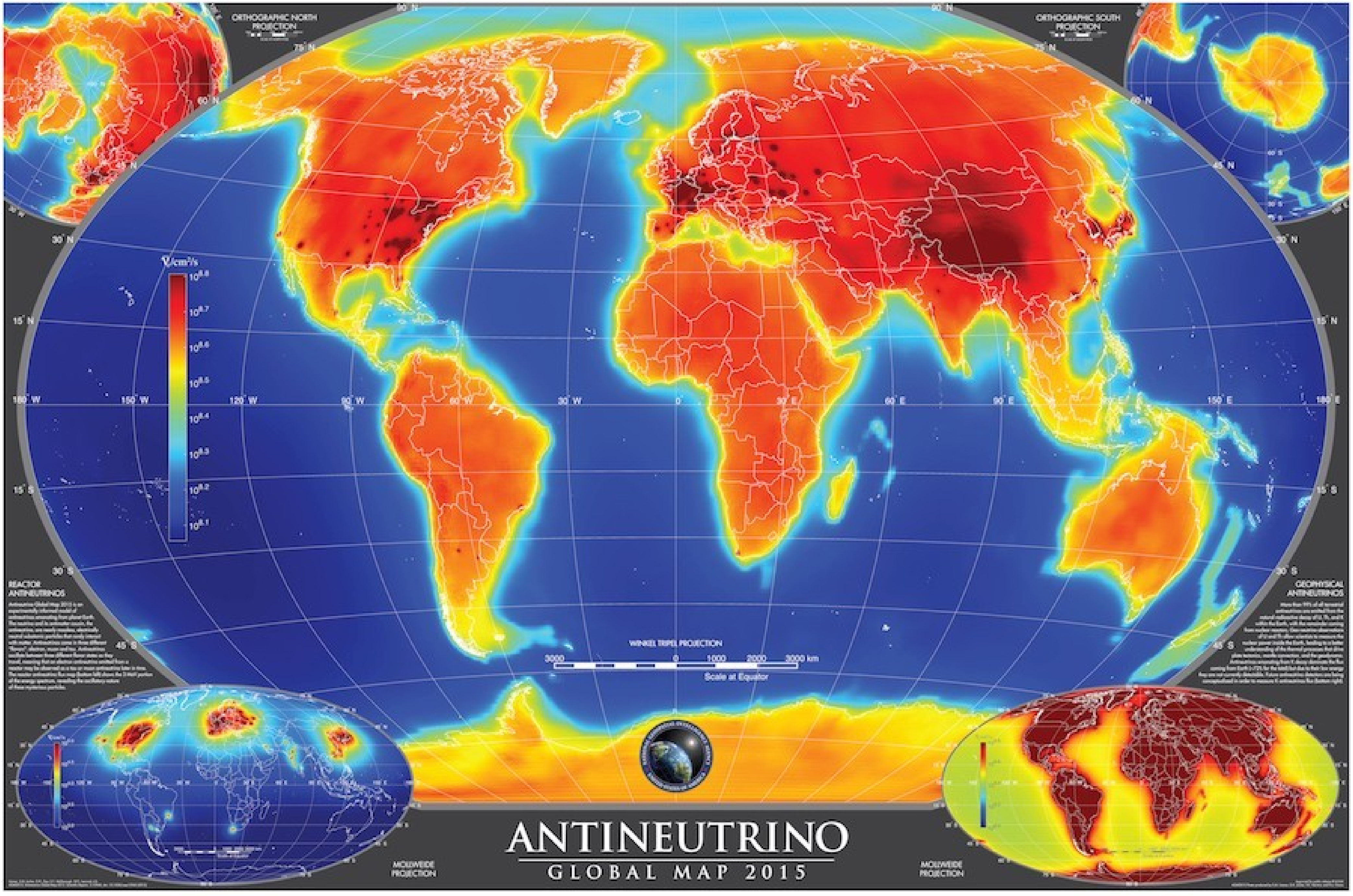
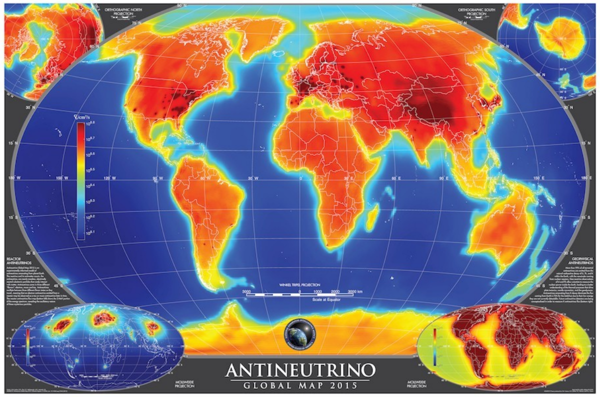
The WATCHMAN Project



Matthew Malek: The University of Sheffield

The WATer Cherenkov Monitor for Anti-Neutrinos: WATCHMAN



Matthew Malek
The University of Sheffield

University of Warwick – Particle Physics Seminar
30 January 2020

Outline

- **Motivation**
  - Overview & project goal
- **Gadolinium & Water Cherenkov Detectors**
  - Evolution of technique
  - Proposed detectors
- **Experiment Description**
  - Detector
  - Reactor fluxes
  - Background measurements
- **Current Status and Timeline**
  - Options for future phases

What is WATCHMAN?

The University Of Sheffield.

Objective:

Remote fission reactor monitoring via detection of antineutrino emissions.

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

In the Beginning...

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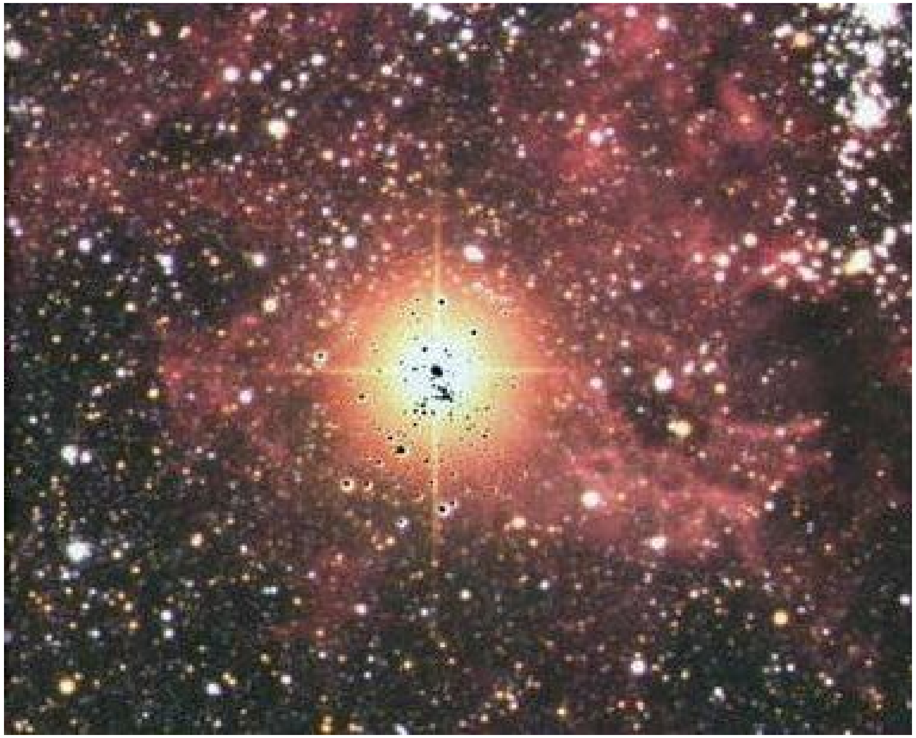
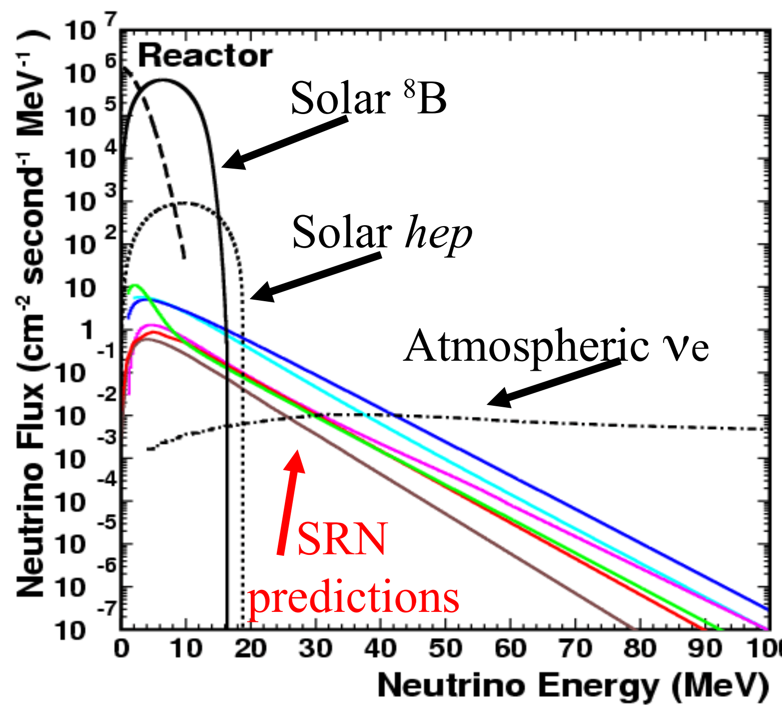
Supernova Relic Neutrino (SRN) search at Super-Kamiokande:



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

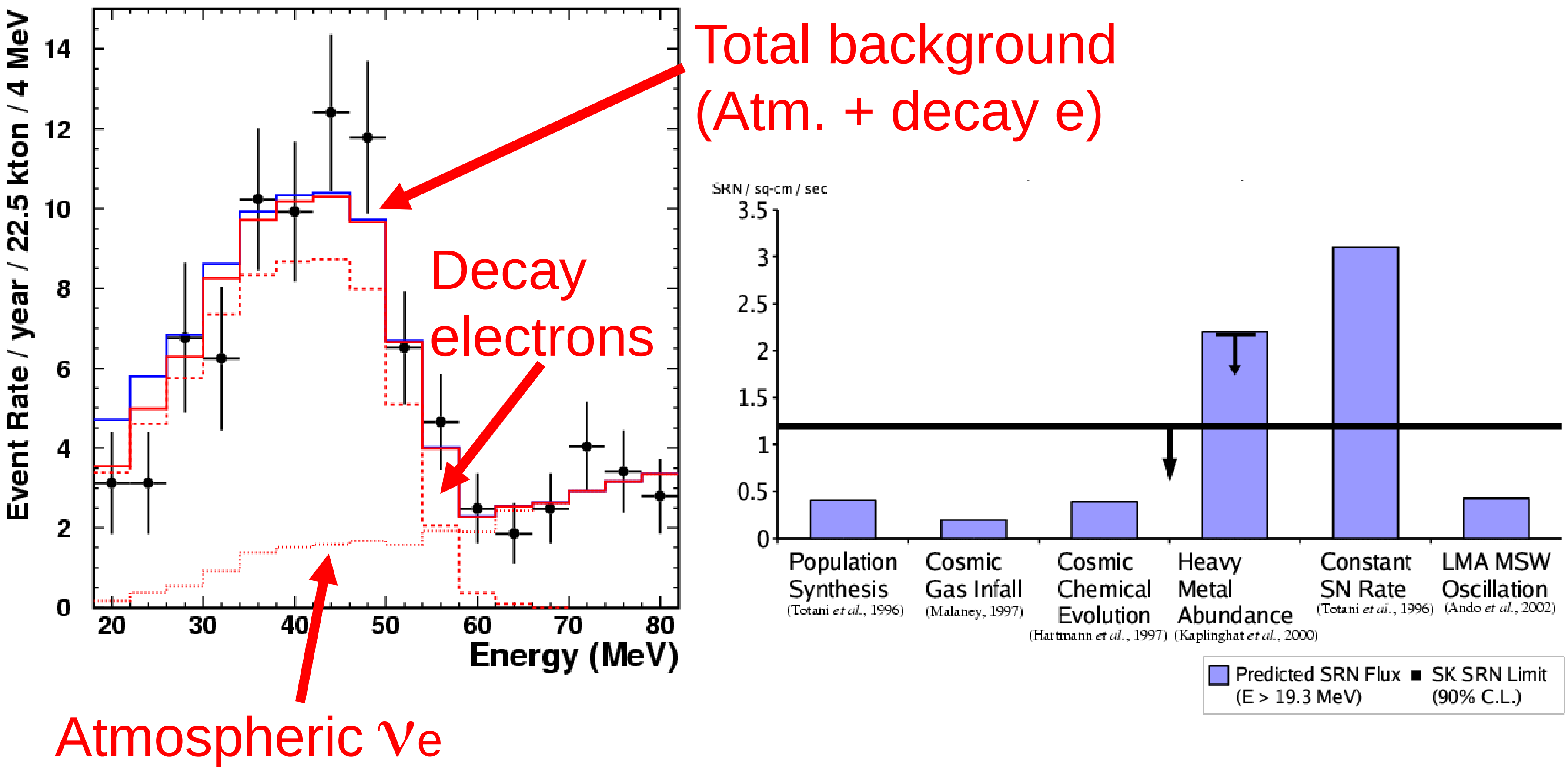
99% is released as neutrinos (all 6 types); mainly from neutrino cooling (also νe from neutronisation burst).



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



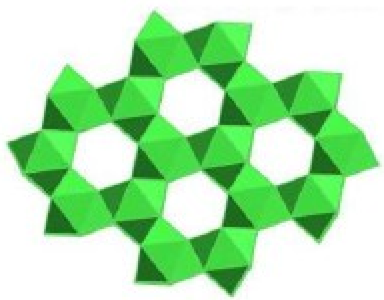
- SRN signal would manifest as distortion of BG
- No such signal seen yet → some models ruled out
- Background limitations form significant challenge!

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

Gadolinium & Water

The University Of Sheffield.

Gadzooks!



[A Serious SK Upgrade Suggestion]

Mark Vagins
University of California, Irvine

Osawano
November 11, 2002

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 $\bar{\nu}_e + p \to e^+ + n$ (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)

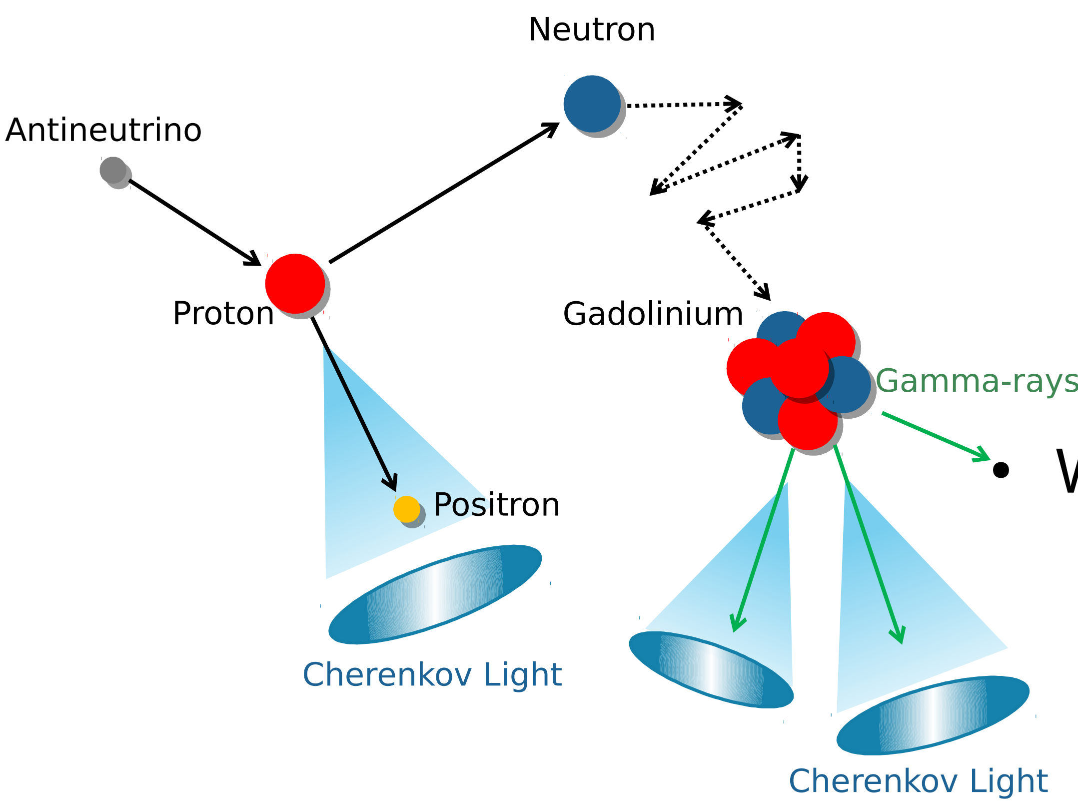
Initial motivation for adding Gd to water Cherenkov detectors was background reduction for SRN experiments.

