Research Opportunities with the Daya Bay Reactor Neutrino Experiment

David E. Jaffe

Who am I?

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Ph.D.	State University of New York at Stony Brook, 1987
Title	"High transverse hadron production in 400 and 800 GeV/c proton-nucleon collisions"
Advisor	Robert L. McCarthy
$\geq$2000	Physicist at Brookhaven National Laboratory

What I'm going to talk about

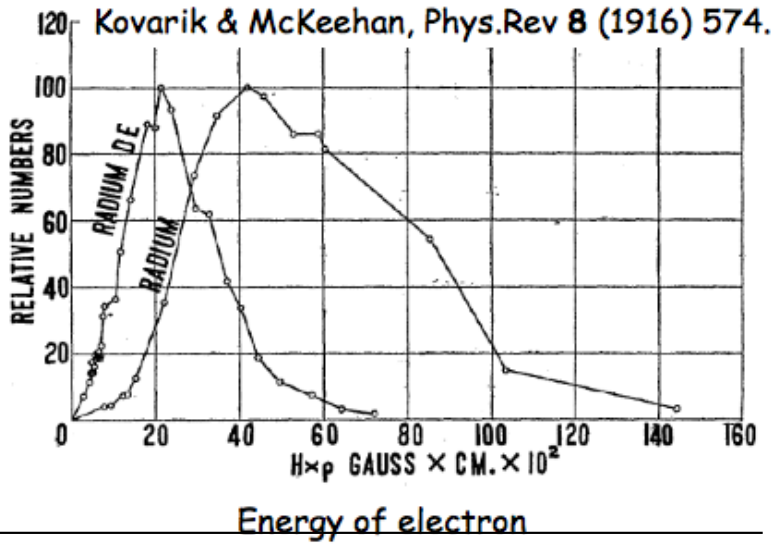
The past: History and discovery of the neutrino

The present: Status of neutrino oscillations

The present/near future: Daya Bay reactor neutrino experiment

Early history[1]

1896 Becquerel discovers radioactivity
1896 Zeeman discovers the electron
1898 Rutherford identifies α and β rays from uranium
1898 1st underground particle physics experiment by Elster & Geitel
1899 β rays are shown to be electrons
1900 Villard observes γ rays
1914 *Chadwick observes continuous β-ray energy spectrum*



$$A(Z) \rightarrow A(Z+1)e^-\bar{\nu}_e$$
$$n \rightarrow pe^-\bar{\nu}_e$$

[1] A.Pais, Rev.Mod.Phys. **49** (1977) 925

The "Neutrino" hypothesis

1930 Pauli proposes "a desperate remedy to save...the law of conservation of energy": a light ($m(\nu) < m(e^-)$), neutral, highly-penetrating particle with spin 1/2. Pauli dubbed it the "neutron".

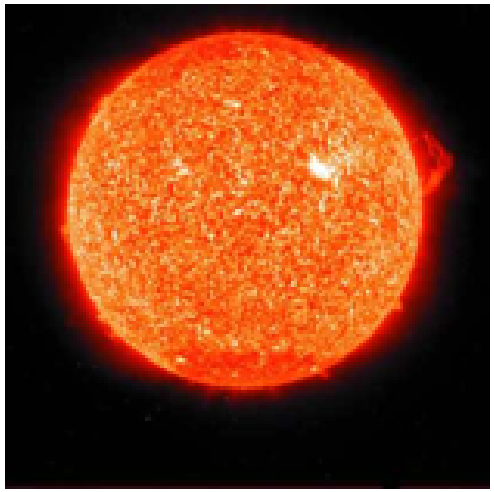
1932 Chadwick discovers the neutron with $m(n) \approx m(p)$

1932-3 Fermi dubs Pauli's particle the "neutrino", develops theory of β-decay and concludes $m(\nu) \ll m(e^-)$

1934 Bethe & Peierls use Fermi's theory and calculate $\sigma(\bar{\nu}_e p \rightarrow n e^+) \sim 10^{-44}$ cm^2 for $E(\bar{\nu}_e) = 2$ MeV or a mean free path in water of $\lambda = \frac{1}{n\sigma} \approx 1.5 \times 10^{21}$ cm ≈ 1600 light-years.

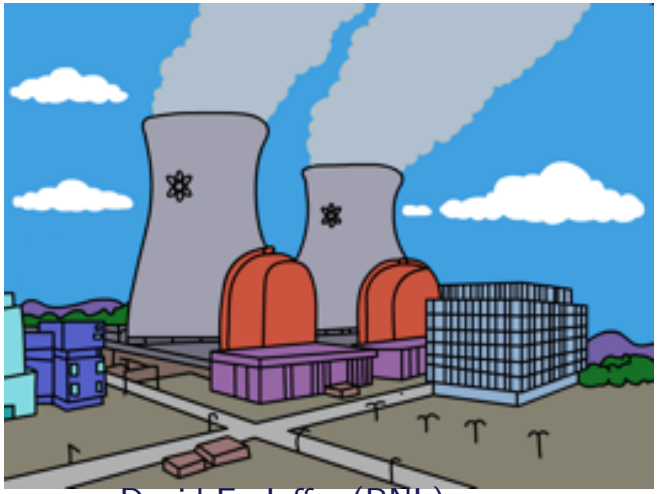
Detecting the neutrino

Tiny cross-section demands a copious source of neutrinos and a massive target/detector.
Some sources of neutrinos:



Sun: Always on.

Nuclear explosion: On/off possible, but destructive to detector

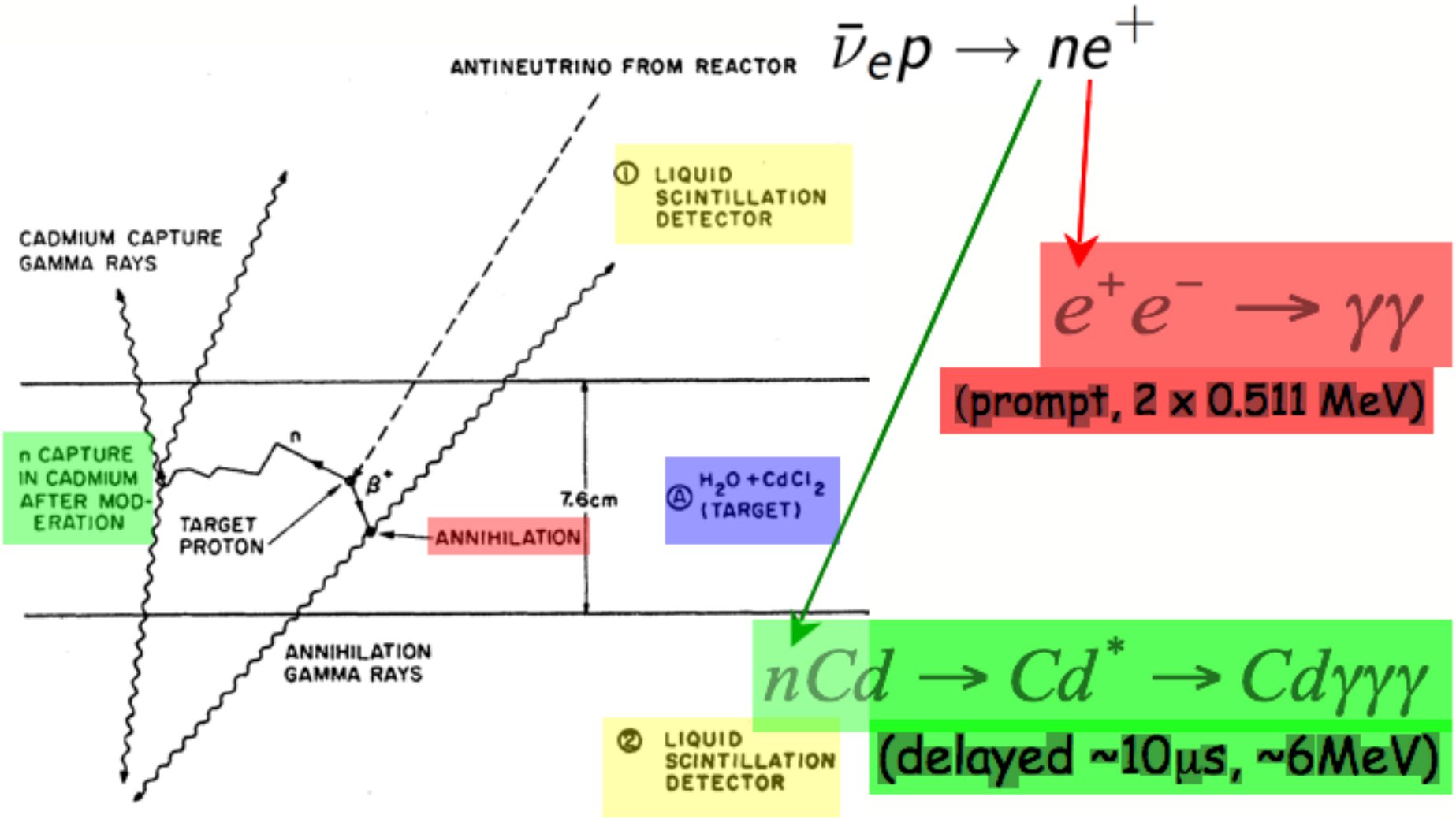


Nuclear reactors: On/off possible.

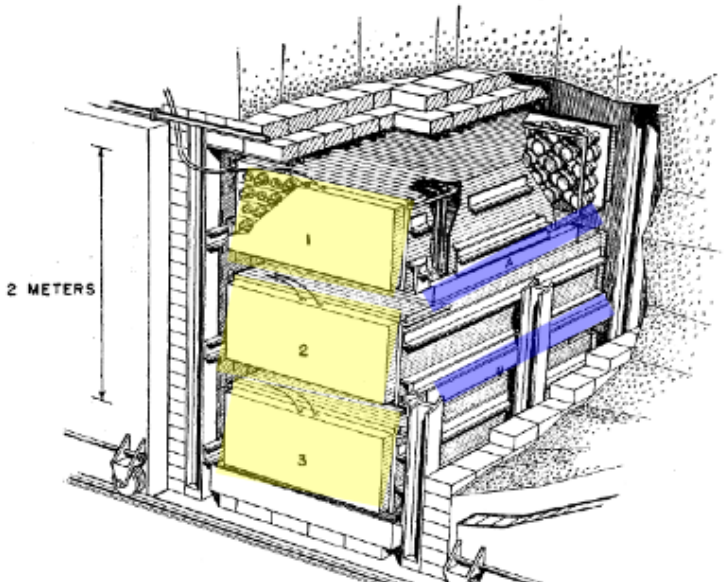
Others sources:

- Earth
- Accelerators
- Cosmic rays
- Supernovae

Observing reactor (anti-)neutrinos



Detection of the Free Antineutrino[2]



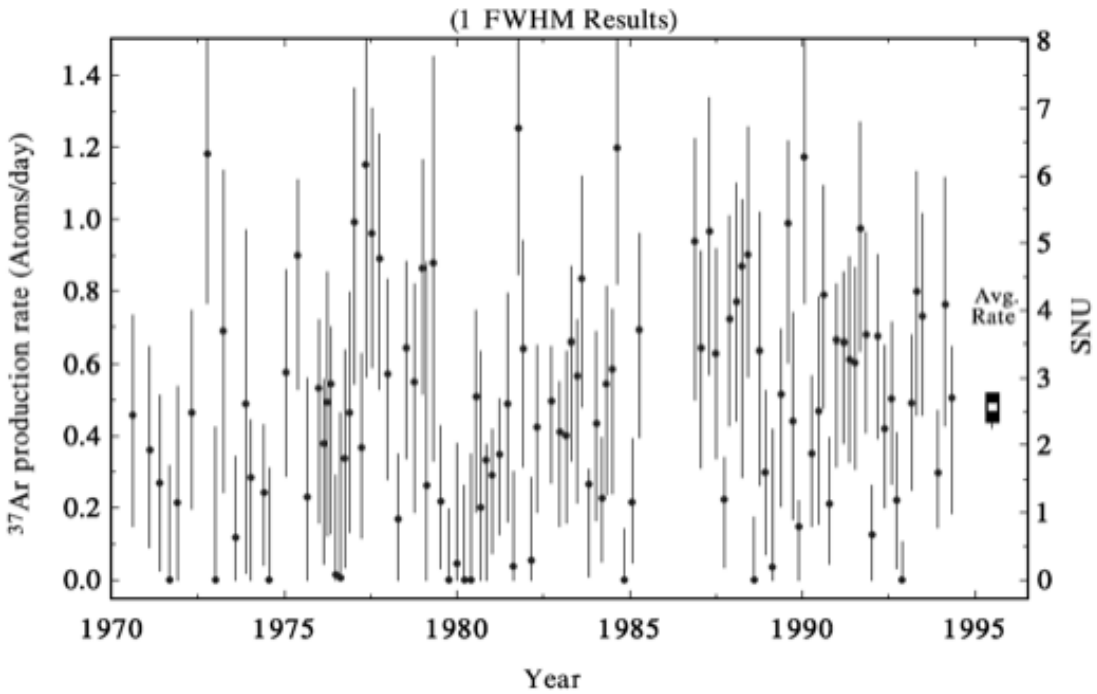
Locate 400 kg (400 liters water) detector 12 m underground to shield against cosmic rays and 11 m from core of reactor. Accumulate data with reactor on and off.

Triad	$\bar{\nu}$ flux factor	Run length (hr)	Counts from 0.75–7 μsec	Counts from 11–25 μsec	Accidental background (hr^{-1})	Net rate (hr^{-1})
Top	1.13	379.1	919	427	0.50 ± 0.02	1.92 ± 0.09
	0	38.8	27	40	0.46 ± 0.07	0.23 ± 0.15
Bottom	1.12	383.5	815	398	0.46 ± 0.02	1.66 ± 0.08
	0	128.0	119	145	0.50 ± 0.04	0.42 ± 0.09

[2] Reines *et al.*, Phys.Rev. **117** (1960) 1.

Disappearing neutrinos from the sun

BNL scientist Ray Davis observed a deficit in the rate of $^{37}\mathrm{Ar}$ produced by ν_e from the sun via $\nu_e {}^{37}\mathrm{Cl} \rightarrow {}^{37}\mathrm{Ar}\ e^-$ in 615 tons (100,000 gallons) of $\mathrm{C_2Cl_4}$ in the Homestake Gold Mine, 1478 m underground.



Observed $0.478 \pm 0.030 \pm 0.029$ $^{37}\mathrm{Ar}$ atoms/day.

The Astrophysical Journal, **496** (1998) 505.

Expected 1.74 ± 0.24 $^{37}\mathrm{Ar}$ atoms/day based on the predicted solar ν_e flux.

Rev.Mod.Phys., **67** (1995) 781.

Analogous deficits have now been observed in other expts and with other neutrino flavors and are interpreted as due to neutrino oscillations.

The physics of flavor change(1)[3]

The amplitude for oscillation from neutrino flavor α to β is

$$\mathrm{Amp}(\nu_\alpha \to \nu_\beta) = \sum_i U^*_{\alpha i} \mathrm{Prop}(\nu_i) U_{\beta i}$$

$U^*_{\alpha i}$ amplitude for ν_α to be the mass eigenstate ν_i,

$\mathrm{Prop}(\nu_i)$ amplitude for ν_i propagation,

$U_{\beta i}$ amplitude for ν_i to be a ν_β

$$\mathrm{Prop}(\nu_i) = \exp(-i m_i \tau_i) = exp(-i(E_i t - p_i L))$$

m_i mass of eigenstate i

τ_i proper time elapsed in ν_i rest frame

L lab-frame distance between source and detector

t lab-frame elapsed time

Neutrino oscillations first described by B.Pontecorvo, Sov.Phys.JETP **6**(1958)429

[3] C. Amsler et al. (Particle Data Group), Phys. Lett. B667, 1 (2008)

The physics of flavor change(2)

Since probability $P(\nu_\alpha \to \nu_\beta) = |\mathrm{Amp}(\nu_\alpha \to \nu_\beta)|^2$, only relative phases matter so, to an excellent approximation,

$$\mathrm{Prop}(\nu_i) \approx \exp(-i m_i^2 L/2E) \quad .$$

For the two flavor case, the unitary mixing matrix is

$$U = \begin{array}{c} \\ \nu_\alpha \\ \nu_\beta \end{array} \begin{array}{c} \begin{array}{cc} \nu_1 & \nu_2 \end{array} \\ \begin{bmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{bmatrix} \end{array}$$

Probabilty of ν_α "appearing" as ν_β is

$$P(\nu_\alpha \to \nu_\beta) = \sin^2 2\theta \sin^2[1.27\Delta m^2 L/E]$$

Survival probability of ν_α is

$$P(\nu_\alpha \to \nu_\alpha) = 1 - \sin^2 2\theta \sin^2[1.27\Delta m^2 L/E]$$

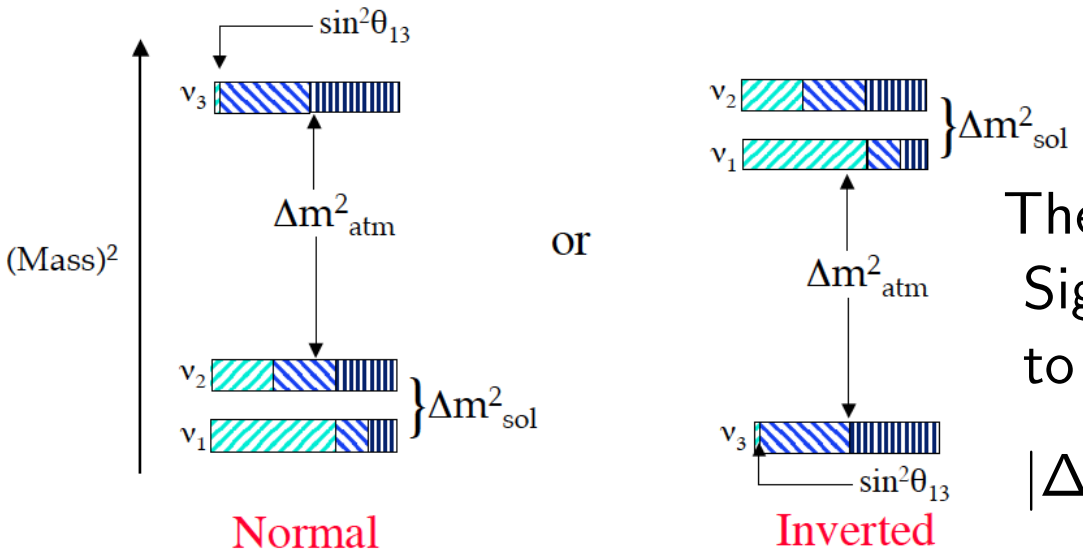
where $\Delta m^2 \equiv m_1^2 - m_2^2$ in eV^2, L in km , E in GeV.

