Daya Bay
and Other New
“Low-Energy” Neutrino Projects
at Brookhaven National Laboratory

Richard L. (Dick) Hahn

Neutrinos/Nuclear-Chemistry Group

Chemistry Department

BNL

CEN Saclay, 7 Avril 2008

APC-Paris, 8 Avril 2008

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

"Finished":

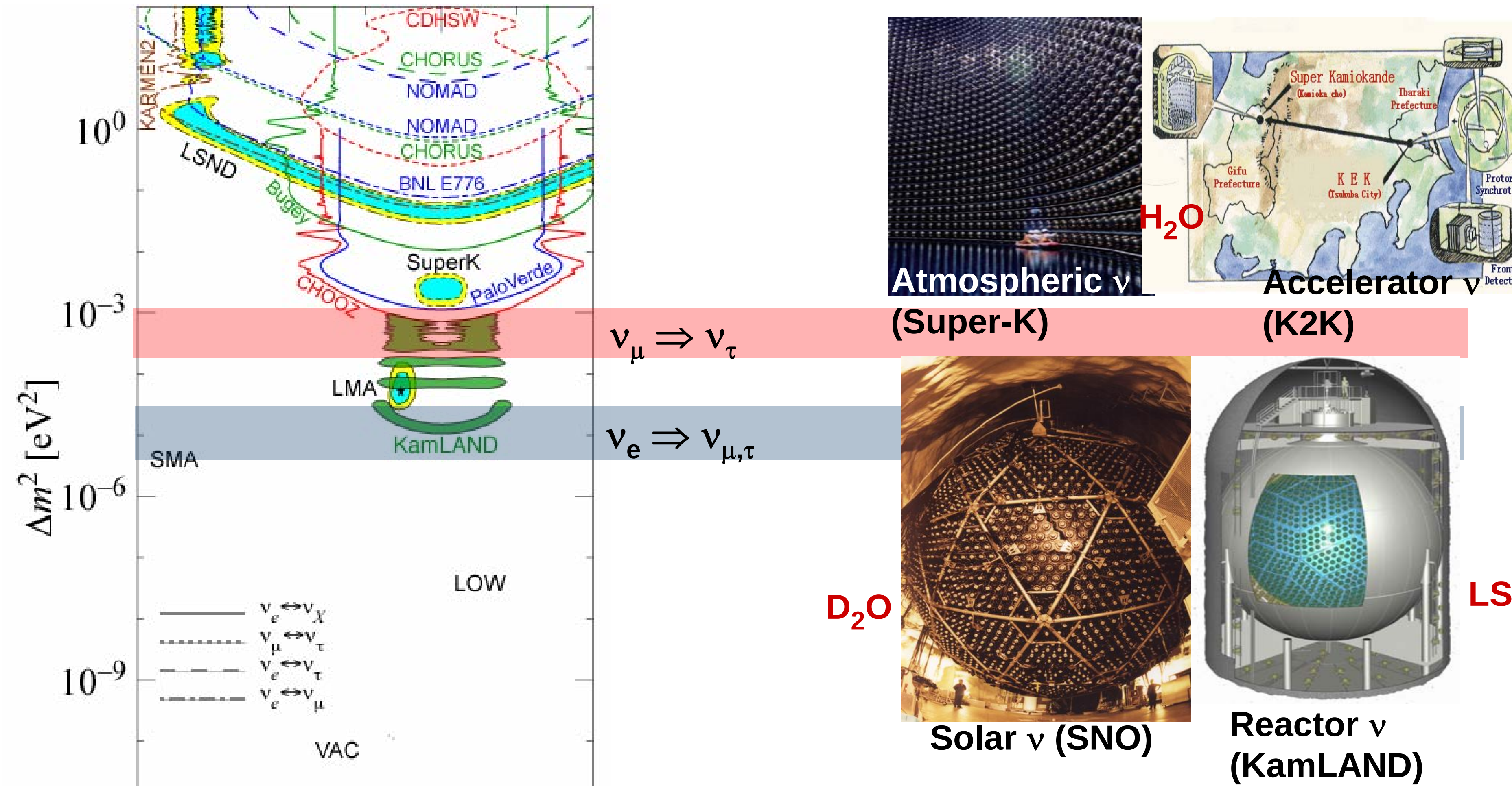
- **Cl,** Radiochemical (**R. Davis,** Homestake)
- **GALLEX,** Radiochemical (**Ga**, Gran Sasso, **1986-98**)
- **SNO,** Real-time (**D_2O**, Sudbury, **1996-2006-present**)

"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"

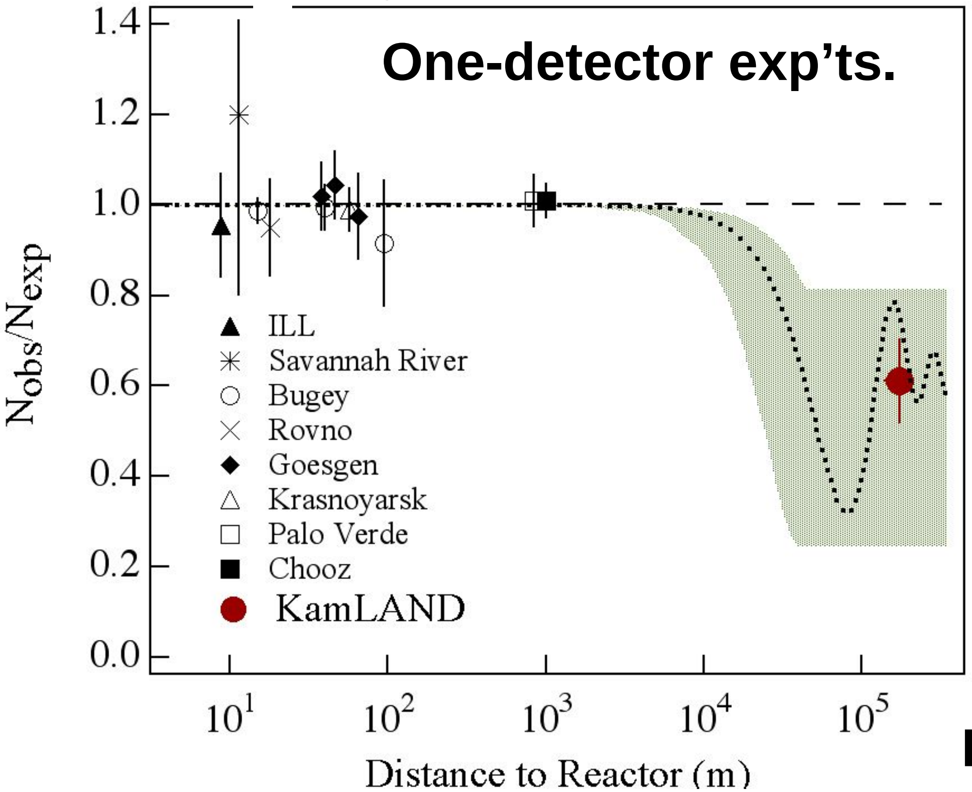


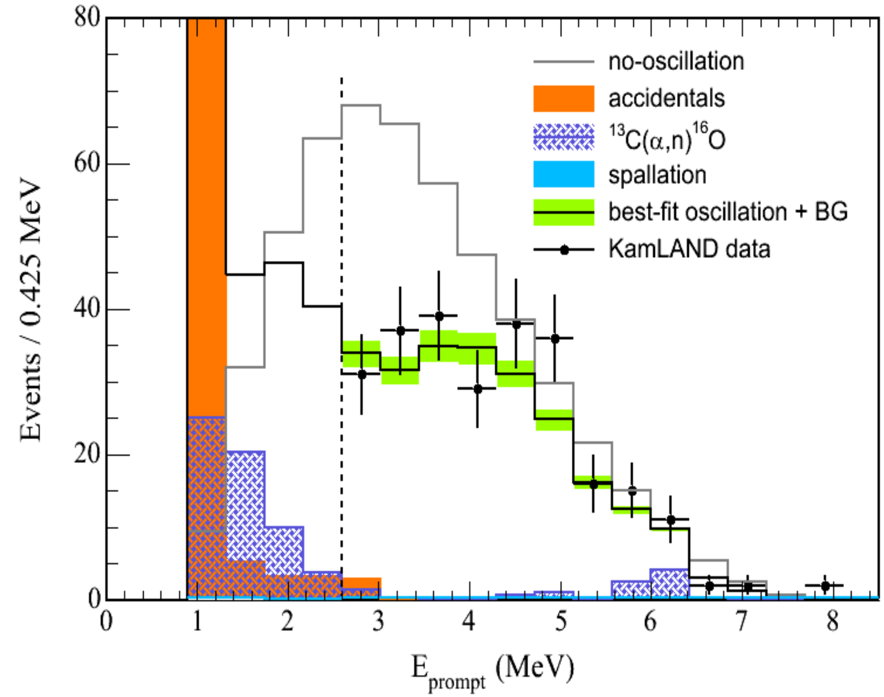
- Neutrinos oscillate, must have mass
- Evidence for neutrino flavor conversion $\nu_e \leftrightarrow \nu_\mu \leftrightarrow \nu_\tau$
- **Entering 'Precision Era'**

