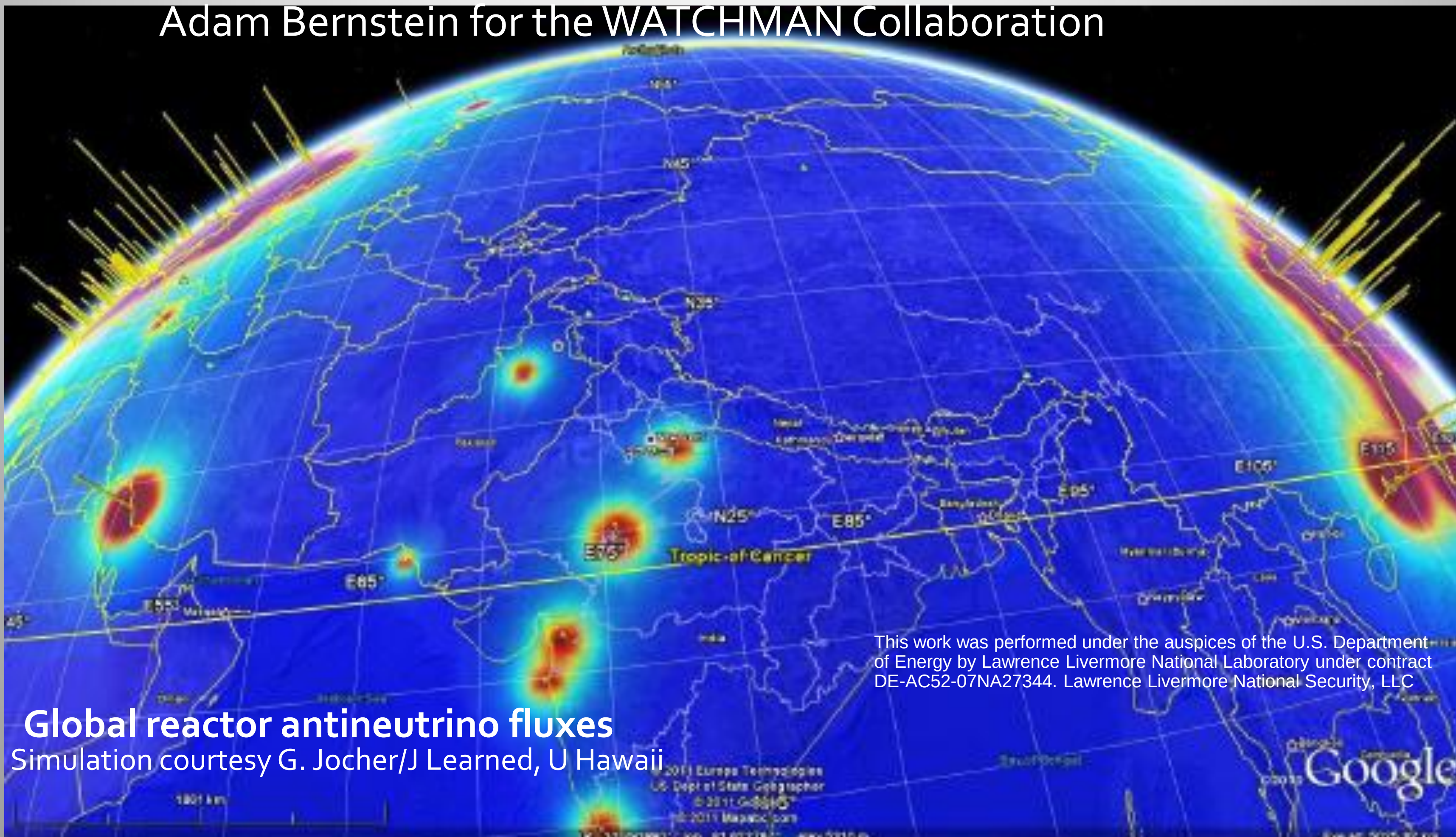
WATCHMAN: A Field Demonstration of Remote Reactor Monitoring

Adam Bernstein for the WATCHMAN Collaboration



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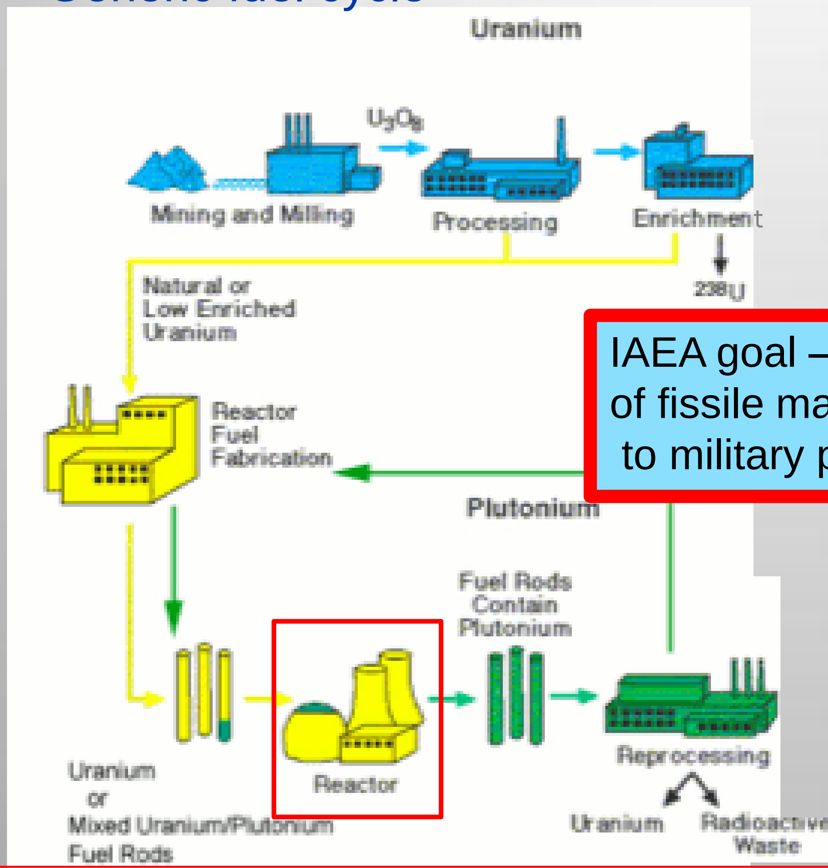
Global reactor antineutrino fluxes
Simulation courtesy G. Jocher/J Learned, U Hawaii

Outline

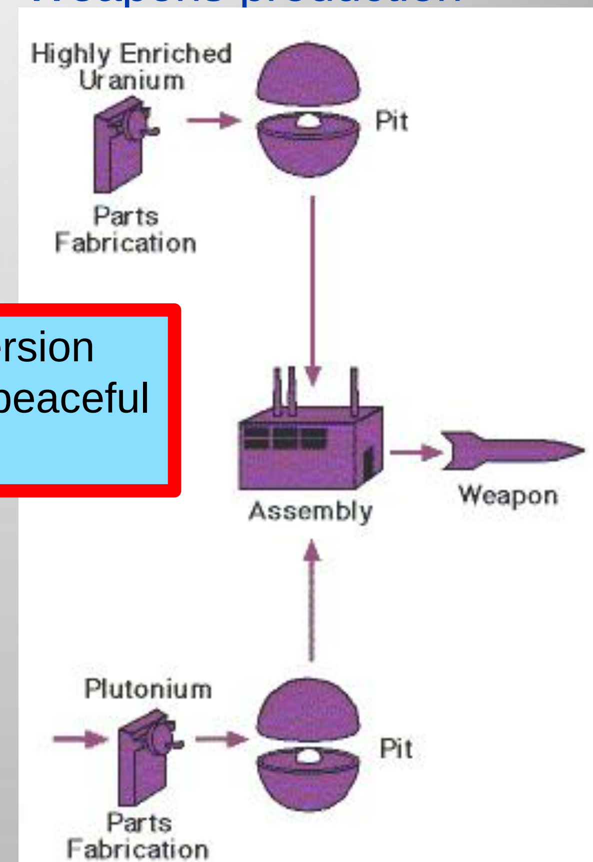
- A one-page nonproliferation tutorial
- Antineutrinos and nonproliferation
- The WATCHMAN project
- The apparently unique advantages of the Boulby Mine
- Nonproliferation, Technology and Fundamental Science

The IAEA Safeguards regime monitors the flow of fissile material through the nuclear fuel cycle in 170 countries