Three neutrino mixing

$c_{ij} \equiv \cos\theta_{ij}$, $s_{ij} \equiv \sin\theta_{ij}$

$$U_{if} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{-i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} e^{\frac{i\alpha_1}{2}} & 0 & 0 \\ 0 & e^{\frac{i\alpha_2}{2}} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

$\theta_{23} \approx 45^\circ$	$\theta_{13} < 10^\circ$	$\theta_{12} \approx 35^\circ$	
Atmospheric ν	**Short-baseline Reactor ν**	Solar ν	Neutrino-less
Accelerator ν	**Future accelerator ν**	Long-baseline Reactor ν	double-beta decay



The phase δ is unknown.

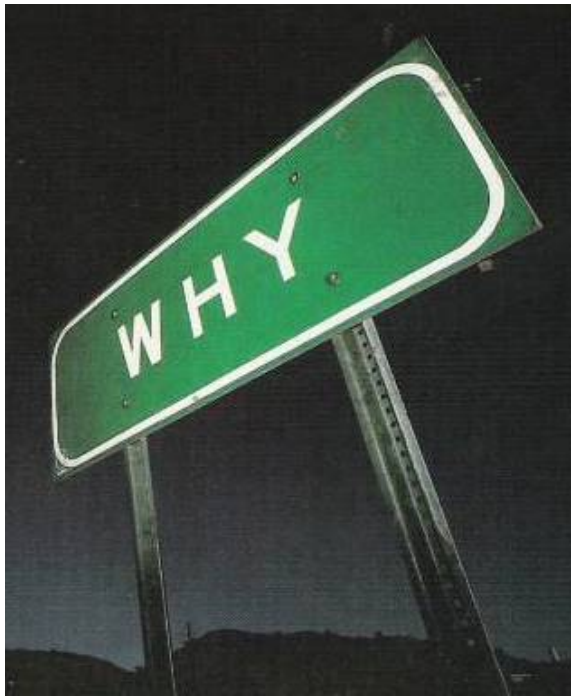
Sign of $\Delta m^2_{21} = \Delta m^2_{\rm sol}$ known due to matter-effects in the sun

$$|\Delta m^2_{\rm atm}| \approx |\Delta m^2_{31}| \approx |\Delta m^2_{32}|$$

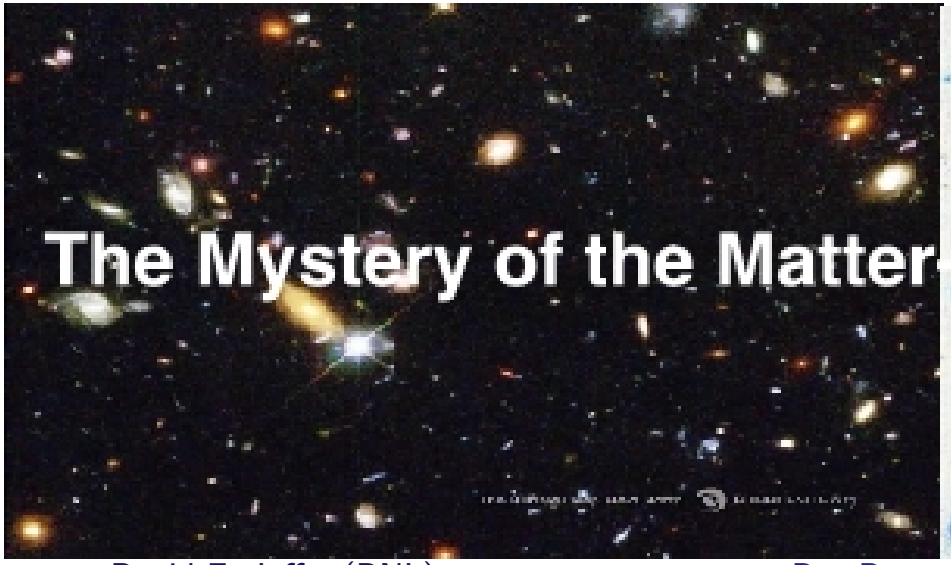
$\Delta m^2_{\rm sol} = \sim 8 \times 10^{-5}\ {\rm eV}^2$, $\Delta m^2_{\rm atm} = \sim 2.5 \times 10^{-3}\ {\rm eV}^2$

$\nu_e\,[|U_{ei}|^2]$ $\nu_\mu\,[|U_{\mu i}|^2]$ $\nu_\tau\,[|U_{\tau i}|^2]$

Obligatory 'big picture' slide



1. The baryon asymmetry of the universe requires *CP*-violation (*CPV*).
2. *CPV* in the quark sector is too small.
3. What about leptonic *CPV* ?
4. Leptonic *CPV* requires $\theta_{ij} \neq 0$, $\forall i, j$ and $\delta \neq 0, \pi$.
5. We need to measure θ_{13} (and δ).



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

1. Accelerator experiments: $\nu_\mu \to \nu_e$ appearance (MINOS, T2K, NOνA, LBNE)

$$P(\nu_\mu \to \nu_e) \approx \sin^2 2\theta_{13} \sin^2 2\theta_{23} \sin^2 \left[\frac{\Delta m^2_{31} L}{4E}\right]$$

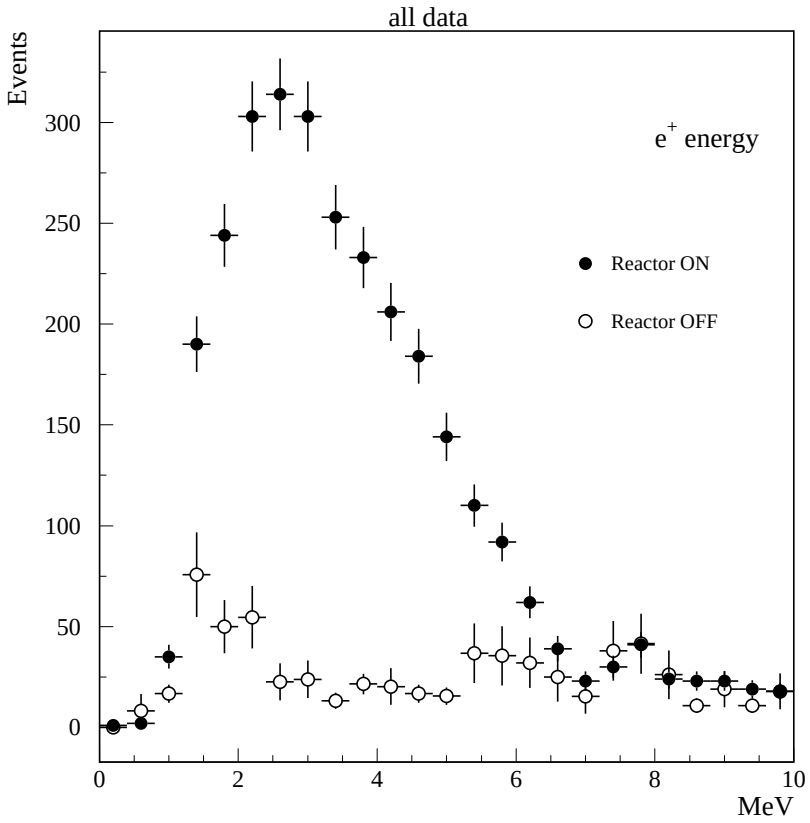
   - Requires powerful ν_μ beam
   - Long $\mathcal{O}(100 - 1000)$ km baseline
   - Dependent on other neutrino parameters

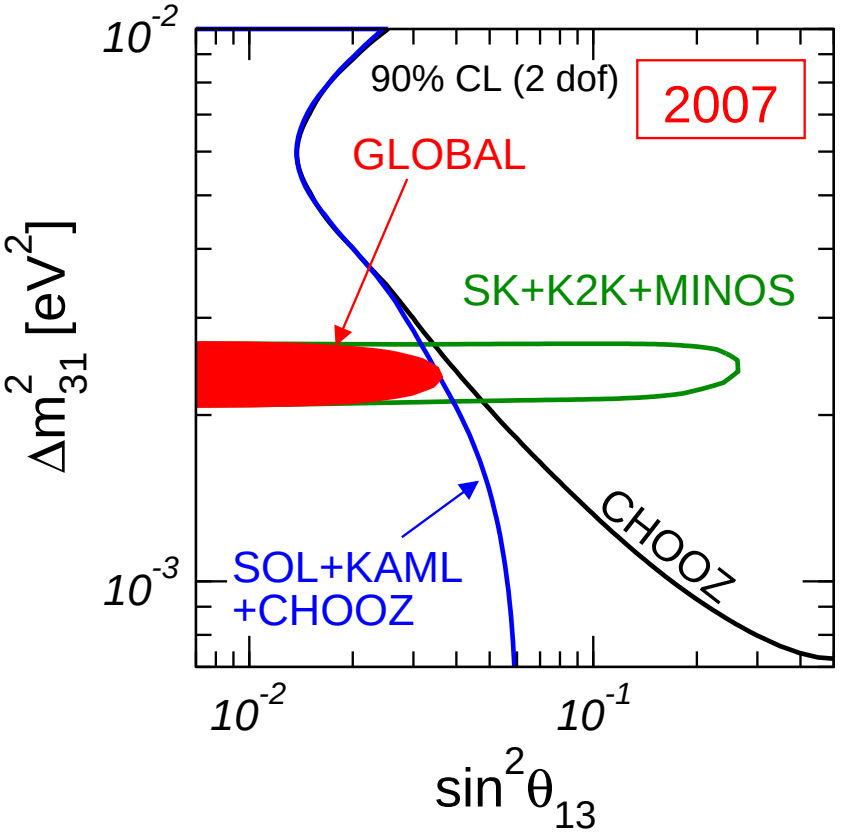
2. Reactor experiments: $\bar{\nu}_e \to \bar{\nu}_e$ disappearance (Double Chooz, Daya Bay, Reno)

$$P(\bar{\nu}_e \to \bar{\nu}_e) \approx 1 - \sin^2 2\theta_{13} \sin^2 \left[\frac{\Delta m^2_{31} L}{4E}\right]$$

   - Requires operating nuclear reactor(s)
   - Short $\mathcal{O}(1)$ km baseline
   - Unambiguous result

Chooz reactor expt: Best limit on $\sin^2 2\theta_{13}$





5 ton target exposed to 2 reactors, total thermal power 8.5 GW, 1 km baseline, $\sim$4 months run Phys.Lett.B**466** (1999) 415

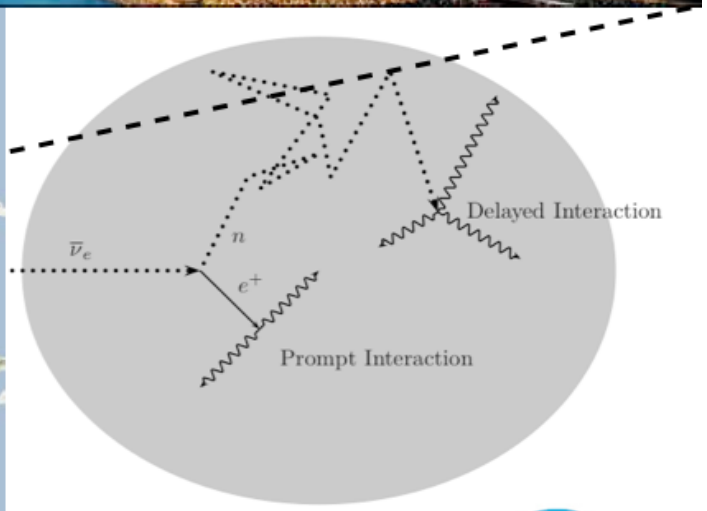
A global ν analysis arXiv:0710.5027

Improving on Chooz – Getting to $\sin^2 2\theta_{13} < 0.01$

Improvements with the Daya Bay reactor neutrino experiment.

- Increase statistics
  - More $\bar{\nu}_e$: 11.6 $\mathrm{GW_{th}}$ (17.4 $\mathrm{GW_{th}}$ in 2011). (Chooz: 8.6 $\mathrm{GW_{th}}$) $1\ \mathrm{GW_{th}} = 2 \times 10^{20} \bar{\nu}_e/\mathrm{s}$
  - Increase target mass: 4× 20 ton target at far site (Chooz: 5 tons)
  - Run longer ∼3 years (Chooz: ∼1/3 year)
- Suppress background
  - Go deeper underground to reduce cosmogenic background
- Optimize baseline
  - Δm^2_{13} known more precisely
- Reduce systematic uncertainties
  - Deploy "identical" near/far detector pairs to do *relative* measurement
  - Comprehensive detector calibration/monitoring program

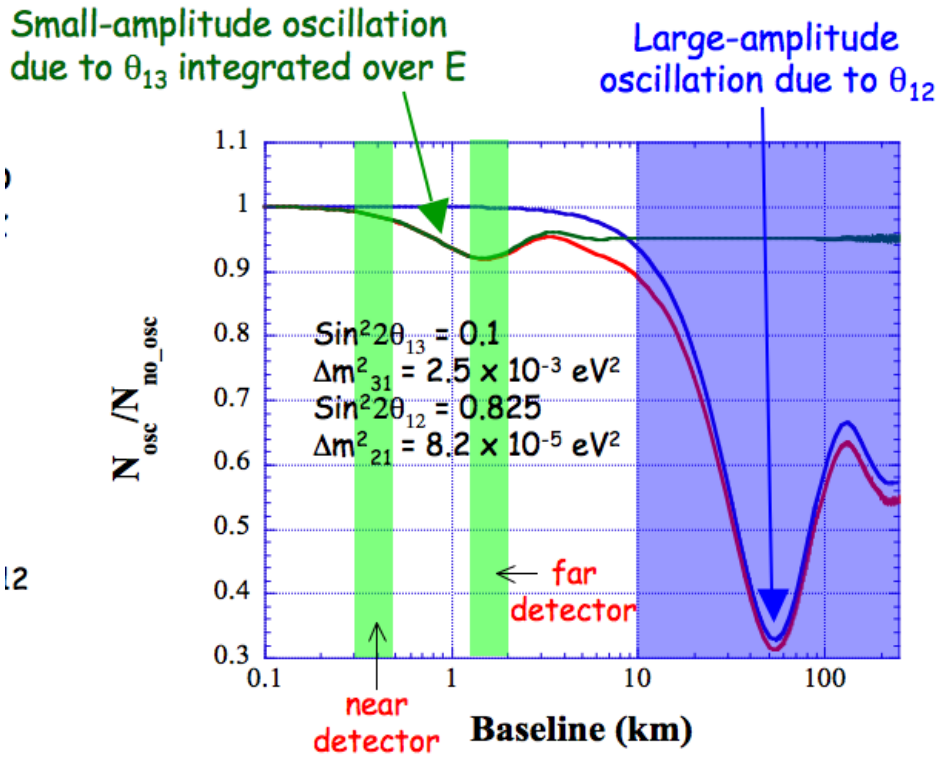
The Daya Bay Reactor Neutrino Experiment

