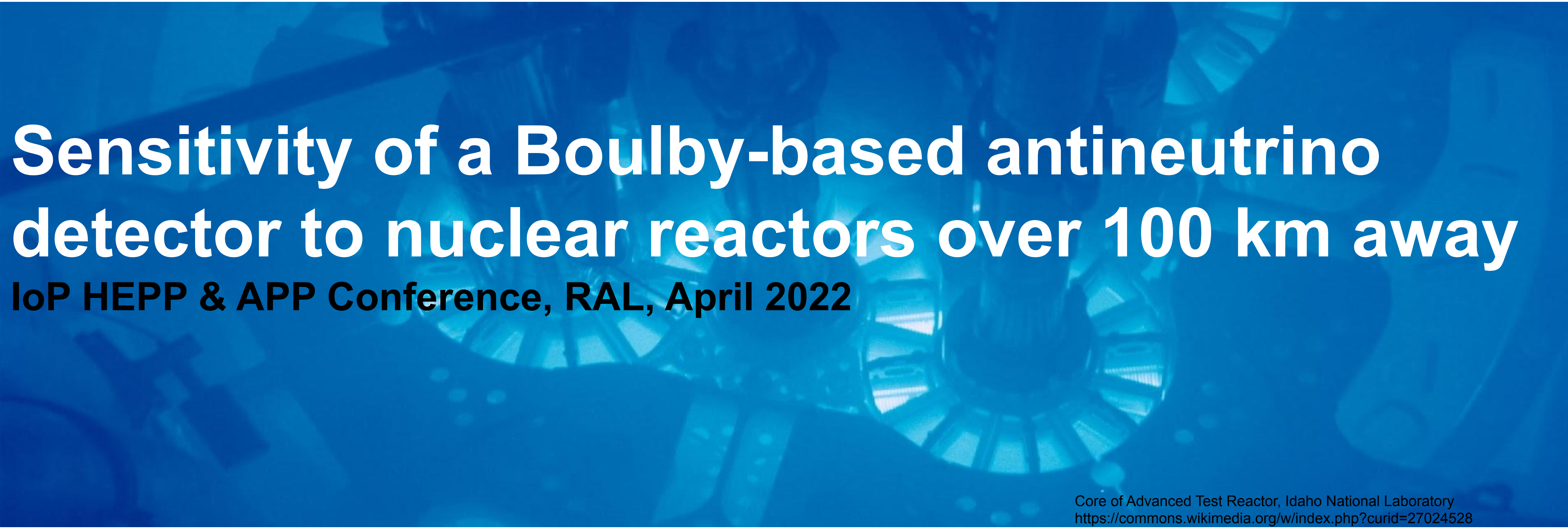
The University Of Sheffield.

Sensitivity of a Boulby-based antineutrino detector to nuclear reactors over 100 km away

IoP HEPP & APP Conference, RAL, April 2022



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

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University of Sheffield

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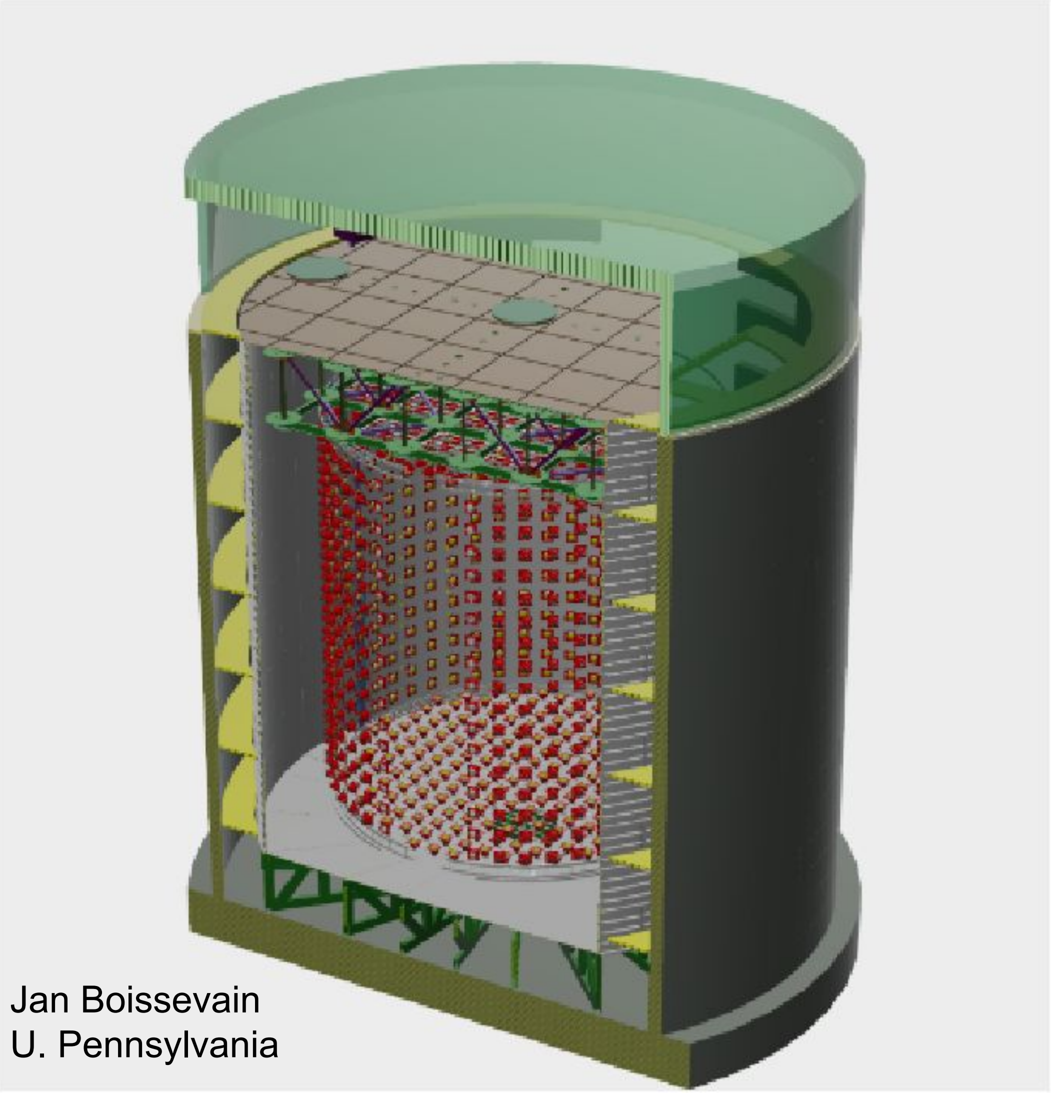
AIT-NEO reactor monitor concept



