The Water Cherenkov Monitor for Anti-Neutrinos (WATCHMAN) at the Advanced Instrumentation Testbed

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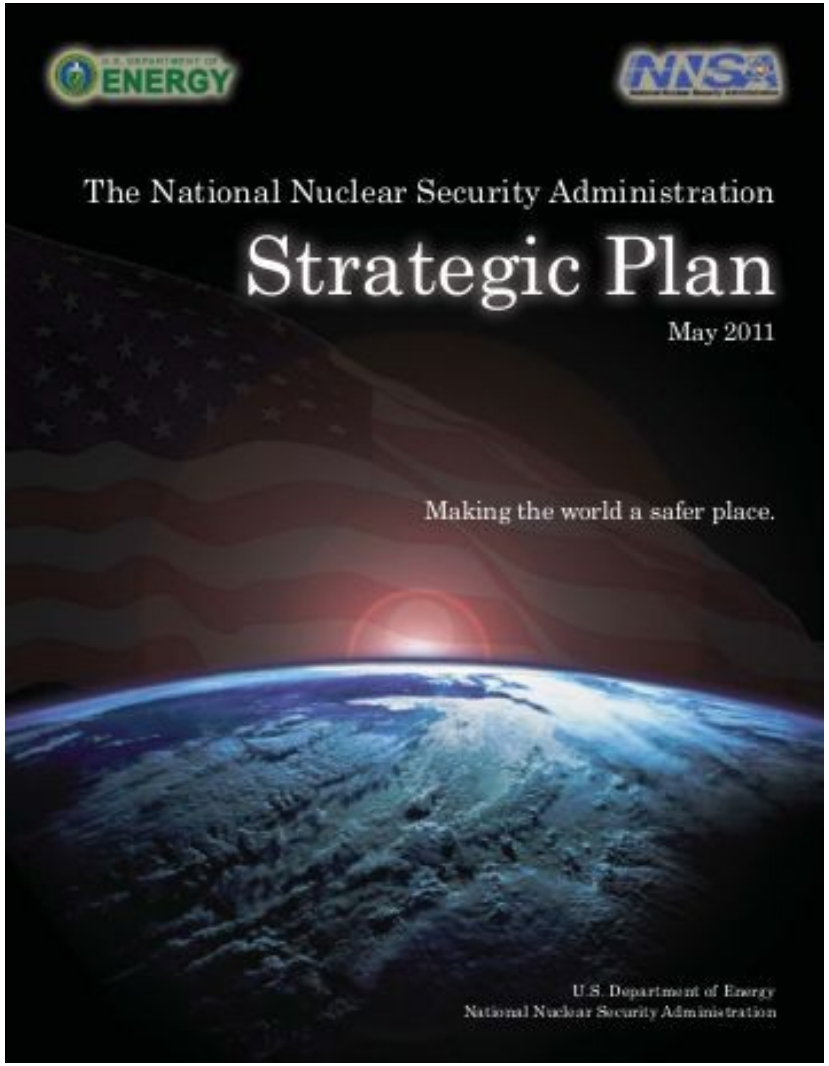
(on behalf of the WATCHMAN Collaboration)

IOP HEPP + APP Annual Meeting
09 Apr 2019

The WATCHMAN Charge



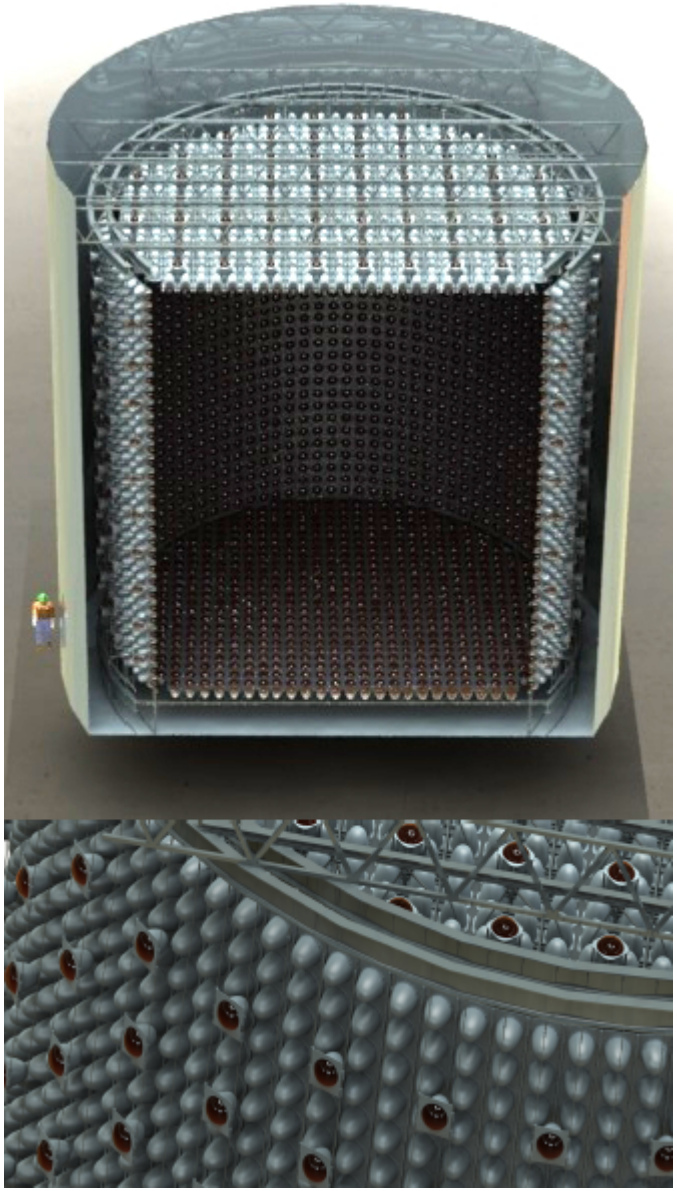
We have been charged by the primary sponsor (US NNSA) with the goal:

Verify, to 3σ confidence, the presence of a nuclear reactor (if one exists) within 30 days.

Assuming a reactor signal of ~10 events per day, this requires reducing backgrounds to ~330 events per day.

→ Applied anti-neutrino physics not pure science!

What is WATCHMAN?



