SAND2007-0388C

Reactor Monitoring and Safeguards using Compact Antineutrino Detectors

A Sandia and Lawrence Livermore National Laboratories Joint Project

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Sandia National Laboratories, CA

Sandia is a multiprogram laboratory operated by Sandia Corporation, a Lockheed Martin Company, for the United States Department of Energy under contract DE-AC04-94AL85000.

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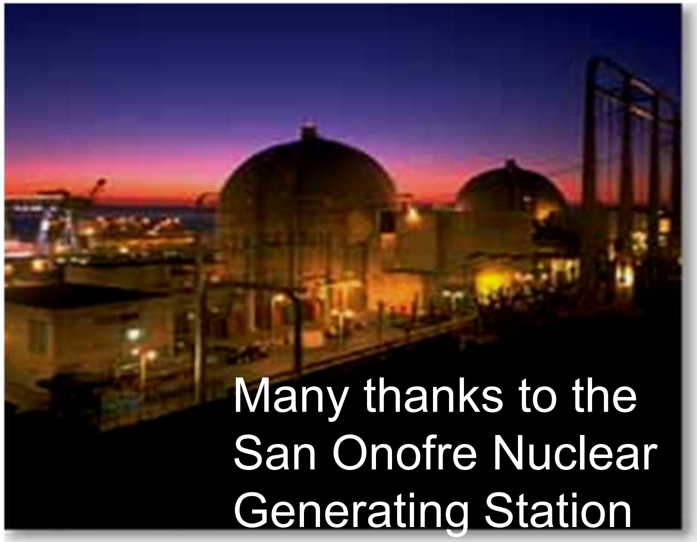

This Work is supported by DOE-NA22
(Office of Nonproliferation Research and Development)

Outline

- Safeguards and Non-proliferation
- How would antineutrino safeguards work?
  - How could antineutrino measurements contribute to reactor safeguards?
- Antineutrino Detection
- Deployment of a demonstration detector
- Experimental data from the detector
- Overlap with current neutrino physics experiments
- Conclusions

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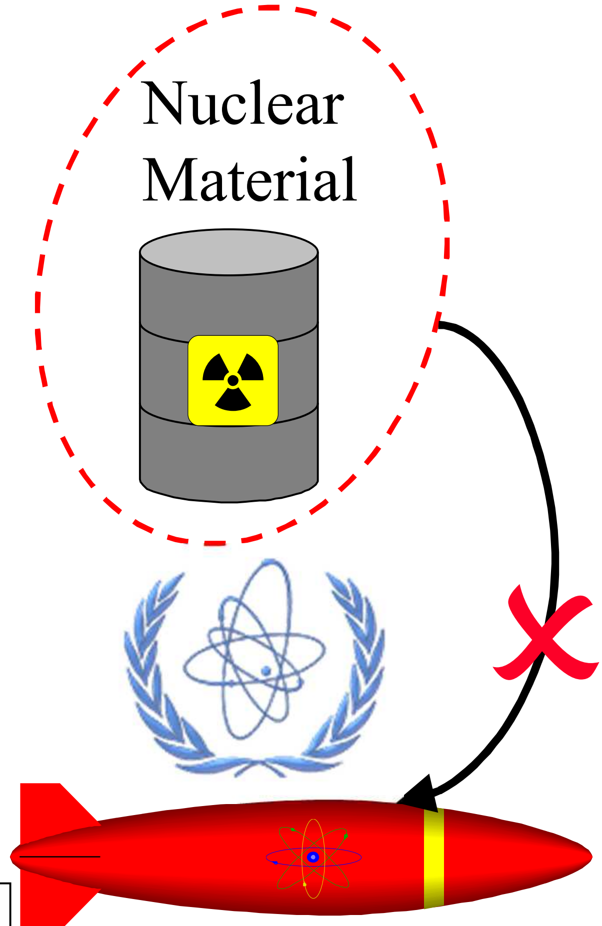
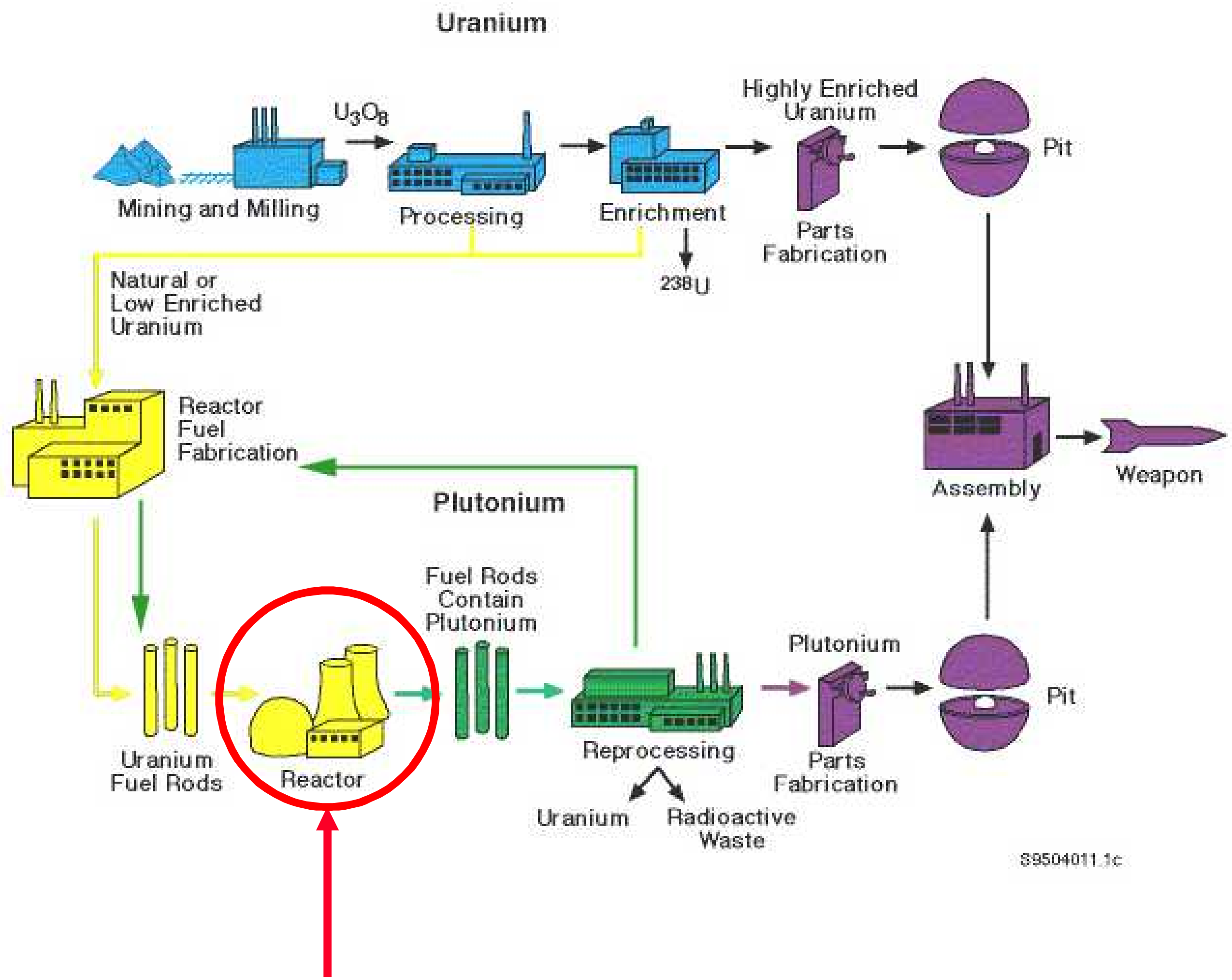
Safeguards Agencies Ensure Fissile Material is Used for Peaceful Purposes

- **Agencies such as the I.A.E.A. track the flow of fissile material through the civil nuclear fuel cycle**
- **Current reactor safeguards involve:**
  - *Checking declarations*
  - *Containment and Surveillance*
  - *Item Accountancy*
- **These are effective, but:**
  - require regular and detailed inspections of the reactor site and records
  - do not directly measure the amount of plutonium produced by a reactor



IAEA has requested member states to develop quantitative, automated, monitoring techniques

Antineutrino Detectors Address One Part Of The Fuel Cycle



Reactor monitoring with antineutrinos touches on only one element in a long fuel cycle

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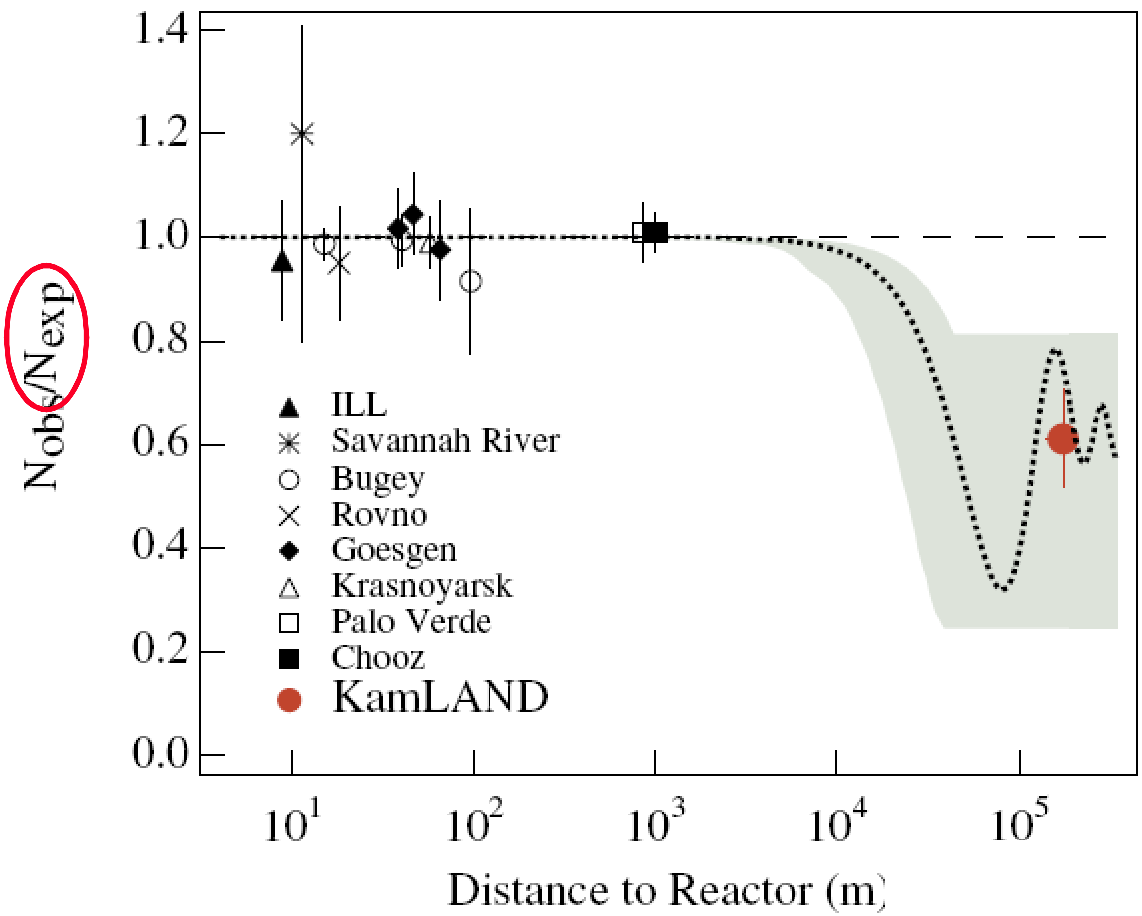
Previous Reactor Antineutrino Experiments

