The Intersection of Nuclear Science and Nuclear Security

Adam Bernstein

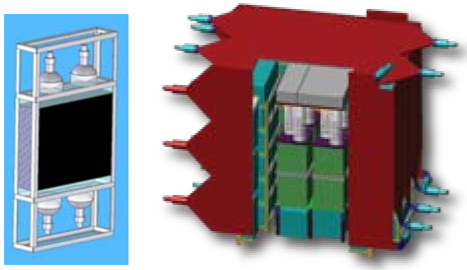
Group Leader, Advanced Detectors Group, Physical Sciences Directorate

October 2008

Outline

- Why and how do Nuclear Science and Global Nuclear Security intersect ?

- A successful application of antineutrino physics to nonproliferation: reactor monitoring with liquid and plastic scintillator detectors

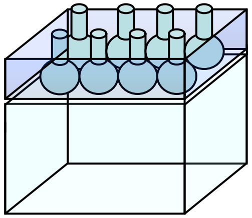


- New frontiers:

Low energy nuclear recoil detectors

- near field monitoring of reactors
- WIMP Dark Matter detection

Doped water Cerenkov detectors



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- neutron and antineutrino detection
- long range reactor monitoring

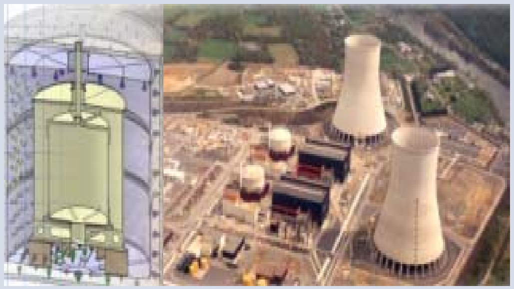
Global nonproliferation regimes require sensitive neutral particle detectors

Detection and monitoring of special nuclear material is a central task for global nonproliferation regimes

- **Critical systems:** Reactors emit huge fluxes of antineutrinos, which can be detected at stand-off distances of tens of meters to hundreds of kilometers
- **Quiescent nuclear material**: Plutonium and HEU emit penetrating gamma rays and neutrons that can be detected from meters to tens of meters

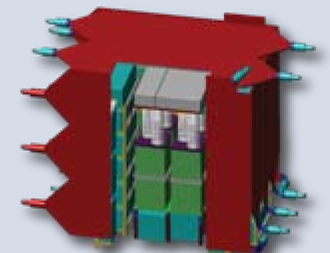
Technology and expertise from fundamental physics directly benefit nonproliferation – and vice-versa

Double Chooz



Precision measurement of the final neutrino oscillation angle theta 1–3

LLNL/SNL antineutrino detector



Reactor power, operational state, Pu content measured with LLNL/SNL antineutrino detector

Antineutrino detection

Oscillation signal = Monitoring signal

KeV to MeV scale neutral particle detectors

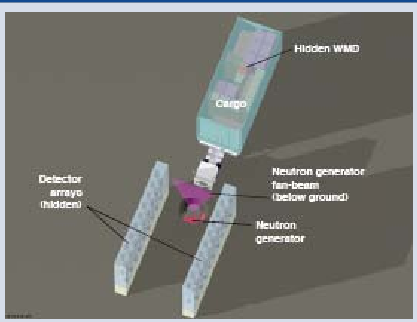
Neutron/Gamma detection

DM background = SNM signal

XENON/LUX

Direct detection of WIMP dark matter

LLNL 'carwash' and coherent scatter detectors

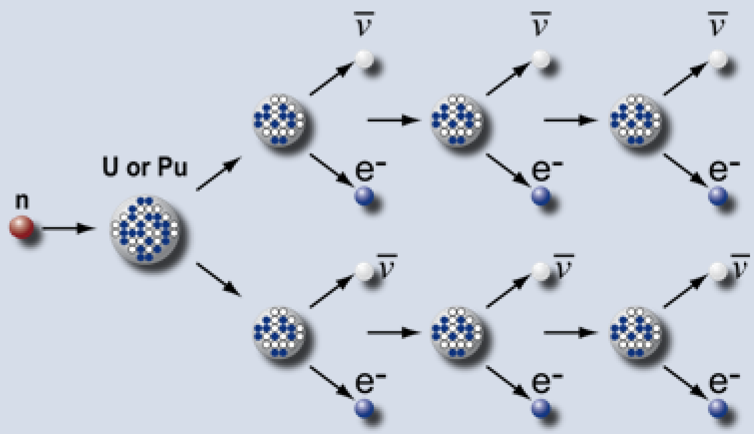


Detection of SNM in cargo and for nuclear monitoring regimes

A worked example: cooperative monitoring of nuclear reactors with antineutrinos

Reactors emit huge numbers of antineutrinos

- 6 antineutrinos per fission from beta decay of daughters
- 10^{21} fissions per second in a 3,000-MWt reactor



About 10^{22} antineutrinos are emitted per second from a typical PWR unattenuated and in all directions

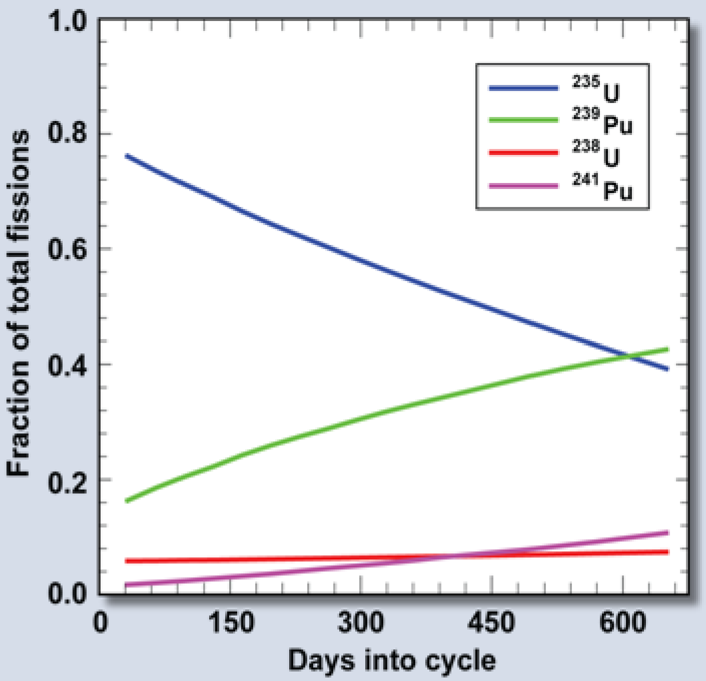
Detected rates are quite reasonable

- 10^{17} antineutrinos per square meter per second at 25-m standoff
- 6,000 events per ton per day with a perfect detector
- 600 events per ton per day with a simple detector (e.g., SONGS1)

Example: detector total footprint with shielding is 2.5 meter on a side at 25-m standoff from a 3-GWt reactor

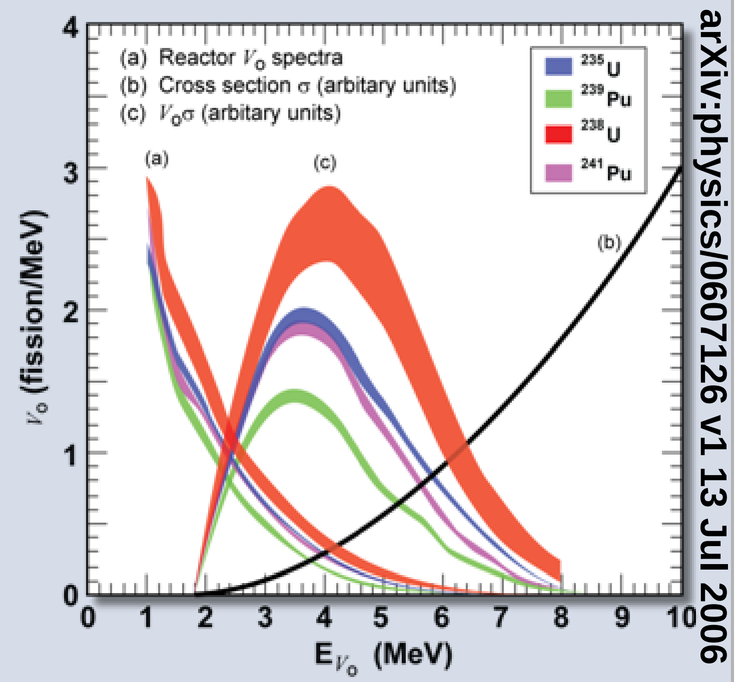
Antineutrino spectrum and rate and are both sensitive to the fissile content of the reactor

Nuclear Engineering 101



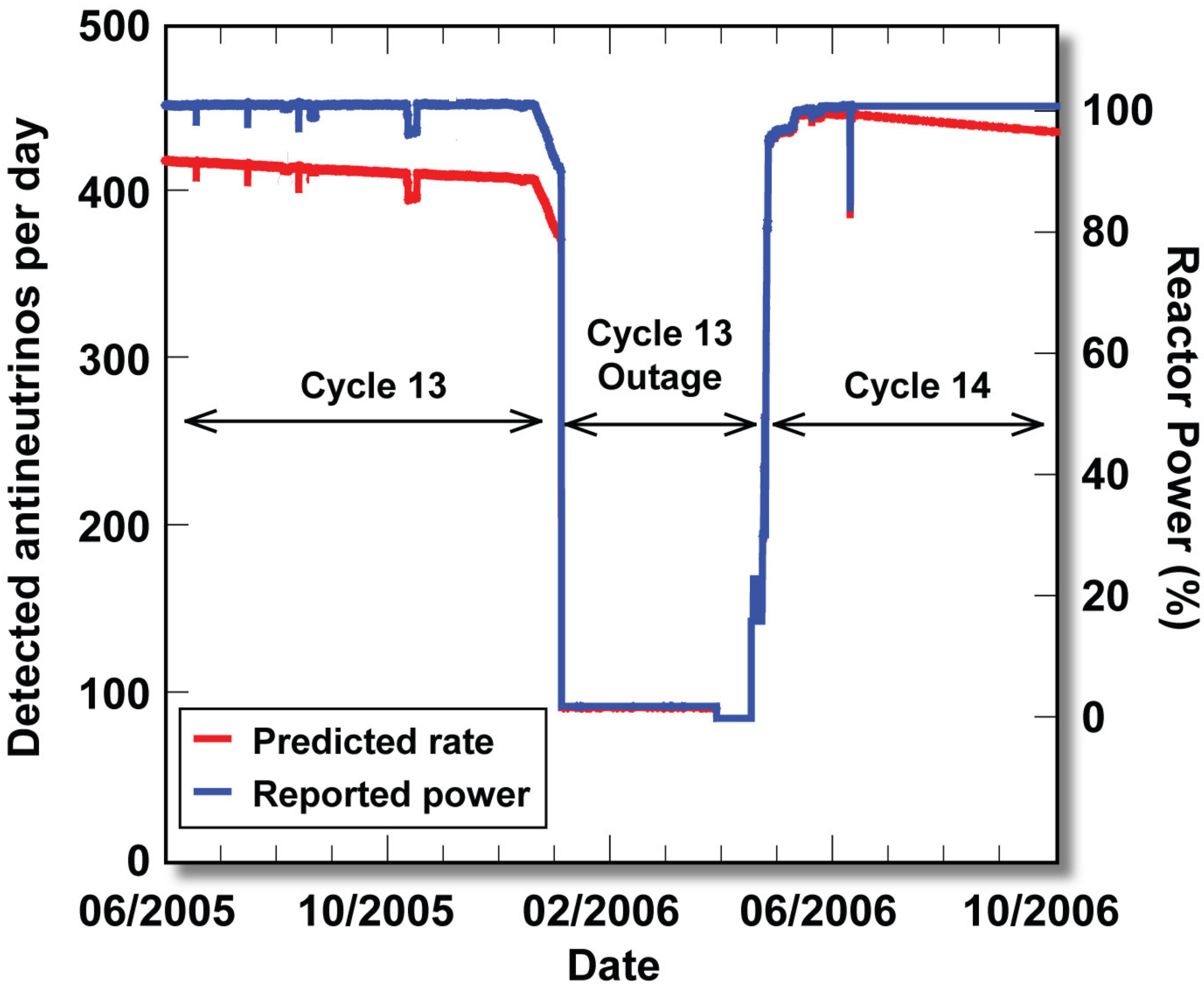
Fission rates vary in time

Antineutrino Engineering 101



Antineutrino rates vary with isotope

Prediction: the antineutrino count rate changes in response to fissile content



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

P_{th} = *thermal power*

k = time-dependent function of isotopics

Some common methods of antineutrino detection

1.Inverse beta decay $\overline{\nu}_e + p \rightarrow e^+ + n$

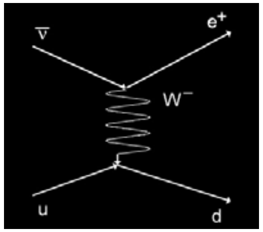
$$\sigma \sim 10^{-43}\ \text{cm}^2 (E_\nu(\text{MeV}))^2$$

