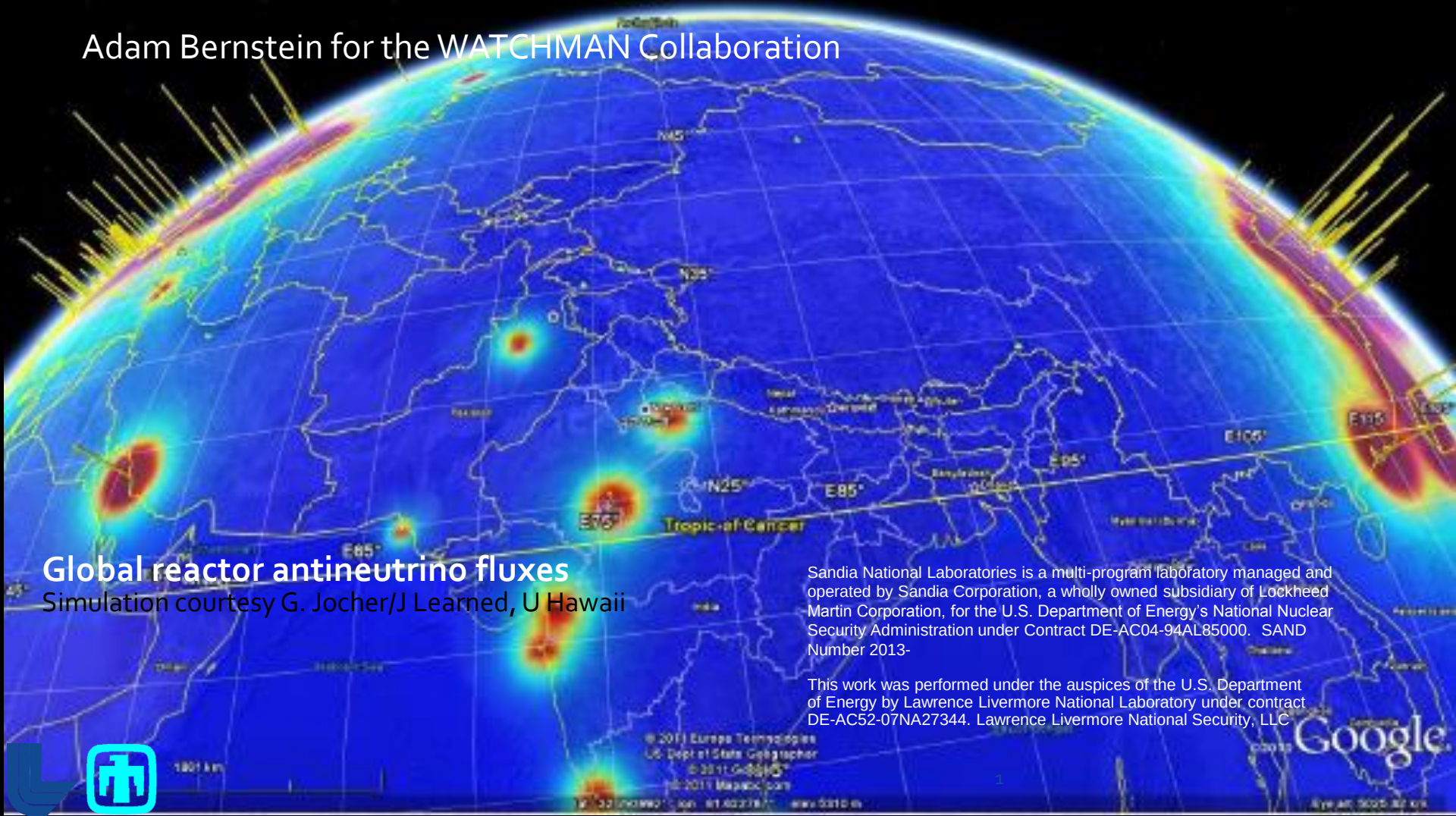
WATCHMAN

WATer CHerenkov Monitoring of Anti-Neutrinos

A Field Demonstration of Remote Reactor Monitoring

Adam Bernstein for the WATCHMAN Collaboration



Global reactor antineutrino fluxes

Simulation courtesy G. Jocher/J Learned, U Hawaii

Sandia National Laboratories is a multi-program laboratory managed and operated by Sandia Corporation, a wholly owned subsidiary of Lockheed Martin Corporation, for the U.S. Department of Energy's National Nuclear Security Administration under Contract DE-AC04-94AL85000. SAND Number 2013-

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Outline

A. What are we trying to accomplish ?

1. By 2016, demonstrate 1-25 km standoff sensitivity to a reactor using a 1000 ton detector.
2. Ultimately: Demonstrate O(500) km sensitivity to a small reactor with a Megaton-scale detector

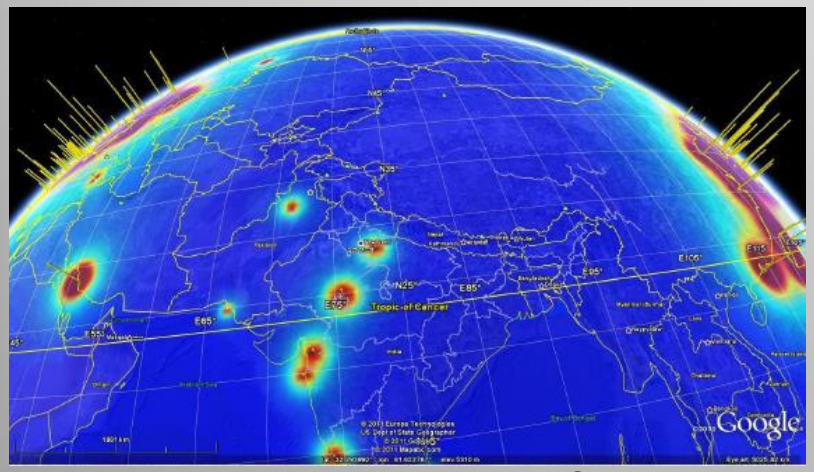
B. KURF background experiments that help us prepare for A.1.

C. Choosing a suitable deployment location for the 1000 ton detector

Ultimate goal: find or exclude hidden 10 MWt reactors at a distance - a 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

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



Global reactor antineutrino fluxes

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

Interim goal: sensitivity at 1-25 km with a kiloton mass Gd-water detector

- Remote reactor monitoring demonstration in the NNSA Strategic Plan


The National Nuclear Security Administration

Strategic Plan

May 2011

Select Initiatives

Strengthen Nuclear Safeguards:

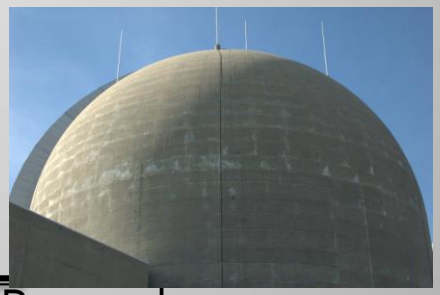
- By 2013, deploy new non-destructive assay technologies to directly quantify plutonium in spent fuel.
- By 2016, demonstrate remote monitoring capabilities for reactor operations.

Counterterrorism and Nuclear Threat Response:

- O(50 M$) project, 4-5 year duration
- NNSA lead with support from DOE Office of Science

WATCHMAN (WATer Cherenkov Monitoring of ANtineutrinos) is now in its first phase in the United States – 2.5 years, NA-22 funded

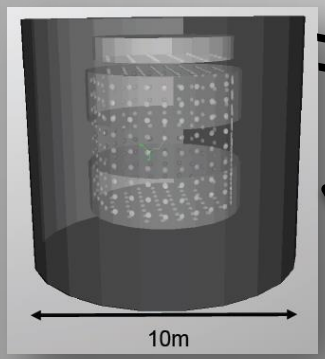
- **Overall Project Goal**: demonstrate sensitivity to reactor antineutrinos using a **gadolinium-doped (light) water detector** at ~1 kilometer standoff from a 10-150 MWt US research reactor, or up to 25 kilometers from a 3000 MWt scale US commercial power reactor.



