capture on Gd
  - muon capture – on nuclei in dead material along muon track can produce several high-energy neutrons
  - ${}^9\text{Li}$  – production by muon spallation inside target. Production mechanism not well-understood. About 50% of  $\beta$  decays produce a neutron. 178 ms half life causes prohibitive downtime if vetoed by muon track in target.

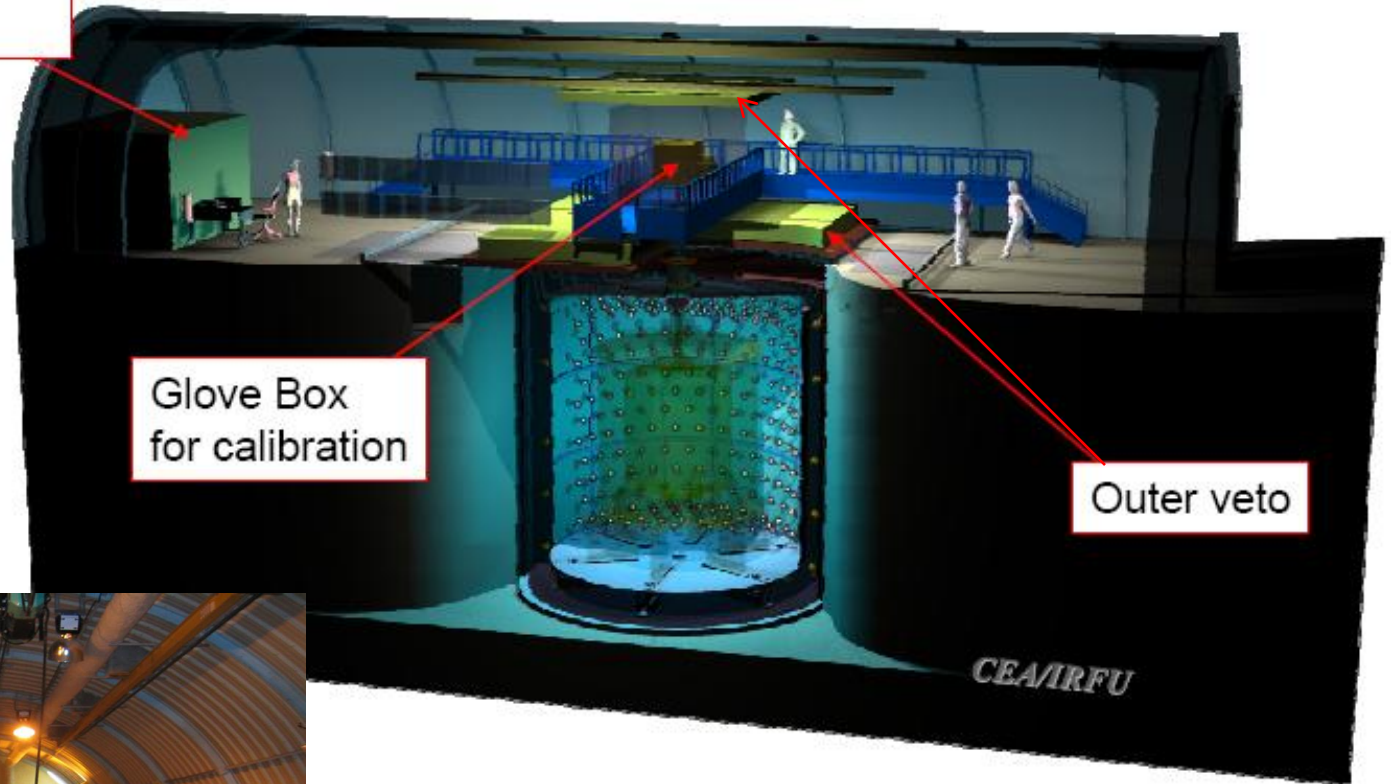
Detector	Site		Background				
			Accidental		Correlated		
			Materials	PMTs	Fast n	$\mu$ -Capture	${}^9\text{Li}$
Double Chooz (69 $\nu$ /d)	Far	Rate ( $d^{-1}$ )	$0.1 \pm 0.1$	$0.3 \pm 0.2$	$0.11 \pm 0.11$	< 0.1	$1.0 \pm 0.5$
		bkg/ $\nu$	0.1%	0.4%	0.2%	< 0.1%	1.4%
		systematics	<0.1%	<0.1%	0.2%	<0.1%	0.7%
Double Chooz (1012 $\nu$ /d)	Near	Rate ( $d^{-1}$ )	$0.5 \pm 0.3$	$1.7 \pm 0.9$	$0.15 \pm 0.15$	0.4	$9 \pm 5$
		bkg/ $\nu$	< 0.1%	0.2%	< 0.1%	< 0.1%	0.9%
		systematics	<0.1%	<0.1%	<0.1%	<0.1%	0.5%

