The Daya Bay Reactor Electron Anti-neutrino Oscillation Experiment

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Physics Motivation

Weak eigenstate ≠ mass eigenstate ⇒

Pontecorvo-Maki-Nakagawa-Sakata Matrix

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix} = \begin{pmatrix} 0.8 & 0.5 & ? \\ 0.4 & 0.6 & 0.7 \\ 0.4 & 0.6 & 0.7 \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

Parametrize the PMNS matrix as:

$$\underbrace{\begin{pmatrix} \cos\theta_{12} & \sin\theta_{12} & 0 \\ -\sin\theta_{12} & \cos\theta_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}}_{\text{Solar, reactor}} \underbrace{\begin{pmatrix} \cos\theta_{13} & 0 & \boxed{\sin\theta_{13} e^{-i\delta}} \\ 0 & 1 & 0 \\ \boxed{-\sin\theta_{13} e^{i\delta}} & 0 & \cos\theta_{12} \end{pmatrix}}_{\text{reactor and accelerator}} \underbrace{\begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\theta_{23} & \sin\theta_{23} \\ 0 & -\sin\theta_{23} & \cos\theta_{23} \end{pmatrix}}_{\text{Atmospheric, accelerator}} \underbrace{\begin{pmatrix} e^{i\delta_1} & 0 & 0 \\ 0 & e^{i\delta_2} & 0 \\ 0 & 0 & 1 \end{pmatrix}}_{0\nu\beta\beta}$$

$\theta_{12} = \sim 32°$

$\theta_{13} = ?$

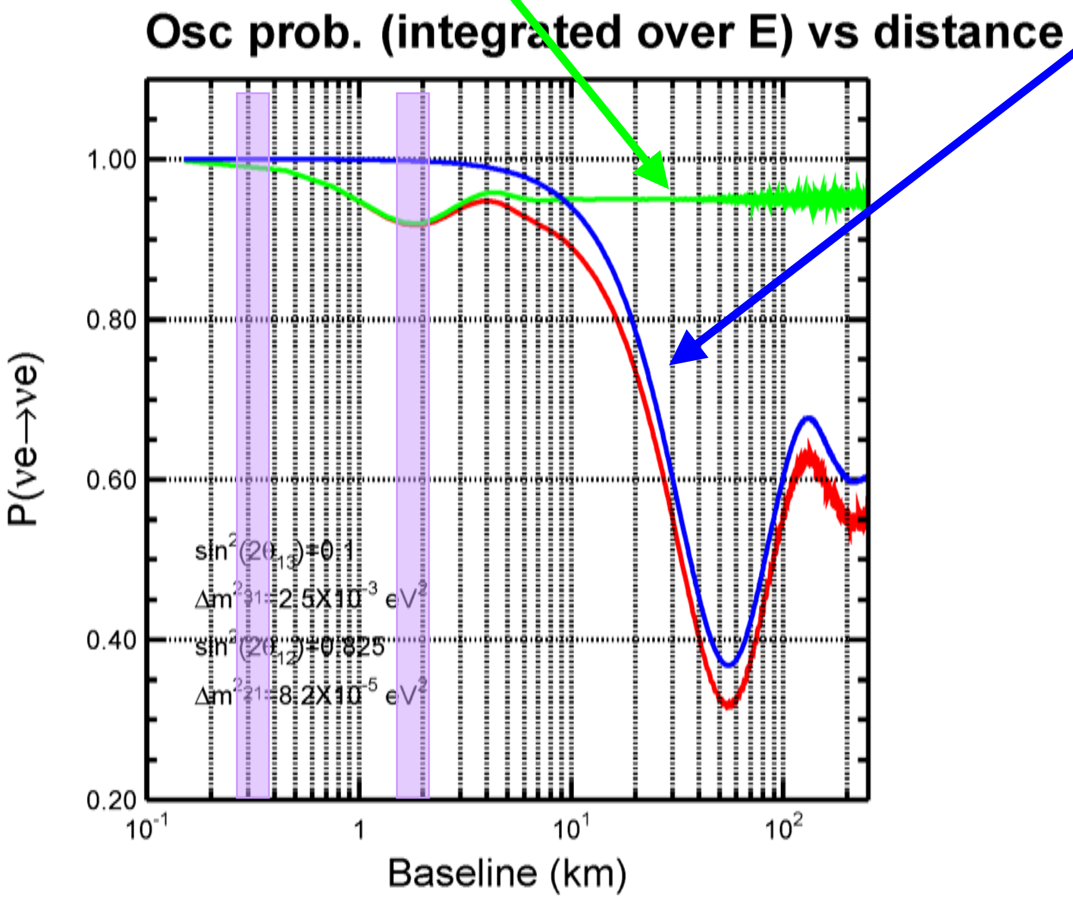
$\theta_{23} \sim 45°$

θ_{13} is the gateway of CP violation in lepton sector!

