The last unknown neutrino mixing angle θ_{13} and the Daya Bay Experiment

David E. Jaffe

BROOKHAVEN NATIONAL LABORATORY

- Motivation
- Antineutrino source
- Detector
- Systematics
- Sensitivity
- Status & summary

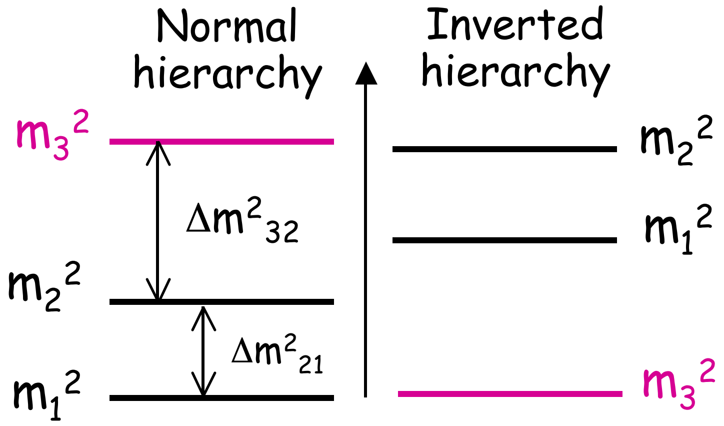
Neutrino Mixing

- For three generations of massive neutrinos, the weak eigenstates are not the same as the mass eigenstates:

$$\Delta m^2_{21} \equiv m^2_2 - m^2_1$$

Pontecorvo-Maki-Nakagawa-Sakata Matrix

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

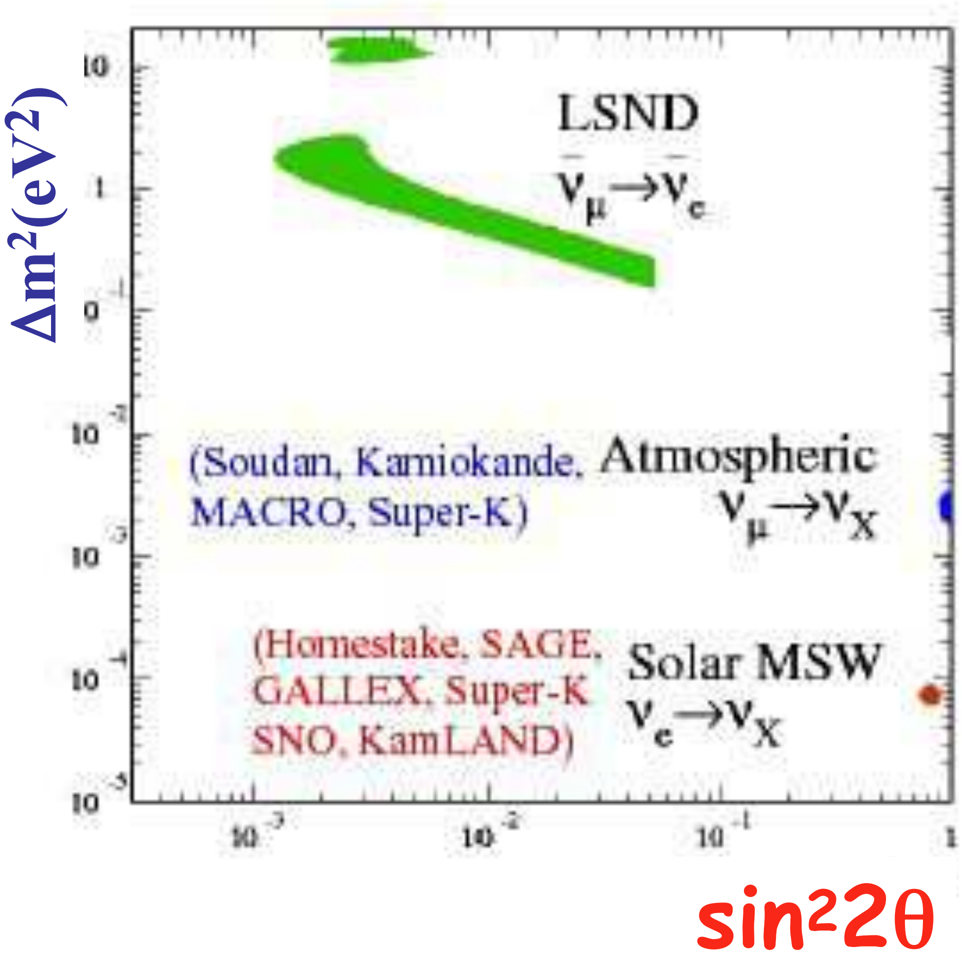


- Parametrize the PMNS matrix as:

$$\underbrace{\begin{pmatrix} \cos\theta_{12} & \sin\theta_{12} & 0 \\ -\sin\theta_{12} & \cos\theta_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}}_{\substack{\text{solar } \nu \\ \text{reactor } \bar{\nu}}} \underbrace{\begin{pmatrix} \cos\theta_{13} & 0 & \sin\theta_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -\sin\theta_{13}e^{i\delta} & 0 & \cos\theta_{12} \end{pmatrix}}_{\substack{\text{reactor } \bar{\nu} \\ \text{accelerator LBL } \nu}} \underbrace{\begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\theta_{23} & \sin\theta_{23} \\ 0 & -\sin\theta_{23} & \cos\theta_{23} \end{pmatrix}}_{\substack{\text{atmospheric } \nu \\ \text{accelerator LBL } \nu}} \overset{\textbf{Majorana phases}}{\underbrace{\begin{pmatrix} e^{i\delta_1} & 0 & 0 \\ 0 & e^{i\delta_2} & 0 \\ 0 & 0 & 1 \end{pmatrix}}_{\substack{\text{neutrinoless} \\ \text{double-}\beta\text{ decay}}}}$$

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

Evidence for neutrino oscillations



Unconfirmed:
LSND: $\Delta m^2 \sim 0.1\text{-}10\ \mathrm{eV}^2$

$|\Delta m^2_{32}| = (2.4^{+0.4}_{-0.3}) \times 10^{-3}\ \mathrm{eV}^2$
$\theta_{23} = (45_{-11})^\circ$

$\Delta m^2_{21} = (7.8^{+0.6}_{-0.5}) \times 10^{-5}\ \mathrm{eV}^2$
$\theta_{12} = (32^{+4}_{-3})^\circ$

$\Delta m^2_{31} \approx \Delta m^2_{32} >> \Delta m^2_{21}$
θ_{12} and θ_{23} are large
θ_{13} is small,
δ and sign of Δm^2_{32} unknown

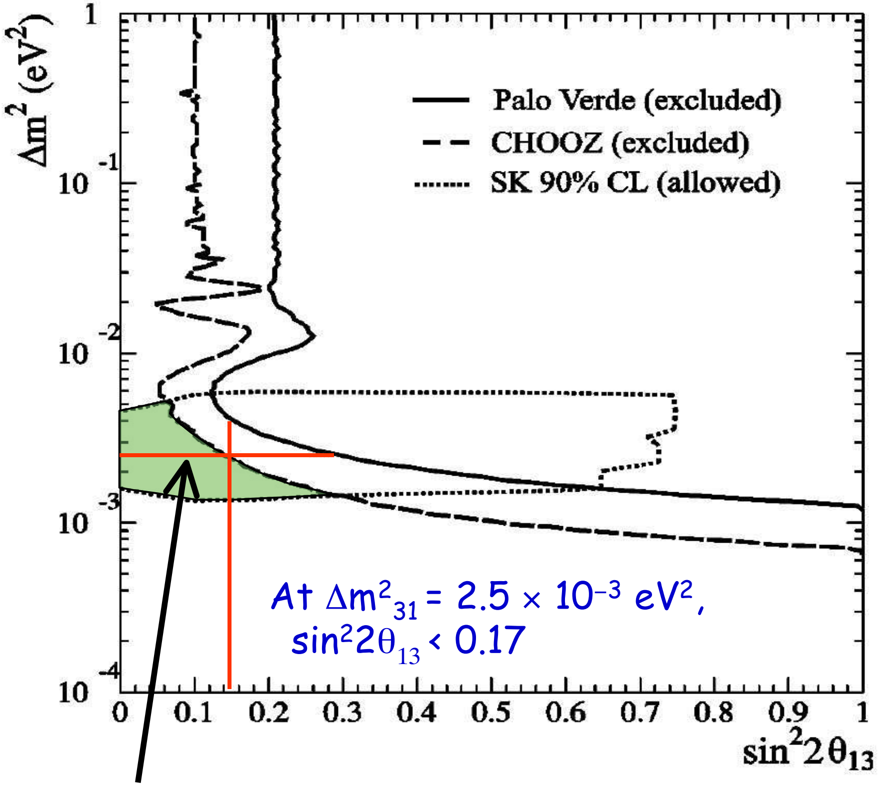
2 flavor oscillation in vacuum:

$P(\nu_1 \to \nu_2) = \sin^2 2\theta \sin^2(1.27 \Delta m^2 L/E)$

Units: $\Delta m^2(\mathrm{eV}^2)$ L(m) E(MeV)

Current Knowledge of θ_{13}

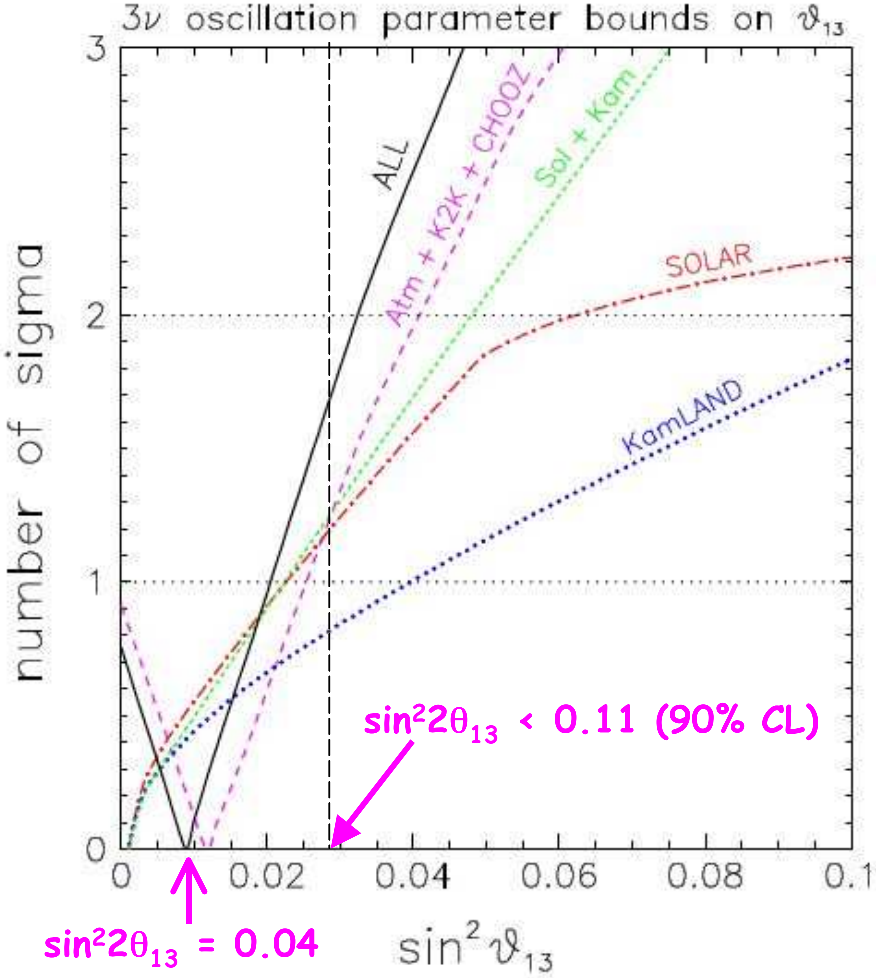
Direct search



At $\Delta m^2_{31} = 2.5 \times 10^{-3}$ eV^2,
$\sin^2 2\theta_{13} < 0.17$

allowed region

Global fit



$\sin^2 2\theta_{13} < 0.11$ (90% CL)

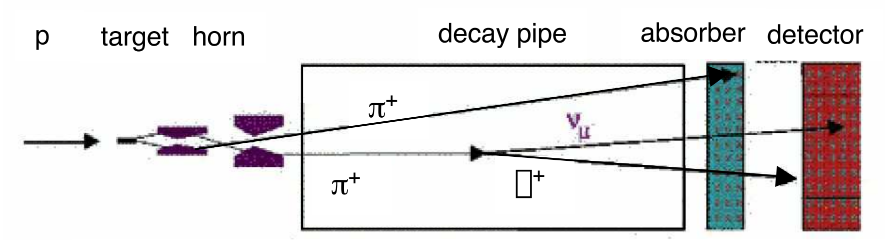
$\sin^2 2\theta_{13} = 0.04$

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

Fogli etal., hep-ph/0506083

Determining θ_{13}

Method 1: Accelerator Experiments

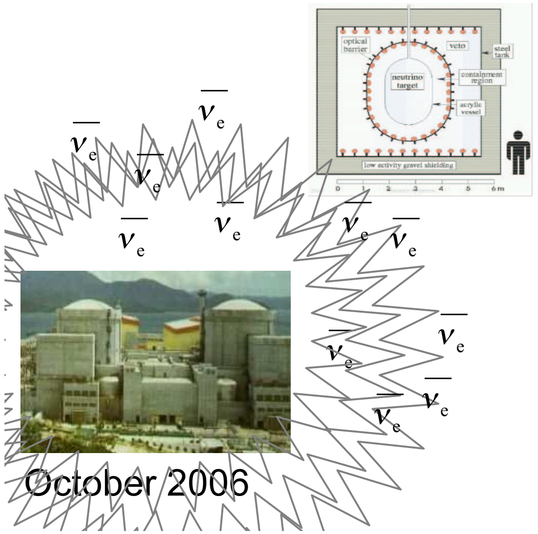


$$P_{\mu e} \approx \sin^2 2\theta_{13} \sin^2 2\theta_{23} \sin^2\left(\frac{\Delta m_{31}^2 L}{4E_\nu}\right) + \ldots$$

- $\nu_\mu \rightarrow \nu_e$ appearance experim
- need other mixing paramete
- baseline *O(100-1000 km)*, m
- expensive

Disagreement between appearance and disappearance experiments would be more evidence of new physics

Method 2: Reactor Experimen



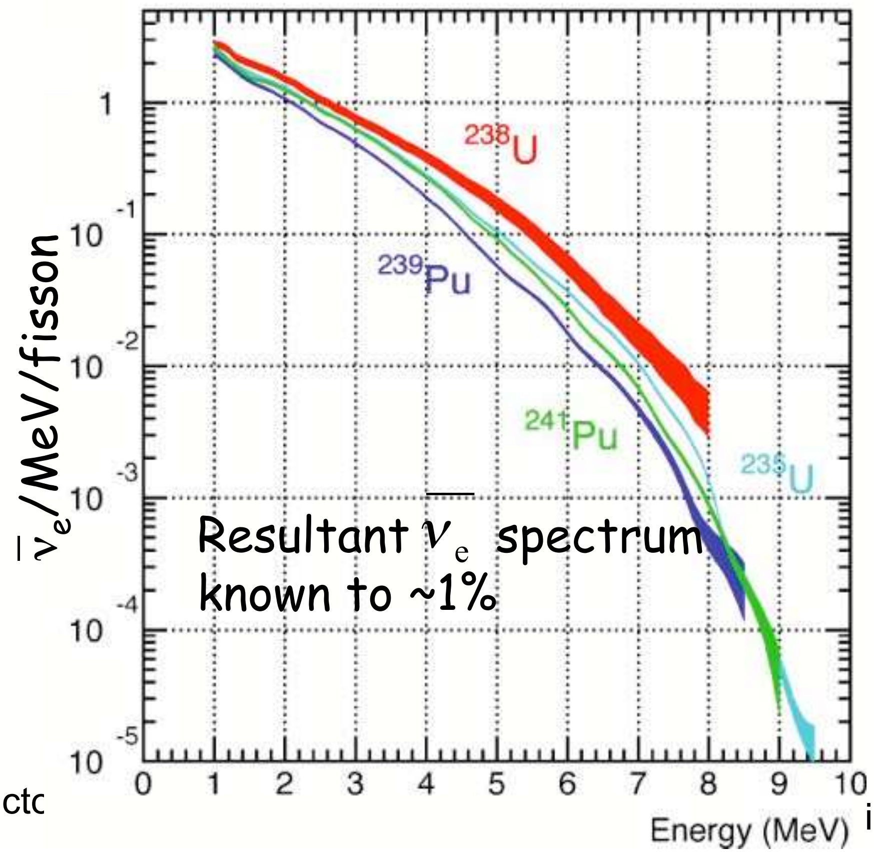
$$P_{ee} \approx 1 - \sin^2 2\theta_{13} \sin^2\left(\frac{\Delta m_{31}^2 L}{4E_\nu}\right) + \cos^4\theta_{13} \sin^2 2\theta_{12} \sin^2\left(\frac{\Delta m_{21}^2 L}{4E_\nu}\right)$$

- $\bar{\nu}_e \rightarrow X$ disappearance experiment
- baseline *O(1 km)*, no matter effect, no ambiguity
- relatively cheap

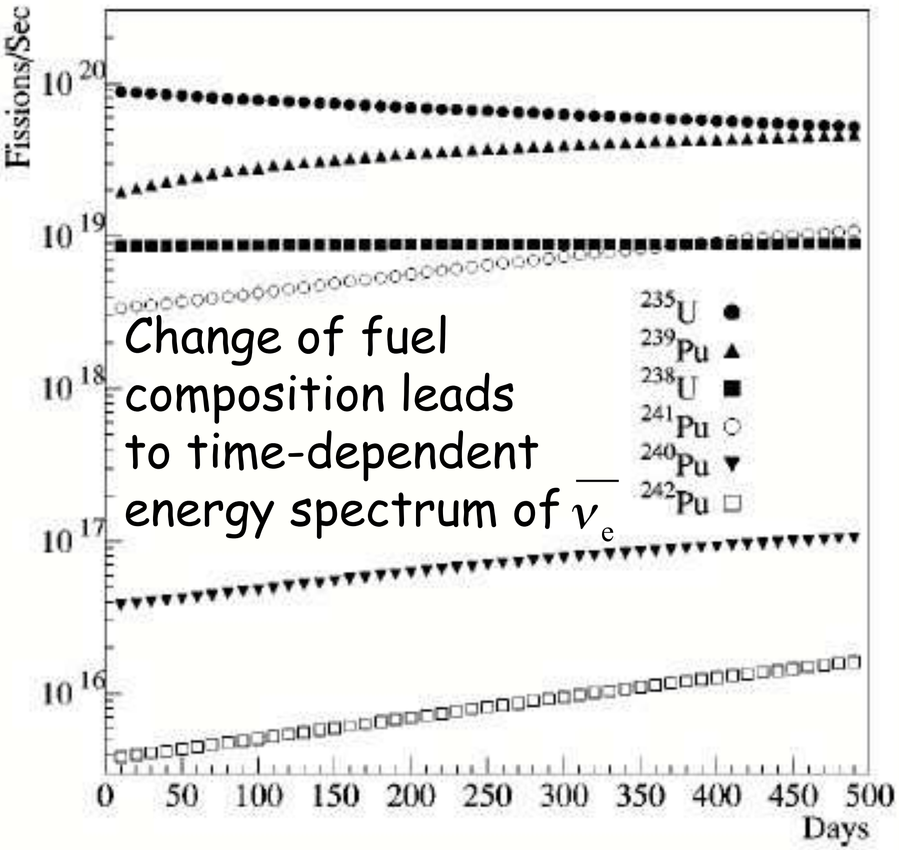
Reactor $\bar{\nu}_e$

- Fission processes in nuclear reactors produce huge number of low-energy $\bar{\nu}_e$:

  1 $GW_{thermal}$ generates 2×10^{20} $\bar{\nu}_e$ per sec



Resultant $\bar{\nu}_e$ spectrum known to ~1%

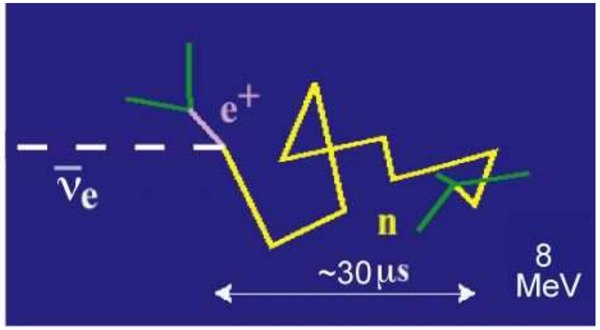


Change of fuel composition leads to time-dependent energy spectrum of $\bar{\nu}_e$

Detecting $\bar{\nu}$ in liquid scintillator: Inverse β Decay

The reaction is the inverse β-decay in 0.1% Gd-doped liquid scintillator:

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



0.3b → + p → D + γ(2.2 MeV) (τ~180μs)

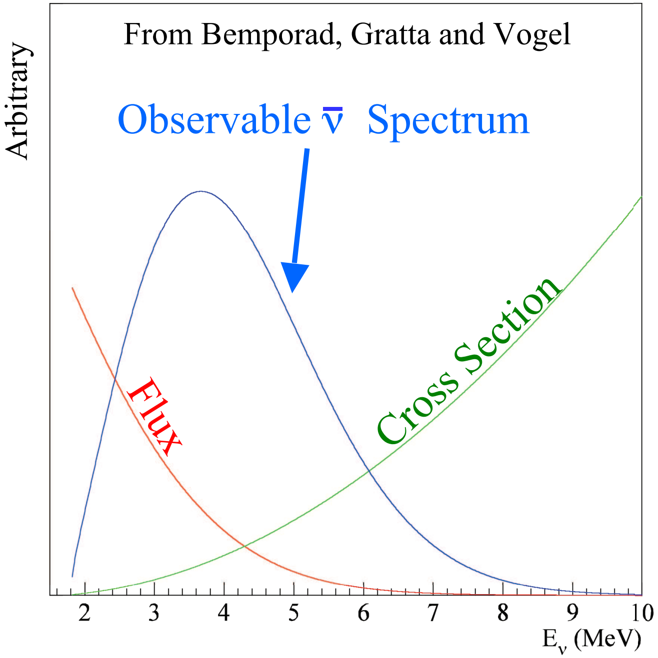
50,000b → + Gd → Gd*

→ Gd + γ's(8 MeV) (τ~30μs)

- Time- and energy-tagged signal is a good tool to suppress background events.