# Expected Sensitivity

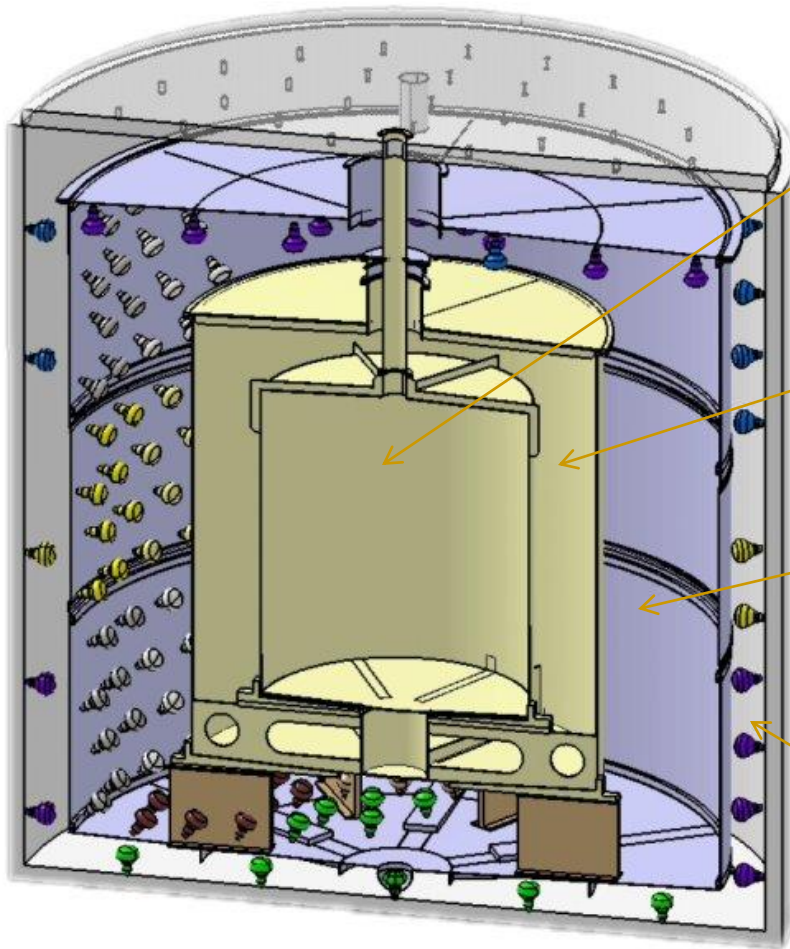


# Far Site Hall

Electronic hut



# Inner Detectors



- Target
  - 10.3 m<sup>3</sup> (8.8 tonnes) of 0.1% Gd-doped LS

h = 2458mm  
d = 2300mm
- Gamma-catcher
  - ~50 cm (22.6 m<sup>3</sup>) of LS

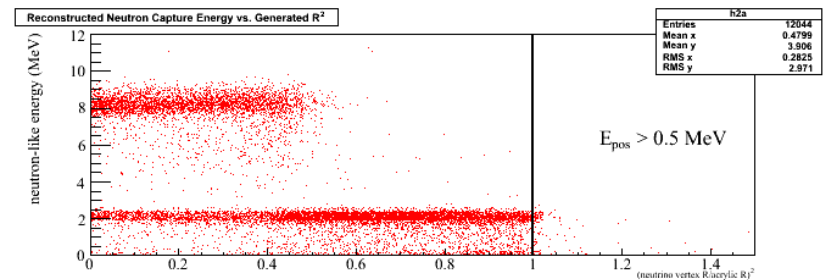
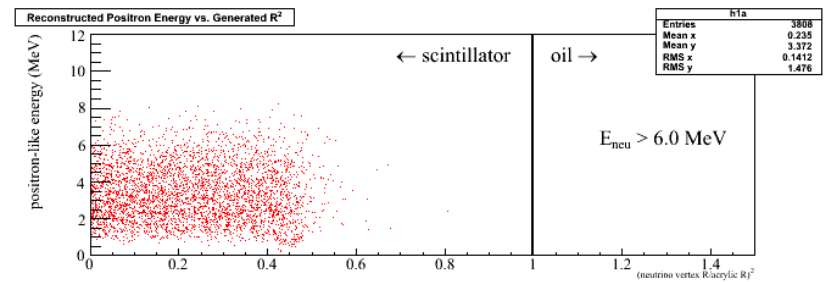
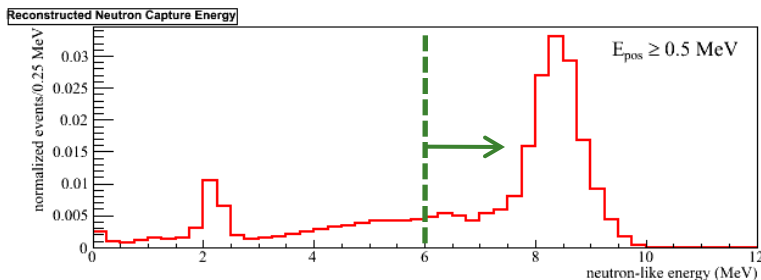
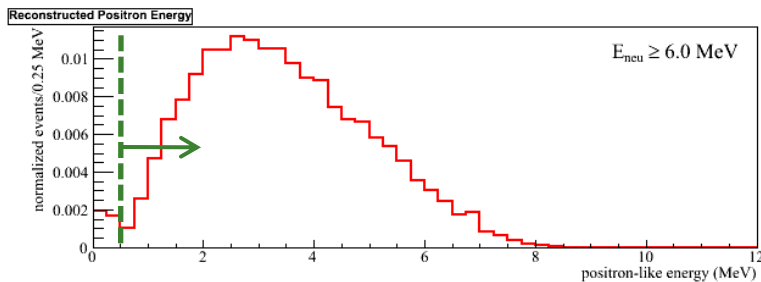
h = 3574mm  
d = 3392mm
- Buffer
  - 105 cm of nonscintillating organic liquid (114.2 m<sup>3</sup>)
  - 390 10" Hamamatsu PMTs

