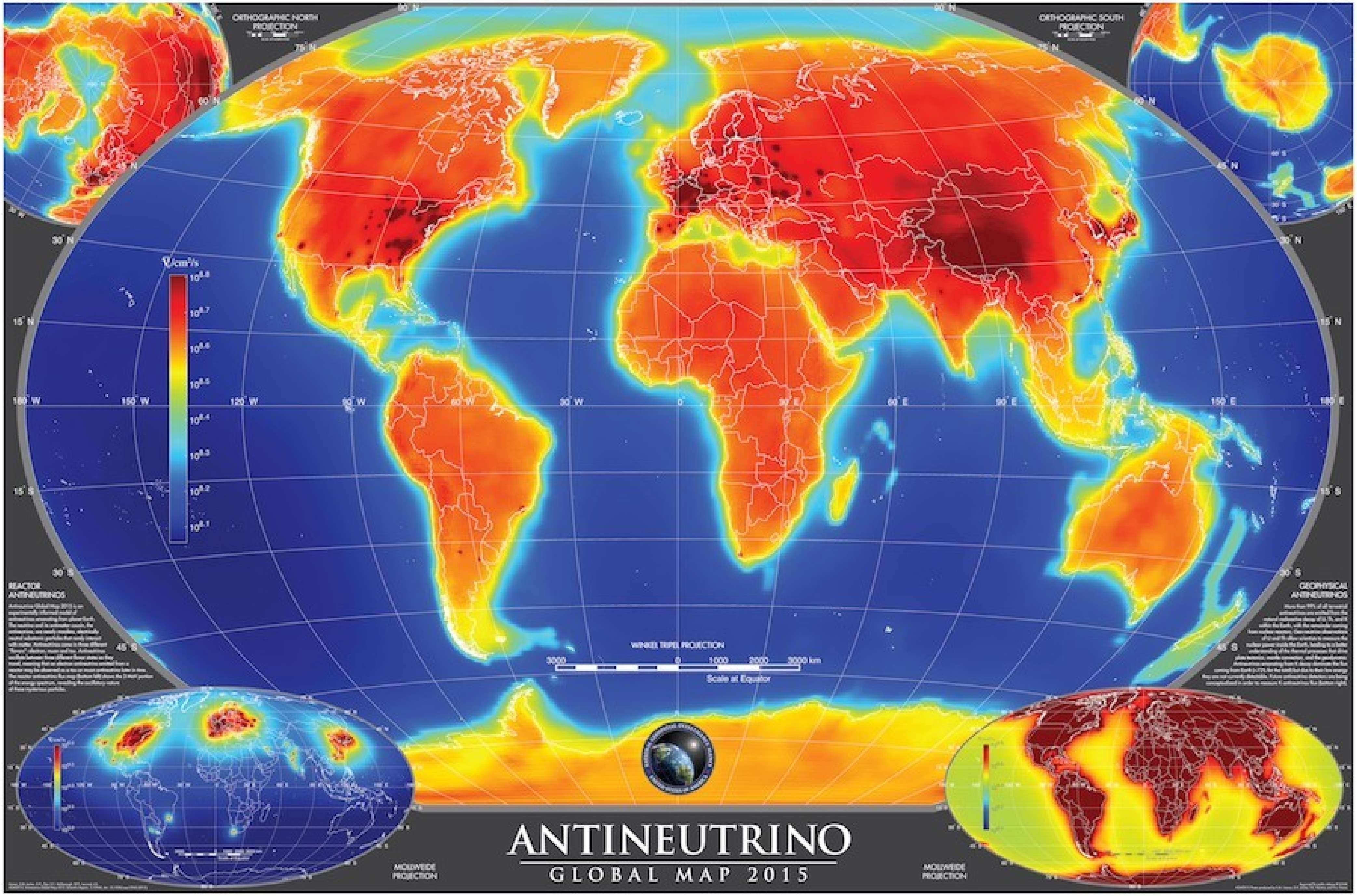
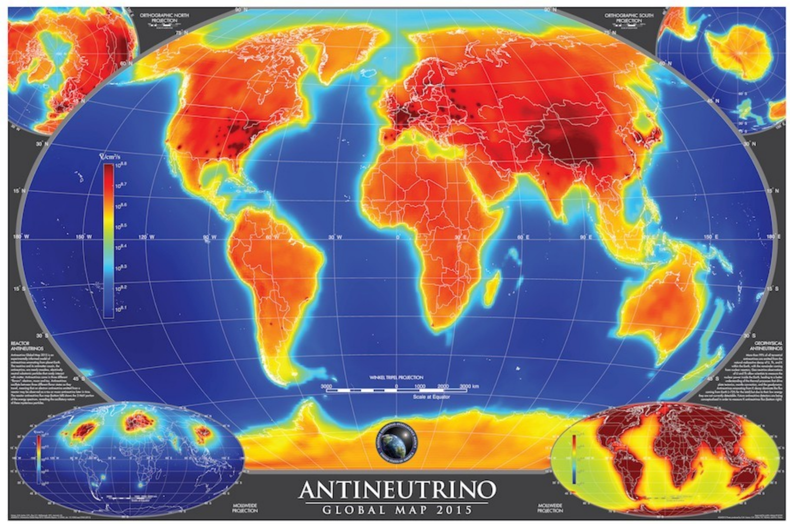
Remote Reactor Monitoring



Matthew Malek

Remote Reactor Monitoring via Antineutrinos



Matthew Malek
The University of Sheffield

University of Birmingham – Particle Physics Seminar
25th January 2023

In the beginning

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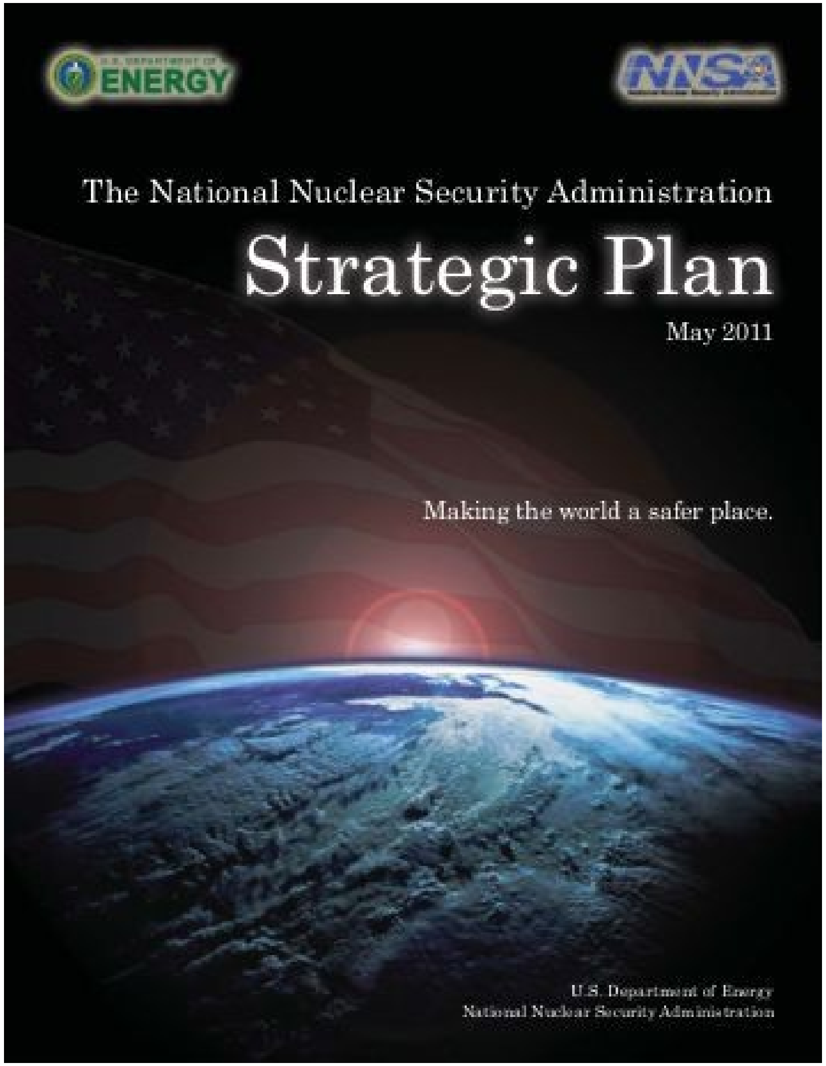


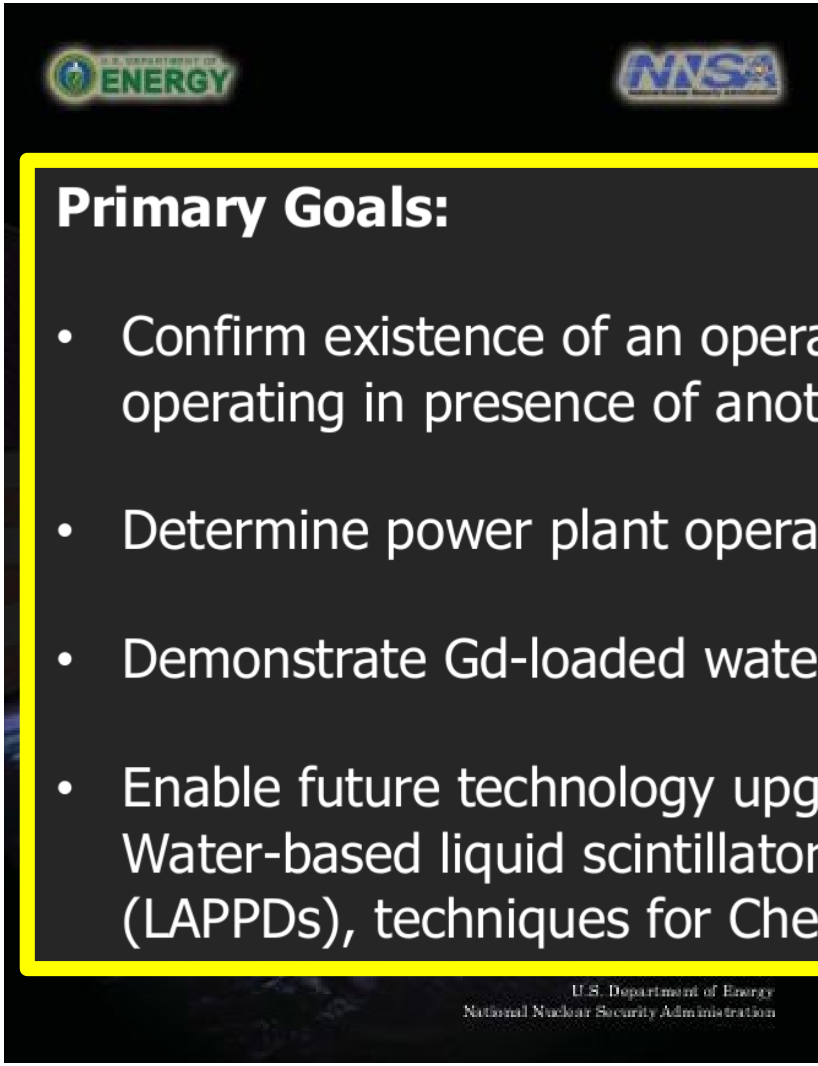
Our objective is to harness the techniques of particle physics for nuclear threat reduction.

Initially launched in 2011 by the **Office of Defense Nuclear Nonproliferation** (DNN) at the **National Nuclear Security Administration** (NNSA) in the United States.

UK involvement from 2016 via **Ministry of Defence** (MoD) under 1958 US-UK Mutual Defence Agreement.

Main funding in UK from **Science & Technology Facility Council** (STFC) via an award from the **UKRI** Fund for International Collaboration.

The Charge



The goal of the WATCHMAN project is to harness the techniques described earlier for

Primary Goals:

- Confirm existence of an operating reactor (ie. determine unknown reactor is operating in presence of another known reactor)
- Determine power plant operational status with and without prior knowledge
- Demonstrate Gd-loaded water as a scalable detector medium
- Enable future technology upgrades:
  Water-based liquid scintillator WbLS, Large-Area Picosecond Photodetectors (LAPPDs), techniques for Cherenkov and scintillation light separation, etc.

Collaboration.

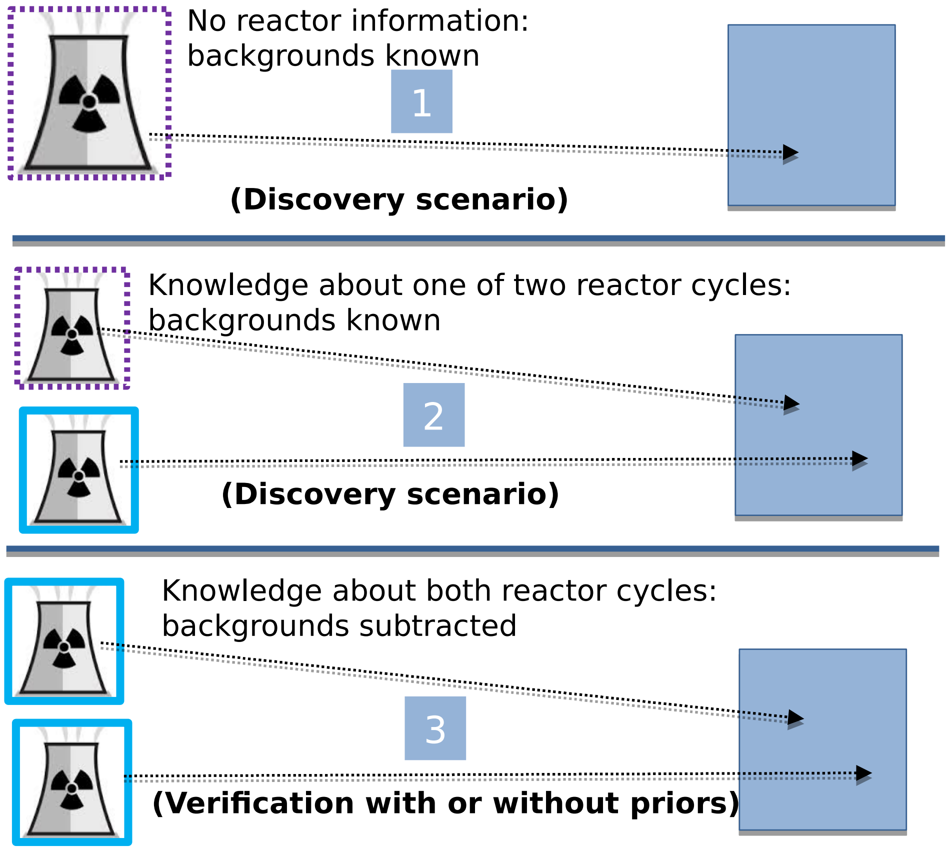
Non-Proliferation Scenarios

Discovery Scenarios (Project Goal 1):

- **Case 1:** Determine whether any reactor is present.
- **Case 2:** Knowing that one reactor is operating, determine that a second reactor has turned on.

Verification Scenario: (Project Goal 2)

- **Case 3:** Confirm operational status <u>with or without prior knowledge</u> of both reactor cycles.



Further non-proliferation use cases are in development, in consultation with sponsors and also with the non-proliferation community. These include reactor ranging and directionality.

What is WATCHMAN?

Objective:

Achieve remote monitoring of fission reactor via detection of antineutrino emissions.