1 - 25 km standoff

Research or power reactor

100-1000 meters overburden



Kiloton scale detector

First Phase, 2012-2014:

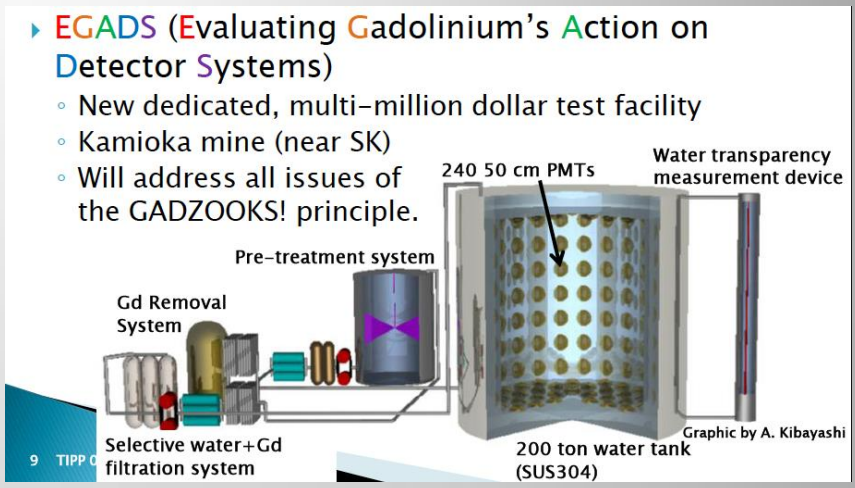
- **measure backgrounds**
- **identify site**
- **develop a design/ cost envelope for the detector**

Complementary experiments worldwide

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

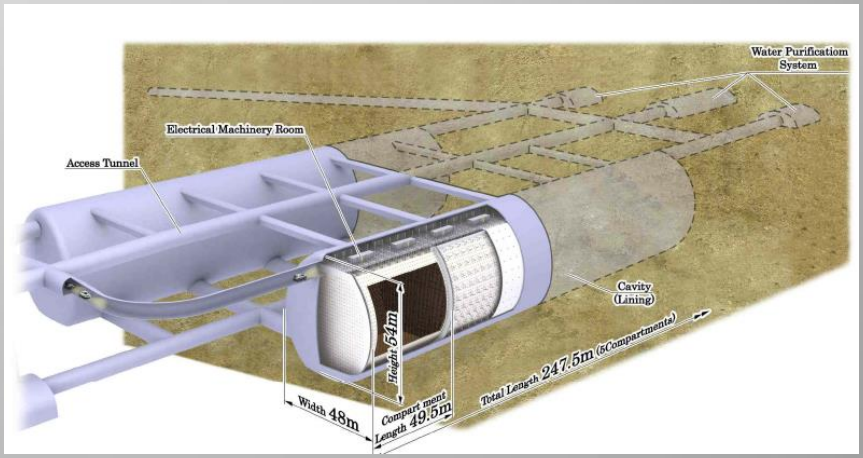
- backgrounds
- materials
- energy thresholds

This detector volume is too small for direct demonstration of sensitivity



- **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



Our demonstration would give strong confidence for exercising the Gd option

The WATCHMAN Collaboration

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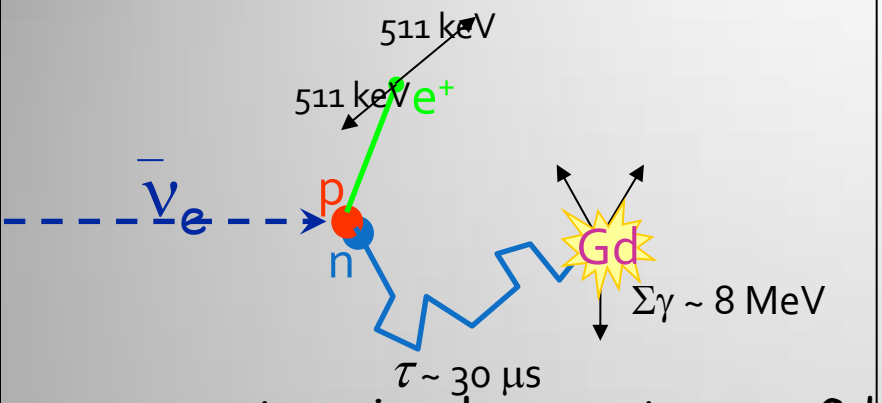
Current Phase: Two U.S. National Laboratories, 6 Universities, 2.25 years

WATCHMAN has five phases

Phase	Activity
I - Now	➢ **measure backgrounds** ➢ **identify site** ➢ **develop a design/cost envelope for the detector**
2104-2015:	**Sponsor approval of large detector deployment**
II	Design and site licensing
III	Construction
IV	Deployment
V	Data-taking and demonstration to end users

Antineutrino signal and background

Signal in 1 kiloton of water



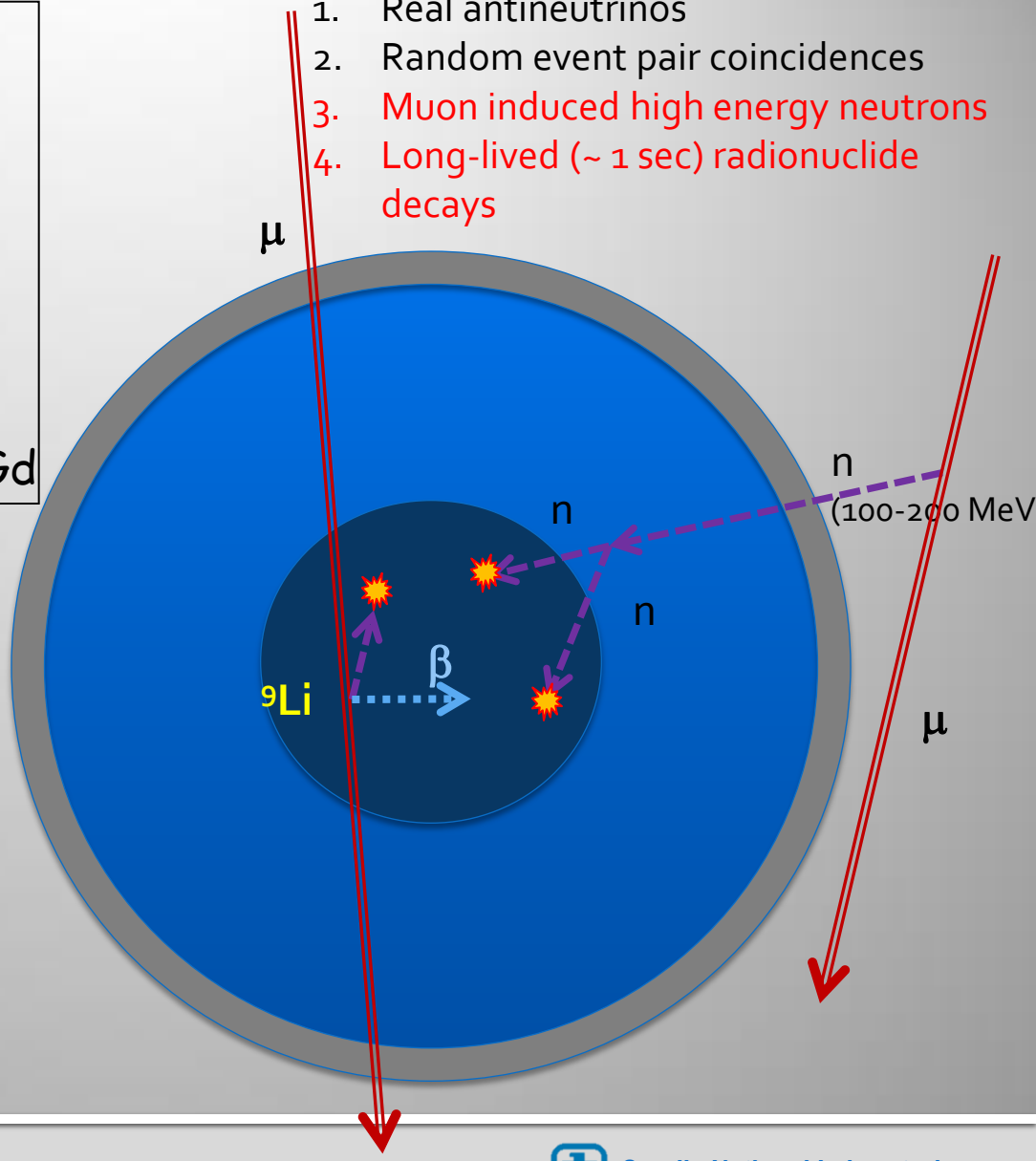
prompt e^+ signal + n capture on Gd

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

'The antineutrino heartbeat'

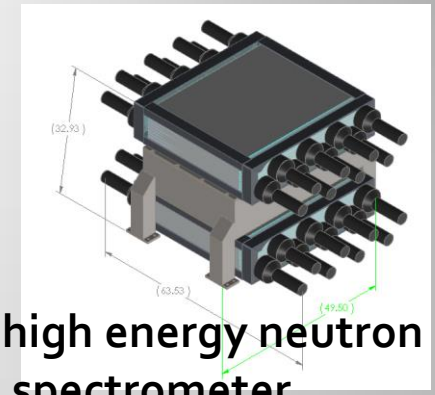
Backgrounds:

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



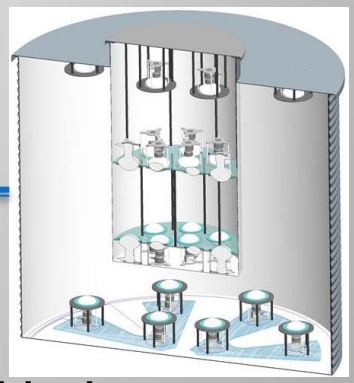
Step 1: Measuring backgrounds

- **Shallow Depths** (100-600 meters): not well known, measure as a continuous function of overburden at the KURF



high energy neutron spectrometer

Based on recent survey and muon data at KURF, **300 400 and 600 mwe** appear to be viable measurement locations



radionuclide detector (Water doped with gadolinium)