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

Basic Idea

Tag antineutrinos via <u>coincidence</u> 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

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			

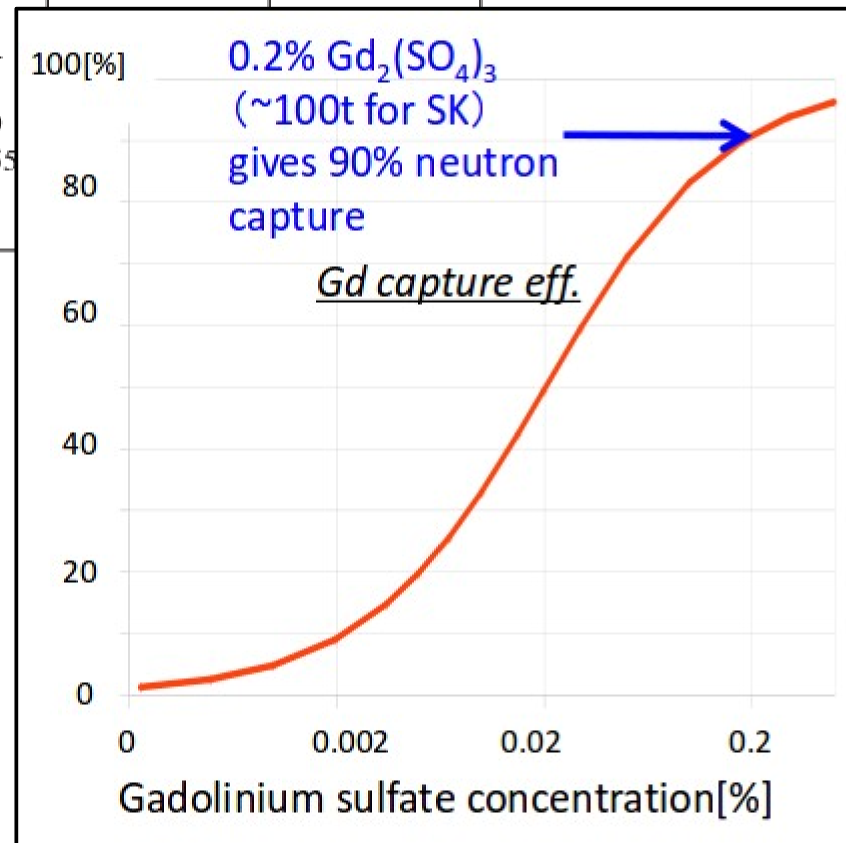
*The units of all cross sections are barns. The units of abundance are percent.

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

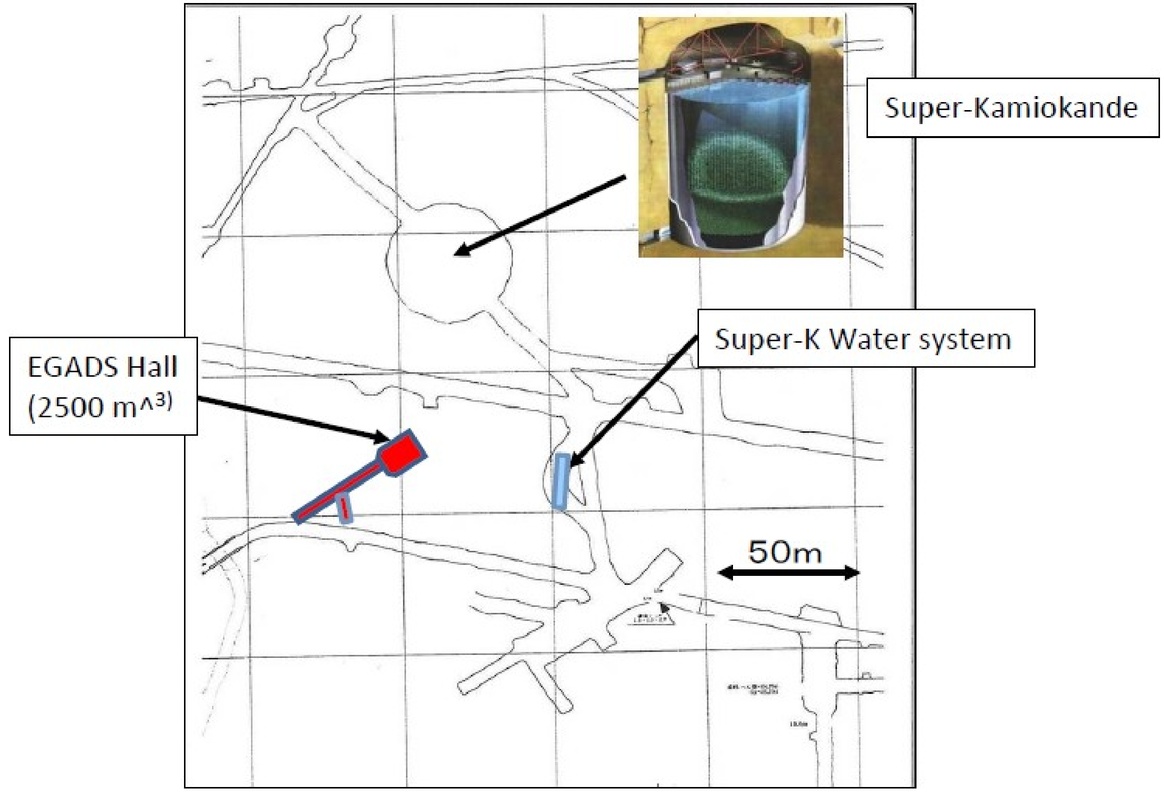
The University Of Sheffield.

EGADS = Evaluating Gadolinium's Action on Detector Systems

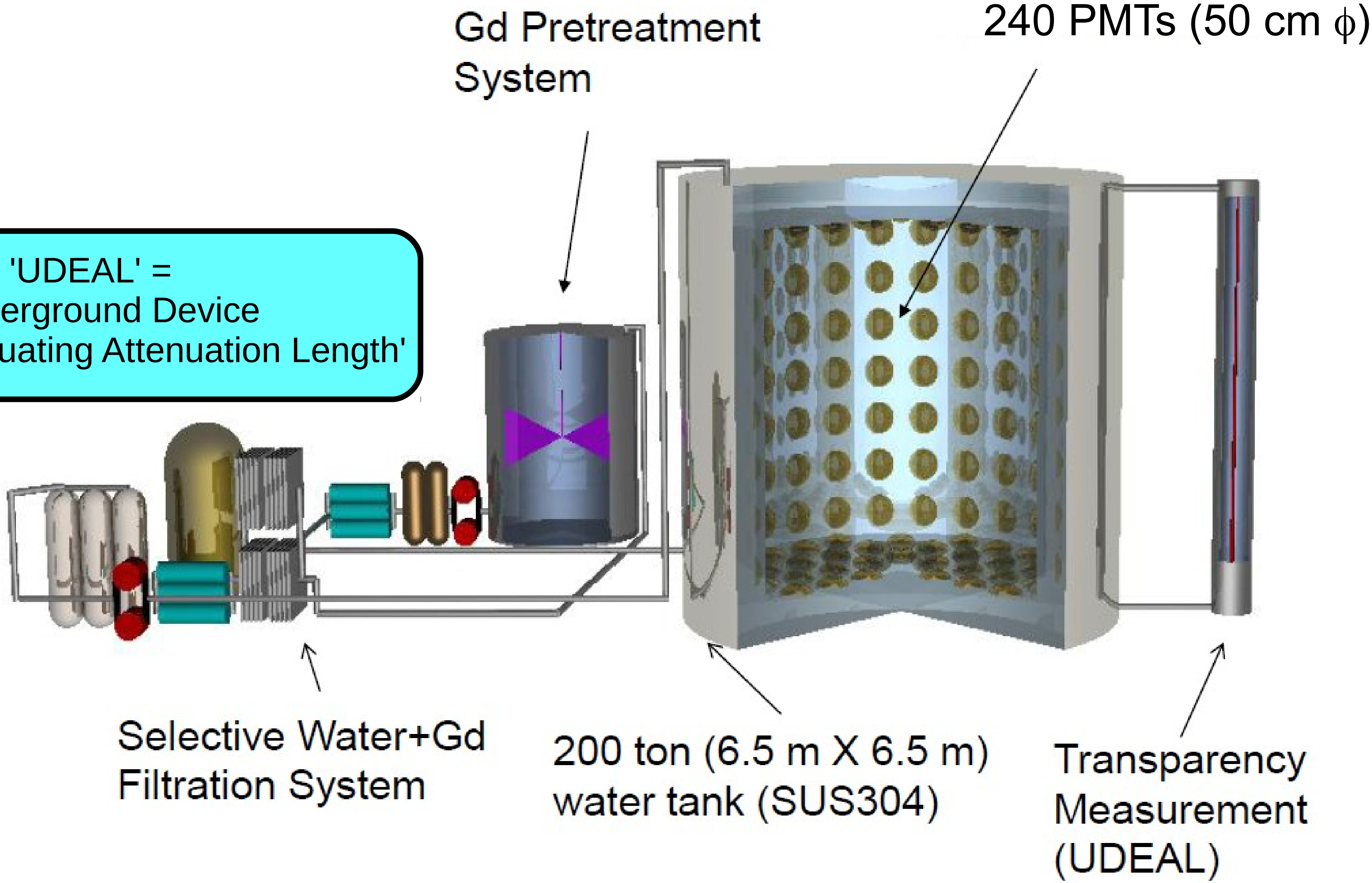
Dedicated test facility commissioned at Kamioka Observatory.

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.

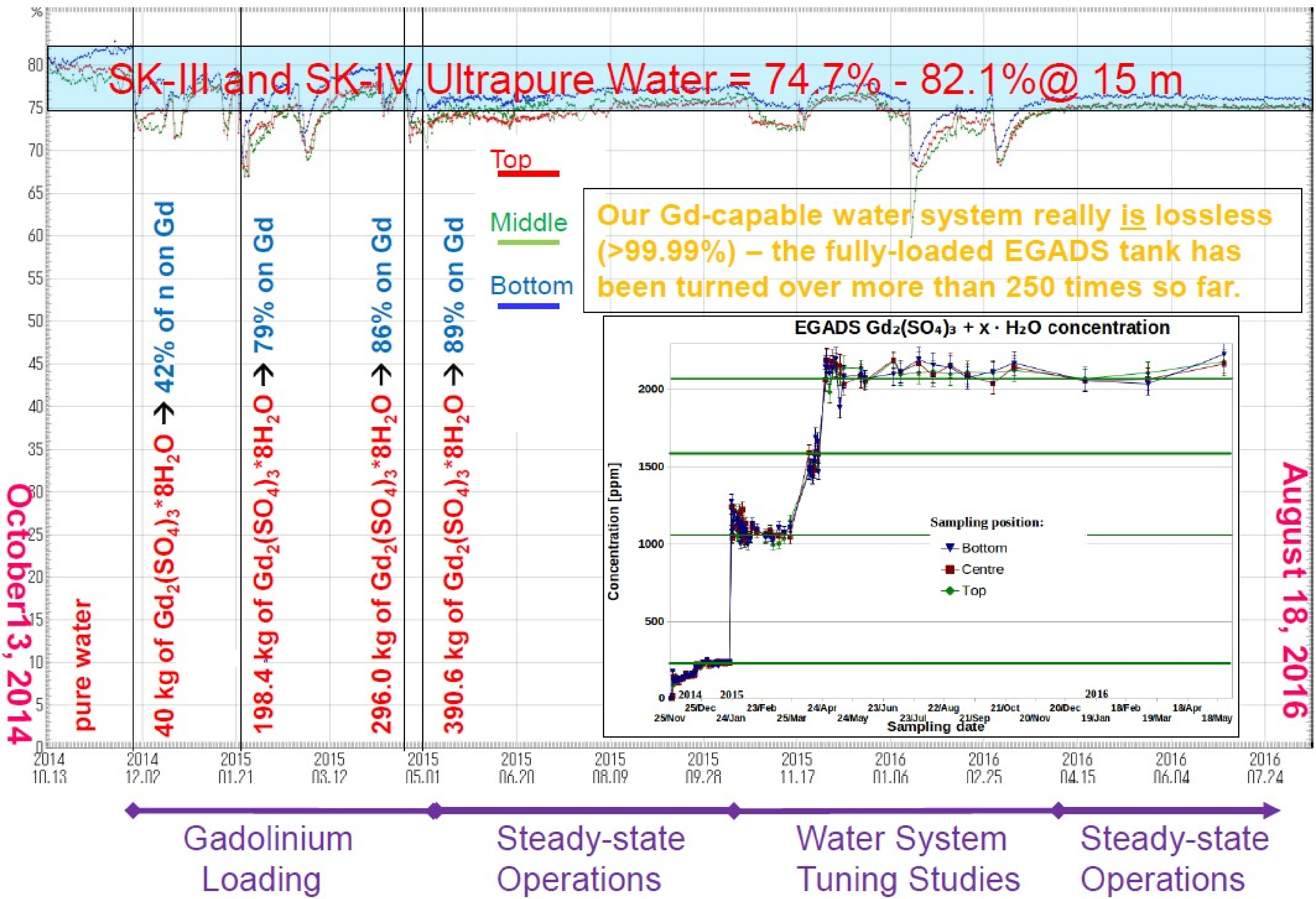


EGADS Facility



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

EGADS Water Attenuation



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.

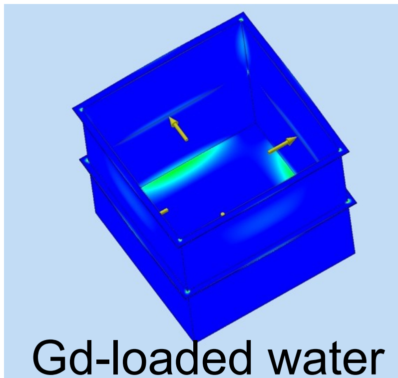
These include.....

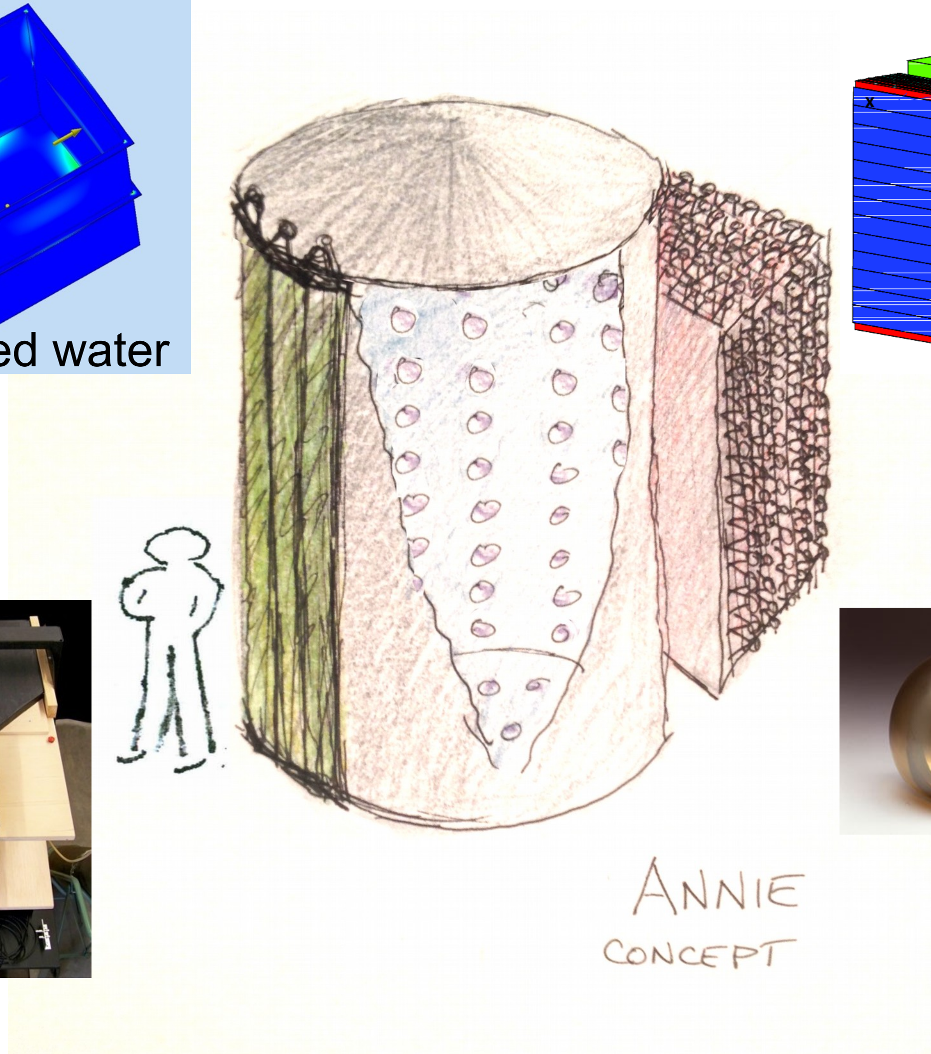
[*] "The Tempest", by William Shakespeare (Act II, Scene 1)

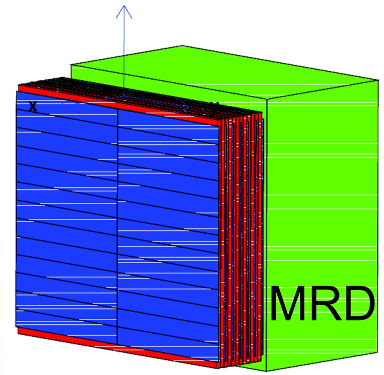
The ANNIE Experiment

The University Of Sheffield.