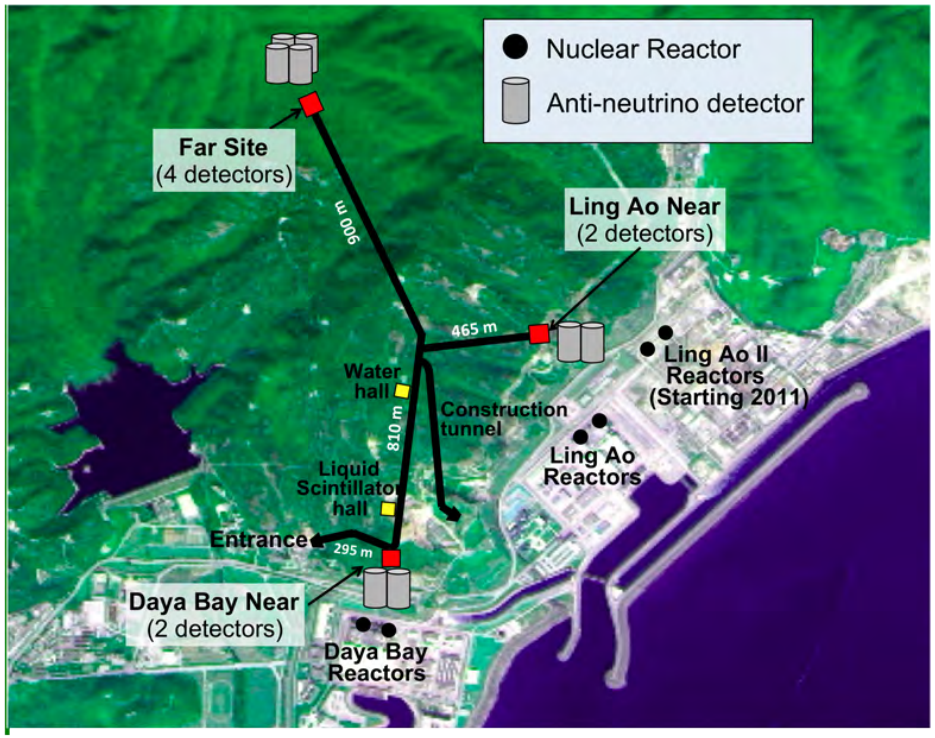


Overview of Daya Bay $\sin^2 2\theta_{13}$ measurement

Multiple detectors, optimal baselines for disappearance of reactor $\bar{\nu}_e$

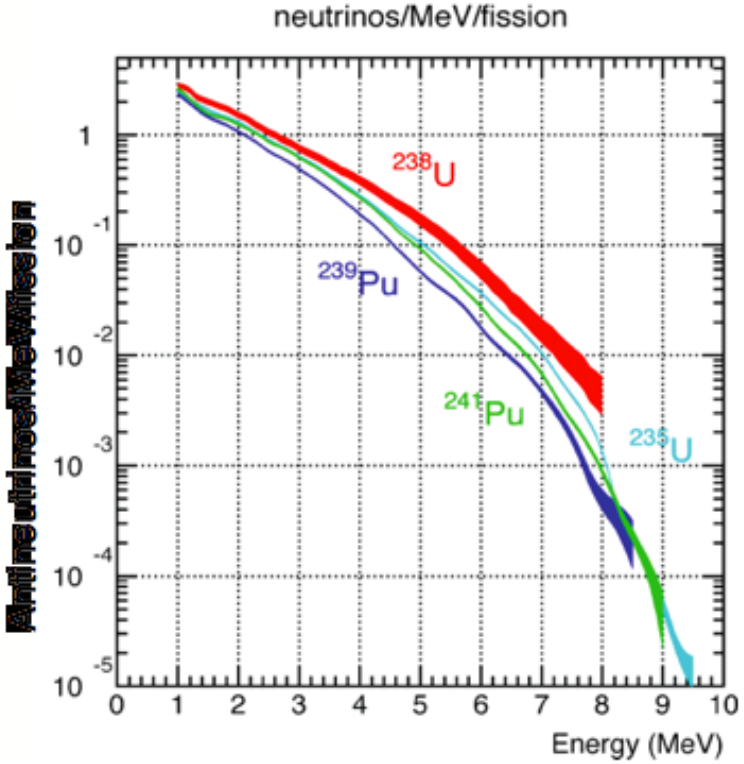
$$P(\bar{\nu}_e \to \bar{\nu}_e) \approx 1 - \sin^2 2\theta_{13} \sin^2\left(\frac{\Delta m^2_{31} L}{4E}\right) - \cos^4\theta_{13} \sin^2 2\theta_{12} \sin^2\left(\frac{\Delta m^2_{21} L}{4E}\right)$$

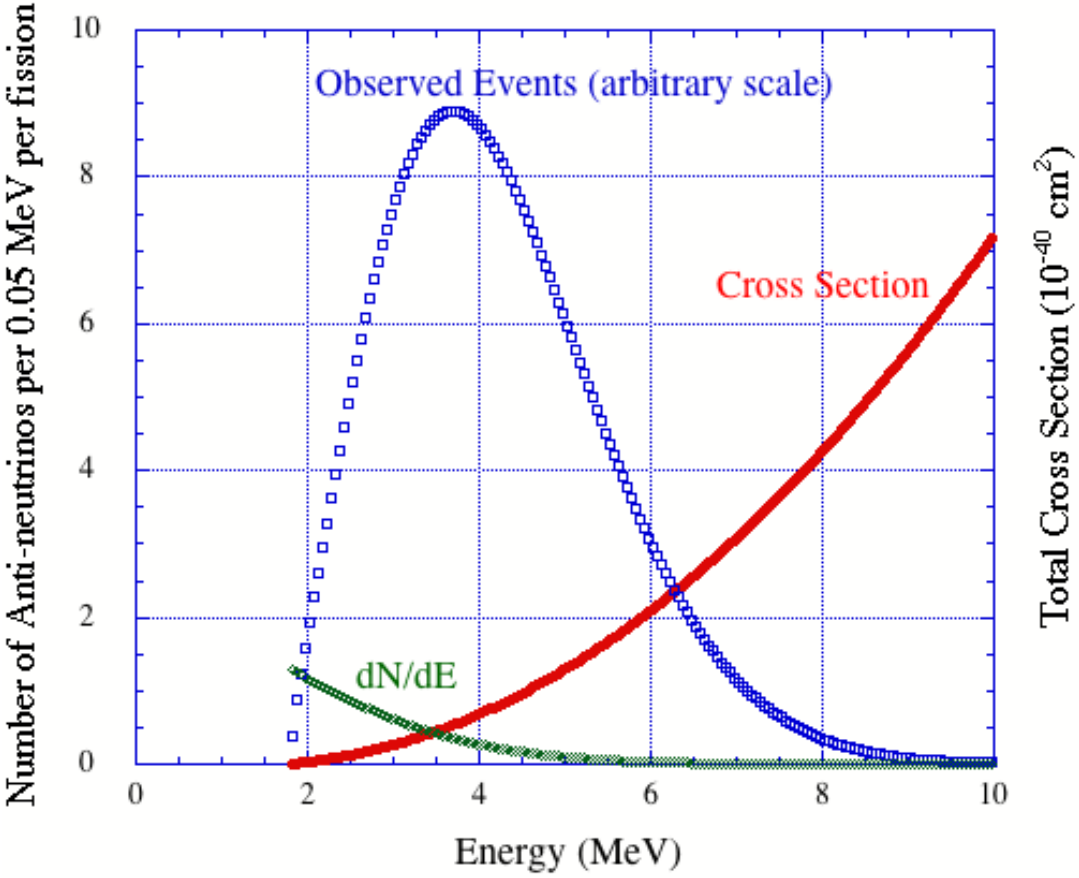




Anti-neutrino production by fission

Beta-decay of unstable nuclei produced by fission provide $\bar{\nu}_e$





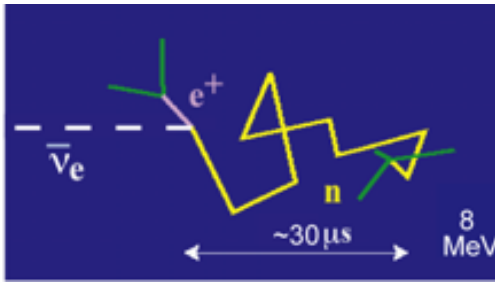
Anti-neutrino detection in the Daya Bay expt

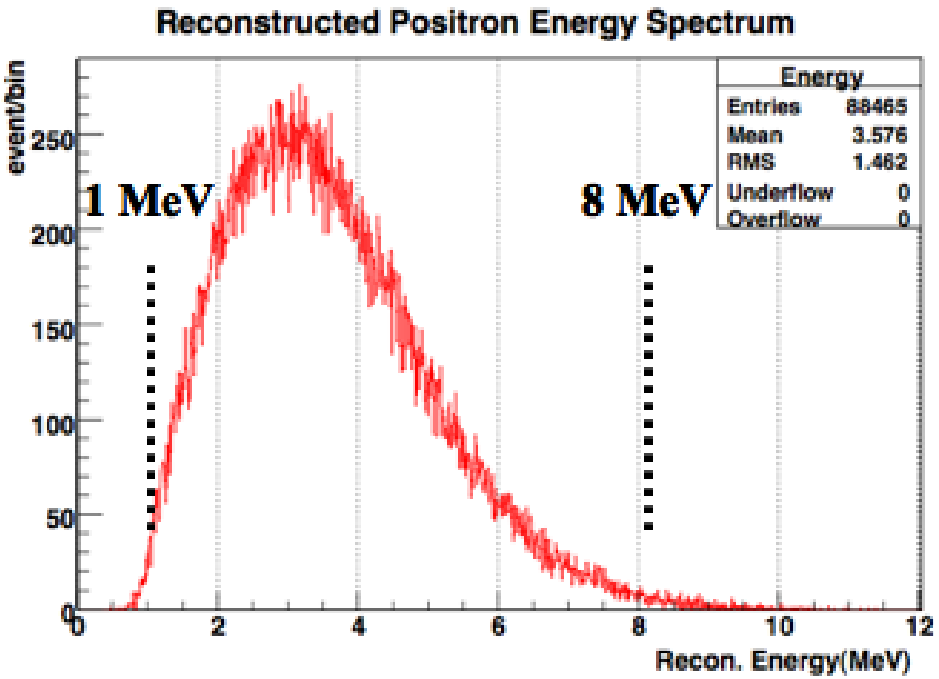
Detection of inverse beta-decay (IBD) in 0.1% Gd-doped liquid scintillator:

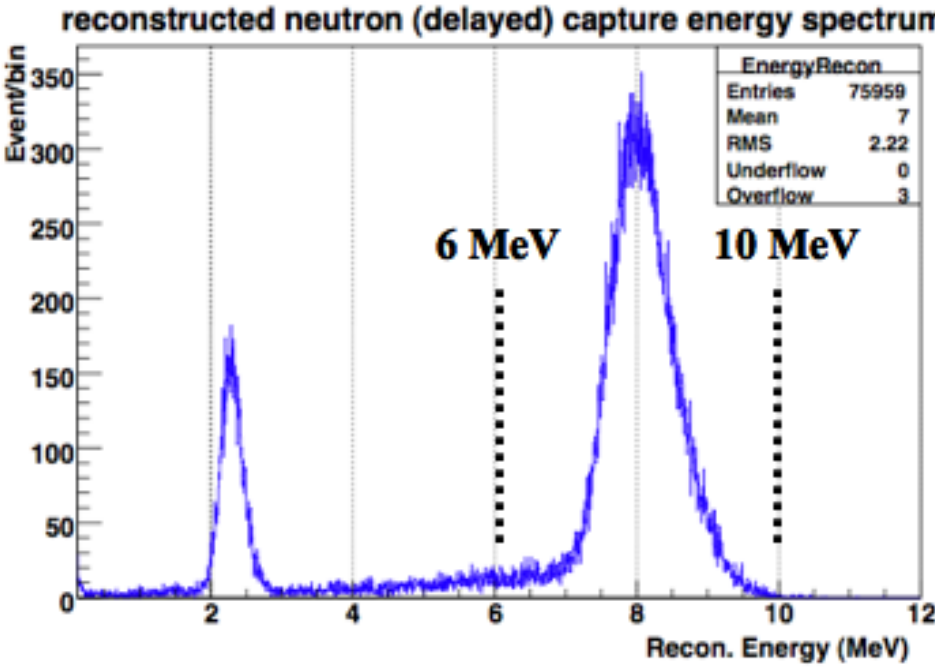
$$\bar{\nu}_e p \rightarrow e^+ n$$

$$(50,000 \text{ barns}) \hookrightarrow +\text{Gd}^* \rightarrow \text{Gd} + \gamma(8 \text{ MeV}) \text{ (delayed)}$$

$$(0.3 \text{ barns}) \hookrightarrow +p \rightarrow d + \gamma(2.2 \text{ MeV}) \text{ (delayed)}$$







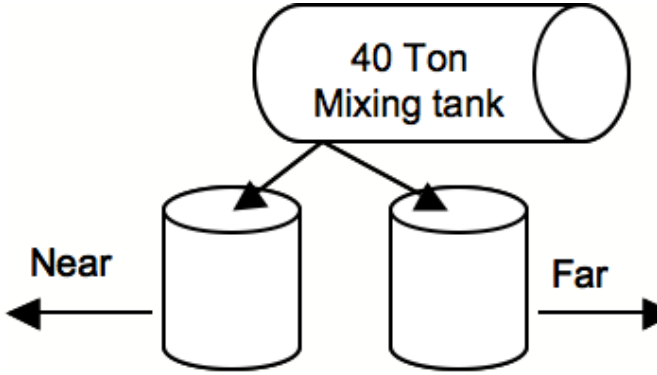
$$E_{\text{vis}} \approx E_\nu - 0.78 \text{ MeV}.$$

Elements of a $\sin^2 2\theta_{13}$ measurement

$$\frac{N_{\rm f} - N_{b,{\rm f}}}{N_{\rm n} - N_{b,{\rm n}}} = \left(\frac{N_{\rm p,f}}{N_{\rm p,n}}\right)\left(\frac{\epsilon_{\rm f}}{\epsilon_{\rm n}}\right)\left(\frac{L_{\rm n}}{L_{\rm f}}\right)^2 \frac{\mathcal{P}(L_{\rm f}, E; \sin^2 2\theta_{13})}{\mathcal{P}(L_{\rm n}, E; \sin^2 2\theta_{13})}$$

- f, n denotes *far* or *near* site
- N Number of inverse beta decay (IBD) candidates
- N_b Measured number of background events
- N_p Number of target protons (target mass)
- ϵ IBD selection efficiency
- $\mathcal{P}$ Disappearance probability $\times$ reactor $\bar{\nu}_e$ flux
- E $\bar{\nu}_e$ energy
- L Baseline (distance from reactor to detector)

Assessment of systematic uncertaintiess



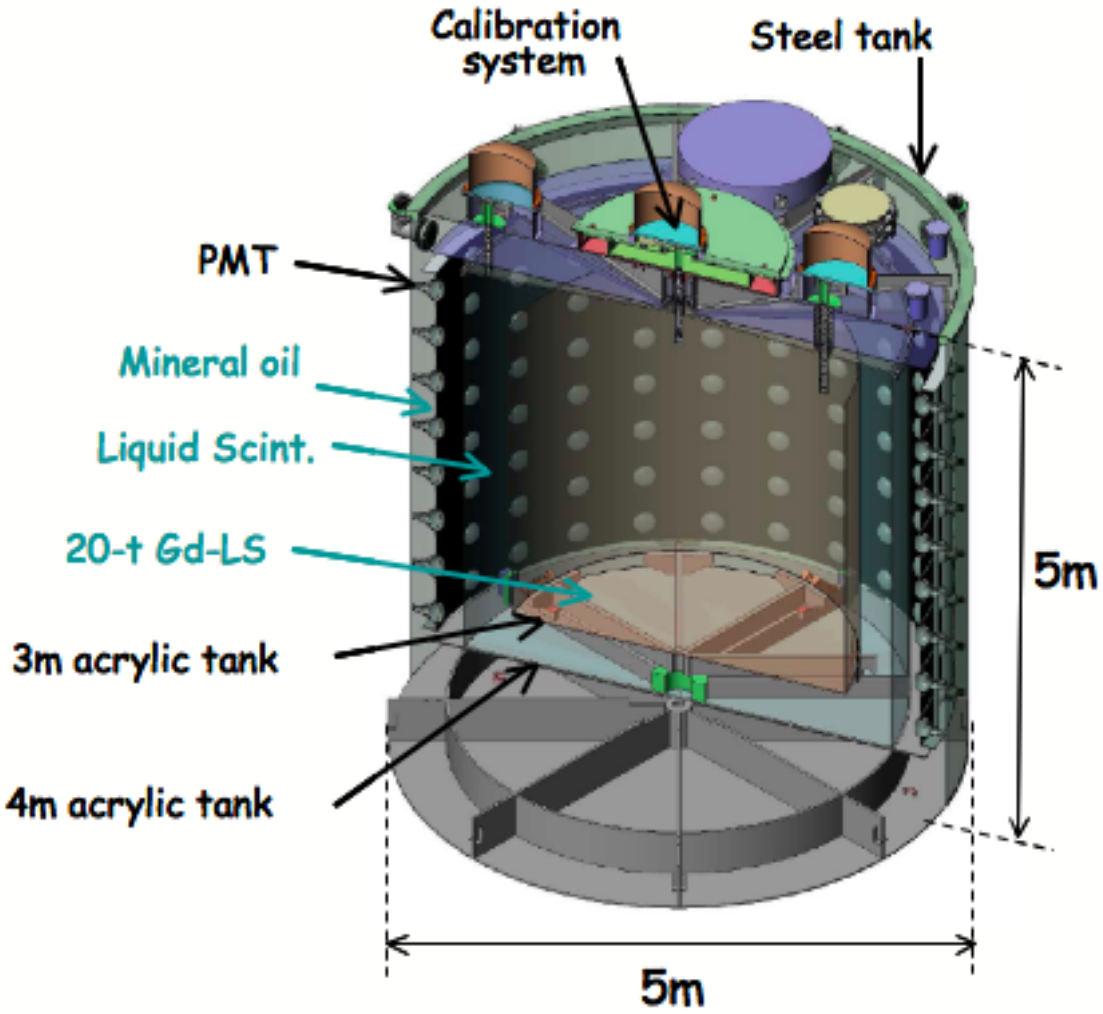
Fill Antineutrino Detectors (ADs) in pairs to minimze differences in liquids.