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

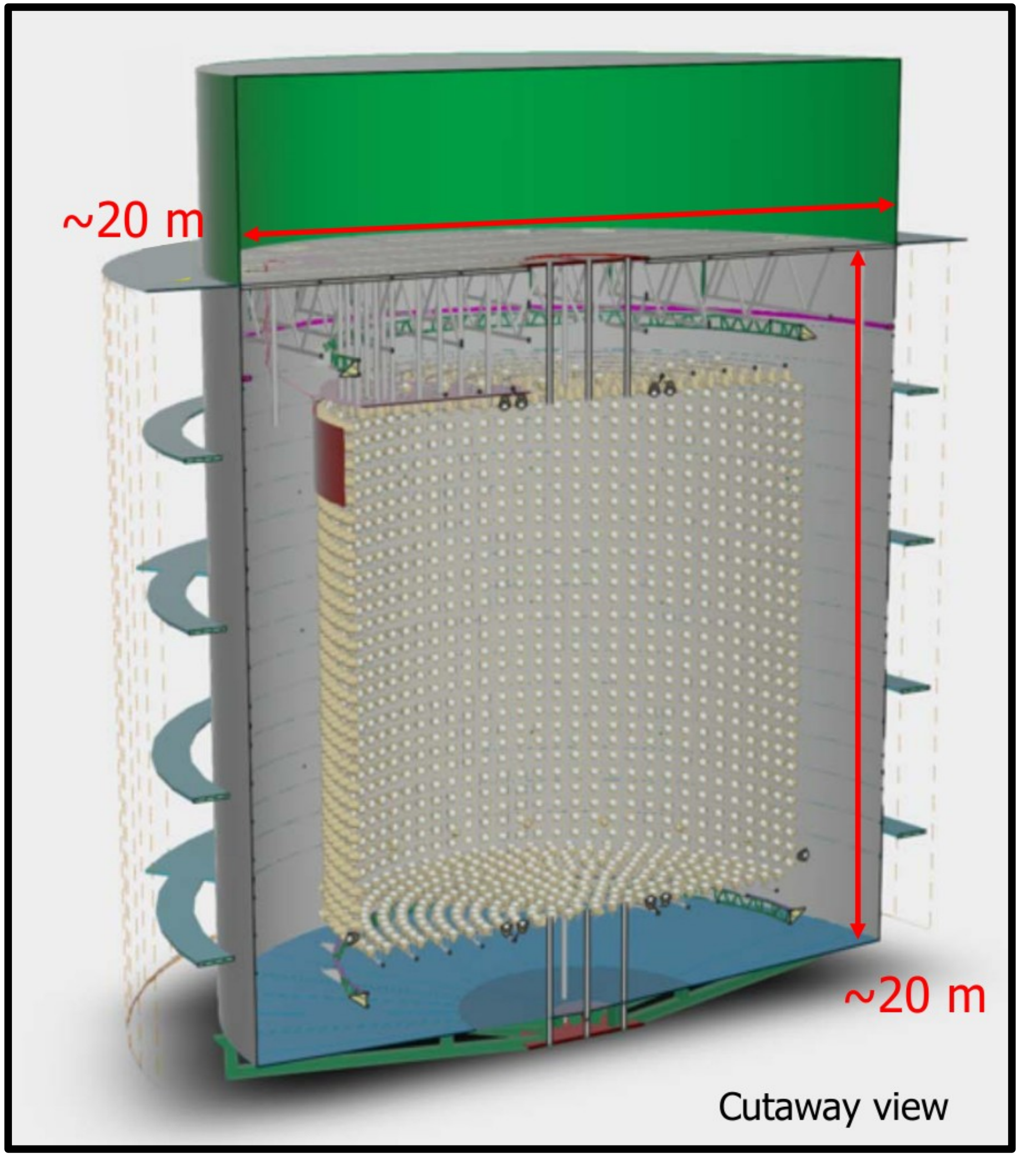
Baseline Design:

- Medium size (ktonne-scale fiducial mass) water-based gadolinium-loaded antineutrino detector
- **Technnology demonstration:** Initial prototype to demonstrate monitoring of a single reactor site
- **Scalability:** Rationale is to develop a detector design that can be scaled to the Mtonne masses that are required for larger standoff distances

The WATCHMAN Design

Baseline design includes:

- ktonne-scale fiducial mass
- 0.1% Gd-loaded water
- ~3600 Hamamatsu 10” PMTs with:
  - High quantum efficiency (~30%)
  - Low radioactivity (esp. U and Th)
  - 15% photocathode coverage
- Active veto region (~1 metre)
- Multiple access points:
  - Calibration ports
  - Large central plug



WATCHMAN Collaboration

The WATCHMAN Collaboration

By the numbers:
- 2 countries (US & UK)
- 21 universities
- 3 US laboratories
- 2 UK laboratories
- 125 total collaborators

UK participation:
- 5 universities: Edinburgh, Glasgow, Liverpool, Sheffield, Warwick
- STFC-Boulby Underground Lab
- Atomic Weapons Establishment
- ~50 total collaborators
- £9.7M funding from STFC (via UKRI Fund for International Collab.)
- £1M funding from Ministry of Defence

WATCHMAN Collaboration

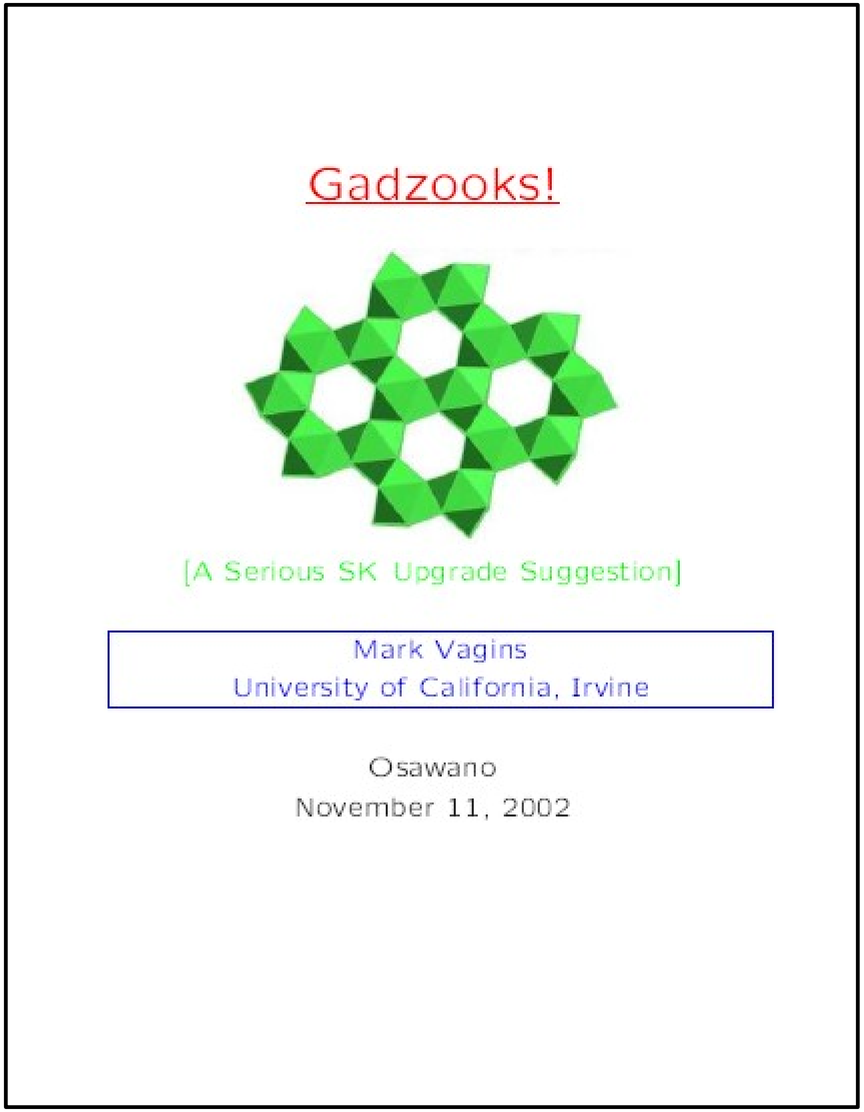
The WATCHMAN Collaboration

The WATCHMAN Spokespersons

- Adam Bernstein (Lawrence Livermore National Laboratory)
- Matthew Malek (The University of Sheffield)

WATCHMAN Collaboration

Gadolinium & Water



GADZOOKS! Antineutrino Spectroscopy with Large Water Čerenkov Detectors

John F. Beacom[1] and Mark R. Vagins[2]

[1] *NASA/Fermilab Astrophysics Center, Fermi National Accelerator Laboratory, Batavia, Illinois 60510-0500*
[2] *Department of Physics and Astronomy, 4129 Reines Hall, University of California, Irvine, CA 92697*
(Dated: 25 September 2003)

We propose modifying large water Čerenkov detectors by the addition of 0.2% gadolinium trichloride, which is highly soluble, newly inexpensive, and transparent in solution. Since Gd has an enormous cross section for radiative neutron capture, with $\sum E_\gamma = 8$ MeV, this would make neutrons visible for the first time in such detectors, allowing antineutrino tagging by the coincidence detection reaction $\bar{\nu}_e + p \rightarrow e^+ + n$ (similarly for $\bar{\nu}_\mu$). Taking Super-Kamiokande as a working example, dramatic consequences for reactor neutrino measurements, first observation of the diffuse supernova neutrino background, Galactic supernova detection, and other topics are discussed.

PACS numbers: 95.55.Vj, 95.85.Ry, 14.60.Pq FERMILAB-Pub-03/249-A

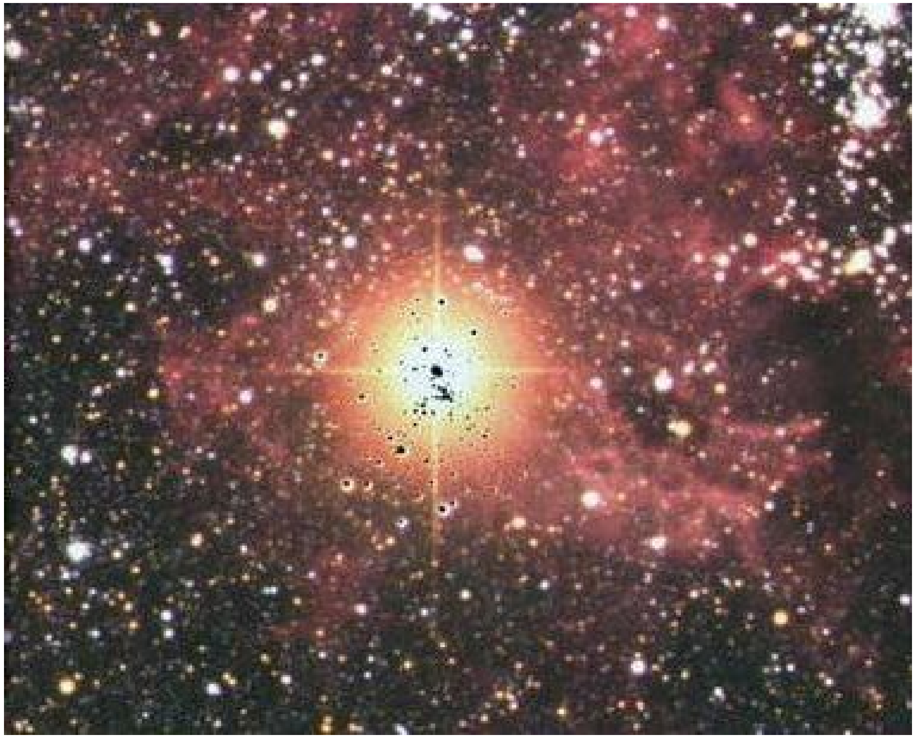
Beacom & Vagins, Phys.Rev.Lett. **93:171101** (2004)

Initial motivation for adding Gd to water Cherenkov detectors was background reduction for SRN experiments (see next slide).

Idea has now spread to many other uses, for both physics and impact applications

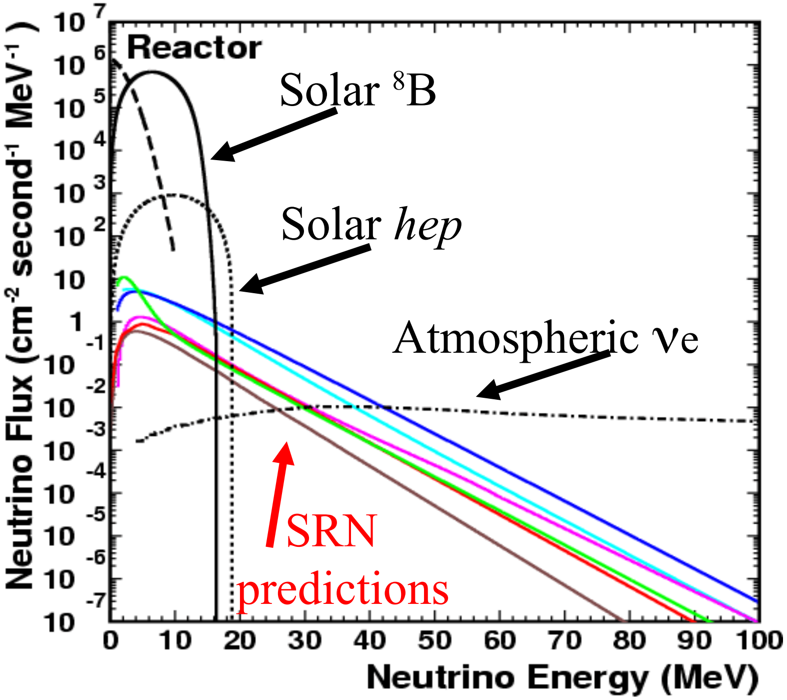
The University Of Sheffield.

Supernova Relic Neutrino (SRN) search at Super-Kamiokande:



Core-collapse supernova emits ~10^{46} J energy

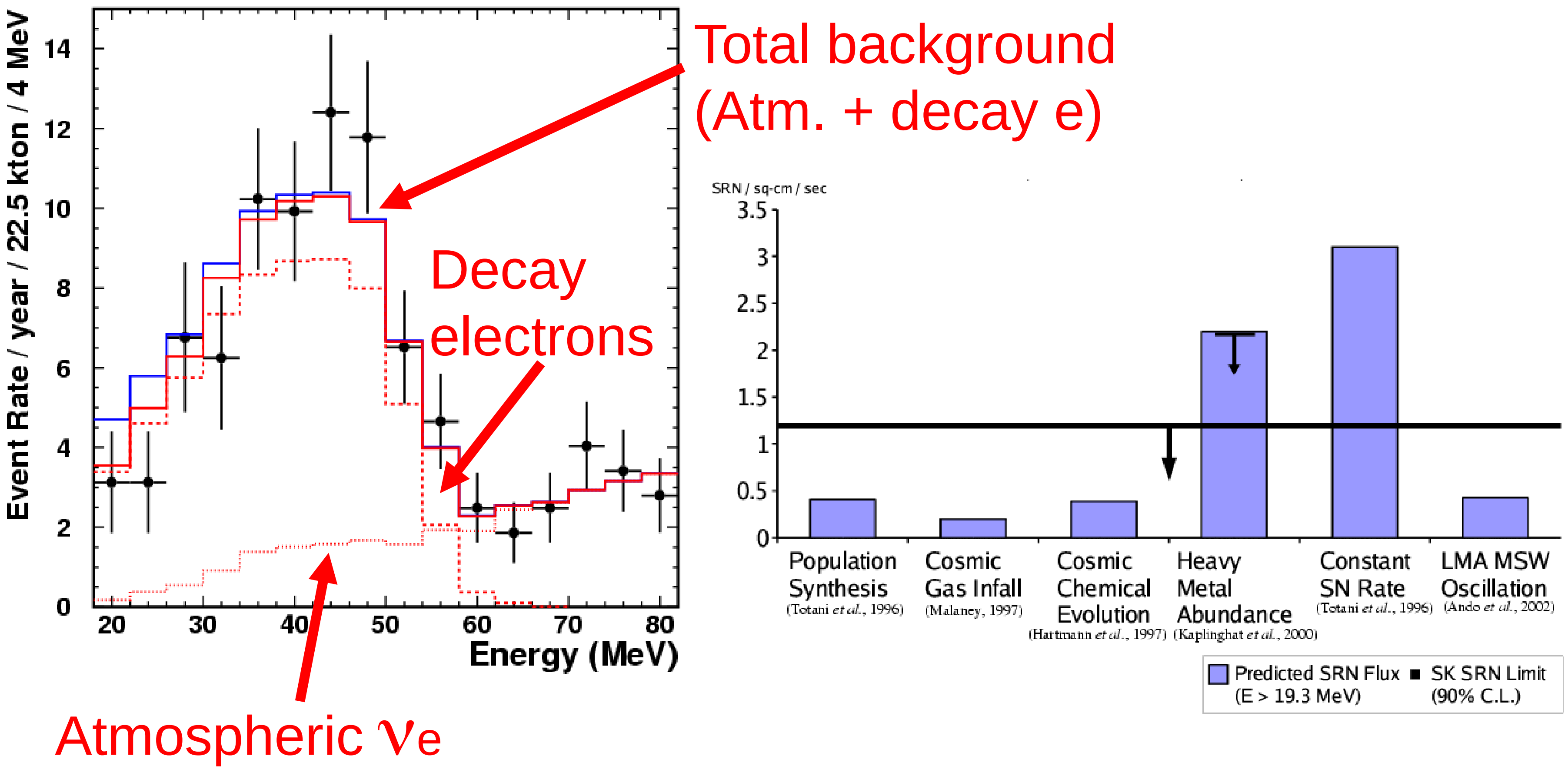
99% is released as neutrinos (all 6 types); mainly from neutrino cooling (also νe from neutronisation burst).