Generic fuel cycle



Weapons production



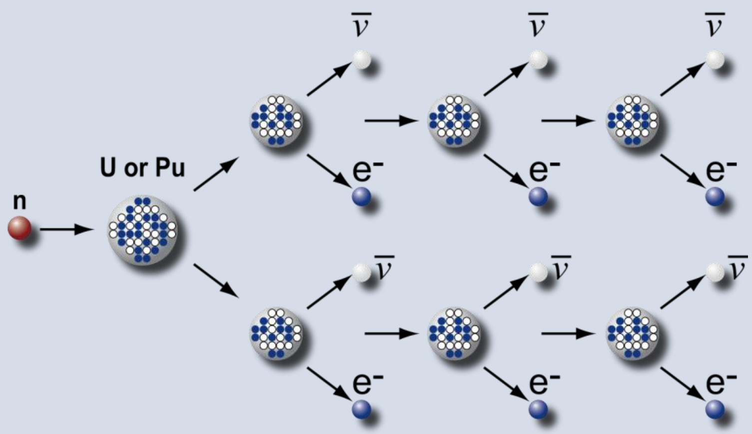
IAEA goal – detect diversion of fissile material from peaceful to military programs

Goal for antineutrino measurements - track fissile inventories in operating reactors

Monitoring 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

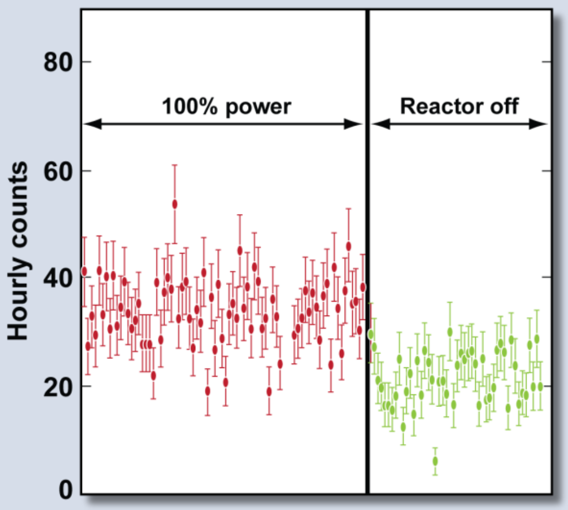
Detected rates are quite reasonable

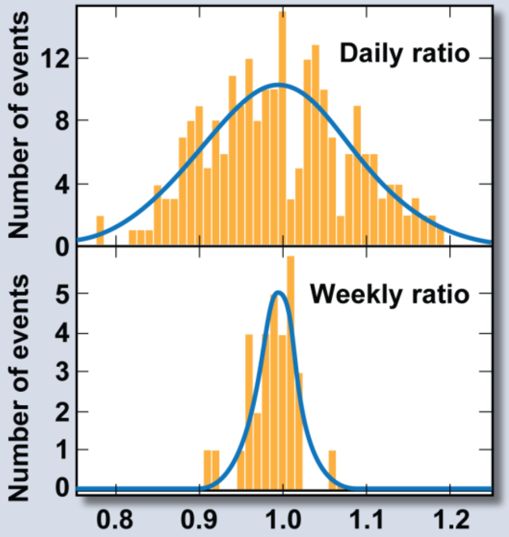
- 10^{17} antineutrinos per square meter per second at 25-m standoff
- 6,000 events per ton per day with a perfect detector
- 600 events per ton per day with a simple detector (e.g., SONGS1)

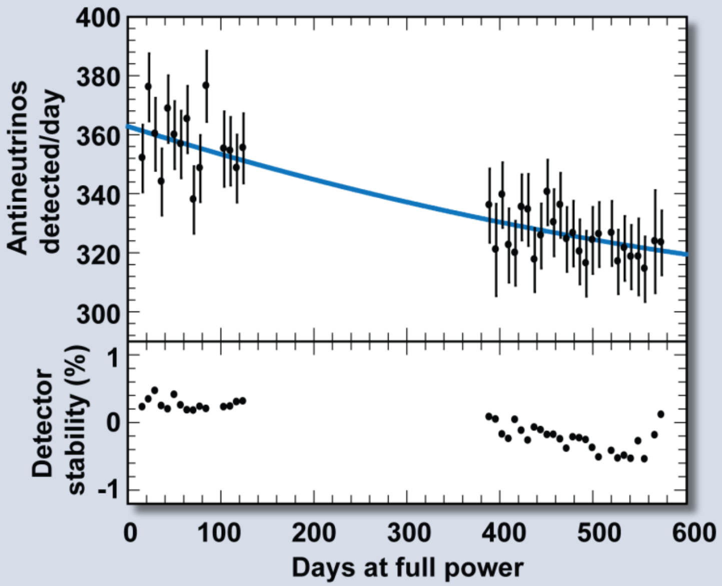
Example: detector total footprint with shielding is 2.5 meter on a side at 25-m standoff from a 3-GWt reactor

Our LLNL/SNL collaboration has helped create the field of applied antineutrino physics for nonproliferation

Determine reactor on/off status within 5 hours with 99.9% C.L.	Measure thermal power to 3% in one week	Sensitivity to 70 kg switch in U/PU: known power and initial fuel content

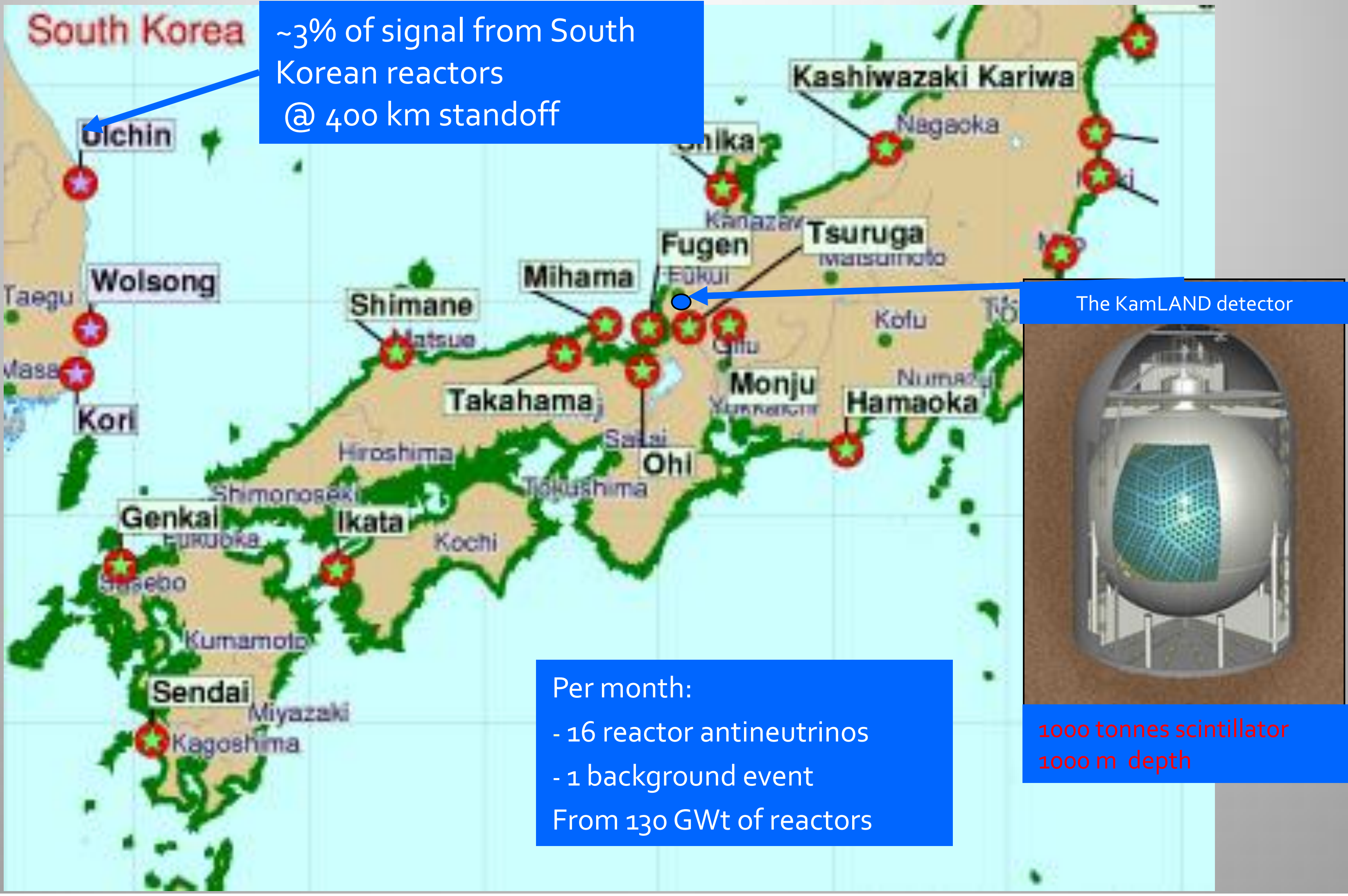






In 2012, IAEA released an official report endorsing continued research into several reactor monitoring applications – including long range reactor monitoring

