Search for θ_{13} at Daya Bay

On behalf of the Daya Bay Collaboration

Deb Mohapatra

Virginia Tech

DPF 2009

2009 Meeting of the Division of Particles and Fields of the American Physical Society (DPF 2009)

26-31 JULY 2009

Wayne State University, Detroit, MI

Outline

- The neutrino mixing matrix and the mixing angle θ_{13}
- Reactor neutrino experiments
- Daya Bay experimental setup
- Expected signal and background rates
- Systematics and sensitivity
- Current status
- Summary

The neutrino mixing (MNS) matrix

- The MNS matrix relates the mass eigenstates (ν_1, ν_2 and ν_3) to the flavor eigenstates (ν_e, ν_μ and ν_τ)

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

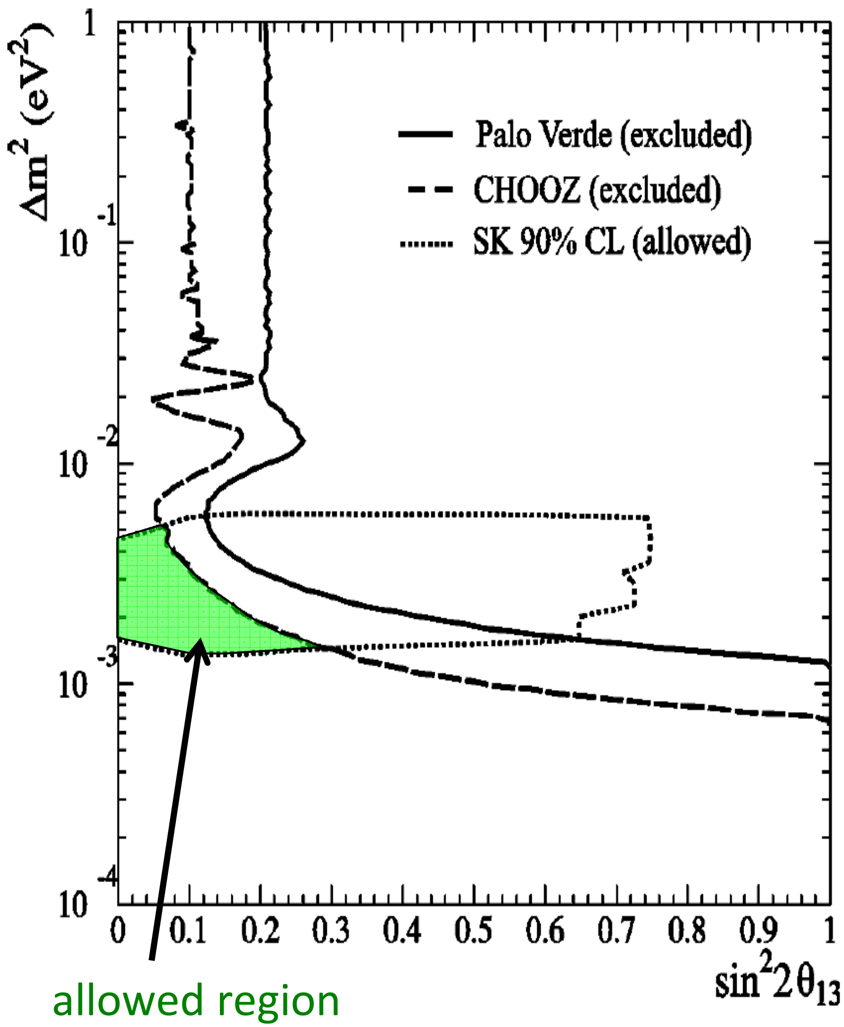
Last unknown matrix element

- It can be described by three 2D rotations

$$U_{MNS} = \underbrace{\begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\theta_{23} & \sin\theta_{23} \\ 0 & -\sin\theta_{23} & \cos\theta_{23} \end{pmatrix}}_{\text{Atmospheric}} \underbrace{\begin{pmatrix} \cos\theta_{13} & 0 & e^{i\delta}\sin\theta_{13} \\ 0 & 1 & 0 \\ -e^{i\delta}\sin\theta_{13} & 0 & \cos\theta_{13} \end{pmatrix}}_{\text{Reactor}} \underbrace{\begin{pmatrix} \cos\theta_{12} & \sin\theta_{12} & 0 \\ -\sin\theta_{12} & \cos\theta_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}}_{\text{Solar}} \underbrace{\begin{pmatrix} 1 & 0 & 0 \\ 0 & e^{i\alpha} & 0 \\ 0 & 0 & e^{i\beta} \end{pmatrix}}_{\text{Majorana Phases}}$$

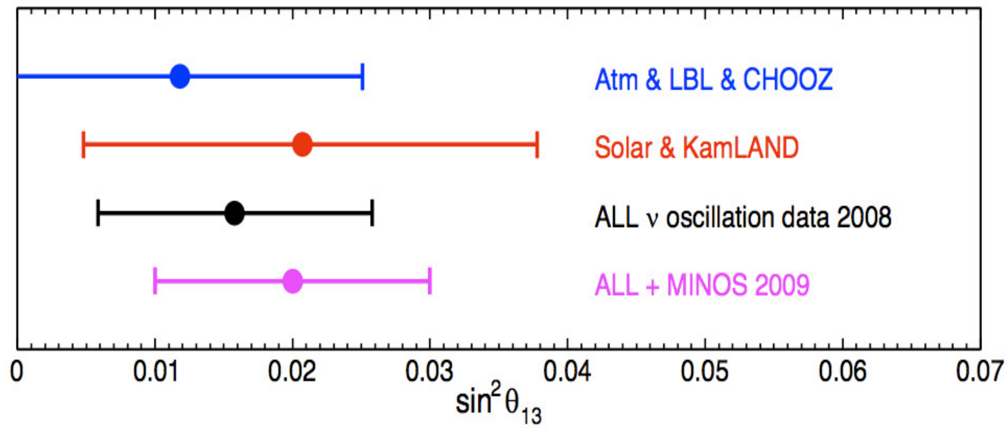
- If θ_{13} is zero there is no CP violation in neutrino mixing

Existing limit on θ_{13}



Hints for $\theta_{13} \neq 0$

Global Fit Results



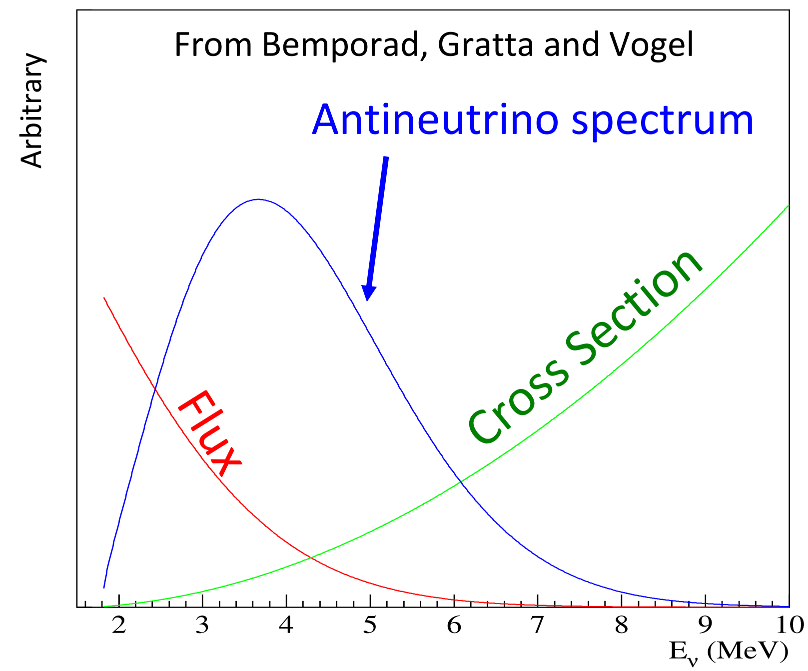
$\mathrm{Sin}^2\theta_{13} = 0.016 \pm 0.010$ or $\mathrm{Sin}^2 2\theta_{13} = 0.06 \pm 0.04$

[E. Lisi, *et al.*, arXiv: 0905.3549]

Nuclear reactors as antineutrino source

- Fission process in nuclear reactor produces huge number of low-energy antineutrino
- A typical commercial reactor, with 3 GW thermal power, produces $6\times10^{20}\,\overline{\nu}_e$/s
- Daya Bay reactors produce 11.6 GW_{th} now, 17.4 GW_{th} in 2011

