BUTTON: a technology testbed for future (anti)neutrino detection

IoP HEPP & APP Conference
3rd April 2023

Core of Advanced Test Reactor, Idaho National Laboratory
https://commons.wikimedia.org/w/index.php?curid=27024528

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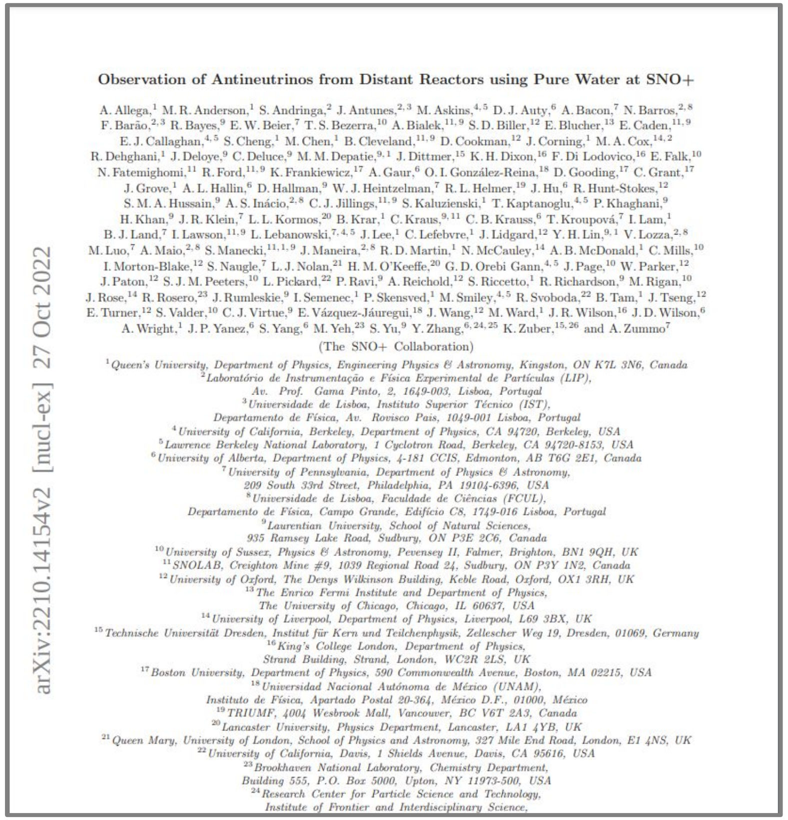
What I'll cover in this talk

1. Why antineutrino detection for remote monitoring?
2. Why are innovative antineutrino detection technologies needed for reactor monitoring?
3. The BUTTON technology testbed.
4. BUTTON for underground science and physics research.
5. The future for BUTTON

Reactor monitoring with antineutrino detection



arXiv:2210.14154v2 [nucl-ex] 27 Oct 2022

Observation of Antineutrinos from Distant Reactors using Pure Water at SNO+

A. Allega,[1] M. R. Anderson,[1] S. Andringa,[2] J. Antunes,[2,3] M. Askins,[4,5] D. J. Auty,[6] A. Bacon,[7] N. Barros,[2,8] F. Barão,[2,3] R. Bayes,[9] E. W. Beier,[7] T. S. Bezerra,[10] A. Bialek,[11,9] S. D. Biller,[12] E. Blucher,[13] E. Caden,[11,9] E. J. Callaghan,[4,5] S. Cheng,[1] M. Chen,[1] B. Cleveland,[11,9] D. Cookman,[12] J. Corning,[1] M. A. Cox,[14,2] R. Dehghani,[1] J. Deloye,[9] C. Deluce,[9] M. M. Depatie,[9,1] J. Dittmer,[15] K. H. Dixon,[16] F. Di Lodovico,[16] E. Falk,[10] N. Fatemighomi,[11] R. Ford,[11,9] K. Frankiewicz,[17] A. Gaur,[6] O. I. González-Reina,[18] D. Gooding,[17] C. Grant,[17] J. Grove,[1] A. L. Hallin,[6] D. Hallman,[9] W. J. Heintzelman,[7] R. L. Helmer,[19] J. Hu,[6] R. Hunt-Stokes,[12] S. M. A. Hussain,[9] A. S. Inácio,[2,8] C. J. Jillings,[11,9] S. Kaluzienski,[1] T. Kaptanoglu,[4,5] P. Khaghani,[9] H. Khan,[9] J. R. Klein,[7] L. L. Kormos,[20] B. Krar,[1] C. Kraus,[9,11] C. B. Krauss,[6] T. Kroupová,[7] I. Lam,[1] B. J. Land,[7] I. Lawson,[11,9] L. Lebanowski,[7,4,5] J. Lee,[1] C. Lefebvre,[1] J. Lidgard,[12] Y. H. Lin,[9,1] V. Lozza,[2,8] M. Luo,[7] A. Maio,[2,8] S. Manecki,[11,1,9] J. Maneira,[2,8] R. D. Martin,[1] N. McCauley,[14] A. B. McDonald,[1] C. Mills,[10] I. Morton-Blake,[12] S. Naugle,[7] L. J. Nolan,[21] H. M. O'Keeffe,[20] G. D. Orebi Gann,[4,5] J. Page,[10] W. Parker,[12] J. Paton,[12] S. J. M. Peeters,[10] L. Pickard,[22] P. Ravi,[9] A. Reichold,[12] S. Riccetto,[1] R. Richardson,[9] M. Rigan,[10] J. Rose,[14] R. Rosero,[23] J. Rumleskie,[9] I. Semenec,[1] P. Skensved,[1] M. Smiley,[4,5] R. Svoboda,[22] B. Tam,[1] J. Tseng,[12] E. Turner,[12] S. Valder,[10] C. J. Virtue,[9] E. Vázquez-Jáuregui,[18] J. Wang,[12] M. Ward,[1] J. R. Wilson,[16] J. D. Wilson,[6] A. Wright,[1] J. P. Yanez,[6] S. Yang,[6] M. Yeh,[23] S. Yu,[9] Y. Zhang,[6,24,25] K. Zuber,[15,26] and A. Zummo[7]

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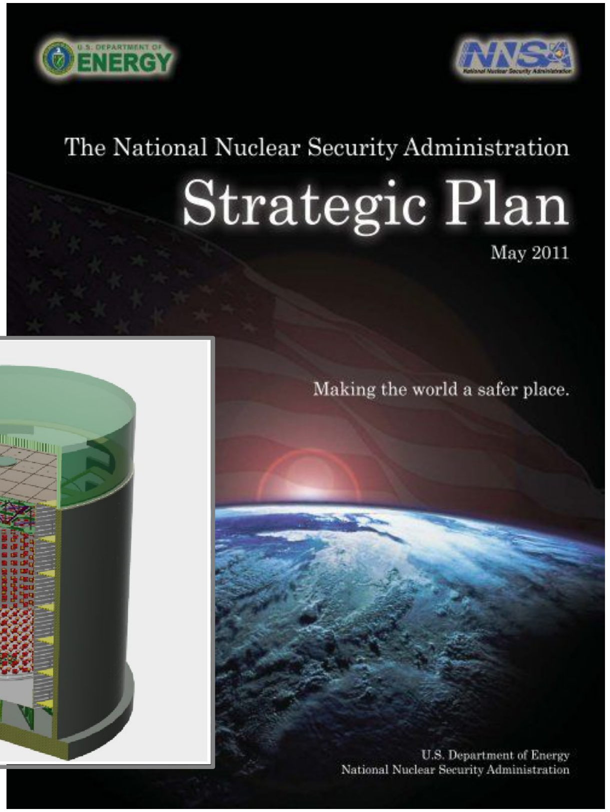
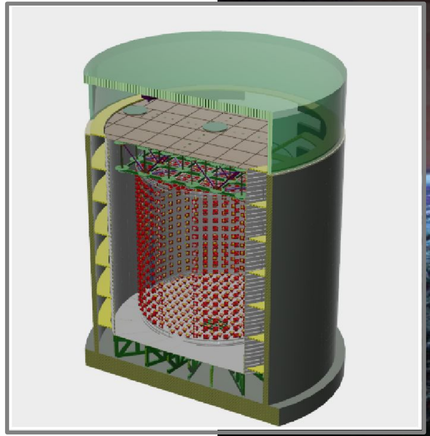




Evidence of antineutrinos from multiple reactors in a Cherenkov detector at 3.5σ
A. Allega et al. (The SNO+ Collaboration)
Phys. Rev. Lett. 130, 091801 (2023)

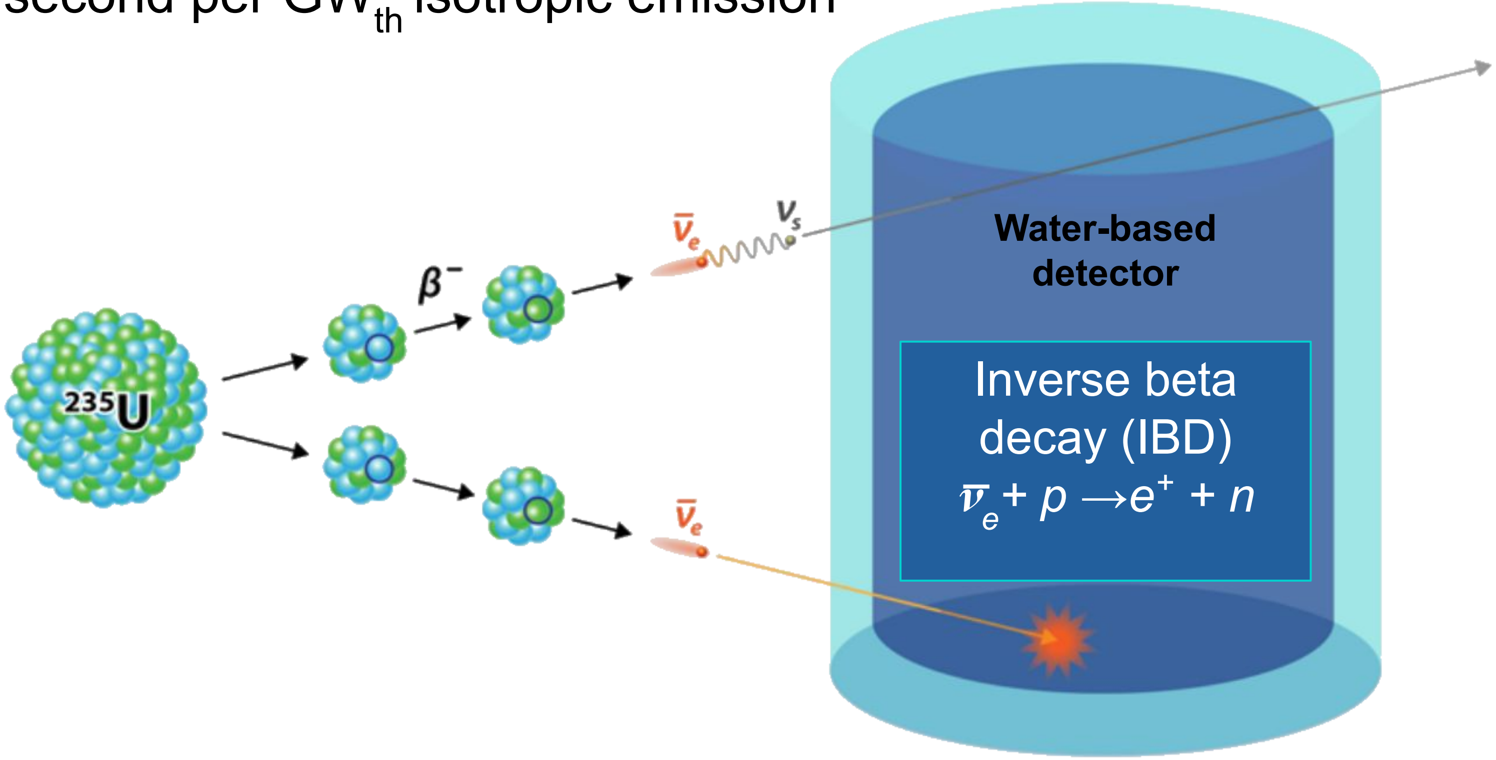
WATCHMAN* scientific collaboration: a water-based detector for remote non-proliferation monitoring.