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

(Relatively) Shallow depth Background Measurements at KURF

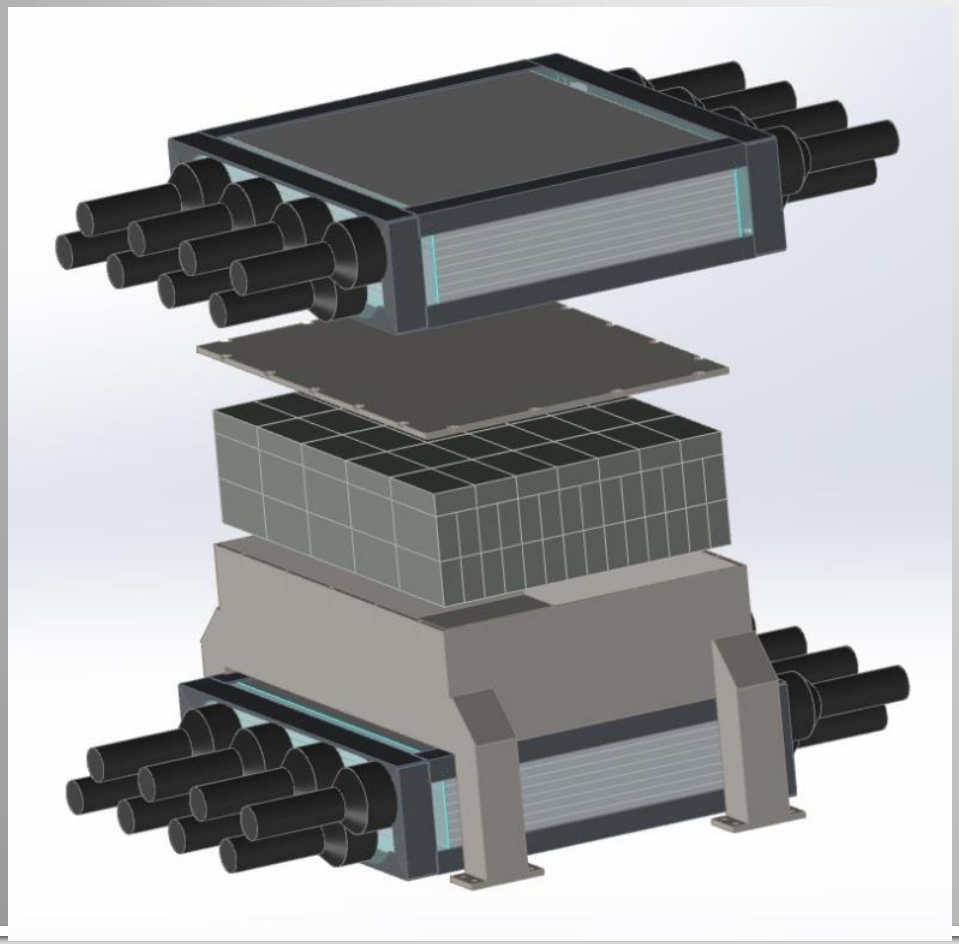
- Drive in access
- Can deploy from 100 feet to 1400 feet of overburden
- Use of the same detector at multiple depths ensures reliable comparison of results
- First-ever continuous measurement as a function of depth

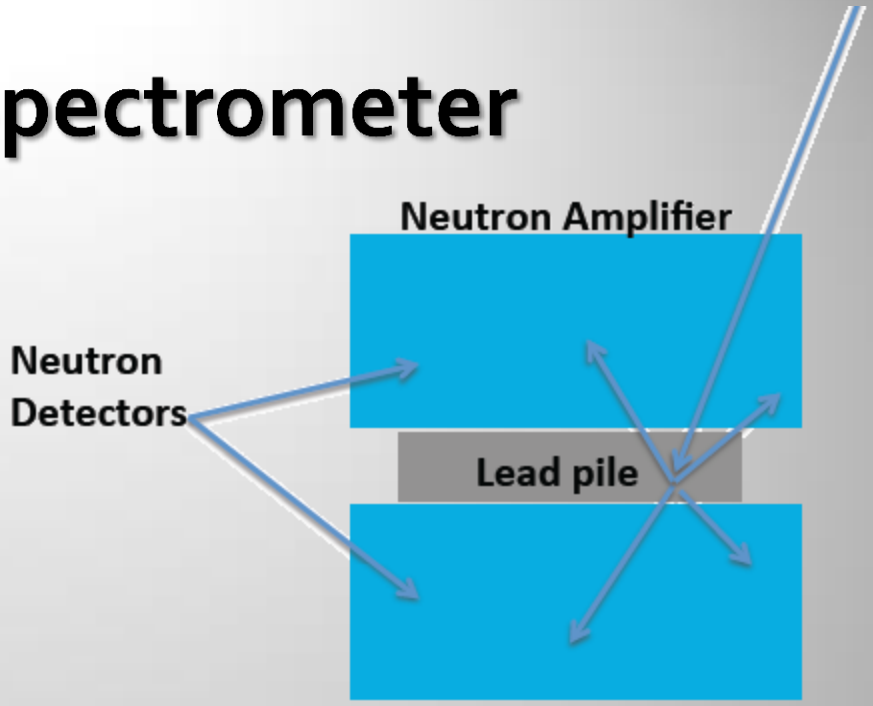
What will we actually measure at shallow depths

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

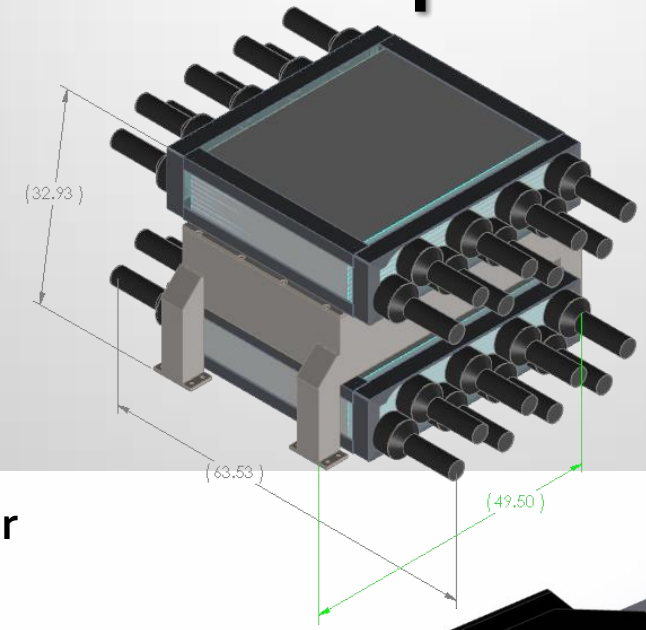


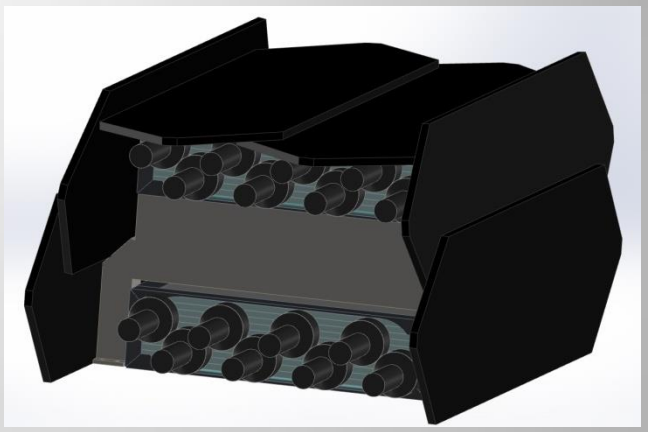


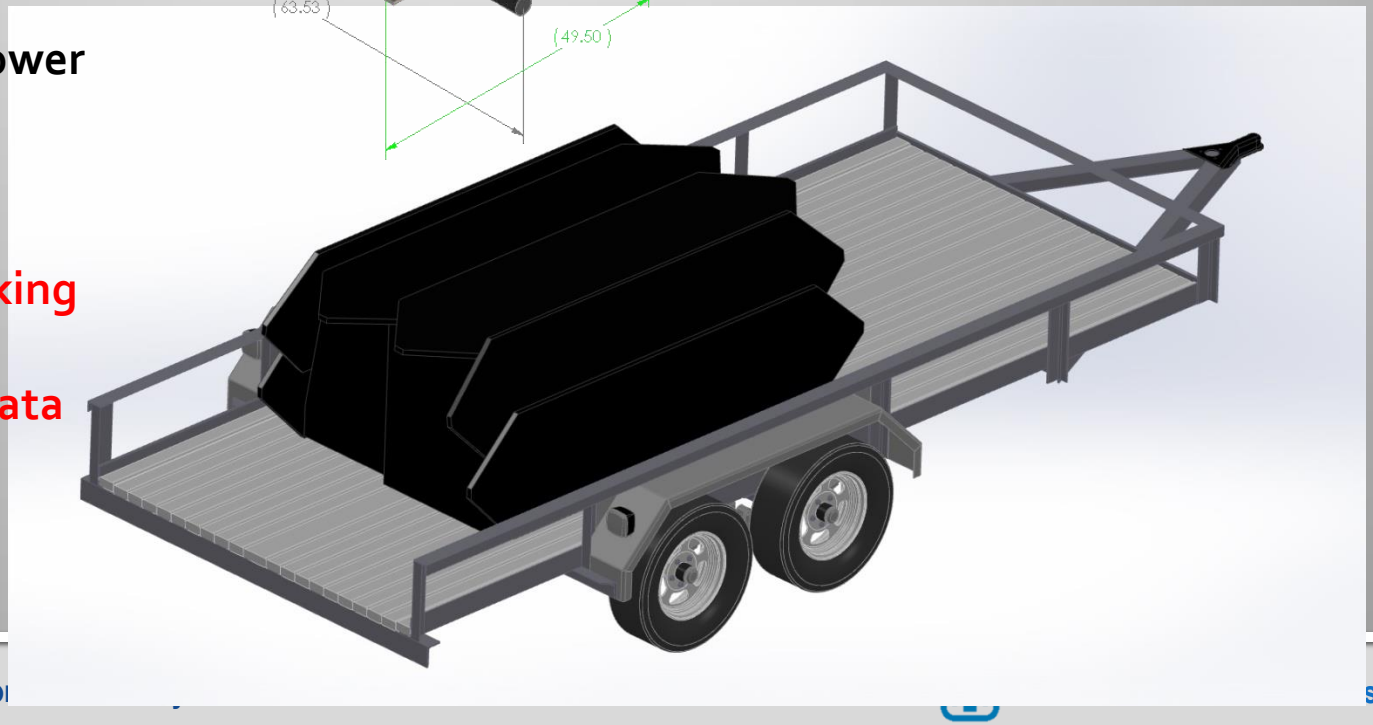
- Plastic scintillator/Gd doped paint detectors sandwich ~4 tons of lead.
- Direct interaction with scintillator for E < ~100 MeV.
- Neutron multiplication off of the lead for E > ~50 MeV.
- Expect 3000-5000 events per month at 100 m.w.e.