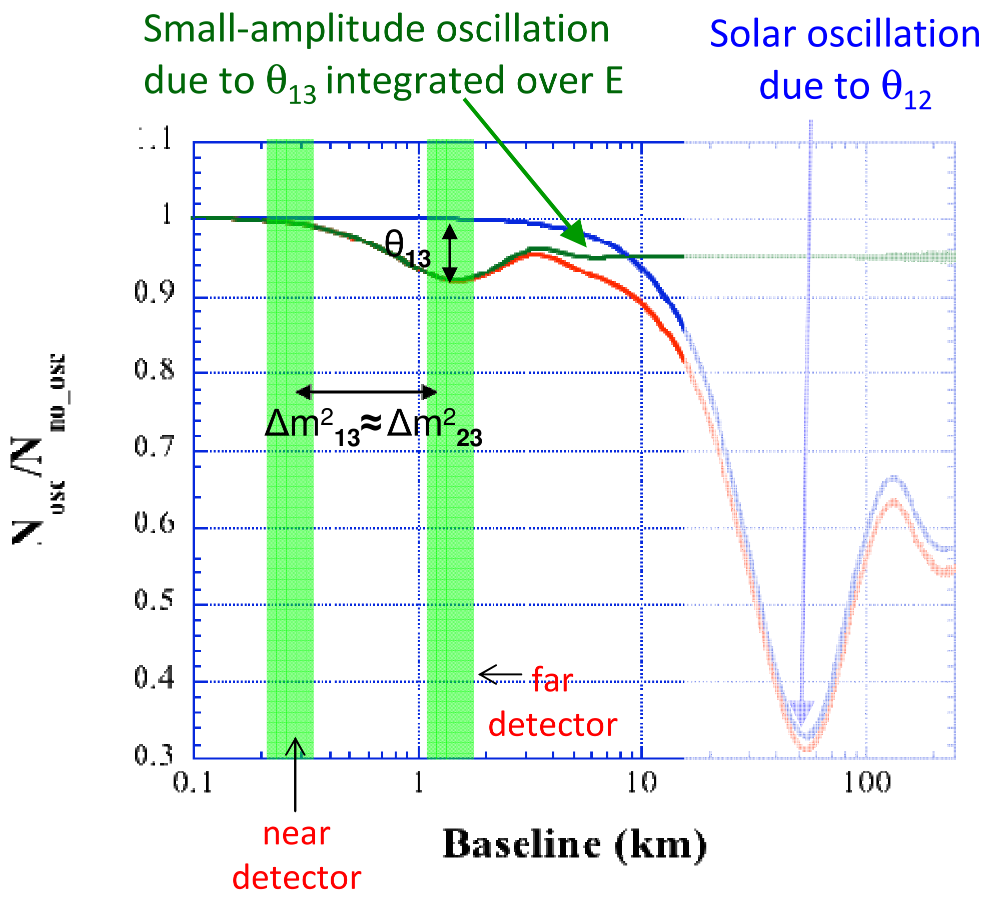
- The observable antineutrino spectrum is the product of the flux and the cross section

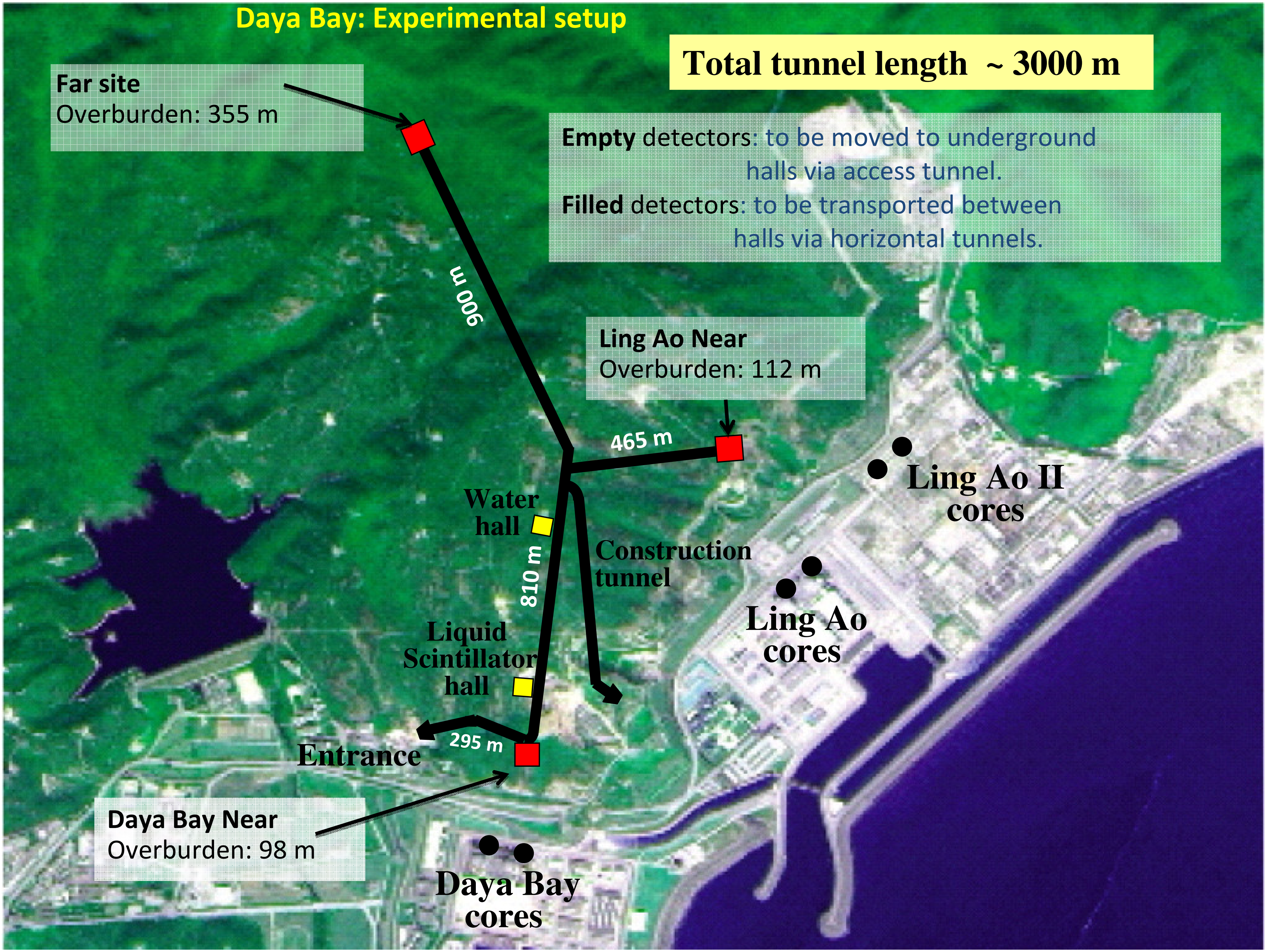


Measuring θ_{13} with reactor antineutrinos

Reactor anti-neutrinos survival probability:

$$P_{ee} \approx 1 - \sin^2 2\theta_{13} \sin^2\left(\frac{\Delta m_{31}{}^2 L}{4E_\nu}\right) + \text{Solar Osc.}$$

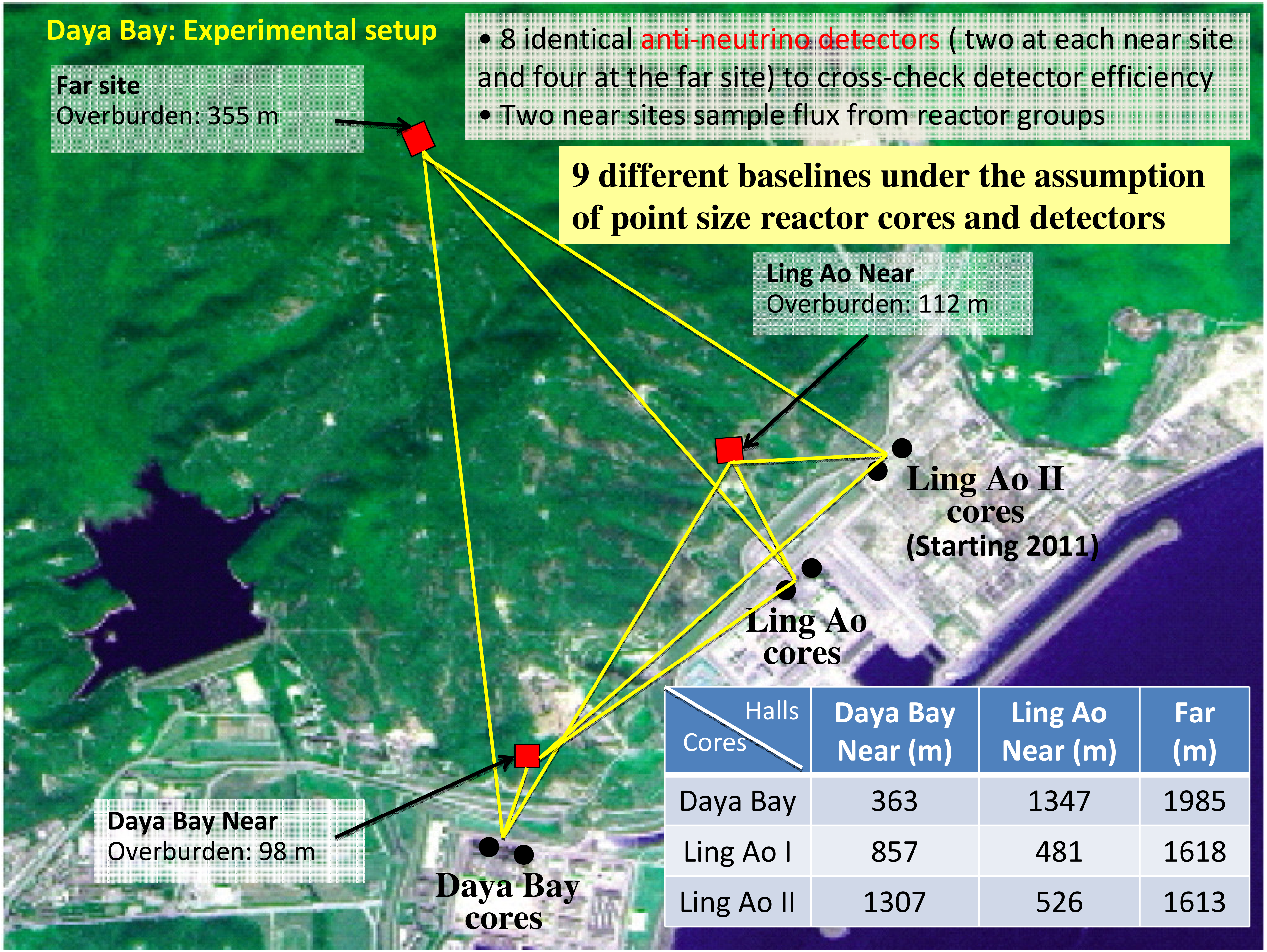



Daya Bay: Experimental setup
Total tunnel length ~ 3000 m
Far site
Overburden: 355 m
Empty detectors: to be moved to underground halls via access tunnel.
Filled detectors: to be transported between halls via horizontal tunnels.
900 m
Ling Ao Near
Overburden: 112 m
465 m
Ling Ao II cores
Water hall
810 m
Construction tunnel
Ling Ao cores
Liquid Scintillator hall
295 m
Entrance
Daya Bay Near
Overburden: 98 m
Daya Bay cores