Cross-border reactor monitoring is going on right now – but only for GWt reactors and with a technology that is difficult to scale



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

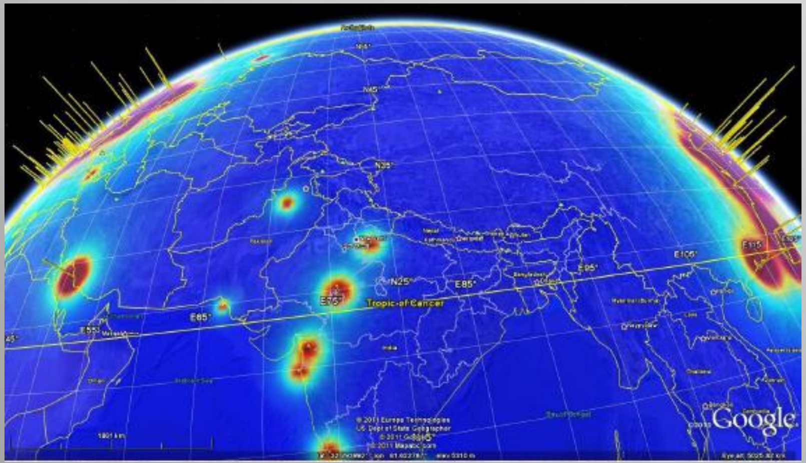
Per month:
- 16 reactor antineutrinos
- 1 background event
From 130 GWt of reactors

The KamLAND detector

1000 tonnes scintillator
1000 m depth

10 MWt reactors at a distance are a very hard problem

Goal	Detector mass	standoff	Required reduction in bg rate relative to KamLAND
16 events in 1 year from a 10 MWt reactor, (25% accurate thermal power)	10 kiloton	~40 km	10x
	1 Megaton	~400 km	100x



Global reactor antineutrino fluxes

http://arxiv.org/abs/0908.4338
Science & Global Security, 18:127–192, 2010

Gadolinium-doped (light) water appears to be the most viable option for scaling to the largest sizes

Advantages of antineutrino detection for remote discovery and monitoring of reactors

1. Cross border detection – ultimate limit is perhaps ~800 km
2. Continuous surveillance
3. Constraints on power and plutonium production rate
4. With long range capability, no cueing information required
5. Eventually: Reactor localization with improved directionality or spectral measurement

My own guess at the most likely use: cooperative deployment to confirm absence of reactors in a prescribed wide area

The WATCHMAN (Water Cherenkov Monitor for Antineutrinos) Collaboration

UC Davis

UC Berkeley

UC Irvine

Virginia Tech.

U of Hawaii

Hawaii Pacific University

Current Phase: Two U.S. National Laboratories, 6 Universities, 4 M$, 2.25 years

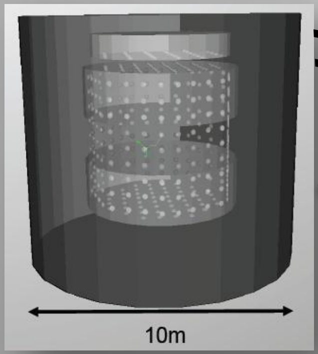
WATCHMAN is now in its first phase in the United States

- **Overall Project Goal**: demonstrate sensitivity to reactor antineutrinos using a **gadolinium-doped (light) water detector** at 0.1-1 kilometer standoff from a 10-150 MWt US research reactor, or 10-20 kilometers from a 3000 MWt scale US commercial power reactor.

Research or power reactor

0.1 - 25 km standoff

100-1000 meters overburden



Kiloton scale detector

First Phase, 2012-2014:

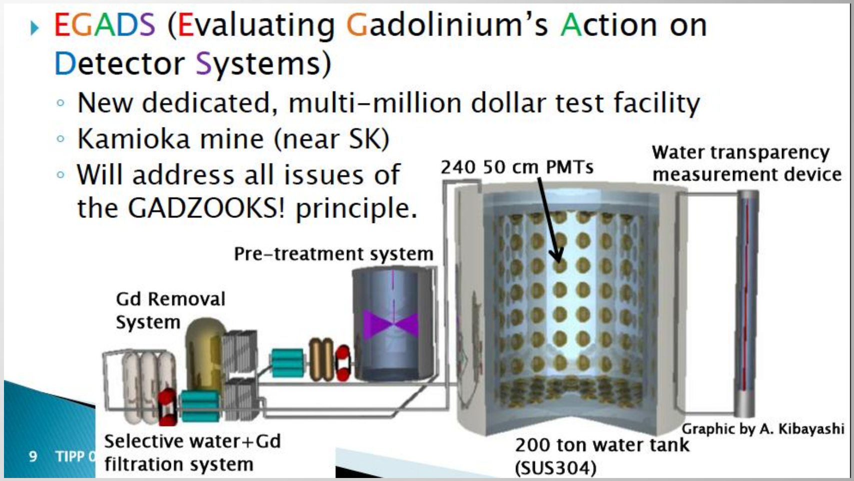
- **identify site**
- **measure backgrounds**
- **develop a design envelope for the detector**

Complementary activities worldwide (OK mostly in Japan)

EGADS- 200 ton deeply buried detector
to evaluate Gd-doped antineutrino detection

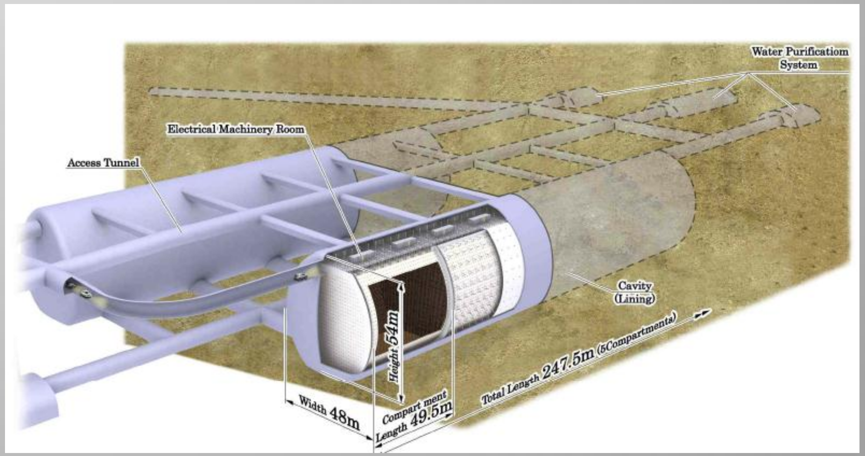
- backgrounds
- materials
- energy thresholds

<u>This detector volume is too small for direct demonstration of sensitivity</u>



- **HyperKamiokande**

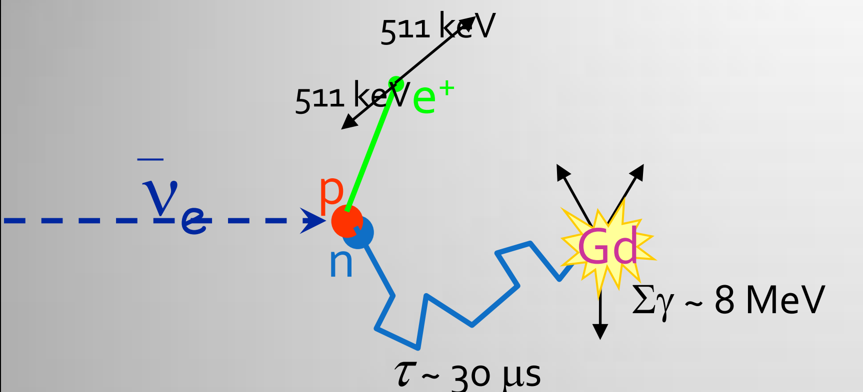
- 560,000 ton multipurpose water detector being planned by Japan
- Time scale: ~12 years
- Interest in U.S. science community in participation will lead to further R&D in this area
- Gd an option but not guaranteed



<u>Our demonstration would give strong confidence for exercising the Gd option</u>