The gold standard for antineutrino detection

A robust time-coincident signal

‘*good old inverse beta*’ - Petr Vogel

Neutrinos *are not* a background for this process

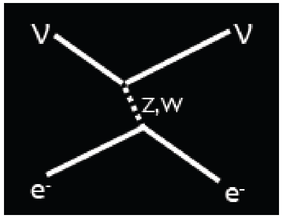


2.Antineutrino-electron scattering

(~100x **smaller** cross section than inverse beta decay)

$$\sigma \sim 10^{-44}\ \text{cm}^2 \frac{E_\nu(\text{MeV})}{10\ \text{MeV}}$$

Neutrinos *are* a background for this process



3.Coherent antineutrino-nucleus scattering

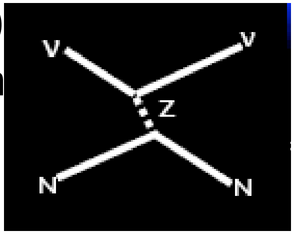
$$\sigma_{coh.} \approx 0.4 \times 10^{-44}\ \text{cm}^2 N^2 E_\nu(\text{MeV})^2$$

(100-1000x **larger** cross section than inverse beta decay)

But - a very weak signal (10s-100s of eV nuclear recoils)

May be interesting for reactor monitoring out to a few km

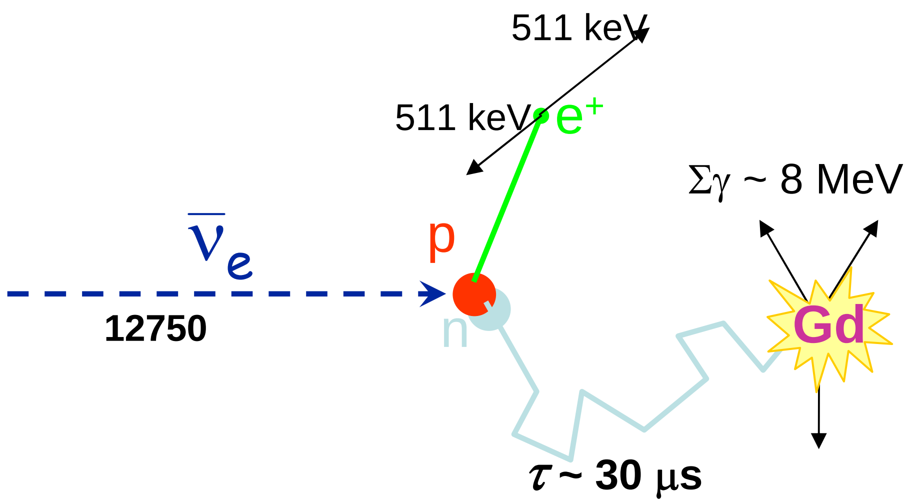
Solar neutrinos *are* a background for this process



Enhanced by square of neutron number

Using the inverse beta process, the antineutrino signal is fairly easy to select

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



prompt signal + n capture on Gd

Two flashes of scintillation light:

1) **Positron absorbs most of antineutrino energy**

First flash of blue light:
e^+ induces scintillation

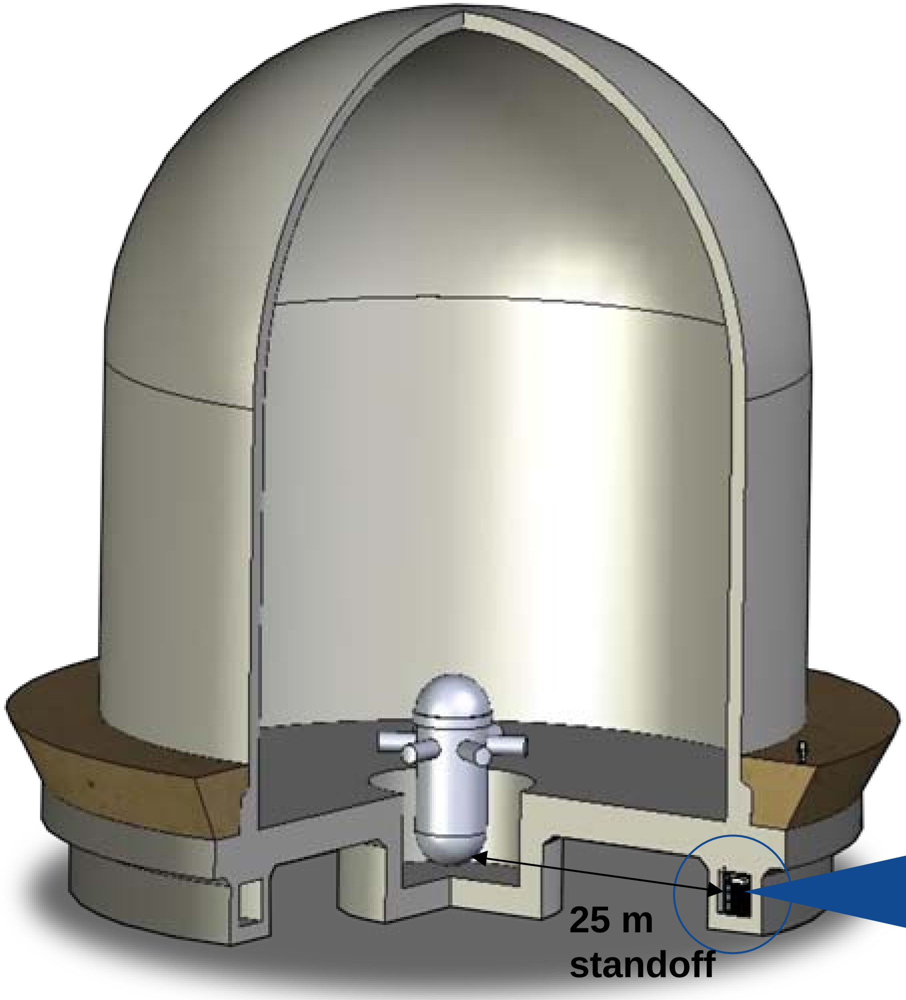
2) **Neutron wanders through scintillator and finds a Gd nucleus in about 28 microseconds**

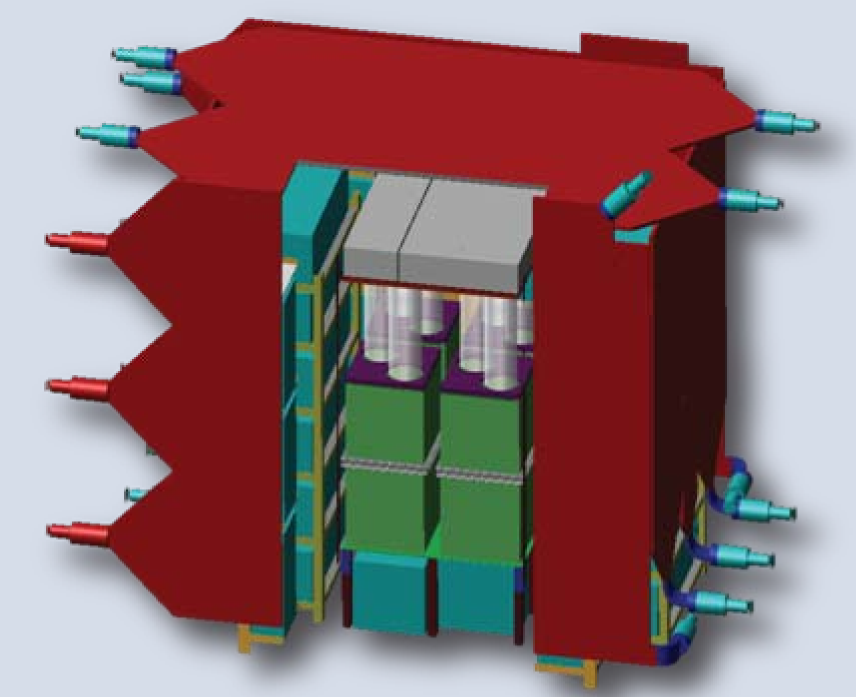
***Second flash of blue light*:**
neutron capture gammas create Compton electrons, which induce scintillation

prompt e^+ signal + n capture on GD

Number of photons in flash $\propto$ deposited energy

The San Onofre nuclear generating station and the SONGS1 detector





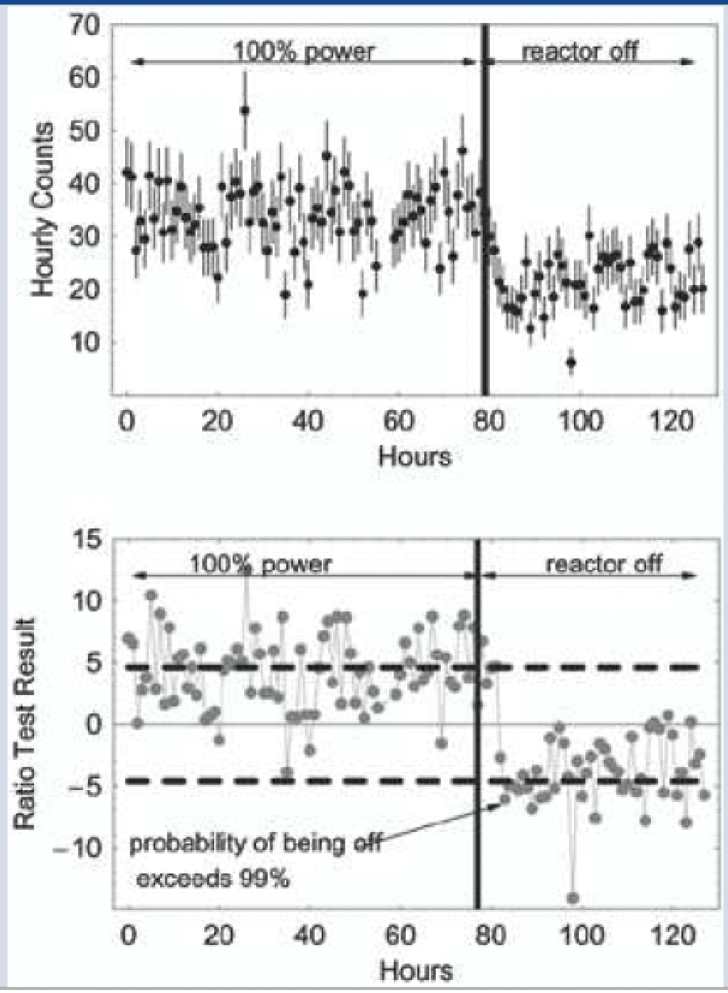
8+16 channels, 2.5 meters on a side, 0.64 tons

The LLNL-SNL antineutrino detector SONGS1

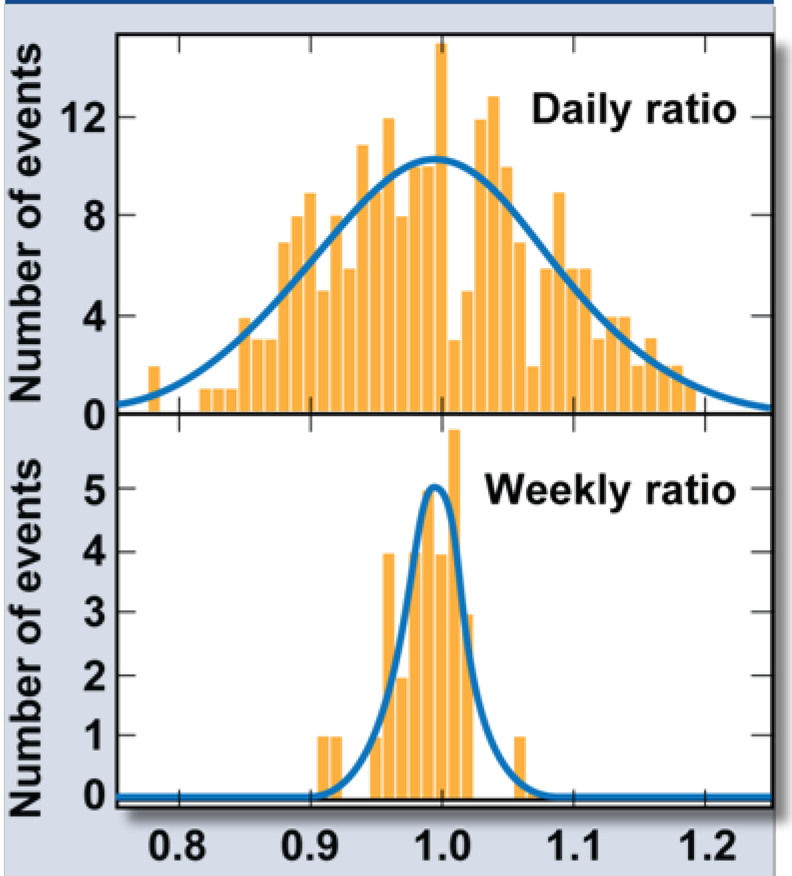
A simple and robust design suitable for IAEA safeguards