To date, only one observation (~25 neutrinos) on 24th February 1987 (SN1987A)

Diffuse background of SNν expected from <u>all</u> core-collapse supernovae that have ever exploded

SRN Search Results



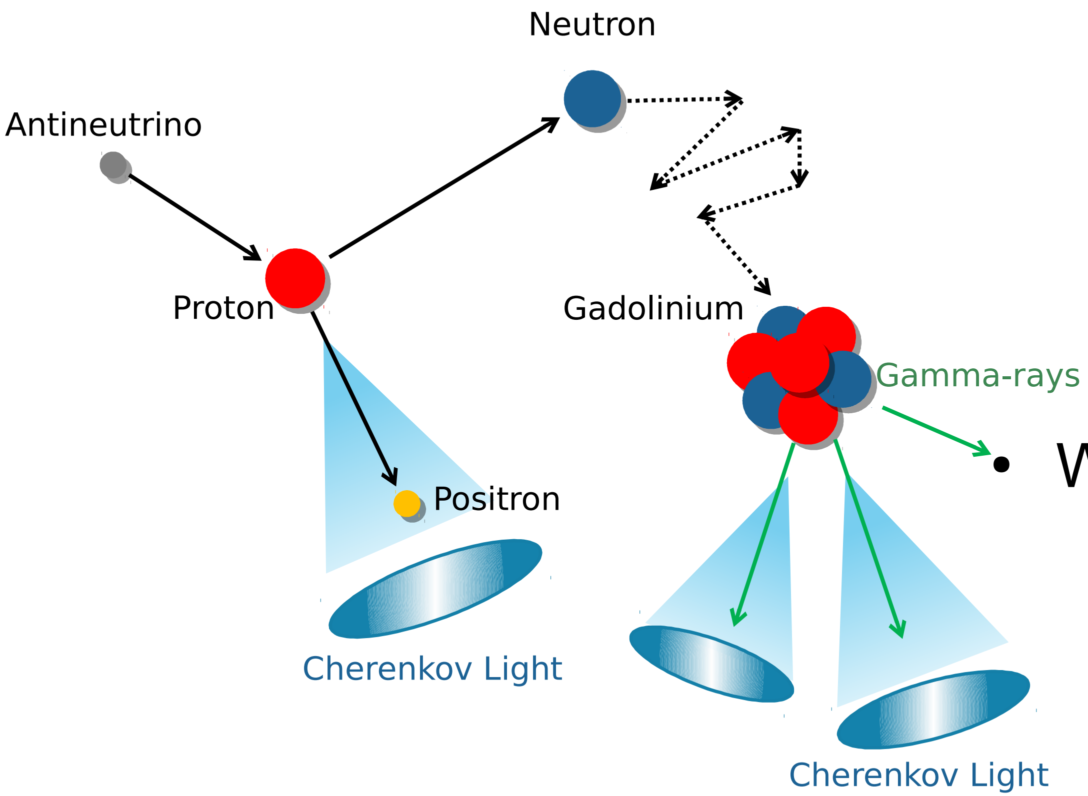
- SRN signal would manifest as distortion of BG
- No such signal seen yet → some models ruled out
- Background limitations form significant challenge!

M. Malek *et al.*, Phys.Rev.Lett. **90:061101** (2003)

How does Gd help?

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

$$\nu_e + p \rightarrow e^+ + n$$



- 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			

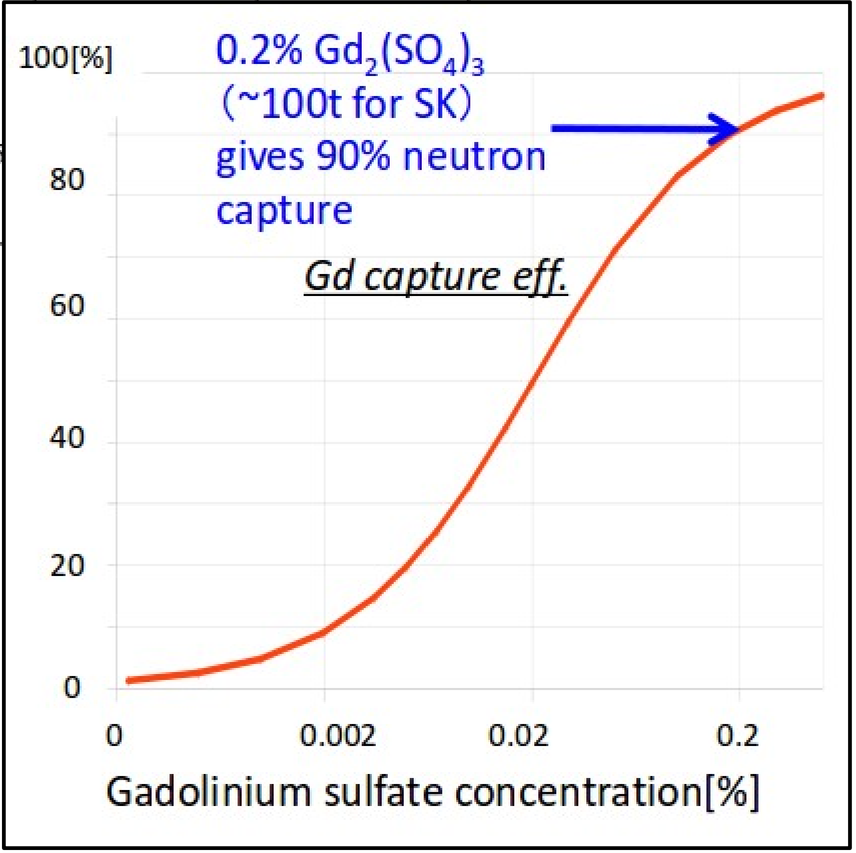
*The units of all cross sections are barns. The units of abundance are percent.

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



The EGADS Facility

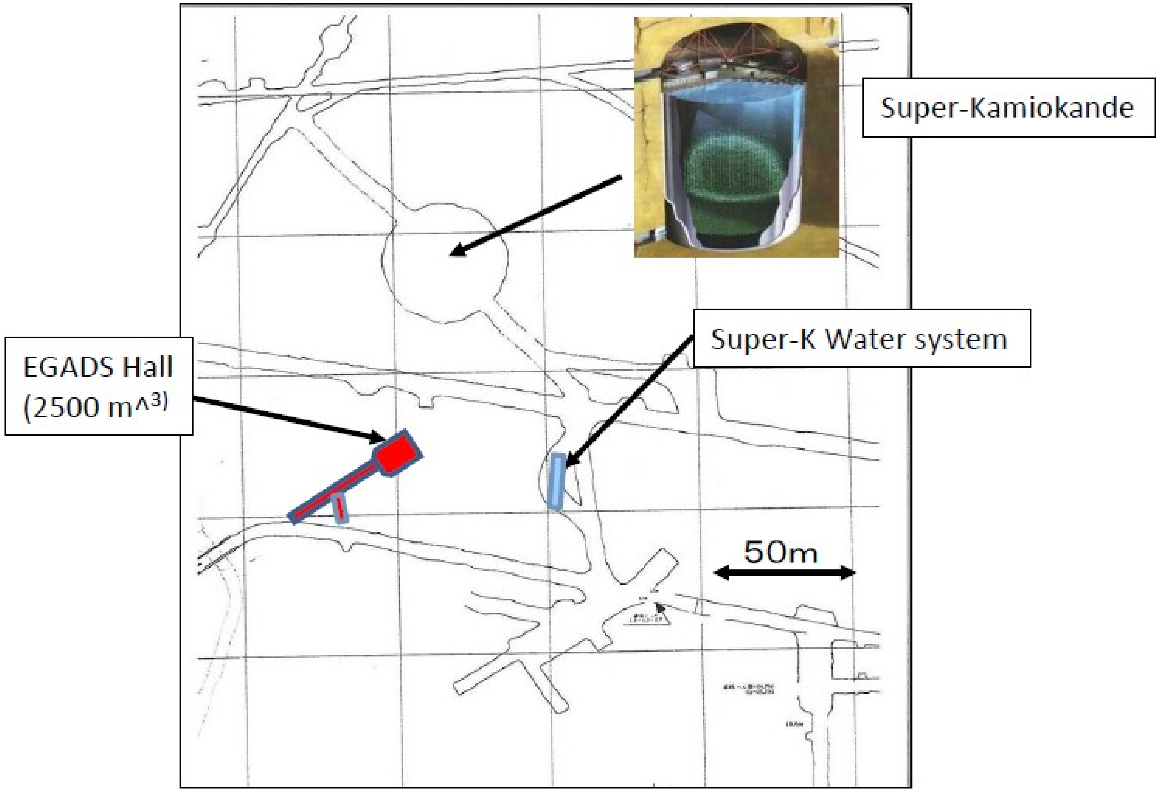
The University Of Sheffield.

EGADS = **E**valuating **G**adolinium's **A**ction on **D**etector **S**ystems

Dedicated test facility commissioned at Kamioka Observatory.

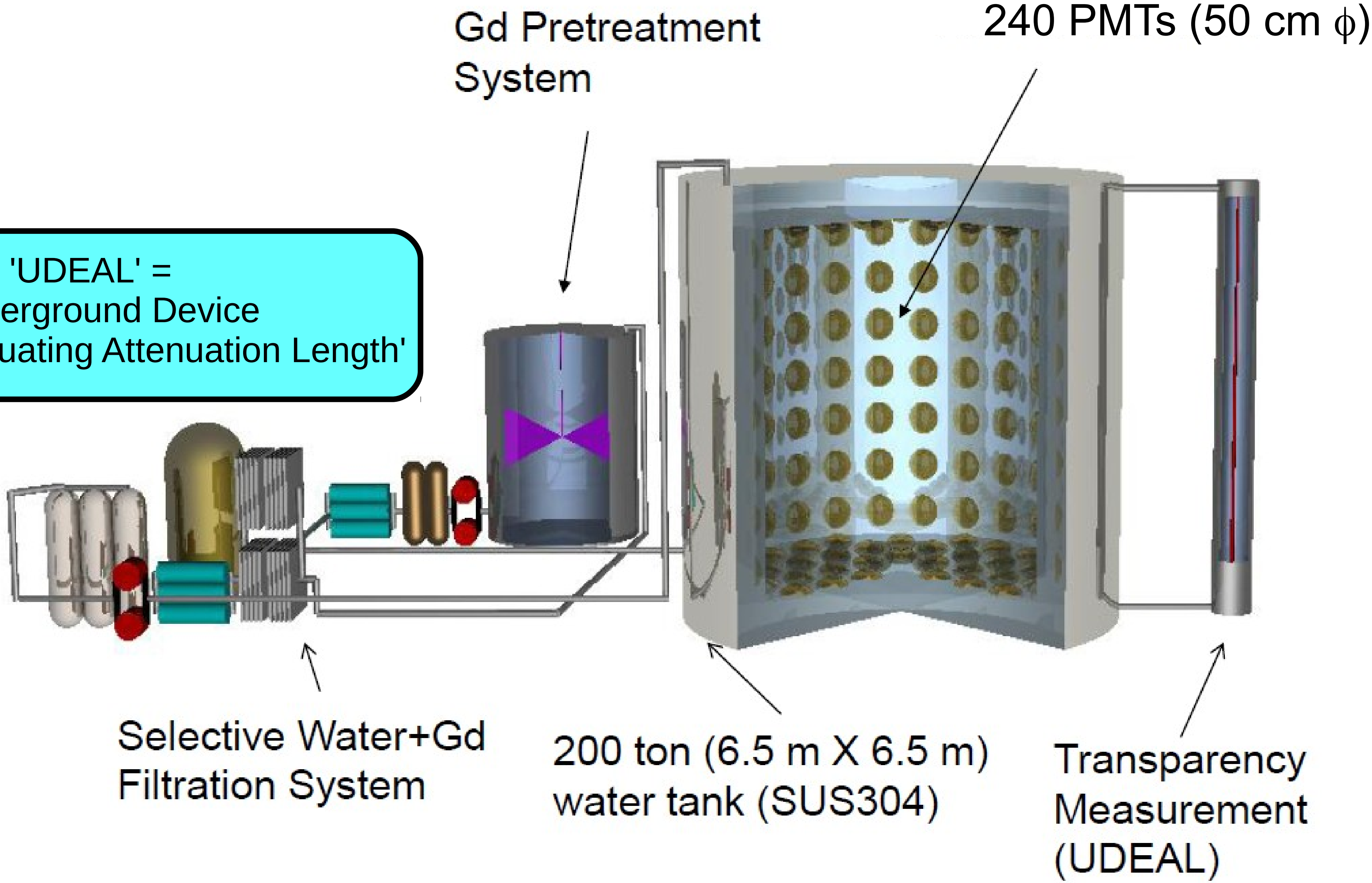
EGADS is a:

- 200 tonne R&D project, charged with establishing the technical viability of loading Gd into water Cherenkov detectors
- Uses $Gd_2[SO_4]_3$ (Gadolinium Sulphate) at 0.2% concentration
- Facility has its own water filtration system, 50 cm PMTs, DAQ, etc.

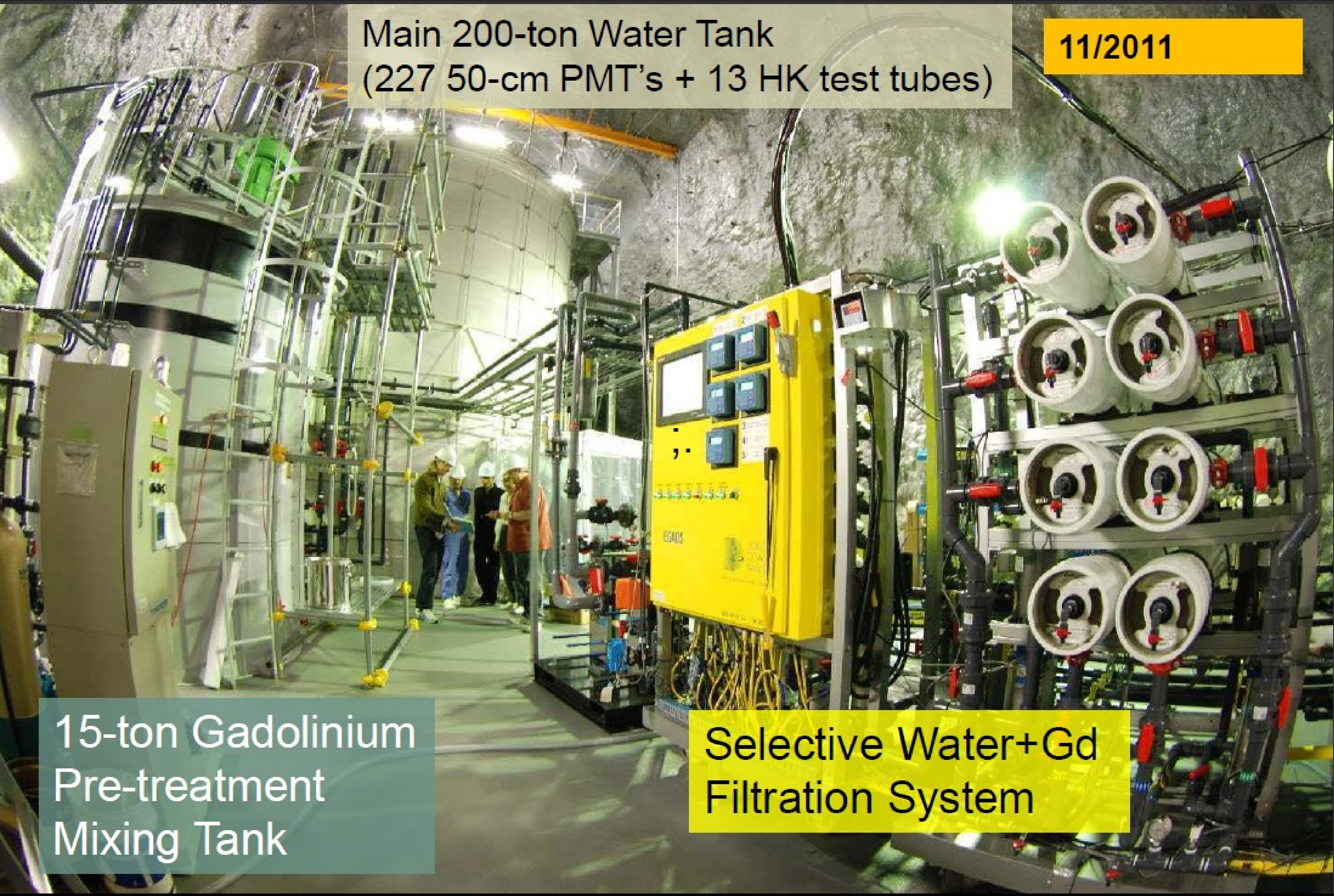


EGADS Facility

N.B. 'UDEAL' = 'Underground Device Evaluating Attenuation Length'



EGADS Facility



Upcoming Experiments:

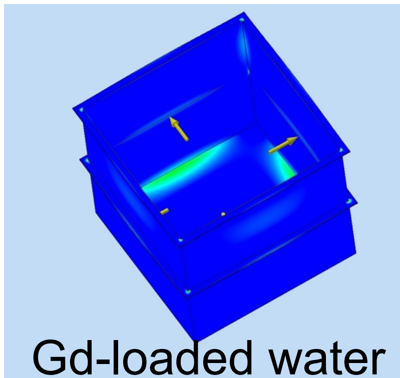
Now that the **concept** of Gd-loaded water Cherenkov experiments has been demonstrated and shown to be technically feasible, there are a host of upcoming experiments that plan to exploit it.