Measuring θ_{13} Using Reactor Anti-neutrinos

Electron anti-neutrino survival probability

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



Large oscillation >50 km; negligible <2 km

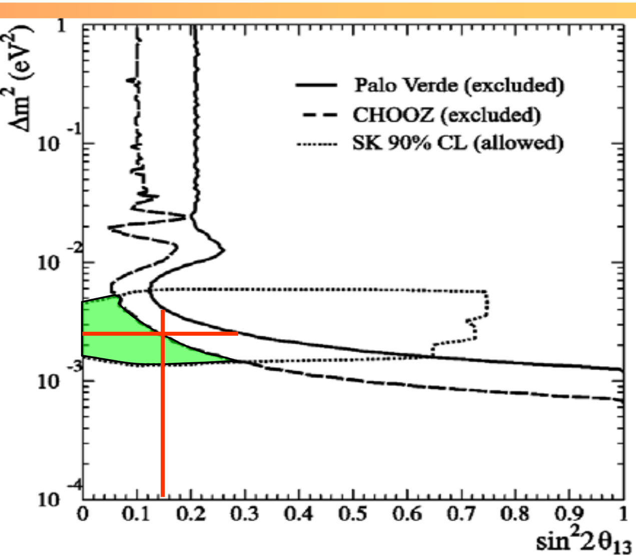
$\overline{\nu}_e$ disappearance at short baseline(~2 km): unambiguous measurement of θ_{13}

Daya Bay: Goal and Approach

Previous best experimental limits from Chooz: $\sin^2(2\theta_{13}) < 0.17$ ($\Delta m^2_{31} = 2.5\times10^{-3}$ eV, 90% c.f.)

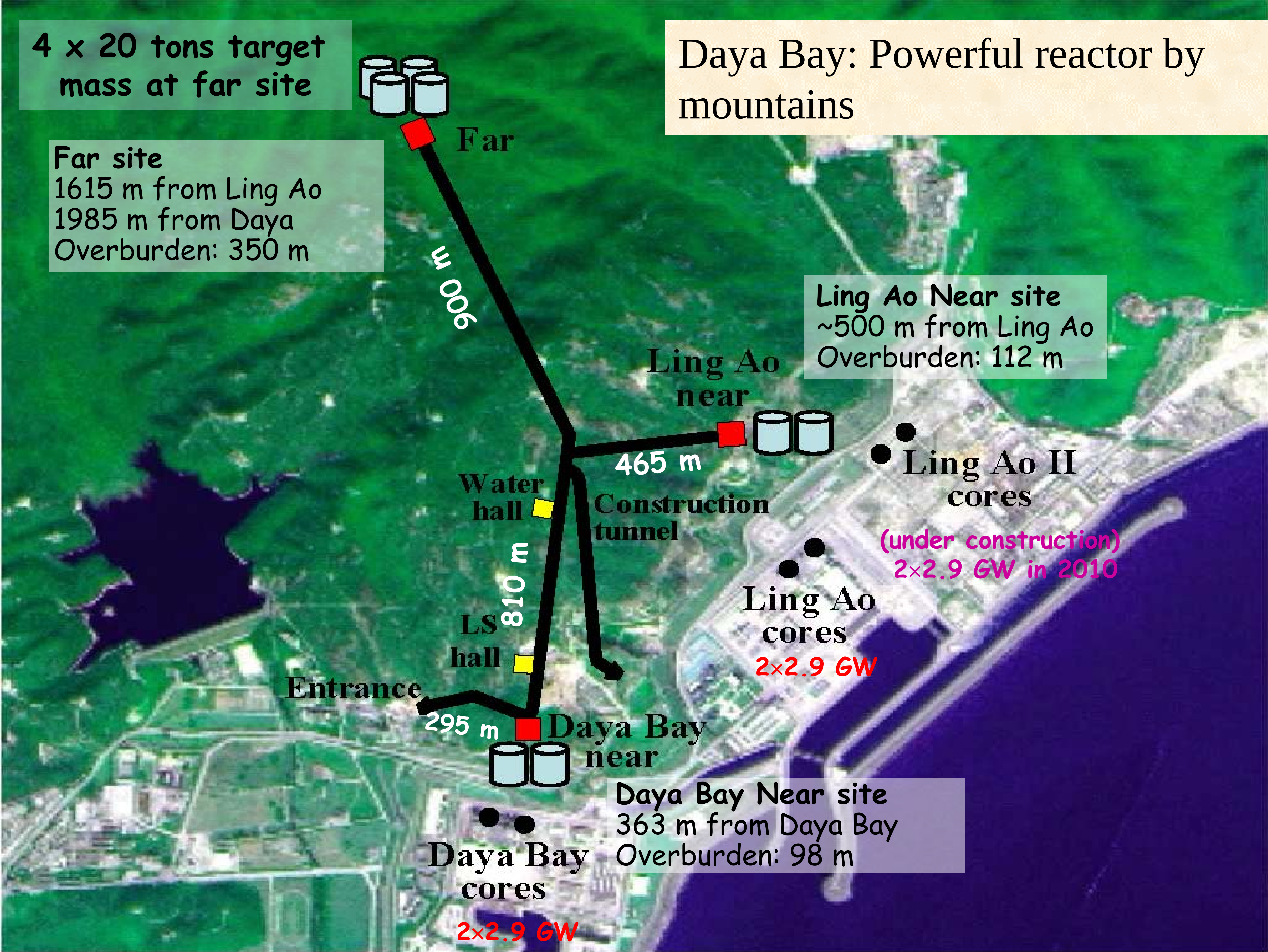
Daya Bay:

determine $\sin^2 2\theta_{13}$ with a sensitivity of 1%



- Increase statistics: Use powerful reactors & large target mass & optimized baseline
- Suppress background:
  - Go deeper underground
  - High performance veto detector to MEASURE the background
- Reduce systematic uncertainties:
  - Reactor-related:
    Utilize near and far detectors to minimize reactor-related errors
  - Detector-related:
    - Use "Identical" pairs of detectors to do *relative* measurement
    - Comprehensive program in calibration/monitoring of detectors

Daya Bay: Powerful reactor by mountains



4 x 20 tons target mass at far site

Far site
1615 m from Ling Ao
1985 m from Daya
Overburden: 350 m

Ling Ao Near site
~500 m from Ling Ao
Overburden: 112 m

Daya Bay Near site
363 m from Daya Bay
Overburden: 98 m

Detection of $\bar{\nu}_e$

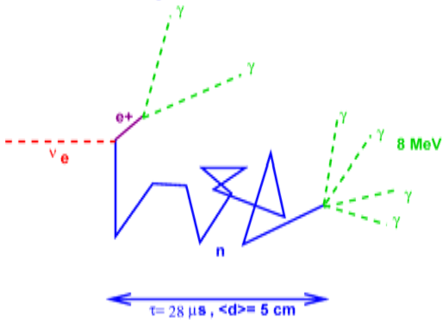
Inverse β-decay in Gd-doped liquid scintillator:

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

$E_{\bar{\nu}} \approx T_{e+} + 1.8$ MeV

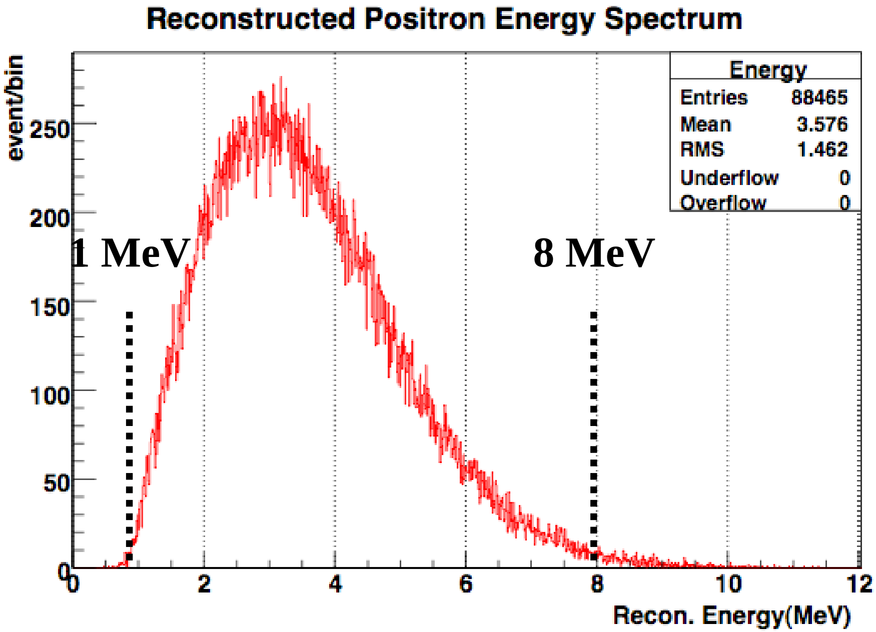
$\rightarrow + p \rightarrow D + \gamma(2.2\ \text{MeV})$ ($t \sim 180\ \mu s$) 0.3b

$\rightarrow + Gd \rightarrow Gd^* \rightarrow Gd + \gamma\text{'s}(8\ \text{MeV})$ ($t \sim 30\ \mu s$) 50,000b