Anti-neutrino Detectors (ADs)

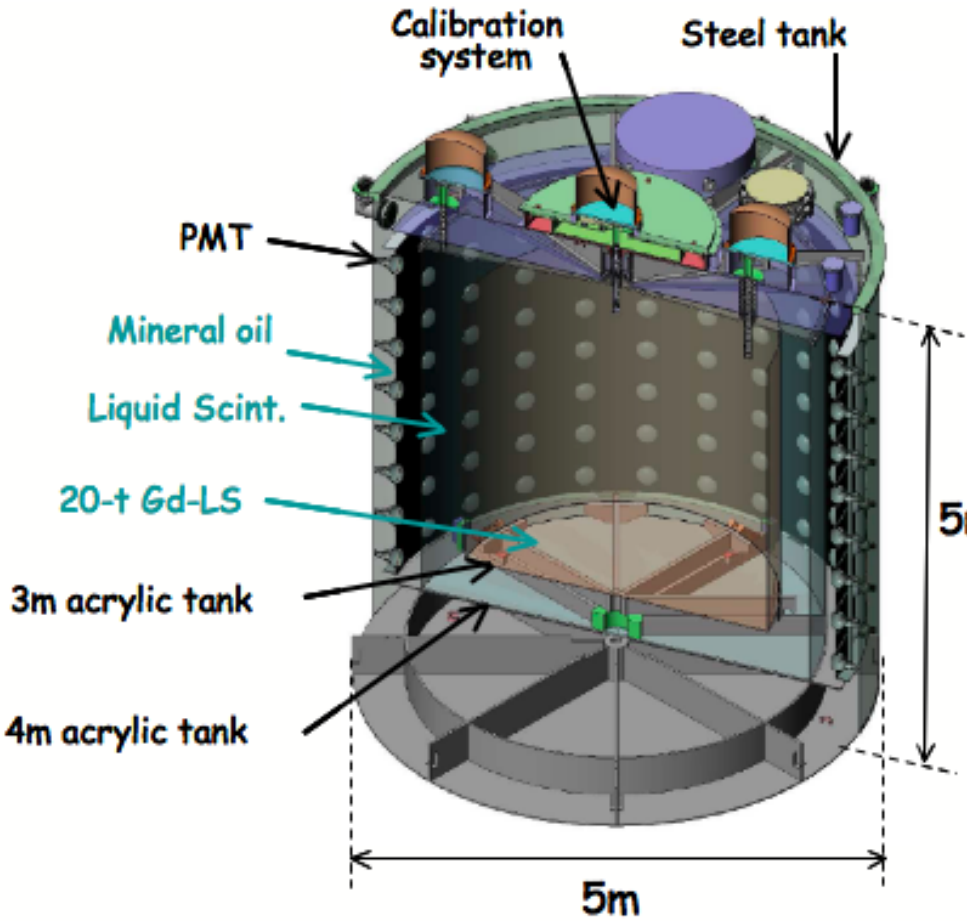
- 8 identical detectors: Reduce systematic uncertainties
- Each detector is 3 nested cylinders:

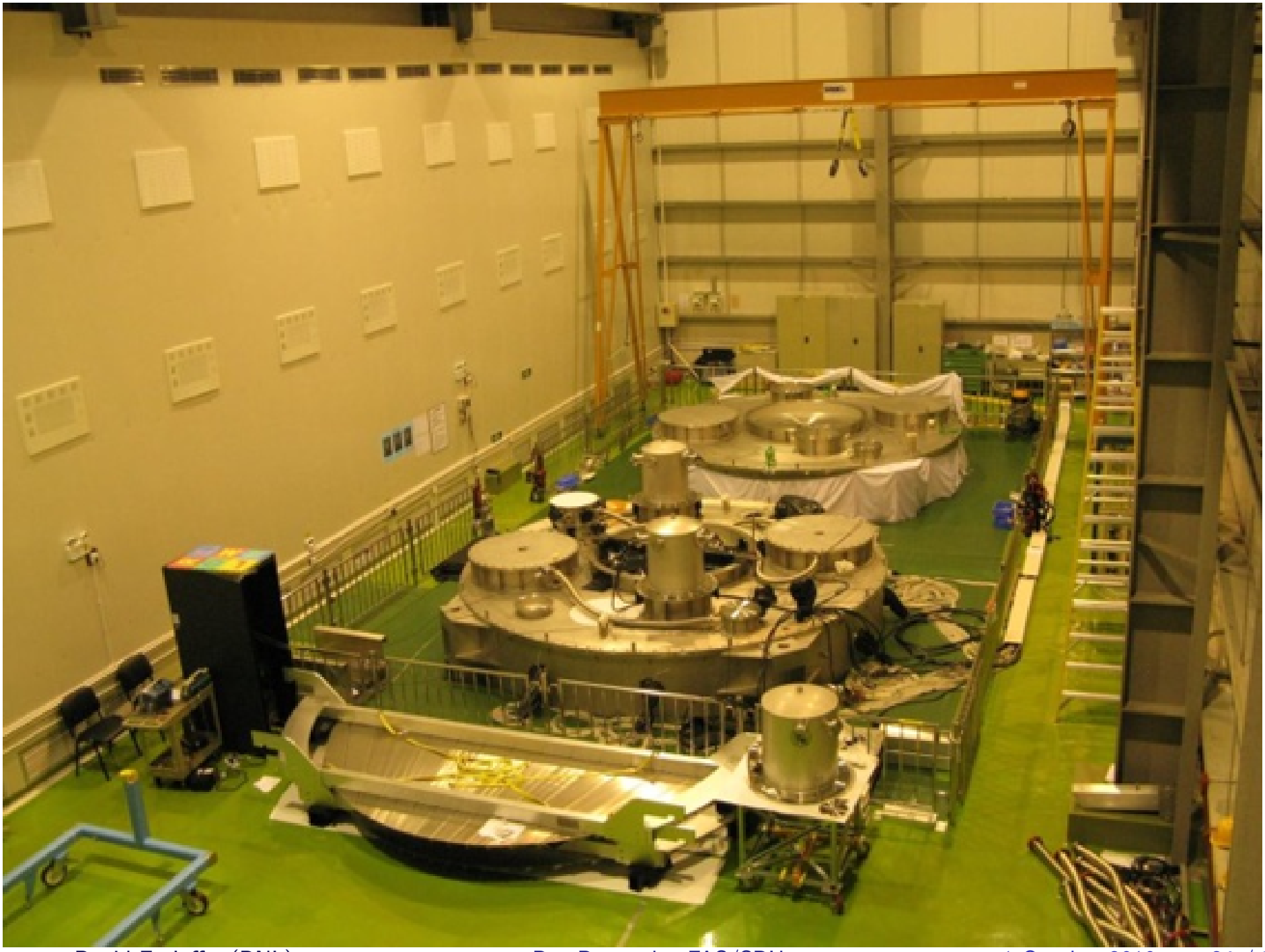
1. Inner: 20t GdLS [a] (d=3m)
2. Mid: 20t LS [b] (d=4m)
3. Outer:40t mineral oil (d=5m)

- 192 8-inch PMTs/detector
- Top/bottom reflectors

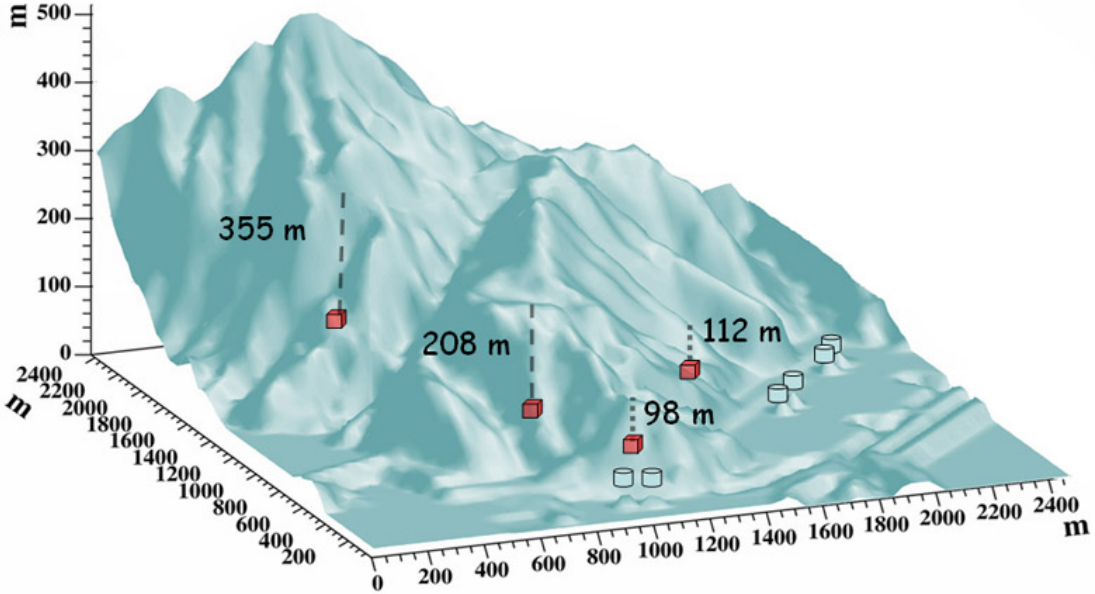


[a] GdLS=Gd-loaded Liquid Scintillator [b] LS=Liquid Scintillator

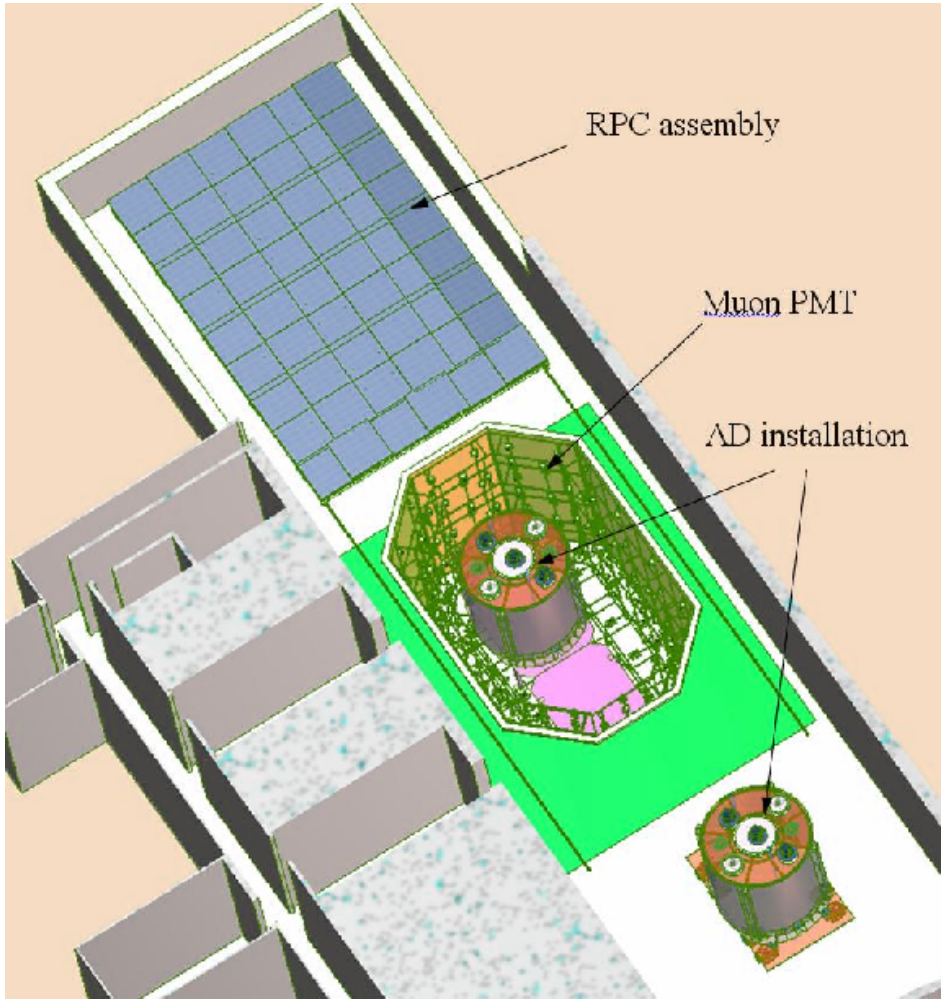

Calibration system
Steel tank
PMT
Mineral oil
Liquid Scint.
20-t Gd-LS
3m acrylic tank
4m acrylic tank
5m



Underground experimental halls and shielding

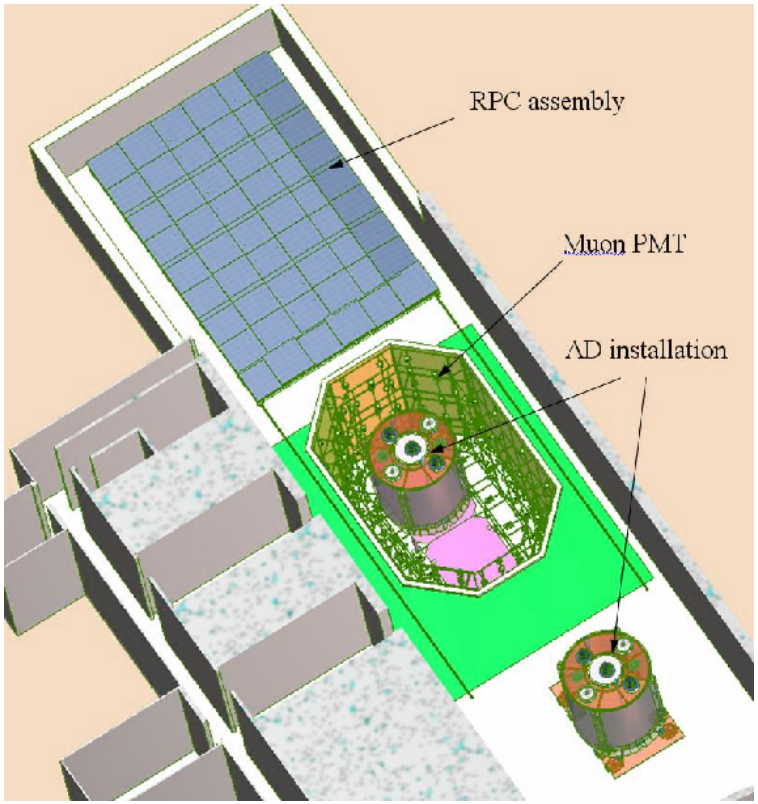


Cosmic veto and shielding



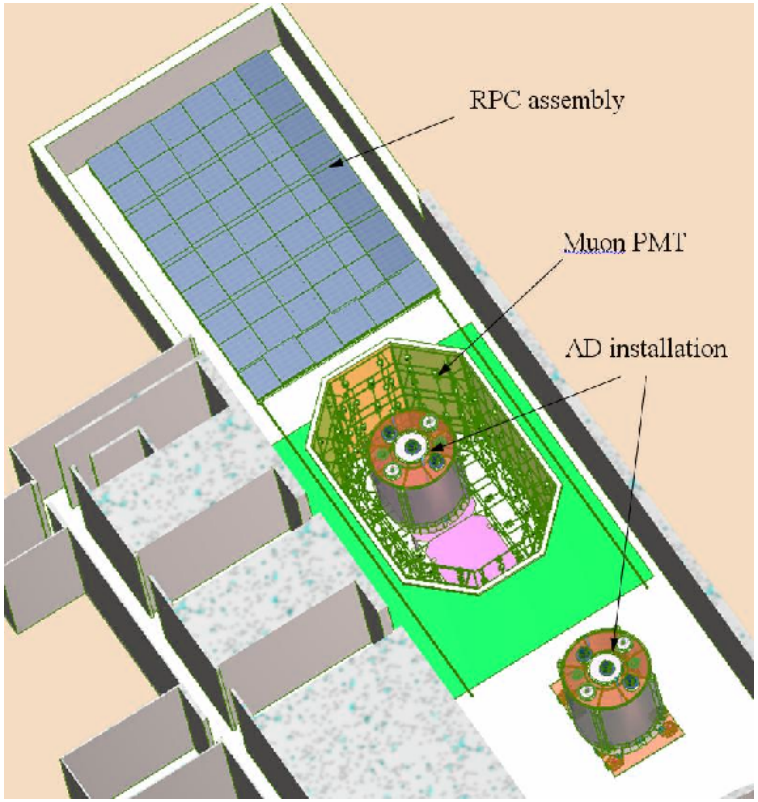
- Multiple muon veto detectors
- Water Čerenkov
  - ADs submerged in water ($\geq 2.5\mathrm{m}$ shielding)
  - Inner/Outer regions optically separated by reflective Tyvek sheets
  - 8-inch PMTs on frames (289/near, 384/far site)
- RPC: Provides independent veto above water pool