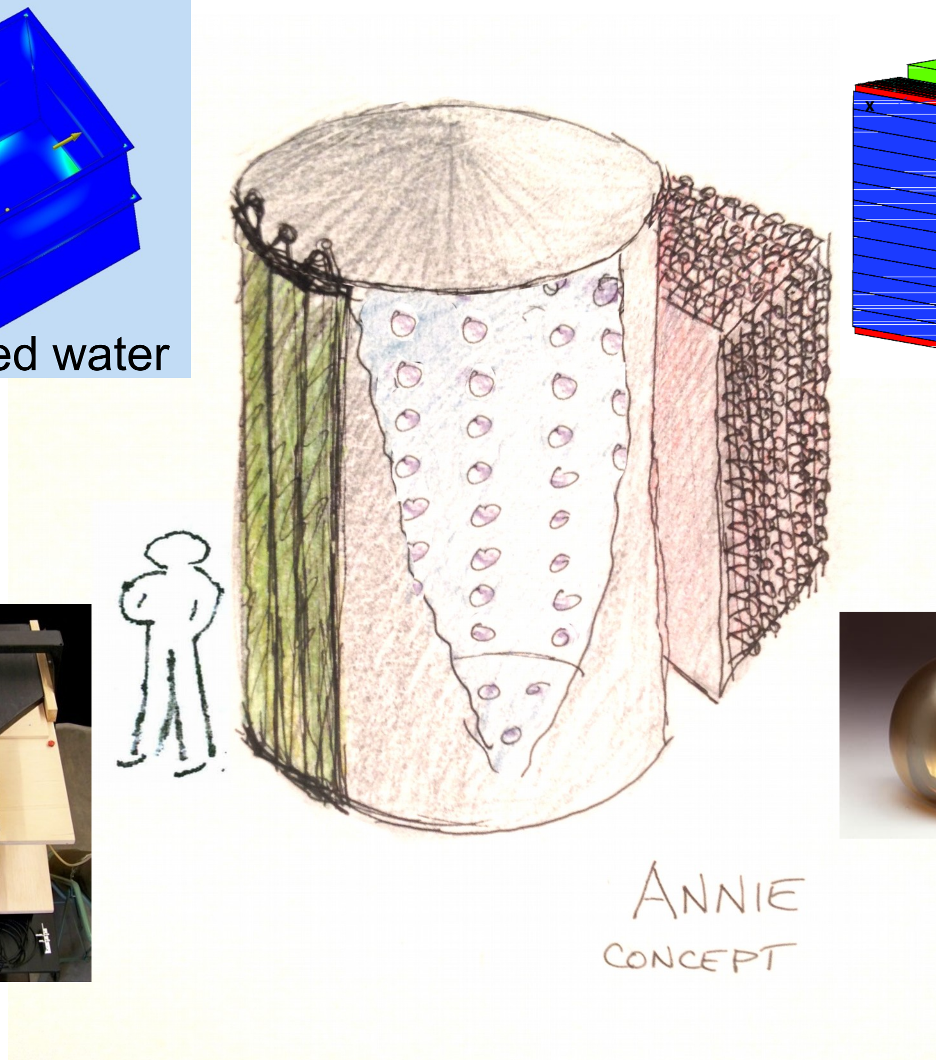
These include.....

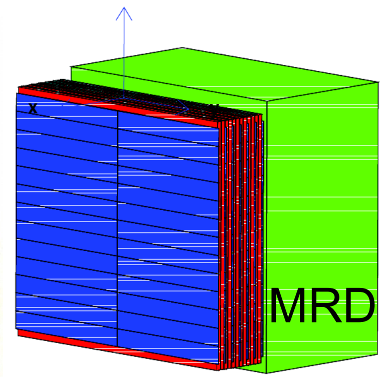
[*] “The Tempest”, by William Shakespeare (Act II, Scene 1)

The ANNIE Experiment

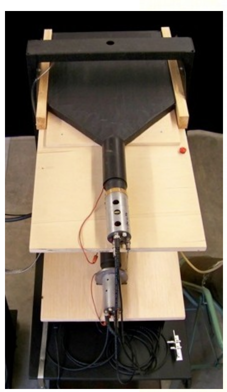
ANNIE: **A**ccelerator **N**eutrino-**N**ucleus **I**nteraction **E**xperiment







Upstream
μ veto



annie

SK-Gd

In 2020, the Super-Kamiokande collaboration added 0.02% $Gd_2[SO_4]_3$ to the detector. In 2022, it was raised to a concentration of 0.06%.

This opens up a new area of physics potential.

Physics goals include:
- Supernova relic neutrinos
- Identification of modes in a galactic supernova neutrino burst
- ν / $\bar{\nu}$ discrimination for atmospheric and accelerator neutrinos
- Reduced atmospheric background for proton decay searches

The next phase of T2K running will use SK-Gd as the far detector.

Back to non-proliferation

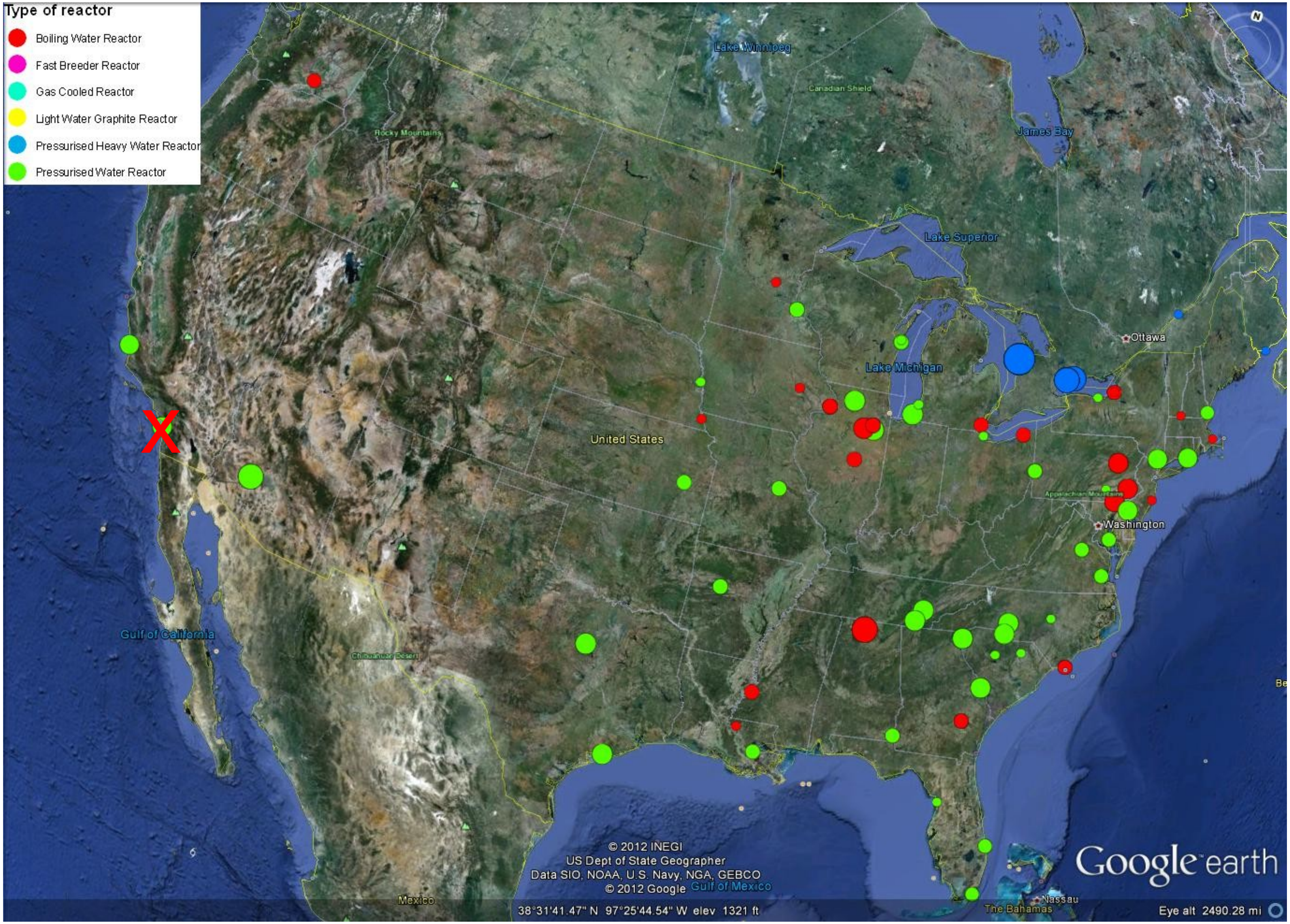
The ideal WATCHMAN prototype site requires:

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

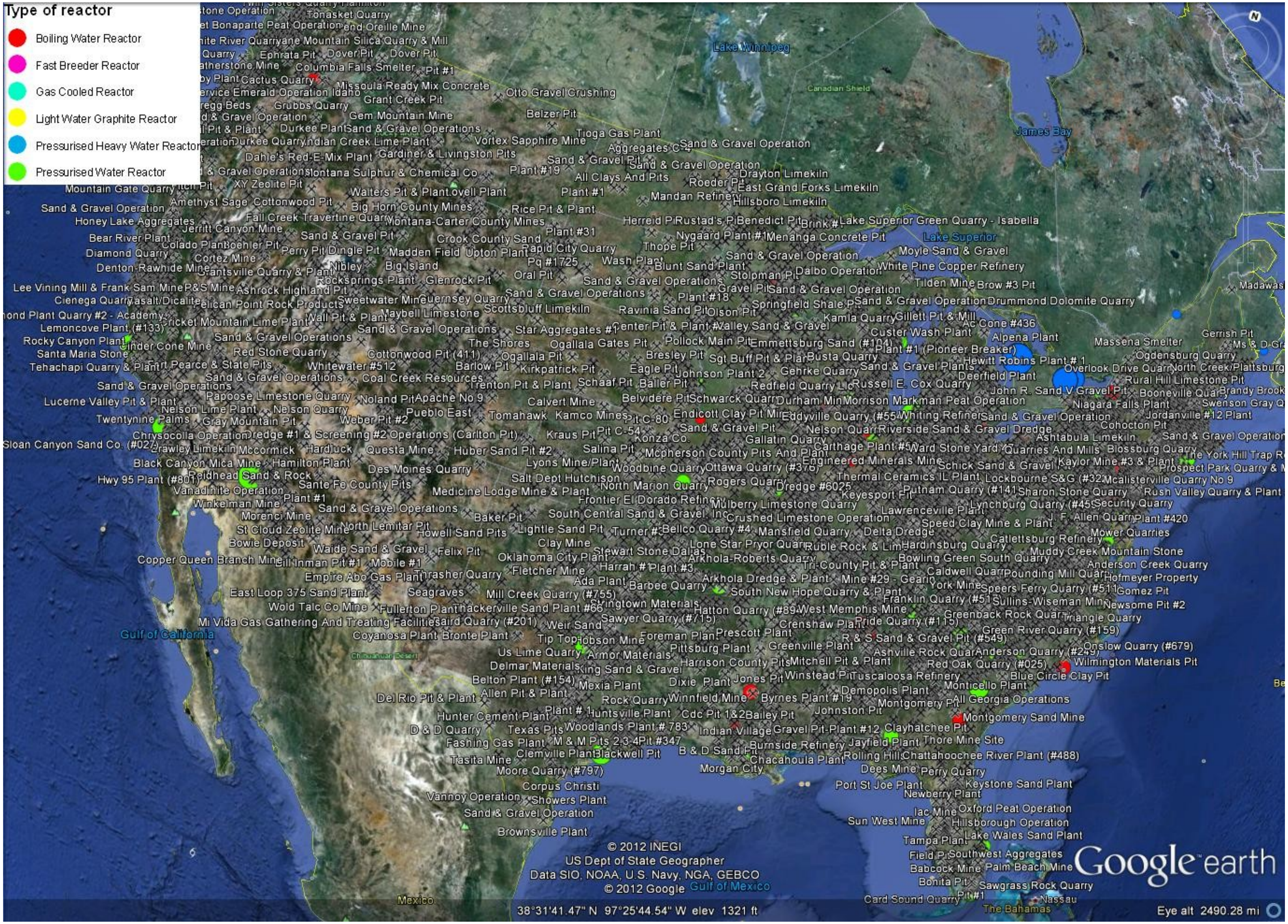
(b) a nuclear reactor

→ This places a significant constraint on the choice of site!