*WATer CHerenkov Monitor for ANtineutrinos

Antineutrino detection for monitoring

Extremely high flux of neutrinos from a nuclear reactor:

~6 antineutrinos per fission
O(10^{21}) per second per GW_{th} isotropic emission



APS/Alan Stonebraker

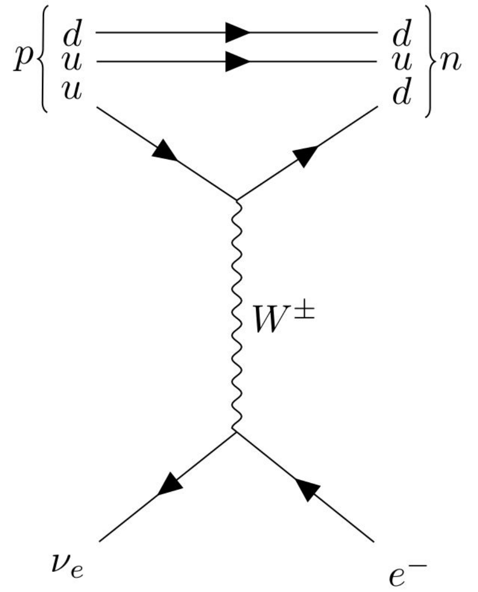
Water-based Cherenkov detector scalable for mid- to long-range monitoring because:

- Inexpensive
- Readily available
- Low absorption

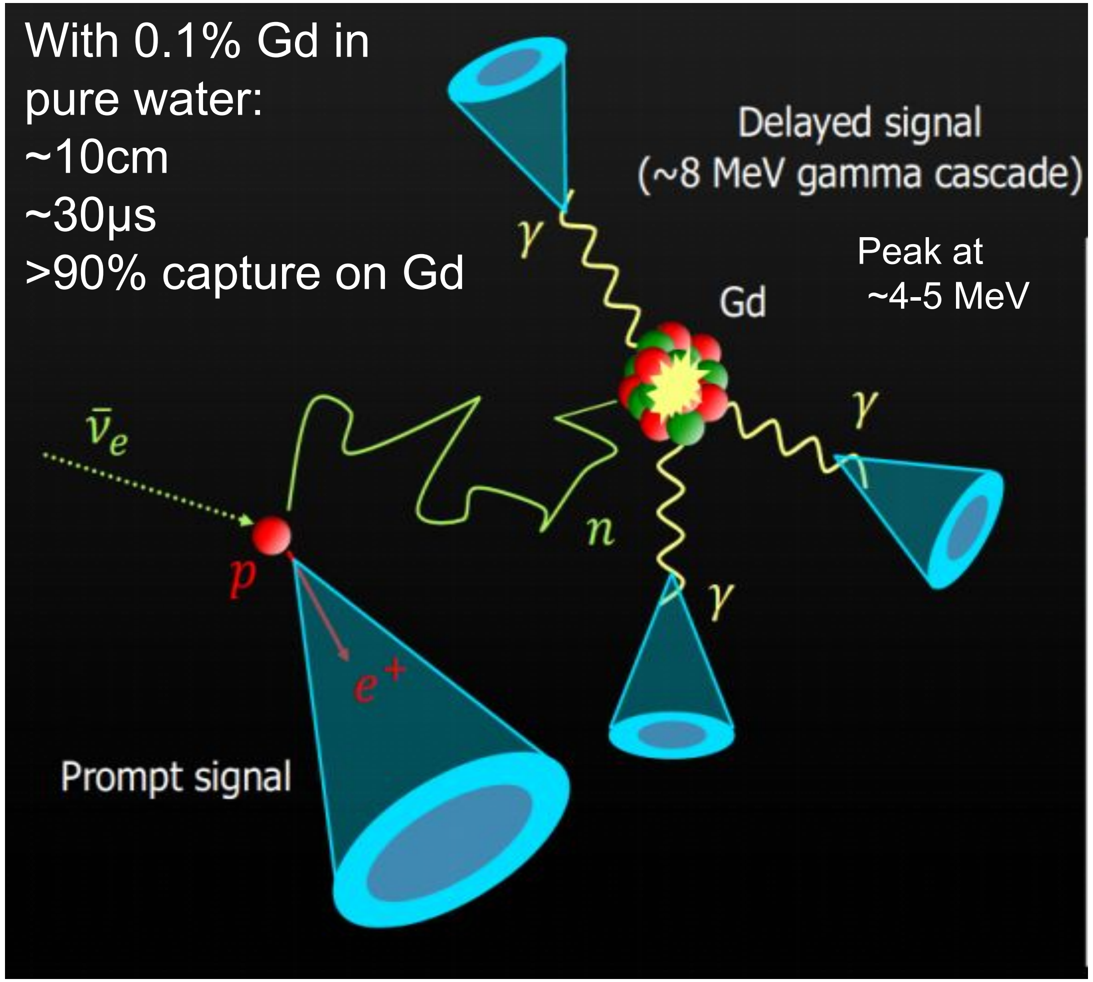
Antineutrino energy range: 0 to 10 MeV

Gd doping required for reactor monitoring

The anti-neutrino interacts with free protons in the detector via inverse beta decay (IBD).



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



With gadolinium (Gd) loading, the IBD is a pair of interactions - important for background rejection.

	H_2O	Gd-H_2O
σ	~0.3 b	~ 49,000 b
τ	~200 μsec	~30 μsec
E	2.2 MeV gamma	~8 MeV gamma cascade

Gd doping is vital for detection of antineutrinos from a single site, or in a non-ideal background environment.

Discovery of a remote reactor

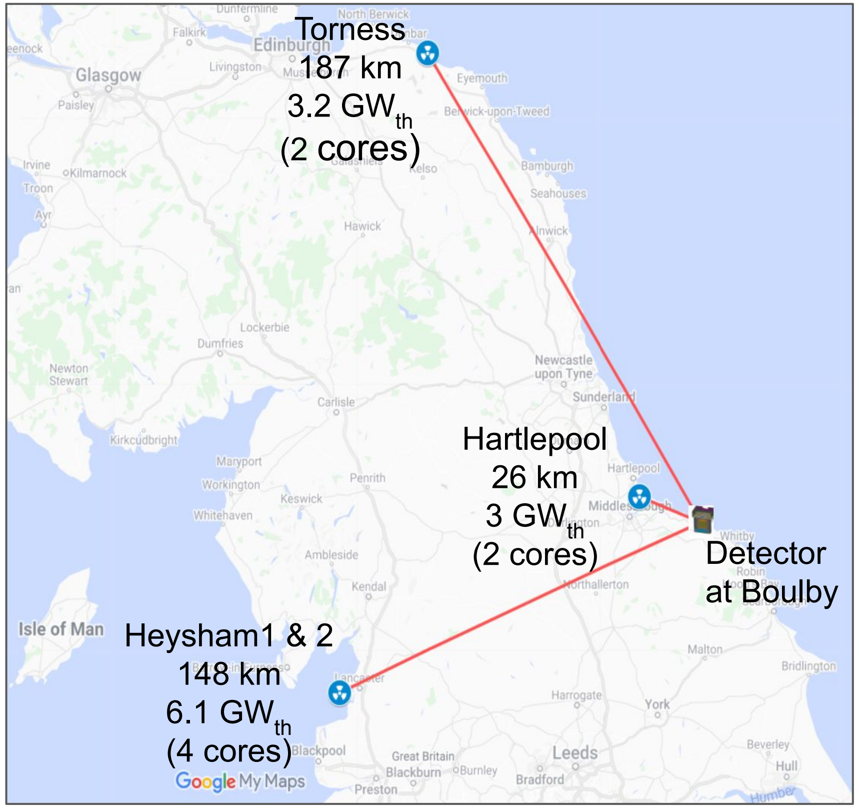
Sensitivity studies have determined the time to detection of reactor antineutrinos from single nuclear reactor sites (Hartlepool and Heysham) with a detector at Boulby Underground Laboratory.

Dwell Time (in days) to reject background-only hypothesis @ 3 sigma

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

L. Kneale *et al*, arXiv:2210.11224 (Submitted to *Phys. Rev. Applied*)

$$t_{dwell} = \frac{N_\sigma^2 \Sigma b_i}{s^2 - N_\sigma^2 \Sigma \sigma^2_{b_i,sys}} \quad (N_\sigma = 3)$$



Innovative technology is needed

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(N_σ = 3)

Possible to see a 3GW_{th} reactor at a distance of ~150 km in less than two years of reactor operation with a 22 m cylindrical detector filled with gadolinium-doped water-based liquid scintillator (Gd-WbLS - see Slide 15).

~3 GW_{th}
~150 km away

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For realistic applications, including more ambitious goals such as reactor ranging,* the development of innovative detector technology is a necessity.

*** See next talk by Steve Wilson on *Remote reactor ranging using neutrino oscillations***

…Enter the BUTTON technology testbed

Boulby Underground Technology Testbed Observing Neutrinos

The BUTTON UK/U.S. Collaboration

~30 members across 10 institutions in the UK and U.S.

AWE

Lawrence Livermore National Laboratory

Pacific Northwest NATIONAL LABORATORY

UKRI Science and Technology Facilities Council

Boulby Underground Laboratory

November 2022 Collaboration Meeting at Boulby Underground Laboratory

THE UNIVERSITY OF WARWICK

University of Sheffield

Penn UNIVERSITY of PENNSYLVANIA

THE UNIVERSITY of EDINBURGH

University of Glasgow

UNIVERSITY OF LIVERPOOL

Funded in the UK by STFC from the UKRI Fund for International Collaboration and the MoD, and in the U.S. by NNSA (National Nuclear Security Administration).

