The Advanced Instrumentation Testbed and WATCHMAN: A WATer CHerenkov Monitor for ANtineutrinos

LLNL-PRES-733327

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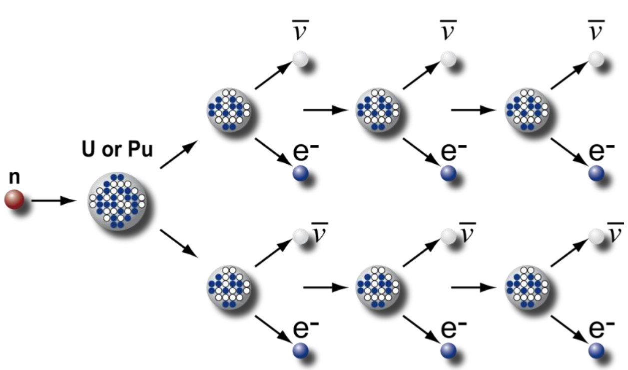
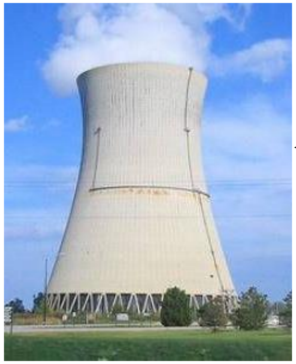
Lawrence Livermore National Laboratory

Huge numbers of antineutrinos from reactors

Very small interaction cross-section

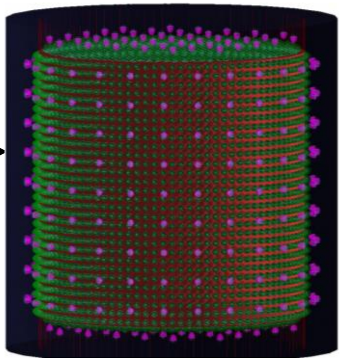
~ 6	×	~ 10^{21}	→	~ 10^{22}	→	~ 6
antineutrinos **per fission**		fissions **per second** in a 3,000-MWt reactor		antineutrinos **per second** from a typical PWR		Antineutrino interactions **per day per kiloton** at 25 km standoff



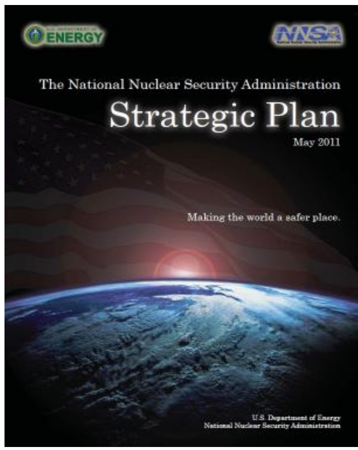


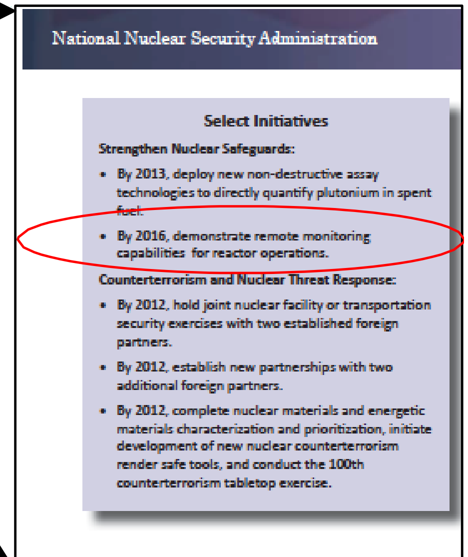
~ 25 kilometer

1000 tons of water instrumented with PMTs



NNSA's Office of Defense Nuclear Nonproliferation has funded an extensive R&D program into water-based antineutrino detectors since 2012





National Nuclear Security Administration

Select Initiatives

Strengthen Nuclear Safeguards:

- By 2013, deploy new non-destructive assay technologies to directly quantify plutonium in spent fuel.
- By 2016, demonstrate remote monitoring capabilities for reactor operations.

Counterterrorism and Nuclear Threat Response:

- By 2012, hold joint nuclear facility or transportation security exercises with two established foreign partners.
- By 2012, establish new partnerships with two additional foreign partners.
- By 2012, complete nuclear materials and energetic materials characterization and prioritization, initiate development of new nuclear counterterrorism render safe tools, and conduct the 100th counterterrorism tabletop exercise.

This program has already had significant success in advancing our understanding of the potential of large-scale detectors for standoff reactor monitoring

Long-range reactor antineutrino detection is feasible now but only for relatively high power reactors and with a hard-to-scale technology

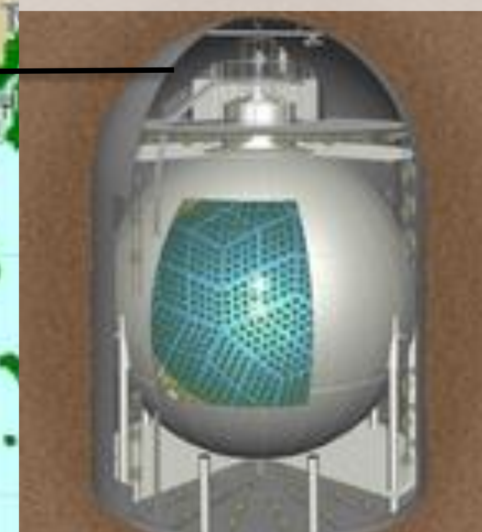
~3% of signal from South Korean reactors @ 400 km standoff