Daya Bay: Experimental setup

- 8 identical anti-neutrino detectors (two at each near site and four at the far site) to cross-check detector efficiency
- Two near sites sample flux from reactor groups

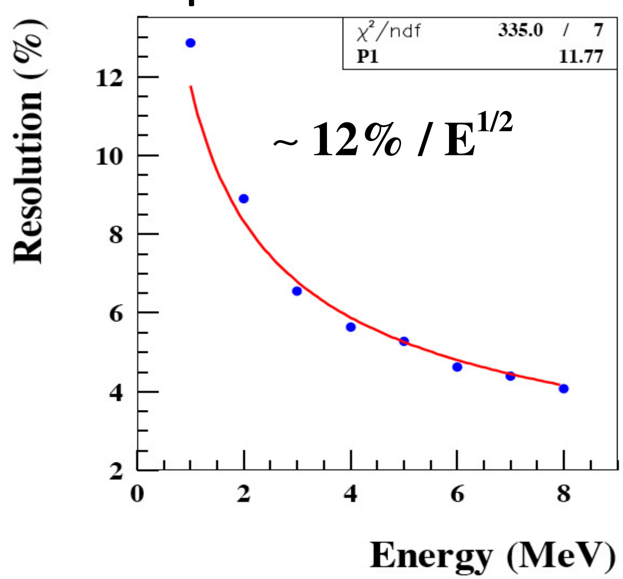
9 different baselines under the assumption of point size reactor cores and detectors

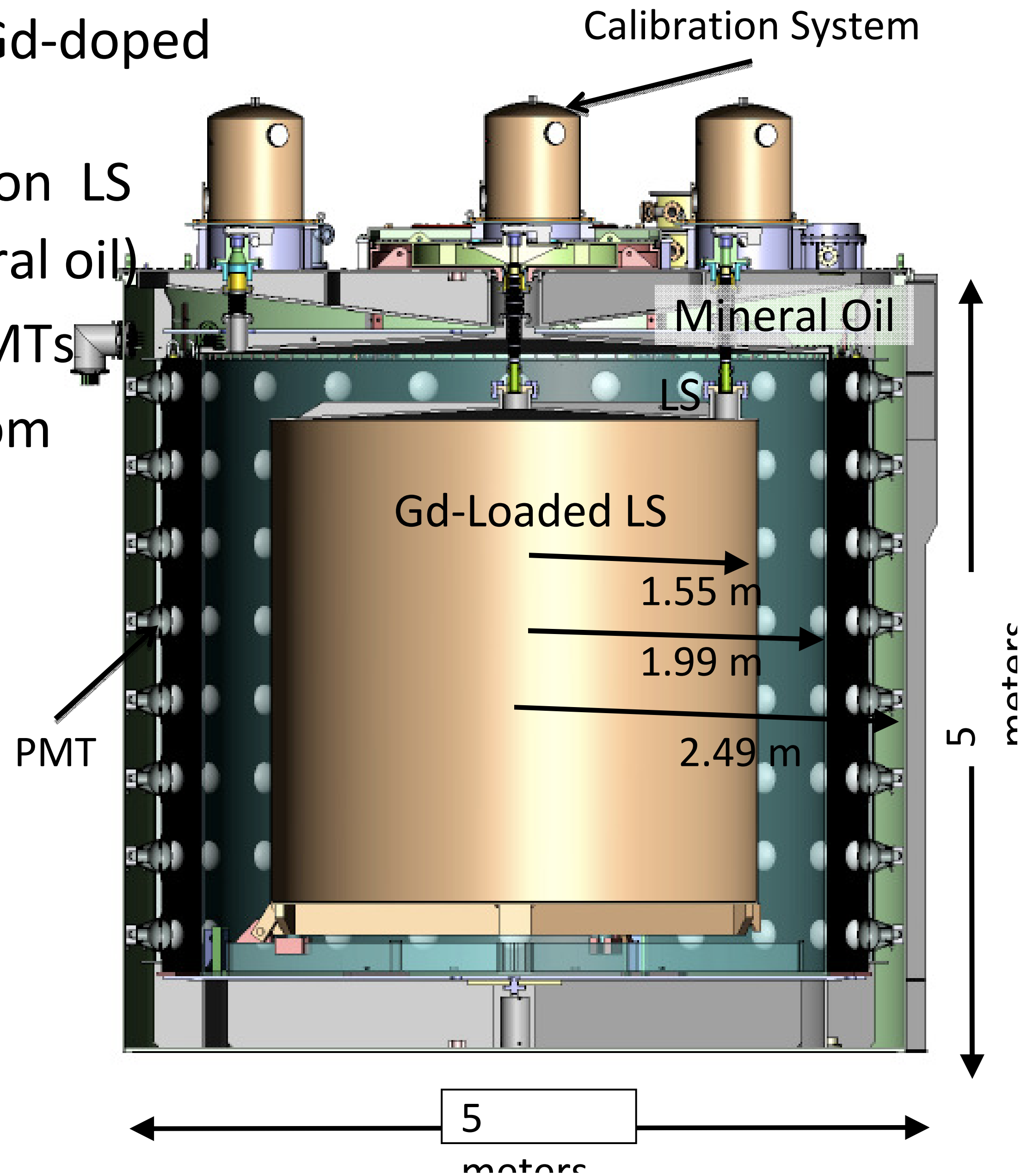


Cores \ Halls	Daya Bay Near (m)	Ling Ao Near (m)	Far (m)
Daya Bay	363	1347	1985
Ling Ao I	857	481	1618
Ling Ao II	1307	526	1613

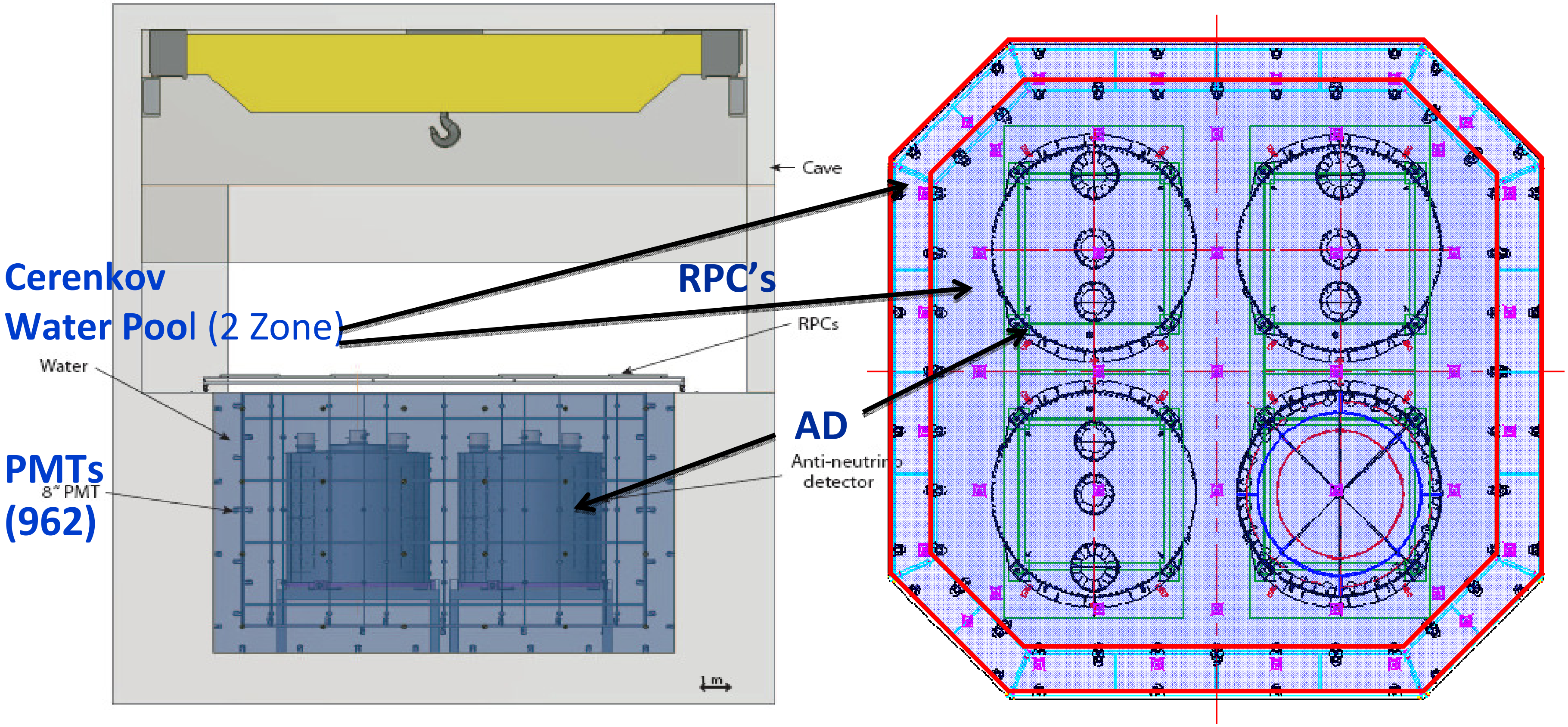
Antineutrino Detector (AD)