Objectives:

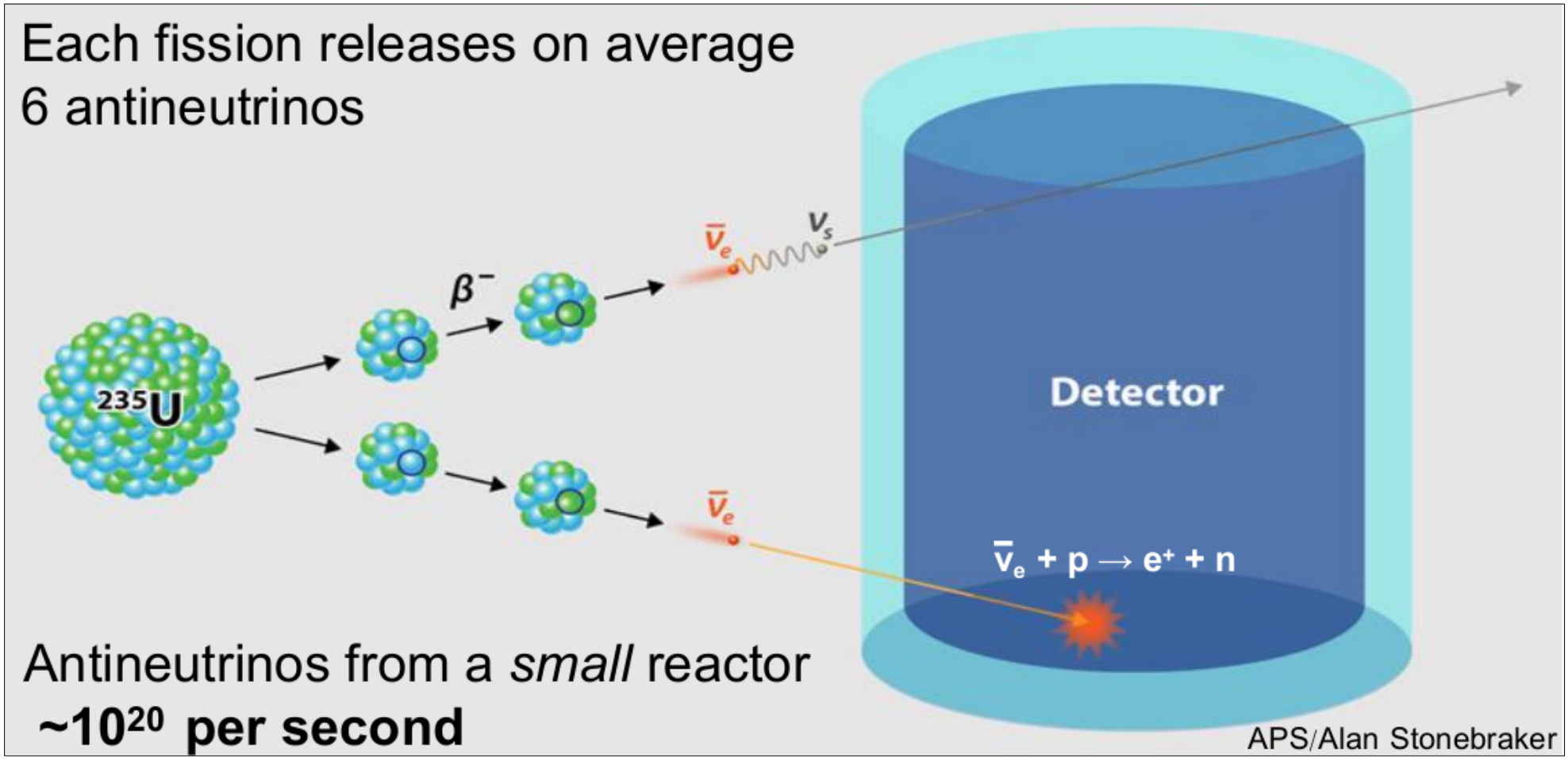
Remote monitoring of small fission reactors (~40 MWth) via detection of antineutrino emissions.

Initial project goal is to observe reactor on/off states at approximately 10 – 30 km distance from reactor.

Prototype Design Features:

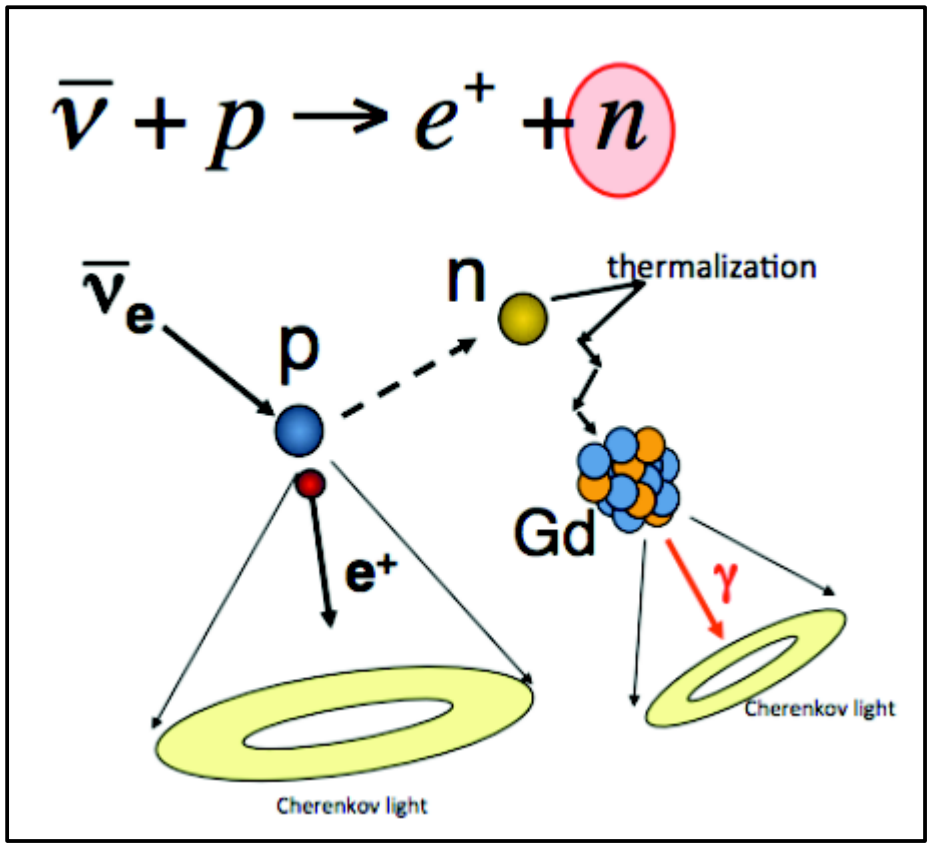
- Medium scale (~1 ktonne fiducial mass) water-based **gadolinium-loaded** anti-neutrino detector
- Initial prototype to demonstrate monitoring of a single known reactor site
- Rationale is to develop a detector design that can be scaled to larger masses for smaller reactors and larger standoff distances

What is WATCHMAN?