Per month:

- 16 reactor antineutrinos
- 1 background event

From 130 GWt of reactors

The KamLAND detector



1000 tonnes scintillator
1000 m depth

Large water Cherenkov antineutrino detectors require efficient water-based neutron detection

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

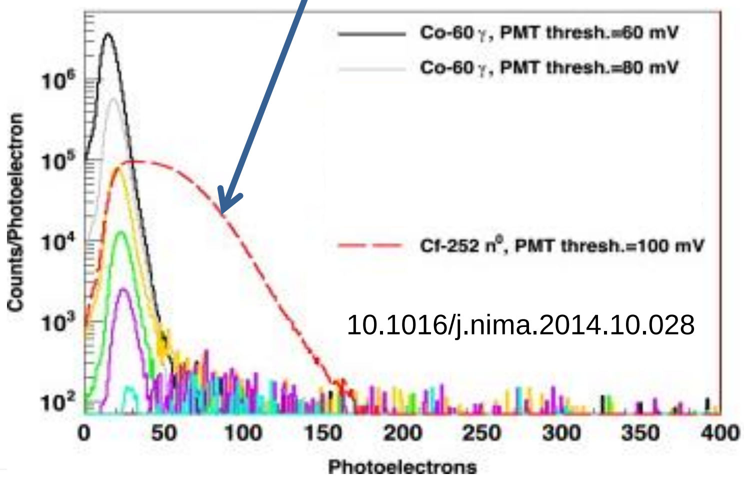
- The signal is two flashes of Cerenkov light, close in time (~100 μsec) and location (~5 cm) – the “antineutrino heartbeat”

- Reduces backgrounds by several orders of magnitude

- Gadolinium doped Water Cerenkov technology offers path to 100-1000 kiloton antineutrino detectors

- LLNL was first to demonstrate this neutron detection capability, in ton-scale detectors

Neutron signal in
4 tons of Gd-doped water



This technology may be useful for cooperative and/or remote monitoring and discovery of operating nuclear reactors

mid-field examples

~25 km:

- ~20 kton detector Fordow site to confirm absence of small reactors in 25 km radius – fulfills US-Iran agreement requirement to exclude proliferant behavior and foster cooperation – proposed to DOE by us and others
- Site-wide monitoring for Fissile Material Cutoff Treaty

This scale to be demonstrated by WATCHMAN

far-field examples

~100 km:

- Exclude new small reactors in a sector of a country

~1000 km:

- exclude new small reactors across a border

These standoffs need directionality and/or 1-10 megaton detectors – AIT will permit study of these approaches

Hypothetical non-directional ten megaton detector

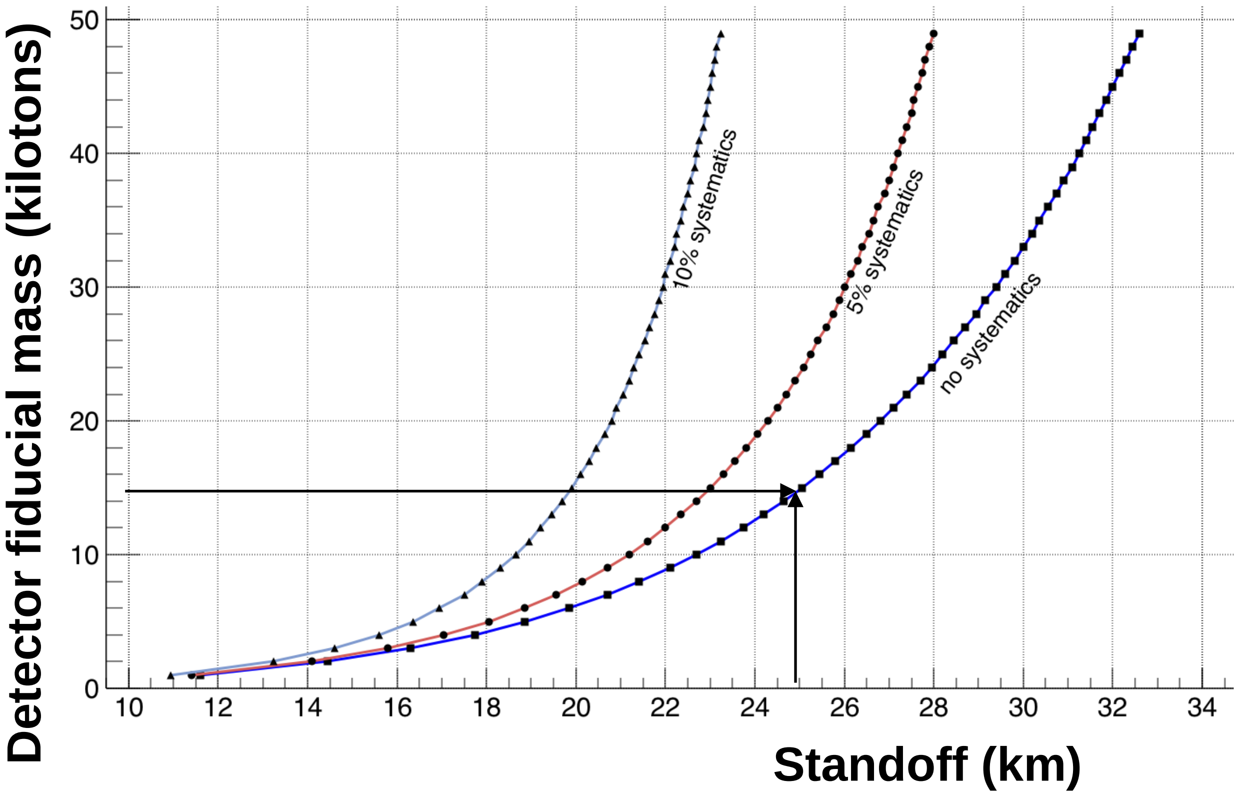
- 4 sigma sensitivity in 1 year
- 10 MWt reactor at 131 km
- Large size dictated by the presence of significant background from SK reactors