Map of US Power Reactors



Map of US Active Mines



Potential WATCHMAN Sites

The WATCHMAN prototype site requires:

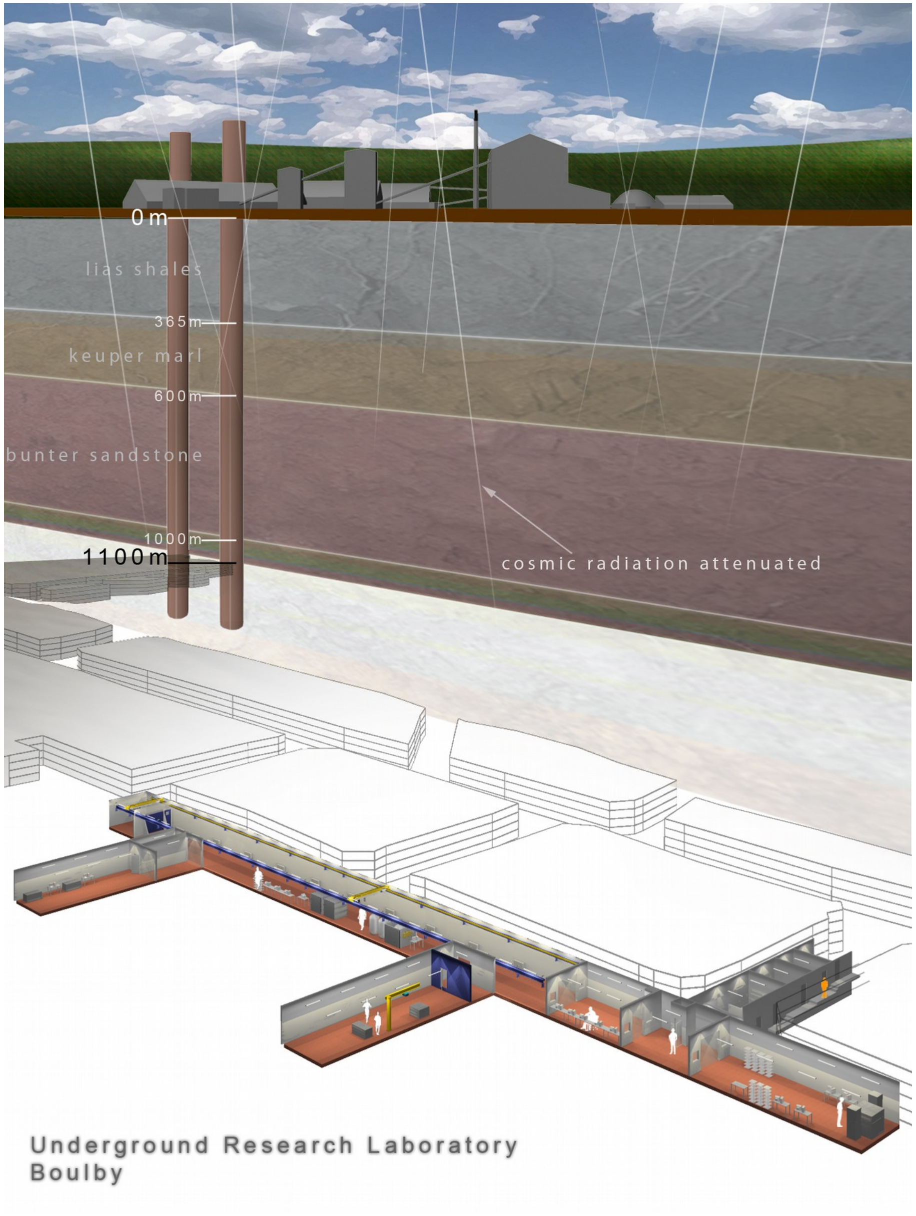
(a) an underground laboratory (or potential to build one) that is within ~30 km of

(b) a nuclear reactor

Search results:

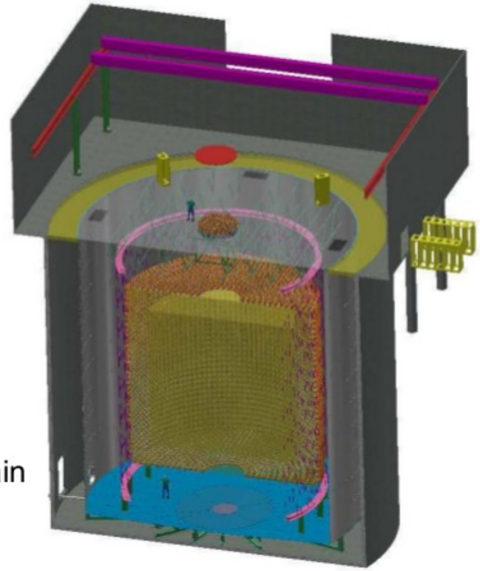
– Only <u>one</u> site in the USA satisfies criteria
– Can go to four if allow underwater deployment, or permit shallow sites with greater backgrounds
– Additionally, another candidate site in UK fits all criteria

STFC / Boulby Underground Lab



Depth:
1100 metres underground
2800 metres water equivalent
10^{-6} cosmic ray muon attenuation

Operating lab for > 20 years
Current lab from 2017

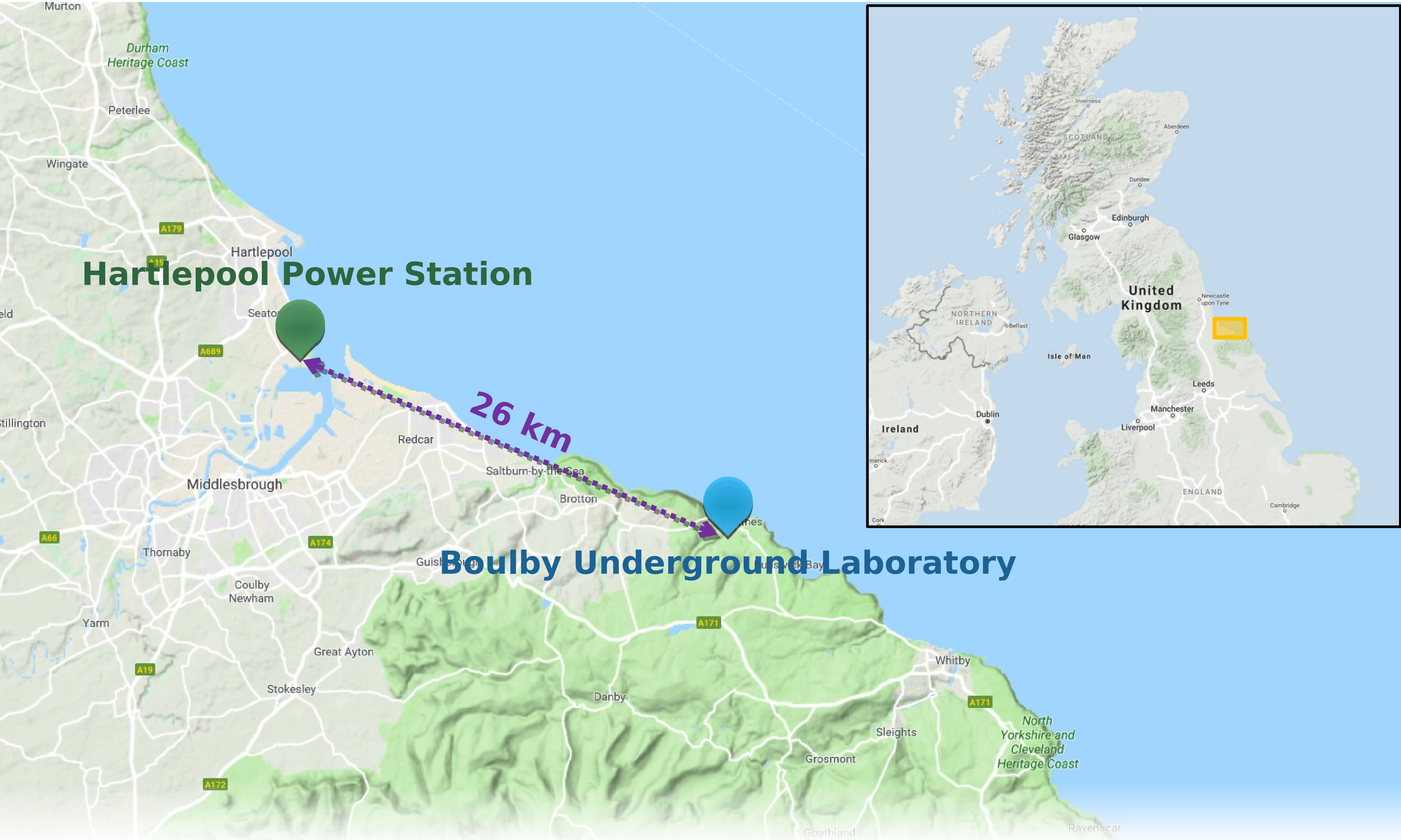


JG Boissevain Design

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

Proximity to Reactor(s)

The University Of Sheffield.

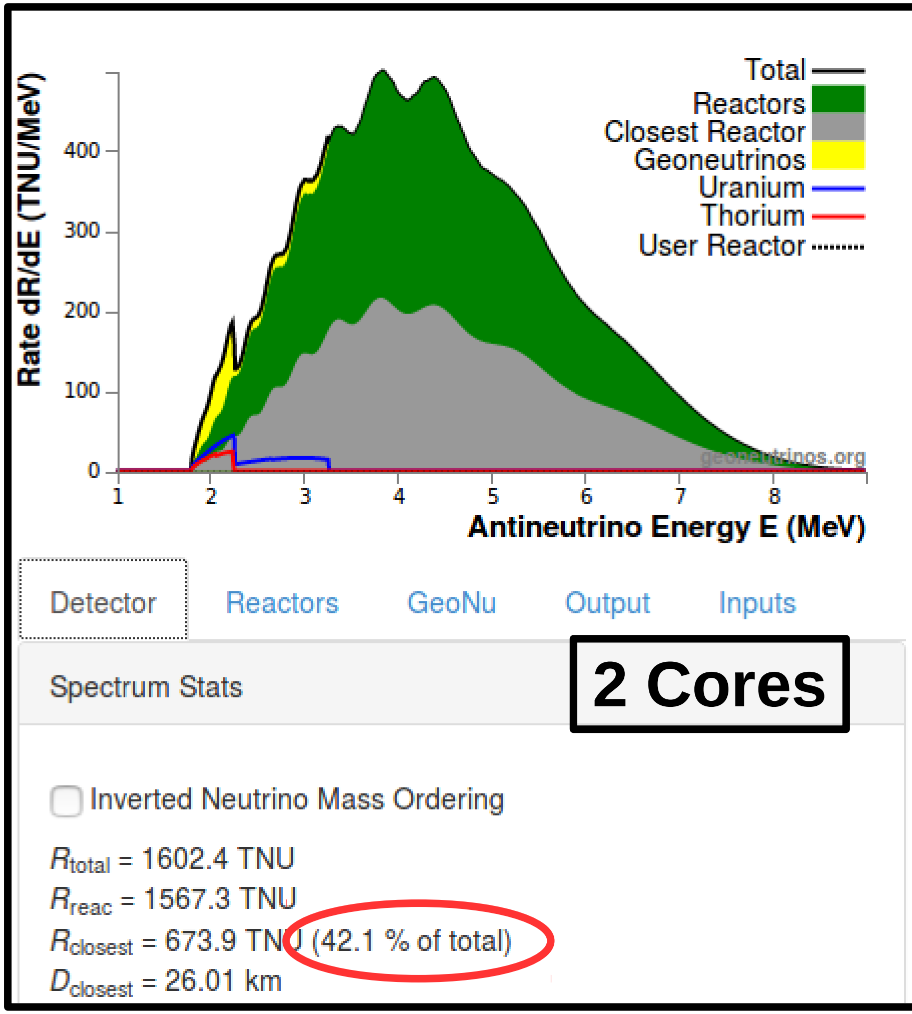


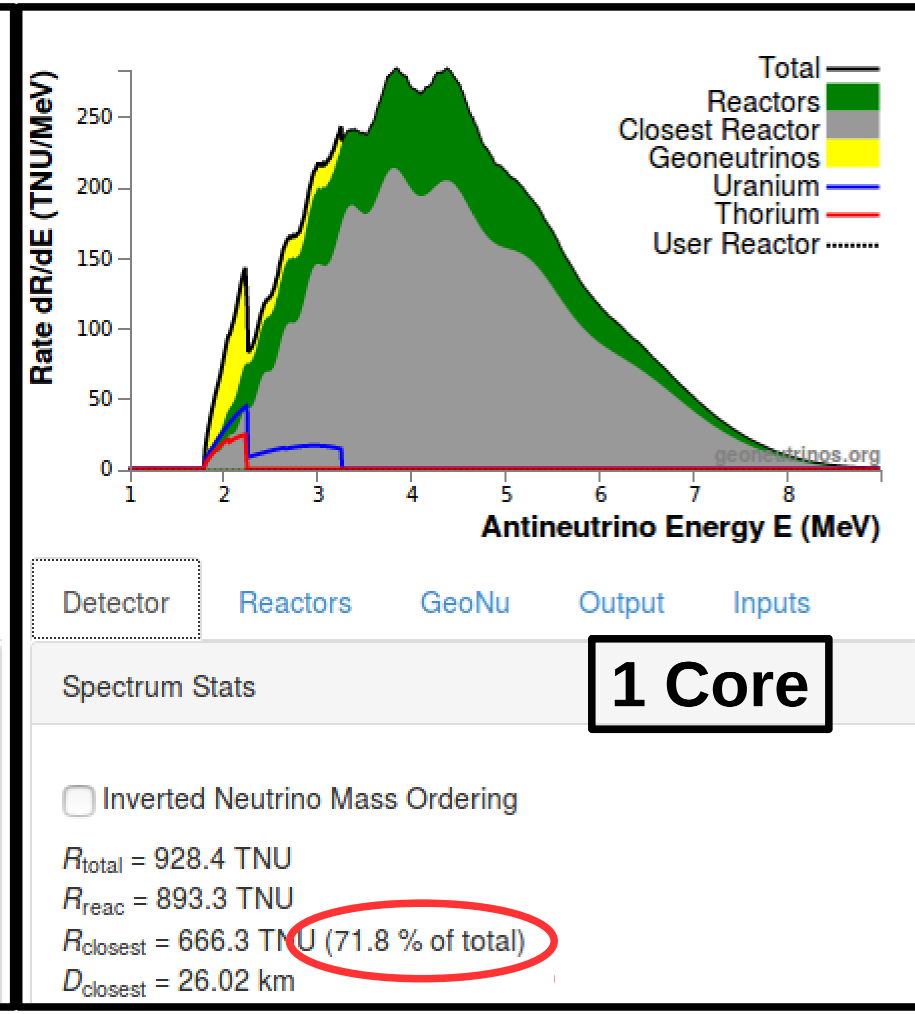
EDF Hartlepool Nuclear Plant

Dual-core reactor complex
Advanced gas-cooled reactors (AGR)
1550 MW_{th} per reactor core
~26 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