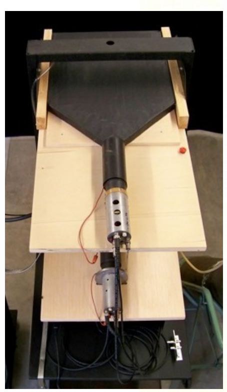
ANNIE: **A**ccelerator **N**eutrino-**N**ucleus **I**nteraction **E**xperiment







Upstream
μ veto

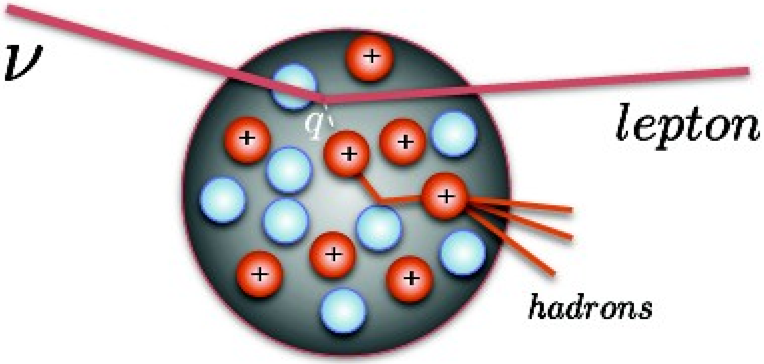


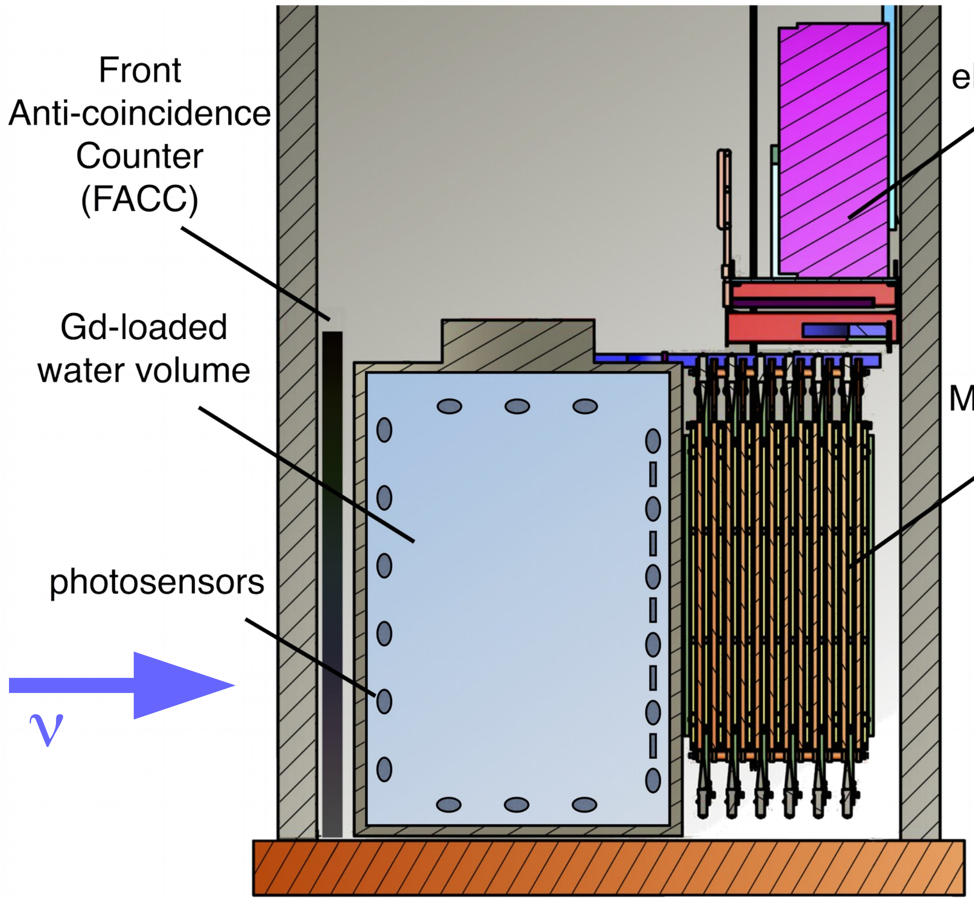
annie

The ANNIE Experiment

Primary physics objective:

A measurement of the abundance of final state neutrons ("neutron yield") from neutrino interactions in water, as a function of energy.





Current status:

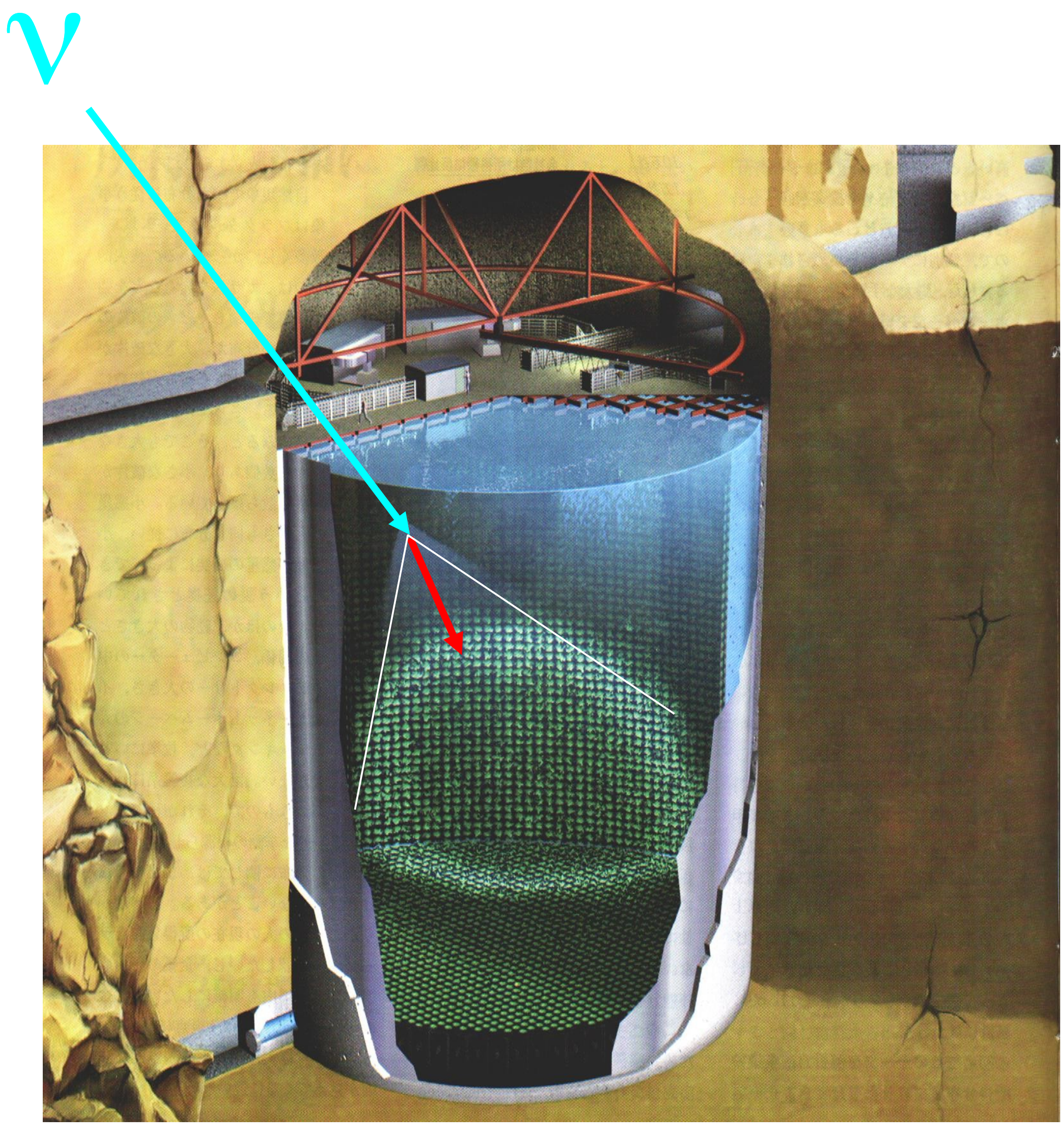
All PMTs installed

26 tonne water volume is fully loaded with Gadolinium

MRD completed
LAPPDs being prepared

Commissioning w/ beam data NOW

SK-Gd



In April 2020, the Super-Kamiokande collaboration will add 0.02% $Gd_2[SO_4]_3$ to the detector, opening up a new area of physics potential.

Possibilities 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.

The Story So Far...

The University Of Sheffield.

To recap:

The motivation is clear; loading water Cherenkov neutrinos detectors with gadolinium brings new life to an old technology.

The **technical** capability has been demonstrated.

The **physics** benefit is well-established, with implementation at scales ranging from 26 tonnes (ANNIE) to 50,000 tonnes (Super-K), starting this year, and other experiments (*e.g.*, WCTE, IWCD) continuing to turn on over the next decade.

That's great... but what about non-proliferation?

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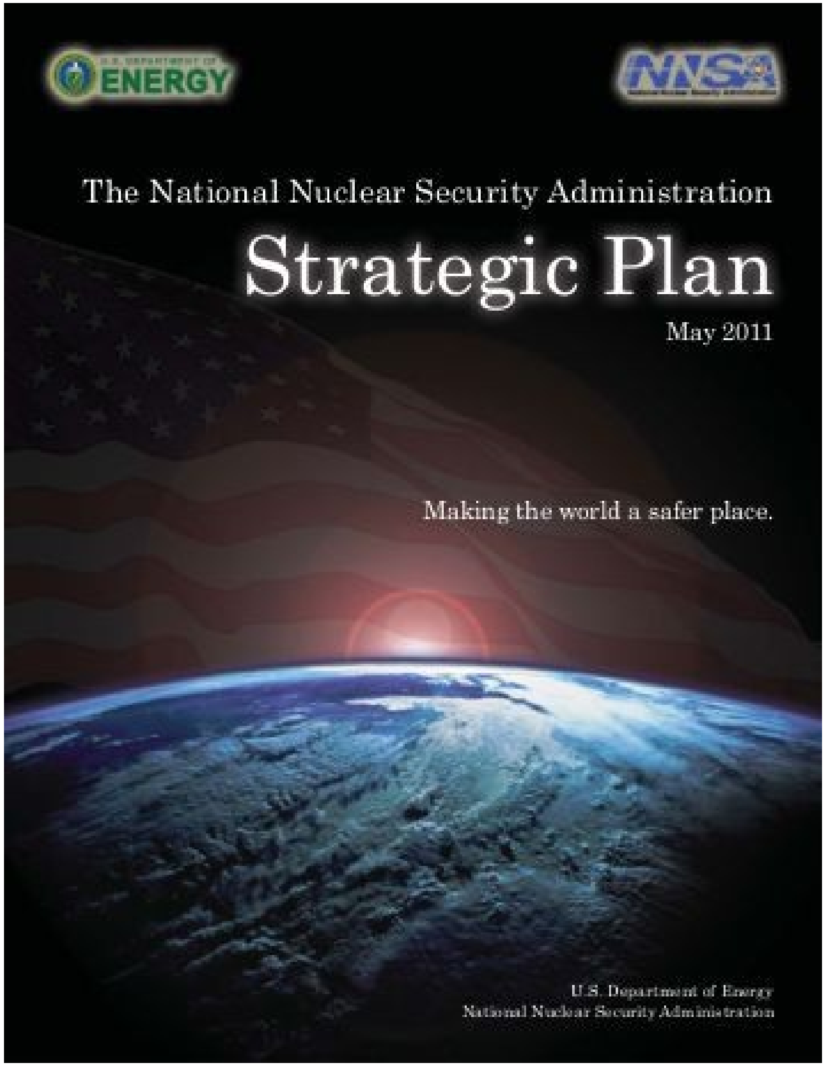
The WATCHMAN Charge

The University Of Sheffield.



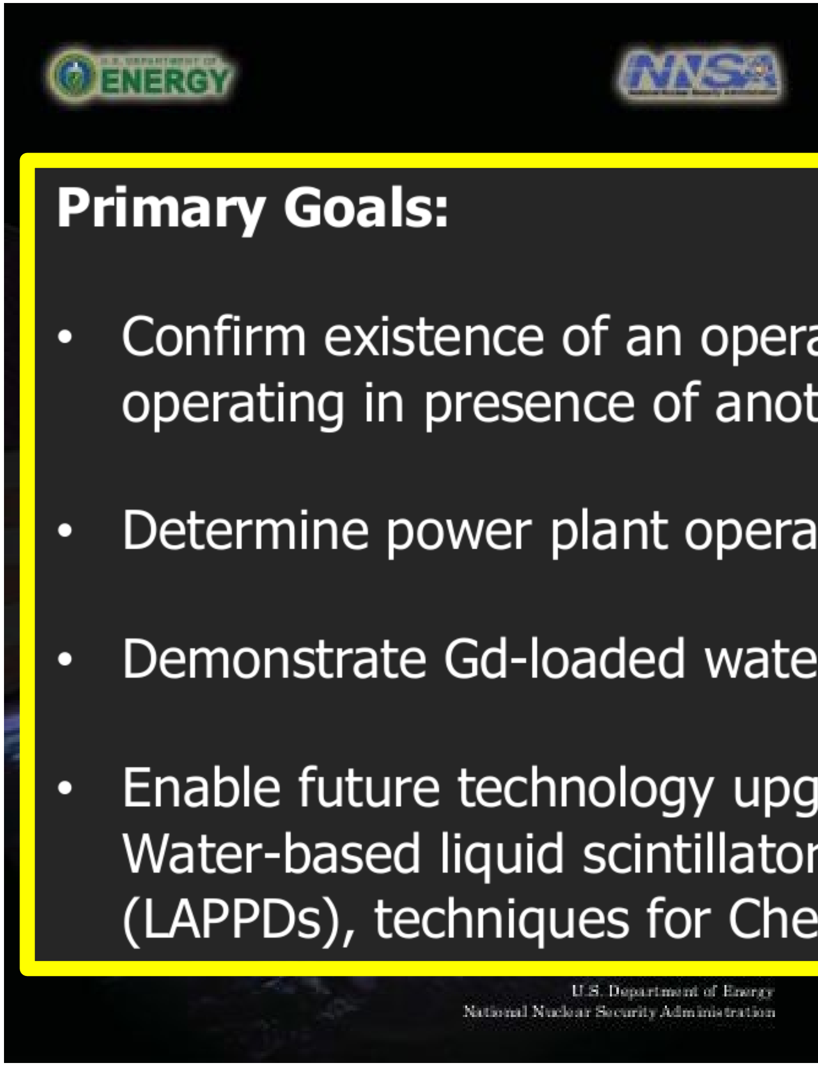
The goal of the WATCHMAN project is to harness the techniques described earlier for nuclear threat reduction.

Primary sponsor is the **Office of Defense Nuclear Nonproliferation** (DNN) at the **National Nuclear Security Administration** (NNSA) in the United States.