Small reactor standard ~40 MWt

A 15 kton water detector can confirm the absence of operating reactors in a wide geographical region

Example:

- A **15 kton** fiducial WATCHMAN-like detector:
- excludes **a 40 MWt reactor**
- in **6 months**
- with **2 sigma confidence**
- to **25 kilometers**

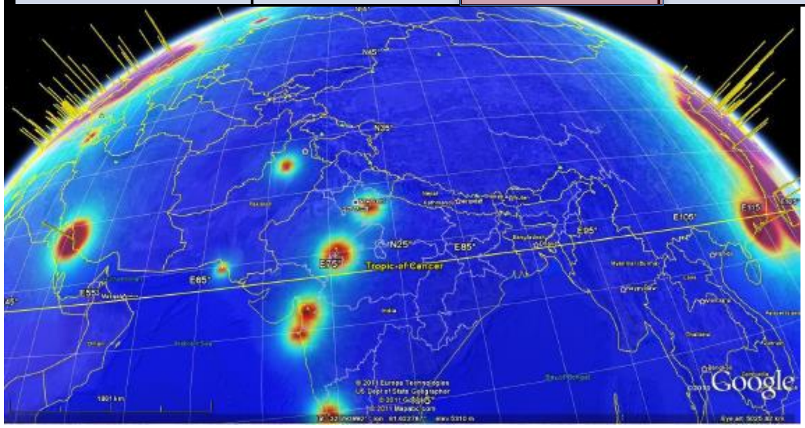


- This estimate based on a detailed Monte Carlo simulation of known backgrounds, and includes oscillations from the reactor of interest
- Other reactor backgrounds are assumed negligible

Existing reactor backgrounds form the ultimate limit on discovery of unknown reactors

					Dwell times for different reactor backgrounds		
Reactor Thermal power (MWt)	Standoff (km)	Detector Mass (Megatons)	Confidence of detection	Total number of signal events	suppressed (1 evt./mo./MT)	Medium (300 evt./mo./MT)	High (2000 evt./mo./MT)
40	100	1	95%	~8	4 days	45 days	9 months
40	1000	2	68%	~9	7 months	-	-
100	1000	2	95%	~20	6 months	-	-

Science & Global Security, 18:127–192, 2010



Global reactor antineutrino fluxes
simulation courtesy Jocher/Learned/Usman NGA/UH

Large detectors are essential for statistics

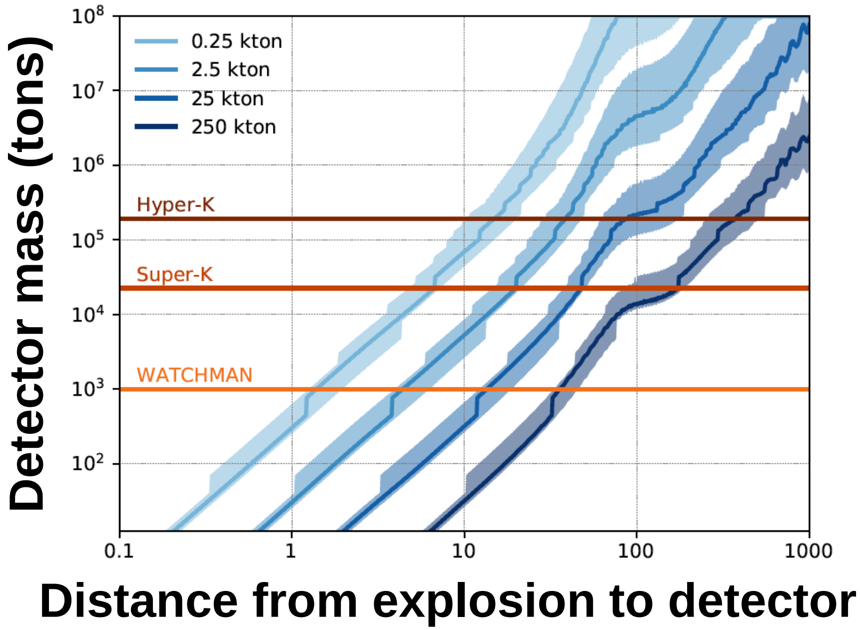
Beyond ~100 km, directionality is essential to reject backgrounds

With seismic cueing, antineutrino detectors could provide definitive yield estimates and confirmation of the fissile nature of an explosion

- About 5x fewer events needed than without cueing
- The largest currently proposed neutrino detector could rapidly identify the nuclear nature of a few-kiloton explosion from a distance of over 100 km.
- Required detector size for some applications of interest is same order of magnitude as proposed Hyper-K experiment
- Explosion monitoring could be a factor to consider when siting future particle physics experiments.