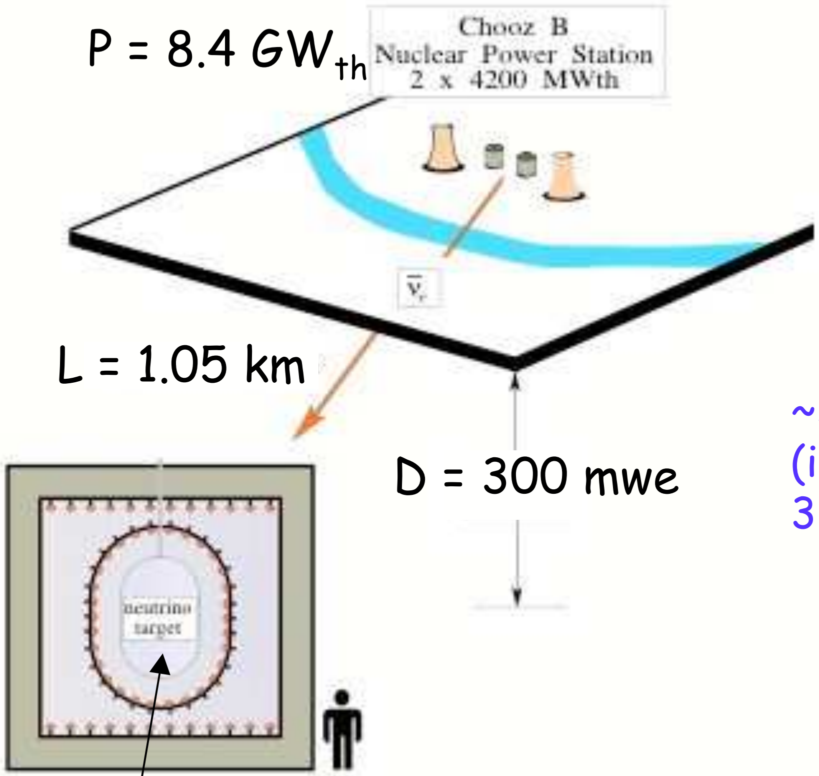
- Energy of $\bar{\nu}_e$ is given by:

$$E_{\bar{\nu}} \approx T_{e+} + \underbrace{T_n}_{\text{10-40 keV}} + (m_n - m_p) + m_{e+} \approx T_{e+} + 1.8\ \text{MeV}$$


From Bemporad, Gratta and Vogel

Summary of Chooz

At $\Delta m^2_{31} = 2.5 \times 10^{-3}$ eV², $\sin^2 2\theta_{13} < 0.17$ @ 90%CL



P = 8.4 GW_{th}

L = 1.05 km

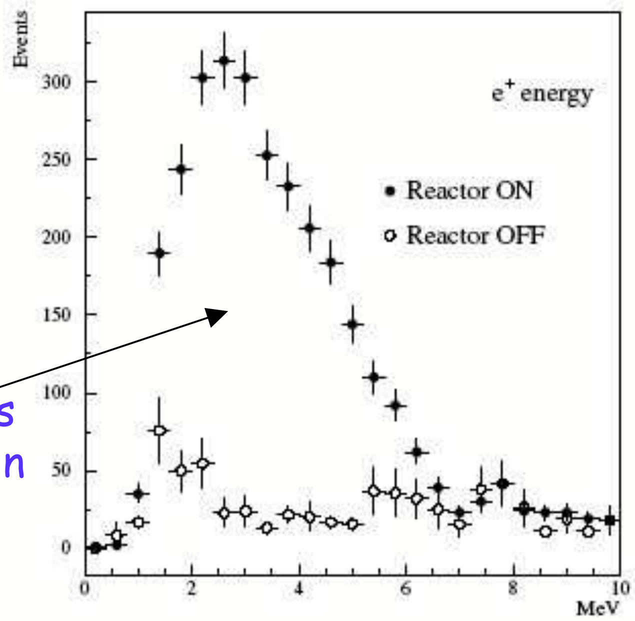
D = 300 mwe

5-ton 0.1% Gd-loaded liquid scintillator to detect $\overline{\nu_e} + p \rightarrow e^+ + n$

Rate:

~5 evts/day/ton (full power)
including 0.2-0.4 bkg/day/ton

~3000 $\bar{\nu}_e$ candidates (included 10% bkg) in 335 days



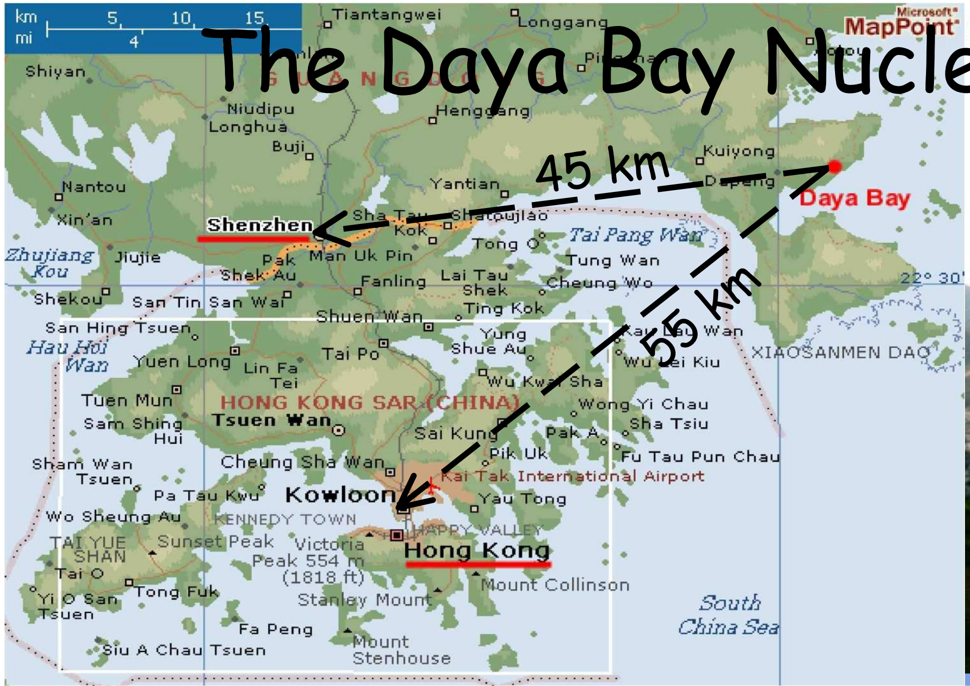
Systematic uncertainties

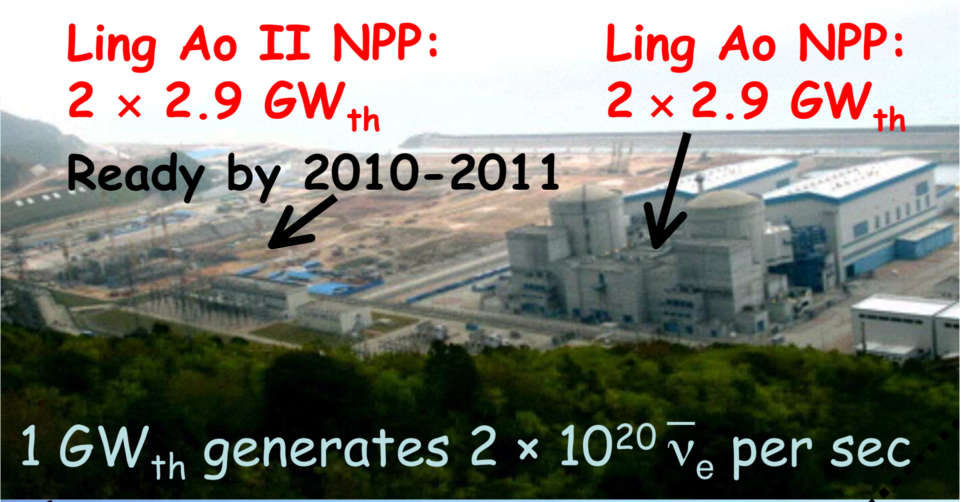
parameter	relative uncertainty (%)
reaction cross section	1.9
number of protons	0.8
detection efficiency	1.5
reactor power	0.7
energy released per fission	0.6
combined	2.7

How To Reach A Precision of 0.01 in $\sin^2 2\theta_{13}$?

- **Increase statistics:**
  - Use more powerful nuclear reactors
  - Utilize larger target mass
- **Suppress background:**
  - Go deeper underground to gain overburden for reducing cosmogenic background
- **Reduce systematic uncertainties:**
  - Reactor-related:
    - Optimize baseline for best sensitivity and smaller residual reactor-related errors
    - Use 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
    - Interchange near and far detectors (optional)

The Daya Bay Nuclear Power Facilities





Ling Ao II NPP:
2×2.9 GW$_{th}$

Ready by 2010-2011

Ling Ao NPP:
2×2.9 GW$_{th}$

1 GW$_{th}$ generates $2 \times 10^{20}\ \overline{\nu}_e$ per sec

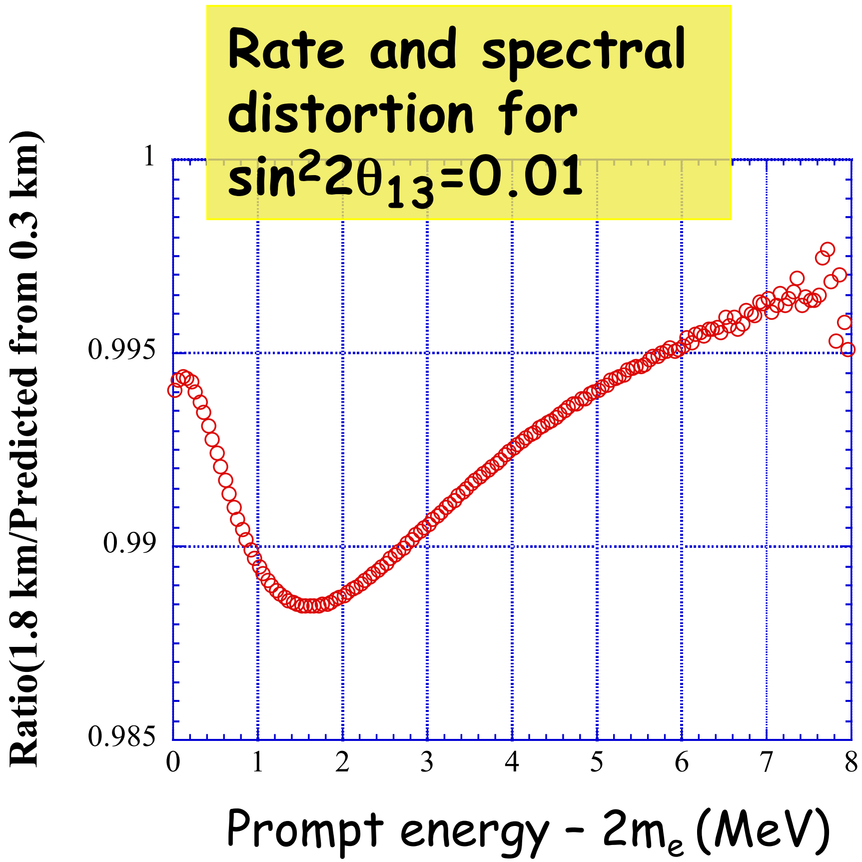
- 12th most powerful in the world (11.6 GW)
- Top five most powerful by 2011 (17.4 GW)
- Adjacent to mountain, easy to construct tunnels to reach underground labs with sufficient overburden to suppress cosmic rays

Daya Bay NPP:
2×2.9 GW$_{th}$

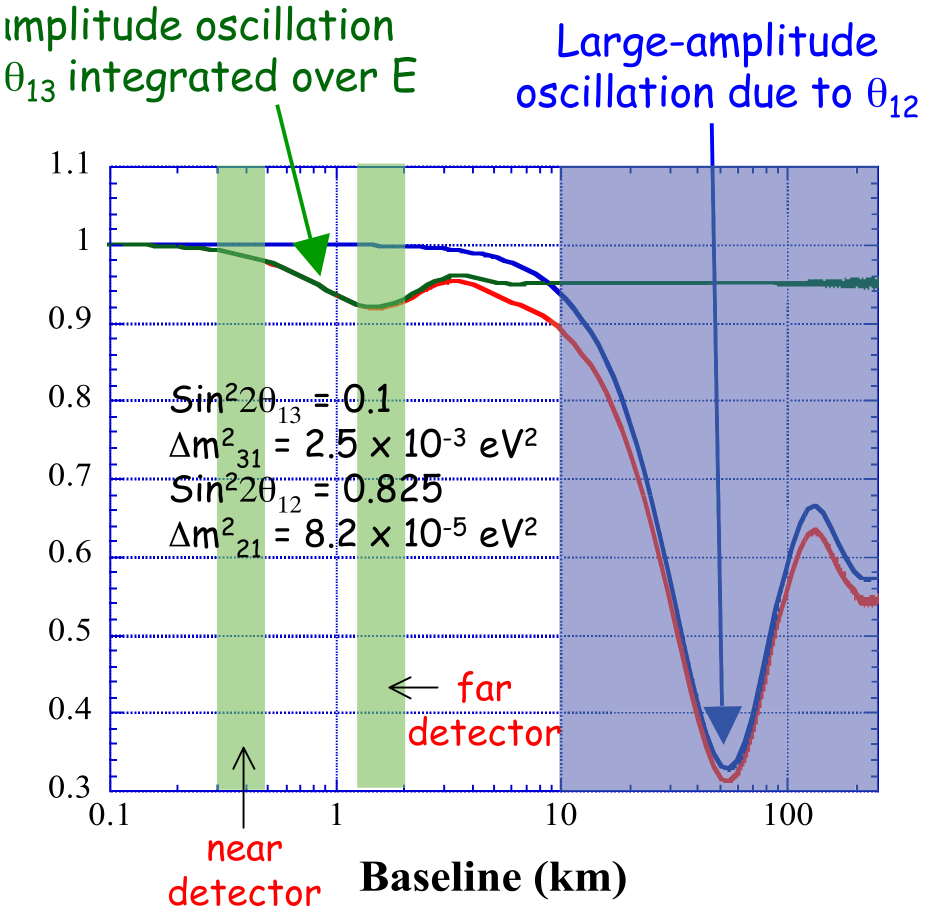
Where To Place The Detectors ?

- Since reactor $\bar{\nu}_e$ are low-energy, it is a disappearance experiment:

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



Rate and spectral distortion for $\sin^2 2\theta_{13}=0.01$



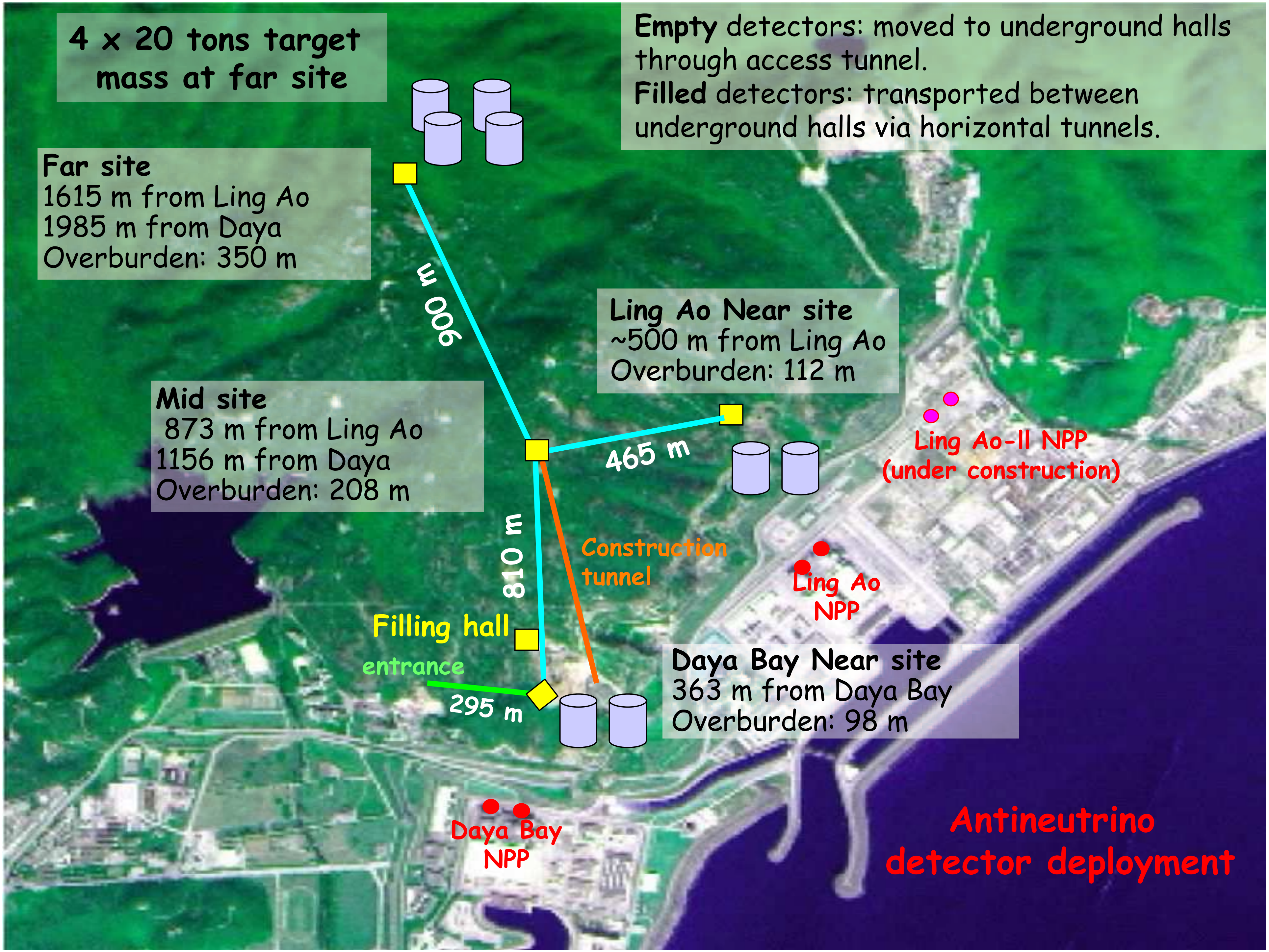
ımplitude oscillation θ_{13} integrated over E

Large-amplitude oscillation due to θ_{12}

$\mathrm{Sin}^2 2\theta_{13} = 0.1$
$\Delta m^2_{31} = 2.5 \times 10^{-3}\ \mathrm{eV}^2$
$\mathrm{Sin}^2 2\theta_{12} = 0.825$
$\Delta m^2_{21} = 8.2 \times 10^{-5}\ \mathrm{eV}^2$

← far detector

near detector



4 x 20 tons target mass at far site

Empty detectors: moved to underground halls through access tunnel.
Filled detectors: transported between underground halls via horizontal tunnels.

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

Mid site
873 m from Ling Ao
1156 m from Daya
Overburden: 208 m

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

Antineutrino detector deployment

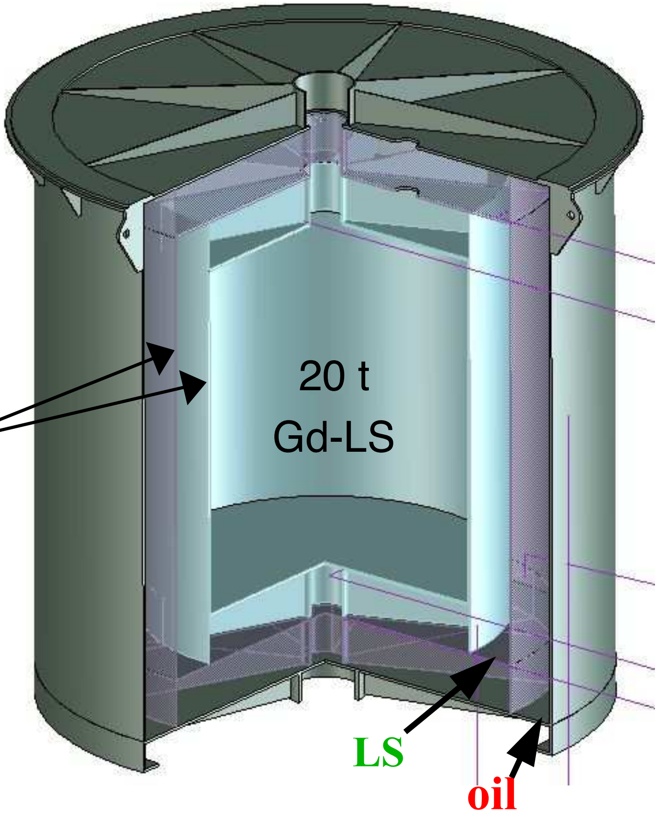
Antineutrino Detector Design

Cylindrical(5m diam., 5m height) three-Zone Structure

I. **Target**: 0.1% Gd-loaded liquid scint., 1.6m

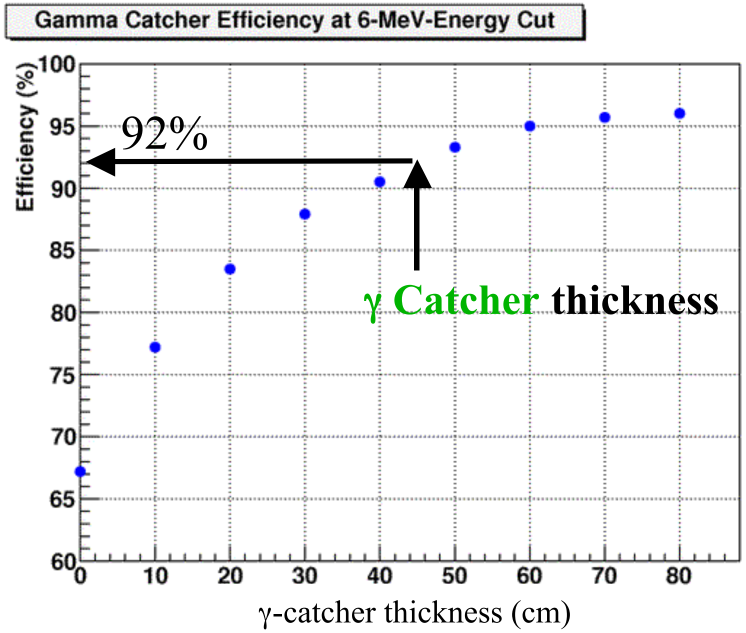
II. **γ-catcher**: liquid scintillator(LS), 45cm

III. **Buffer**: mineral oil, ~45cm



With 224 PMT's on circumference and diffuse reflector on top and bottom:

$$\frac{\sigma}{E} \sim \frac{12.2\%}{\sqrt{E(\mathrm{MeV})}}, \quad \sigma_{\mathrm{vertex}} = 13\mathrm{cm}$$



Oil buffer thickness

Isotopes (Rate from PMT glass)	Purity (ppb)	20cm (Hz)	25cm (Hz)	30cm (Hz)	40cm (Hz)
^{238}U(>1MeV)	40	2.2	1.6	1.1	0.6
^{232}Th(>1MeV)	40	1.0	0.7	0.6	0.3
^{40}K(>1MeV)	25	4.5	3.3	2.3	1.2
Total		7.7	5.6	4.0	2.1

A 45cm buffer provides ~20cm of shielding against PMT glass

Event Rates and Signal

Baselines (meters)