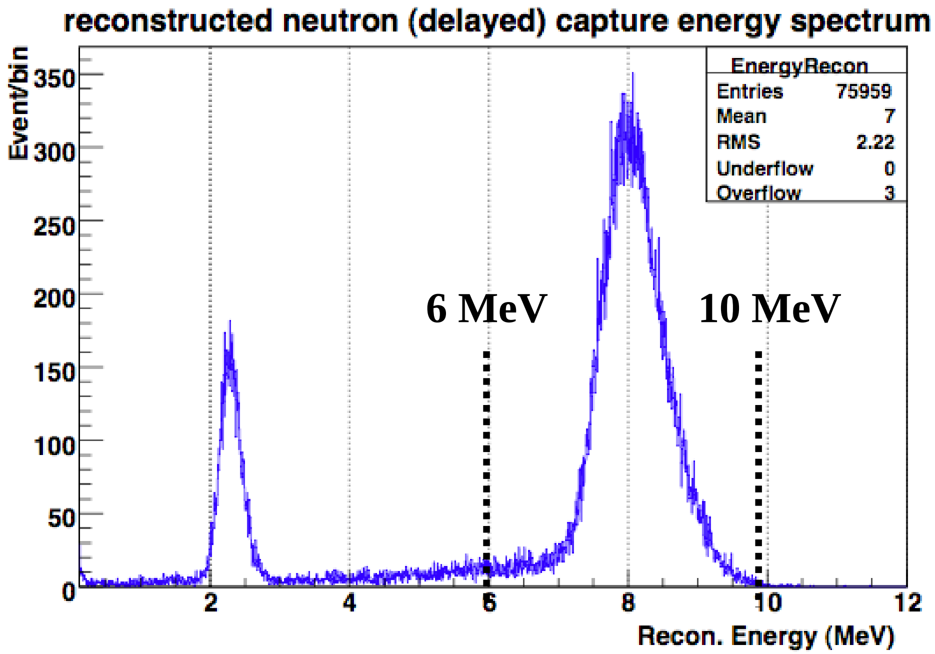


Time, space and energy-tagged signal
⇒ suppress background events.

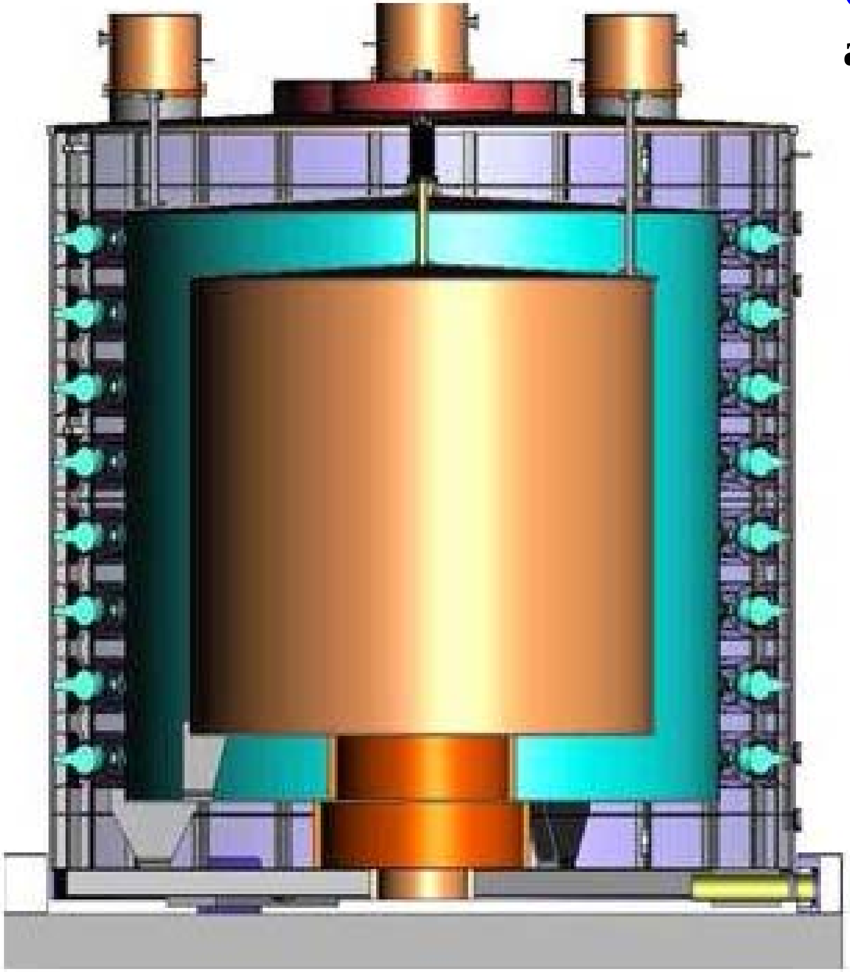
Prompt Energy Signal



Delayed Energy Signal



Antineutrino Detector



Cylindrical 3-Zone Structure separated by acrylic vessels:

- **I. Target: 0.1% Gd-loaded liquid scintillator,**
  radius=half height= 1.55 m, 20 ton
- **II. γ-catcher: liquid scintillator, 42.5 cm thick**
- **III. Buffer shielding: mineral oil, 48.8 cm thick**

