Dark Matter, Neutrinos and Nonproliferation: Advanced Detectors for Nuclear Security and their Relevance for Fundamental Physics

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www.llnl.gov/neutrinos

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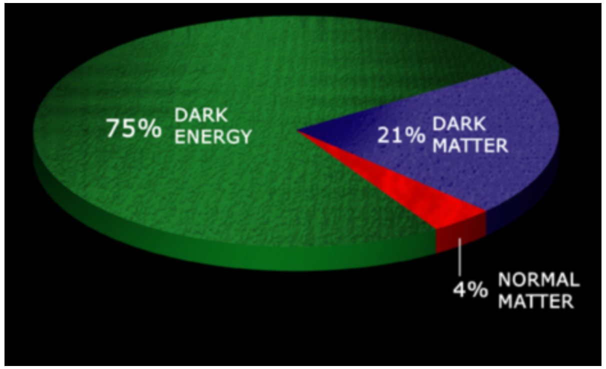
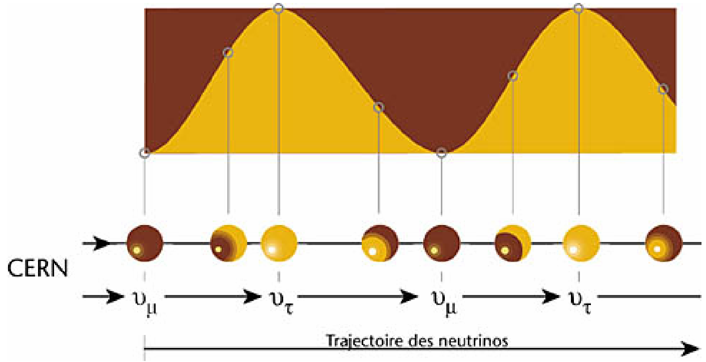
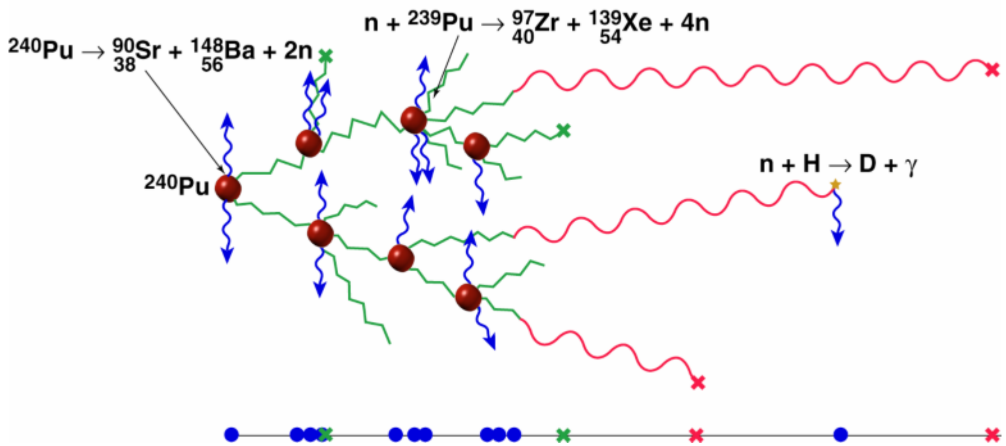
Neutral Particle Detection is Essential to both Particle Astrophysics and Nuclear Security

Dark Matter and Neutrino Experiments require exquisite sensitivity for finding neutral particles (WIMPS, neutrinos)





The need to control of Nuclear Materials drives us to create detectors for measuring the penetrating radiations from fissile and radioactive decay (gammas, neutrons, antineutrinos)



A fission chain initiated by ^{240}Pu (antineutrinos not shown)

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The Nuclear Security Problem Writ Large

Find all the "Special Nuclear Material" (read: Highly Enriched Uranium and Plutonium) in the world, and track it or eliminate it as best we can

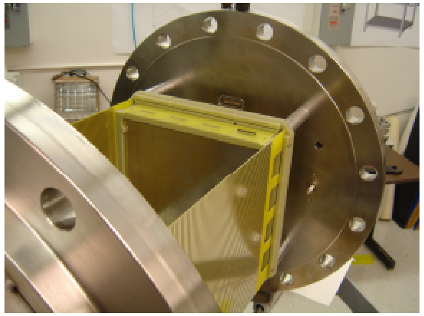
- **International Atomic Energy Agency IAEA *Safeguards***: Verify that civil material is not transferred to weapons programs – part of the Nuclear Nonproliferation Treaty
- **Arms/materials reductions** – drawdown of nuclear weapons and materials in weapons states – e.g. Plutonium Disposition Agreements, Fissile Material Cutoff Treaty, Strategic Offensive Reductions Treaty
- **National Technical Means** – Detection capabilities deployed by individual nations

Approximate Worldwide Inventories **(source - isis.org)**	**Where is it**	**Approximate Equivalent in Number of Nuclear Weapons**
1,830,000 kg of Pu	Most in civil spent fuel, several hundred tons of *separated Pu* in global civil and military stockpiles	**230,000** (@ 8 kg Pu per weapon)
1,900,000 kg of HEU	mostly in military stockpiles -	**60,000** (@ 25 kg HEU per weapon)

Our Group works at the intersection between Nuclear Security and Particle Astrophysics

Light Gas

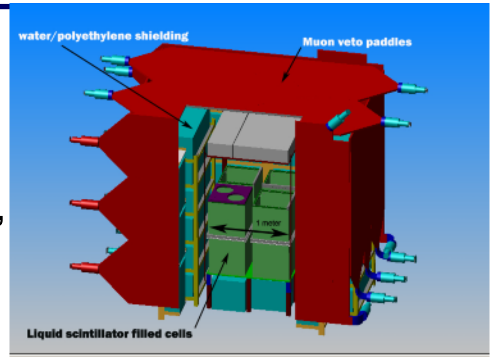
Time Projection Chambers



Mike Heffner, Celeste Winant, Adam Bernstein LLNL
Leslie Rosenberg, UW – Norm Madden – at large

Antineutrino Monitoring of Reactor Cores

Adam Bernstein/Steve Dazeley,
LLNL ADG
Nathaniel Bowden, SNL



Superconducting Calorimetric Gamma and Neutron Spectrometers

Stefan Friedrich,
LLNL ADG

Doped Water Detectors

Bob Svoboda,
LLNL/UC Davis
Hank Sobel/ Mark Vagins UCI
Adam Bernstein/Steve Dazeley LLNL

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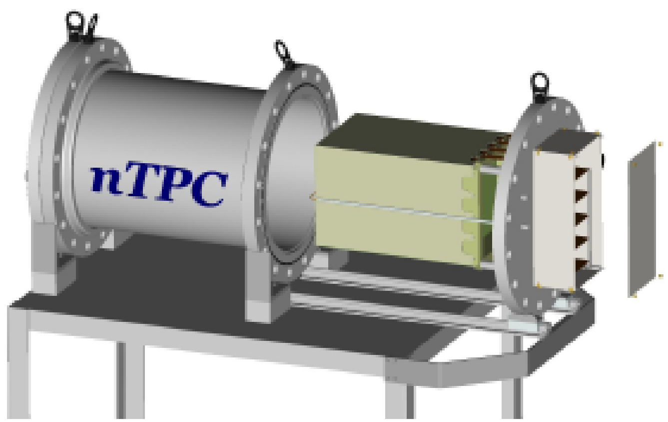
Neutron Time Projection Chambers May Be Able To Locate Plutonium Passively In The Field

Pu has a high rate of MeV-scale neutrons - ~60,000 per kg per second

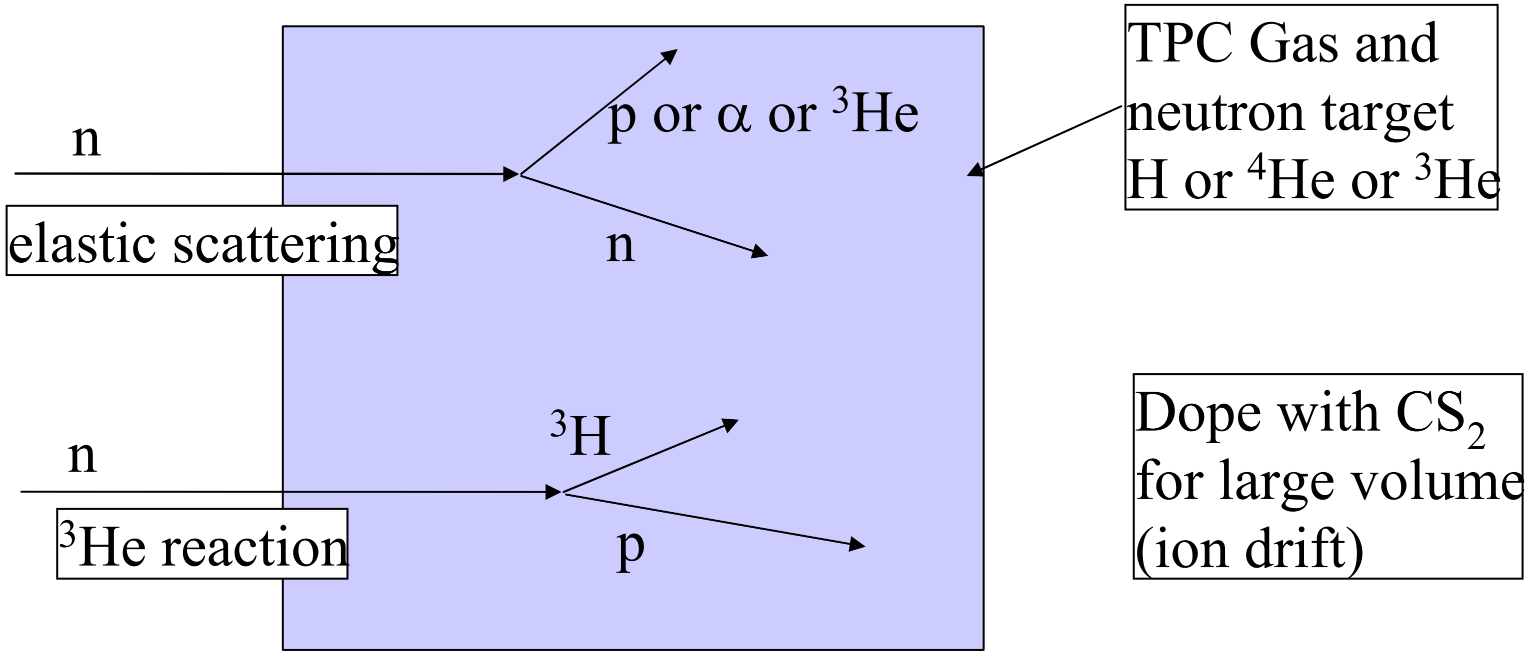
Hydrogen, ^{3}He, and Alkane gas (butane, methane..) based TPCs should all have 5%-20% intrinsic efficiency for >1 MeV neutron recoils at pressures from 1 to 10 atm

In Principle: Location of 1 kg Pu within a 20 degree cone in 1 minute at tens of meters standoff with a cubic meter detector



The Research Question: Can we make TPCs a fieldable, useful device for detecting plutonium ?