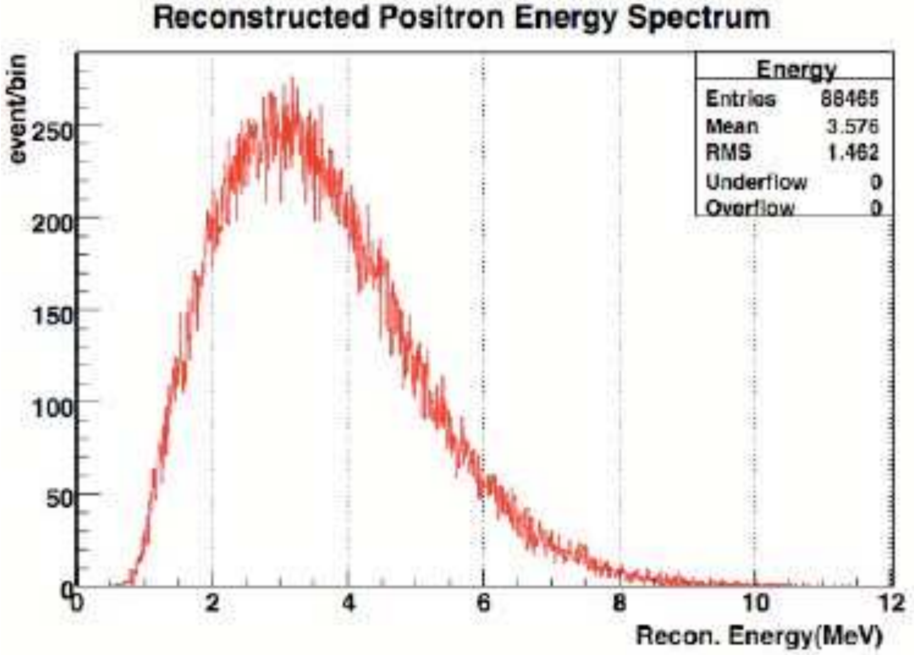
Sites	DYB	LA	Far
DYB cores	363	1347	1985
LA cores	857	481	1618
LA II cores	1307	526	1613

Antineutrino Interaction Rate

(events/day per 20 ton module)

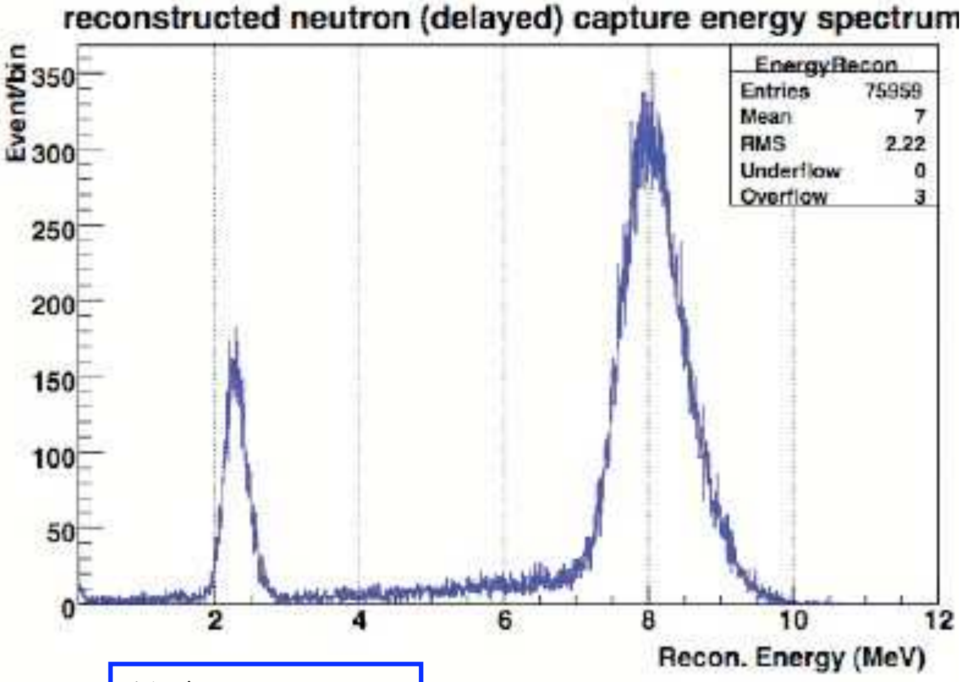
Daya Bay near site	960
Ling Ao near site	760
Far site	90

Prompt Energy Signal



Statistics comparable to single detector in far hall

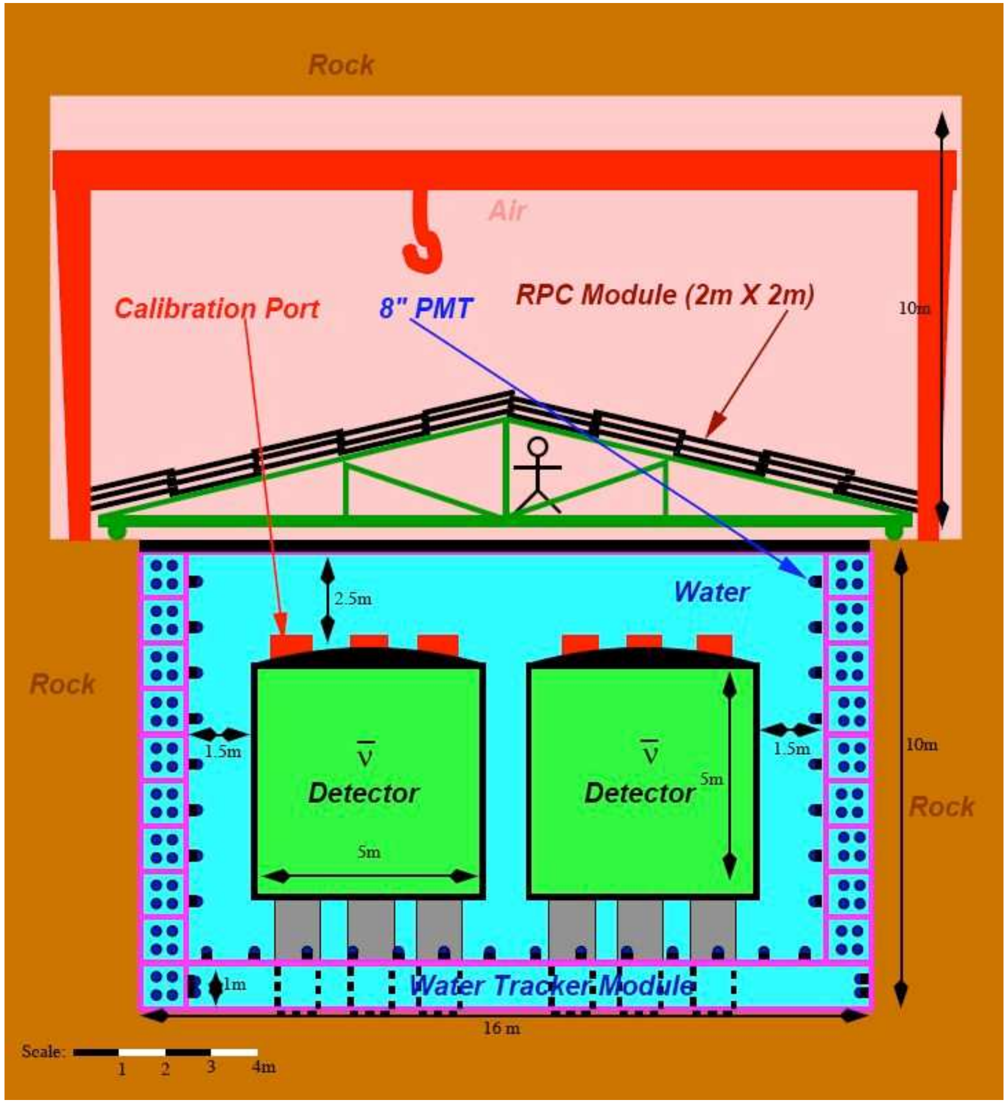
Delayed Energy Signal



Hydrogen capture

Gd capture

Shield and veto system



- Surround detectors with at least 2.5m of active water shield
- Water shield also serves as a Cherenkov counter for tagging muons
- Water Cherenkov modules along the walls and floor
- Augmented with a muon tracker: RPCs
- Combined efficiency of Cherenkov and tracker > 99.5% with error measured to better than 0.25%

Backgrounds

Assuming 99.5% muon veto, even with delayed coincidence event signature, the following backgrounds remain:

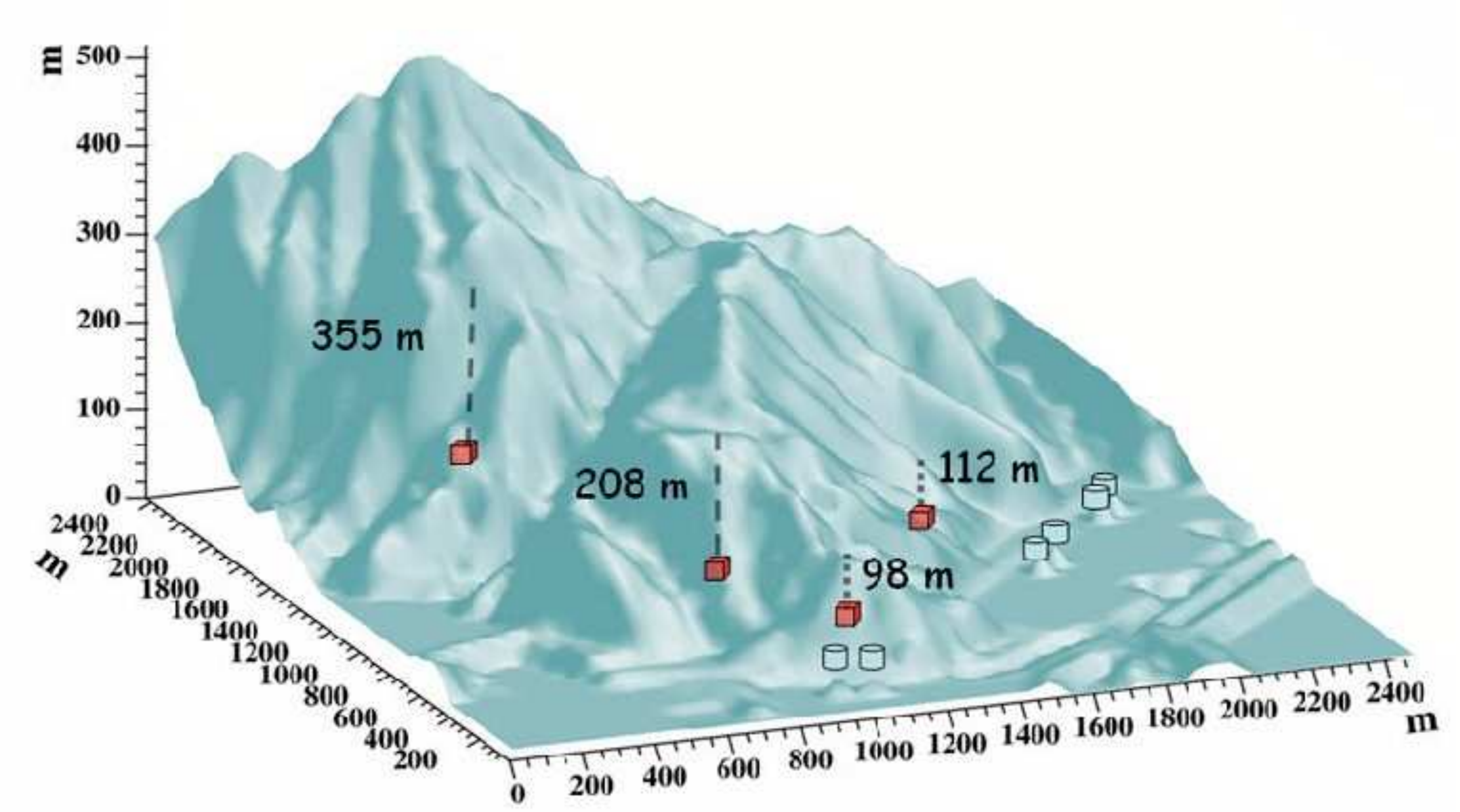
- Fast neutrons (prompt recoil, delayed capture)
- ^{9}Li/^{8}He ($T_{1/2}$= 178 msec, β decay w/neutron emission, delayed capture)
- Accidental coincidences

(Other smaller contributions can be neglected)

All three are small (Bkgd/signal <1%) and can be measured and/or constrained using data.

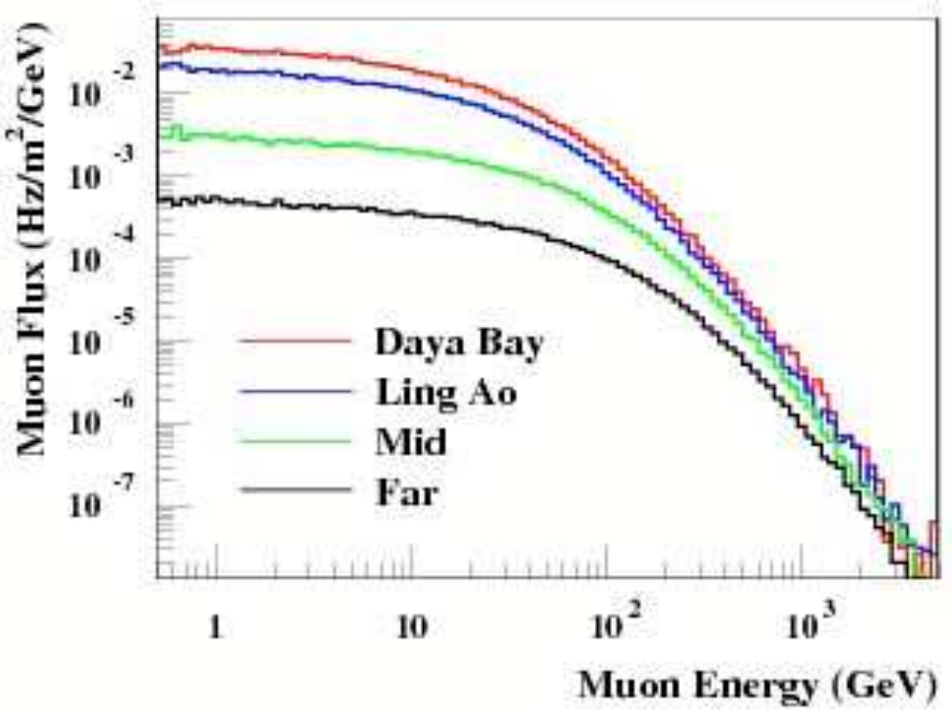
Cosmic Muons

Fast neutrons and ^{9}Li/^{8}He are produced by cosmic muons, so we need to simulate muons



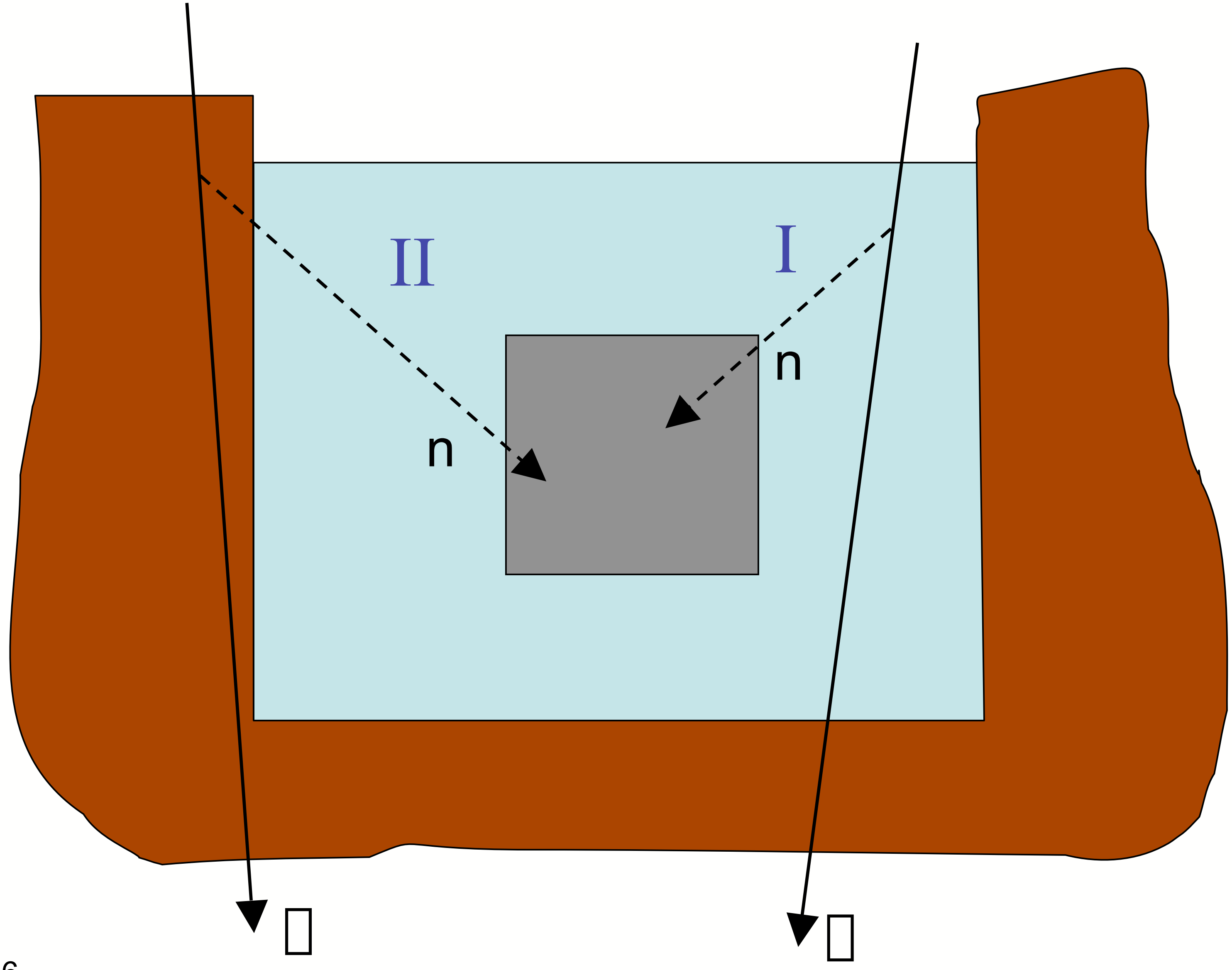
Cosmic Muons

Detailed topo map, modified Gaisser formula, and MUSIC

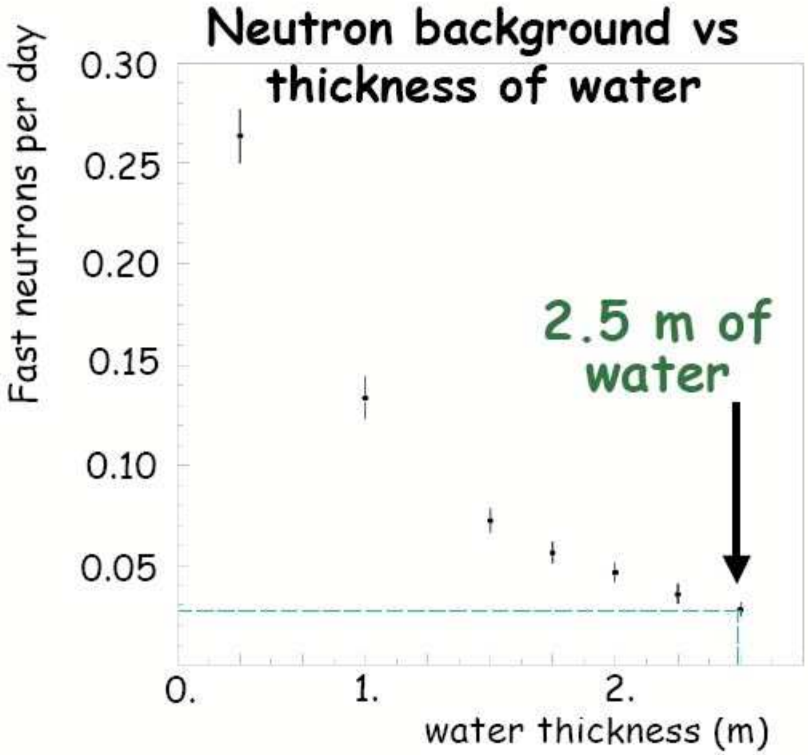


	DYB site	LA site	Mid site	Far site
Vertical overburden (m)	98	112	208	355
Muon Flux (Hz/m^2)	1.16	0.73	0.17	0.041
Muon Mean Energy (GeV)	55	60	97	138

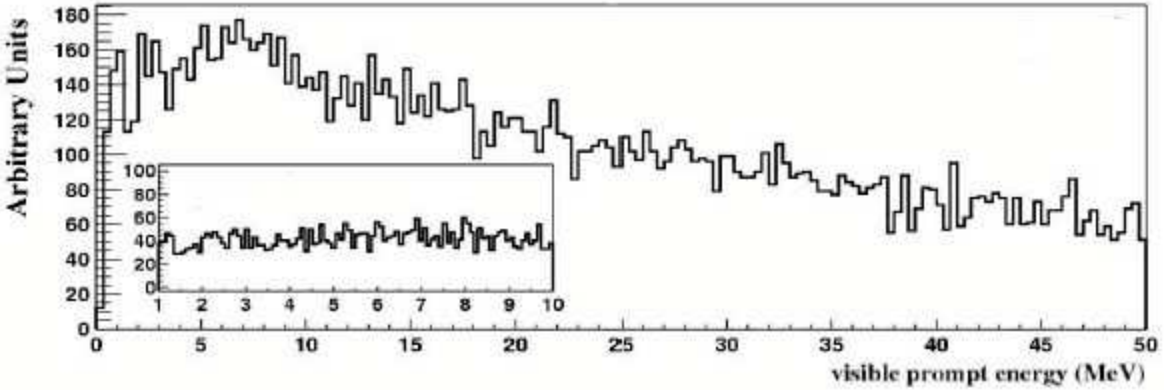
Fast Neutrons



Fast Neutron Simulations



2.5 m of water



Fast Neutron Simulations

Rates per day per 20T module

	I: missed veto rate	II: rock neutron rate	Total/Signal
DYB	0.10	0.5	6×10^{-4}
LA	0.07	.35	6×10^{-4}
Far	0.01	.03	4×10^{-4}

Cosmogenically produced ^{9}Li/^{8}He

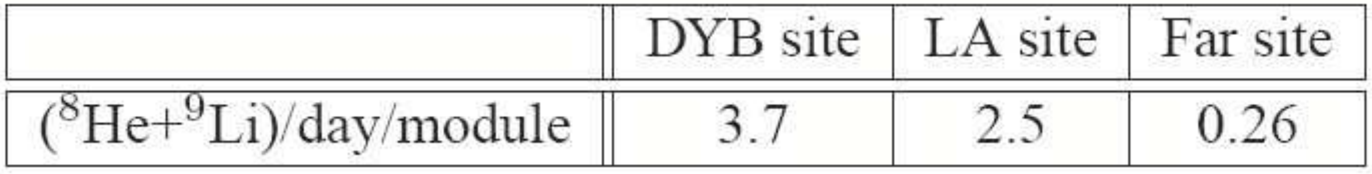
$$^{9}\mathrm{Li} \rightarrow e^{-} + \bar{\nu}_e + {}^{9}\mathrm{Be}^{*} \rightarrow {}^{8}\mathrm{Be} + n$$

Q=13 MeV

$T_{1/2}$= 178 msec

(Long $T_{1/2}$ & poor spatial correlation with □ track make rejection problematic.)