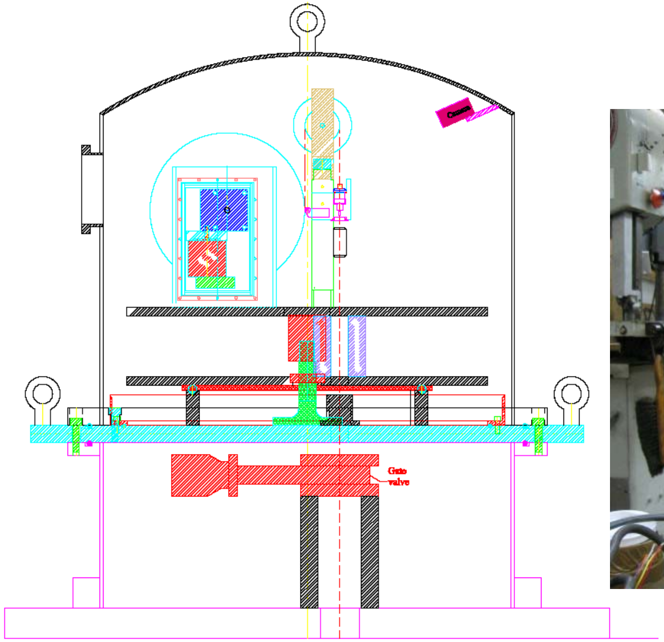
With 192 PMT's on circumference and reflective reflectors on top and bottom:

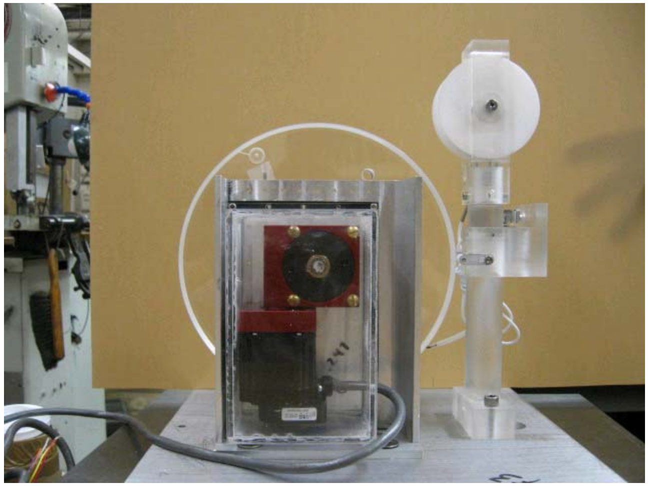
$$\frac{\sigma}{E} \sim \frac{11.6\ \%}{\sqrt{E\,(\mathrm{MeV})}}, \quad \sigma_{\mathrm{vertex}} = 12.5 \text{ cm for } 8 \text{ MeV } e^{-}$$

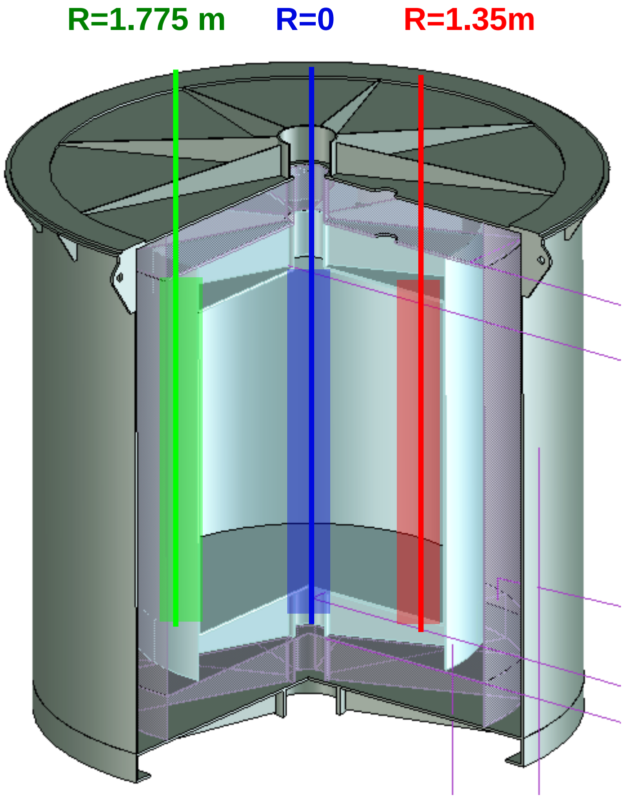
Calibrating Energy Cuts

Automated deployed radioactive sources to calibrate the detector energy and position response within the entire range.