Testing advanced fills and photodetection

Boulby Underground Technology Testbed Observing Neutrinos

AWE

Lawrence Livermore National Laboratory

Pacific Northwest National Laboratory

The University of Warwick

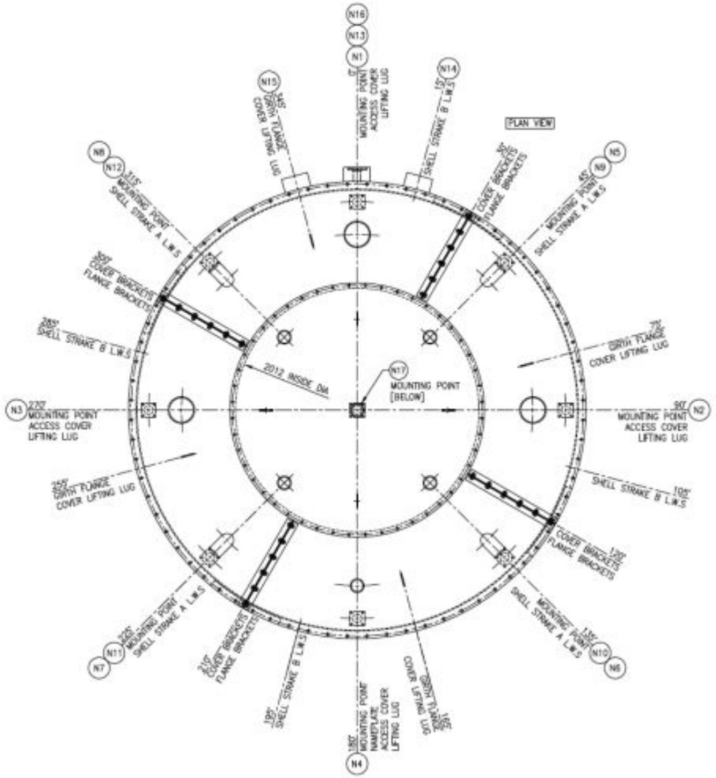
University of Sheffield

Penn University of Pennsylvania

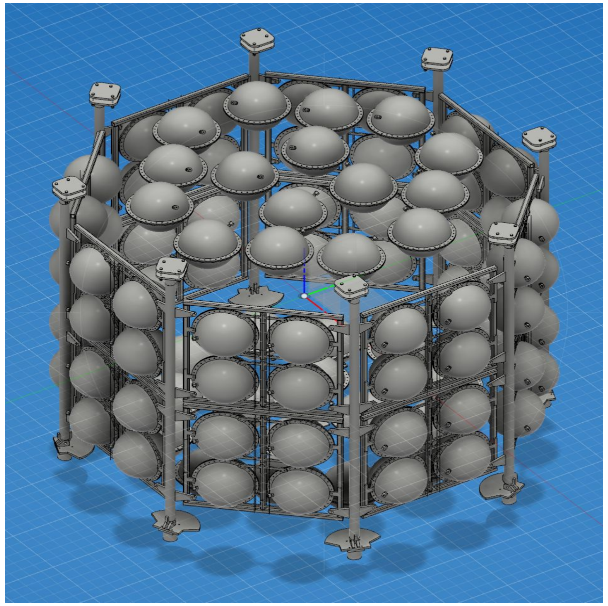
The primary goal of BUTTON is to develop the innovative technology required for a remote reactor monitor prototype.

BUTTON-30 flexible design

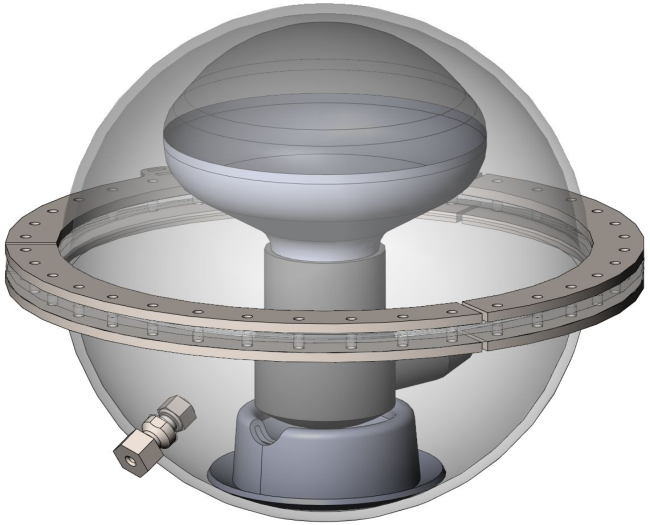
BUTTON low-background testbed for neutrino detector hardware and fill media.



- ~30 tonnes
- ~100 Hamamatsu R7081 10” PMTs



- Modular support structure to facilitate swapping out **advanced photosensor technology**.

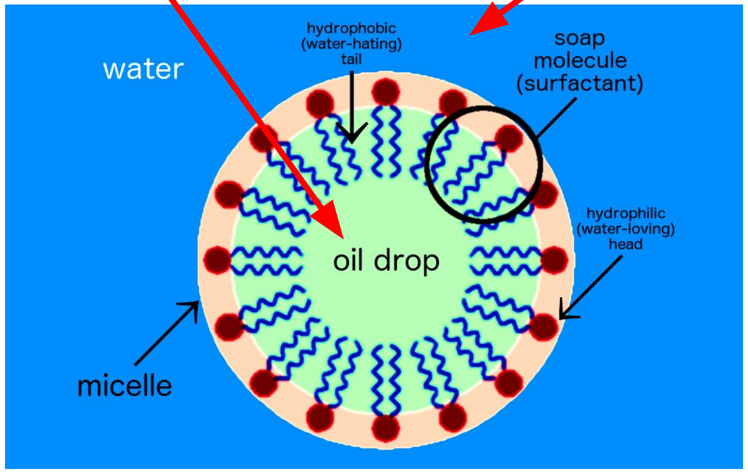


- Compatible with **novel fill materials**.

Advanced detection media

Scintillation Detectors:
- ✅ High light yield
- ✅ Low energy threshold
- ✅ Good energy and position resolutions
- 🚫 Limited in size by absorption and cost
- 🚫 No directionality

Cherenkov Detectors:
- ✅ Directional information
- ✅ Can be very large (low absorption)
- ✅ Particle ID at high energies
- 🚫 No access to physics below the Cherenkov threshold
- 🚫 Low light yield



Courtesy of Zara Bagdasarian U.C. Berkeley

Water-based liquid scintillator (WbLS)*

Primary objective:
Gadolinium-doped water-based liquid scintillator (Gd-WbLS).

WbLS has been deployed in ANNIE and is planned for THEIA.

WbLS cocktails are being refined for the best balance and separation of Cherenkov and scintillation light.

Gd-WbLS is under development.

Other potential fills:
slow scintillator, LiquidO, etc.

***See poster by Adam Tarrant: Attenuation of WbLS for future neutrino experiments**

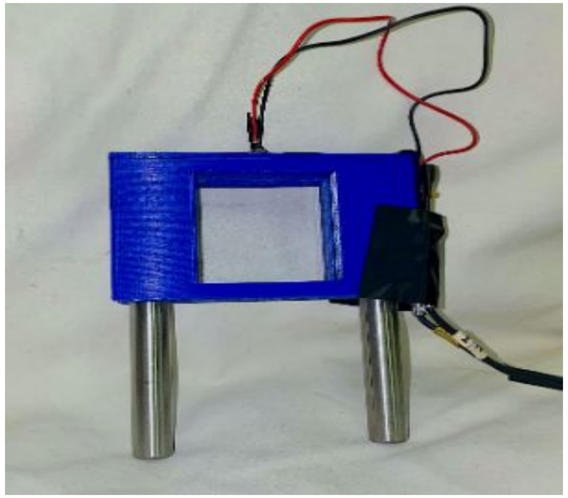
Advanced photodetection

Fast timing

Large Area Picosecond Photo-Detector (LAPPD):

50 ps timing
Imaging

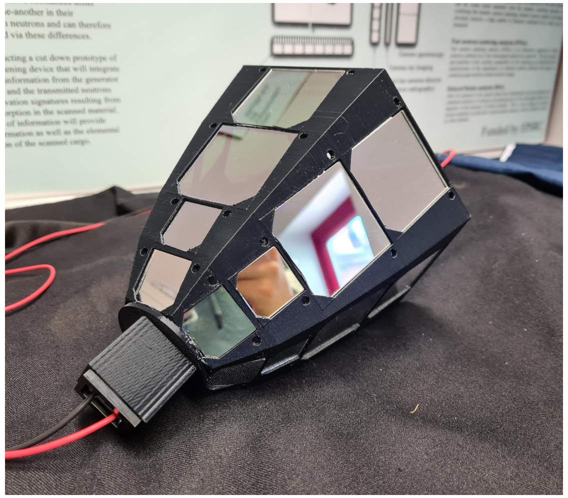
Fast, high efficiency



Wavelength-shifting plate with SiPM strip readout:

50% efficiency at peak
Timing < 100 ps

Spectral sorting



Dichroicons: light cones with dichroic filters:

Increased light collection
Photon sorting by wavelength

Cherenkov-scintillation separation in WbLS

BUTTON-30 for UK underground science & physics

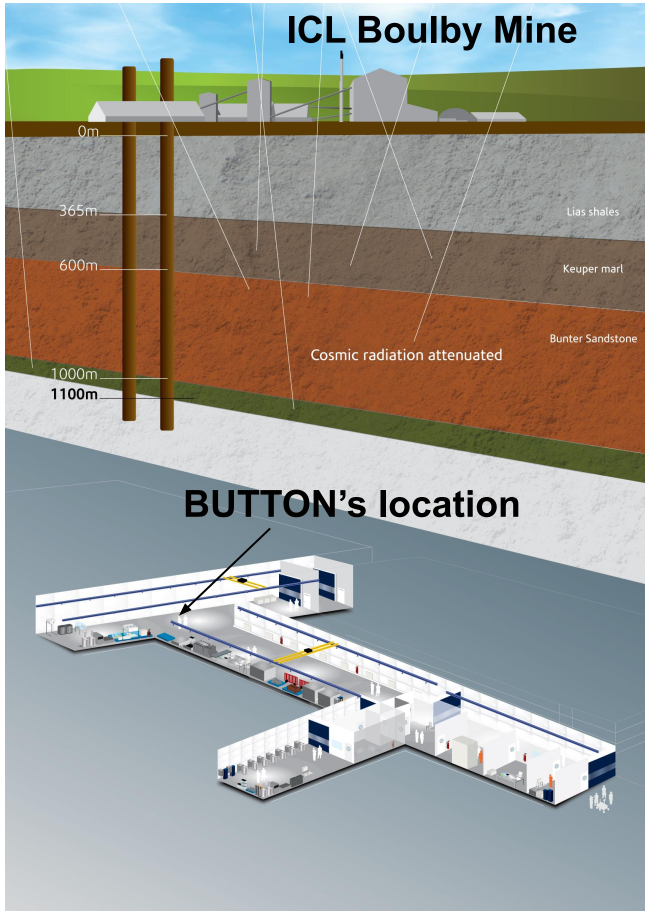
2023 Construction (starting imminently!)
2024 Begin data taking
2025 Arrival of Gd-WbLS & filtration from US

Practical benefits for Boulby Infrastructure Development Project*:

- First large-scale underground welding at Boulby.
- Detailed costing - template for larger underground projects.
- Logistics for transport and construction underground.