Anti-Neutrino Detection via Gd

Basic idea:
Tag antineutrinos via coincidence between positron and neutron from inverse beta decay:



- In ordinary water:

  Neutron thermalizes, then is captured on a free proton

  - Capture time is ~200 μsec
  - 2.2 MeV gamma emitted
  - Detection efficiency @ SK (40% coverage) is ~20%

- When n captured on Gd:
  - Capture time ~30 μsec
  - ~8 MeV gamma cascade
  - 4 - 5 MeV visible energy
  - > 70% detection efficiency

Gd Capture X-Sections

The University Of Sheffield.

Thermal Capture Cross Sections: A Comparison of ENDF/B-VI to RPI Results*

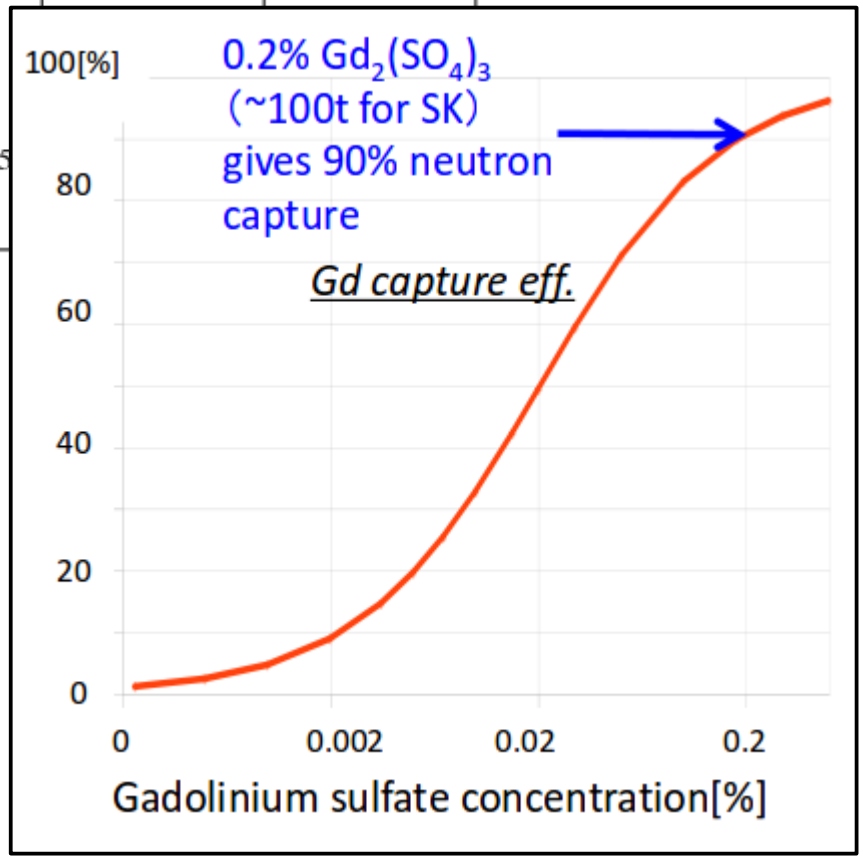
Thermal Capture Cross Sections							
		ENDF			RPI		
Isotope	Abundance	Thermal Capture	Contribution to Elemental	Percent	Thermal Capture	Contribution to Elemental	Percent
^{152}Gd	0.200	1 050	2.10	0.00430	1 050	2.10	0.00430
^{154}Gd	2.18	85.0	1.85	0.00379	85.8	1.87	0.00422
^{155}Gd	14.80	60 700	8 980	18.4	60 200		
^{156}Gd	20.47	1.71	0.350	0.000717	1.74		
^{157}Gd	15.65	254 000	39 800	81.6	226 000		
^{158}Gd	24.84	2.01	0.499	0.00102	2.19		
^{160}Gd	21.86	0.765	0.167	0.000342	0.755		
Gd	—		48 800	100.0			

*The units of all cross sections are barns. The units of abundance are percent.

G. Leinweber *et al*., Nucl.Sci.Eng. **154:261** (2006)

Cross-section for neutron capture is:
- ~49,000 barns for natural Gd
- 0.3 barns for H