- Three-zone cylindrical design
  - ✓ Target: 20 ton 0.1% Gd-doped Liquid Scintillator (LS)
  - ✓ Gamma catcher: 20 ton LS
  - ✓ Buffer : 40 ton (mineral oil)
- 192 low-background 8” PMTs
- Reflectors at top and bottom
- AD sits in a pool of ultra-pure water



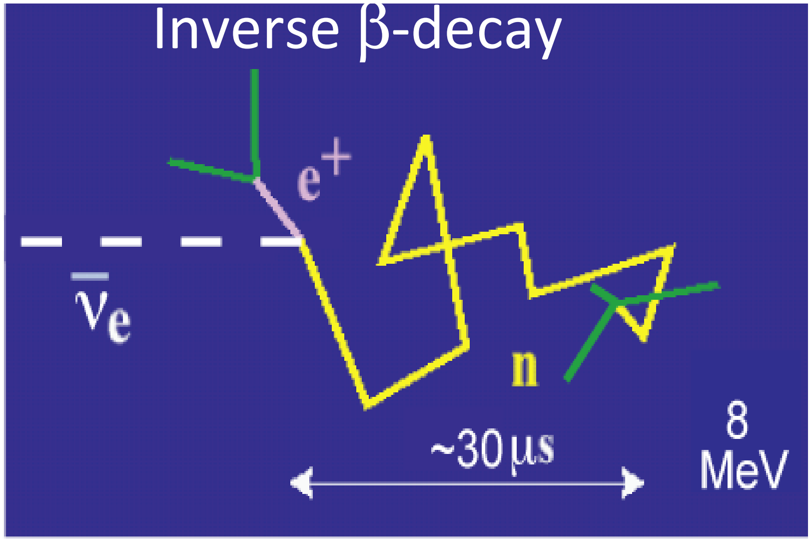


Muon veto system



- Two tagging systems to detect cosmic ray and fast neutron background: 2.5 meter thick two-section water shield and RPCs
- Efficiency 99.5% with uncertainty <0.25%

Antineutrino event signature in AD



- Two part coincidence is crucial for background reduction
- Neutron capture on Gd provides a secondary burst of light approximately 30 μs later

$\bar{\nu}_e + p \to e^+ + n$ (prompt)

~ 0.3b $\to + p \to D + \gamma(2.2\ \text{MeV})$ (delayed)

~ 50,000b $\to + Gd \to Gd^* \to Gd + \gamma's(8\ \text{MeV})$ (delayed)

Measuring θ_{13} with reactor antineutrinos at Daya Bay

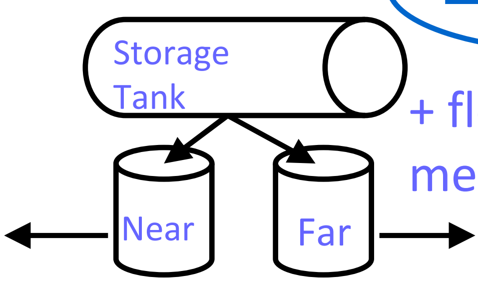
$$\frac{N_f}{N_n} = \left(\frac{N_{p,f}}{N_{p,n}}\right)\left(\frac{L_n}{L_f}\right)^2\left(\frac{\epsilon_f}{\epsilon_n}\right)\left[\frac{P_{ee}(E,L_f)}{P_{ee}(E,L_n)}\right]$$

Measured Ratio of Rates

Proton Number Ratio

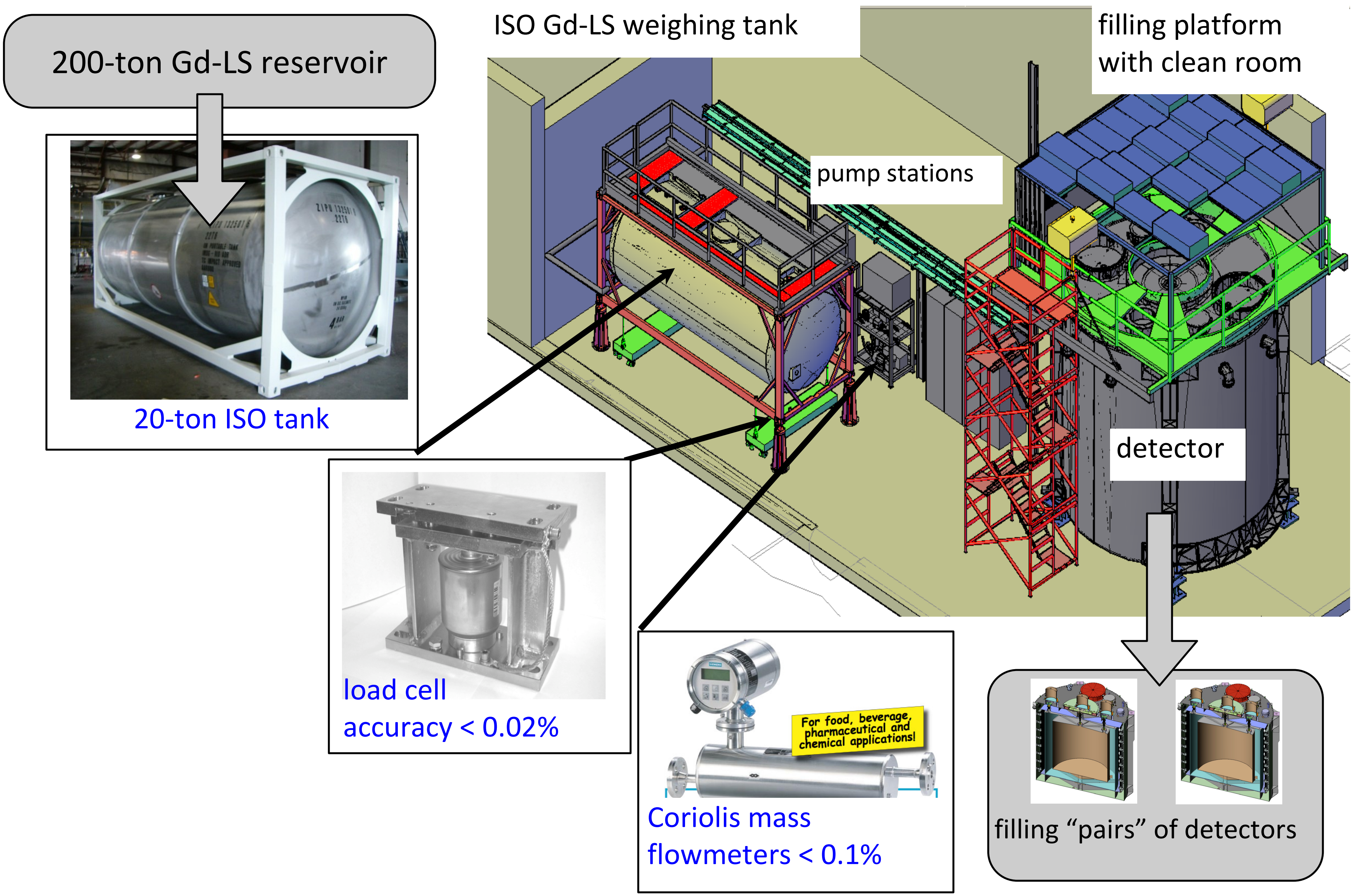
$\pm$ 0.3%

+ flow & mass measurement



$\sin^2 2\theta_{13}$

Target mass measurement



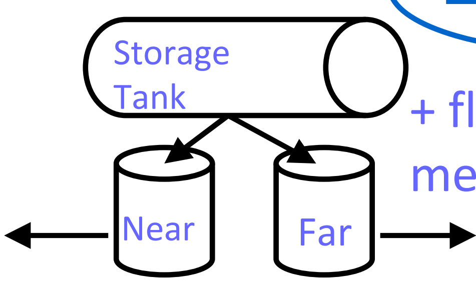
Measuring θ_{13} with reactor antineutrinos at Daya Bay

$$\frac{N_f}{N_n} = \left(\frac{N_{p,f}}{N_{p,n}}\right)\left(\frac{L_n}{L_f}\right)^2\left(\frac{\epsilon_f}{\epsilon_n}\right)\left[\frac{P_{ee}(E,L_f)}{P_{ee}(E,L_n)}\right]$$

