The Antineutrino Oscillation Experiment at the Daya Bay Nuclear Power Plant

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NO-VE, IV International Workshop on

"Neutrino Oscillations in Venice"

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Neutrino-'ν_e' Experiments/R&D in BNL Chemistry

"Finished":

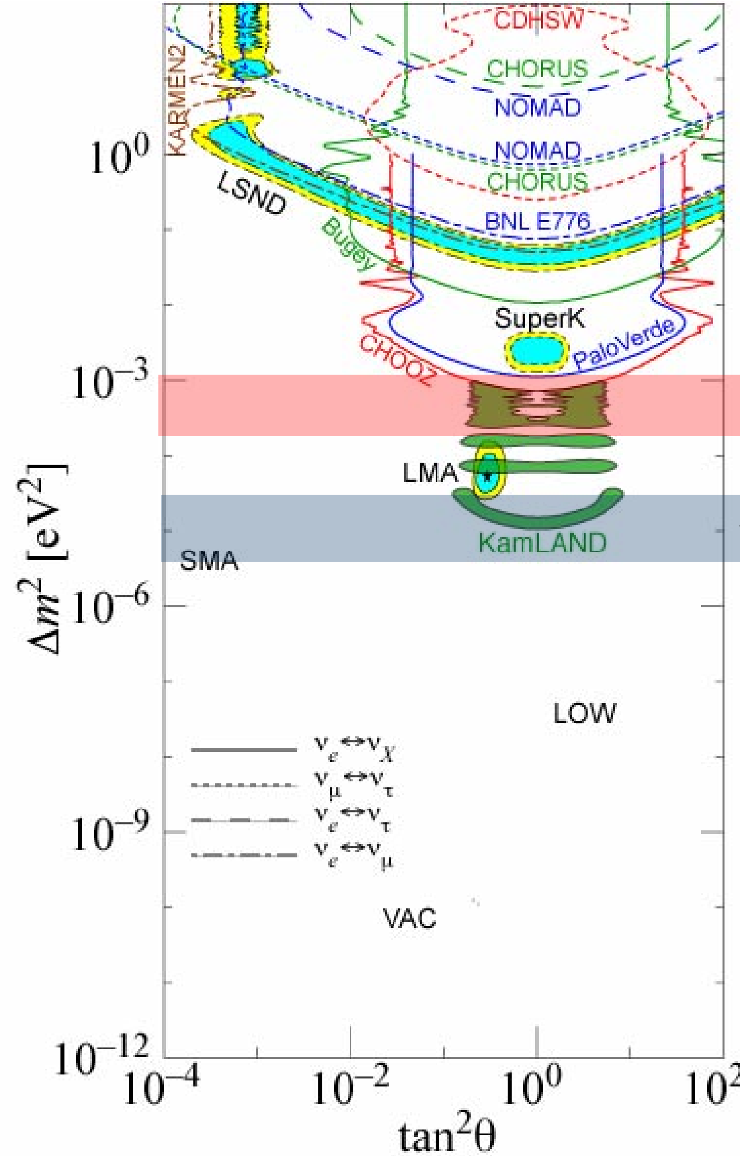
- **Cl,** Radiochemical (**R. Davis,** Homestake)
- **GALLEX,** Radiochemical (**Ga**, Gran Sasso, **1986-98**)
- **SNO,** Real-time (**D_2O**, Sudbury, **1996-2006-present**)

"Future":

- **Daya Bay**, Real-time (**Gd-LS**, Shenzhen, **ongoing**)
- **SNO+,** Real-time (**Nd-LS**, Sudbury, **near future**)
- **MiniLENS,** Real-time (**In-LS**, DUSEL, **future**)
- **Very Long-Baseline Neutrino Oscillations, VLBNO**

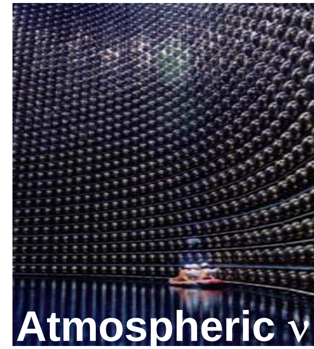
  (ν_μ beam from FNAL to DUSEL, **far future**)

Discovery Era in Neutrino Physics Is Finished: the Revised "Map"



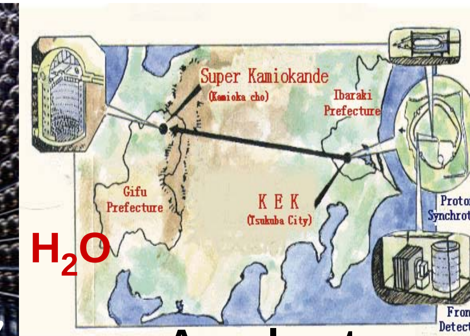
$\nu_\mu \Rightarrow \nu_\tau$

$\nu_e \Rightarrow \nu_{\mu,\tau}$



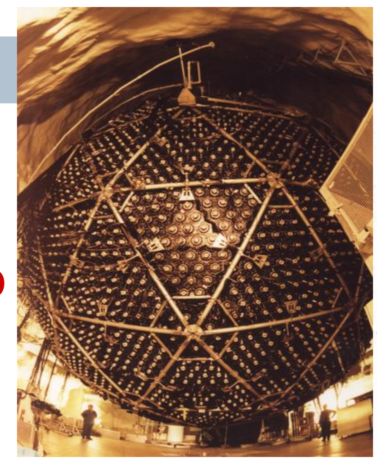
Atmospheric ν (Super-K)

H_2O



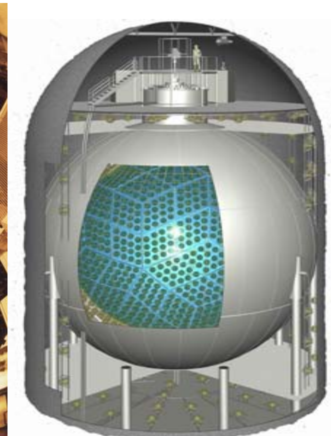
Accelerator ν (K2K)

D_2O



Solar ν (SNO)

LS

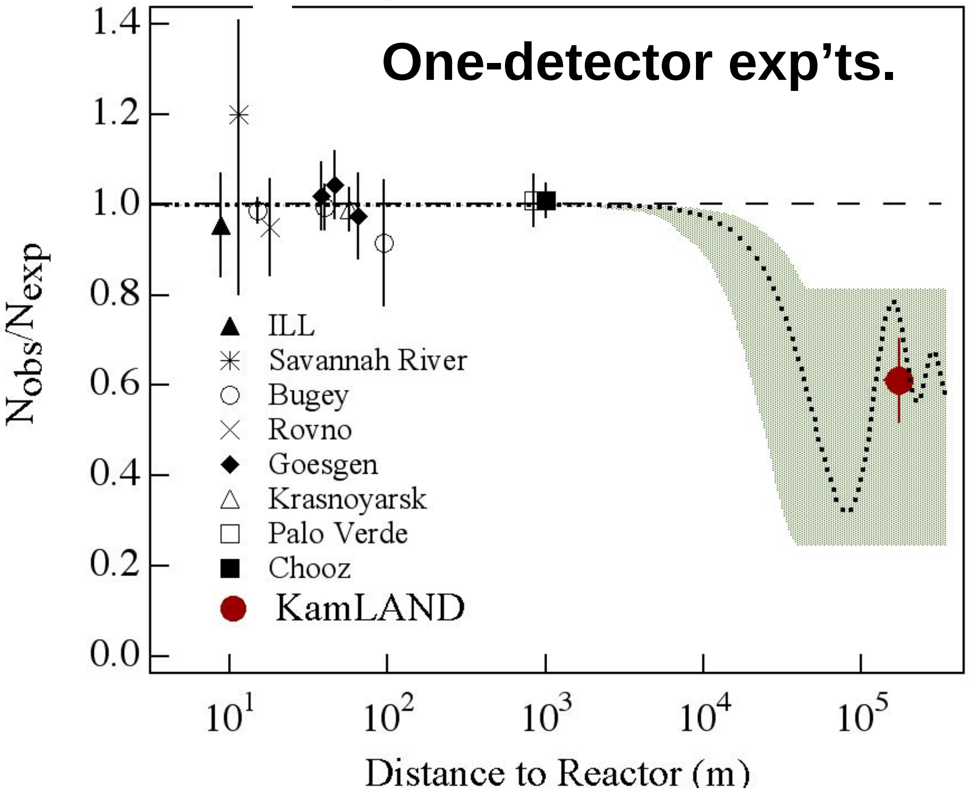


Reactor ν (KamLAND)

- Neutrinos oscillate, must have mass
- Evidence for neutrino flavor conversion $\nu_e \Leftrightarrow \nu_\mu \Leftrightarrow \nu_\tau$
- **Entering 'Precision Era'**

