Monitoring nuclear reactor (anti-)neutrinos with AIT-WATCHMAN

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On behalf of the AIT-WATCHMAN collaboration

NuSec Nuclear Security Science Network

The University Of Sheffield.

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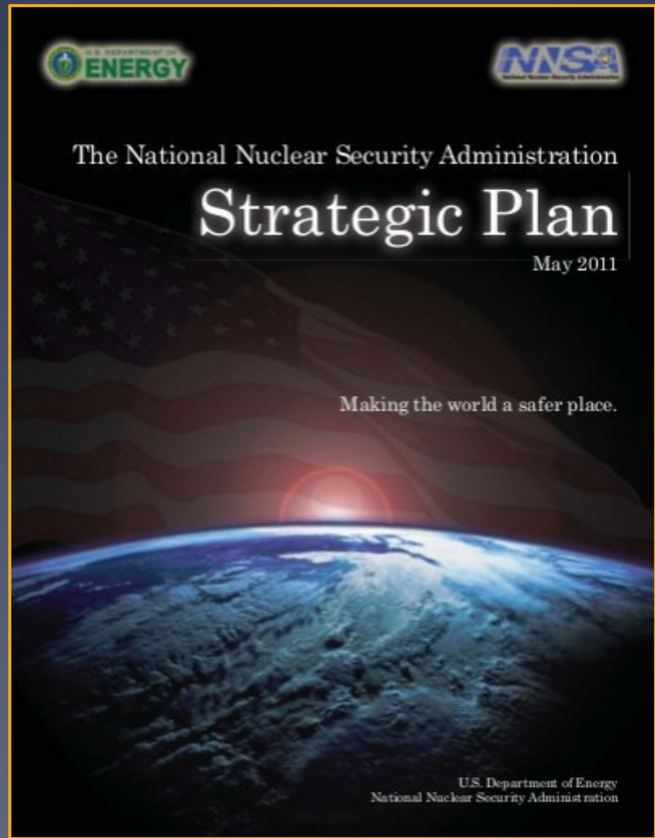
What is AIT-WATCHMAN?

- Non-proliferation remote monitoring demonstrator of a single reactor site
- Specifically: "**To verify, to 3 sigma confidence, the presence of a nuclear reactor (if one exists) within 30 days**"
- A 1kTon scale Gd-loaded water-based anti-neutrino detector for the remote monitoring of small fission reactors
- Project goal is to observe reactor on/off at ~30 km standoff from the reactor
- Rationale is to develop a medium sized detector that can be scaled to MTon masses – required for smaller reactors and/or larger standoff distances
- AIT = **A**dvanced **I**nstrumentation **T**estbed
- Physics goals include directional supernova detection, geoneutrinos, solar neutrinos, etc.
- Also provides an R&D test bench for future technologies (WbLS, LAPPDs …)

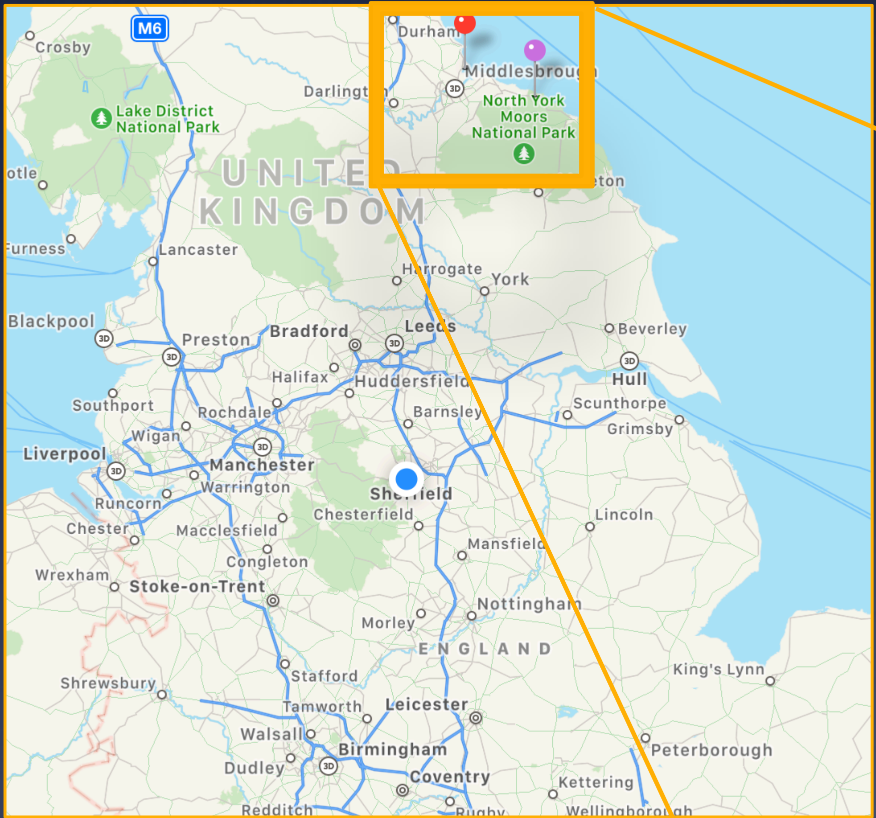


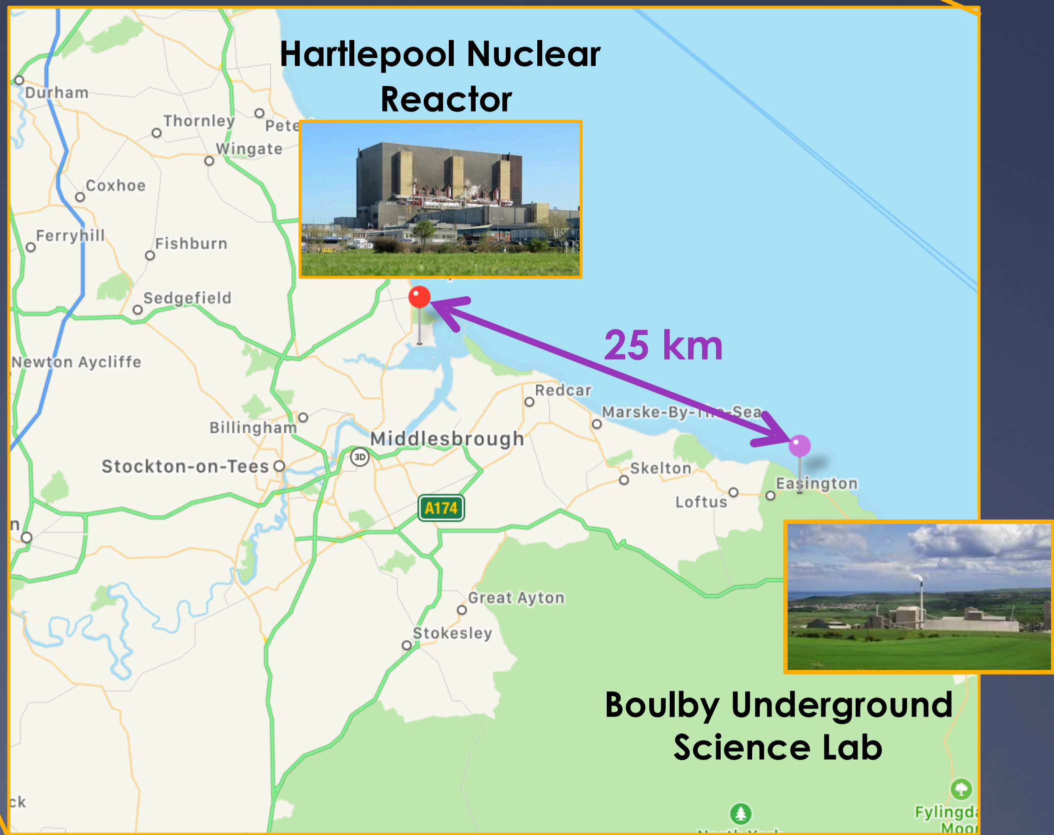
AIT-WATCHMAN collaboration

The WATCHMAN Collaboration

- **Collaboration**
  - 21 universities (UK: Sheffield, Edinburgh, Liverpool)
  - 3 US laboratories
  - 2 UK laboratories (AWE, Boulby)
  - ~90 collaborators