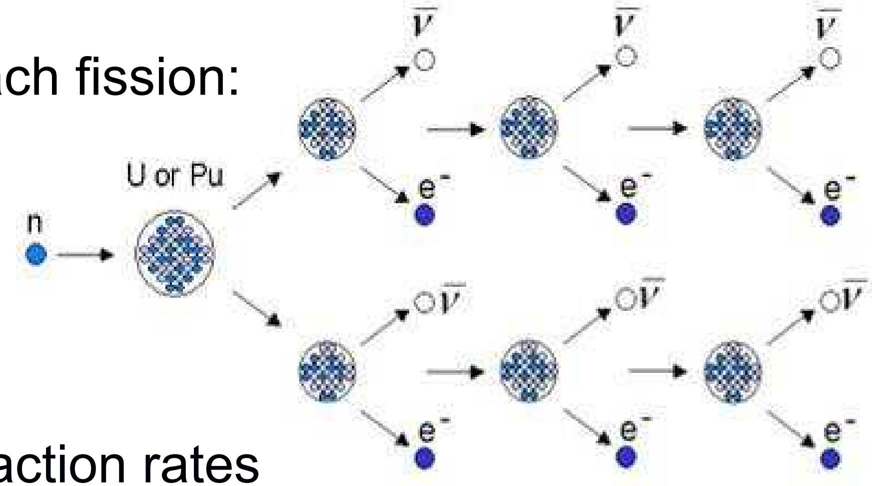


- **Reactors have been used as the source for many oscillation searches**
- **These experiments developed detection technology and an understanding of reactors as an antineutrino source**
- **We seek to invert this, applying the knowledge for a practical purpose**

Reactors Produce Antineutrinos in Large Quantities

- ~ 6 Antineutrinos are produced by each fission:

$$\Rightarrow N_{\bar{\nu}} \propto P_{th}$$



- Antineutrinos interact so weakly that they cannot be shielded, but small detectors have useful interaction rates
  - **0.64 ton** detector, **24.5 m** from **3.46 GW** reactor core
  - 3800 events/day for a 100% efficient detector

- Rate is sensitive to the isotopic composition of the core
  - Detailed reactor simulations show antineutrino rate change of about 5-10% through a 300-500 day PWR fuel cycle, caused by Pu ingrowth

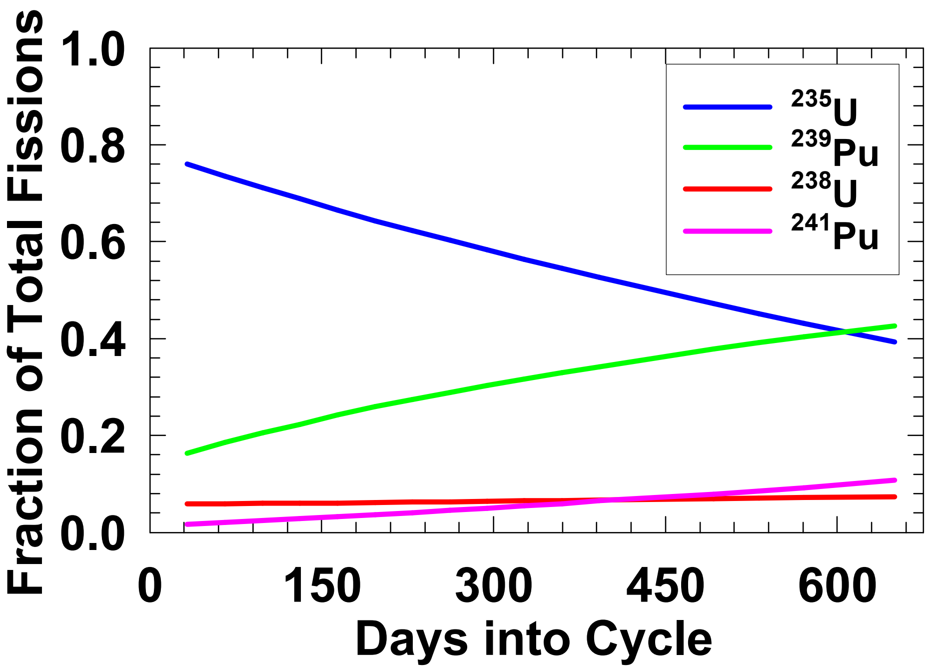
$$N_{\bar{\nu}} = \gamma \left(1 + k\right) P_{th}$$

Constant (Geometry, Detector mass)

Fuel composition dependent
Sum over fissioning isotopes, Integral over energy dependent cross section, energy spectrum, detector efficiency

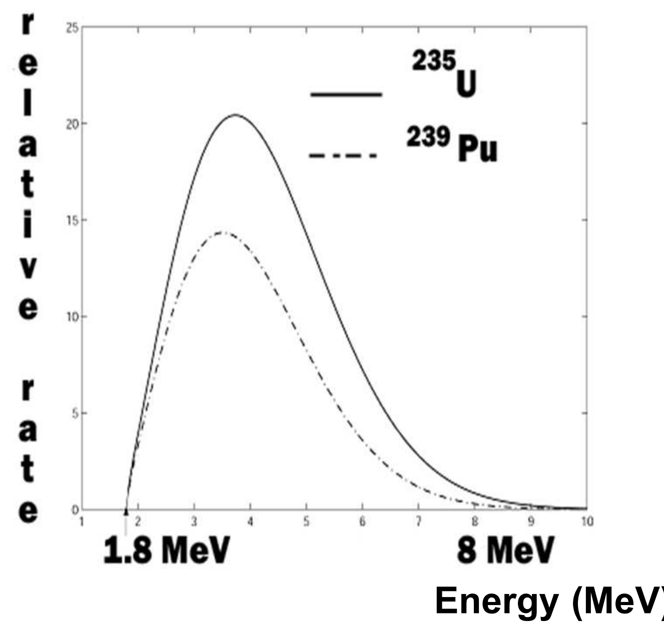
The Antineutrino Production Rate varies with Fissioning Isotope

The fuel of a reactor evolves under irradiation: ^{235}U is consumed and ^{239}Pu is produced



(A. Misner, OSU)

The energy spectrum and integral rate produced by each fissioning isotope is different



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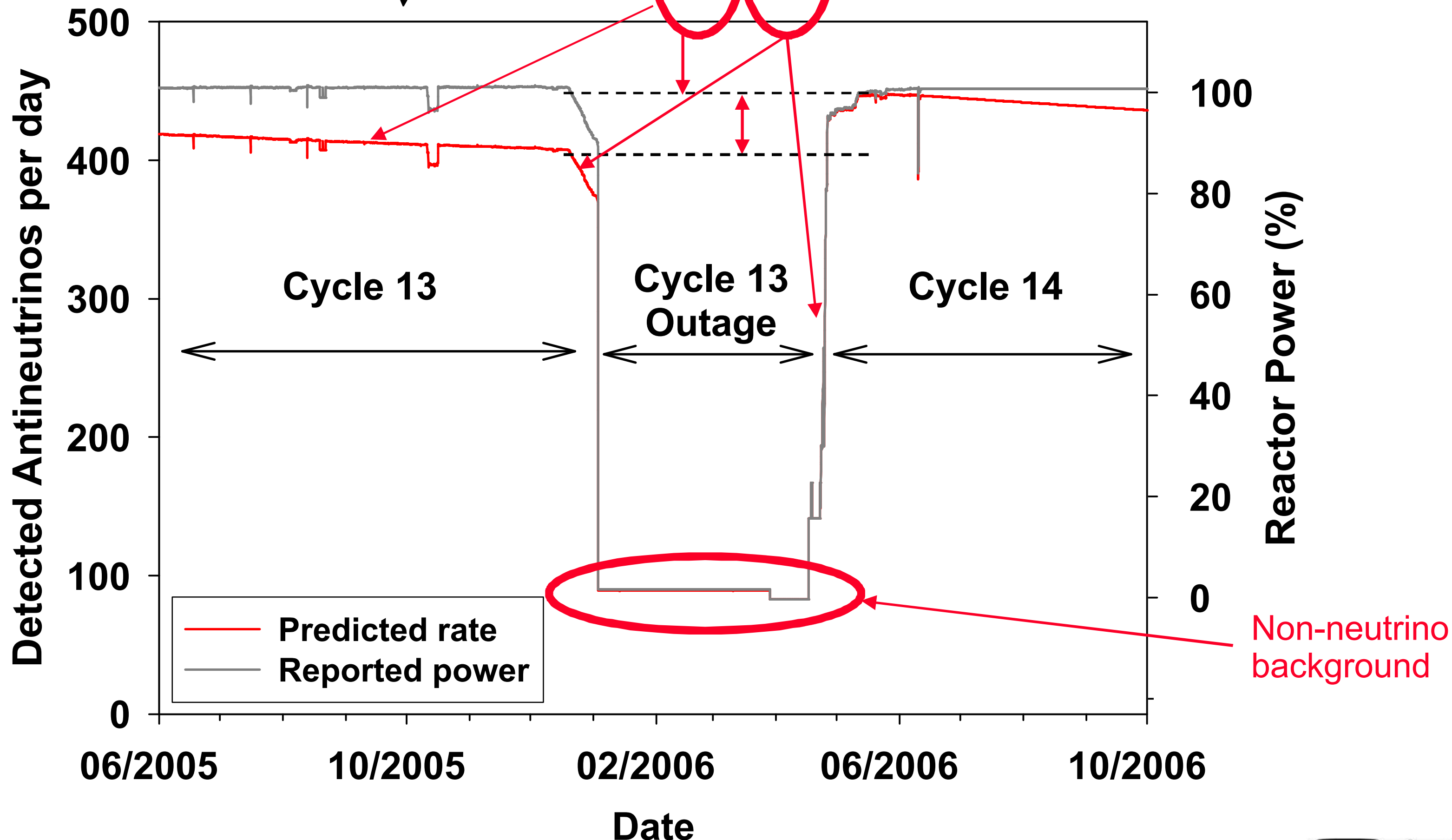
Prediction for our Dataset

$$N_{\bar{\nu}} = \gamma(1+k)P_{th}$$



LLNL (Burnup model - R. Svoboda)

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Antineutrino Safeguards?

- Direct measurements at reactors using antineutrinos could:
  - Verify declarations of power history and plutonium content of spent fuel destined for reprocessing or storage
  - Give early detection of unauthorized production of plutonium outside of declarations
  - Check progress of plutonium disposition, and ensure burnup is appropriate to core type

- Compact antineutrino detectors could provide continuous, non-intrusive, unattended measurements suitable for IAEA and other reactor safeguards regimes

- Utilities might benefit from independent power measurement or knowledge of fuel burnup – this would change the cost-benefit calculus of detector deployment

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20 July 1956, Volume 124, Number 3212

SCIENCE

that work the reaction

$$\nu_- + p^+ \rightarrow \beta^+ + n^0 \qquad (1)$$

and so verifies the neutrino hypothesis suggested by Pauli (*4*) and incorporated in a quantitative theory of beta decay by Fermi (*5*).

a hydrogenous liquid scintillator. The re-

A tentative identification of the free neutrino was made in an experiment performed at Hanford (*1*) in 1953. In that work the reaction

$$\nu_- + p^+ \rightarrow \beta^+ + n^0 \qquad (1)$$

was employed wherein the intense neutrino flux from fission-fragment decay in a large reactor was incident on a detector containing many target protons in a hydrogenous liquid scintillator. The re-

present work was done (*3*). This work confirms the results obtained at Hanford and so verifies the neutrino hypothesis suggested by Pauli (*4*) and incorporated in a quantitative theory of beta decay by Fermi (*5*).

In this experiment, a detailed check of each term of Eq. 1 was made using a detector consisting of a multiple-layer (club-sandwich) arrangement of scintillation counters and target tanks. This

both triads. The detector was completely enclosed by a paraffin and lead shield and was located in an underground room of the reactor building which provides excellent shielding from both the reactor neutrons and gamma rays and from cosmic rays.