- ^{68}Ge (0 KE e^+ = 2×0.511 MeV γ's)
- ^{252}Cf (~4 neutrons/fission, 2.2 MeV n-p and 8 MeV n-Gd captures)
- LEDs (timing and PMT gains)

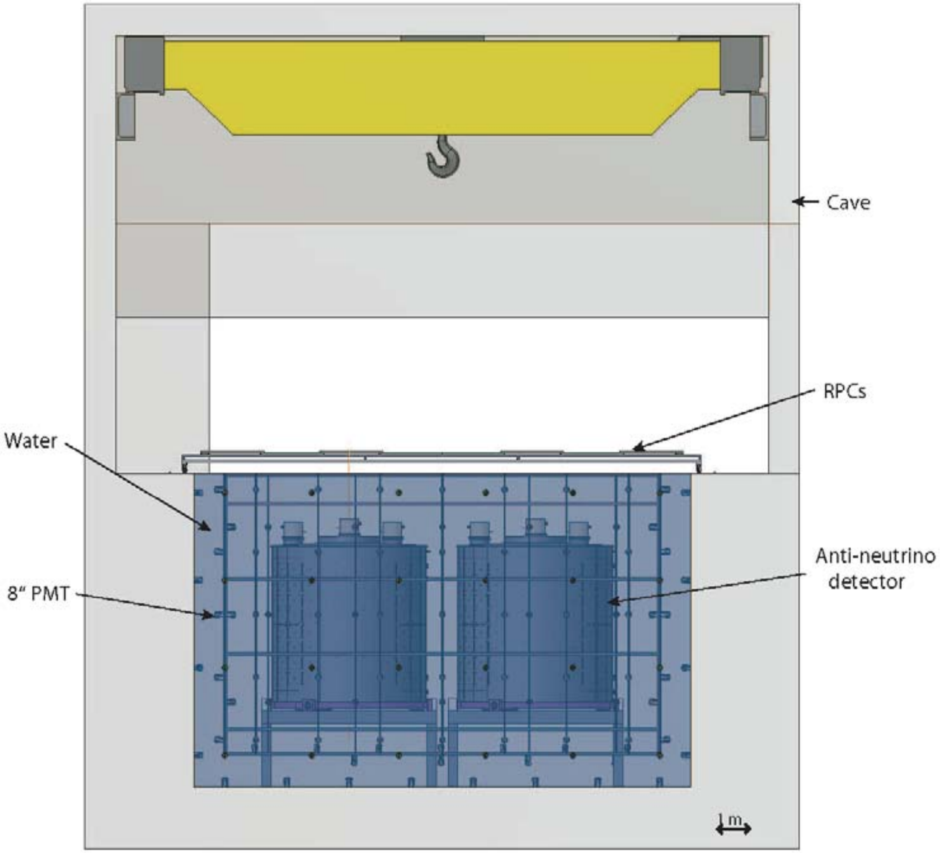


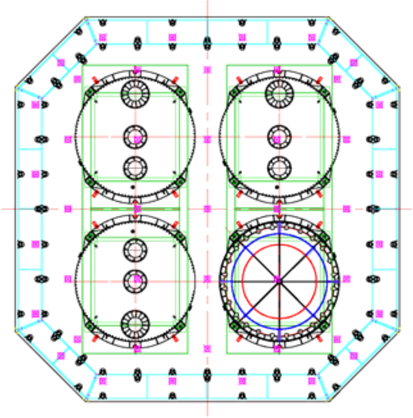




In addition, cosmogenic background (n and beta emitters) provide additional energy scale calibration sampled over the entire fiducial volume

Muon Veto System





- Surround detectors with at least 2.5m of water, which shields the external radioactivity and cosmogenic background

- Water shield is divided into two optically separated regions (with reflective divider, 8" PMTs mounted at the zone boundaries), which serves as two active and independent muon tagger

- Augmented with a top muon tracker: RPCs

- Combined efficiency of tracker > 99.5% with error measured to better than 0.25%