UK involvement 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 WATCHMAN Charge



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

Primary Goals:

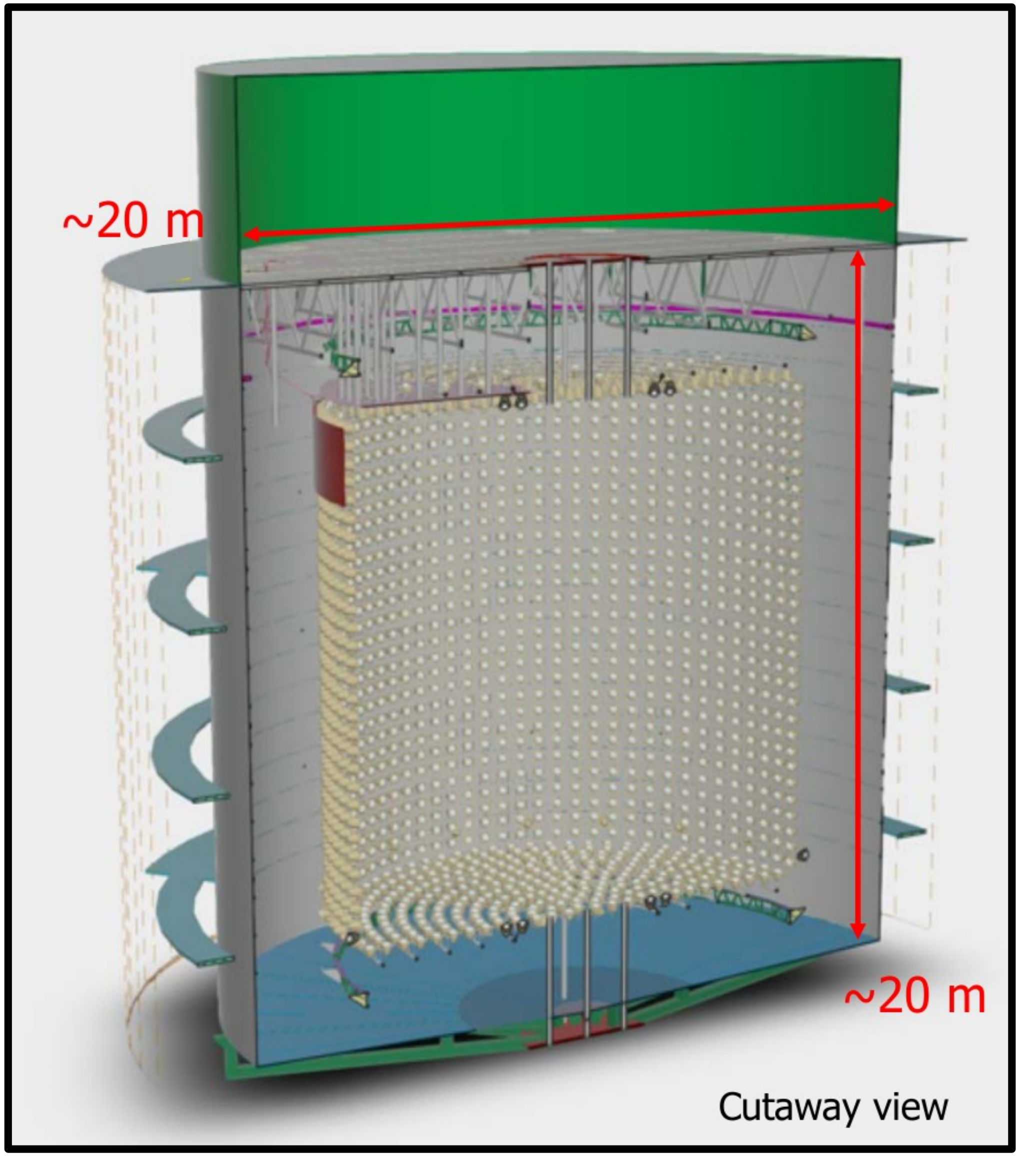
- Confirm existence of an operating reactor (ie. determine unknown reactor is operating in presence of another known reactor)
- Determine power plant operational status with and without prior knowledge
- Demonstrate Gd-loaded water as a scalable detector medium
- Enable future technology upgrades:
 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

Collaboration.

The WATCHMAN Design

Baseline design includes:

- ~1 ktonne fiducial mass
- 0.1% Gd-loaded water
- ~3600 Hamamatsu 10" PMTs with:
  - High quantum efficiency (~30%)
  - Low radioactivity (esp. U and Th)
  - 20% 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:

- 4 universities (so far):
  Sheffield, Edinburgh, Liverpool, 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 Spokespersons (2016 – 2020):

- Adam Bernstein (Lawrence Livermore National Laboratory)
- Mark Vagins (University of California at Irvine)

and Spokespersons-Elect (2020 –):

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

WATCHMAN Collaboration

WATCHMAN Site

The University Of Sheffield.

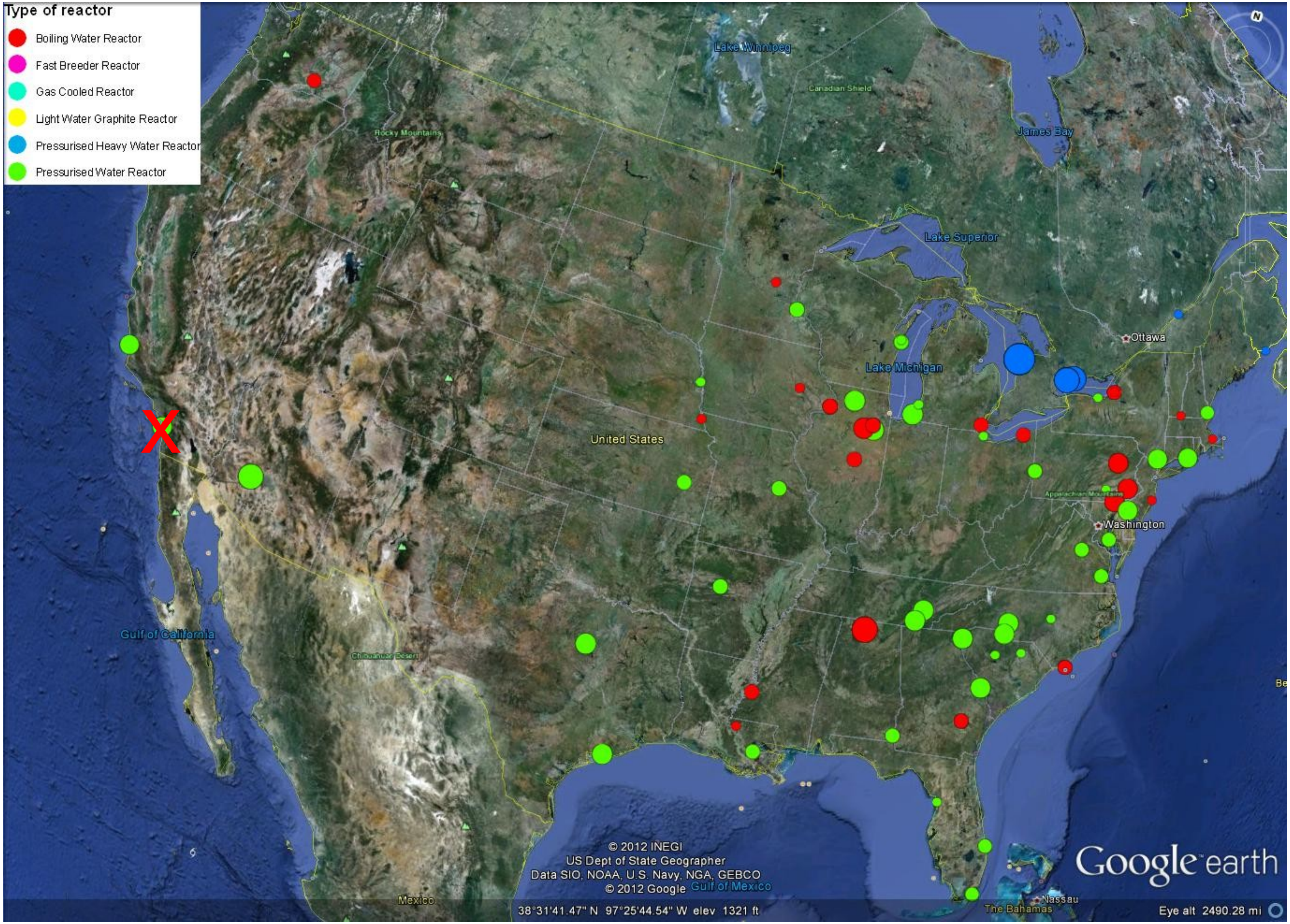
The ideal WATCHMAN prototype site requires:

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

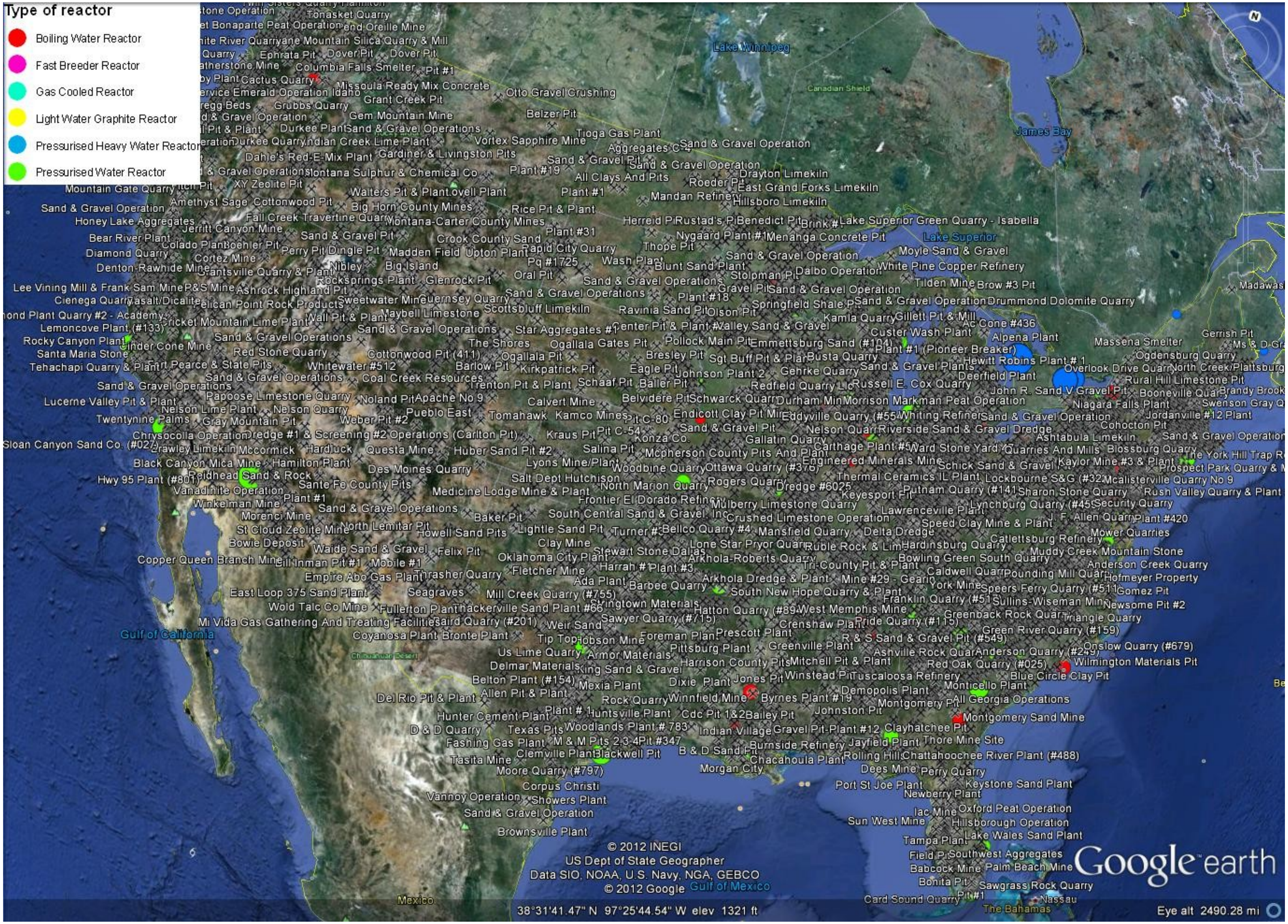
(b) a nuclear reactor

→ 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:

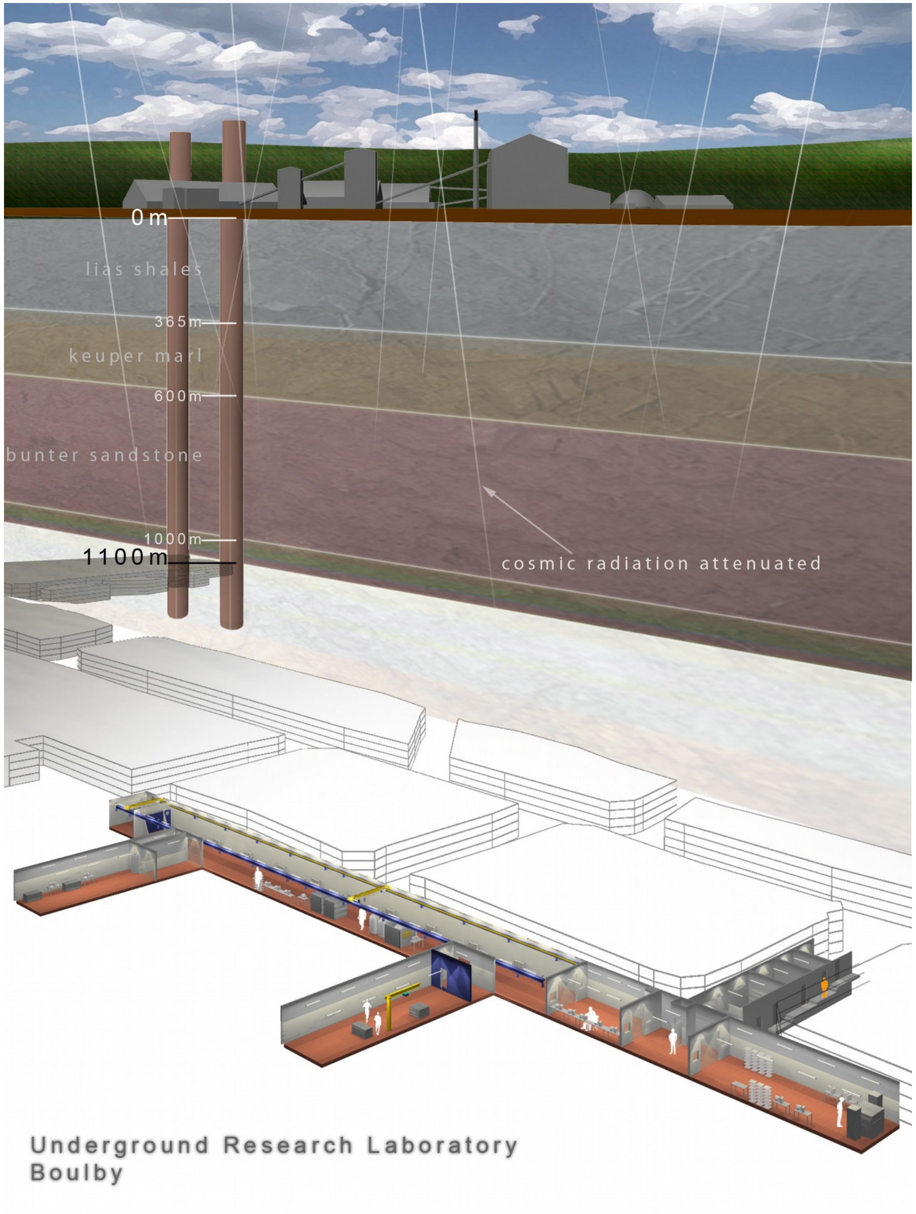
(a) an underground laboratory (or potential to build one) that is within ~30 km of

(b) a nuclear reactor

Search results:

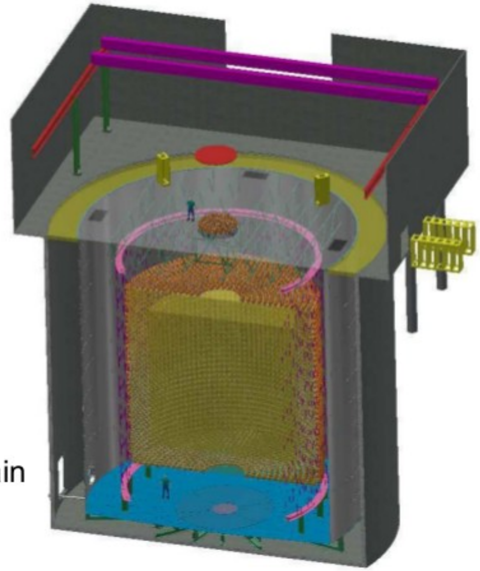
– Only <u>one</u> site in the USA satisfies criteria
– Can go to four if allow underwater deployment, or permit shallow sites with greater backgrounds
– Additionally, another candidate site in UK fits all criteria

