Closing in on θ_{13}

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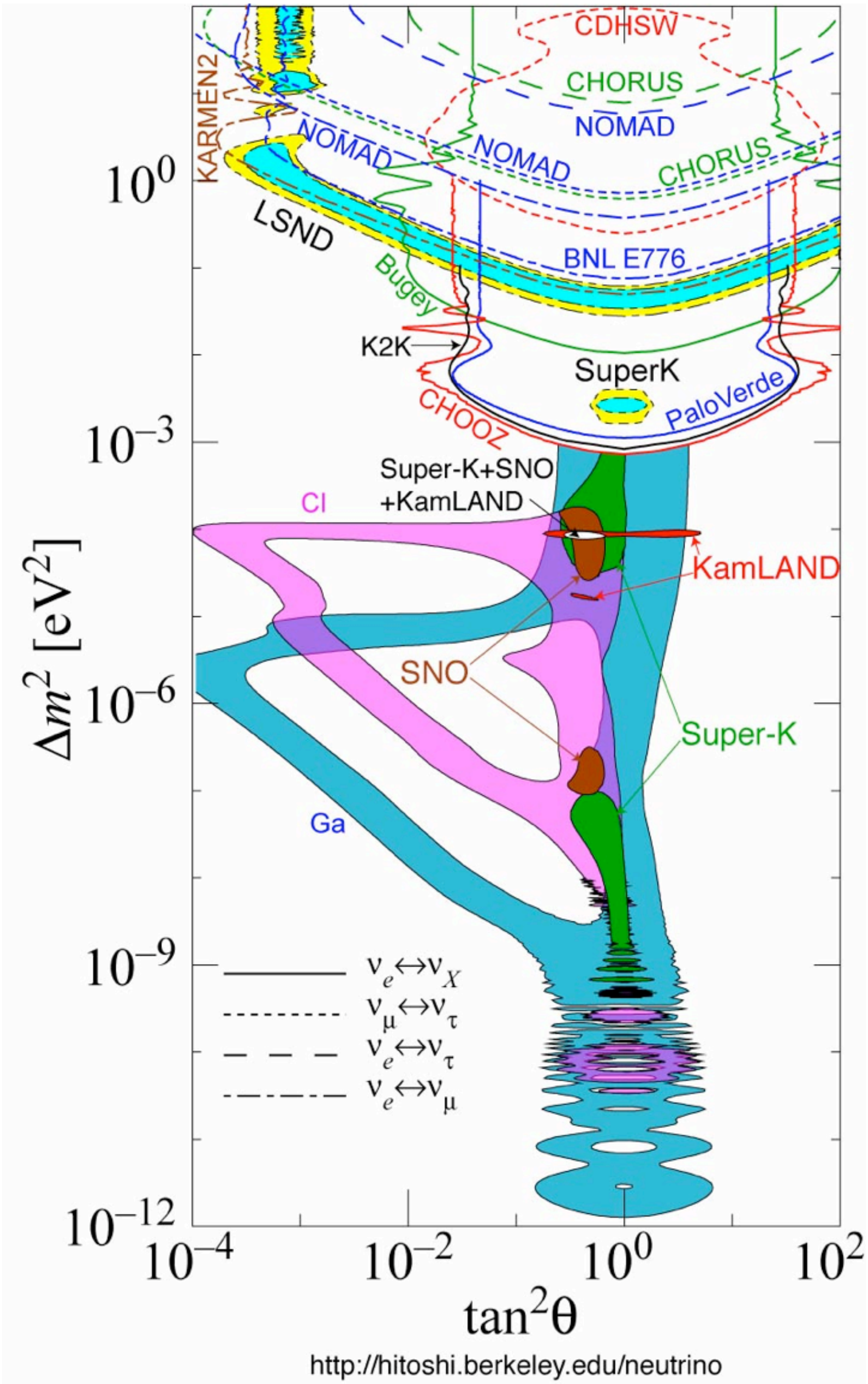
INT, June 2011



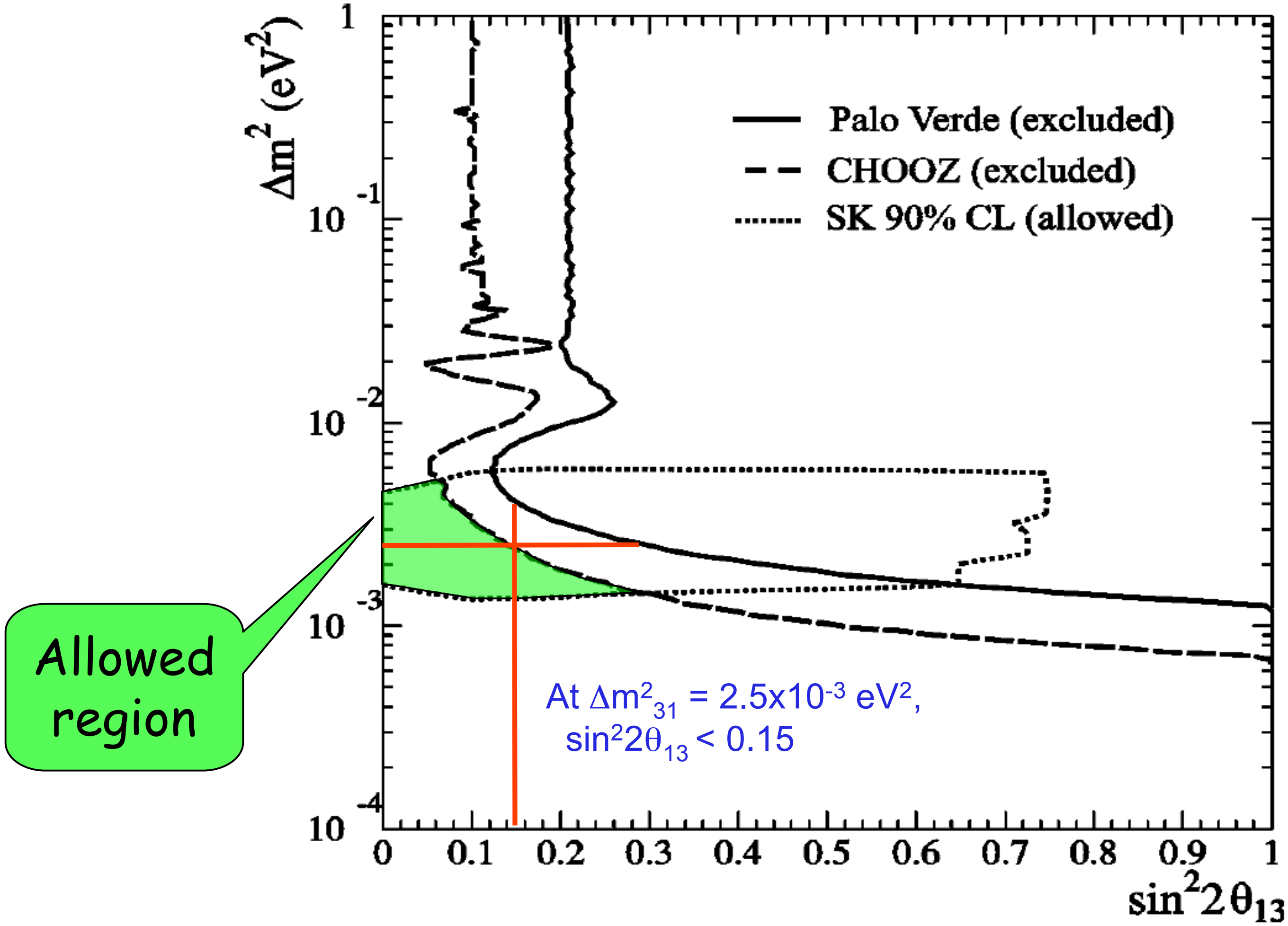
We learned a lot about ν-mixing from recent experiments!

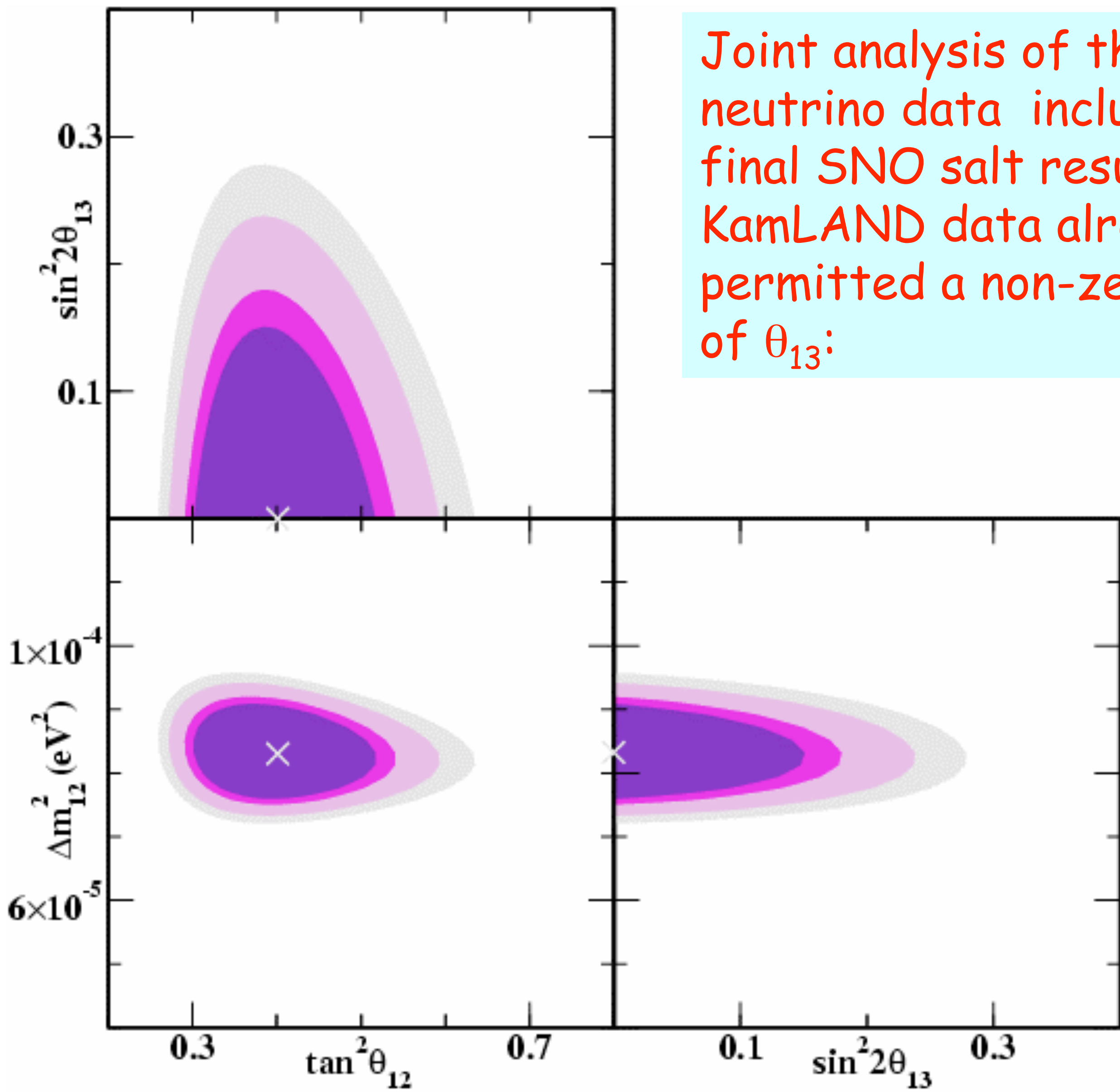
$\theta_{atmospheric}$ (primarily θ_{23})

θ_{solar} (primarily θ_{12})

Yet our current knowledge of θ_{13} is very limited!

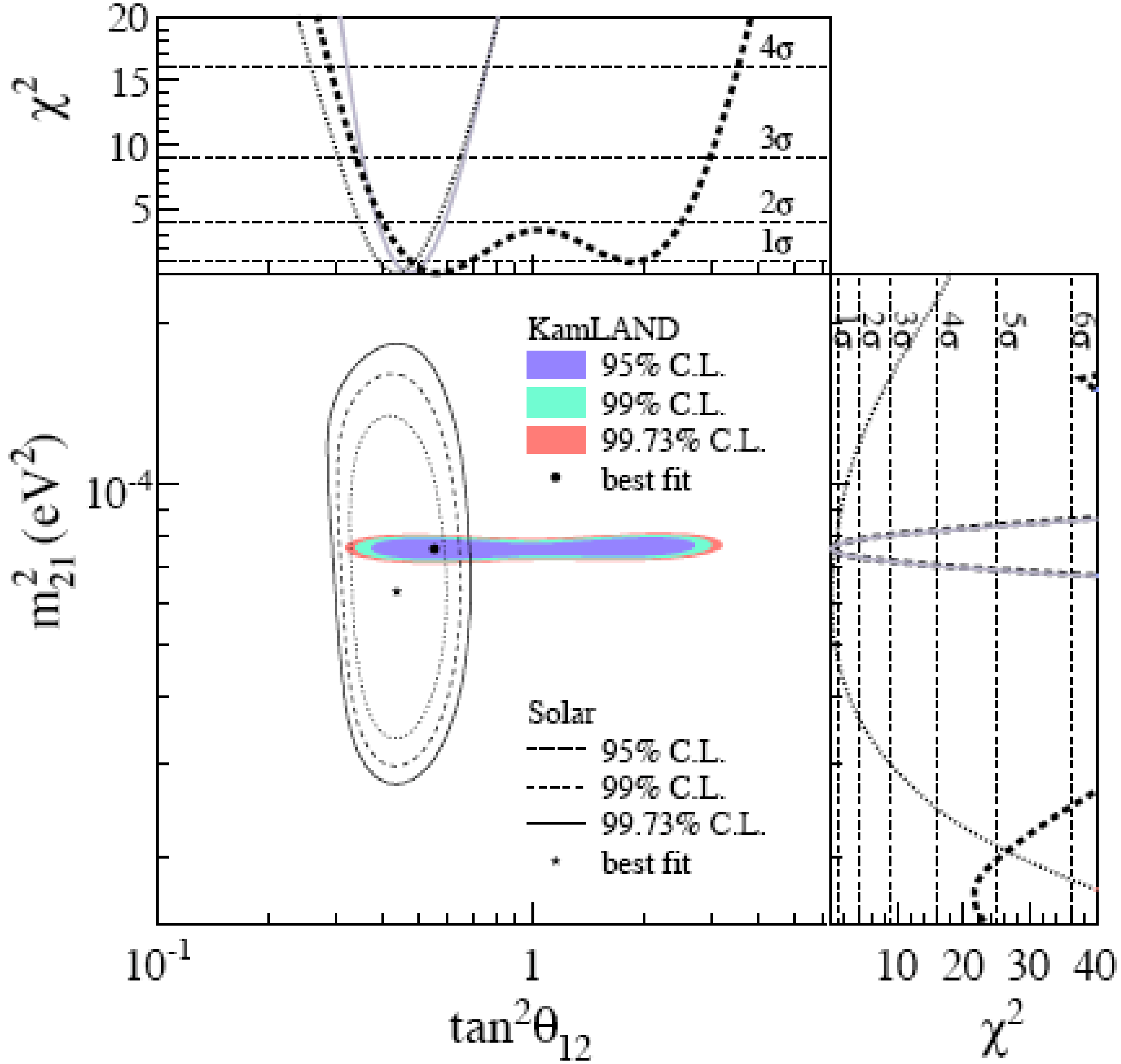
Current direct search limits





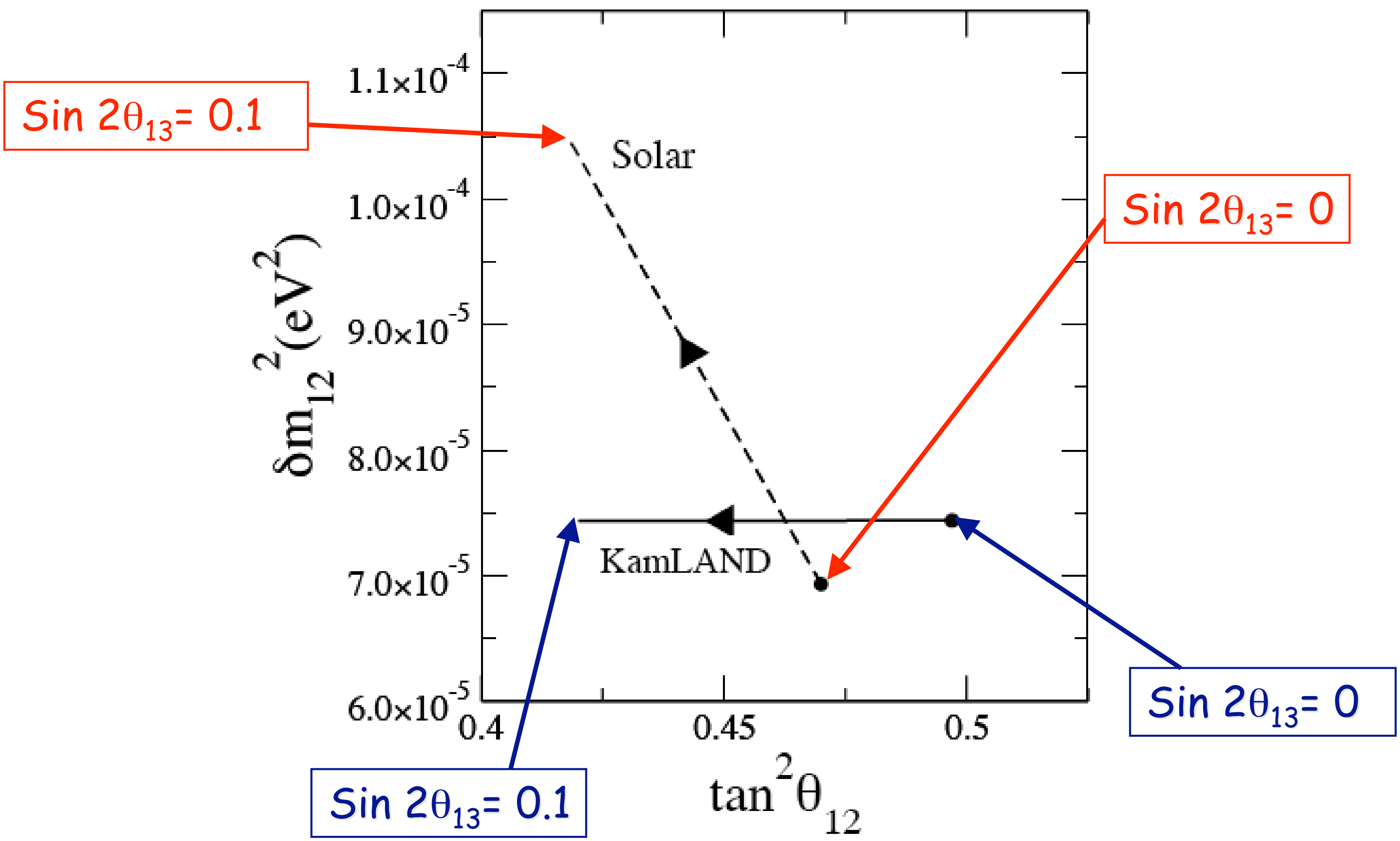
Joint analysis of the solar neutrino data including final SNO salt results and KamLAND data already permitted a non-zero value of θ_{13}:

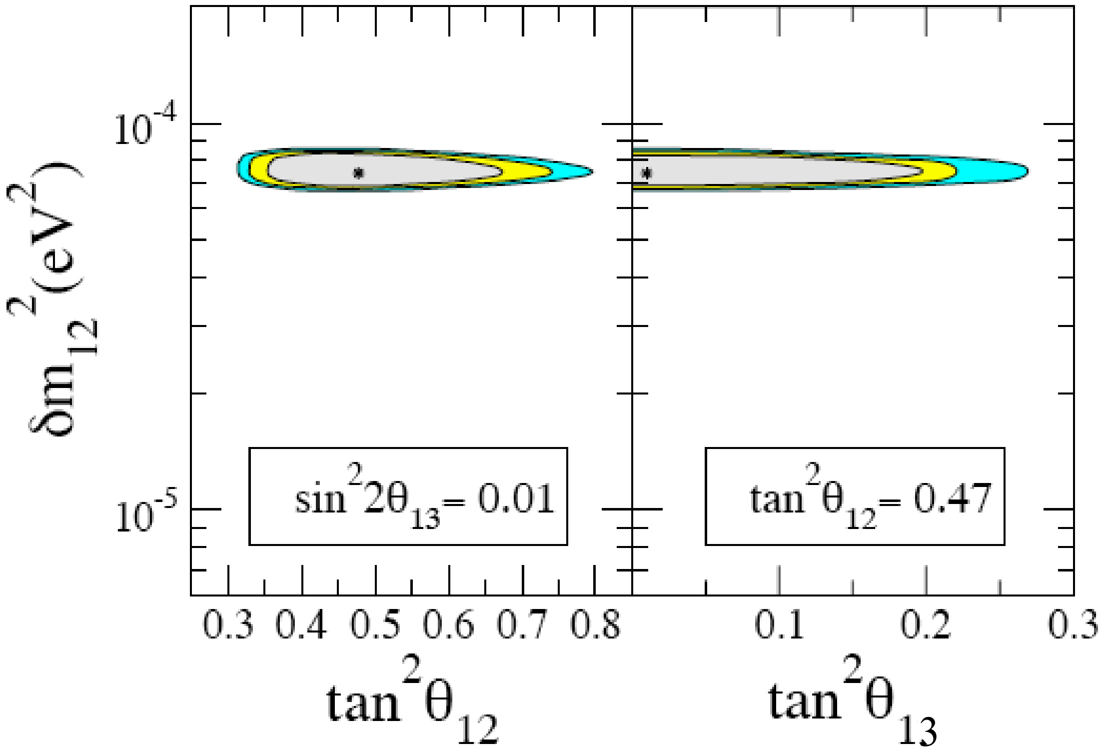
Balantekin, et al., PLB 613, 61 (2005)

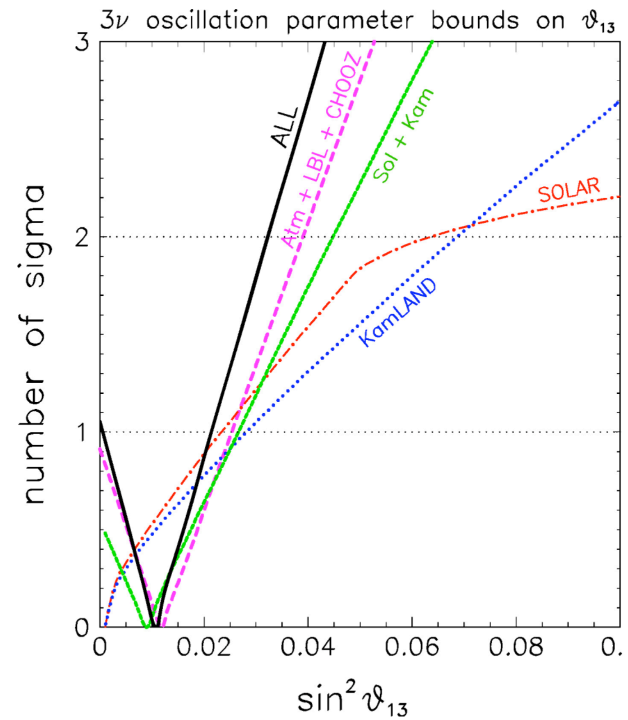


KamLAND and solar best fit values are not the same!
CPT-violation? Other new physics?

….or is it simply ignoring θ_{13} ?



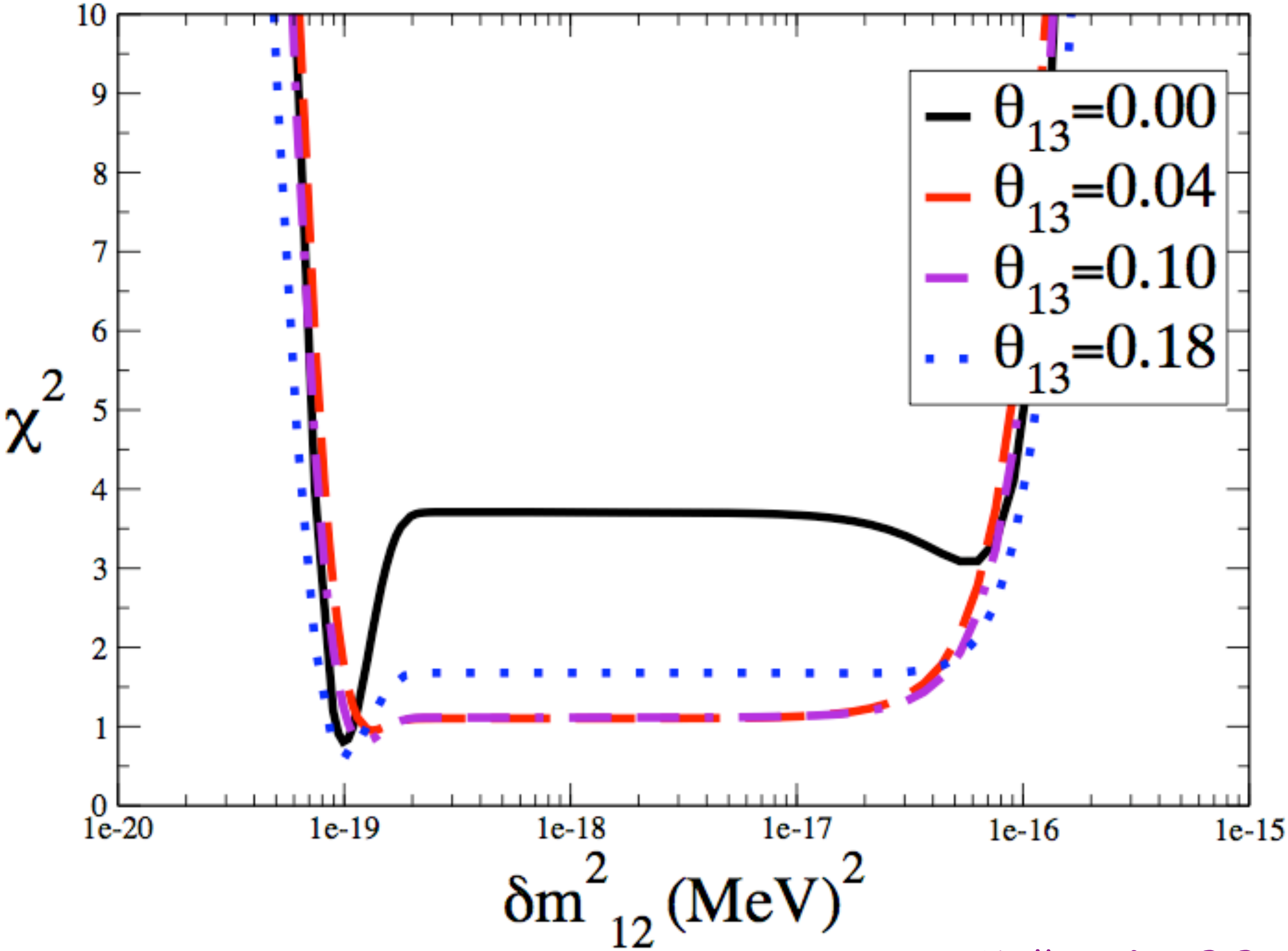




Balantekin & Yilmaz, J. Phys. G **35**, 075007 (2008) (arXiv:0804.3345 [hep-ph]).

Fogli *et al.*, Venice ν-oscillation workshop(2008) and arXiv:0806.2649 [hep-ph]

SNO LTE with $\tan^2\theta_{12}$ = = 0.53

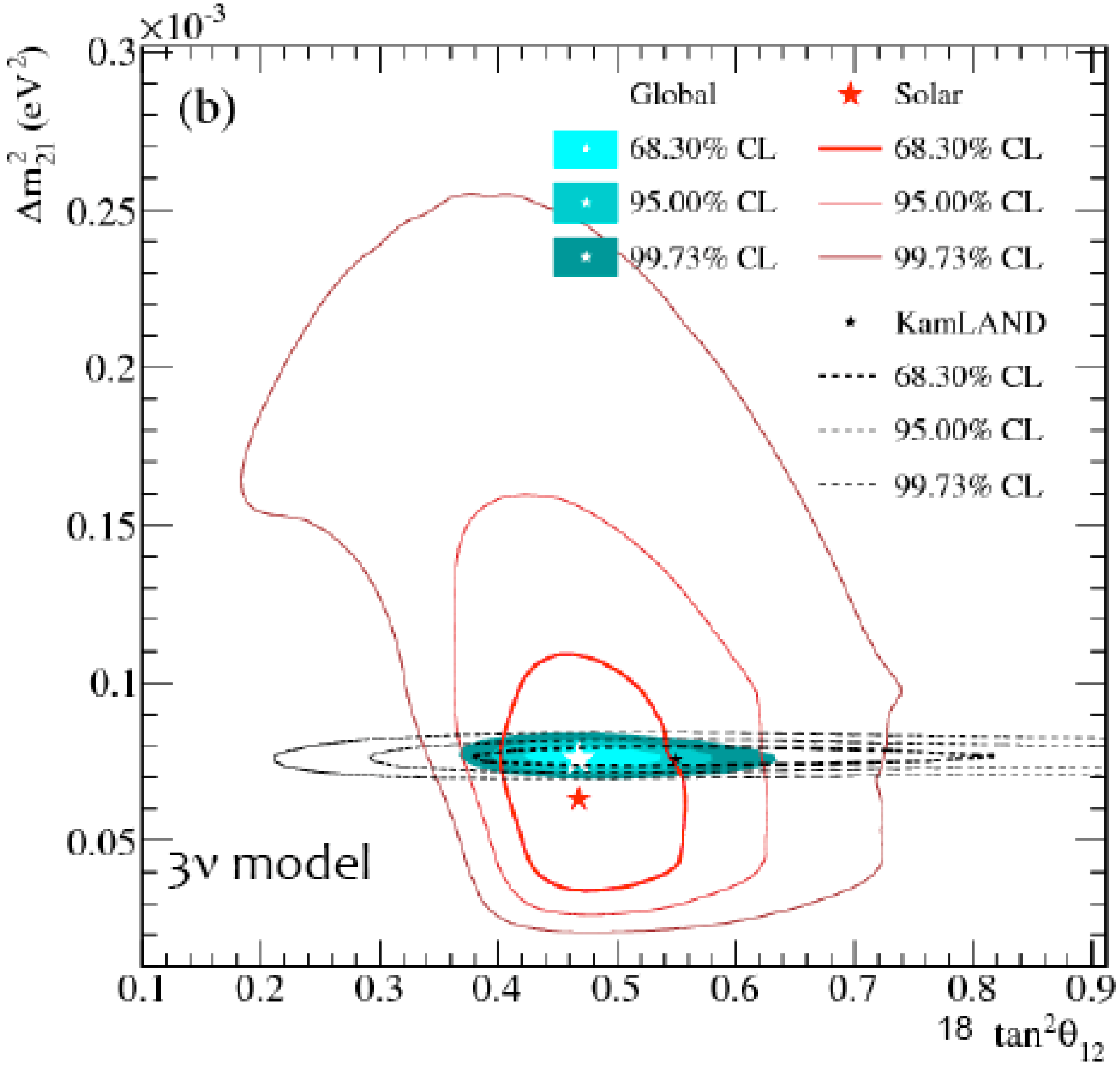


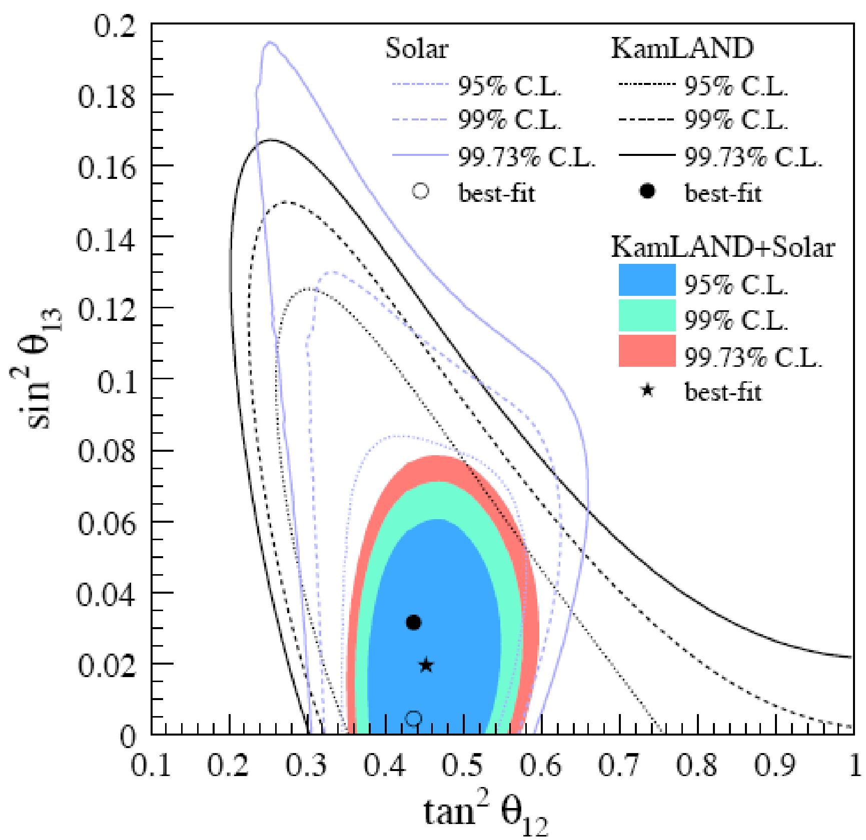
A. Malkus & A.B.B.

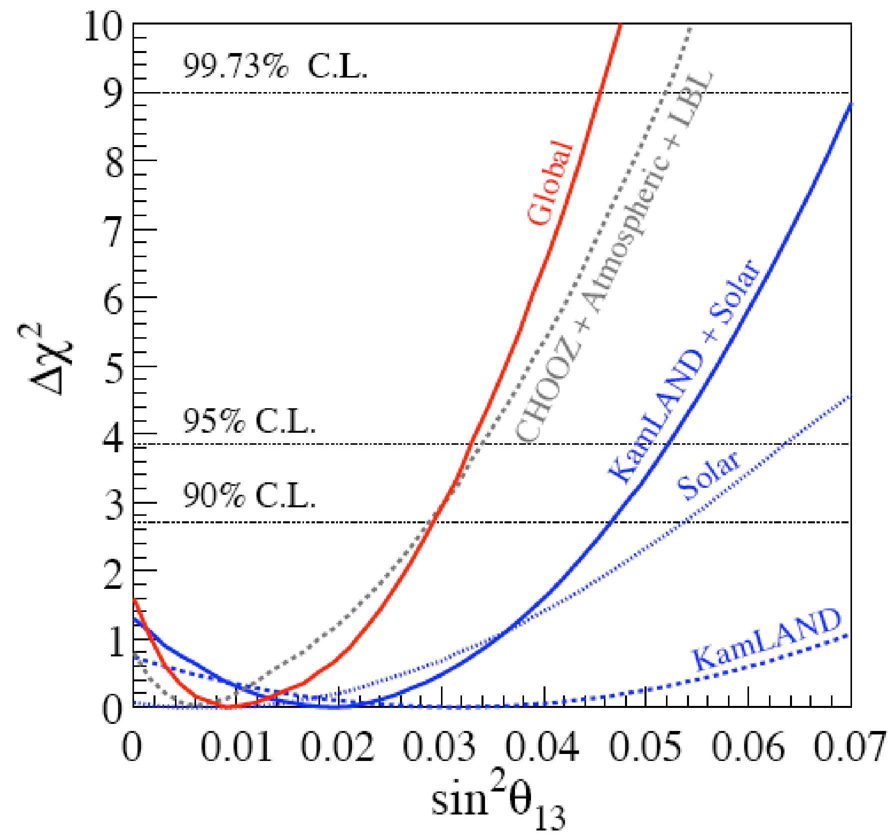
SNO's own low-energy threshold analysis

$\theta_{13} = 7.2^{+2.0}_{-2.8}$ deg

Note: Non-Gaussian errors







KamLAND Collaboration, 2011

A note of caution:

- The value of θ_{13} is a small. Theory has other small quantities that are not yet well-determined!
- One example is the neutrino cross sections.