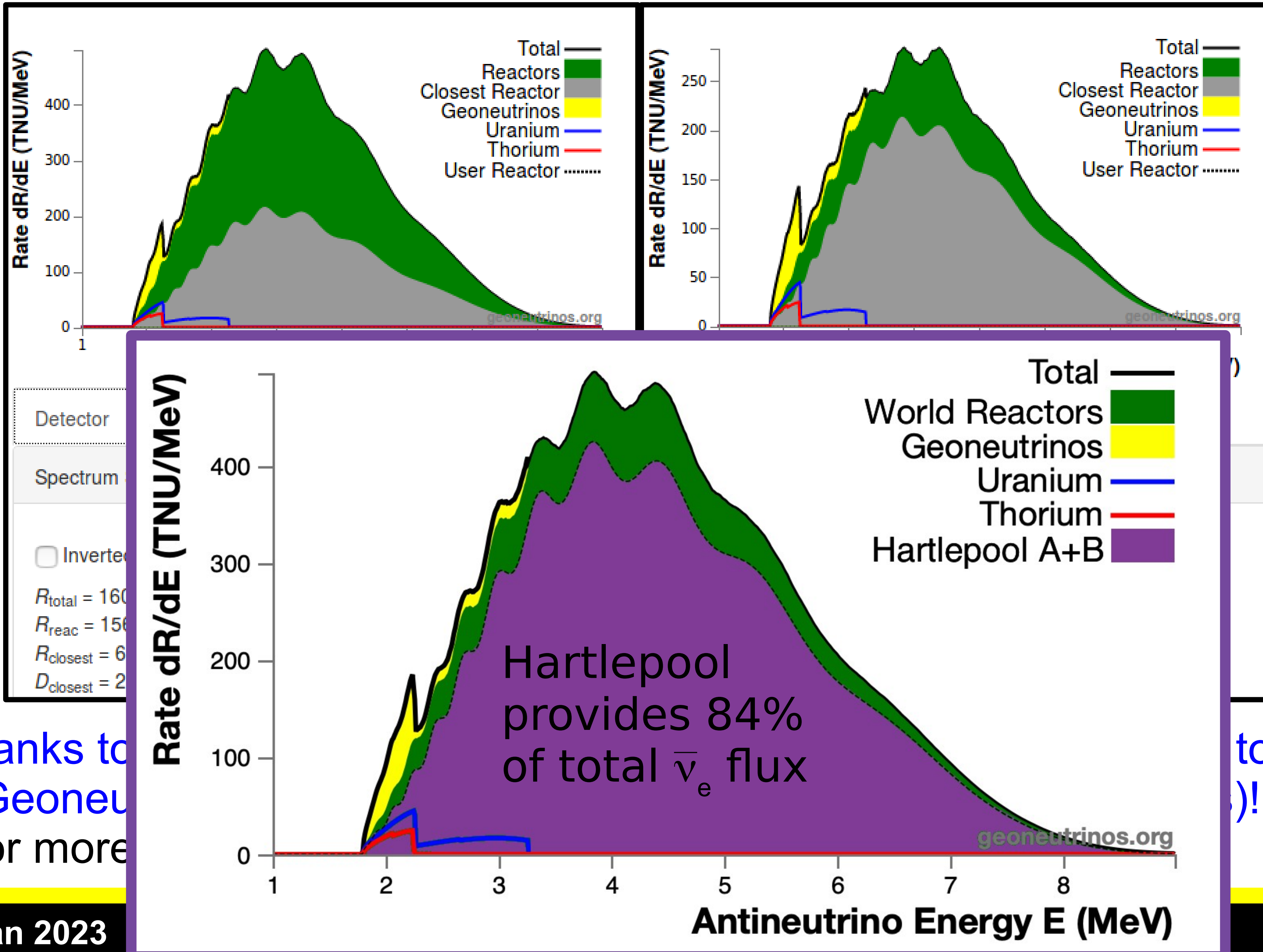
Hartlepool Signal @ Boulby





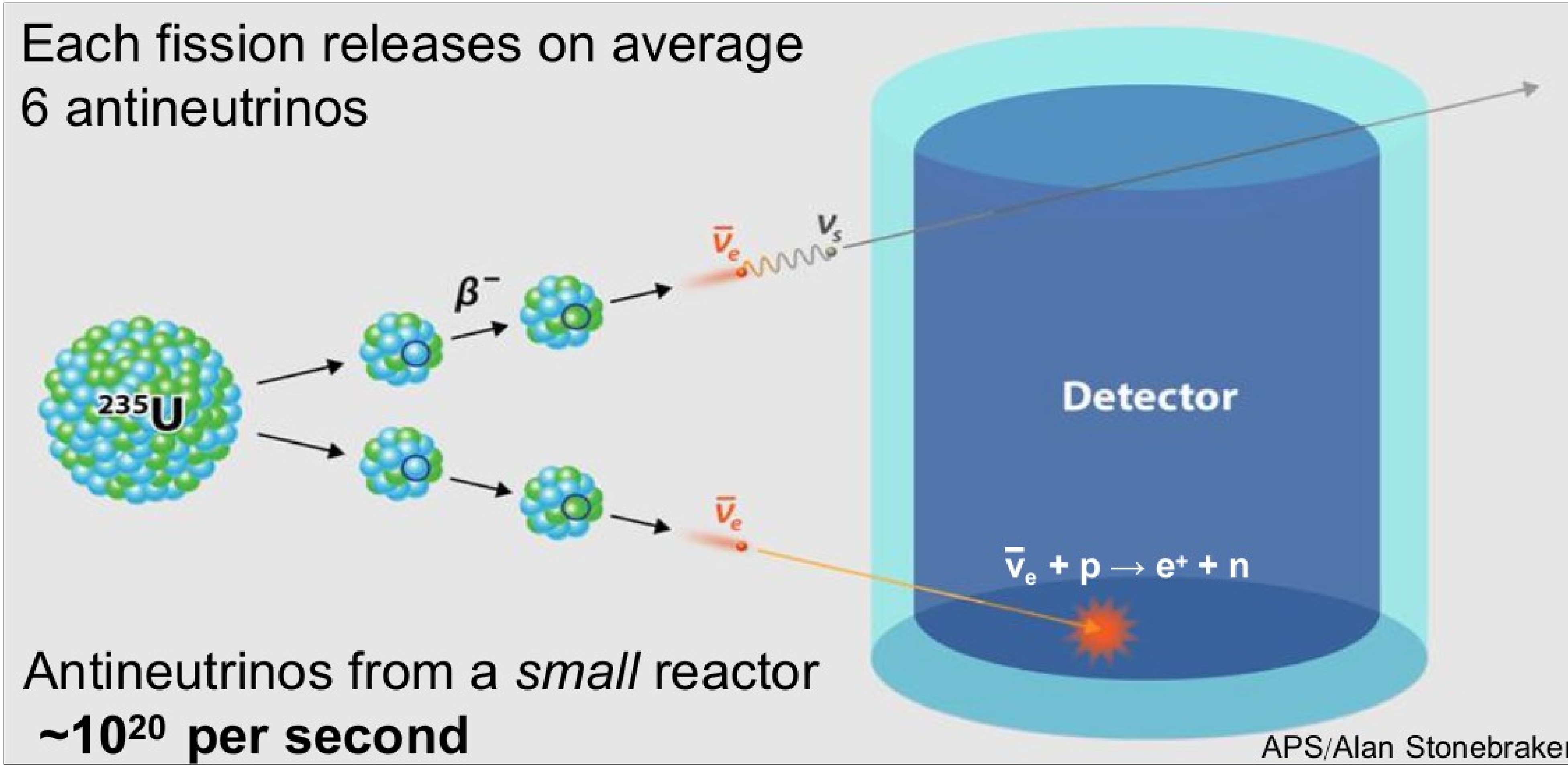
Thanks to Antineutrino Global Map project, there is now an online tool – Geoneutrinos.org – to get such reactor fluxes (and backgrounds)!
(For more detail, see S.Dye's preprint at **nucl-ex:1611.01575**)

Hartlepool Signal @ Boulby



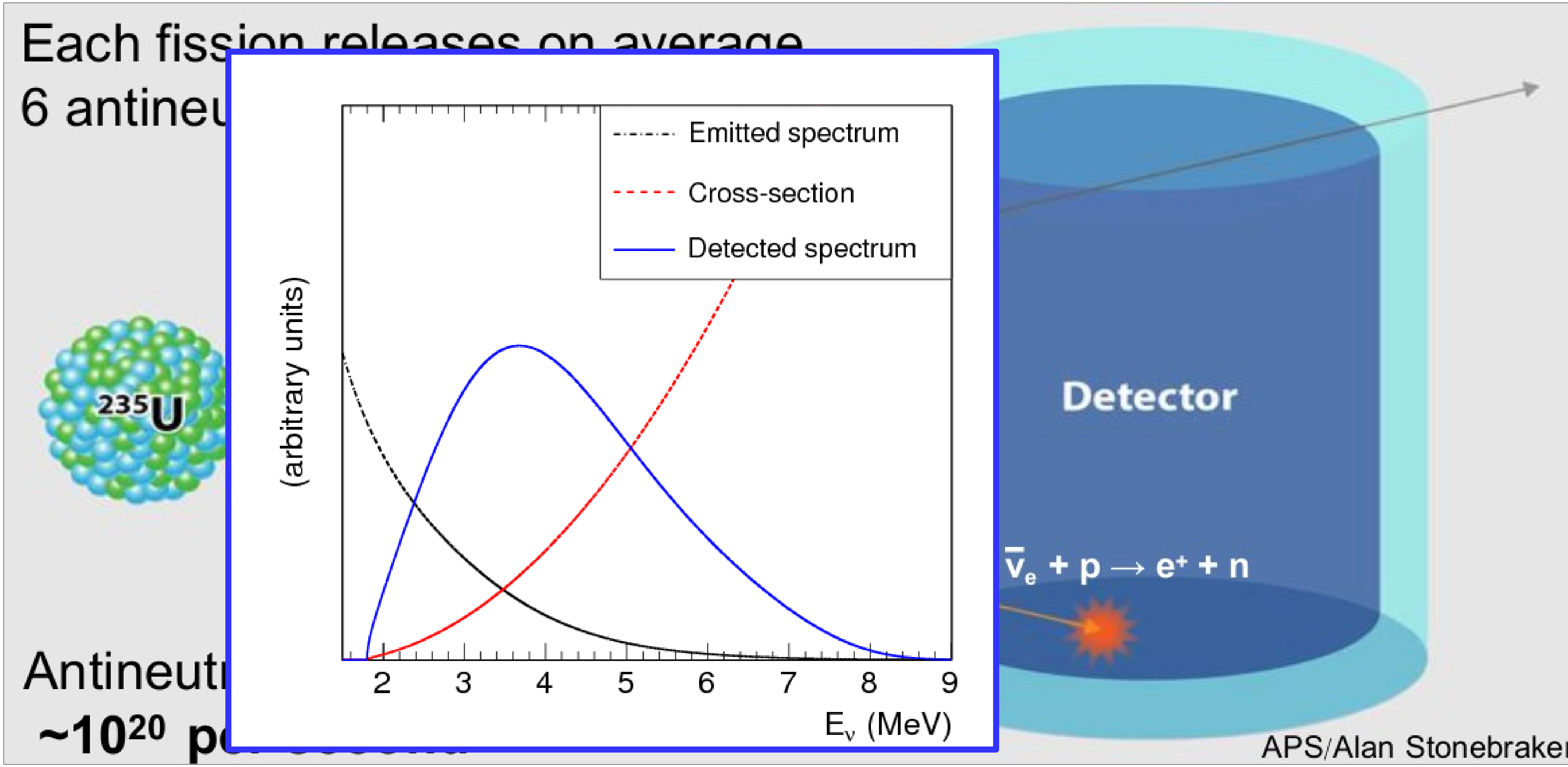
Thanks to … tool
– Geoneu…)!
(For more

WATCHMAN Concept



For a 3 GWth reactor complex (*e.g.*, Hartlepool), O(10^{21}) fissions per second, resulting in O(10^{22}) $\bar{\nu}_e$ emitted *isotropically* per second.

WATCHMAN Concept

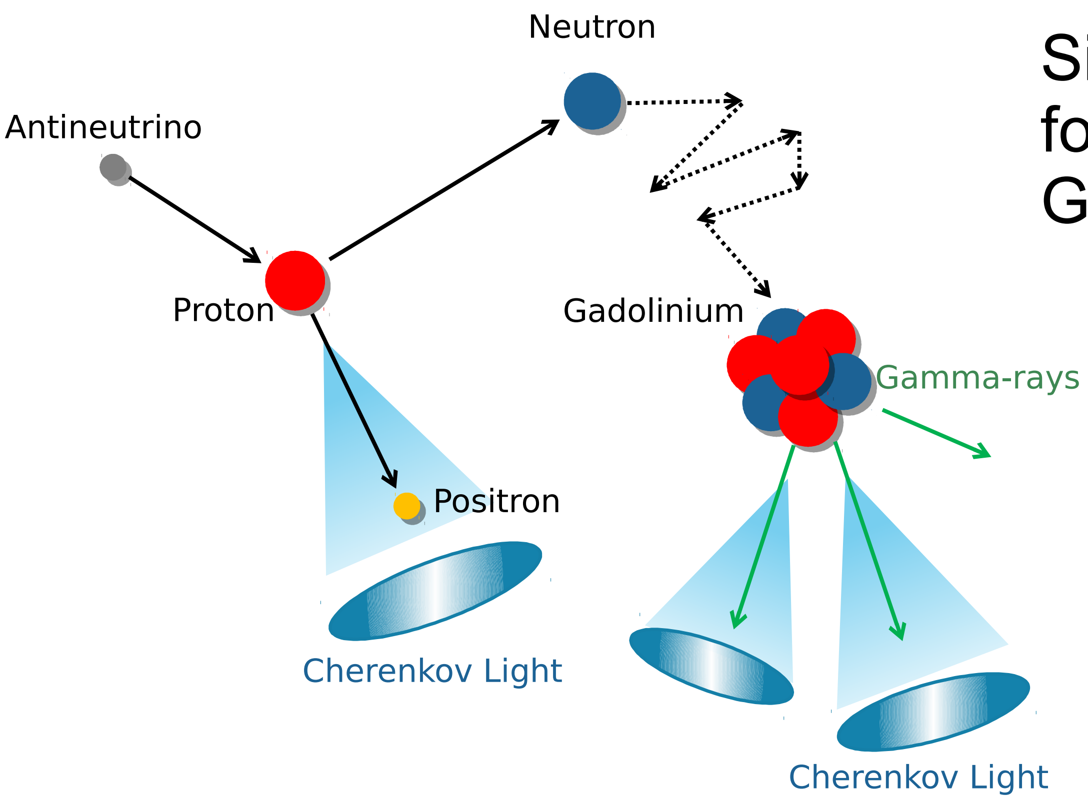


For a 3 GWth reactor complex (*e.g.*, Hartlepool), O(10^{21}) fissions per second, resulting in O(10^{22}) $\bar{\nu}_e$ emitted *isotropically* per second.

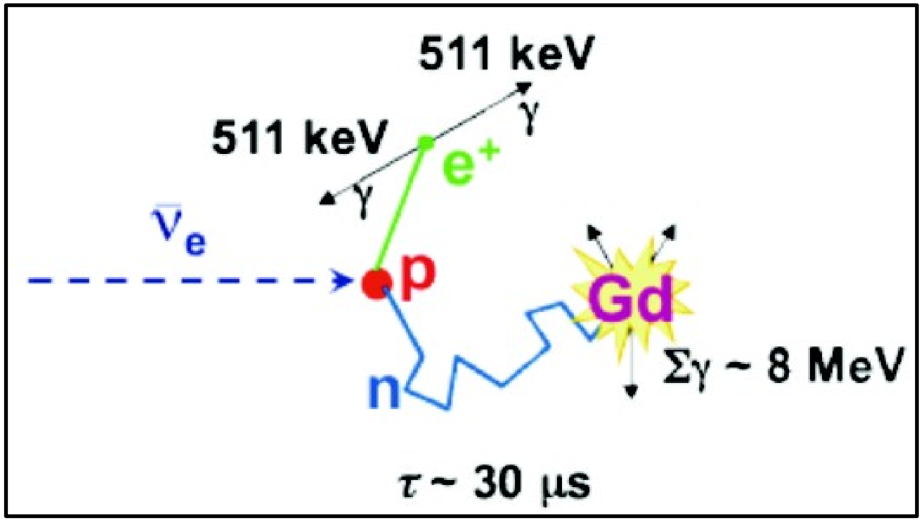
→ For 26 km standoff, expect “several” events per day per kilotonne

WATCHMAN Signal

The University Of Sheffield.



Signal is positron annihilation, followed by ~8 MeV γ cascade from Gd de-excitation ~30 μs after.