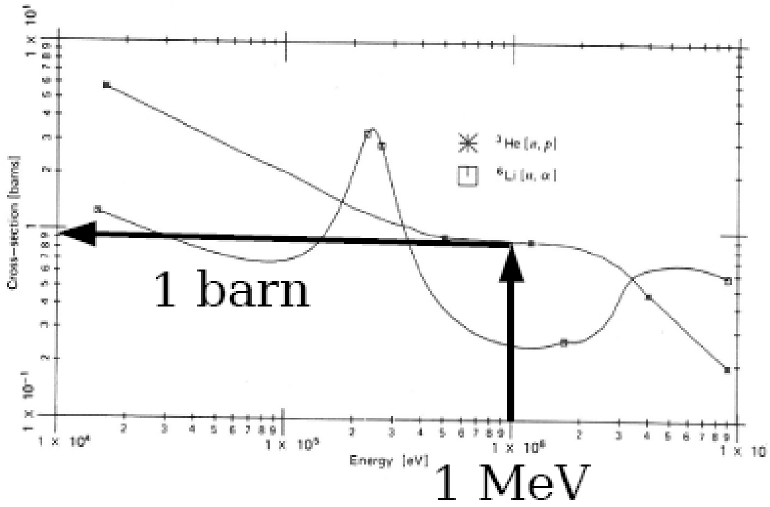
Directional Neutron Detection



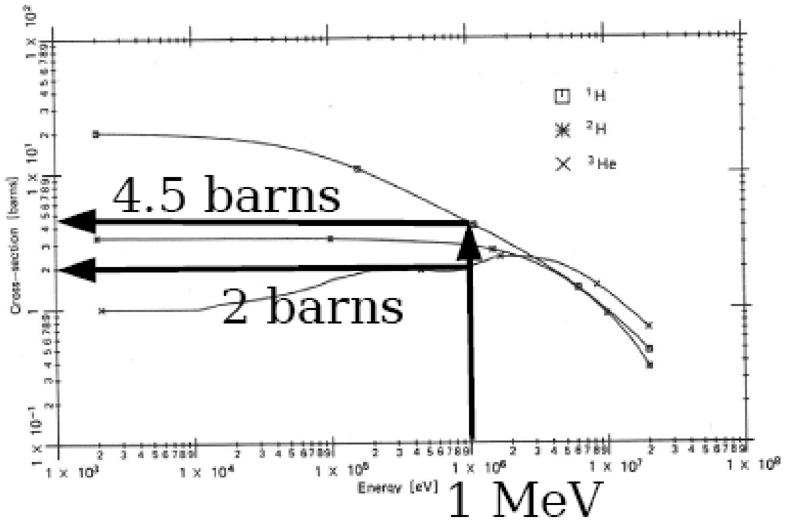
A fairly old principle (scattering on H, ^{3}He reaction)
A fairly new detector technology (TPC)
Neutron Direction and Energy are measured in a TPC
Thermal neutron and gamma backgrounds are low; fast neutrons removed by directionality

Cross Sections

n+ ^{3}He-->p + ^{3}H



elastic scattering



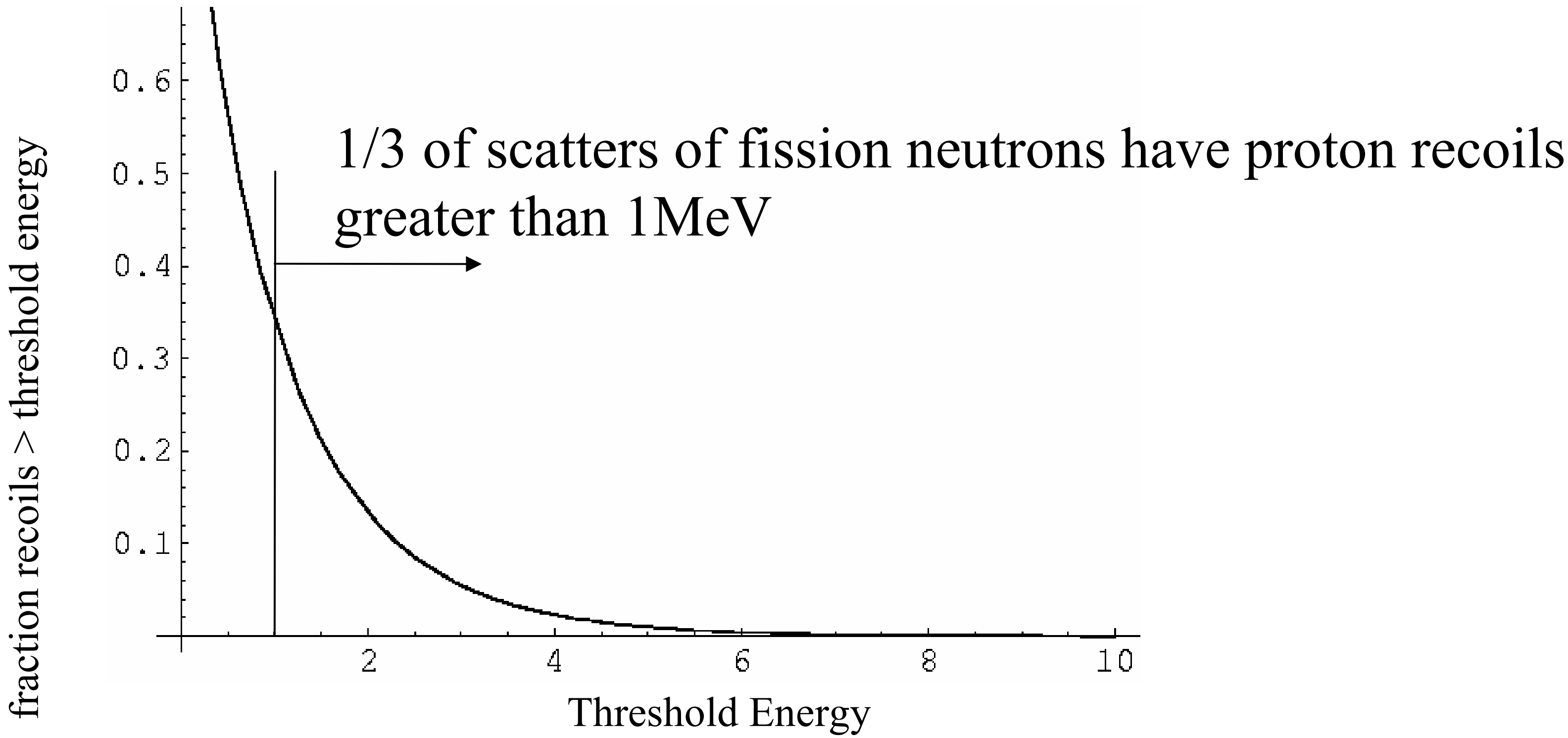
<u>Big Advantage:</u>
- ^{3}He constrained fit

<u>Disadvantages:</u>
- cross section < scattering
- High thermal cross section

<u>H elastic scattering:</u>
- larger cross section
- best kinematics
- low thermal cross section

Elastic Scattering and the Efficiency for Making Tracks

We convolve the **proton cross section** with the **fission neutron spectrum**...



1 MeV neutron: Scattering length: 4m [10 atm]

Detection efficiency [10 atm]: 20% [1 m column]

Pointing Resolution for Elastic Scattering

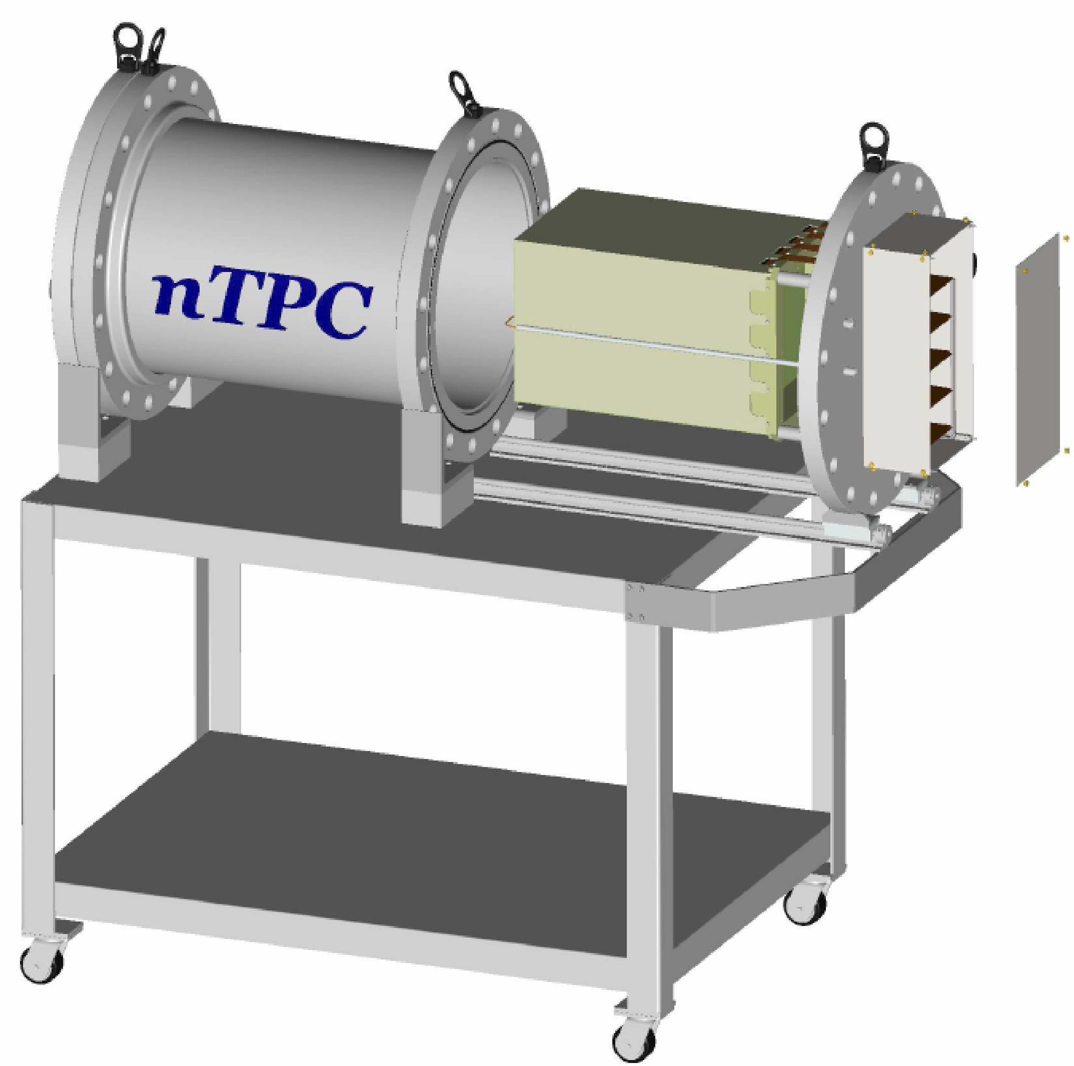
A few events suffice to give useful pointing capability