An approach from the first principles: Using effective field theory for low-energy neutrino-deuteron scattering

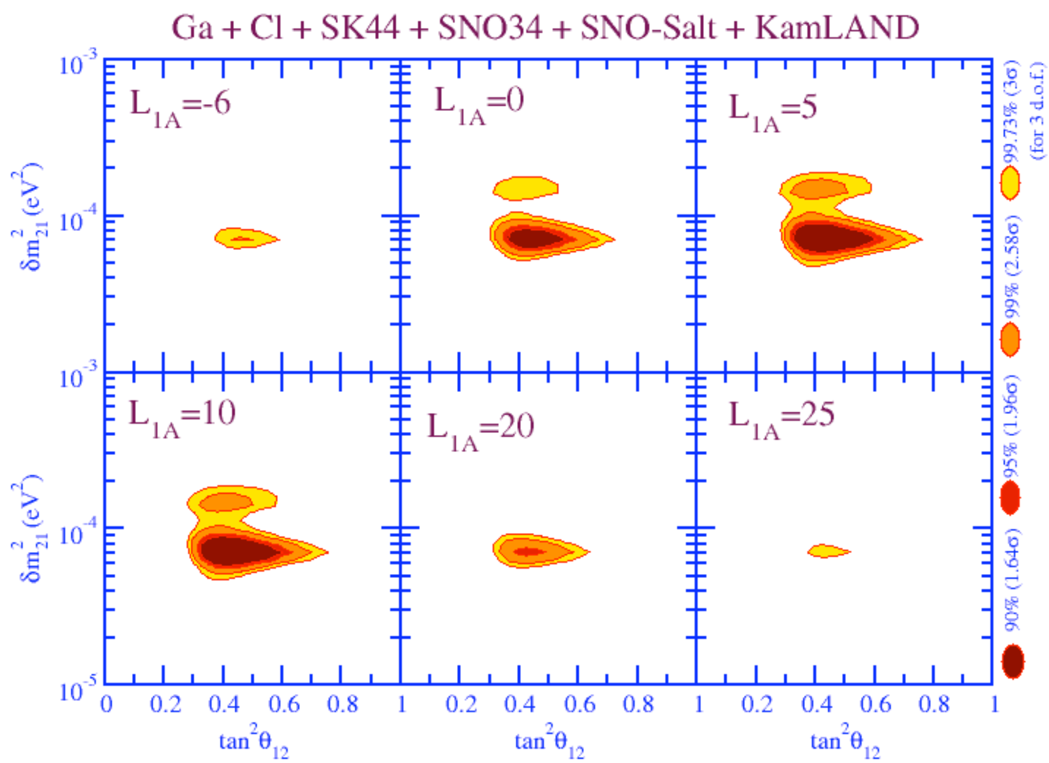
Butler, Chen

Below the pion threshold $^3S_1 \rightarrow {}^1S_0$ transition dominates and one only needs the coefficient of the two-body counter term, L_{1A} (isovector two-body axial current)

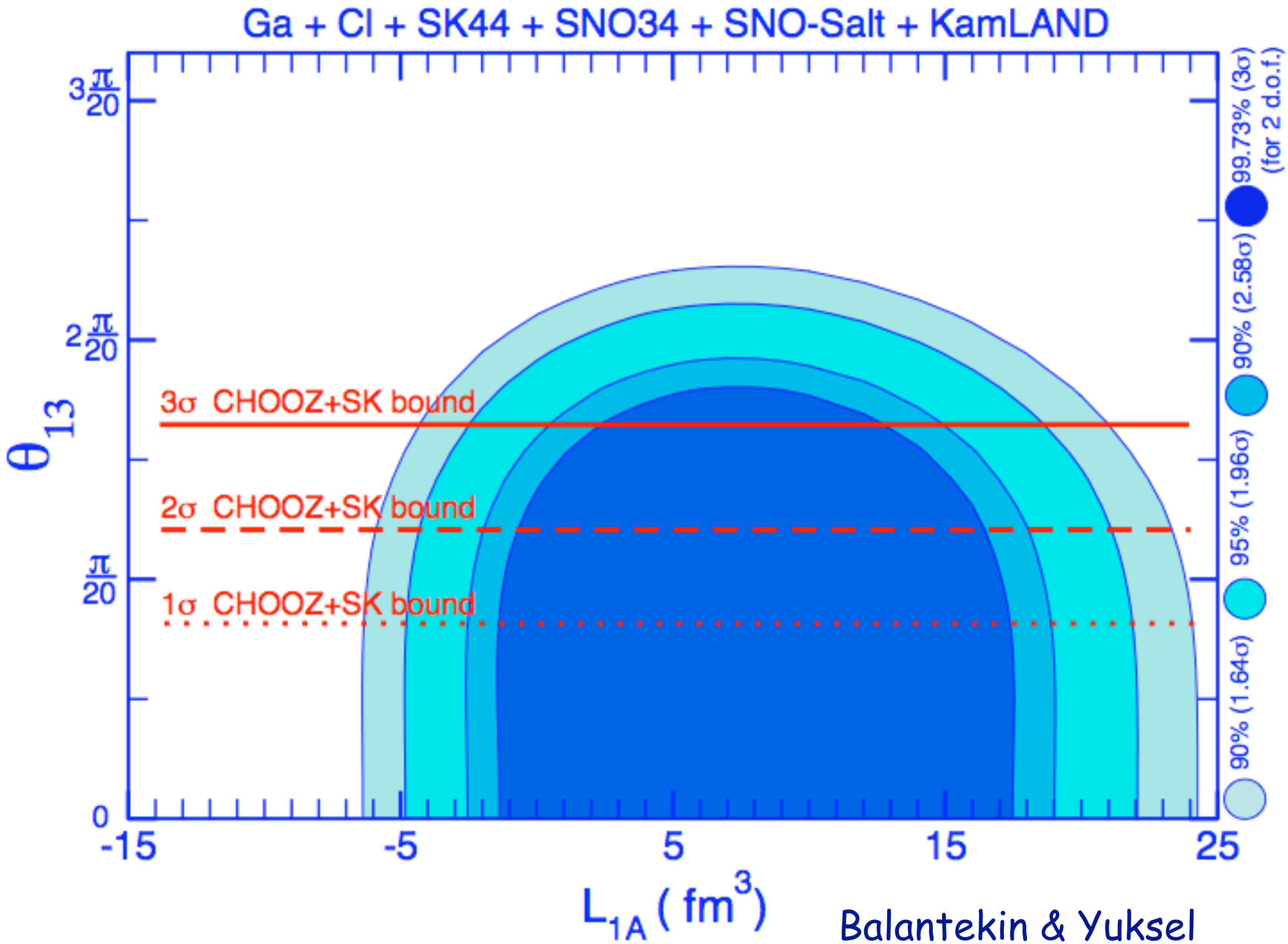
L_{1A} can be obtained by comparing the cross section $\sigma(E) = \sigma_0(E) + L_{1A}\, \sigma_1(E)$ with cross-section calculated using other approaches or measured experimentally.

(e.g. use solar neutrinos as a source)

Difficult to go beyond two-body systems!



A.B. Balantekin and H. Yuksel



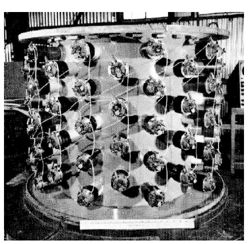
Balantekin & Yuksel

CP-violation

$$P(\bar{\nu}_\mu \to \bar{\nu}_e) - P(\nu_\mu \to \nu_e) \propto \sin\theta_{12} \sin\theta_{13} \sin\theta_{23}$$

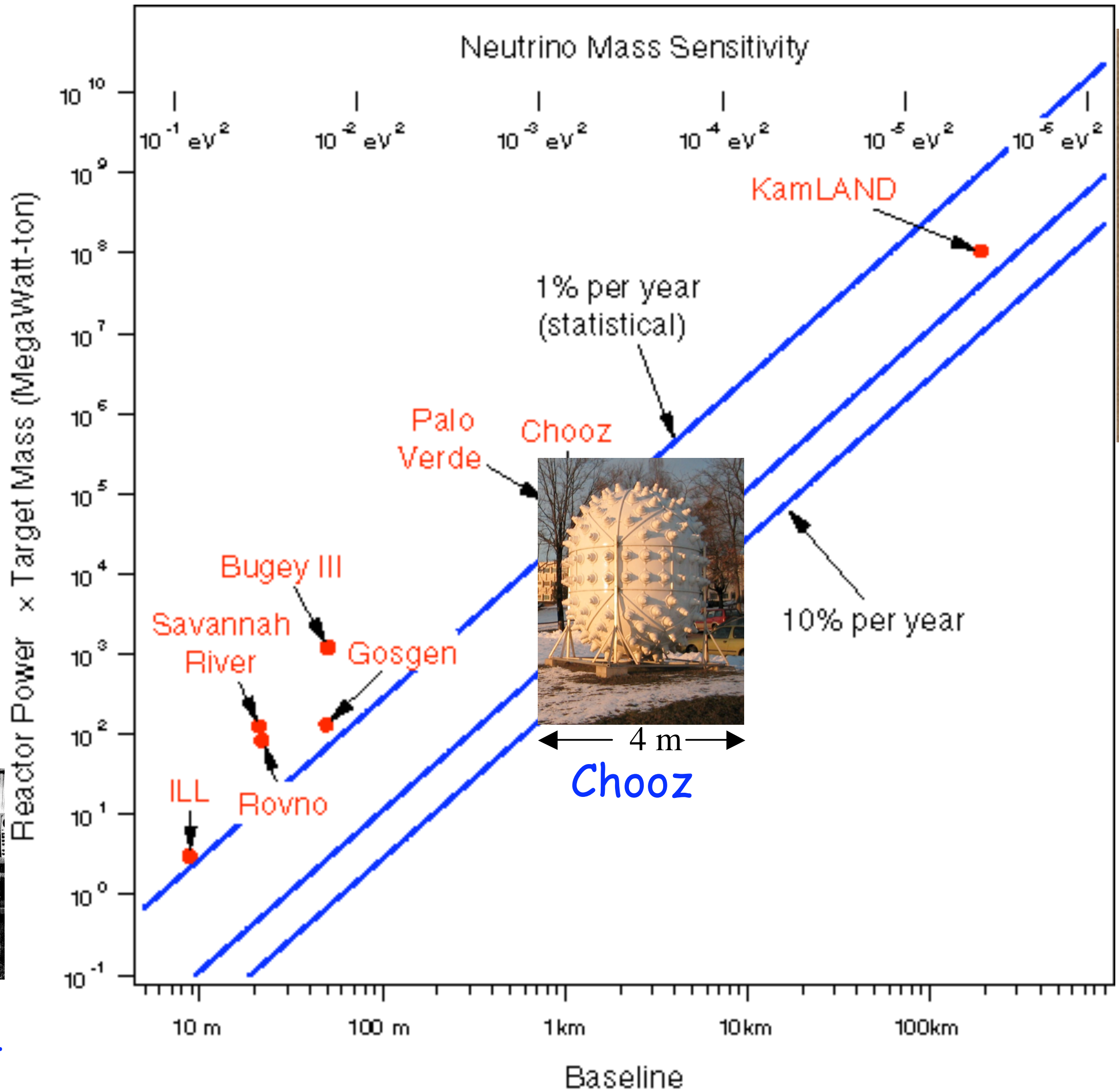
Since we know the other mixing angles are *non-zero*, observation of CP-violation in neutrino oscillations hinges on a non-zero value of θ_{13}.

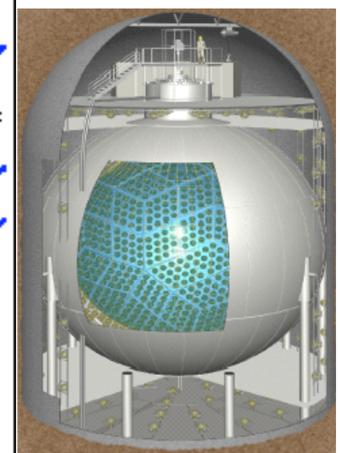
Reactor (Anti)neutrino Experiments



← 1m →

Poltergeist



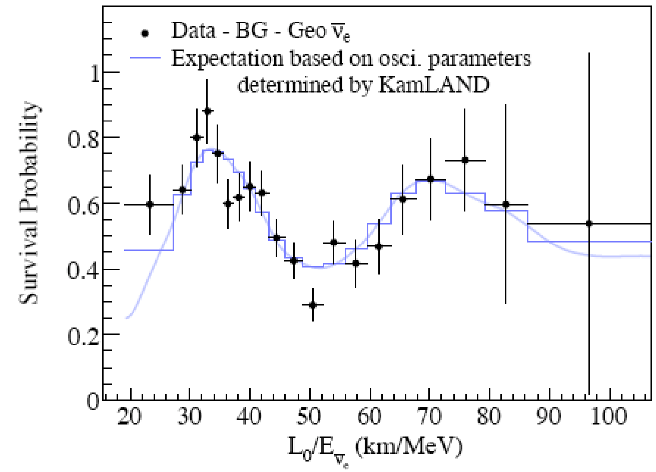


← 20 m →

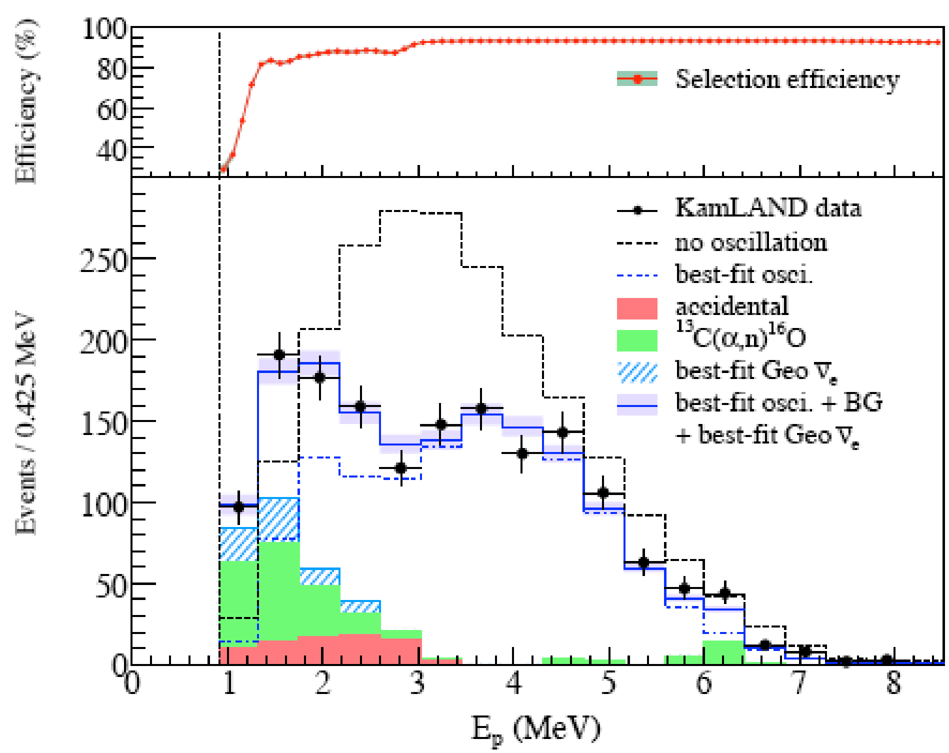
KamLAND

KamLAND

Primorskaya
Russia
Vladivostok
Chongjin
Kimchaek
China
West Asia
South Korea
Ulchin
Wolsong
Taegu
Kori
Genkai
Sasebo
Kumamoto
Sendai
Miyazaki
Kagoshima
Shimane
Matsue
Hiroshima
Shimonoseki
Ikata
Kochi
Takahama
Mihama
Fugen
Tsuruga
Monju
Ohi
Tokushima
Shika
Kashiwazaki Kariwa
Nagaoka
Hamaoka
Tokai
Kofu
Tomari
Asahikawa
Kushiro
Hakodate
Hirosaki
Akita
Onagawa
Fukus
Fukus
46°N
44°N
42°N
40°N
130°E
132°E
134°E
136°E
138°E
140°E
142°E
International Nuclear Safety C

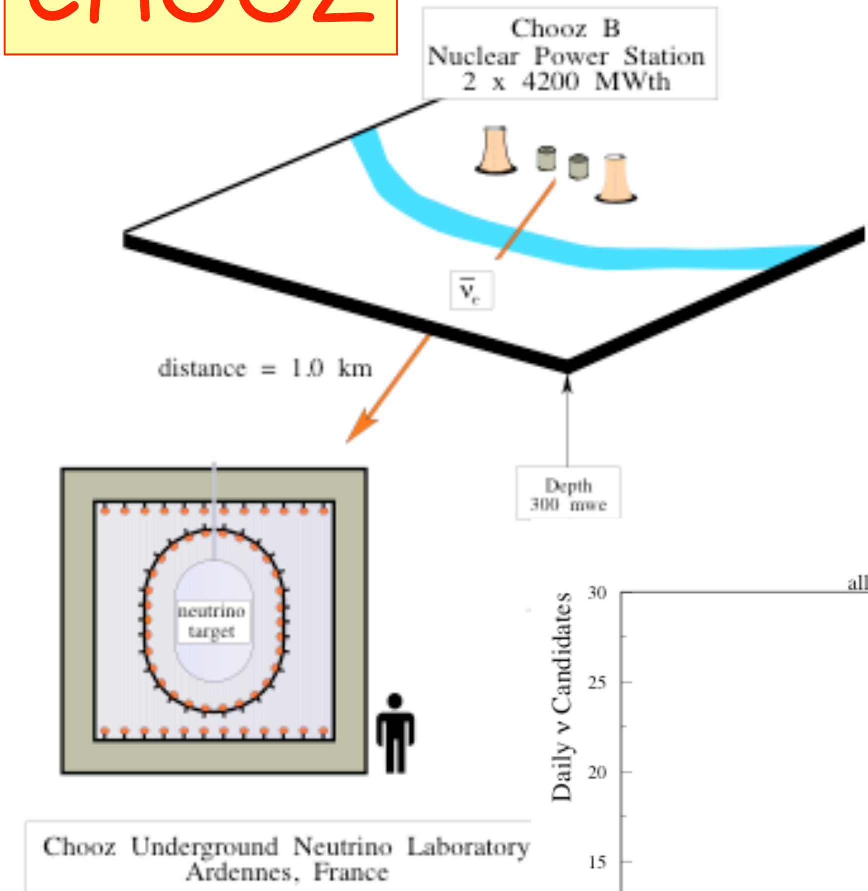


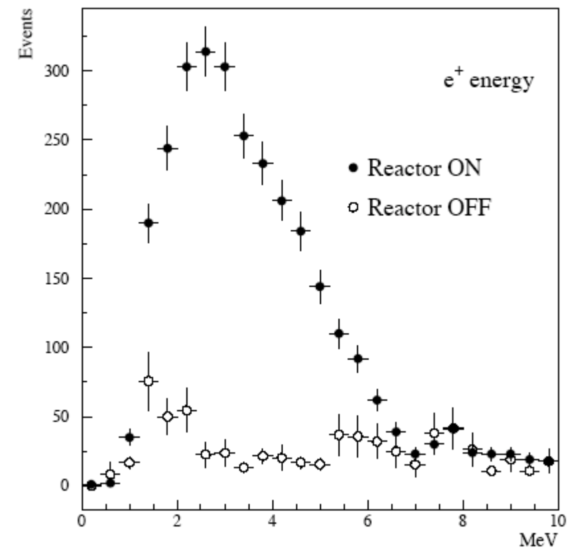
Data - BG - Geo $\bar{\nu}_e$
Expectation based on osci. parameters determined by KamLAND
Survival Probability
$L_0/E_{\bar{\nu}_e}$ (km/MeV)
0
0.2
0.4
0.6
0.8
1
20
30
40
50
60
70
80
90
100