Results: Short term monitoring of operational status and power

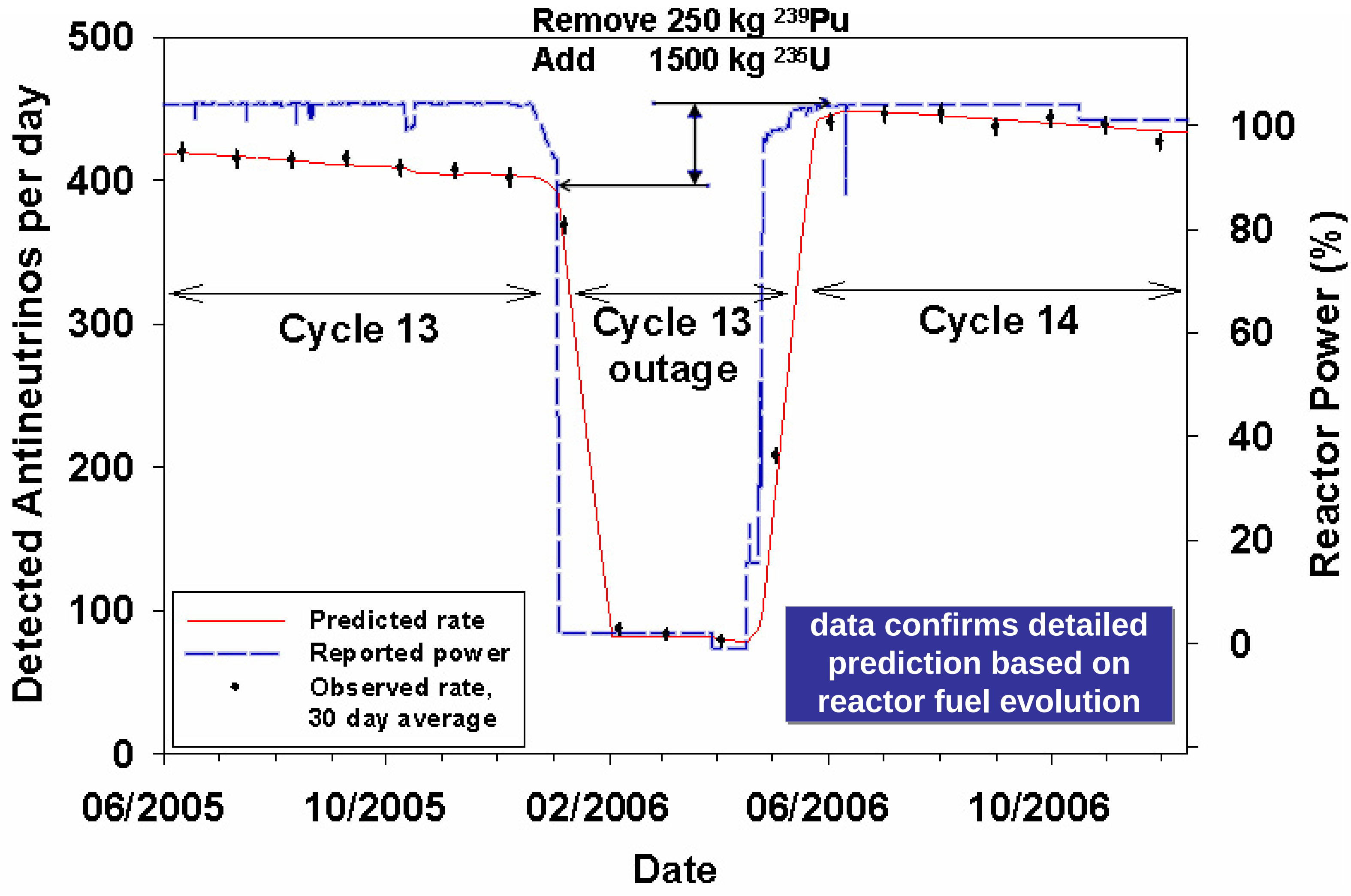
Determine reactor on/off status within 5 hours with 99% C.L.



Measure thermal power to 3% in one week



Long term predicted antineutrino rate and reactor power in SONGS1.. detected antineutrino rate



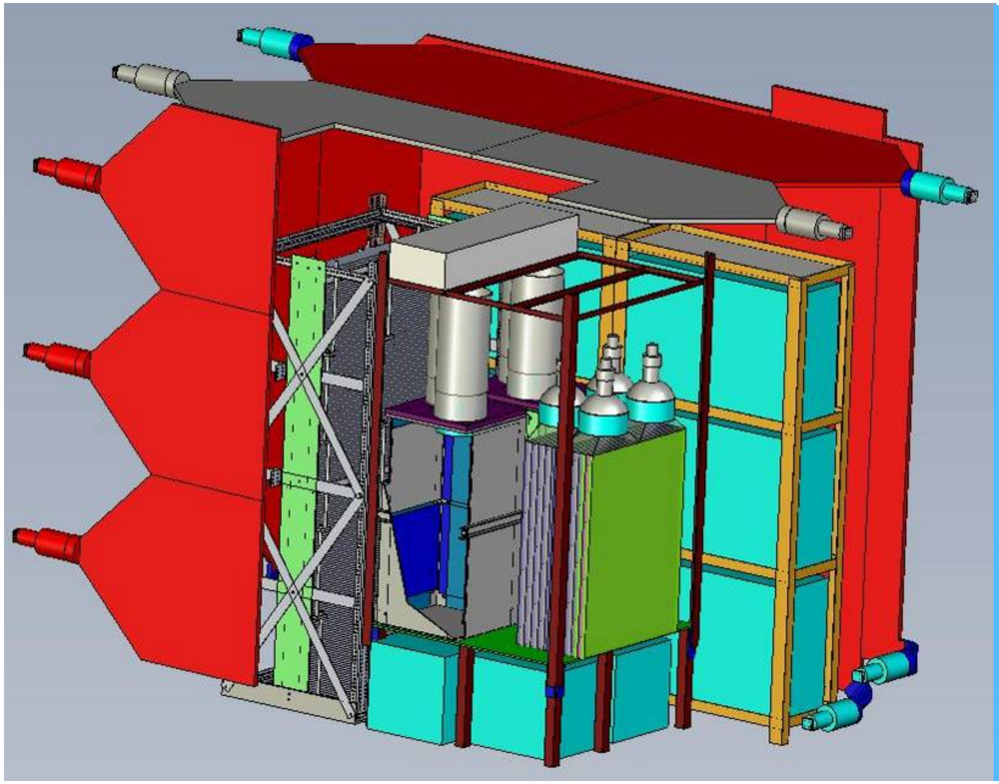
SONGS1 was very successful, but….

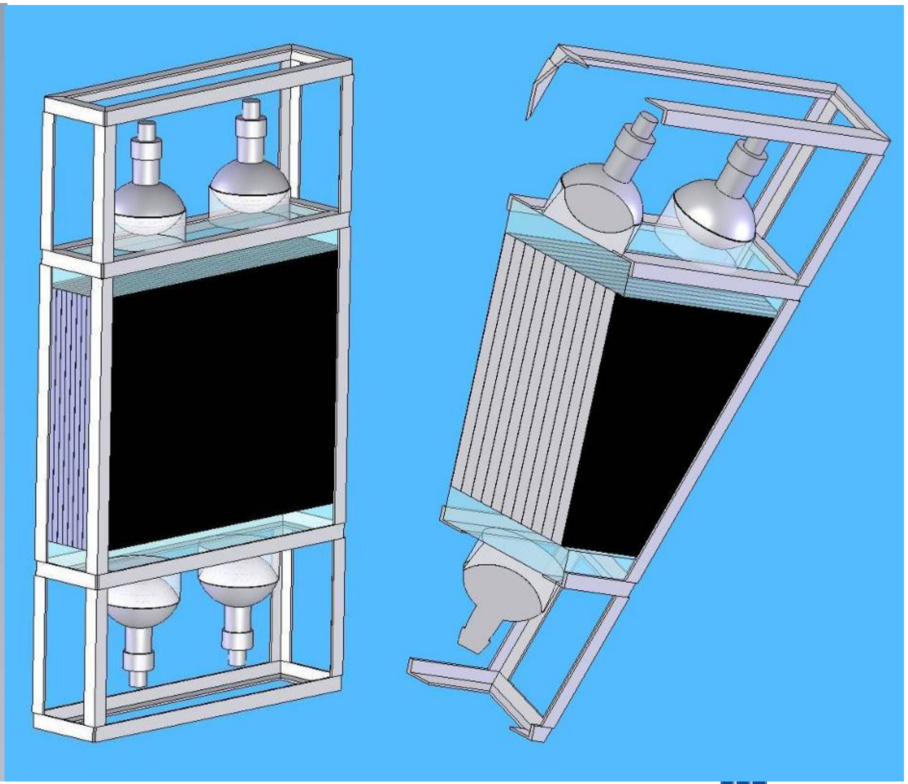
- Liquid scintillator is flammable, combustible, toxic, carcinogenic, and can spill
- It must be transported as a hazardous material, and transferred onsite into the detector

- With the SONGS1 run completed, we have investigated ideas for more deployable detectors
  - Use of non flammable, less combustible, more robust, plastic scintillator
  - Use of doped water Cerenkov detectors instead of scintillator

A solid, non-flammable, less combustible, and non-toxic alternative: a sandwich plastic detector

- **Replace liquid scintillator with plastic scintillator (PS):**
  - **Must retain neutron capture capability, ideally on Gd - commercial neutron capture Plastic scintillator is not suitable**
  - **Final design: 2 cm slabs of undoped BC-408 PS, interleaved with mylar sheets coated in Gd loaded paint**





This design trades sensitivity for deployability

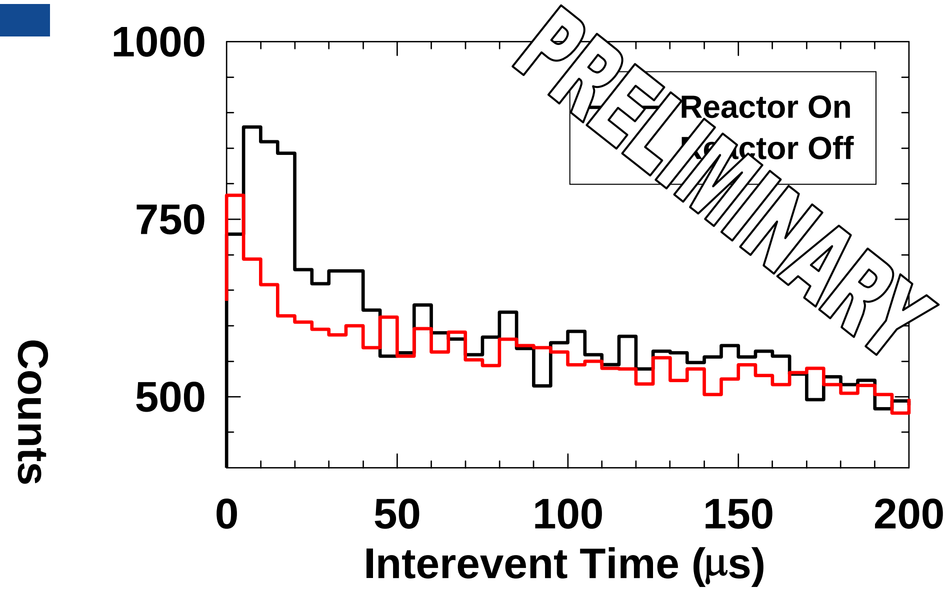
<u>Reactor Operator/ Safeguards Agency</u>

- ✓ Reduction in combustible inventory of ~ 50%
- ✓ No leakage or flammable vapour concerns
- ✓ No transportation of hazardous material required
- ✓ Preassembled

<u>Physics</u>

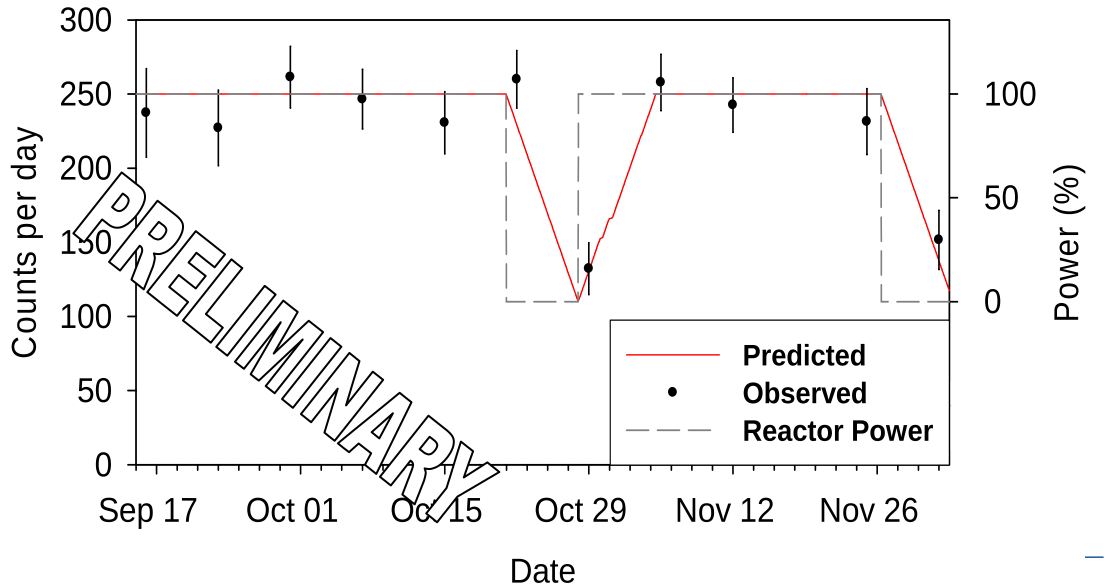
- X Lower neutron capture efficiency on Gd
  (LS: 80% / 20% Gd/H
  PS: 60% / 40% Gd/H)
- X ~ 10% fewer protons/cc (but higher density)
- X Some inactive material in main detector volume

It appears to work !