Cosmic veto and shielding



Daya Bay experimental hall

Cosmic veto and shielding



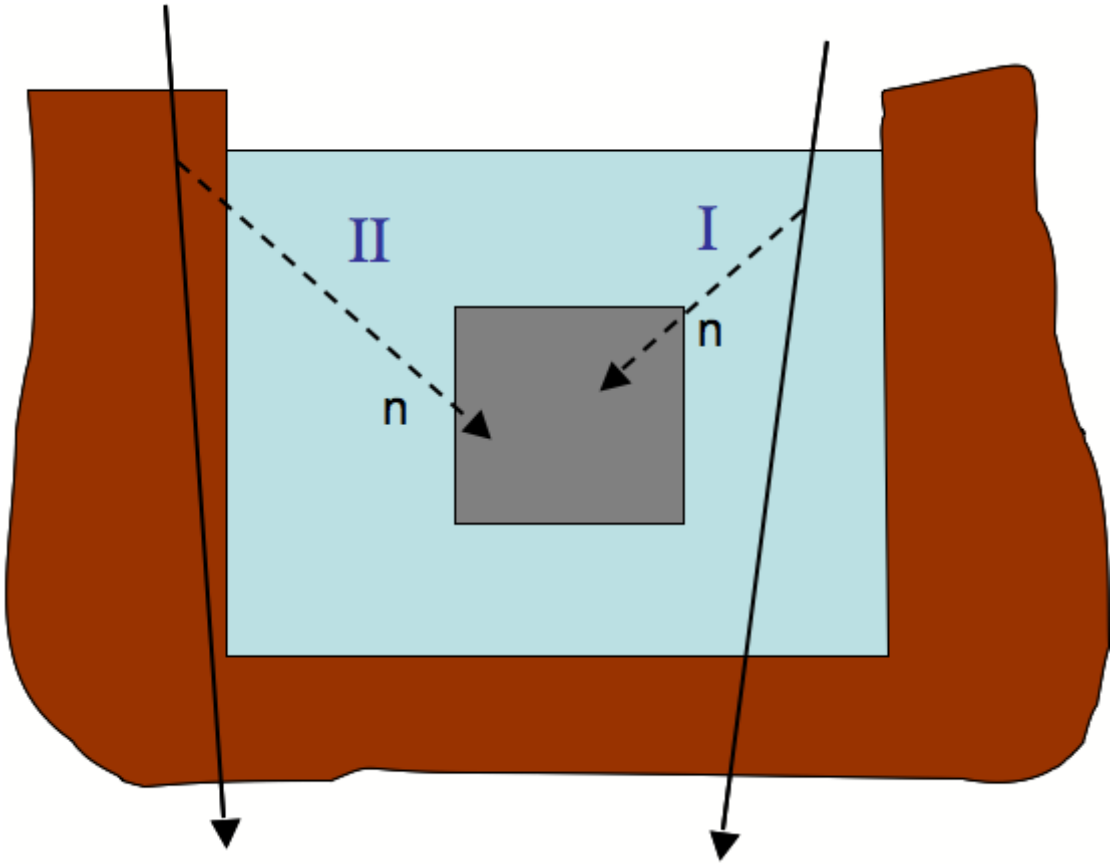
Background processes

Processes involving cosmic ray interactions and natural radioactivity can mimic the delayed-coincidence signature of inverse beta decay.

1. Fast neutrons (prompt p recoil, delayed n capture)
2. $^9Li/^8He$ (β decay with n emission, $T_{1/2} \approx 200\ \mathrm{ms}$)
3. Accidental coincidences

All three rates are small ($< 1\%$) with respect to signal and can be measured or constrained with data.

Fast neutron background

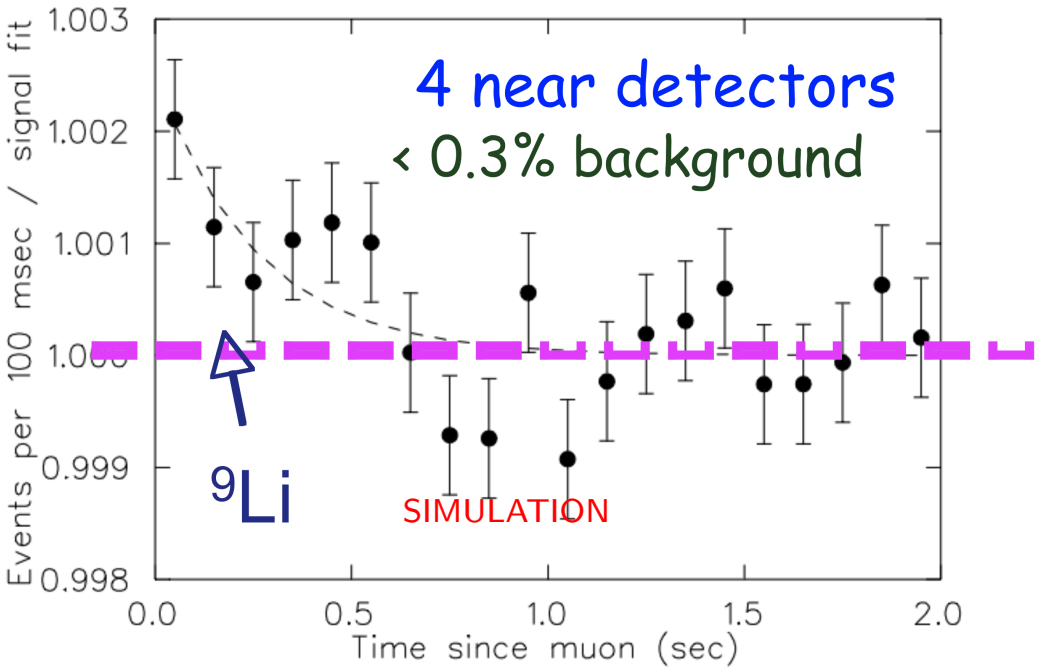


Expected rate/day/AD

Site	I: Missed μ	II: Rock n	Bkgd/Signal
Daya Bay	0.10	0.50	0.0006
Ling Ao	0.07	0.35	0.0006
Far	0.01	0.03	0.0004

$^9Li/^8He$ background

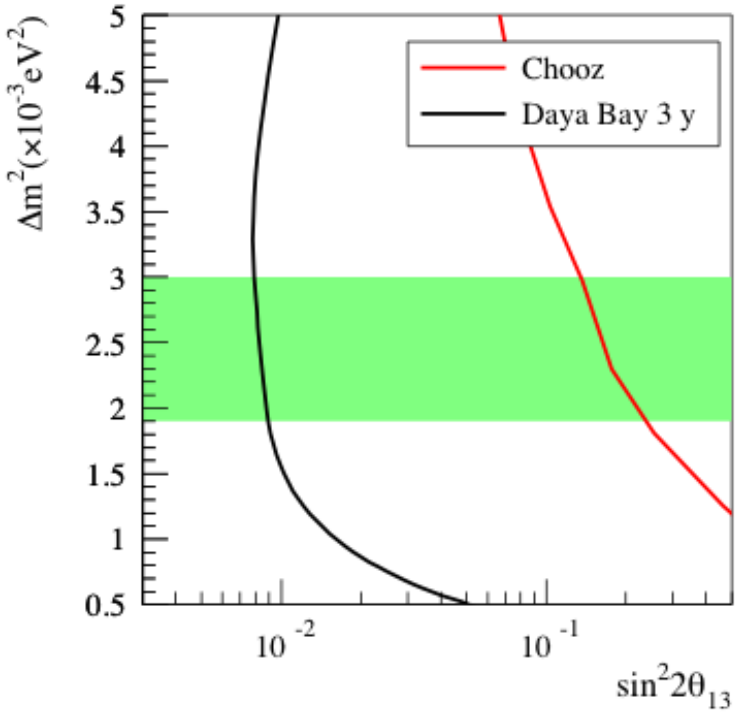
- Interaction of cosmic muons in liquid scintillator ($C_{11.6}H_{18.6}$) produces $^9Li/^8He$.
- $^9Li \rightarrow e^- + \bar{\nu}_e + {}^9Be^*$ $\quad$ $^9Be \rightarrow {}^8Be + n$ ($T_{1/2} = 178$ msec)
- Long-$T_{1/2}$ and poor spatial correlation with muon track makes rejection difficult.
- Strategy: Measure time of IBD candidate since previous muon



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

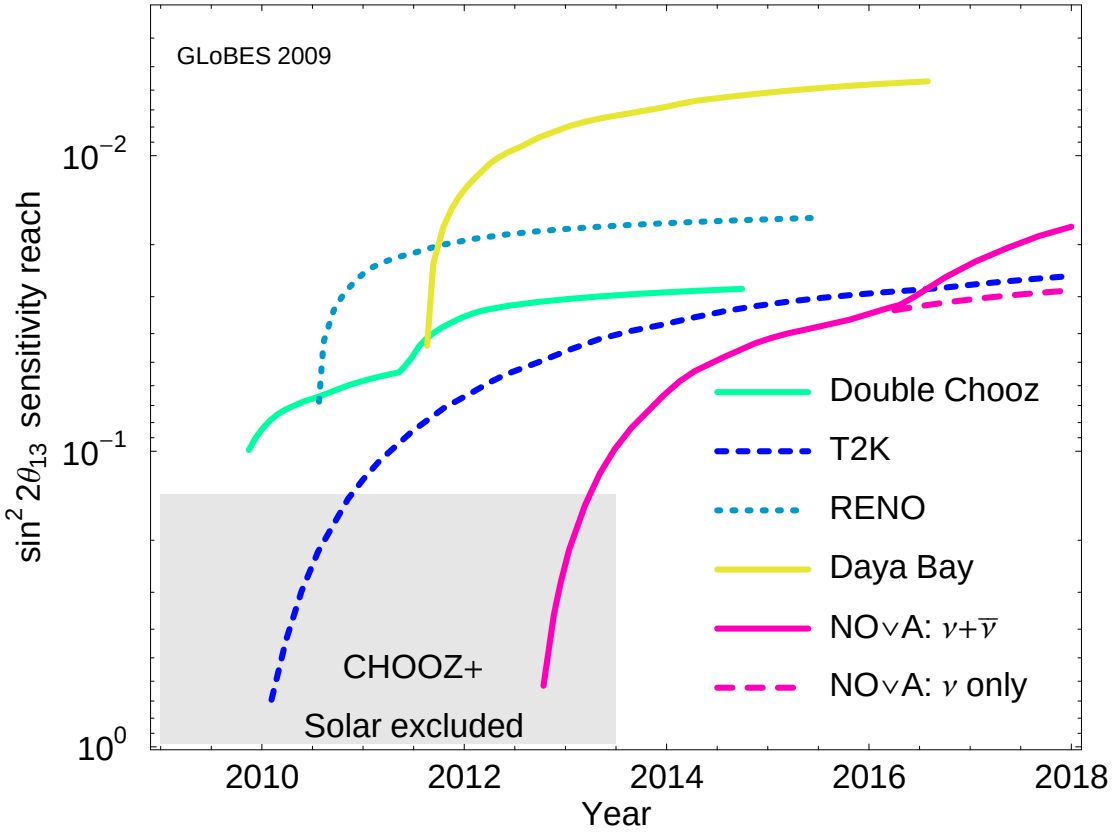
Assuming $\theta_{13} = 0$, what limit would be set by the Daya Bay expt?

90% CL limit on $\sin^2 2\theta_{13}$ with 3 years of data

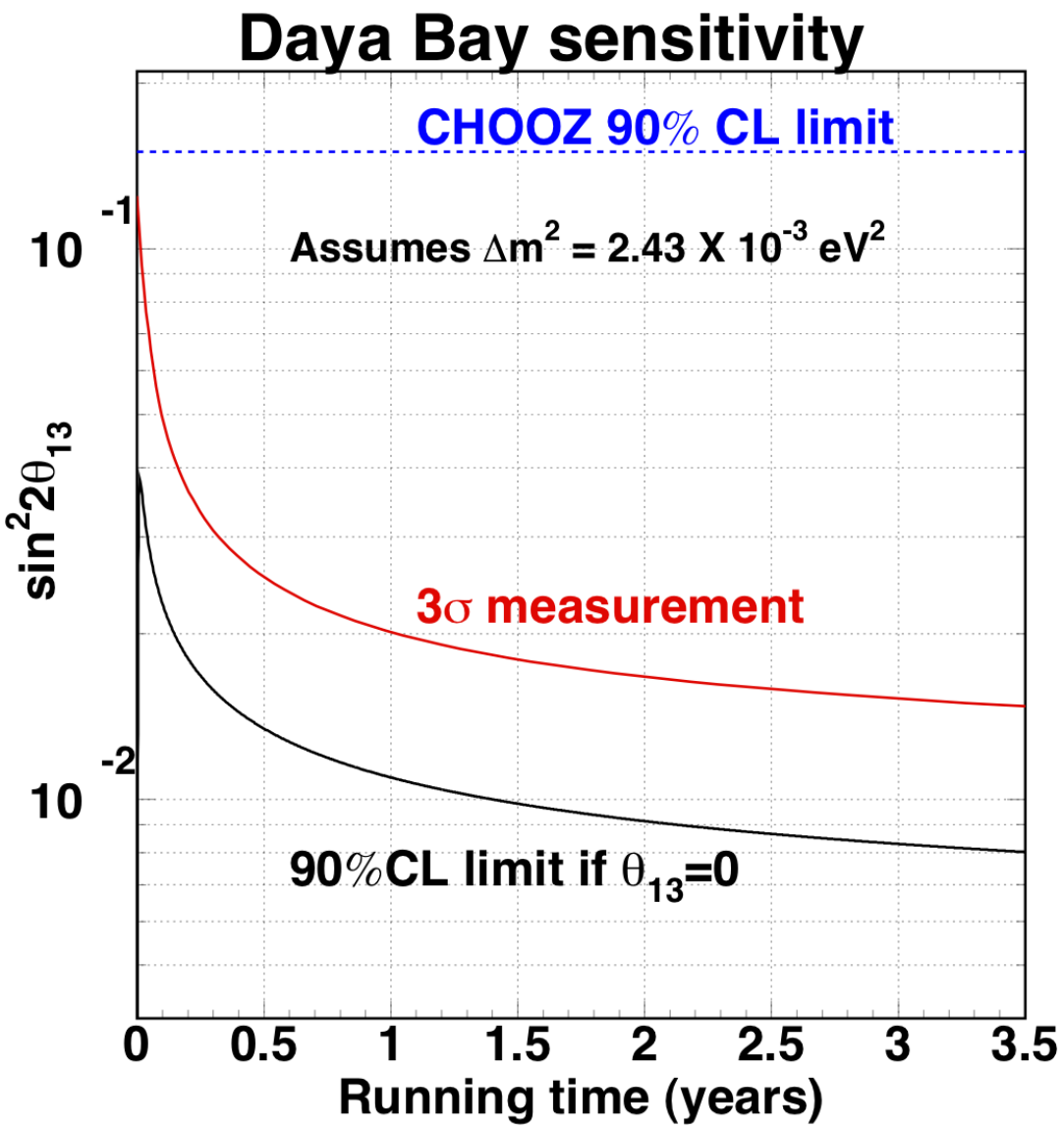


Sensitivity comparison (arXiv:0907.1896) actual dates differ

$\sin^2 2\theta_{13}$ sensitivity limit (NH, 90% CL)



Expected ability to measure $\sin^2 2\theta_{13}$



90% CL limit on $\sin^2 2\theta_{13}$ or 3σ measurement as a function of running time assuming baseline systematics

What's going on at Daya Bay?

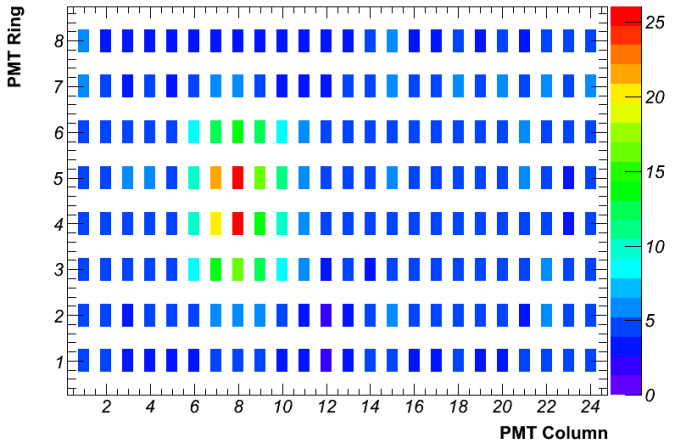
Oct 07 Ground breaking

Spring 08 CD3 review completed

Mar 09 Surface Assembly Building occupied

2011 Daya Bay near hall ready for data

2012 All 3 halls ready for data



The last slide

- The Daya Bay reactor neutrino experiment will soon begin to take data and will provide the most accurate measurement of $\sin^2 2\theta_{13}$ in the history of the universe.
- Excellent opportunities for Ph.D. theses.