Carr, Dalnoki-Veress, Bernstein arxiv:1712.04001

90% confidence level confirmation of fissile explosion



The AIT-WATCHMAN collaboration

The WATCHMAN Collaboration

32 collaborators
9 Universities
4 National Laboratories

Co-spokespersons:
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- N. Spooner
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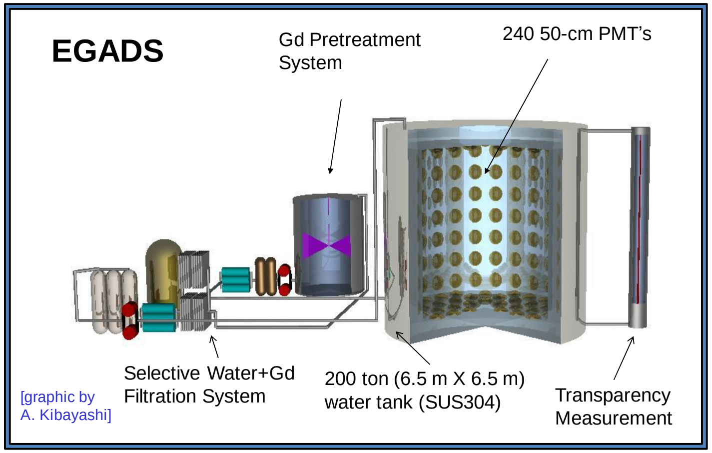
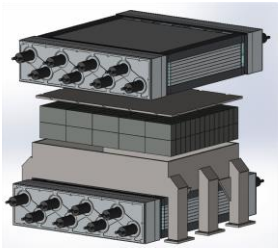
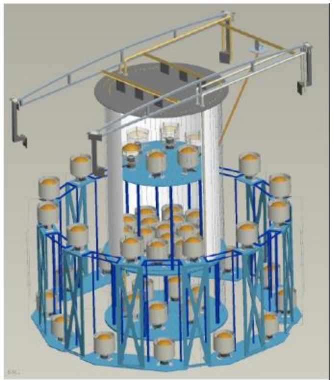
R&D studies in 2012-2017 that demonstrate key elements needed for WATCHMAN

- ✓ **EGADS**: Continuous purification of Gd-H2O without removing the Gd
- ✓ **LLNL detector:** First neutron detection with Gd-doped water
- ✓ **WATCHBOY/MARS**:Direct measurement of relevant backgrounds versus depth
- ✓ **RAT-PAC, WATCHMAKER, web-based tool for background predictions**: High-fidelity signal and background simulations;
- ✓ **Boulby site**: Confirmation of the geologic suitability of cavern space;
- ✓ **PMT studies**: Identification of suitable low activity, high efficiency photomultiplier tube meeting all requirements for deployment





Multiplicity and Recoil Spectrometer (MARS) (Sandia) submitted to PRL



WATCHBOY 40 ton water detector

Site and configuration choices

	Option 1	Option 2
Reactor Location	Perry, Ohio, United States	Hartlepool, England, United Kingdom
Thermal Power (MWt)	1 x 3875	2 x 1500
		
Detector Location	Morton Salt/IMB mine Painesville, Ohio	Boulby underground science lab, Boulby, England
Standoff	~13 km	~25 km
Overburden (mwe)	~1500	~3000
Signal Events	110 per month	11 per month
Background Events	50 per month	20 per month

The Advanced Instrumentation Testbed (AIT) at the Boulby mine

- AIT is a new, collaborative nonproliferation research initiative between the U.S. and the U.K.

- AIT will permit real-world at-scale testir monitoring capabilities for nuclear reac media, photodetectors and algorithms

- Why did we select the UK site ?
  - **A 30-year record of safe science at Boulby**
  - **longstanding cooperation with AWE**
  - **strong University partnership**
  - **greater standoff** vs. other options
  - **two-reactor site** gives a more stringent nonproliferation test for the new technology

The WATCHMAN demonstration

Main Project Objective:

Detect the ON/OFF power cycle of a single reactor:

- at 10-25 km standoff
- with a kiloton-scale Gd-H2O detector
- at 3 sigma confidence level
- Choose water based on cost and scalability

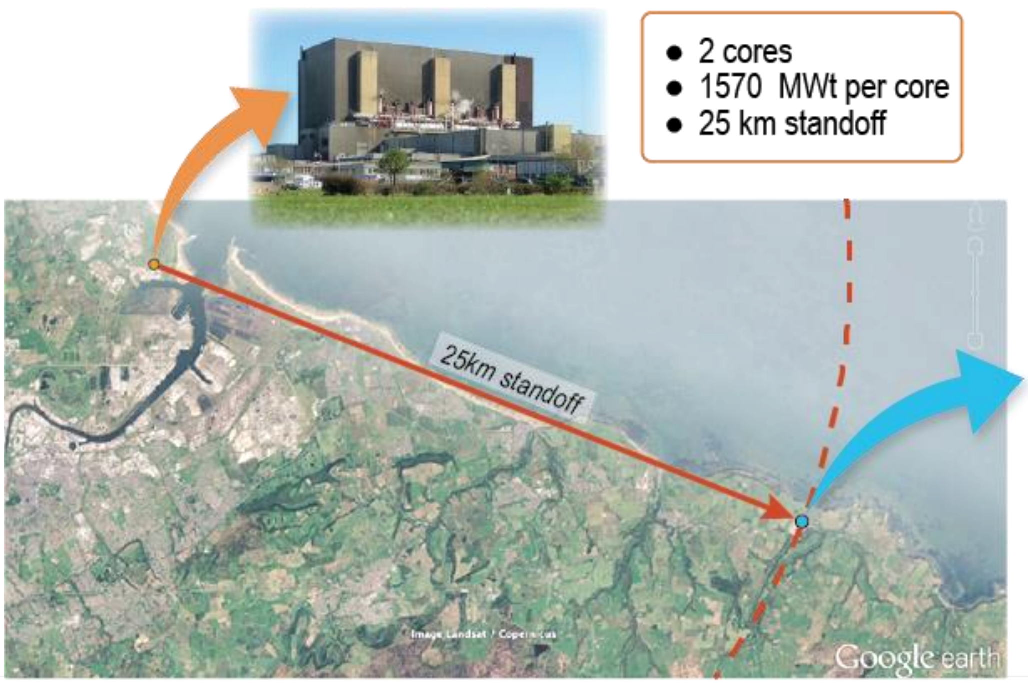
WATCHMAN: A WAter CHerenkov Monitor of Antineutrinos