Backgrounds

Background = “prompt”+”delayed” signals that fake inverse-beta events

Three main contributors, **all can be measured:**

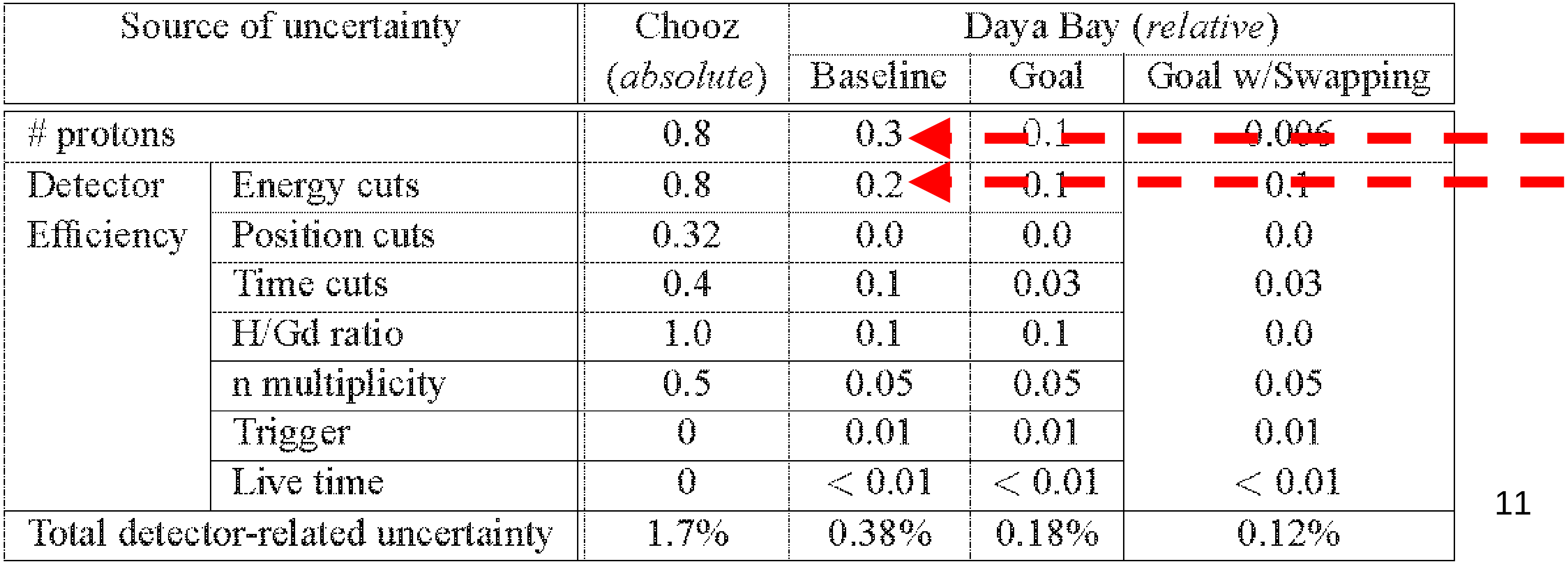
Background type	Experimental Handle
Muon-induced fast neutrons (prompt recoil, delayed capture) from water or rock	>99.5% parent “water” muons tagged ~1/3 parent “rock” muons tagged
^{9}Li/^{8}He ($T_{1/2}$= 178 msec, b decay w/neutron emission, delayed capture)	Tag parent “showing” muons
Accidental prompt and delay coincidences	Single rates accurately measured

B/S:

	DYB site	**LA site**	**Far site**
Fast n / signal	0.1%	0.1%	0.1%
^{9}Li-^{8}He / signal	0.3%	0.2%	0.2%
Accidental/signal	<0.2%	<0.2%	<0.1%

Baseline Systematics Budget

Detector Related	0.38%
Reactor related	0.13%
Backgrounds	0.3% (Daya Bay near), 0.2% (Ling Ao near and far)
Signal statistics	0.2% (3 years of running)

