WATCHMAN: a WATer CHerenkov Monitor for Antineutrinos

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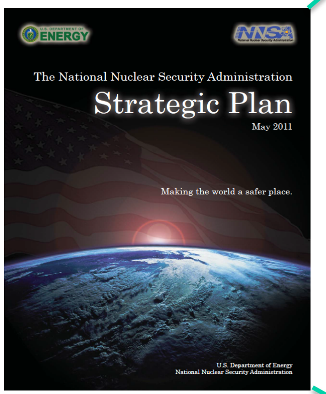
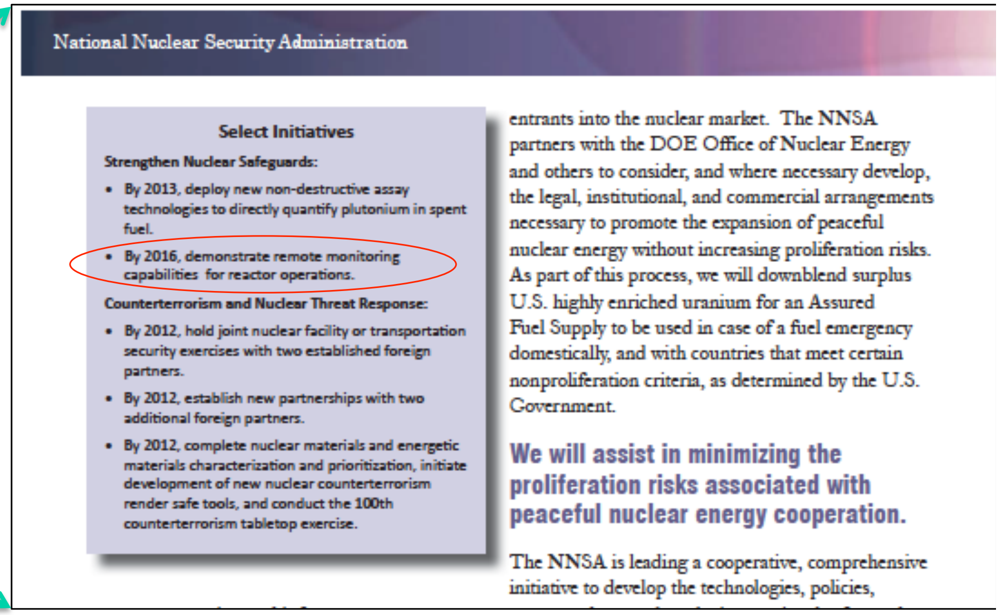
On behalf of the WATCHMAN collaboration

Remote Reactor Monitoring is an NNSA Strategic Nonproliferation Goal





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.

entrants into the nuclear market. The NNSA partners with the DOE Office of Nuclear Energy and others to consider, and where necessary develop, the legal, institutional, and commercial arrangements necessary to promote the expansion of peaceful nuclear energy without increasing proliferation risks. As part of this process, we will downblend surplus U.S. highly enriched uranium for an Assured Fuel Supply to be used in case of a fuel emergency domestically, and with countries that meet certain nonproliferation criteria, as determined by the U.S. Government.

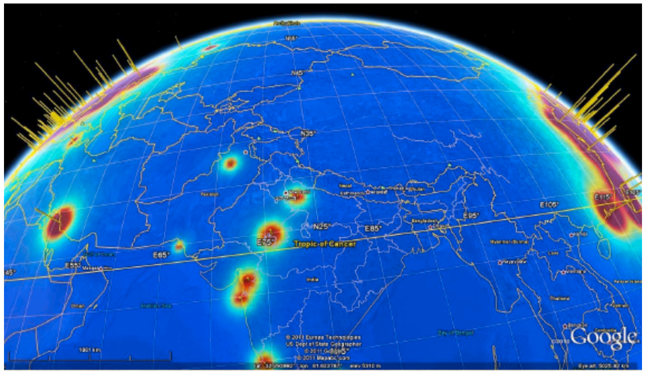
We will assist in minimizing the proliferation risks associated with peaceful nuclear energy cooperation.

The NNSA is leading a cooperative, comprehensive initiative to develop the technologies, policies,

- **WATCHMAN in its first phase is a kiloton scale gadolinium-doped Water Cherenkov antineutrino detector, ~10 km from a US reactor**
- **Proposed joint funding from NNSA Defense Nuclear Nonproliferation and DOE Office of Science**
- **Total project cost 35-50 M$ - mostly depending on PMT coverage**

Eventual goal: find or exclude small hidden reactors at up to ~1000 km

Best Possible Result *Science & Global Security, 18:127–192, 2010*	Detector target mass	standoff
5 events in **6 mo.** from a **20 MWt** reactor (**negligible background, 50% efficiency, includes oscillations**) >99% exclusion <<1% false positive	24,000 ton	100 km
	2 Megaton	1000 km



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

- **Gadolinium-doped (light) water** viable option for scaling to the largest sizes
- **Strong synergy** with **fundamental physics research** – Many groups/countries are already investing in this technology
- **SuperKamiokande** is today's closest analog - 50,000 tons of H_2O with no gadolinium

The WATCHMAN collaboration December 2014

LLNL — A. Bernstein, S. Dazeley, D. Dobie, D. Hellfeld

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UC Davis — R. Svoboda, M. Askins, M. Bergevin, T. Pershing

U of Hawaii — J. Learned, J. Maricic

Hawaii Pacific — S. Dye

UC Irvine — M. Vagins, M. Smy

Virginia Tech — S.D. Rountree, B. Vogelaar, P. Jaffke

U. Tenn — Y. Kamyshkov, T. Handler

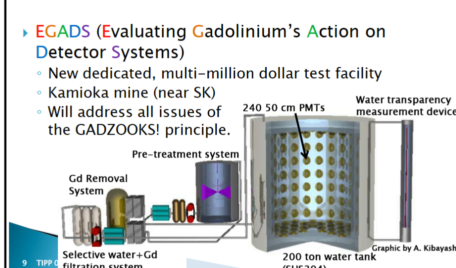
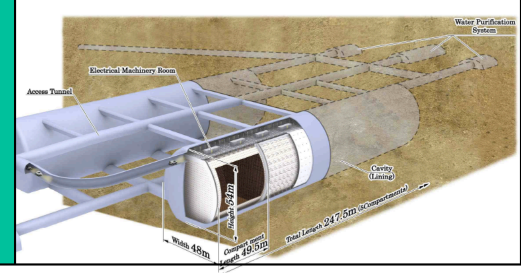
31 collaborators
4 National Laboratories
8 Universities
22 physicists
5 engineers
1 Post-doc
5 Ph.D students
1 M.A. student