`http://dayawane.ihep.ac.cn/twiki/bin/view/Public/`
Daya Bay Experiment Proposal - arXiv: hep-ex/0701029
NuFact09 Proceedings - arXiv: hep-ex/0910.4605

Extras

Some additional (non-θ_{13}) physics topics

1. Anti-neutrino decay (appearance measurement)
2. Lorentz violation (search for sidereal variations in rate)
3. Cosmic muon charge ratio
4. Atmospheric neutrinos analysis using upgoing muons
5. Neutron and alpha emission after μ^- capture: multiplicity and/or energy spectra
6. Cosmic air showers: 3 sites & 8 detectors
7. Cosmogenic background measurements: overburden and topology of 3 sites allow measurement of muon energy dependence of cosmogenic background
8. Supernova neutrinos (require a nearby supernova)

Current global fit results (Ref: Gonzalez-Garcia, Maltoni, Salvado, arXiv:1001.4524)

Fitted ranges for the six neutrino oscillation parameters at the 1σ (3σ) level:

$$\Delta m^2_{21} = 7.59 \pm 0.20 \left(^{+0.61}_{-0.69}\right) \times 10^{-5}\ \mathrm{eV}^2$$

$$\Delta m^2_{31} = \begin{cases} -2.40 \pm 0.11 \left(^{+0.37}_{-0.39}\right) \times 10^{-3}\ \mathrm{eV}^2 \text{ (inverted)} \\ +2.51 \pm 0.12 \left(^{+0.39}_{-0.36}\right) \times 10^{-3}\ \mathrm{eV}^2 \text{ (normal)} \end{cases}$$

$$\theta_{12} = 34.4 \pm 1.0 \left(^{+3.2}_{-2.9}\right) \text{ degrees}$$

$$\theta_{23} = 42.3\,^{+5.3}_{-2.8} \left(^{+11.4}_{-7.1}\right) \text{ degrees}$$

$$\theta_{13} = 6.8\,^{+2.6}_{-3.6}\ (\leq 13.2) \text{ degrees}$$

$$\delta_{\mathrm{CP}} \in [0,\ 360] \text{ degrees}$$

Electron antineutrino disappearance

Survival probability for reactor antineutrinos:

$$P(\bar{\nu}_e \to \bar{\nu}_e) = 1 - \cos^4\theta_{13}\sin^2 2\theta_{12}\sin^2\left(\frac{\Delta m^2_{21}L}{4E}\right)$$
$$- \sin^2 2\theta_{13}\left[\cos^2\theta_{12}\sin^2\left(\frac{\Delta m^2_{31}L}{4E}\right) + \sin^2\theta_{12}\sin^2\left(\frac{\Delta m^2_{32}L}{4E}\right)\right]$$
$$\approx 1 - \sin^2 2\theta_{13}\sin^2\left(\frac{\Delta m^2_{31}L}{4E}\right)$$

Matter effects can be ignored and the approximation is good if $\Delta m^2_{21} << E/L$ which is valid if $\Delta m^2_{21} \leq 3 \times 10^{-4}\ \mathrm{eV}^2$.

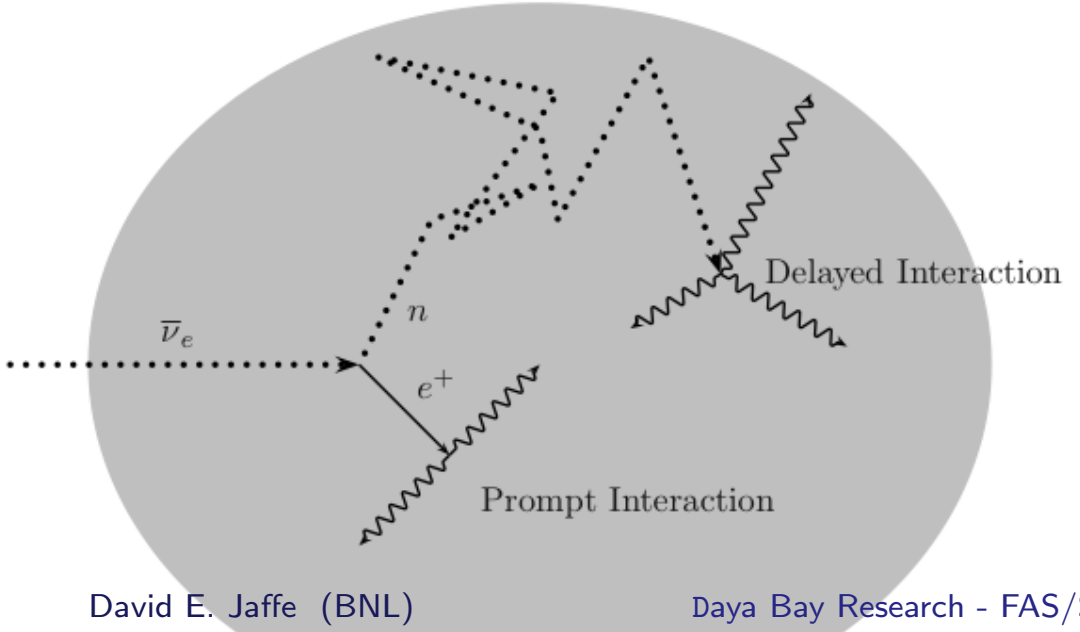
Ref: M.C. Gonzalez-Garcia, Michele Maltoni, Phys. Rept. **460** (2008) 1.

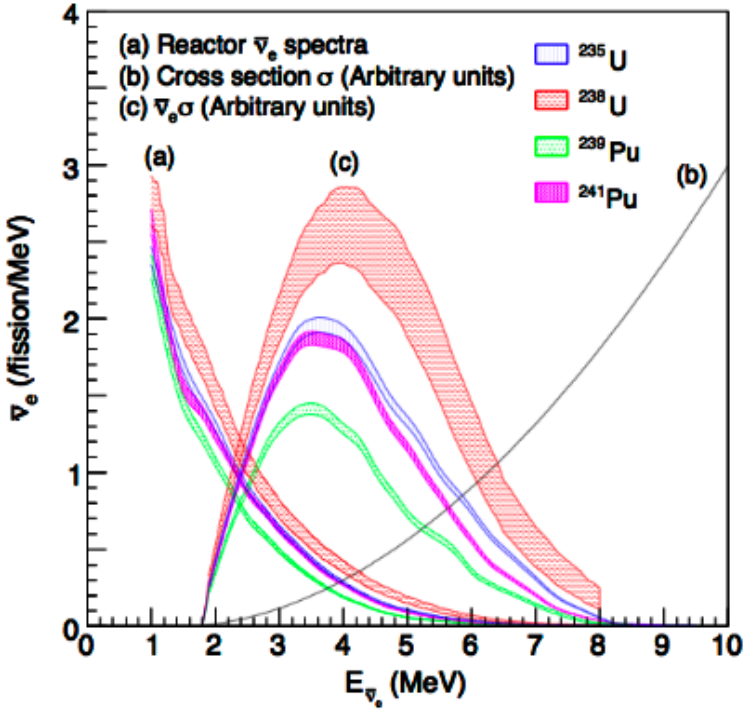
The Daya Bay Collaboration

The Daya Bay Collaboration

$\bar{\nu}_e$ detection method

- Inverse-beta decay: $\bar{\nu}_e p \rightarrow e^+ n$
- Target: 0.1% Gd-loaded Liquid Scintillator
  $nGd \rightarrow Gd^* \rightarrow Gd + \gamma s(8\ \mathrm{MeV})$
- $\sim 30\mu s$ mean neutron capture time
- Delayed coincidence provides powerful background rejection





Reactor anti-neutrino spectrum

arXiv:physics/0607126

Reducing systematic uncertainties

Detector Uncertainty Source		Baseline	Goal	Chooz Experience
Number of protons		0.3%	0.1%	0.8%
Detection Efficiency	Energy cuts	0.2%	0.1%	0.8%
	H/Gd ratio	0.1%	0.1%	1.0%
	Time cut	0.1%	0.03%	0.4%
	Neutron mult.	0.05%	0.05%	0.5%
	Trigger	0.01%	0.01%	0.01%
	Live time	$< 0.01\%$	$< 0.01\%$	$< 0.01\%$
Total Uncertainty		0.38%	0.18%	1.7%
		Two detector **relative** uncertainty		One detector **absolute** uncertainty

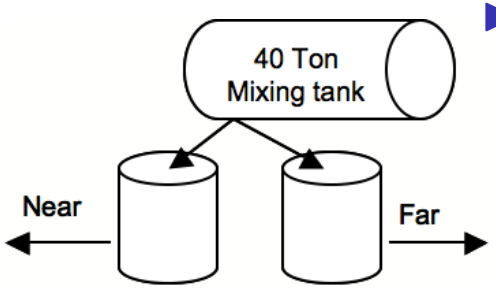
Requirements on systematic uncertainties

$$\frac{N_{\mathrm{f}}}{N_{\mathrm{n}}} = \left(\frac{N_{\mathrm{p,f}}}{N_{\mathrm{p,n}}}\right)\left(\frac{L_{\mathrm{f}}}{L_{\mathrm{n}}}\right)^2\left(\frac{\epsilon_{\mathrm{f}}}{\epsilon_{\mathrm{n}}}\right)\frac{\mathcal{P}(L_{\mathrm{f}}, E; \sin^2 2\theta_{13})}{\mathcal{P}(L_{\mathrm{n}}, E; \sin^2 2\theta_{13})}$$

Measured ratio of rates

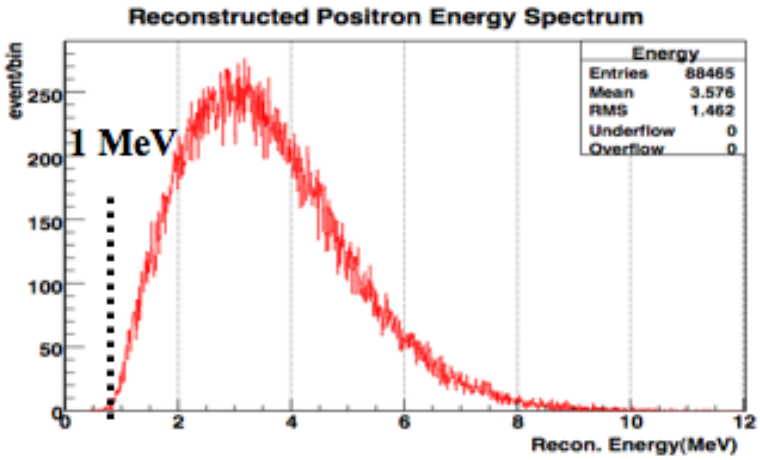
Number of protons

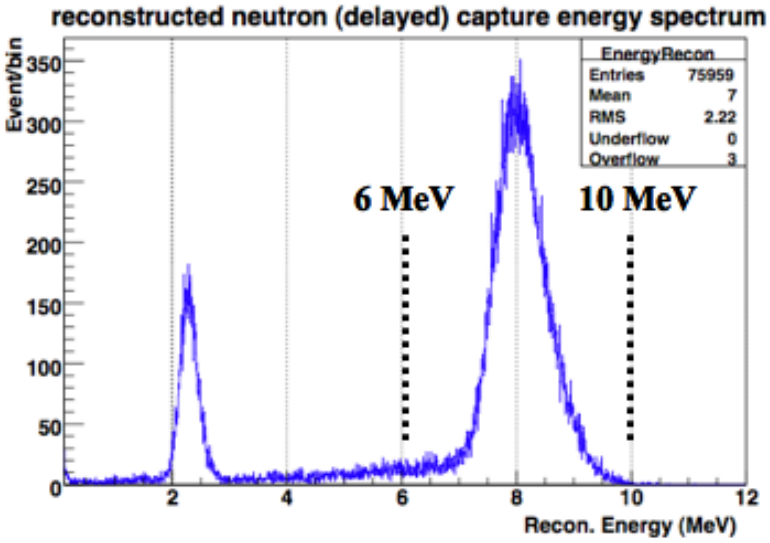
Efficiency ratio



- Attain $\leq 0.3\%$ on proton ratio by monitoring filling mass with load cells(accuracy $< 0.02\%$) and Coriolis mass flowmeters(accuracy $< 0.1\%$). Fill ADs in pairs.
- Attain $\leq 0.2\%$ on efficiency ratio with calibration

Detector efficiency





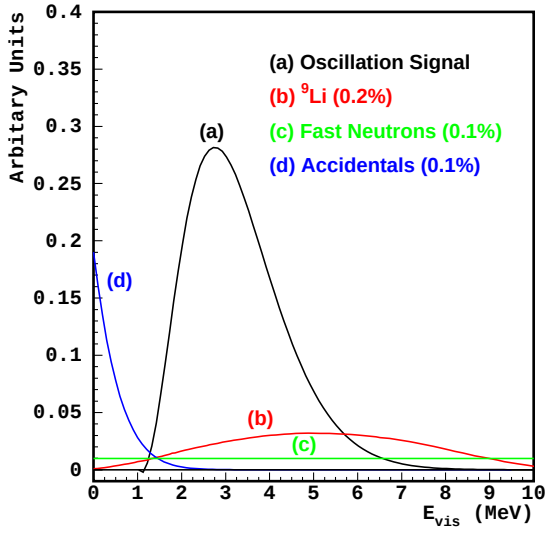
Simulation: Achieving 0.2% eff'y systematic, implies knowing e^+ threshold to 2% (easy) and relative neutron threshold to 1% (more difficult)

- Positron energy cuts at 1 & 8 MeV. Calibrate e^+ threshold with ^{68}Ge source.
- Neutron capture energy cut at 6 MeV. Calibrate with spallation nGd capture over full fiducial volume + weekly deployment of AmC source on 3 vertical axes.

Background processes and rates

Background due to natural radioactivity & cosmic ray interactions

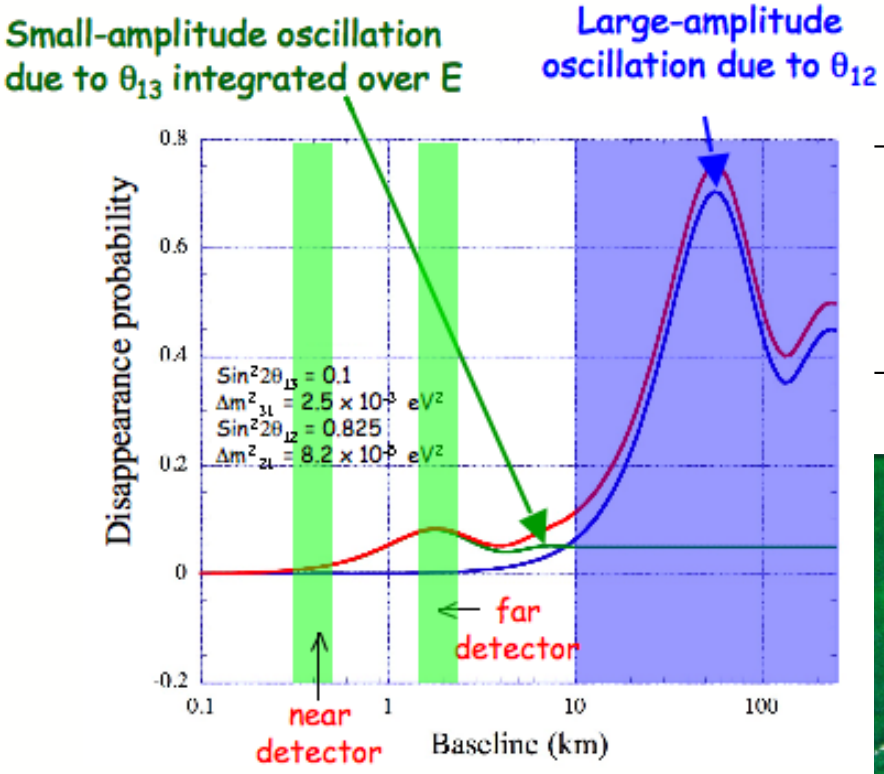
1. Muon interactions in the LS produce $^{9}\mathrm{Li}/^{8}\mathrm{He}$. A β^{-}, n emitter with Q=13 MeV, τ=0.178s. Expect bkgd/signal $\sim$0.003. Can be measured with data (NIMA**564**(2005)081801).
2. Muon interactions outside AD in water and rock produce "fast" neutrons that interact in GdLS, LS. Expect bkgd/signal $\sim$0.001. Can estimate rate from data and simulation.
3. Accidental coincidences of radioactive background with cosmogenic background. Expect bkgd/signal $\sim$0.01. Calculable from observed singles rates.