Correlated Event Rate

Daily Rate versus Time



IAEA's first idea for a safeguards application: thermal power monitoring

IAEA is considering antineutrino detectors as a non-intrusive replacement for thermal power monitoring systems, which are attached directly to reactor primary coolant loop

ATPM system cabinet

Current IAEA power monitor

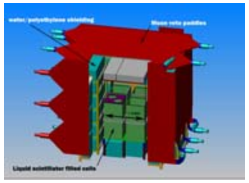
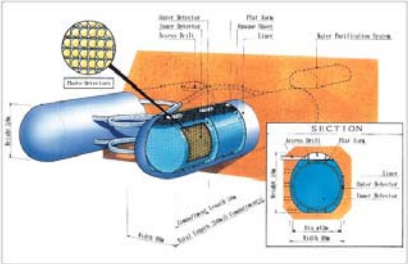
At 10 meter standoff, SONGS1 would provide 3% accurate relative thermal power measurement for a 100 MWt reactor in 1.5 weeks

"…The American group has done the first practical demonstration, and its detector is promising, because it is not much bigger than other systems the IAEA currently deploys at reactors," Whichello says.

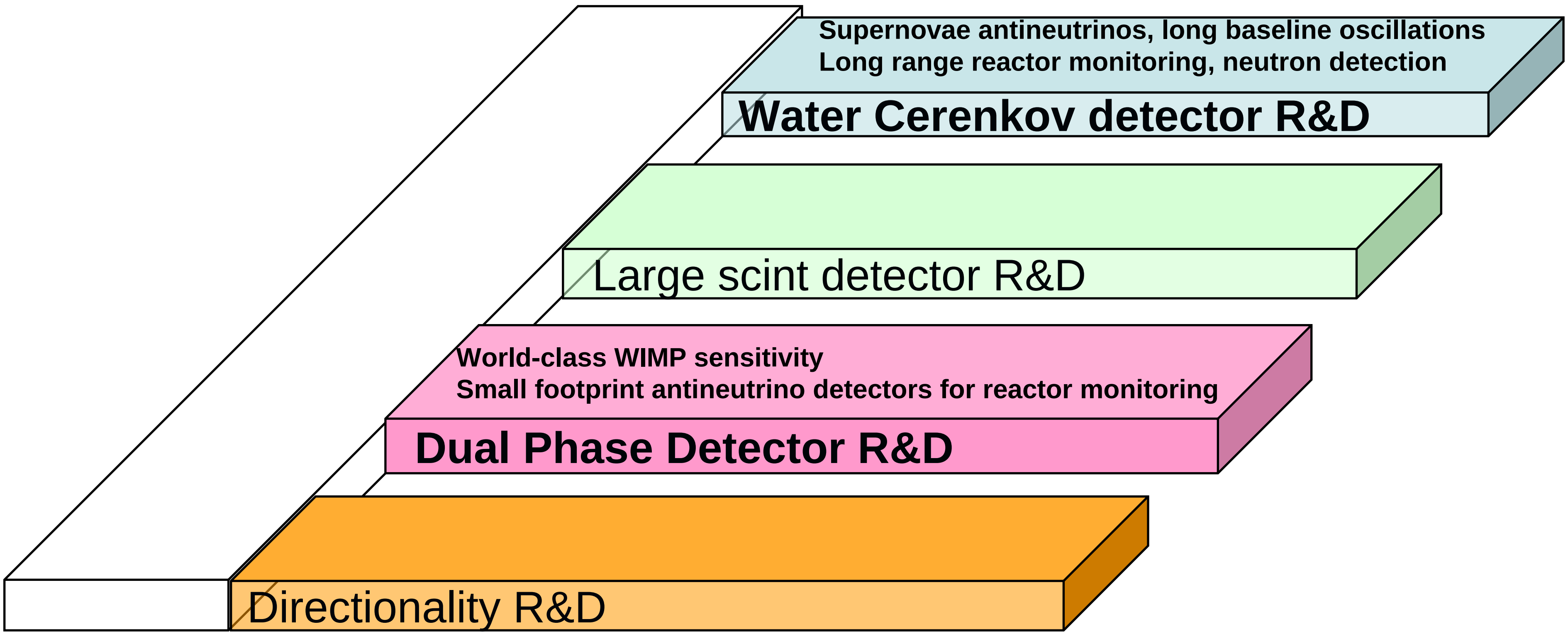
IAEA representative, qoted in *IEEE Spectrum article, April '08*

October 2008 workshop in Vienna to consider how to integrate into the safeguards regime

What could be next, and what is needed to get there

Application	Scale	Status
1. IAEA *Safeguards* – Plutonium Disposition – FMCT	**Near-field** → 5-1000 m **Detector Scale** → 1-100 tons	**Demonstrated with simple detectors (LLNL, Kurchatov)** 
2. Verification and Cooperative Monitoring • Confirm cessation of plutonium production - e.g. in North Korea, Iran	**Mid-Field** → 1– 10 km **Detector Scale** → 1-10 kiloton	**Detectors at this scale exist now** 
3. Remote Detection • Observe reactors and explosions across borders	**Far-Field** →10– 500 km **Detector Scale** → 1 Megaton (n.b. - *mass* not *yield*)	**Proposed for physics experiments** 

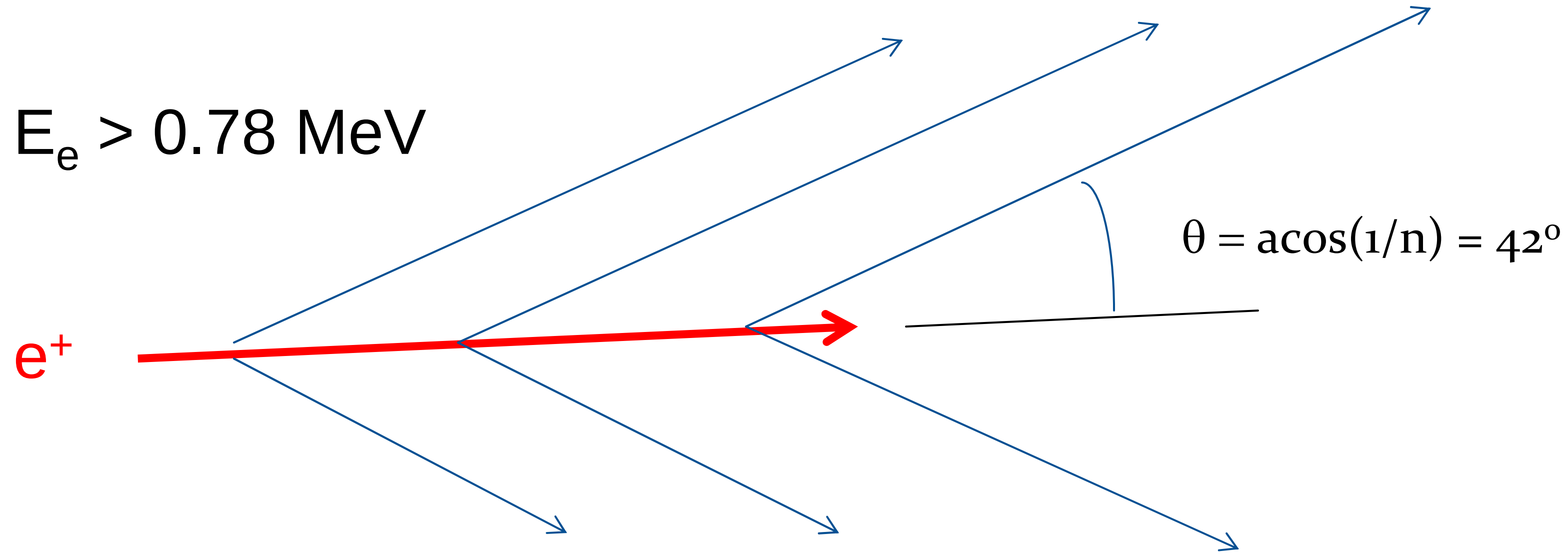
Some research topics of interest for Applied Antineutrino Physics - and Dark Matter and Neutrino Science



Water Cerenkov neutrino detectors measure neutral current neutrino-electron interactions

- Used for many years in neutrino detection
- IMB, Kamiokande, Super-Kamiokande, SNO
- Veto for KamLAND and Borexino
- Above the Cerenkov threshold (v>c/n), the number of emitted photons nearly proportional to energy.

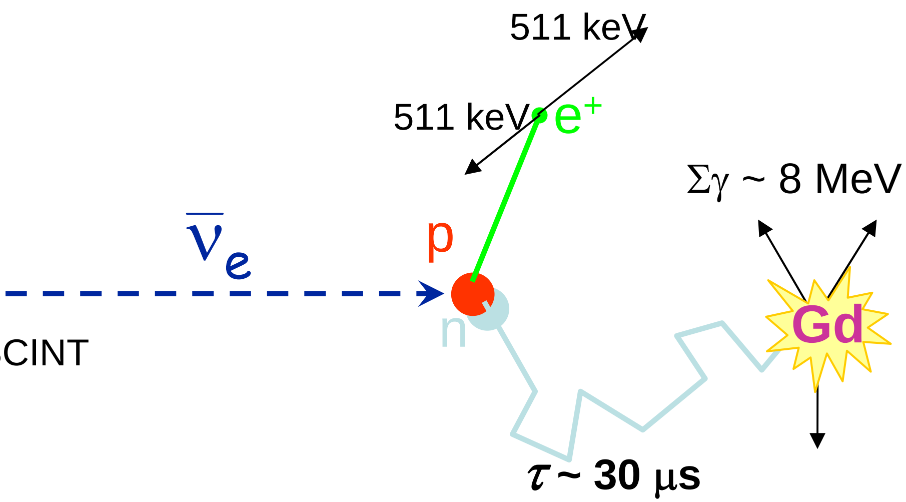
$E_e > 0.78$ MeV



Water Cerenkov antineutrino detectors ?
For that, we must be able to detect neutrons in water

Use Gd to detect the neutron, as in liquid scintillator
Gd-doped water (Bernstein, 1999)
GdCl3 (Beacom & Vagins, 2003)

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



The same prompt e+ signal + n capture on Gd as LSCINT
But - 100x less light output

Possible Uses in Fundamental Science

- Active neutron shields for WIMP detectors
- Make Super-K-like detectors, sensitive to antineutrinos from many sources:
  - relic supernovae, galactic supernovae, reactor, solar and beam neutrinos

Possible Nuclear Security Uses

- Large detectors for 100 km standoff reactor monitoring
- Close reactor monitoring with *no passive shield*
- Large and efficient neutron/gamma detector for nuclear materials monitoring and search

Gd-doped neutron/antineutrino detectors – research questions

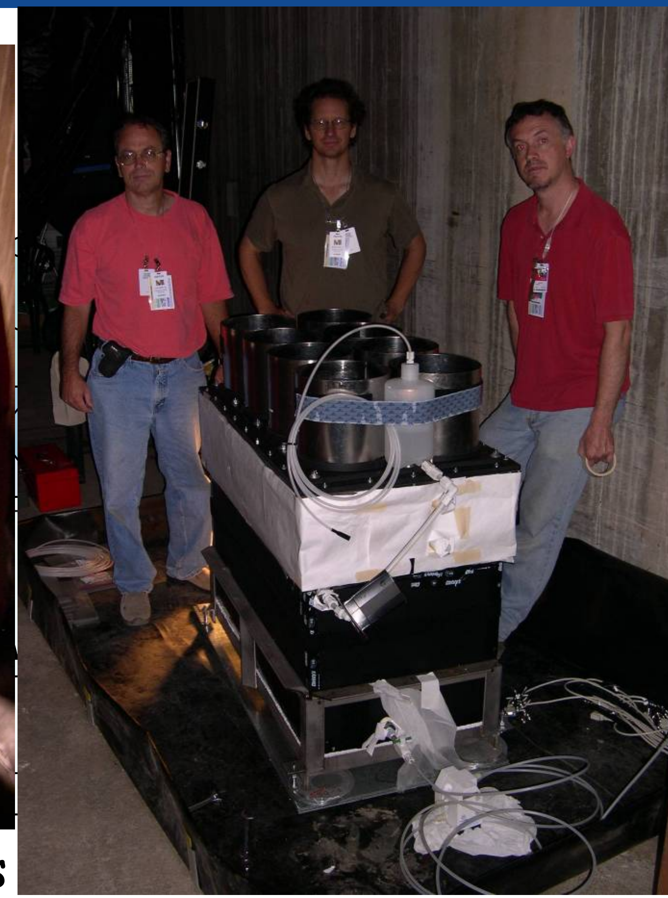
- Known
  - Gd cost - relatively inexpensive
  - Gd availability – plenty of it in several places worldwide
  - Gd quantity - 0.1% sufficient for 85% capture
  - Gd capture signature (8 MeV γ- cascade) -tens of p.e. predicted

- To be studied
  - Can we see the relatively weak neutron signal, time coincidence, and actual antineutrino signals in Gd-water ? **Remarkably, not done until recently**
  - What are the effects of Gd compounds on detector components and on attenuation? **2008-2009 DUSEL R&D activities at LLNL**
  - Can wavelength shifting dopants boost light output ? **-2009 DUSEL R&D activities at LLNL**

A prototype small water antineutrino detector: 8 PMTs, external muon veto*, no passive shield

Features:

- Very reflective walls (TIR + Tyvek)
- 8 8″ PMTs on top only
- 0.1% Gd (same as Double Chooz, Super-K (Gadzooks) proposal)
- Sealed target volume (no O_2 access)
- NO NEED FOR A SHIELD
- Record of Invention and journal article submitted