0.1% Gd concentration results in ~90% of neutrons capturing on Gd



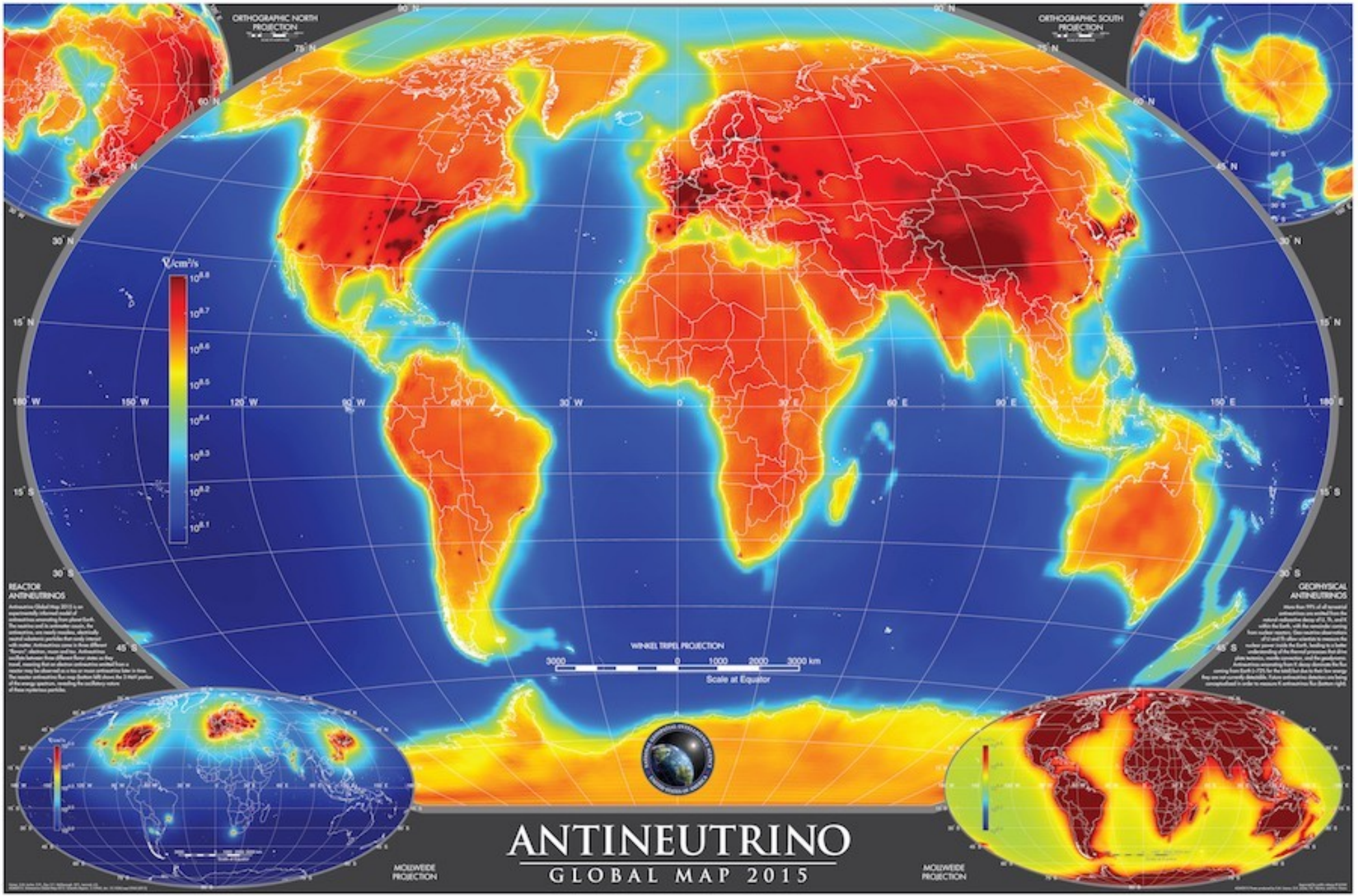
Advanced Instrumentation Testbed

The WATCHMAN prototype site requires:

(a) an underground laboratory (or potential to build one) that is within ~30 km of

(b) a nuclear reactor

The World In Anti-Neutrinos



(see geoneutrinos.org for more)

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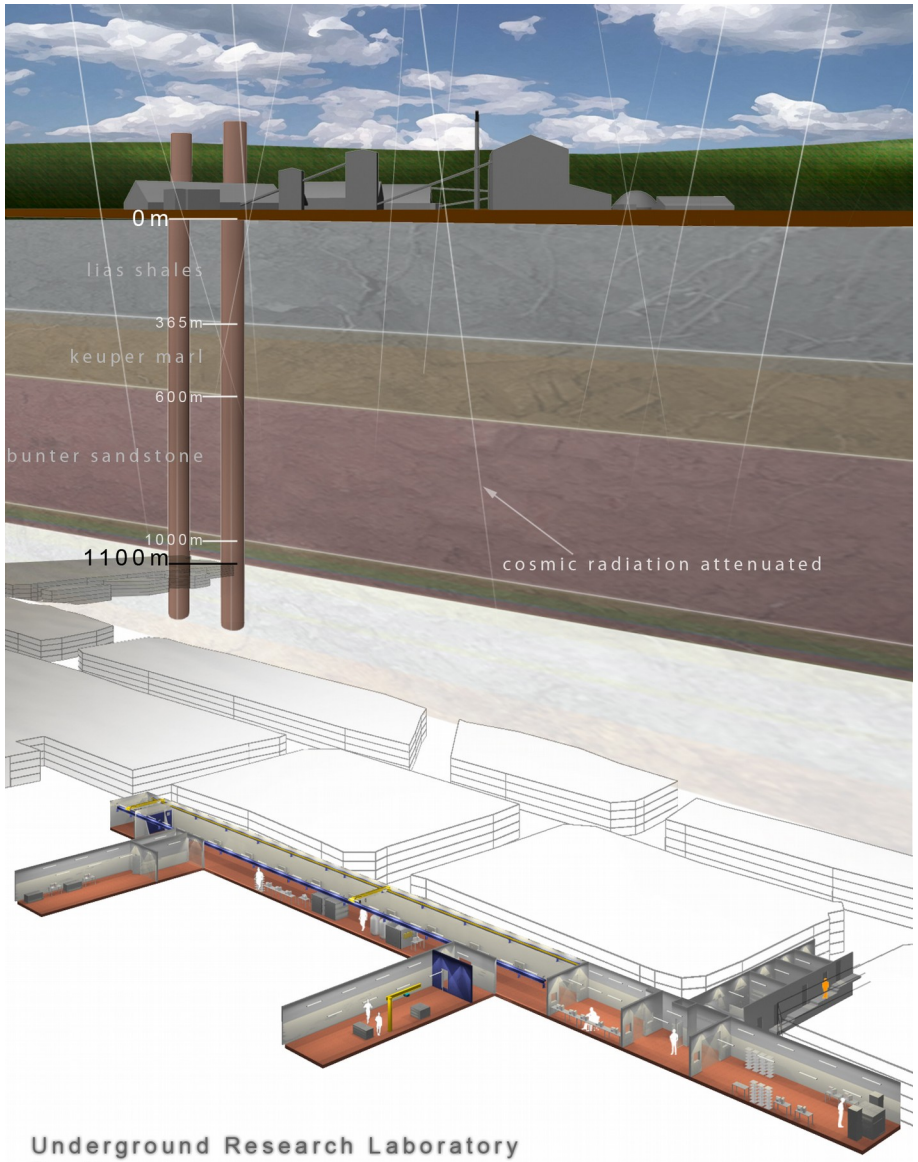
2017:
STFC Boulby Underground Laboratory chosen as site!