Measured Ratio of Rates

Proton Number Ratio

$\pm$ 0.3%



+ flow & mass measurement

Detector Efficiency Ratio

$\pm$ 0.2%

Calibration systems

$\sin^2 2\theta_{13}$

AD calibration system

Automated calibration system

⟶ routine weekly deployment of sources

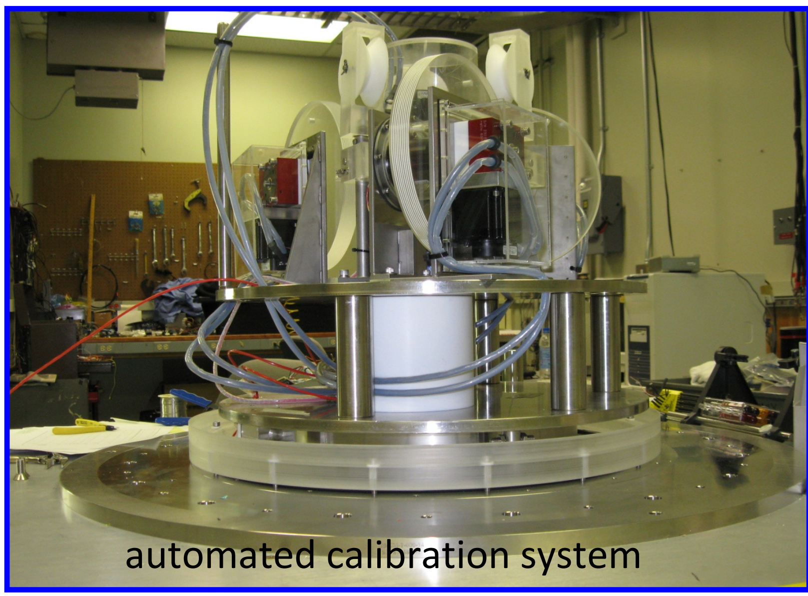
LED light sources

⟶ monitoring optical properties

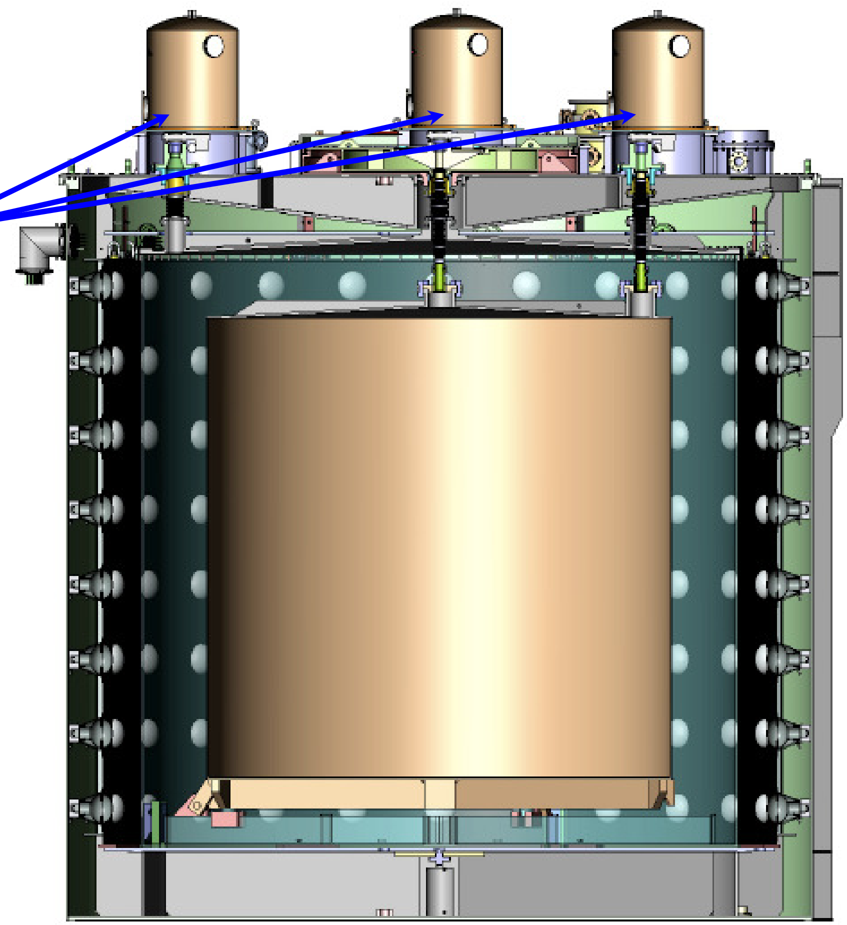
e^+ and n radioactive sources

⟶ energy calibration

- ^{68}Ge source
- Am-^{13}C + ^{60}Co source
- LED diffuser ball

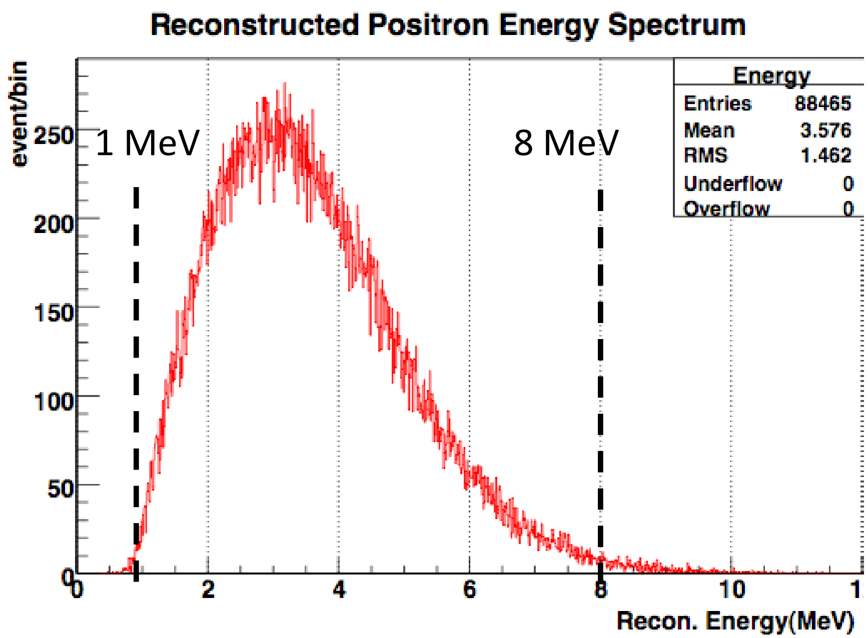


automated calibration system

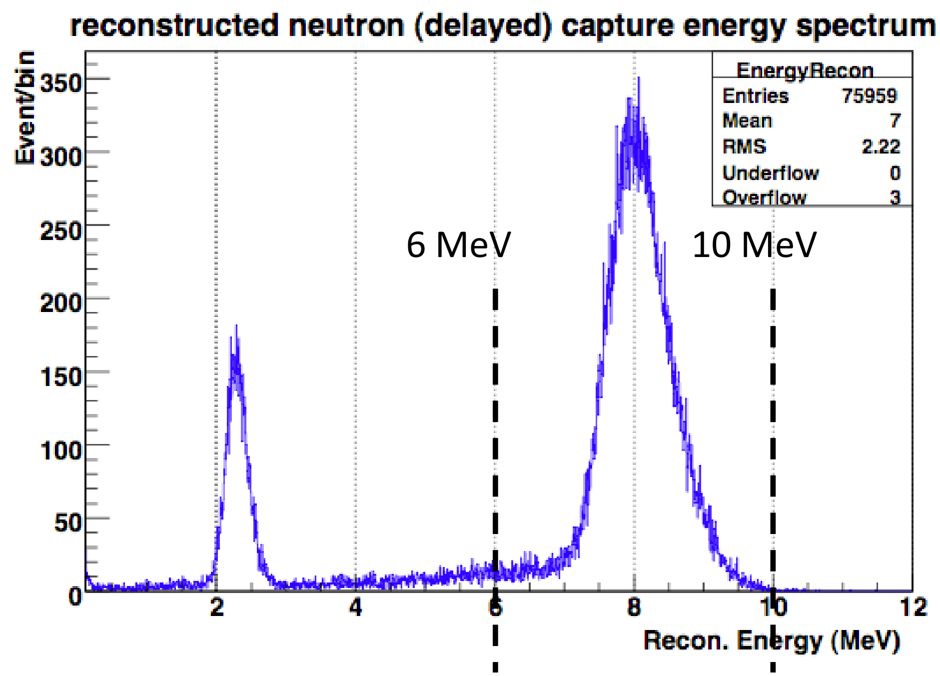


Energy calibration

Prompt Energy Signal



Delayed Energy Signal



e^+ threshold: stopped positron signal using ^{68}Ge source (2x0.511 MeV)
e^+ energy scale: 2.2 MeV neutron capture signal (n source, spallation)

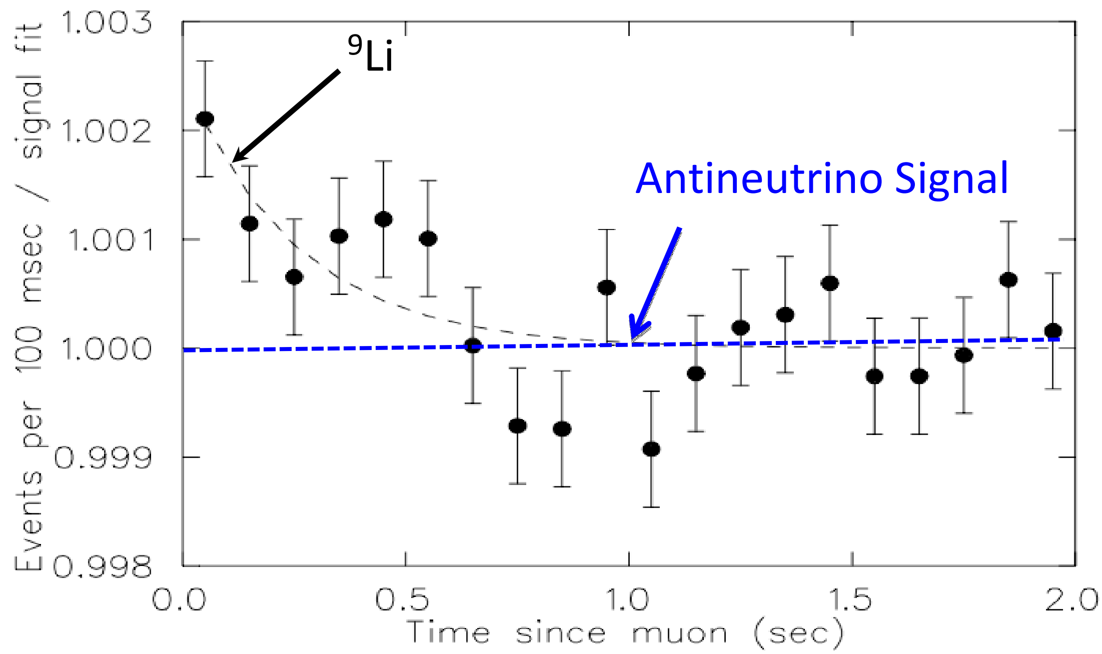
1 MeV cut for prompt positrons: >99%, uncertainty negligible