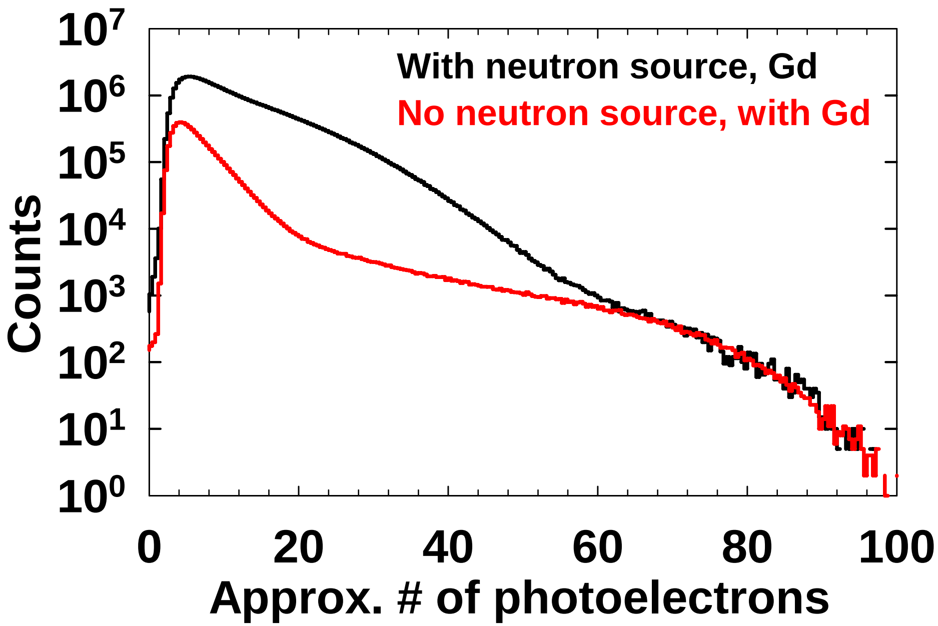


- total external dimensions ht

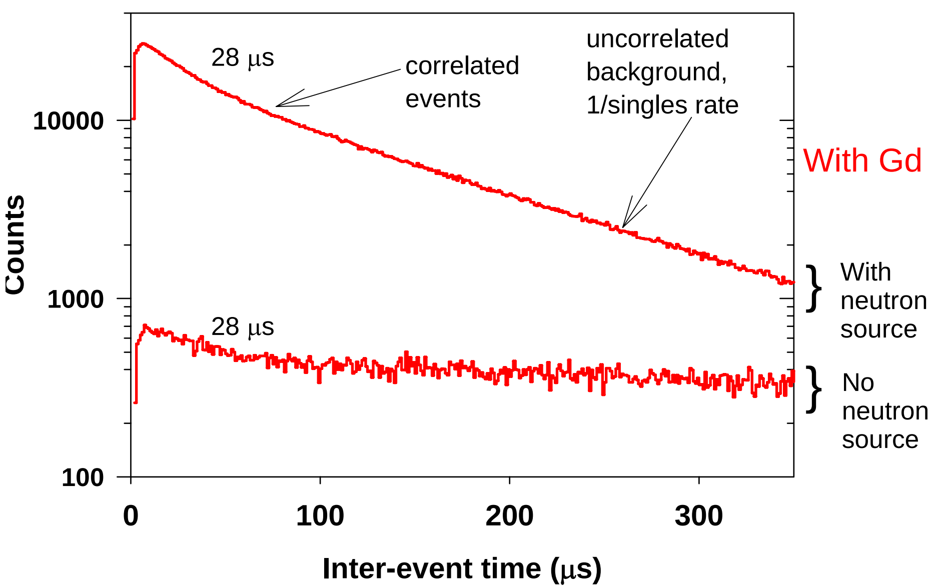
* http://www.youtube.com/watch?v=Y2JM_-pj2yE **- Harvey Mudd undergrad construction of muon veto featured on youtube**

LLNL data (*aboveground*) show sensivity to neutrons, and to time correlated events

A) Neutron captures on Gd



B) correlated (gamma,neutron) events from a ^{252}Cf neutron source



http://arxiv.org/abs/0808.0219

What about reactor antineutrinos… ?

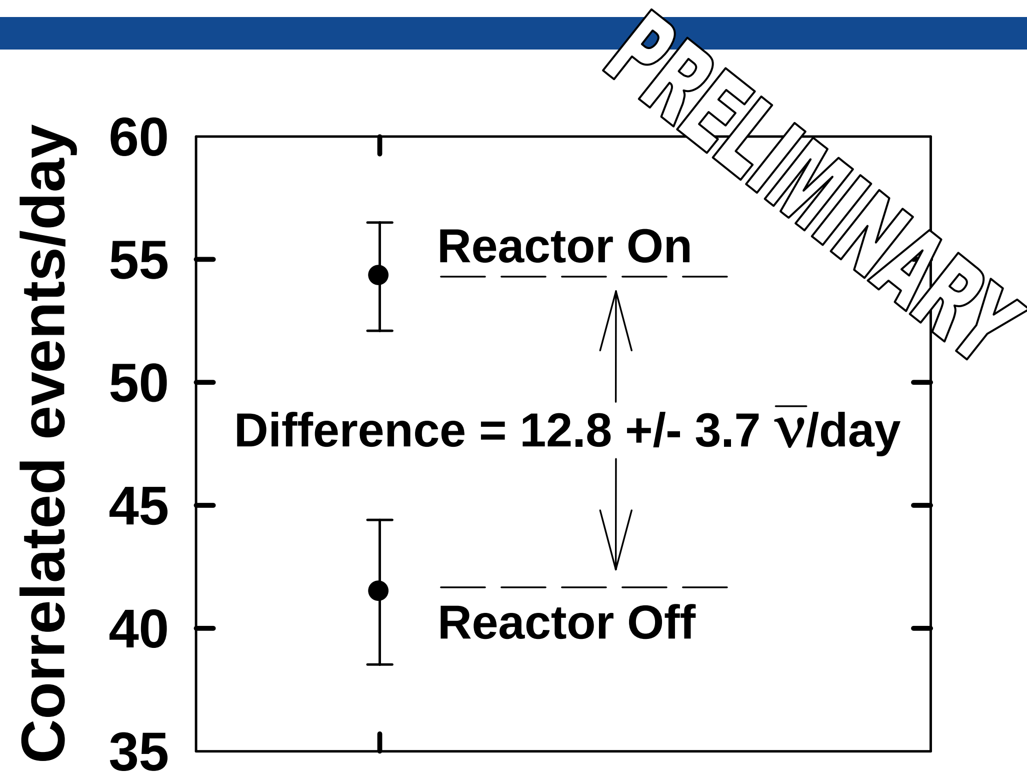
Preliminary: First demonstration of reactor antineutrino detection with Gd in water

REACTOR ON

Versus

REACTOR OFF

May be visible using the water signal



Advantage – no fast neutron shielding required ! – large reduction in footprint possible
Disadvantage – sensitivity and energy resolution much inferior to plastic/liquid

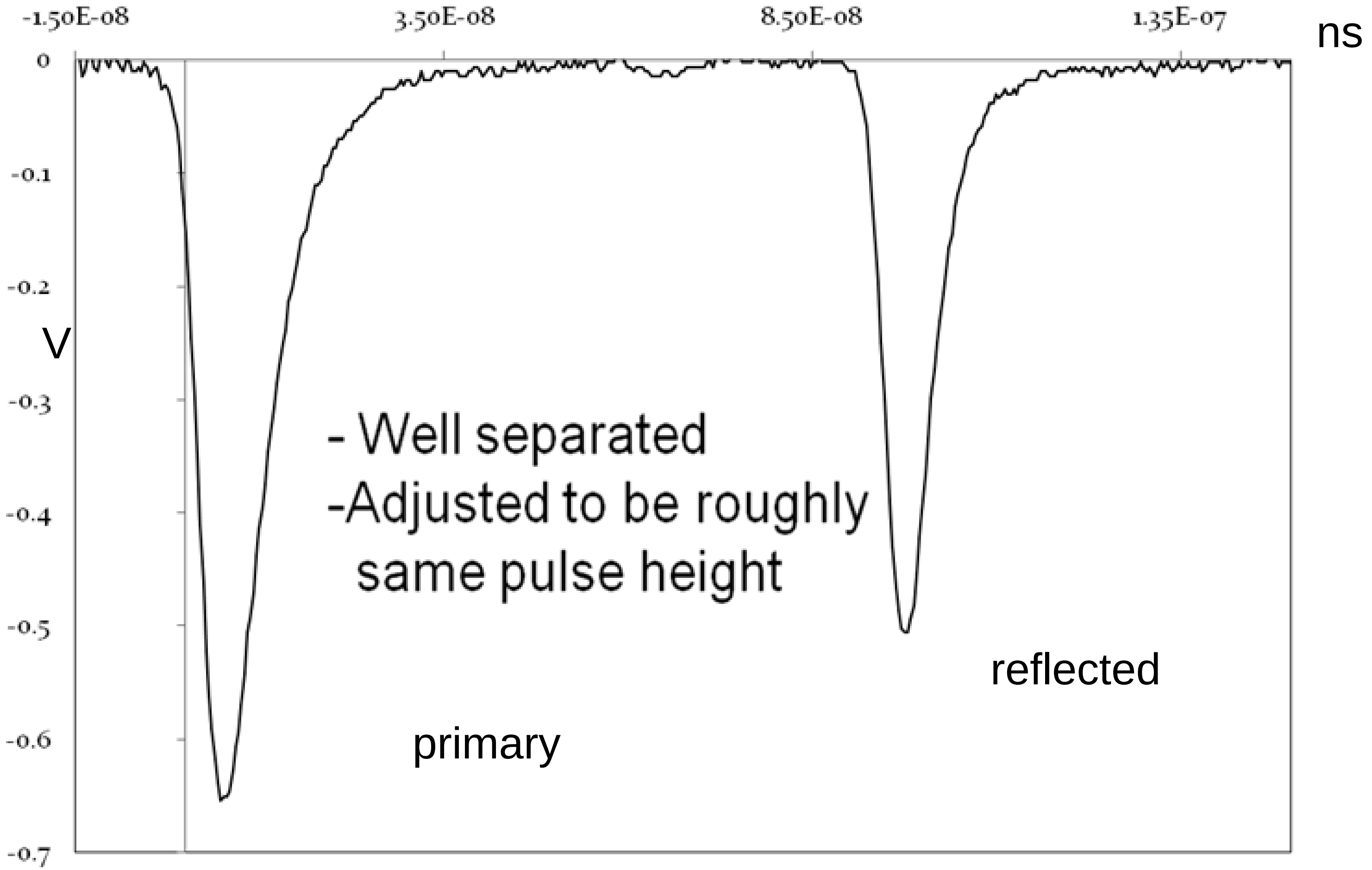
Transparency studies at LLNL - R. Svoboda, LSU student W. Coleman

Gd-water Transparency test apparatus

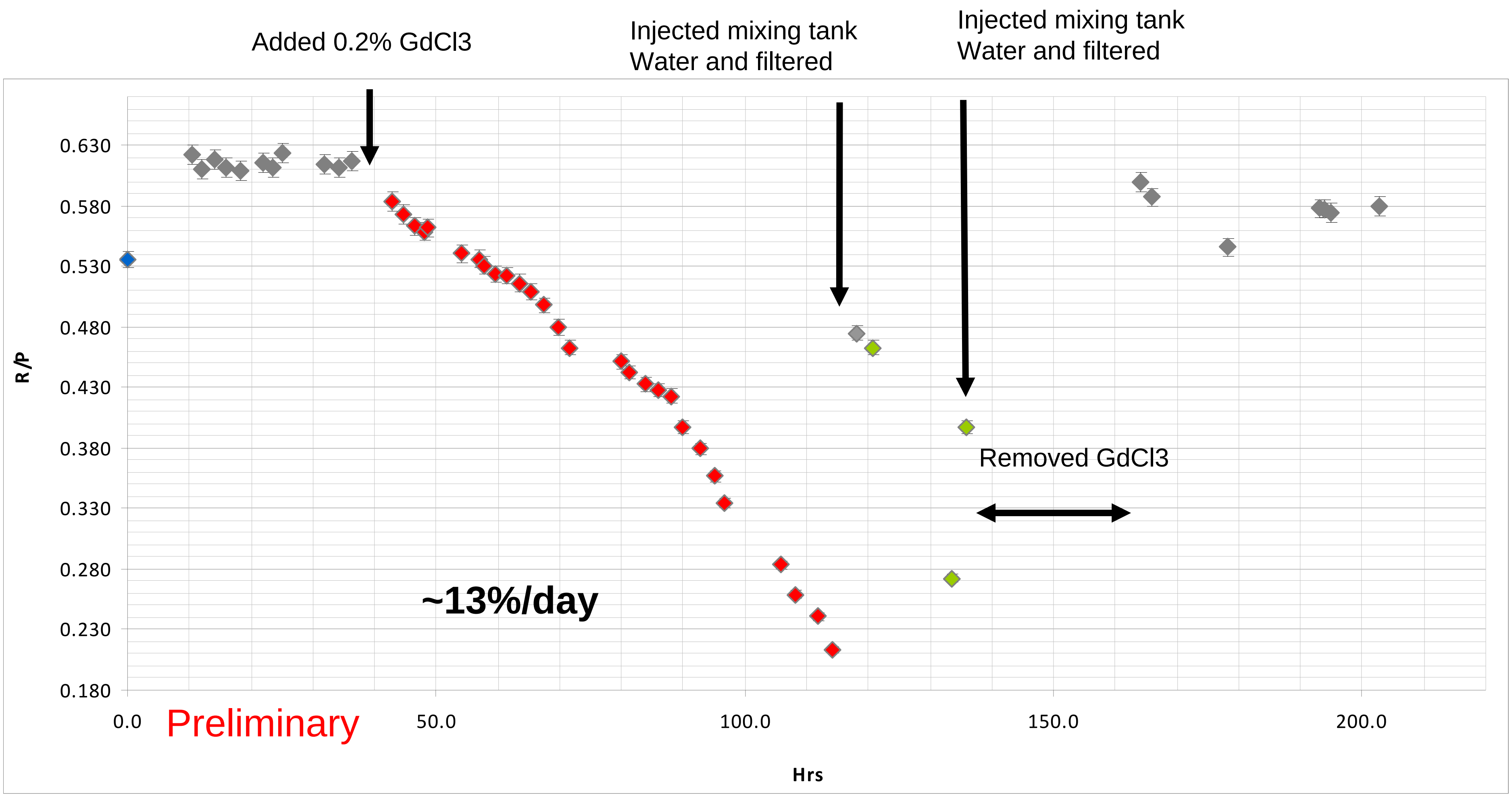
For big detectors we need 50 meter attenuation lengths