AIT-WATCHMAN location

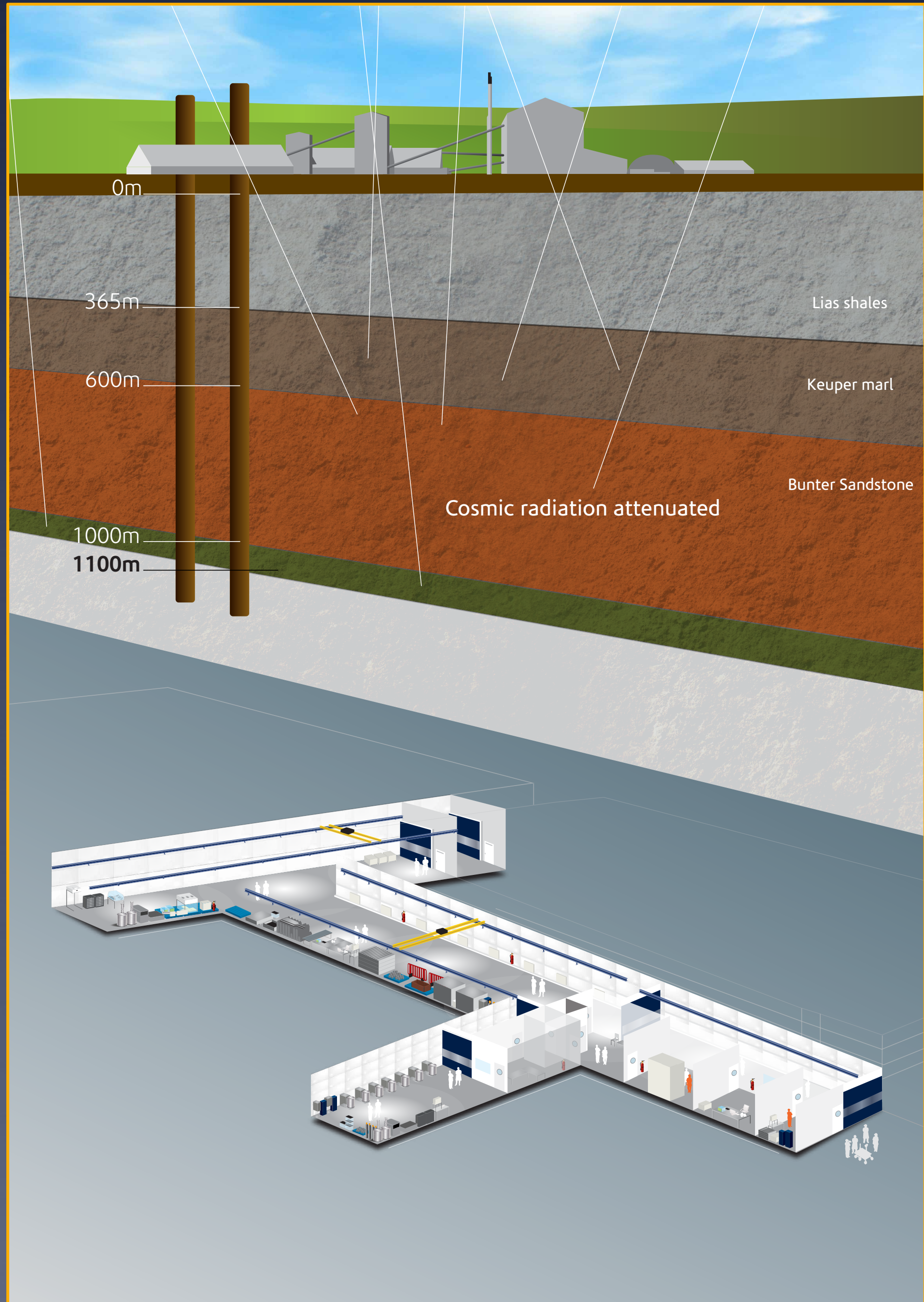




Hartlepool Nuclear Reactor

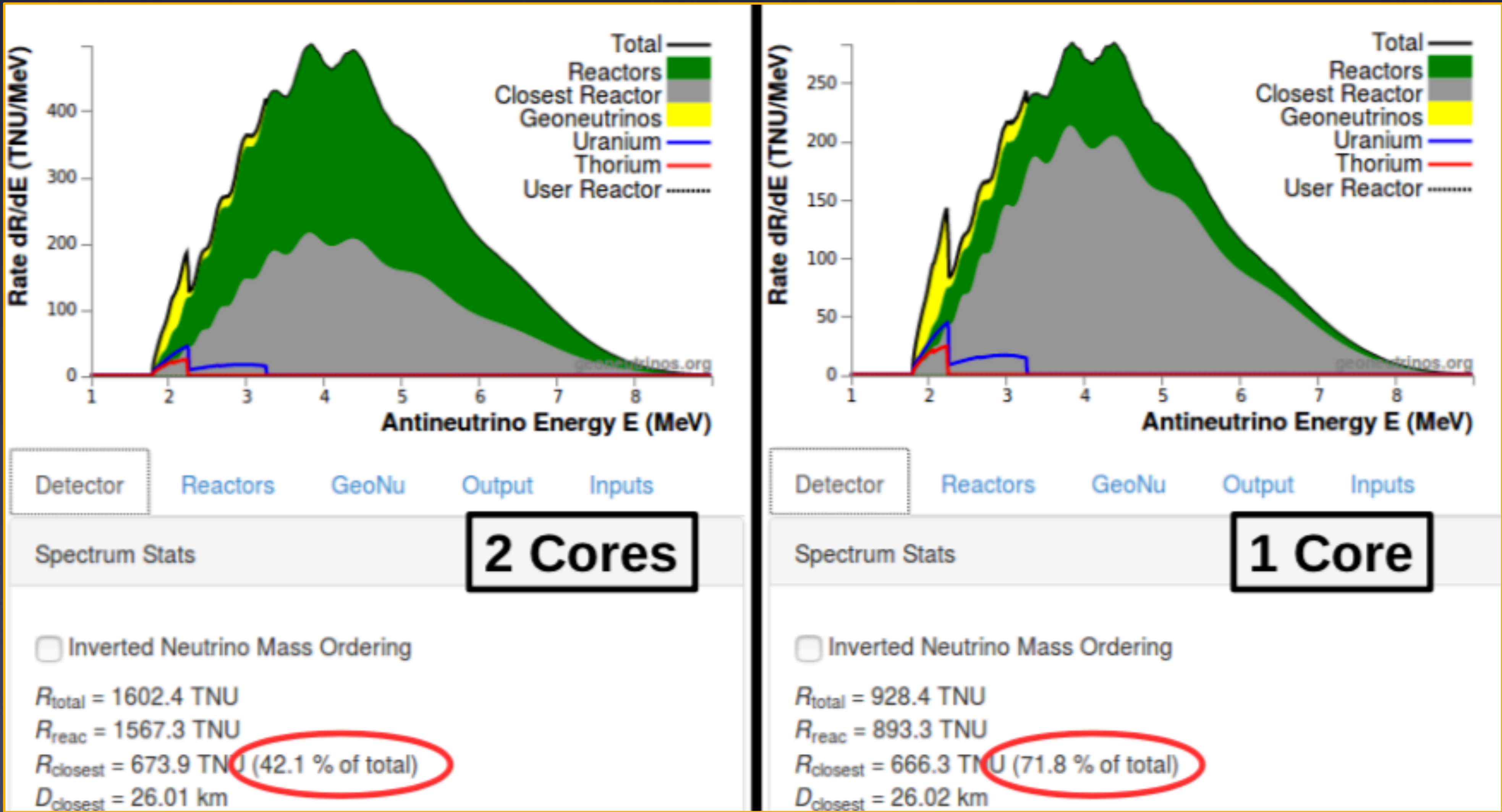
- Dual-core reactor complex
- Advanced gas-cooled reactors (AGR), 1575 MWth per reactor core
- Look for flux difference between 1-core and 2-core operation
- Scope for future complementary work with near-field detection