Rates computed from CERN measurements (Hagner et al.,)



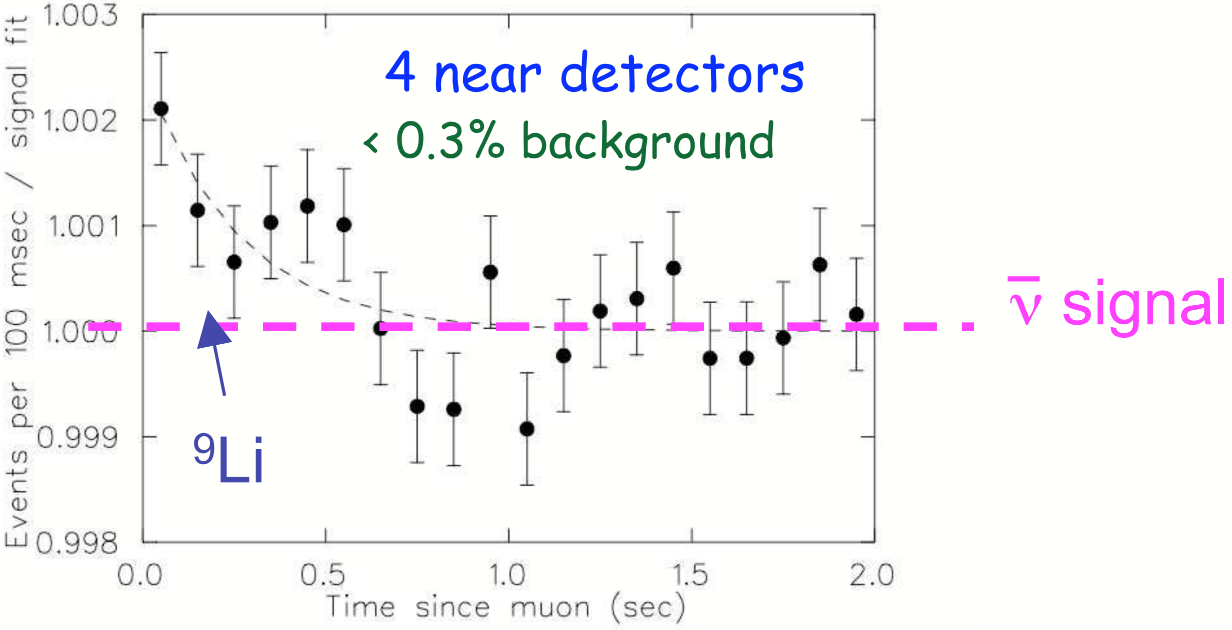
	DYB site	LA site	Far site
(^{8}He+^{9}Li)/day/module	3.7	2.5	0.26

Note: Background/Signal ~ 0.3% for all sites

Strategy: measure rate and statistically subtract from event sample.

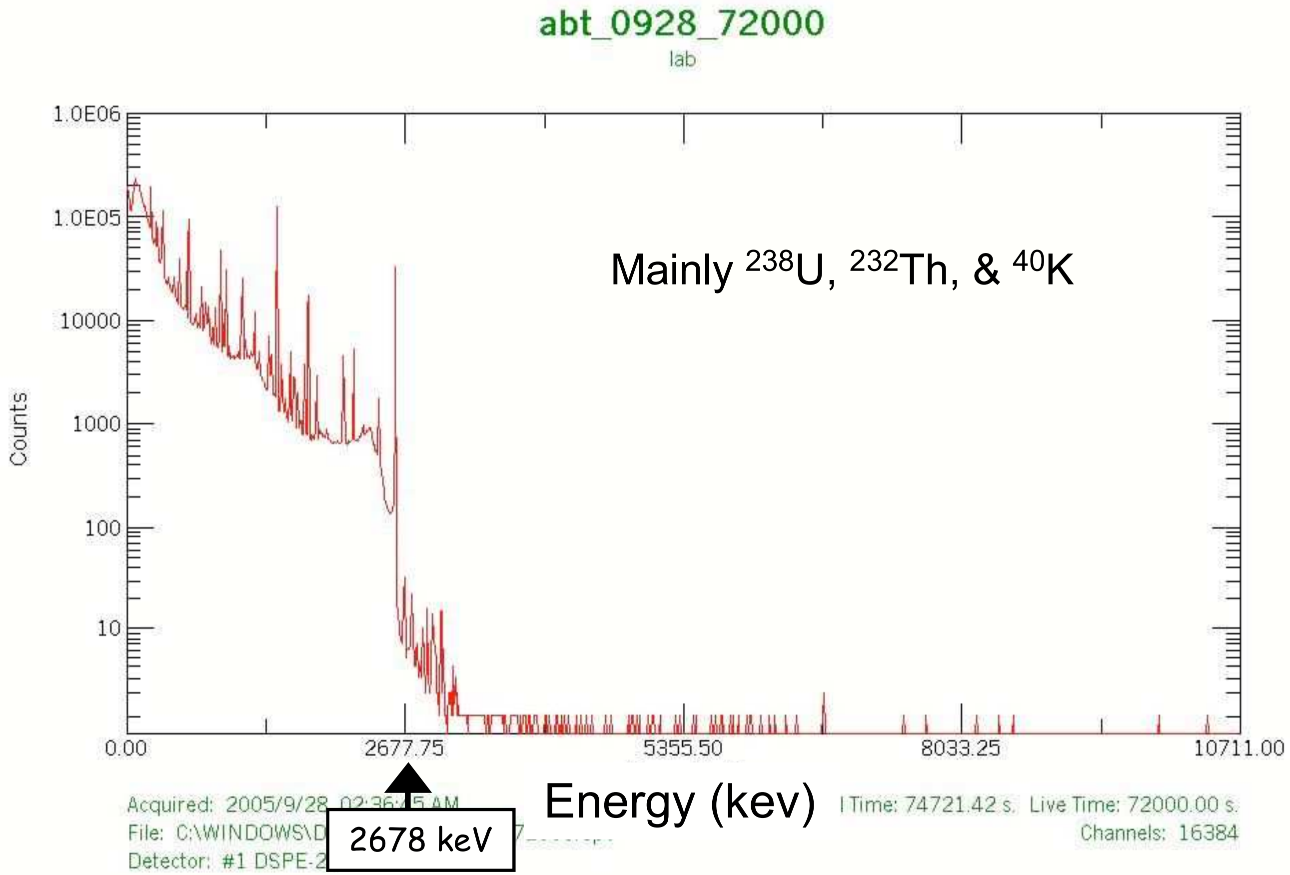
Measuring ^{9}Li/^{8}He

Can measure time of e^+ candidate since time of muon passage through antineutrino detector for candidate events:



Projected results: $\sigma(B/S) = 0.3\%$ (near), 0.1%(far)

Photon energy spectrum of radioactive background



Mainly ^{238}U, ^{232}Th, & ^{40}K

2678 keV

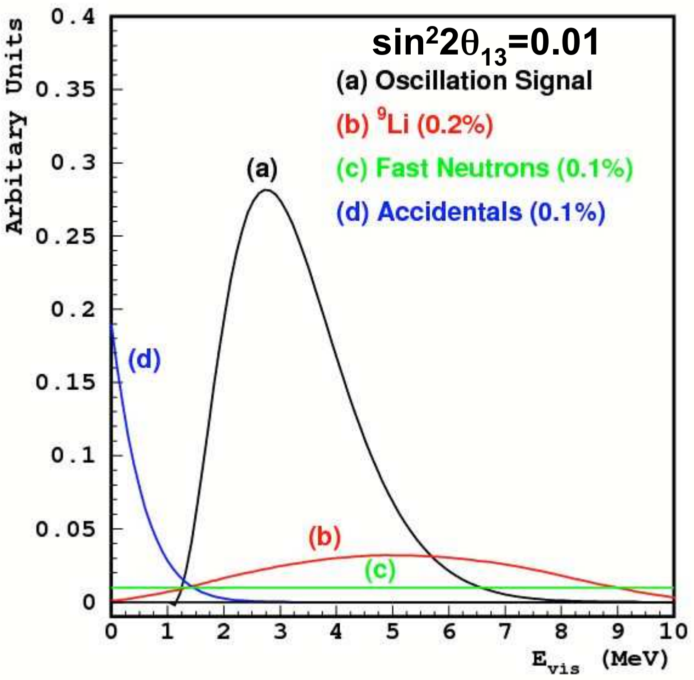
Energy (kev)

Measured energy spectrum in Aberdeen tunnel (Hong Kong). Site has similar rock composition as Daya Bay.

Background Summary

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

- B/S ~ same for near and far sites
- constrained by measurements to required precision
- input to sensitivity calculations (assume 100% uncertainty)



Systematic Uncertainties

Two types:

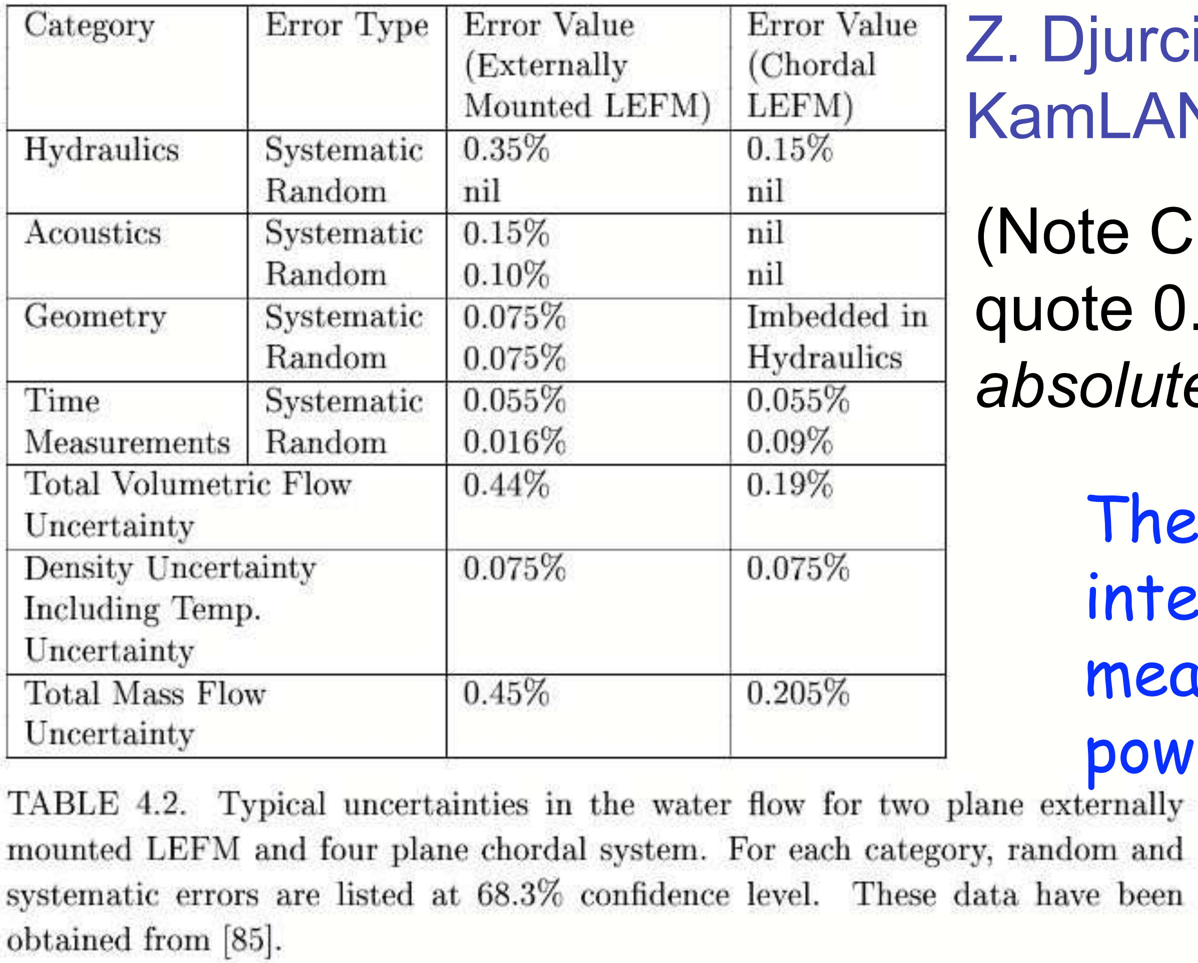
- Reactor-related
- Detector-related

Reactor Uncertainties

- Power levels of each reactor core
  - thermal power measurements: 2% correlated, 2% uncorrelated errors
- Non-trivial arrangement of reactor cores
- Relative location of each reactor core and each detector (i.e. baseline)

Reactor Power Measurements

Coolant flow rate, steam enthalpy, temperatures



Category	Error Type	Error Value (Externally Mounted LEFM)	Error Value (Chordal LEFM)
Hydraulics	Systematic Random	0.35% nil	0.15% nil
Acoustics	Systematic Random	0.15% 0.10%	nil nil
Geometry	Systematic Random	0.075% 0.075%	Imbedded in Hydraulics
Time Measurements	Systematic Random	0.055% 0.016%	0.055% 0.09%
Total Volumetric Flow Uncertainty		0.44%	0.19%
Density Uncertainty Including Temp. Uncertainty		0.075%	0.075%
Total Mass Flow Uncertainty		0.45%	0.205%

TABLE 4.2. Typical uncertainties in the water flow for two plane externally mounted LEFM and four plane chordal system. For each category, random and systematic errors are listed at 68.3% confidence level. These data have been obtained from [85].

Z. Djurcic, U. Alabama, KamLAND

(Note CHOOZ and Palo Verde quote 0.6% and 0.7% *absolute* power uncertainty.)

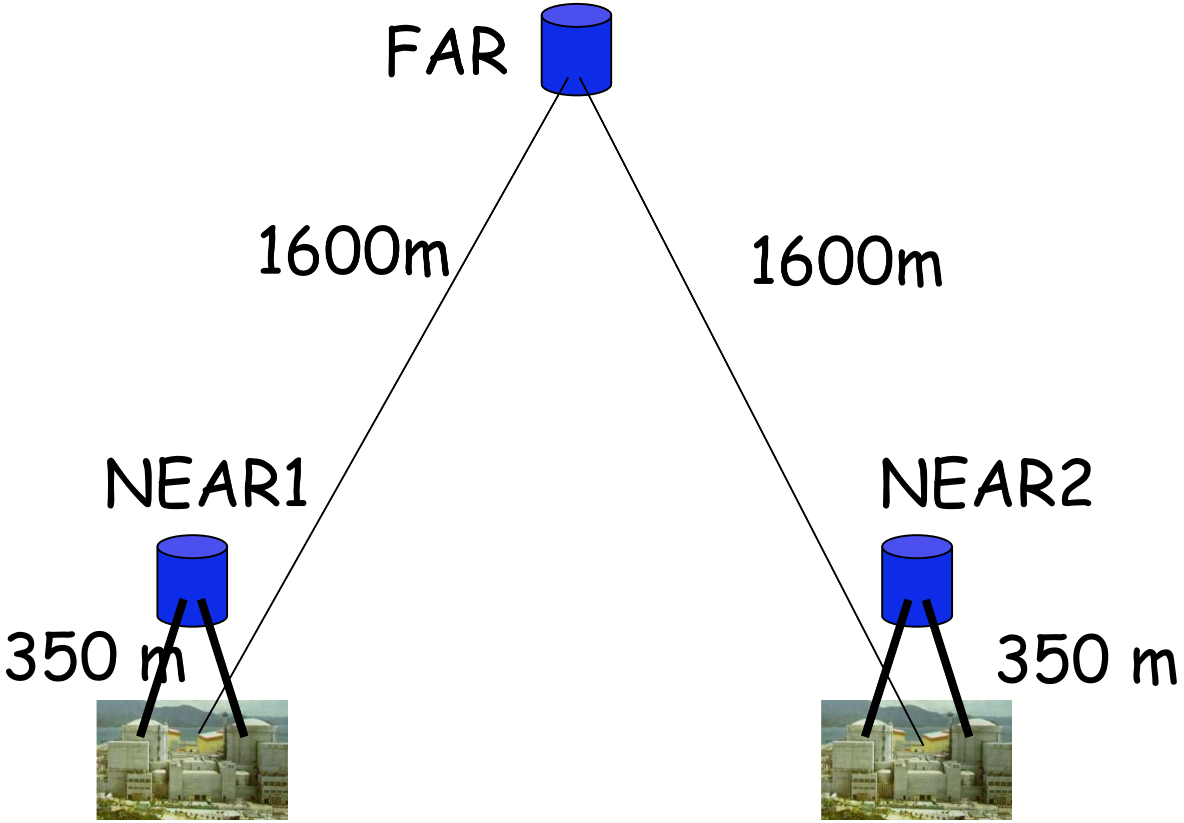
There is great (financial) interest in reactor power measurements for the power company

Future studies with DB NPP collaborators will determine the level of precision we can achieve for the DB reactors.

Cancellation of Fluctuations in Reactor Power

Hypothetical Example #1

Note that FAR and NEAR1+NEAR2 sample all 4 reactors with equal weight



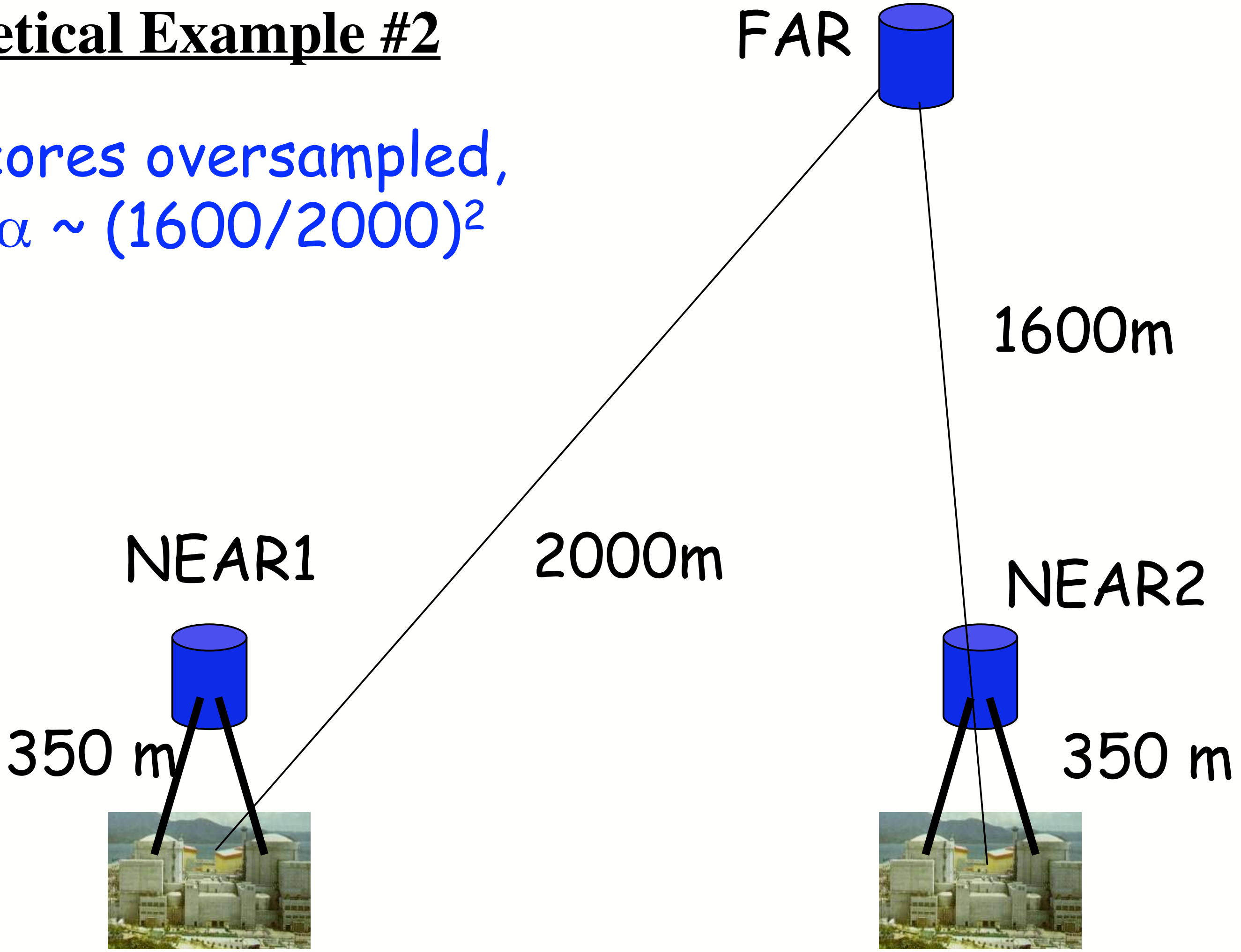
→"Perfect" cancellation in ratio combination :

$$\boxed{\frac{\text{NEAR1}}{\text{FAR}} + \frac{\text{NEAR2}}{\text{FAR}}}$$

Cancellation of Fluctuation in Reactor Power

Hypothetical Example #2

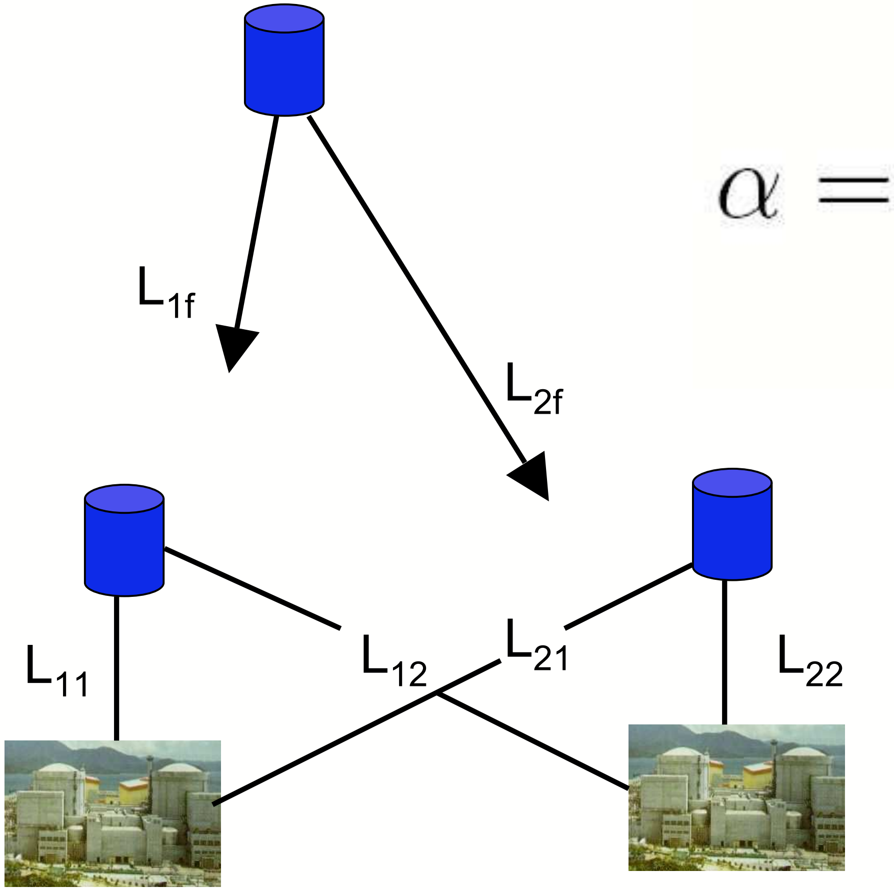
Near2 cores oversampled,
define $\alpha \sim (1600/2000)^2$