Fast Neutron Spectrometer with muon veto on platform

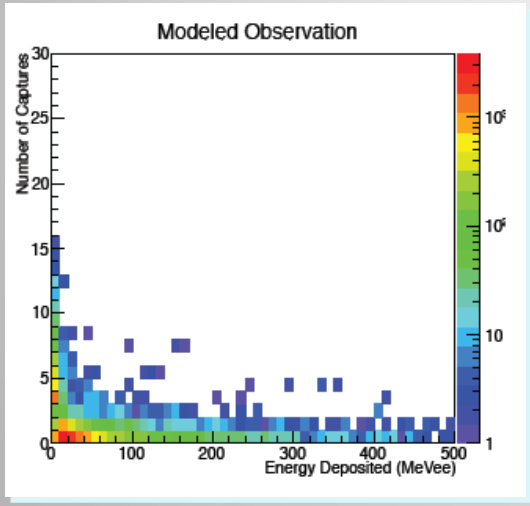
- Detector + muon veto + data acquisition and peripherals are less than 9 tons.
- Platform is a standard trailer outfitted with power and AC.
- Platform now deployed and taking data at Level VI (No pictures or data yet !)



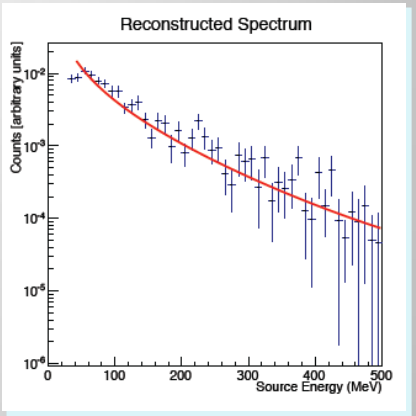




MARS: Expected Data, Reconstructed Spectrum and Rates



Simulation of detector response
trigger on recoil and multiiplicity
trigger logic:
Neutron recoil: > 8.5 MeV
AND
Neutron Gd-capture: >3 events, 1-8.5 MeV
AND
no muon (defined by veto)



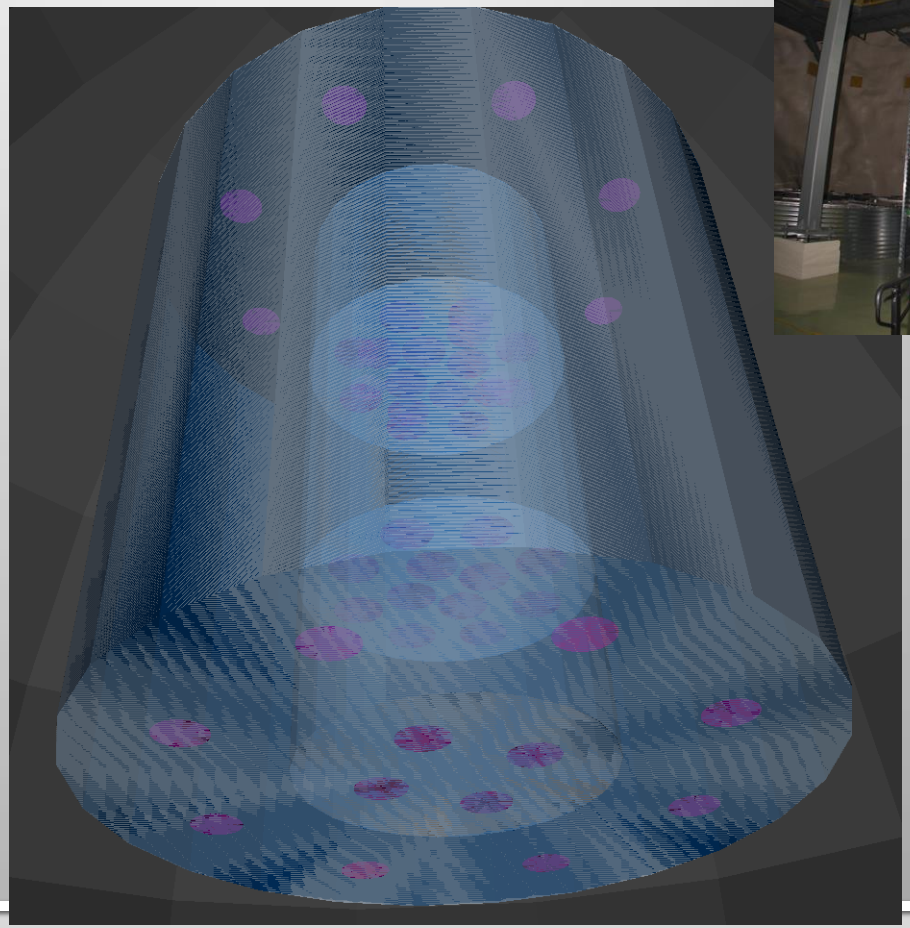
Reconstructed spectrum based on multiplicity and recoil information

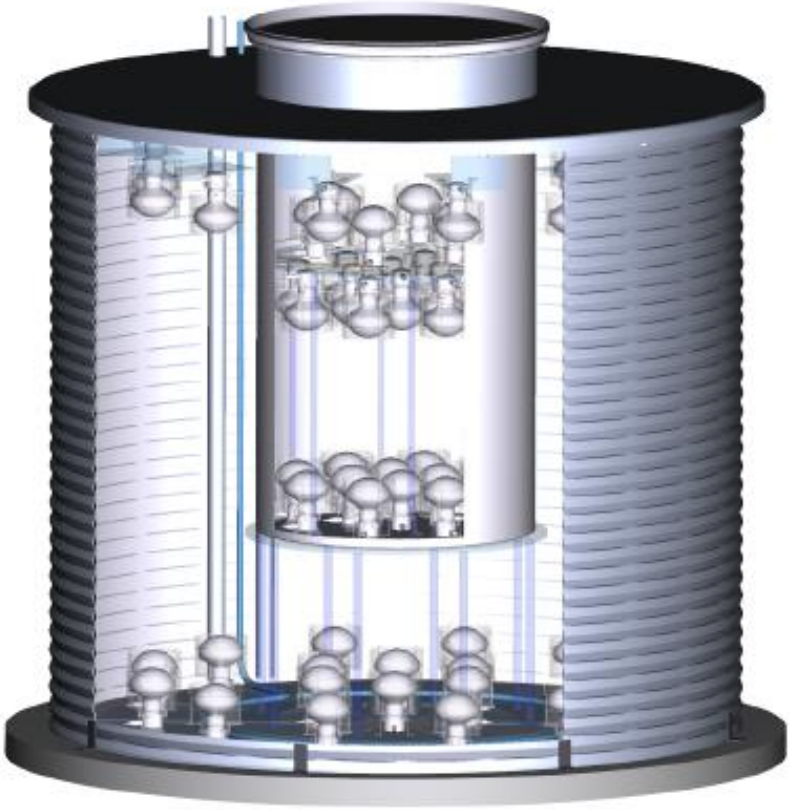
Depth (m.w.e.)	Events in 3 Months
100	18293
200	8303
300	4854
400	3393
500	2473

Integral number of events versus depth

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.