Boulby Underground Laboratory



Depth:

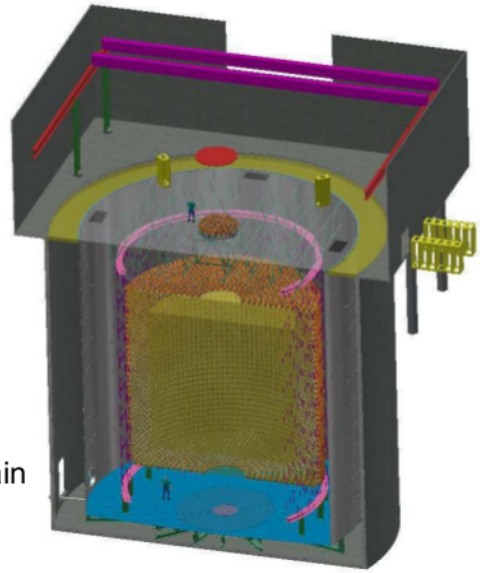
1100 metres underground

2800 metres water equivalent

10^{-6} cosmic ray muon attenuation

Operating lab for > 20 years

Current lab from 2017



JG Boissevain Design

New cavern needed to accommodate AIT-WATCHMAN (~25m ϕ x ~25m h)

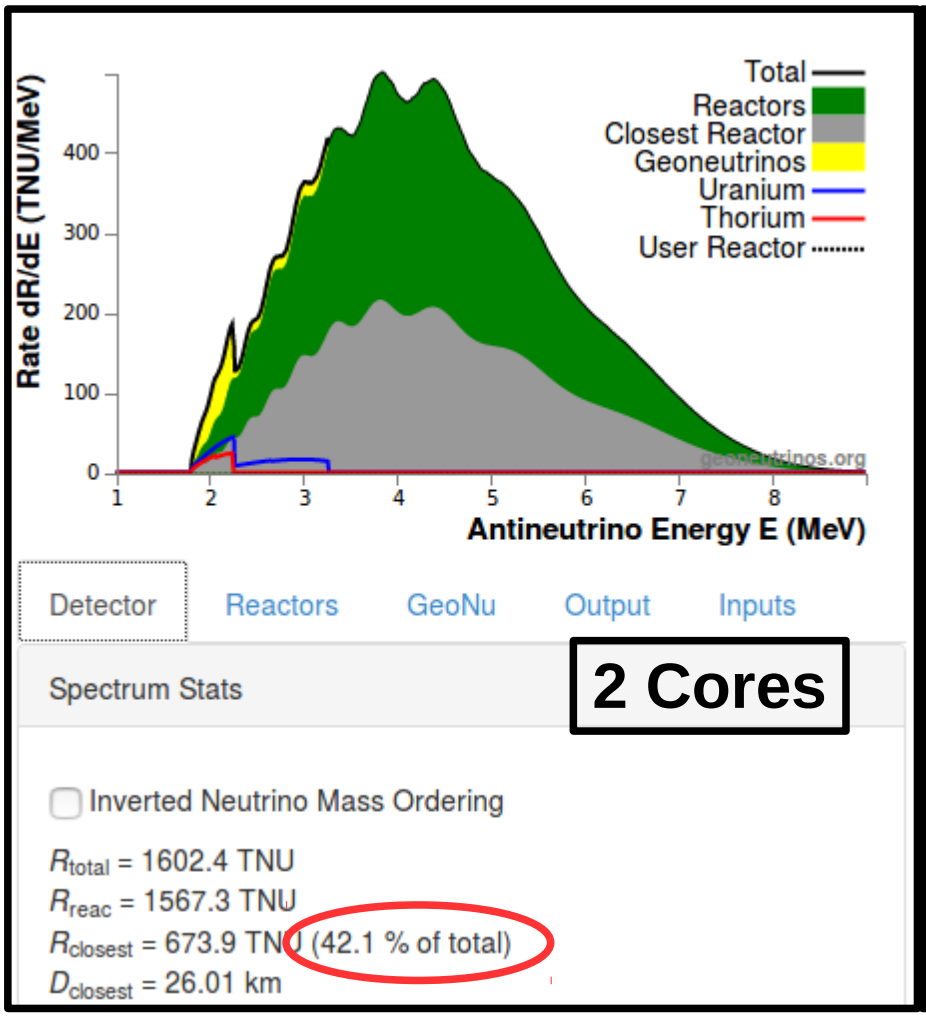
Hartlepool Nuclear Reactors

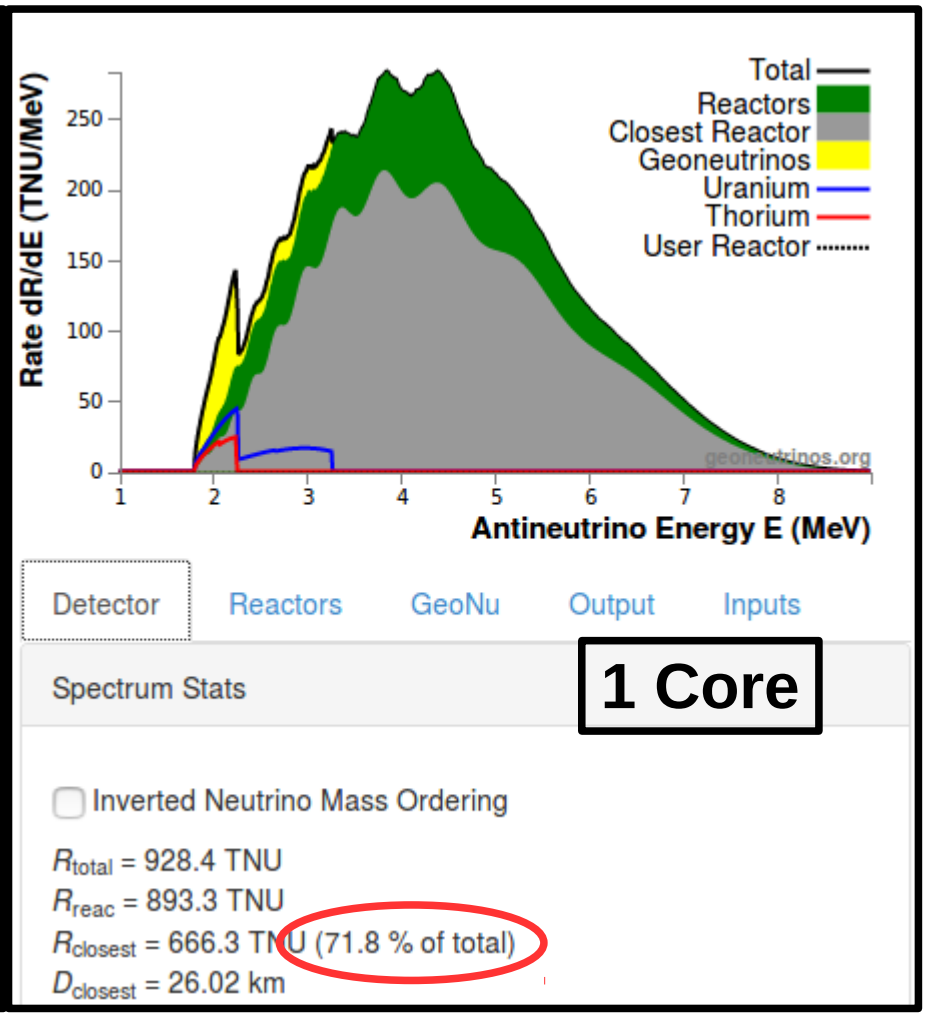
Dual-core reactor complex
Advanced gas-cooled reactors (AGR)
1550 MW_{th} per reactor core
~25 km standoff from Boulby Lab