WATCHMAN Phases and Physics/R&D Goals

	WATCHMAN		Post-WATCHMAN
	Phase I (2016-2019)	Phase II (2019-2023)	**Advanced Scintillator Detector Concept – 50-100 kton**
Detector R&D	1 kton Gd+H2O	Gd+Water-based LS	50-100 kTon Water-based Liquid Scintillator, LAPPD coverage
	Partial LAPPD coverage	Full LAPPD coverage	
Physics	Supernova detection with directionality and $\nu / \bar{\nu}$ discrimination		Supernova burst & DSNB
		Sterile neutrino search with IsoDAR beam	Long-baseline (mass hierarchy, CP violation)
			Neutrinoless double beta decay
			Geo-antineutrinos
			Nucleon decay
			Source-based sterile searches
			Solar neutrinos (solar metallicity, luminosity)

arxiv:1409.5864

WATCHMAN Phase I in context

Detector	EGADS	WATCHMAN	Hyper-K
Status	Ongoing	2016 start	2021 start (approx.)
Mass (kton)	0.2	1 – 10	560
Type	Gd-WCD	Gd-WCD	Pure H2O or Gd-WCD
Purpose	Measure background materials, energy threshold Too small to see reactor antineutrinos	Remotely detect reactor antineutrinos – beam and reactor physics potential	Neutrino oscillations, proton decay, supernovae… WATCHMAN would demonstrate Gd option for Hyper-K or other future big detectors
			

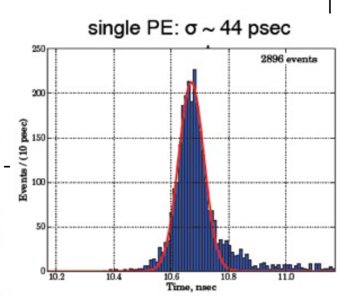
WATCHMAN Phase II Technology Development

Water-based Liquid Scintillator (WbLS)

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

Large Area Picosecond Photon Detectors (LAPPD)

- Chicago, ANL/LBL initiative
- Large area (8” sq.) low cost MicroChannel plate-based PMTs with fast timing
- Opens the possibility of very precise TOF in accelerator detectors - "Optical TPC”



Key elements of the Advanced Scintillator Detector Concept

WATCHMAN ACTIVITIES 2012-2014

Site selection

Preliminary design

Simulations of reactor, supernova and IsoDAR neutrino signals

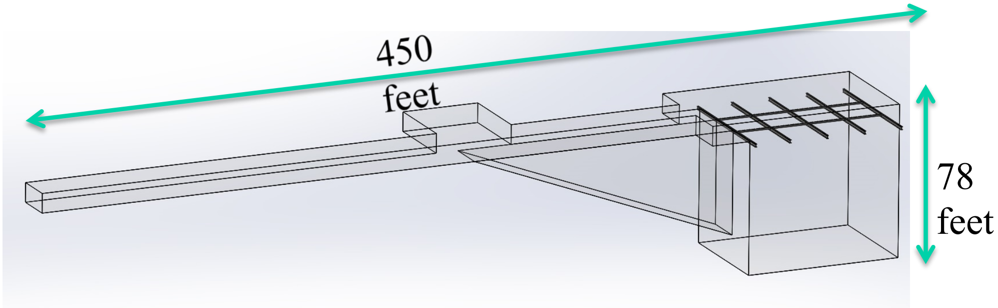
First results from depth-dependent background measurement campaign

Identified deployment sites

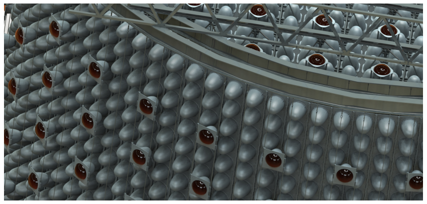
	Preferred	Backup	Backup to Backup ?
Reactor Location	PERRY Reactor Perry Ohio	Advanced Test Reactor, Idaho Falls, Idaho	Hartlepool, England
Thermal Power (MWt)	3875	120	2 x 1575
			
Detector Location	Morton Salt/IMB mine (!) Painesville, Ohio	New excavation Idaho National Laboratory	Boulby underground science lab
Standoff	13 km – only US at a suitable distance from a deep mine	1 km	~25 km
Overburden (mwe)	1430	~360	3000
Approval status	**Morton Salt has approved installation !**	INL approved excavation studies	Strong encouragement from mine mgmt. and science director

Preliminary design completed

- 3.5:1 kton total:fiducial
- 1 meter veto and 1 meter buffer
- PMTs mounted on a frame inside a stainless steel tank.
  - 4810 Target PMTS looking "in"
  - 480 Veto PMTs on same frame looking "out"
- Considered two PMT types (Hamamatsu 12", ADIT/Eljen 11")
- Option for LAPPD sub-modules