6 MeV threshold: n capture signals at 8 and 2.2 MeV (n source, spallation)

6 MeV cut for delayed neutrons: 91.5%, uncertainty 0.22% assuming 1% energy uncertainty

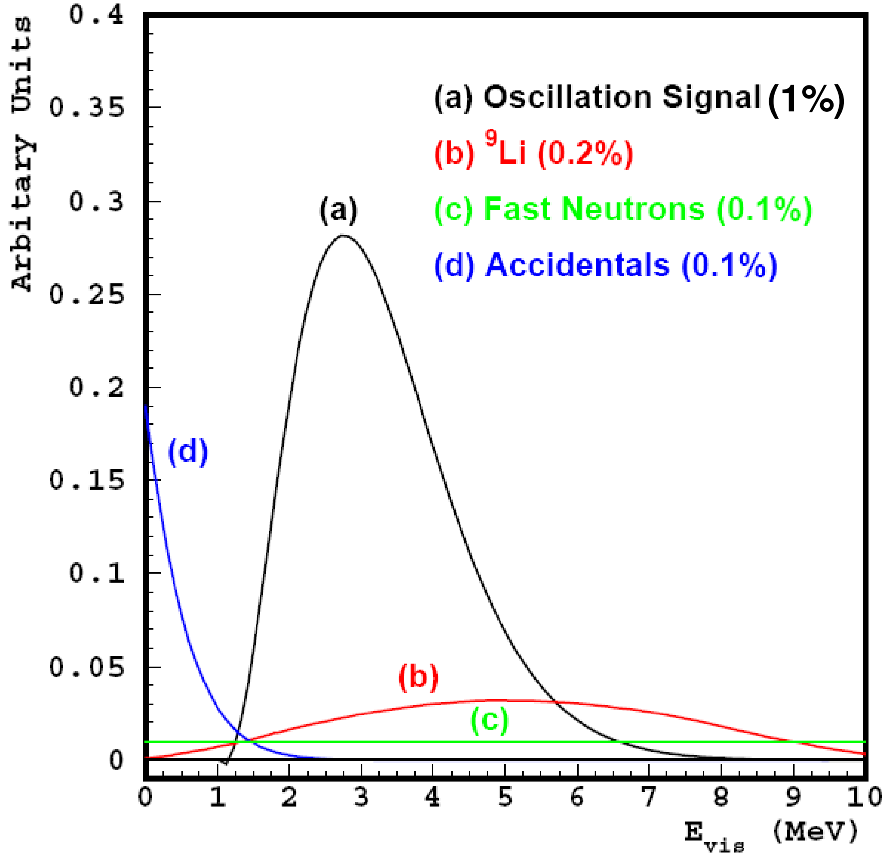
Backgrounds

- Fast neutron — fast neutron enters detector, creates prompt signal, thermalizes, and is captured
- β+n decays of ^{9}Li and ^{8}He created in AD via μ - ^{12}C spallation



- Random coincidence — two unrelated events happen close together in space and time

Signal, background and systematic



Signal rates:

far site < 90 events/det/day

Daya Bay site < 840 events/det/day

Ling Ao site < 740 events/det/day

Total expected background rates:

far site < 0.4 events/det/day

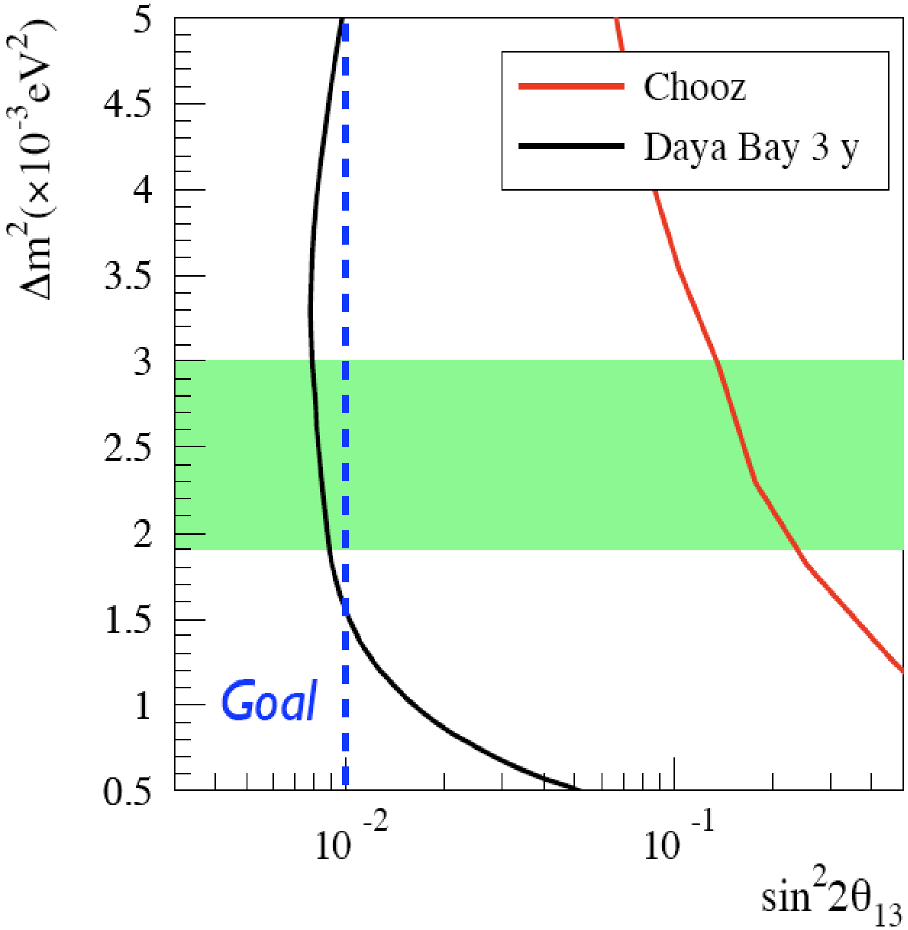
Daya Bay site < 6 events/det/day

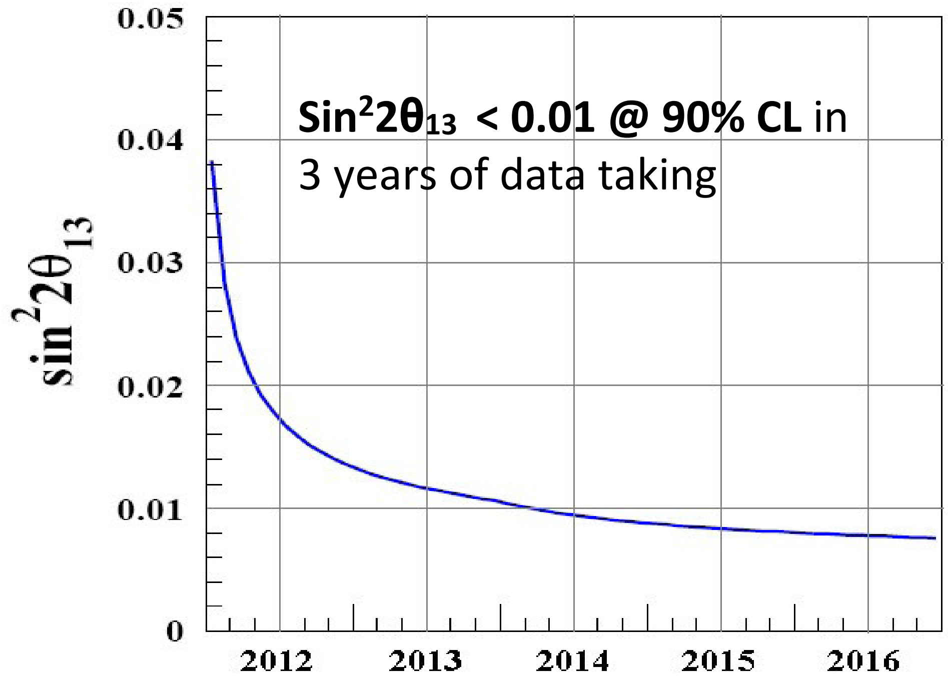
Ling Ao site < 4 events/det/day

Systematic and statistical budgets summary

Source	Uncertainty
Reactor power	0.13%
Detector (per module)	0.38% (baseline) 0.18% (goal)
Signal statistics	0.2%