Doping the water with gadolinium greatly increases sensitivity to inverse beta interactions of antineutrinos

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

UK deployment option

HARTLEPOOL REACTORS



- 2 cores
- 1570 MWt per core
- 25 km standoff

WATCHMAN detector at the Boulby mine

- 3500 tons, ~3000 photomultiplier tubes
- Water Cherenkov detector, doped with gadolinium

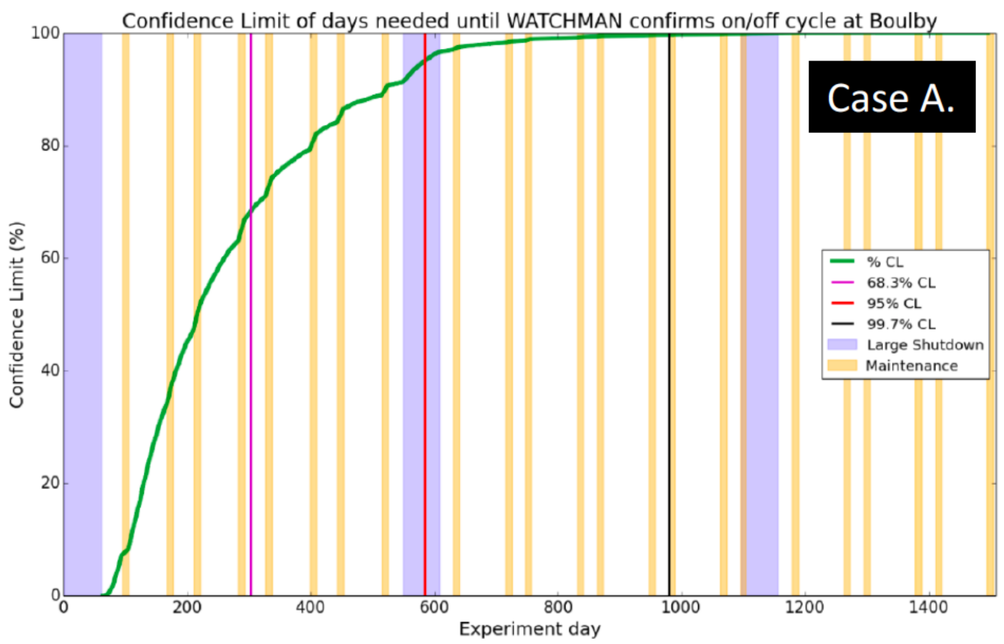
Detector performance and sensitivity metrics – early and non-optimized results