Technology benefits beyond non-proliferation monitoring:

- BUTTON leading UK involvement with WbLS.
- First tonne-scale demonstration of Gd-WbLS.
- Testing hardware and media to be used in other experiments at Boulby.



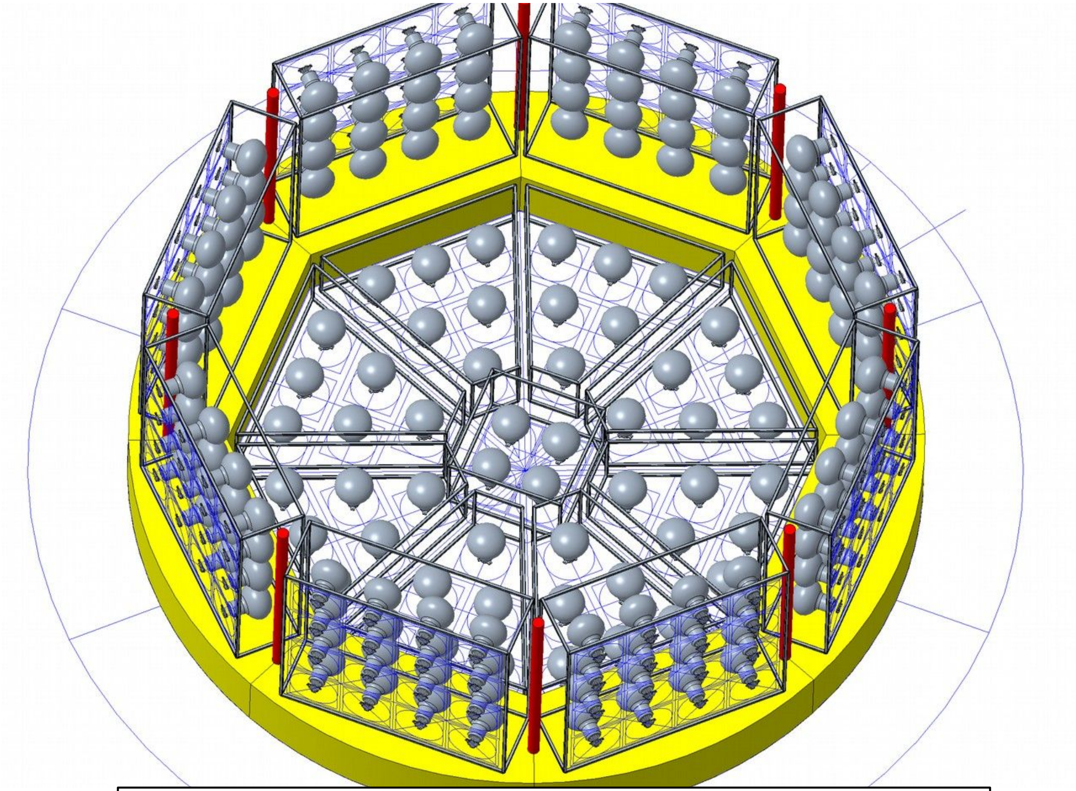
*** See plenary talk by Hannah Newton on Tuesday at 1.30 pm**

The future for BUTTON

BUTTON-30

Possible R&D:
- Measuring the intrinsic backgrounds of a LiquidO (opaque liquid scintillator) detector.

Possible science goals:
- Measurement of the two-neutrino double beta decay of ^{160}Gd.
- Supernova pointing in Gd-WbLS.



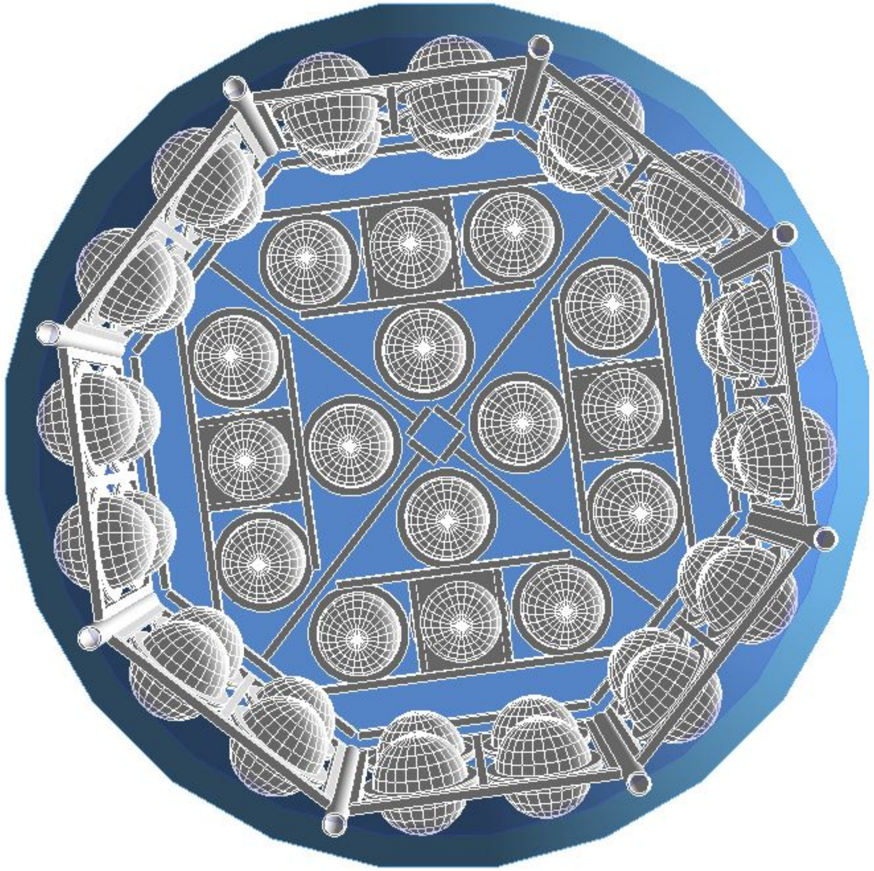
BUTTON-100 conceptual sketch

BUTTON-100

Potential for a follow-up, 100-tonne experiment.
An at-scale demonstrator for a remote reactor monitoring experiment.

BUTTON for reactor monitoring and more

- **Antineutrino detection suited to remote non-proliferation monitoring due to very high flux from reactors.**
- **BUT it will require innovative detection technology.**
- **BUTTON-30 will have a flexible design to test out a range of hardware and detection media.**
- **Primary objective: test a Gd-WbLS system and advanced photodetection.**
- **BUTTON will bring logistical and technology benefits to underground science in the UK.**
- **Future uses of BUTTON-30 could include measuring backgrounds for a LiquidO detector and $2\nu\beta\beta$ decay search.**
- **Potential for a larger BUTTON-100 detector.**



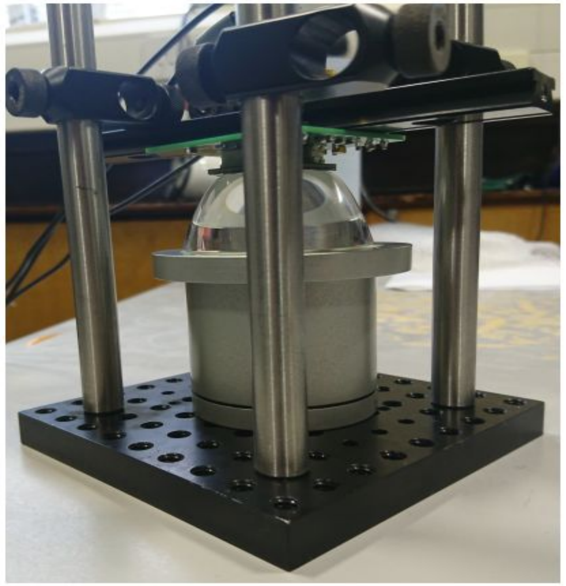
BUTTON simulation*

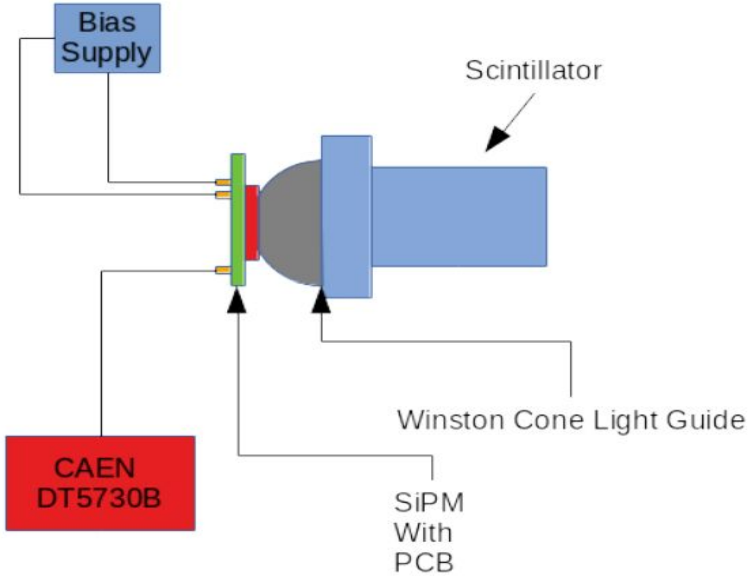
***See poster by Alex Morgan: Development of simulations for the BUTTON testbed**

For more information…

160Gd decay

- **Kobayashi/Kobayashi experiment: T1/2(0v) > 3.0 × 10^{20} y (68 % CL) Nucl. Phys. A586(1995)457**





Four modules ~ double target mass of Kobayashi

modular approach - for each module:

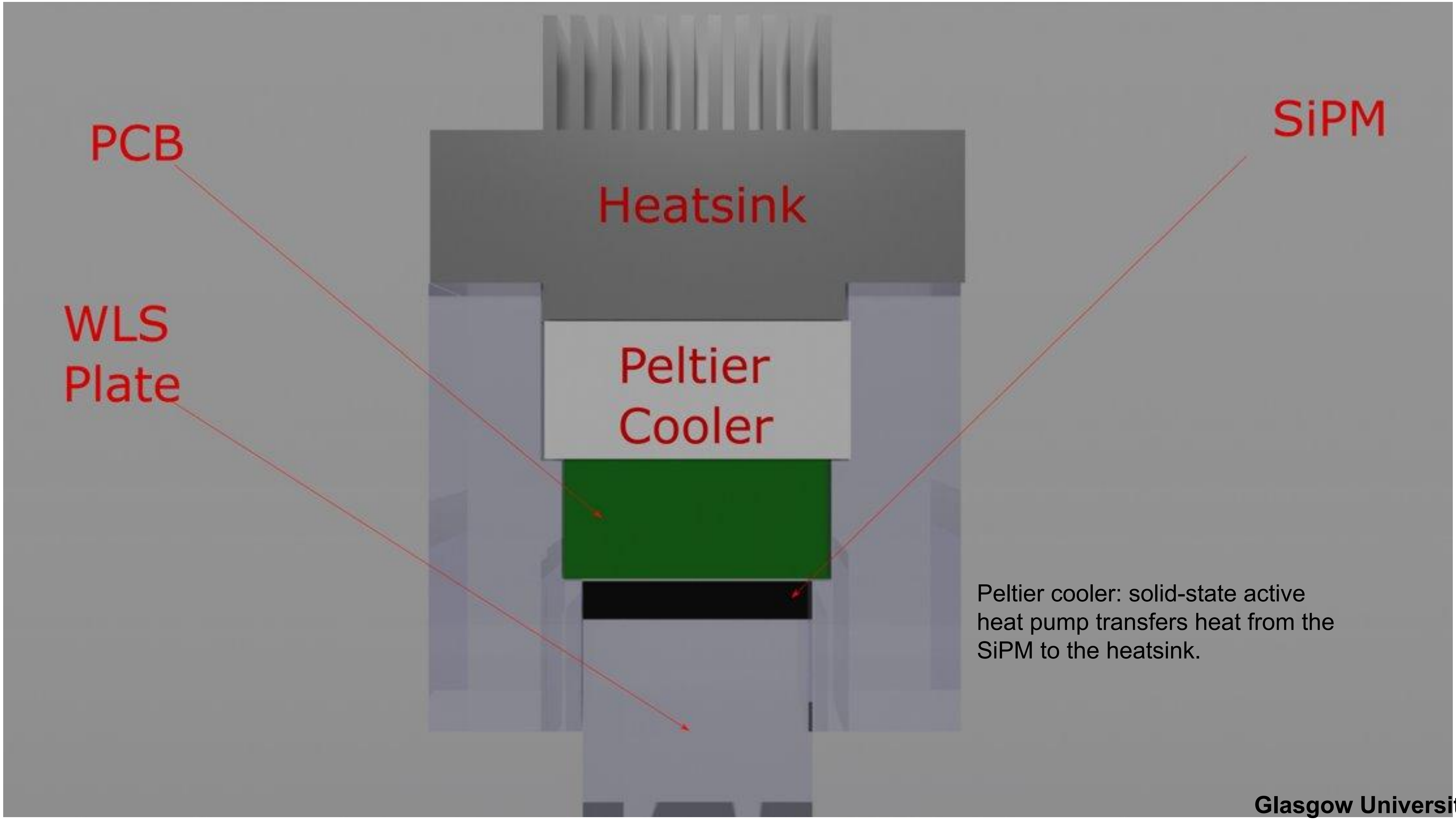
- 50mm ⌀ x 150mm long GAGG crystals (294cm³)
- 8x8 array of SiPM couple with perspex light guide
- simulation suggests energy resolution 3-5%

4

from F. Thomson, PhD thesis, Glasgow 2019

Kobayashi/Kobayashi
GSO (Ce) crystal (Gadolinium Orthosilicate)
8-10 photons per KeV
In BUTTON
GAGG crystal (Gadolinium aluminium gallium garnet)
40-60 photons per KeV
2 x target mass
Underground

FRANCIS Frame and Cooling design

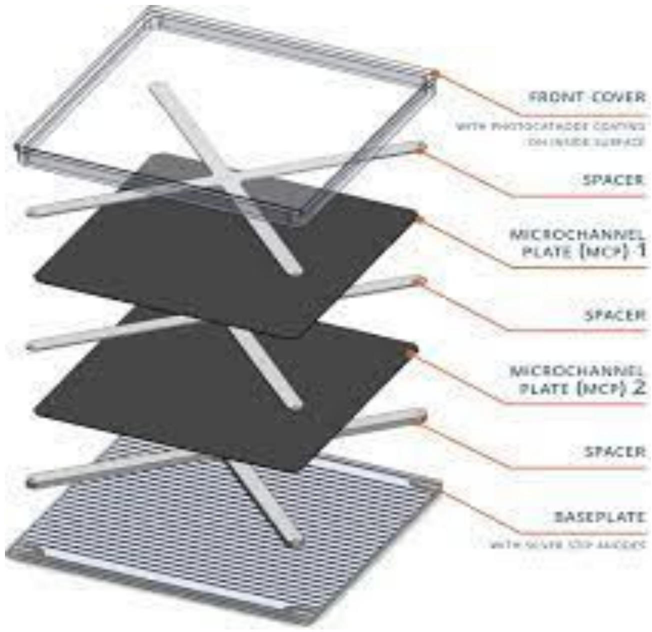


Peltier cooler: solid-state active heat pump transfers heat from the SiPM to the heatsink.

LAPPD

LAPPDs have:

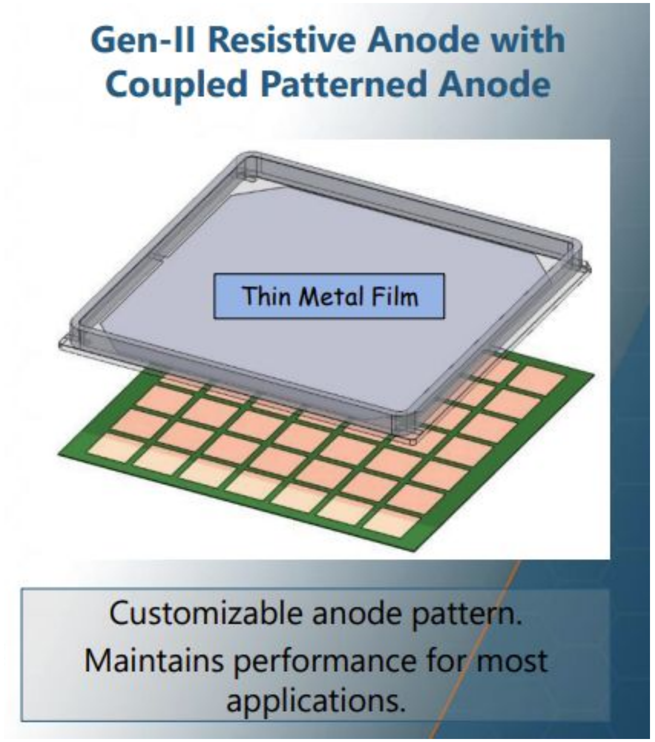
- quantum efficiency between 20% and 30%,
- mm-scale spatial resolution
- up to ~50 picosecond single-photoelectron timing resolution (6 GHz readout).



The Large Area Picosecond PhotoDetector (LAPPD) is a fast, planar-geometry photosensor with millimetre spatial resolution and picosecond timing resolution.

The LAPPD has a 350-cm^2 detection area coated with a bialkali Na_2KSb photocathode.

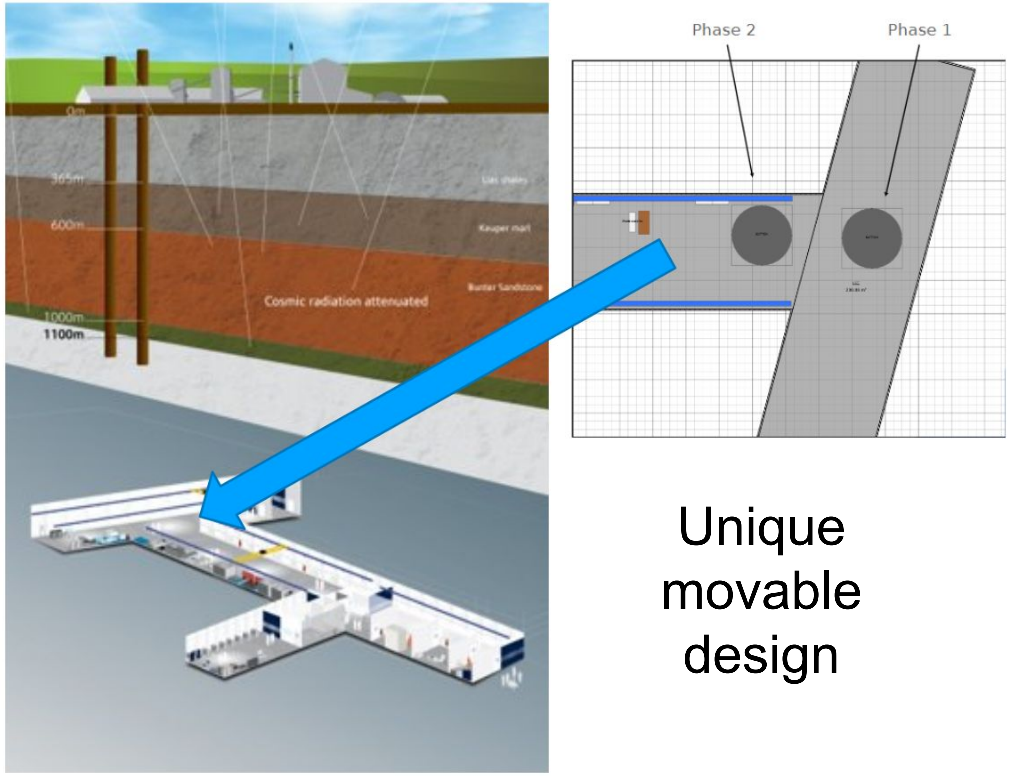
The signal produced at the photocathode is amplified, with a 10^7 gain, by a pair of micro-channel plates stacked behind the front plate. The amplified signal is then read out at the anode.



…Enter the BUTTON technology testbed

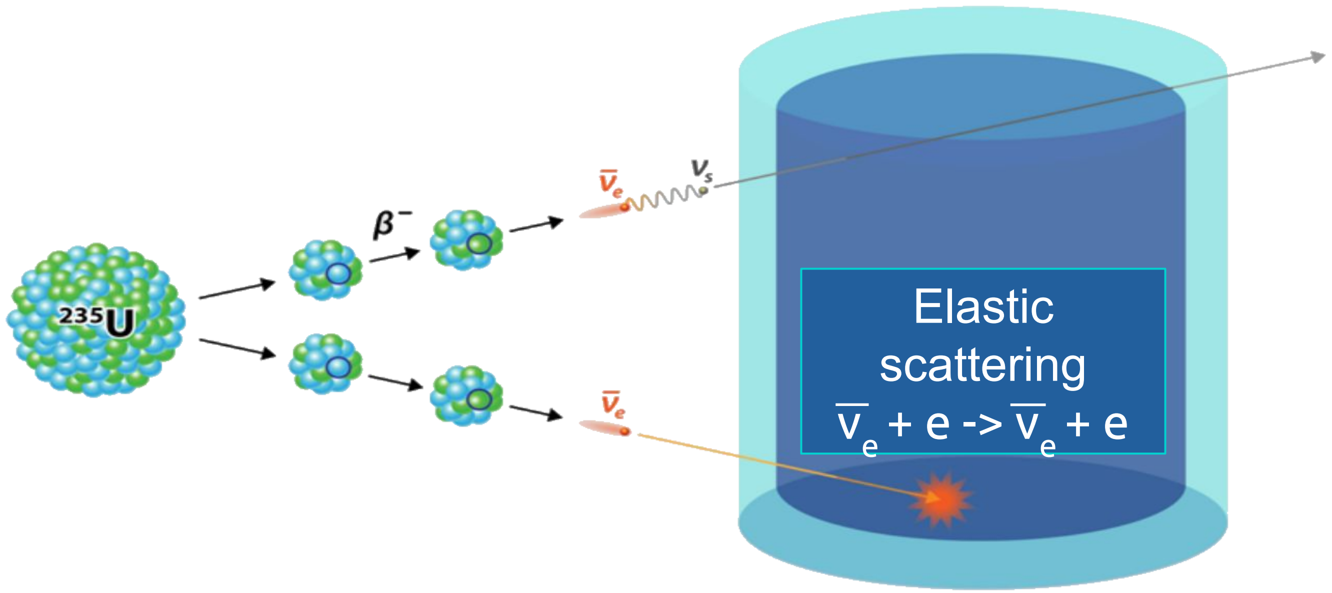
Boulby Underground Technology Testbed Observing Neutrinos