Boulby Underground Lab



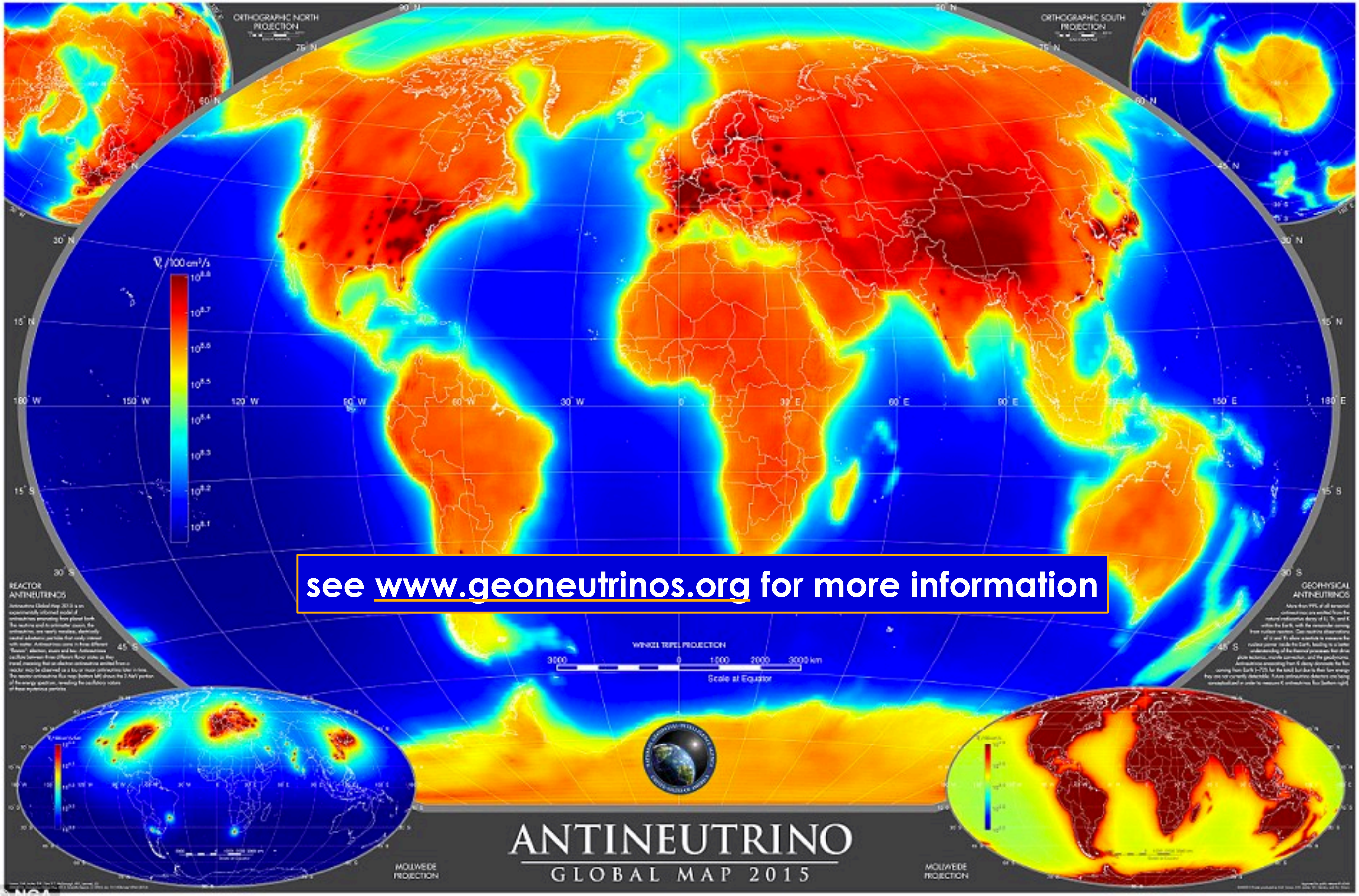
- STFC-operated science facility 1100 m underground
- 2800 m.w.e.
- Cosmic ray flux attenuation ~ 10^6
- Working potash/polyhalide mine
- AIT-WATCHMAN will be constructed and commissioned in a completely new cavern ~25m (h) x 25m (d)

Anti-neutrino fluxes at WATCHMAN site



- Flux information taken from online tool (see Antineutrino Global Map project)
- (Ref: Steve Dye, Reactor Anti-neutrinos at Morton and Boulby, nucl-ex:1611.01575)
- Note: reactor signal is no more than 10 events per day!

The world in anti-neutrinos …

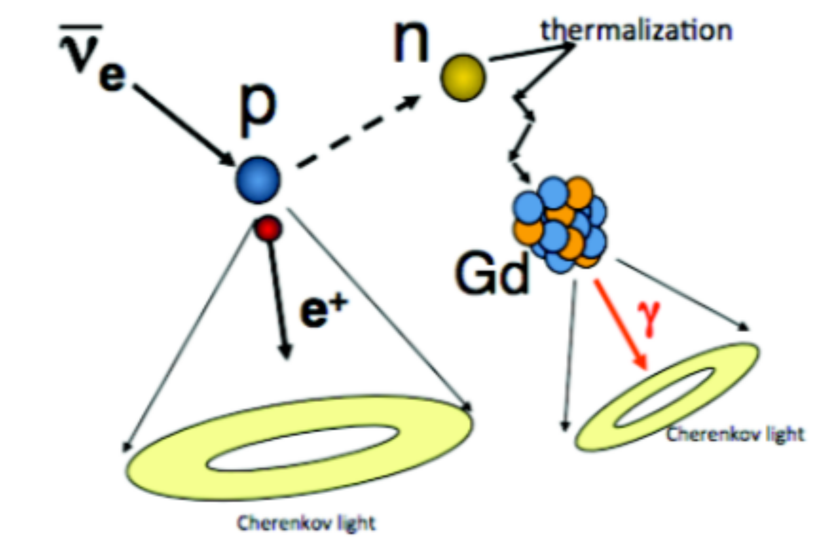


see www.geoneutrinos.org for more information

AIT-WATCHMAN: an anti-neutrino detector

- The basic principle of the WATCHMAN detector is that of a water Cerenkov detector
- However, by loading the water with Gd (in the form of Gd sulphate) anti-neutrino interactions can be identified
- Anti-neutrinos undergo inverse beta decay to give a neutron and a positron
- Signal is positron annihilation followed by ~8 MeV gamma cascade (4-5 MeV of visible energy) from Gd de-excitation ~30 μs later
- ~70% detection efficiency

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



- The experimental signature is thus:
  - exactly 2 Cerenkov flashes …
  - .. which occur within 100 μs …
  - … and within a voxel of 1m^3