STFC / Boulby Underground Lab



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

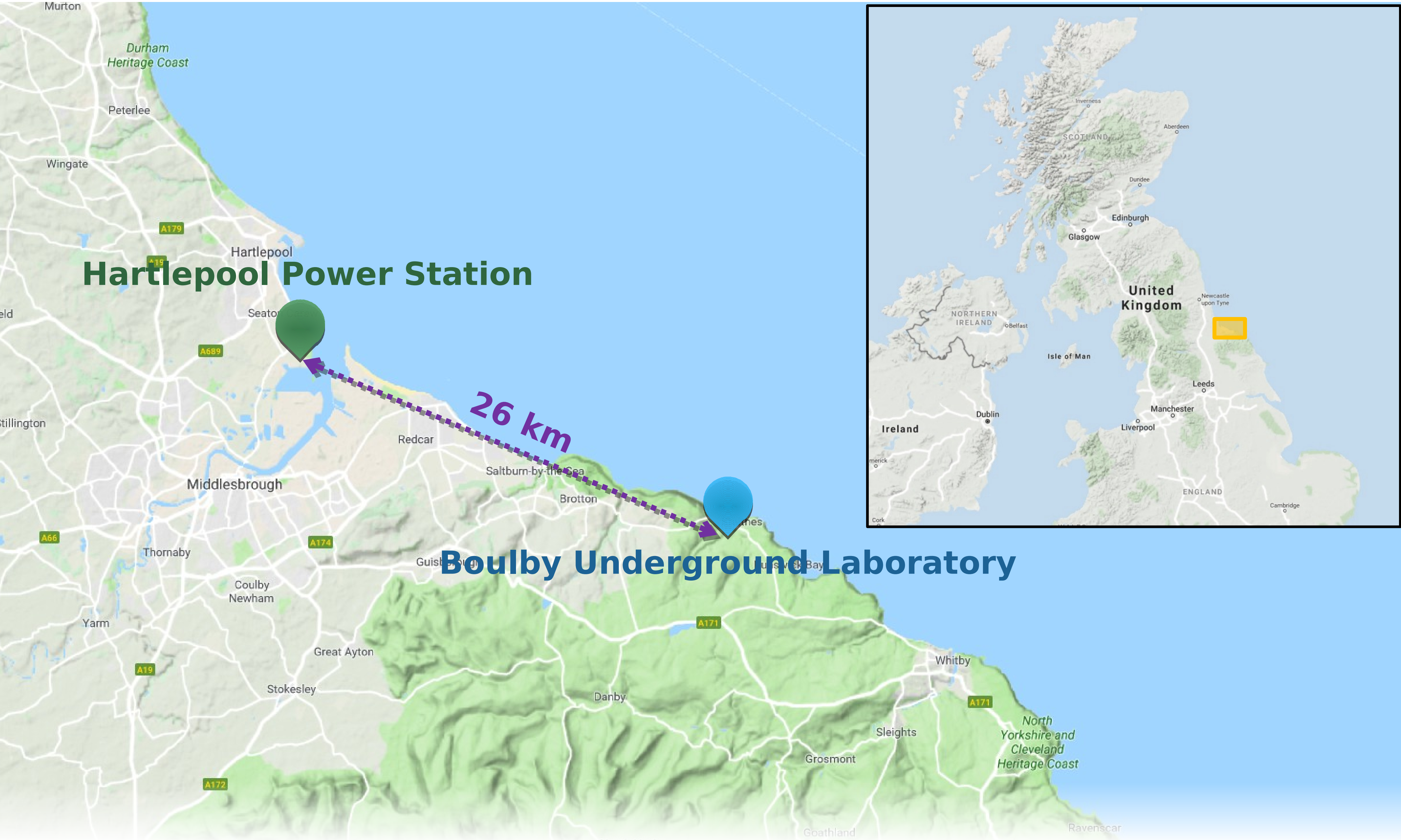
Operating lab for > 20 years
Current lab from 2017



JG Boissevain Design

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

Proximity to Reactor(s)

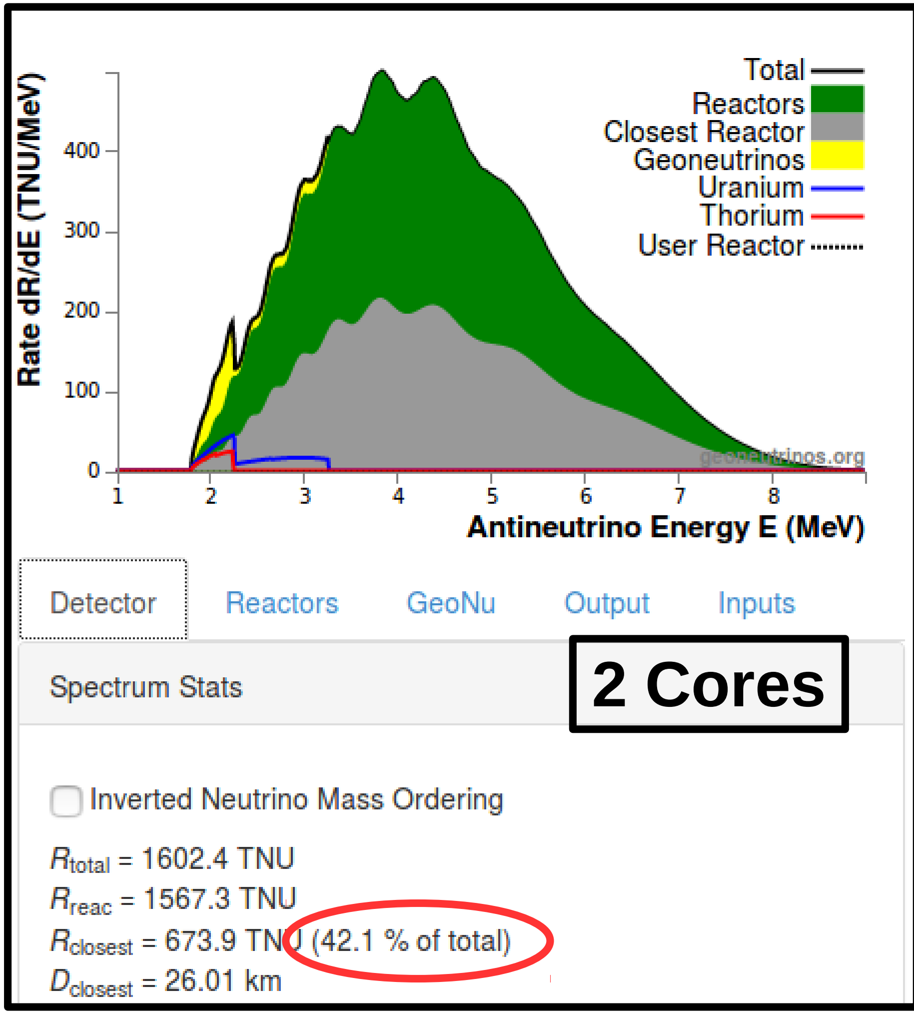


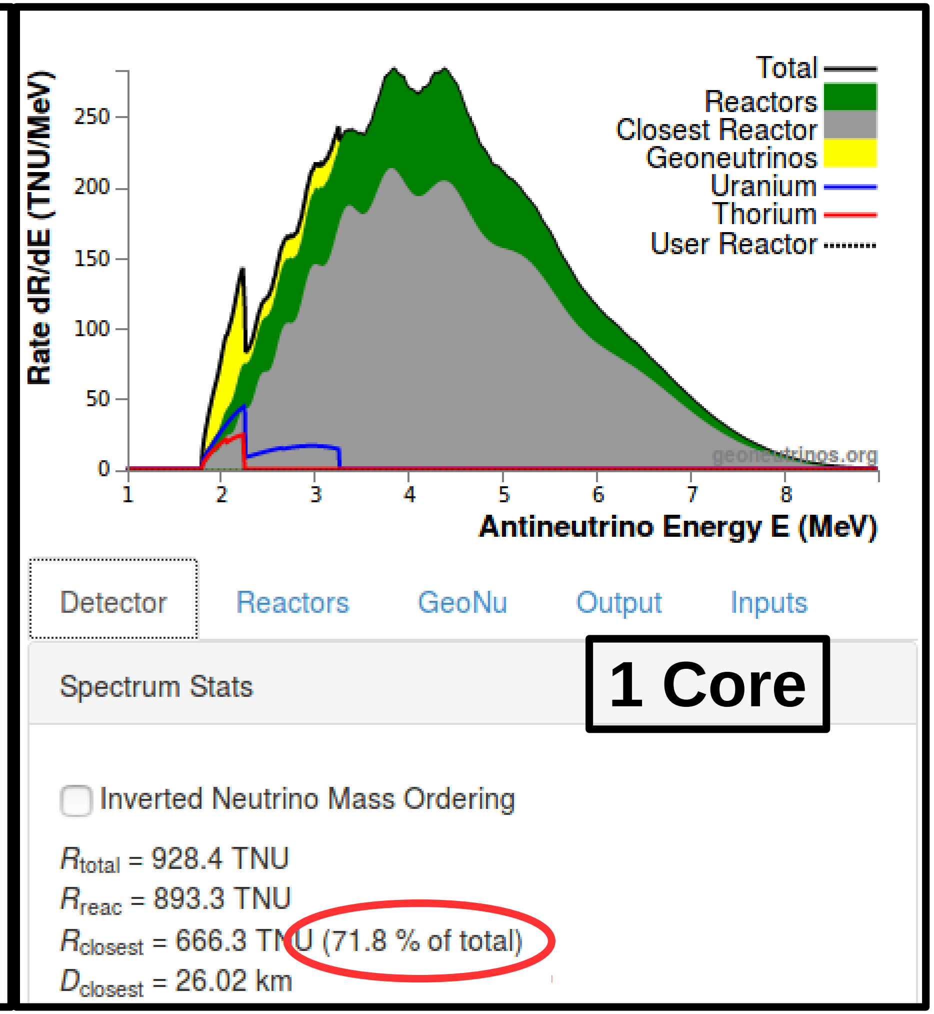
EDF Hartlepool Nuclear Plant

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

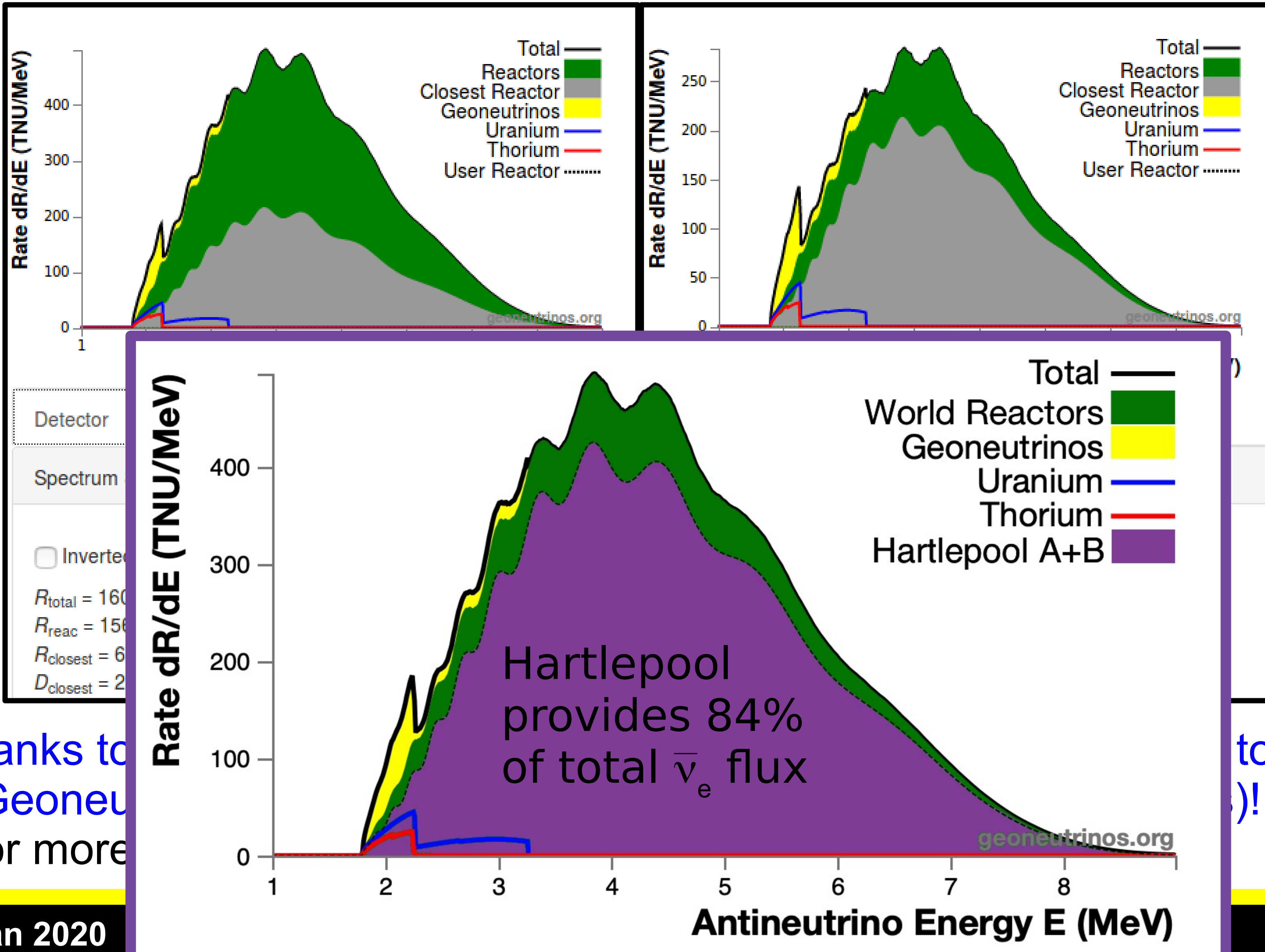
Hartlepool Signal @ Boulby





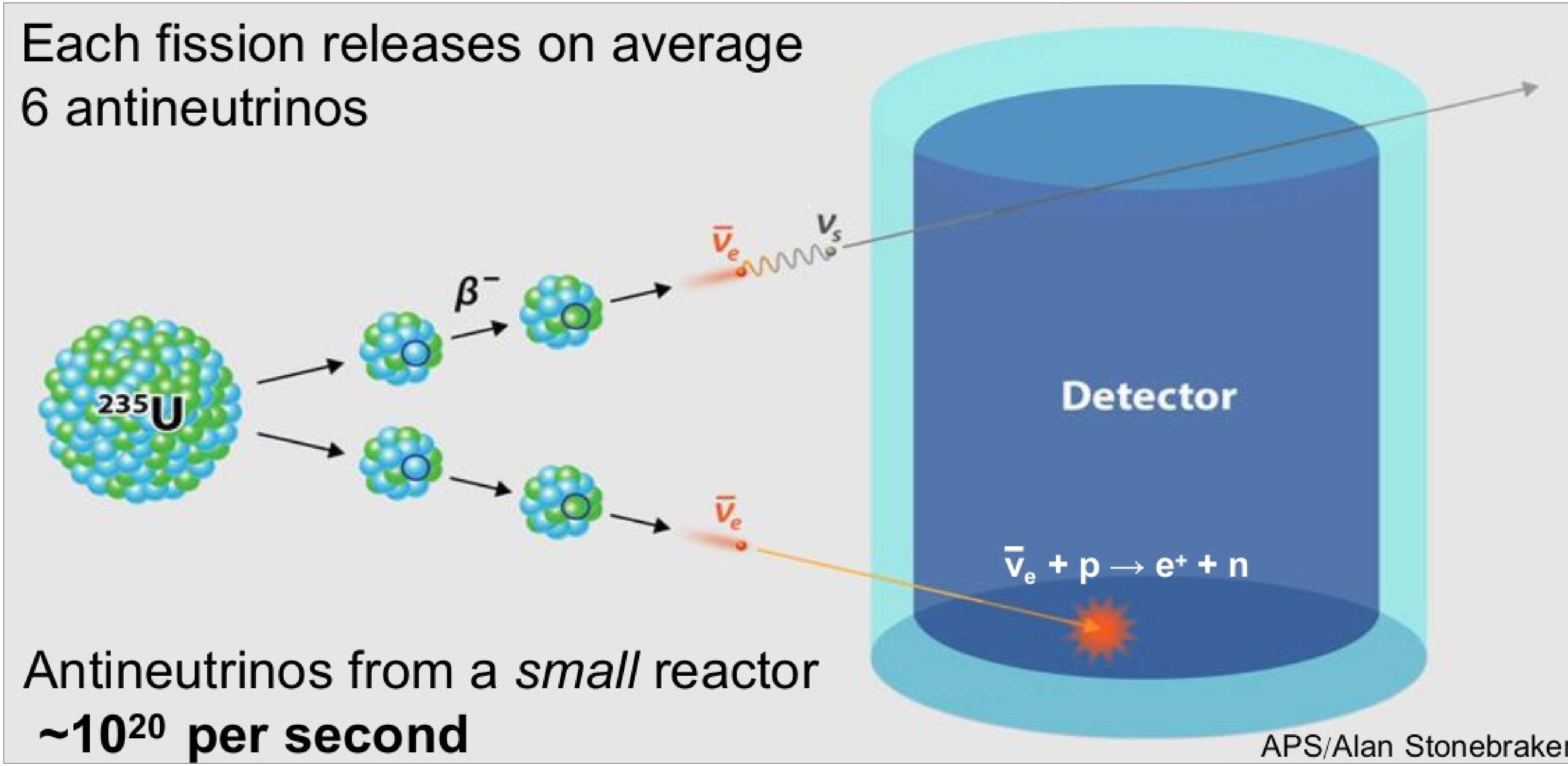
Thanks to Antineutrino Global Map project, there is now an online tool – Geoneutrinos.org – to get such reactor fluxes (and backgrounds)!
(For more detail, see S.Dye's preprint at **nucl-ex:1611.01575**)