Can look for flux difference between 1-core & 2-core operation
Potential for future complementary work with near-field detection

WATCHMAN fluxes

The University Of Sheffield.





Thanks to Antineutrino Global Map project, there is now an online tool to get such reactor fluxes (and natural backgrounds)!

(For more detail, see S.Dye's preprint at **nucl-ex:1611.01575**)

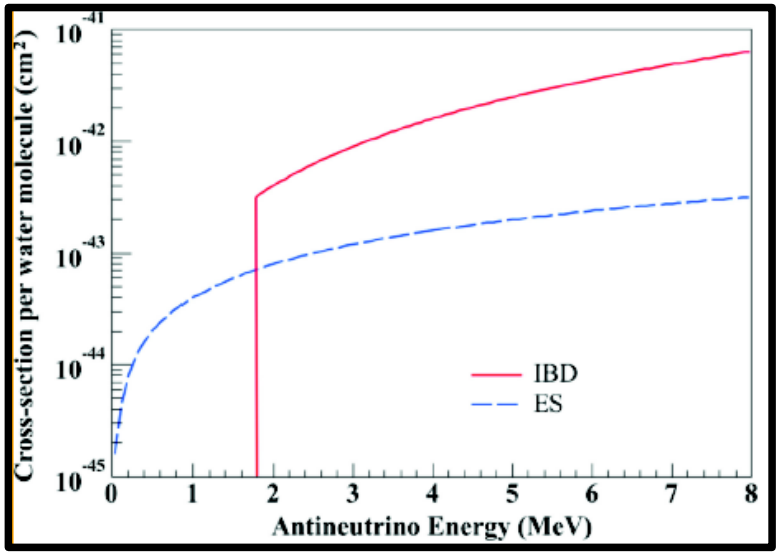
Stretch Goals: Directionality

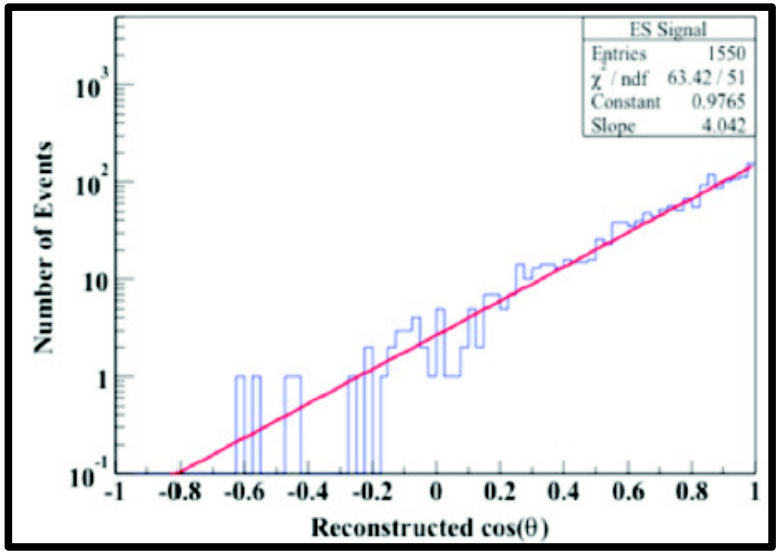
Other possibilities exist for expanding on the WATCHMAN concept, like using the elastic scattering events for directionality.

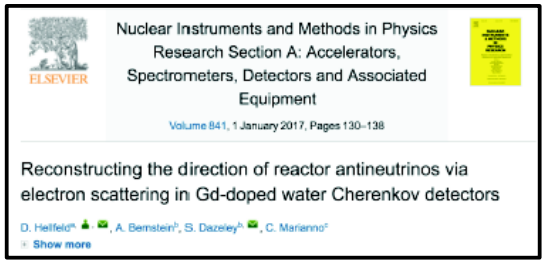
Benefits:

– Ability to distinguish sources when multiple reactors are present
– Ability to locate a clandestine reactor that has been found

Directionality enhances the potential of WATCHMAN, but is not necessary for the original charge.






Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment

Volume 841, 1 January 2017, Pages 130–138

Reconstructing the direction of reactor antineutrinos via electron scattering in Gd-doped water Cherenkov detectors

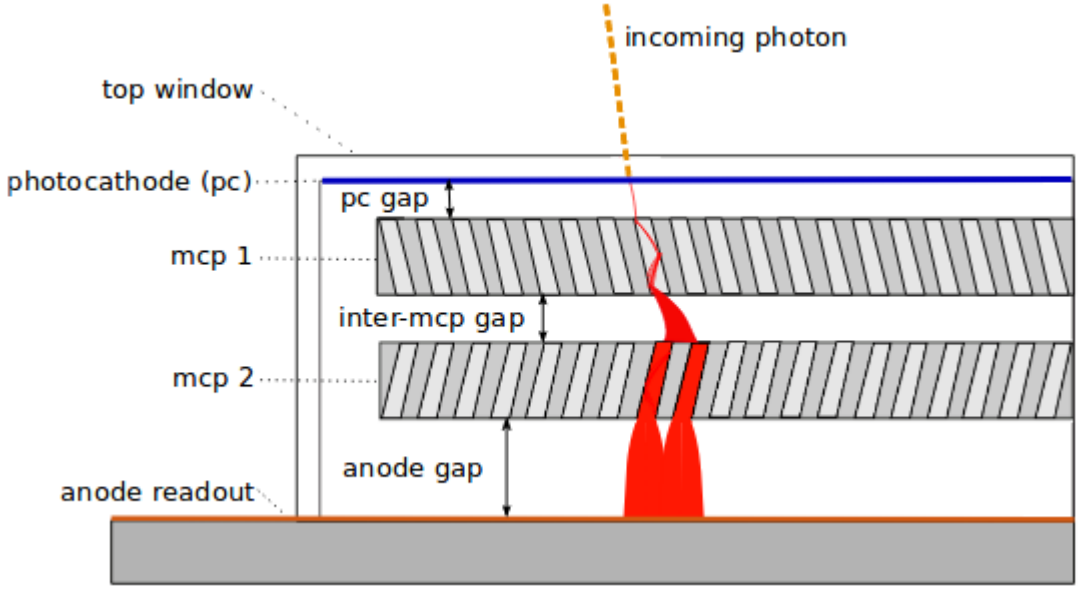
D. Helfeld, A. Bernstein, S. Dazeley, C. Marianno

Show more

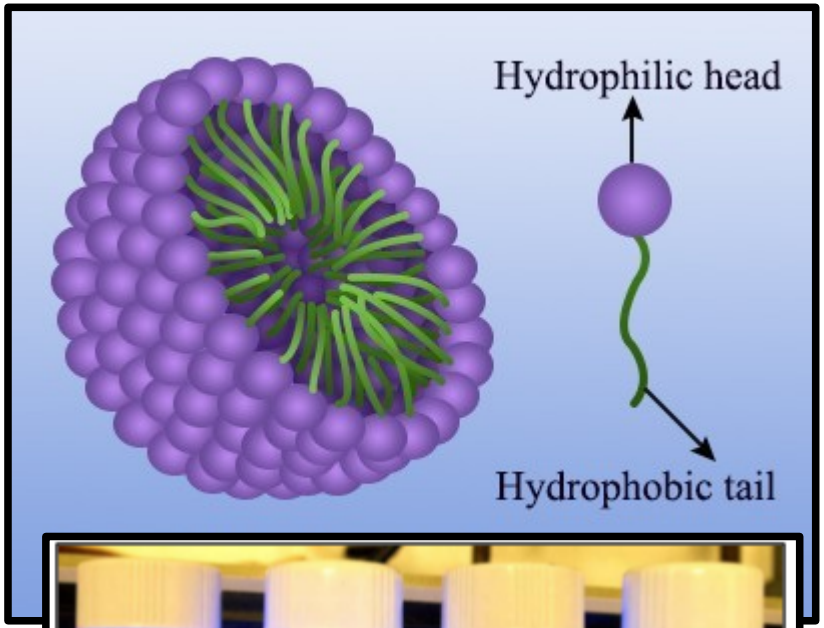
Future Technologies

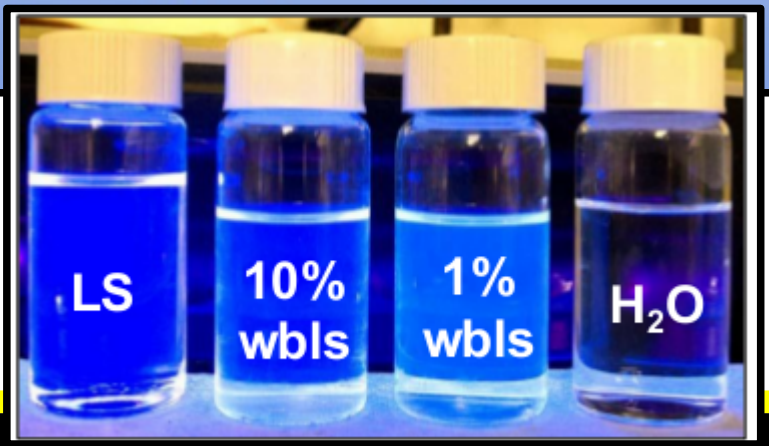
WATCHMAN is the 1st phase of the Advanced Instrumentation Testbed. AIT is also engaged with R&D for enhanced detection technologies:

Large Area Picosecond Photo-Detectors (LAPPDs):



Water-based Liquid Scintillator (WbLS):