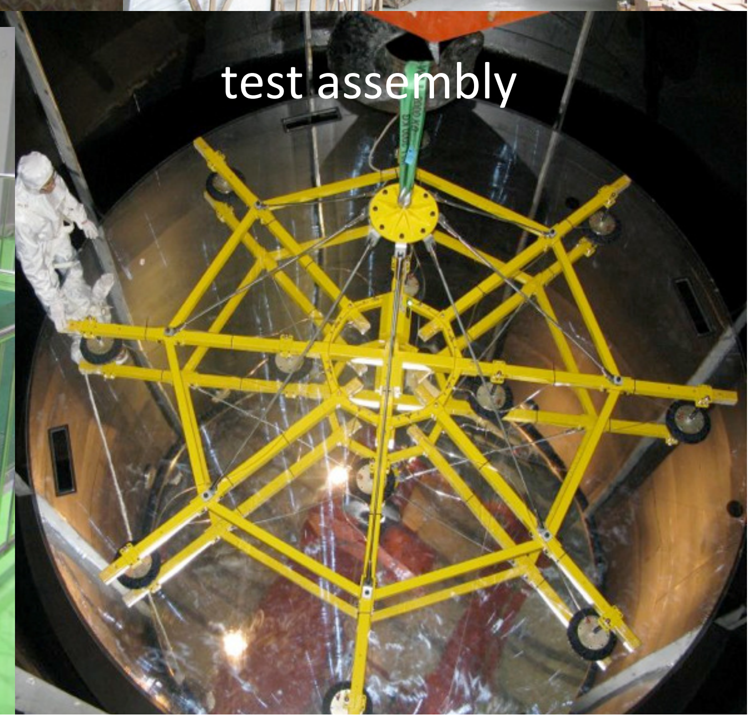
Daya Bay sensitivity to $\sin^2 2\theta_{13}$





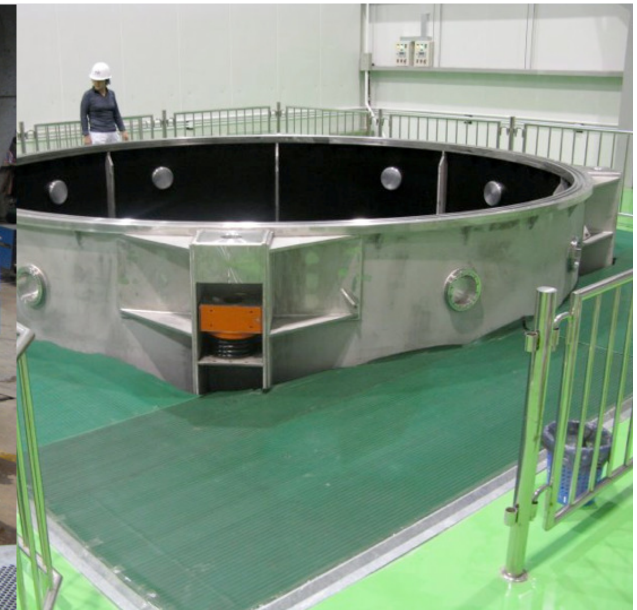
2011 start data taking with full experiment
nominal running period: 3 years

Site preparation



Fabrication and delivery of detector components

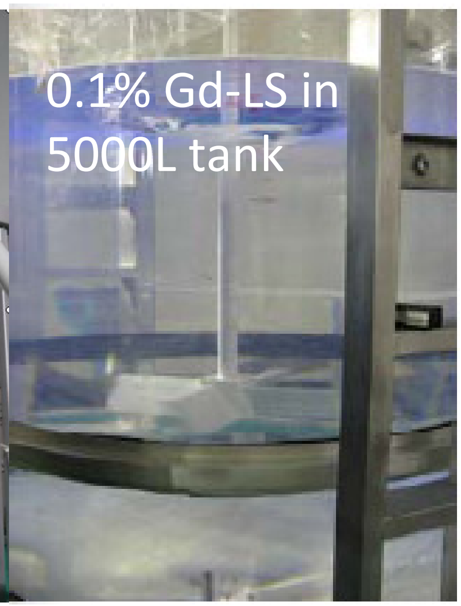
detector tank

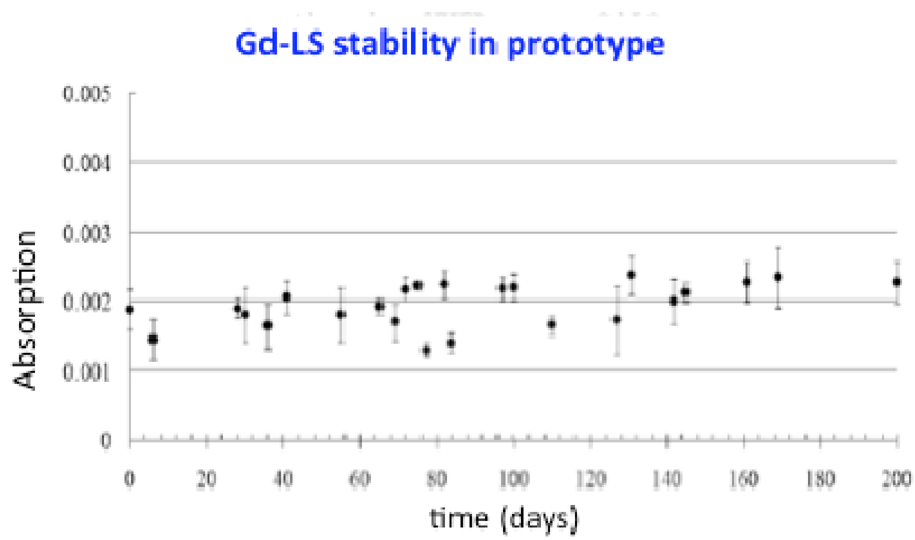


acrylic target vessels

Gd-Liquid scintillator test production

Daya Bay experiment uses 200 ton 0.1% gadolinium-loaded liquid scintillator (Gd-LS).





Gd-LS will be produced in multiple batches but mixed in reservoir on-site, to ensure identical detectors.

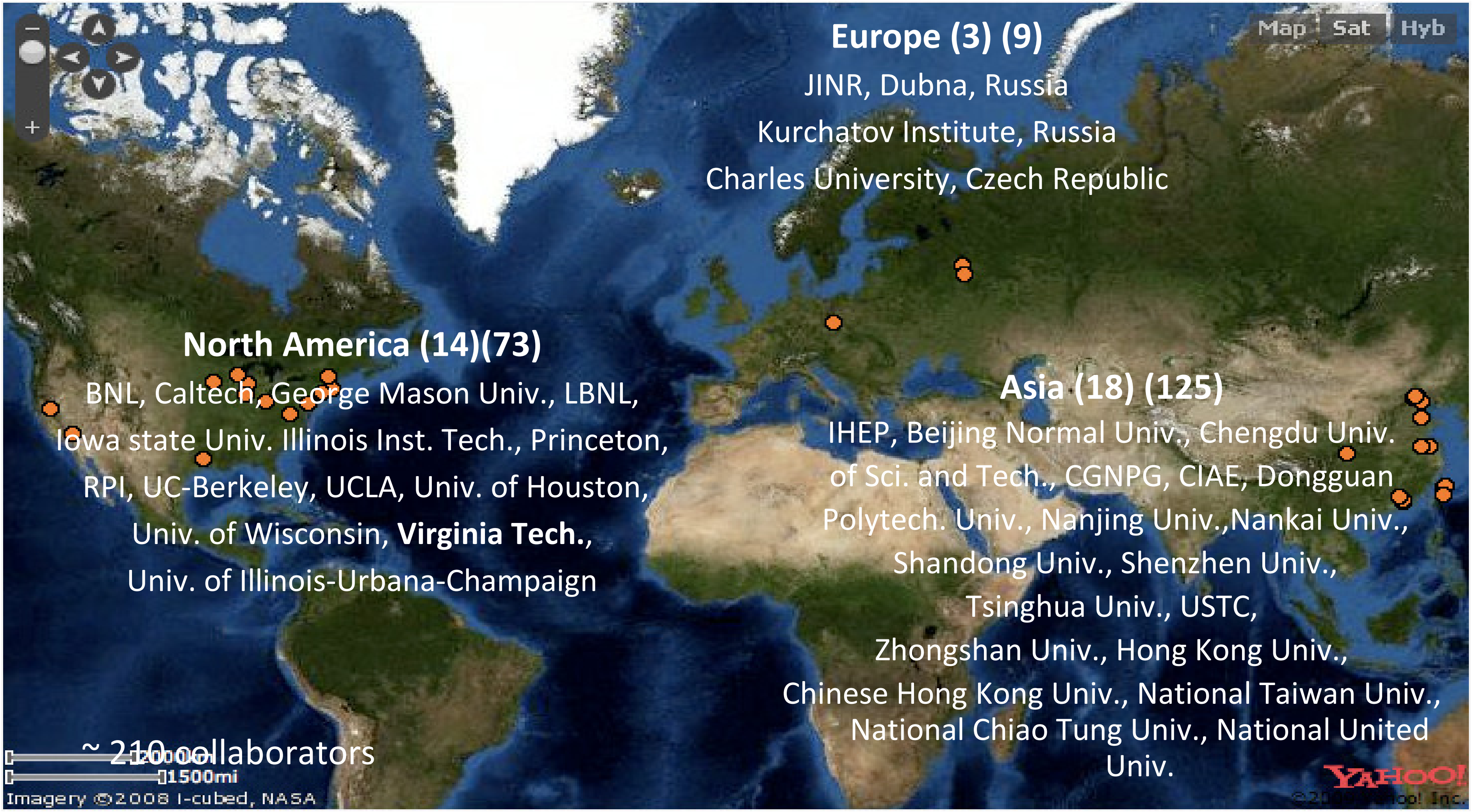
Summary

Daya Bay is the most sensitive reactor θ_{13} experiment.