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

KamLAND: in 2003, First Evidence for Reactor ν_e Disappearance

in 2004, Evidence of Spectral Distortion

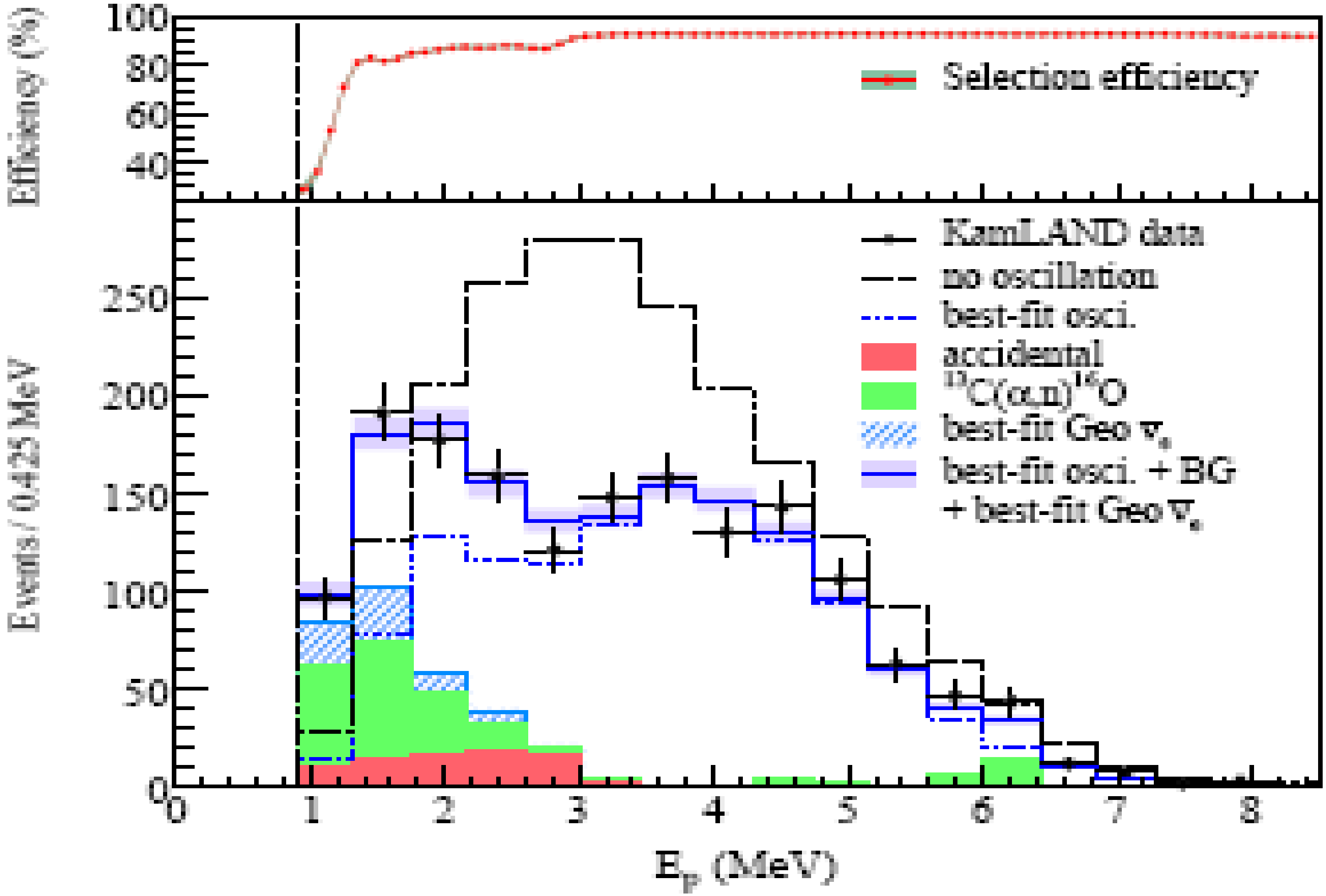




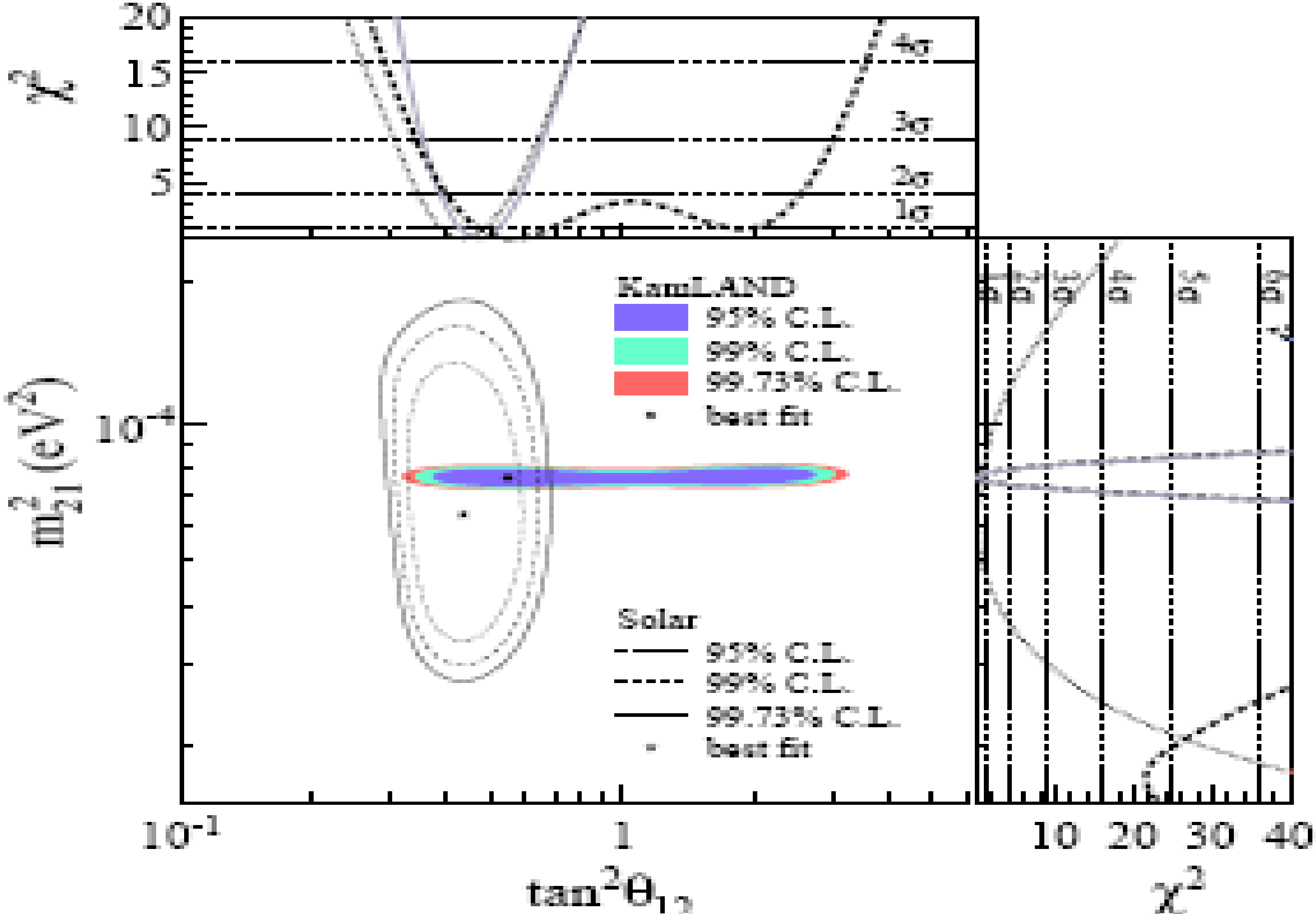
RESULTS CONSISTENT WITH SNO

	2003	2004
Observed ν_e	**54 events**	**258 events**
No-Oscillation	**86.8 ± 5.6 events**	**365.2 ± 23.7**
Background	1 ± 1 events	17.8 ± 7.3
Livetime:	162.1 ton-yr	766.3 ton-yr

KamLAND Results, Jan08 - 2.44×10^{32} proton-yr (2881 ton-yr).



KamLAND + Solar Results, Jan08

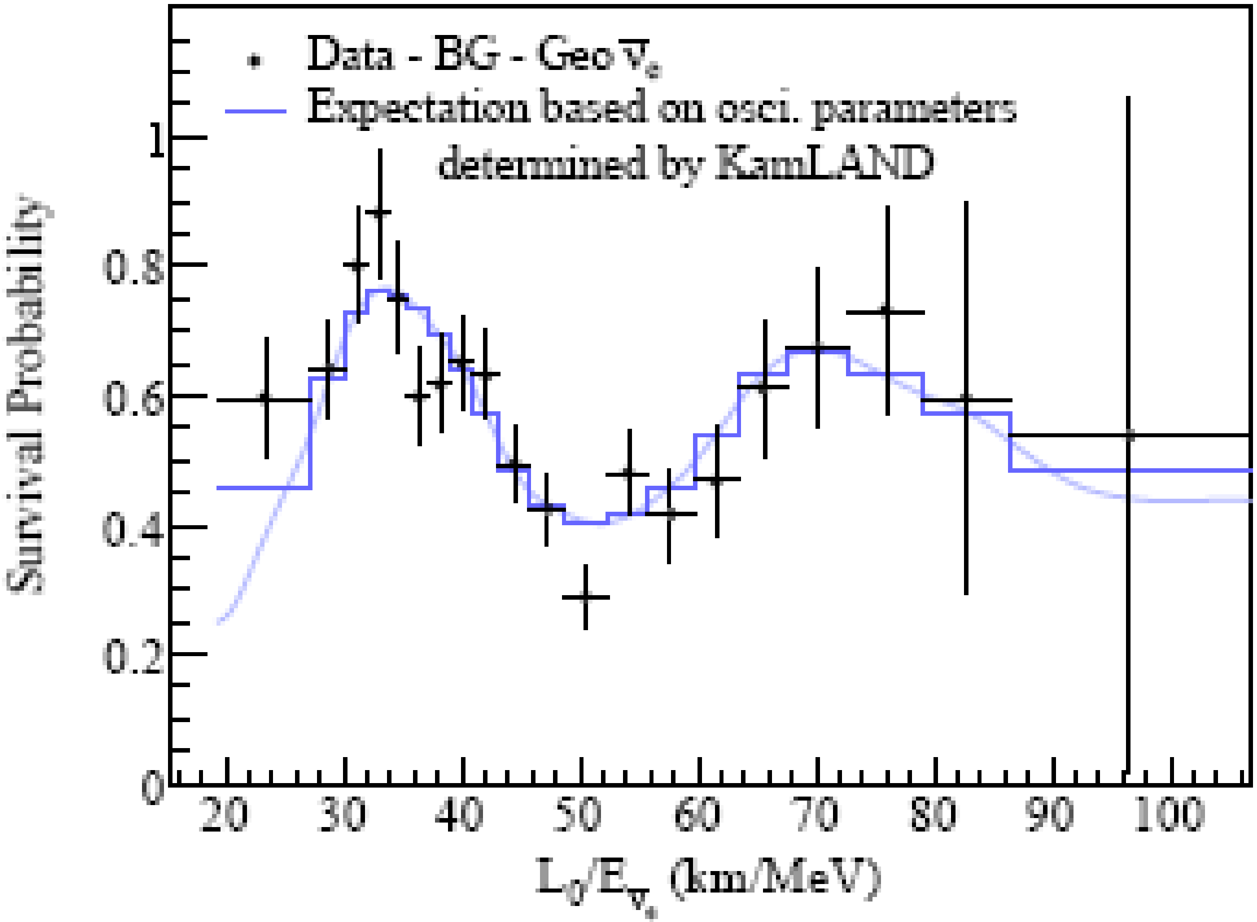


$\Delta m^2 = 7.58 \times 10^{-5}$
(KL only 7.59)

$Tan^2\theta = 0.47$
$\theta \sim 34^o$
(KL only,
$Tan^2\theta = 0.56$)

KamLAND Oscillations, Jan08

L_0 = effective baseline, 180 km



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

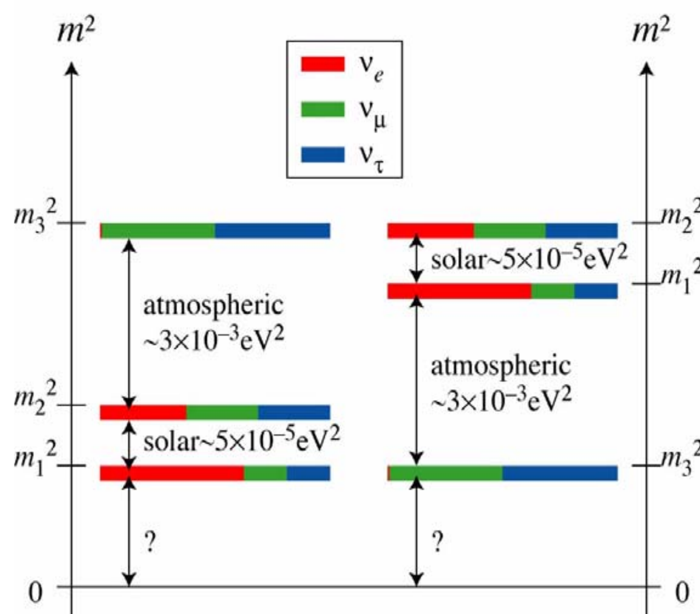
θ_{13} = IS NOT KNOWN. Limit from CHOOZ, Small < 11°

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

$0\nu\beta\beta$

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

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



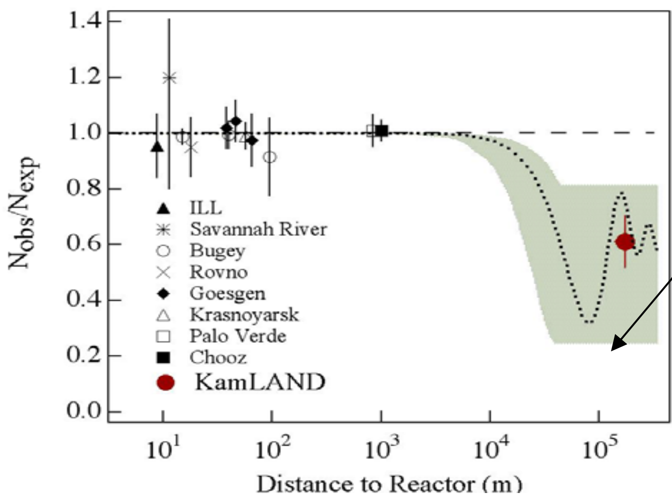
Endorsements of Precision Measurement of θ_{13}

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.

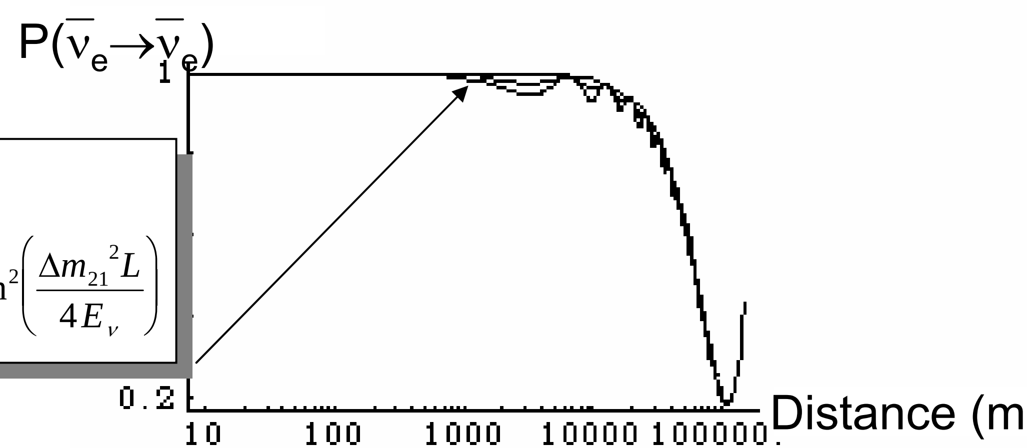
A reactor experiment is unambiguous technique to measure θ_{13}, is key for planned long-baseline experiments to measure CP violation and mass hierarchy



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
Δm_{12}^2~3(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
Δm_{12}^2~3(10^{-5}), Δm_{13}^2~8(10^{-3})

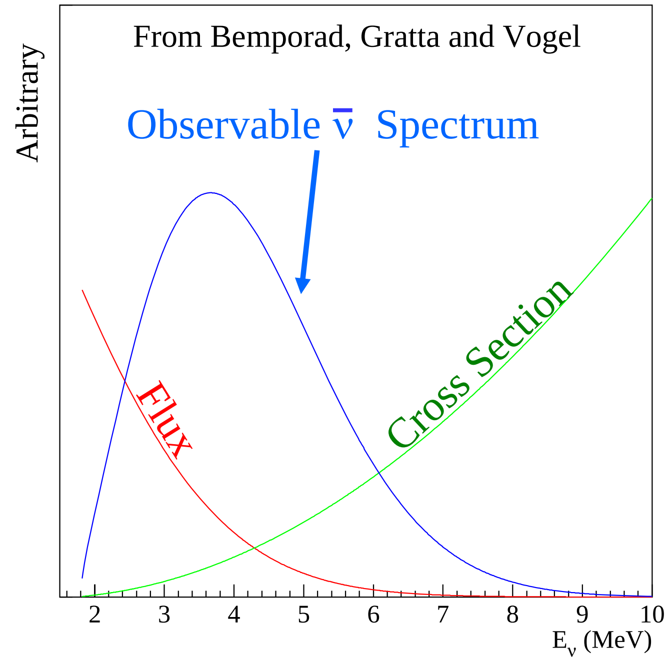
Reactor Measurements of θ_{13}

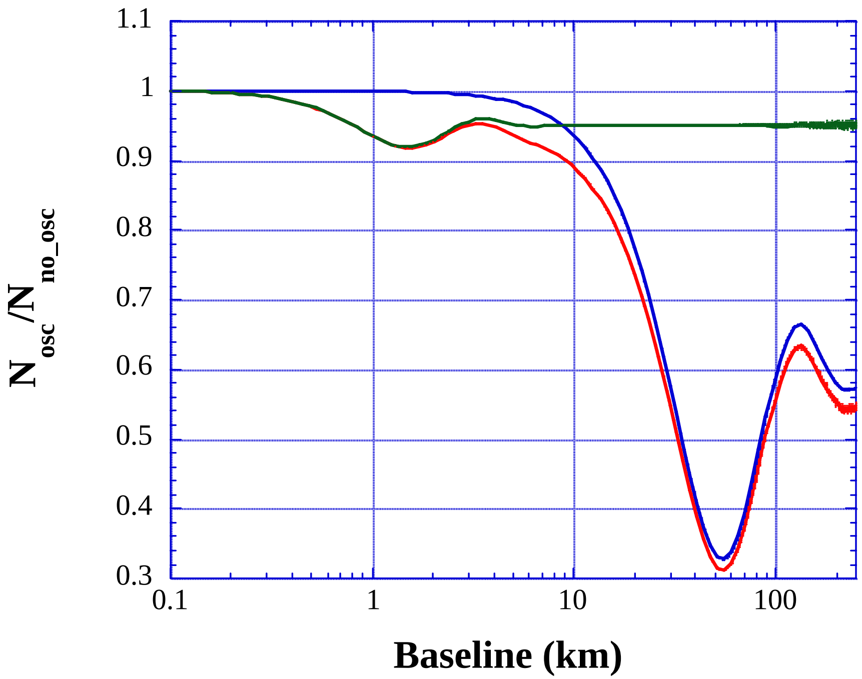
- Nuclear reactors are very intense sources of $\bar{\nu}_e$ from β-decay of fission products, with a well understood spectrum