History: (Anti)Neutrinos from β Decay in Nuclear Reactors

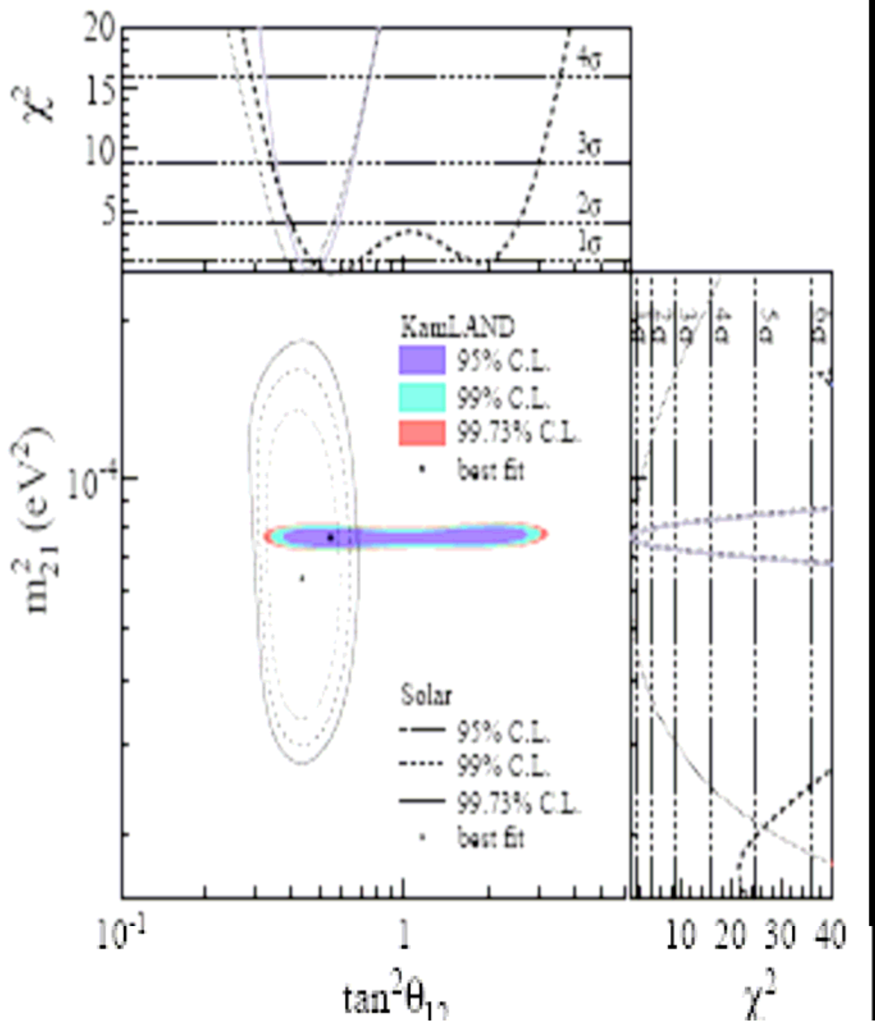
KamLAND: in 2003, First Evidence for Reactor ν_e Disappearance



RESULTS CONSISTENT WITH SNO

KamLAND + Solar Results, Jan08

$\Delta m^2_{12} = 7.58 \times 10^{-5}$;
$\mathrm{Tan}^2\theta_{12} = 0.47$, $\theta \sim 34^o$



Current Knowledge of ν Mixing & Masses

$$U = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} = \begin{pmatrix} 0.8 & 0.5 & U_{e3} \\ 0.4 & 0.6 & 0.7 \\ 0.4 & 0.6 & 0.7 \end{pmatrix}$$

Pontecorvo-Maki-Nakagawa-Sakata Matrix

Six parameters: 2 Δm^2, 3 angles, 1 CP phase
+ 2 Majorana phases

$$= \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\theta_{23} & \sin\theta_{23} \\ 0 & -\sin\theta_{23} & \cos\theta_{23} \end{pmatrix} \times \begin{pmatrix} \cos\theta_{13} & 0 & e^{-i\delta_{CP}}\sin\theta_{13} \\ 0 & 1 & 0 \\ -e^{i\delta_{CP}}\sin\theta_{13} & 0 & \cos\theta_{13} \end{pmatrix} \times \begin{pmatrix} \cos\theta_{12} & \sin\theta_{12} & 0 \\ -\sin\theta_{12} & \cos\theta_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \times \begin{pmatrix} 1 & 0 & 0 \\ 0 & e^{i\alpha/2} & 0 \\ 0 & 0 & e^{i\alpha/2+i\beta} \end{pmatrix}$$

?

Atmospheric
SK, K2K
θ_{23} = ~45° Big

reactor and accelerator

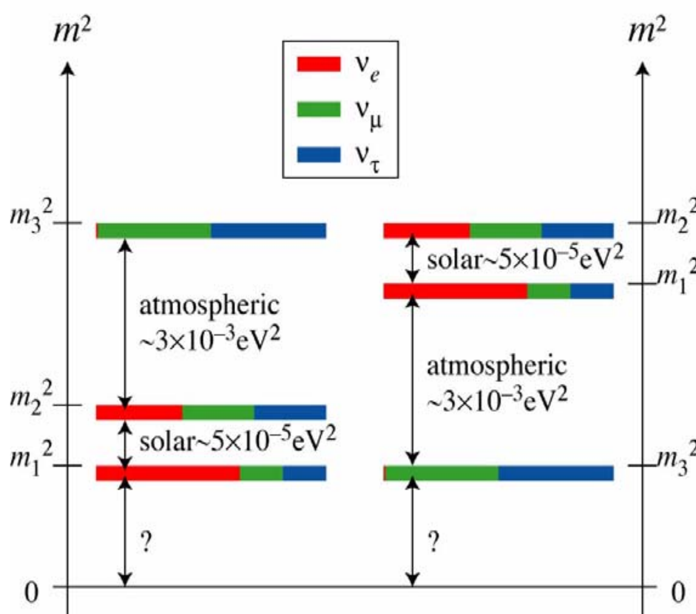
θ_{13} = IS NOT KNOWN. Limit from CHOOZ, Small < 11°

Solar: SNO, SK, KamLAND, Cl, Ga
θ_{12} ~ 32° Big

0νββ

$\Delta m^2_{32} = \Delta m^2_{31}$
$= 2.4\times10^{-3}$ eV^2

$\Delta m^2_{21} = 7.6\times10^{-5}$ eV^2



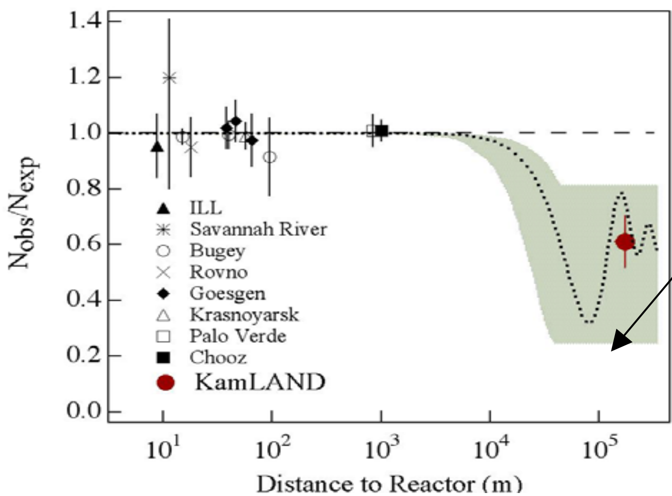
Endorsements of Precision Measurement of θ_{13}

APS: DNP/DPF/DAP/DPB **"The Neutrino Matrix: Joint Study on the Future of Neutrino Physics"** – Oct. 04 – **Recommends as a High Priority**

- An expeditiously deployed multi-detector reactor experiment with sensitivity to $\overline{\nu}_e$ disappearance down to $\sin^2 2\theta_{13} = 0.01$, an order of magnitude below present limits.

NuSAG, the Neutrino Science Advisory Group, endorsed this view in summer 2005. OHEP in 2006 began to fund Daya Bay R&D.

A reactor experiment is unambiguous technique to measure θ_{13}, is key for planned long-baseline experiments to measure CP violation and mass hierarchy



Dominant θ_{12} Oscillation

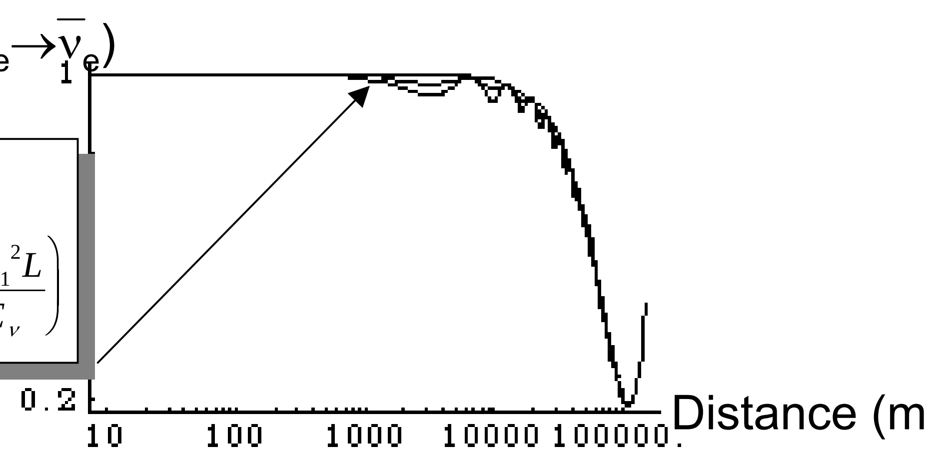
$$P_{ee} \approx 1 - \cos^4\theta_{13}\left[1 - \sin^2\theta_{12}\sin^2\left(\frac{\Delta m_{12}^2 L}{4E_\nu}\right)\right]$$

L=180,000 m
E=4 MeV
$\Delta m_{12}^2 \sim 3(10^{-5})$

Subdominant θ_{13} Oscillation

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

L=1,000 m, E=4 MeV
$\Delta m_{12}^2 \sim 3(10^{-5})$, $\Delta m_{13}^2 \sim 8(10^{-3})$