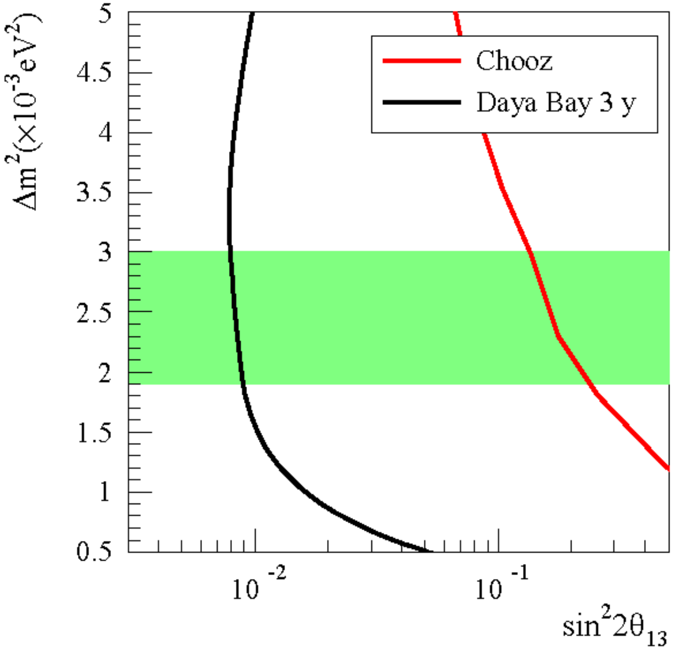


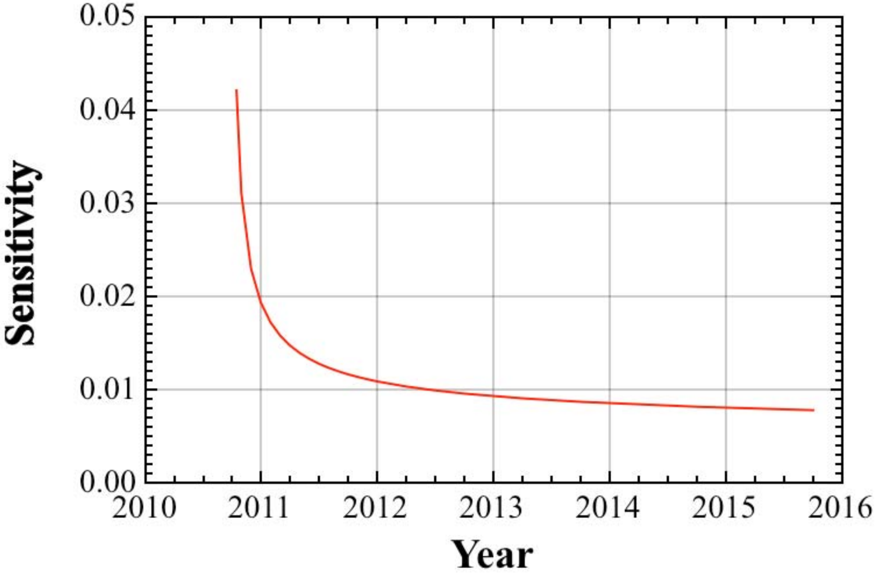
Source of uncertainty		Chooz	Daya Bay (*relative*)		
		(*absolute*)	Baseline	Goal	Goal w/Swapping
# protons		0.8	0.3	0.1	0.006
Detector Efficiency	Energy cuts	0.8	0.2	0.1	0.1
	Position cuts	0.32	0.0	0.0	0.0
	Time cuts	0.4	0.1	0.03	0.03
	H/Gd ratio	1.0	0.1	0.1	0.0
	n multiplicity	0.5	0.05	0.05	0.05
	Trigger	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%

Daya Bay Sensitivity

90% confidence level, “baseline” detector uncertainties

Use rate and spectral shape



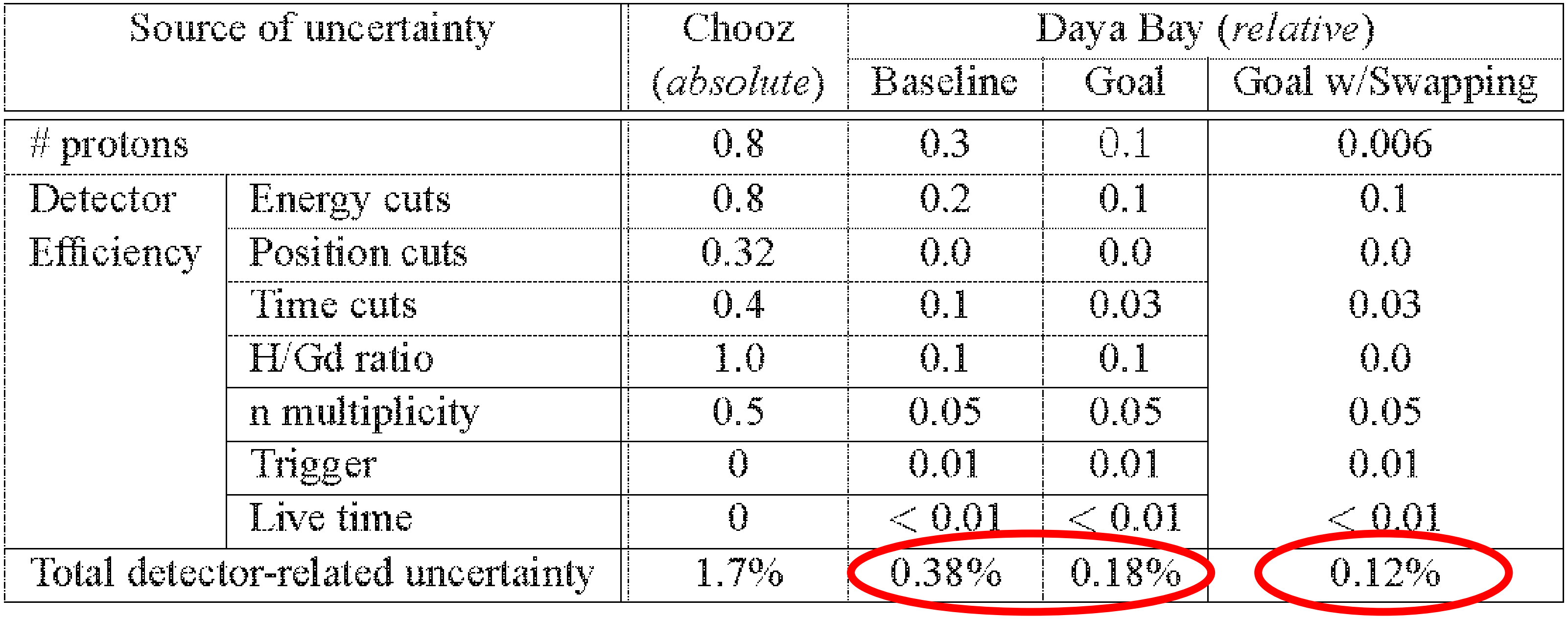


Milestones

- DoE CD1 review, April 2007, approved
- Oct. 13 (**Today!**) Tunnel construction groundbreaking
- DoE CD2 review, Jan 2008
- July 09 Deployment of the first pair of detectors
- Sept. 2010 Begin data taking with near-far

Backup

Detector-related



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	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%

Baseline: currently achievable **relative** uncertainty without R&D

Goal: expected **relative** uncertainty after R&D

Swapping: can reduce **relative** uncertainty further