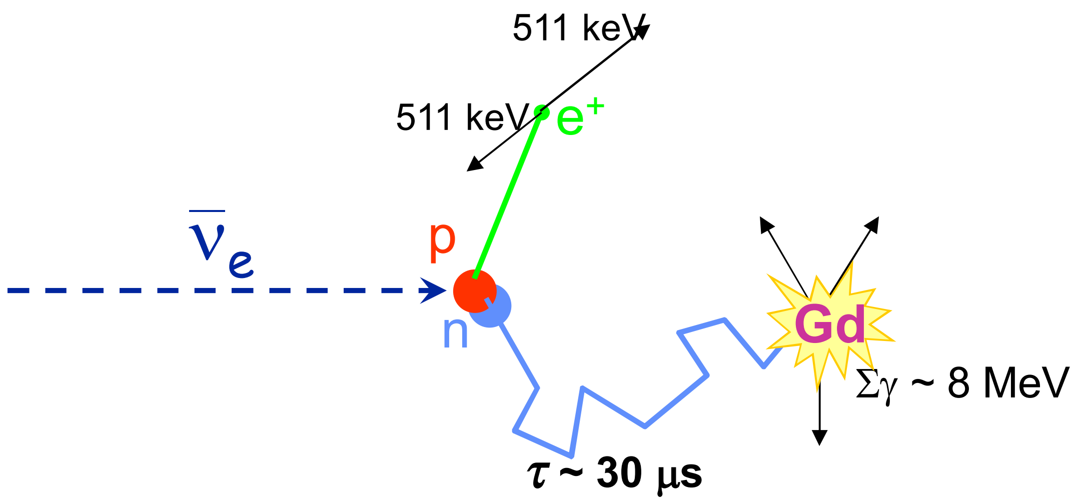
The signals from a bank of preamplifiers connected to the scintillation tanks were transmitted via coaxial lines to an electronic analyzing system in a trailer van parked outside the reactor building. Two independent sets of equipment were used to analyze and record the operation of the two triad detectors. Linear amplifiers fed the signals to pulse-height selection gates and coincidence circuits. When the required pulse amplitudes and coincidences (prompt and delayed) were satisfied, the sweeps of two triple-beam oscilloscopes were triggered, and the pulses from the complete event were recorded photographically. The three beams of both oscilloscopes recorded signals from their respective scintillation tanks independently. The oscilloscopes were thus operated in parallel but with different gains in order to cover the requisite pulse-amplitude range. All am-

Antineutrino Detection

- We use the same antineutrino detection technique used to first detect (anti)neutrinos:

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

  - inverse beta-decay produces a pair of correlated events in the detector – very effective background suppression
- Gd loaded into liquid scintillator captures the resulting neutron after a relatively short time



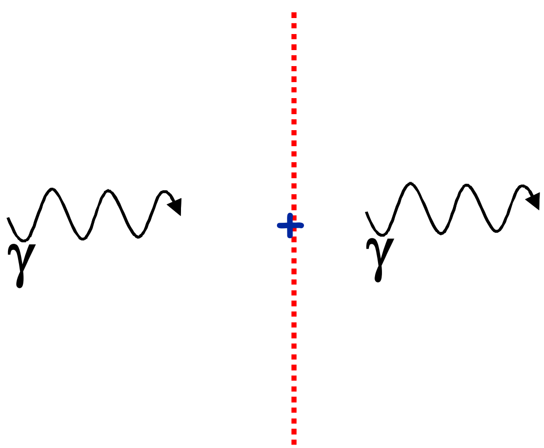
prompt signal + n capture on Gd

- **Positron**
  - Immediate
  - 1- 8 MeV (incl 511 keV γs)
- **Neutron**
  - Delayed (τ = 28 μs)
  - ~ 8 MeV gamma shower

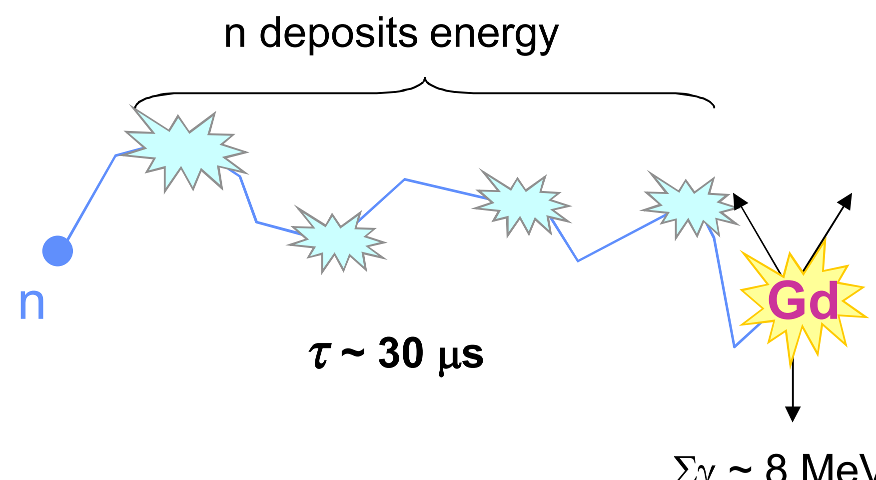
(200 μs and 2.2 MeV for KamLAND)

Backgrounds

- **Uncorrelated Backgrounds**
  - Are the random coincidence of two unrelated events in the detector
  - Have a different time structure to antineutrino interactions
  - Can be reduced by:
    - using radiopure materials
    - Adding gamma and neutron shielding



- **Correlated Backgrounds**
  - Have the same time structure as antineutrino interactions
  - Cosmic ray muons produce fast neutrons, which scatter off protons and can then be captured on Gd
  - Can be reduced by:
    - going underground
    - Tagging muons near the detector
    - Adding neutron shielding



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Deployment Goals/Design Principles

- Previous experiments have demonstrated the physics behind this monitoring concept. Our goal is to demonstrate that such monitoring is possible using a system that is:
  - Automated
  - Noninvasive (must not interfere with reactor operation)
  - Simple (~ 3 FTEs vs. 10-100 for physics expt.)
  - Inexpensive (< 10 PMTs vs. 100-1000 for physics expt.)
- Use well known detection concepts/technology
  - Antineutrino detection via inverse beta decay
  - Gd loaded scintillator
  - central target surrounded by various shielding layers
- Physically robust for reactor environment (e.g. steel scintillator vessels)

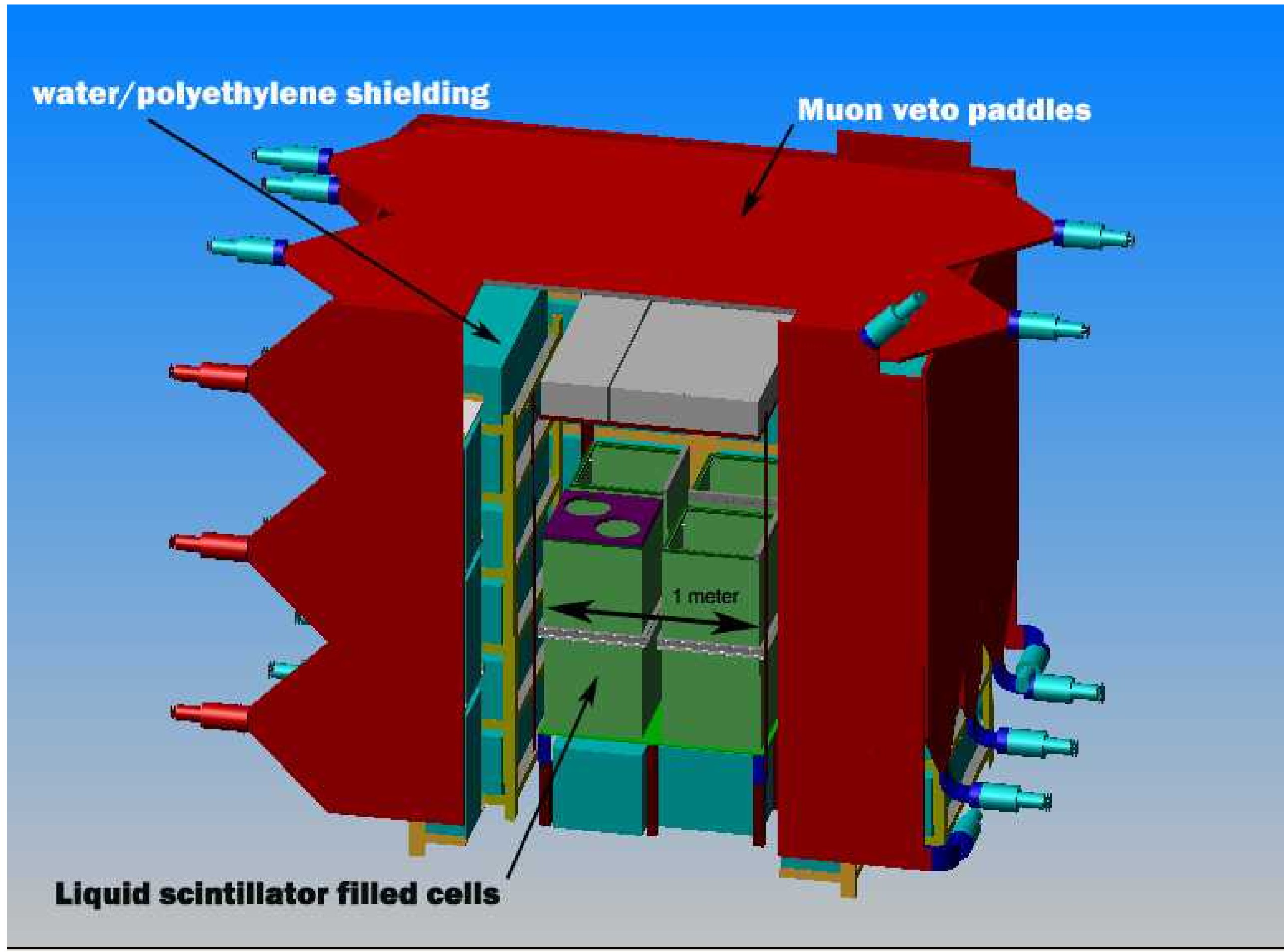
Prototype deployment –
San Onofre Nuclear Generating Station

SONGS Unit 2 Tendon Gallery

- Tendon gallery is ideal location
  - Rarely accessed for plant operation
  - As close to reactor as you can get while being outside containment
  - Provides ~20 mwe overburden
- 3.4 GW_{th} => 10^{21} ν / s
- In tendon gallery ~10^{17} ν / s per m^2
- Around 3800 interactions expected per day (~ 10^{-2} / s)

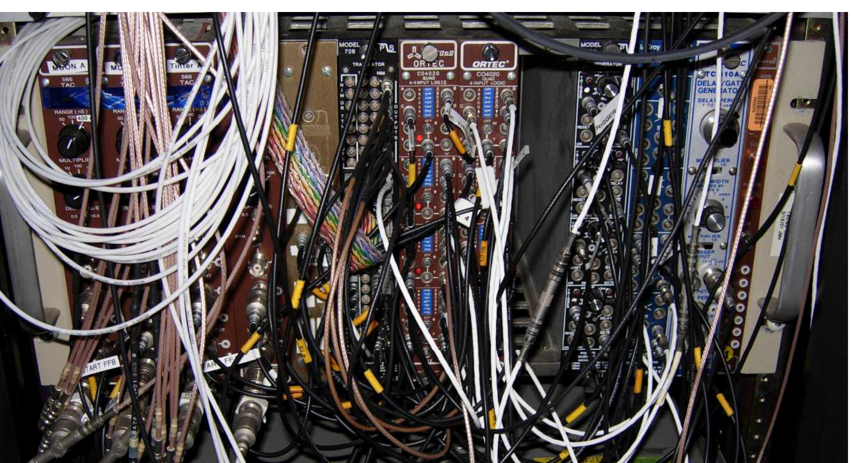
Sandia/LLNL Antineutrino Detector

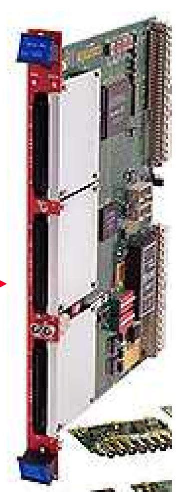
- Detector system is…
  - ~1 m^3 Gd doped liquid scintillator readout by 8x 8” PMT
  - 6-sided water shield
  - 5-sided active muon veto



Readout

- Currently based upon standard NIM/VME
  - Items that were available, rather than ideal
- Care must be taken to efficiently measure intervals
  - Analog TACs have long reset times
- Pairs of TACs and ADCs are used to reduce deadtime