Antineutrino signal and background

Signal in 1 kiloton of water



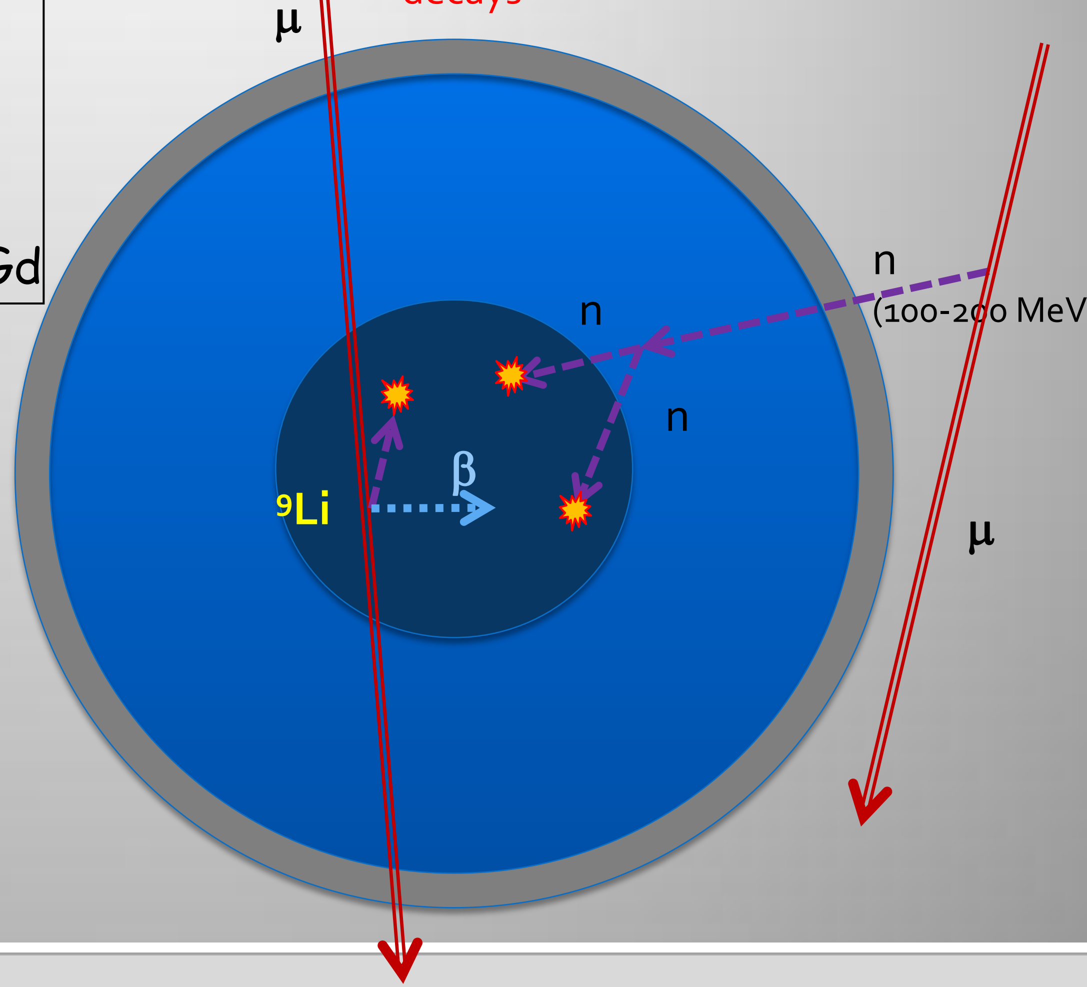
prompt e^+ signal + n capture on Gd

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

'The antineutrino heartbeat'

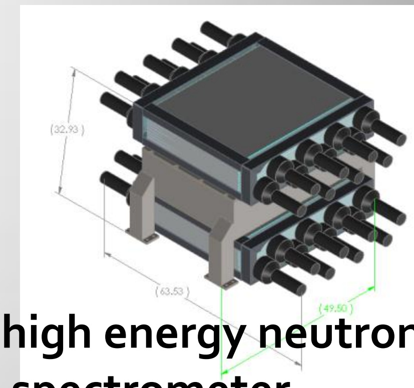
Backgrounds:

1. Real antineutrinos
2. Random event pair coincidences
3. Muon induced high energy neutrons
4. Long-lived (~ 1 sec) radionuclide decays

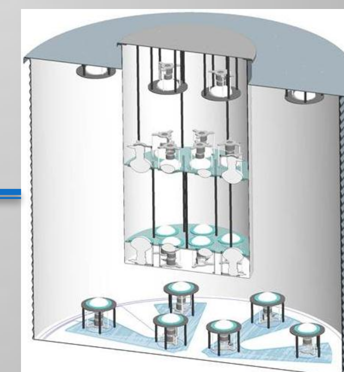


Step 1: What are the backgrounds ?

- **Shallow Depths** (100-600 meters): not well known, measure as a function of overburden at a US facility (Kimballton)



high energy neutron spectrometer



radionuclide detector
(Water doped with gadolinium)

- **Boulby: (1 km)** reasonable extrapolations from past and ongoing experiments (KamLAND, Soudan mine water detector)

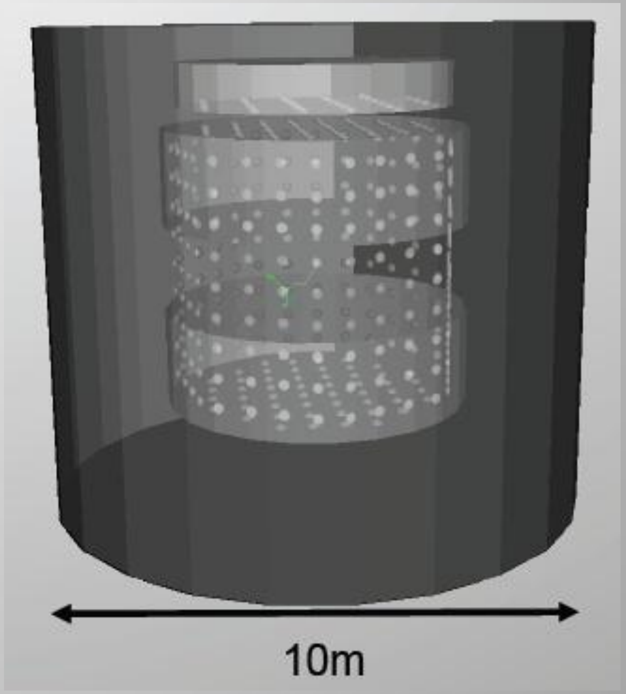
Step 2: Choose a location

1. **Detect <u>as few as ~1 but no greater than 10</u> signal events per day.**

2. **Three sigma detection of the presence of the reactor in <~1 month.**
   - For 1 signal event per day → tolerable background is **2** events per day.
   - Greater standoff can be compensated by greater overburden

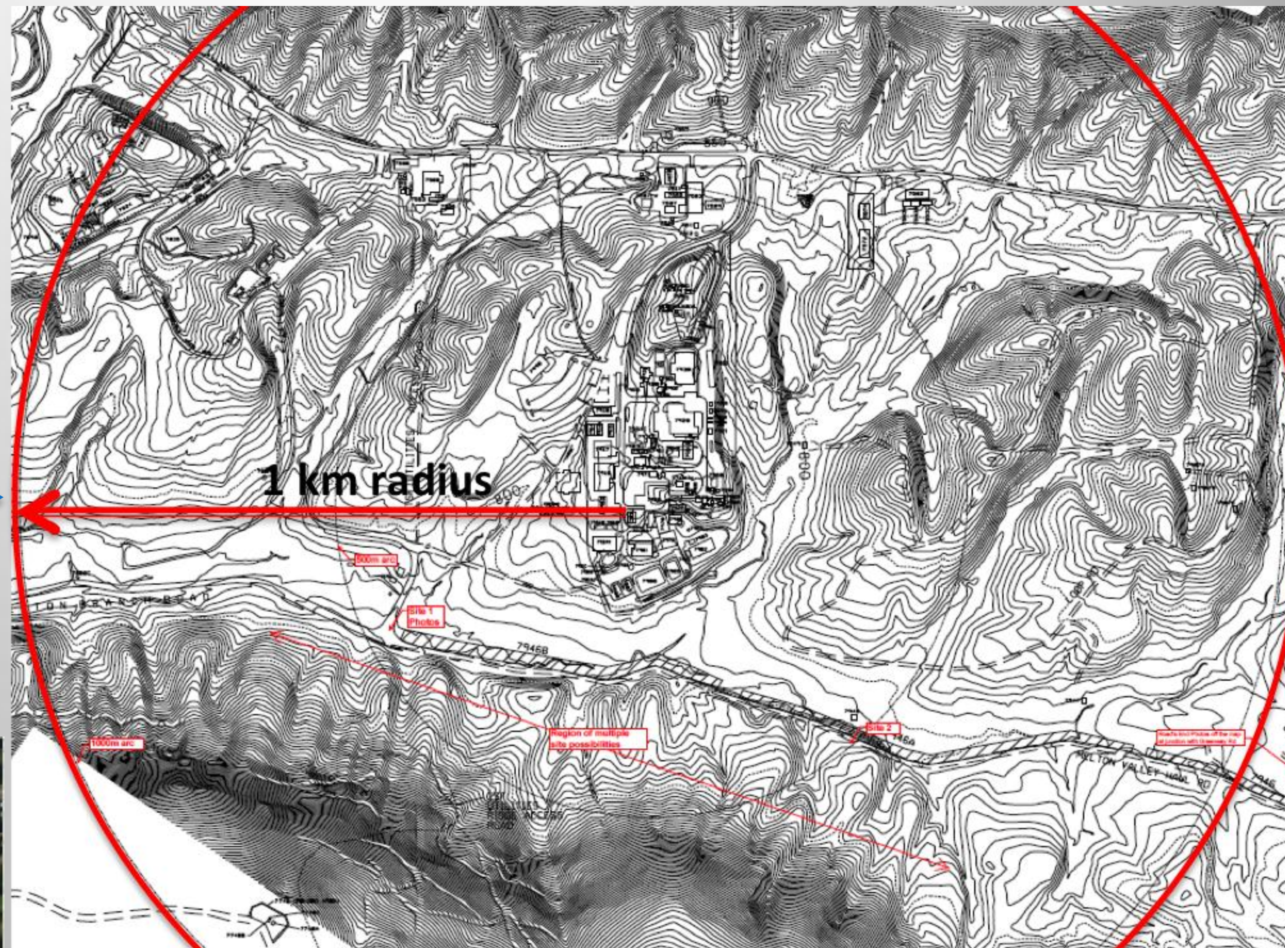
3. **Overburden:**
   - Existing overburden preferred (cost savings)