h = 5674mm  
d = 5516mm
- Inner Veto
  - 90 m<sup>3</sup> LS with 78 8" PMTs

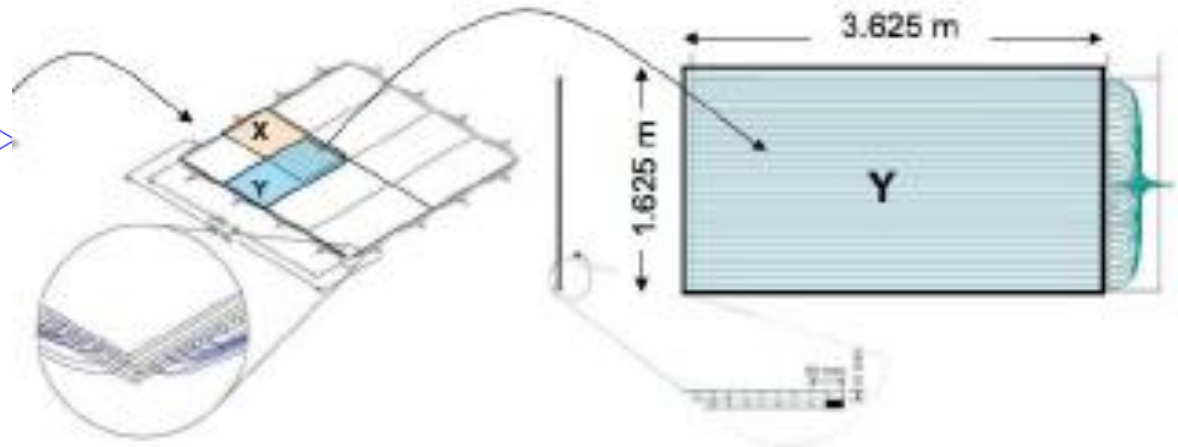
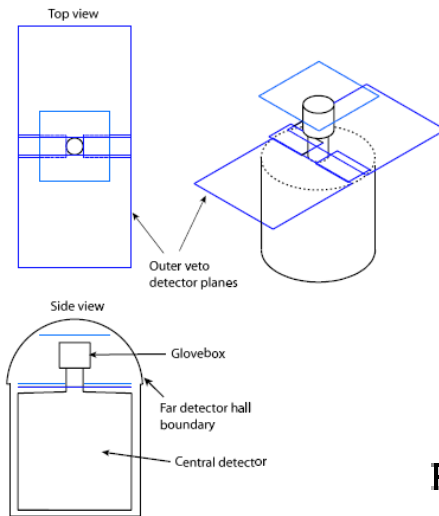
h = 6640mm  
d = 6590mm

# Detector Simulation

- Geant4-based Monte Carlo with ROOT output
  - detailed detector geometry and pulse modeling
  - $\bar{\nu}_e$  events generated throughout central detectors
  - two reconstructed events within 100  $\mu$ sec window



# Outer Veto



## LAYOUT

- two 7.0 x 7.2 meter panels ~1 m above the inner detectors
  - overlapped vertically for continuous active coverage
  - mounted to retractable steel shielding
- one 3.6 x 3.6 m upper panel above glove box
  - protects neck and provides tracking