- All logic and timing has been incorporated onto V1495 FPGA card

Installation at SONGS

Installation at SONGS

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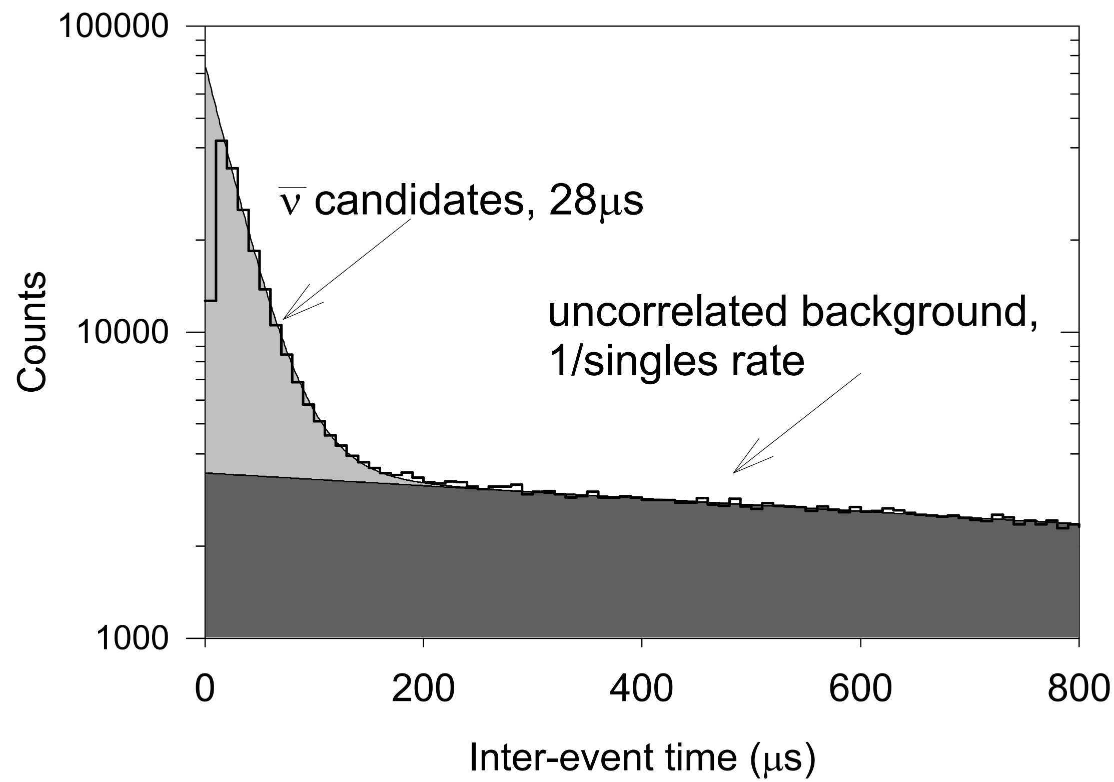
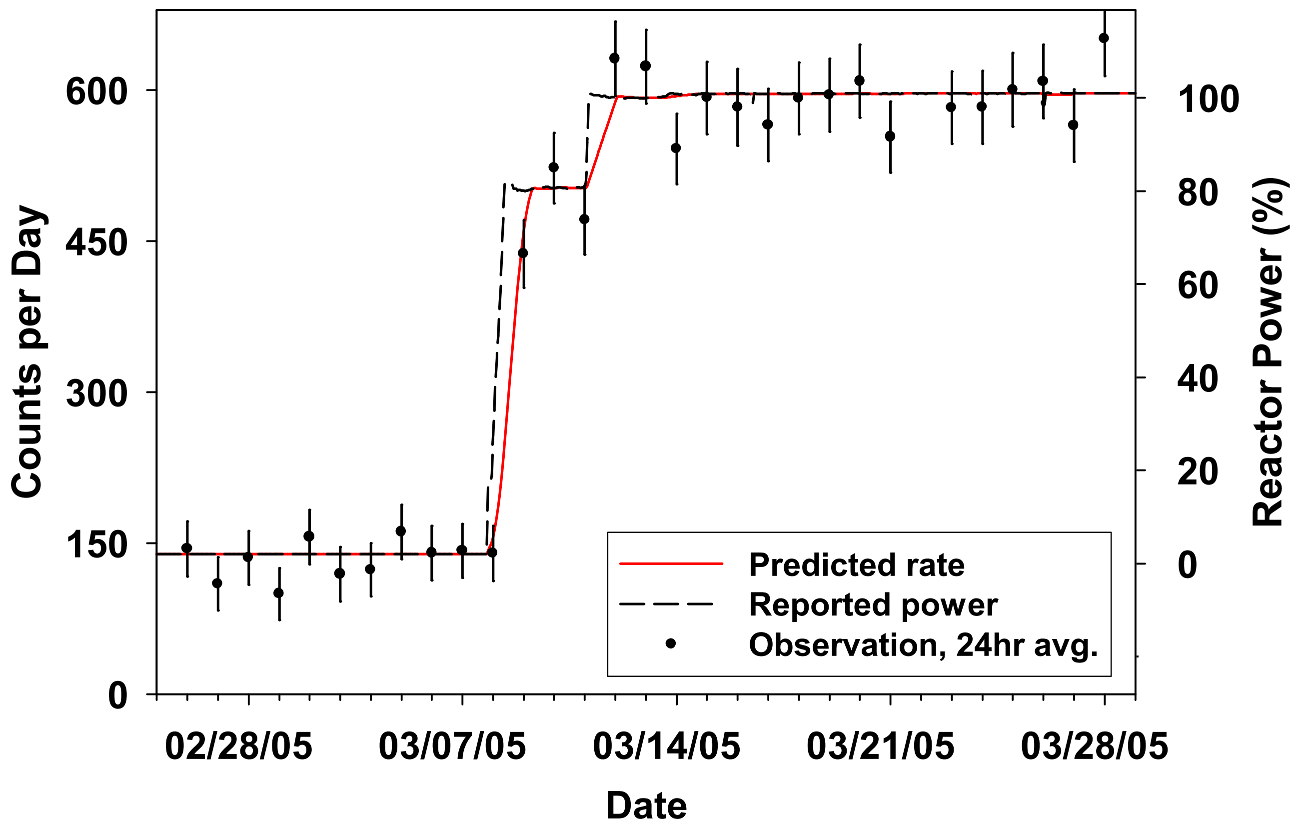
Candidate event extraction

- We record ~30 million events per day, only a handful of which are antineutrino interactions
- An automatic energy calibration is performed using background 2.6 MeV gamma
- Cuts are applied to extract correlated events:
  - energy cuts
    >2.5 MeV prompt
    >3.5 MeV delayed
  - at least 100μs after a muon in the veto detector
- Examine time between prompt and delayed to pick out neutron captures on Gd

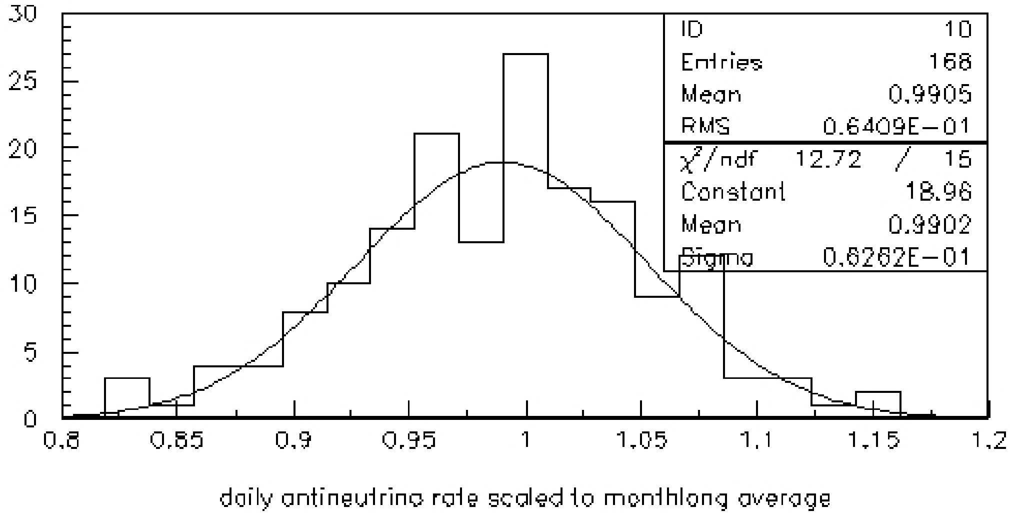


Reactor Monitoring using <u>only</u> $\bar{\nu}$

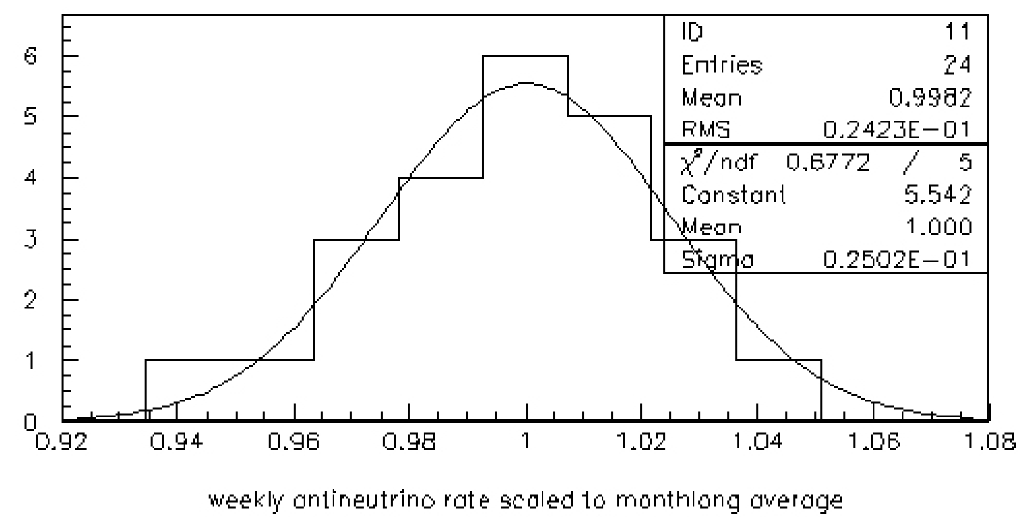


- In this example, the reactor is restarted after unscheduled maintenance
- The reactor off period allows us to measure the correlated background rate
- Large power changes are readily observed with no connection to the plant except antineutrinos

Relative power monitoring precision



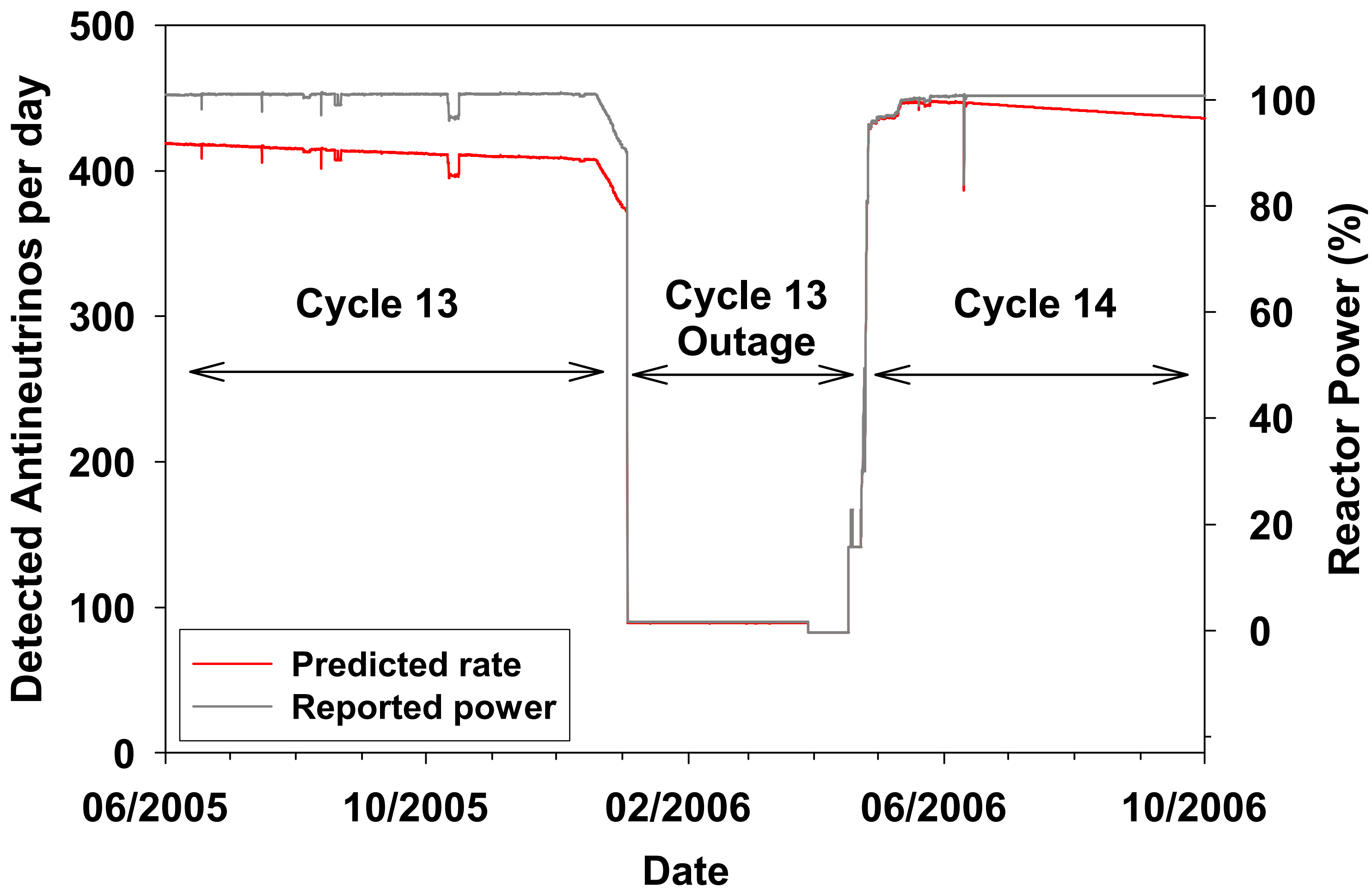
Daily average
6.2% relative uncertainty
in thermal power estimate
(normalized to 30 day avg.)