- 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

<u>Relative Measurements for Precision</u>

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") 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

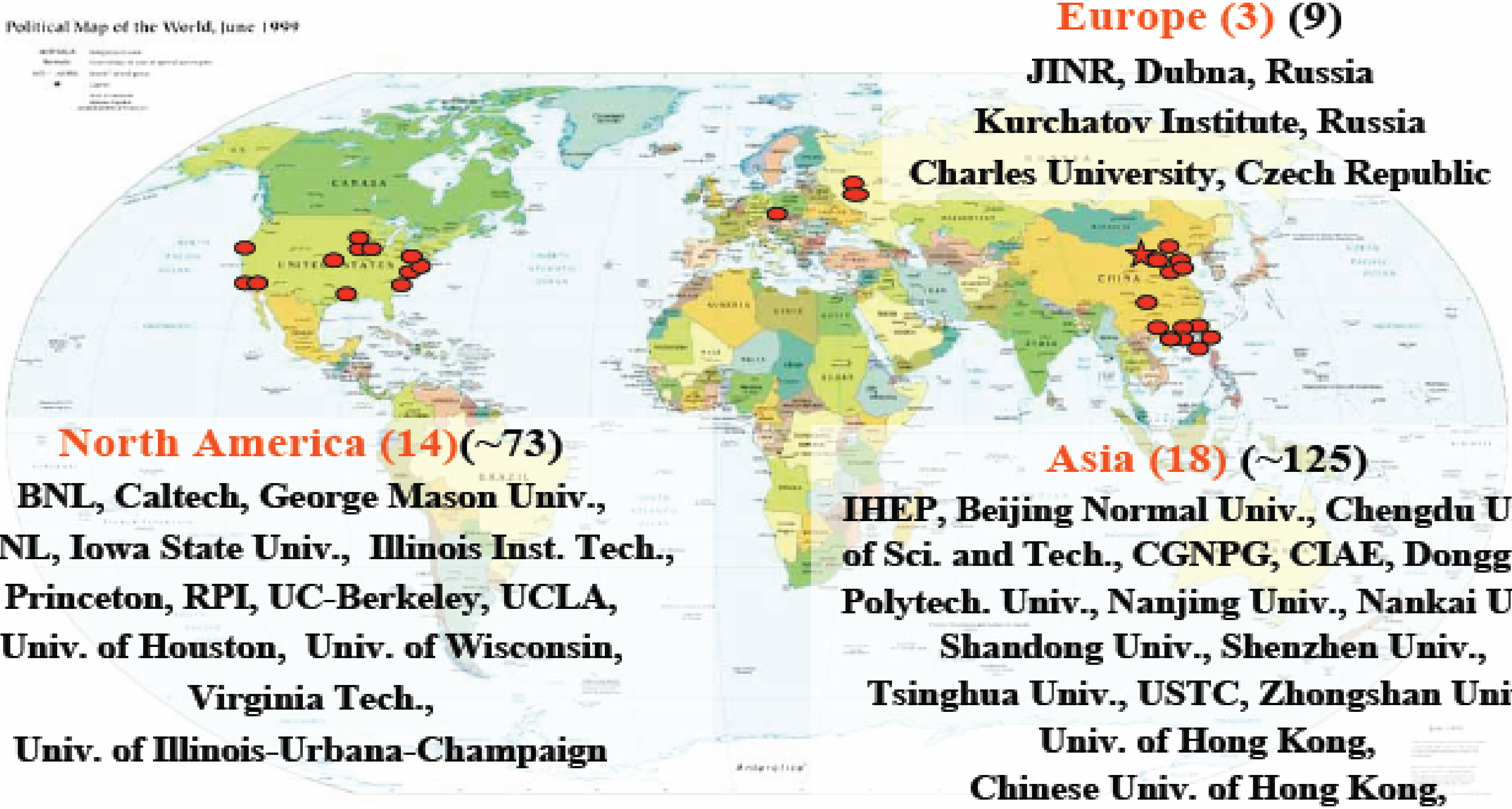
  (b) Want detectors to be as "identical" as possible

BROOKHAVEN NATIONAL LABORATORY

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.

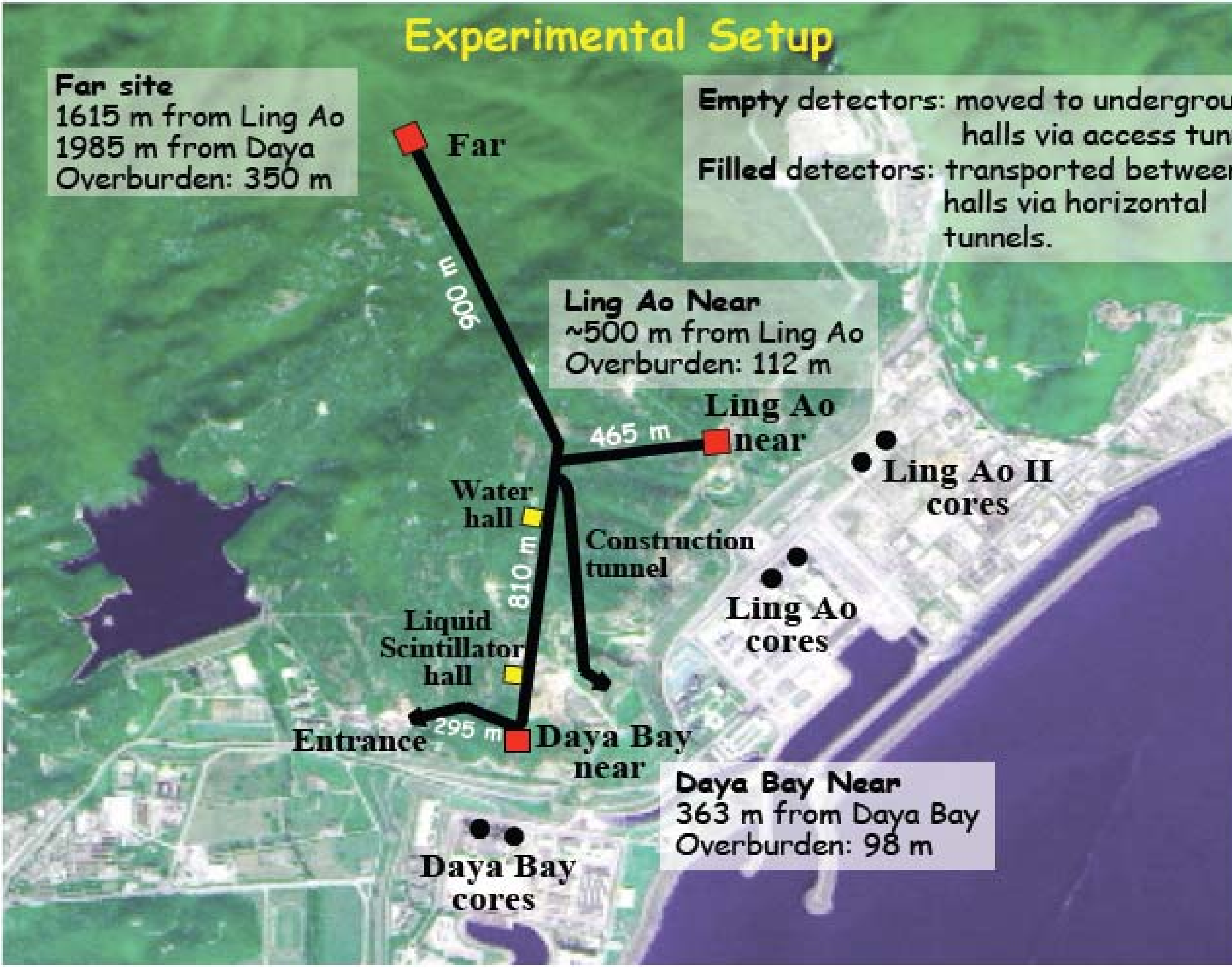
~ 207 collaborators

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

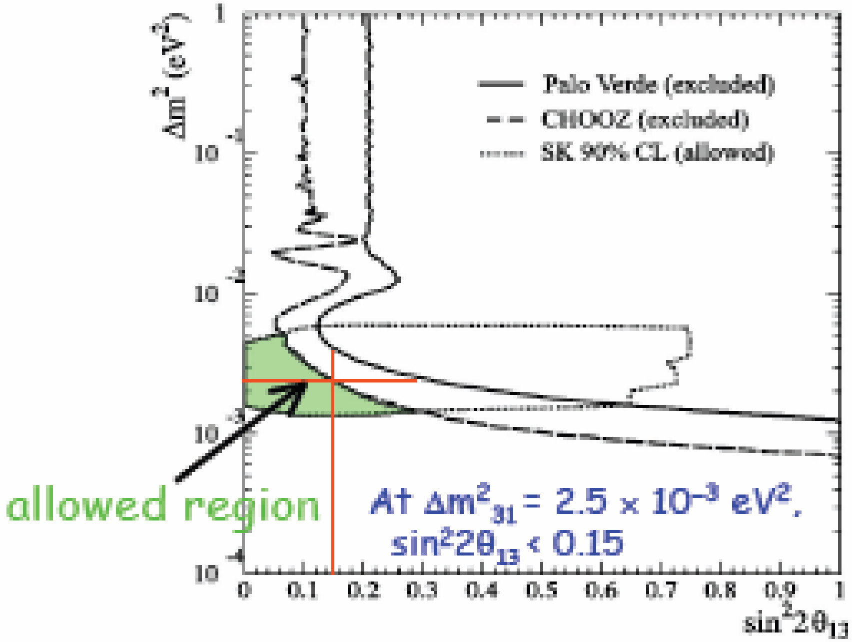


Experimental Setup
Far site
1615 m from Ling Ao
1985 m from Daya
Overburden: 350 m
Far
Empty detectors: moved to underground halls via access tunnel.
Filled detectors: transported between halls via horizontal tunnels.
900 m
Ling Ao Near
~500 m from Ling Ao
Overburden: 112 m
Ling Ao near
465 m
Ling Ao 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

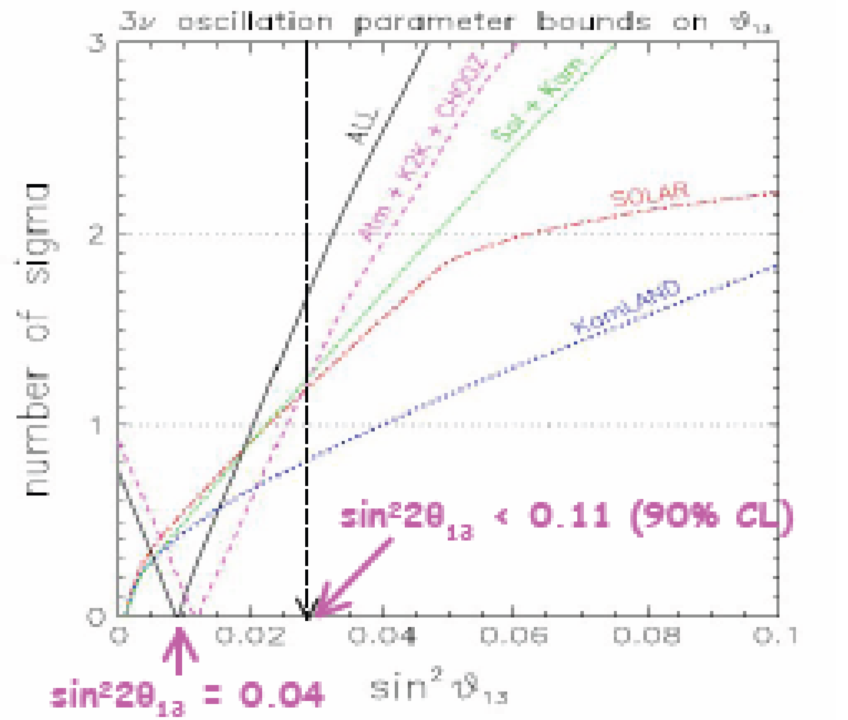
Daya Bay: Goal

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

Direct search



Global fit



Best fit value of Δm^2_{32} = 2.4 x 10^{-3} eV^2

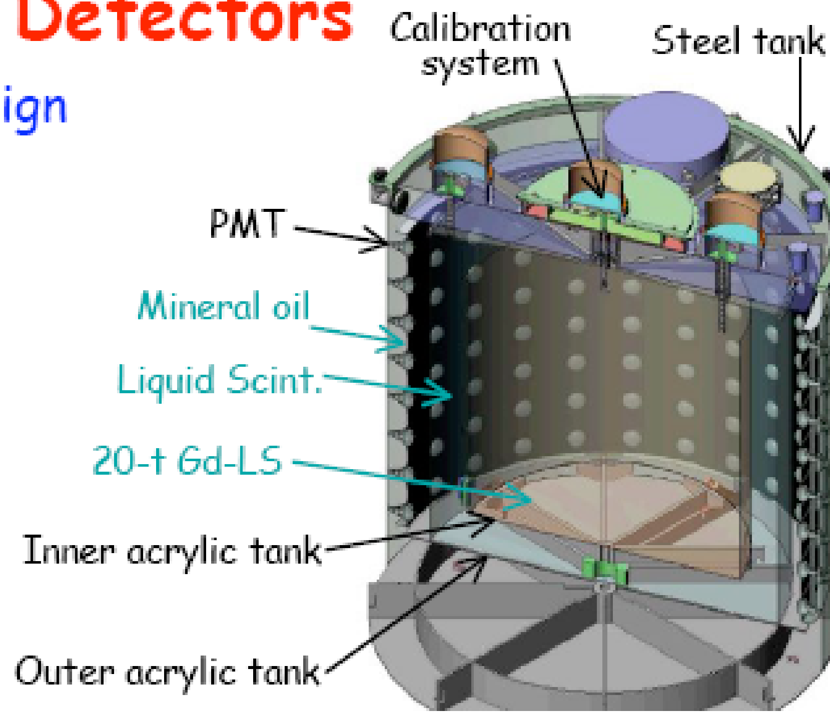
- NuSAG's recommendation (2006):

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

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

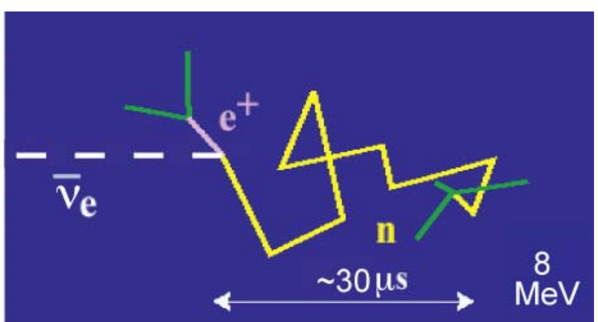
Daya Bay Antineutrino Detectors

- 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

$$E_{\bar{\nu}} \approx T_{e+} + T_n + (m_n - m_p) + m_{e+} \approx T_{e+} + 1.8 \text{ MeV}$$
$$E_{\bar{\nu}} \approx 1 - 9 \text{ MeV}$$



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

Claude Musikas, consultant, CEA

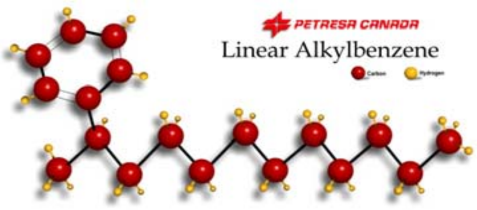
History of BNL R&D on Metal-loaded LS, M-LS

- 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 (first with Pseudocumene - PC, now with Linear Alkyl Benzene - LAB) that avoided 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.