Recoil Energy threshold (MeV)	90% C.L. θ <...
0.5	56°
1	**49°**
1.5	46°
2	42°

It only takes a few events to get reasonable directionality

Number of events (Recoil Energy = 1 MeV)	63% C.L. θ <...	90% C.L. θ <...
1	36°	49°
2	30°	42°
5	22°	32°
10	**16°**	**24°**

The LLNL nTPC



FY06-07 research goals

Measure pointing accuracy with a working prototype

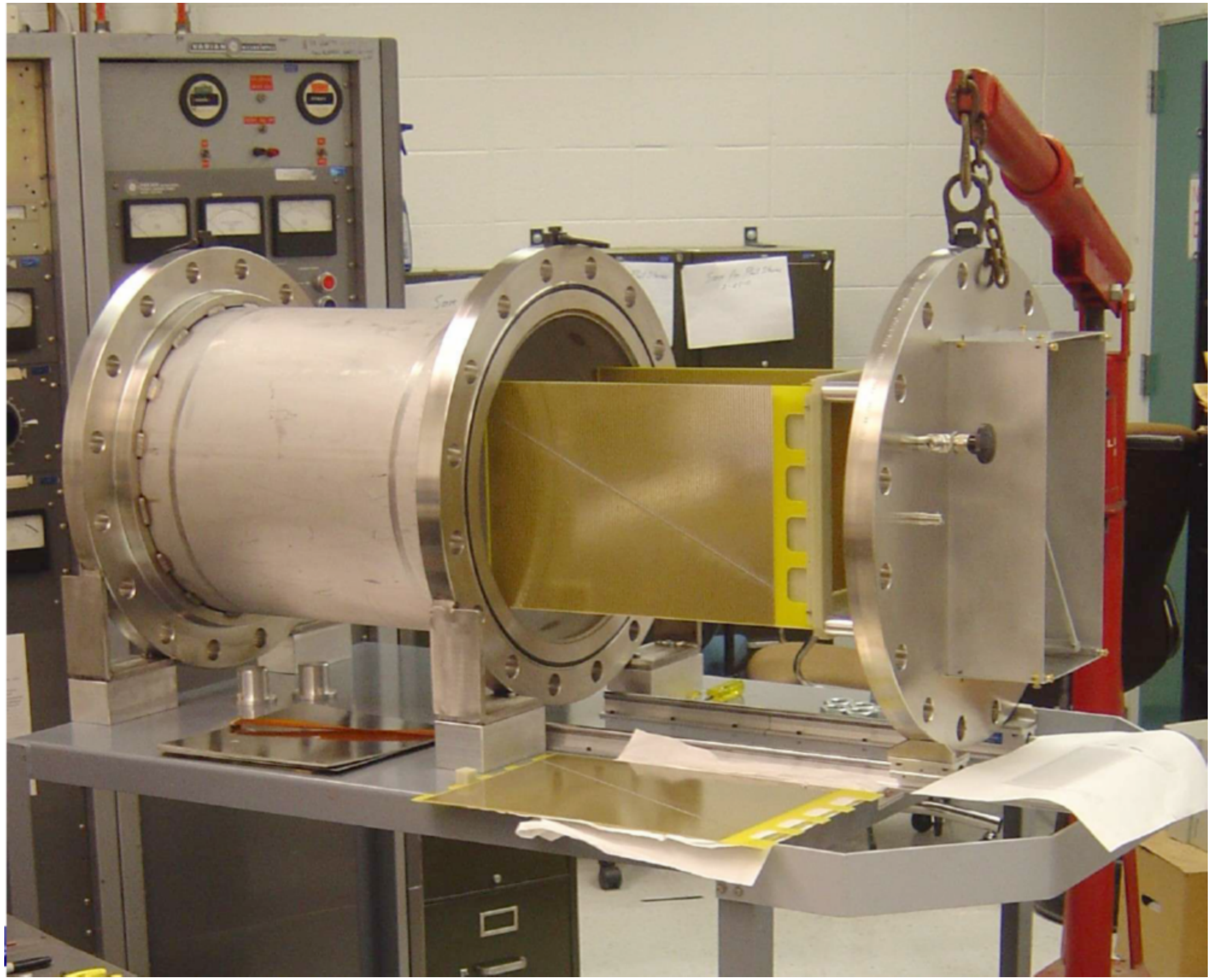
Evaluate trade-offs among different gas targets

Evaluate background rejection

Low energy cut-off = ?

Study readout simplifications and other issues related to deployment

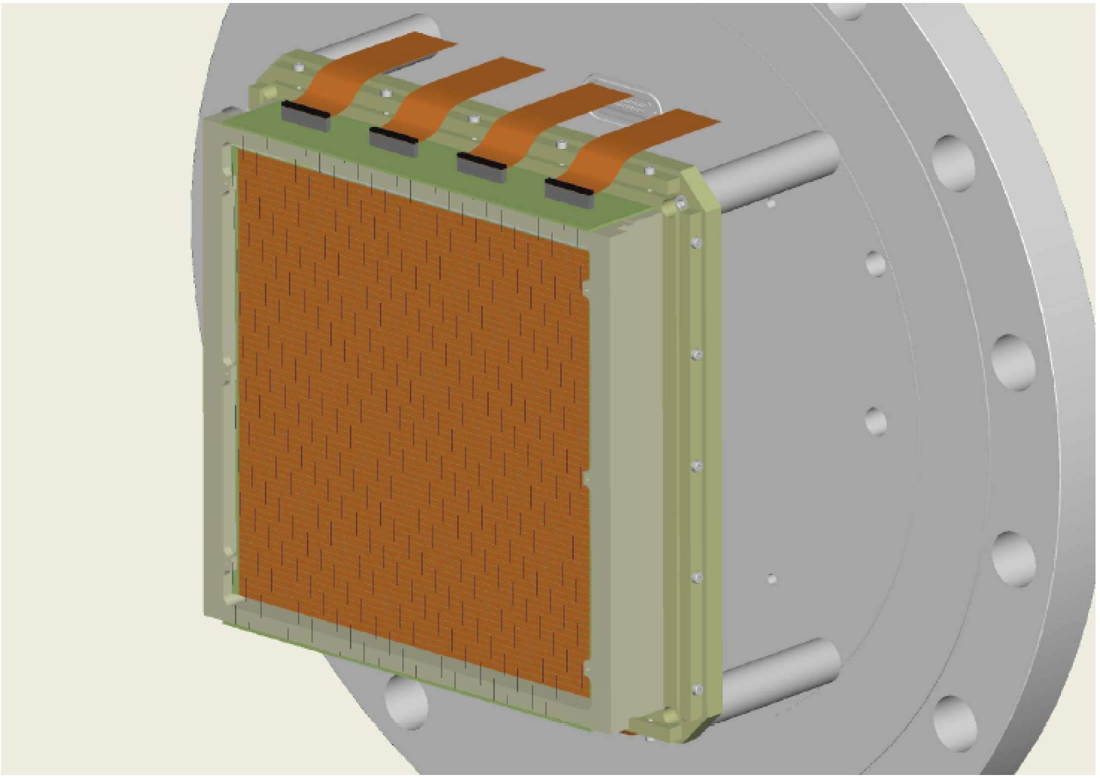
The prototype TPC pressure vessel



316 Stainless
18” diameter
20” long
10 bar operating pressure
Hydrogen compatible
~1200 lb weight
Made from standard pressure flanges

Readout Planes

crossed anode wire and cathode strip readout – low multiplicity



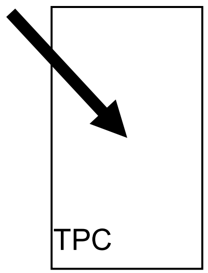
<u>Cathode strips:</u>
pcb manufacture
4.0 mm pitch
3.8 mm width
64 total

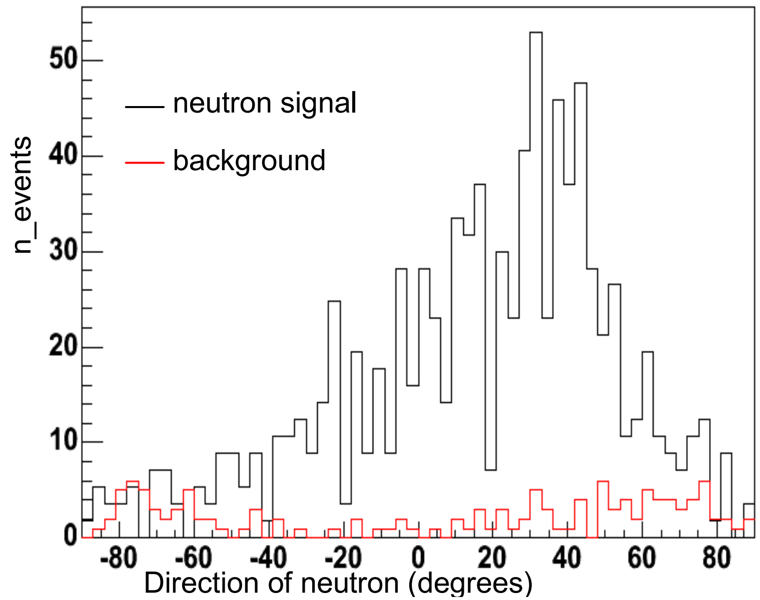
<u>Anode Wires:</u>
20 μm 316 stainless
128 total
2mm pitch
6mm from strips