Weekly average
2.5% relative uncertainty
in thermal power estimate
(normalized to 30 day avg.)

(A. Bernstein)

Prediction for our Dataset



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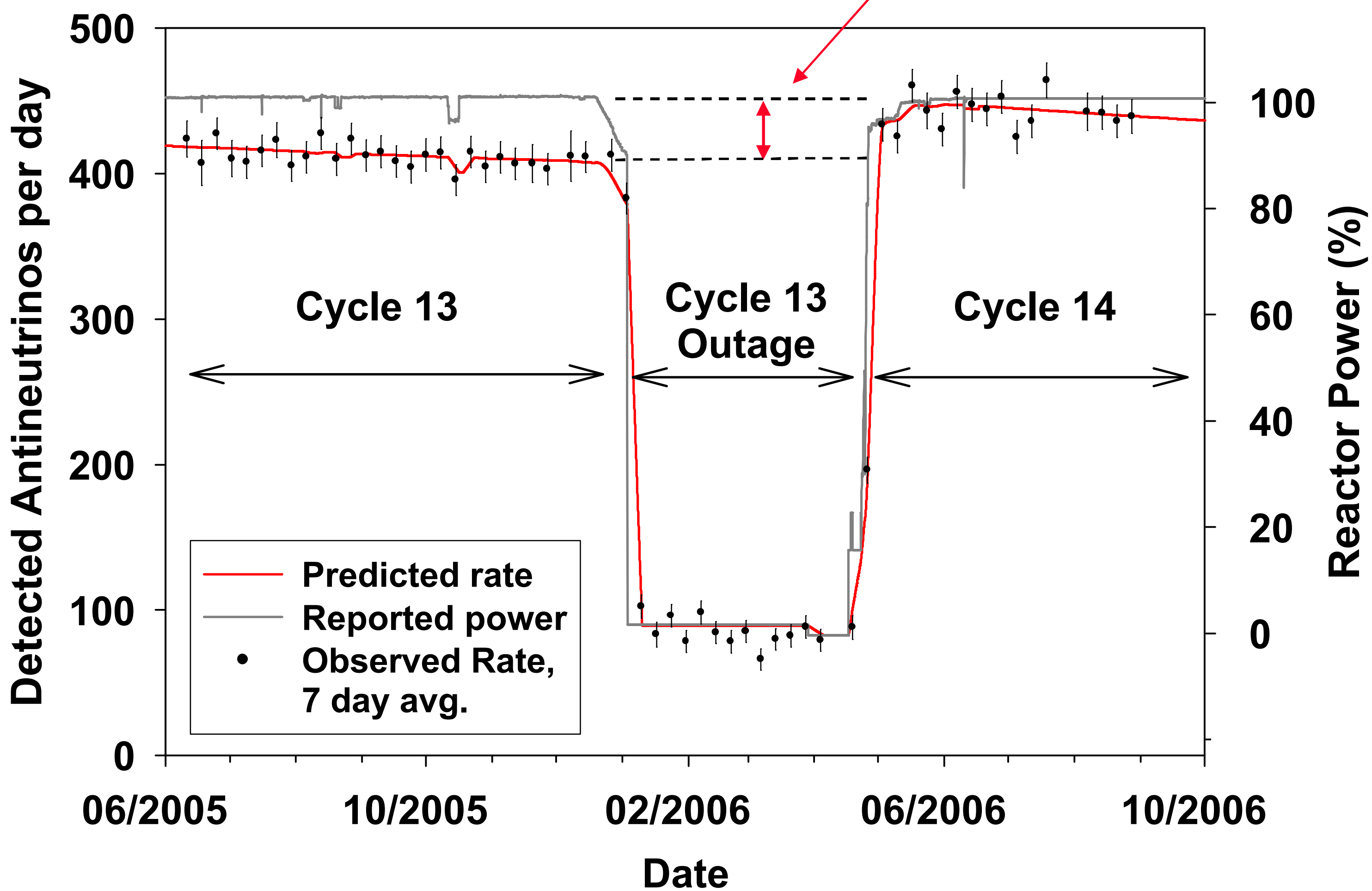
Our Dataset

- Removal of 250 kg ^{239}Pu, replacement with 1.5 tons of fresh ^{235}U fuel



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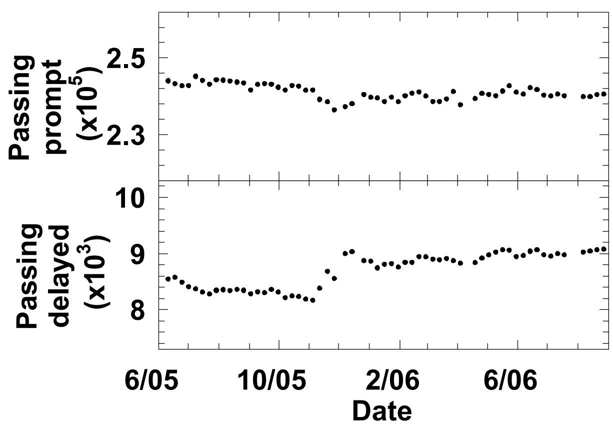
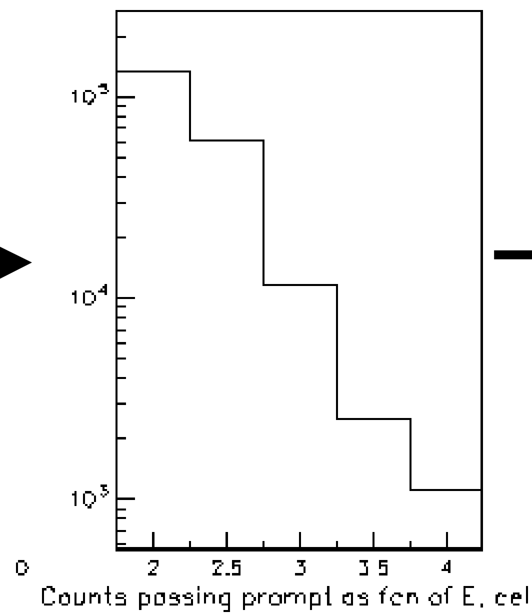
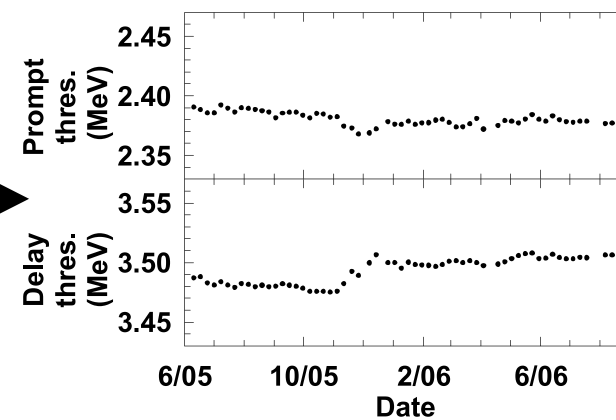
Detector Stability

- **To observe the effect of fuel burnup, we must ensure that our detector is stable over the data taking period**
- **We count the number of events passing the energy cuts, and from this estimate the effectiveness of energy calibration.**







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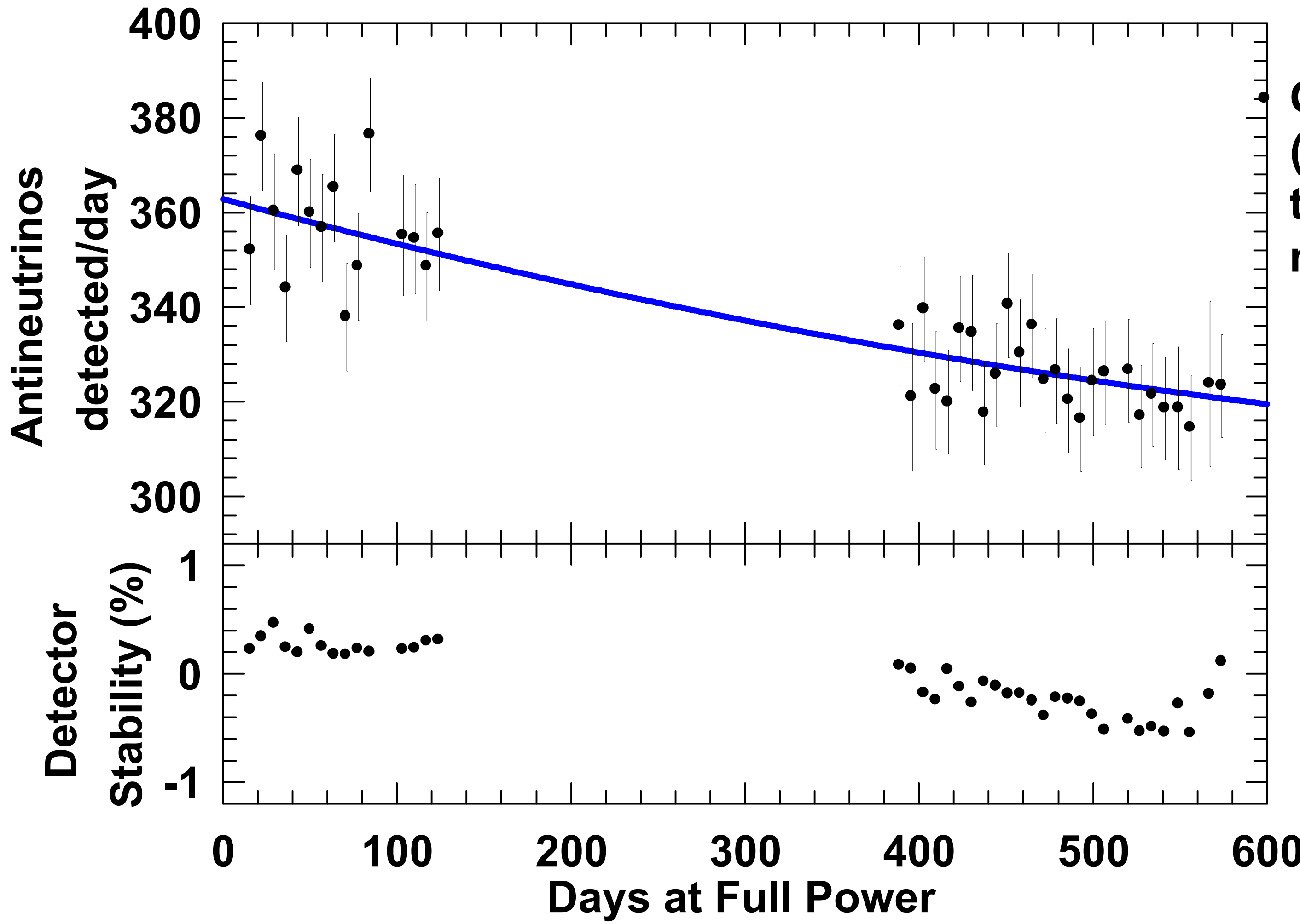
Burnup Measurement



- One parameter (normalization) fit to our burnup model

  (Consumption of 1.5 tons of ^{235}U
  Production of 250 kg of ^{239}Pu)