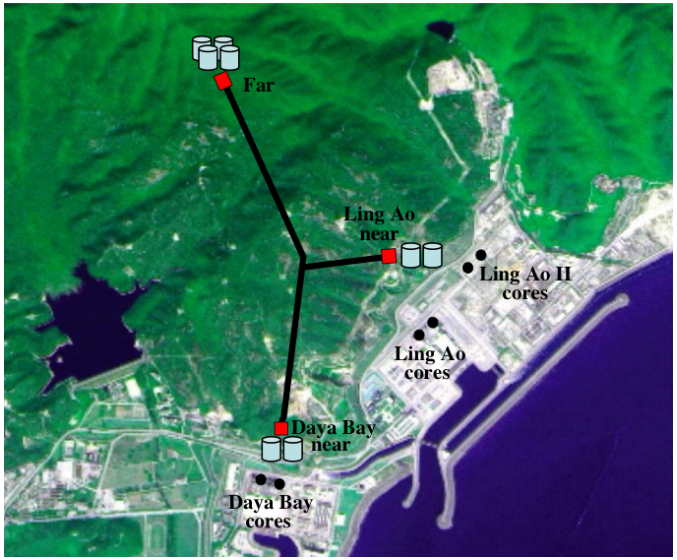
Oscillation signal for $\sin^2 2\theta_{13} = 0.01$

Optimize baseline

$$1-\mathcal{P}(\bar{\nu}_e \to \bar{\nu}_e) = \sin^2 2\theta_{13} \sin^2 \frac{1.27\Delta m^2_{31} L}{E} - \cos^4 \theta_{13} \sin^2 2\theta_{12} \sin^2 \frac{1.27\Delta m^2_{21} L}{E}$$



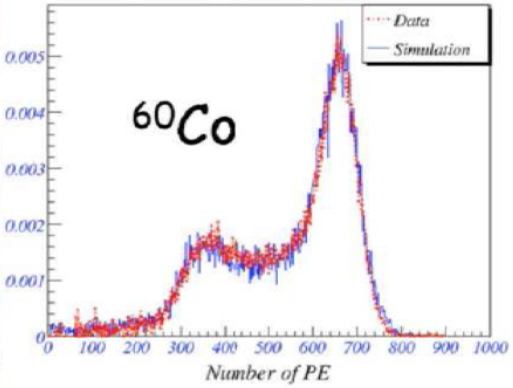
(meters)	Expt'l site		
Reactors	DyB	LA	Far
DayaBay	363	1348	1986
LingAo I	857	481	1618
LingAo II	1307	526	1613
Overburden	98	112	355

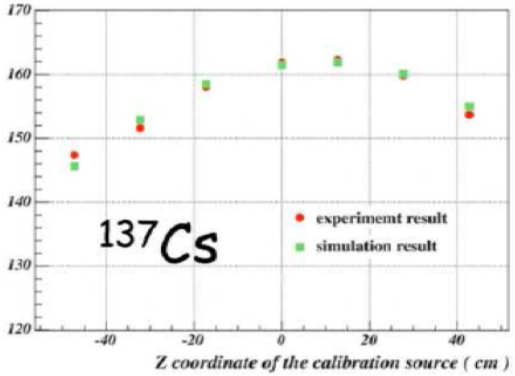


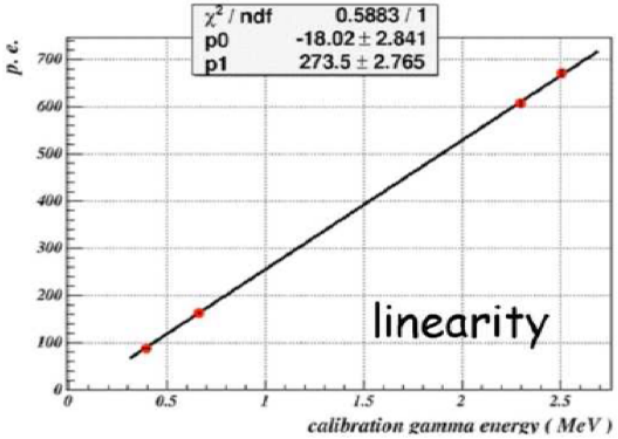
Prototype Antineutrino Detector Performance

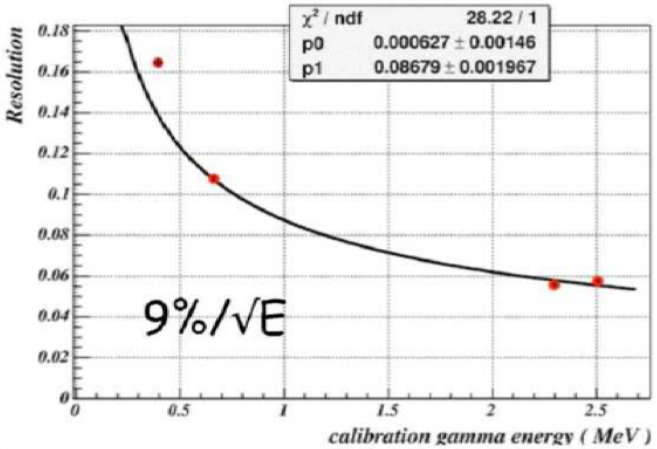
2-zone Prototype at IHEP

- 0.5 ton unloaded LS
- 45 8" PMTs with reflecting top and bottom



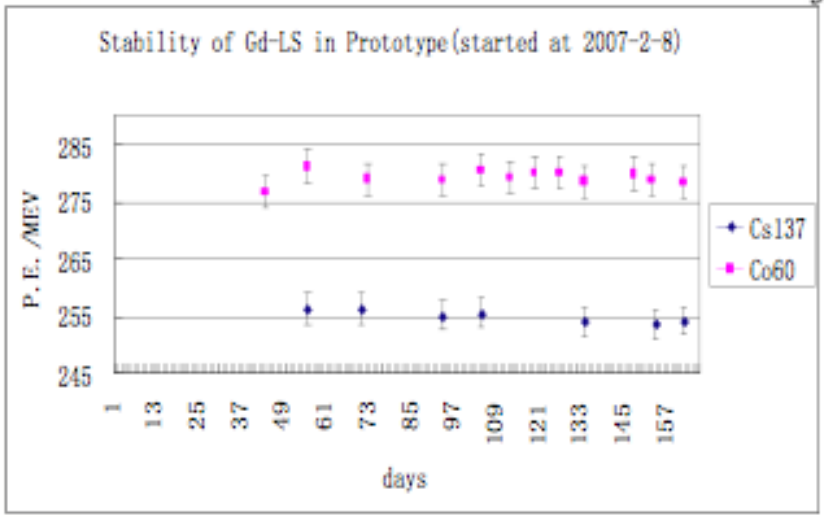


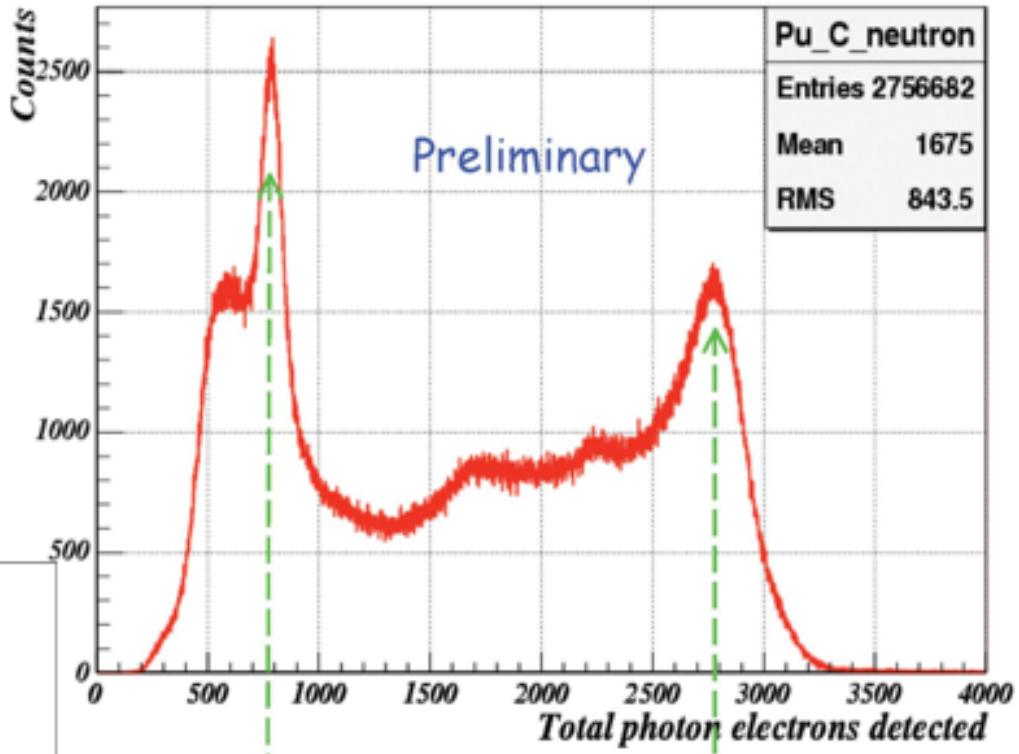




Kam-Biu Luk Daya Bay 22

IHEP Prototype Filled With 0.1% Gd-LS





2.2 MeV
(neutron captured
by proton)

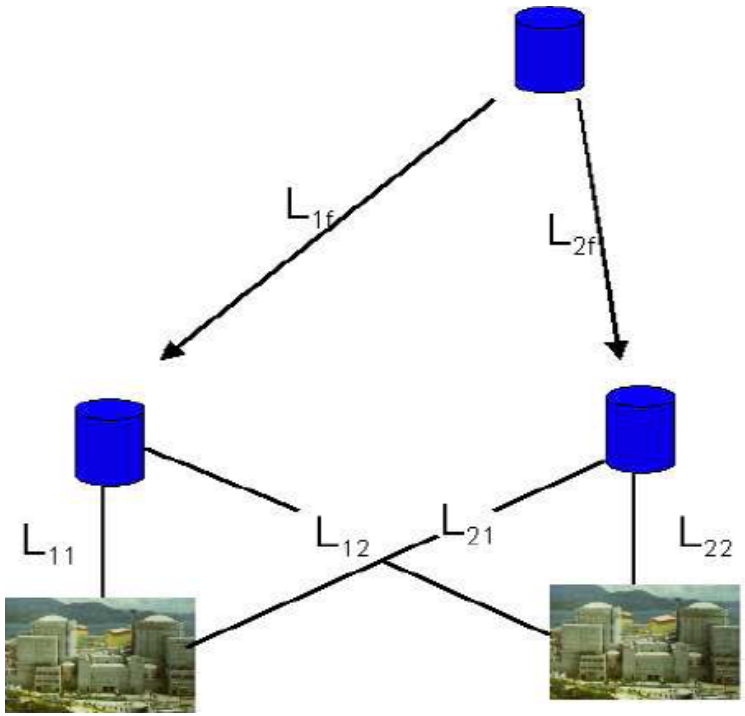
8 MeV
(neutron captured
by Gd)

Daya Bay

Cancellation of Flux Uncertainty with Multiple Reactors

Q: Cancellation $\bar{\nu}_e$ flux uncertainty with multiple reactor sites?

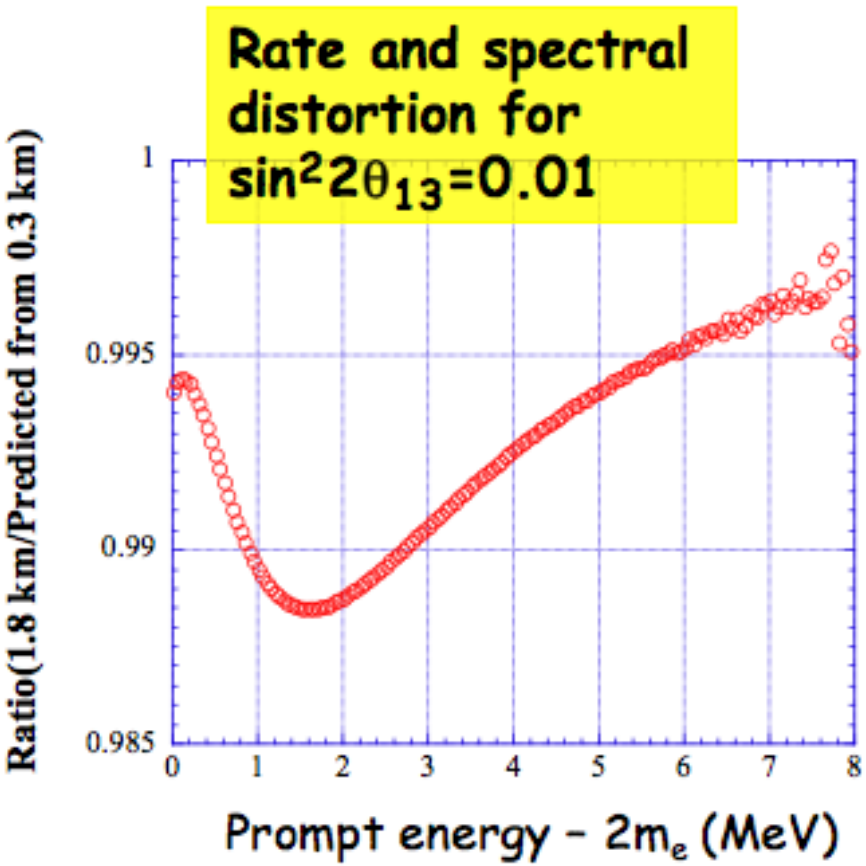
A: Deweight the oversampled cores by a factor α:
$\mathrm{Ratio} = \alpha \frac{\mathrm{Near1}}{Far} + \frac{Near2}{Far}$

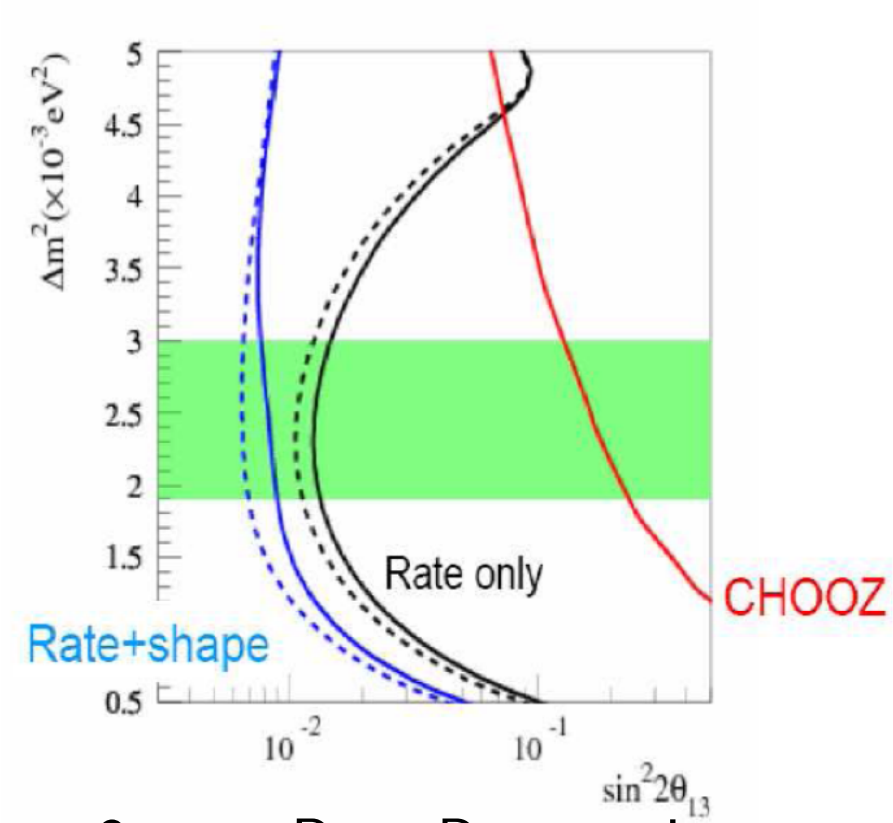


$$\alpha = \frac{(L_{22}^2 L_{1F}^2)^{-1} - (L_{21}^2 L_{2F}^2)^{-1}}{(L_{11}^2 L_{2F}^2)^{-1} - (L_{12}^2 L_{1F}^2)^{-1}}$$

For 4(6) cores, $\alpha = 0.34(0.39)$ and 2% reactor flux uncertainty is reduced to 0.035% (0.1%). Slightly more complicated expression if flux/reactor differs.

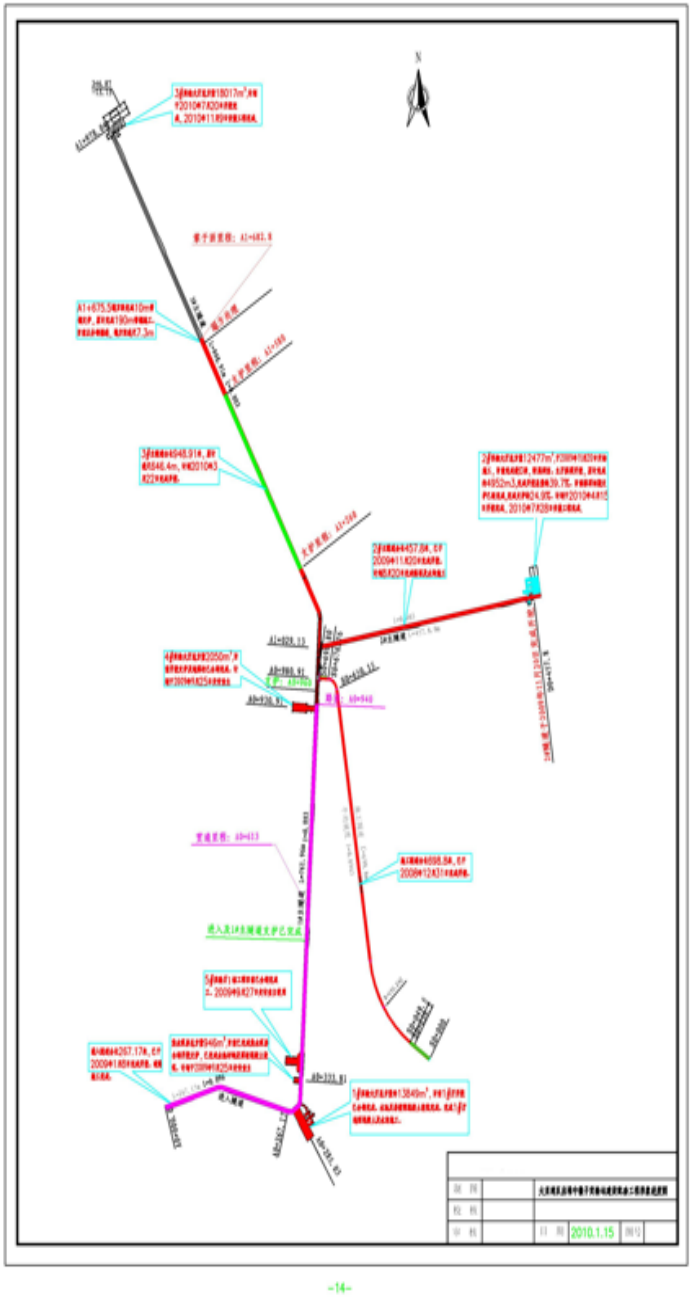
Sensitivity of rate and shape analyses

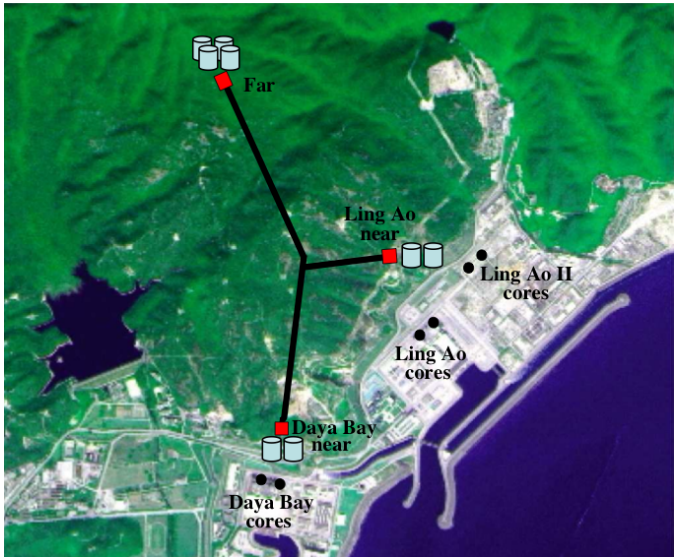




3 years Daya Bay running
Solid: 0.38% baseline syst. unc.
Dashed: 0.18% goal syst. unc.