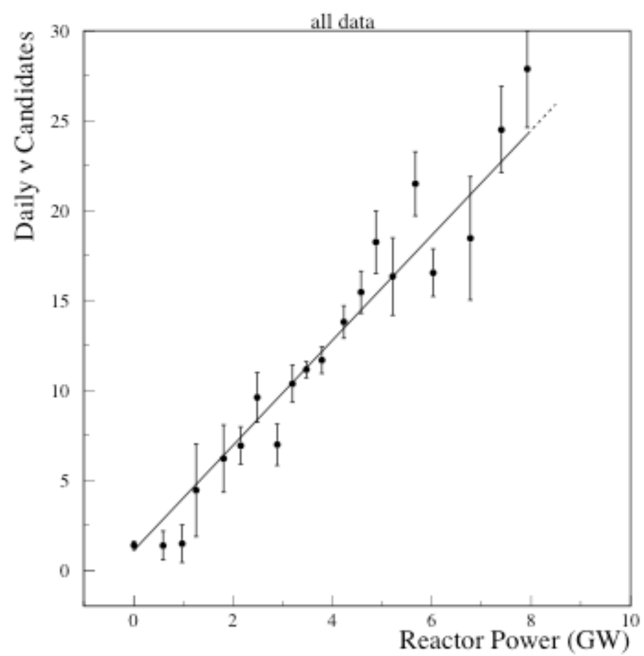


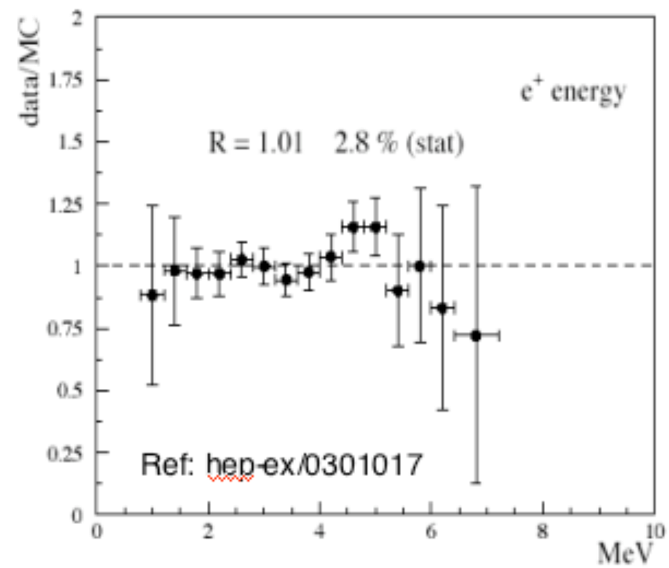
Efficiency (%)
Selection efficiency
Events / 0.425 MeV
KamLAND data
no oscillation
best-fit osci.
accidental
$^{13}C(\alpha,n)^{16}O$
best-fit Geo $\bar{\nu}_e$
best-fit osci. + BG
+ best-fit Geo $\bar{\nu}_e$
E_p (MeV)
0
1
2
3
4
5
6
7
8
50
100
150
200
250
40
60
80
100

CHOOZ


Chooz B
Nuclear Power Station
2 x 4200 MWth
distance = 1.0 km
Depth
300 mwe
neutrino
target
Chooz Underground Neutrino Laboratory
Ardennes, France


Events
e+ energy
Reactor ON
Reactor OFF
MeV

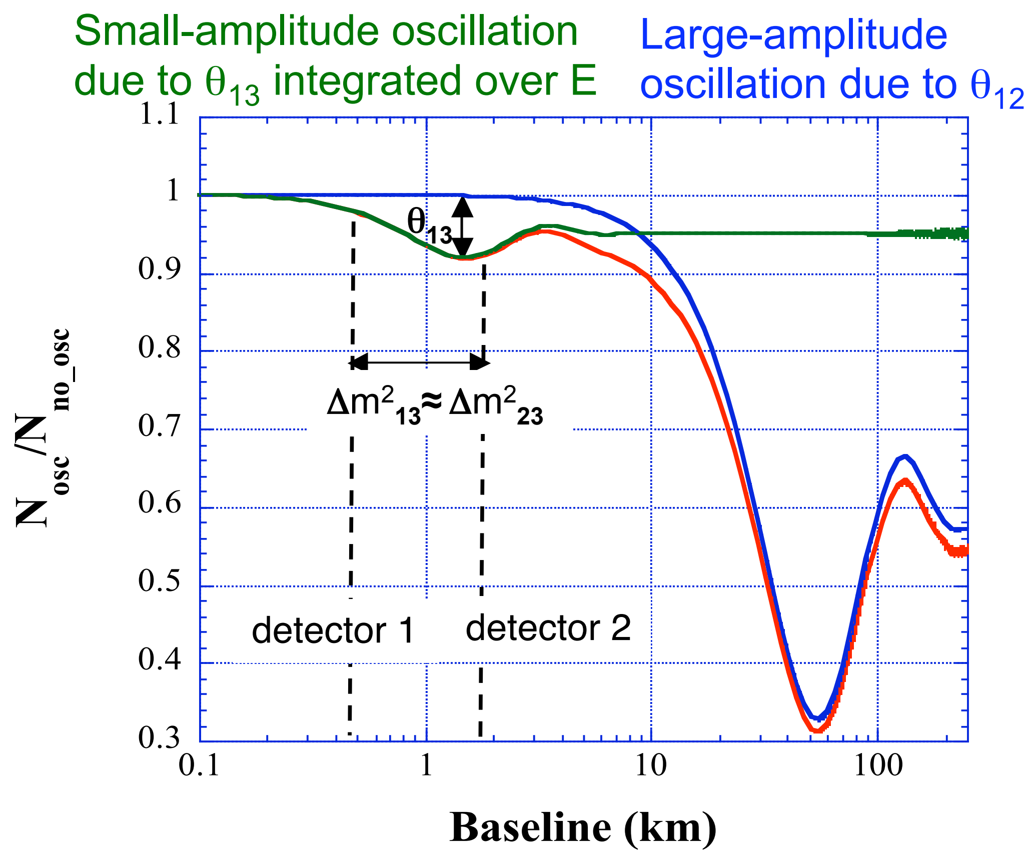

all data
Daily ν Candidates
Reactor Power (GW)


data/MC
e+ energy
R = 1.01 2.8 % (stat)
Ref: hep-ex/0301017
MeV

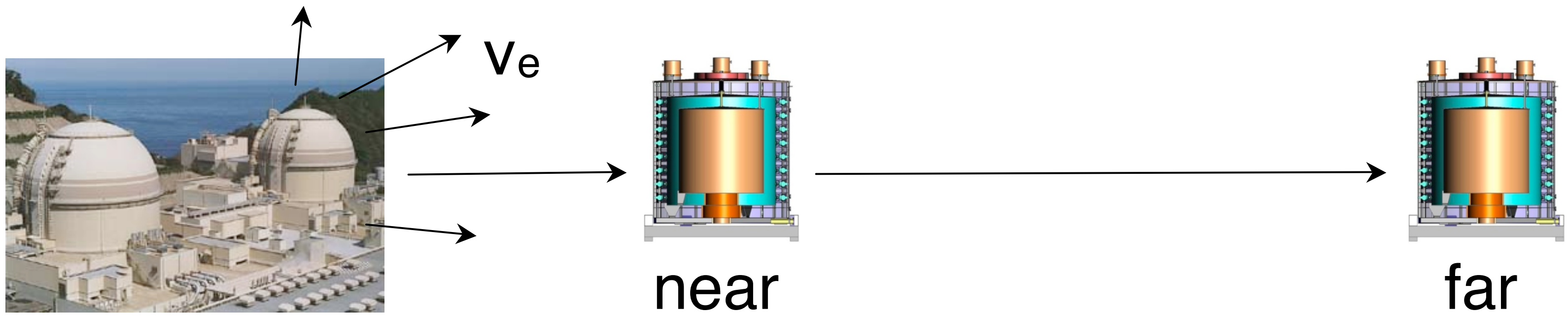
Measuring θ_{13} with Reactor Antineutrinos

$$P_{ee} \approx 1 - \sin^2 2\theta_{13} \sin^2\left(\frac{\Delta m_{31}{}^2 L}{4E_\nu}\right) - \cos^4\theta_{13} \sin^2 2\theta_{12} \sin^2\left(\frac{\Delta m_{21}{}^2 L}{4E_\nu}\right)$$

- Reactor neutrino energies are too low to produce muons. Hence this is an antineutrino disappearance experiment (also no matter effects).
- Measure ratio(s) of interaction rates in two or more detectors to cancel systematic errors.
- Those detectors will never be identical, hence one should try to control mass differences, detection efficiencies, etc.



From K. Heeger

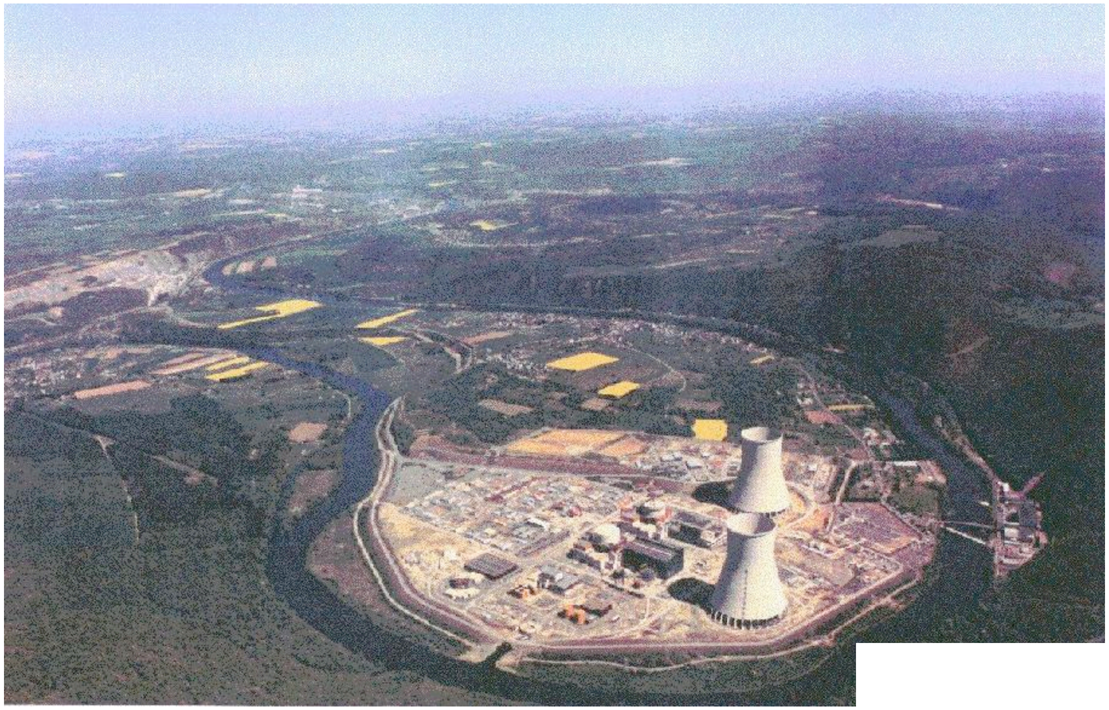


$$\frac{N_{\rm f}}{N_{\rm n}} = \left(\frac{N_{\rm p,f}}{N_{\rm p,n}}\right)\left(\frac{L_{\rm n}}{L_{\rm f}}\right)^2\left(\frac{\epsilon_{\rm f}}{\epsilon_{\rm n}}\right)\left[\frac{P_{\rm sur}(E,L_{\rm f})}{P_{\rm sur}(E,L_{\rm n})}\right]$$