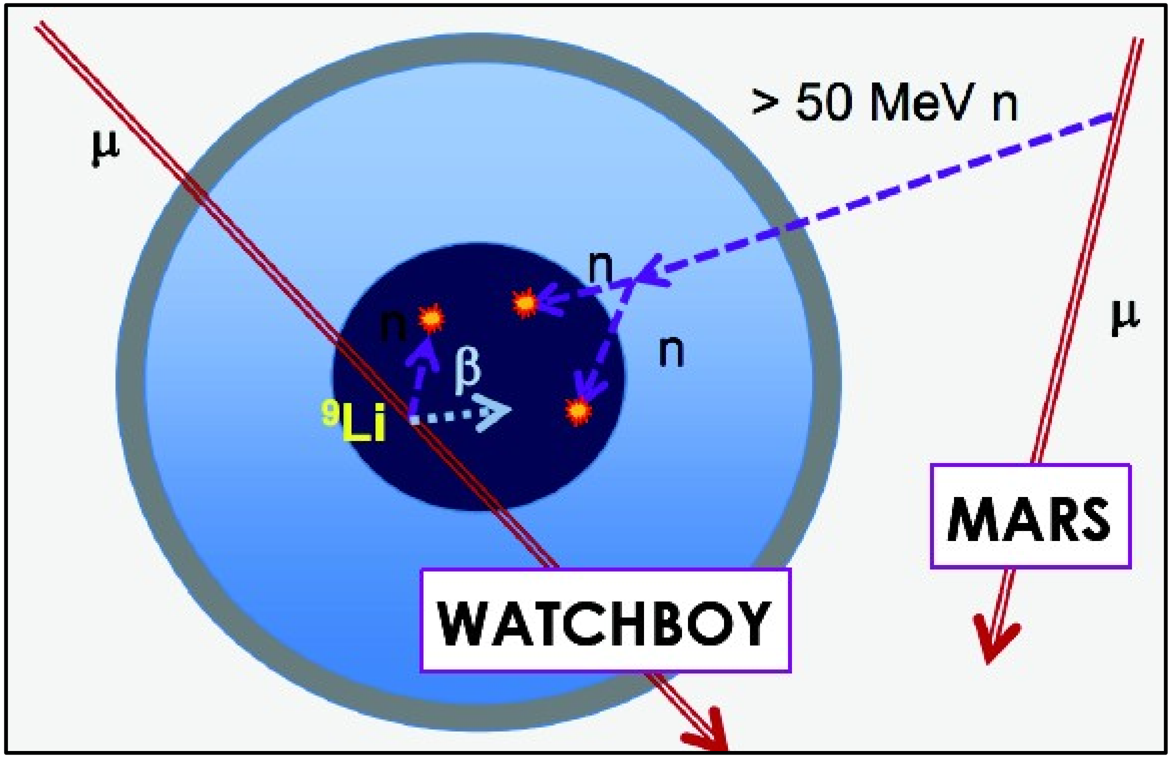
Experimental signature:

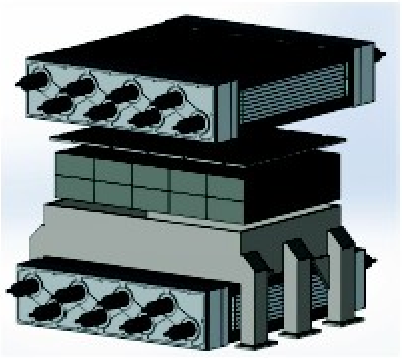
(a) exactly two Cherenkov flashes

(b) occurring within a ~100 μs window

(c) and also within a 1m^3 voxel

WATCHMAN Backgrounds





MARS

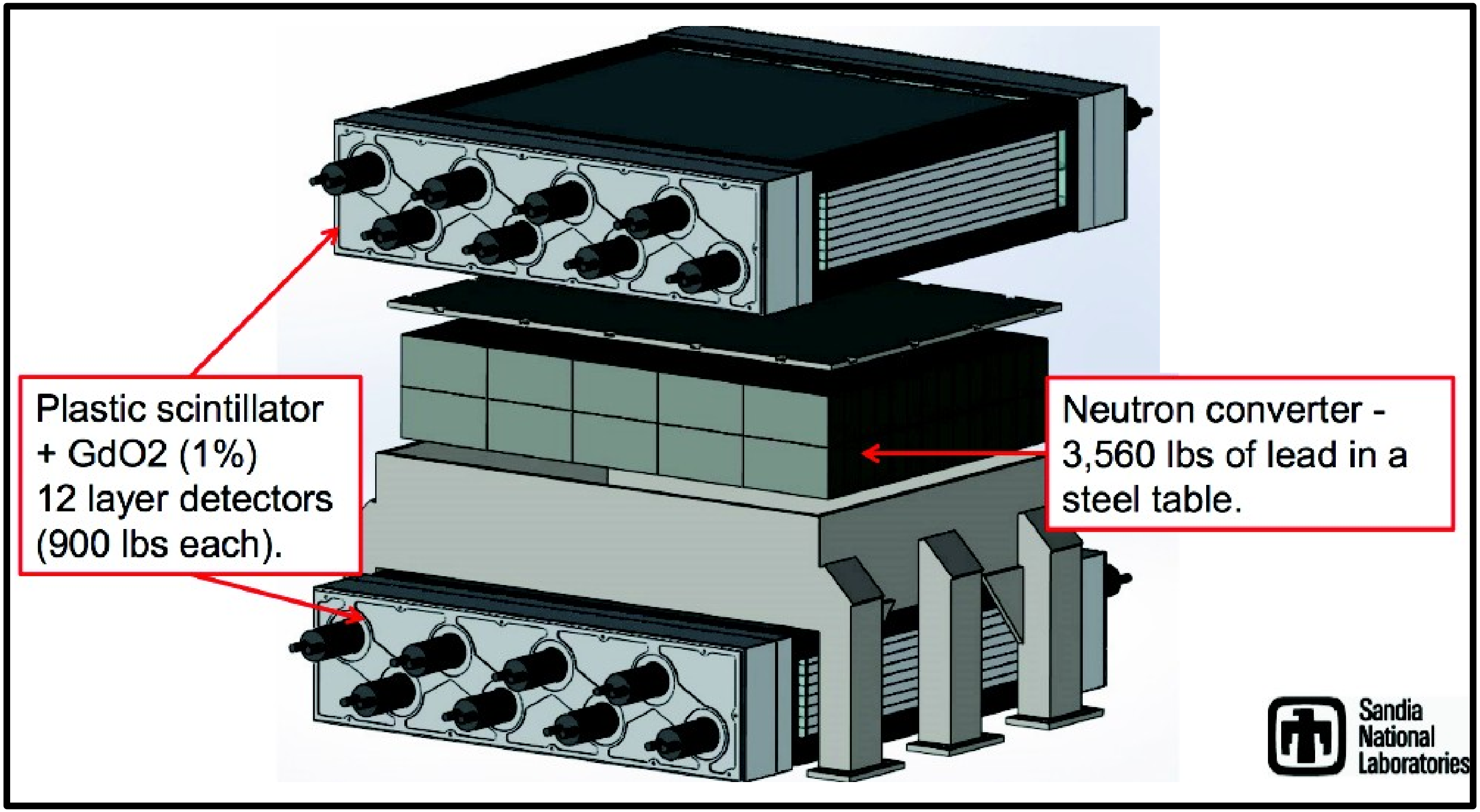
WATCHBOY

<u>Backgrounds sources:</u>

1) Real antineutrinos (*e.g.*, geoneutrinos)
2) Random coincidences
3) Muon-induced high energy neutrons
   → Can be measured with MARS
4) Long-lived radionuclide decays
   → Can be measured with WATCHBOY

BG Study: MARS

MARS = Multiplicity And Recoil Spectrometer

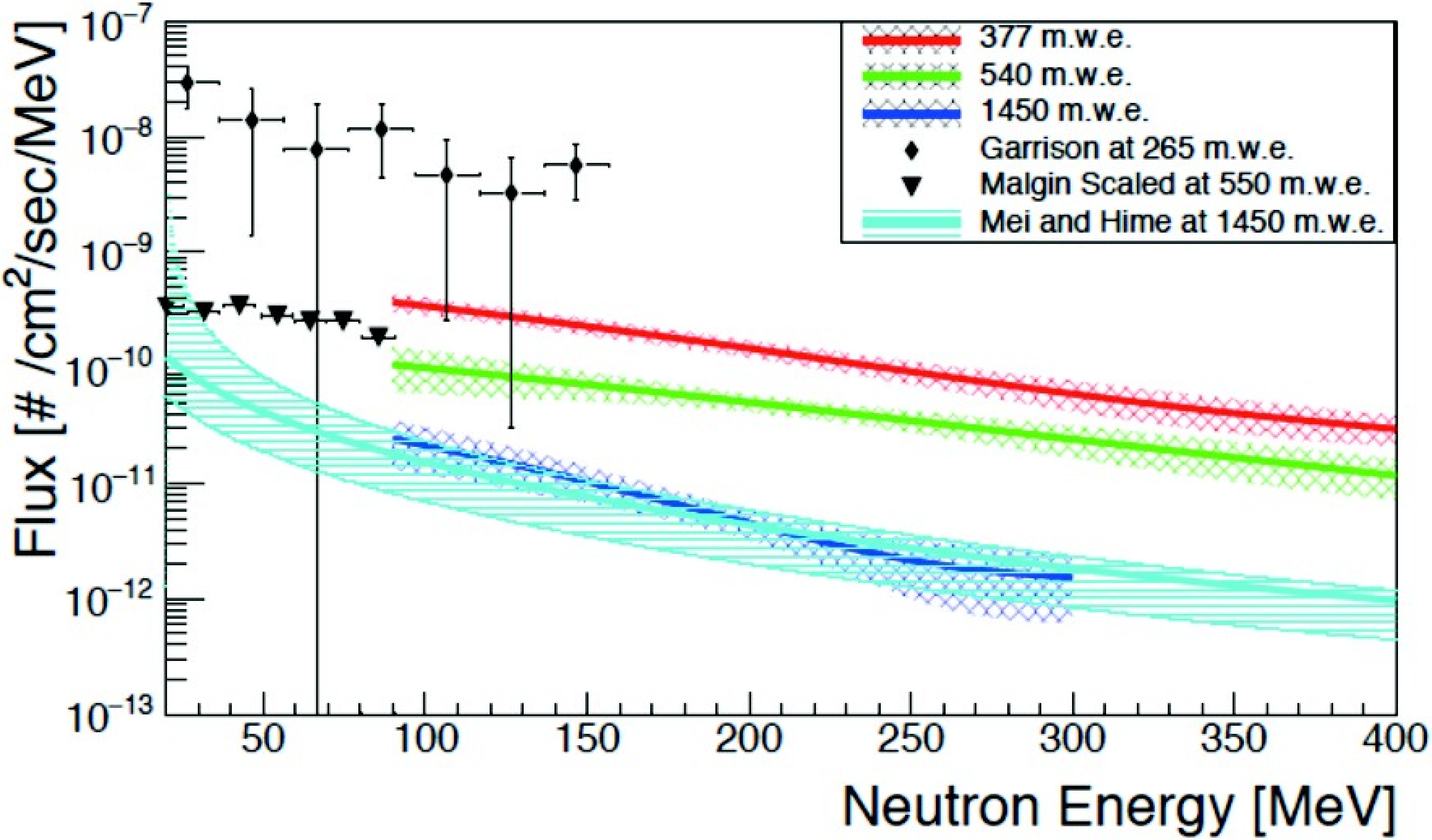


- A single fast neutron can produce a multiplicity of particles that can mimic an antineutrino signal in water
- Muon veto rejects muon-induced neutron production within detector

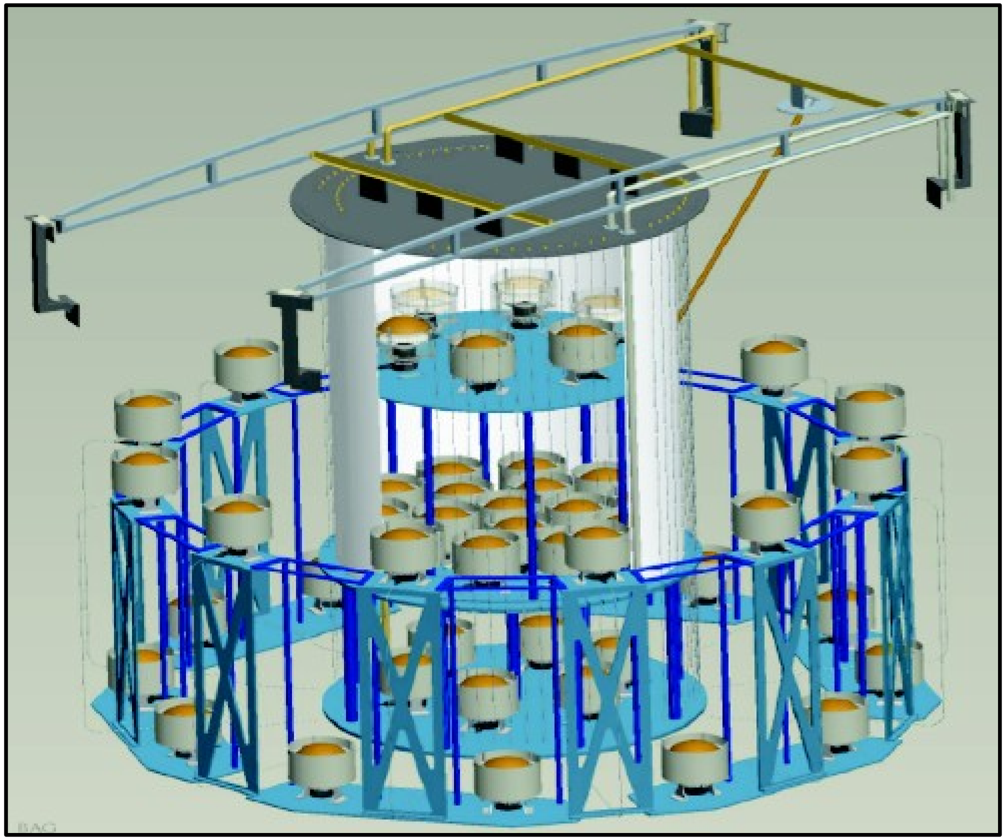
MARS Results

The University Of Sheffield.

Data taken from 2013 – 2015 at KURF (Kimballton, Virginia)



BG Study: WATCHBOY



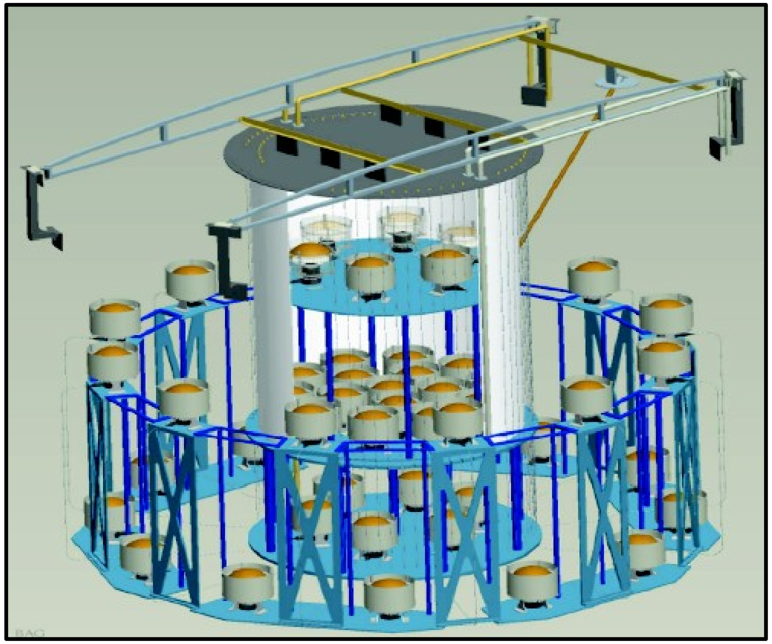
WATCHBOY is a 'mini-WATCHMAN' ('WATCHMANino'?) with:

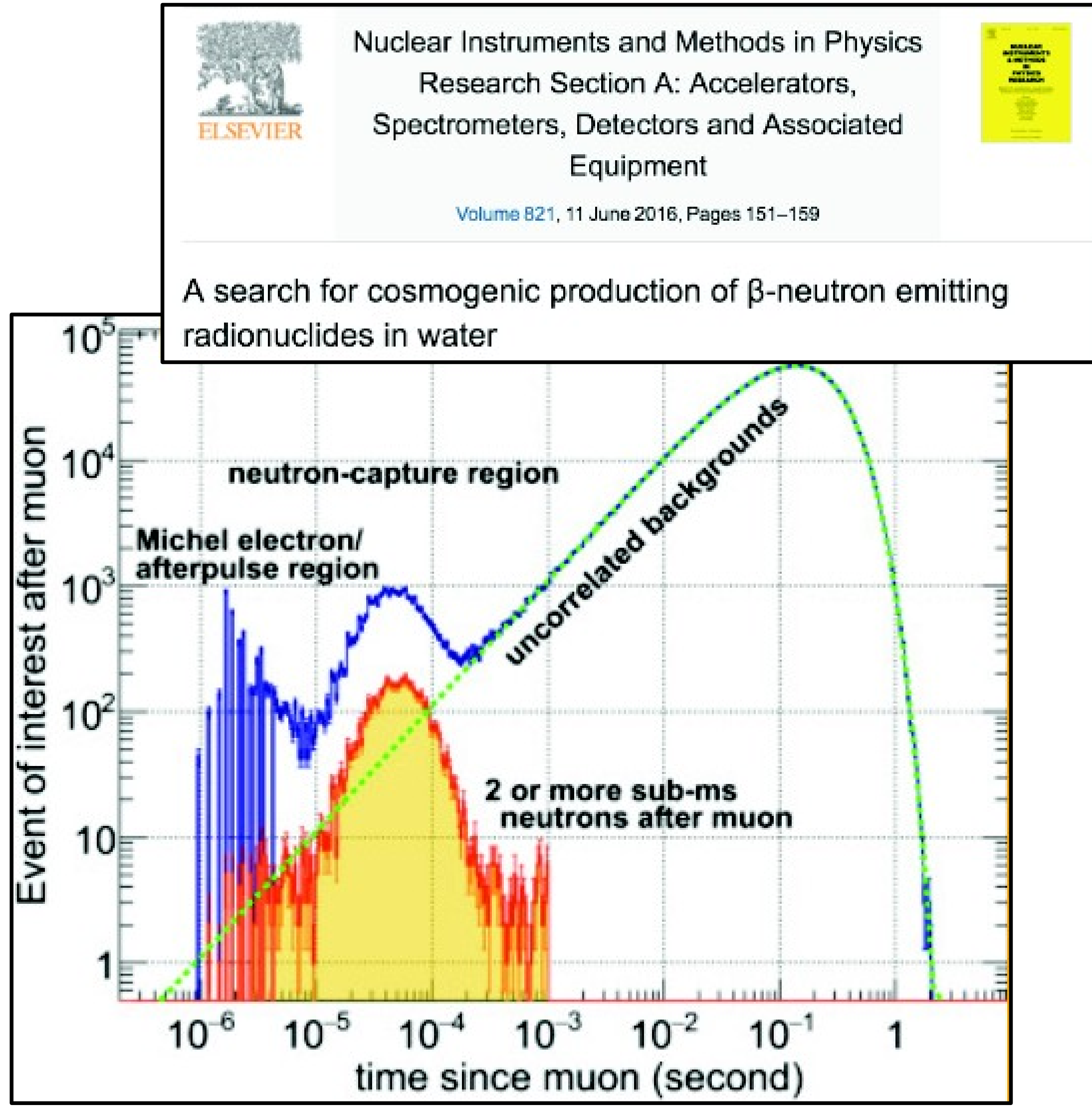
- 2 tonne target (water + Gd_2Cl_3)
- 10 tonne veto (pure water)

Built to measure long-lived radionuclides (*e.g.*, ^{9}Li, ^{8}He)

Event is tagged with preceeding muon; allows removal of nearly all backgrounds due to pile-up from other muons.