A 20 meter photometer lets us study long attenuation lengths

A typical 337 nm waveform



Test of $GdCl_3$ addition at 337 nm (similar results at 420 and 440 nm)

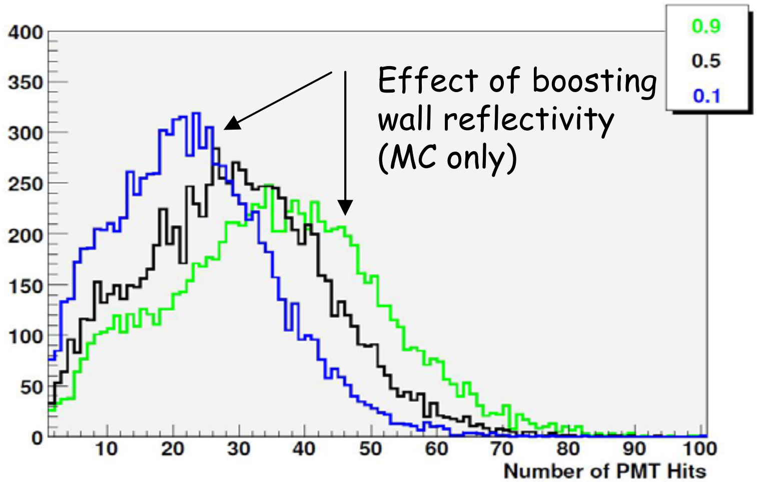


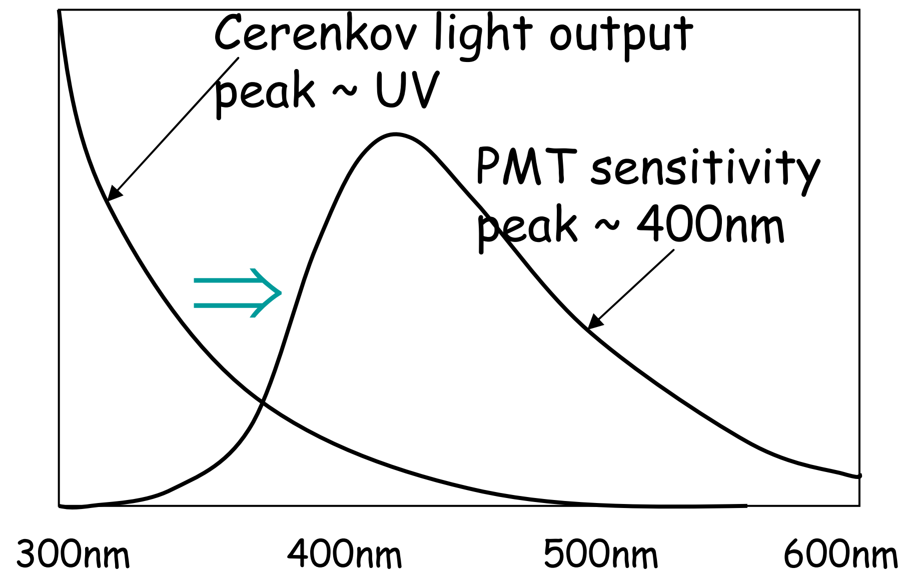
Transparency results and plans at LLNL

- $GdCl_3$ is not a suitable additive for detectors made with steel.

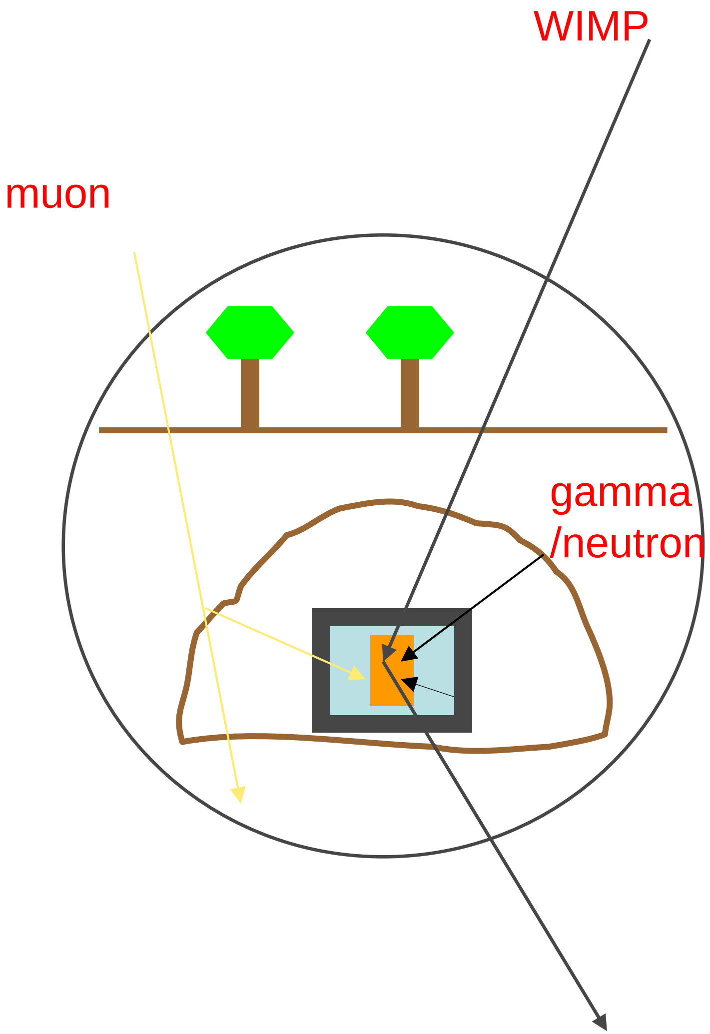
http://arxiv.org/abs/0805.1499
Transparency of 0.2% $GdCl_3$ Doped Water in a Stainless Steel Test Environment
Authors: W. Coleman, A. Bernstein, S. Dazeley, R. Svoboda (Submitted 10 May 2008)

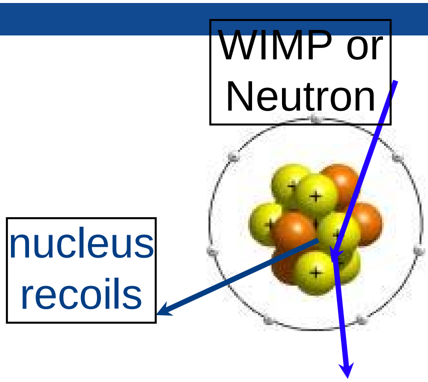
- Other Gd additives, wavelength shifting dopants, reflectivity - DUSEL R&D activities in FY09





Isolating Dark Matter Events





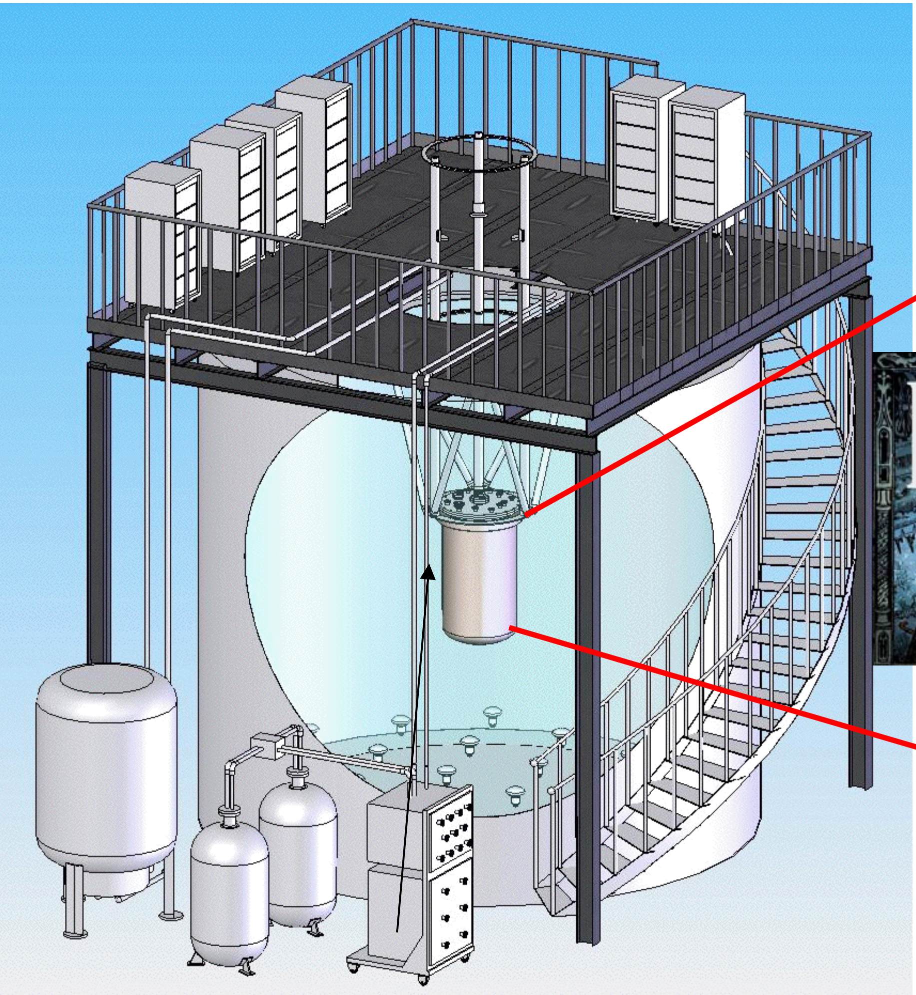
WIMPs (and neutrons) induce nuclear recoils

Dark Matter interactions are extremely *rare* (low rate) but not *unique*

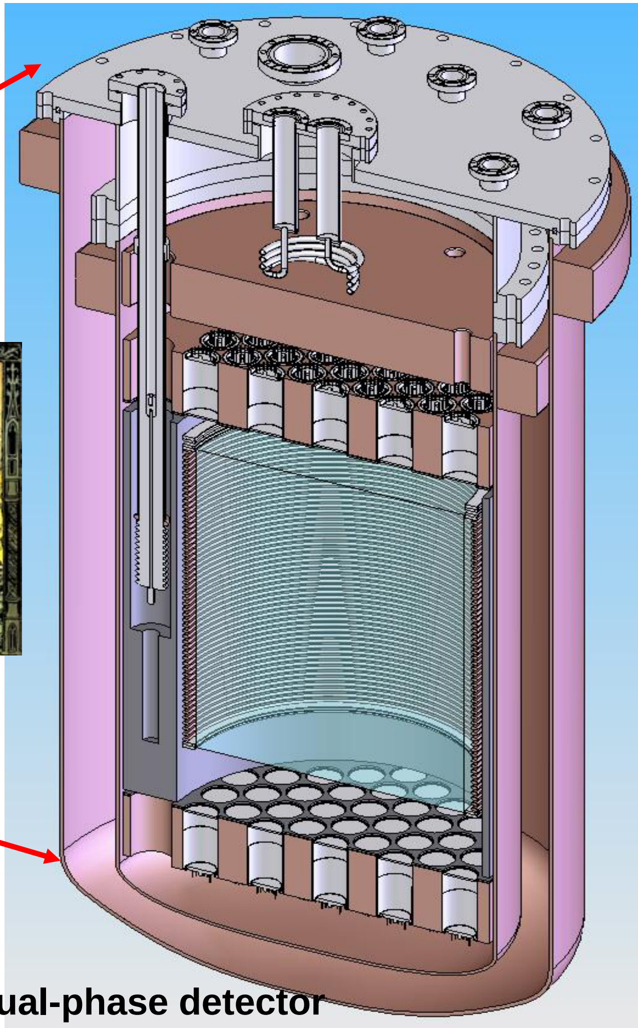
- **Assemble as much material as practical**
- **Bury** it to reduce cosmic ray backgrounds
- Build detectors from **radioactively pure materials**
- **Shield** the detector from local backgrounds
- **Use available discriminants** particular to the medium in question

A lot in common with neutrino detection !