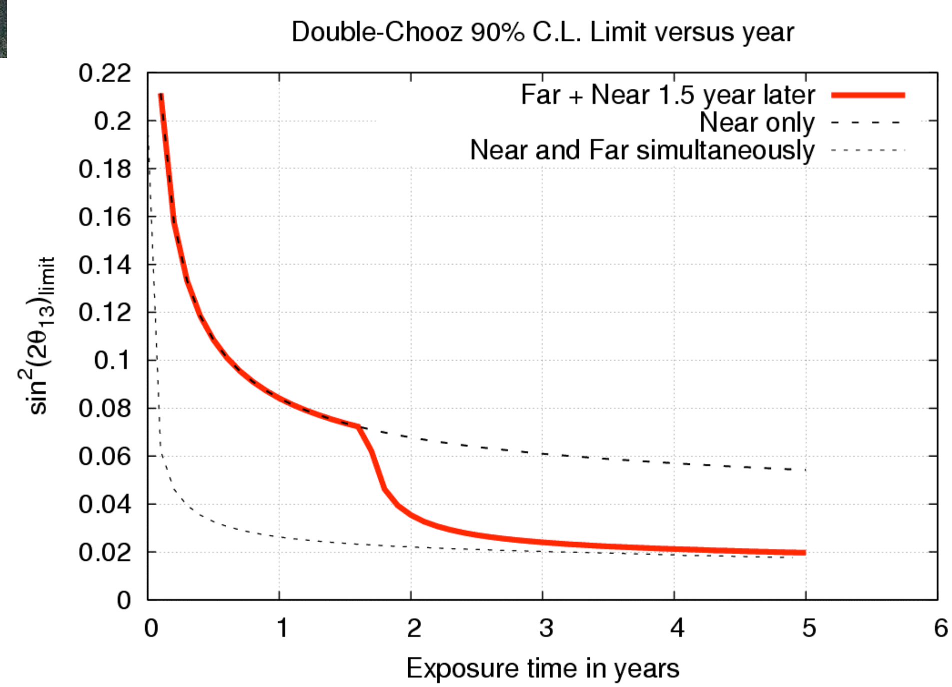
Ratio of detector masses

Ratio of detector efficiencies

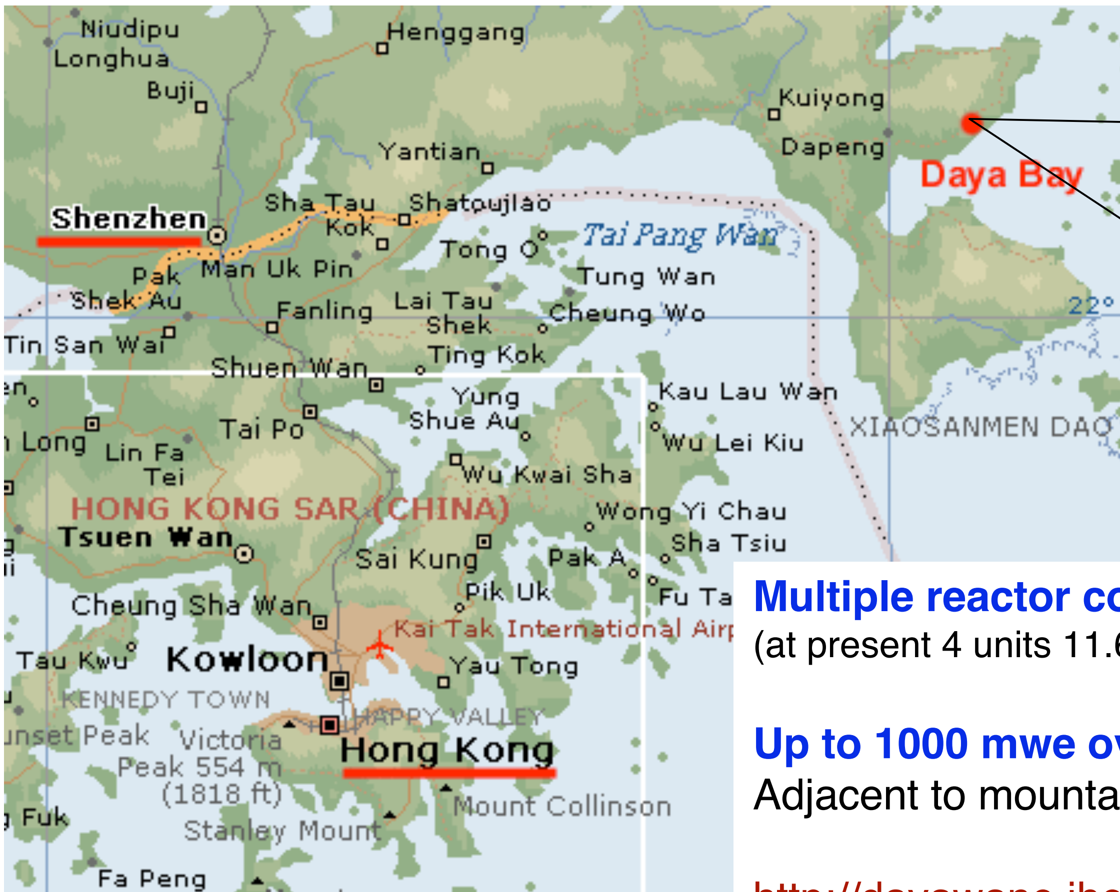
$\to \mathrm{Sin}^2\, 2\theta_{13}$

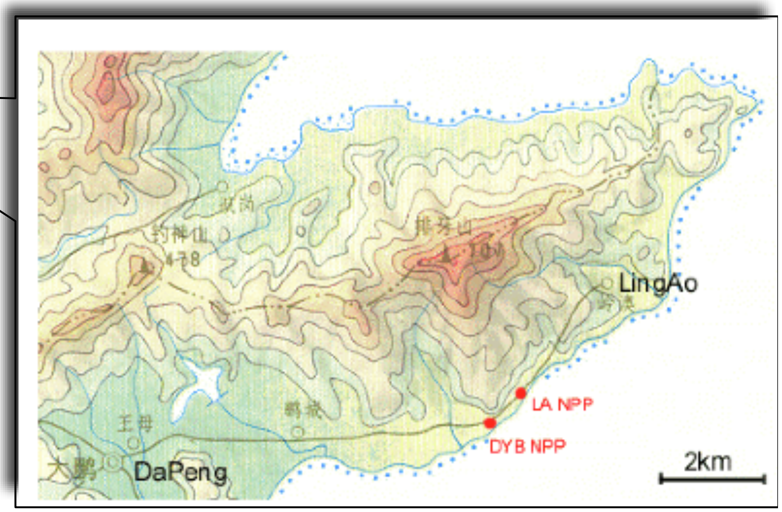


Double Chooz



Daya Bay, China

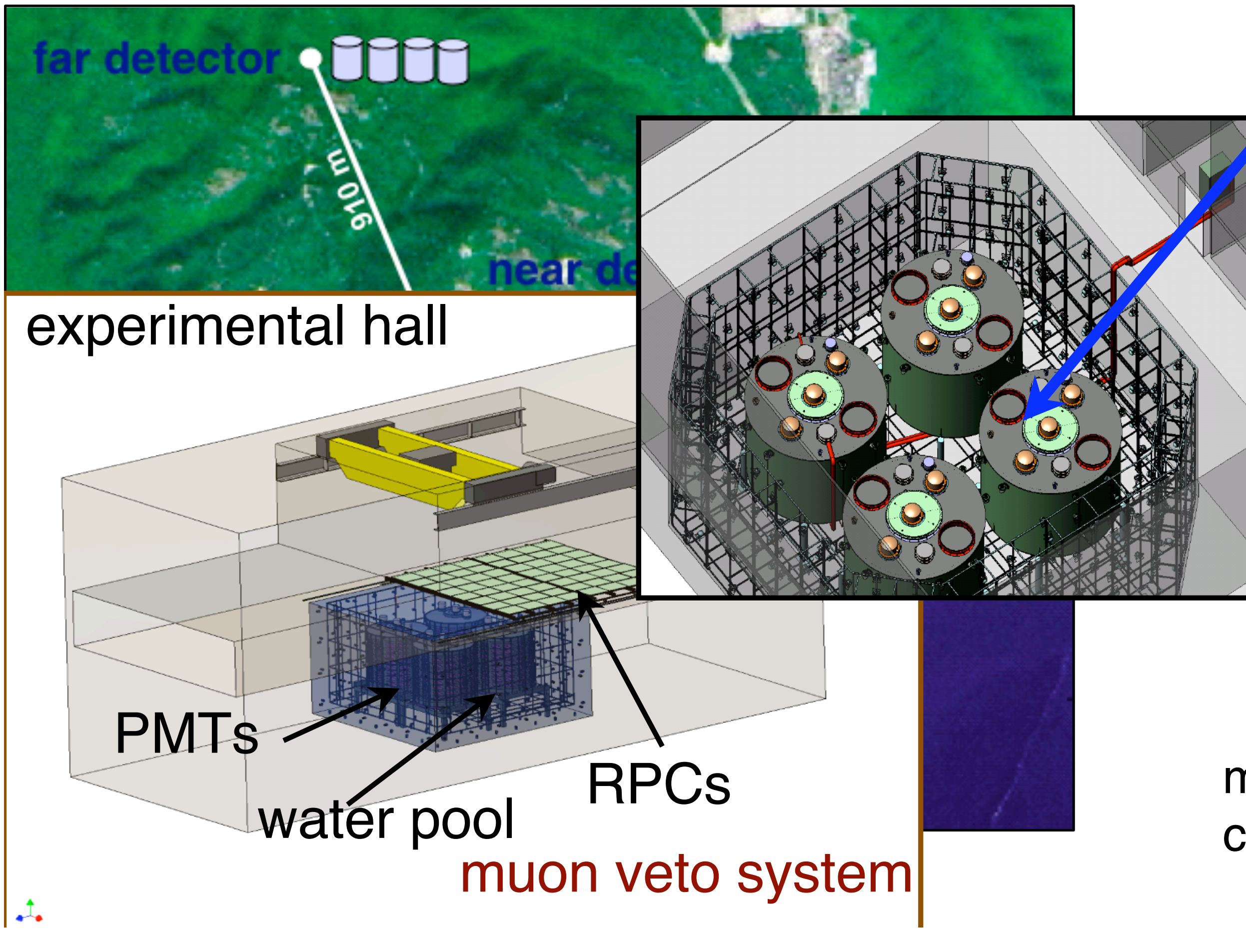


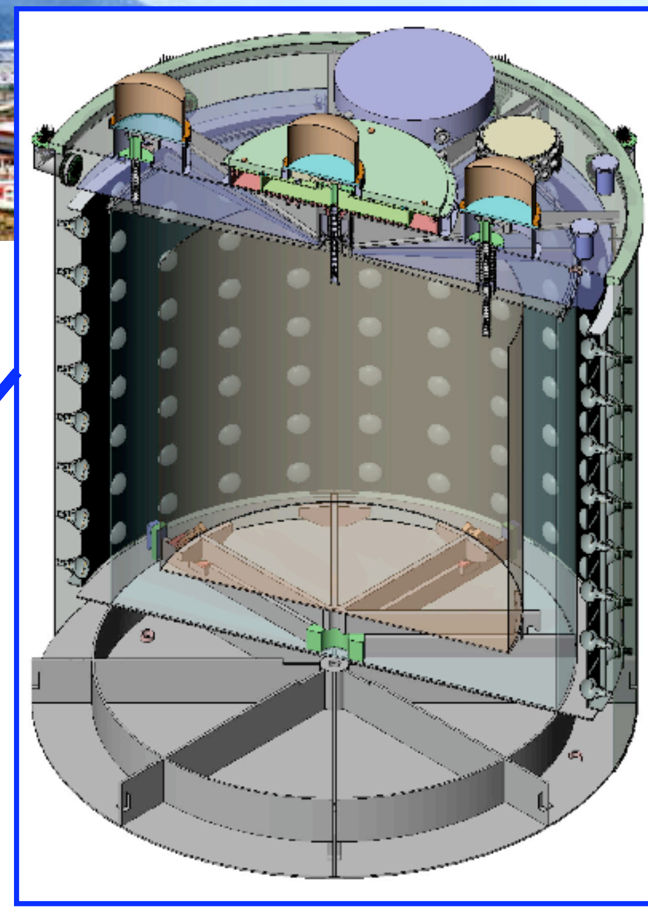


Multiple reactor cores.
(at present 4 units 11.6 GW_{th}, in 2011 6 units with 17.4 GW_{th})

Up to 1000 mwe overburden nearby.
Adjacent to mountains.

http://dayawane.ihep.ac.cn/



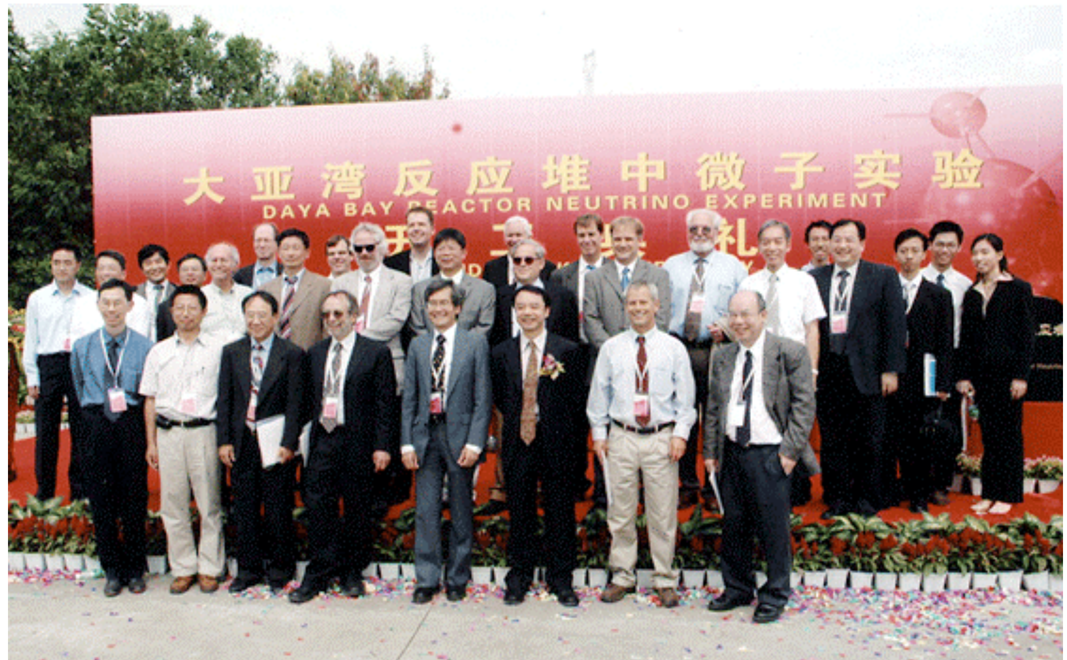


antineutrino detectors

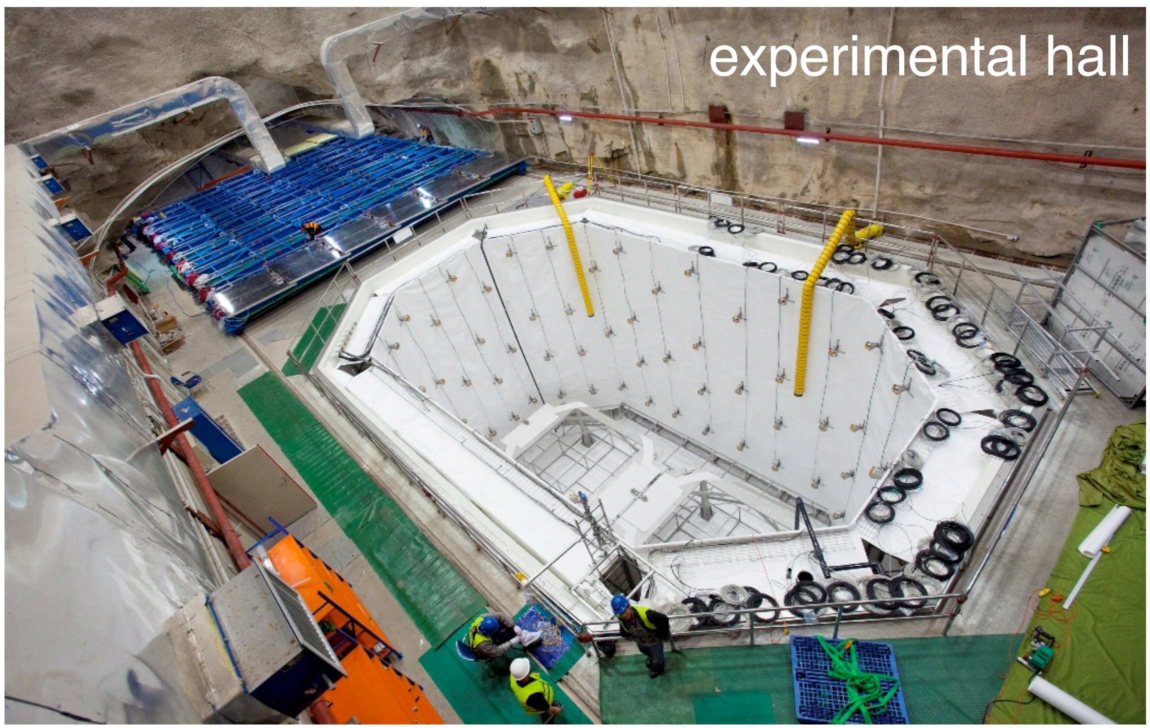
multiple detectors per site
cross-check efficiency

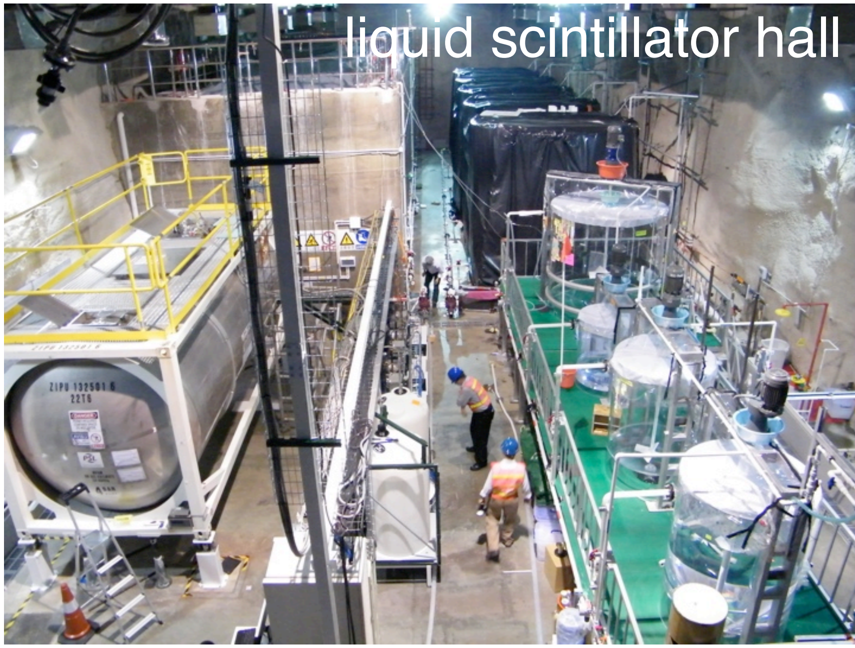
Highlights of recent progress

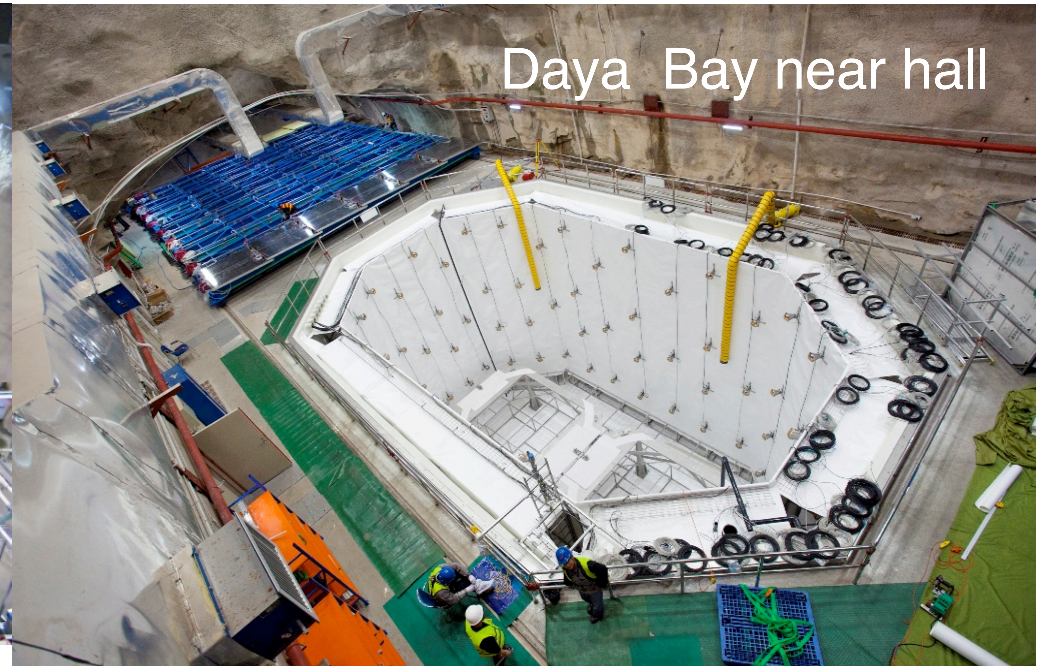
- DOE CD-3B approval on Aug. 6, 2008.
- Civil construction started blasting on Feb. 19, 2008.
- Daya Bay Ground Breaking Ceremony (Oct. 13, 2007).