4. **Reactor Power:**
   - A small reactor is preferred, (greater similarity with the ultimate intended use)



A shallow site: Oak Ridge High Flux Isotope Reactor, 100 m depth

- 1000 ton det. target mass
- Power = 85 MWth

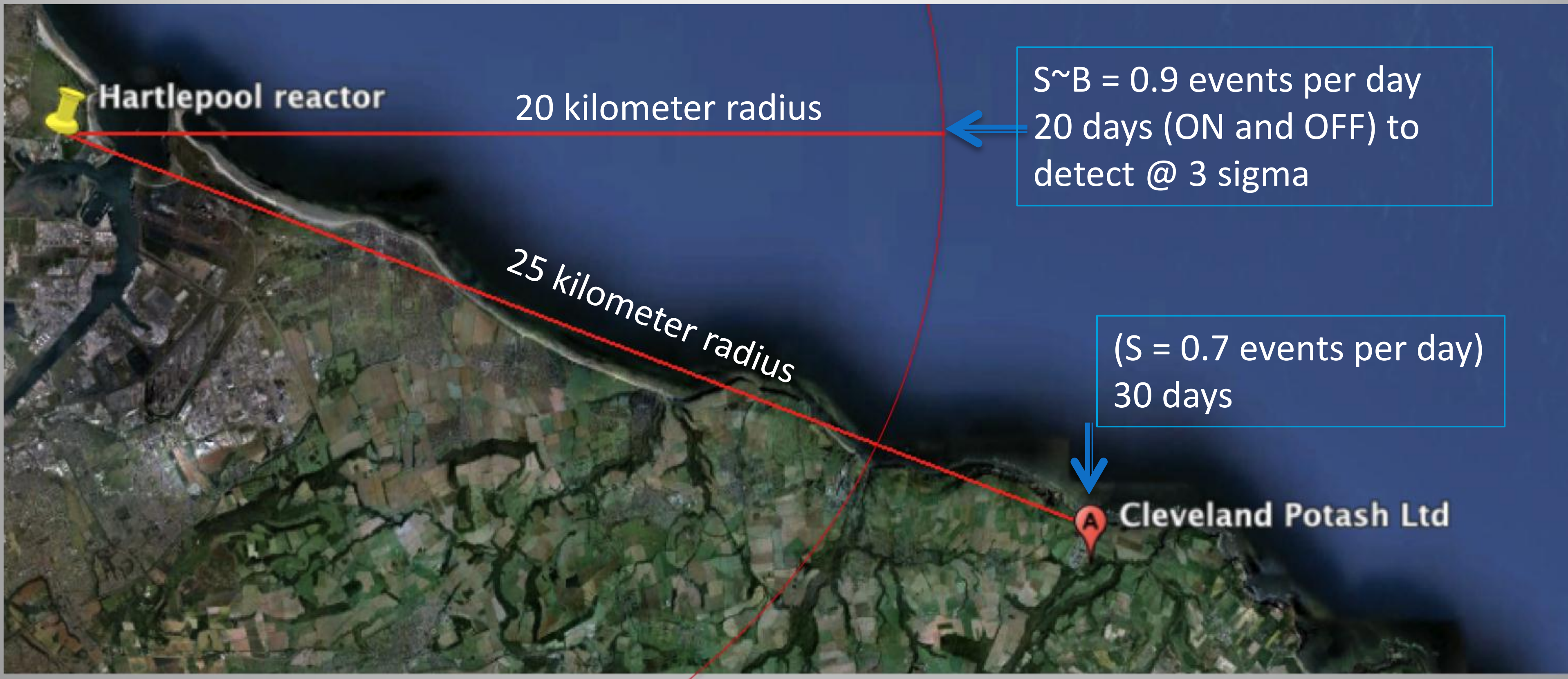


S = 13 events per day
B = 164 events per day
10 days ON and OFF to detect @ 3 sigma

Main problem: excavation costs are high

A deep site: the Boulby mine, 1000 meter depth

- 1000 ton detector target mass
- Power = 1570 MWth (2 cores)



Why is Boulby an interesting site ?

- Event rate meets our detection goal
- Depth suppresses most backgrounds
- Relatively large standoff provides a convincing demonstration
- Mature, well-run, well supported underground science infrastructure
- Excavation costs lower than ‘greenfield’ options
- Recent mine activity allows for larger cavern (15x15x15 m)
- International cooperative deployment underscores and reinforces nonproliferation commitments of all participants
- World-class science and a path towards very large detectors

A shot of the scientific bow: WATCHMAN will also be one of the world's largest supernova watch detectors

- A 1000 ton detector even with moderate overburden (few 100 m.w.e.) could detect ~700 events from a supernova at the galactic center. Any detector capable of detecting reactor antineutrinos can do this by default (SN antineutrinos are higher energy and easier to detect).

Pre-1987 1987

WATCHMAN would see antineutrinos from a supernova like 1987a, shown here in the visible

Nonproliferation, Technical and Scientific objectives are all met with this proposal

Nonproliferation

- First ever demonstration of sensitivity to reactor antineutrinos at appreciable standoff from a reactor using a gadolinium-doped water detector – probably the only scalable technology choice
- A concrete example to policy makers of a reliable low event rate antineutrino-based measurement system, with unambiguous detection of only a few events per day

Technology

- Detection efficiencies and backgrounds for large Gd-WCD detectors
- Well-benchmarked detector and background simulation tools
- Experience with gadolinium-doped water handling, purification monitoring in order to scale to next generation experiment

Fundamental Physics

Now:

- Core-collapse supernovae in this galaxy

Eventually ?

- Megaparsec supernovae detection
- Diffuse supernova neutrino detection
- proton decay
- long baseline neutrino CP phase and mass-hierarchy experiments
- 60 km standoff mass hierarchy measurements at reactors

Conclusions

- Antineutrino detectors deployed a few hundred meters from reactors detect operational status, thermal power and Pu production
- Attempts at the far more ambitious long-range capability are underway in both the nonproliferation and scientific communities
- WATCHMAN aims to meet a nonproliferation need and become a source of interesting science and detector technology for the neutrino community

Backup slides

Applied Antineutrino Physics – a growing global community with strong ties to Dark Matter and Neutrino Science