Radionuclide detector installation

Top of detector vessel

Inside the vessel

Assembling the inner detector

Inner detector PMTs installed

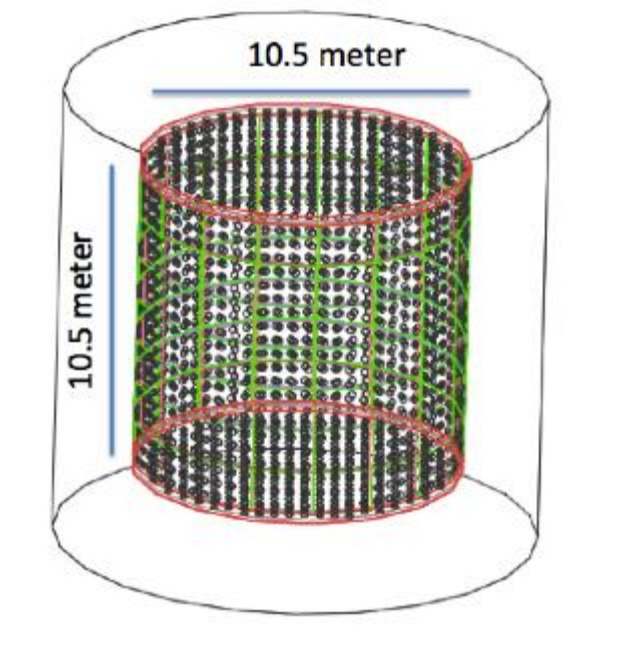
Step 2: Choose a location suitable for nonproliferation demonstration

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

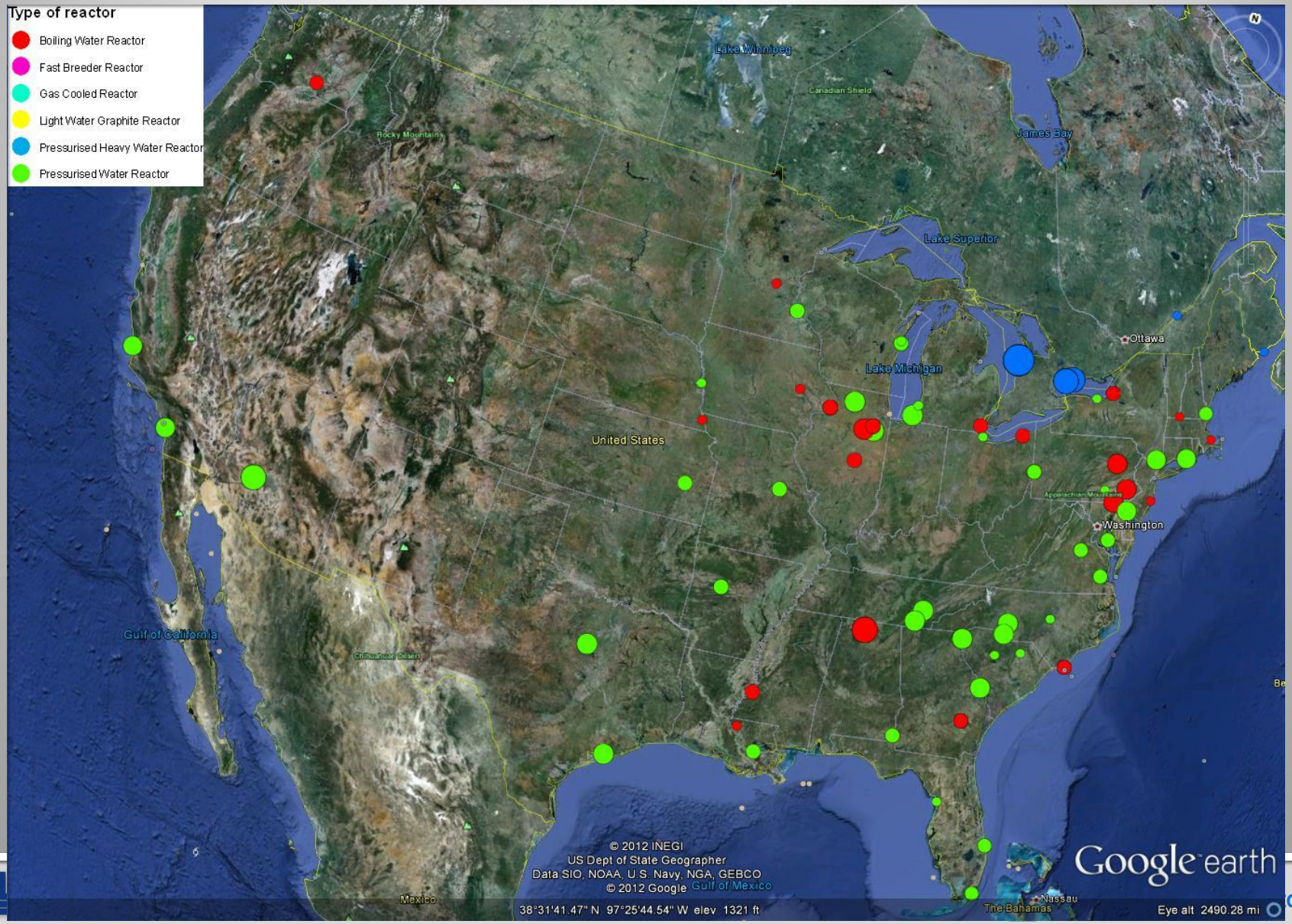
2. **Three sigma detection of the presence of the reactor in <~1 month.**
   - For 1 signal event per day → tolerable background is ~**2** events per day.
   - Greater standoff can be compensated by greater overburden

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

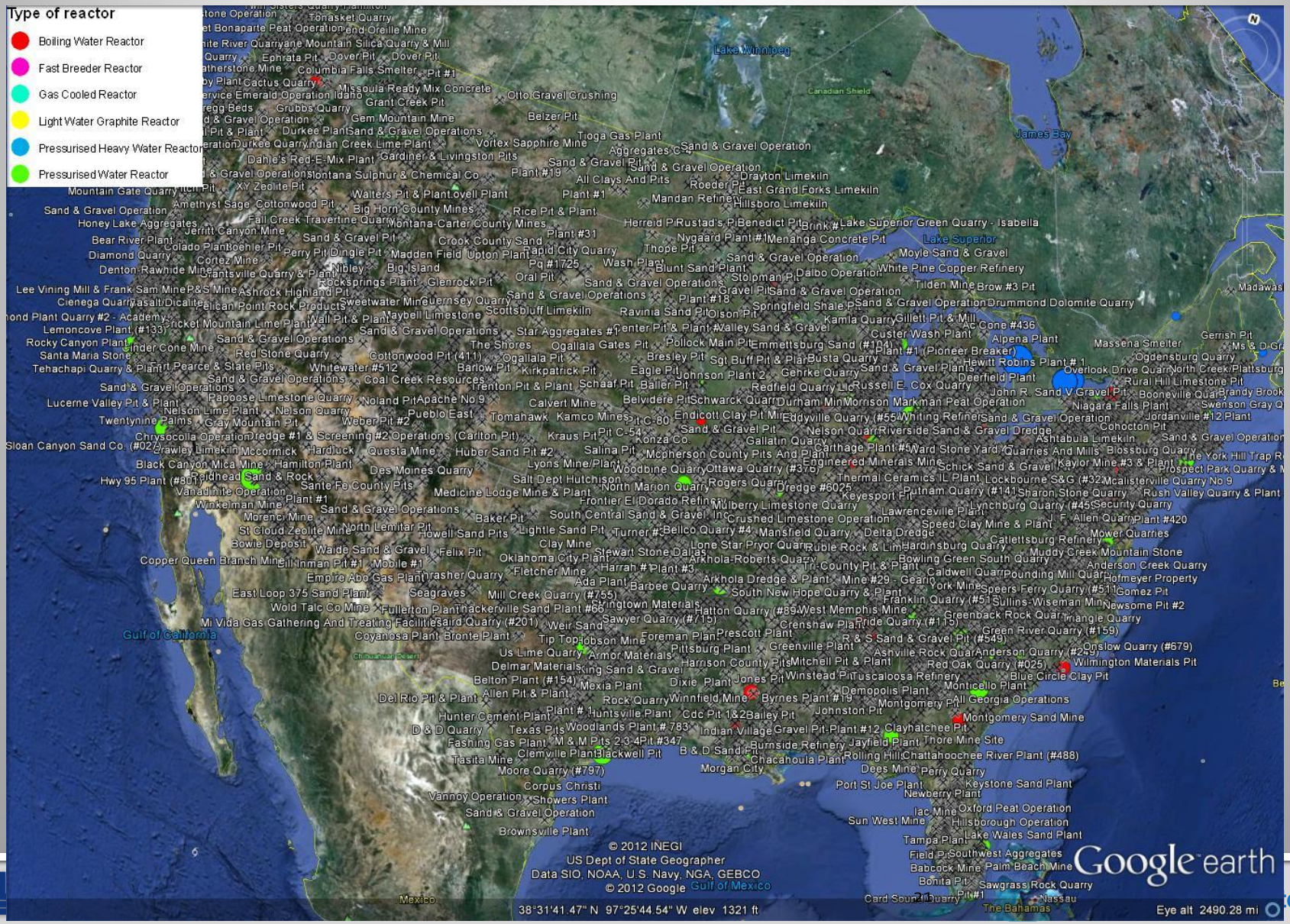
4. **Reactor Power:**
   - A small reactor is preferred, (greater similarity with the ultimate intended use)