"Perfect" cancellation
in ratio combination:

$$\boxed{\alpha \frac{\text{NEAR1}}{\text{FAR}} + \frac{\text{NEAR2}}{\text{FAR}}}$$

More Generally:



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

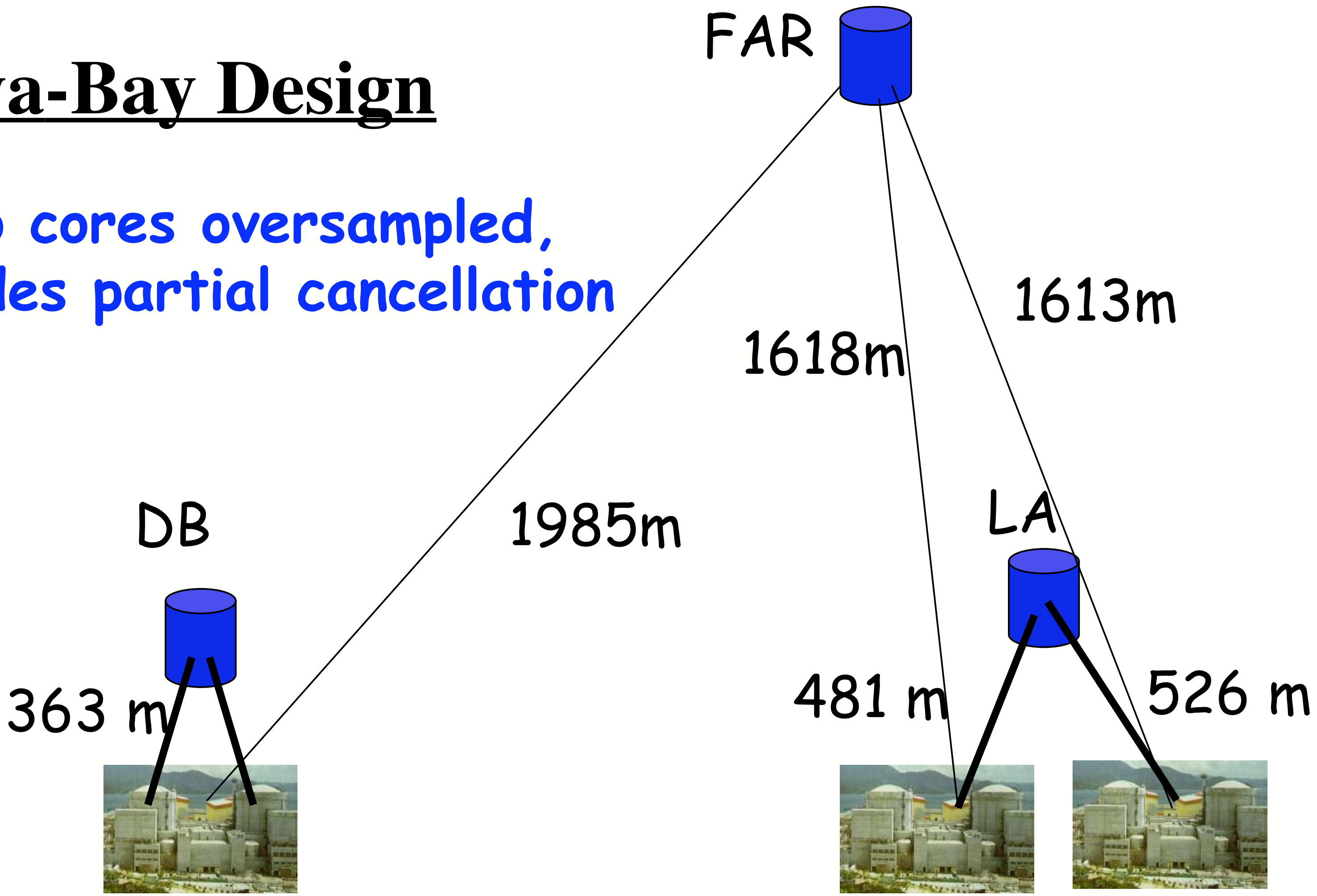
Exactly cancels relative power deviations

For Daya Bay, 4 cores
$\alpha = 0.34$

Cancellation of Fluctuation in Reactor Power

Daya-Bay Design

Ling-Ao cores oversampled,
α provides partial cancellation



Factor 20 cancellation
in ratio combination:

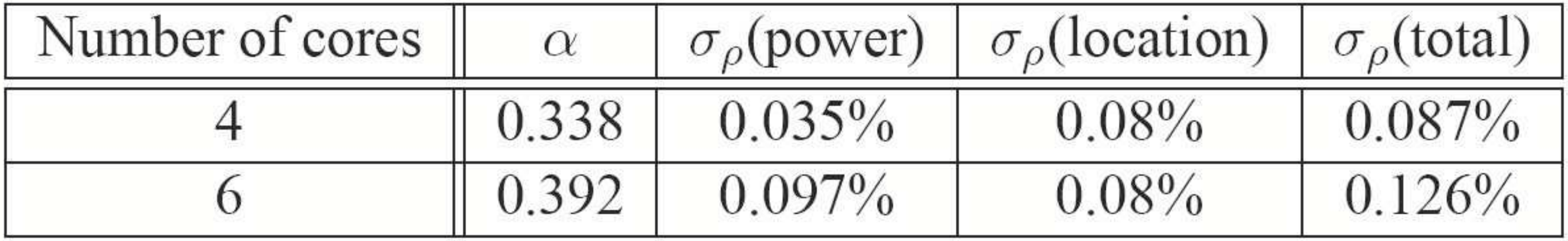
$$\boxed{\alpha\,\frac{DB}{FAR} + \frac{LA}{FAR}}$$

Cancellation of Fluctuation in Reactor Power

- Symmetric case ⇒ perfect cancellation
- Realistic case ⇒ adjust weight of near sites
  - 4 cores: Factor 50 cancellation: 2% → 0.035%
  - 6 cores: Factor 20 cancellation: 2% → 0.1%
- Can preserve cancellation under swapping

Reactor Uncertainties

We estimate that relative locations
of detectors and cores can be determined to 30 cm.



Number of cores	α	σ_ρ(power)	σ_ρ(location)	σ_ρ(total)
4	0.338	0.035%	0.08%	0.087%
6	0.392	0.097%	0.08%	0.126%

Controlling Detector Systematics

- Careful fabrication, measurements of vessels
- Fill modules in pairs from common scintillator tank with common precision instrumentation,

  then split the pairs and deploy 1 module at a near site and 1 module at far site to provide cancellation of LS differences.
- Calibrate and monitor status of each module.
- Swap detectors between near and far site (option)

Measuring Acrylic Vessels

- Survey walls using many "targets" before filling
- <0.1mm → 0.01% volume measurement
- Goal is 0.1% volume uncertainty when vessel is full

Filling Procedure

- Fill pair of detectors from a single tank of Gd-LS

(deploy one detector at near site and one detector at far site, thus no chemical differences between near and far sites)

- Use high precision flow devices

    flowmeters (0.02% repeatable)

    mass flow meters (0.1% repeatable)

- Load cell measurements of filling tank

Calibration/Monitoring Scheme

- Initial commissioning of detector module:
  - complete characterization of detector properties

- After moving/swapping module or if a significant change occurs:
  - simplified procedure to assess condition and decide whether commissioning procedure is necessary

- Routine monitoring of detector modules:
  - weekly or daily procedure
  - automated system

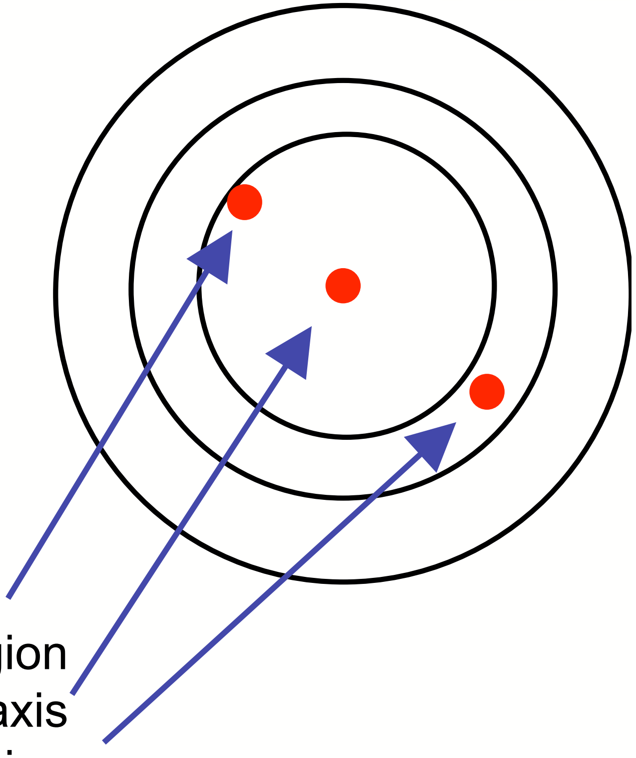
Routine Monitoring Goals

- Establish 8 MeV energy scale
  → neutron efficiency (~0.1%)
- Determine 1 MeV threshold energy
  → positron efficiency (~0.02%)
- Monitor different scintillator regions
- Overall detector health and status
  - optical attenuation
  - scintillation yield
  - reflectivity, transmission of surfaces
  - dead PMT's
- Provide input to corrections

→ All detectors should have "identical", "constant" response

Basic Requirements

- Identical radioactive sources
  → energy stability = "perfect"
- >10,000 counts per measurement
  → energy precision of ~0.1%
- Automatic insertion and removal of several sources, 1 MeV < E < 10 MeV.



Source deployment

Outer radius of target region
Central axis
Gamma catcher region

Fixed point source measurements combined with uniform cosmogenic data to realize high precision over complete central region of detector module.

Source selection

- ^{68}Ge ($T_{1/2}$=271 days)

  EC → ^{68}Ga

  ($T_{1/2}$=68 min), β^+, Q=2.921 MeV

  → 2 x 0.511 MeV γ 's, E_{total}=1.022 MeV (e^+ threshold!)

- ^{60}Co ($T_{1/2}$=5.3 yrs)

  → 2 γ's, E_{total} = 2.505 MeV

- ^{252}Cf ($T_{1/2}$=2.6 yrs)

  Fission → ~4 x 2 MeV neutrons (neutron efficiency)

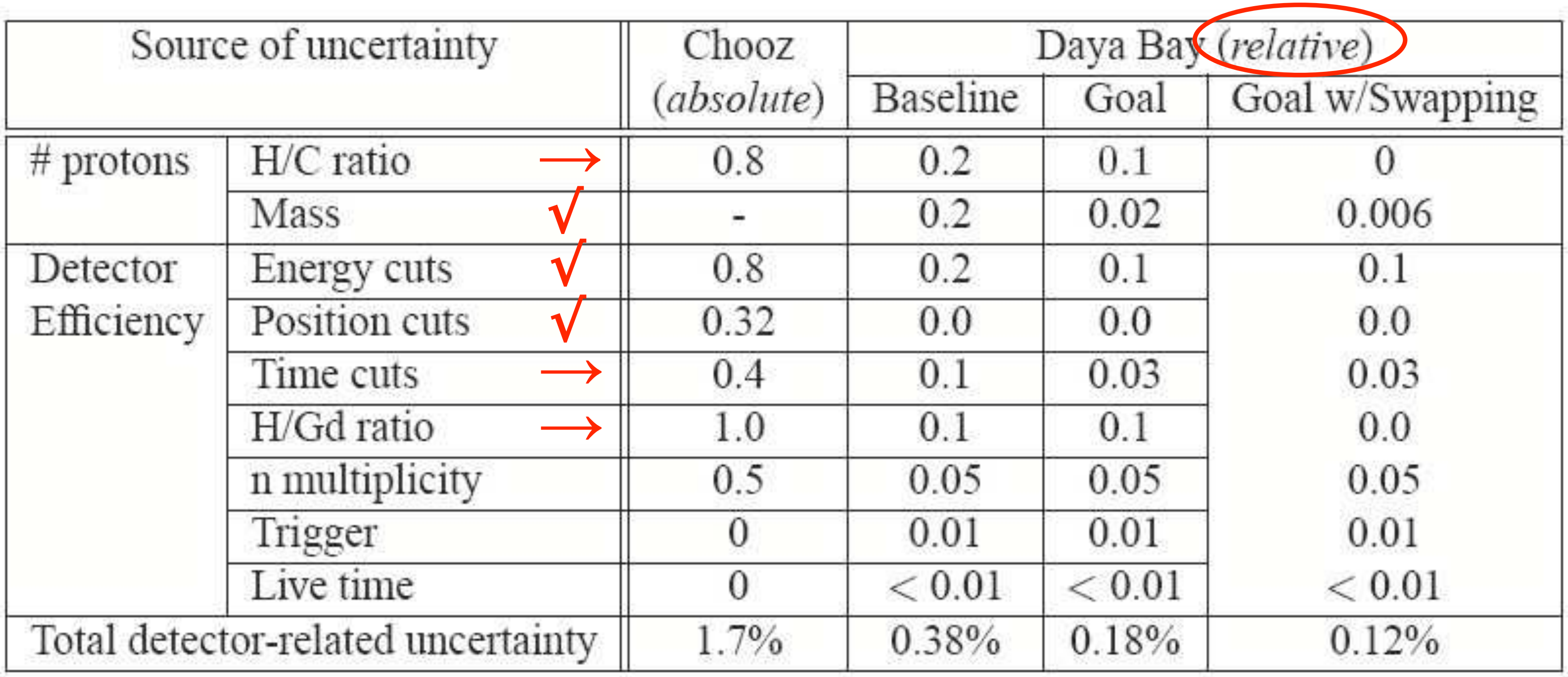
Comparison of estimated cosmogenic data and signal rates

	Near Site (per 20T module)	**Far Site** (per 20T module)
Spallation neutrons	9000/day	400/day
^{12}B(β source, τ =29.1ms, Q=13.4MeV)	300/day	28/day
Reactor signal	1000/day	90/day

Notes: - ~1000 events needed to monitor 8 MeV energy to 0.1%

- **Uniform** distribution in detector

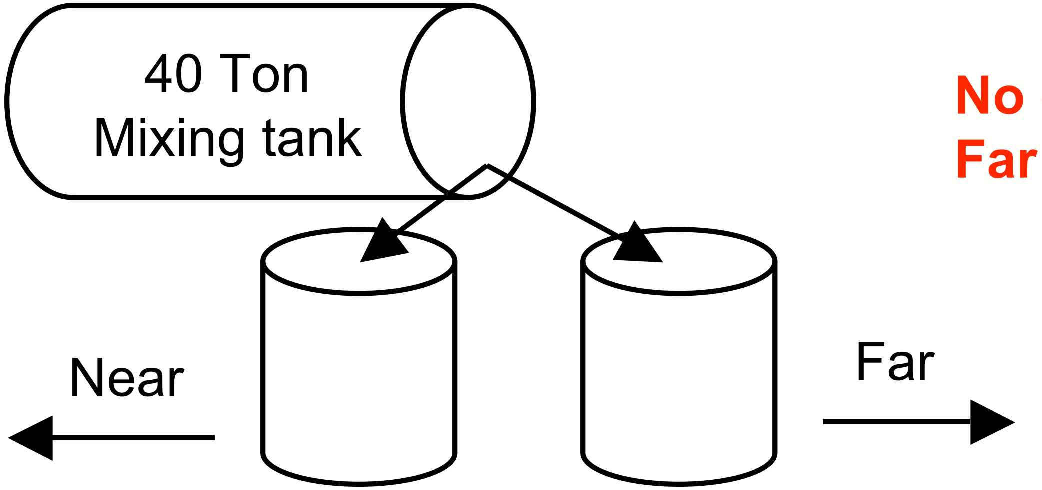
Summary and comparison of detector-related systematic uncertainties



Source of uncertainty		Chooz (*absolute*)	Daya Bay (*relative*)		
			Baseline	Goal	Goal w/Swapping
# protons	H/C ratio →	0.8	0.2	0.1	0
	Mass √	-	0.2	0.02	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%

H/C ratio options

- Combustion analysis (<0.3%?)
- Neutron capture/scattering (needs R&D)
- **Filling detector pairs from common batch**



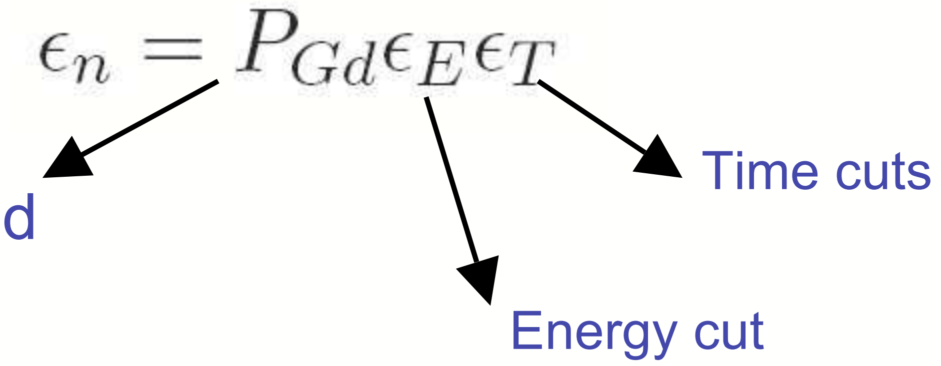
No difference in H/C between Far and Near sites

Neutron Efficiency

I.) Tagged n source at center

(^{252}Cf or AmBe) → direct measurement (>10^6 events)

II.) Measure components of neutron detection efficiency ε_n



$$\epsilon_n = P_{Gd}\epsilon_E\epsilon_T$$

H/Gd

Time cuts

Energy cut

Gd fraction

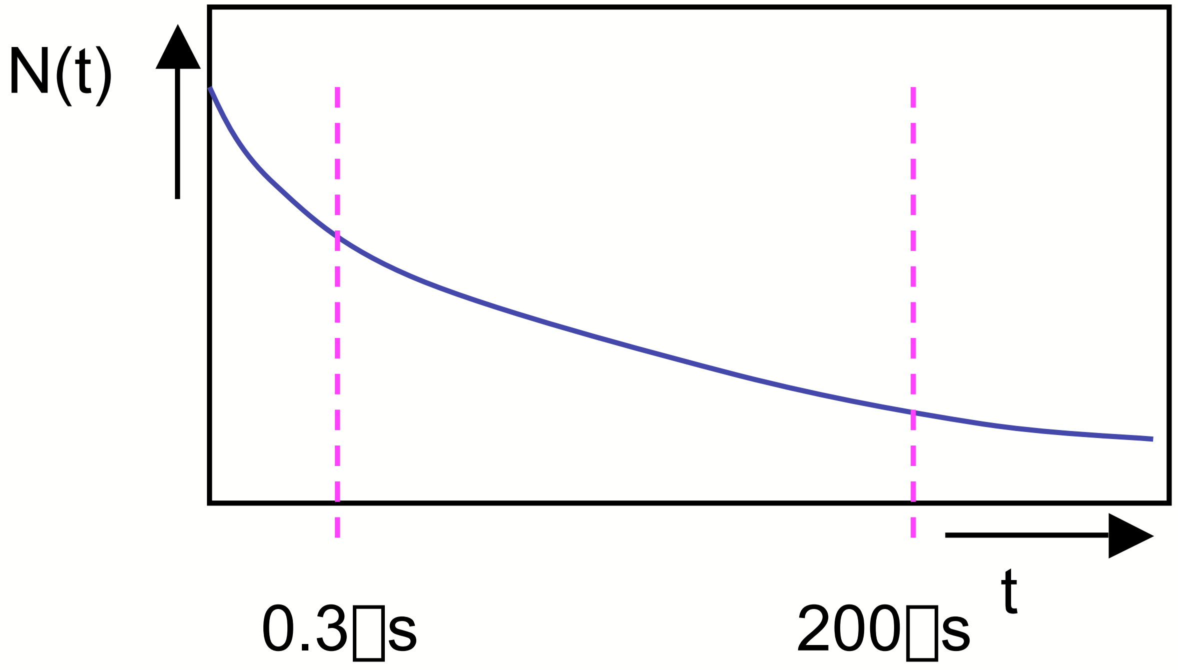
Thermal neutron capture rate:

$$\Gamma = \Gamma_{Gd} + \Gamma_{H} = \left\langle [n_{Gd}\sigma_{Gd} + n_{H}\sigma_{H}]v \right\rangle$$

$$P_{Gd} = \frac{1}{1 + \Gamma_{H}/\Gamma_{Gd}}$$

- $N(t) = N_0 \exp(-\Gamma t)$; $t > 10$ μsec
- → Measure Γ to <1% for each module during commissioning (need ~10^5 captures)
- $\Gamma(\text{meas.}) - \Gamma_H \rightarrow \Gamma_{Gd} \rightarrow \delta P_{Gd} < 0.1\%$

Neutron time cuts

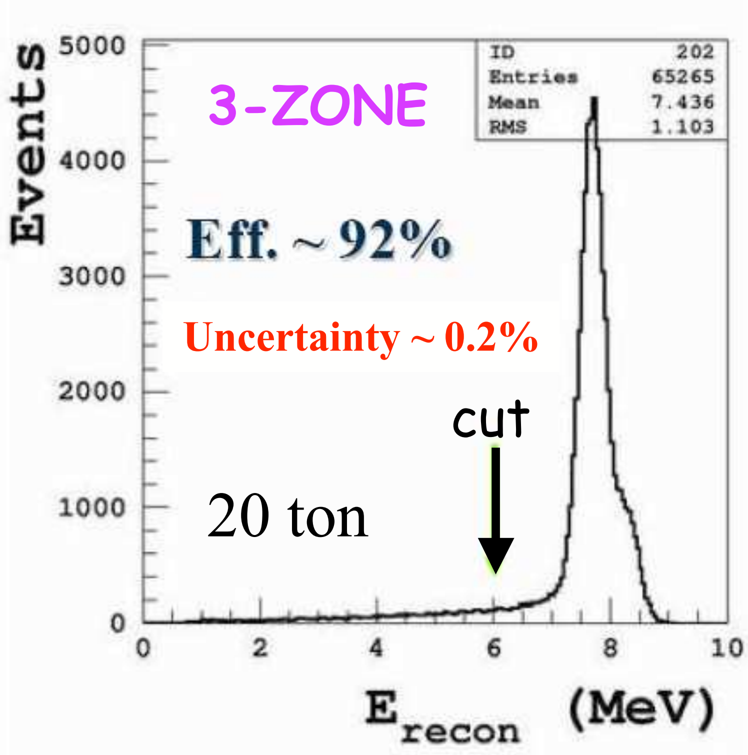


These cut times must be the same to ~10ns for all modules
→ use common clock
→ 0.05% contribution to neutron efficiency