Hartlepool Signal @ Boulby



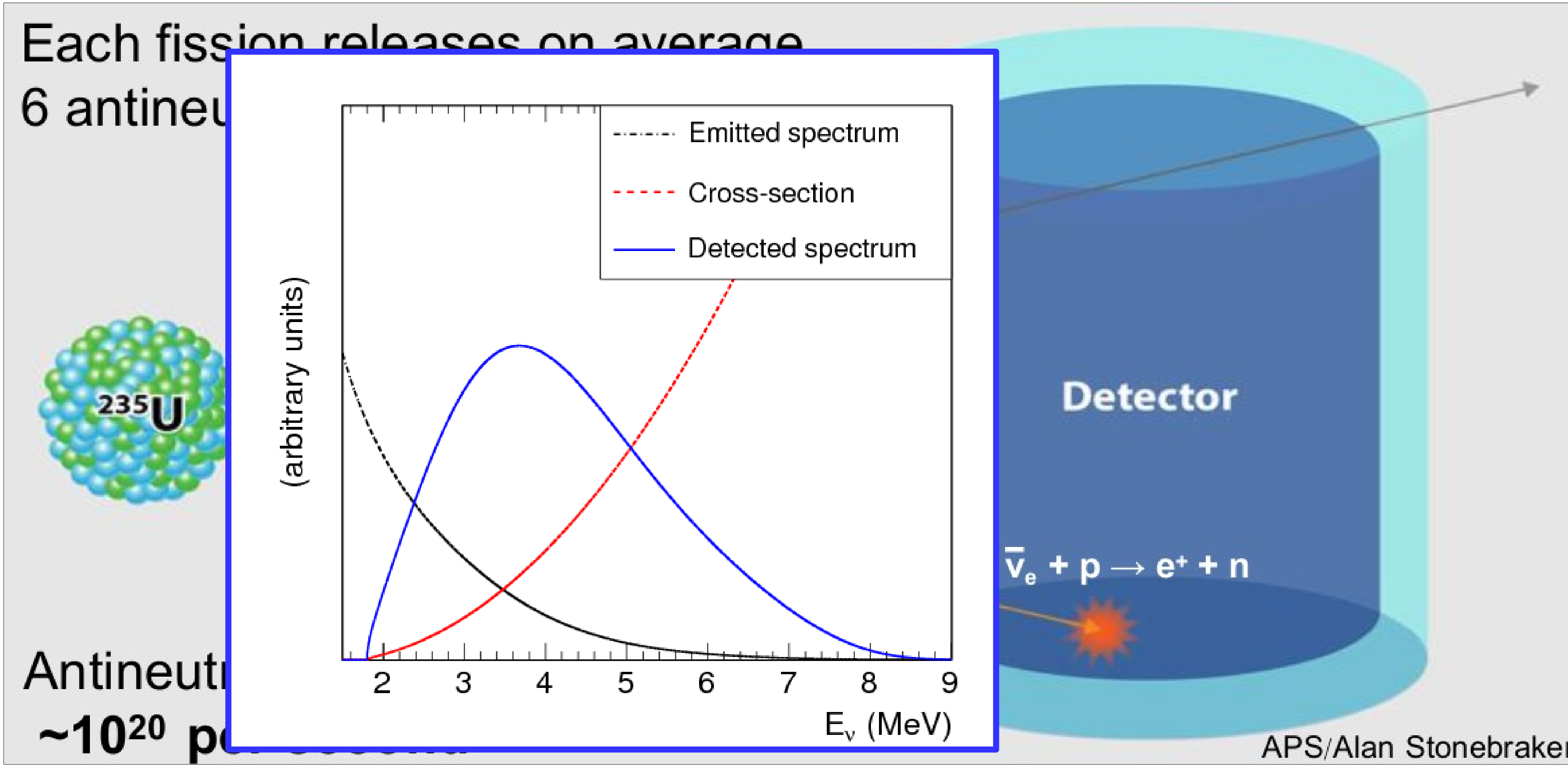
Thanks to … tool
– Geoneu …)!
(For more

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

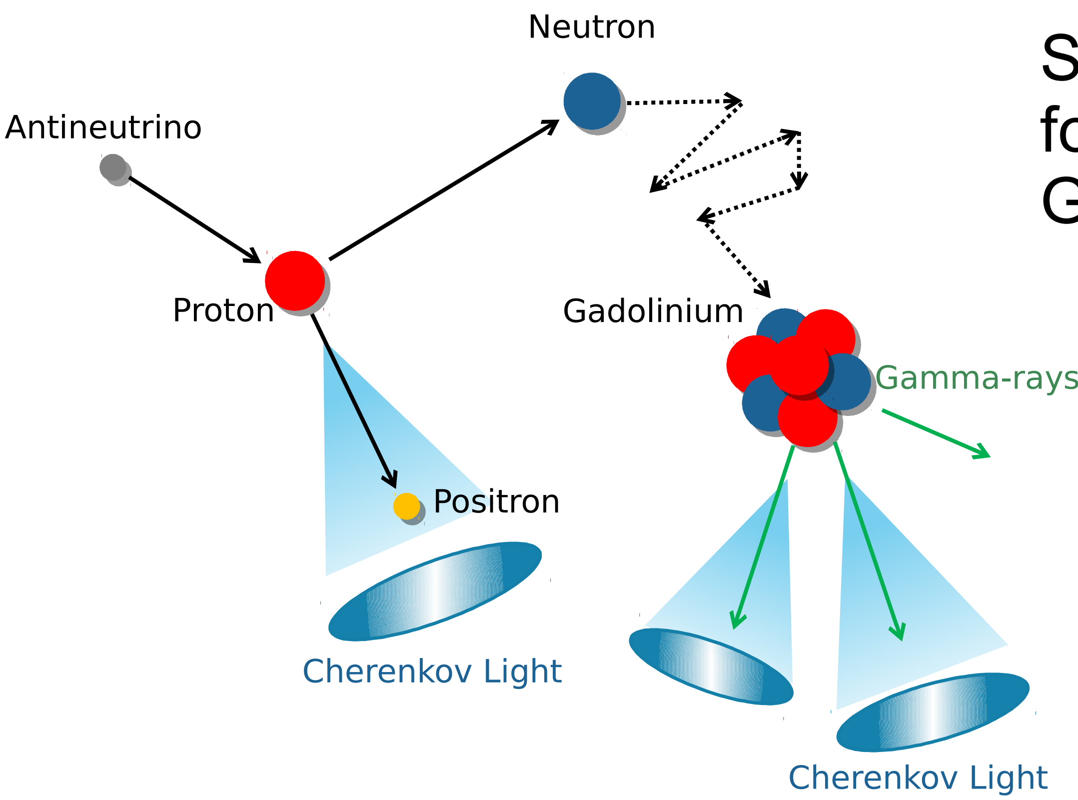


For a 3 GWth reactor complex (*e.g.*, Hartlepool), O(10^{21}) fissions per second, resulting in O(10^{22}) $\bar{\nu}_e$ emitted *isotropically* per second.

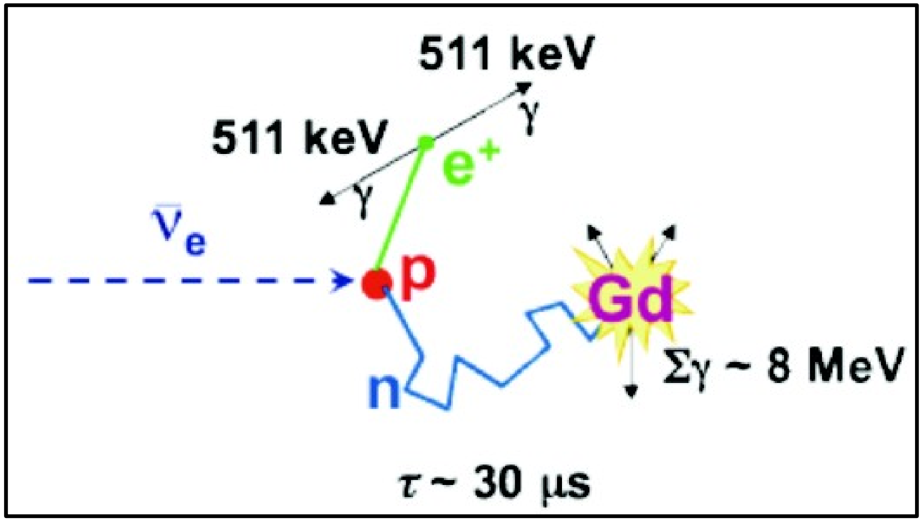
→ For 26 km standoff, expect “several” events per day per kilotonne

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

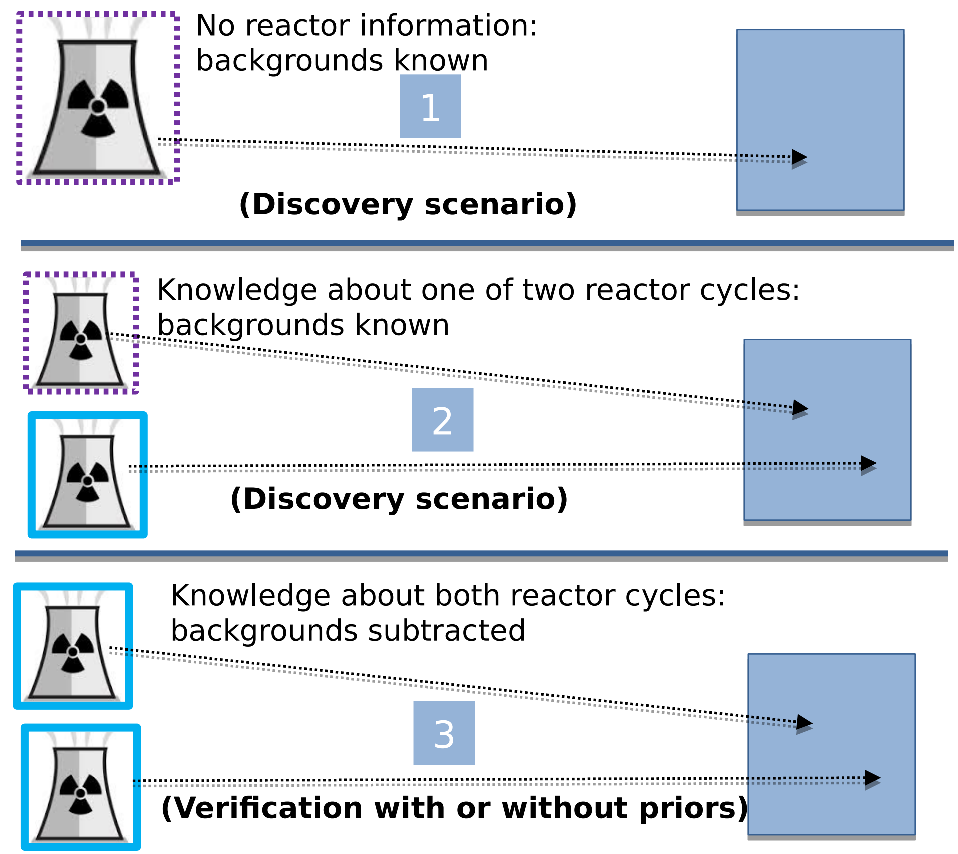
Non-Proliferation Scenarios

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.

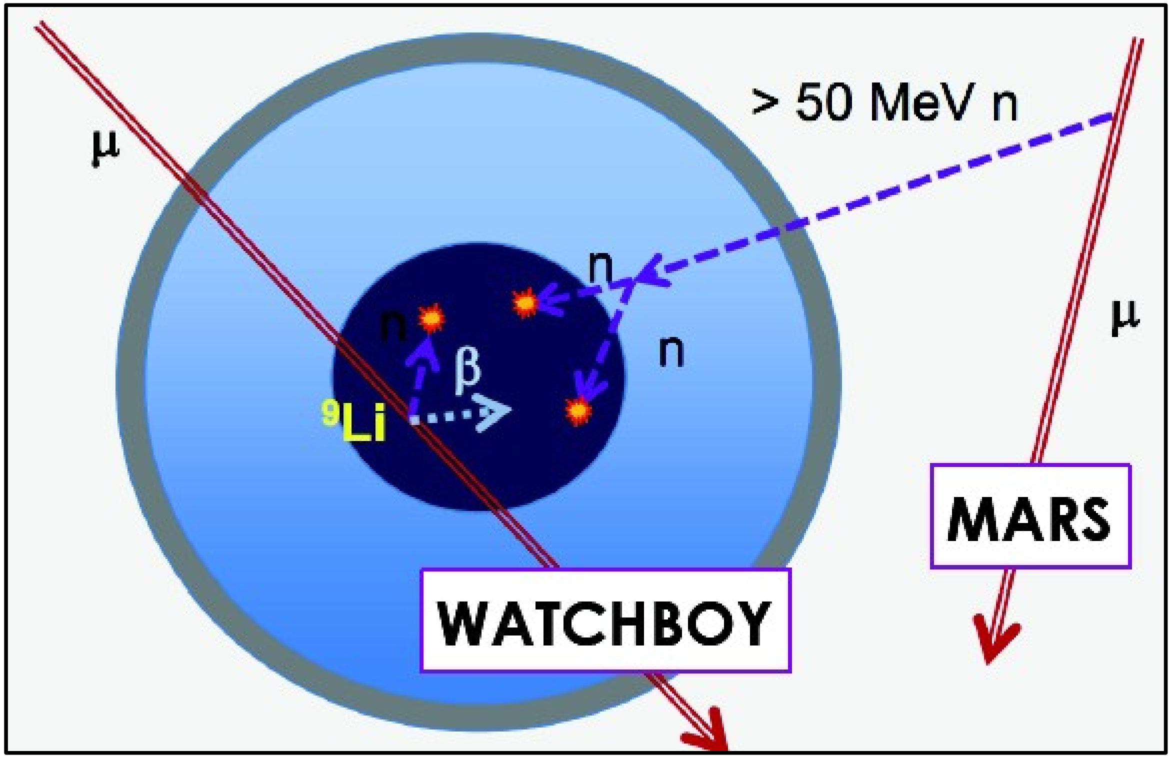


Non-proliferation use cases are in development within the collaboration. These will be further developed in consultation with sponsors and also with the non-proliferation community.