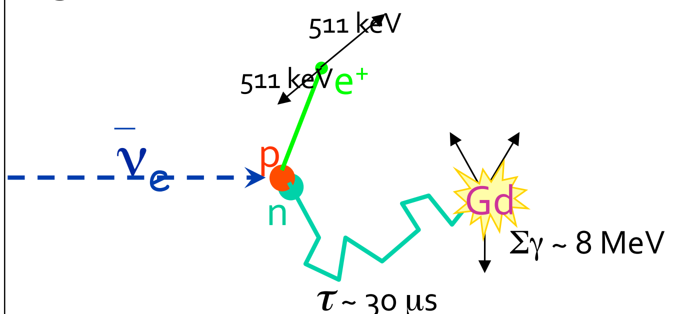
Drift layout at Morton Salt Mine



Close-up of Veto PMT Wall

Antineutrino inverse beta decay signal and background

Signal in 1 kiloton of water



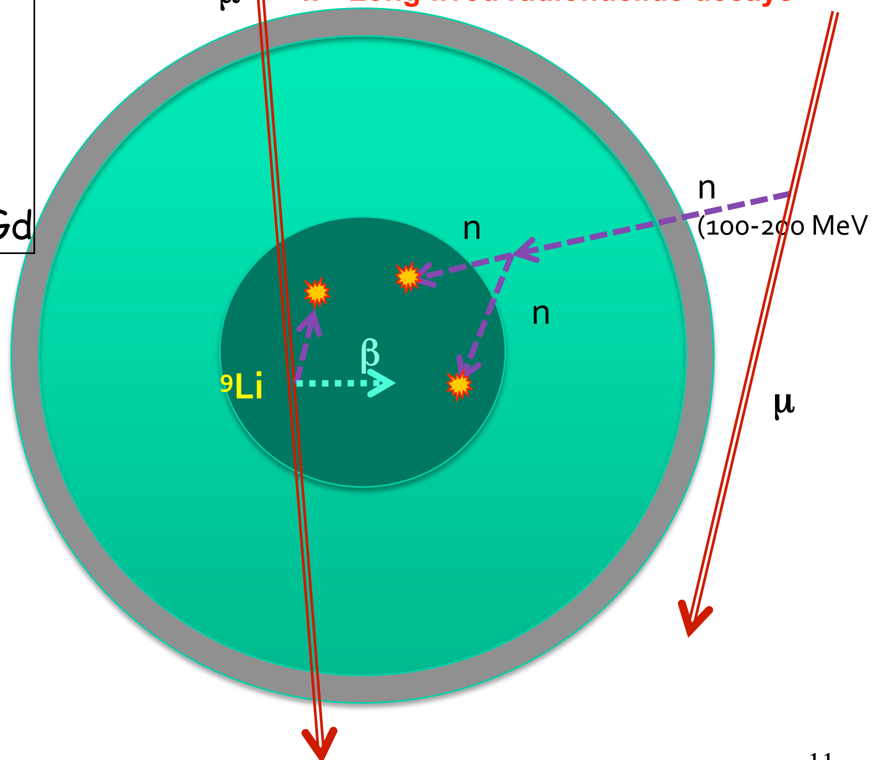
prompt e+ signal + n capture on Gd

- Exactly two Cerenkov flashes
- within ~100 microseconds
- Within a cubic meter voxel

'The antineutrino heartbeat'

Backgrounds:

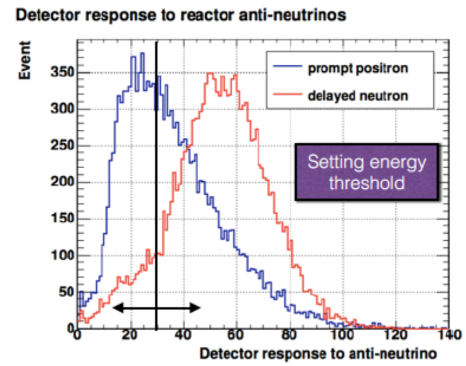
1. Real antineutrinos
2. Random pair coincidences
3. **Muon induced high energy neutrons**
4. **Long-lived radionuclide decays**

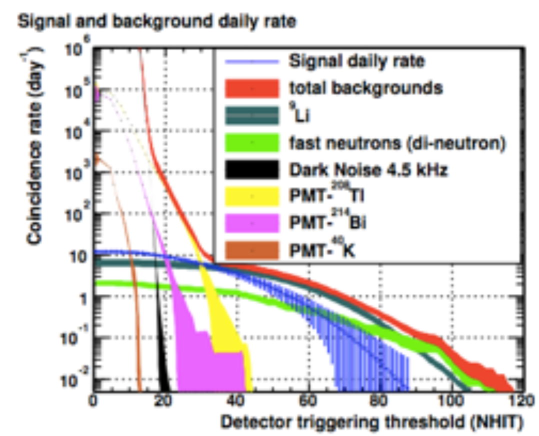


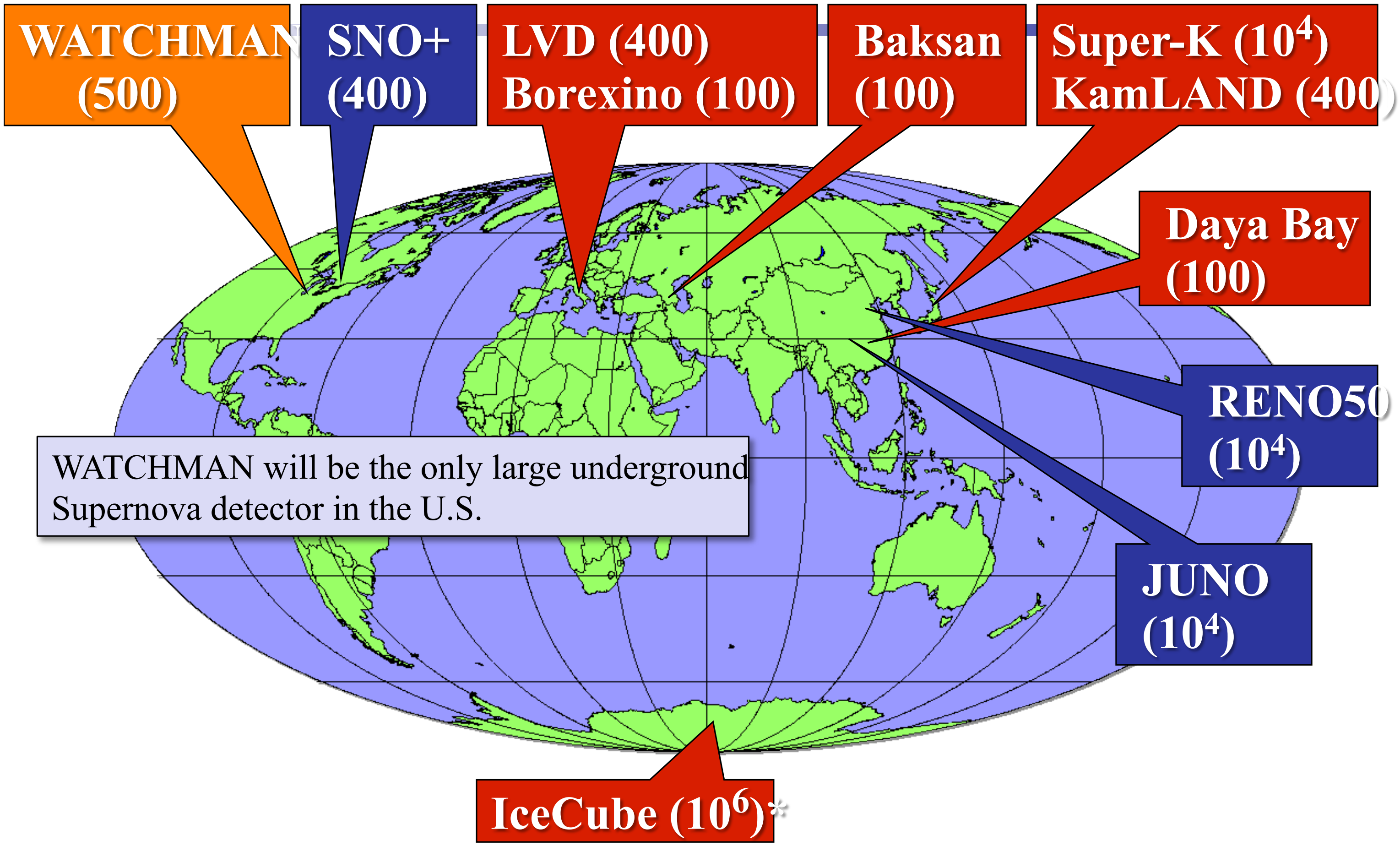
Full Signal and Background Monte Carlo (M. Bergevin)