BROOKHAVEN NATIONAL LABORATORY

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)

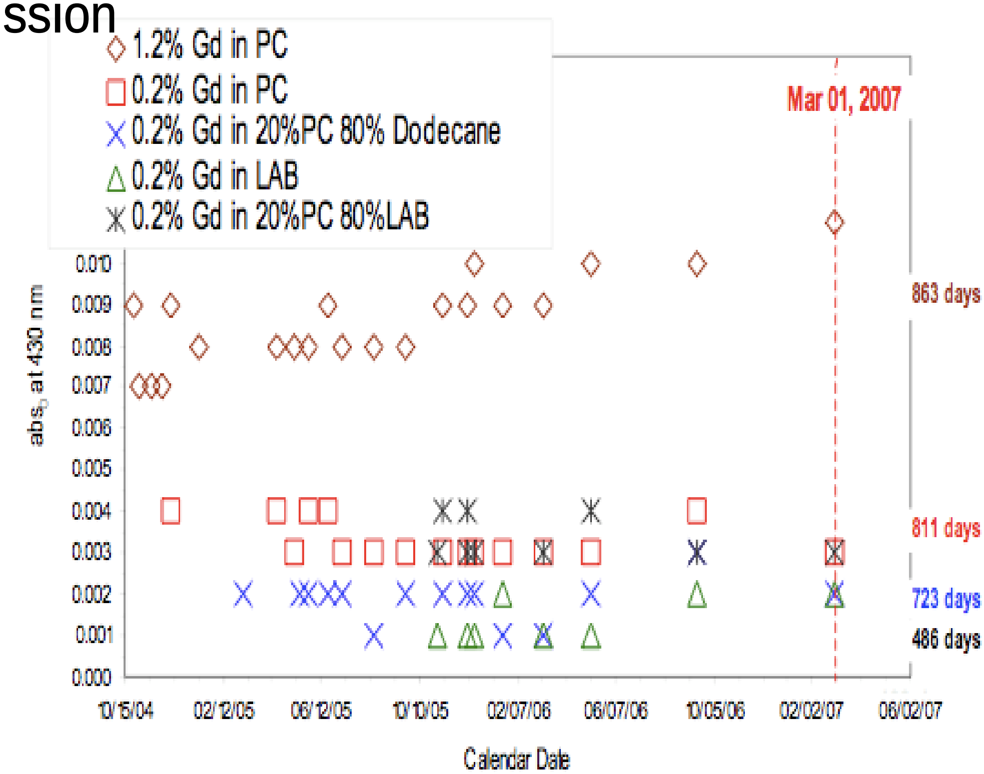
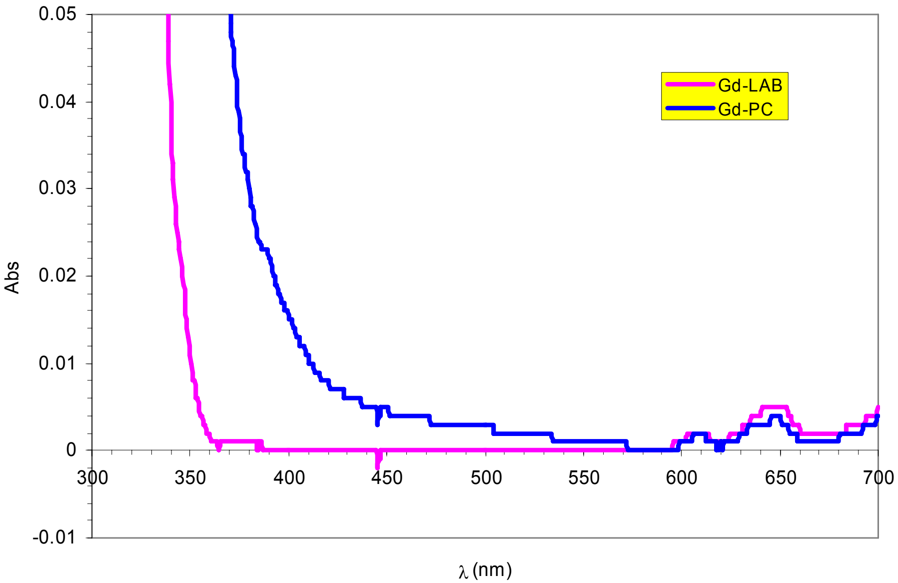


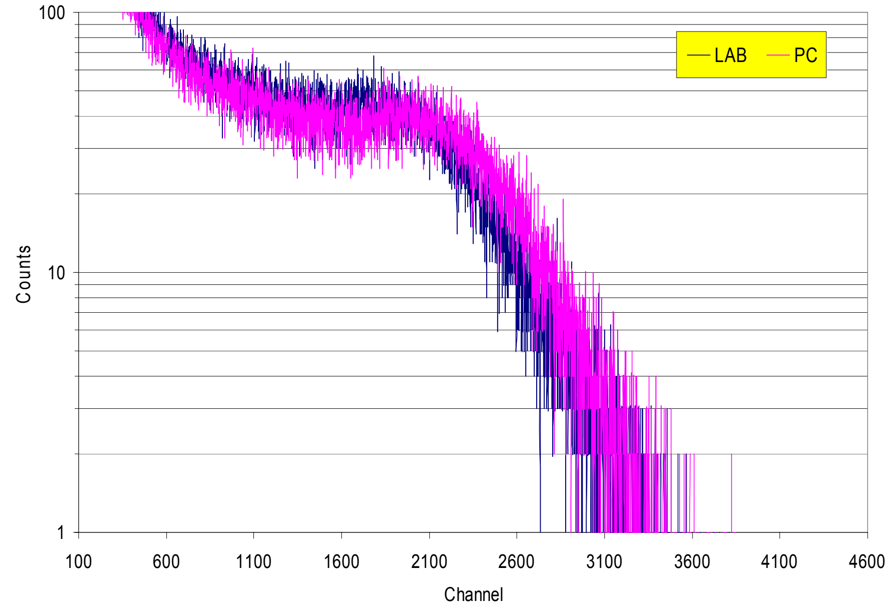
Fig. 6.23. The UV absorption values of BNL Gd-LS samples at 430 nm as a function of time

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.

BROOKHAVEN NATIONAL LABORATORY

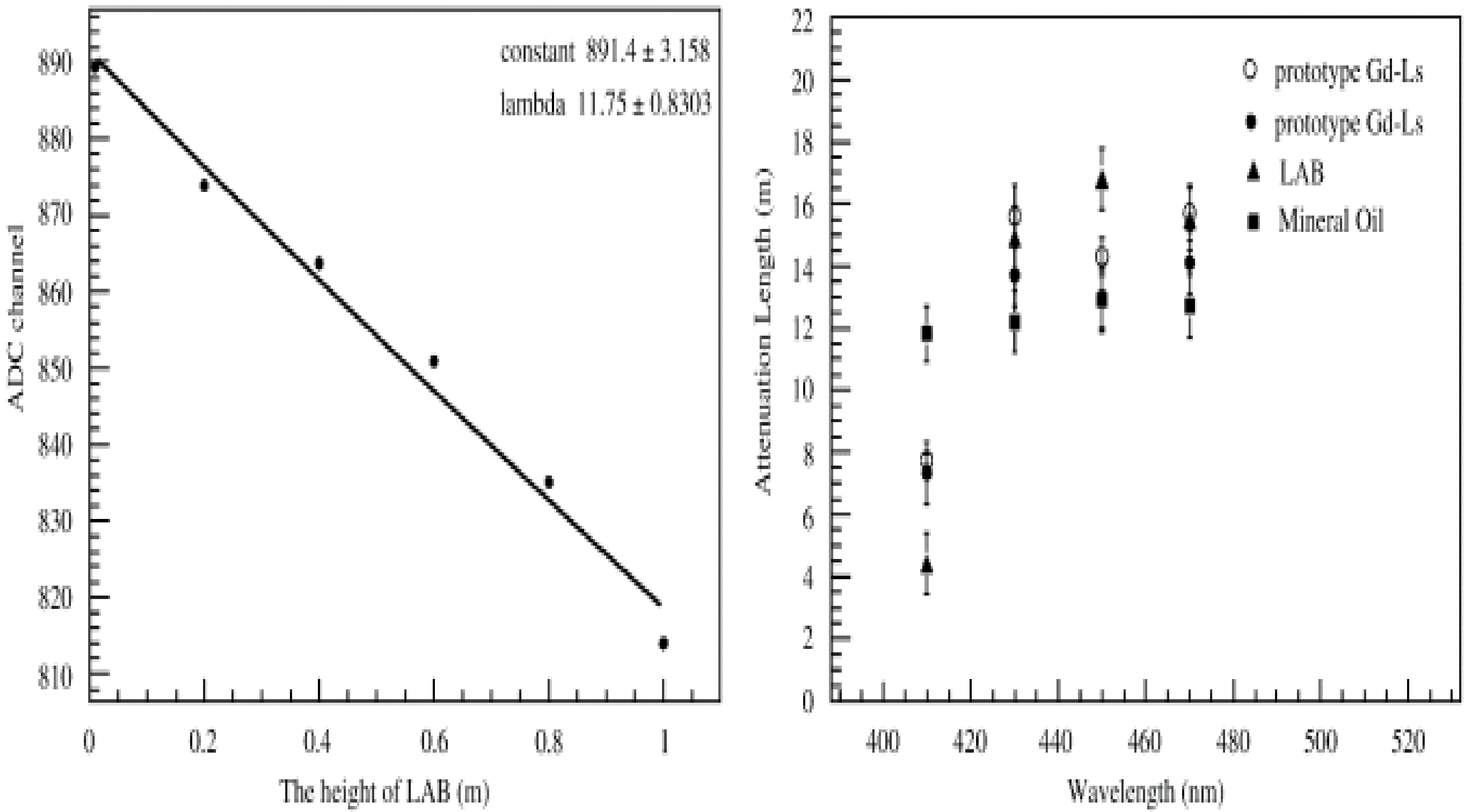


Fig. 4. *Left*: an example of the attenuation length measurement using the 1-m tube system. The transmissions of different path lengths (Gauss fitting) are fitted to an exponential curve. *Right*: black dots and cycles are attenuation lengths of the 800 L LAB-based Gd-LS used in the prototype experiment.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

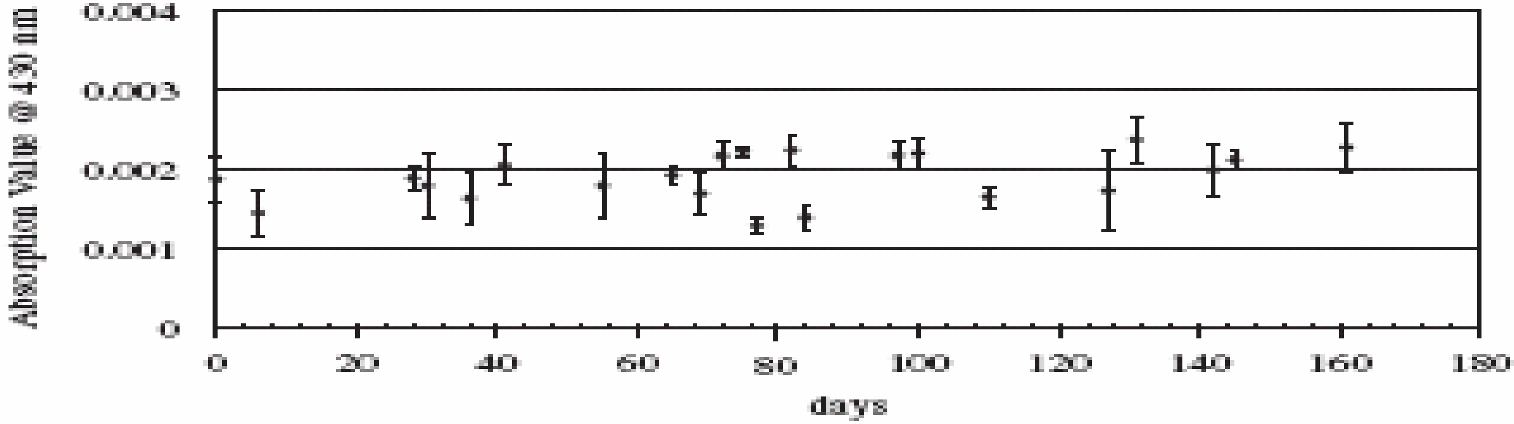


Fig. 5. Absorption of Gd-loaded liquid scintillator at 430 nm as a function of time.