Map of US Power Reactors



Map of US Reactors + Active Mines



One US deep site: Perry Nuclear Generating Station

IMB

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

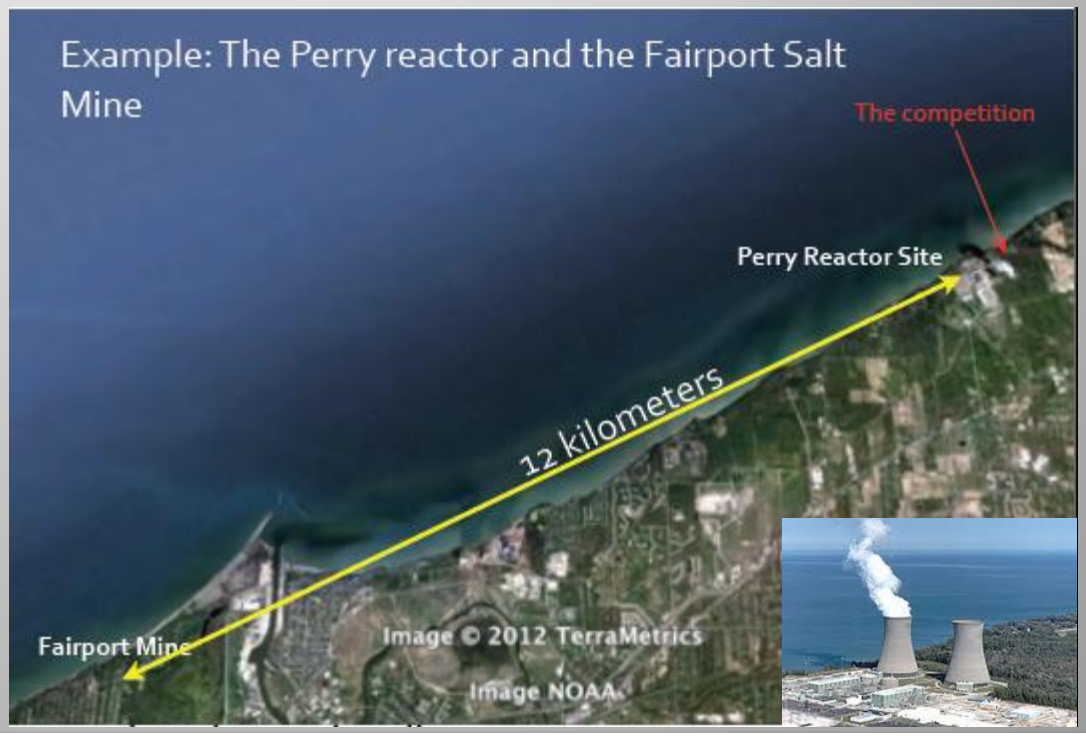
- 1570 m.w.e.
- cavity was 18m x 17m x 22.5m
- ~13 km standoff
- 3875 MWth

Pros

- Existing cavern in active mine (IMB).
- Large depth for low background (more physics overlap).

Cons

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



Shallow sites: Oak Ridge High Flux Isotope Reactor and Idaho Advanced Test Reactor

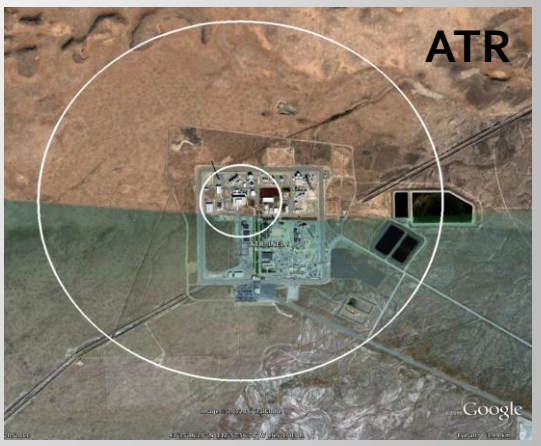
INL – ATR

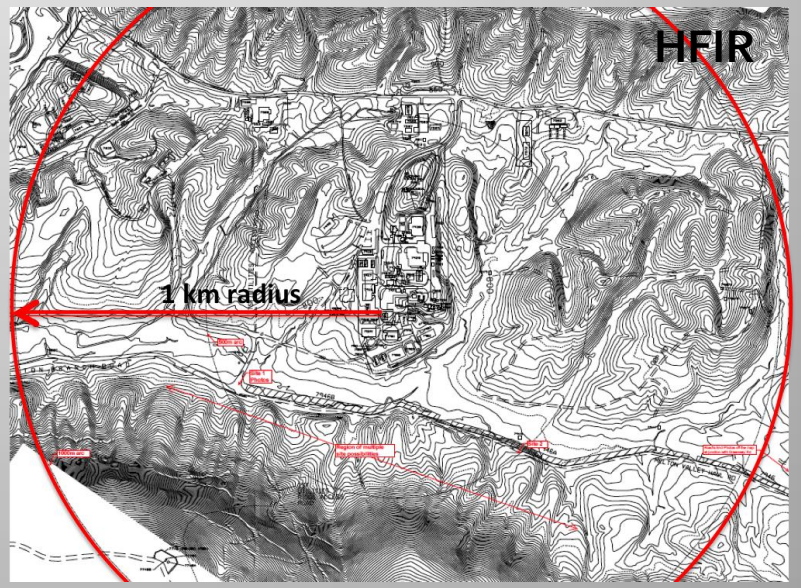
- Very attractive power and duty cycle - ~2:1
- ~150 MW_{th}

ORNL - HFIR

- 50% duty cycle –
- 85 MWth

Both offer highly enriched ^{235}U fission sources





1000 ton det. target mass
S = 13 events per day
B = 164 events per day @100 m
10 days ON and OFF to detect @ 3 sigma

Initial estimate: 10-15 M$ for tunnel/cavern

WATCHMAN as a US Water Testbed

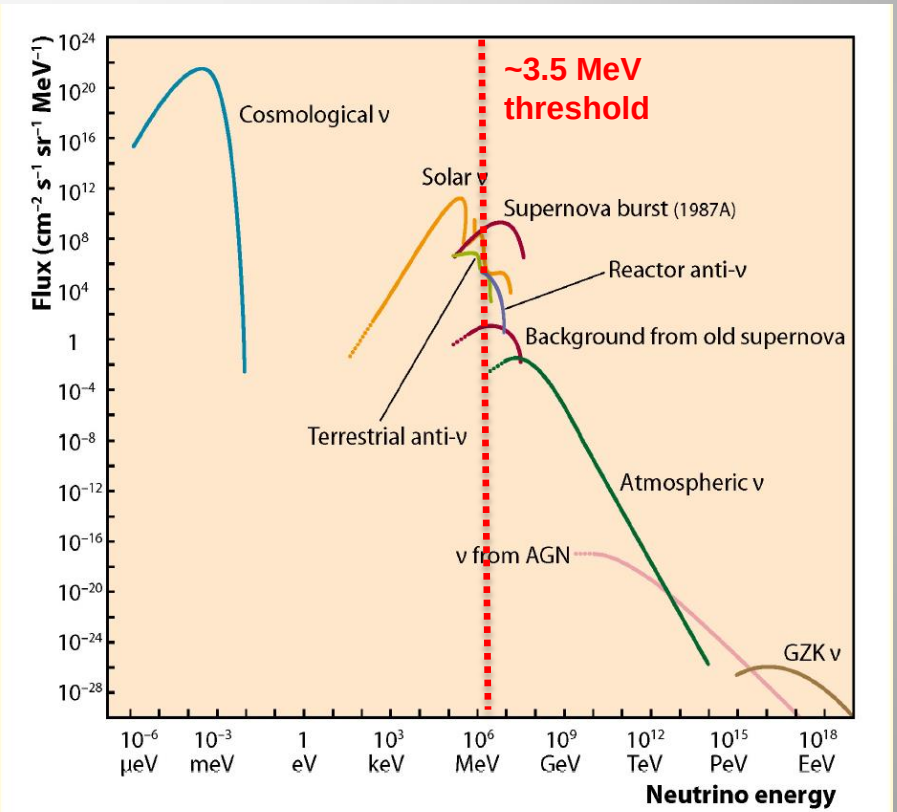
- New PMTs (ADIT, ANL prototypes..)
- WLS plates (CSU, UC Davis)
- Water Based Liquid Scintillator (BNL)
- Gd-recirculation (UC Davis) *

WATCHMAN lets the US water detector community make major contributions to the design and understanding of the next large water detector, wherever it is built … HyperK, LBNE, LAGUNA, etc..

At any depth, WATCHMAN will be one of the world's largest supernova watch detectors

- A kiloton 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.

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



A synoptic view of neutrino fluxes. (from ASPERA roadmap)

Conclusions

- both the nonproliferation and scientific communities are working towards building giant water detectors that are sensitive to low energy antineutrinos
- A kiloton scale Gd-water detector is a logical next step towards these large, low threshold detectors
- Deployment of such a detector at intermediate depths is a cost-effective approach to demonstrating sensitivity to reactor antineutrinos
- The KURF deployments will help us establish the minimum tolerable overburden for such a deployment

Possible Additional Physics at a Deep Site

Boulby Mine in Northern England

Currently this option is beyond scope in NA planning, but the Fairport Salt Mine near the Perry reactor remains a possibility.