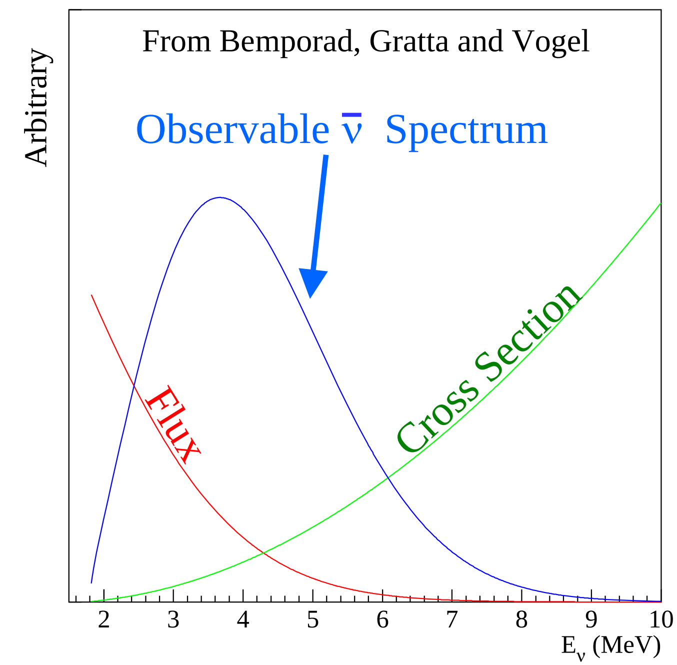
Reactor Measurements of θ_{13}

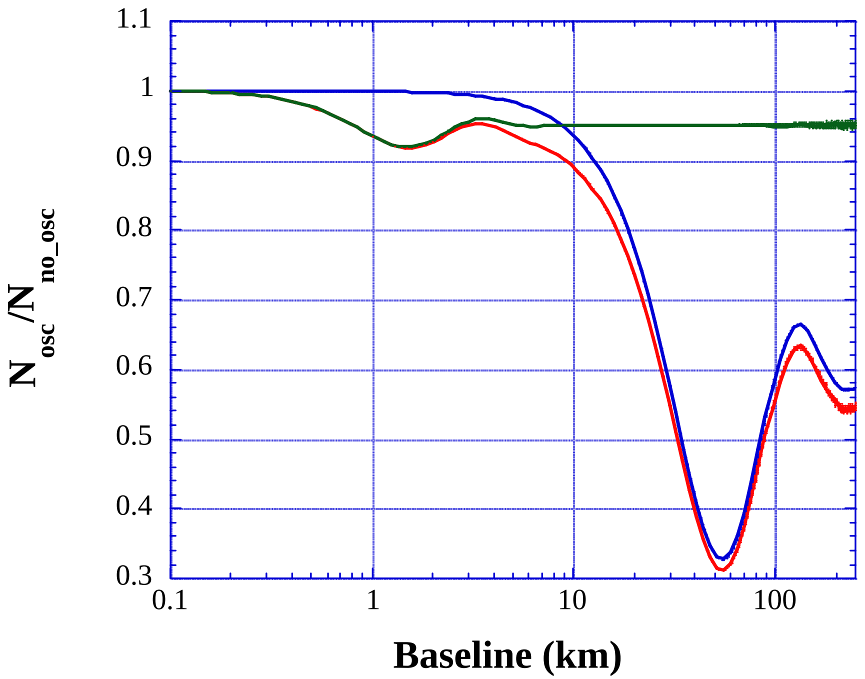
- Nuclear reactors are very intense sources of $\bar{\nu}_e$ from β-decay of fission products, with a well understood spectrum

- 3 GW → 6×10^{20} $\bar{\nu}_e$/s

- - Reactor spectrum peaks at ~3.7 MeV

- Oscillation Max. for $\Delta m^2_{31} = 2.5\times10^{-3}$ eV^2 at L near 1500 m





Disappearance Measurement:

Look for small rate deviation from $1/r^2$ measured at near and far baselines

Relative Measurements for Precision

Compare event rates near and far

Compare energy spectra near and far

Summary: Design Considerations for θ_{13} ~1% Sensitivity

- Power station ~ several GW output
- Multiple *Movable* ("interchangeable") Antineutrino Detectors: each containing tens of tons of liquid scintillator. ~ 450 m.w.e. or more overburden
- Horizontal distance from the reactor vessel to detectors - "near" ~200 m (with no oscillations) and "far" ~1500-2000 m (maximum for oscillations)
- Crucial aspects:

  (a) Taking ratios of near and far data eliminates many experimental "unknowns" and systematic errors

  (b) Want detectors to be as "identical" as possible

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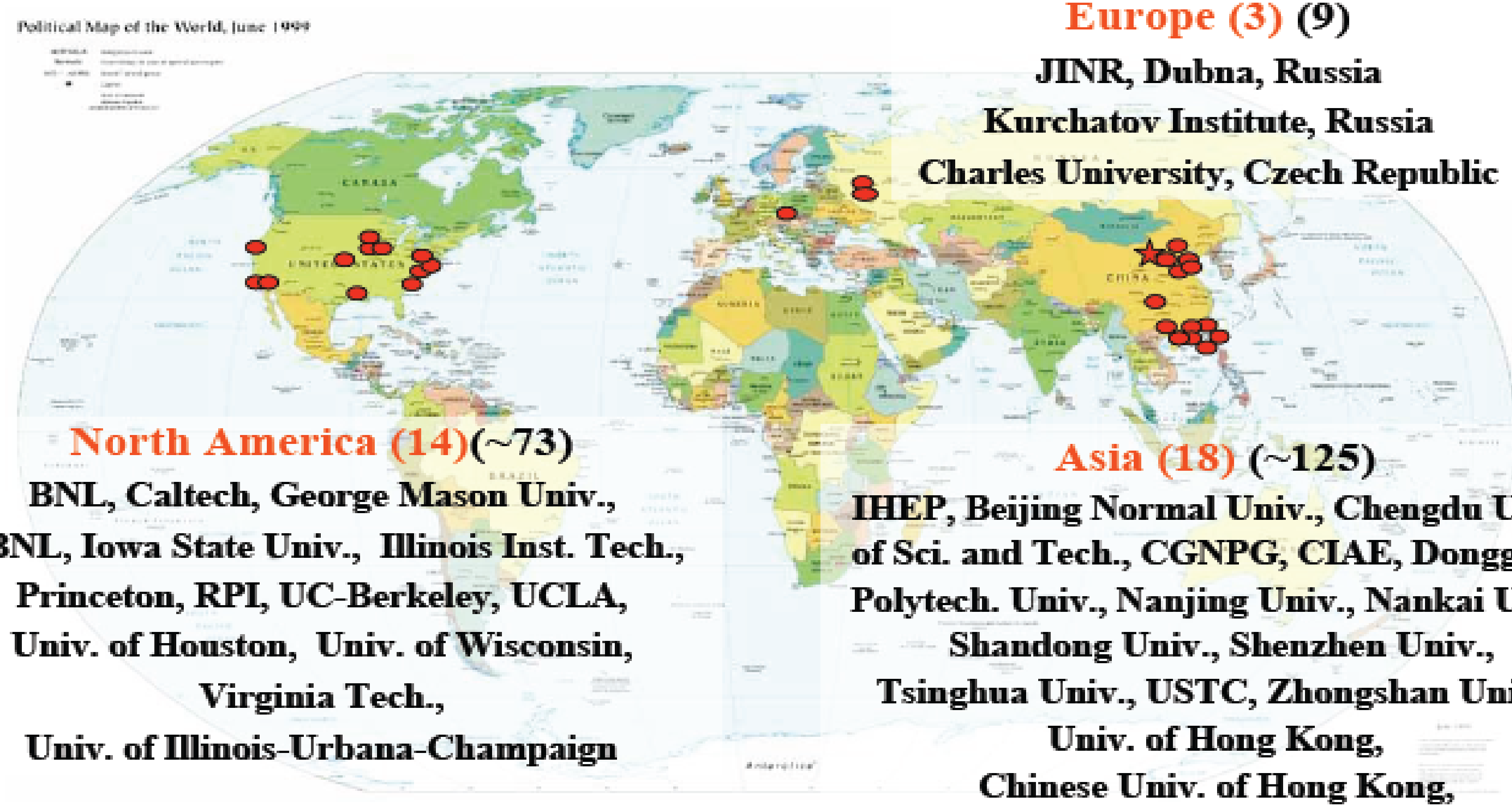
Proposed Reactor Oscillation Experiments (~2004)

2008: Two have survived, Daya Bay and Double Chooz (+ RENO, Korea)

The Daya Bay Collaboration



Europe (3) (9)

JINR, Dubna, Russia
Kurchatov Institute, Russia
Charles University, Czech Republic

North America (14)(~73)

BNL, Caltech, George Mason Univ., LBNL, Iowa State Univ., Illinois Inst. Tech., Princeton, RPI, UC-Berkeley, UCLA, Univ. of Houston, Univ. of Wisconsin, Virginia Tech., Univ. of Illinois-Urbana-Champaign

Asia (18) (~125)

IHEP, Beijing Normal Univ., Chengdu Univ. of Sci. and Tech., CGNPG, CIAE, Dongguan Polytech. Univ., Nanjing Univ., Nankai Univ., Shandong Univ., Shenzhen Univ., Tsinghua Univ., USTC, Zhongshan Univ., Univ. of Hong Kong, Chinese Univ. of Hong Kong, National Taiwan Univ., National Chiao Tung Univ., National United Univ.