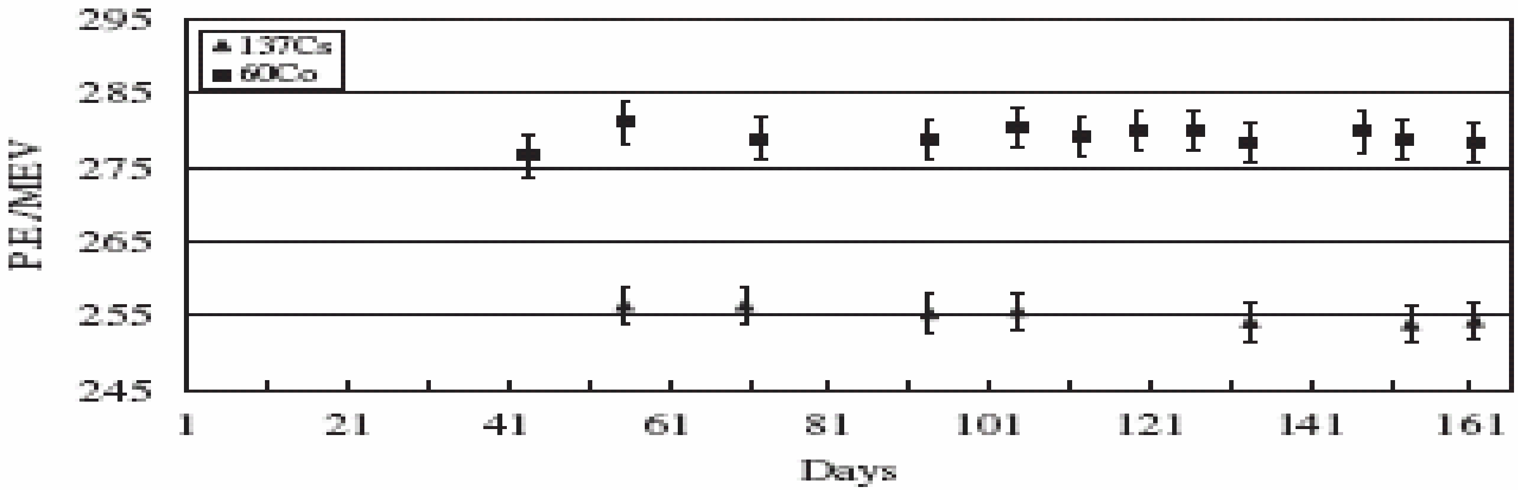


Fig. 6. Long-term stability monitoring of Gd-loaded scintillator by the energy response of the prototype detector to radioactive sources (located at the center of the detector).

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 detectors
- Hahn is U.S. co-leader of LS Task Force, Yeh is U.S. project Level-3 co-manager for LS (project management team)
- 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

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 these contaminants, using Ge γ-ray detectors, LS cocktails, solid-state α detectors
- 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 be synthesizing the solid Gd carboxylate at IHEP (using ~1 ton of $GdCl_3.6H_2O$; need ~200 kg Gd)
- 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 in one large vessel
- UG, will fill the Antineutrino Detectors from the common supply of Gd-LS (likely, 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

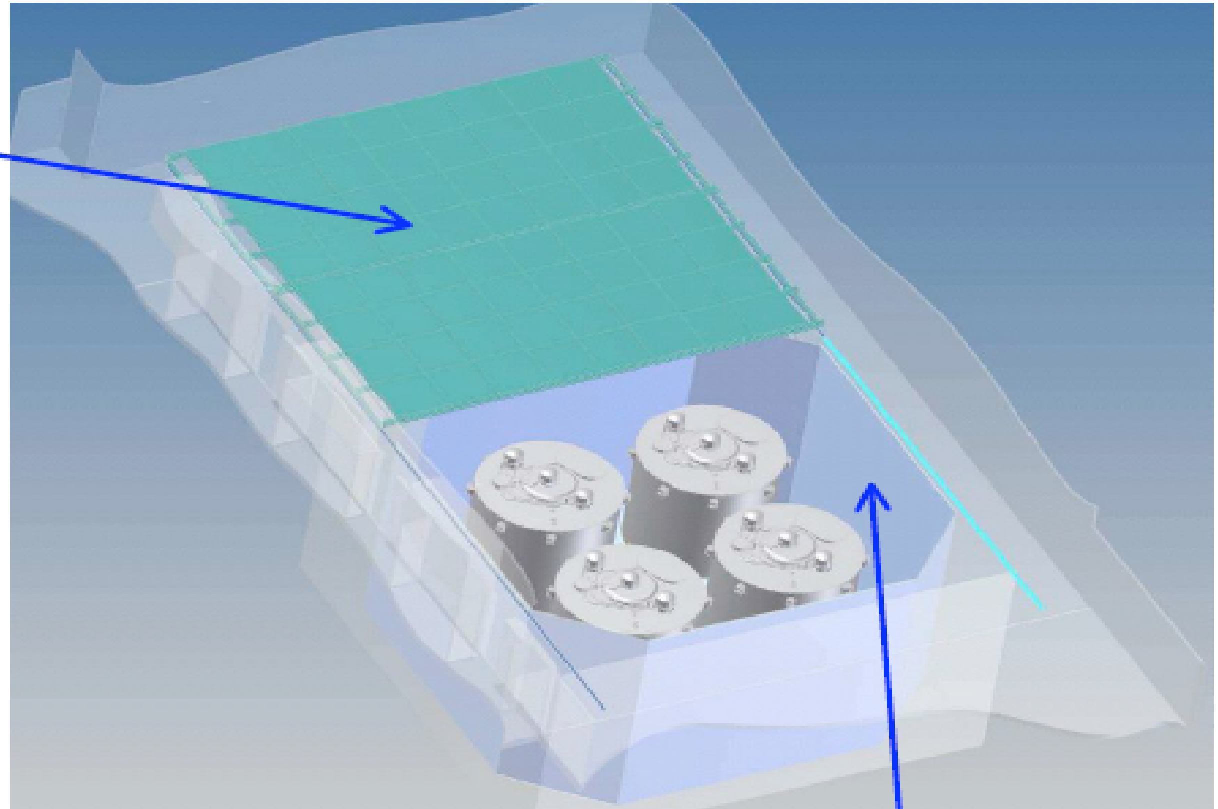
  4-5 MeV from U, Th chains; 2-3 MeV from neutron-deficient rare earths
- Maximum acceptable levels in the solid $GdCl_3.6H_2O$ of U and Th are < 5 and <10 ppb respectively (→ 0.1% Gd in LS)

  Note: formula weights, Gd / GdCl3.6H2O = 0.42
- 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

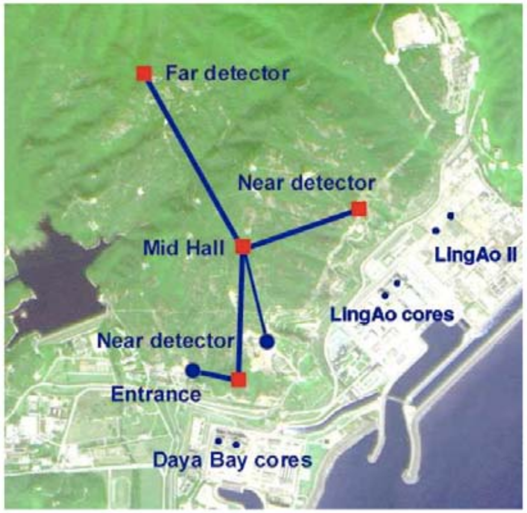
Four RPC's for tracking muons



- 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

Rates and Spectra



Distances to Sites (m)

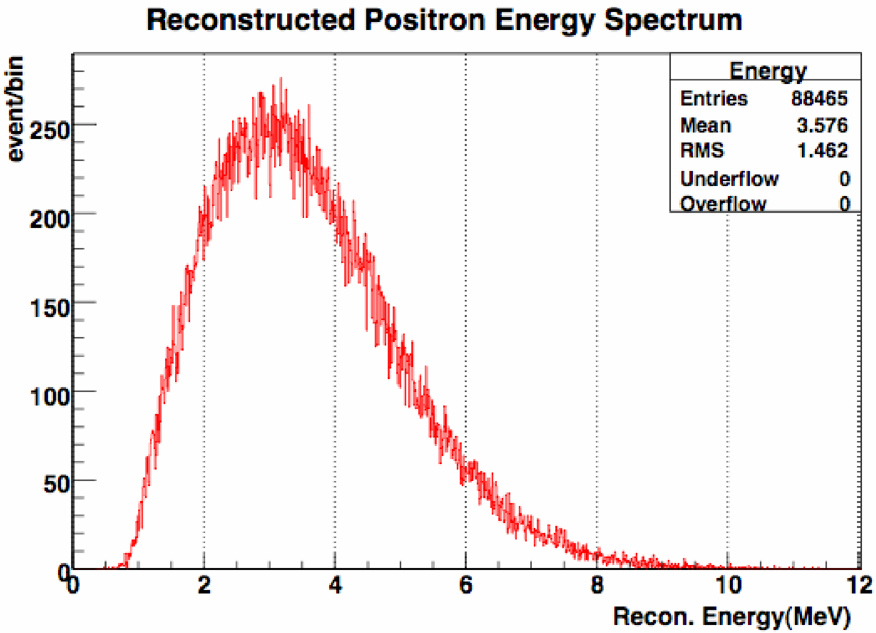
Sites	DYB	LA	Far
DYB cores	363	1347	1985
LA cores	857	481	1618
LA II cores	1307	526	1613

Antineutrino Interaction Rate

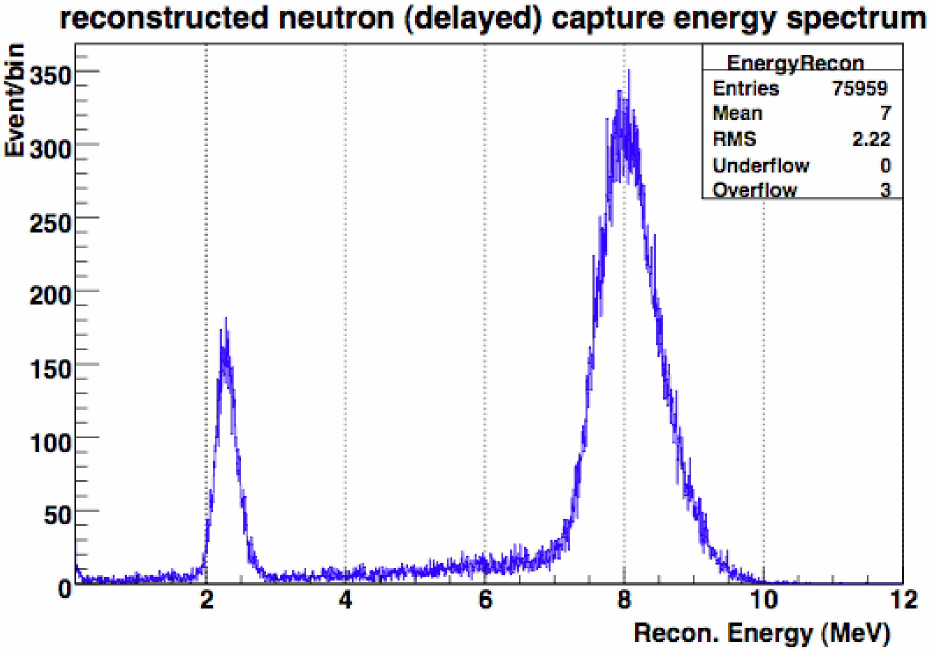
(events/day per 20 ton module)

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

Prompt Energy Signal

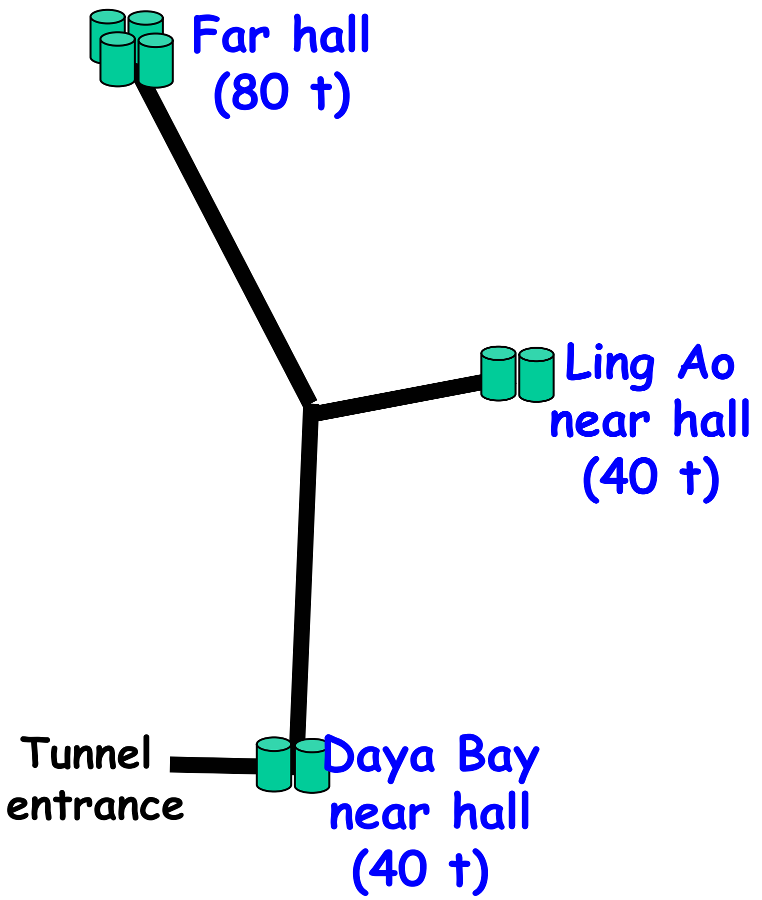


Delayed Energy Signal

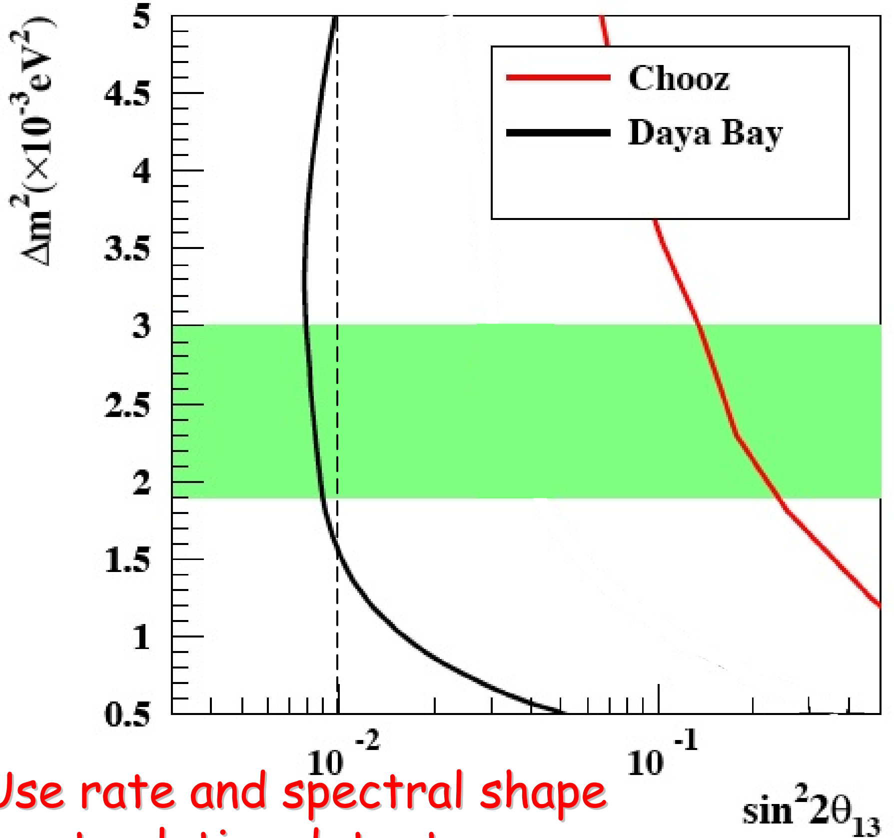


Statistics comparable to single detector in far hall

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

- 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 Fund Allocations began March 2008**
- **US Project Cost ~$34 M over 3 years**
- **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