Neutrinos and Arms Control Workshop

5-7 February 2004, University of Hawaii

Neutrino Sciences 2005

Neutrino Geophysics

Honolulu, Hawaii

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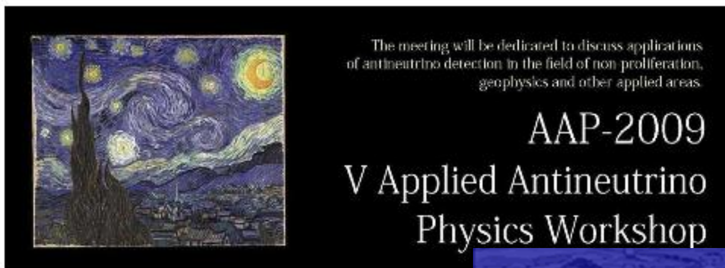
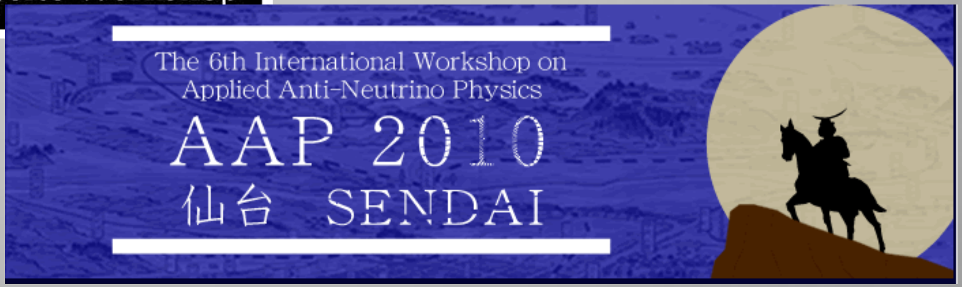
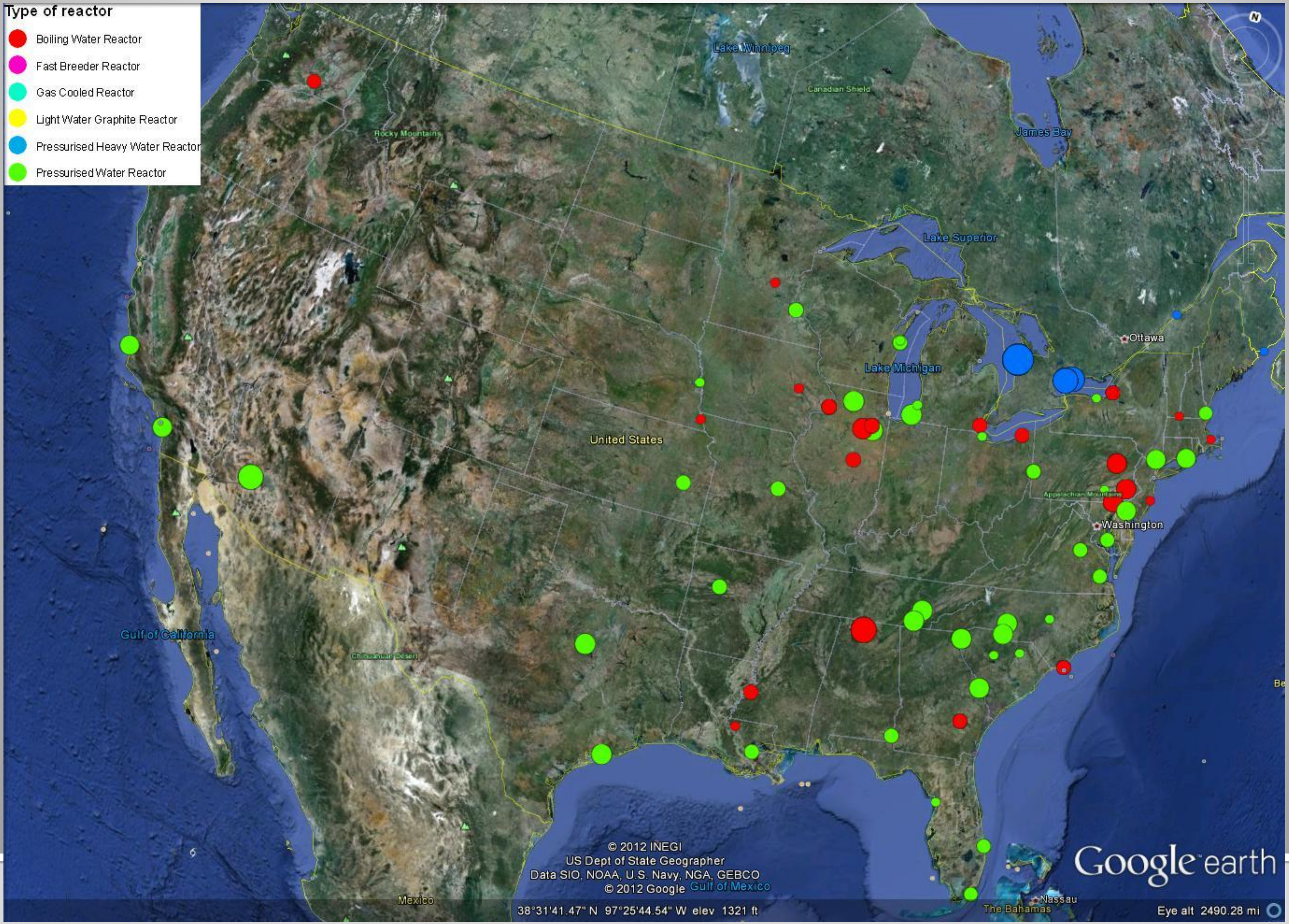
AAP2006
WORKSHOP
SEPT 24-26
LIVERMORE, CA

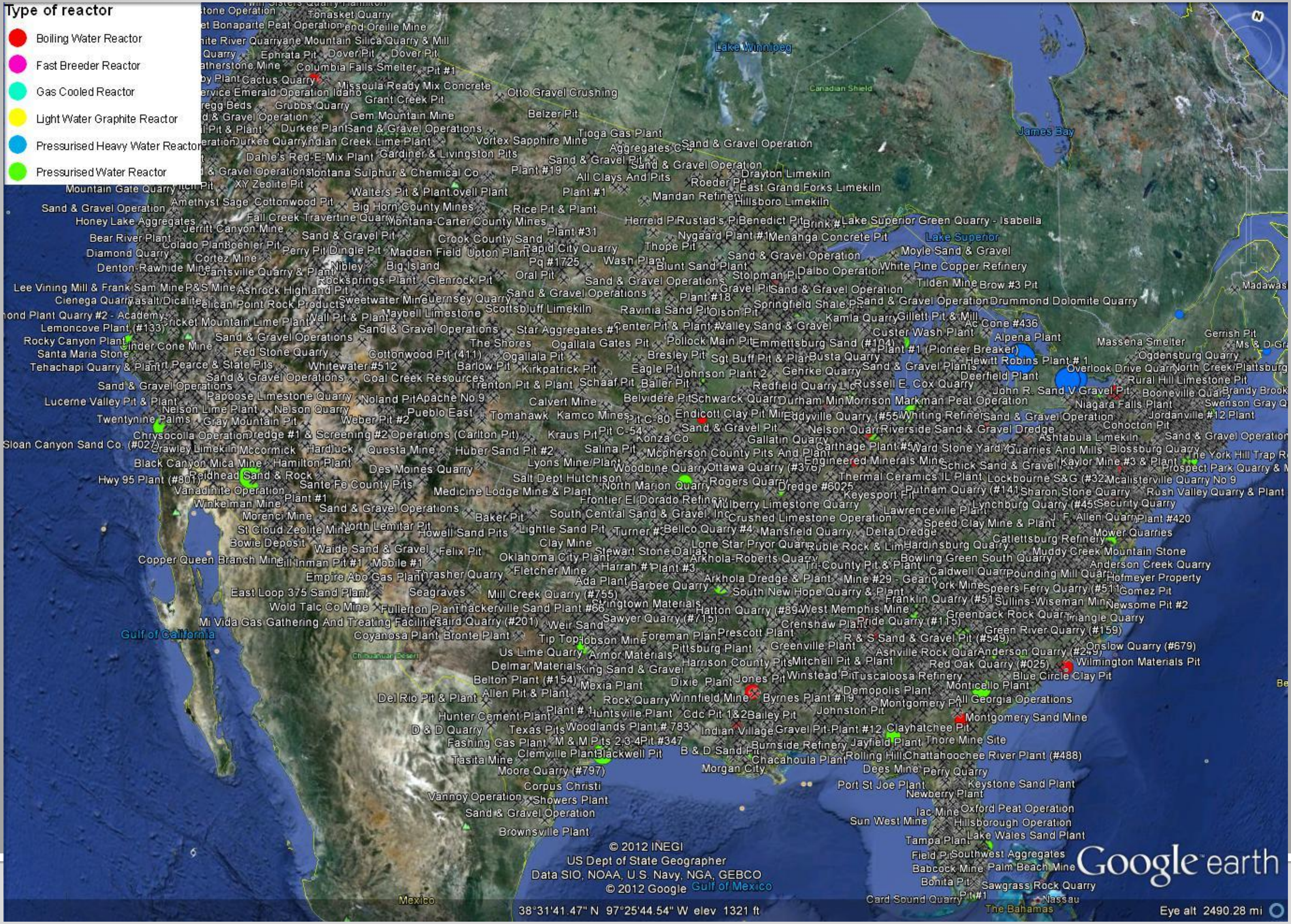




Map of US Power Reactors



Map of US Reactors + Active Mines



Perry Nuclear Generating Station

Perry Reactor Nuclear Generating Station to IMB cavern in the Fairport Salt Mine (Ohio)