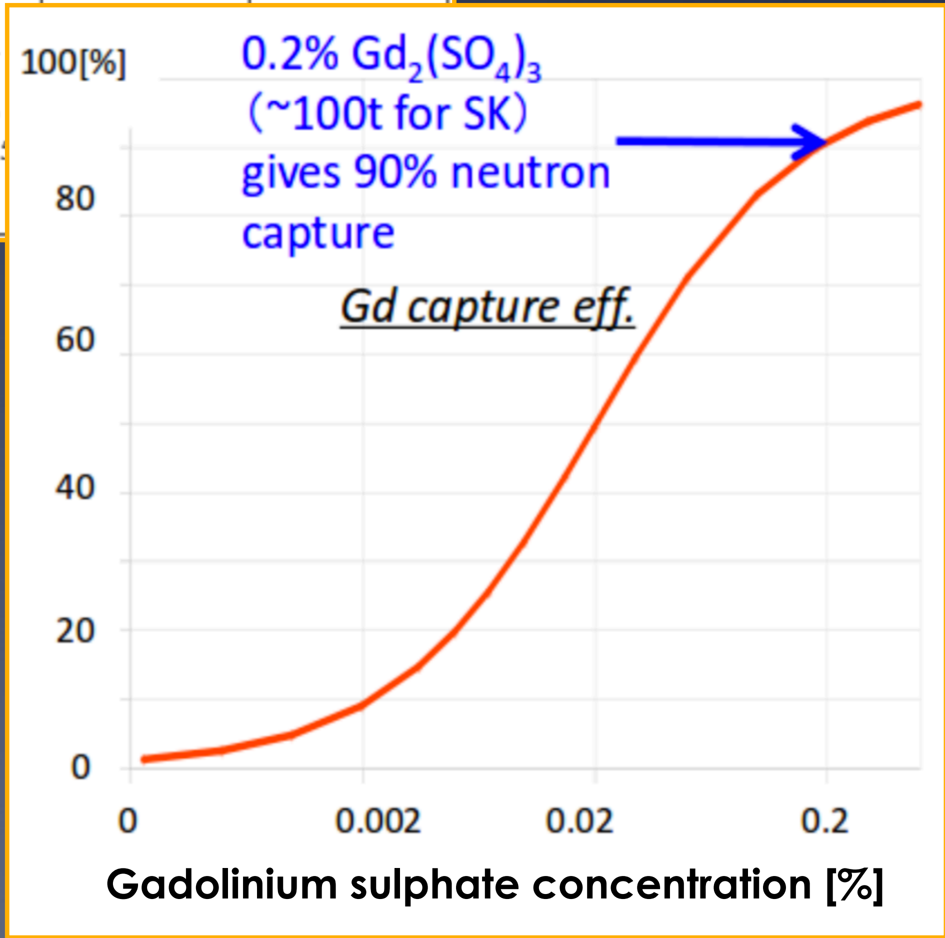
Why Gadolinium?

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	0.75		
Gd	—		48 800	100.0			

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
- 0.2% Gd concentration results in ~90% of neutrons capturing on Gd



AIT-WATCHMAN analysis goals

- 1. Perform the experiment with full knowledge of both reactors' ON/OFF status (unblinded)
- 2. Perform the experiment with knowledge of a single reactor as a background, with a remaining unknown reactor.
- 3. Perform the experiment with no knowledge of either reactor (fully blinded)

Component	Events/week
Core 1 (signal)	4.8
Core 2 (background)	4.8
World Reactors	1.5
Cosmogenic radionuclides	0.1
Fast neutrons	0.6
Accidentals	0.6

From reactor to detector ...

Distance to detector, small interaction cross section

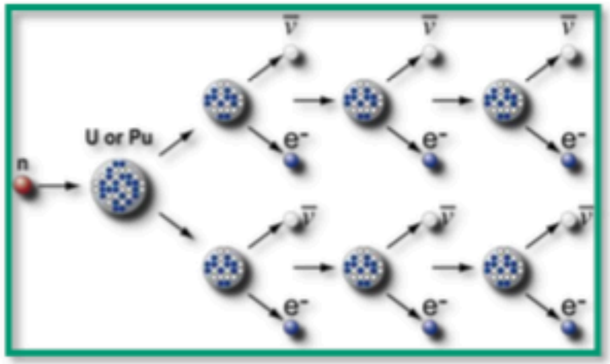
$$\sim 6 \quad \times \quad 10^{21} \quad \rightarrow \quad 10^{22} \quad \rightarrow \quad \text{“a few”}$$

Antineutrinos per nuclear fission

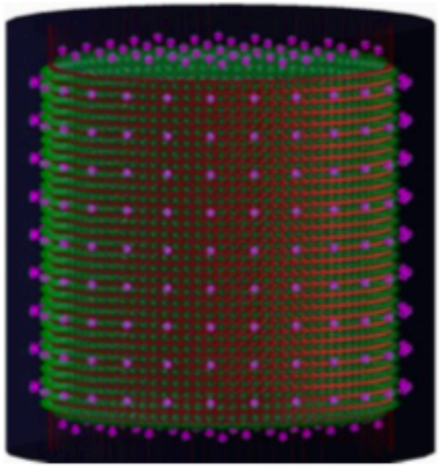
Fissions per second in a 3 GWt reactor

Antineutrinos per second from a 3 GWt reactor (all directions)

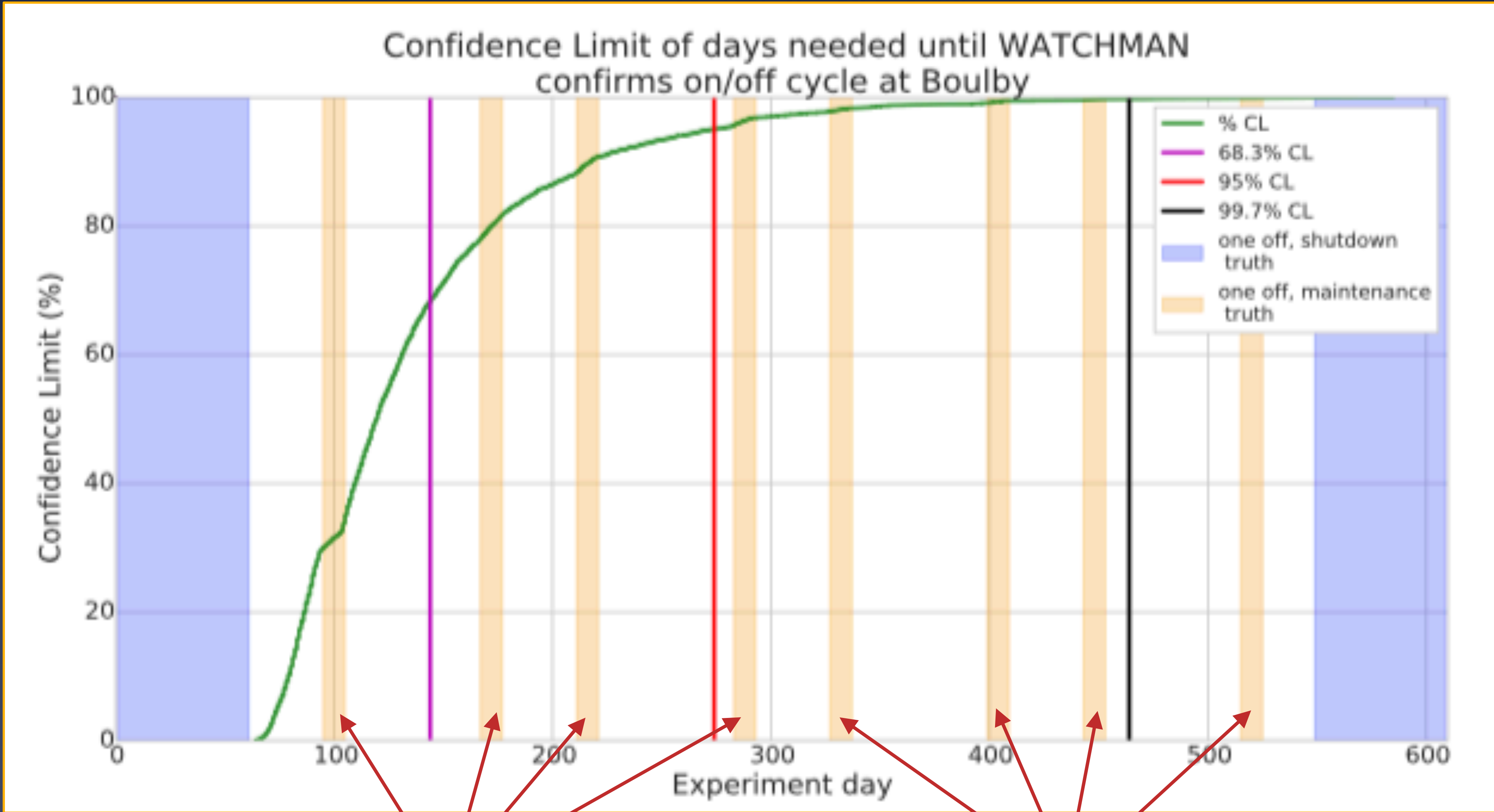
Antineutrino interactions per day (per 1 kton volume, at ~25 km standoff)