Energy cut and 2- or 3-zone detector

- 2-zones implies simpler design/construction, some cost reduction but with increased risk to systematic effects (neutron ε and E_ν spectrum)
- 3-zones provides increased confidence in systematic uncert. associated with detection efficiency and fiducial volume, but smaller volume

n capture on Gd yields 8 MeV with 3-4 γ's(2.2MeV γ from n capture on H not shown)

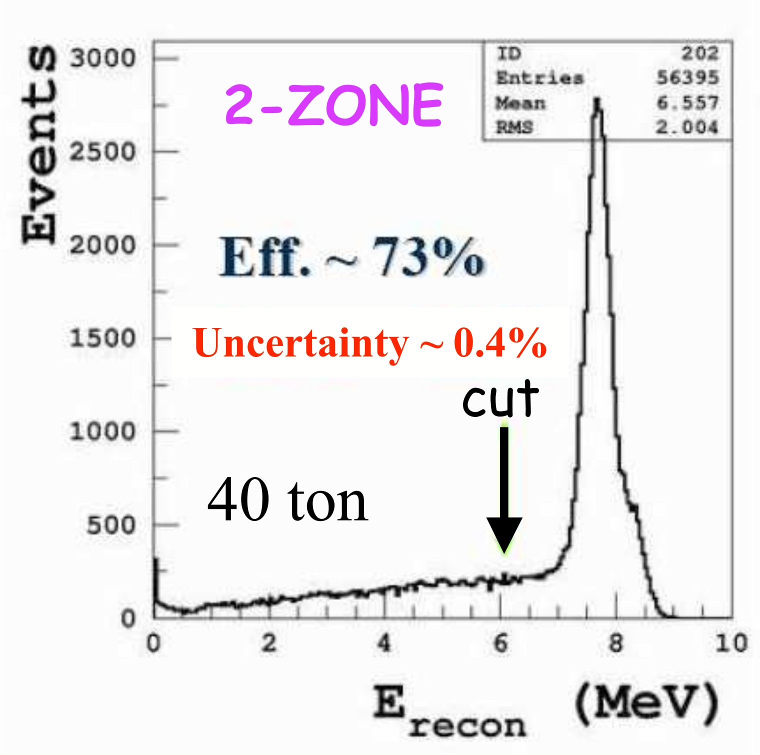

3-ZONE

Eff. ~ 92%

Uncertainty ~ 0.2%

cut

20 ton


2-ZONE

Eff. ~ 73%

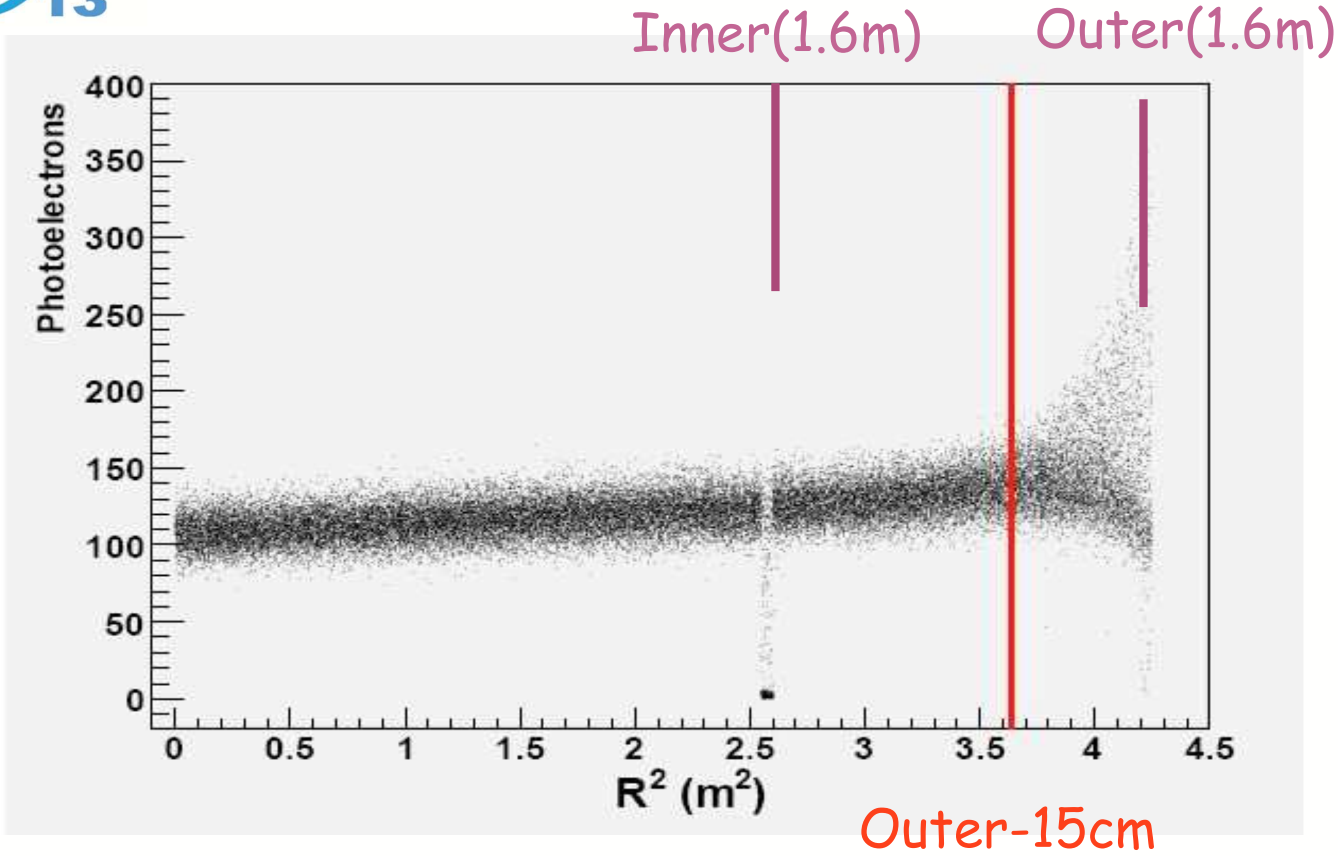
Uncertainty ~ 0.4%

cut

40 ton

4 MeV cut can reduce the error by x2, but residual radioactivity in LS volume does not allow us to do so

Uniform response of 3zone detector

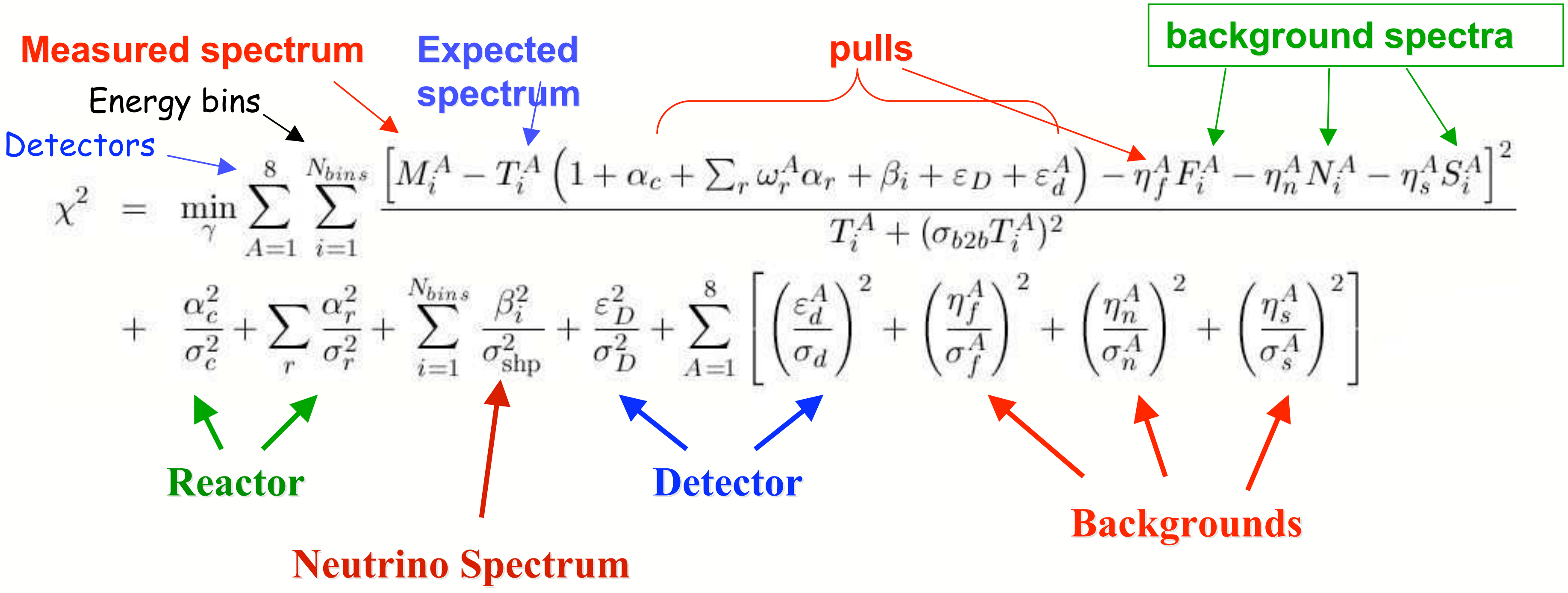


Simulated response as a function of radial location of a 1 MeV e^- energy deposit. The mineral oil volume is removed and the PMTs are directly outside the γ-catcher.

Systematics Summary

- Reactor-related systematics ~0.1%
- Detector-related systematics ~0.38%/module
  - could be reduced to 0.18% or lower (R&D)
  - requires care in construction, assembly, calibration, and monitoring

Expt'l sensitivity from χ^2 analysis



Measured spectrum

Expected spectrum

pulls

background spectra

Energy bins

Detectors

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

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

Reactor

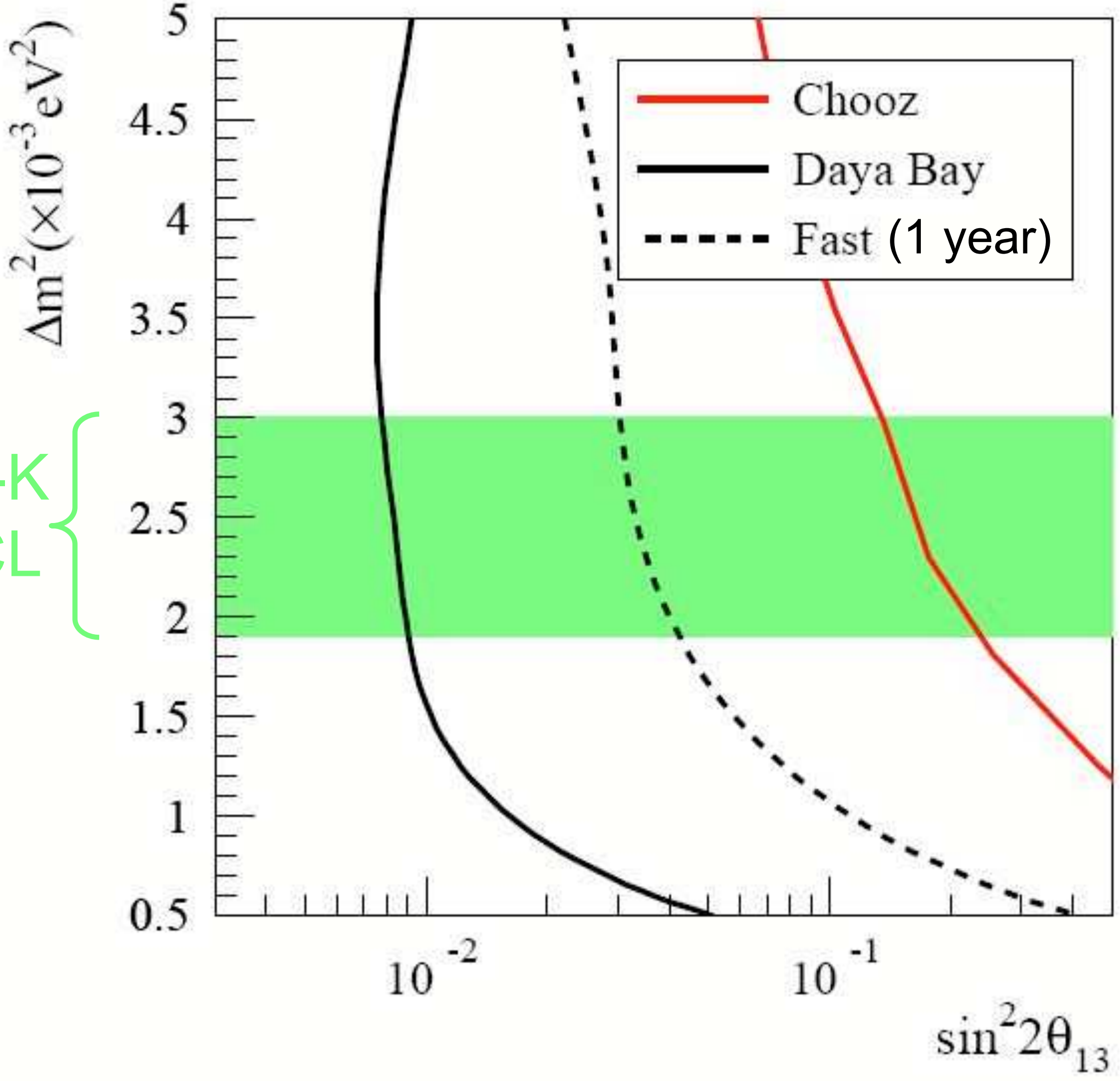
Detector

Backgrounds

Neutrino Spectrum

- χ^2 with pull terms to take into account the correlation of systematic errors. (SK, PRL81 (1998) 1562)
  - Raster scan in $\Delta m^2 - \sin^2 2\theta_{13}$
  - Minimize χ^2 at each point
  - $\Delta\chi^2 = 2.71 \rightarrow$ 90% CL contour

Sensitivity



Super-K
90% CL

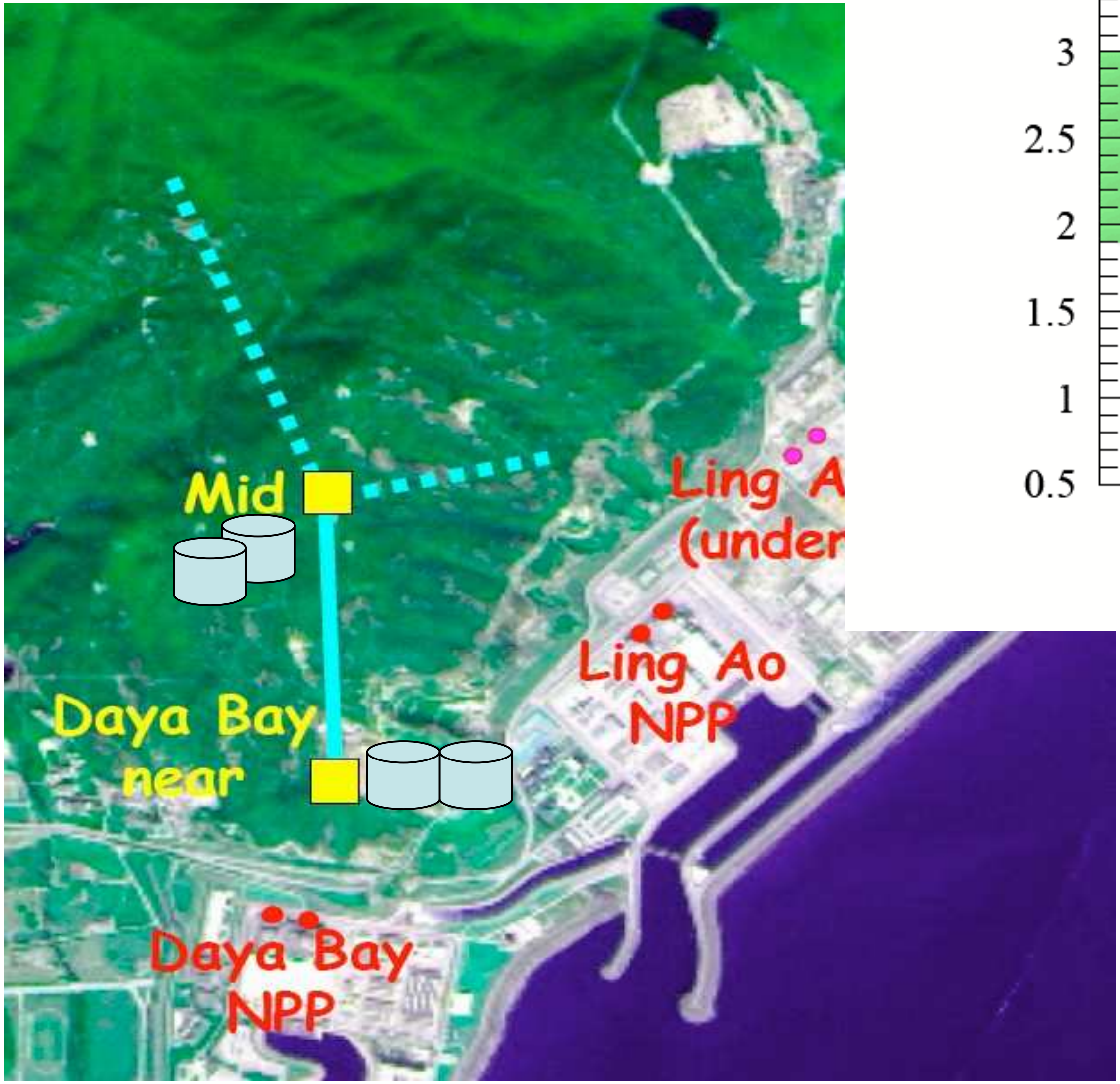
- 90%CL
- 3 years running
- 0.38% detector systematic
- 2% reactor power uncertainty (uncorrelated)

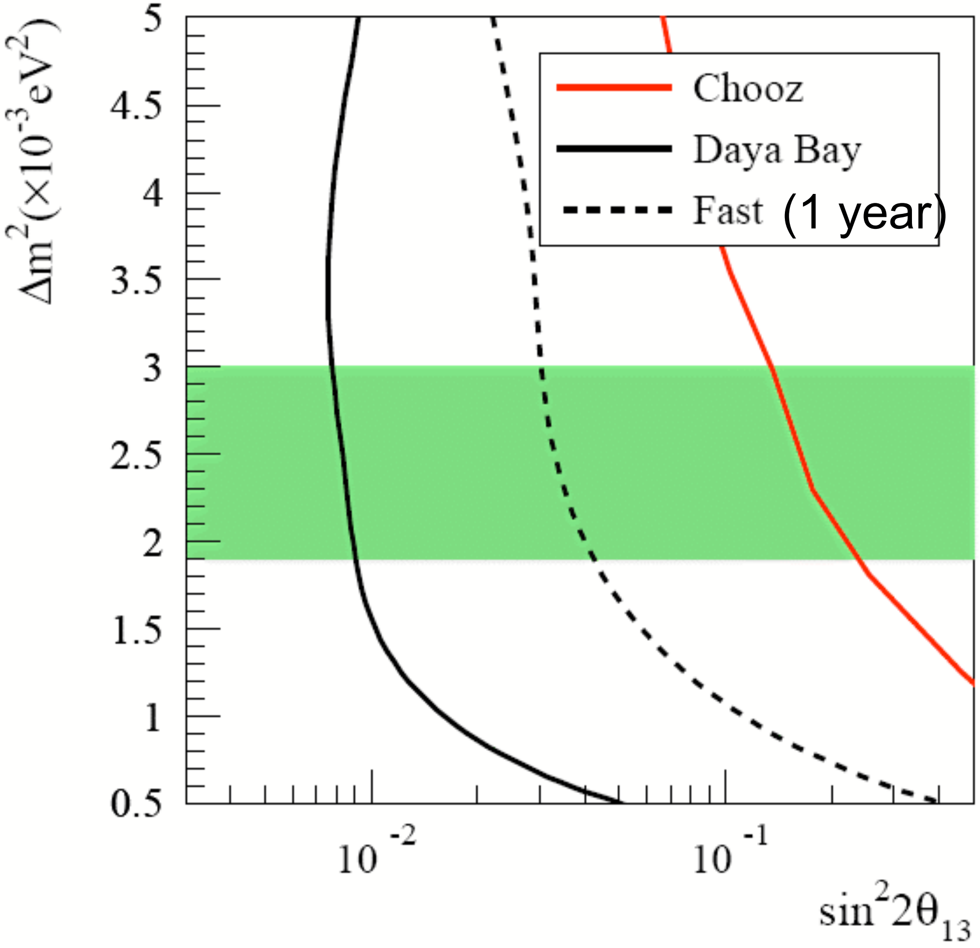
"Fast" deployment:

- 40tons at Daya Bay near site
- 40tons at Mid site

-0.7% reactor systematic error

- 1 year of data taking



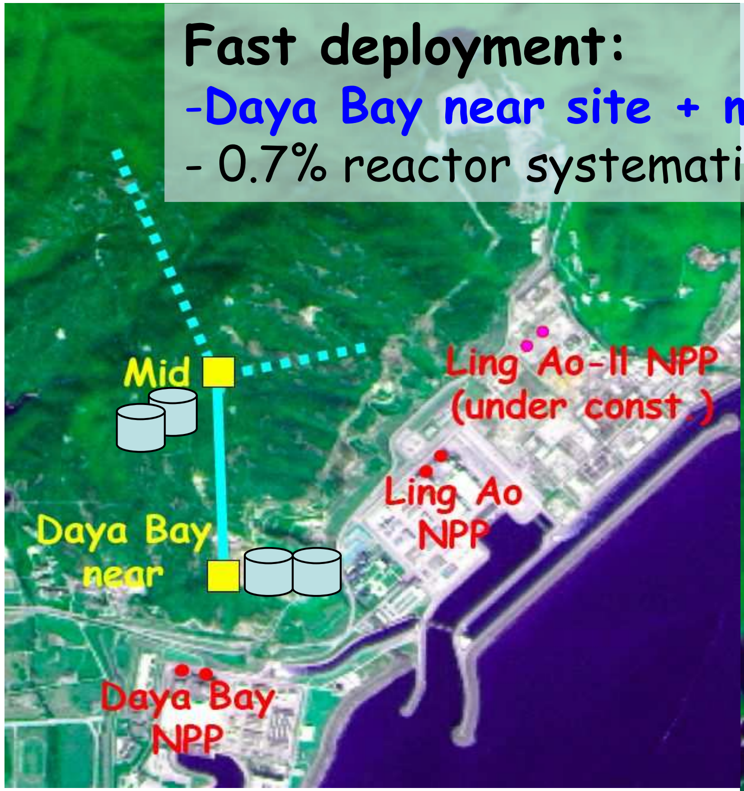


Daya Bay experiment versatility

Fast deployment:

-Daya Bay near site + mid site

- 0.7% reactor systematic error



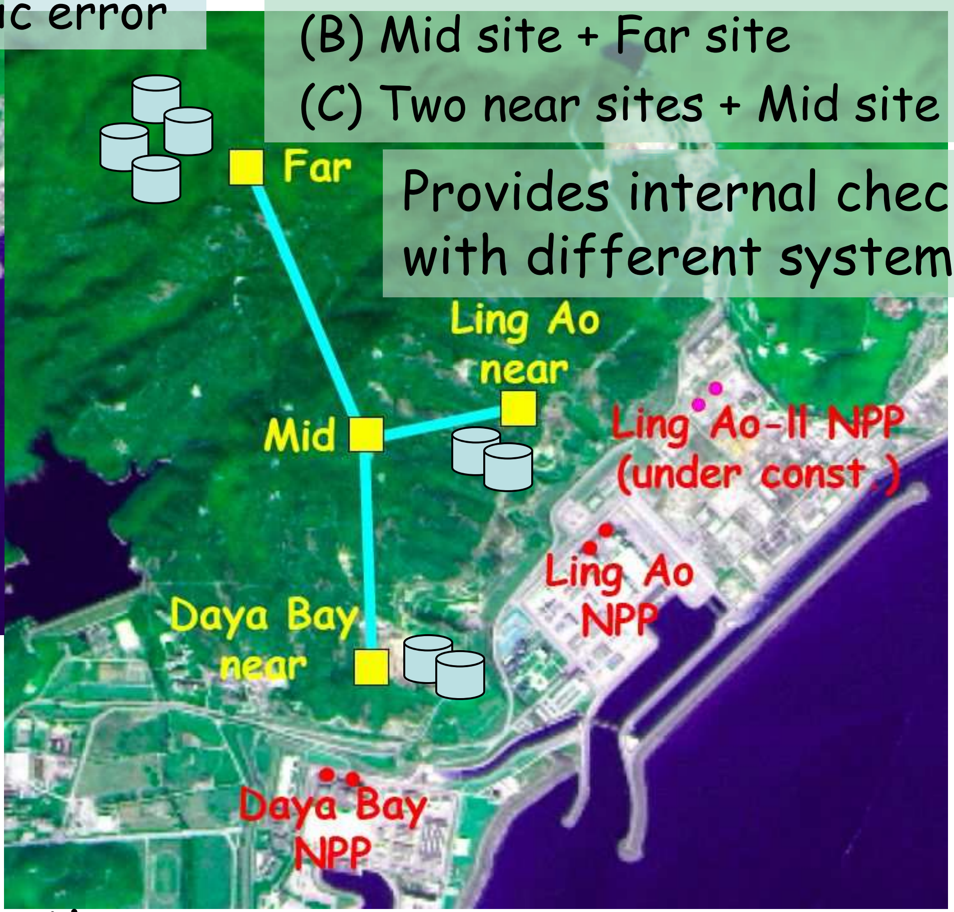
Full operation:

(A) Two near sites + Far site

(B) Mid site + Far site

(C) Two near sites + Mid site + Far site

Provides internal checks, each with different systematic



Preliminary schedule

June 06 Begin civil design

April 07 Begin tunnel construction

Feb 09 Daya Bay near & mid halls complete

Nov 09 Ling Ao near & far halls complete

Sept 09 Begin Daya Bay near, mid data taking

Jun 10 Begin data taking with far & near halls

Mar 13 Measure $\sin^2 2\theta_{13}$ to ≤ 0.01

Summary and status

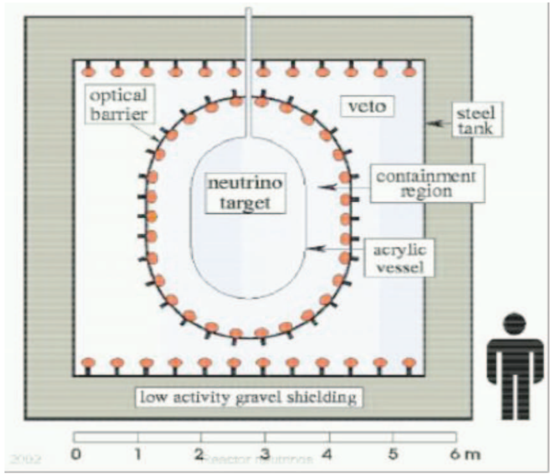
- The Daya Bay reactor neutrino experiment is designed to reach a sensitivity of ≤ 0.01 for $\sin^2 2\theta_{13}$ and have the versatility to perform internal systematic checks of a $\sin^2 2\theta_{13}$ measurement.
- The Daya Bay project has been approved by the Chinese Academy of Science, Natural Science Foundation and Ministry of Science and Technology for 150M RMB.
- The US DOE has provided 0.8M$ for R&D for FY06. We have passed the first step toward becoming a US project starting in FY08.
- We are seeking new collaborators
- Will complete preliminary design of detectors and detailed design of tunnels and underground facilities in early 2007.
- Plan to start with the near-mid data taking in 2009, and begin full operation in 2010.

Thanks to my Daya Bay colleagues for help in preparing this presentation.

EXTRAS

What do we learn from the past?

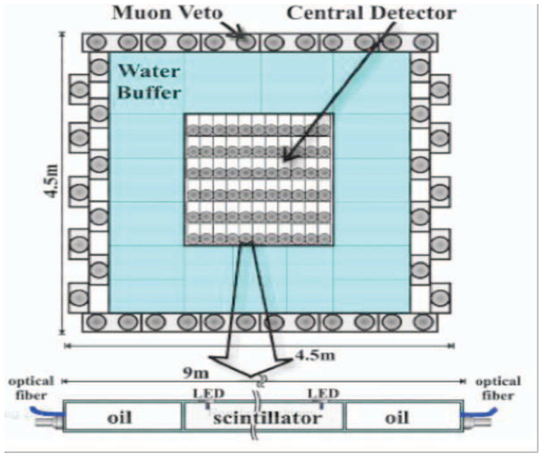
CHOOZ



5t 0.1% Gd-loaded scintillators

- Not stable Gd-loaded scintillator (*L* ~ 2 - 5 m) ➔ turned yellow after few months of deployment (0.4% degradation per day)
- Homogeneous detector ➔ *n* capture peak at 8 MeV
- Detector Efficiency ~70%

Palo Verde



12t 0.1% Gd-loaded scintillators

- Good Gd-loaded scintillator (*L* ~ 11 m) ➔ deterioration with time (0.03% degradation per day)
- Segmentation detector ➔ *n* capture peak < 6MeV
- Detector Efficiency ~10%

Past Problems in Reactor Experiments with Gd-LS

CHOOZ, 5t 0.1% Gd-LS in a homogeneous detector

- Used "brute force" chemical method to load Gd into LS: dissolved $Gd(NO_3)_3$ in Alcohol, which was then dissolved into aromatic (benzene-like) liquid.
- To a chemist, nitrates plus organics is not a good choice.
- The resulting Gd-LS ($\mathcal{L}$(attenuation) ~ 2 - 5 m) was not stable,
- **Turned yellow after few months of deployment (0.4% degradation per day)**

Palo Verde, 12t 0.1% Gd-LS in a segmented detector

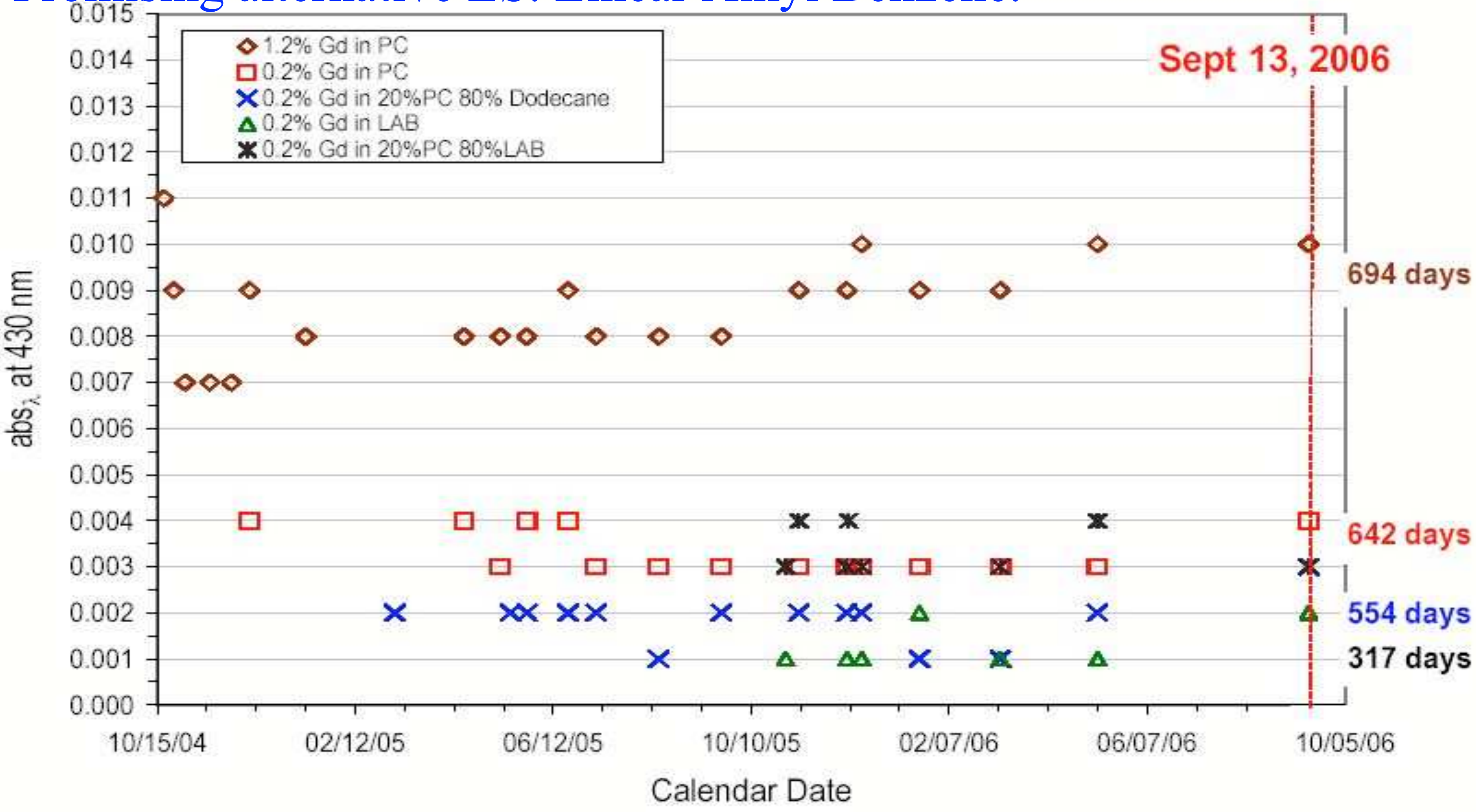
- Obtained Gd-LS, BC-521, from Bicron.
- Was prepared by making an Gd-organic complex,
  a carboxylate (of 2-ethylhexanoic acid) that was soluble in pseudocumene, PC.
- Diluted it with mineral oil. (***L***(attenuation) ~ 11 m).
- Reported that PV had deterioration with time (0.03% degradation per day)
- However, users (e.g., Gratta) say that there was some initial deterioration but then the Gd-LS stabilized. It is still usable today (Bernstein at San Onofre), several years after PV ended.

BNL Gd-LS Optical Attenuation: Stable So Far ~700 days

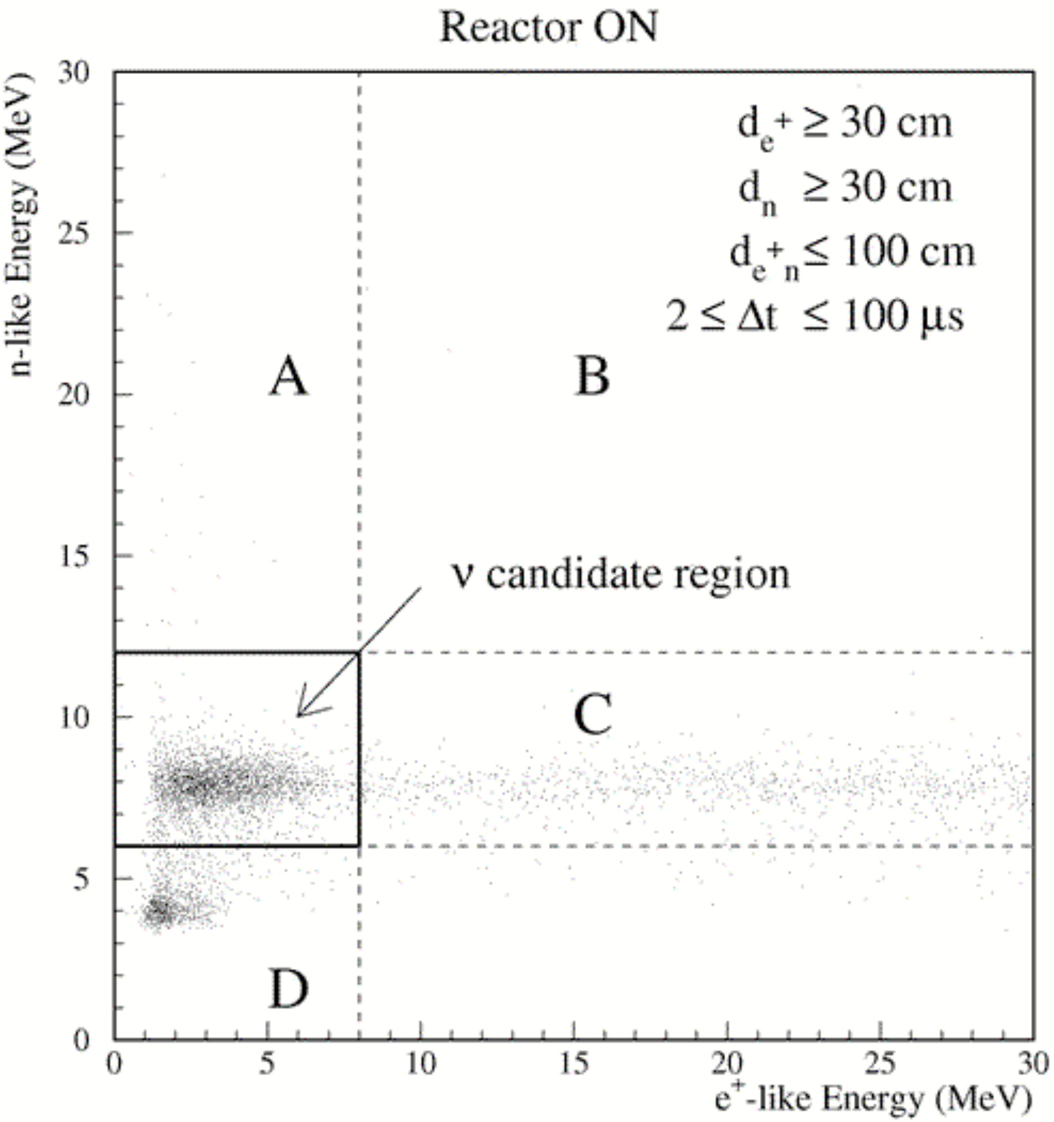
-Gd-carboxylate in pseudocumene(PC)-based LS stable for **~2 years.**

- Attenuation Length **>15m**

- Promising alternative LS: Linear Alkyl Benzene.



Chooz Data


Reactor ON
$d_{e^+} \geq 30$ cm
$d_n \geq 30$ cm
$d_{e^+n} \leq 100$ cm
$2 \leq \Delta t \leq 100\ \mu s$
A
B
C
D
ν candidate region
n-like Energy (MeV)
e⁺-like Energy (MeV)
0
5
10
15
20
25
30

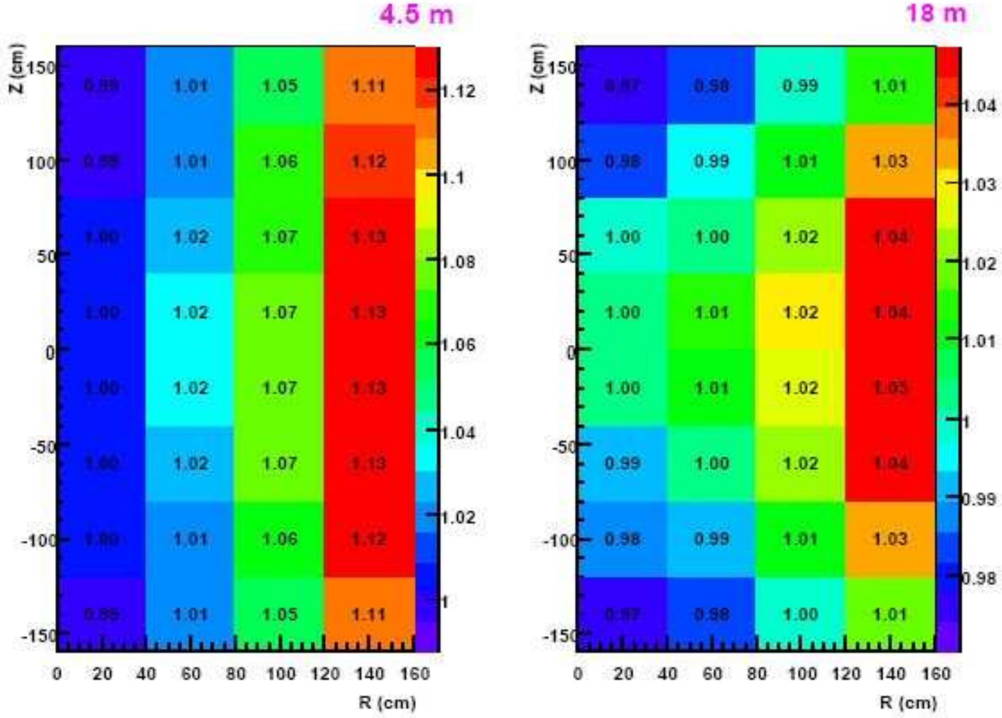
Monitoring Detector Changes/Differences

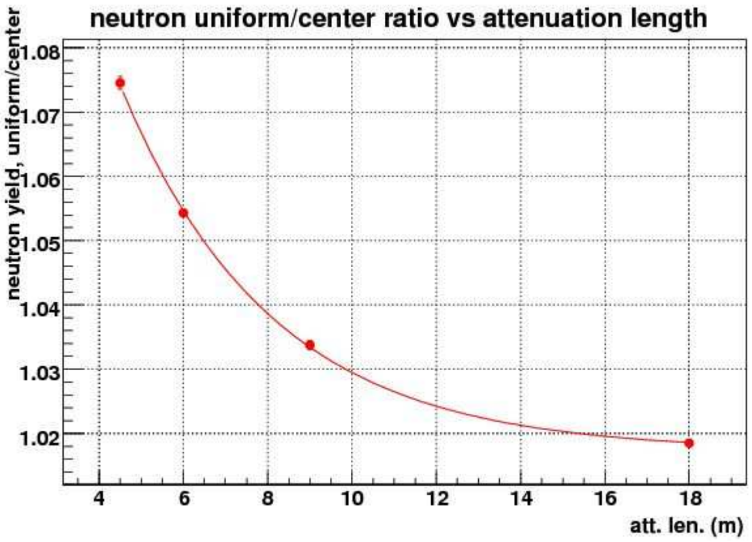
Simulation Studies to date:

- Scintillation yield (inner /outer relative)
- Optical attenuation
- Acrylic transmission
- Dust on bottom of acrylic vessel
- Loss of PMT's
- SS Tank reflectivity

Change of Attenuation Length

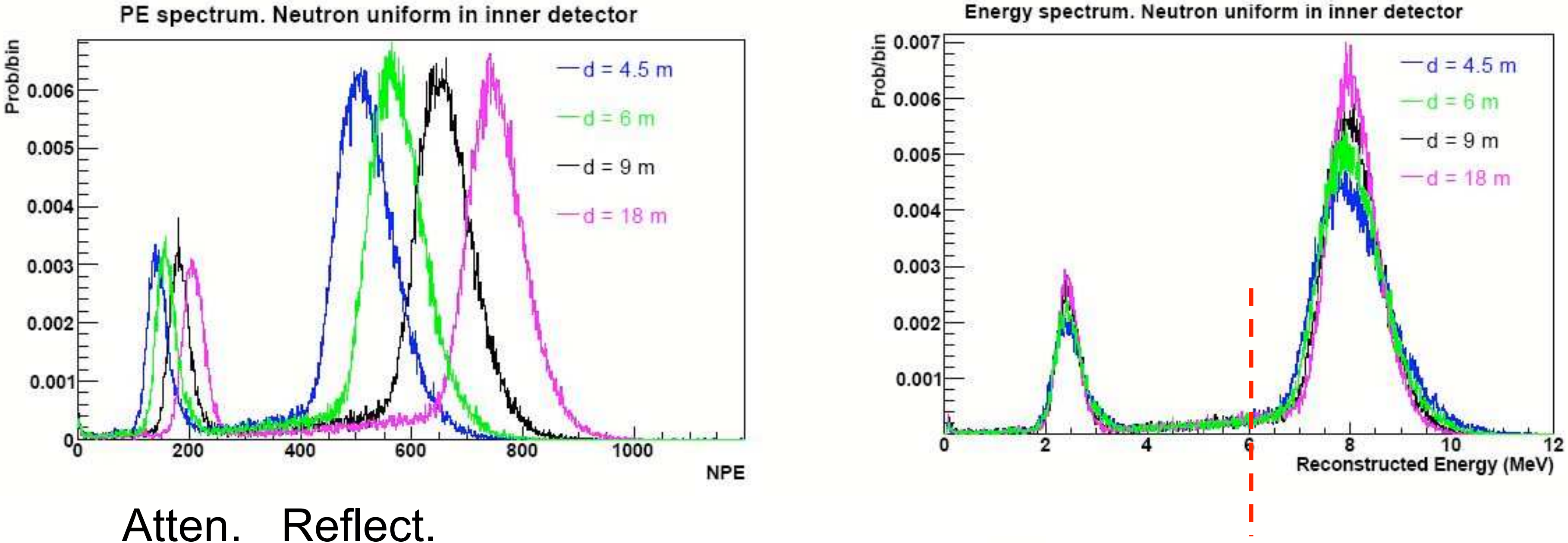
n-Gd capture signal vs position for two att. len.





“uniform”/”center” yield ratio can be used as a measure of the attenuation length

Effect of Attenuation on Neutron Detection Efficiency



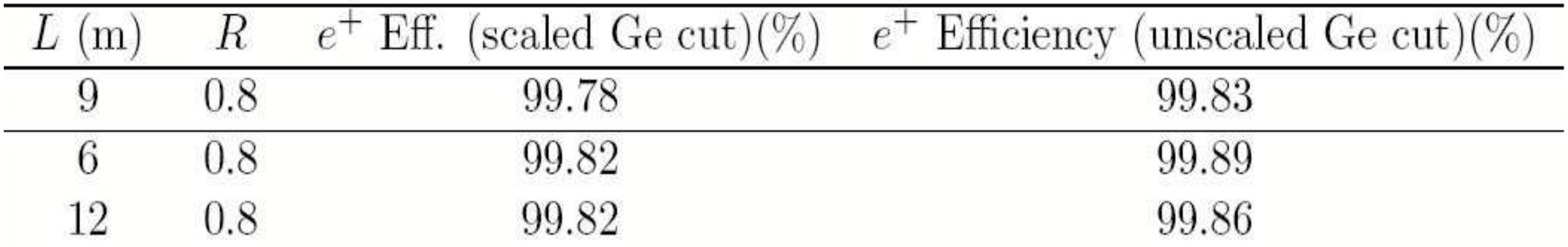
Threshold

Atten. Reflect.