Non-Proliferation Scenarios

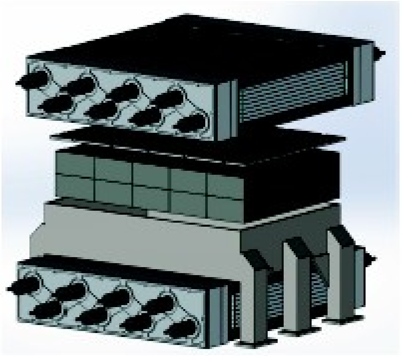
Scenario	Dwell Time	Metric
1	Two Core: 2.9 – 8.9 Days	TP/FP: 95%/9%
	One Core: 1.1 – 3.7 Months	TP/FP: 94%/7%
2	2.8 – 7.5 Weeks	TP/FP: 95%/7%
	1.6 – 4.4 Months	TP/FP: 99%/1%
3	6 – 17.9 Months	95% Confidence

WATCHMAN Backgrounds



Backgrounds sources:

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

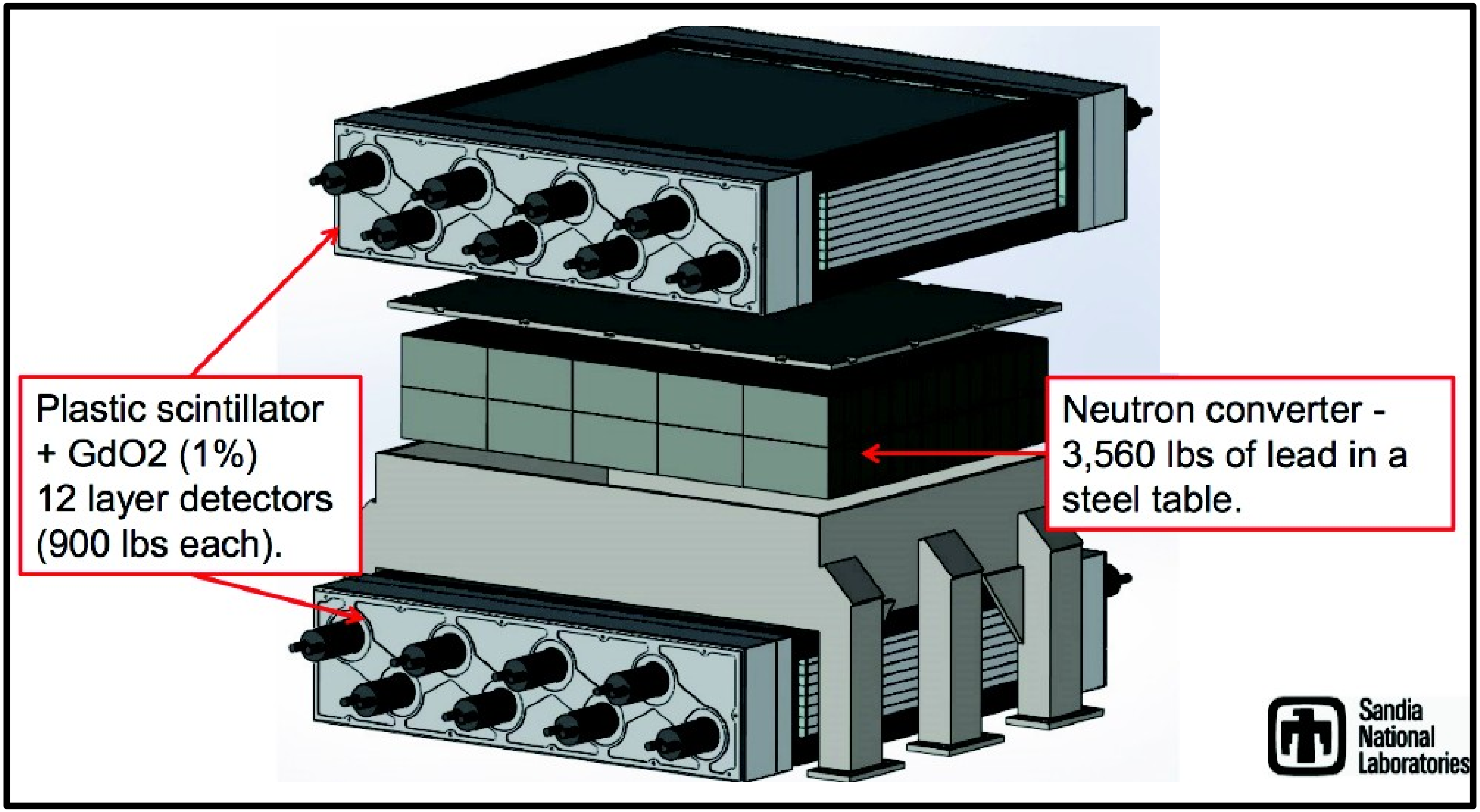


MARS

WATCHBOY

BG Study: MARS

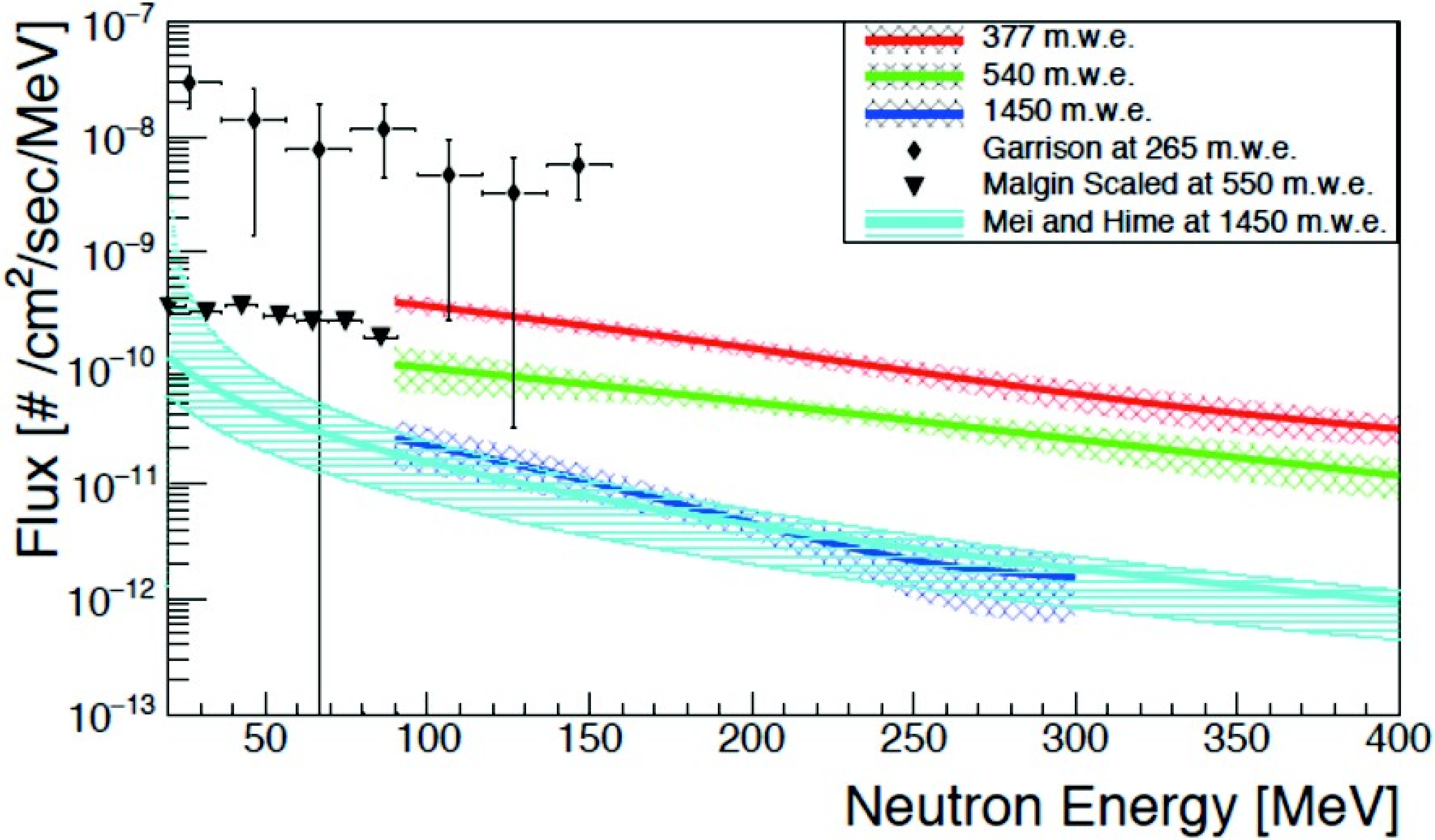
MARS = Multiplicity And Recoil Spectrometer



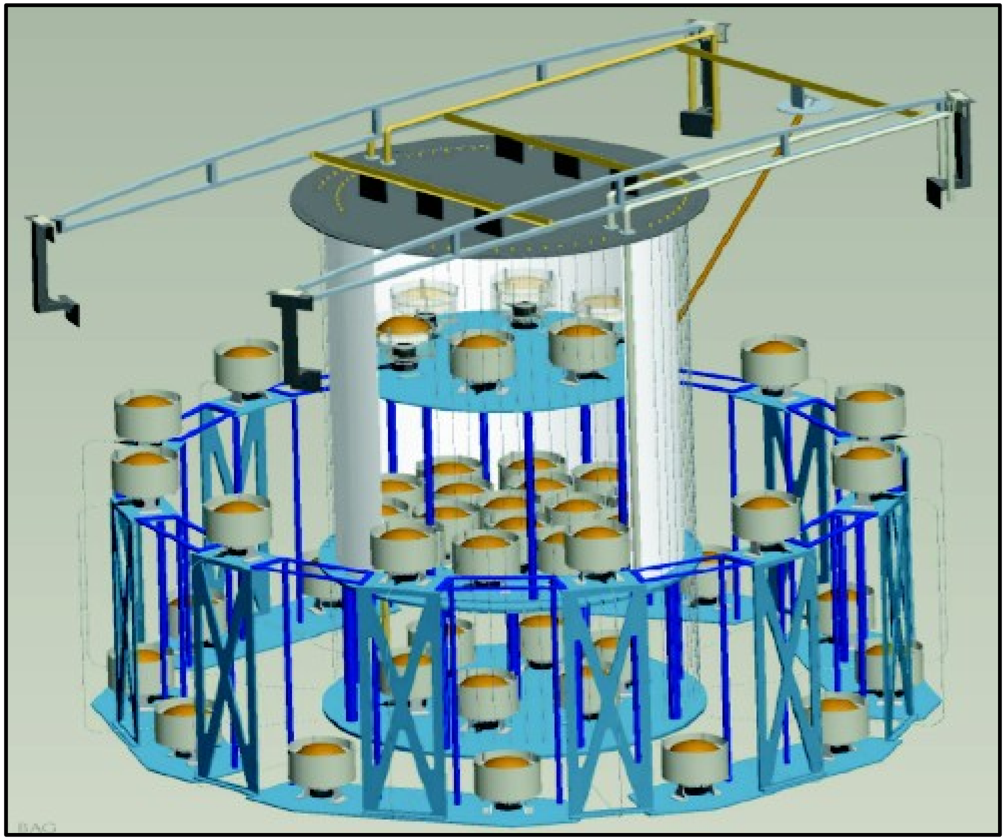
- A single fast neutron can produce a multiplicity of particles that can mimic an antineutrino signal in water
- Muon veto rejects muon-induced neutron production within detector

MARS Results

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



BG Study: WATCHBOY



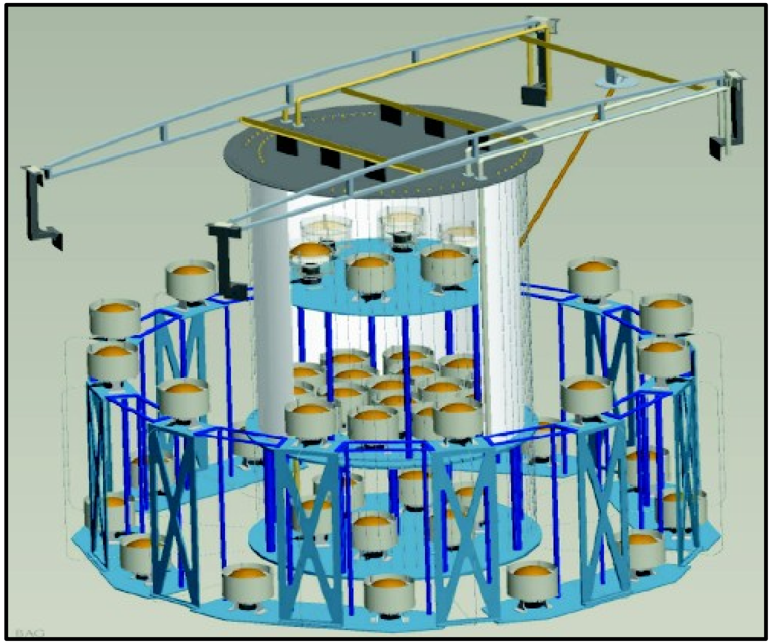
WATCHBOY is a 'mini-WATCHMAN' ('WATCHMANino'?) with:

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

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

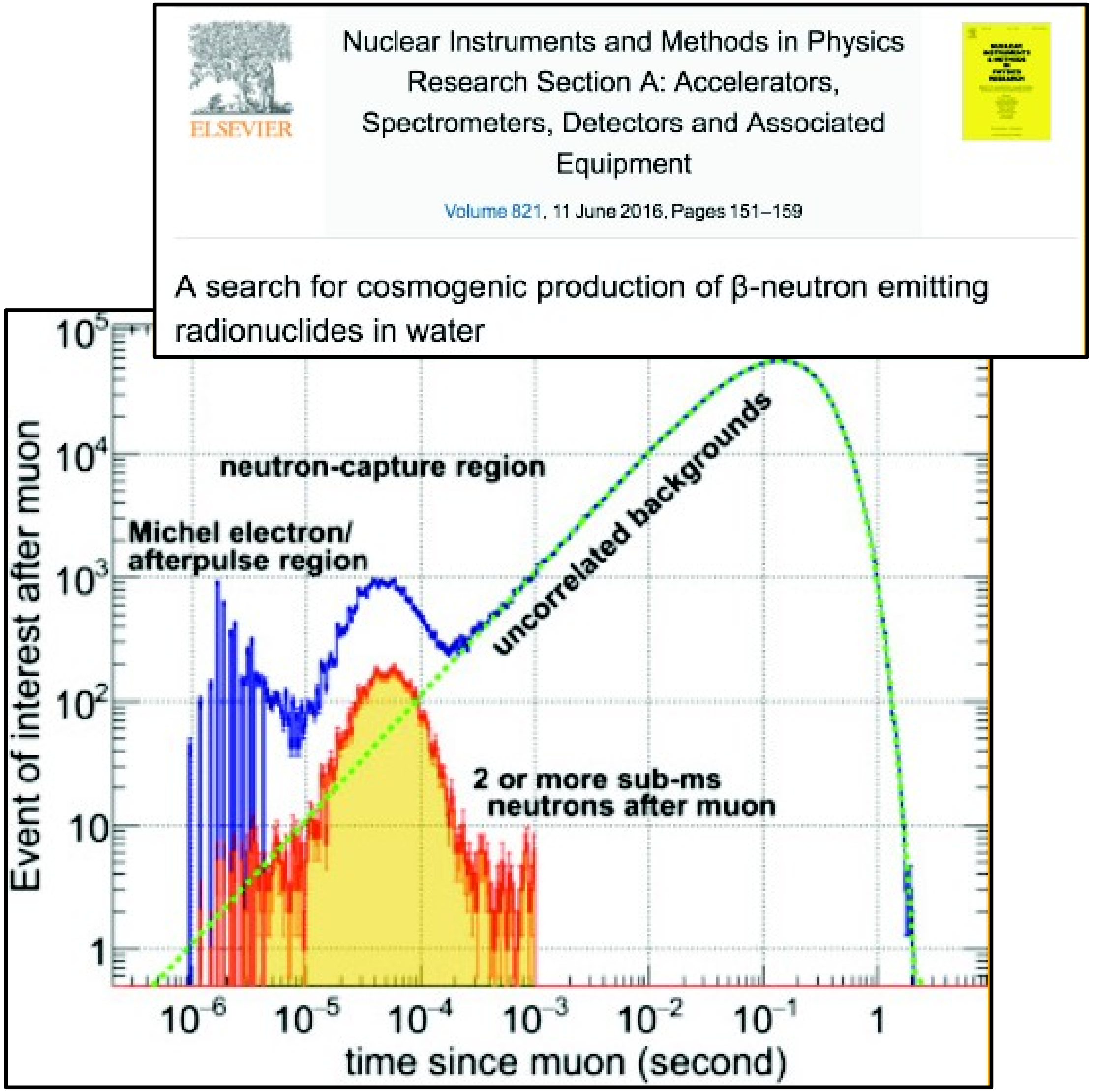
Event is tagged with preceeding muon; allows removal of nearly all backgrounds due to pile-up from other muons.