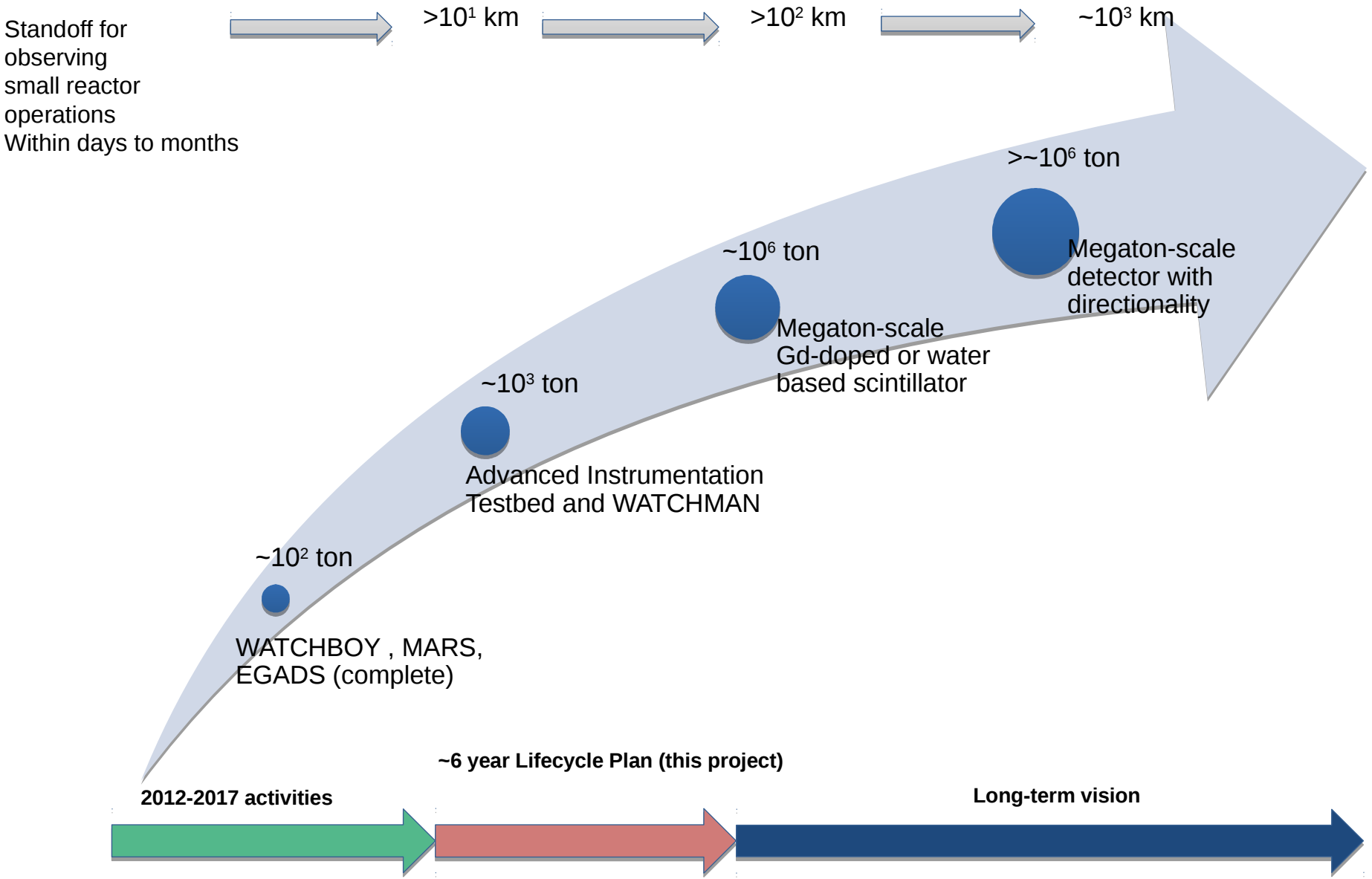




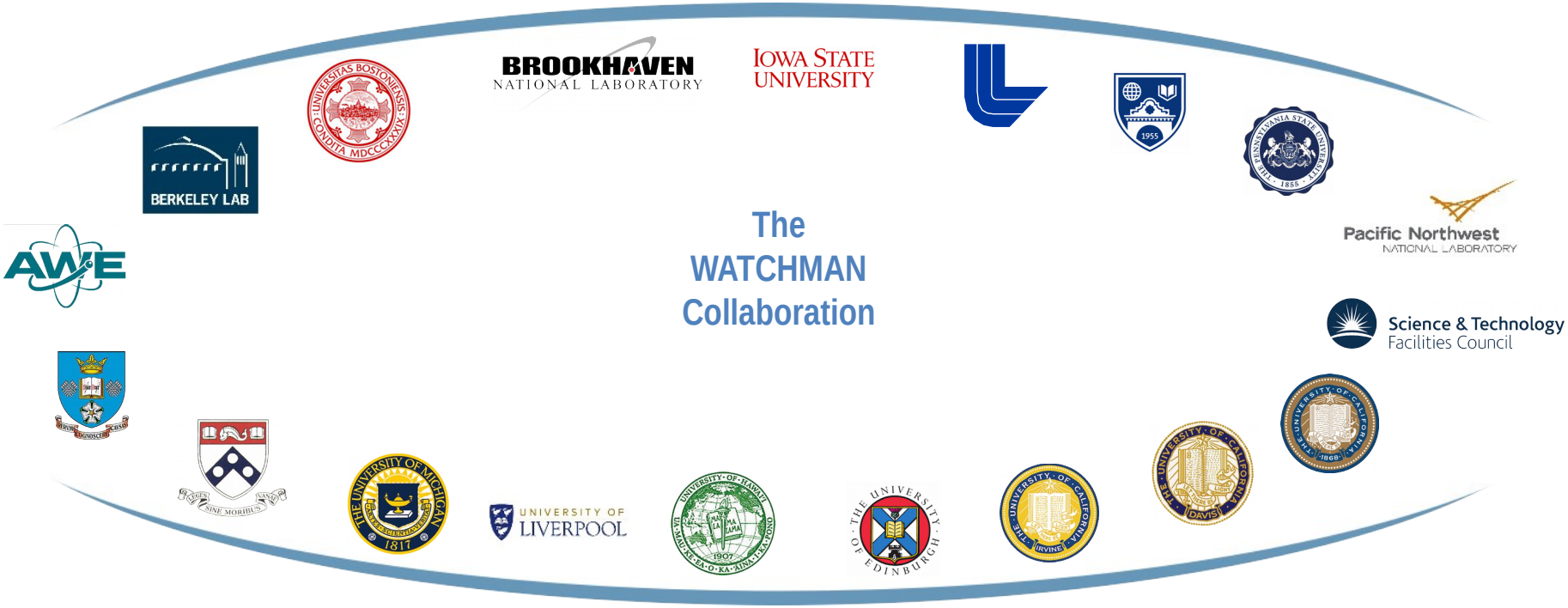
Future goals include enhancing capacity for **non-proliferation** as well as science goals like: **geoneutrinos**, **CNO solar ν**, **neutrinoless double-beta decay (0νββ)**

AIT-WATCHMAN Plan

The University Of Sheffield.



The WATCHMAN Collaboration



By the numbers:

- 2 countries (US & UK)
- 21 universities
- 3 US laboratories
- 2 UK laboratories
- ~90 total collaborators

UK participation:

- 3 universities (so far):
  Sheffield, Edinburgh, Liverpool
- STFC-Boulby Underground Lab
- Atomic Weapons Establishment
- ~30 total collaborators
- £9.7M funding from STFC
  (via UKRI Fund for International Collab.)
- £1M funding from Ministry of Defence

Thank you for listening!