- Detector is stable to ~ 1%; burnup is ~ 10%

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Neutrino Oscillations

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta} & s_{23}c_{13} \\ s_{12}s_{23} - c_{12}c_{23}s_{13}e^{i\delta} & -c_{12}s_{23} - s_{12}c_{23}s_{13}e^{i\delta} & c_{23}c_{13} \end{pmatrix} \begin{pmatrix} \nu_1 \\ e^{i\phi_2}\nu_2 \\ e^{i\phi_3}\nu_3 \end{pmatrix}$$

$$= \begin{pmatrix} 1 & & \\ & c_{23} & s_{23} \\ & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & & s_{13}e^{-i\delta} \\ & 1 & \\ -s_{13}e^{i\delta} & & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & \\ -s_{12} & c_{12} & \\ & & 1 \end{pmatrix} \begin{pmatrix} \nu_1 \\ e^{i\phi_2}\nu_2 \\ e^{i\phi_3}\nu_3 \end{pmatrix}$$

$\sin^2(2\theta_{23}) \sim 1$

Measured using atmospheric ν (Super K), ν beams (K2K, MINOS)

$\sin^2(2\theta_{13}) < 0.2$

Constrained by Chooz using Reactor ν

$\sin^2(2\theta_{12}) \sim 0.8$

Measured using solar ν, Reactor ν (KamLAND)

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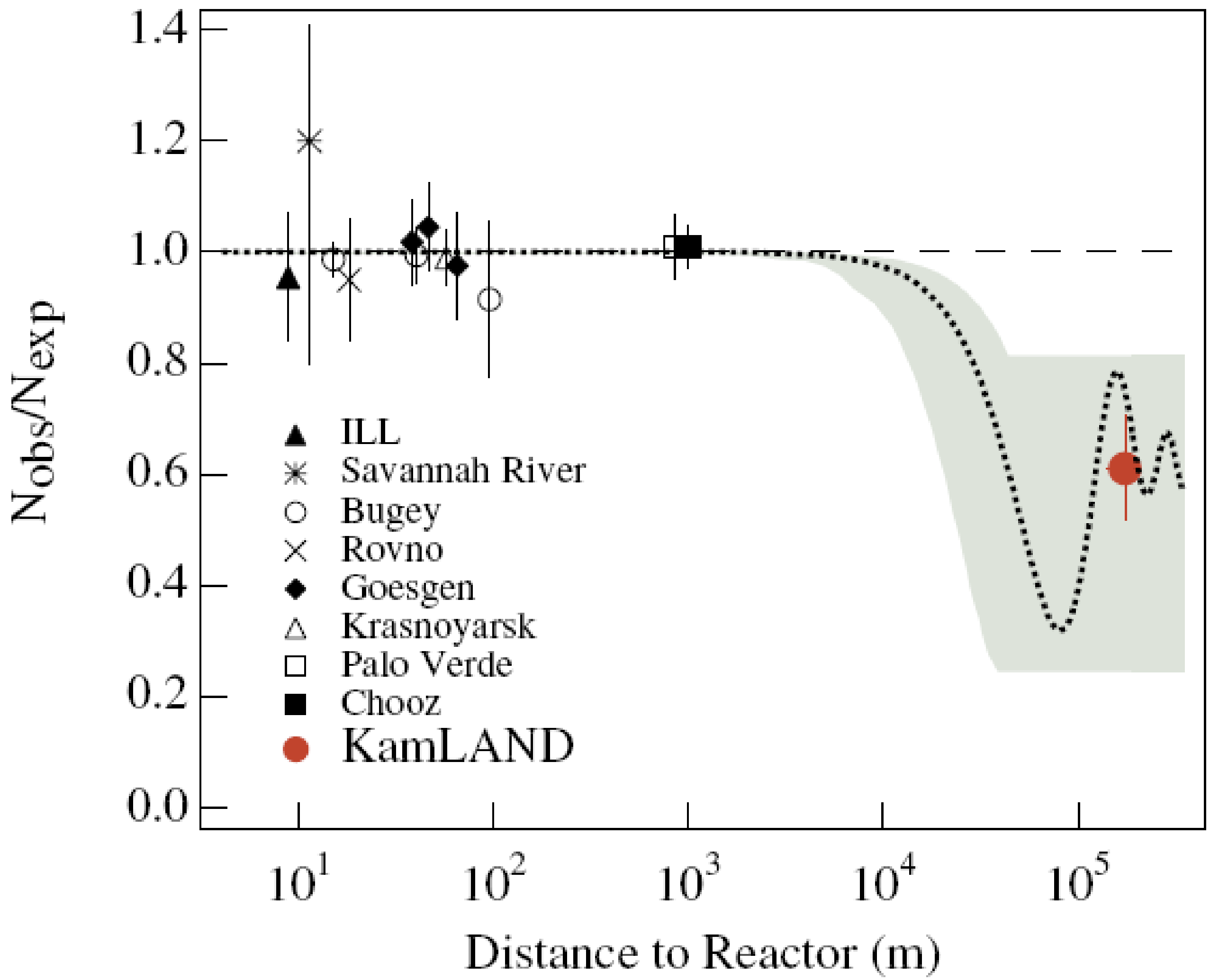
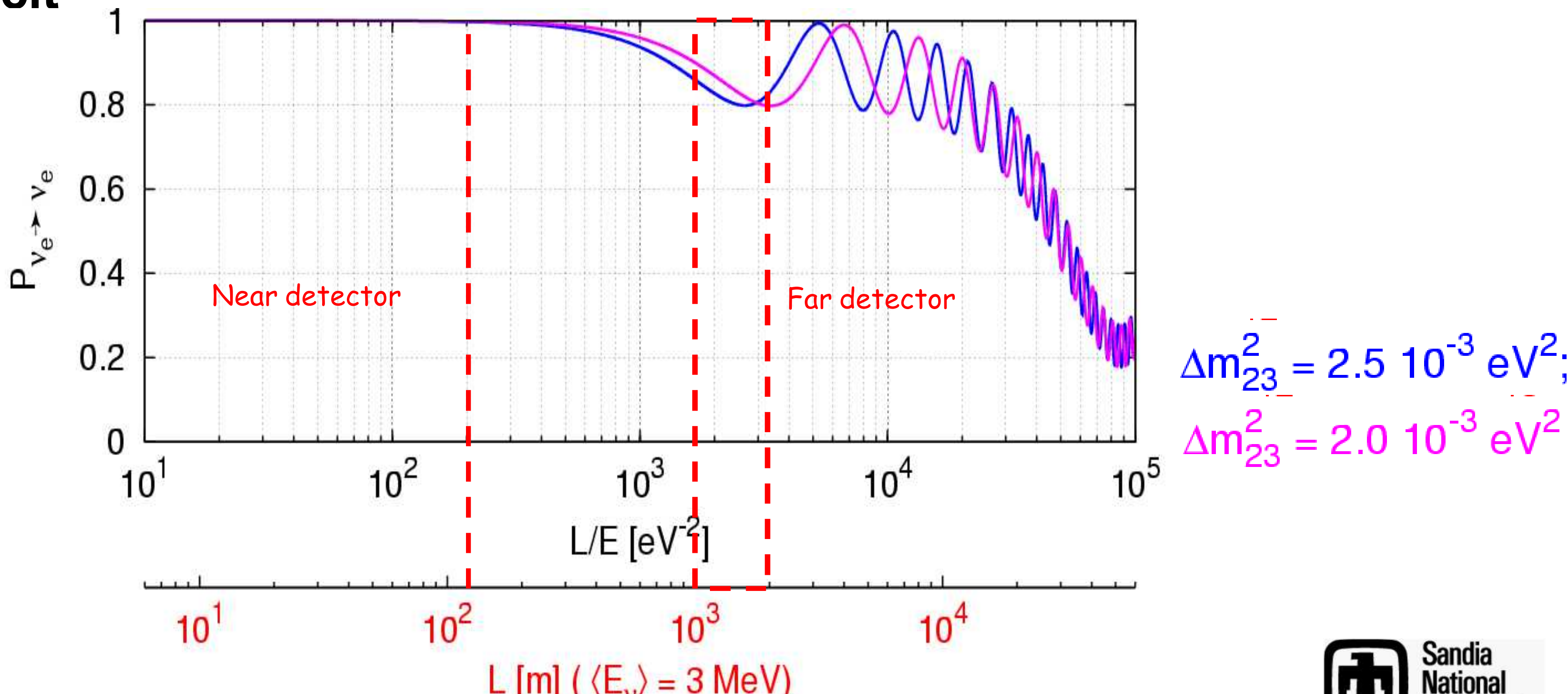
Previous Reactor Antineutrino Experiments



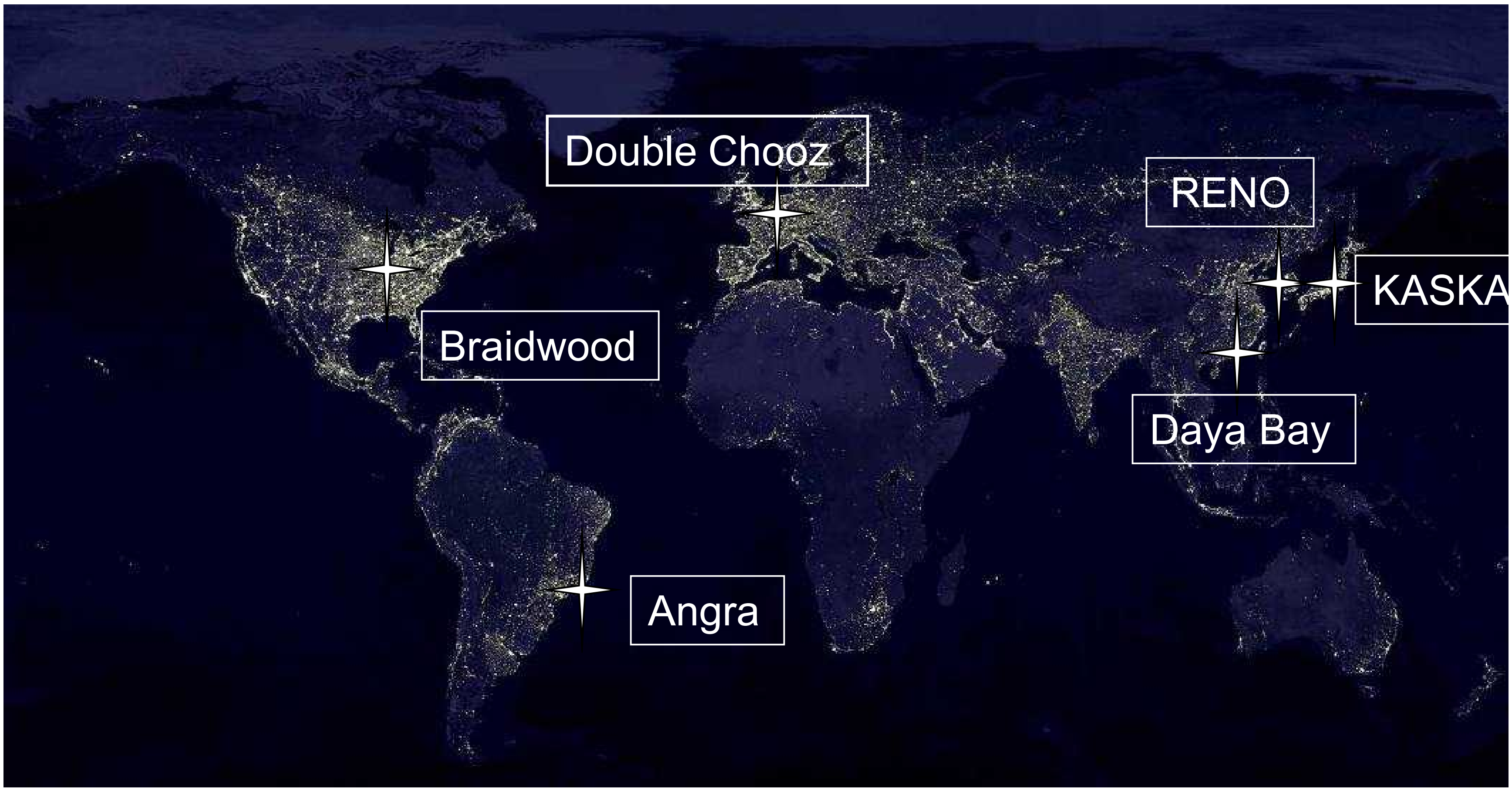
Overlap with current physics – proposed measurements of θ_{13}