WATCHBOY Results



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

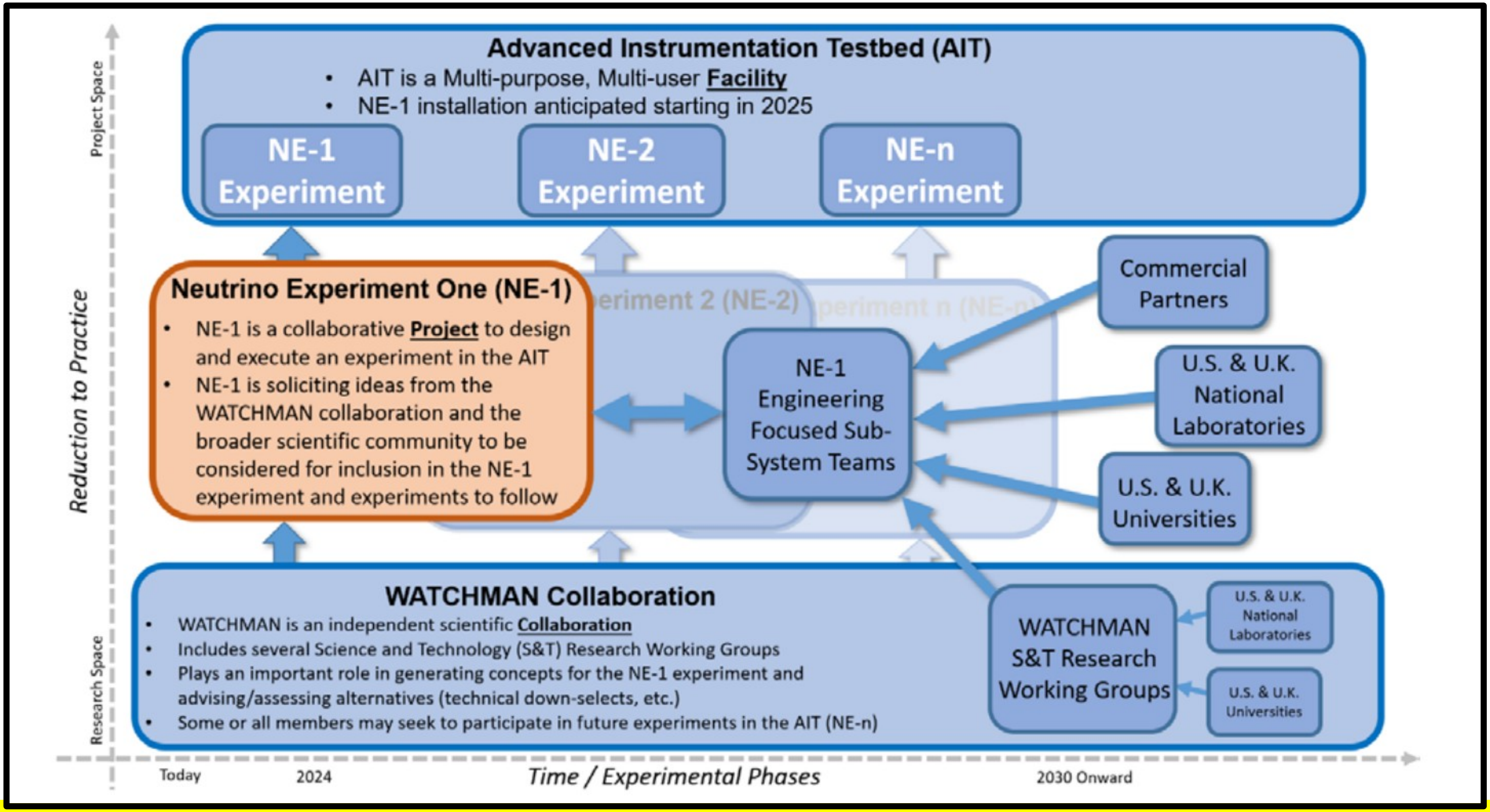
Good agreement between data and expectation!



Current Status: AIT & NE-1

AIT is the 'Advanced Instrumentation Testbed', a new facility at Boulby

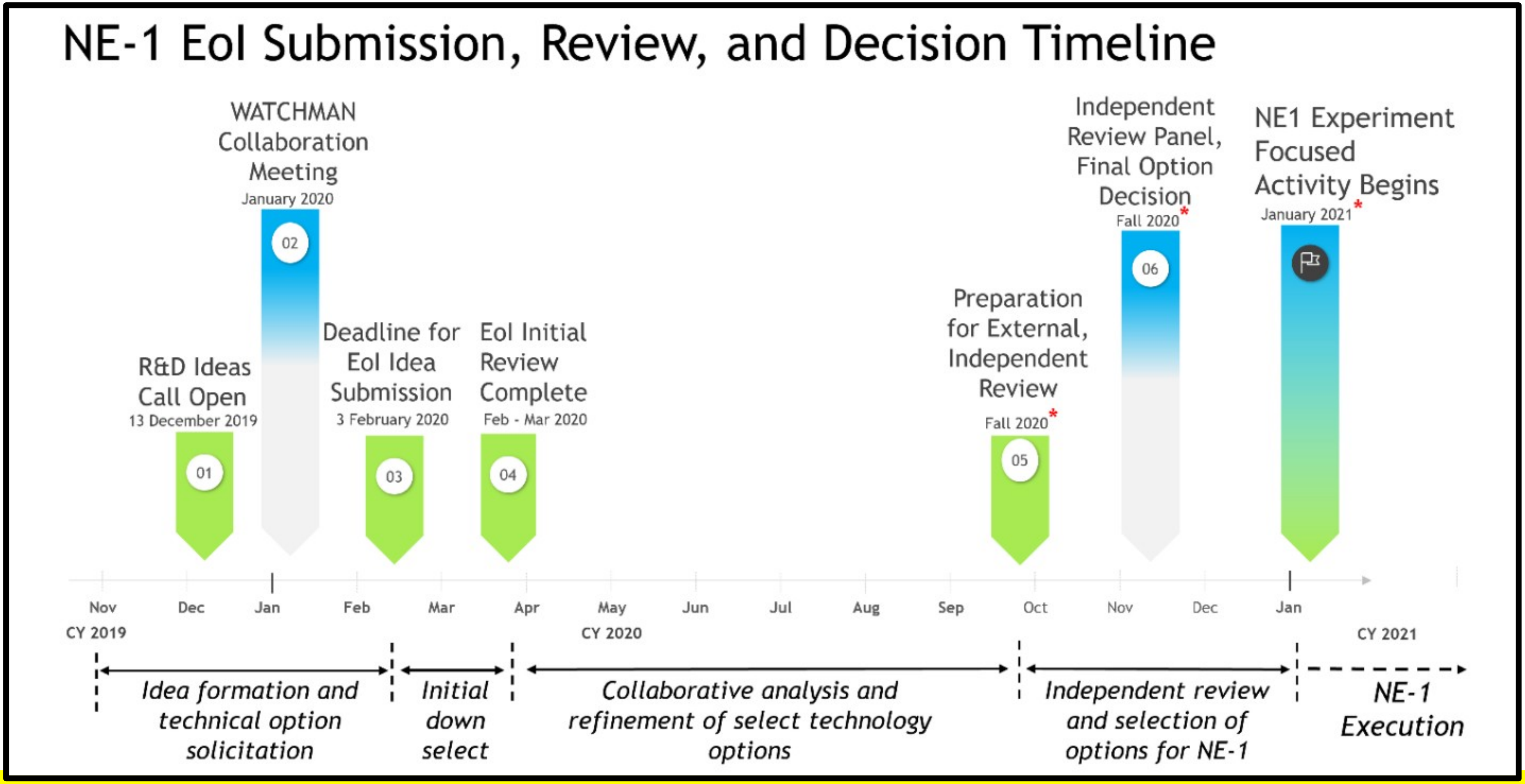
Neutrino Experiment One (**NE-1** or **NEO**) is the first experiment that will be sited in the AIT facility.



Current Status: AIT & NE-1

AIT is the critical path. Mainly consists of DNN and STFC.

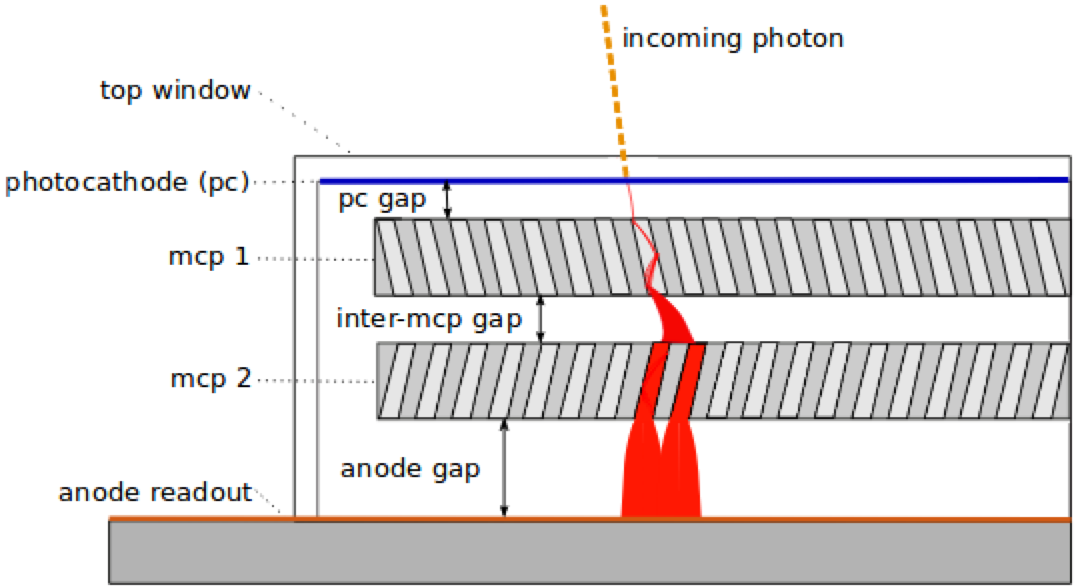
NE-1 currently has an open call for ideas, including future upgrades… and pure science projects that could be sited at the AIT facility.



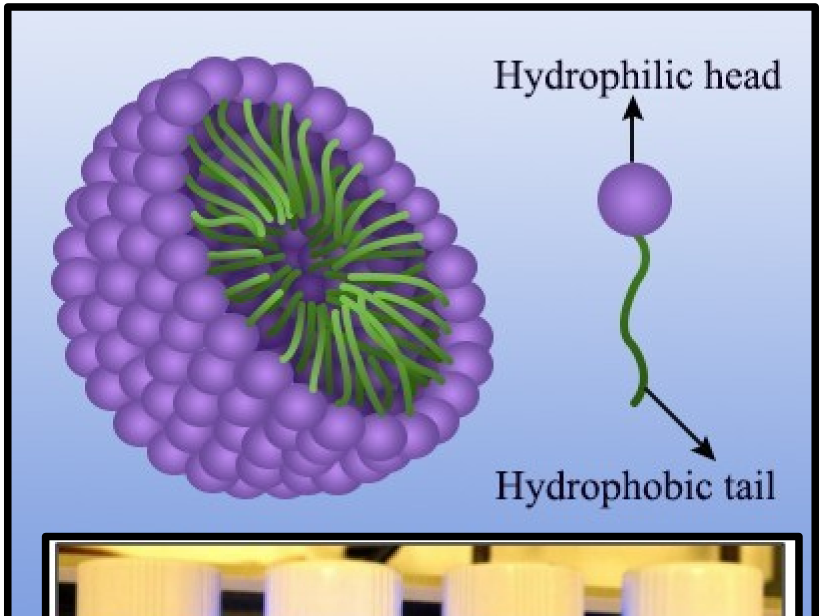
Future Options

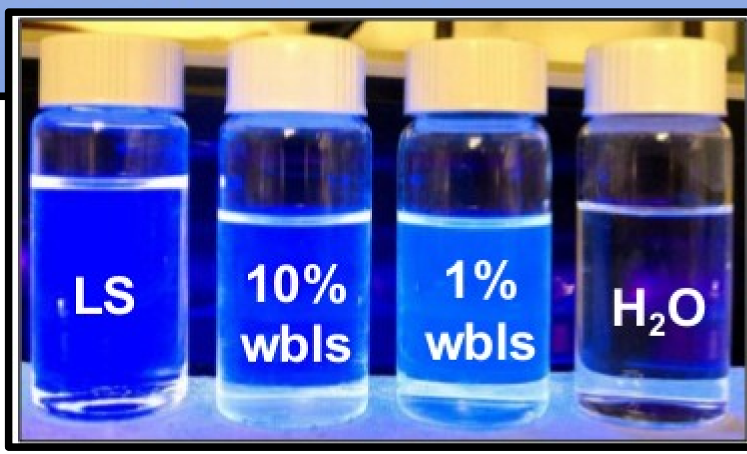
We are exploring other options for enhanced detection technologies:

Large Area Picosecond Photo-Detectors (LAPPDs):



Water-based Liquid Scintillator (WbLS):

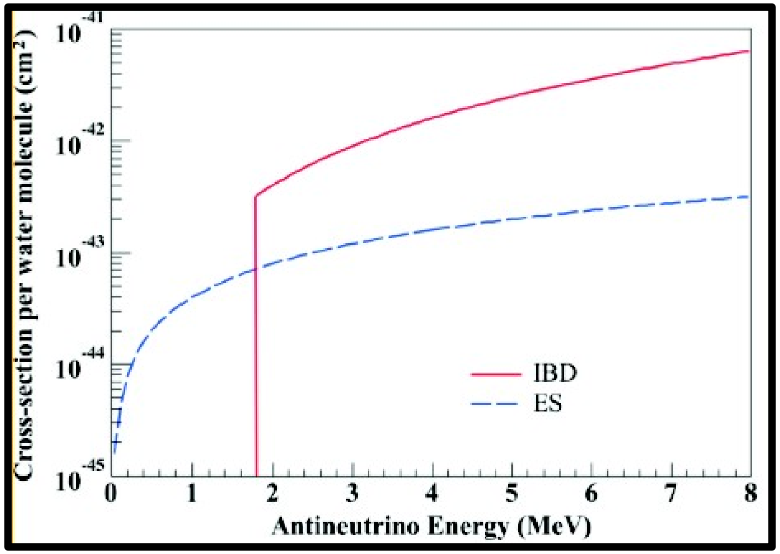




Future goals include enhancing capacity for **non-proliferation** as well as science goals like: **geoneutrinos**, **CNO solar ν**, **neutrinoless double-beta decay (0νββ)**, and **direct detection of dark matter**.

Directionality

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

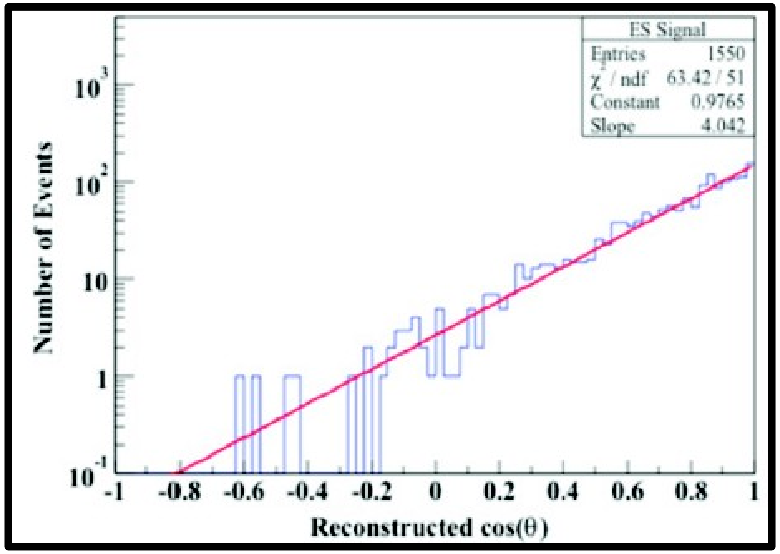


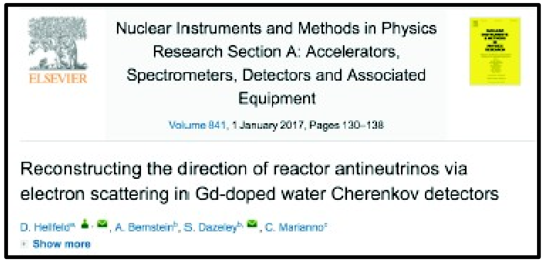
Benefits:

– 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.




ELSEVIER

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. Hellfeld, A. Bernstein, S. Dazeley, C. Marianno

Show more

Summary

- **After ~18 years of extensive R&D, gadolinium loaded water is ready!**
- **Many experiments about to adopt to enhance physics reach:**
  - ANNIE, SK-Gd (this year!)

- **Application of Antineutrino Physics also relevant for security**
  - Hope to minimize a source of global catastrophic risk
  - Defens/ce agencies are very interested, in strong collaboration with universities

- **Advanced Instrumentation Testbed is proceeding at Boulby Underground Lab**
- **WATCHMAN submitting mulitple options for Neutrino Experiment One**
  - Variants include enclosing photosensors in optical modules, alternative photosensors (*e.g.*, SiPMs), techniques to increase light collections (*e.g.*, wavelength shifting plates, retro reflectors, Winston cones)
  - Options also being explored for alternative target material (*e.g.*, liquid scintillator, WbLS, 4-MU)

- **Significant physics potential for WATCHMAN as well:**
  - Excellent supernova neutrino detector; UK group is currently designing supernova trigger
  - With suitable upgrades, WATCHMAN can be used for reactor neutrino physics, CNO-cycle solar neutrinos, neutrinoless double beta decay, geoneutrinos… and possibly even direct detection of dark matter!

Thank you for listening!