	Raw muon rates
Near	5.9 Hz/m <sup>2</sup>
Far	0.62 Hz/m <sup>2</sup>

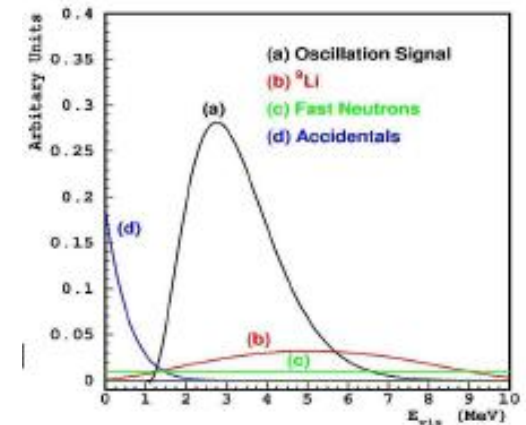
# Veto Effect

## No Veto System

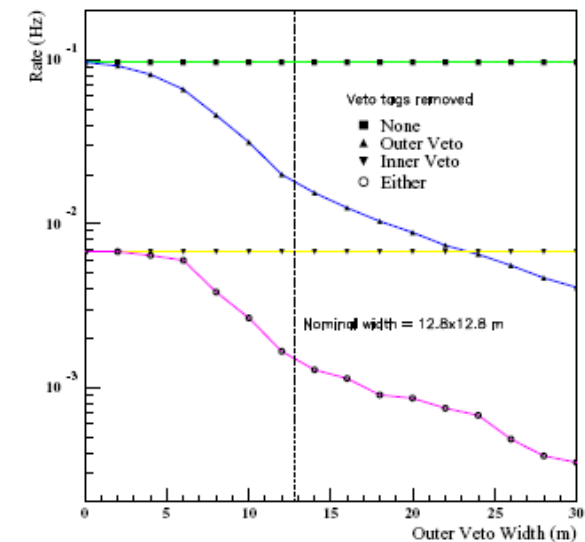
Detector	Site		Background				${}^9\text{Li}$
			Accidental		Correlated		
			Materials	PMTs	Fast n	$\mu$ -Capture	
Double Chooz (69 $\nu$ /d)	Far	Rate ( $d^{-1}$ )	$0.5 \pm 0.3$	$1.5 \pm 0.8$	$2.0 \pm 2.0$	28	$1.0 \pm 0.5$
		bkg/ $\nu$	0.7%	2.2%	2.9%	40%	1.4%
Double Chooz (1012 $\nu$ /d)	Near	Rate ( $d^{-1}$ )	$5 \pm 3$	$17 \pm 9$	$9.1 \pm 9.1$	266	$9 \pm 5$
		bkg/ $\nu$	0.5%	1.7%	0.8%	26%	0.9%

## With Inner and Outer Veto System

Detector	Site		Background				${}^9\text{Li}$
			Accidental		Correlated		
			Materials	PMTs	Fast n	$\mu$ -Capture	
Double Chooz (69 $\nu$ /d)	Far	Rate ( $d^{-1}$ )	$0.1 \pm 0.1$	$0.3 \pm 0.2$	$0.11 \pm 0.11$	< 0.1	$1.0 \pm 0.5$
		bkg/ $\nu$	0.1%	0.4%	0.2%	< 0.1%	1.4%
		systematics	< 0.1%	< 0.1%	0.2%	< 0.1%	0.7%
Double Chooz (1012 $\nu$ /d)	Near	Rate ( $d^{-1}$ )	$0.5 \pm 0.3$	$1.7 \pm 0.9$	$0.15 \pm 0.15$	0.4	$9 \pm 5$
		bkg/ $\nu$	< 0.1%	0.2%	< 0.1%	< 0.1%	0.9%
		systematics	< 0.1%	< 0.1%	< 0.1%	< 0.1%	0.5%



Near site, 100% efficient detectors



## Background candidate neutron study

- rate of neutrons (from “near-miss” muons) entering the central detector as a function of OV width
  - muons which deposit energy in the central detectors are removed
- FLUKA generated muon sample