L (m)	R	Neutron Efficiency(%)
9	0.8	92.76
4.5	0.8	93.05
6	0.8	93.03
18	0.8	92.69

Reasonable variations
→ 0.1% relative eff.

Effect of Attenuation on e^+ efficiency



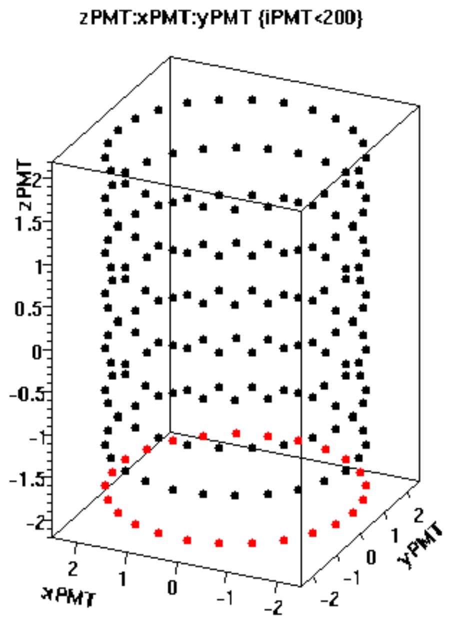
L (m)	R	e^+ Eff. (scaled Ge cut)(%)	e^+ Efficiency (unscaled Ge cut)(%)
9	0.8	99.78	99.83
6	0.8	99.82	99.89
12	0.8	99.82	99.86

Very Stable!

Dead PMTs

Easy to detect dead PMTs: no hits in N events.

The “dentist” approach: filling the holes with adjacent good tubes.



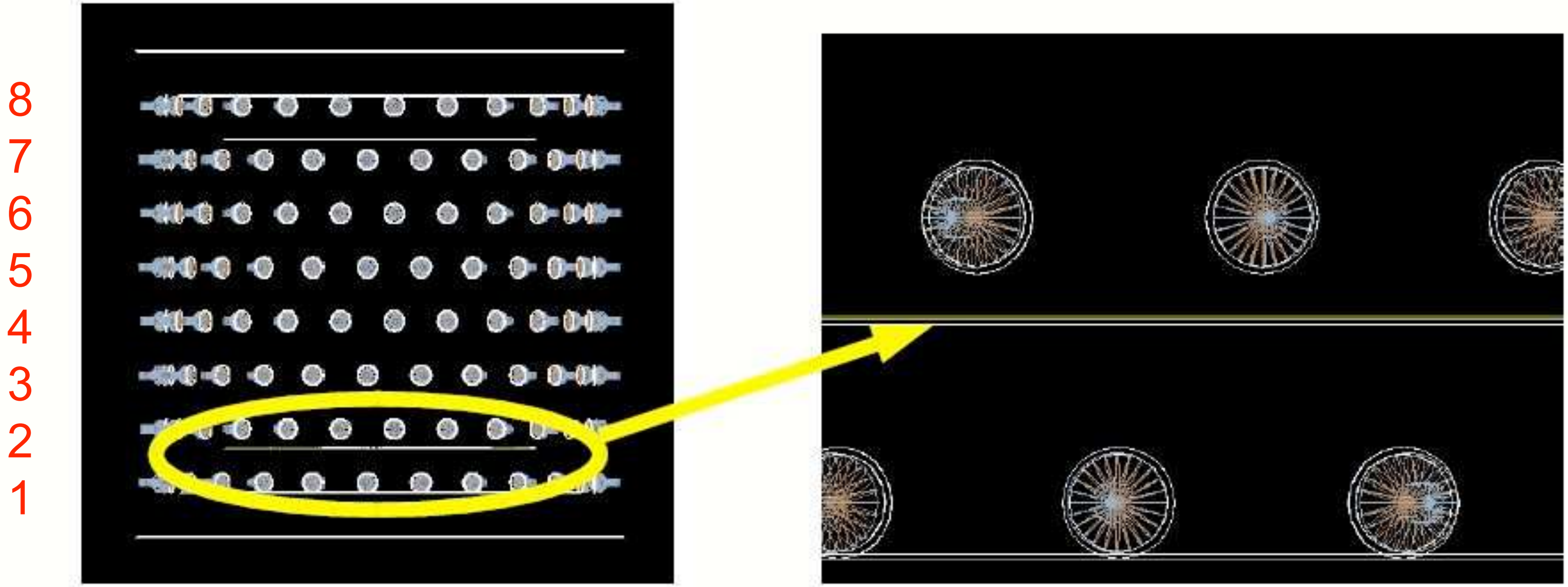
E.g., kill 25 PMTs at the bottom, and try measure e^+ rates

Condition	Total	Above thresh.	e^+ eff. (%)
All tubes good	24920	24874	99.82(0.03)
Bottom 25 dead	24920	24766	99.38(0.05)
“dentist” correction	24920	24877	99.82(0.03)

(Similar results for neutron efficiency)

Use a fixed 116 PE cut based on ^{68}Ge calibration

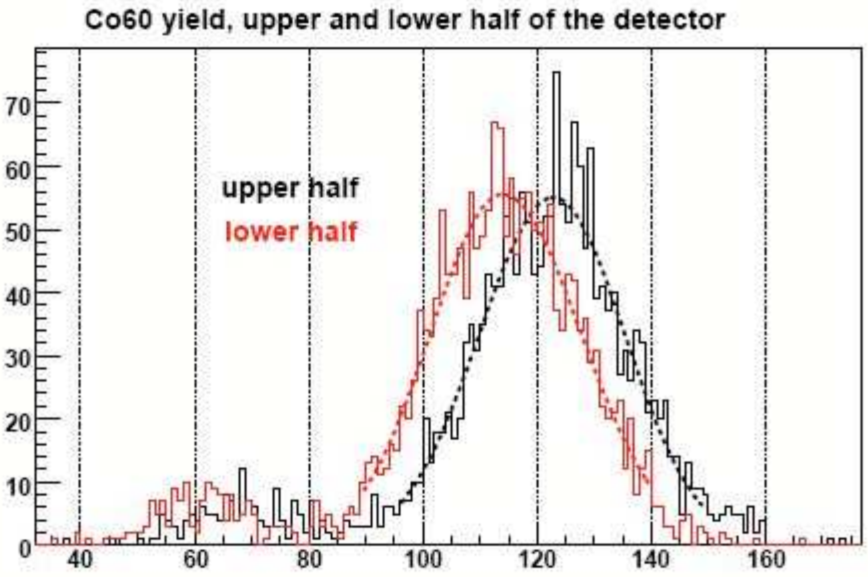
“Modeling” of a layer of “Dirt” at the bottom of acrylic



Add 1cm layer of absorbing (λ=1cm) acrylic at bottom of central region

"Dirty" Acrylic Effect

With 2000 Co60 center events



Method A

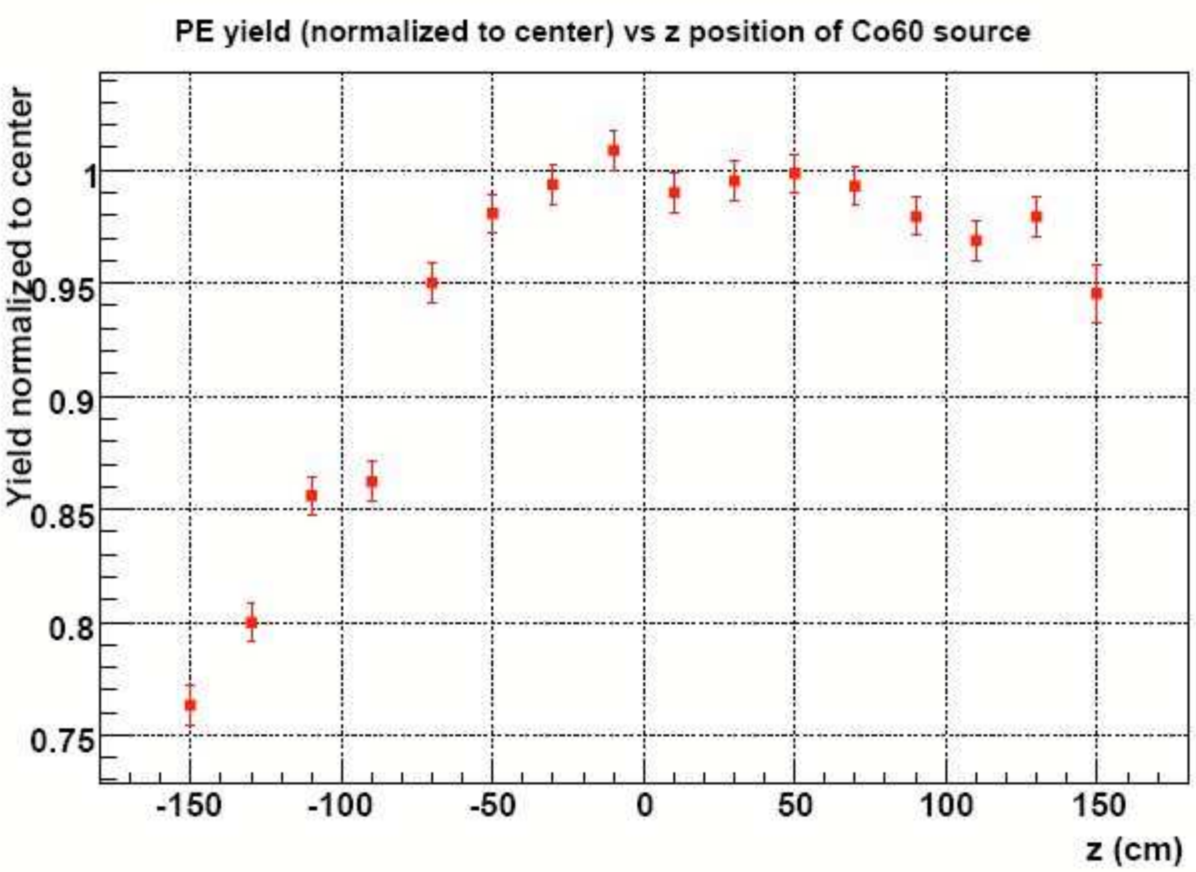
Upper	123(1)
Lower	114(1)
Upper/Lower	1.079(0.014)
"No Dirt"	1

Method B

"8/7" (top)	0.843(6)
"1/2" (bottom)	0.739(7)
"8/7"/"1/2"	1.141(0.014)
"No Dirt"	1

Positron efficiency changes 99.8% → 98.9%

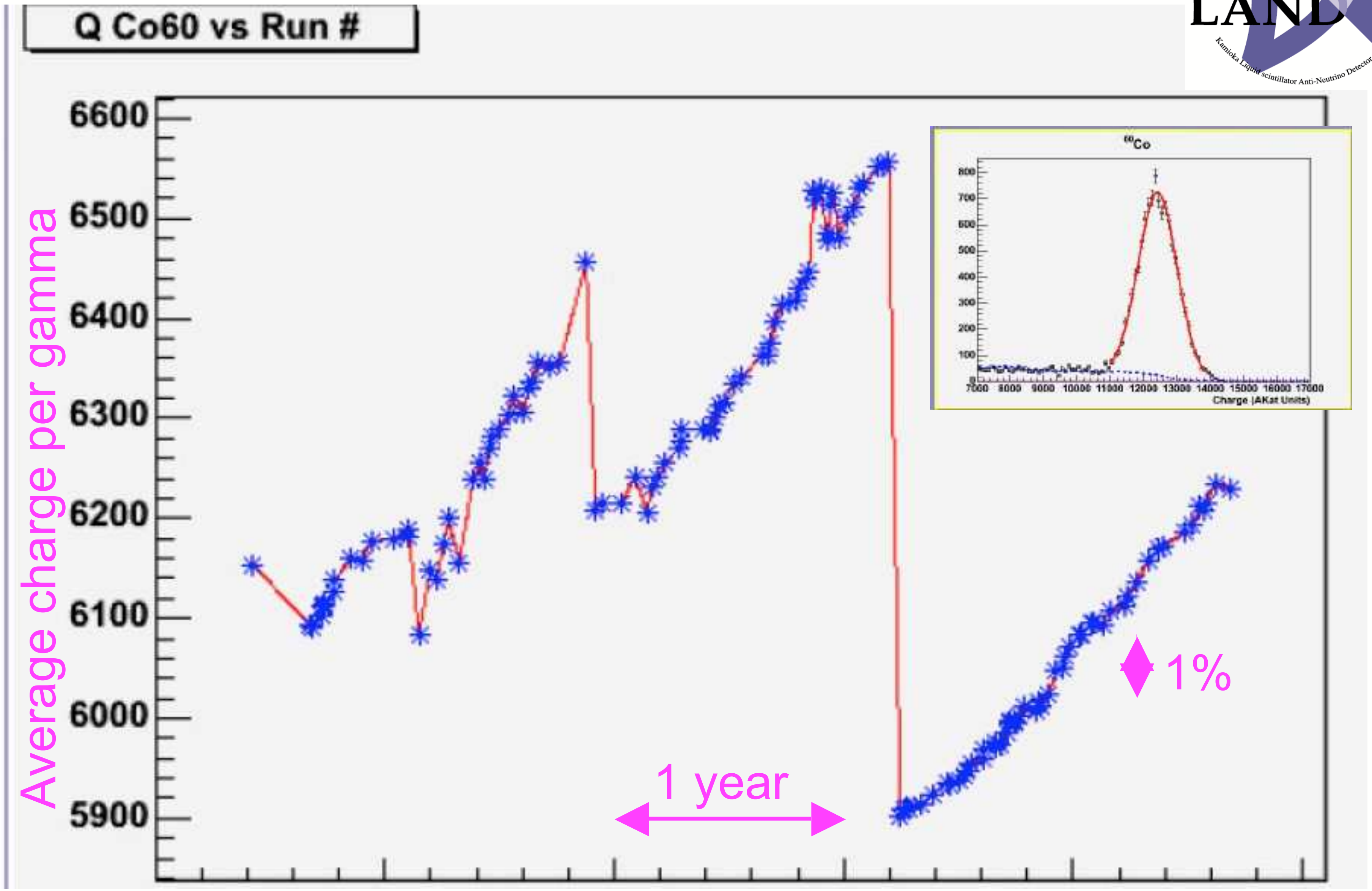
“Dirty” Acrylic Effect



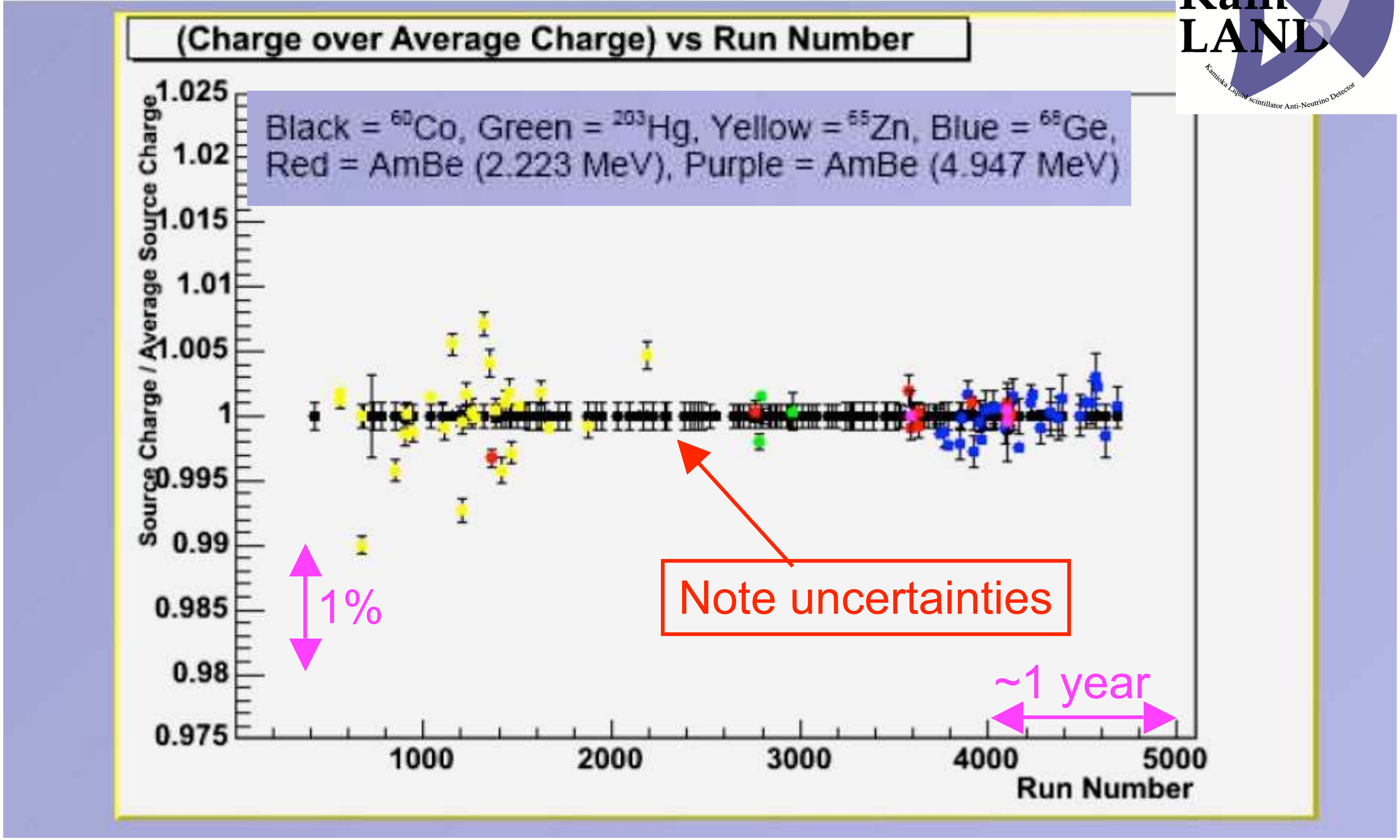
A Co60 source moving along z axis

- Simple fixes restore positron efficiency to ~99.6%, (vs. 99.8% w/o dirt)
- Further studies in progress.

Monitoring KamLAND Stability



Monitoring KamLAND Stability

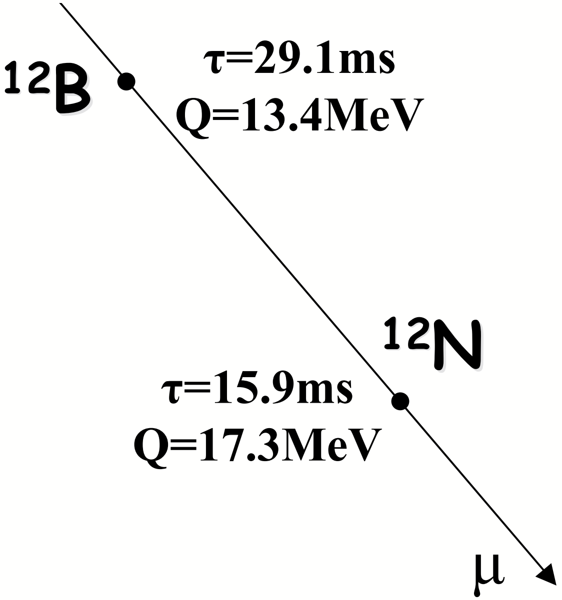


1%

Note uncertainties

~1 year

Tagged cosmogenics can be used for calibration



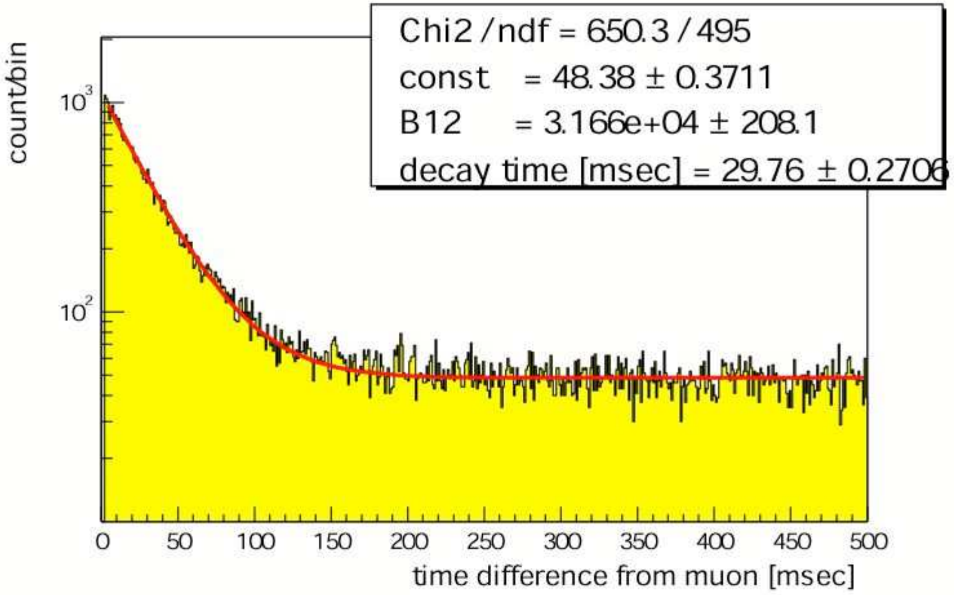
^{12}B

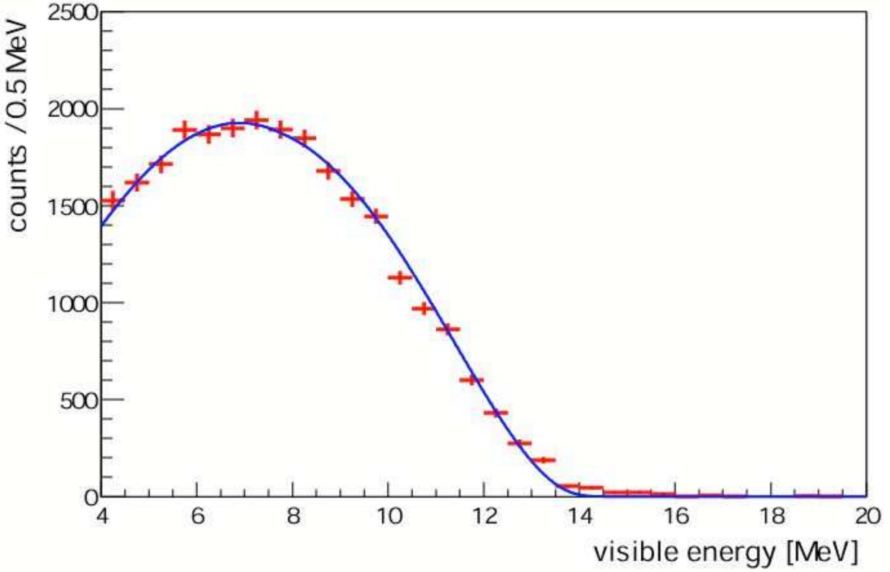
τ=29.1ms
Q=13.4MeV

^{12}N

τ=15.9ms
Q=17.3MeV

μ





Fit to data shows that ^{12}B:^{12}N ~ 100:1