November 2022 Collaboration Meeting
at Boulby Underground Laboratory

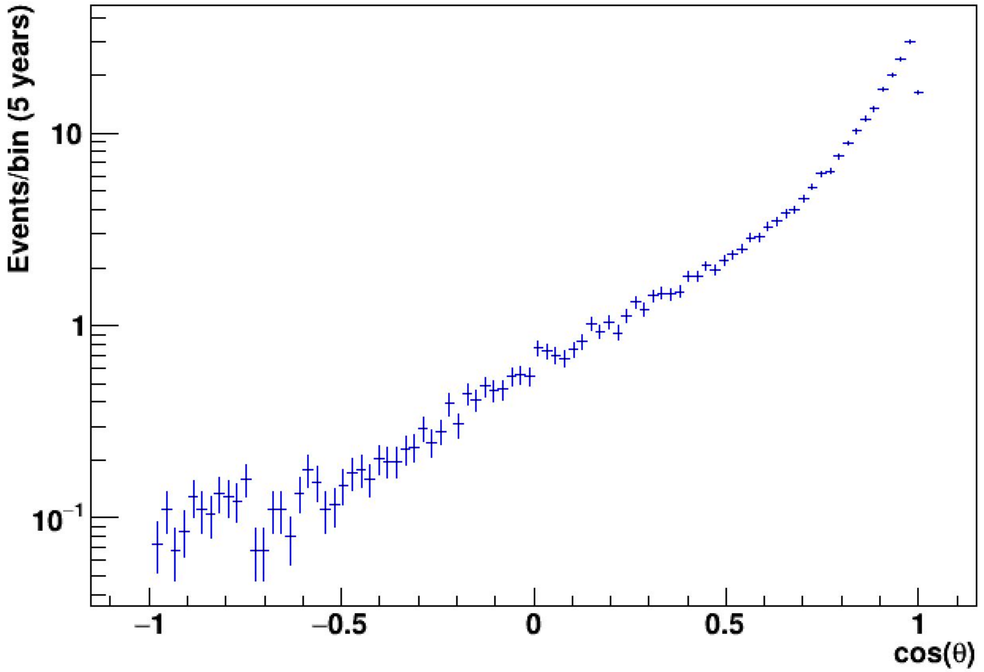


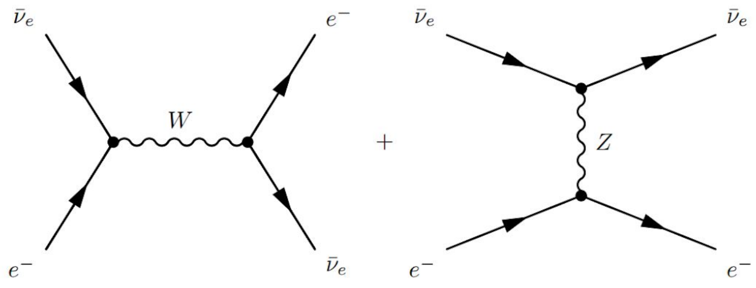
Unique movable design

Reactor directionality



APS/Alan Stonebraker



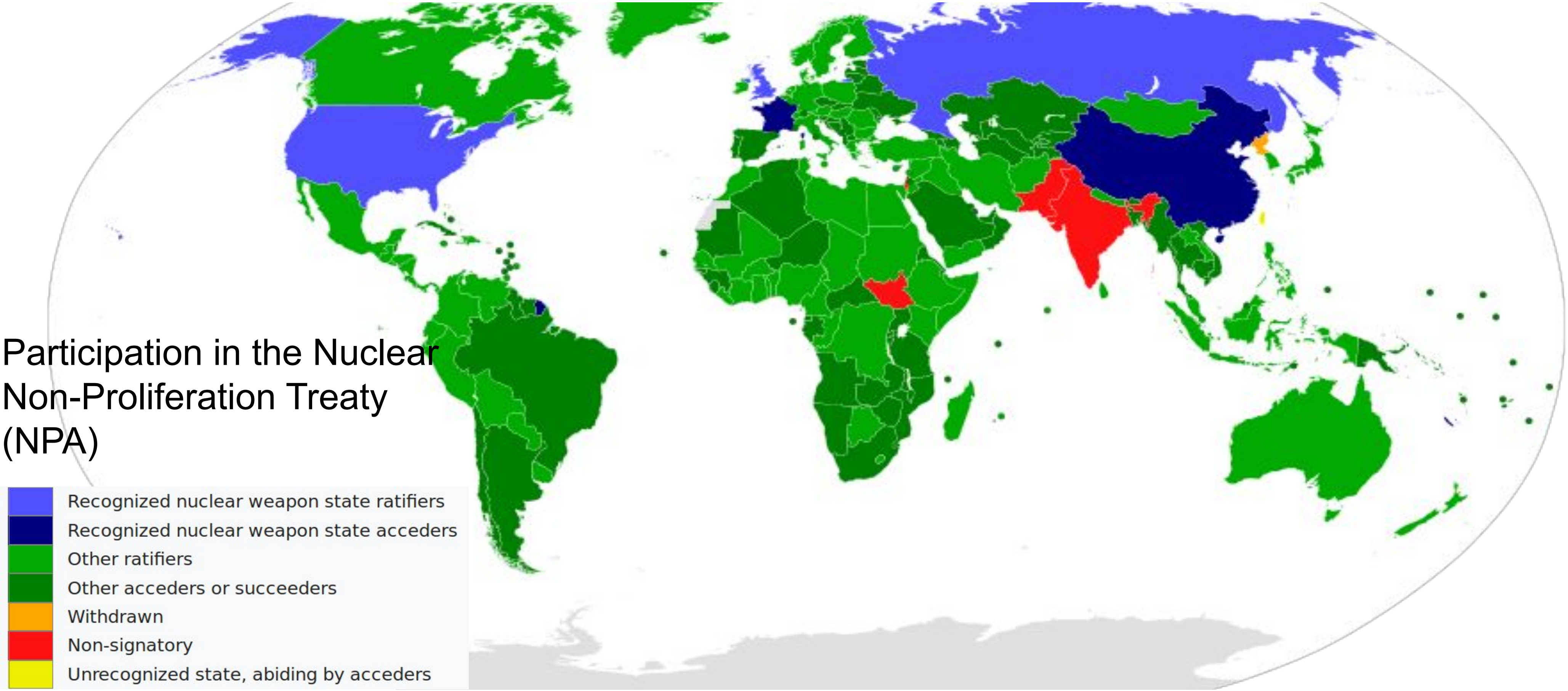


Anti-neutrino elastic scattering on electrons points back towards the reactor.

Remote monitoring supports NPT

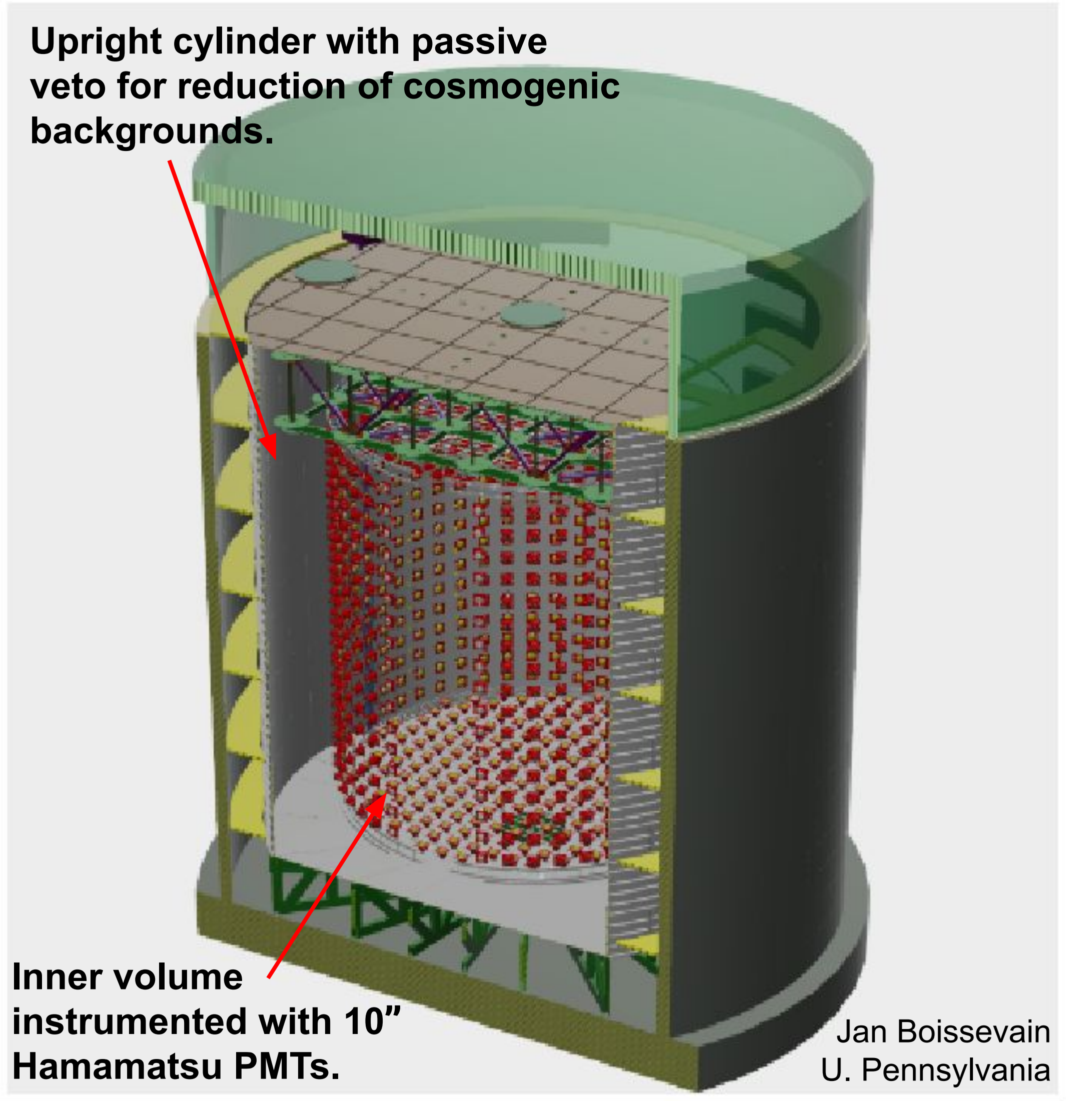
Peaceful use of nuclear energy, non-proliferation of nuclear weapons and nuclear disarmament

Participation in the Nuclear Non-Proliferation Treaty (NPA)



Non-Proliferation Treaty supported by **Comprehensive Safeguard Agreements** provide the framework for IAEA to monitor nuclear reactors.