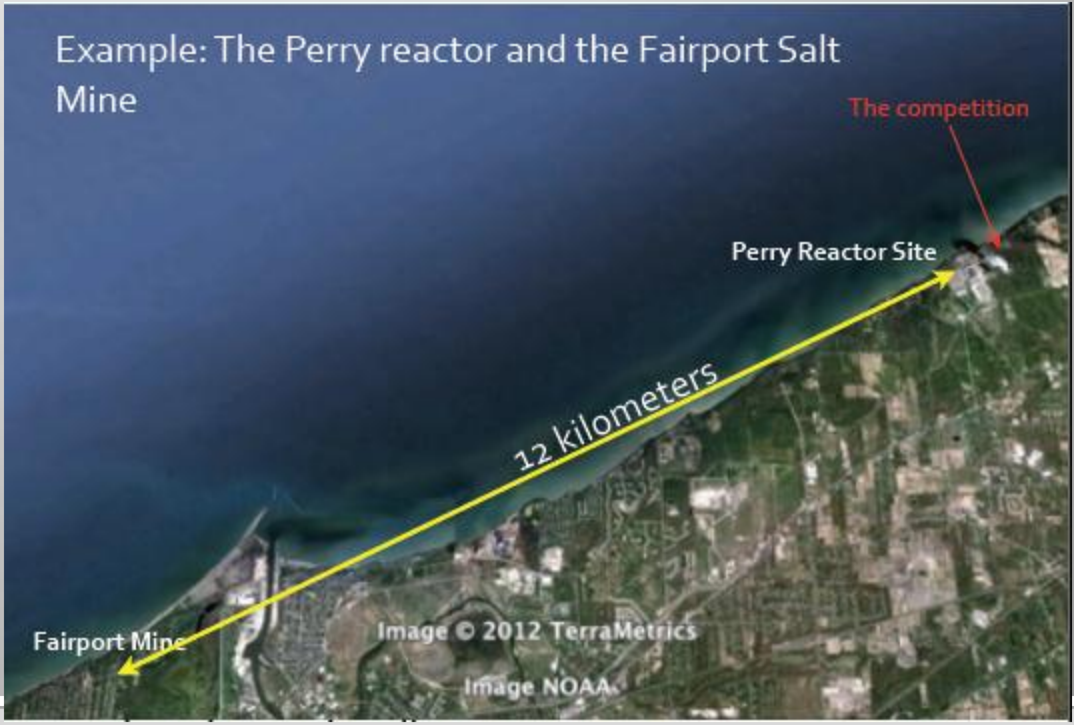
- 1570 m.w.e.
- cavity was 18m x 17m x 22.5m
- ~13 km standoff
- 3875 MWth

Pros

- Existing cavern in active mine.
- Large depth for low background.

Cons

- Large stand-off will give low signal rate (0.5-1.0 per day).
- Old cavern likely to require renovation.

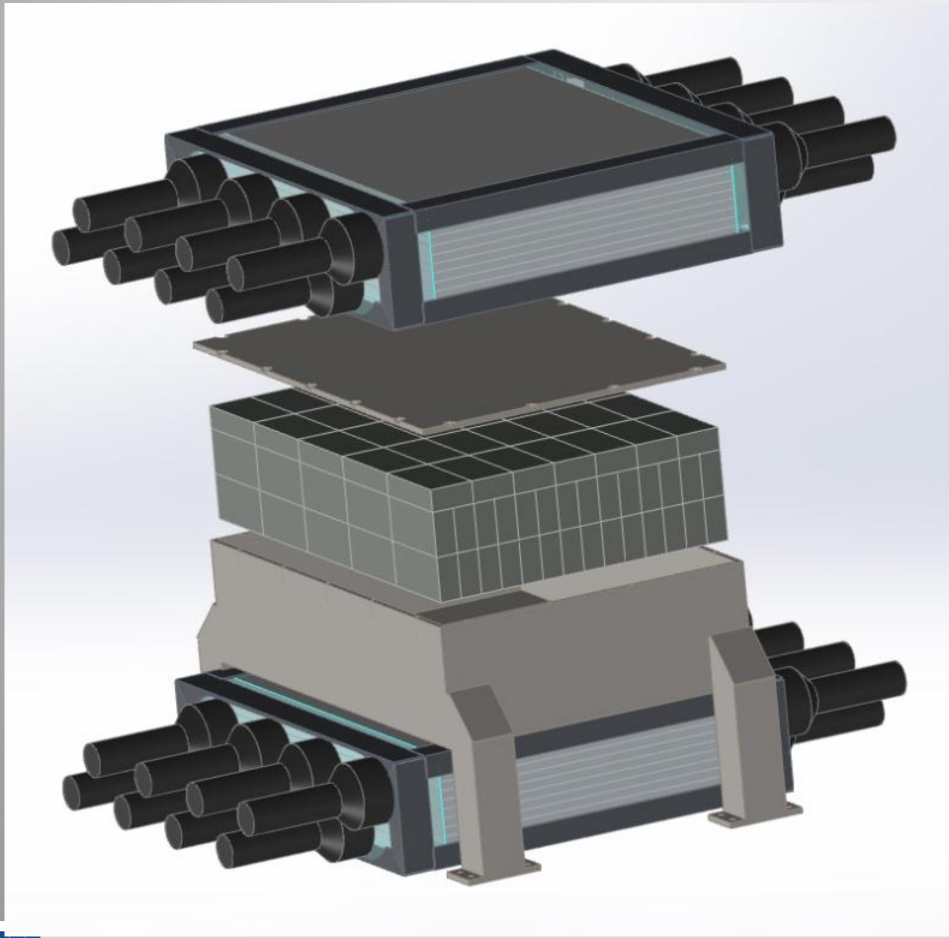


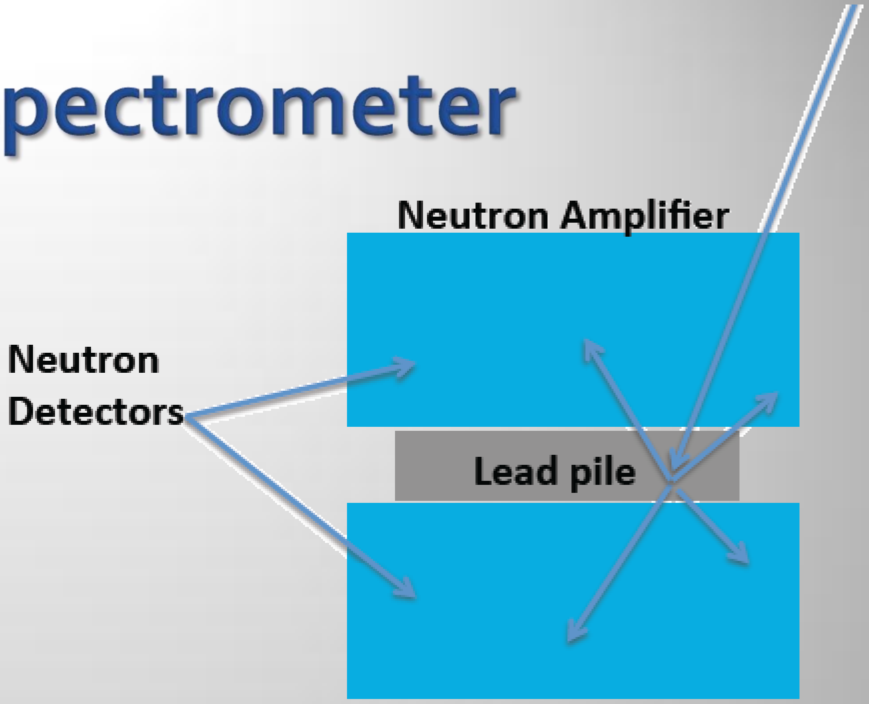
What will we actually measure at shallow depths

1. The energy spectrum of muogenic fast neutrons as a function of depth below the Earth's surface
   - Allows us to model double-neutron antineutrino-like backgrounds in a kiloton scale detector

2. The rate of muogenic radionuclides such as 9Li
   - Allows us to set an upper limit on the contamination of our signal by these antineutrino-like backgrounds