<u>Ground Grid:</u>
75 μm 316 stainless
1mm pitch
6mm from Anode

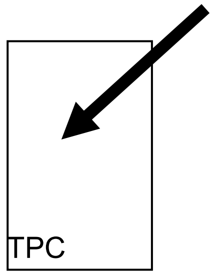
Real Neutron Data from our TPC

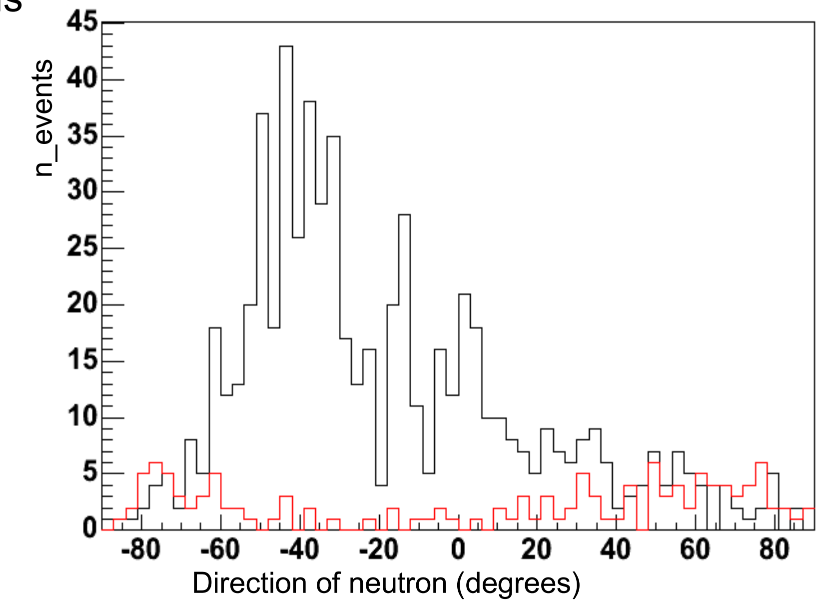
Direction of neutrons



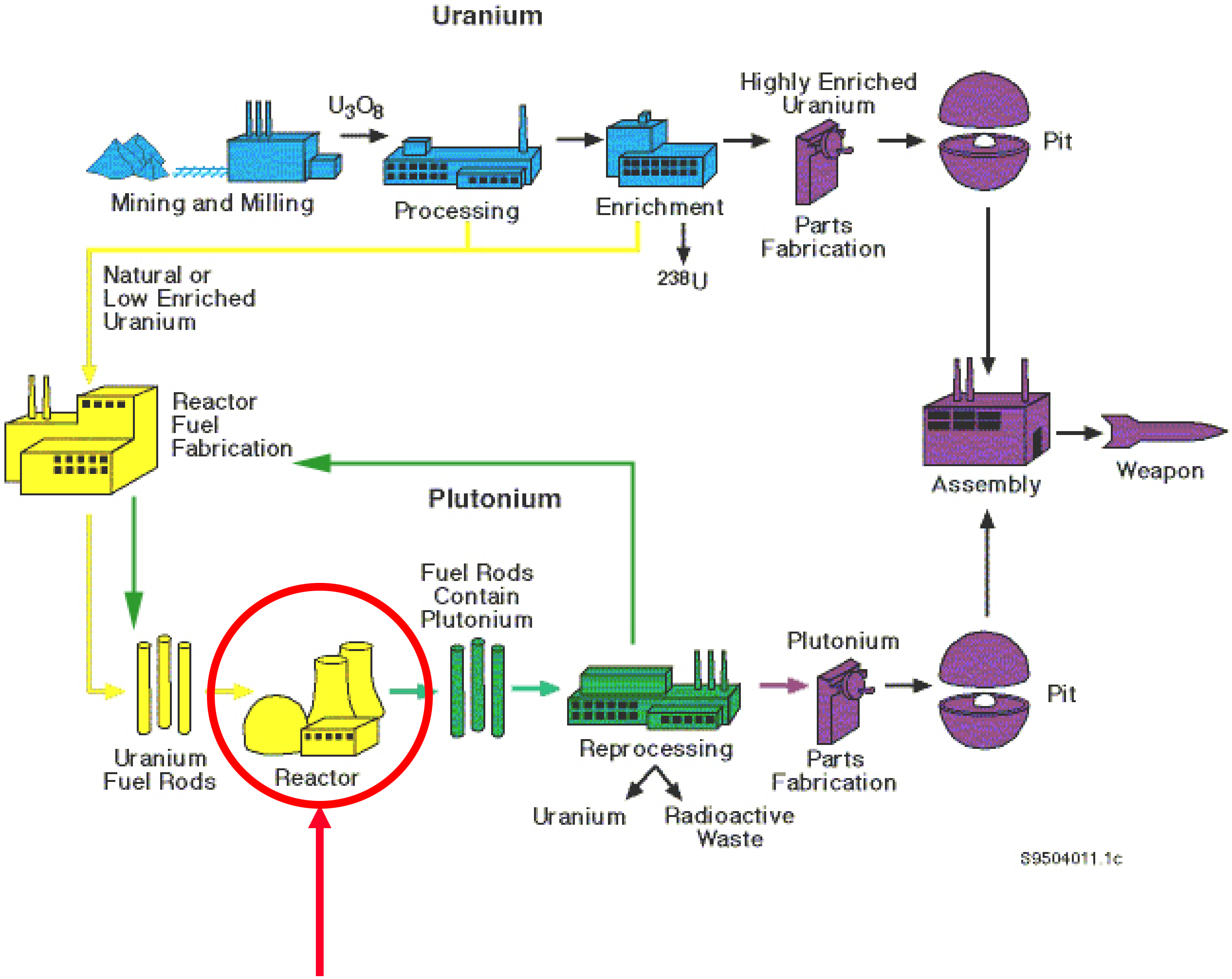


Direction of neutrons





Antineutrino Detectors Address The Nuclear Security Problem "Upstream"



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

The IAEA Monitors Fissile Material Inventories in Civil Nuclear Cycles

(1-1.5 years)	**(months to years)**	**(months)**	**(forever)**

1. Check Input and Output Declarations 2. Verify with **Item Accountancy** 3.Containment and Surveillance	1 'Gross Defect' Detection 2 Continue Item Accountancy 3. Containment and Surveillance	1 Check Declarations 2 Verify with **Bulk Accountancy**:

Operators Report Fuel Burnup and Power History

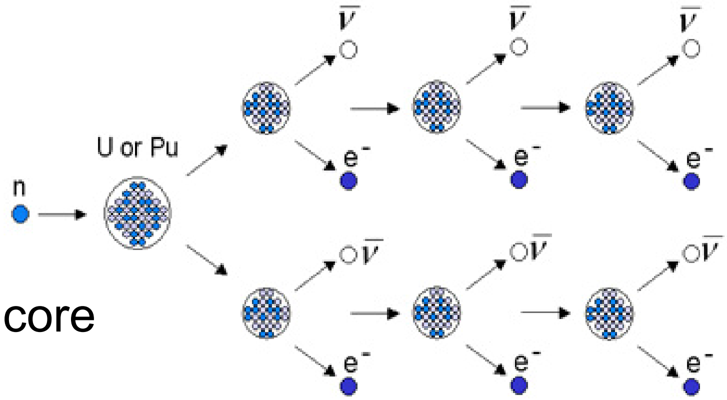
No Direct Pu Inventory Measurement is Made Unless and Until Fuel is Reprocessed

Antineutrino Detectors Can Provide an Independent Estimate of the Amount of Plutonium and Uranium in Reactor Cores

1. **Directly track fissile content to ~50 kg precision on Pu, as it is produced**
2. **Measure thermal power to 1-3%, constraining fissile content**
3. **Operate continuously, non-intrusively, and remotely**
4. **Self-calibrated, unattended, few channels, low cost materials, operable for months to years with rare maintenance**

- Reactor antineutrinos first detected by Reines and Cowan in 1956
- Russian group accomplished steps 1-2 at Rovno in the late 1980s
- Our LLNL/SNL collaboration has demonstrated steps 1-4
- France, Brazil are now proposing similar deployments

The Properties of Antineutrinos and the Maturity of Antineutrino Detectors Allow us to Monitor Reactors



Rates near reactors are high

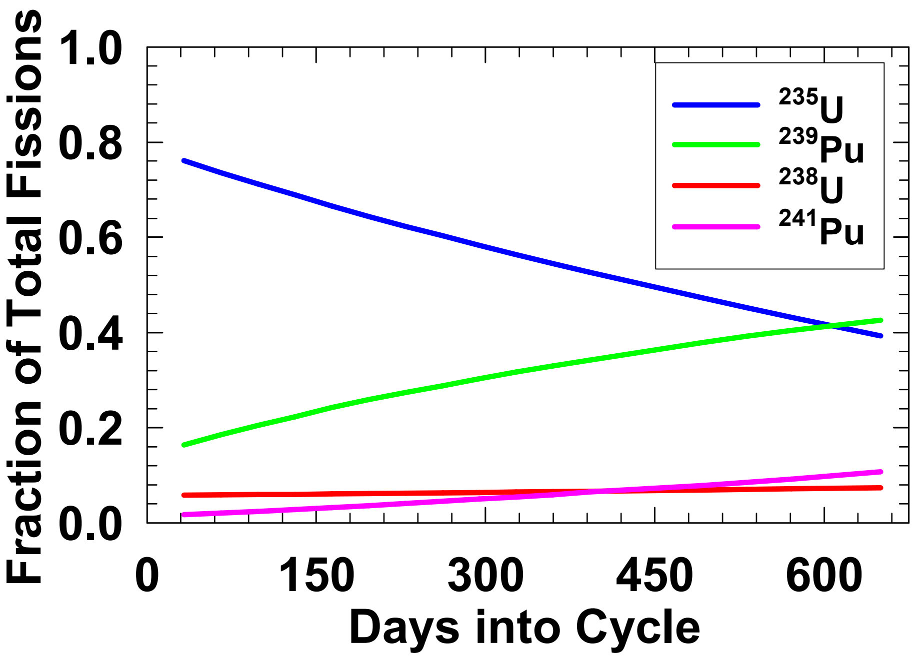
- 0.64 ton detector, 25 m from reactor core
- Thermal power = 3.46 GW
- 4000 events/day/0.64 ton with a 100% efficient detector
- Our prototype is about 10% efficient and counts 400 events per day

Rate and energy spectrum are sensitive to the fissile content of the core

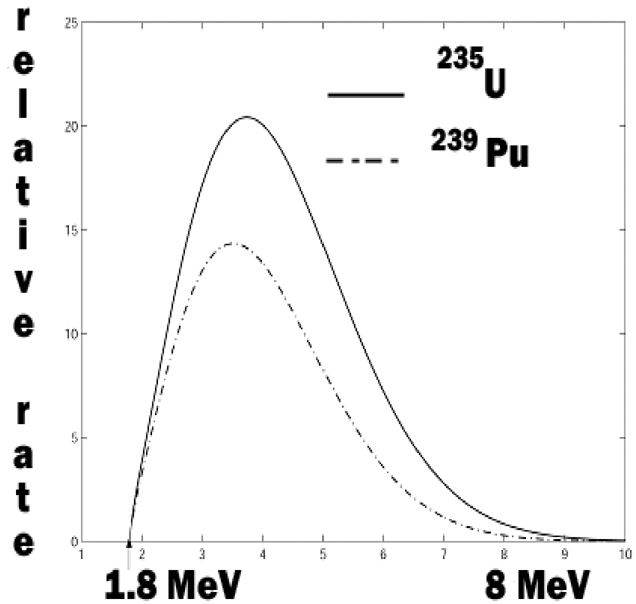
- 200-300 kg of new plutonium is generated in a typical cycle

- Real data and detailed reactor simulations show a **reduction in the antineutrino rate** of about 12% through a 600 day cycle - **caused by Pu ingrowth and U fission**

Fission Rates Vary with Time and Isotope, Antineutrino Interaction Probability Varies with Isotope