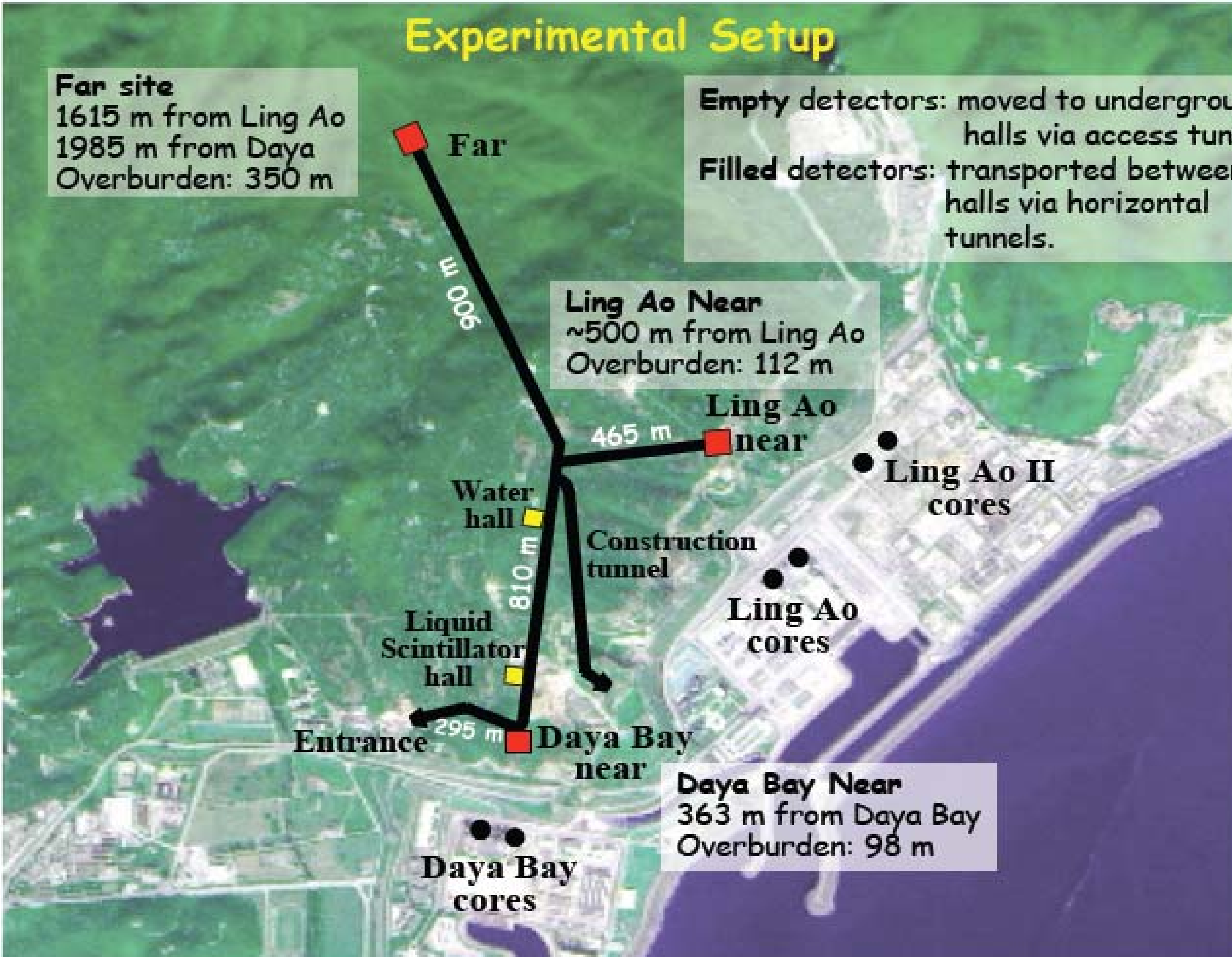
~ 207 collaborators

Large contingent from the BNL Physics and Chemistry Departments

Daya Bay: Approach

- Precisely measure deficit in rate and spectral distortion using $\bar{\nu}_e$ from the Daya Bay Nuclear Power Facility in Shenzhen, China.

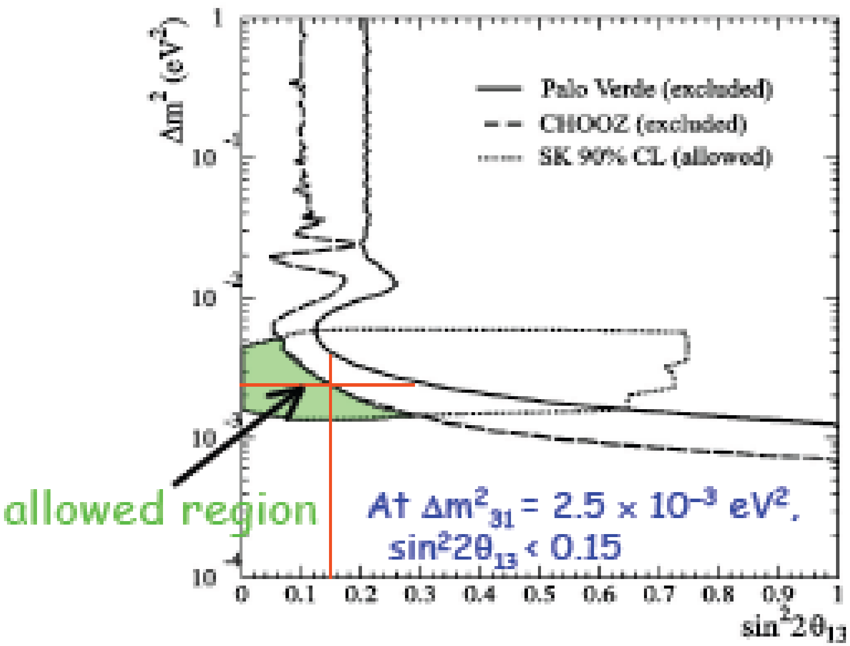
- Deploy multiple large detectors at different baselines to reduce reactor-related systematic uncertainties.
- Build all detectors with tight tolerance and rigorous quality control to reduce detector-related systematic uncertainties.
- Use near-by mountains to suppress cosmic rays to such a level that the cosmogenic background is insignificant w.r.t. signal, and is measurable.
- Carry out a comprehensive program of monitoring and calibrating the detectors


Experimental Setup
Far site
1615 m from Ling Ao
1985 m from Daya
Overburden: 350 m
Far
Empty detectors: moved to underground halls via access tunnel.
Filled detectors: transported between halls via horizontal tunnels.
900 m
Ling Ao Near
~500 m from Ling Ao
Overburden: 112 m
Ling Ao near
465 m
Ling Ao II cores
Water hall
810 m
Construction tunnel
Ling Ao cores
Liquid Scintillator hall
Entrance
295 m
Daya Bay near
Daya Bay Near
363 m from Daya Bay
Overburden: 98 m
Daya Bay cores

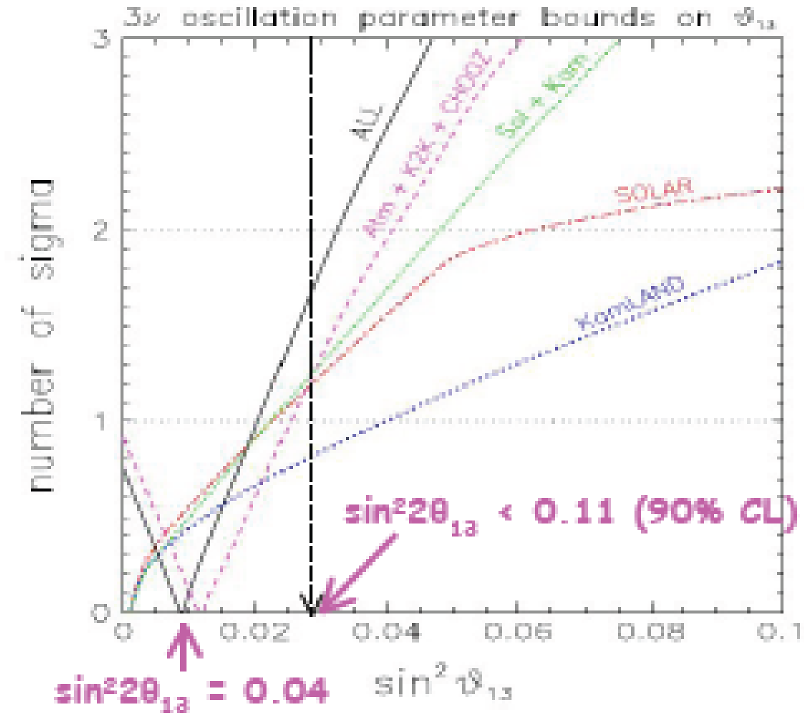
Daya Bay: Goal

- Current knowledge of $\sin^2 2\theta_{13}$:

Direct search



Global fit



Best fit value of $\Delta m^2_{32} = 2.4 \times 10^{-3}$ eV^2

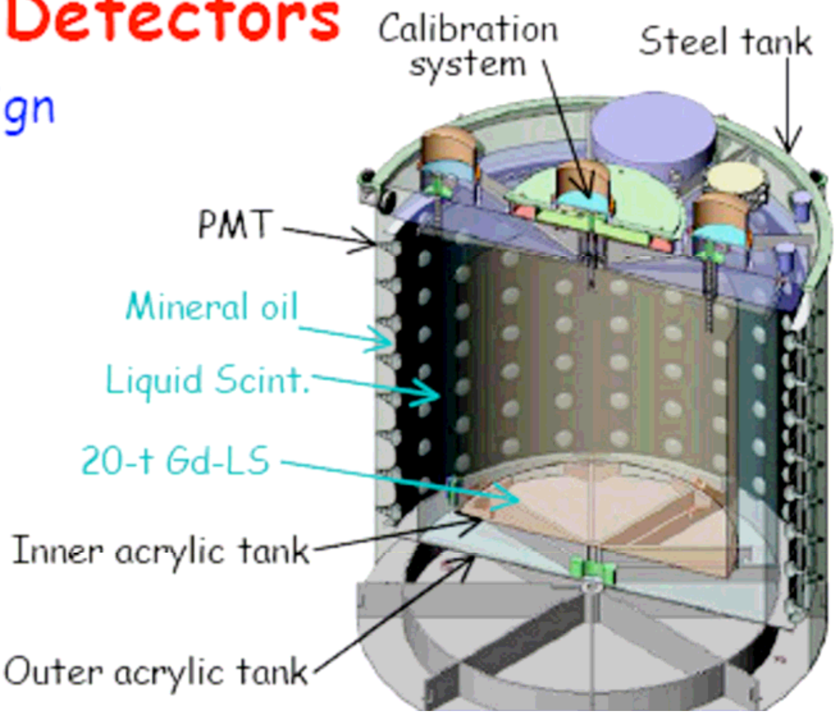
- NuSAG's recommendation (2006):

> The United States should mount one multi-detector reactor experiment sensitive to $\overline{\nu}_e$ disappearance down to $\sin^2 2\theta_{13} \sim 0.01$.