Fast Neutron Spectrometer

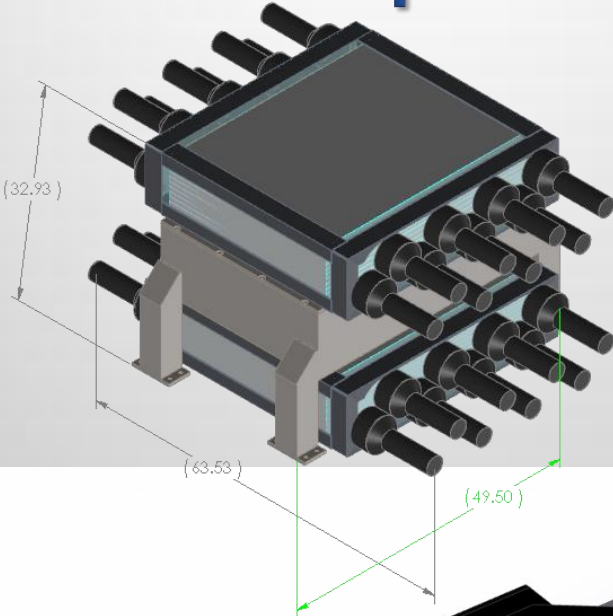


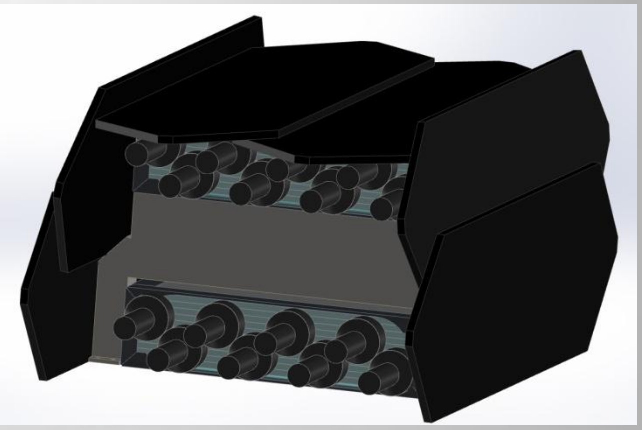


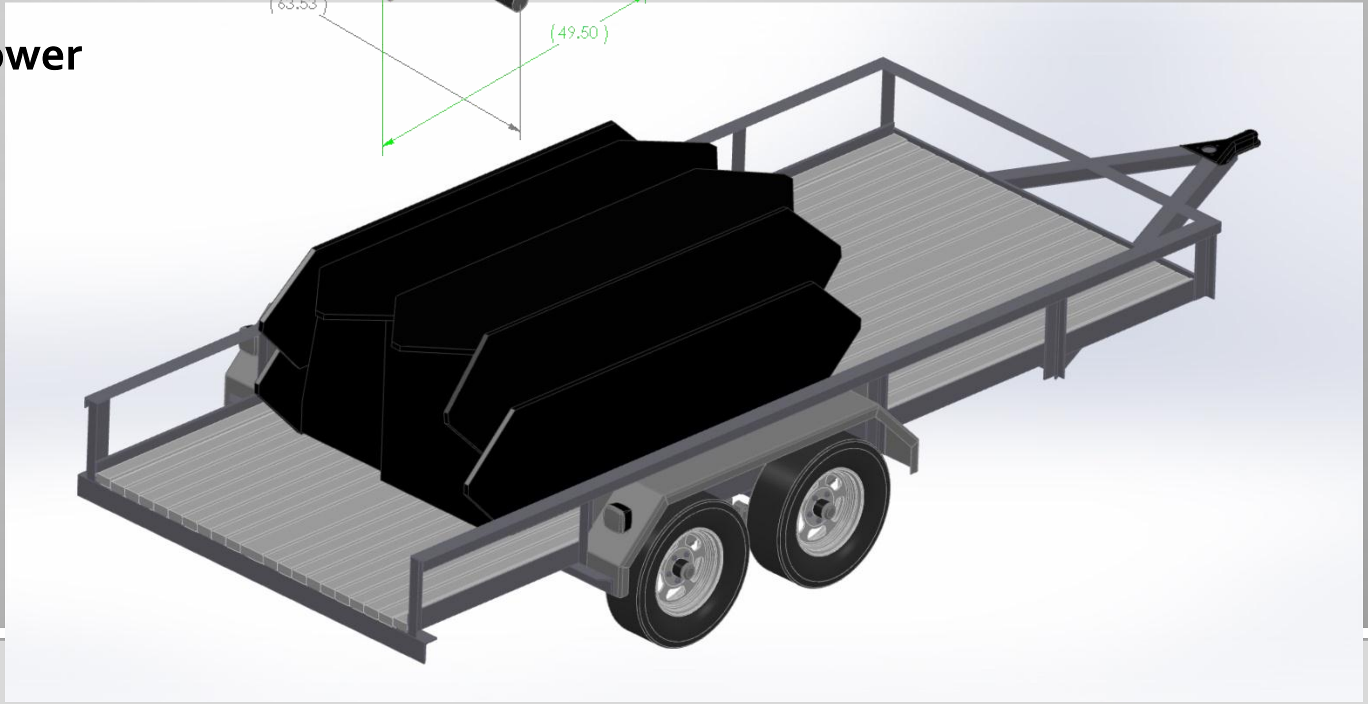
- Plastic scintillator/Gd doped paint detectors sandwich ~4 tons of lead.
- Direct interaction with scintillator for E < ~100 MeV.
- Neutron multiplication off of the lead for E > ~50 MeV.
- Expect 3000-5000 events per month at 100 m.w.e.

Fast Neutron Spectrometer – muon veto on platform

- Detector + muon veto + data acquisition and peripherals are less than 9 tons.
- Platform will be standard trailer outfitted with power and AC.

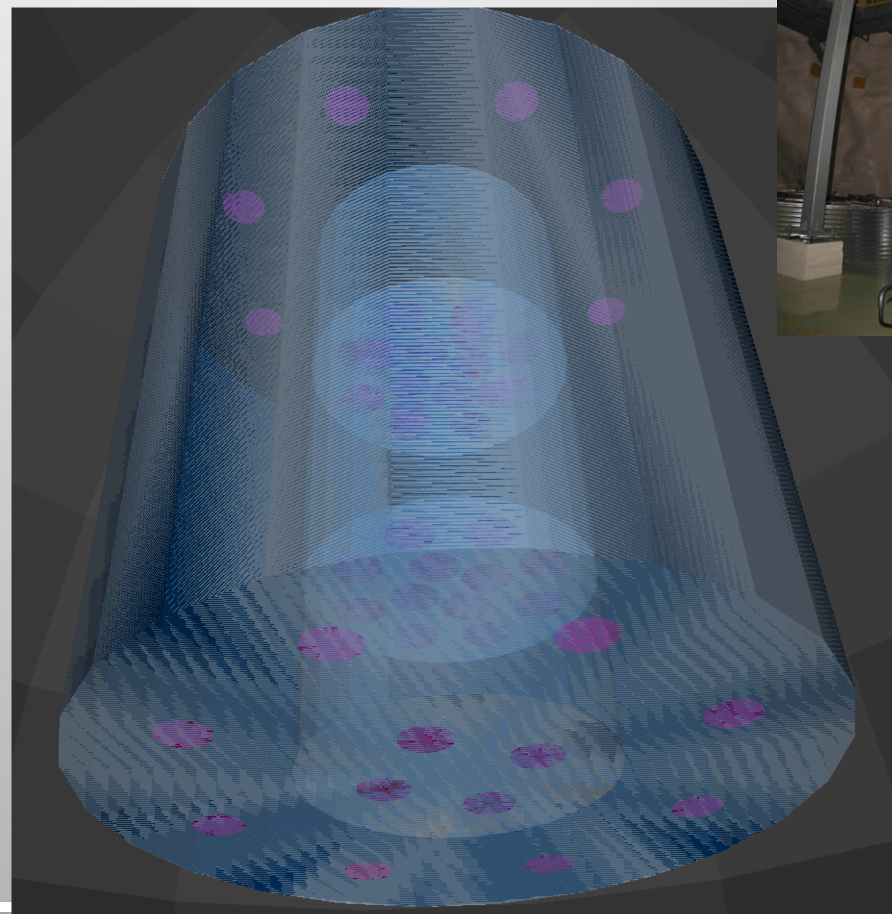






Radionuclide Background Detector

- 3.5x3.5 meter detector with 1.5x1.5 meter active inner volume.
- Four optically segmented volumes with 0.1% $GdCl_3$ doping.
- Three inner volumes define a muon 'telescope'
- The central volume is the search region.
- The outer volume is the muon/neutron veto.



Background Measurements at the Kimbleton Underground Research Facility

- Drive in access
- Can deploy from 100 feet to 1400 feet of overburden
- Use of the same detector at multiple depths ensures reliable comparison of results
- First-ever continuous measurement as a function of depth

A groundswell of experimental activity worldwide

World Activities

| Done | Running | Proto | In construction|

	Site	Techno	Comment
SANDS	San Onofre, US	0.5 t LS @20mwe	Done
SANDS	San Onofre, US	PS & Gd-H2O @20mwe	On Going
ANGRA	Angra, Brazil	LS	On Site R&D
DANSS	KNPP, Russia	Plastic	**In construction**
Kaska	Joyo, Japan	Gd-LS	**Prototype**
Panda	Japan	Plastic, Gd foil	Prototype
NUCIFER	Osiris	Gd-LS	**Just Funded**
Texono	Taiwan	HPGe	On Going – CNS –
Pt Lepreu	Canada	Gd-LS	CANDU, with USA
Cormorad	Italy	Plastic	Prototype
MARS	ILL	Plastic + ^{6}Li	Prototype

WATCHMAN has five phases – Phase I (two years) currently funded

Phase	Activity
I	Siting and Scoping, including site identification and detailed estimates of signal, background, required overburden and total project cost, and experimental measurement of backgrounds
	→ Sponsor approval of large detector
II	Design and site licensing
III	Construction
IV	Deployment
V	Data-taking and demonstration to end users