Sensitivity Study - a detector at Boulby Mine



Prototype at Advanced Instrumentation Testbed (AIT) site at Boulby Mine:
Gadolinium-doped Cherenkov detector.

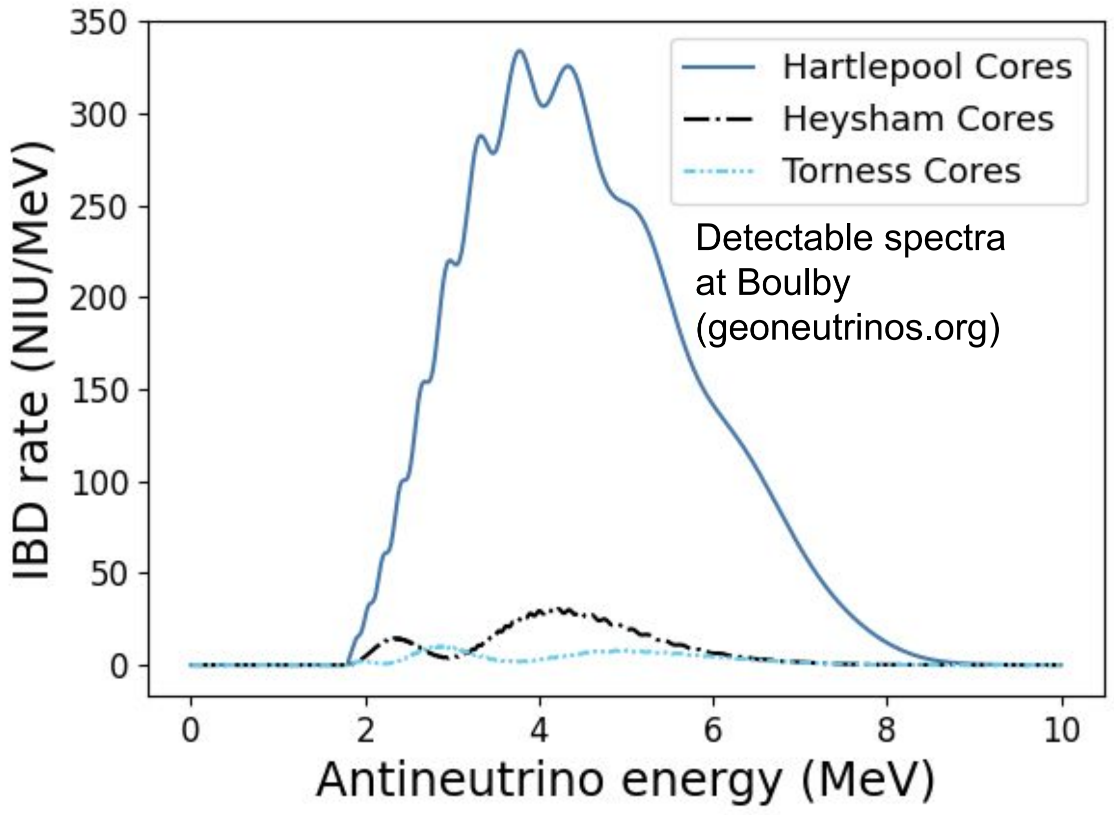
Located underground in Boulby Mine for low backgrounds:
10^6 cosmic muon reduction compared to surface.
3 Bq m^{-3} air radon concentration.

Detector configurations:
22m tank / 9m inner-PMT radius / 4600 PMTs.
16m tank / 5.7m inner-PMT radius / 1824 PMTs.
(15% photocoverage.)

Fill options:
Gd-H_2O,
Gd-WbLS (1% water-based liquid scintillator).

Sensitivity to real signals at Boulby Mine

Reactors at Hartlepool detectable within a month.
More challenging to see the reactors at Heysham and Torness.

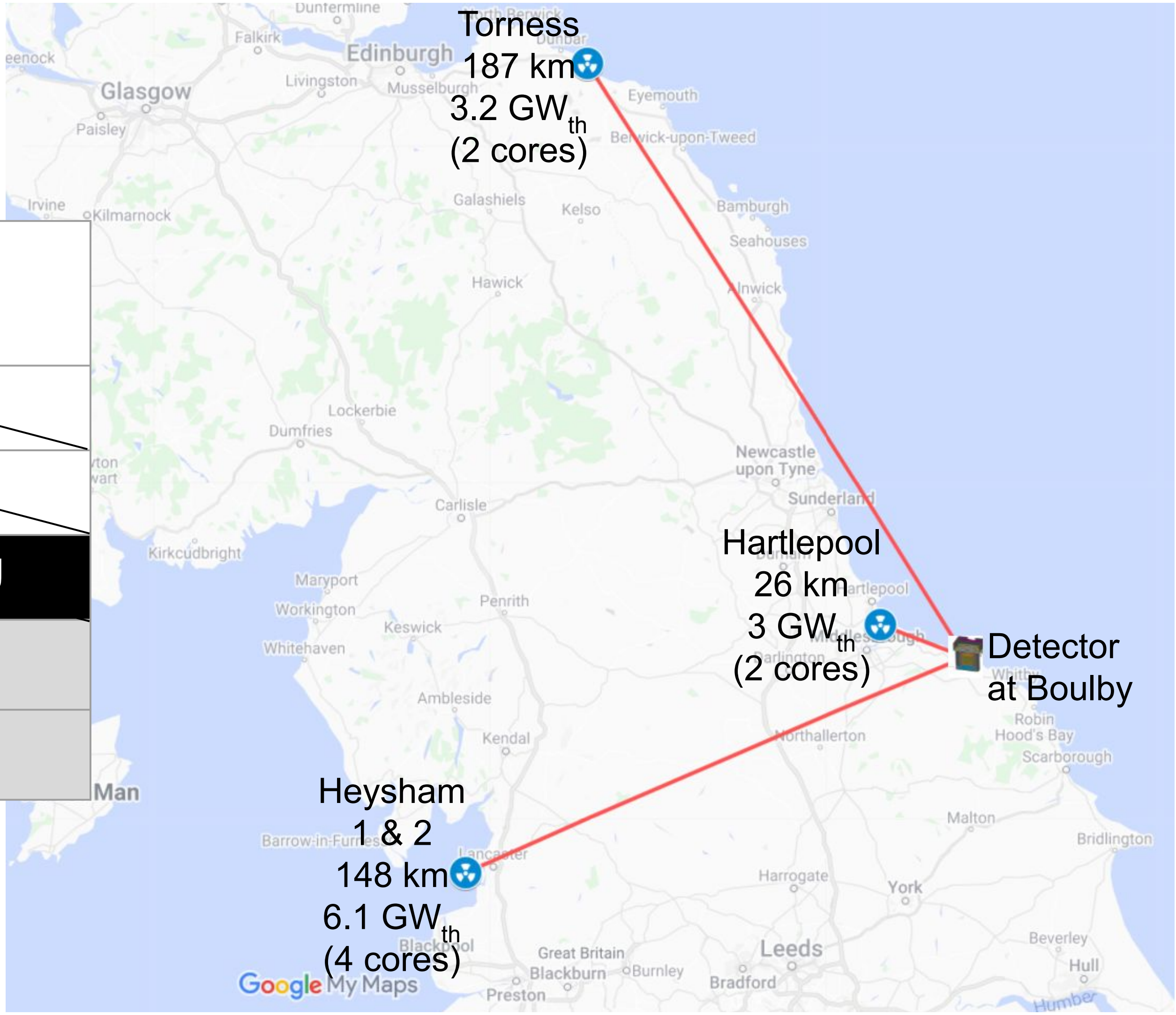


NIU (Neutrino Interactions Units) = interactions per 10^{32} targets (i.e. free protons for IBD) per year.

Signals from reactors over 100 km away

Three signal combinations of the reactors at Heysham and Torness.

<table>
<tr><th></th><th>Heysham 1&2</th><th>Heysham 2 +Torness</th><th>Heysham 2</th></tr>
<tr><td>Hartlepool</td><td></td><td></td><td></td></tr>
<tr><td>Heysham 1</td><td rowspan="2">69.6 NIU</td><td></td><td></td></tr>
<tr><td>Heysham 2</td><td rowspan="2">64.6 NIU</td><td>39.6 NIU</td></tr>
<tr><td>Torness</td><td>25 NIU</td><td>25 NIU</td></tr>
<tr><td>World reactors</td><td colspan="3">161 NIU</td></tr>
</table>