# Far Detector Construction

Original CHOOZ hall and pit refurbished and new cleanliness standards achieved



Shield of 15 cm demagnetized iron

Construction pictures from CEA/CNRS/IRFU

# Far Detector Progress

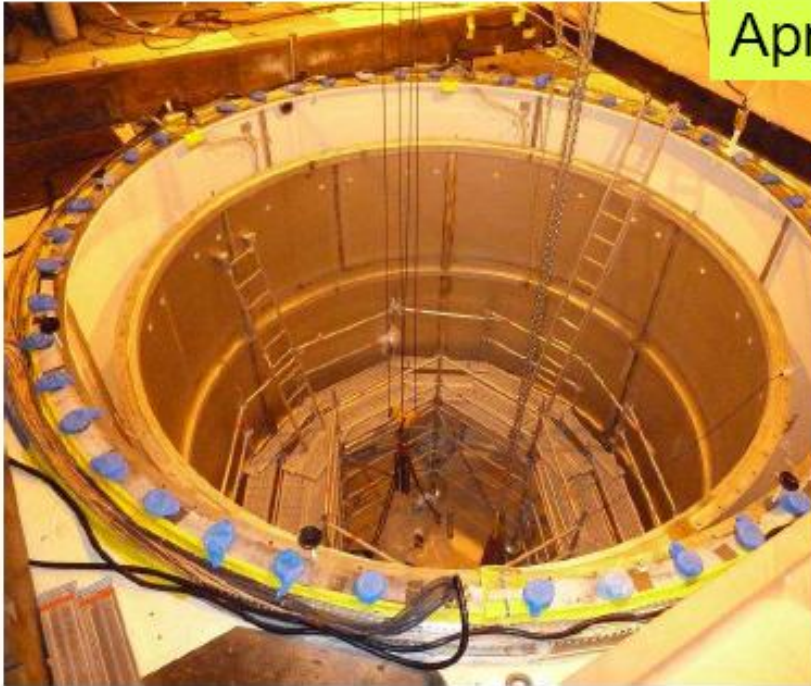


February 2009

Inner Veto PMTs  
Installation completed