25 km



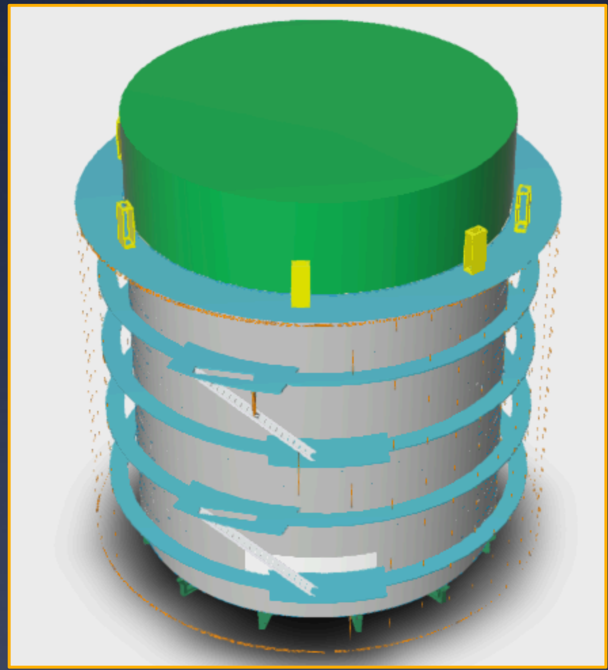
Dwell time to reactor on/off determination

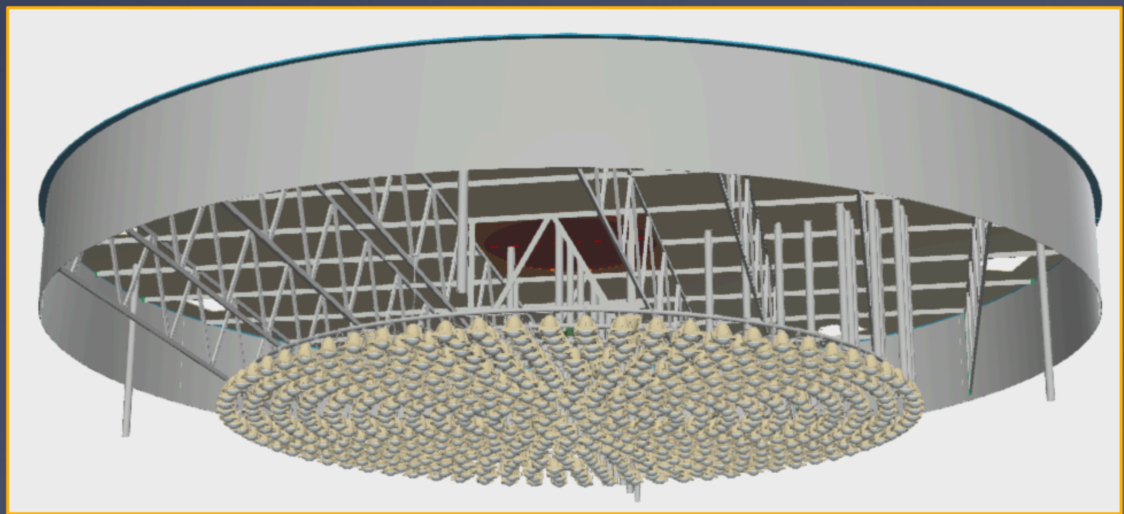


Periods of time when one reactor core is off

AIT-WATCHMAN detector design

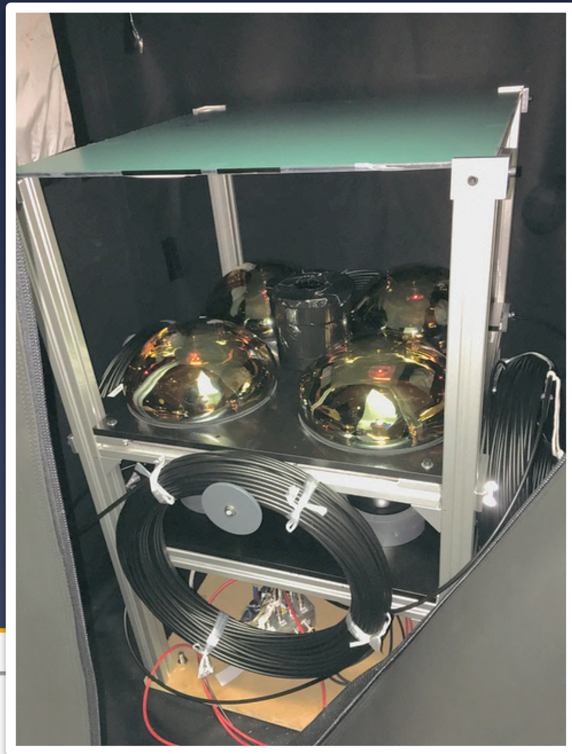
- ~1 kTon fiducial volume
- ~1.5m active veto region
- ~20m tank height and diameter
- 0.1% Gd-loaded water
- Inward-facing PMTs mounted on stainless steel frame inside tank
- 20%-25% PMT coverage
- 10" HQE low radioactivity PMTs under characterisation (approx. 3600-4400 required)

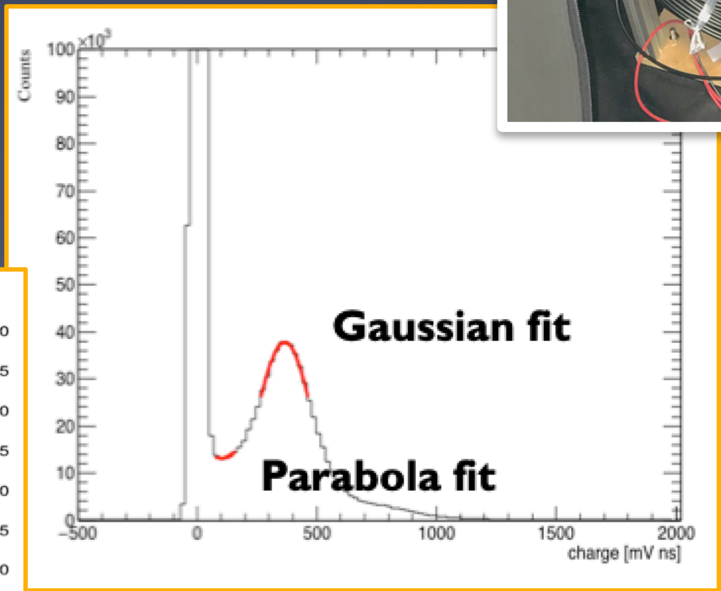


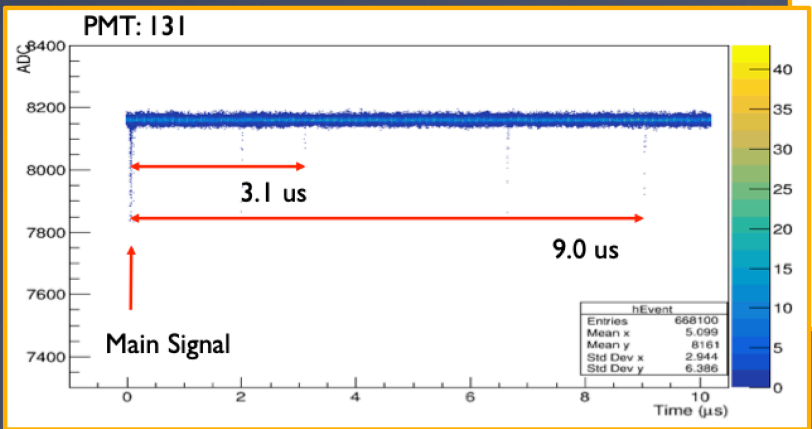


UK activity: PMT testing

- Develop procedures for PMT testing at Boulby, both one the surface and underground
- A long list of PMT characteristics to be determined including:
  - Gain calibration, reproducibility
  - Peak to valley ratio
  - Dark rate
  - Afterpulsing, etc.