tunnel


experimental hall

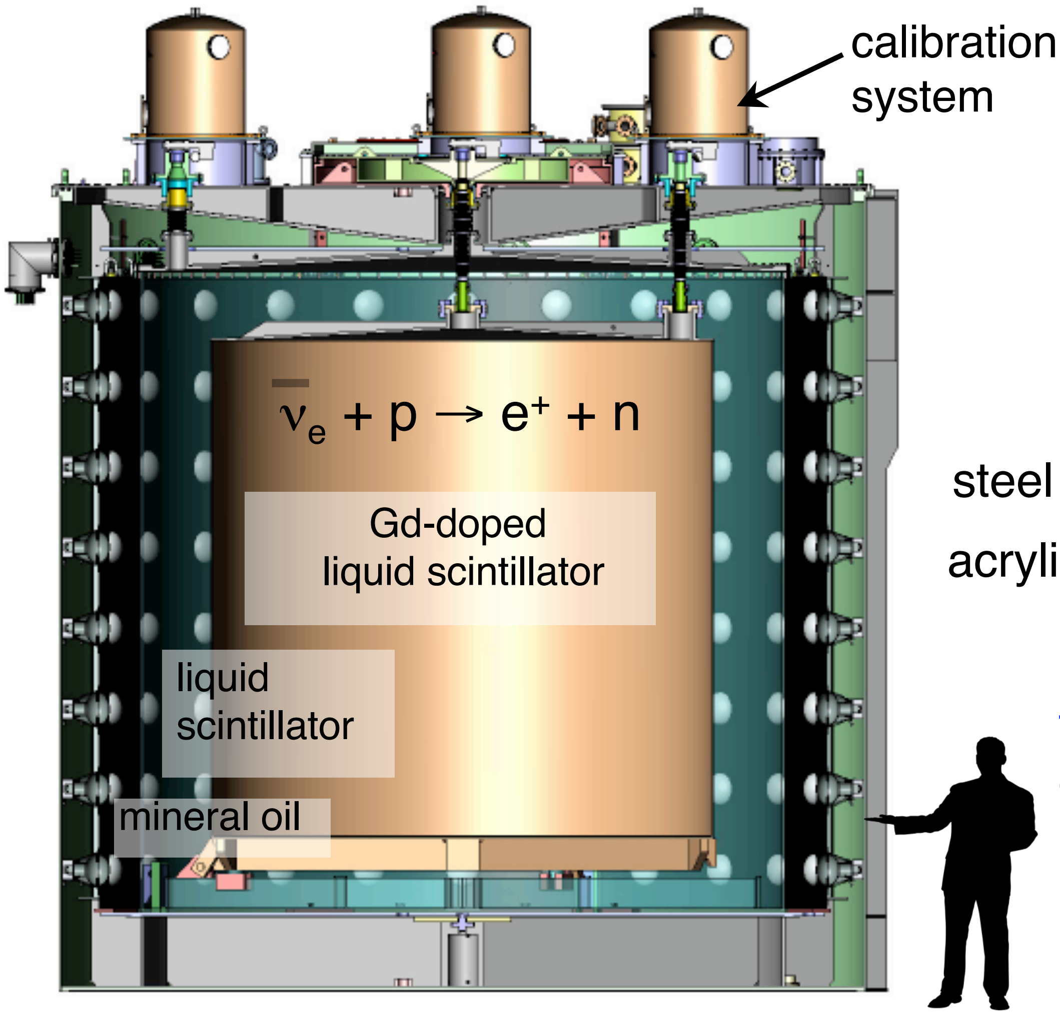

liquid scintillator hall

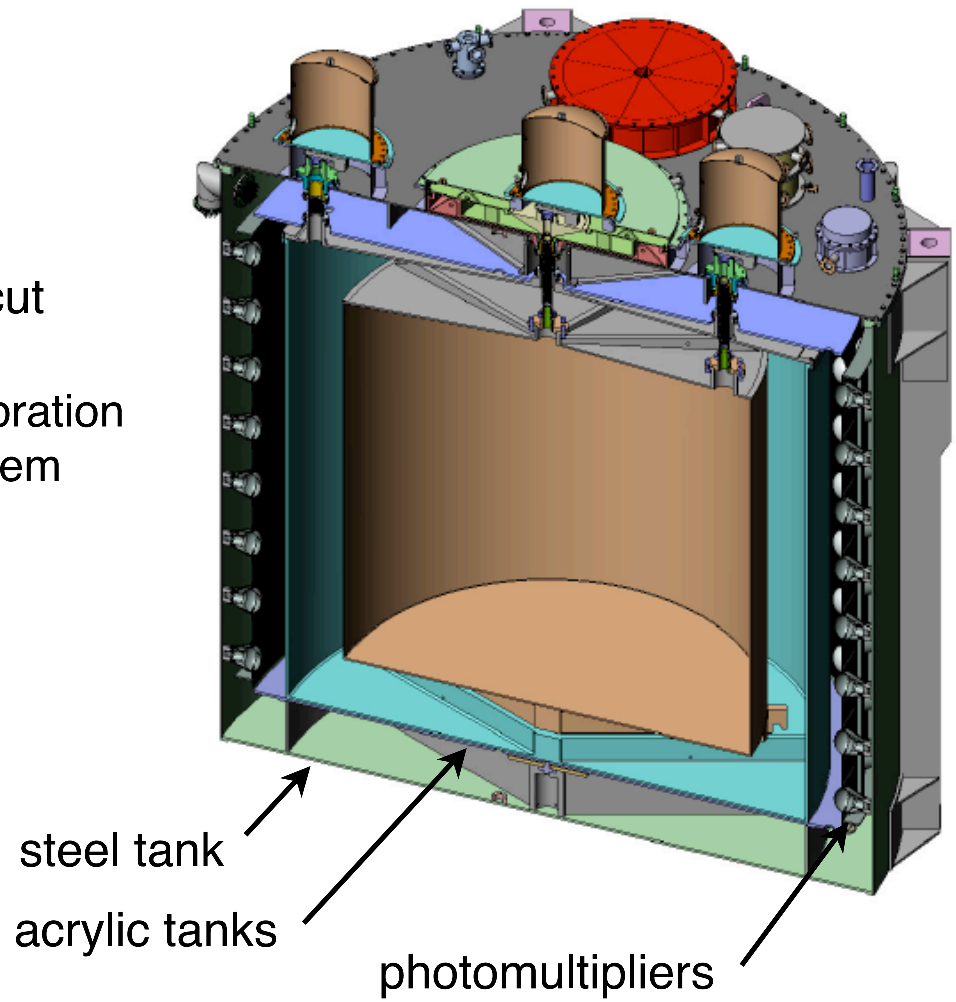

Daya Bay near hall


Ling Ao near hall

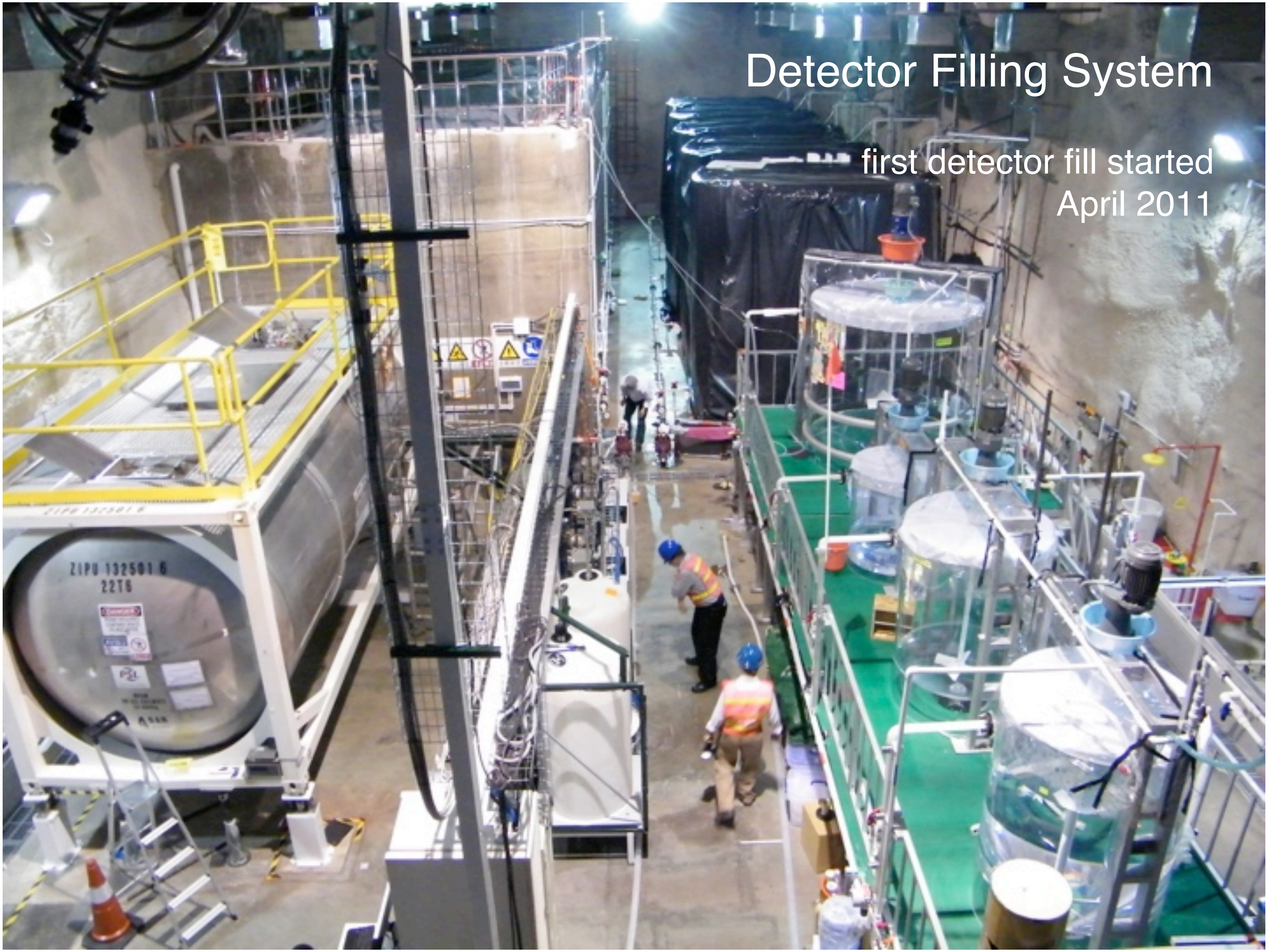

Far hall
January 2011

- 8 “identical”, 3-zone detectors
- no position reconstruction, no fiducial cut



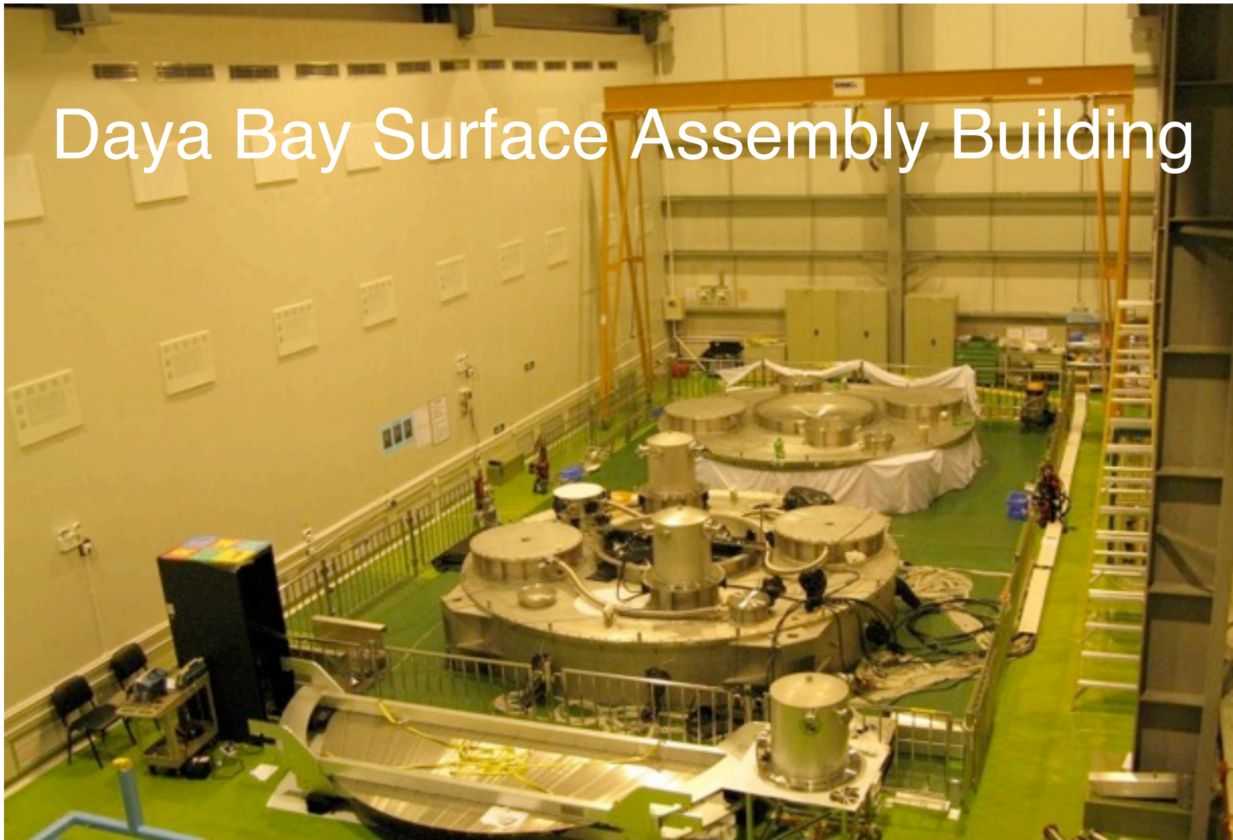


target mass:	20t per detector
detector mass:	~ 110t
photosensors:	192 PMTs
energy resolution:	12%/√E

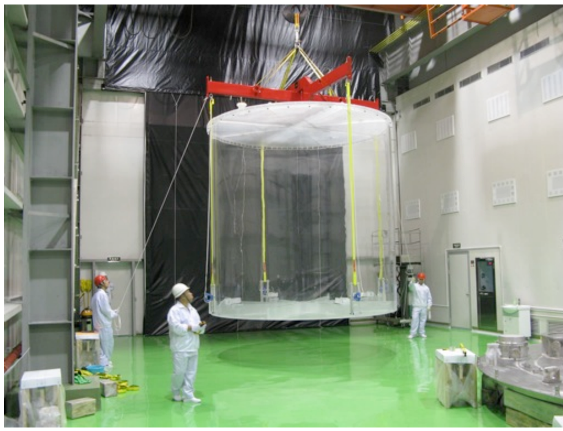

Detector Filling System
first detector fill started
April 2011
ZIPU 132501 6
22T6

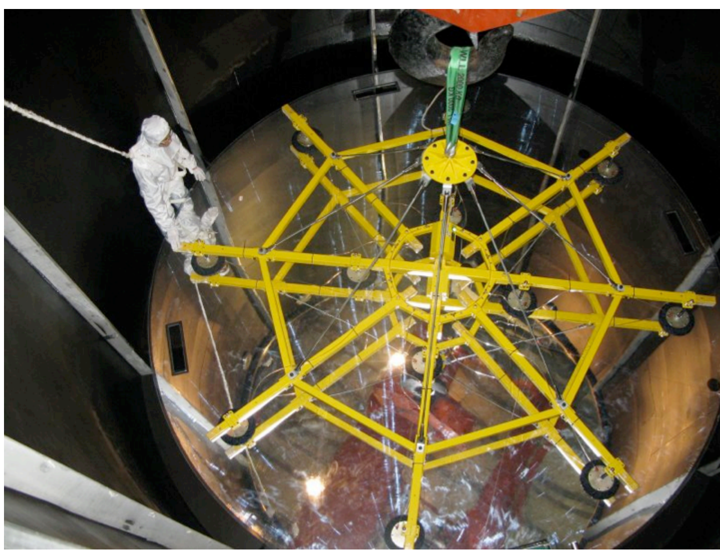

Detector Filling System
first detector fill in April 2011
ZIPU 132501 6
22T6
DANGER
PSL
4 BAR