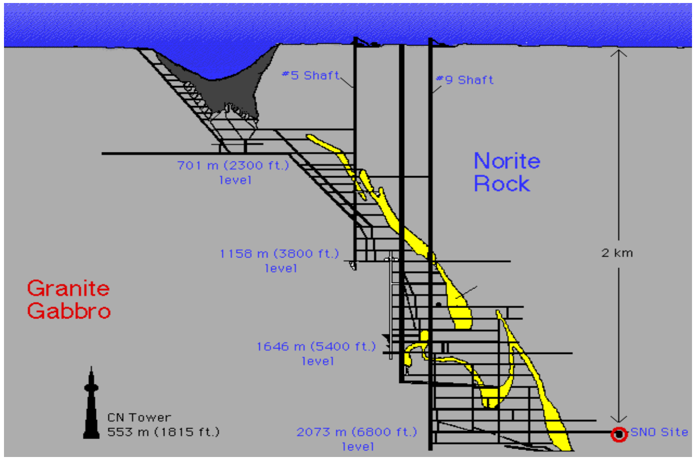
Version #6 March 20, 2008

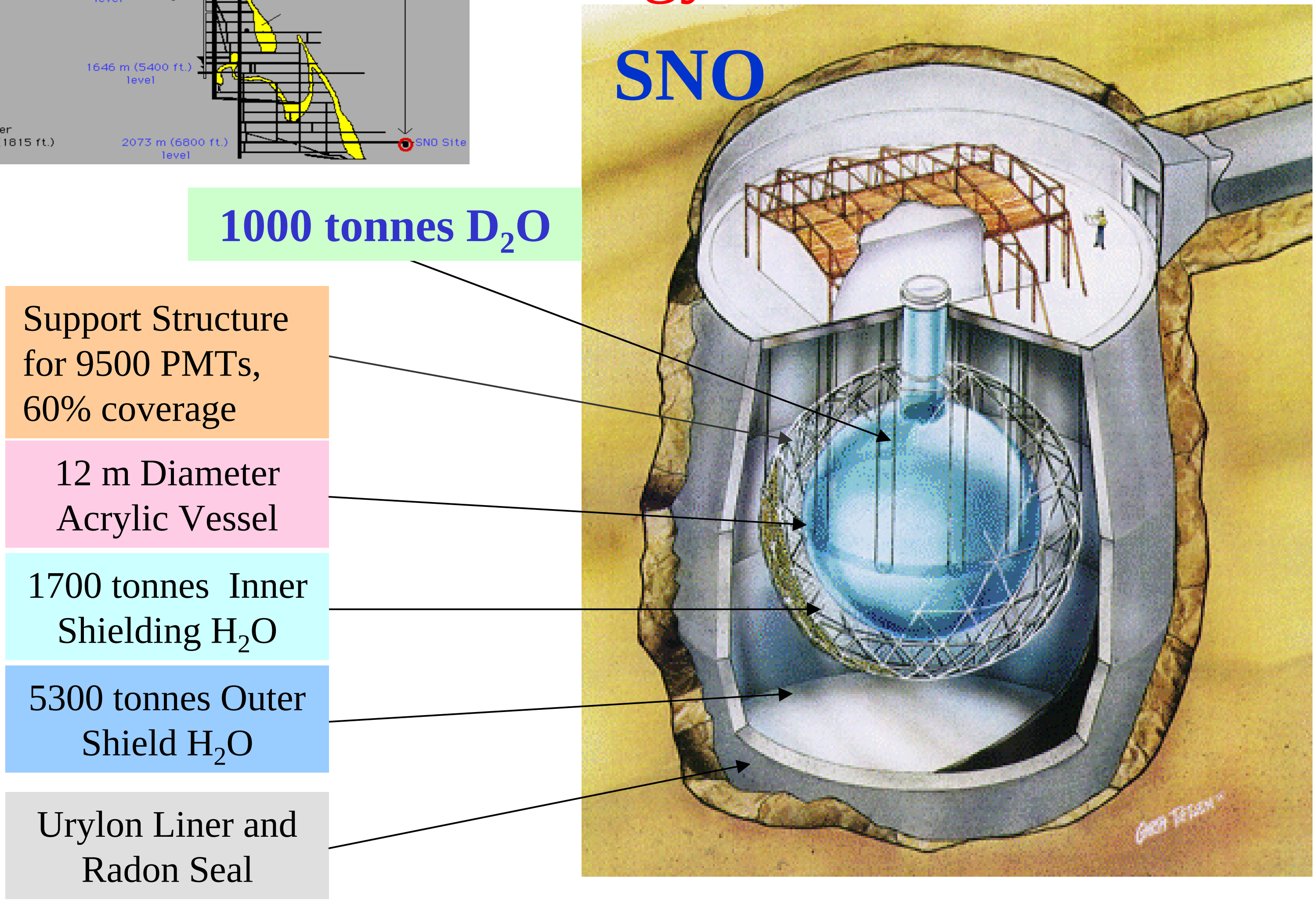
For the Project team.
For questions please contact:
Project Manager: Bill Edwards (wredwards@lbl.gov)
Chief Scientist: Steve Kettell (kettell@bnl.gov)

Now a Brief Discussion of SNO+

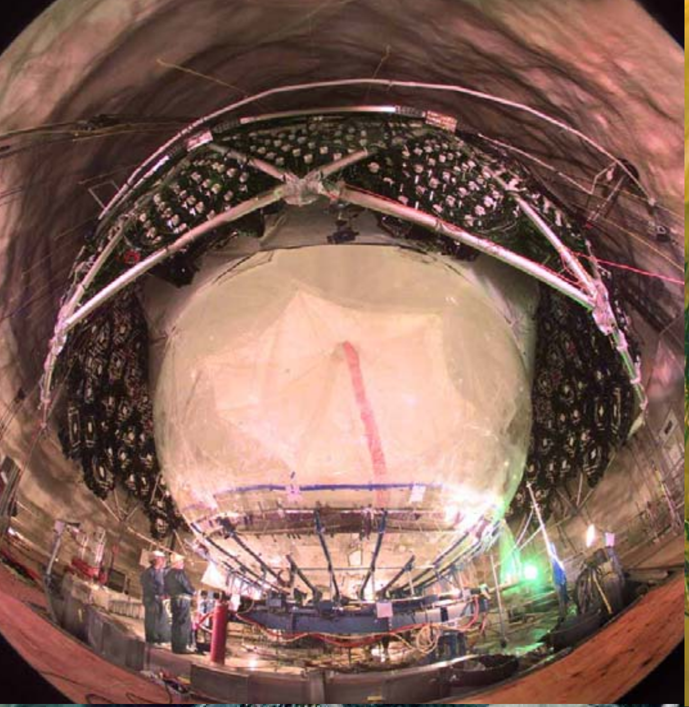
(with some excerpts from a proposal to the Canadian funding agencies)

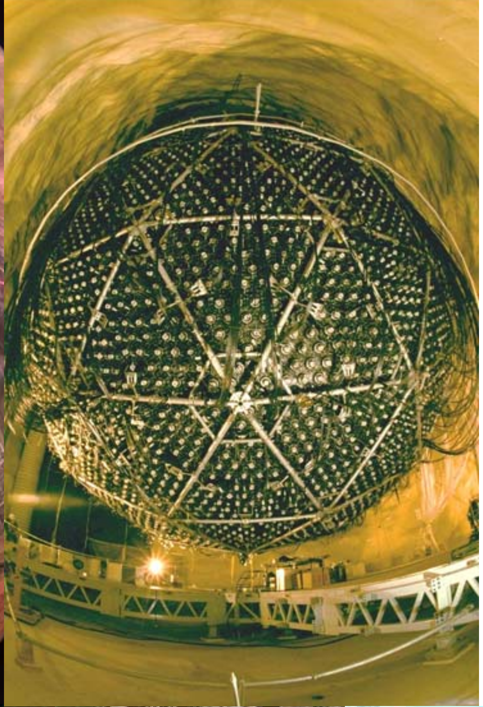
Sudbury Neutrino Observatory: Real-Time Detector 24/7 Gives Energy, Time, Direction…$^{8}B\ \nu$





New: SNOLAB Users Facility





One million pieces transported down in the 10 foot square mine cage and re-assembled under ultra-clean conditions.

A chemical factory underground!

Transforming SNO into a liquid scintillator detector would boost the light yield by a factor of ~50-100 and would place protons in the detector instead of deuterons. This would enable:

- the detection of low-energy solar neutrinos, such as *pep*, *CNO*, and ^{7}Be; the detection of these neutrinos, especially the *pep* solar neutrinos, would enable a sensitive test of matter effects on neutrino oscillations, including non-standard effects
- the detection of electron antineutrinos from natural radioactivity in the Earth (geo-neutrinos)
- the detection of electron antineutrinos from distant nuclear power reactors (e.g. Bruce, Darlington, Pickering) providing a way to demonstrate that KamLAND's observation of reactor neutrino oscillations depends upon L/E (i.e. a sharp spectral distortion from oscillations would be observed in SNO+ at a different energy); this would improve the precision of the determination of neutrino oscillation parameters
- perhaps most interesting is that the liquid scintillator can be used as a medium in which a large quantity of double beta decay isotope, such as ^{150}Nd, could be dissolved, resulting in a neutrinoless double beta decay experiment with leading sensitivity
- a liquid scintillator in SNO+ would preserve excellent supernova neutrino capabilities, including CC and NC reactions on both protons and carbon.

2.1. Neodymium Double Beta Decay in SNO+

The search for neutrinoless double beta decay is a high priority goal in nuclear and particle physics. Understanding whether neutrinos are Majorana or Dirac particles is a fundamental question that may impact upon cosmology, helping to understand the origin of the matter-antimatter asymmetry of the Universe. Neutrinoless double beta decay rates are related to the absolute scale for neutrino mass. A claim that neutrinoless double beta decay has been observed [1], with a neutrino mass scale of 150-400 meV, is presently unconfirmed.

[1] Klapdor-Kleingrothaus et al.

$2\nu\beta\beta$ decay gives β continuous spectrum. This has been observed several times.

New: $0\nu\beta\beta$ would give peak at Q-value.

table from F. Avignone Neutrino 2004

^{150}Nd ββ decay

$$\overline{\eta} \equiv \langle G^{0\nu} |\mathcal{M}^{0\nu}|^2 \rangle \times 10^{13}$$

Isotope	$\overline{\eta}$
^{48}Ca	0.54
^{76}Ge	0.73
^{82}Se	1.70
^{100}Mo	10.0
^{116}Cd	1.30
^{130}Te	4.20
^{136}Xe	0.28
^{150}Nd	57.0

- 3.37 MeV endpoint
- $(9.7 \pm 0.7 \pm 1.0) \times 10^{18}$ yr = 2νββ half-life measured by NEMO-III
- Some uncertainty about $M^{0\nu}$
- Natural isotopic abundance 5.6%

(Other ββ experiments are in R&D with Ge, Te, Xe, Mo, and Nd. SNO+ may be able to get going on a fast track.)

2νββ decay gives β continuous spectrum.

0νββ gives Peak at Q-value.