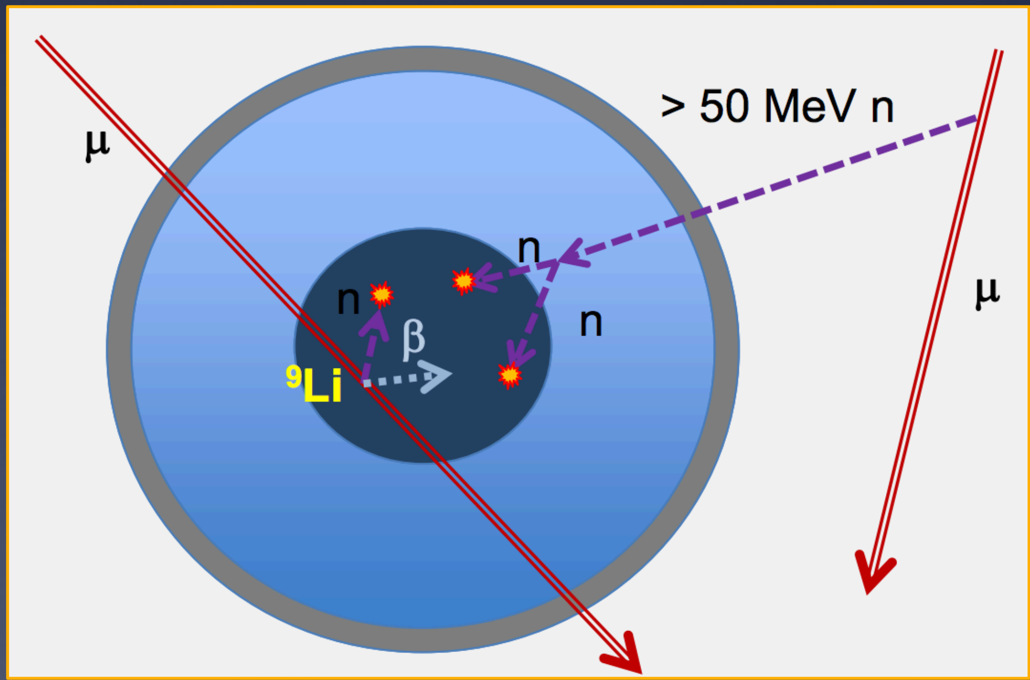




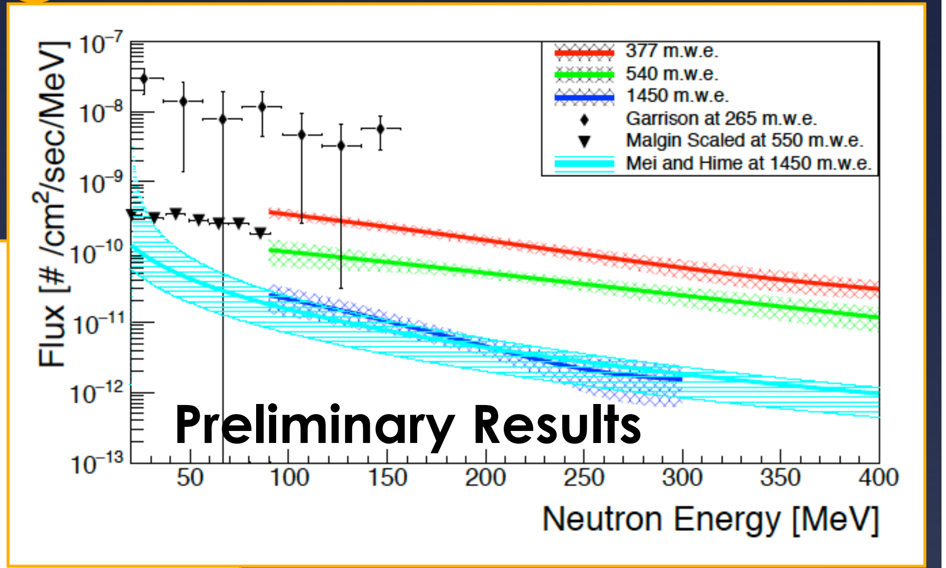


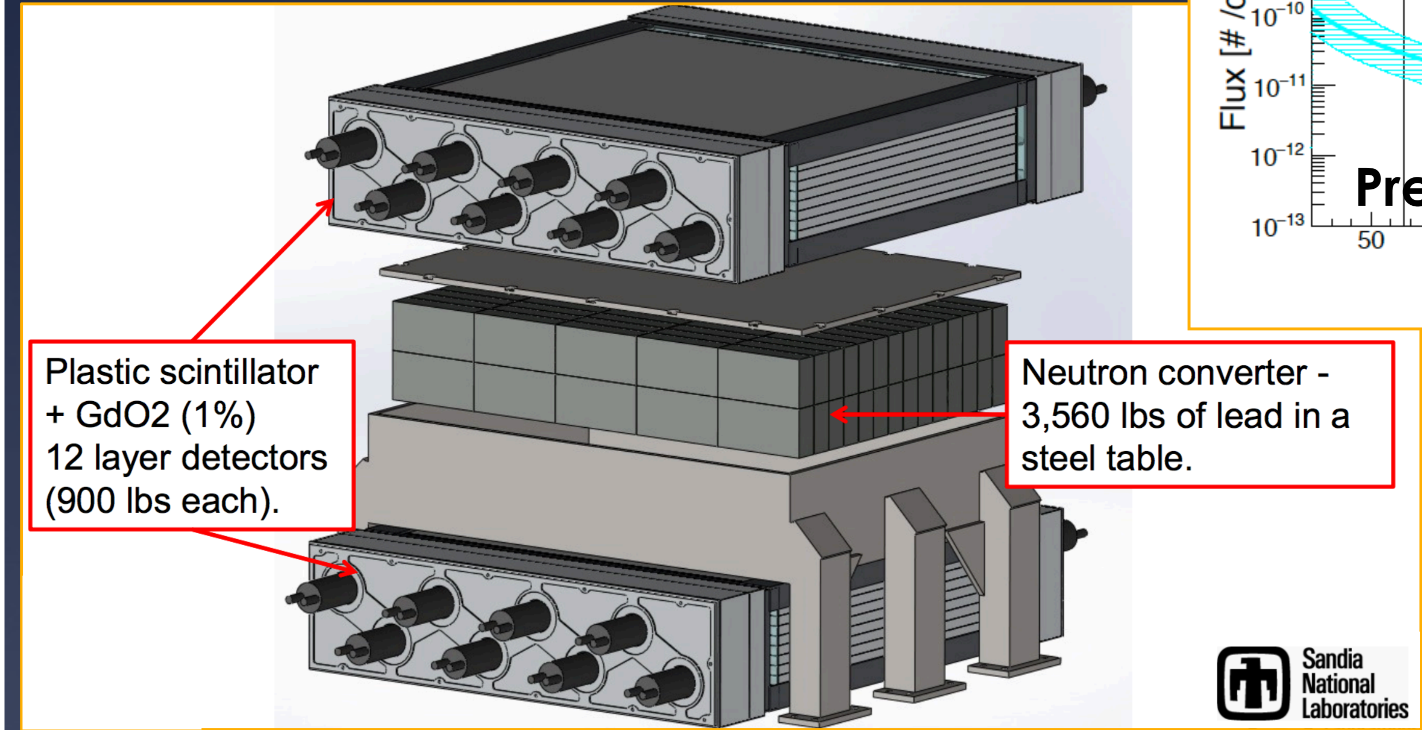
AIT-WATCHMAN: backgrounds

- Scaling up to kTon masses requires a good understanding of background sources and rates
- (Left) Muogenic beta delayed precursors
- (Right) Fast neutron rate capable of producing two correlated events in a detector