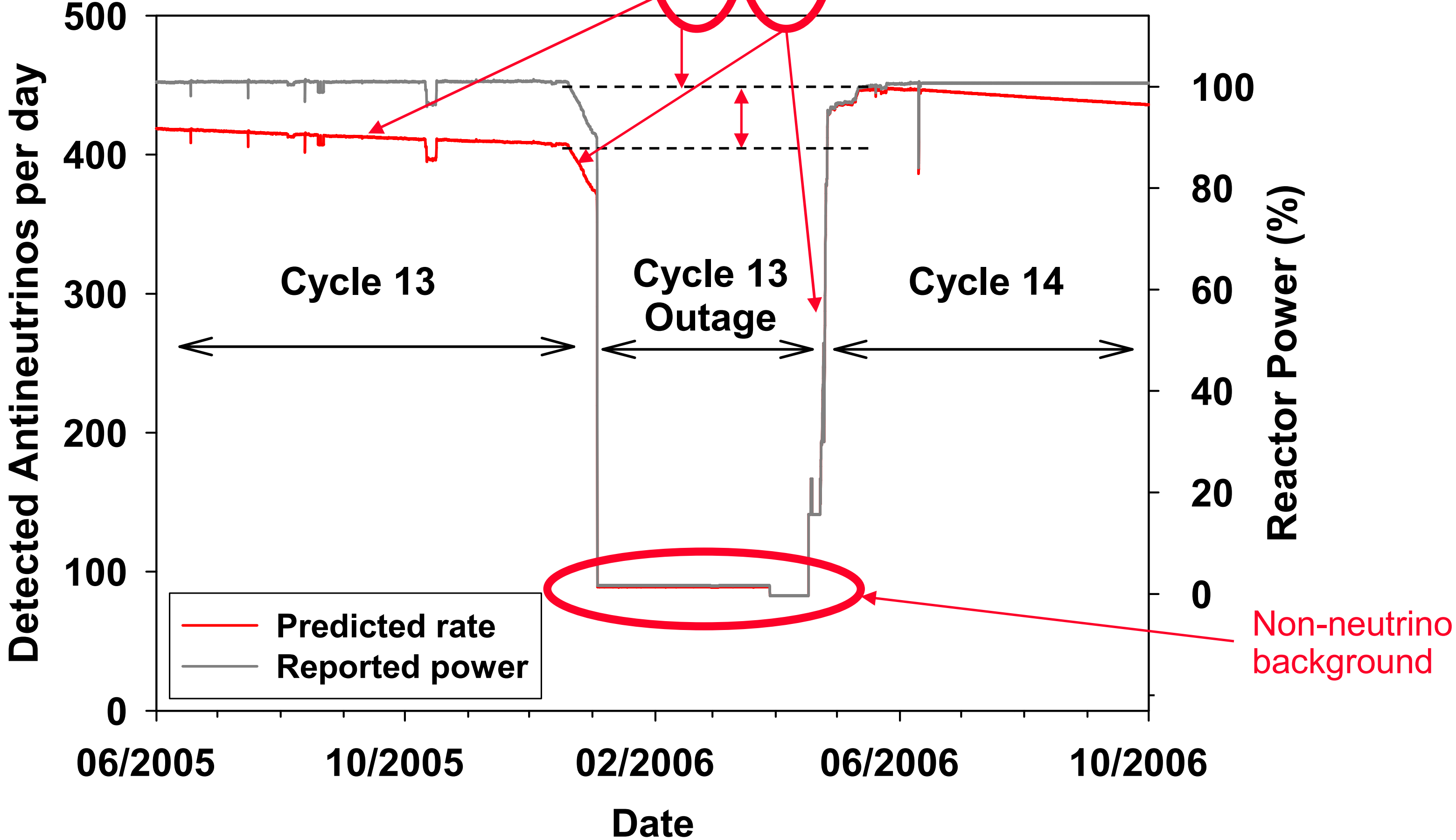
Relative Fission Rates Vary in Time



Rate of Antineutrinos/Fission Varies With Isotope

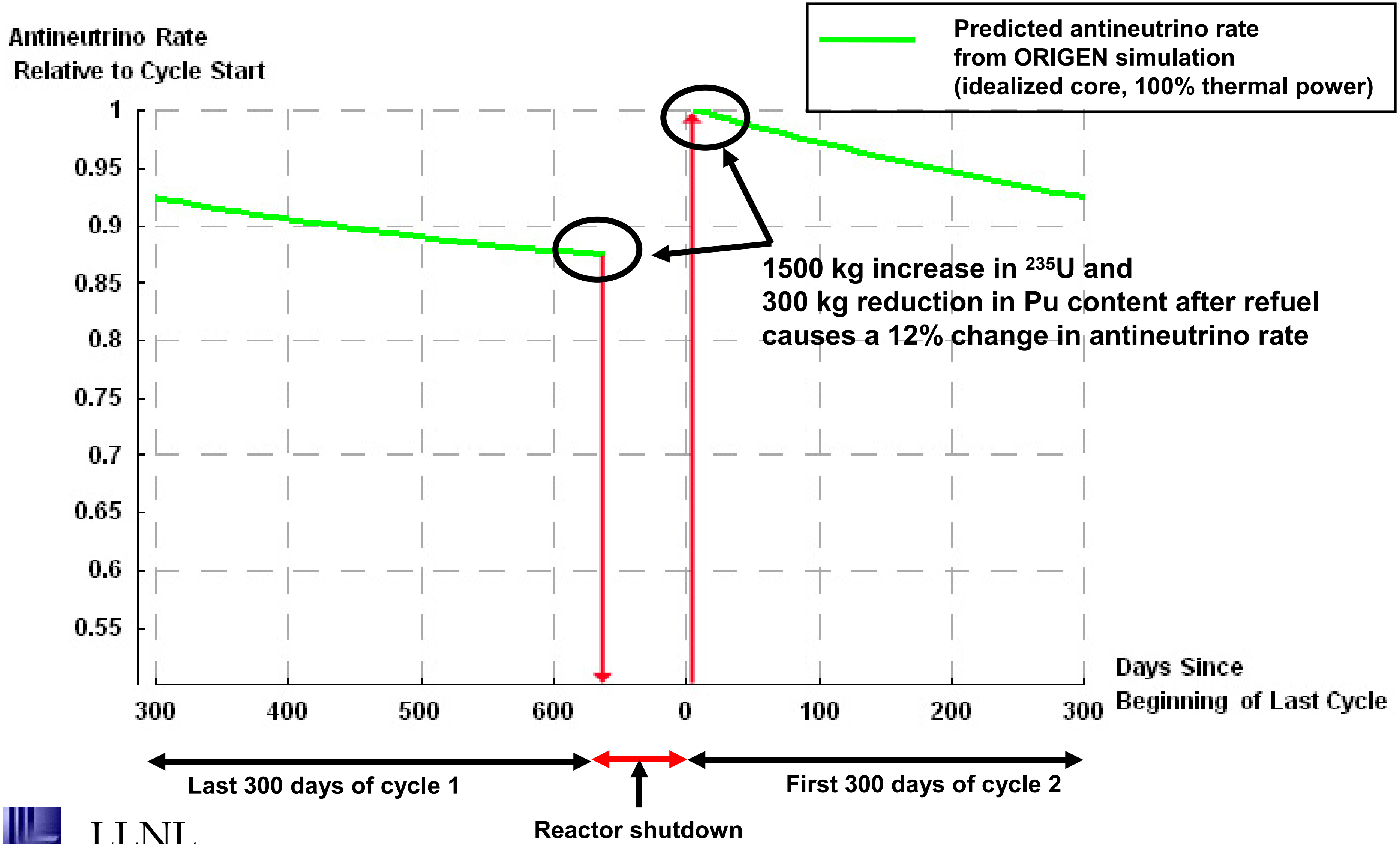
The Number of Antineutrinos is Approximately Proportional to Thermal Power Up To a Correction that Depends on the U/Pu Ratio

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



LLNL Predicted Antineutrino Rate and Reported Reactor Power

The Simplest Implementation – Monitor Relative Antineutrino Count Rate Within and Across Cycles



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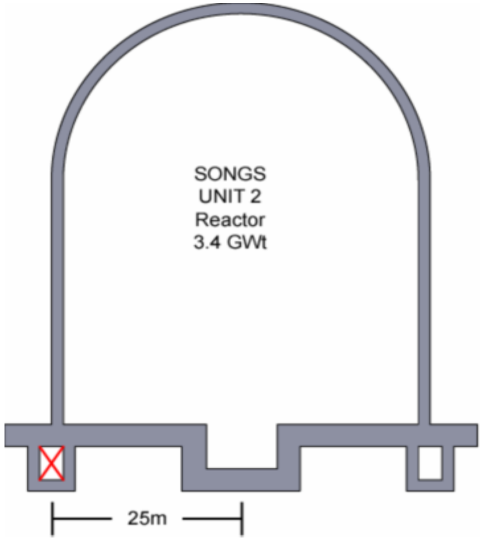
An Experimental Test at a Reactor Site

25 meters standoff from core

20 meter overburden



San Onofre Nuclear Generating Station
Unit II – 3.46 GWt

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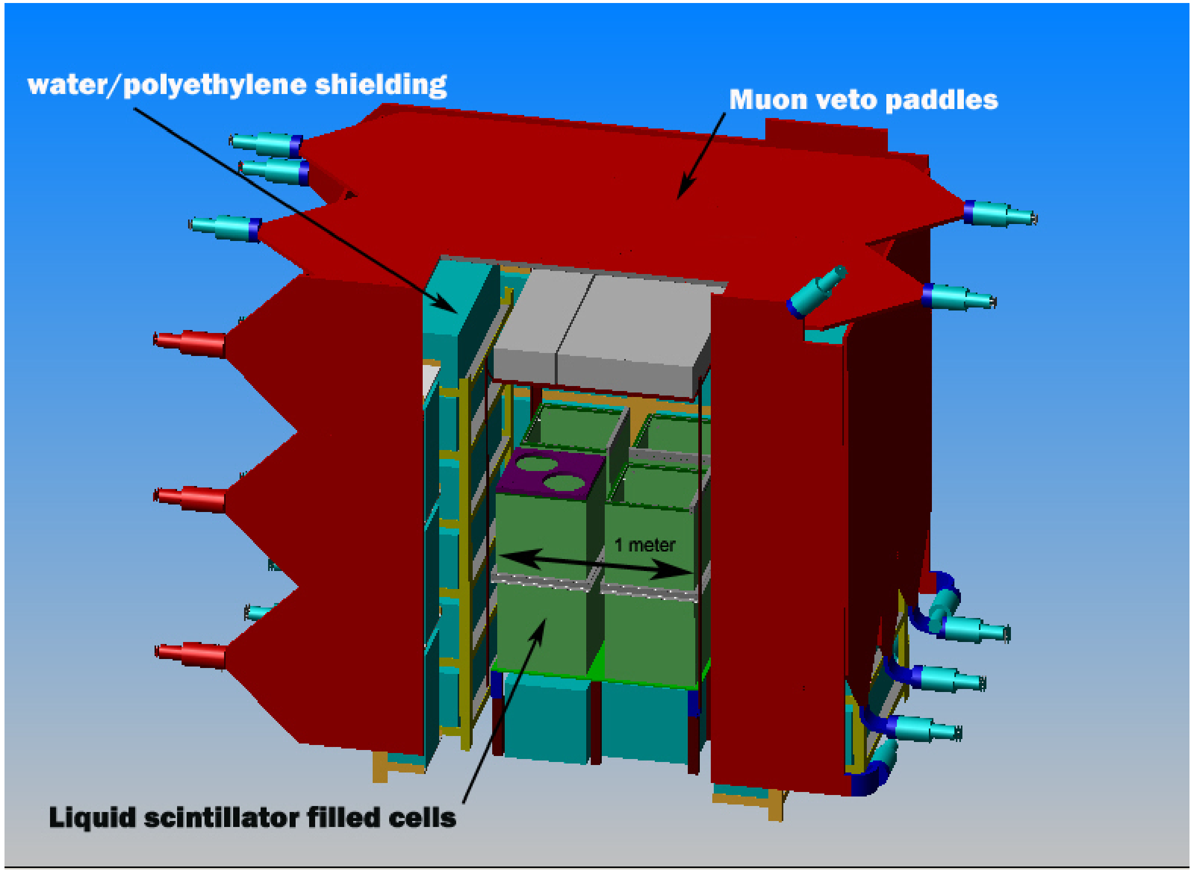
Cutaway Diagram of the LLNL/Sandia Antineutrino Detector