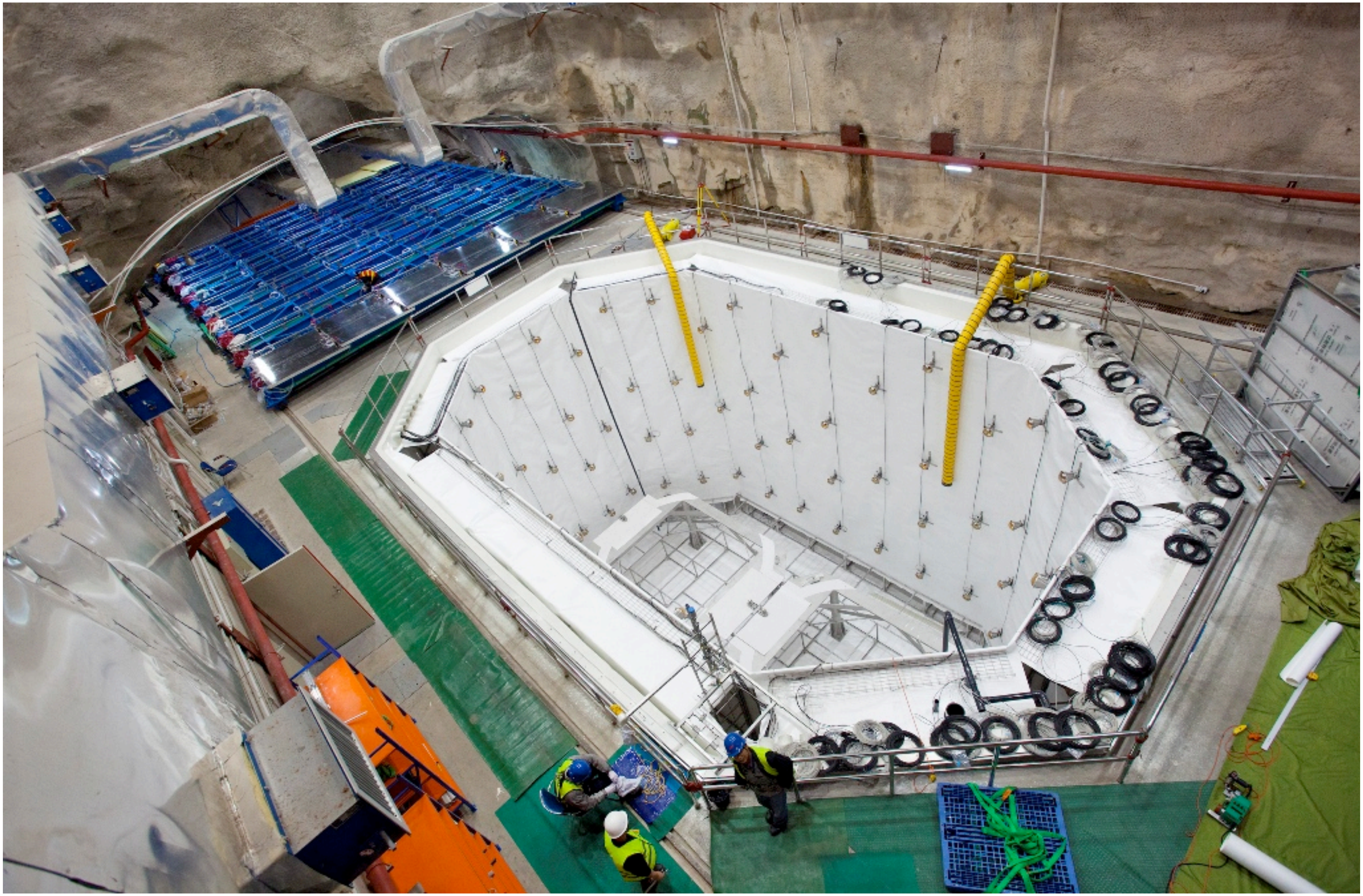
Daya Bay Surface Assembly Building

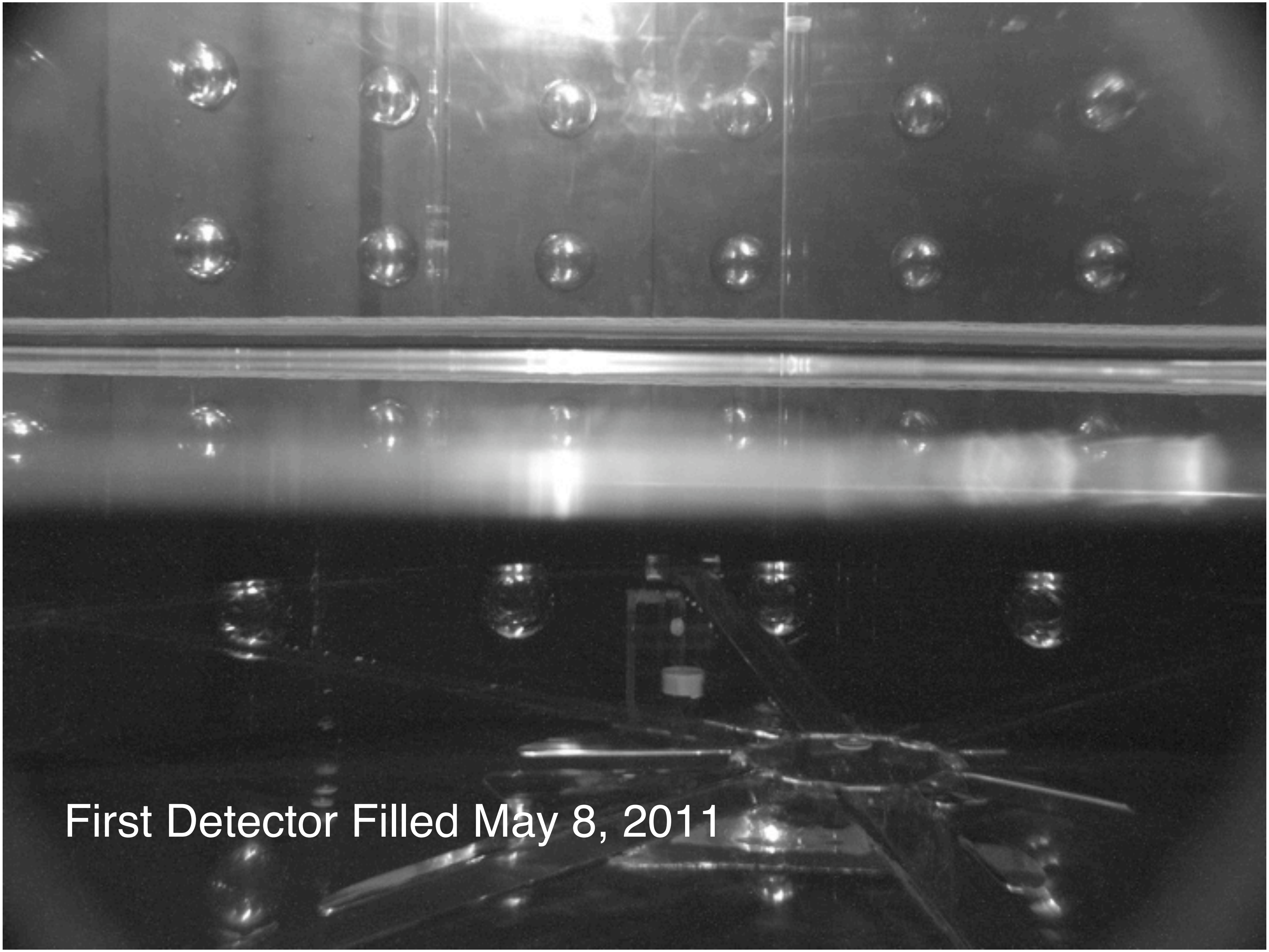


Antineutrino Detector

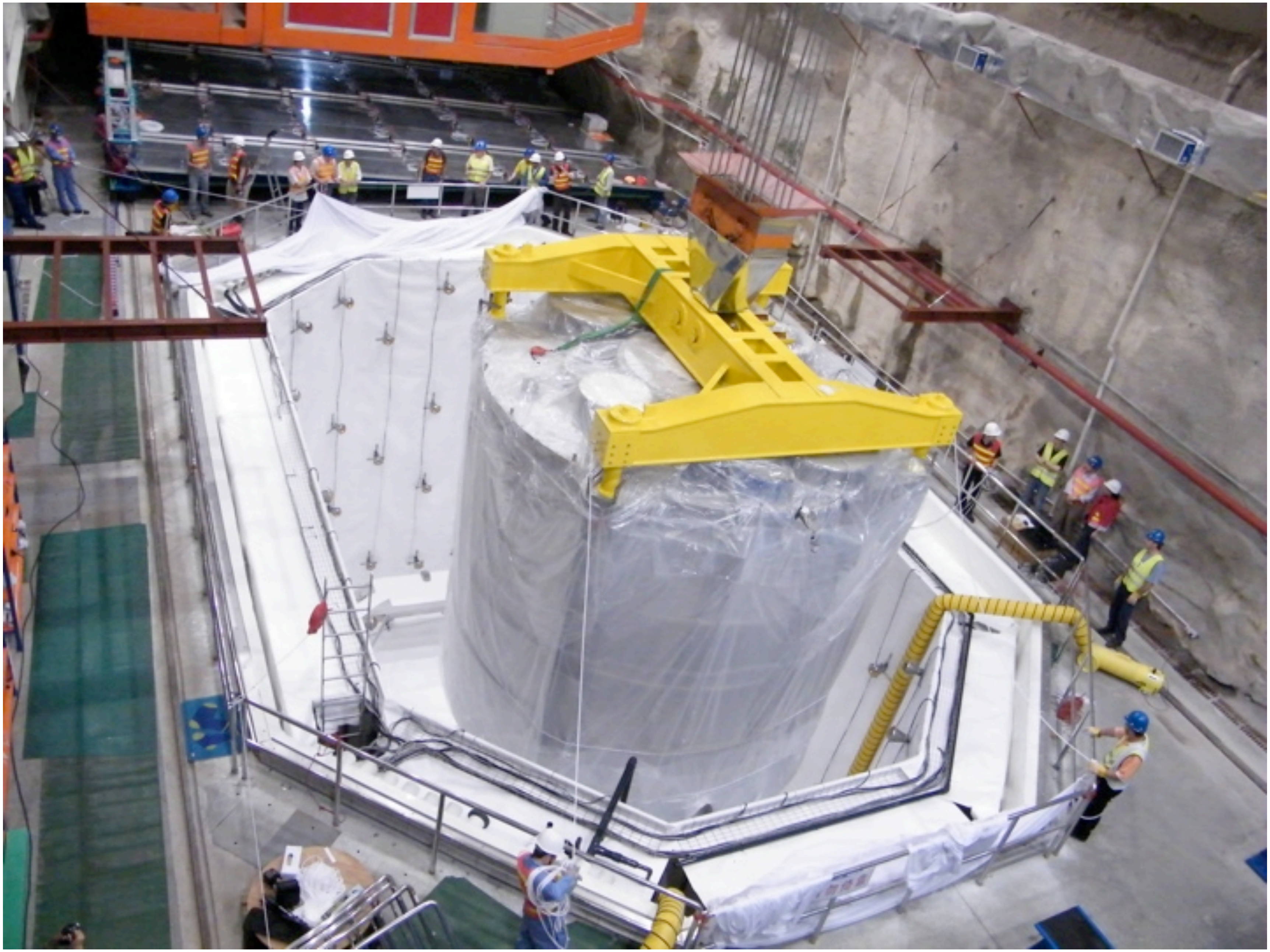


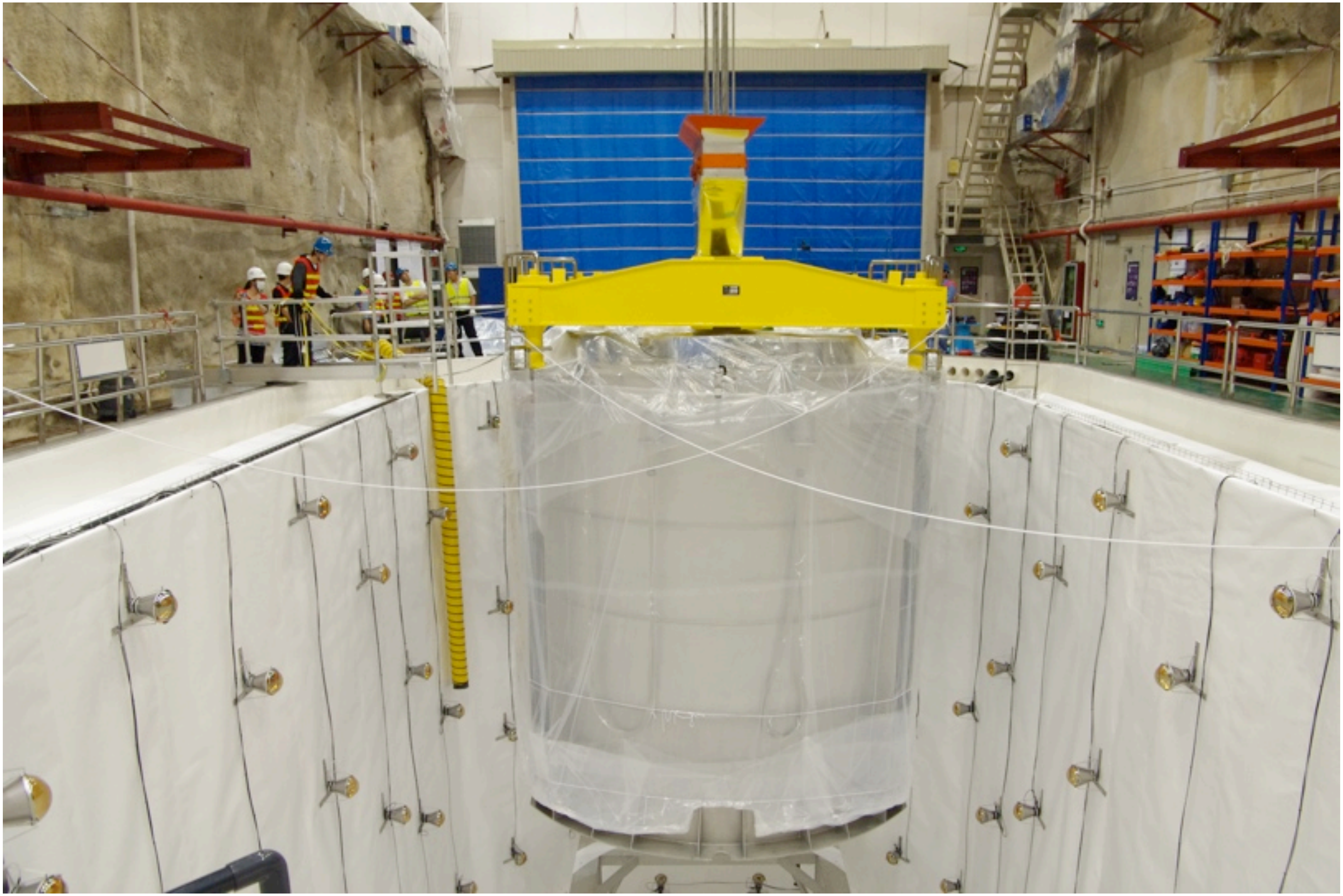



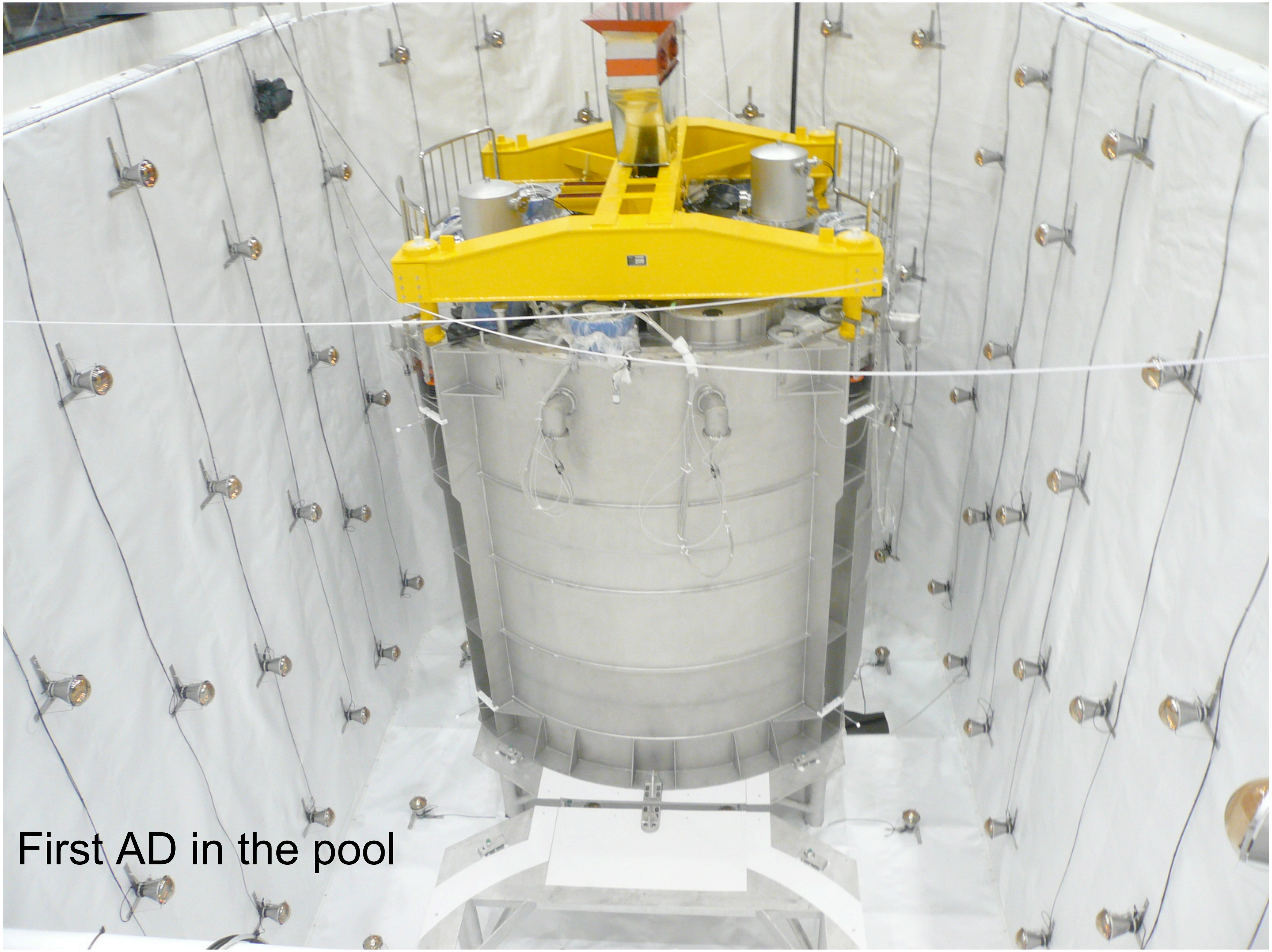




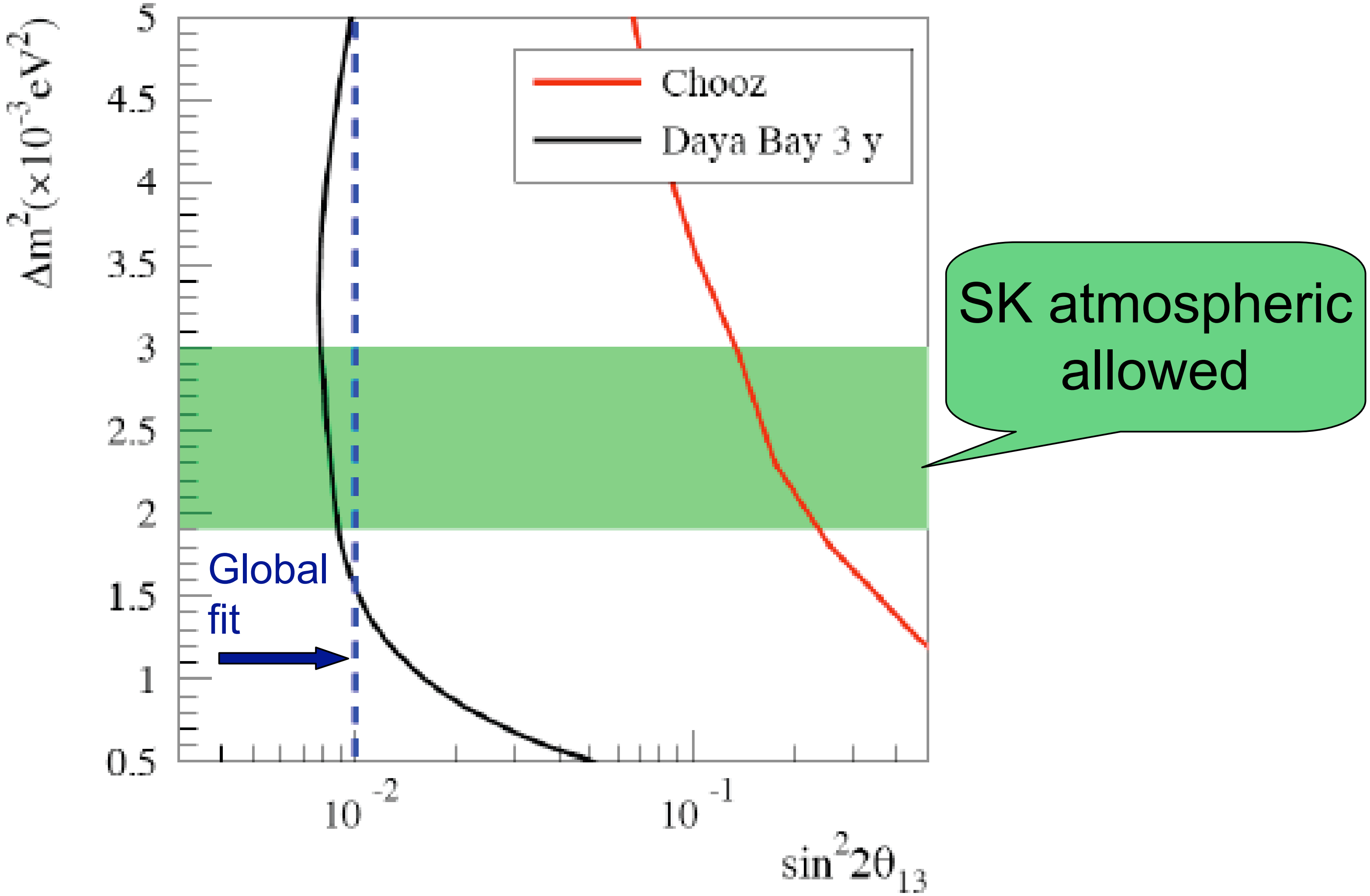
First Detector Filled May 8, 2011






First AD in the pool

Daya Bay - Site Layout

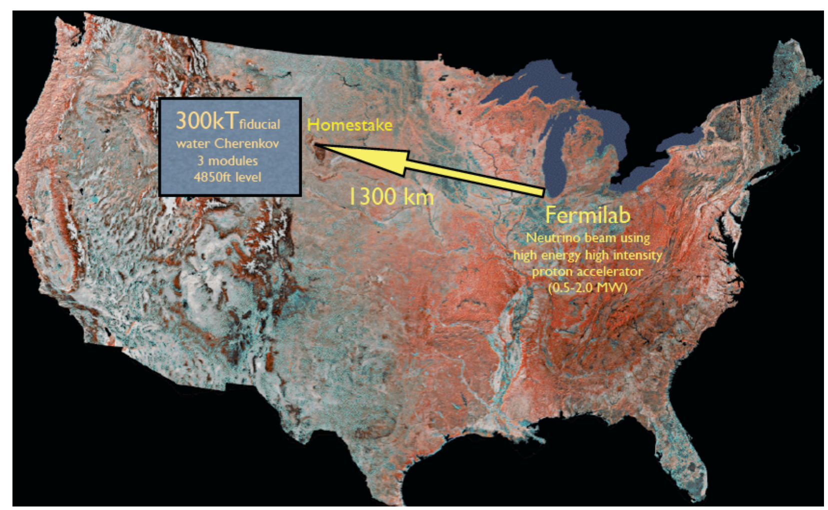

Chooz
Daya Bay 3 y
SK atmospheric allowed
Global fit
$\Delta m^2(\times 10^{-3} eV^2)$
$\sin^2 2\theta_{13}$
5
4.5
4
3.5
3
2.5
2
1.5
1
0.5
10^{-2}
10^{-1}