- Daya Bay will reach a sensitivity of $\leqslant$ 0.01 for $\sin^2 2\theta_{13}$
- Civil and detector construction are progressing. Data taking will begin in summer 2010 with 2 detectors at near site.
- Full experiment will start taking data in 2011.

The Daya Bay Collaboration

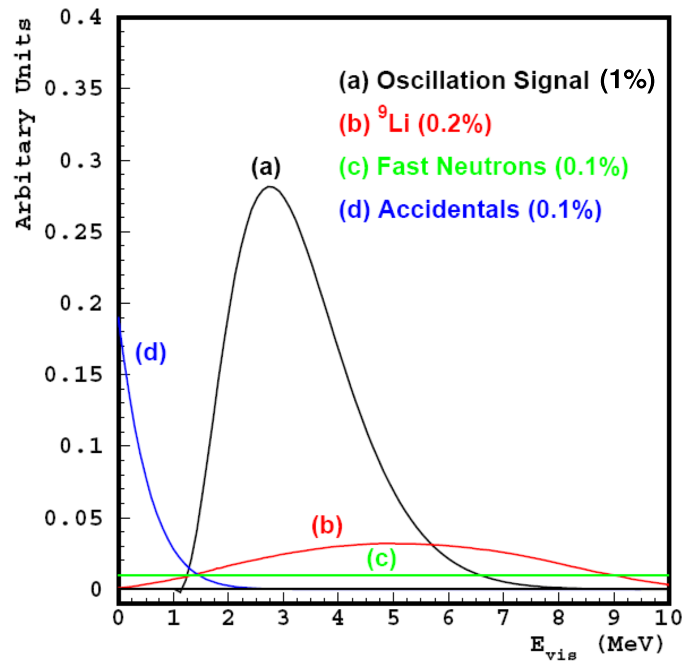
Daya Bay Collaboration participating institutions



Thank You

Backup

Background Summary



		Daya Bay Near	Ling Ao Near	Far Hall
	Baseline (m)	363	481 from Ling Ao 526 from Ling Ao II	1985 from Daya Bay 1615 from Ling Ao's
	Overburden (m)	98	112	350
	Radioactivity (Hz)	<50	<50	<50
	Muon rate (Hz)	36	22	1.2
(a)	Antineutrino Signal (events/day)	930	760	90
(d)	Accidental Background/Signal (%)	<0.2	<0.2	<0.1
(c)	Fast neutron Background/Signal (%)	0.1	0.1	0.1
(b)	$^{8}He+^{9}Li$ Background/Signal (%)	0.3	0.2	0.2

Detector-related systematic uncertainties

Absolute measurement **Relative measurement**

Source of uncertainty		Chooz (*absolute*)	Daya Bay (*relative*) Baseline	Goal	Goal w/Swapping
# protons		0.8	0.3	0.1	0.006
Detector Efficiency	Energy cuts	0.8	0.2	0.1	0.1
	Position cuts	0.32	0.0	0.0	0.0
	Time cuts	0.4	0.1	0.03	0.03
	H/Gd ratio	1.0	0.1	0.1	0.0
	n multiplicity	0.5	0.05	0.05	0.05
	Trigger	0	0.01	0.01	0.01
	Live time	0	<0.01	<0.01	<0.01
Total detector-related uncertainty		1.7%	0.38%	0.18%	0.12%

Ref: Daya Bay TDR

Experimental sensitivity calculation

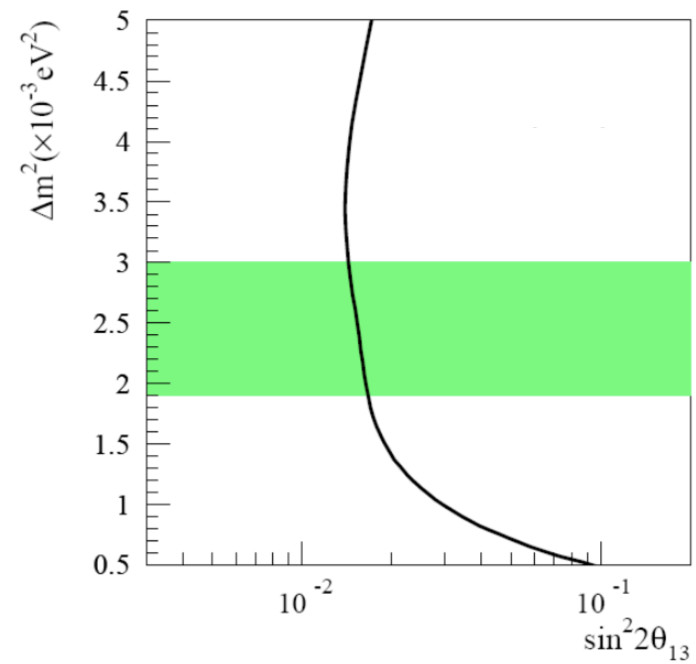
Backgrounds

Reactor power

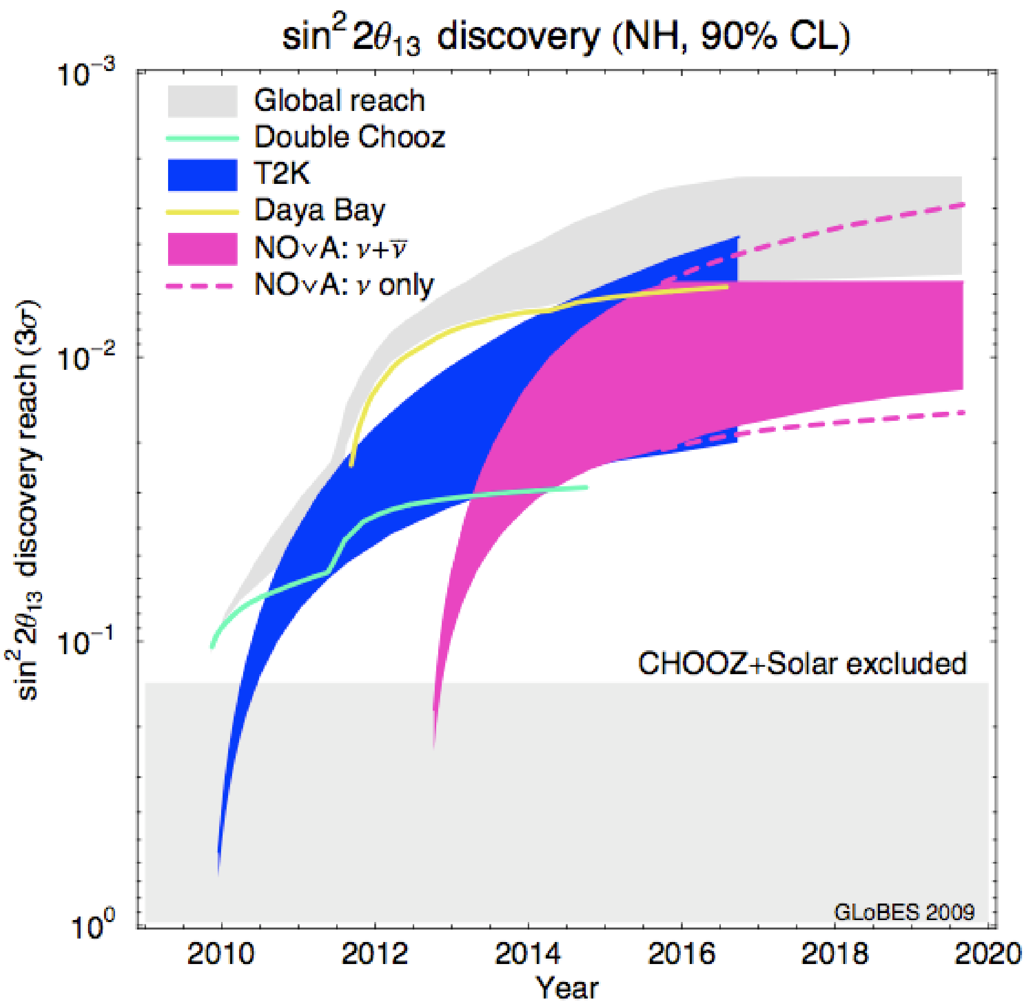
$$\chi^2 = \min_{\gamma} \sum_{A=1}^{8} \sum_{i=1}^{N_{bins}} \frac{\left[M_i^A - T_i^A\left(1 + \alpha_c + \sum_r \omega_r^A \alpha_r + \beta_i + \varepsilon_D + \varepsilon_d^A\right) - \eta_f^A F_i^A - \eta_n^A N_i^A - \eta_s^A S_i^A\right]^2}{T_i^A + \sigma_{b2b}^2}$$

$$+ \frac{\alpha_c^2}{\sigma_c^2} + \sum_r \frac{\alpha_r^2}{\sigma_r^2} + \sum_{i=1}^{N_{bins}} \frac{\beta_i^2}{\sigma_{\mathrm{shp}}^2} + \frac{\varepsilon_D^2}{\sigma_D^2} + \sum_{A=1}^{8} \left[\left(\frac{\varepsilon_d^A}{\sigma_d}\right)^2 + \left(\frac{\eta_f^A}{\sigma_f^A}\right)^2 + \left(\frac{\eta_n^A}{\sigma_n^A}\right)^2 + \left(\frac{\eta_s^A}{\sigma_s^A}\right)^2\right] \quad (29)$$

- Scan in $\Delta m^2 - \mathrm{Sin}^2 2\theta_{13}$
- Minimize χ^2 at each point



Global fit to to $\sin^2 2\theta_{13}$



[P. Huber, *et al*., arXiv: 0907.1896]