# Far Detector Progress



April 2009

Buffer tank  
assembled on site



# Far Detector Progress

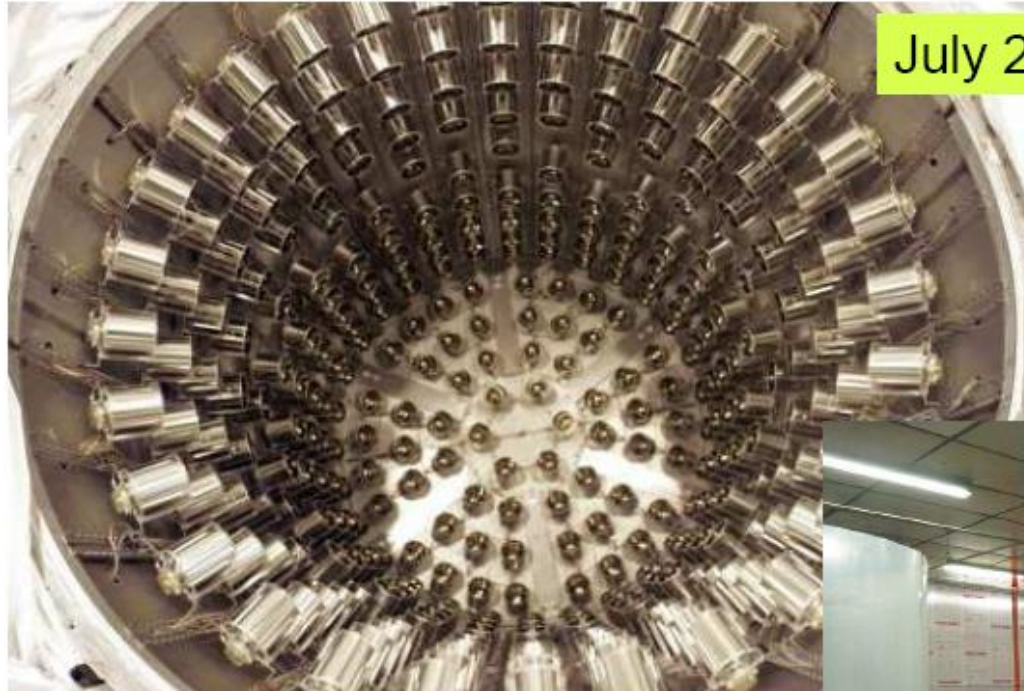


May 2009

PMT Installation



# Far Detector Current Status



July 2009



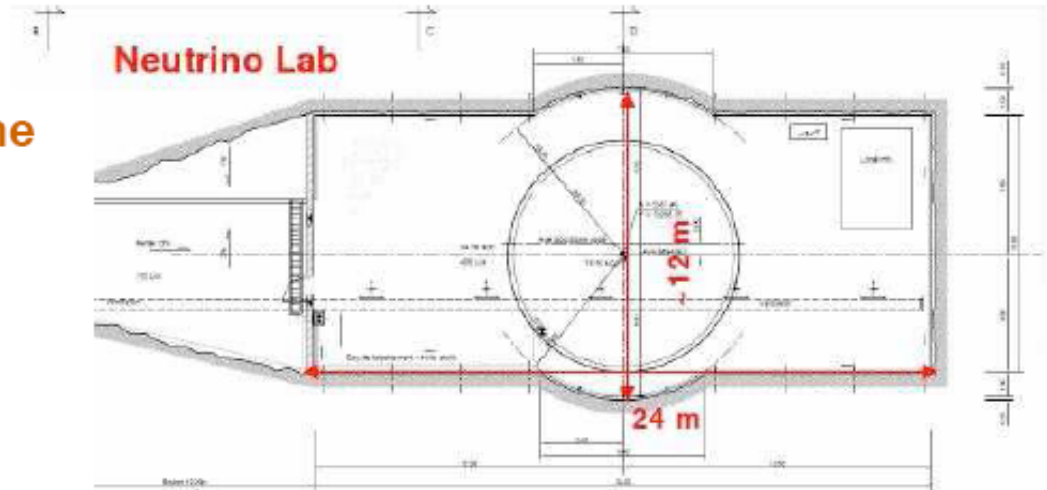
PMT Installation completed  
Acrylic vessels ready to be  
assembled on site