These results: GEANT/RMSIM → 2015: transition to **R**eactor **A**nalysis **T**ool **P**lus **A**dditional **C**odes **'RAT-PAC'** – adapted by UCB

Predicted background and signal – 1 kton fiducial	
Depth Dependent	events per day
Fast Punch-through Neutrons	1
Radionuclides → not well known	1-5
Depth-Independent	
PMT and Rock Gamma/Neutrons	<1
Other Reactors	<1
Geoantineutrinos	<<1
Total Background	**2-6**
Perry Reactor Signal	**4-5**





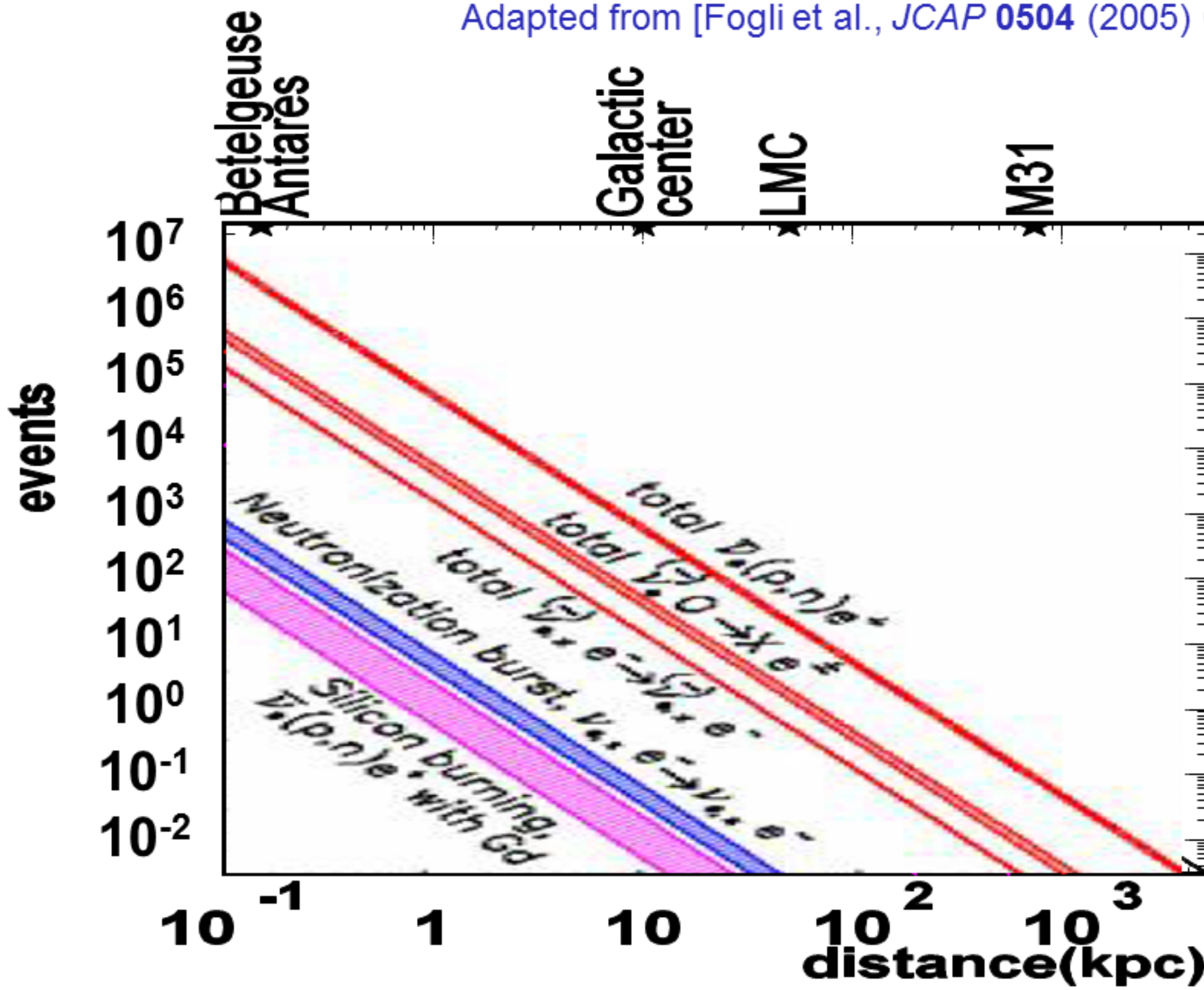


* sees only change in noise rate, not individual events

In brackets: predicted number of counts from a SN

Expected Supernovae rates in WATCHMAN

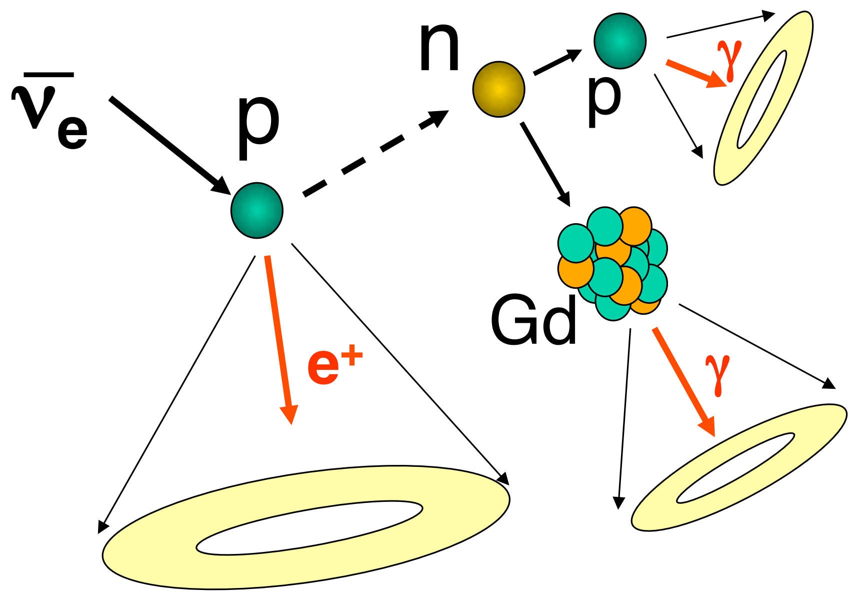
Adapted from [Fogli et al., *JCAP* **0504** (2005) 002]