Current
Footprint:
2.5 x 3 m

Projected
Footprint:
About 1.2 x 1.2 m



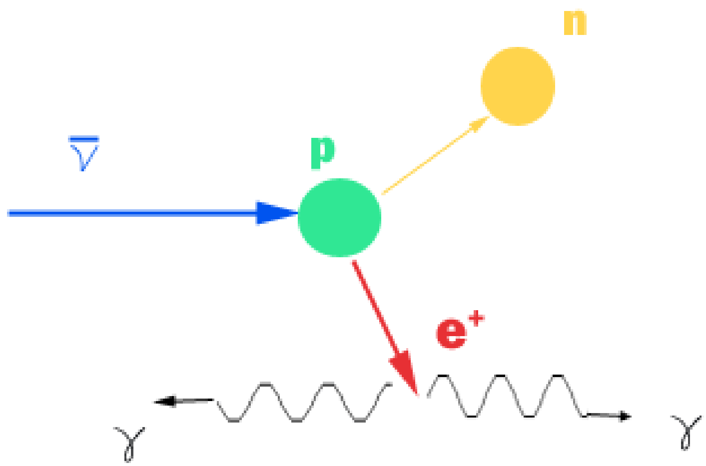
Currently operational:
4 cells with 640 kg of scintillator;
quasi-hermetic muon veto; hermetic water shield

Detection of Antineutrinos

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

- **The antineutrino interacts with a proton producing…**

  - **A 1-7 MeV positron(+gammas)**
  - **A few keV neutron**
  - **mean time interval 28 μsec**

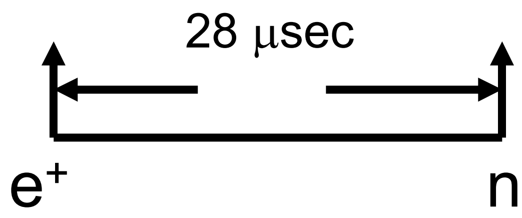


- **Both final state particles deposit energy in a scintillating detector over 10s or 100s of microsecond time intervals (depending on the medium)**
- **Both energy depositions and the time interval are measured**

How to Select 400 Antineutrino Events from 43 Million Background Events

Step 1: Look for two scintillation flashes within about 28 microseconds

Mean interevent time is 28 μsec



Step 2: Demand that the energy of each event in the pair be high

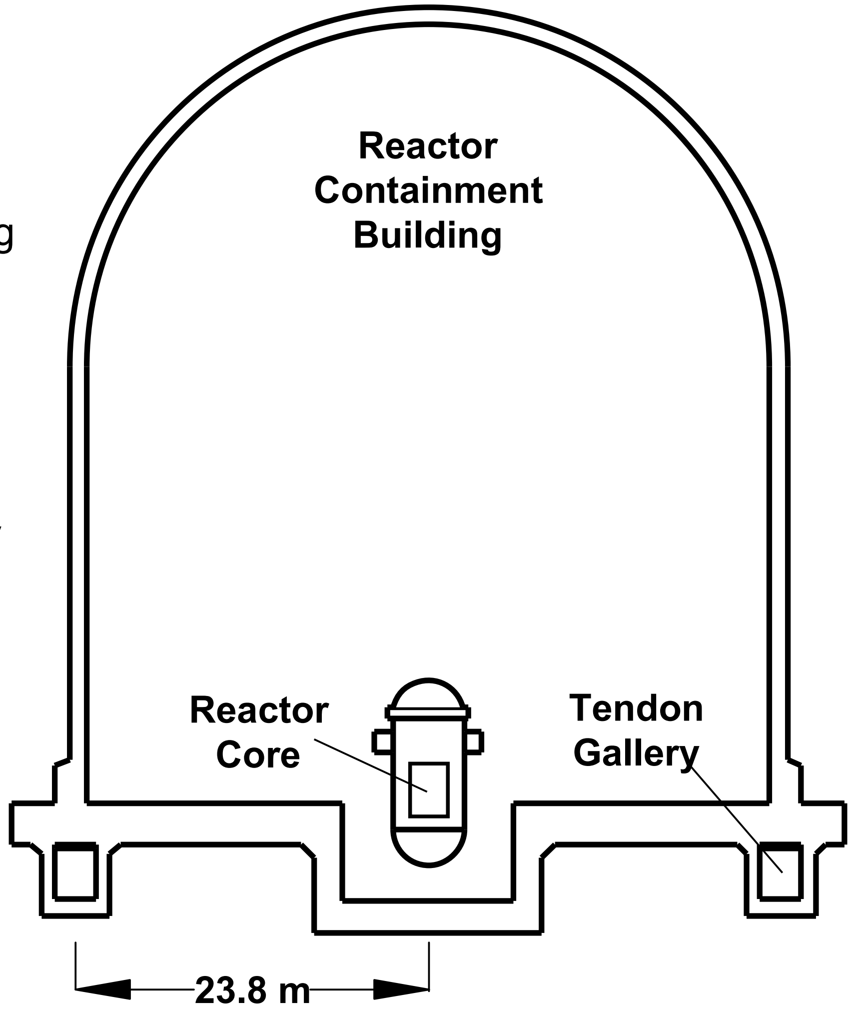
- > 2.45 MeV for the first event (positron-like")
- > 3.5 MeV for the second event (neutron-like")

Step 3: Demand that the event pair be far from a muon

Prototype deployment – San Onofre Nuclear Generating Station

The Unit 2 Tendon Gallery at the San Onofre Nuclear Generating Station

- **The tendon gallery is tailor made for antineutrino detection and nonintrusive monitoring**
  - Rarely accessed for plant operation
  - As close to reactor as you can get while being outside containment
  - Provides ~20 mwe overburden
- **3.4 GWt => 10^{21} ν / s**
- **In tendon gallery ~10^{17} ν / s per m^2**
- **Around 3800 interactions expected per day**



Installation at SONGS

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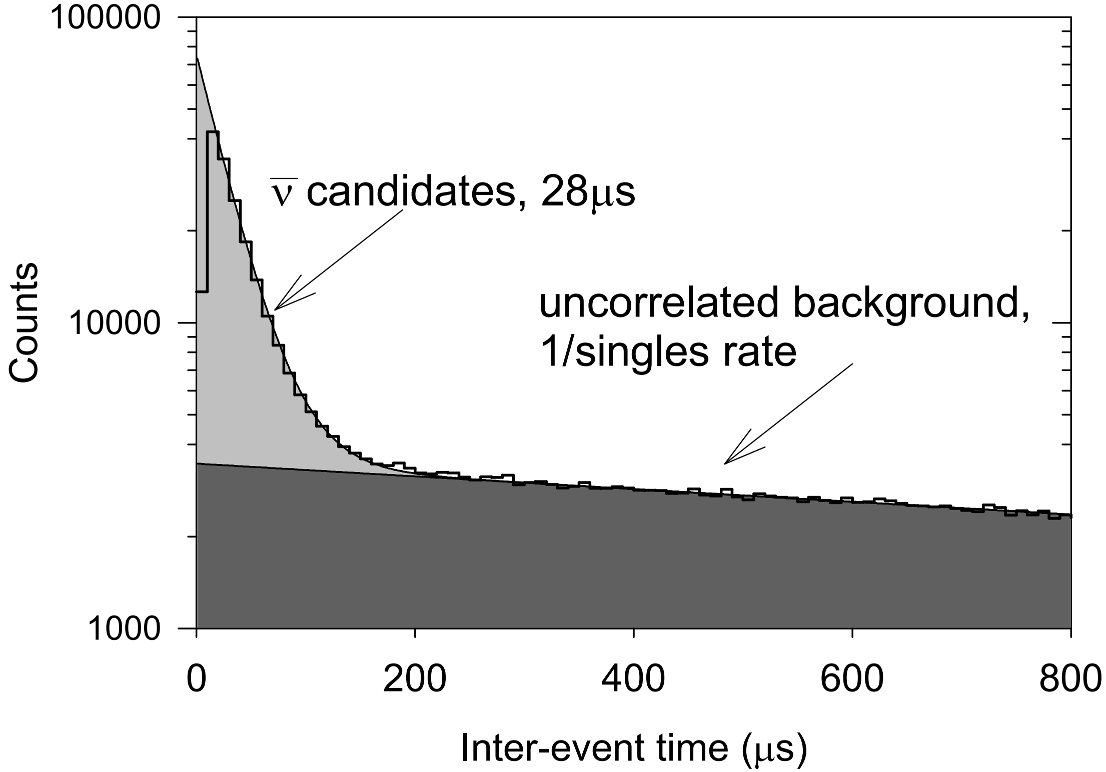
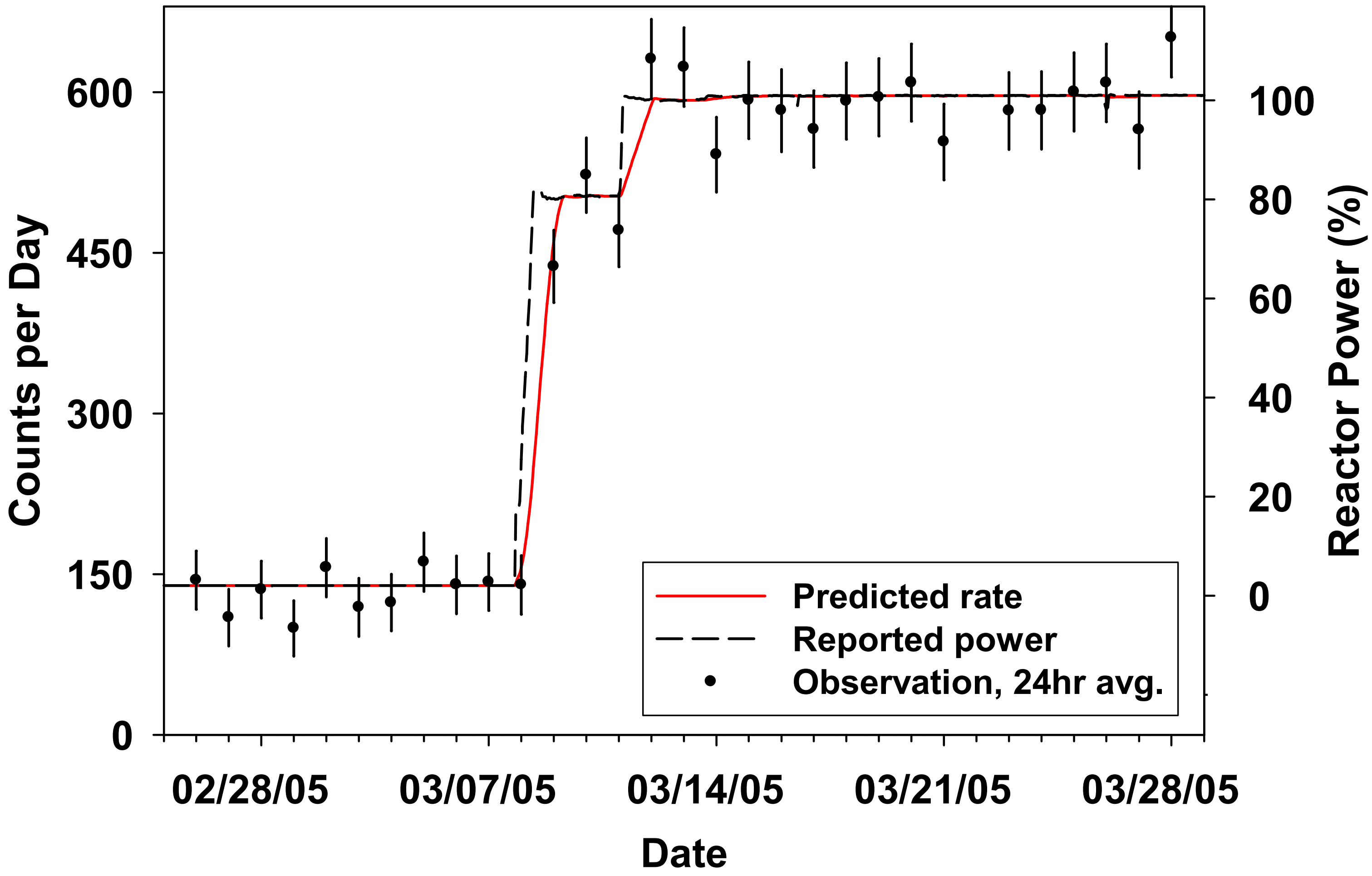
Candidate Event Extraction