Goals for detector performance

A. Observe reactor operations with full knowledge of both reactors ON/OFF status (unblinded)

B. Knowledge of only one reactor ON/OFF status (partially blinded)

C. No knowledge of either reactors ON/OFF status (fully blinded)



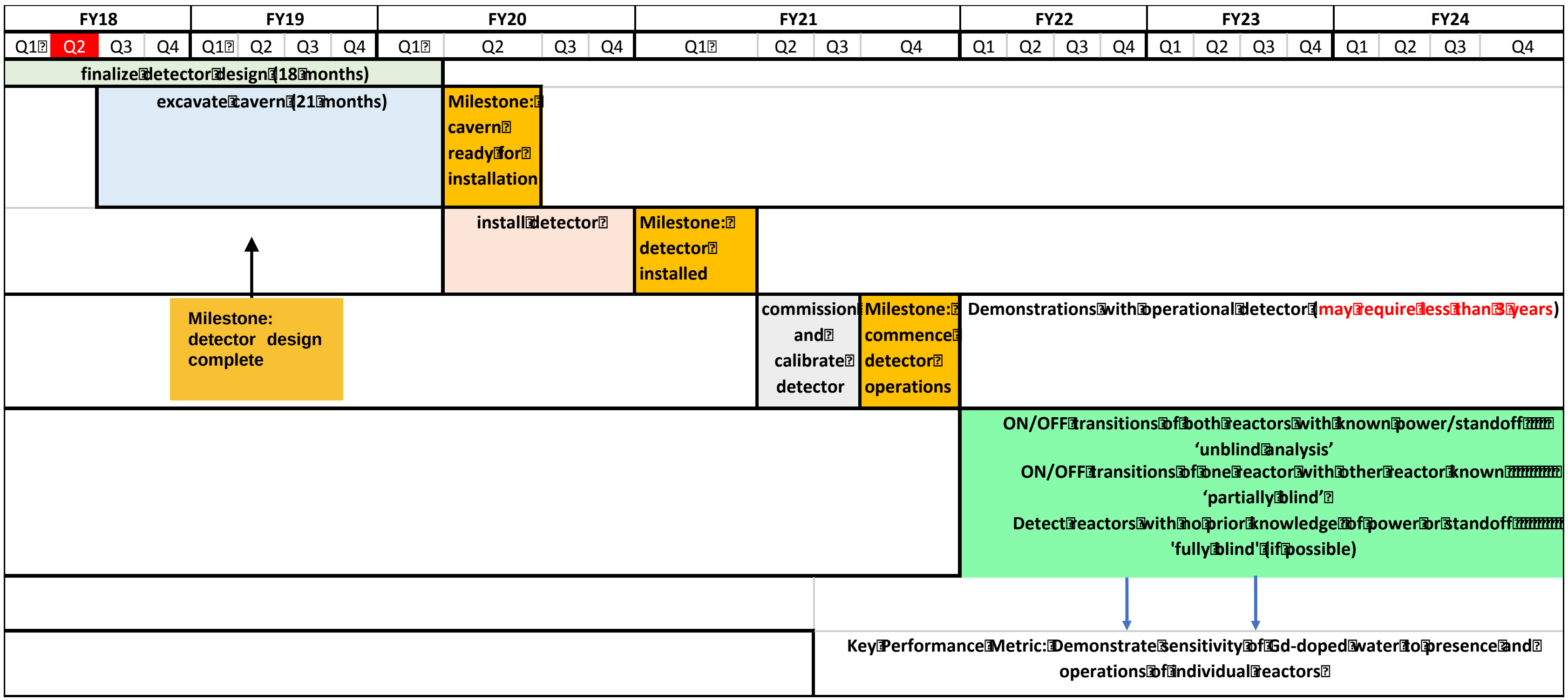
Assumed detector parameters

Photocoverage: 25%
Tank size: 16 m right-cylinder
Fiducial Volume: 1 kton

Core-1 (signal) : 2.6 events per week
Core-2 (bkgd) : 2.6 events per week
World reactors : 0.8 events per week
Accidentals : 0.7 events per week
Fast Neutrons : 0.6 events per week
Radionuclides : 0.1 events per week

Work is underway to optimize the detector design and analysis techniques in order to optimize the signal to background ratio

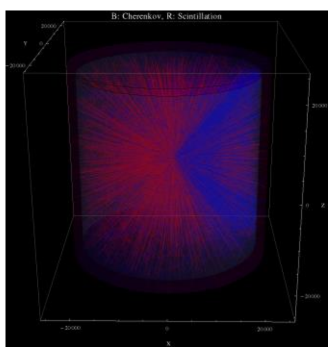
WATCHMAN approximate timeline



On beyond WATCHMAN

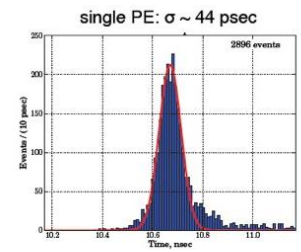
Water-based Liquid Scintillator (WbLS) (BNL, SNL)

- A water soluble mixture with fast timing, good spectral response, tunable light yield
- Leads to very large combined scintillator/Cherenkov detectors, ~50x KamLAND/SNO+



Large Area Picosecond PhotoDetectors (LAPPD) (U. Chicago, Argonne, Iowa State)

from vacuum tubes
to flat panel technology



Unprecedented fast timing can give centimeter vertex resolution

Advanced Instrumentation Testbed goals and nominal timeline

FY18	FY19	FY20	FY21	FY22	FY23	FY24	FY25	FY26	FY27	FY28	...
WATCHMAN Design, Installation and Operational Phases						**End WATCHMAN Operations**					
Water-based Liquid Scintillator studies			prototype demonstrations (~100 ton)			upgrade with fast photosensors and WBLS	operate with fast photosensors and WBLS				
Fast Photosensor studies			prototype demonstrations (~100 photosensors)								
antineutrino-electron-scattering (ES) sensitivity studies; radon suppression studies							upgrade for ES sensitivity	test directional or background suppression concepts			
study IBD and ES directional algorithms/techniques											
					advanced near-field deployment (Inverse Beta or Coherent Scatter)			test near-field + far-field applications			
identify and develop nonproliferation use cases											

Blue	R&D
Pink	Prototyping
Orange	Upgrades
Green	Operations and Testing

The long-term nonproliferation research program can help speed the development of detectors like THEIA, DUNE and Hyperkamiokande

Standoff for observing small reactor operations in weeks to months

>10^1 km → >10^2 km → ~10^3 km

~10^2 ton
WATCHBOY , MARS, EGADS (complete)

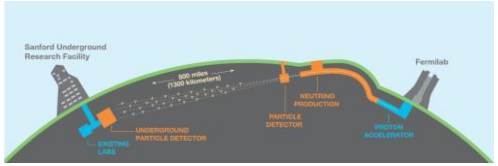
~10^3 ton
AIT-WATCHMAN Gd-H2O fill

~10^3 ton
AIT-'Proto-THEIA' WBLS fill

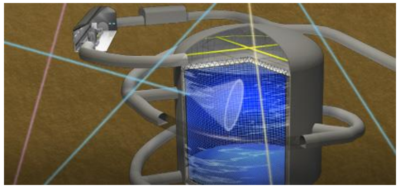
~$10^{4.8}$ ton
THEIA
~0.1 MT WBLS

>~10^6 ton
Megaton-scale detector with directionality

DUNE



Hyperkamiokande



2012-2017 activities → **~6 year Lifecycle Plan (this project)** → **long-term vision consistent with fundamental science planning – THEIA, DUNE, Hyper-K**