IBD tagging also allows discrimination of the highly directional elastic scattering events improving pointing accuracy to SN

Inverse Beta Decay

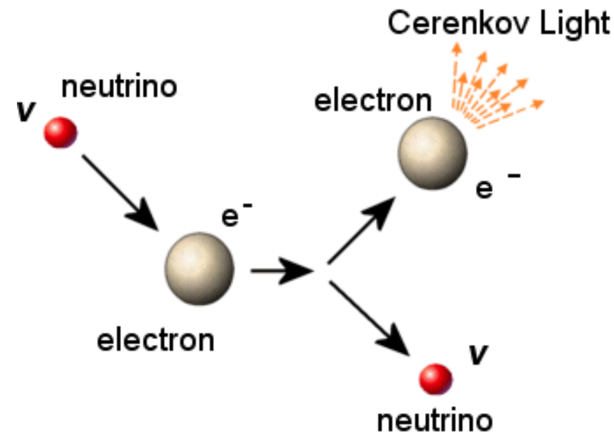
(~88% of events)



WATCHMAN tags these events and measures their energy

Elastic Scattering

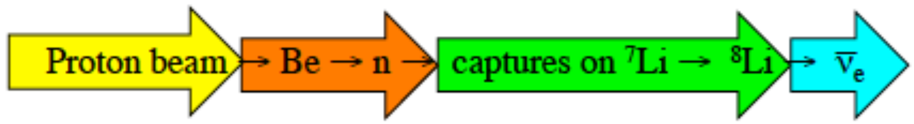
(~3% → directional)

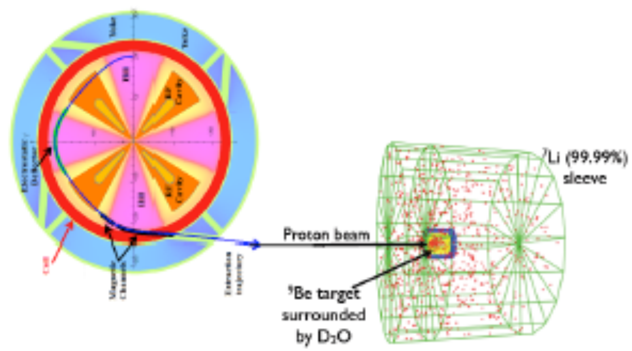


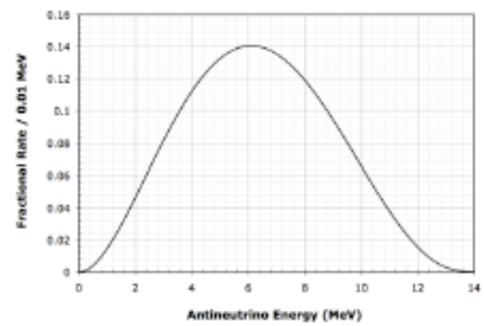
WATCHMAN isolates these events and measures their energy AND DIRECTION – difficult or impossible in pure water detector or scintillator

IsoDAR (Isotopic Decay At Rest)

A Neutrino Beam generated by a compact source







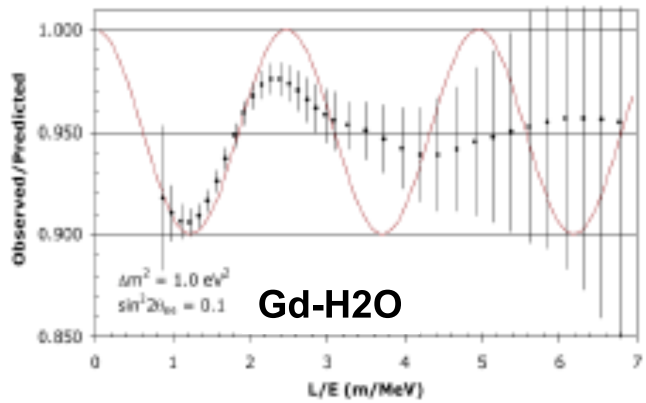
5 mA H_2^+ @ 60 MeV/n
(600 kW proton beam)

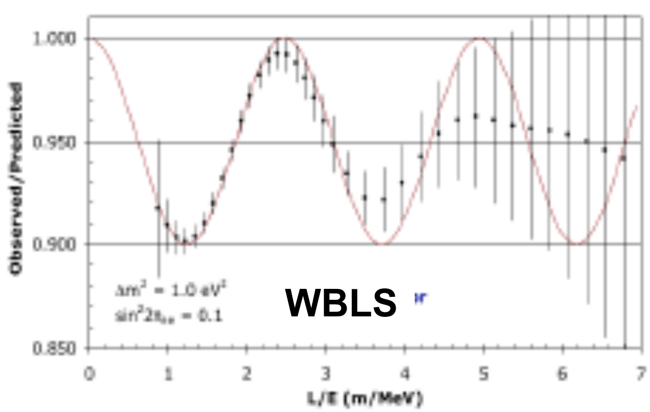
$^8\mathrm{Li} \rightarrow {}^8\,\mathrm{Be} + e^- + \bar{\nu}_e$