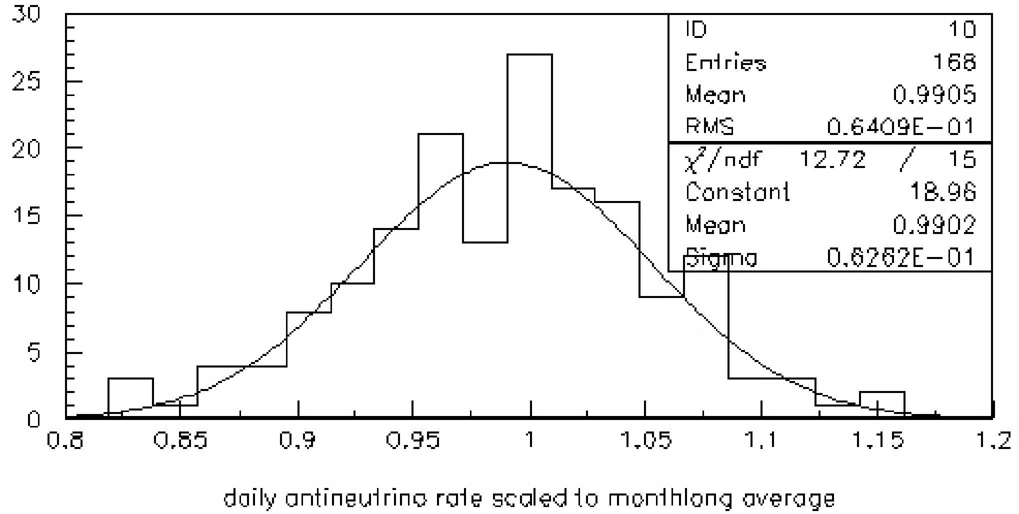
- **"Cuts" are applied to extract correlated events:**
  - energy cuts
    >2.39 MeV prompt
    >3.5 MeV delayed
  - at least 100μs after a muon in the veto detector
- **Examine time between prompt and delayed to pick out neutron captures on Gd**
- **Event-by-event can not distinguish antineutrinos from random coincidences – perform statistical separation**



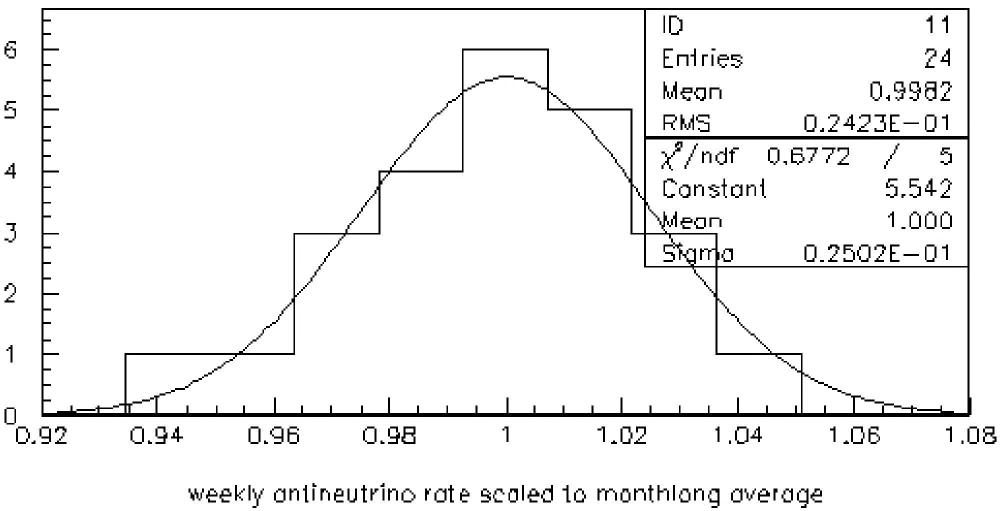
Reactor Monitoring using only $\bar{\nu}$



Current Relative Power Monitoring Precision

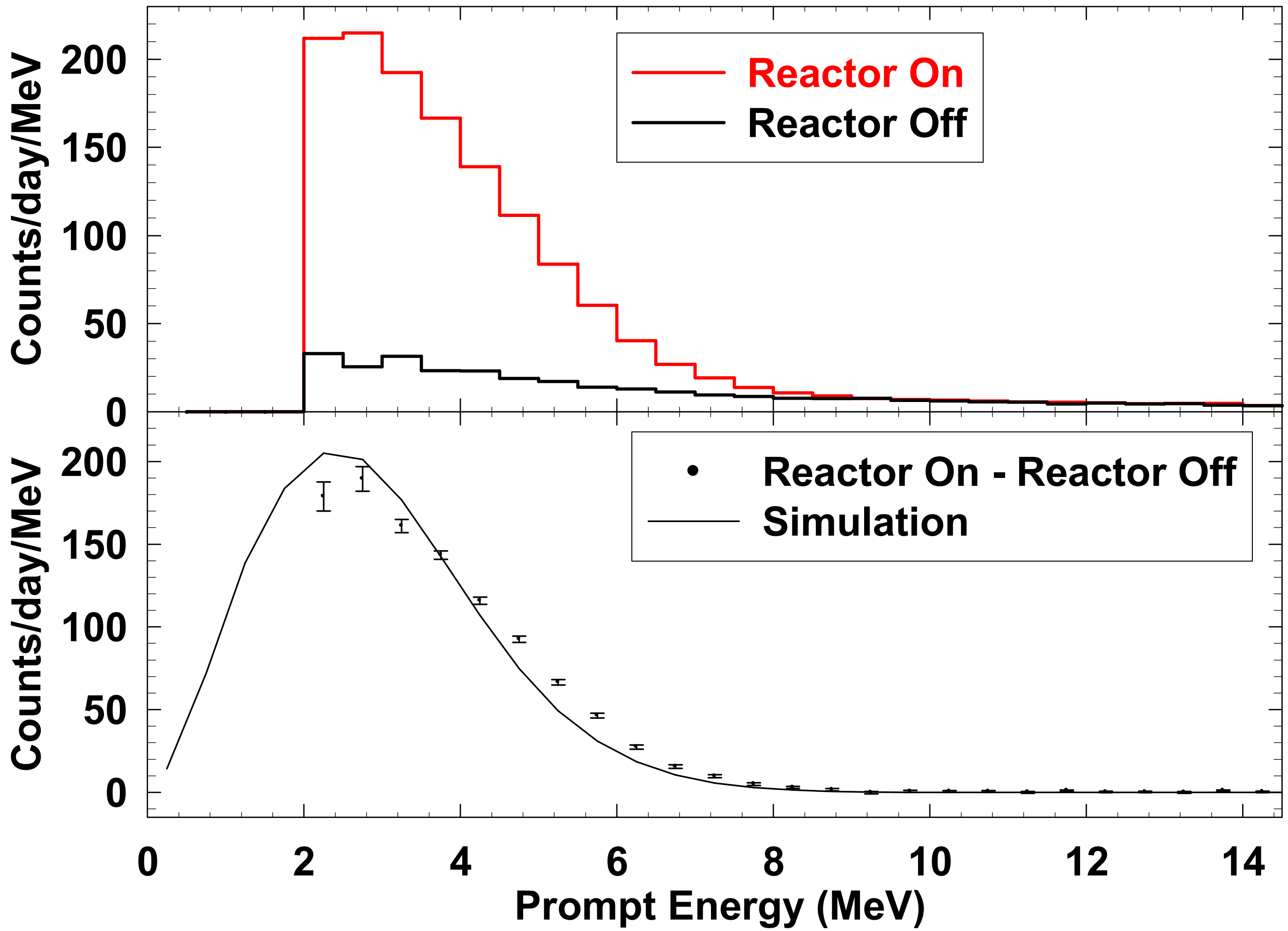


Daily average
6.2% relative uncertainty
in thermal power estimate
(normalized to 30 day avg.)