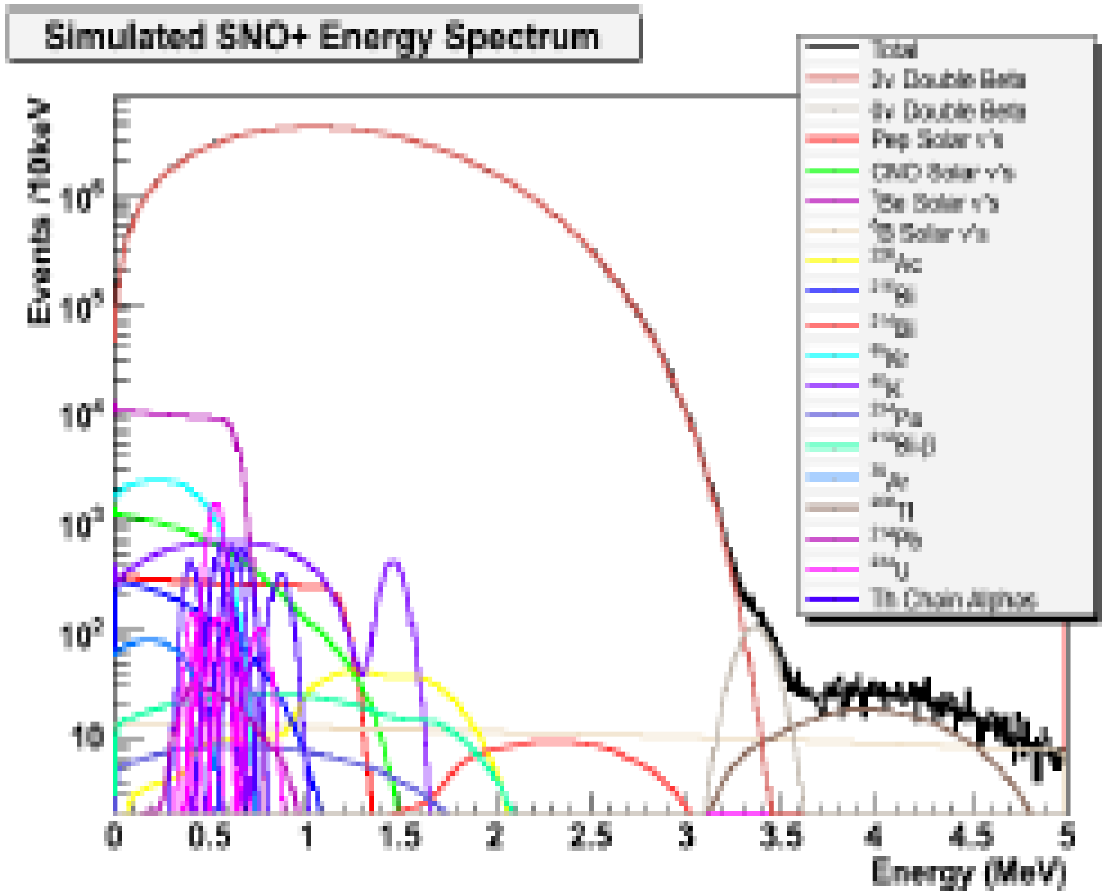


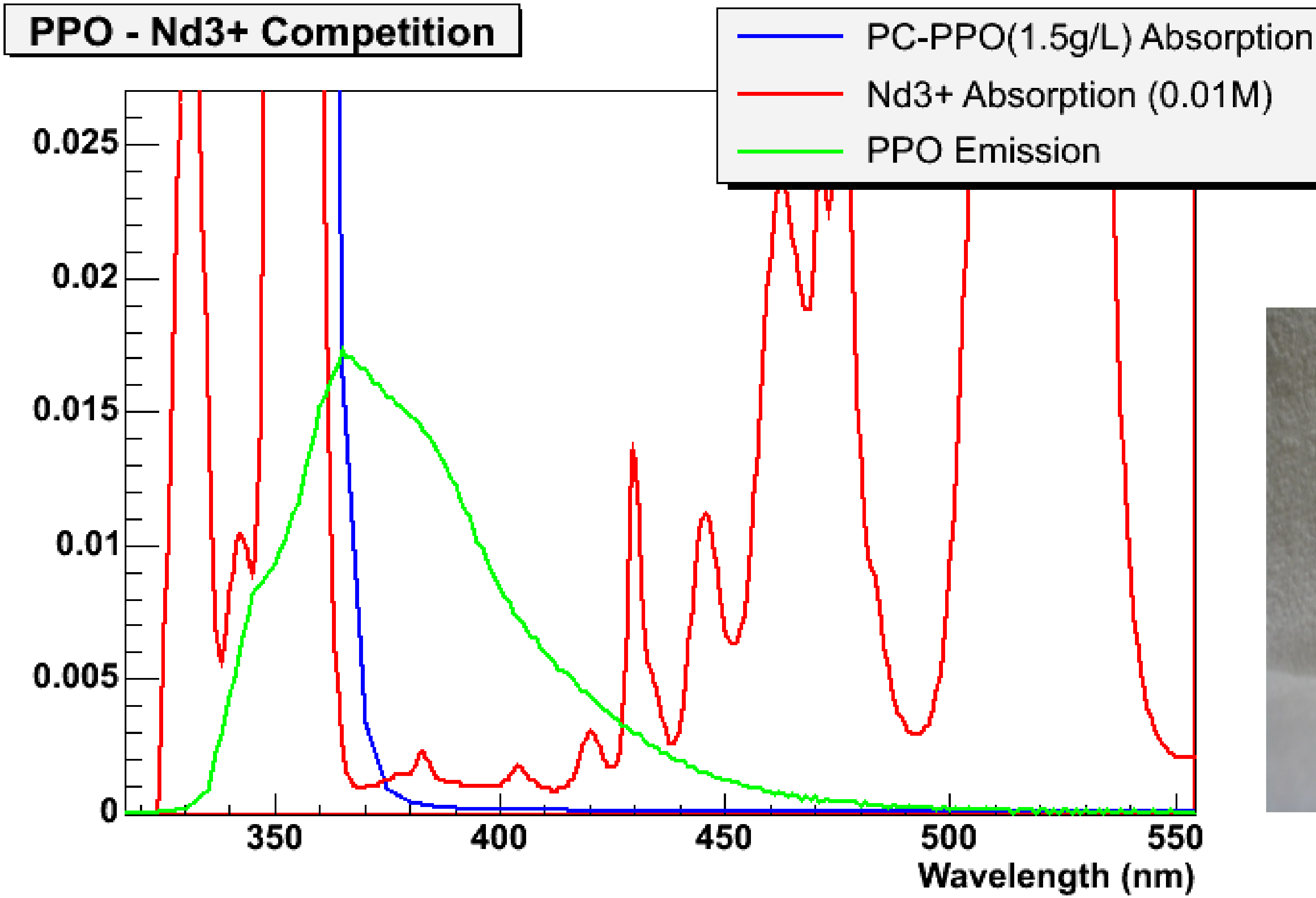
Fig. 3. Energy spectrum from signals and backgrounds in SNO+ with 500 kg of ^{150}Nd.

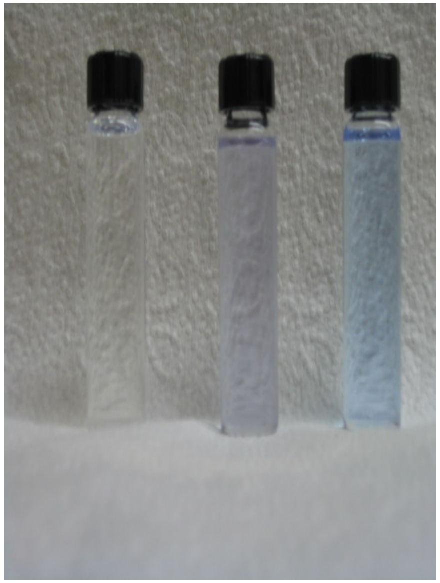
Peak at 3.4 MeV due to 0νββ.
Broad peak out to ~5 MeV due to ^{208}Tl from ^{232}Th decay chain

SNO+, A New Experiment at SNOLAB

- **Note that neutrinoless double beta decay received one of the two "high priority" ratings in the 2004 APS Study.**
- **SNO+ will study double beta decay of ^{150}Nd. The goal is to (a) use the existing SNO detector, apparatus, and infrastructure and (b) replace the D_2O in the acrylic vessel with ~1 kton of Nd-loaded liquid scintillator (Nd-LS) from BNL.**
- Note: Density D_2O = 1.10, so must "hold up" the acrylic vessel in the H_2O so it does not sink. Density LAB = 0.85, so must "hold down" the acrylic vessel in the H_2O so it does not rise to surface.
- **Much of the existing SNO apparatus was supplied by DOE/ONP. Its value ~$18 M. The idea is that SNO+ would leverage this large investment, and need only ~$11 M from Canada.**

Nd-LS from BNL:
Nd-carboxylate in Pseudocumene





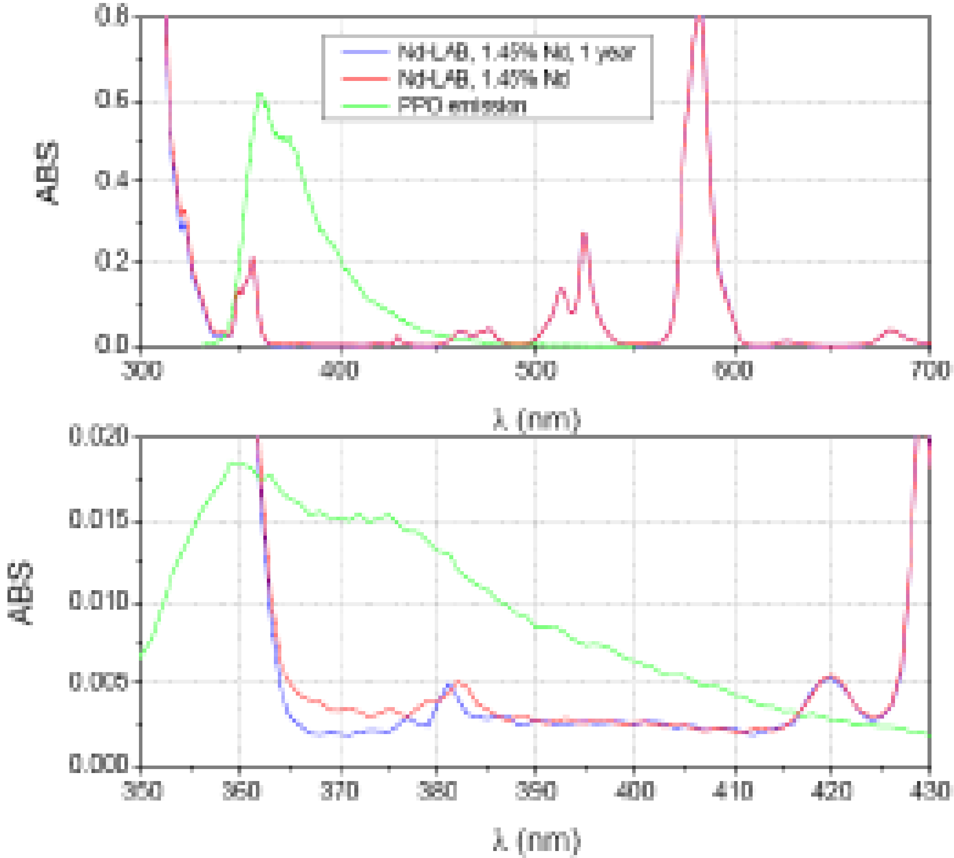


Fig. 1. The absorption spectrum of Nd-LAB scintillator, comparing original data to data taken one year later. The emission spectrum from PPO is also shown.