Physics reach at Boulby

- Potential for precision θ_{12} measurement (LS or Water-based LS)
- Potentially sensitive to mass hierarchy (if can at 30 km with 5 ktons LS)
- Supernovae sensitivity (water, LS, WbLS) (like other sites)

Nuclear power plants in United Kingdom (**view**)

- Active plants
- *Closed plants*

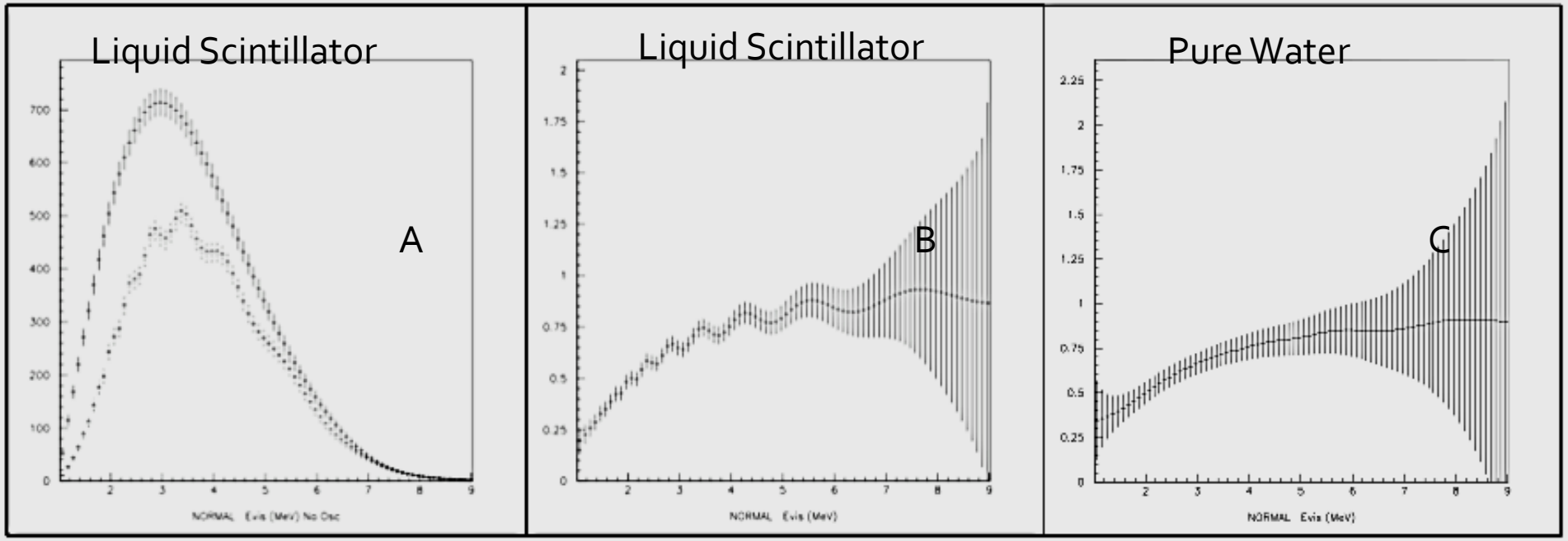
Boulby is fairly isolated

82.2% of antineutrino flux is from Hartlepool (if detector at 25 km distance at Boulby)

11.5% from other British reactors. This Is dominated by Haysham 1&2, which is 148 km distant and accounts for 8.4%.

4.9% from France
1.4% from Belgium, Netherlands, and Germany

Potential for Measurement of θ_{12}



A: E_{vis} spectrum showing effects due to "theta12" oscillations (overall suppression) and theta13 (small wiggles). Resolution is 3%/sqrt(E). Distance is 25 km.
B: Ratio showing low energy suppression due to theta12. Error bars assume 20 kton-yr exposure at Boulby. The theta12 sensitivity comes from the low energy shape.
C: With pure water, this is still there but much less apparent due to 20%/sqrt(E) resolution and Cherenkov threshold.

Studies to determine the exact sensitivity for theta12 are still underway

Nonproliferation, Technical and Scientific objectives are all met by WATCHMAN

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

Kiloton detector:

- Core-collapse supernovae in this galaxy

100 kiloton- 1 Megaton

- 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

DOE Office of Science High Energy Physics Strategic Planning

- For the first time, Neutrinos and Nonproliferation are two explicit elements in the HEP Long Range Strategic Planning Process –
- Bernstein chair of the relevant subgroups
- 5 whitepapers on
  - Coherent scatter
  - Spectral measurements for SBL and for fissile inventory estimates
  - **WATCHMAN for LBL and reactor exclusion prototype demonstrations and for supernovae search**
- NNSA-NA Office plan/goal is to seek FY15 funding for this project

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

ecember

AAP2006 WORKSHOP SEPT 24-26 LIVERMORE, CA

AAP 2007

The meeting will be dedicated to discuss applications of antineutrino detection in the field of non proliferation, geophysics and other applied areas.

AAP-2009
V Applied Antineutrino Physics Workshop

The 6th International Workshop on Applied Anti-Neutrino Physics

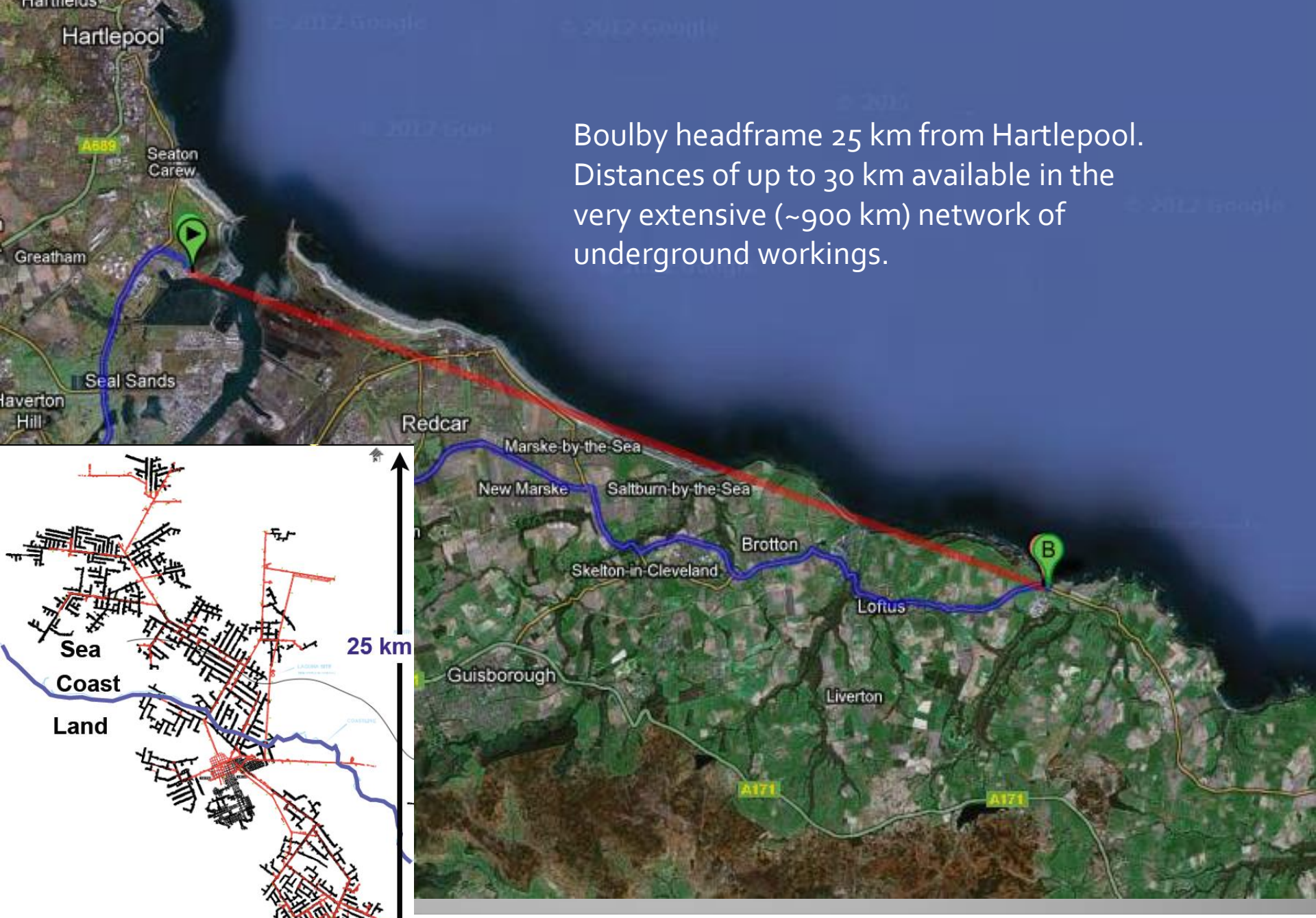
AAP 2010
仙台 SENDAI

Advantages of antineutrino detection for remote discovery and monitoring of reactors