Long-baseline oscillations at GeV energies

Osc. max. L ~ E **+** Flux at source ~ E^2; Flux (L) = Flux (L=0)/L^2

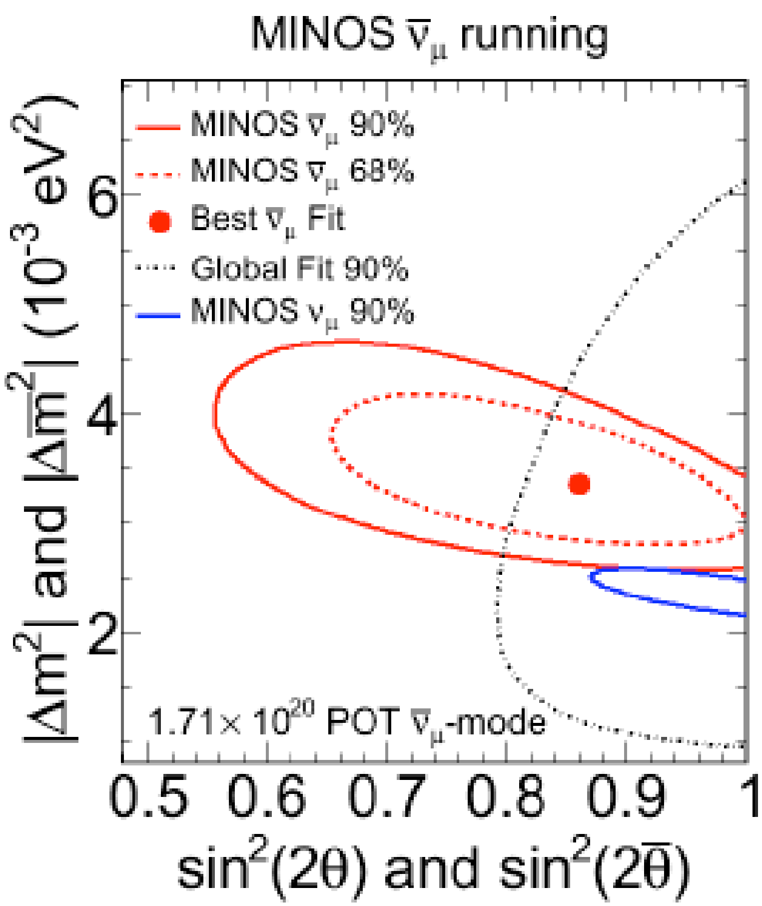
→ Flux (L) ~ 1 **+** σ ~ E (DIS)

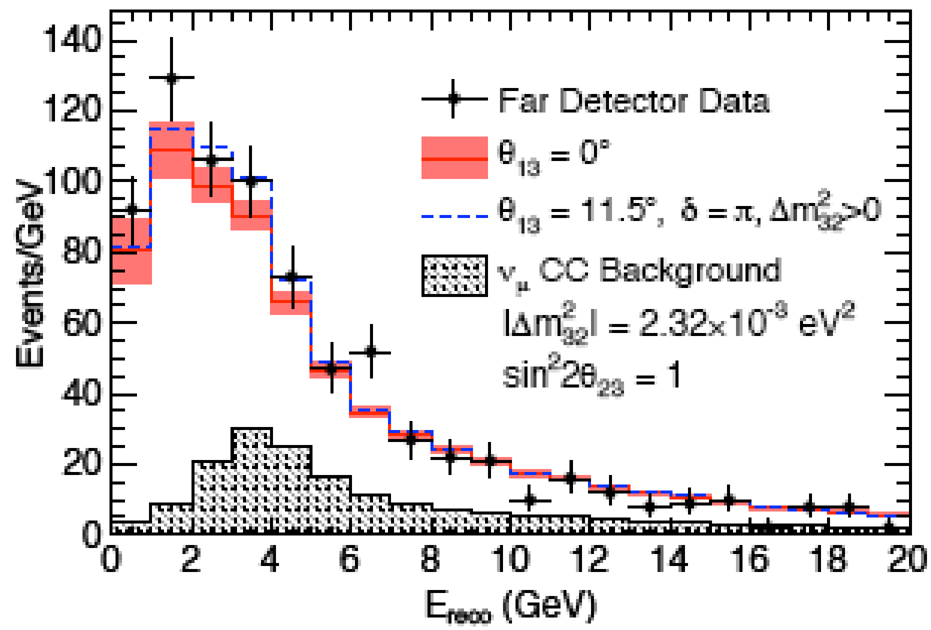
→ Event rate ~ E



MINOS results

Search for active neutrino disappearance





E_{reco} (GeV)	N_{Data}	S_{NC}	$B_{CC}^{\nu_\mu}$	$B_{CC}^{\nu_\tau}$	$B_{CC}^{\nu_e}$
0 – 3	327	248.4	33.2	3.2	3.1 (21.5)
3 – 120	475	269.6	156.0	9.2	31.2 (53.8)
0 – 3	$R = 1.16 \pm 0.07 \pm 0.08 - 0.08(\nu_e)$				
3 – 120	$R = 1.02 \pm 0.08 \pm 0.06 - 0.08(\nu_e)$				
0 – 120	$R = 1.09 \pm 0.06 \pm 0.05 - 0.08(\nu_e)$				

$$f_s = \frac{P_{\nu_\mu \to \nu_s}}{1 - P_{\nu_\mu \to \nu_\mu}} < 0.22\ (0.40)\ \text{at } 90\%\ \text{CL}$$

Matter effects in long-baseline oscillations

Example: two flavors and normal hierarchy

$$P(\nu_\mu \rightarrow \nu_e) = \mathrm{Sin}^2 2\theta \, [1 + (4\sqrt{2} G_F N_e E/\delta m^2) \, \mathrm{Cos} 2\theta]$$

$$\times \; \mathrm{Sin}^2 [(\delta m^2/4E + ..)L]$$

$$P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e) = \mathrm{Sin}^2 2\theta \, [1 - (4\sqrt{2} G_F N_e E/\delta m^2) \, \mathrm{Cos} 2\theta]$$

$$\times \; \mathrm{Sin}^2 [(\delta m^2/4E + ..)L]$$

This can be used to distinguish normal from inverted hierarchy

Matter effects mimic CP-violation!

Matter effects increase with energy, $E_{MSW} \sim 10$ GeV for Earth's mantle

Is there any reason to believe that CP-violating phase in the neutrino mixing matrix is observable? Is there an analog of the MSW effect: does the dense matter (such as in a core-collapse supernova) amplify or suppress the effects of δ?

Evolution Equation

$$i\frac{\partial}{\partial t}\begin{pmatrix}\Psi_e\\ \Psi_\mu\\ \Psi_\tau\end{pmatrix} = \left\{\mathbf{T}_{23}\mathbf{T}_{13}\mathbf{T}_{12}\begin{pmatrix}E_1 & 0 & 0\\ 0 & E_2 & 0\\ 0 & 0 & E_3\end{pmatrix}\mathbf{T}_{12}^\dagger\mathbf{T}_{13}^\dagger\mathbf{T}_{23}^\dagger + \begin{pmatrix}V_{e\mu} & 0 & 0\\ 0 & 0 & 0\\ 0 & 0 & V_{\tau\mu}\end{pmatrix}\right\}\begin{pmatrix}\Psi_e\\ \Psi_\mu\\ \Psi_\tau\end{pmatrix}$$

Evolution Equation in Rotated Basis

$$\tilde{\Psi}_\mu = \cos\theta_{23}\Psi_\mu - \sin\theta_{23}\Psi_\tau$$

$$\tilde{\Psi}_\tau = \sin\theta_{23}\Psi_\mu + \cos\theta_{23}\Psi_\tau$$

$$i\frac{\partial}{\partial t}\begin{pmatrix} \Psi_e \\ \tilde{\Psi}_\mu \\ \tilde{\Psi}_\tau \end{pmatrix} = \left\{ \mathbf{T}_{13}\mathbf{T}_{12}\begin{pmatrix} E_1 & 0 & 0 \\ 0 & E_2 & 0 \\ 0 & 0 & E_3 \end{pmatrix}\mathbf{T}_{12}^\dagger\mathbf{T}_{13}^\dagger \right.$$

$$\left. + \begin{pmatrix} V_{e\mu} & 0 & 0 \\ 0 & S_{23}^2 V_{\tau\mu} & -C_{23}S_{23}V_{\tau\mu} \\ 0 & -C_{23}S_{23}V_{\tau\mu} & C_{23}^2 V_{\tau\mu} \end{pmatrix} \right\} \begin{pmatrix} \Psi_e \\ \tilde{\Psi}_\mu \\ \tilde{\Psi}_\tau \end{pmatrix}$$

"Hamiltonian" in the Rotated Basis

We define

$$\tilde{H} = \mathbf{T}_{13}\mathbf{T}_{12}\begin{pmatrix} E_1 & 0 & 0 \\ 0 & E_2 & 0 \\ 0 & 0 & E_3 \end{pmatrix}\mathbf{T}_{12}^{\dagger}\mathbf{T}_{13}^{\dagger} + \begin{pmatrix} V_{e\mu} & 0 & 0 \\ 0 & S_{23}^2 V_{\tau\mu} & -C_{23}S_{23}V_{\tau\mu} \\ 0 & -C_{23}S_{23}V_{\tau\mu} & C_{23}^2 V_{\tau\mu} \end{pmatrix}$$

μ - τ Symmetry

If we can neglect the potential $V_{\tau\mu}$ we can write

$$\tilde{H} = \mathbf{T}_{13}\mathbf{T}_{12}\begin{pmatrix} E_1 & 0 & 0 \\ 0 & E_2 & 0 \\ 0 & 0 & E_3 \end{pmatrix}\mathbf{T}_{12}^{\dagger}\mathbf{T}_{13}^{\dagger} + \begin{pmatrix} V_{e\mu} & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix}$$

It is straightforward to show that

$$\tilde{H}(\delta) = \mathbf{S}\tilde{H}(\delta = 0)\mathbf{S}^{\dagger}$$

with

$$\mathbf{S} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & e^{i\delta} \end{pmatrix}$$

Neutrino Evolution Equations

We need to solve

$$i\frac{d\mathbf{U}}{dt} = \tilde{H}\mathbf{U}, \quad \text{with } \mathbf{U}(t=0) = 1.$$

It is easy to show that

$$\tilde{H}(\delta) = \mathbf{S}\tilde{H}(\delta = 0)\mathbf{S}^\dagger \Leftrightarrow \mathbf{U}(\delta) = \mathbf{S}\mathbf{U}(\delta = 0)\mathbf{S}^\dagger.$$

Survival Amplitude Relations

Define the amplitude for the process $\nu_x \to \nu_y$ to be

$$A_{xy} \quad \text{when} \quad \delta \neq 0$$

$$B_{xy} \quad \text{when} \quad \delta = 0$$

$$P(\nu_x \to \nu_y, \delta \neq 0) = |A_{xy}|^2$$

$$P(\nu_x \to \nu_y, \delta = 0) = |B_{xy}|^2$$

$$\mathbf{U}(\delta) = \mathbf{S}\mathbf{U}(\delta = 0)\mathbf{S}^\dagger \Longrightarrow$$

$$\begin{pmatrix} A_{ee} & A_{e\tilde{\mu}} & A_{e\tilde{\tau}} \\ A_{\tilde{\mu}e} & A_{\tilde{\mu}\tilde{\mu}} & A_{\tilde{\mu}\tilde{\tau}} \\ A_{\tilde{\tau}e} & A_{\tilde{\tau}\tilde{\mu}} & A_{\tilde{\tau}\tilde{\tau}} \end{pmatrix} = \begin{pmatrix} B_{ee} & B_{e\tilde{\mu}} & B_{e\tilde{\tau}}e^{-i\delta} \\ B_{\tilde{\mu}e} & B_{\tilde{\mu}\tilde{\mu}} & B_{\tilde{\mu}\tilde{\tau}}e^{-i\delta} \\ B_{\tilde{\tau}e}e^{i\delta} & B_{\tilde{\tau}\tilde{\mu}}e^{i\delta} & B_{\tilde{\tau}\tilde{\tau}} \end{pmatrix}$$

These considerations give us interesting sum rules:

- Electron neutrino survival probability, P ($\nu_e \rightarrow \nu_e$) is independent of the value of the CP-violating phase, δ; or equivalently

- The combination P ($\nu_\mu \rightarrow \nu_e$) + P ($\nu_\tau \rightarrow \nu_e$) at a fixed energy is also independent of the value of the CP-violating phase. Balantekin, Gava, Volpe

- It is possible to derive similar sum rules for other amplitudes. Kneller, McLaughlin

Matter Potentials including Loop Corrections

$$V_{e\mu} = 2\sqrt{2} G_F N_e \left\{ 1 + \mathcal{O}\left(\alpha \frac{m_\mu}{m_W}^2 \right) \right\}$$

$$V_{\tau\mu} = -\frac{3\sqrt{2} G_F \alpha}{\pi \sin^2 \theta_W} \left(\frac{m_\tau}{m_W} \right)^2 \left\{ (N_p + N_n) \log \frac{m_\tau}{m_W} + \left(\frac{N_p}{2} + \frac{N_n}{3} \right) \right\}$$

Probably too small in most cases!

Typical Appearance Experiment

$$P_{\nu_\mu \to \nu_e} \sim \frac{\sin^2 2\theta_{13} \sin^2 \theta_{23}}{(1 - 2\sqrt{2} G_F N_e E / \delta m^2)^2} \sin^2 \left[\left(\frac{\delta m^2_{31}}{4E} - \frac{G_F N_e}{\sqrt{2}} \right) L \right]$$

$$+\mathcal{O}(g)$$

$$g = \frac{\delta m^2_{21}}{\delta m^2_{31}} \sim 0.03$$

Typical Appearance Experiment

$$P_{\nu_\mu \to \nu_e} \sim \frac{\sin^2 2\theta_{13} \sin^2 \theta_{23}}{(1 - 2\sqrt{2} G_F N_e E / \delta m^2)^2} \sin^2 \left[\left(\frac{\delta m^2_{31}}{4E} - \frac{G_F N_e}{\sqrt{2}} \right) L \right]$$

$$- \quad g \frac{\sin 2\theta_{13} \sin 2\theta_{12} \sin 2\theta_{23}}{(1/2 - 2\sqrt{2} G_F N_e E / \delta m^2_{31}) - 1/4} \cos \left(\delta + \frac{\delta m^2_{31} L}{4E} \right)$$

$$\times \quad \cos \left(\frac{\delta m^2_{31} L}{4E} \right) \sin \left(\frac{G_F N_e L}{\sqrt{2}} \right) \sin \left[\left(\frac{\delta m^2_{31}}{4E} - \frac{G_F N_e}{\sqrt{2}} \right) L \right]$$

$$+ \quad \mathcal{O}(g^2)$$

$$g = \frac{\delta m^2_{21}}{\delta m^2_{31}} \sim 0.03$$

Typical Appearance Experiment

$$
\begin{aligned}
P_{\nu_\mu \to \nu_e} &\sim \frac{\sin^2 2\theta_{13} \sin^2 \theta_{23}}{(1 - 2\sqrt{2} G_F N_e E / \delta m^2)^2} \sin^2 \left[\left(\frac{\delta m^2_{31}}{4E} - \frac{G_F N_e}{\sqrt{2}} \right) L \right] \\
- \quad & g \frac{\sin 2\theta_{13} \sin 2\theta_{12} \sin 2\theta_{23}}{(1/2 - 2\sqrt{2} G_F N_e E / \delta m^2_{31}) - 1/4} \cos \left(\delta + \frac{\delta m^2_{31} L}{4E} \right) \\
\times \quad & \cos \left(\frac{\delta m^2_{31} L}{4E} \right) \sin \left(\frac{G_F N_e L}{\sqrt{2}} \right) \sin \left[\left(\frac{\delta m^2_{31}}{4E} - \frac{G_F N_e}{\sqrt{2}} \right) L \right] \\
+ \quad & \mathcal{O}(g^2)
\end{aligned}
$$

Is equal to
zero for
the magic baseline

$$g = \frac{\delta m^2_{21}}{\delta m^2_{31}} \sim 0.03$$

Reactor and long-baseline neutrino experiments aim to answer a long list of physics questions:

• The value of θ_{13}.

• Mass hierarchy.

• Deviations from maximal θ_{23} (*i.e.* deviations from the peculiar ν_μ-ν_τ symmetry).

• Testing the unitarity of the neutrino mixing matrix (*i.e.* sterile neutrinos).

• The value of the CP-violating phase, δ.

• Possible new physics, non-standard interactions, *etc.*

After the ongoing reactor experiments the next step is an experiment with L/E sensitive to atmospheric δm^2 (L/E ~ 500 km/GeV)!