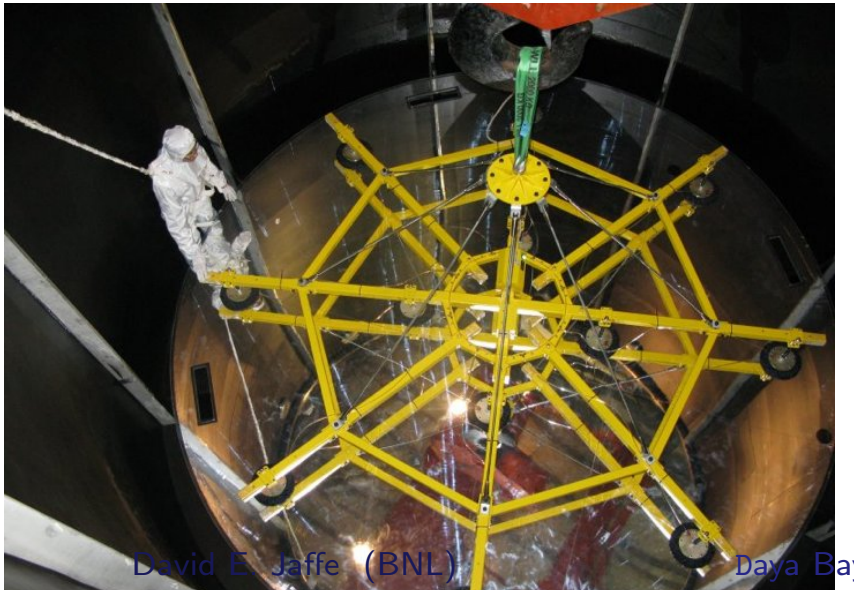
Civil construction

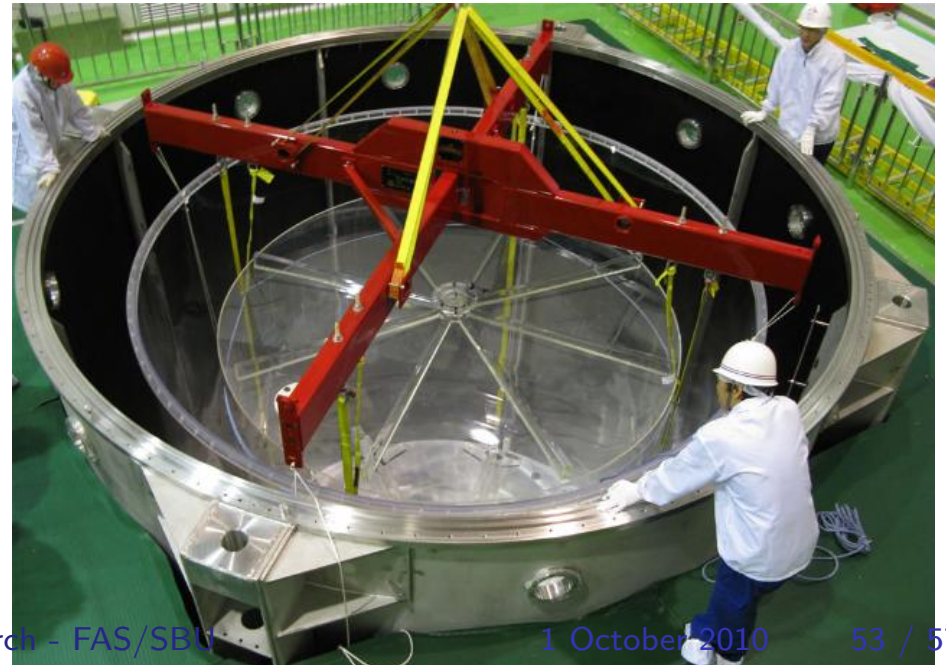




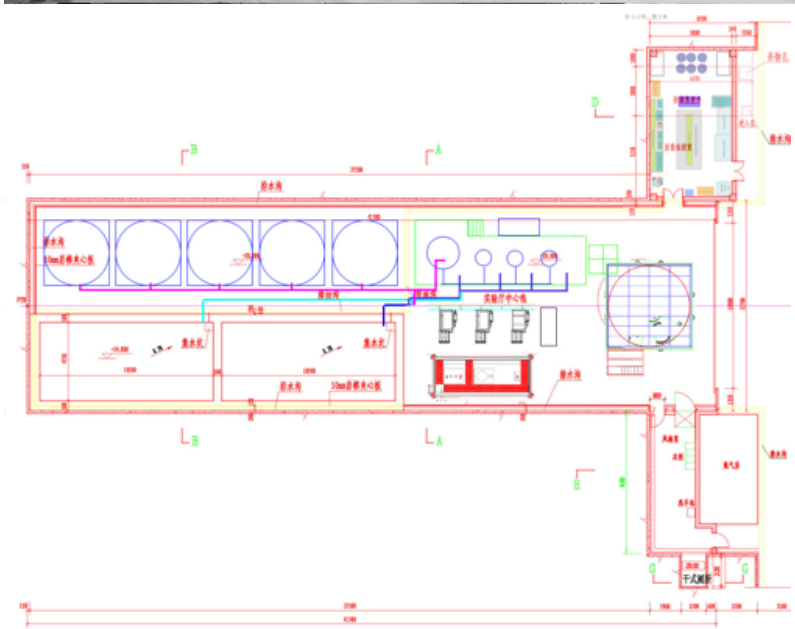
Excavated, paved and lighted tunnel

Antineutrino detector test assembly





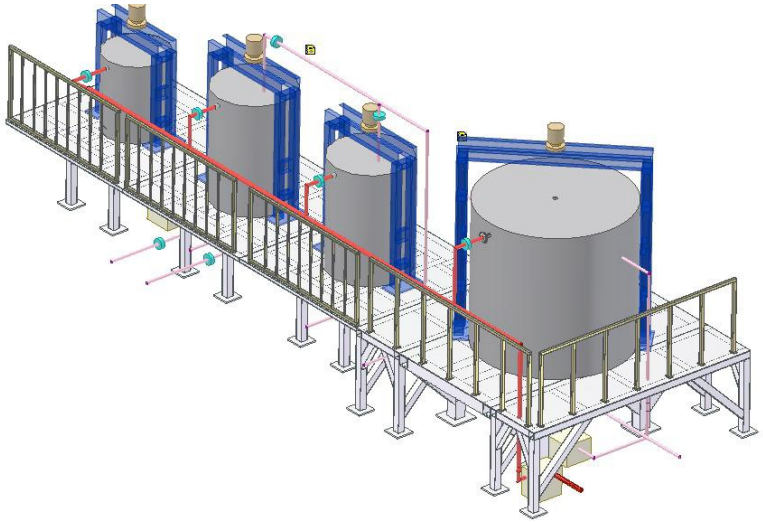
Liquid-filling hall



Gd – Liquid Scintillator test production

Require 200 ton 0.1% gadolinium-loaded liquid scintillator (Gd-LS).

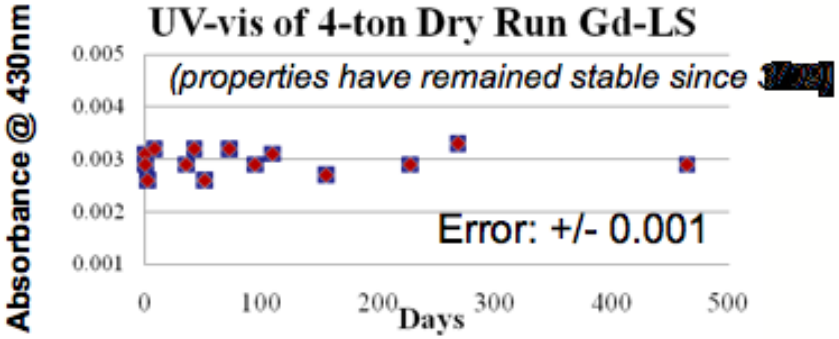
4 ton test batch 2009/03



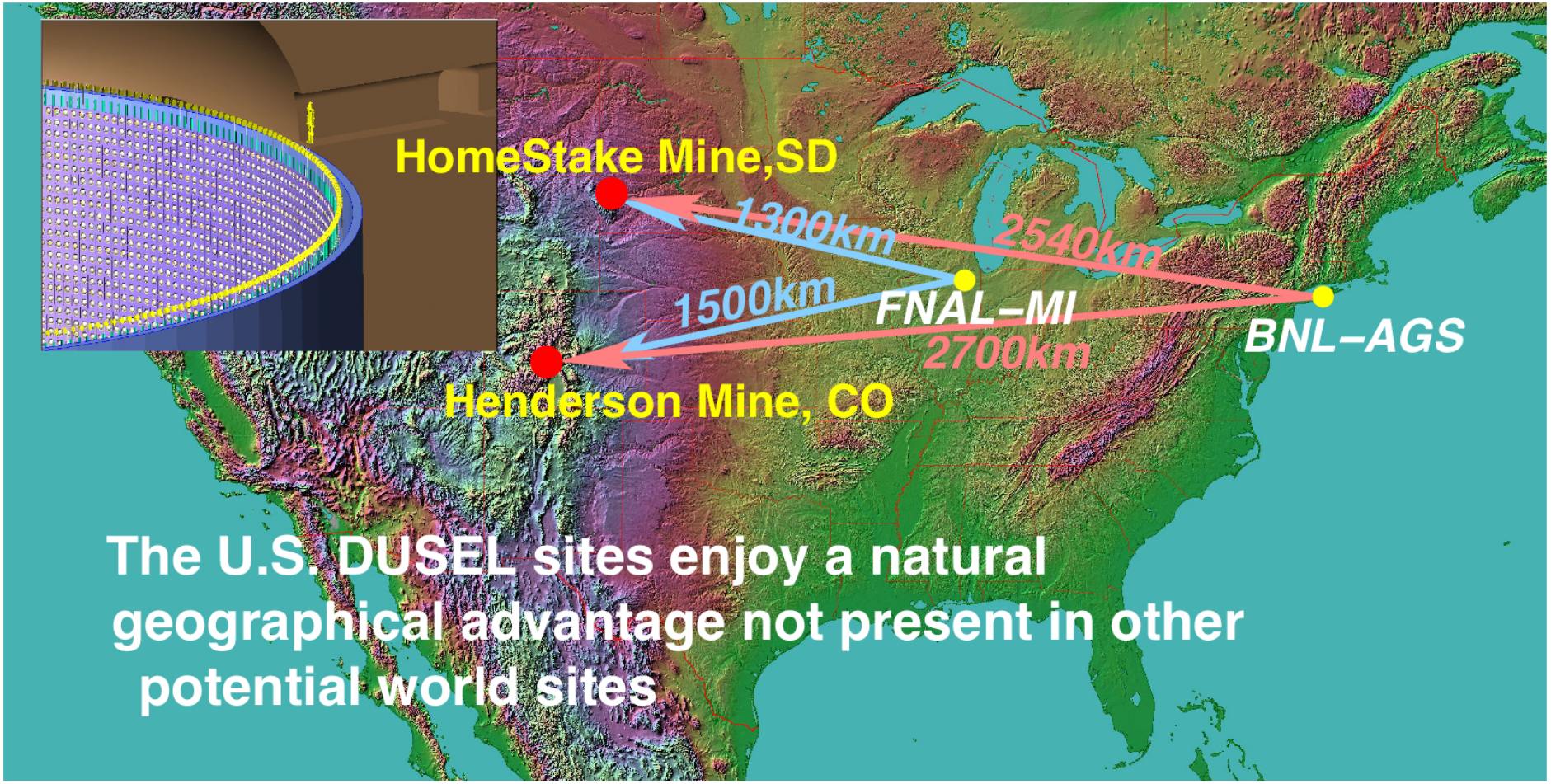
0.1% Gd-LS in 5000L tank.

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

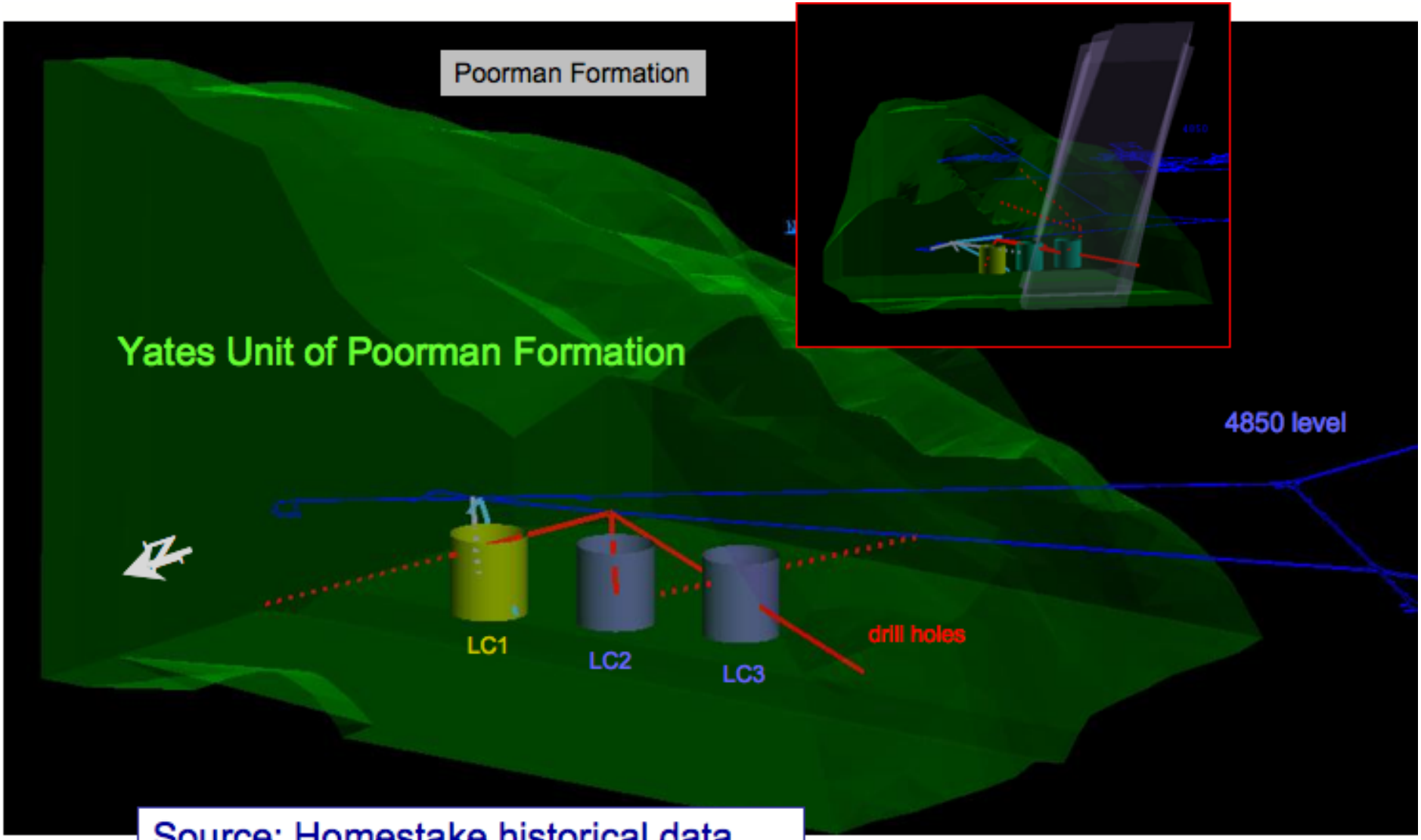
At right: Gd-LS absorption stable for $\sim$500 days and $\lambda > 10$m



LBNE - Long Baseline Neutrino Experiment



LBNE - Long Baseline Neutrino Experiment



Source: Homestake historical data