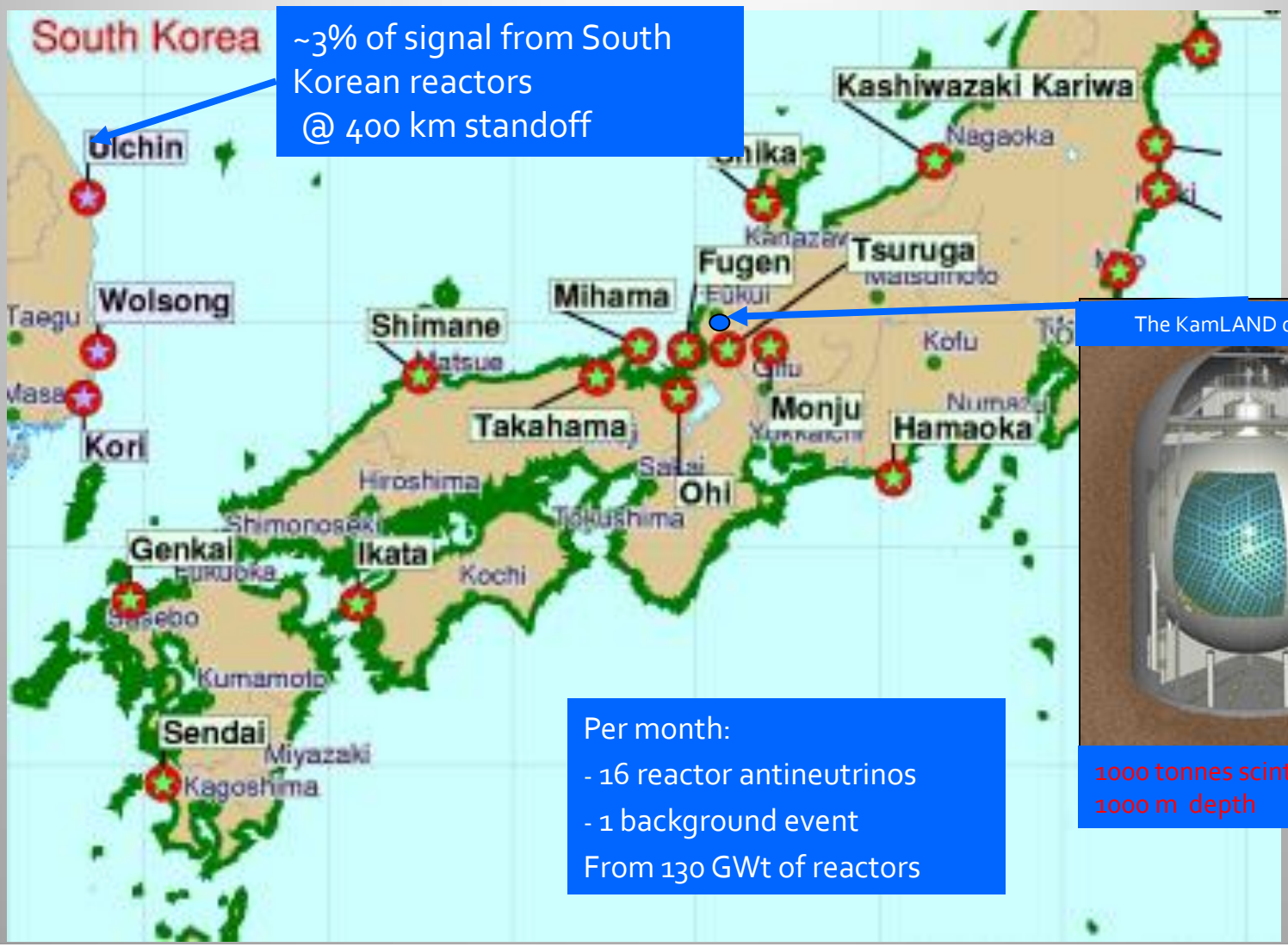
1. Cross border detection – ultimate limit is perhaps ~800 km
2. Continuous surveillance
3. Constraints on power and plutonium production rate
4. With long range capability, no cueing information required
5. Eventually: Reactor localization with improved directionality or spectral measurement

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

Boulby headframe 25 km from Hartlepool. Distances of up to 30 km available in the very extensive (~900 km) network of underground workings.



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

The KamLAND detector

1000 tonnes scintillator
1000 m depth

Per month:
- 16 reactor antineutrinos
- 1 background event

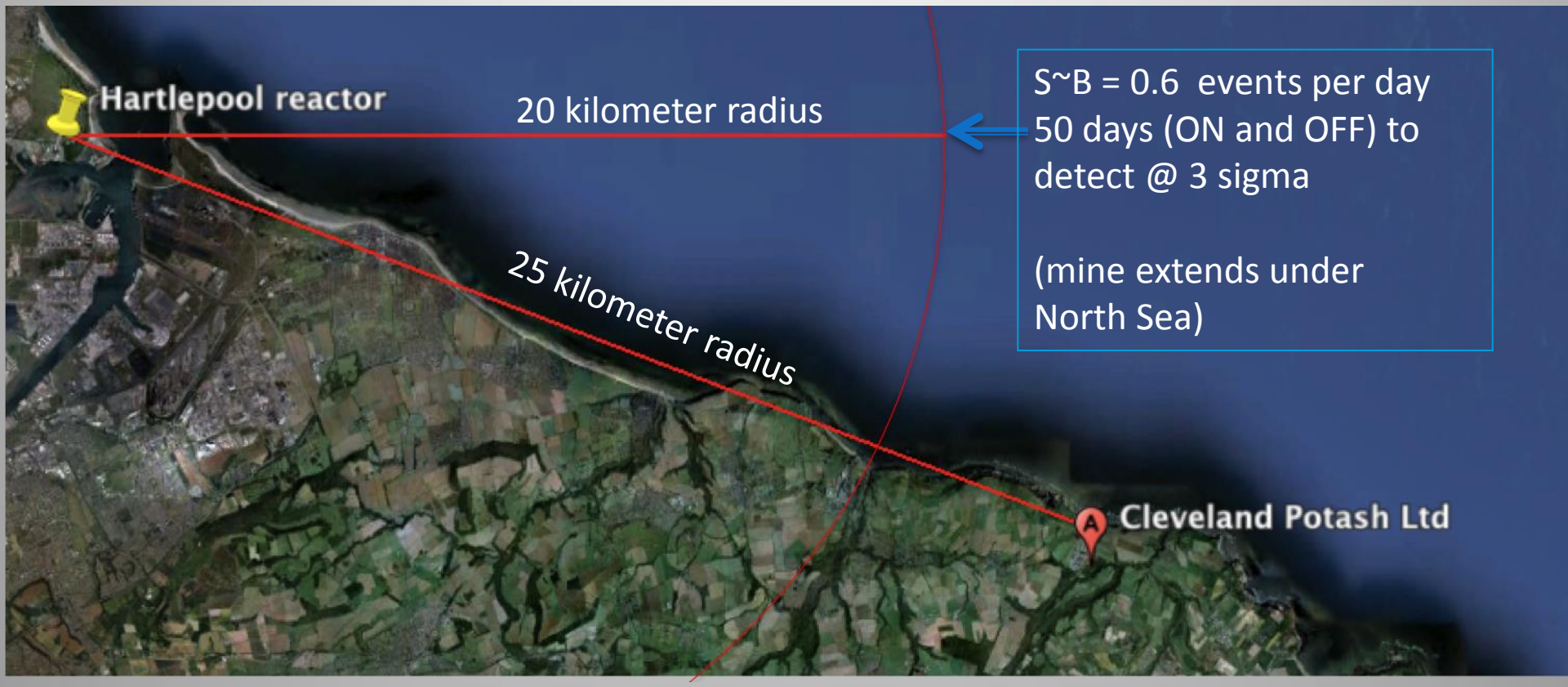
From 130 GWt of reactors

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 deep site: the Boulby mine, 1000 meter depth

- 1000 ton detector target mass, 2.5 m water shield
- Power = 1570 MWth (2 cores)

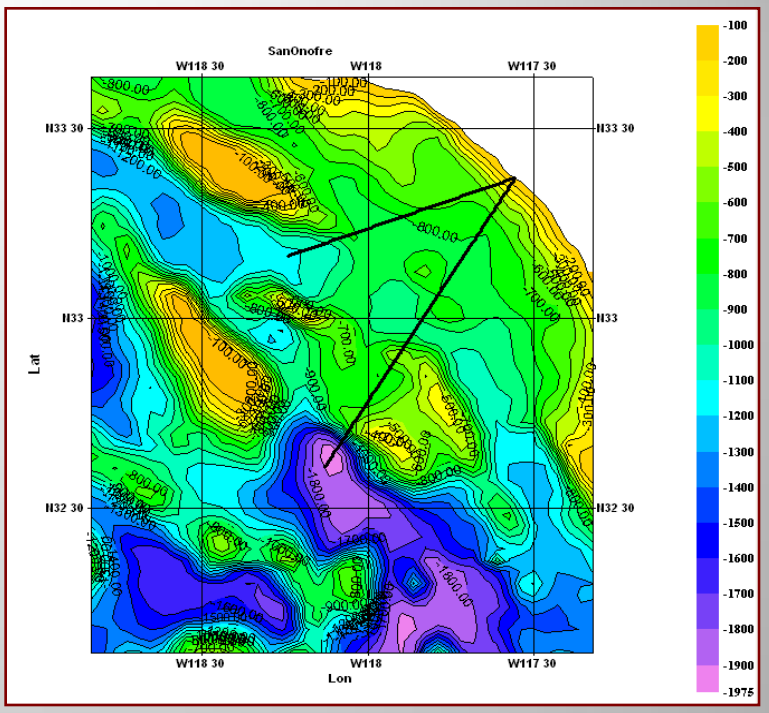


S~B = 0.6 events per day
50 days (ON and OFF) to detect @ 3 sigma

(mine extends under North Sea)

Other Options – Ocean deployment off SONGS

- Under water options (Hanohano type deployment) near reactors off California.
- San Onofre Nuclear Generating Station (SONGS) - two 3.4 GWth reactors.
- Mobile detector may offer benefits.



Ocean bottom topography off SONGS (~700 mwe at ~12 km is possible)

Hanohano