- Daya Bay: determine $\sin^2 2\theta_{13}$ with a sensitivity of ≤ 0.01

Daya Bay Antineutrino Detectors

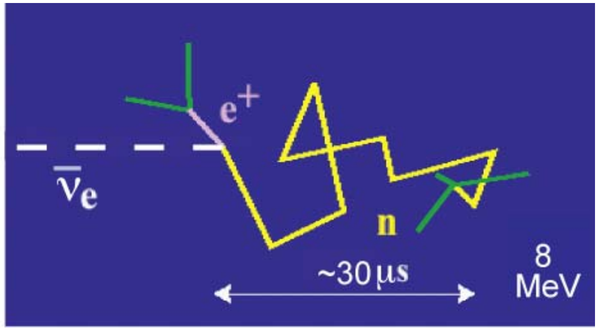
- Three-zone cylindrical detector design
  - Target: 20 t (0.1% Gd-LS)
  - Gamma catcher: 20 t (LS)
  - Buffer : 40 t (mineral oil)
- Low-background 8" PMT: 192
- Reflectors at top and bottom



$\bar{\nu}_e + p \rightarrow e^+ + n$ in 0.1% Gd-loaded organic (C-H) liquid scintillator

$E_{\bar{\nu}} \approx T_{e+} + T_n + (m_n - m_p) + m_{e+} \approx T_{e+} + 1.8$ MeV

$E_{\bar{\nu}} \approx 1 - 9$ MeV



Detect n:

0.3b → n + p → D + γ (2.2 MeV) (~200 μs delay)

49,000 b → n + Gd → Gd + γ's (8 MeV) (~30 μs)

Signal tagged by energy and n-time delay suppresses background events.

Antineutrino Detector Requirements

Physics Design Criteria

3-zone detector with the following general characteristics

Item	Requirement	Justification
Target mass at far site	$\geq$80 T	Achieve sensitivity goal in three years over allowed Δm^2_{31} range
Precision on target mass	$\leq$0.3%	Meet detector systematic uncertainty baseline per module
Energy resolution	$\leq 15\%/\sqrt{E}$	Assure accurate calibration to achieve required uncertainty in energy-threshold cuts (dominated by energy threshold cut)
Detector efficiency error	<0.2%	Should be small compared to target mass uncertainty
Positron energy threshold	$\leq$1 MeV	Fully efficient for positrons of all energies
Radioactivity singles rate	$\leq$50 Hz	Limit accidental background to less than other backgrounds and keep data rate manageable

key feature of experiment: > "identical detectors" at near and far sites

detectors will never be identical but we can control
relative target mass & composition to < 0.30%
relative antineutrino detection efficiency to < 0.25% between pairs of detectors

Recent Members
Neutrinos/Nuclear-Chemistry Group
BNL

Richard L. Hahn, Senior Chemist

Minfang Yeh, Chemist

Yuping Williamson, RA postdoc

Zhi Zhong, technician-collaborator

Alex Garnov, former RA postdoc

Zheng Chang, former RA postdoc

History of BNL R&D on Metal-loaded LS, M-LS

- Dilute (<<1%) Gd in LS had been successfully used to detect neutrons in nuclear-physics and neutrino experiments.
- However, prospects were dim to prepare *high* concentrations of M-LS (~10% Yb, In, or Nd) in multi-ton quantities for *years-long* solar-neutrino (LENS) and ββ experiments (SNO+).
- In 2002-05, we at BNL developed *new chemical methods to solve these problems*, following approach from radiochemistry and nuclear-fuel reprocessing. Prepare M-carboxylates that are soluble in LS.
- **We successfully applied our methods to make suitable ~0.1% Gd in LS to serve as the central antineutrino detector**, (first with Pseudocumene - PC, now with Linear Alkyl Benzene - LAB) and to avoid the chemical/optical degradation problems encountered in the Chooz experiment (and to a much lesser extent, Palo Verde).
- LAB is attractive: has high flashpoint, is biodegradable, and millions of tons of it are produced annually for detergent industry.

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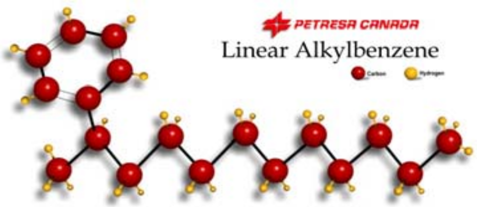
BNL's Gadolinium-Loaded Liquid Scintillator (Gd-LS)

- Required LS Properties: chemical stability >3 years; low light absorption (= high light transmission); high light output
- LS, Linear Alkyl Benzene, LAB



- BNL LS has very low light absorption, unchanged for >700 days,

Optical Abs. ~.003 = ~15 m transmission

BNL Paper on Gd-LS, Yeh, Garnov, Hahn, NIM A, 578, 329 (2007)

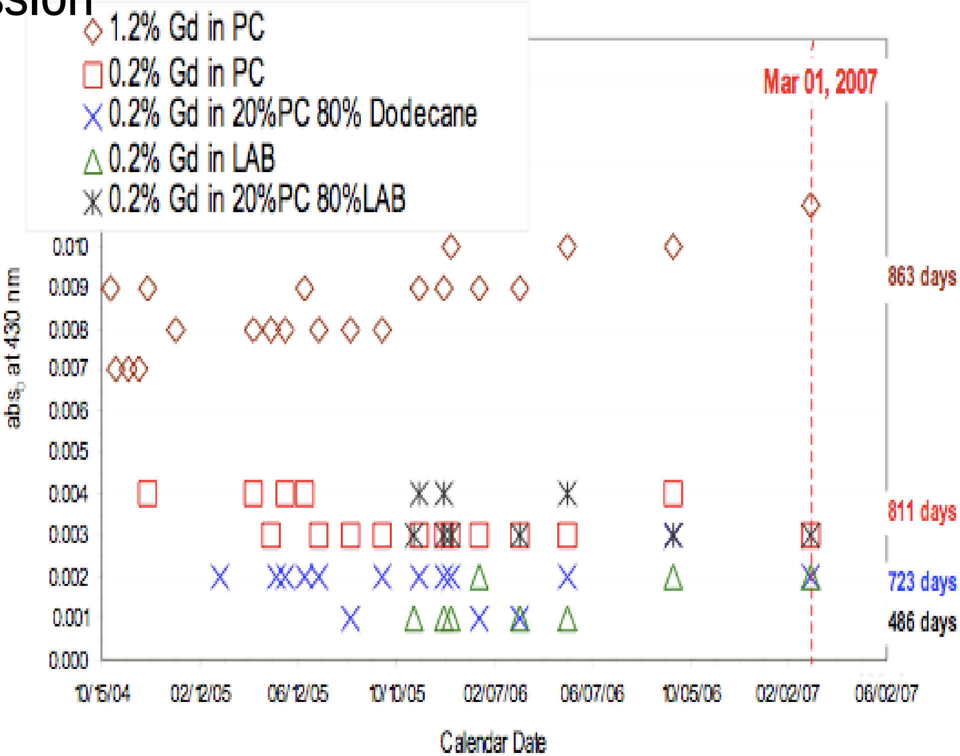
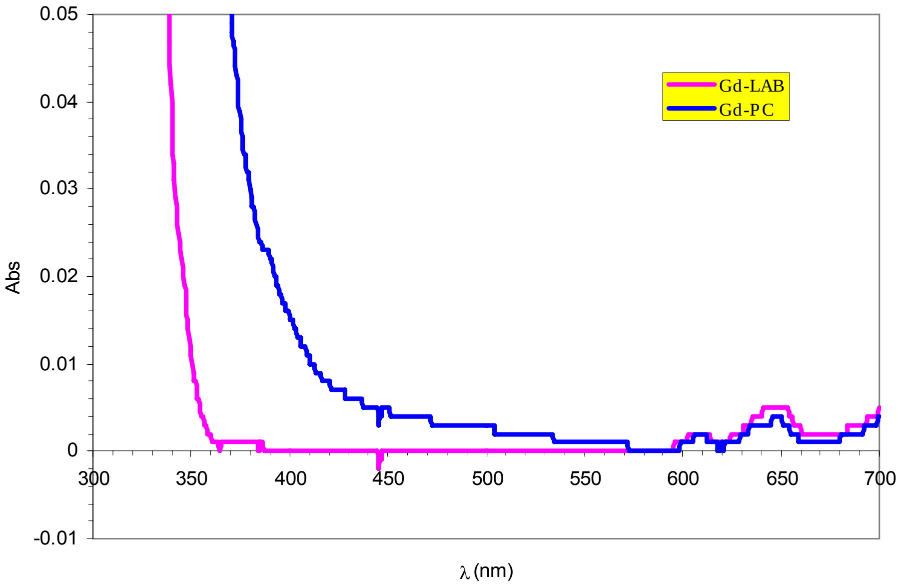