LUX: a dual-phase xenon Dark Matter detector with an active water shield



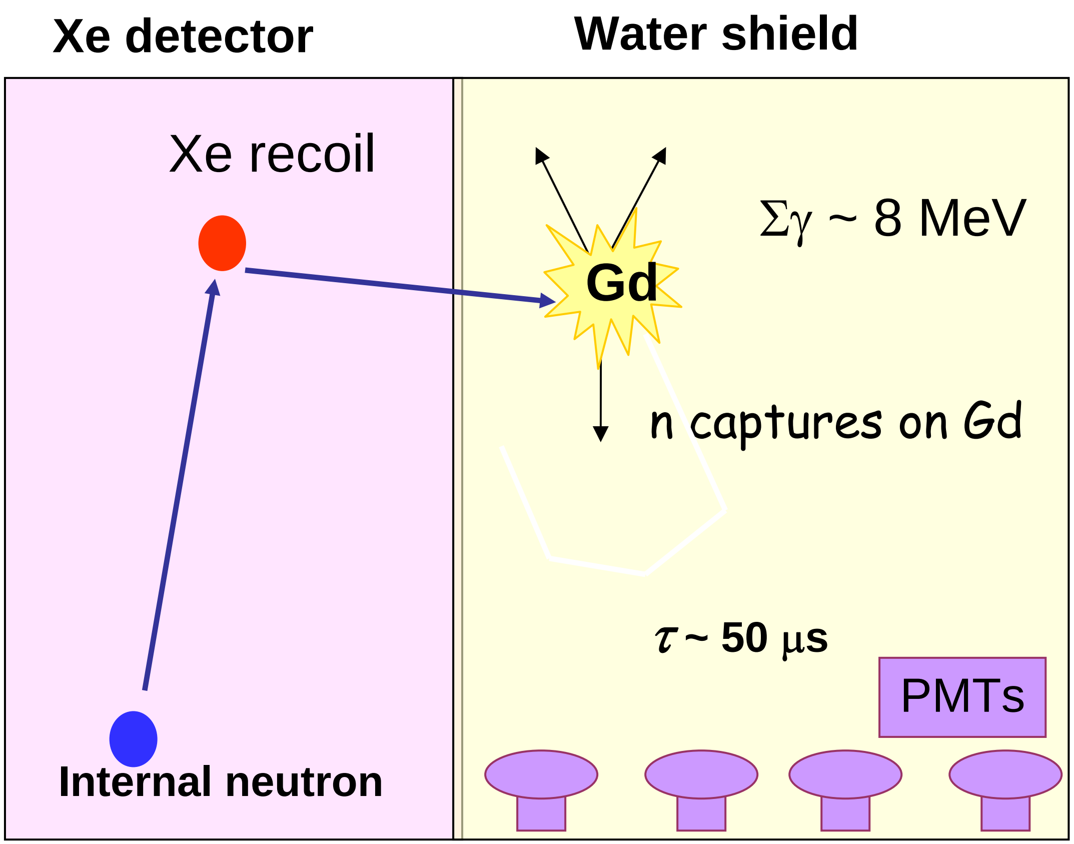
6 m diameter water shield



300 kg dual-phase detector

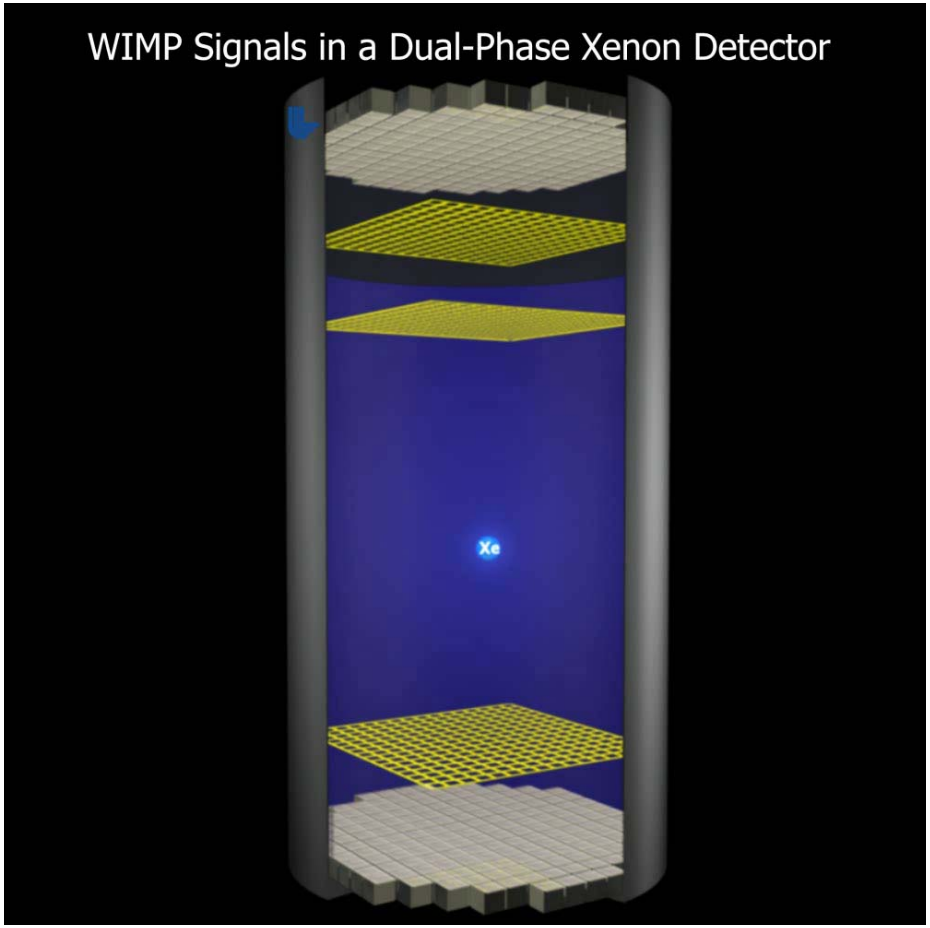
LUX Water Shield & Veto – can it be made neutron sensitive ?

- Default: veto incoming muons via Cherenkov light signal.
- Possiblity: tag thermalized neutrons generated within the detector
  - reject WIMP like events
- Gd (0.1%) in water gives a capture efficiency of > 90% for thermal neutrons, followed by an 8 MeV gamma cascade *K. Kazkaz Monte Carlo, LLNL*

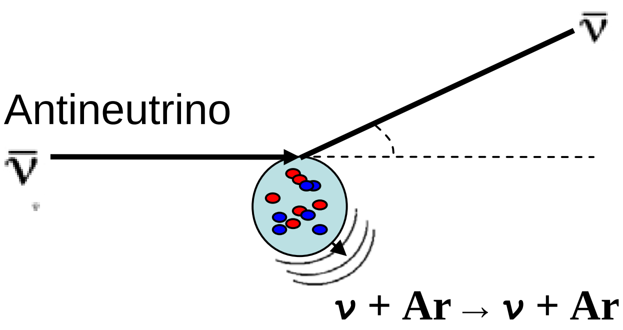


internal components are an important source of background neutrons in LUX and superLUX

Signals in a Dual-Phase Xenon detector



The basic principles of coherent scattering in argon – A nuclear recoil – virtually identical to a WIMP recoil



Energies	E_ν (MeV)	$\langle E_{recoil} \rangle$ (keV)
Reactor ν	1 → 8	0.018 → 1.15
Solar ν	2 → 15	0.07 → 4.0
Supernova ν	10 → 50	1.8 → 44.8

Neutrino-nucleus scatter is coherent for

$E_n < 50$ MeV in Argon

Recoil energies

$$\langle E_{recoil} \rangle = 716 \text{ eV} \frac{E_\nu^2(\text{MeV})}{\boxed{A}}$$

Atomic Number

among noble elements Argon (Z=18) gives the greatest number of detectable ionizations per unit mass

Cross-section

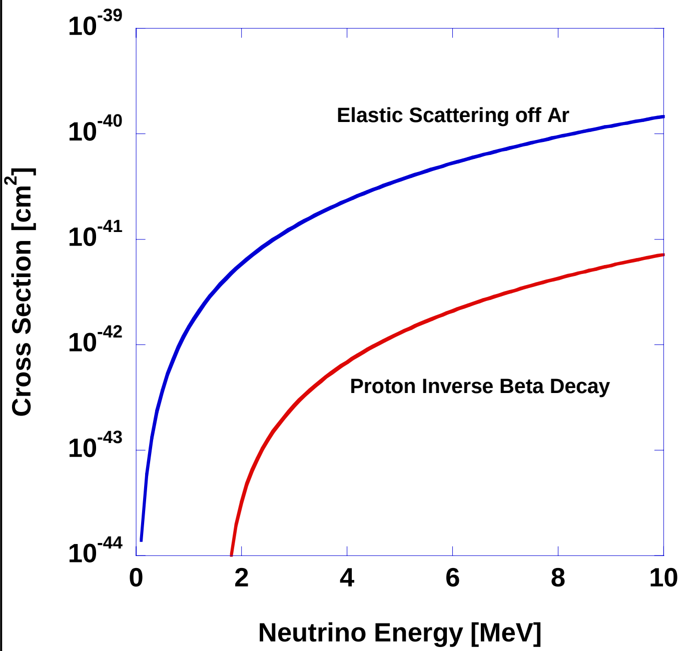
Neutron Number

$$\sigma_{elastic} = \frac{G_F^2}{4\pi} N^2 E_\nu^2$$

$$\approx 0.4 \times 10^{-44} \text{ cm}^2 \boxed{N^2} E_\nu(\text{MeV})^2$$

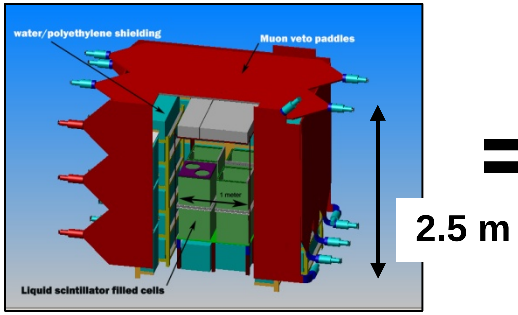
Smaller reactor monitoring detectors are within reach

Predicted coherent scattering cross section (for Argon) ~100 times larger than Inverse β-decay



Flux of reactor antineutrinos

(25m from core): **10^{13}** $\bar{\nu}$ / *(cm^2 sec)*



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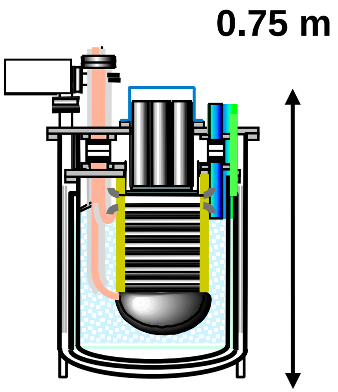


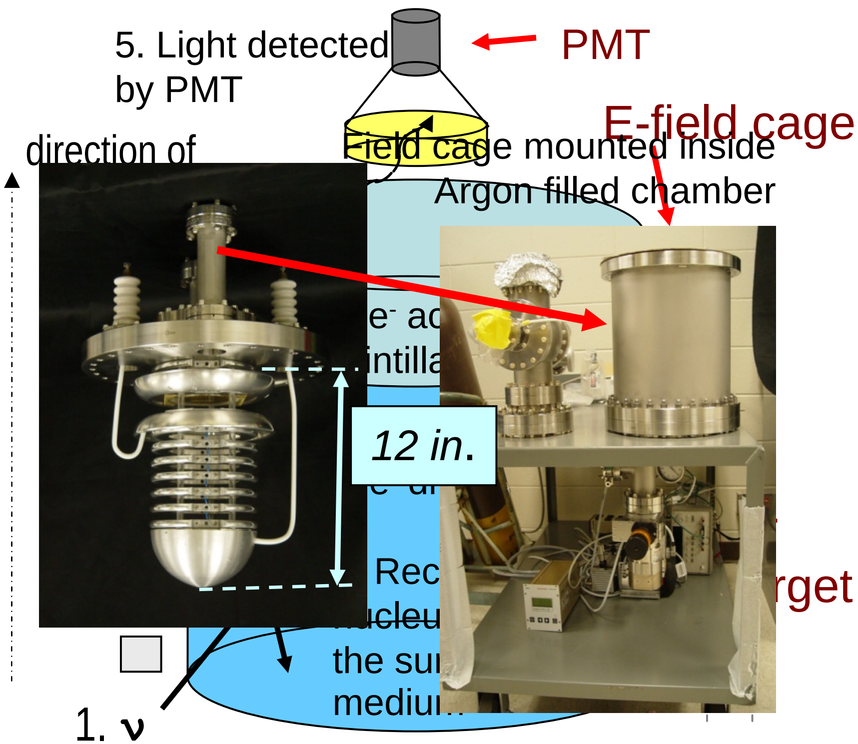
LLNL-SNL Reactor Monitor:0.64Tonne (San Onofre, Calif.)