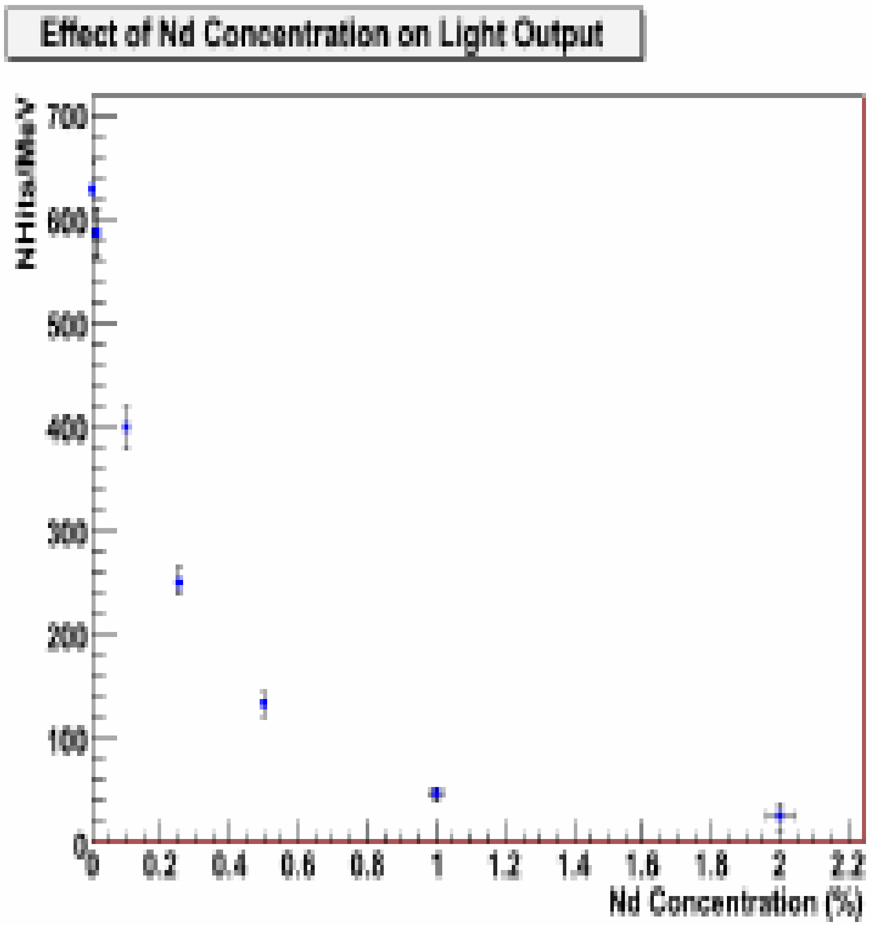


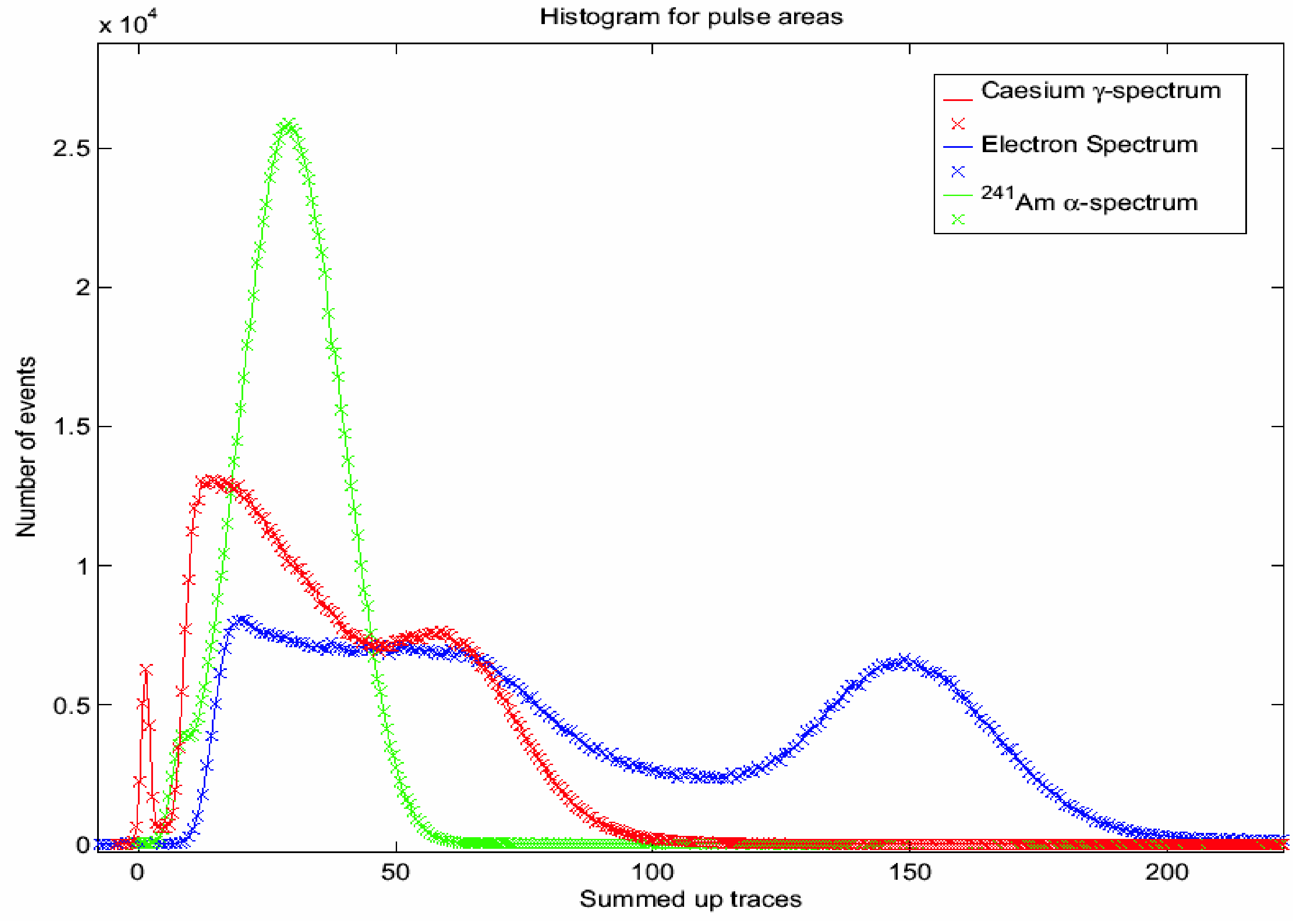
Fig. 2. The effect of Nd concentration on light output. The light output was calculated using a complete scintillation optical model accounting for the propagation of light and using the SNO+ detector geometry and PMT characteristics.

A New Wrinkle: Enrichment of ^{150}Nd?

Want to avoid this loss of light with low Nd concentration and large amount of ^{150}Nd

- Scientists from SuperNEMO, SNO+, MOON, and DCBA (Drift Chamber β Analyzer) have joined together to try to keep an existing French AVLIS facility "alive". (Atomic Vapor Laser Isotope Separation)
- **The reason: this facility is capable of producing 100's of kg of enriched Nd**
- This facility was used to demonstrate that 204 kg of U could be enriched to 2.5% from 0.7% (natural abundance of ^{235}U) in several hundred hours
- Russians have done demonstration enrichment of Nd with AVLIS

The BNL Nd-LS Detects Radiation!



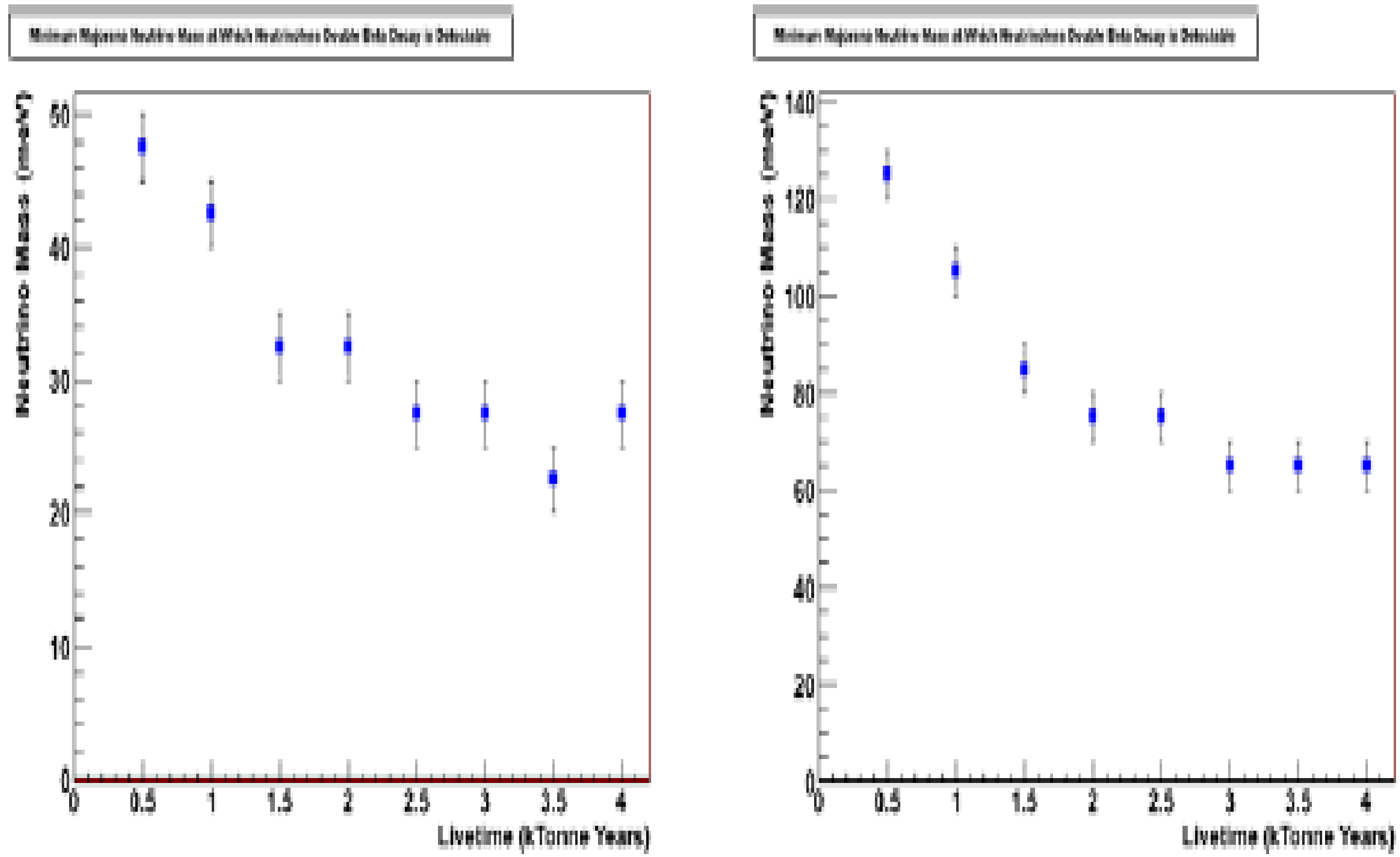


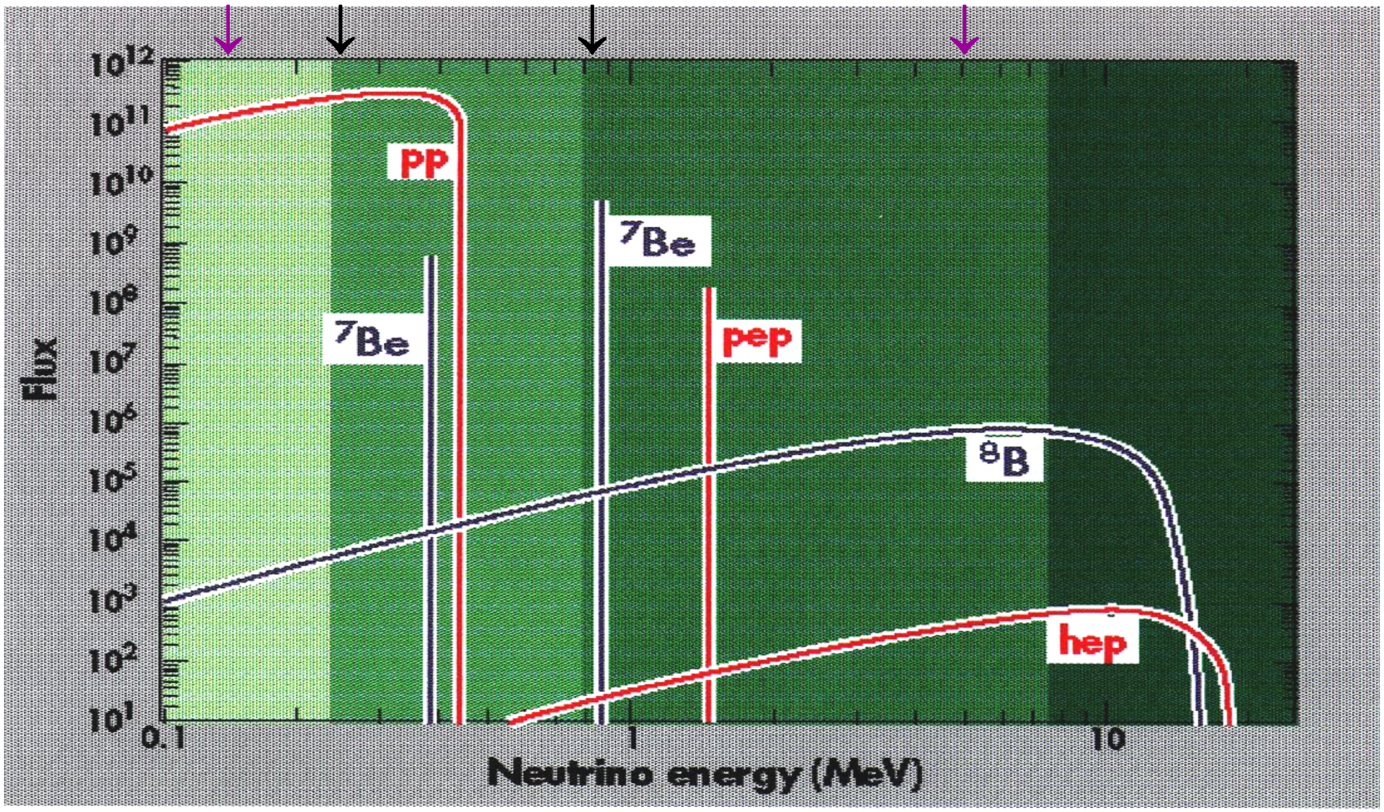
Fig. 4. Sensitivity to neutrino mass reached versus livetime for enriched Nd (left) and for natural Nd (right) in SNO+. from fitting the endpoint spectral shape

Predicted SSM Energy Spectra of Solar Neutrinos

The energy region where there is a maximum effect from new physics (the "resonance" from matter and vacuum terms) is between 1-2 MeV, and the *pep* solar neutrinos lie in **1.44 MeV**

Super-K, SNO
Water

LENS ^{71}Ga ^{37}Cl



Arrows ↓ Denote Experimental Thresholds

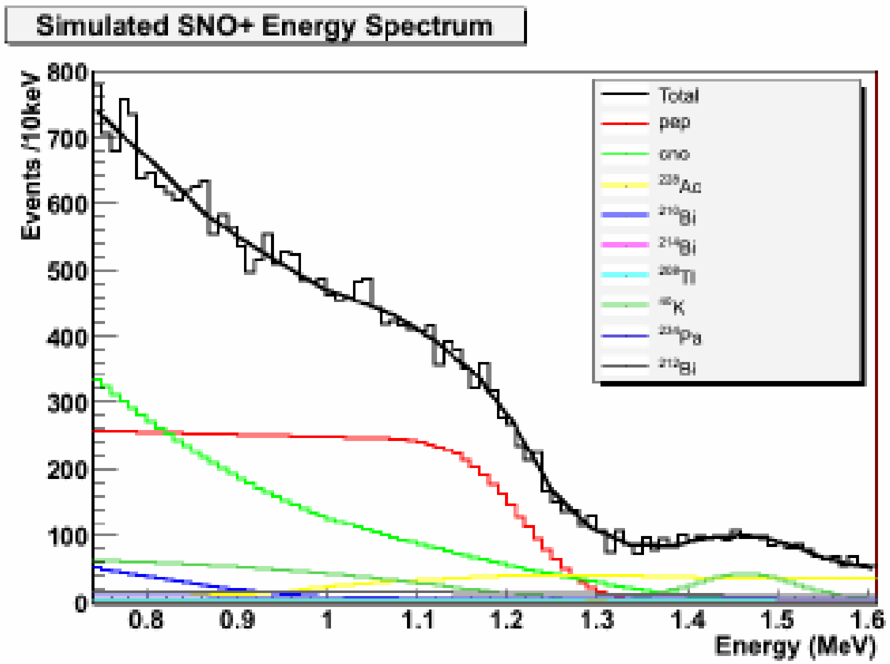


Fig. 7. Recoil electron spectrum for low-energy solar neutrinos in SNO+. Backgrounds are shown at KamLAND post-purification target levels.

IMPORTANT: Low energy solar neutrino physics in SNO+ and the search for double beta decay with Nd cannot be done together because of the large background that would arise from two-neutrino double beta decay of ^{150}Nd. We plan to carry out the SNO+ Nd experiment first because of the importance of this measurement and the potential for discovery. Nd carboxylate can be easily removed from the liquid scintillator using solvent-solvent extraction or distillation and such capability is being designed (and is a natural part) of the SNO+ purification system.

THE END

Comments about Needed Expertise in Nuclear Physics and Nuclear Chemistry in the (OHEP) Daya Bay Project

- At the May 2007 OHEP Review at BNL, one reviewer commented that it would be the nuclear scientists in the US collaboration, not the particle physicists, who would have the expert knowledge to handle the ~MeV antineutrino signals and the low-energy backgrounds from radioactivity.
- The reviewer's point was that it would take a mix of particle and nuclear physicists to pull off such a difficult experiment as the Daya Bay high-precision oscillation experiment.