Understanding backgrounds - MARS



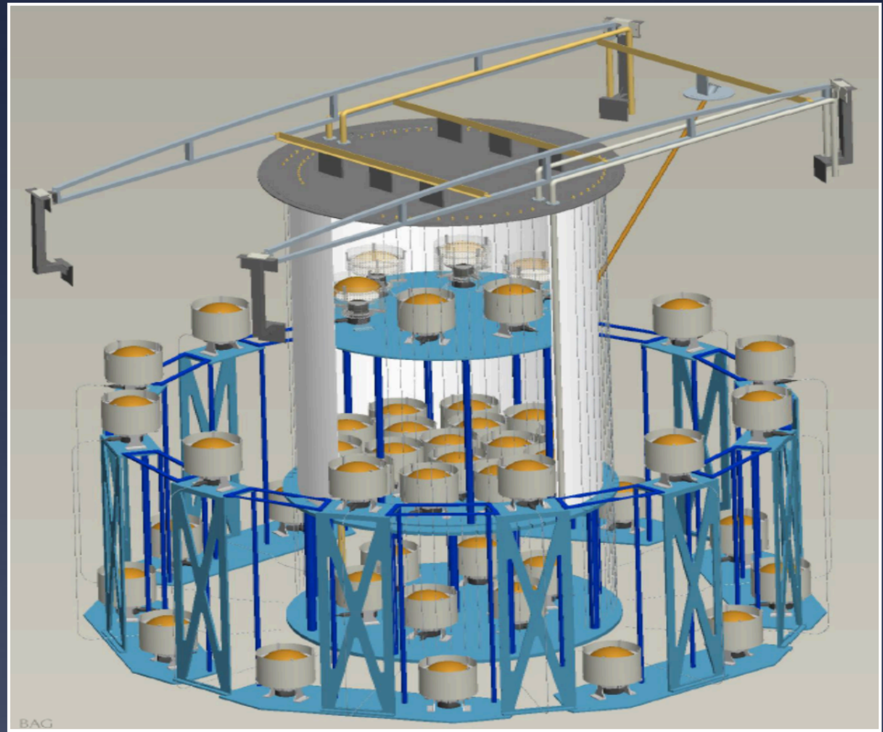


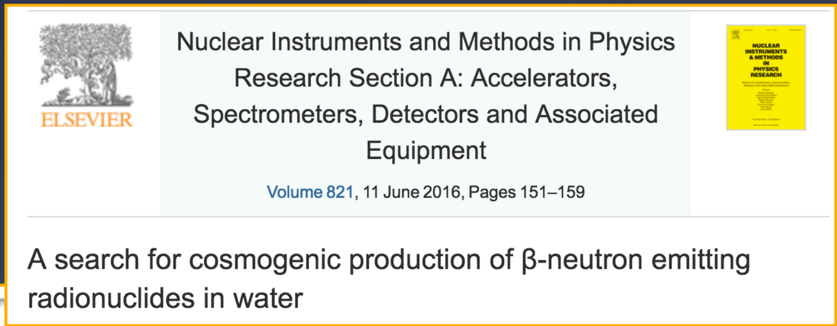
- **Multiplicity and Recoil Spectrometer**
- Muon veto added around detector Muon veto to reject muogenic neutron production within MARS
- A single fast neutron entering the detector can produce a multiplicity of particles that may mimic an anti-neutrino signal in water

Understanding backgrounds - WATCHBOY

- WATCHBOY - a “mini-WATCHMAN” detector with 2 ton target and 10 ton veto

- Designed to measure muogenic radionuclides, e.g.: ^{9}Li, ^{8}He, etc.





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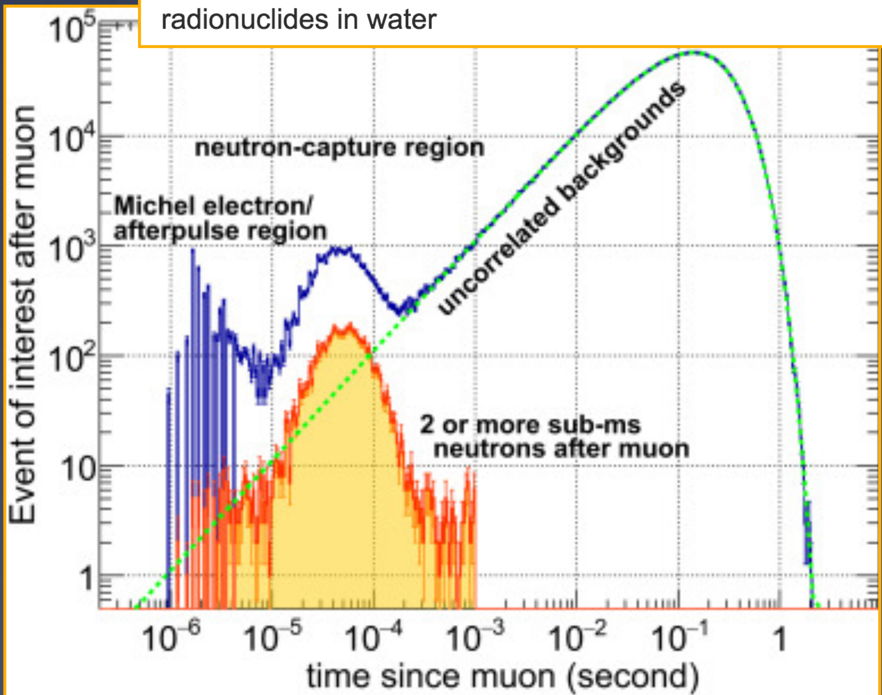
A search for cosmogenic production of β-neutron emitting radionuclides in water



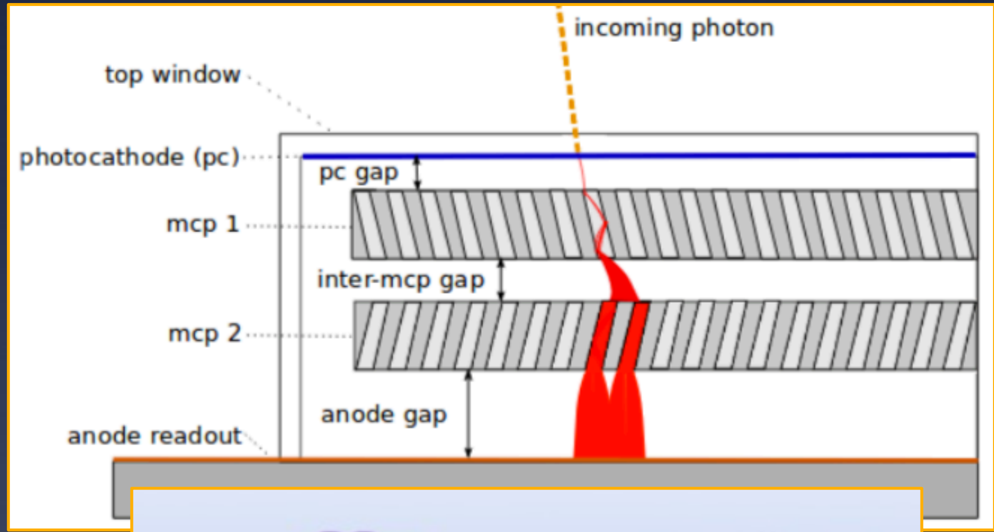
- Event time after identified muon in WATCHBOY.