**Now:** acrylic vessels complete  
and integration is ongoing.



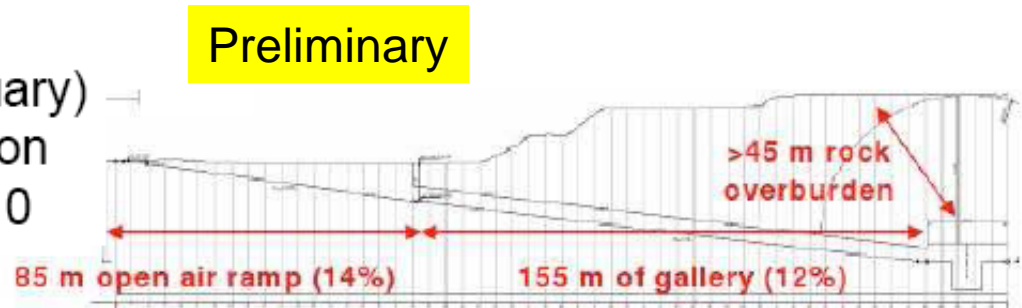
# Near Detector Status

May 20th the **agreement for the Near laboratory construction** has been signed.  
The agreement includes the region Champagne-Ardennes, EDF and French agencies.



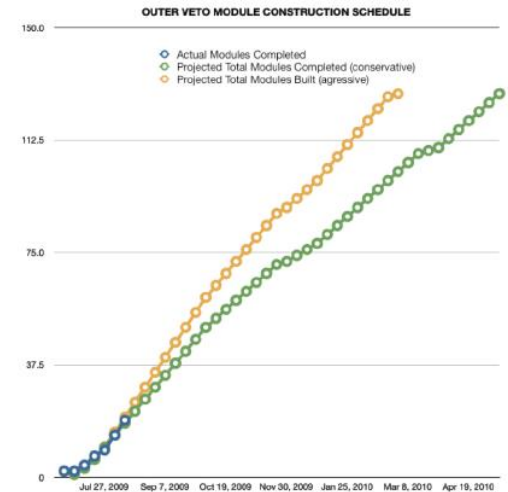
## Schedule

- Geological study done (February)
- Tender process for construction
- Constructed at the end of 2010



# Schedule

- Geological survey completed for near lab February 2009
- Far detector
  - Now installing acrylic vessels
  - Outer veto module construction on schedule →
  - Inner detector closed at the end of 2009
  - Liquid scintillator filling through April 2010
  - Begin data-taking with inner far detector in April
  - Outer veto installed after filling (not required for inner detector data taking)
- Near hall construction begins end of 2010
- Near detector data taking in 2011



# Conclusion

- Double Chooz will be the first new generation detector reactor neutrino experiment to measure  $\theta_{13}$
- April 2010 begin far detector data taking
  - achieve current limit of  $\sin^2 2\theta_{13} < 0.15$  at 90% CL with approximately one month of data
- near detector data taking in 2011
- five years after start of data taking (3 yrs of two detectors):  **$\sin^2 2\theta_{13} < 0.03$  at 90% CL**