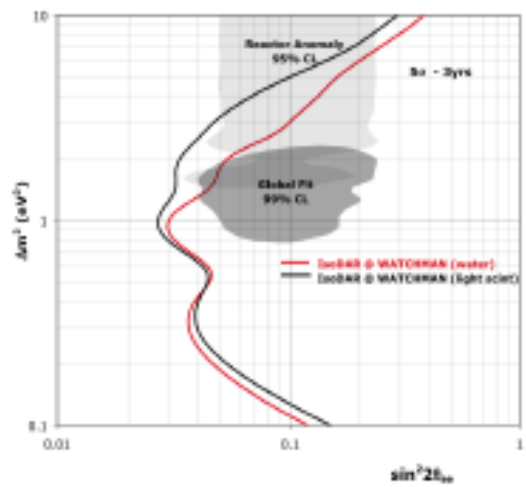
Produces 1.29×10^{23} $\bar{\nu}_e$ in
5 years (with 90% duty factor)

Trade-off – complex beam, but simpler and harder spectrum compared to reactors

Sensitivity to Sterile Neutrino oscillations even in water





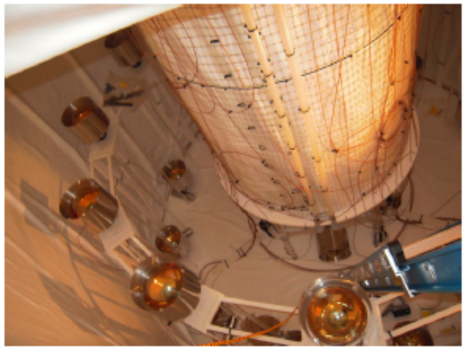


Water-based liquid scintillator would improve sensitivity

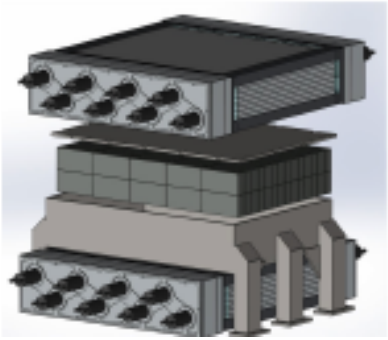
Background Measurements at the Kimballton Underground Research Facility

- Drive in access down to 1500 foot depth
- First-ever continuous measurement as a function of depth
- Most important at shallow depths (300 feet, alternative site)
- <u>Final measurement will be at the 1400 foot depth of preferred site</u>

Entering KURF



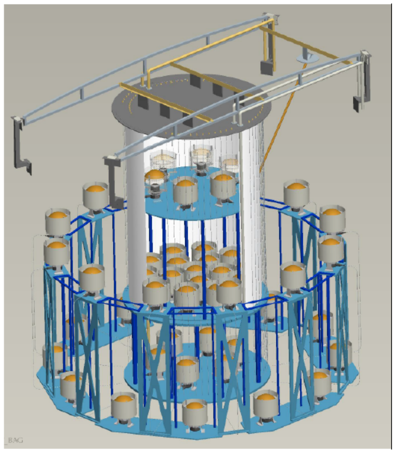
Small version of WATCHMAN (WATCHBOY)
to measure muogenic radionuclide backgrounds



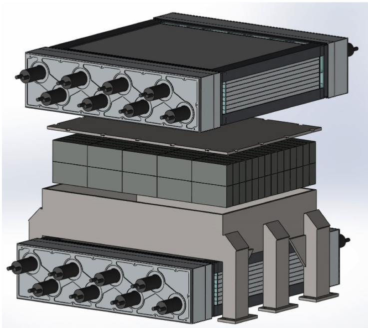
Multiplicity and Recoil Spectrometer for fast neutron energy spectrum

Results from the KURF deployments

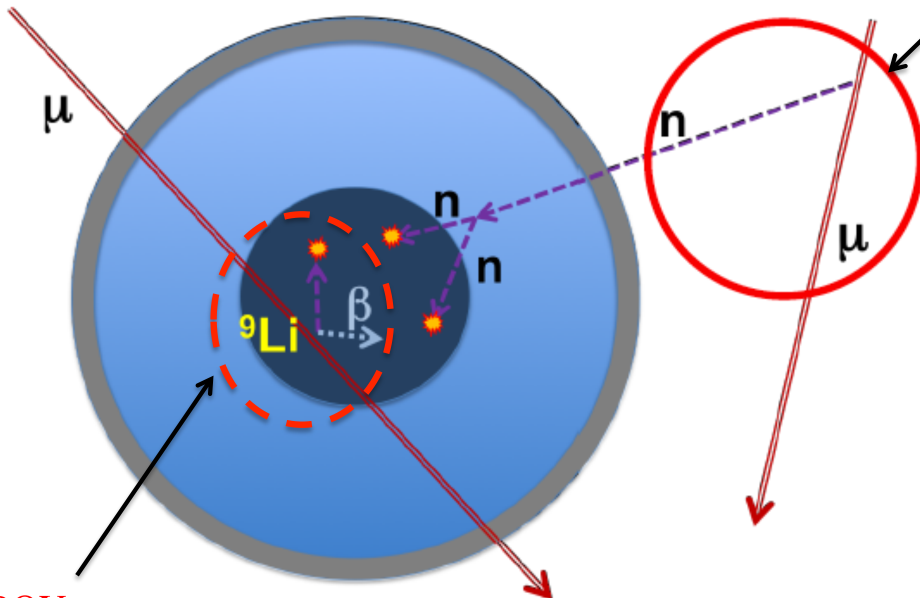
WATCHBOY:
- mini-WATCHMAN – 2 ton target, 10 ton veto
- Designed to measure **muogenic radionuclides** 9Li, 8He
- First ever measurement of correlated events in water



MARS:
- Multiplicity and Recoil Spectrometer
- Designed to measure **muogenic neutron spectrum** First ever variable depth measurement with one detector
- Variation with depth is important to inform simulations