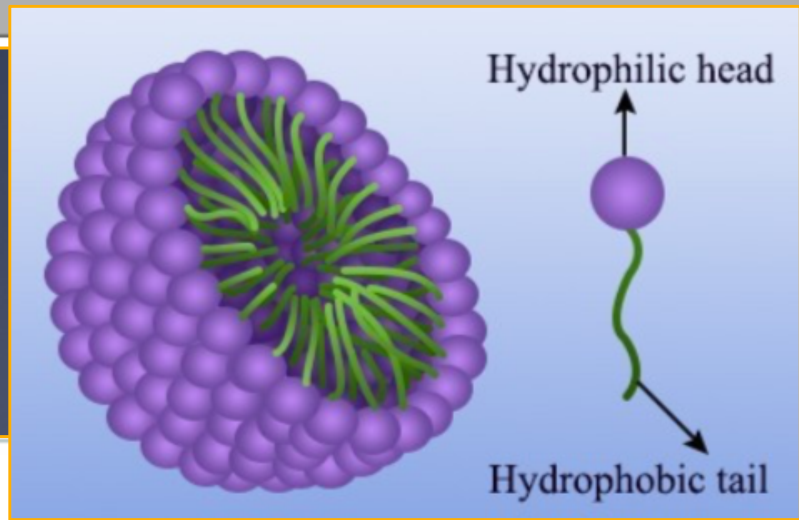
- Tagging procedure allows removal of nearly all backgrounds due to pile up of other muons.

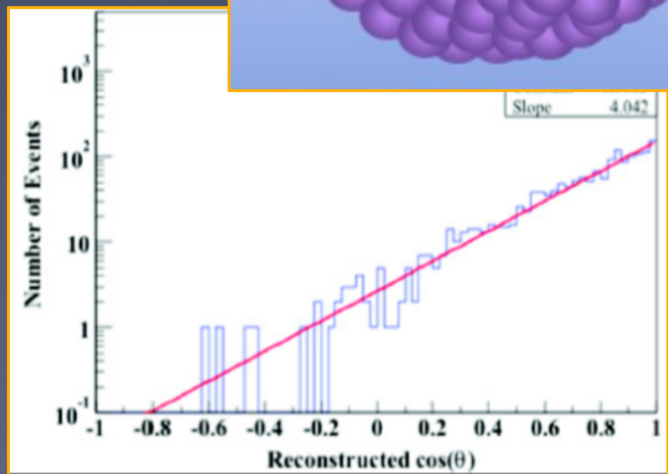
- Uncorrelated events are fitted between 1 ms and 2 s - good agreement between the data and the uncorrelated expectation.

Beyond WATCHMAN: AIT

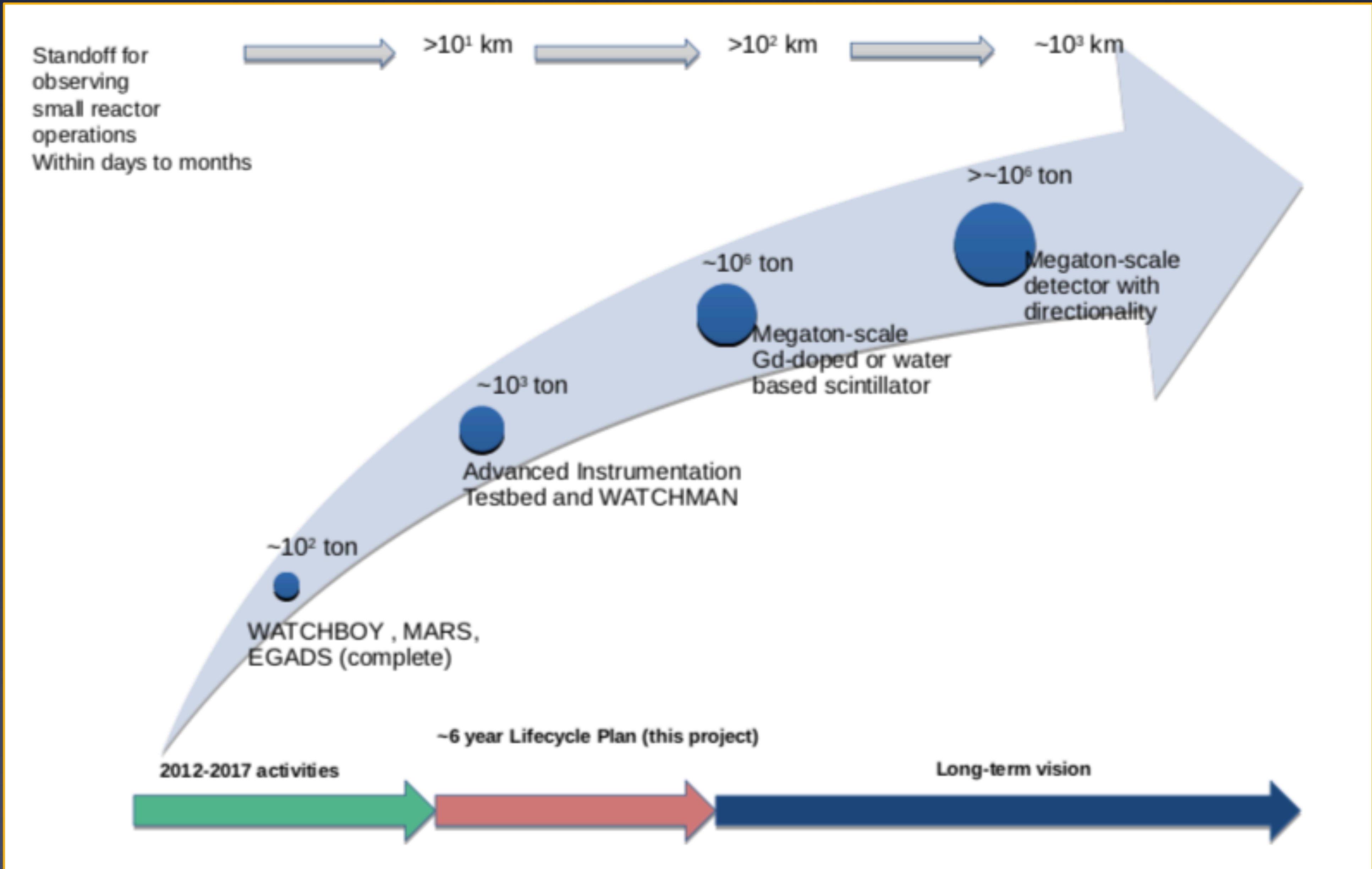
- Once the primary goal of AIT-WATCHMAN is complete the experiment may be used as a testbed for novel instrumentation and techniques including, e.g.:
  - LAPPDs (large area MCP photodetectors with picosecond timing resolution and high gain)
  - WbLS (water-based liquid scintillator with significant increase in light yield compared with water Cerenkov)
  - Directionality studies (use of elastic scattering events to provide some directional information on the incoming anti-neutrino)
- This would enhance capability for non-proliferation but also open up the possibility of scientific studies such as geo-neutrinos, CNO solar neutrinos, neutrino less double beta decay, etc.







AIT-WATCHMAN timescales



Conclusions

- AIT-WATCHMAN will build a ~1 kTon Gd-loaded water Čerenkov detector as a nuclear non-proliferation demonstrator
- Hartlepool/Boulby in the UK has been selected for the site for AIT-WATCHMAN
- Tank design is almost complete, cavern excavation to start in 2020, large scale PMT tests underway
- Once the non-proliferation demonstration is complete AIT-WATCHMAN is well-suited for use in sterile neutrino searches, supernova studies, as well as a testbed for advanced light sensors and water-based scintillator studies.