2-phase Argon coherent scatter detector : 10 kg *(Proposed)*

Both detectors would report similar rates

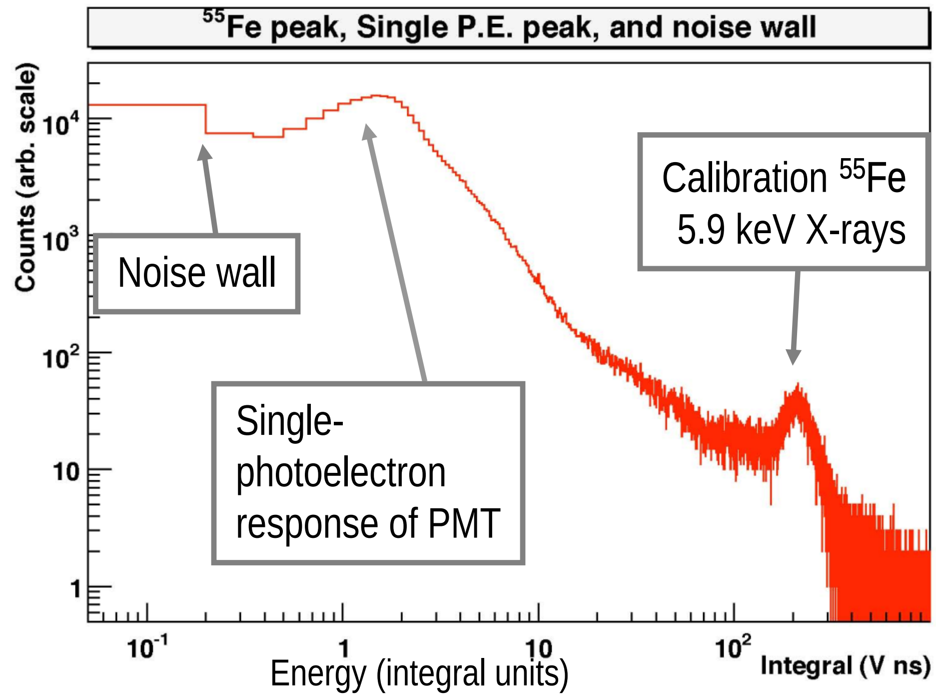
2-phase detector ~100 times less mass

Testing with gas-phase argon at LLNL



By studying gas phase nuclear recoils we learn about ionization, light collection, and electron transport in the dual phase detection system

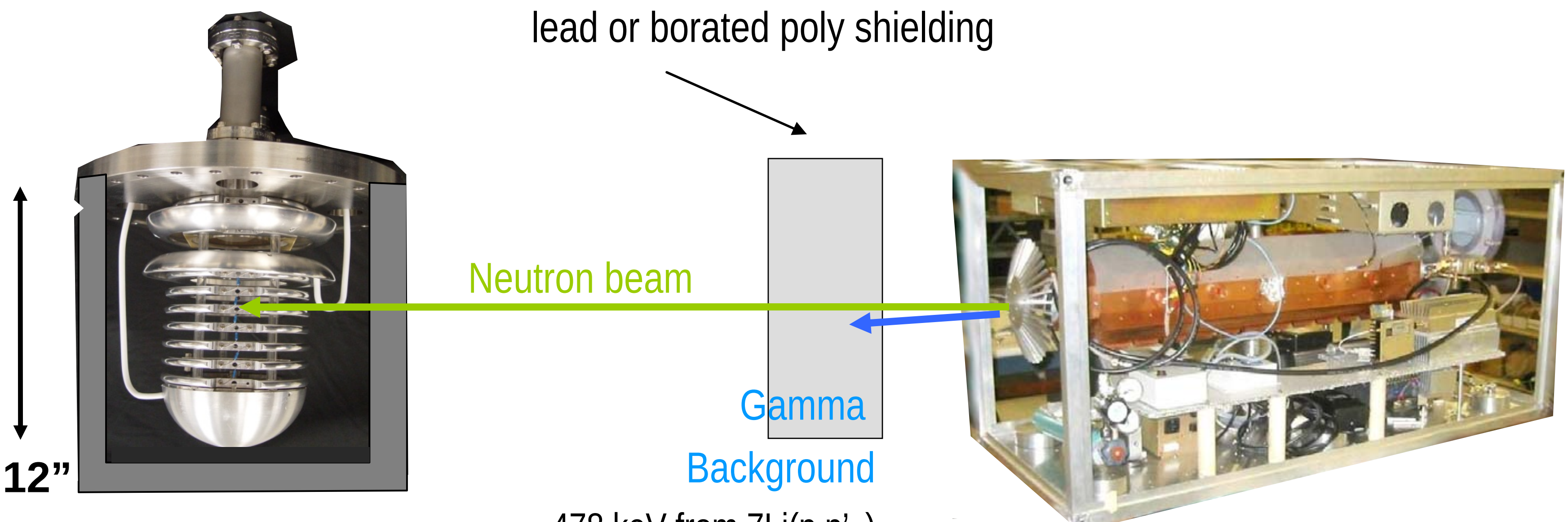
Calibration & Noise-floor estimation



Single p.e. resolution above noise floor is essential for a coherent scatter detector

Neutron-nuclear recoil measurement

Nuclear collisions produce fewer ionizations than electronic collisions.
We want to measure this **quenching factor.**



478 keV from 7Li(p,p’γ)

Argon detector

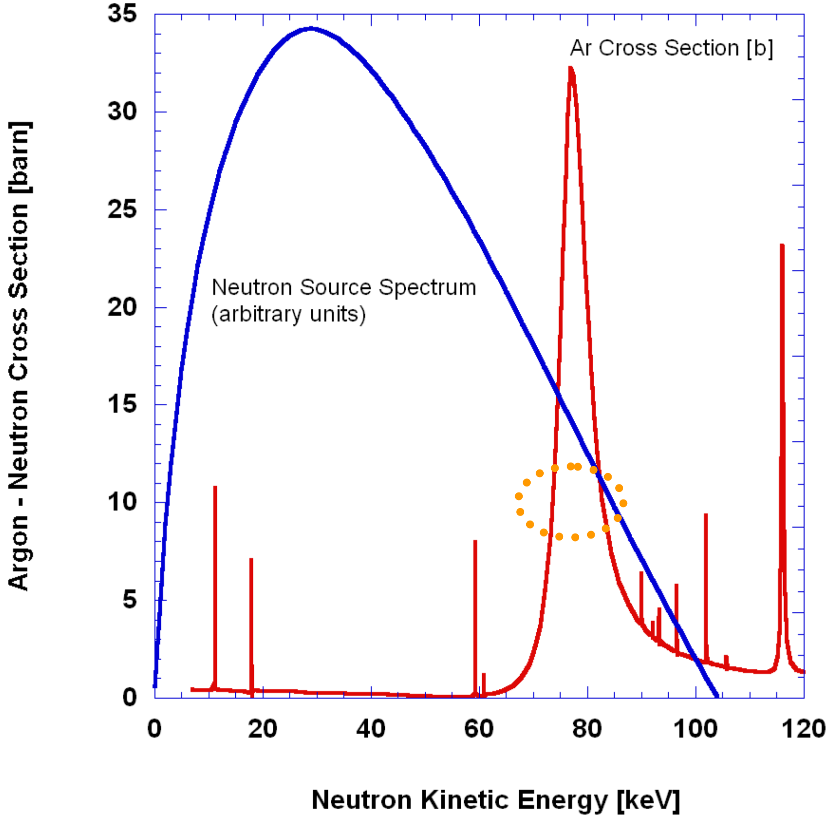
7Li (p,n) 7Be, **10-100 keV neutrons**

2-MeV LINAC Li-target neutron generator

100 Hz rep. rate, ~105 neutrons / spill

Predicted nuclear recoil spectrum – very low energy recoils generated by 10-100 keV source overlap with the antineutrino (and WIMP) recoil region

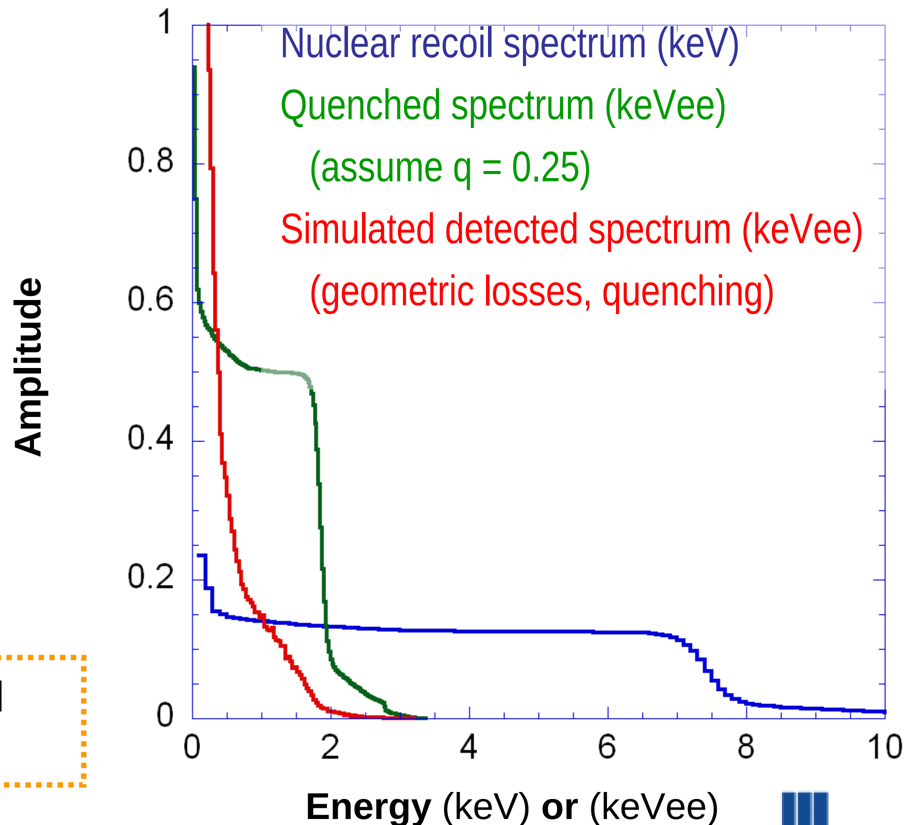
Incident neutron spectrum



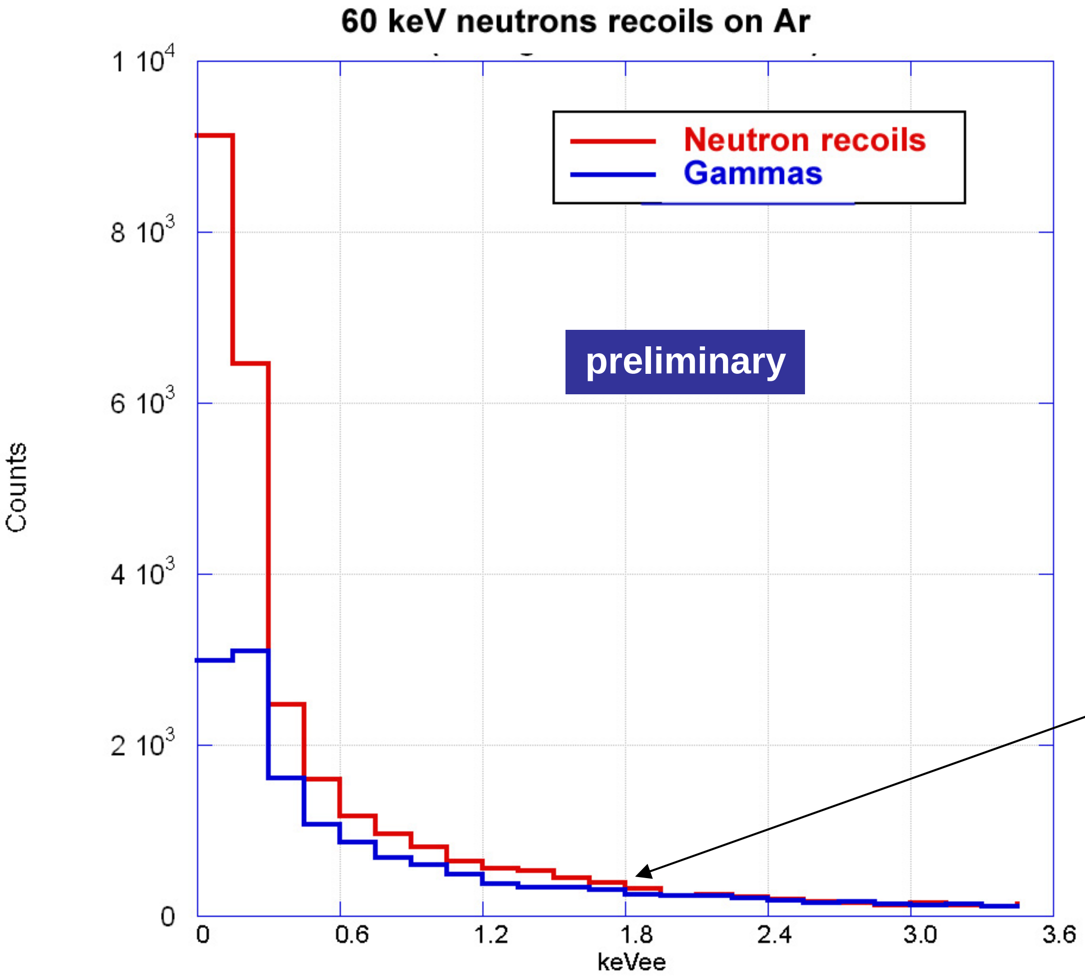
Incident neutrons within this 80keV resonance will contribute to the bulk of measured n-Ar recoils

Predicted nuclear recoil spectrum

(With an assumed quenching factor)



Preliminary - nuclear recoil data analysis using neutrons



Lead data:

neutrons **&** residual gammas

Poly data:

Mostly residual gammas

Result 8 keVr, 1.8 keVee recoil maybe the lowest ever in Ar

Momenta comparable to what is needed for coherent scatter

Germanium-based coherent scatter with a low noise readout – J. Collar U of Chicago

- Existing Ge crystal being tested at U. Chicago (purchased originally with NNSA funds)
- Calibrated in ROI by using recoil neutrons at KSU
- Frond-end electronics development work done at ANL supported by LDRD
- Preparing for first deployment tests in deep underground location
- Detector deployed at LLNL/SNL site at SONGS May 1 2008 !