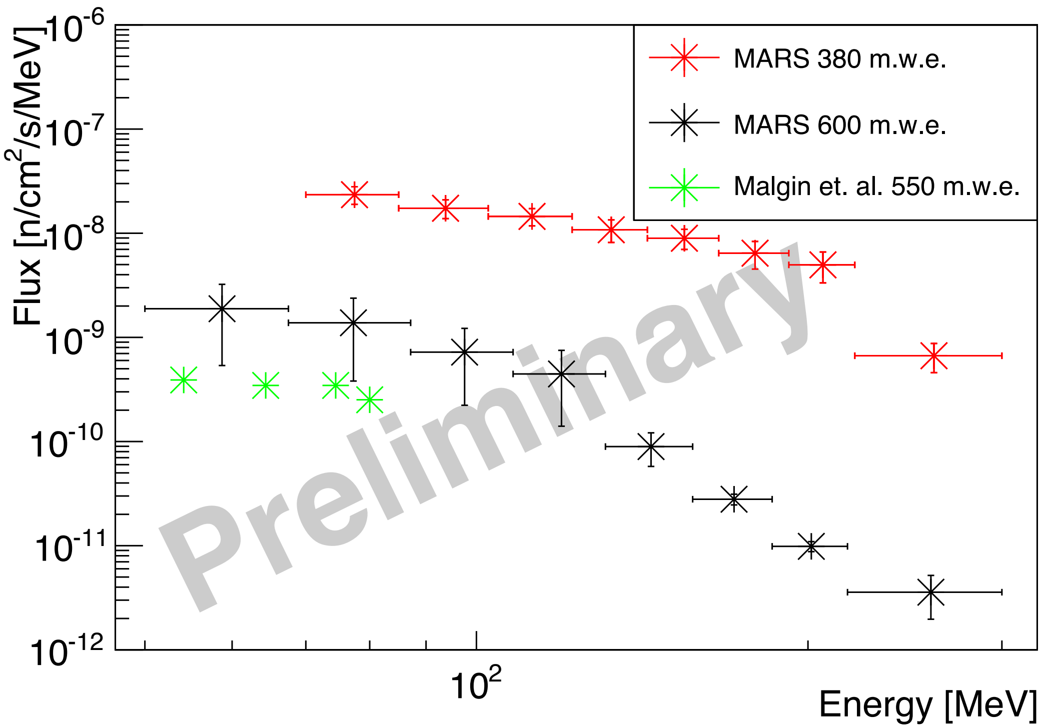
The backgrounds we are looking for



MARS measures the energy of these muogenic neutrons

WATCHBOY measures the production rate in water of these muogenic radionuclides

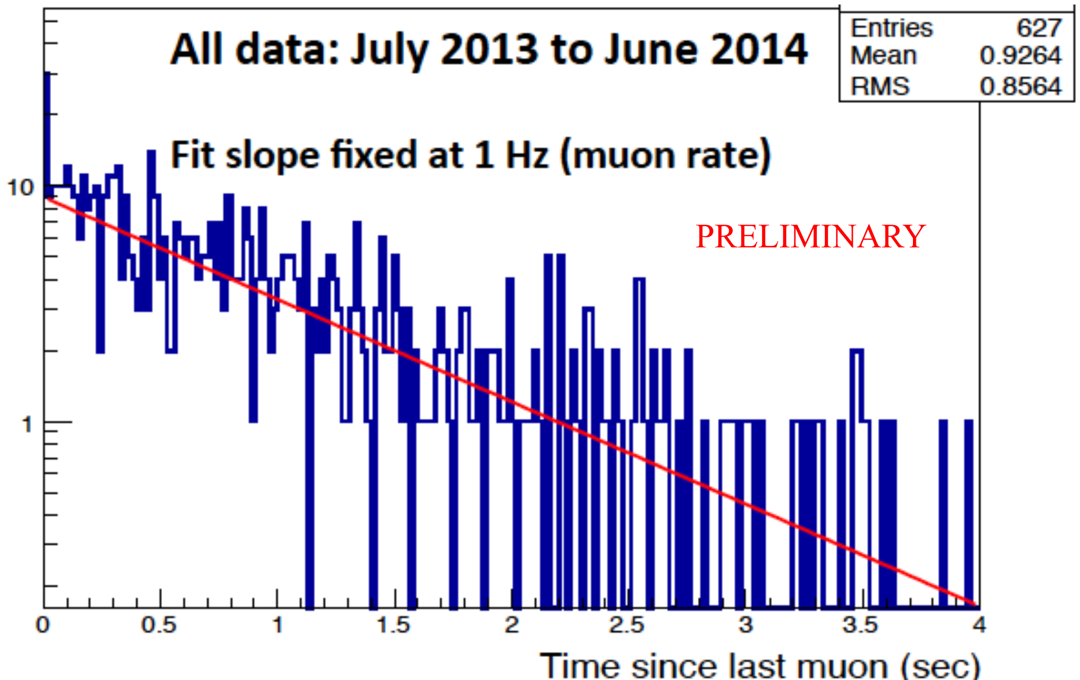
First result from MARS



- First ever depth-dependent neutron spectra
- performed with the same detector at two different depths
- Measurement at 1400 mwe ongoing

First result from WATCHBOY

of correlated neutron-like event pairs since most recent muon



- 221 live days – first direct search for radionuclides event pairs generated in water
- An exponential rise above the red curve from about 0 - 1 second would indicate presence of a strong radionuclide background with a ~250 ms halflife (^{9}Li)
- **Absence of this feature** allows us to place a limit on the rate of radionuclides in WATCHMAN
- 3 candidate events per day (RN + correlated neutrons) is consistent with expectations and favorable for WATCHMAN

Conclusions

- WATCHMAN has strong interest and significant initial investment from nonproliferation sponsors
- Natural bridge to very large water-based detectors for LBNF and other physics goals
- Site selection, initial design, initial background measurements completed
- First investment from DOE-SC-HEP in 2014-15 - now under consideration as a mid-scale Intensity Frontier project

Backups

For a galactic supernova, a $Gd_2(SO_4)_3$ -loaded WATCHMAN will provide many important benefits:

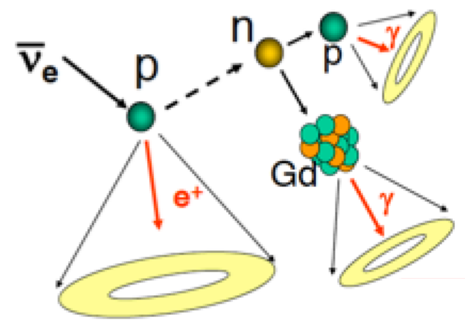
- Allows the exact $\bar{\nu}_e$ flux, energy spectrum, and time profile to be determined via the extraction of a tagged, pure sample of inverse beta events.
- Instantly identifies a burst as genuine via “Gd heartbeat”
- Tagging doubles the electron scatter pointing accuracy. Error circle cut by 75%.
- Helps to identify other neutrino signals, especially the CC events on oxygen and weak neutronization burst of ν_e.
- Very early warning of the most spectacular, nearby explosions for optical telescopes