WATCHBOY Results





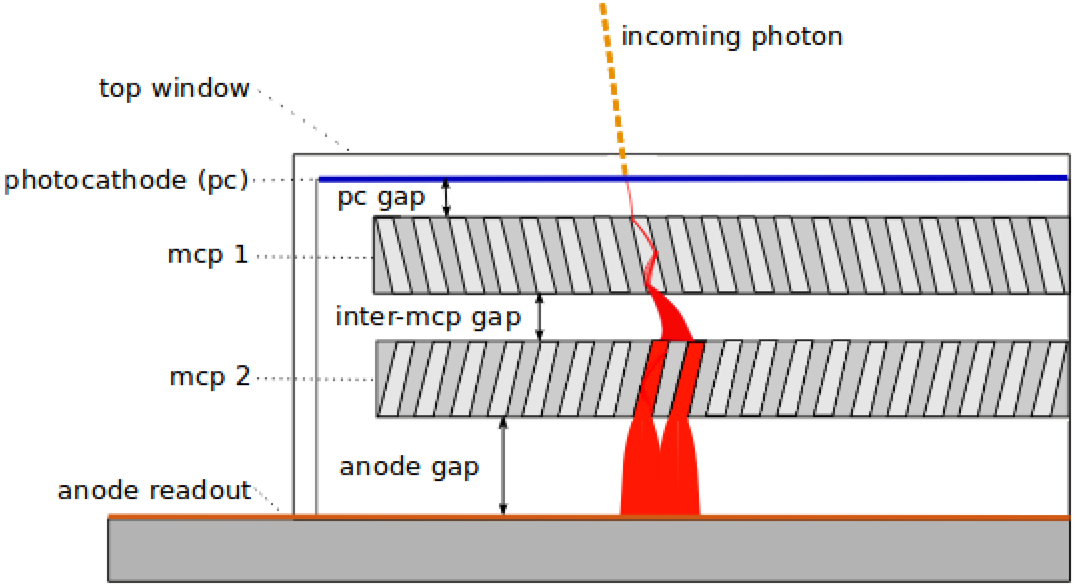
The uncorrelated events are fit between 1 ms and 2 s.

Good agreement between data and expectation!

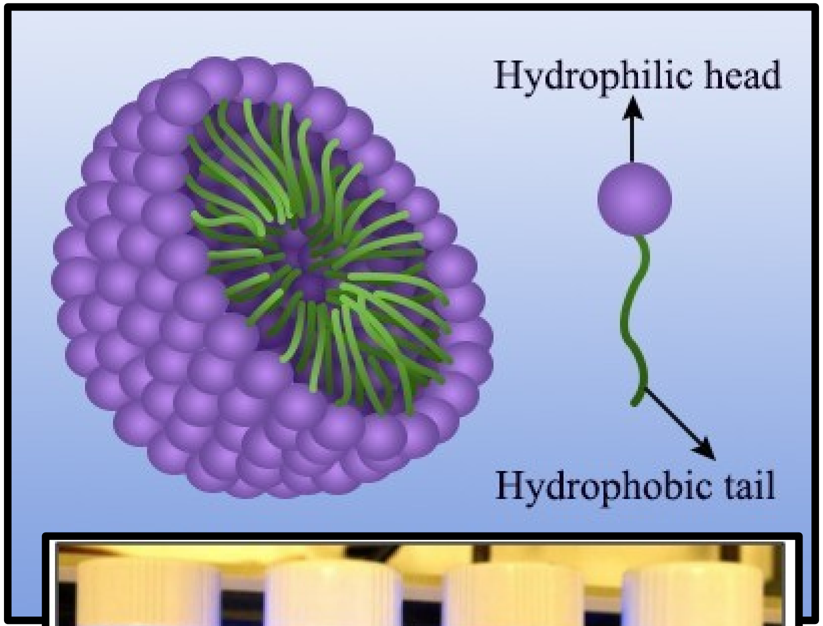
Additional Technologies

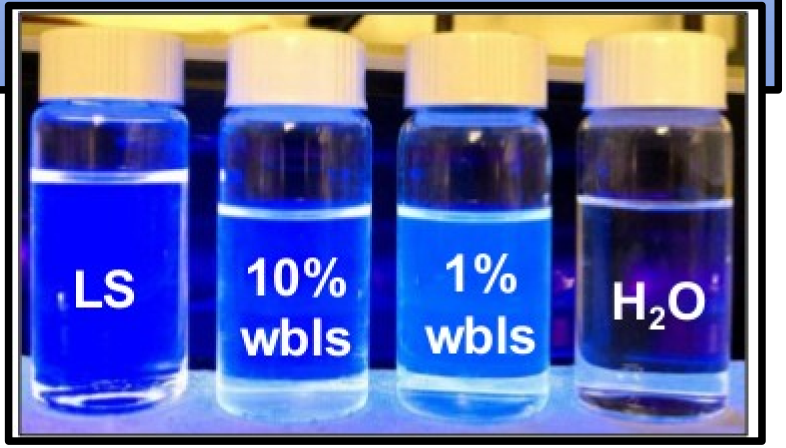
We are exploring other options for enhanced detection technologies:

Large Area Picosecond Photo-Detectors (LAPPDs):



Water-based Liquid Scintillator (WbLS):





Reactor Sensitivity

• Aggregate detection of the world's reactor neutrino flux was detected by the SNO+ collaboration during water phase (arXiv:2210.14154).

• For non-proliferation purposes, detection of a single site is required
- Ongoing efforts at Super-Kamiokande, exploiting the Gd loading

• Sensitivity studies were conducted for a proposed Gd+H2O and Gd+WbLS deployment at the STFC Boulby Underground Laboratory
- Reactor complexes considered are shown in the map

Reactor Sensitivity

- Sensitivity studies were conducted for a proposed Gd+H2O and Gd+WbLS deployment at the STFC Boulby Underground Laboratory
    - Reactor complexes considered are shown in the map

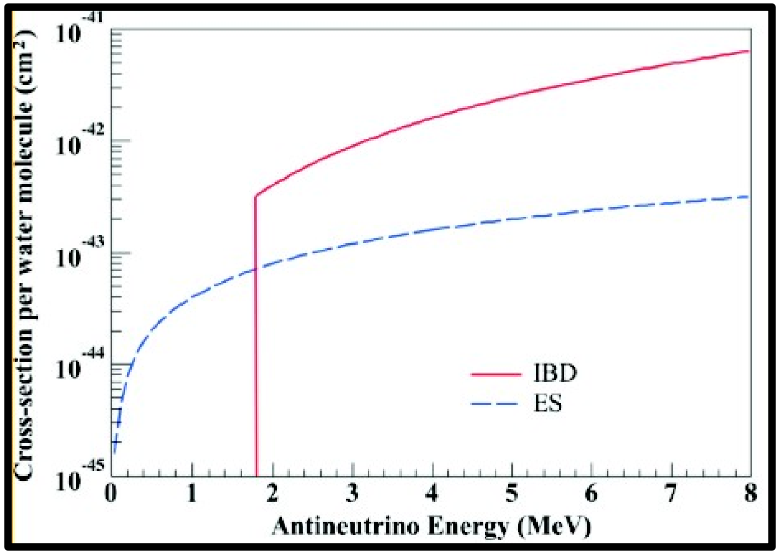
- Results in table below are from a recent paper (arXiv:2210.11224) submitted to *Phys. Rev. Applied*

TABLE VI: Cobraa results summary for anomaly detection - dwell time in days for rejection of the background-only hypothesis to 3σ significance assuming normal reactor operation.

Detector	Hartlepool 1 & 2	Hartlepool 1	Heysham 1 & 2	Heysham 2 + Torness	Heysham 2
16 m Gd-H_2O	12	61	2327	3488	8739
16 m Gd-WbLS	7	35	738	1022	3008
22 m Gd-H_2O	3	11	241	232	985
22 m Gd-WbLS	2	8	152	192	647

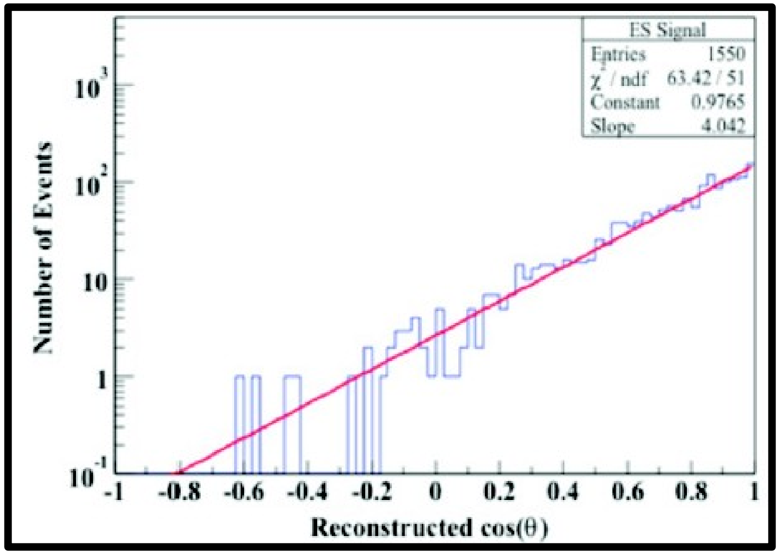
Directionality

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

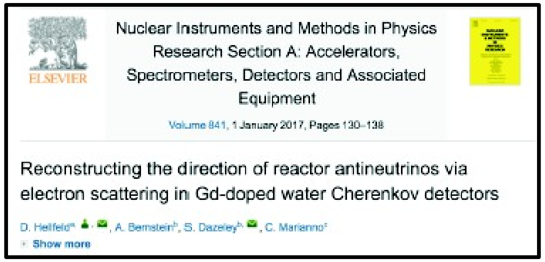


Benefits:

- 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.



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

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

D. Hellfeld[a], A. Bernstein[b], S. Dazeley[b], C. Marianno[c]

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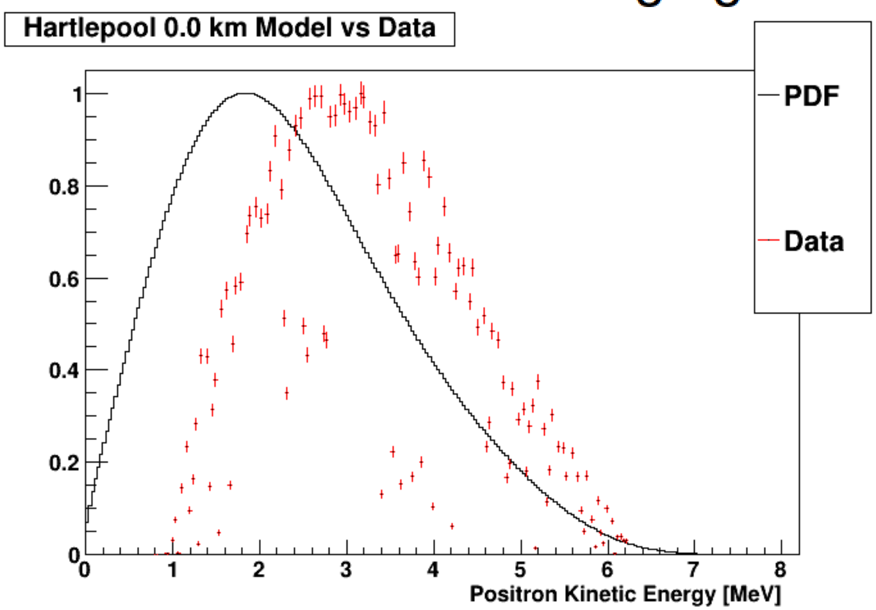
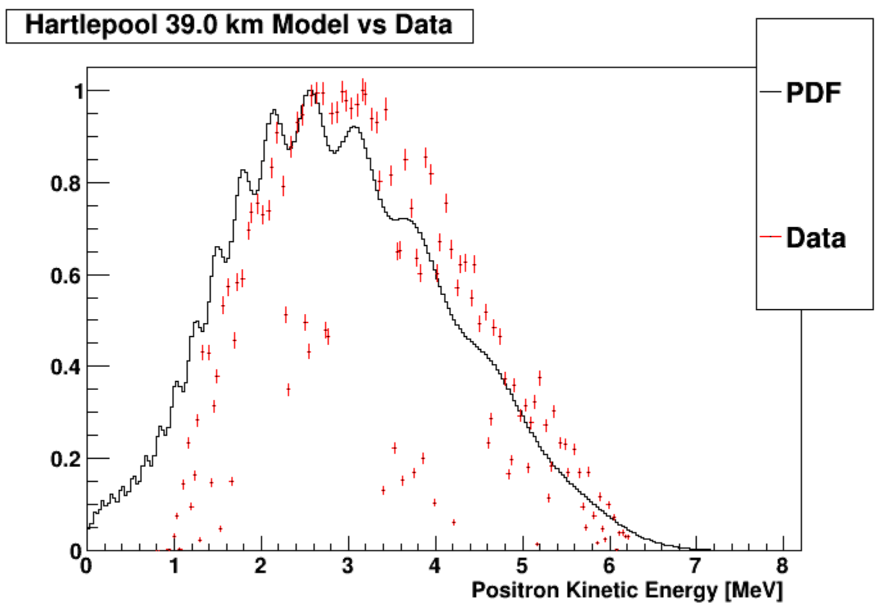
Reactor ranging

- Reactor ranging relies on the fact that neutrinos carry information about their distance travelled, in the form of oscillation probabilities
- Two ranging analyses were attempted – minimum χ^2 and Fourier analysis
- In general, the χ^2 method worked well for nearby reactors (< 50 km), but could not handle low signal-to-noise ratios at greater distances
- In contrast, the Fourier analysis is more robust at greater distances, but cannot resolve the wiggles for nearby reactors (see below)
- WbLS is not the ideal medium for such analysis; pure liquid scintillator would be better suited to reactor ranging.





Status & Summary

- **Antineutrinos offer potential for remote reactor monitoring for non-proliferation purposes**
  - Gadolinium-loaded water is a mature technology ready for use
  - Alternative technologies (*e.g.*, gadolinium-loaded water-based liquid scintillator) under development

- **Initial observations of remote reactors happening <u>now</u>!**
  - Aggregate detection by SNO+
  - Single site observation being attempted by Super-Kamiokande

- **The WATCHMAN collaboration is pursuing the non-proliferation goal**
  - Significant studies done for the STFC Boulby Underground Laboratory
  - This option brought to an end when EDF announced closure of all AGR reactors by 2028
  - Facility at Boulby still being explored for dark matter (XLZD), etc.
  - Collaboration now exploring alternative options for non-proliferation in USA
  - Technology development (LAPPDs, Gd+WbLS) ongoing at Boulby via the BUTTON testbed facility

Thank you for listening!