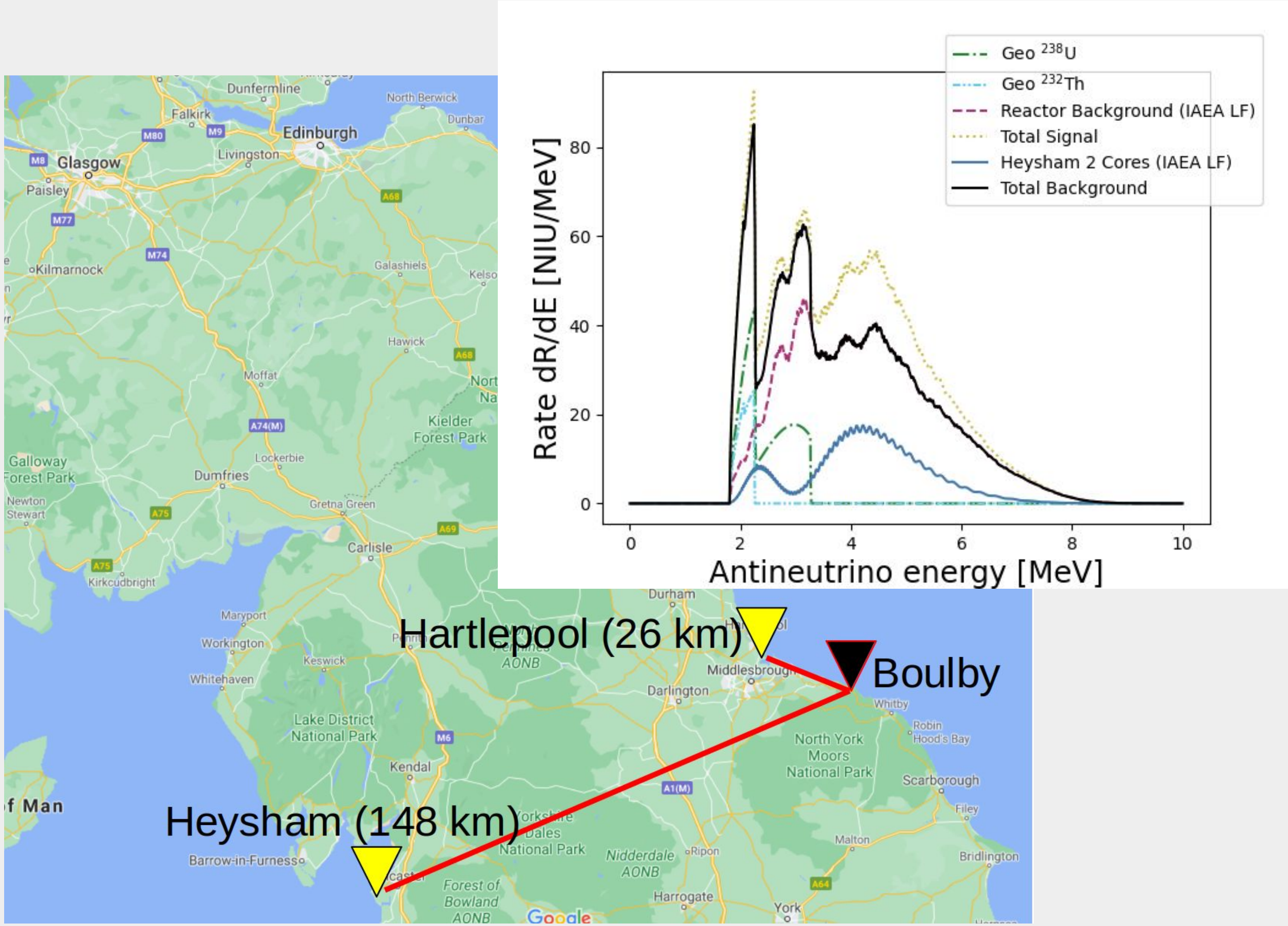


Signal combinations with signal reactors in black, background reactors in grey and the other reactors taken to be shut down.

NIU (Neutrino Interactions Units) = interactions per 10^{32} targets (i.e. free protons for IBD) per year.

Steve Wilson, University of Sheffield

Heysham 2

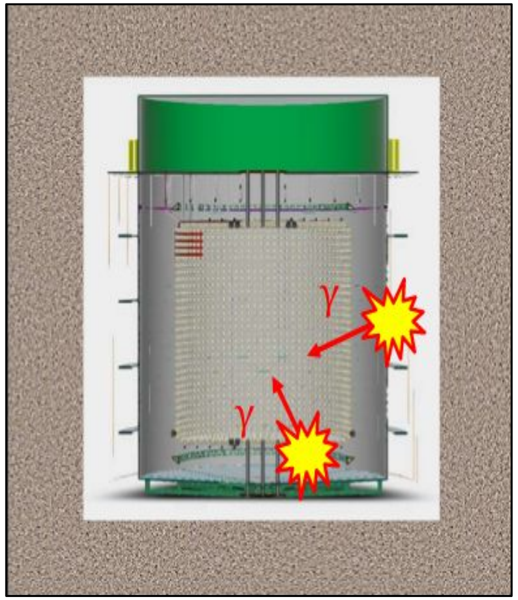


Coincident signal and background simulations

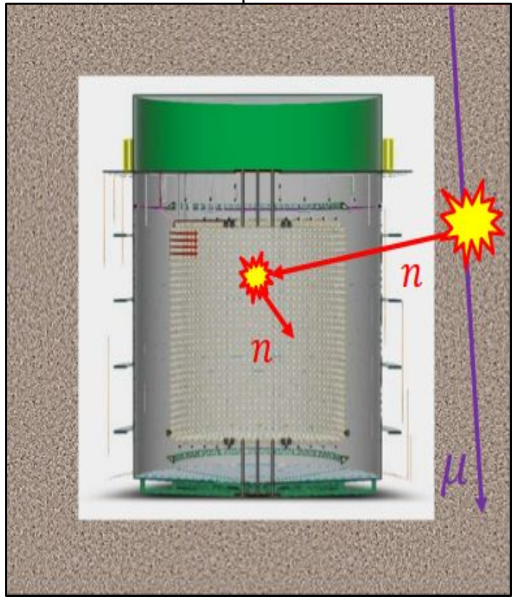
Neutron tagging in Gd-doped media removes many of the backgrounds but there remain backgrounds which can mimic the coincident signal pair.

False pairs - uncorrelated

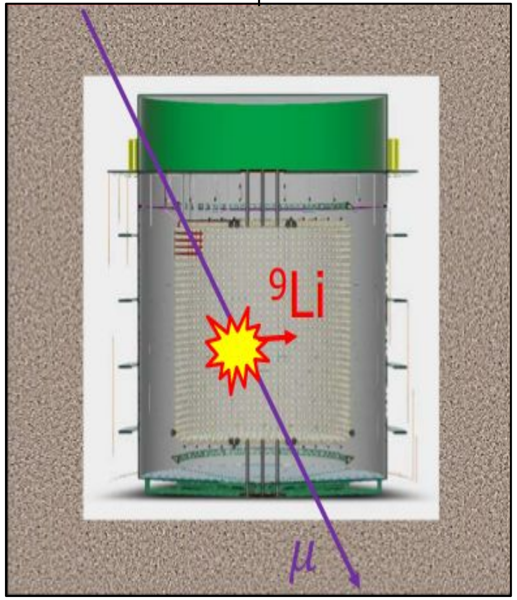
‘True’ pairs - correlated



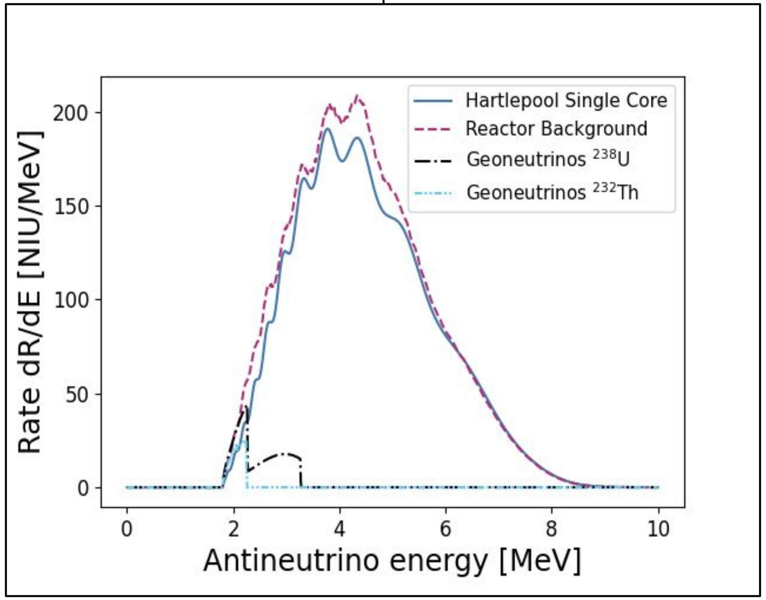
Radioactive decay *‘accidental coincidences’*



Fast neutron pairs



β-n decays (^{9}Li, ^{8}He, ^{17}N)



Antineutrino signal and backgrounds

Coincident signal and background simulations

MC simulation performed using an adaptation of the Geant4-based RAT-PAC*.

*Reactor Analysis Tool - Plus Additional Codes

False pairs -

correlated

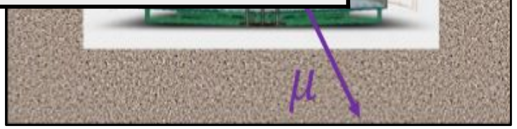
Type of background	Raw rate (Hz) in 16 m detector
Cosmogenic radionuclide β-n decays	2.0×10^{-5}
Cosmogenic fast neutrons	1.9×10^{-2}
Reactor IBD (beyond Hartlepool)	2.2×10^{-6}
Geoneutrino IBD	3.6×10^{-7}
Radioactive isotope β decays (singles)	3.4×10^{5}

Systematic uncertainties:

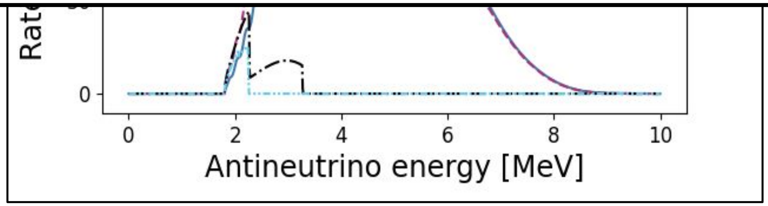
- Fast neutron 27% theoretical uncertainty.
- 6% reactor IBD flux uncertainty.
- 70% geoneutrino IBD flux uncertainty.
- Radionuclide uncertainties <1%.

Radioactive decay *'accidental coincidences'*

Fast neutron pairs



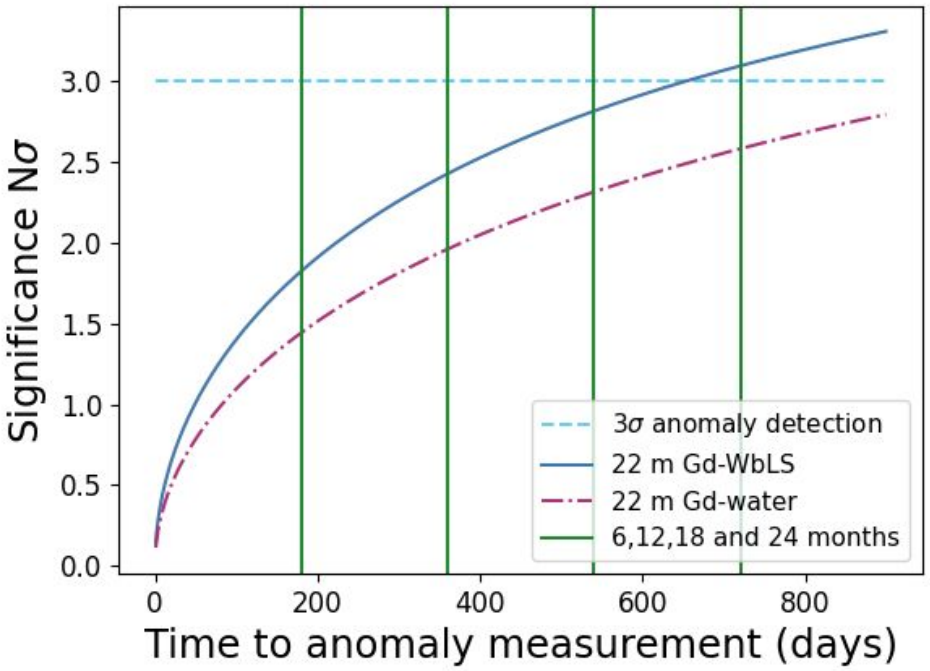
β-n decays (^{9}Li, ^{8}He, ^{17}N)



Antineutrino signal and backgrounds

Cobraa-CoRe - 22 m sensitivity to Heysham 2

Significance of anomaly measurement sensitivity to Heysham 2 reactor complex with 22 m detector. Time is total reactor operation time (excluding shutdowns for maintenance, etc.).



Fill medium	6 months	12 months	18 months	24 months
Gd-H_2O	1.50	2.03	2.40	2.68
Gd-WbLS	1.83	2.43	2.82	**3.10**