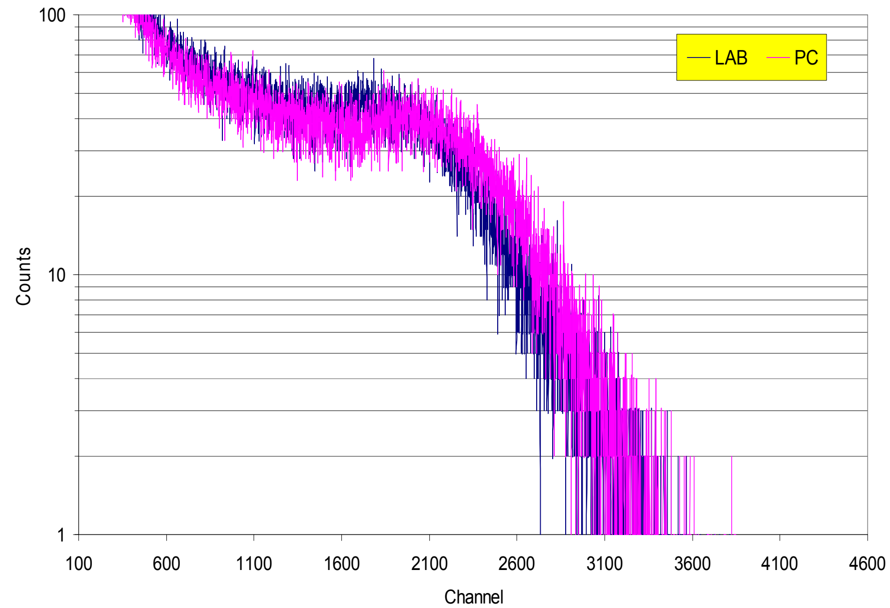
Fig. 6.23. The UV absorption values of BNL Gd-LS samples at 430 nm as a function of time

BNL Data: Performance of Gd in PC and LAB

Optical Spectra



Light Output Spectra, with ^{137}Cs



- Have ~1% Gd in 100% LAB and 100% PC. Will use ~0.1% Gd in θ_{13} experiment. Can dilute by factor 10.
- LAB has lower optical absorption, longer attenuation length, better chemical and ESH properties, than PC.
- LAB and PC have very similar light output efficiency.

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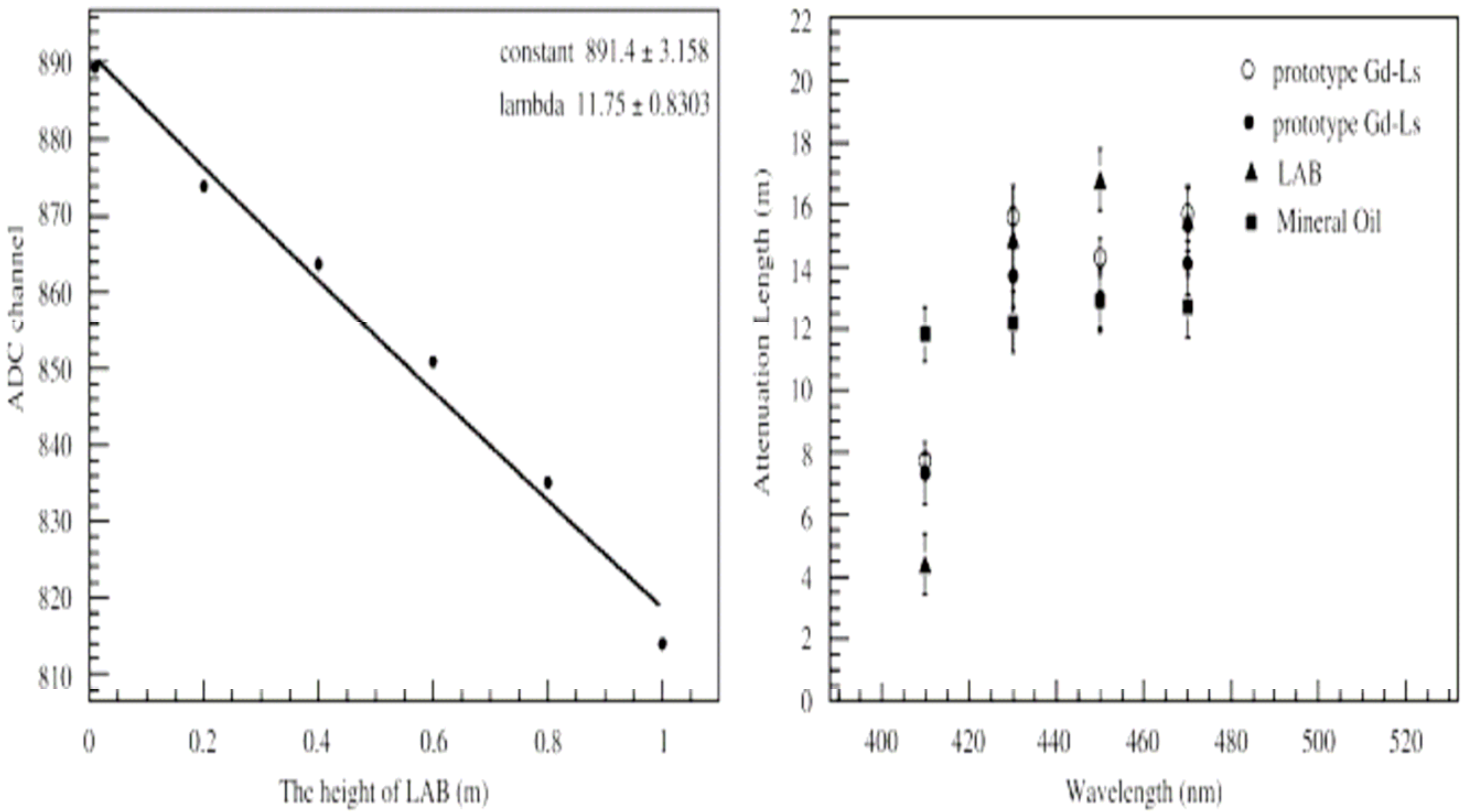


Fig. 4. *Left*: an example of the attenuation length measurement using the 1-m tube system. The transmissions of different path lengths (Gauss fitting) are fitted to an exponential curve. *Right*: black dots and cycles are attenuation lengths of the 800 L LAB-based Gd-LS used in the prototype experiment. Triangles are that for pure LAB and squares are that for mineral oil.

IHEP Paper on Gd-LS, Ding et al., NIM A, 584, 238 (2008)

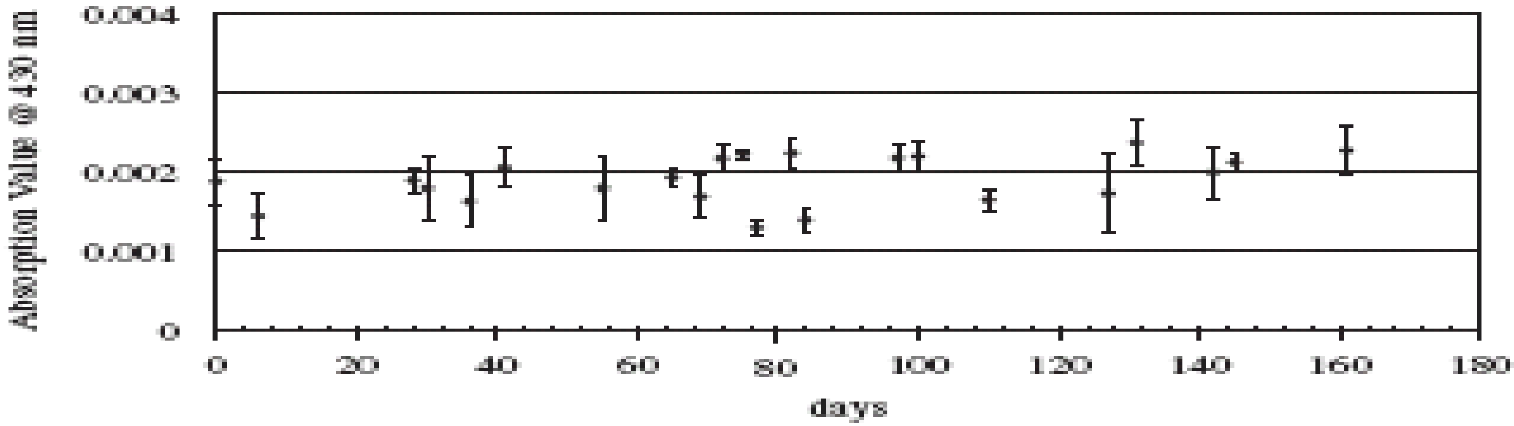


Fig. 5. Absorption of Gd-loaded liquid scintillator at 430 nm as a function of time.

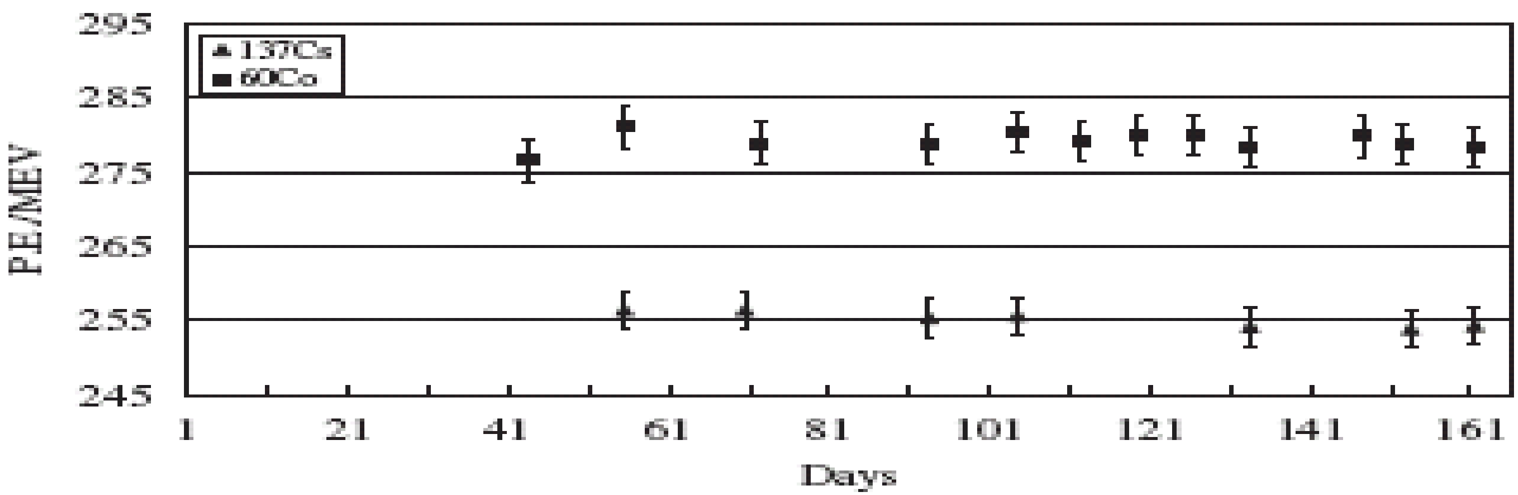


Fig. 6. Long-term stability monitoring of Gd-loaded scintillator by the energy response of the prototype detector to radioactive sources (located at the center of the detector).