- In previous experiments (Palo Verde, Chooz) the largest systematic uncertainty was knowledge of antineutrino flux from reactor
  - Eliminate by having two (identical) detectors – one near to measure the flux pre-oscillation and one at ~ 1km to measure deficit

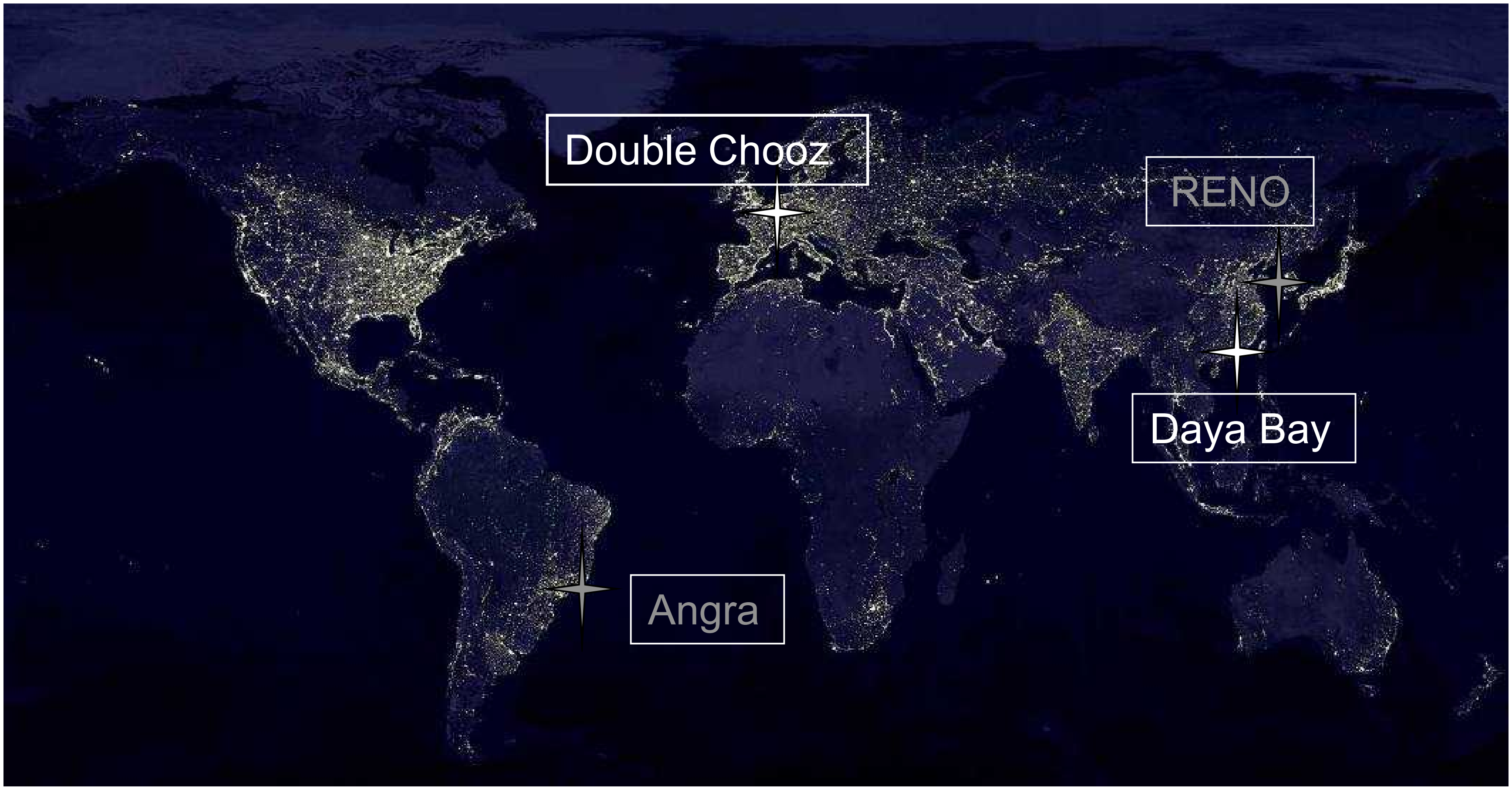


G. Mention, Double Chooz Colab.

Proposed Sites for a θ_{13} experiment



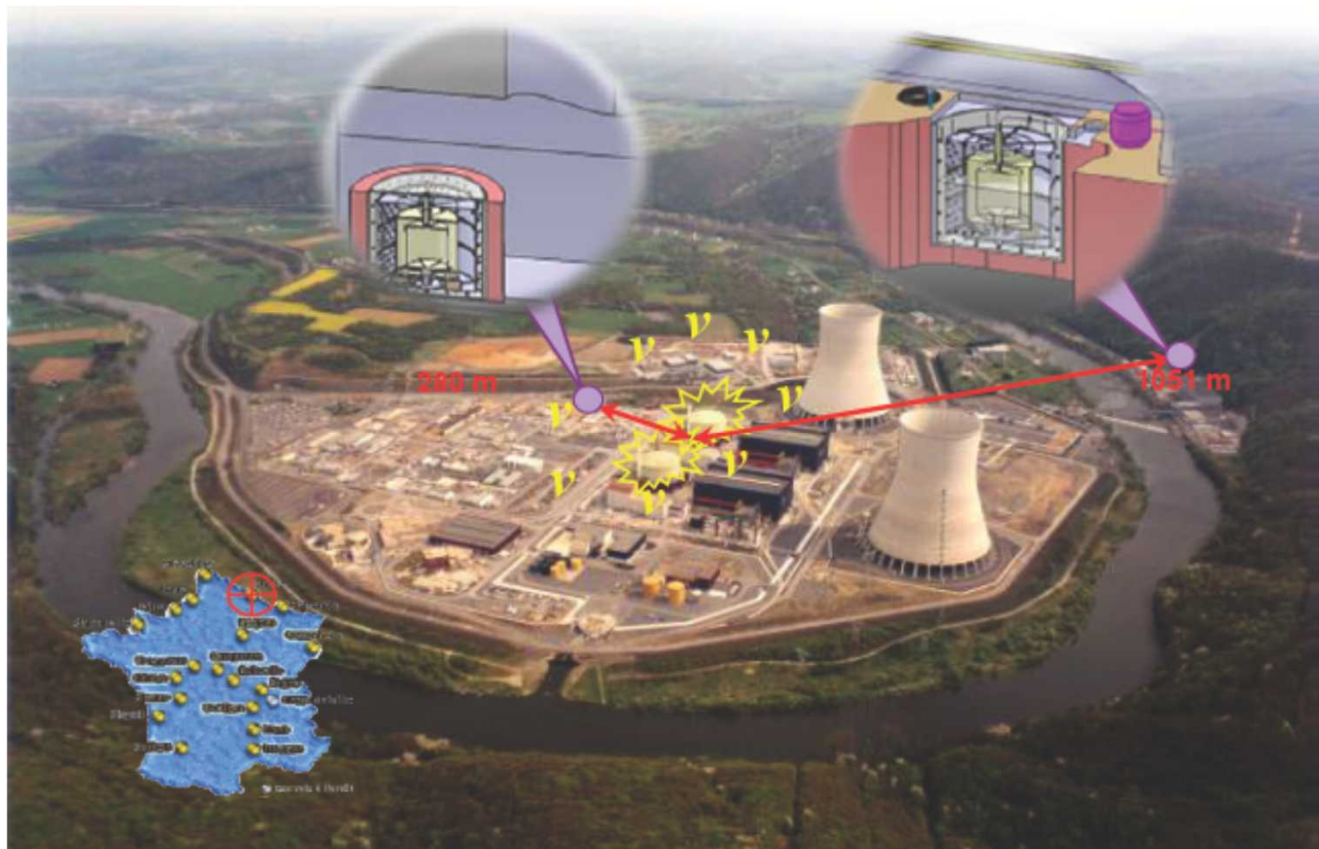
Confirmed Sites for θ_{13} experiments



Double Chooz Experiment

- Uses existing far cavity for a fast, inexpensive theta13 search
- Two identical detectors at ~280 m and 1 km

- Extensive detector development, e.g. less flammable liquid scintillator
- Near detector will provide an excellent (absolute) rate and spectral measurement



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What Would It Take for the IAEA to Adopt this Method?

- Antineutrino monitoring could provide:
  - A fissile inventory measurement early in the fuel cycle
  - Verification of operator power and inventory declarations
  - Reduced frequency of inspection visits
  - Reduction in reliance on surveillance and bookkeeping

But there are uncertainties:

- Footprint may be too large
  - Shielding makes up 80% of footprint in current design
- Not enough reactors with suitable deployment locations?
  - Possible to deploy on surface?
- IAEA may have more pressing safeguards problems

IAEA has expressed recent interest in our results

Conclusion

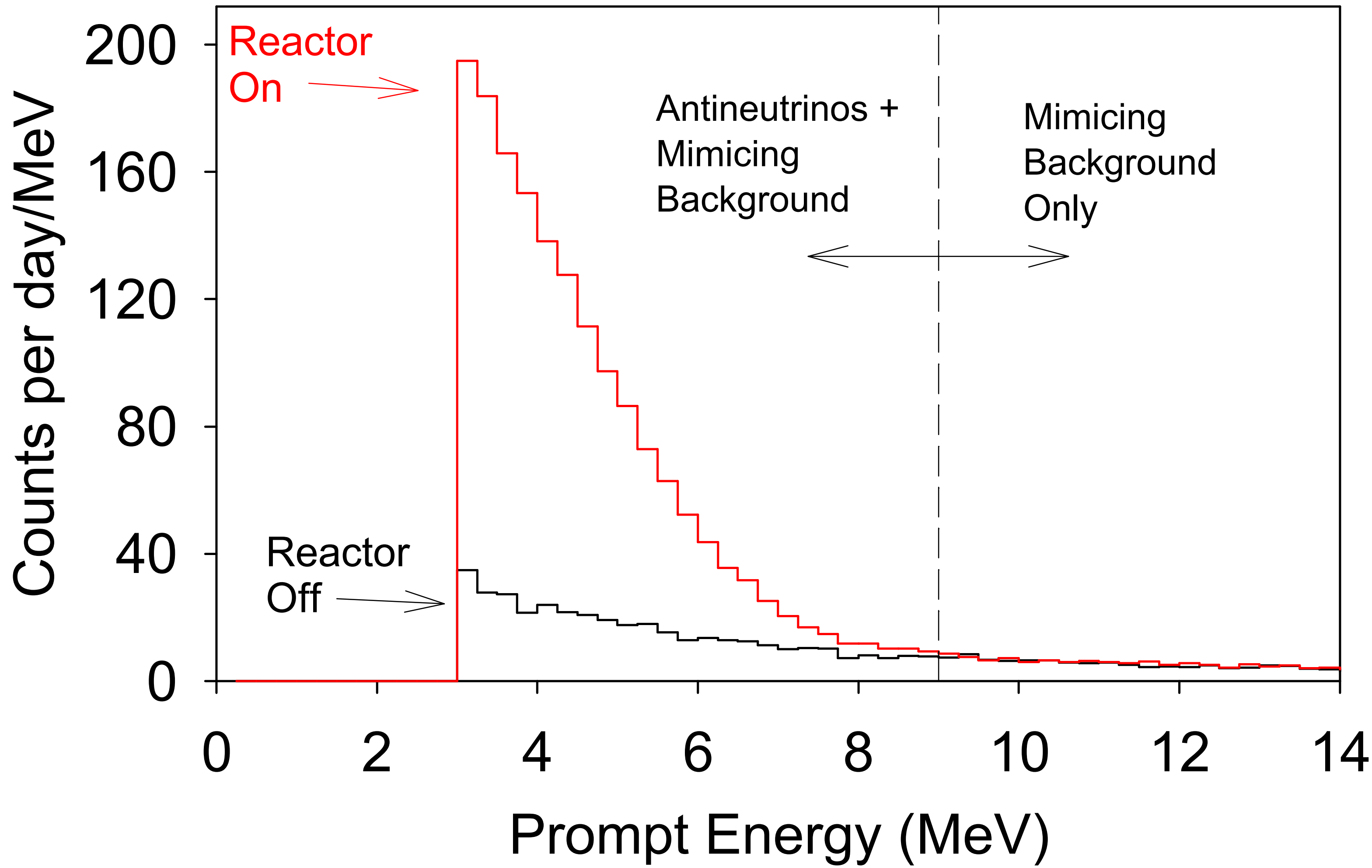
- **Antineutrino detectors can be used to monitor nuclear reactors remotely and non-invasively**
  - **This has been firmly established by prior experiments and has been demonstrated by our collaboration with a more practical/simple device**