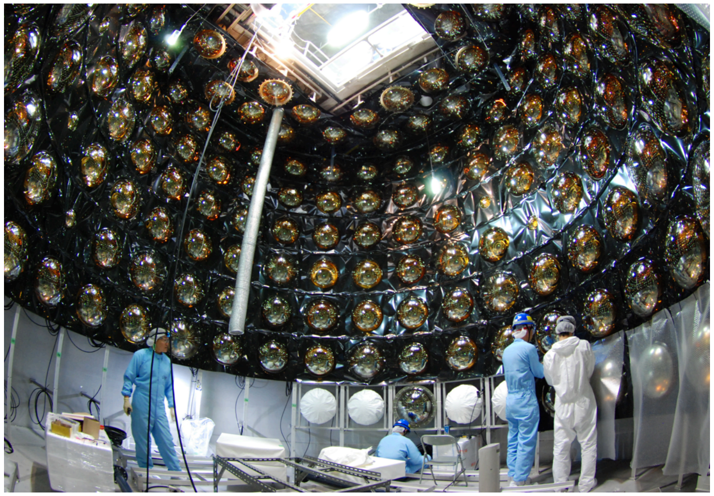
WATCHMAN Phase I – Gd Loading

Gadolinium doping in water

- <u>Gadolinium sulfate </u>as a neutron capture agent - UC Irvine / University of Tokyo

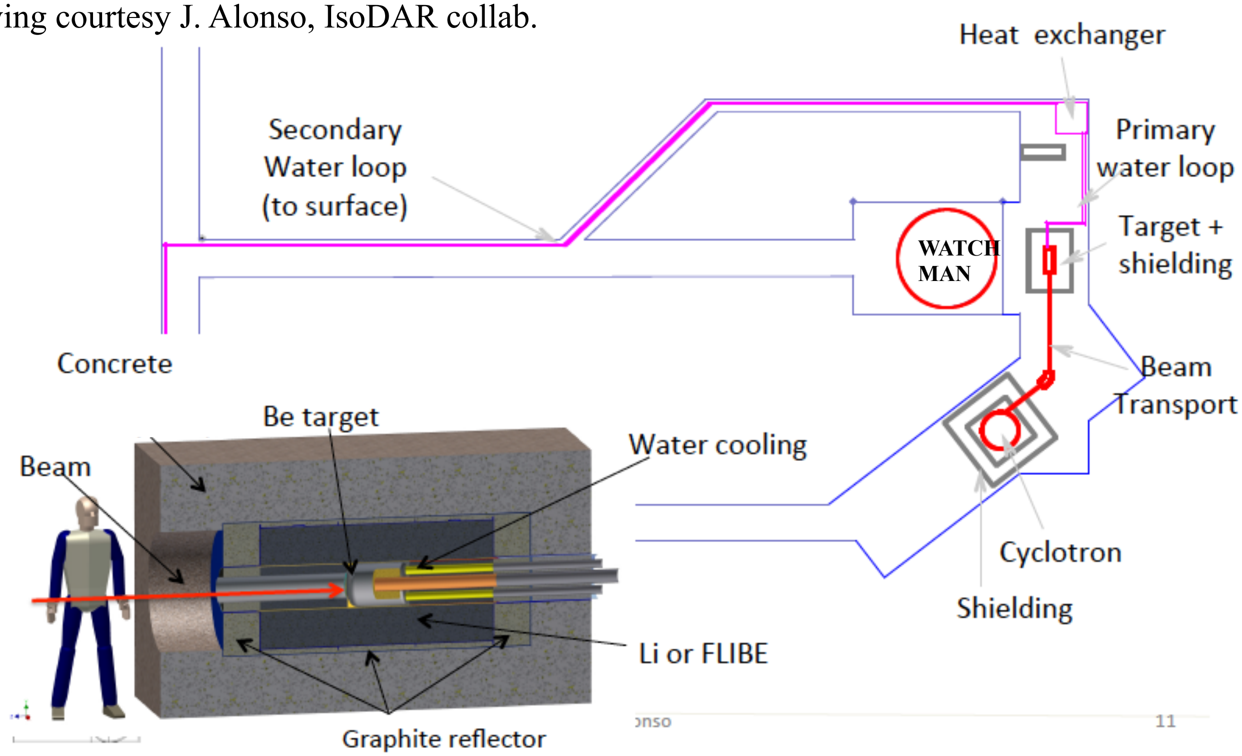
- Gd + H2O provides
  - efficient neutron detection in large water detectors
  - Antineutrino tagging





IsoDAR could be installed 16 m from the center of WATCHMAN

Drawing courtesy J. Alonso, IsoDAR collab.



Cyclotron, target, and shielding cost estimate 30 M$

Possible nonproliferation uses for large Gd-H2O detectors

Ensure no reactors are operating at several hundred km standoff

- **Simplest approach**
  Excludes new reactors in areas without existing reactors
- **Potential countermeasures are politically or financially costly**
  - Build another reactor
  - Attack the detector
- **Range extension possible with directionality**

Ensure only declared reactors are operating at a known site – tens of km standoff

- **More complex**
  Requires knowledge of signal from declared reactors
- **Adjusting power of declared reactors a potential countermeasure**
- **Discrimination possible with directionality**

Arms Control, Nonproliferation, Nuclear Security

Arms Control: reduce stockpiles in weapons states

Military nuclear materials control and monitoring
HEU transparency, Plutonium disposition
Weapons reduction/control treaties –CTBT, START

Nonproliferation: Prevent new weapons states

Civil nuclear fuel cycle monitoring: IAEA safeguard,EURATOM, ABACC
HEU fuel replacement in research reactors

IAEA
International Atomic Energy Agency
Atoms For Peace

ABACC

Domestic nuclear security: find nuclear threats

Detection of fissile/radioactive materials within borders

'National Technical Means'

Satellites and other assets not shared with other countries
Used for counterproliferation or treaty verification

'Public Technical Means'

Publicly available tools to aid treaty verification – 'Societal Verification'
Using the internet, satellite data, other media