BNL Chemical Tasks for Daya Bay

We have been focusing mainly on perfecting the Gd-LS:

- For the past ~2 years, BNL, IHEP (Institute of High Energy Physics) in China, and JINR (Joint Institutes of Nuclear Research) in Russia have been collaborating on Gd-LS, first on the R&D, more recently on procedures for the Gd-LS production and filling of the Inner Detectors
- Initially we did solvent extraction of the Gd carboxylate from aqueous phase into LAB
- For logistical reasons, we have decided instead to prepare the solid Gd carboxylate and dissolve it in LAB
- We previously used MVA, the 6-carbon methylvaleric acid; now use TMHA, the 9-carbon trimethylhexanoic acid, that produces a very stable Gd-LS

BNL Chemical Tasks for Daya Bay

In Addition:

- Are developing nuclear chemical methods to assay, reduce or eliminate radioactive contaminants (U,Th, Rn, K) in materials
- Counting for low levels of contaminants, using Ge γ-ray detectors, LS cocktails, solid-state α detectors
- These are some practical matters that are essential for the successful operation of the detectors; e.g.
- Are evaluating chemical compatibility of Gd-LS with acrylic vessel and other construction components
- Also leaching from materials into Gd-LS and H_2O
- …

Project Chemical Tasks for Daya Bay

- Have been developing mass-production chemical techniques to go from current scale of tens of kg to multi-tons (many thousands of Liters)

Our Plan for Production and Detector Filling:

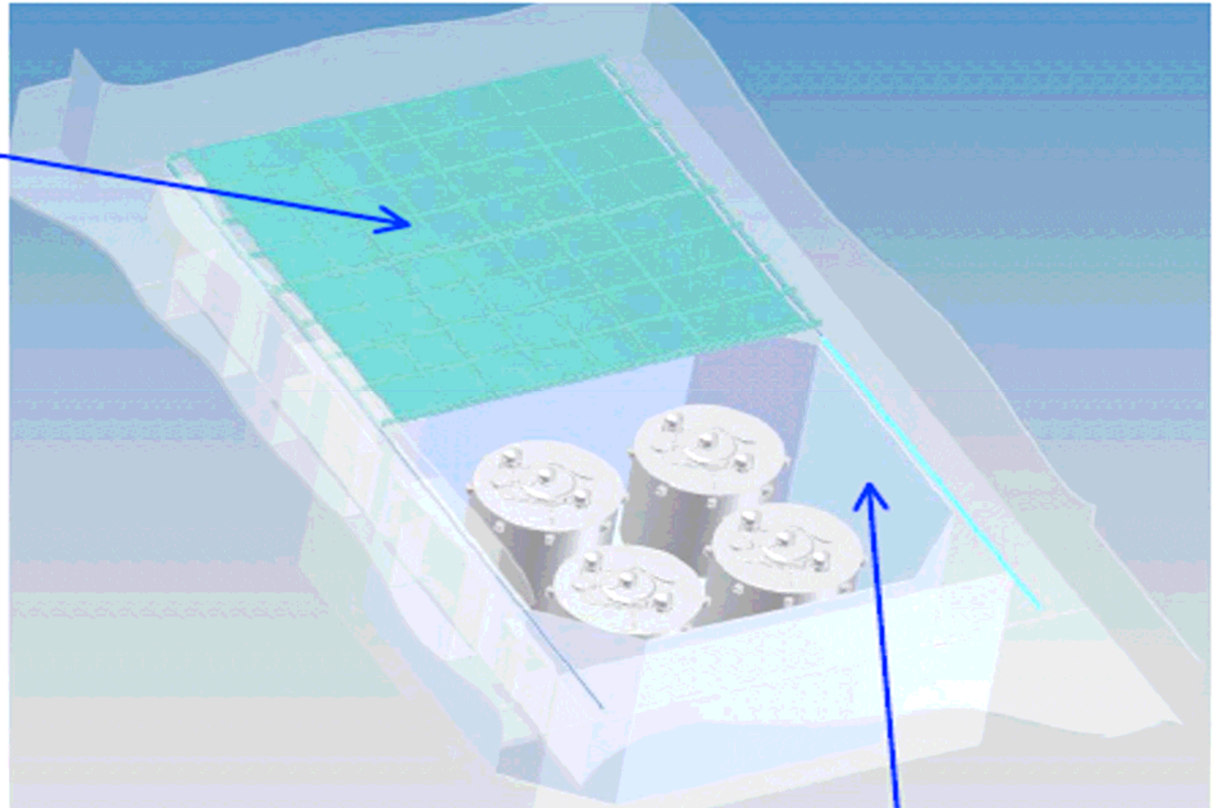
- Over the next year, we will synthesize the solid Gd carboxylate at IHEP (using ~200 kg Gd, as $GdCl_3.6H_2O$)
- Ship it to Daya Bay, to dissolve in LAB to prepare ~200 tons 0.1% Gd-LS + fluors, typically 3 g/L PPO (2,5-diphenyloxazol), 15 mg/L bis-MSB (1,4- bis 2-methyl styrylbenzene)
- Underground (UG), mix the Gd-LS in batches and store all of it as a uniform liquid in one large vessel
- UG, will fill the Antineutrino Detectors from this common supply of Gd-LS (likely, will do in pairs, “two at a time”)

Various Nuclear Physics Backgrounds

- The "usual" γ rays from rock, PMT's, contaminants
- The "usual" cosmic ray muons
- Since detect neutrons, worry about them as backgrounds:
- Fast neutrons from muon interactions in the rock…
- α particles from natural radioactivity, 4-5 MeV from U, Th chains;
  2-3 MeV from neutron-deficient rare earths
- Maximum acceptable levels in the solid $GdCl_3.6H_2O$ of U and Th
  are < 5 and <10 ppb respectively (→ 0.1% Gd in LS)
- α particles quench strongly in the LS, have apparent energies ~20% of true energy, so they are not mistaken for γ rays
- However, they can initiate (α,n) nuclear reactions on low-Z elements, e.g., $^{13}C(\alpha,n)$ is exoergic, produces neutrons
- Cosmogenic "delayed neutron" radioactivity,
  0.12-s ^{8}He, 0.18-s ^{9}Li, both β^- decay to excited states that emit n

Shield and Muon System

Four RPC's for tracking muons



- At least 2.5 m of water surrounding AD's to attenuate ambient gamma rays and spallation neutrons from rock
- Instrumented to serve as water Cherenkov counters

This activity is centered in BNL Physics Dept.,
with some help from Chemistry on H_2O optical clarity and leaching tests

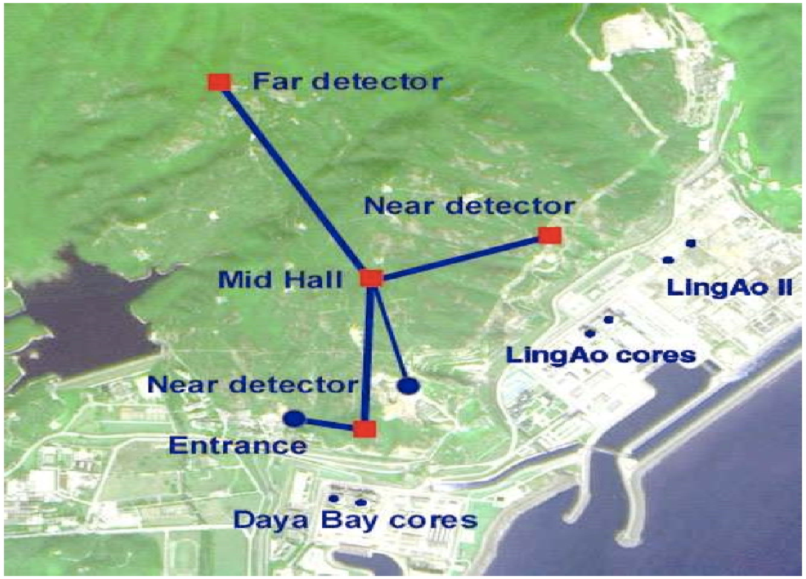
Signal, Background, and Systematic

- Summary of signal and background:

	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
Overburden (m)	98	112	350
Radioactivity (Hz)	<50	<50	<50
Muon rate (Hz)	36	22	1.2
Antineutrino Signal (events/day)	930	760	90
Accidental Background/Signal (%)	<0.2	<0.2	<0.1
Fast neutron Background/Signal (%)	0.1	0.1	0.1
^{8}He+^{9}Li Background/Signal (%)	0.3	0.2	0.2

- Summary of statistical and systematic budgets:

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

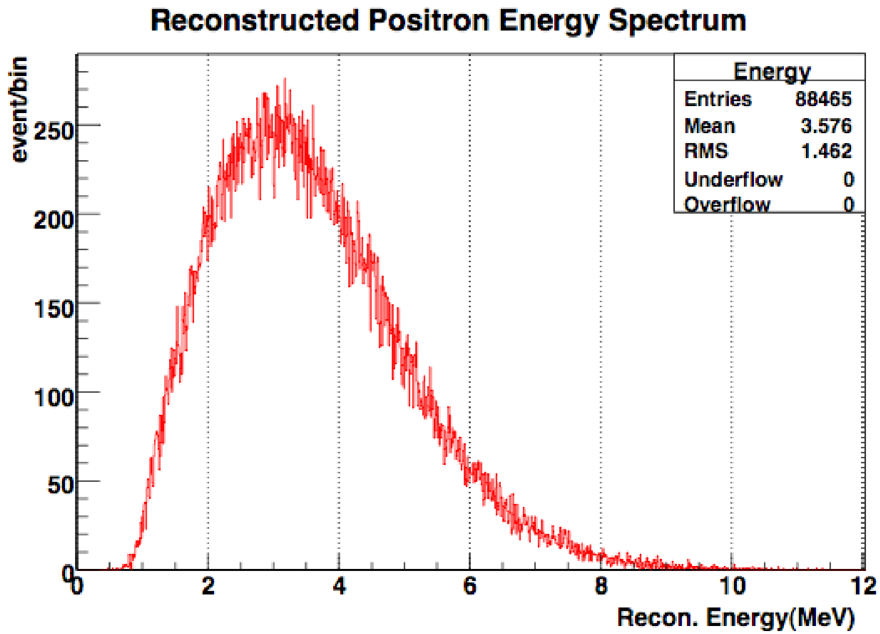


Rates and Spectra

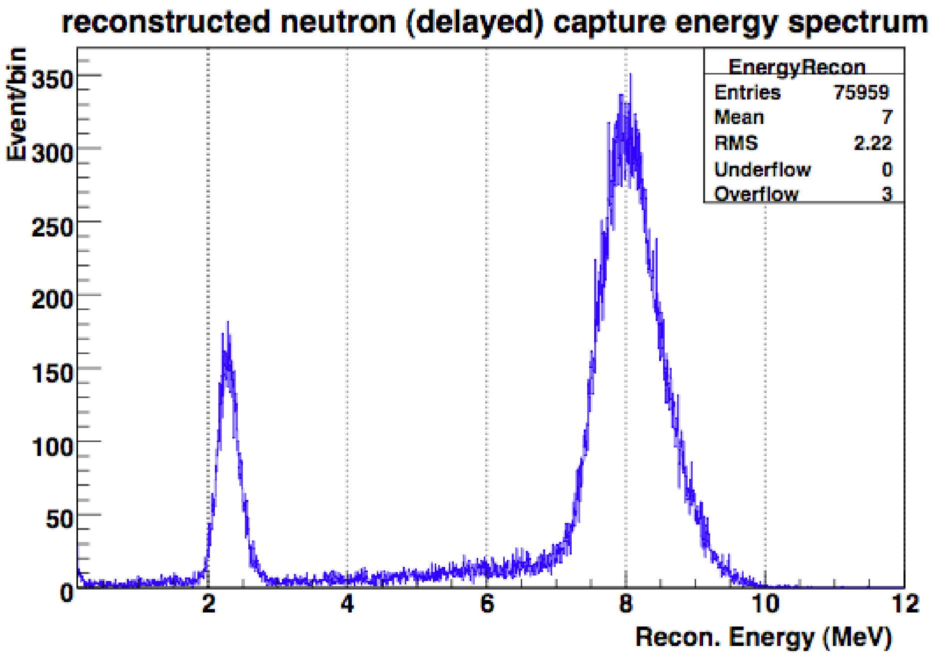
Antineutrino Interaction Rate
(events/day)

Daya Bay near site	**960**
Ling Ao near site	**760**
Far site	**90**

Prompt Energy Signal

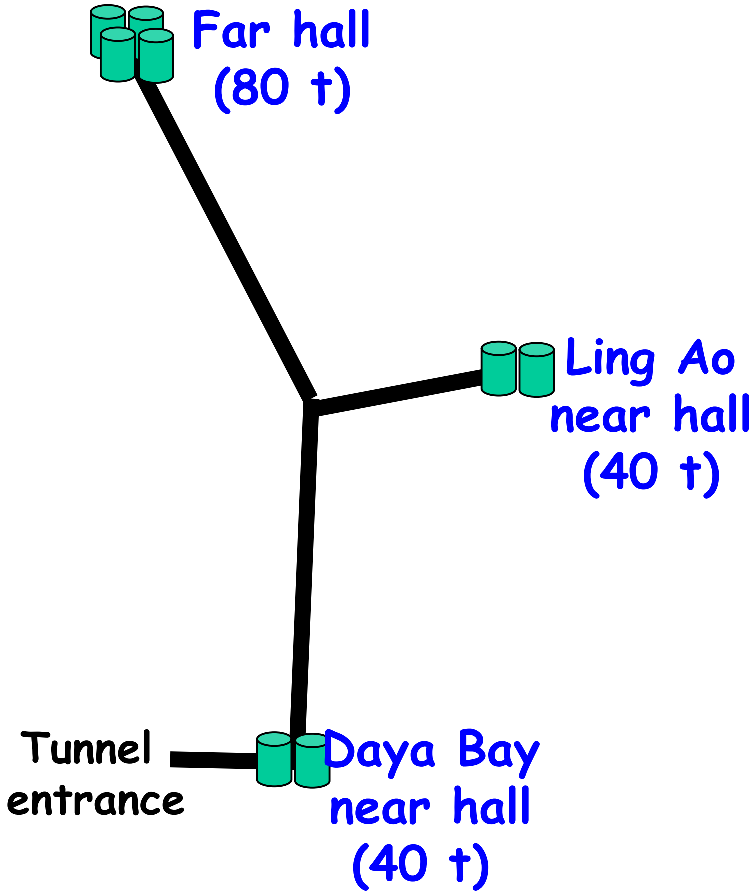


Delayed Energy Signal

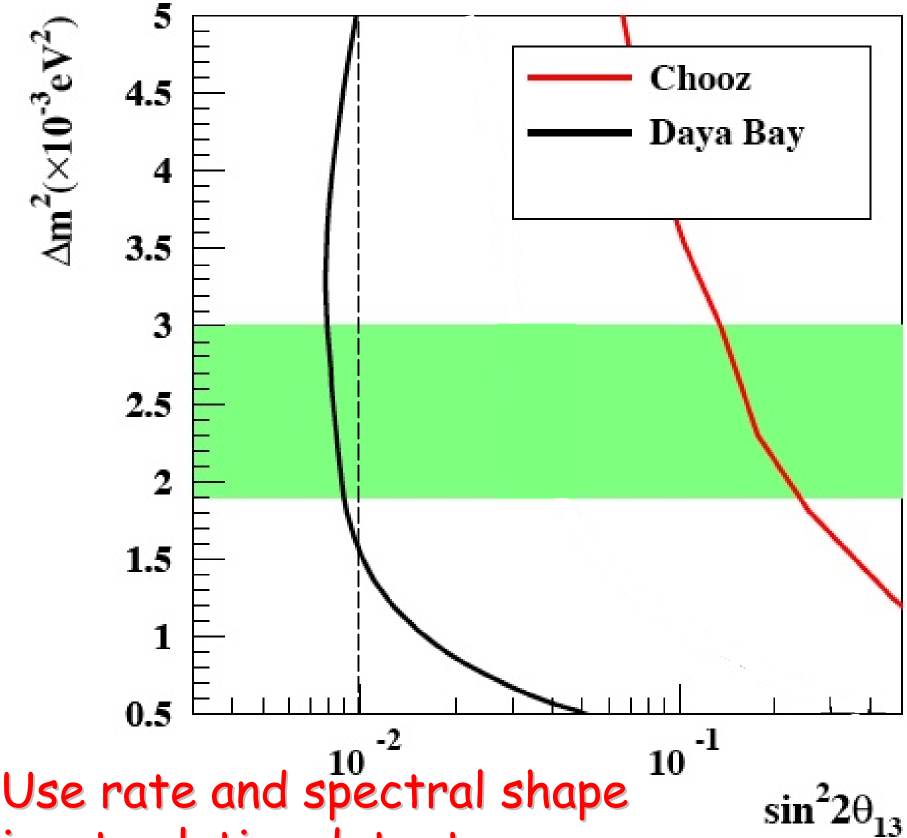


Statistics comparable to single detector in far hall

Planned Sensitivity at Daya Bay with 160 tons of Gd-LS



3-year run with 80 t at far site



- Use rate and spectral shape
- input relative detector systematic error of 0.2%

The Daya Bay Project: Current Status

- **PRC funding assured by 2007**
- US Daya Bay R&D proposal 1/2006
- **US - P5 Roadmap: Recommends Daya Bay 10/2006**
- **OHEP/DOE Daya Bay R&D funds allocated 2006-08**
- **Have had successful DOE "CD-i" Project Reviews CD-0 November 2005; CD-1 April 2007; CD-2/3a January 2008**
- **DOE Project Funds in March 2008, ~$34 M in 3 yrs.**
- **Ongoing work:**
- **Civil construction began late 2007**
- **Fabrication of the two AV's, calibration systems**
- **Preparation of Gd-LS, LS, MO, outer shield for μ's**
- **Full operations to start by Year's End 2010**

Civil Construction

- Groundbreaking took place on Oct 13, 2007; civil construction has begun

Ready to build construction tunnel

Construction near entrance portal of access tunnel

图片1： 进入隧道施工现场

February 2008,

At the main entrance tunnel

- Daya Bay is on schedule:
  - Commission first two detectors in Daya Bay Hall by November 2009
  - Data taking with all eight detectors in three halls by December 2010

U.S. Daya Bay Project
Monthly Report

February 2008

Daya Bay Main Access Tunnel

Version #8 March 20, 2008

For the Project team.
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THE END