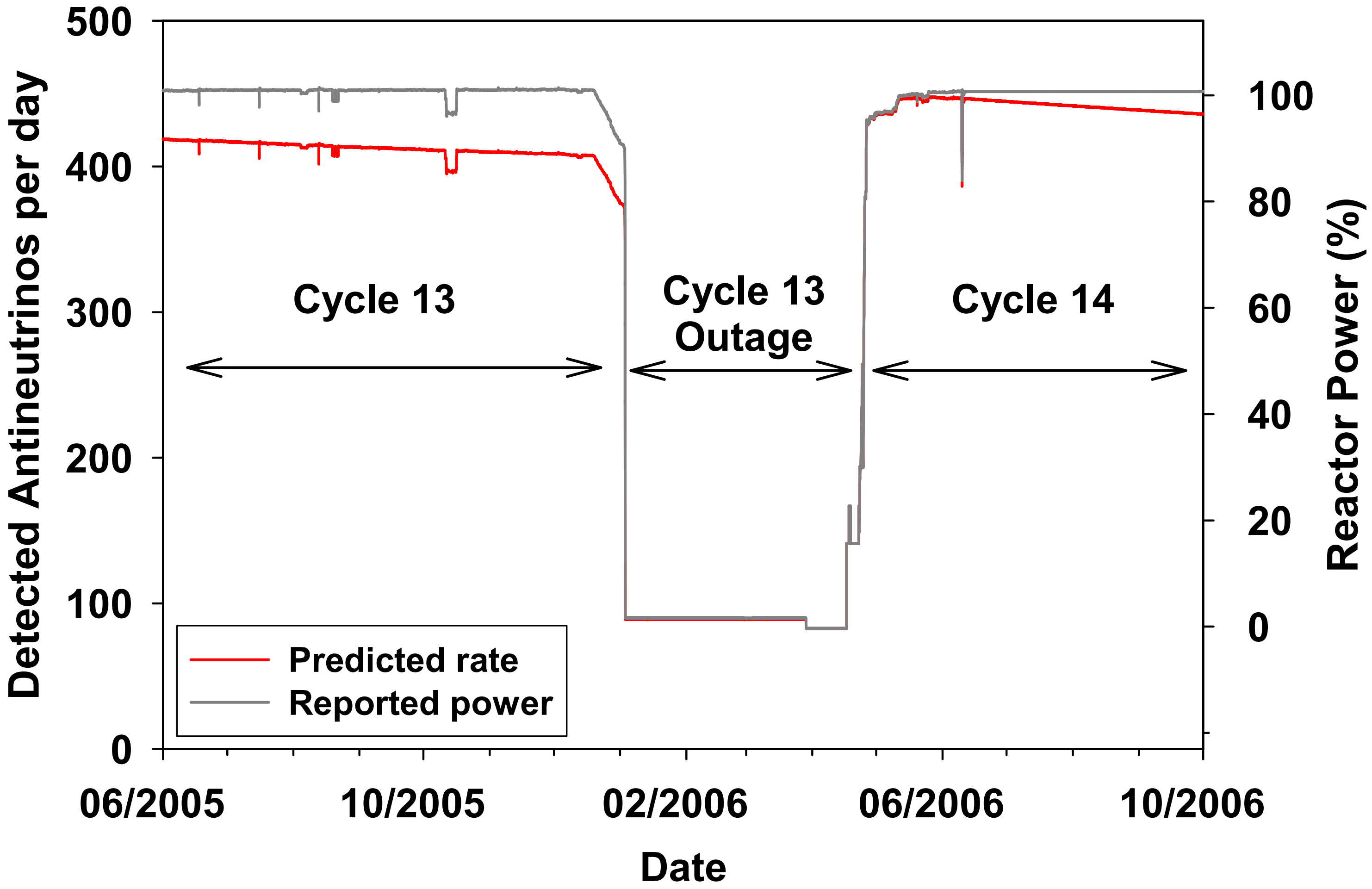


Weekly average
2.5% relative uncertainty
in thermal power estimate
(normalized to 30 day avg.)

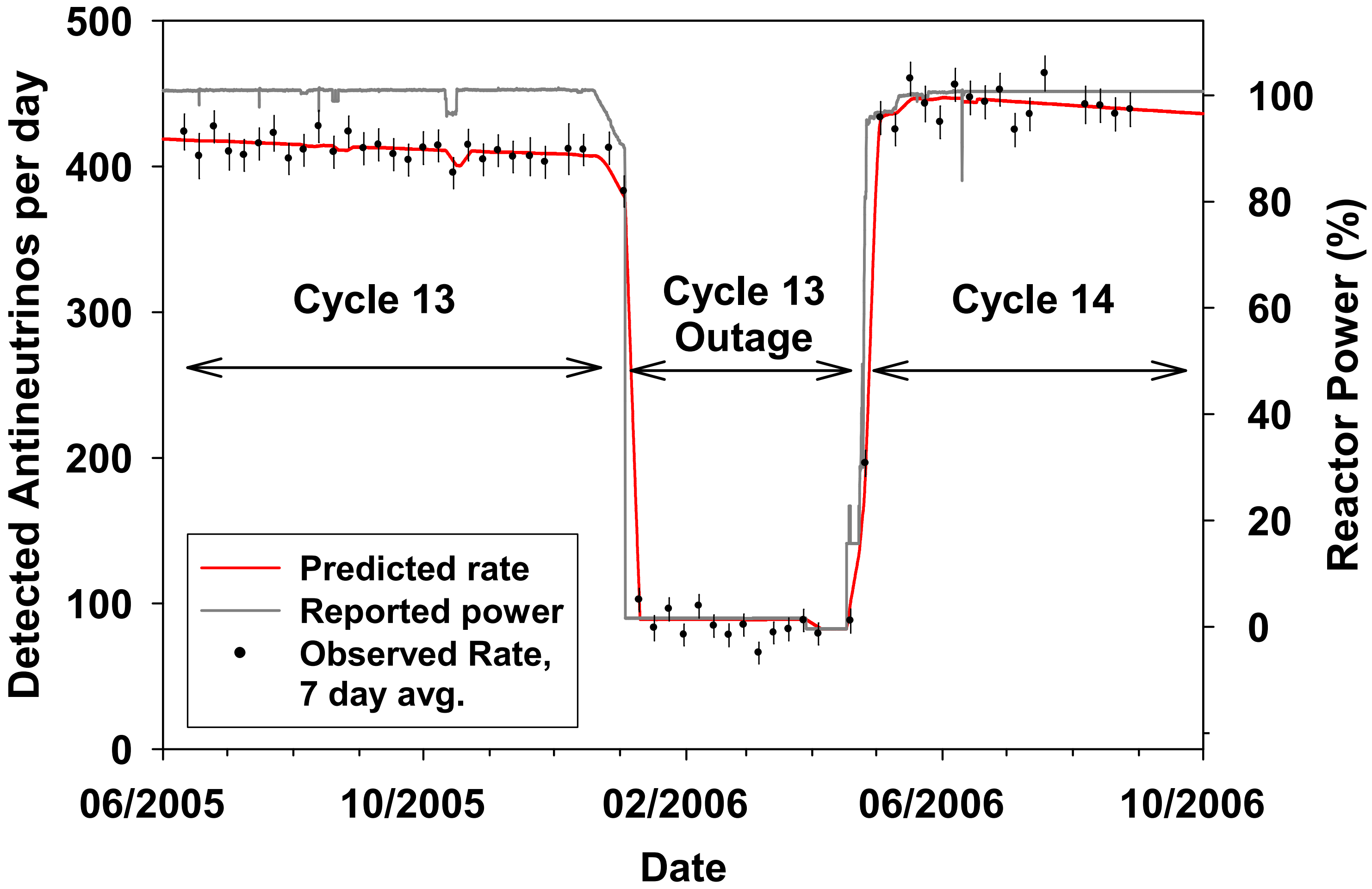
Our Positron Energy Spectrum Gives Another Clear Indication That We Are Really Seeing Antineutrinos



A Prediction of the Long Term Behavior of our Dataset…



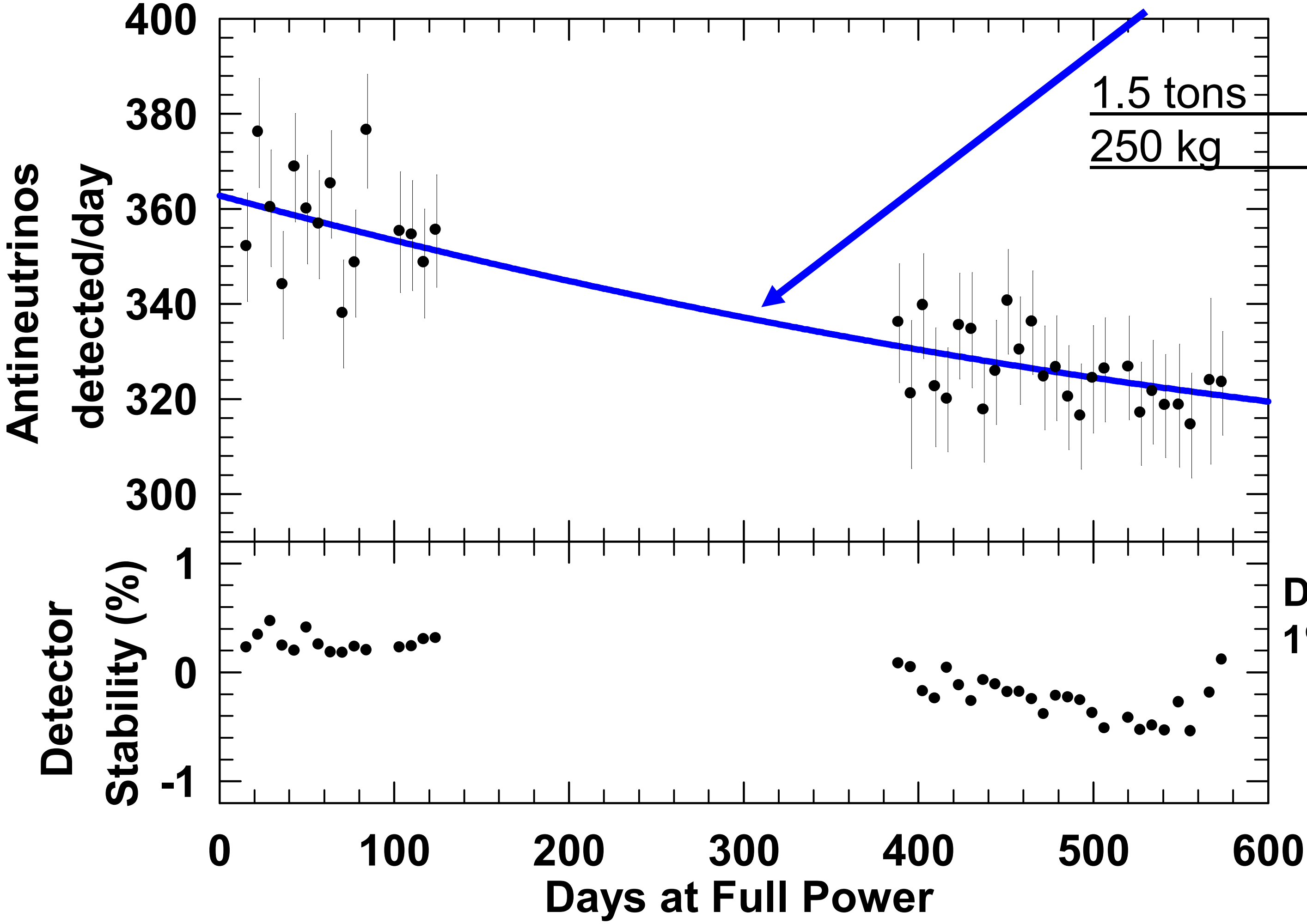
Our Dataset



500
400
300
200
100
0
Detected Antineutrinos per day
100
80
60
40
20
0
Reactor Power (%)
Cycle 13
Cycle 13 Outage
Cycle 14
Predicted rate
Reported power
Observed Rate, 7 day avg.
06/2005
10/2005
02/2006
06/2006
10/2006
Date

A Burnup Measurement Using Antineutrinos

One parameter fit to our burnup model



1.5 tons	^{235}U consumed
250 kg	^{239}Pu produced

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

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Current Status of our Detector and Data

- We can track power at the 2-3% level with a 1 week integration time
- We can see an correlation (anti-correlation) between fissile U (Pu) mass and antineutrino count rate, consistent with predictions to about 2%
- We have operated stably and with little maintenance for about 1.5 years

Deployment has been and remains essential for demonstrating practical utility and improving the detector

Conclusion

• Detectors invented for fundamental scientific research have interesting applications in international nuclear security

•Many of the detection issues that have to be solved for field applications can benefit fundamental science

There are many more examples