Today's Water Cherenkov detectors are 50x larger than scintillator detectors, but can't distinguish neutrino from antineutrino

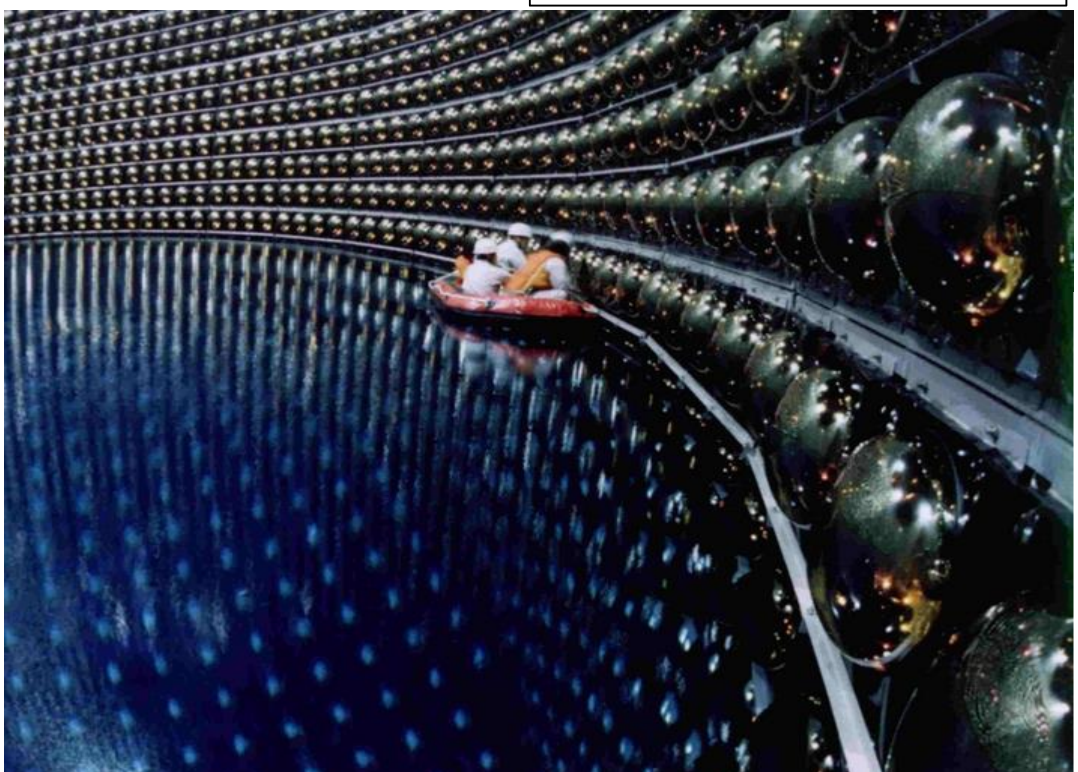
$\overline{\nu}_e + p = e^+ + n$

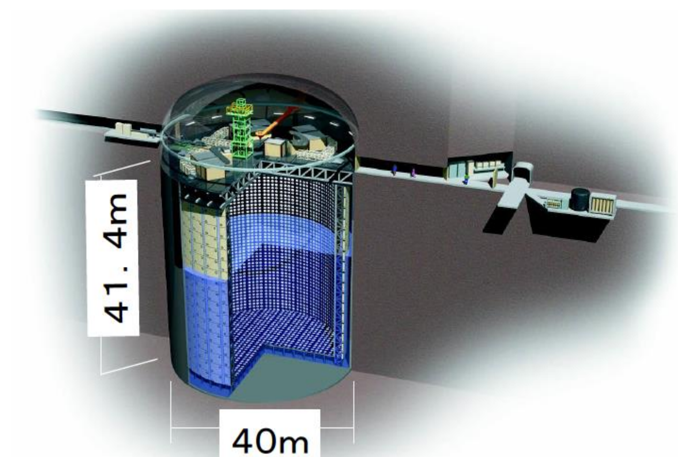
Inverse beta decay from reactor $\overline{\nu}_e$

Identical signals from both processes:
a **single flash of Cerenkov light**

$\nu_e + e^- = \nu_e + e^-$

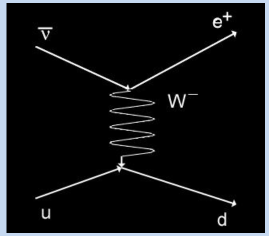
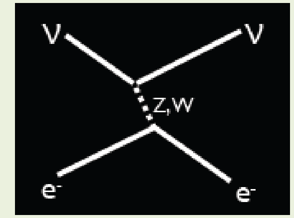
Elastic scatter (solar neutrinos, reactors)