- **The technology may fill an important niche by providing quantitative measurements early in the fuel cycle**
  - **But IAEA must be convinced that it really improves their regime**

- **Strong overlap with detector development for next generation of neutrino oscillation experiments (θ_{13})**

- **Ongoing effort:**
  - **Shrink footprint and improve efficiency**
  - **Quantify benefits relative to existing safeguards methods**

Clear indication of antineutrino detection



SONGS1 Efficiencies

We estimate:

- DAQ efficiency: 58%
  - Muon deadtime, shortest time measured between events is 10μs
- Positron detection (2.45 MeV cut): 55%
  - High uncorrelated background rate <2.45 MeV
- Neutron detection : 40%
  - Poor containment of Gd shower with only $1m^3$ ($0.25\ m^3$)
- Fiducial Volume: <u>60%</u>

- Total: 8%

Figure of Merit: Detected $\bar{\nu}$/ Total Volume

$400/day/20\ m^3 = 20\ \bar{\nu}\ /\ m^3\ day$

SONGS~~1~~2 Efficiencies

We estimate:

• DAQ efficiency:	~~58%~~	85%
• Positron detection (1.5 MeV cut?):	~~55%~~	65%
• Neutron detection :	~~40%~~	50%
• Fiducial Volume:	~~60%~~	95%
• Total:	~~8%~~	26%

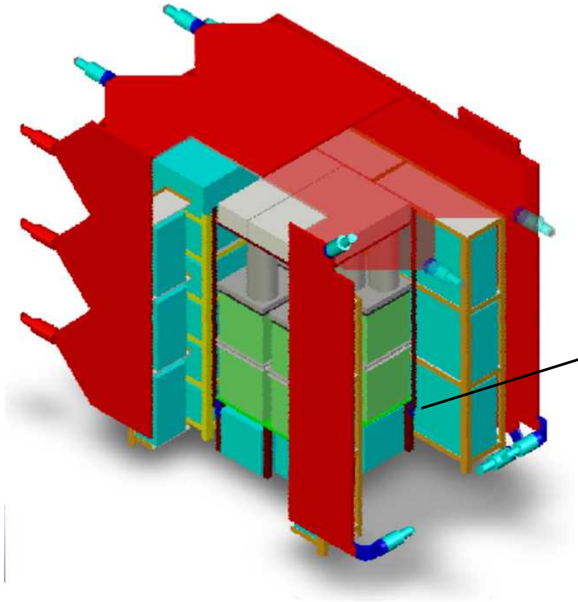
Figure of Merit: High: 1300/day/4.5 m^3 = 280 $\bar{\nu}$ / m^3 day

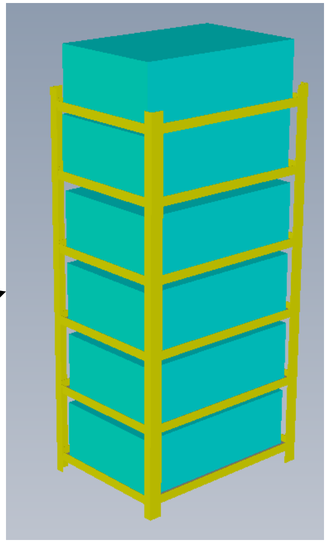
Low: 800/day/8.0 m^3 = 100 $\bar{\nu}$ / m^3 day

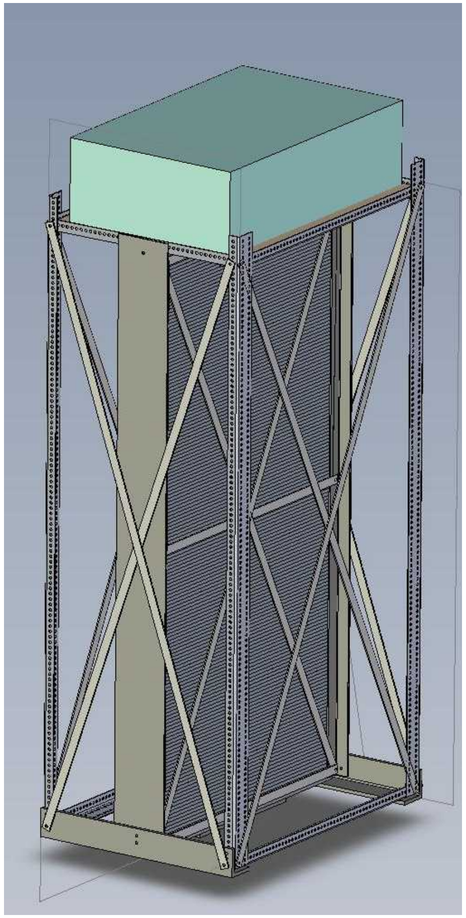
400/day/20 m^3 = 20 $\bar{\nu}$ / m^3 day

Validate use of steel shielding

- **Must be careful not to increase correlated background (reactor off background) by the introduction of high Z material**
- **Replace one wall of water shield with steel in CY06 to test**

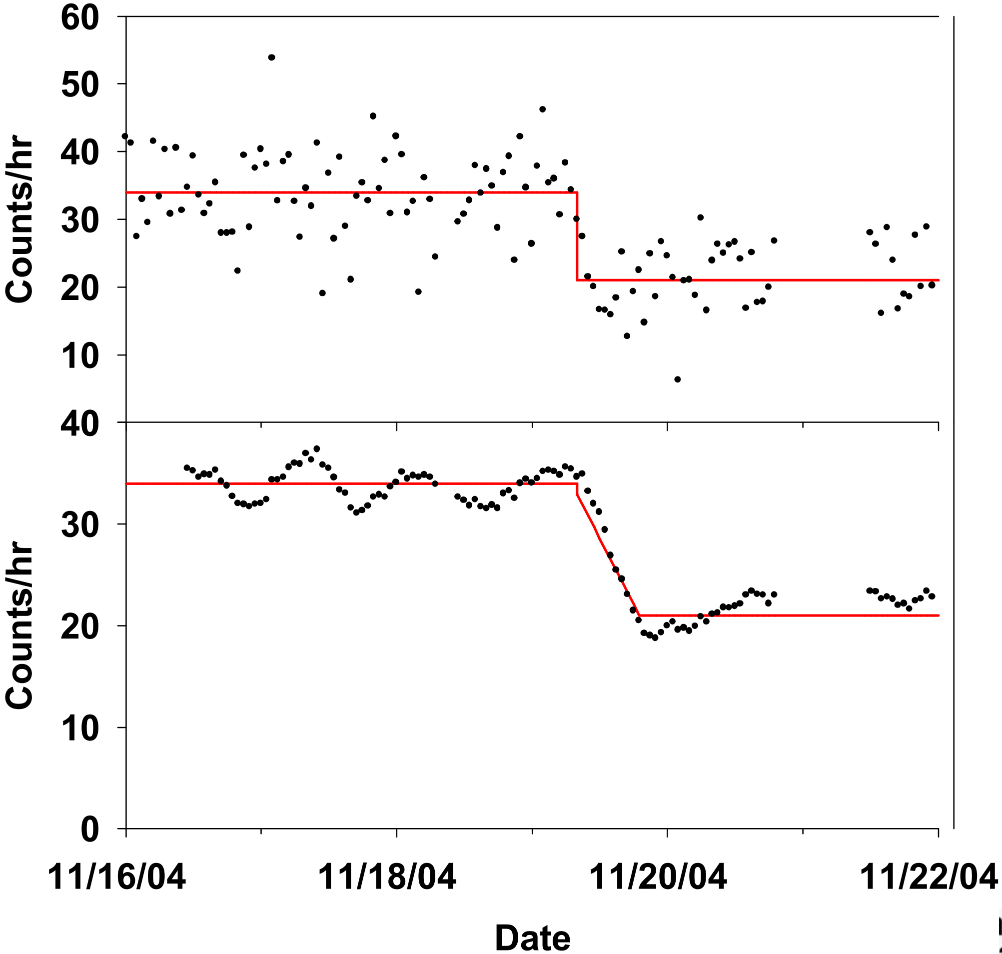






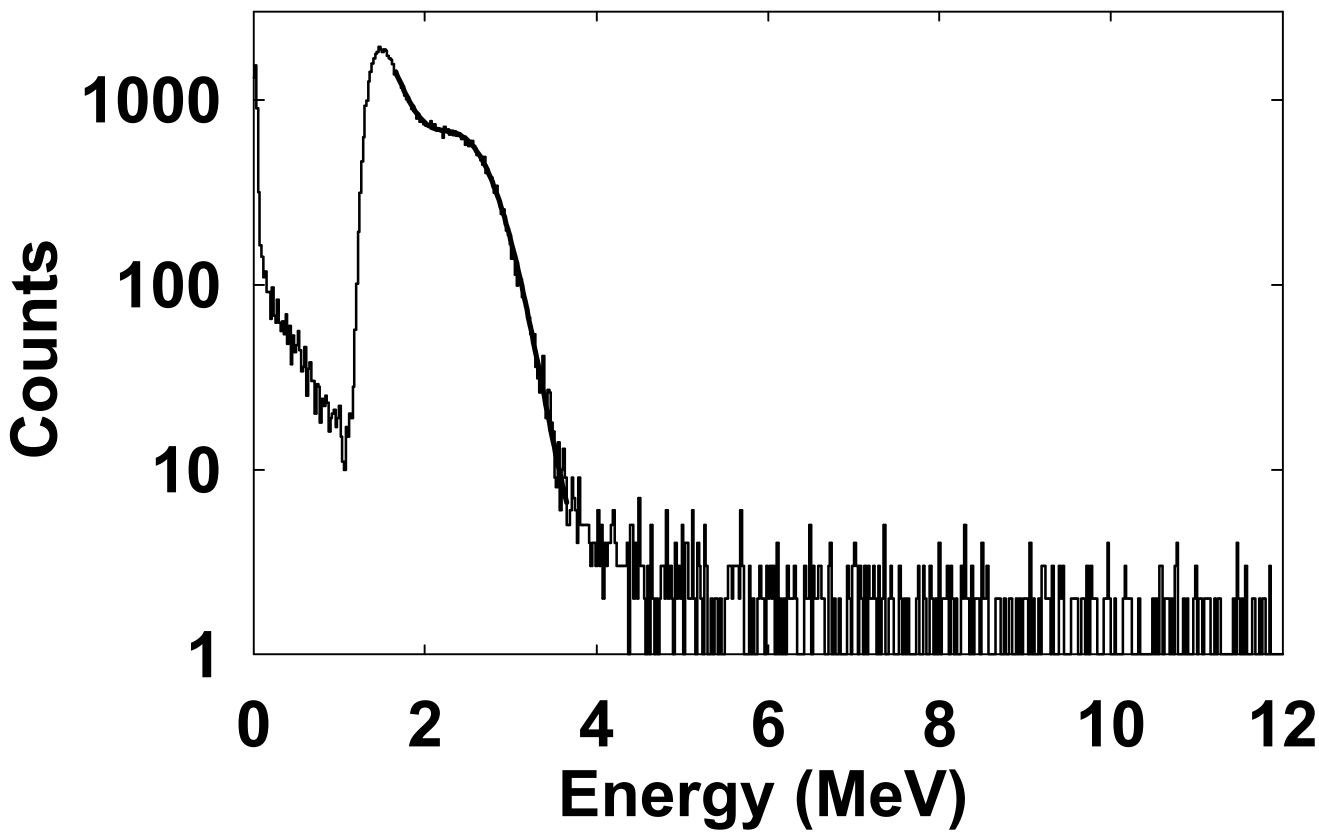
A Reactor Scram

- A reactor scram can be identified in a few hours



Calibration

- **An automatic energy calibration is performed using the 2.6 MeV line from the Th chain**
  - **this relatively simple procedure is sufficient**



Some History

- Began at Sandia (Bernstein – LDRD?) 1999
- First background measurements at SONGS in 2000
- Detector Installation at SONGS 2002-2003 (0.5 m^3)
- Data taking began late 2003
- First confirmation of ν detection during Feb. 2004 outage
- Full target installation July 2004