The Super-Kamiokande water Cherenkov detector

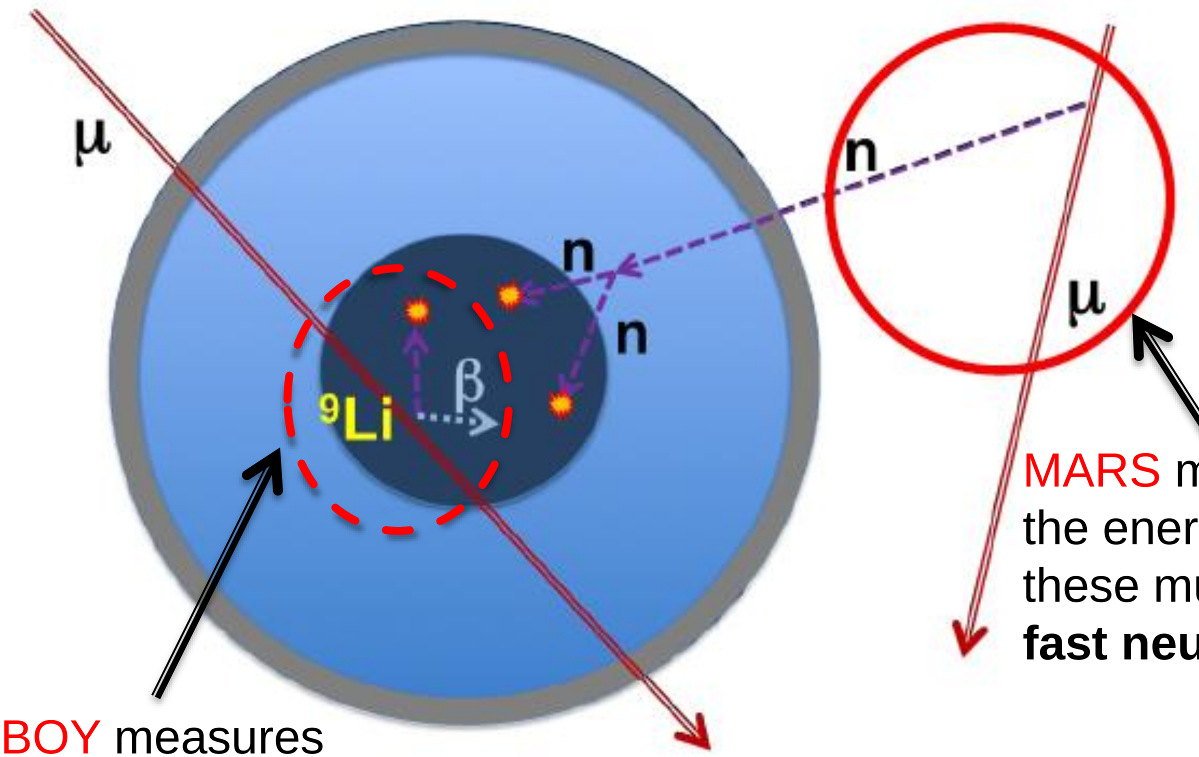
Two kinds of interactions for MeV-scale antineutrinos (and neutrinos)

Feynman diagram		
Name	Antineutrino-proton (Inverse beta decay)	antineutrino-electron or neutrino-electron
Initial/final states	$\bar{\nu} + p \rightarrow e^{+} + n$	$\bar{\nu} + e^{-} \rightarrow \bar{\nu} + e^{-}$
Cross section	$s \sim 10^{-42}\,\mathrm{cm}^2\, E_{\bar{n}}^{2}$	$s \sim 10^{-44}\,\mathrm{cm}^2\, E_{\bar{n}}$
Experimental signature	• Two MeV scale energy depositions • Δt ~ 100 μsec • Δr ~ 5 cm	Any MeV scale energy deposition
Backgrounds	Rare cosmogenic neutrons and radionuclides - **easy**	Solar neutrinos, ambient gamma-rays, muons… **hard**
Industry opinion	‘*good old inverse beta*’ - Petr Vogel	

If this neutron is undetected, these interactions appear nearly identical and background rejection becomes much harder

Backgrounds in large gadolinium doped water detectors – how else can we get two flashes of Cherenkov light in ~100 μsec ?

1: long lived radionuclides
2: fast neutrons
3: coincidences of:
single gamma-rays,
neutrons,
muons,
radon...



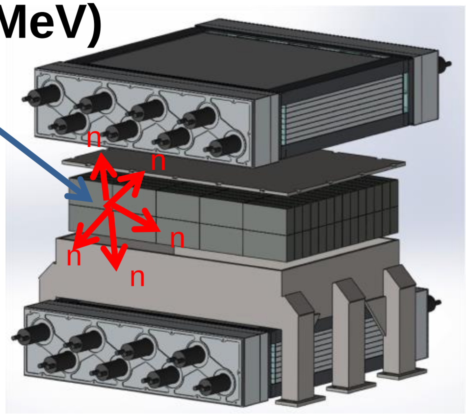
MARS measured the energy of these muogenic **fast neutrons**

WATCHBOY measures the production rate in water of these muogenic **long-lived radionuclides**

Our depth-dependent measurements of high energy neutrons have shown these backgrounds are manageable

MARS:

- Multiplicity and Recoil Spectrometer
- Measures **muogenic neutron spectrum**
- Fast neutrons induce multiple neutrons in a lead target
- Neutron multiplicity correlates with incident neutron energy
- First ever variable depth measurement with one detector
- Necessary to understand backgrounds in large water detectors like WATCHMAN



Key result: benchmarks the "industry standard" Mei and Hime model

(PRD 73 (2006) 053004)

Paper submitted to PRL May 2017