Jan Boissevain
U. Pennsylvania

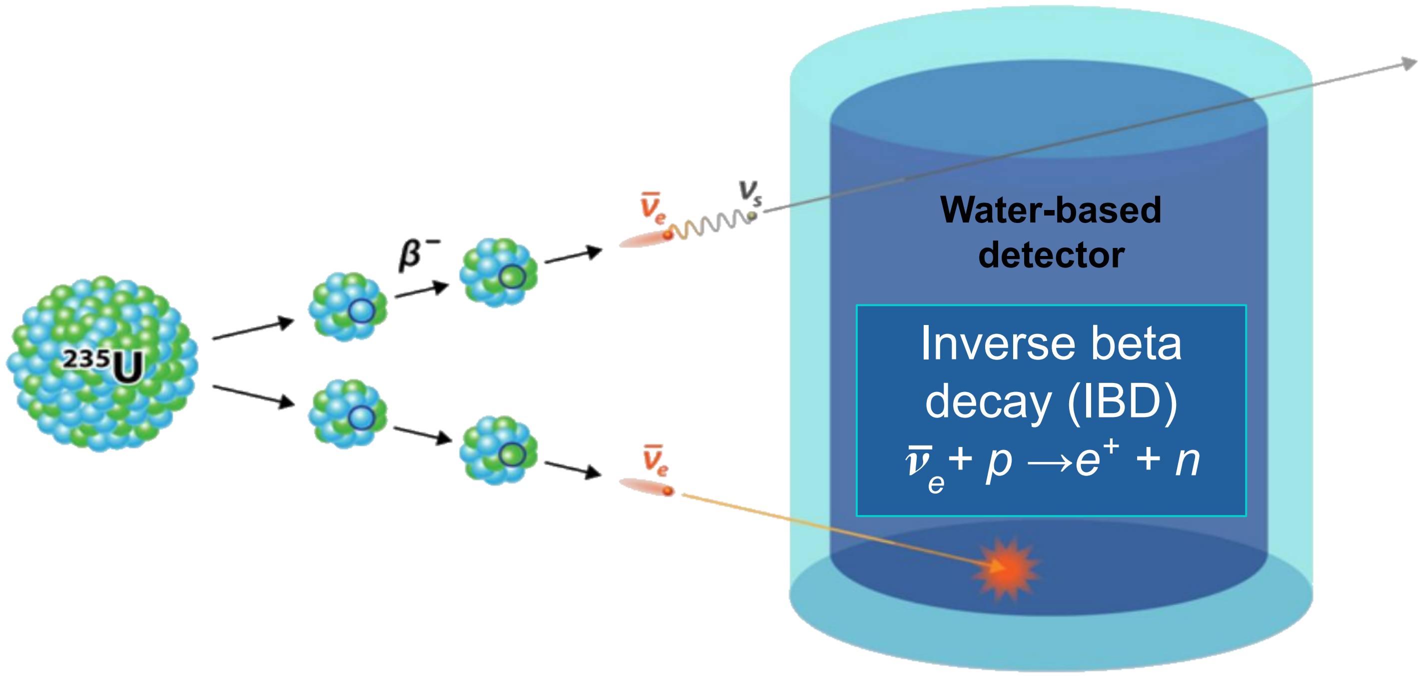
Advanced Instrumentation Testbed - Neutrino Experiment One (AIT-NEO)
Gadolinium-doped Cherenkov detector.

Located underground in Boulby Mine for low backgrounds:
10^6 cosmic muon reduction compared to surface.
3 Bq m^3 air radon concentration.
(See talk by Sean Paling on Wednesday for more information.)

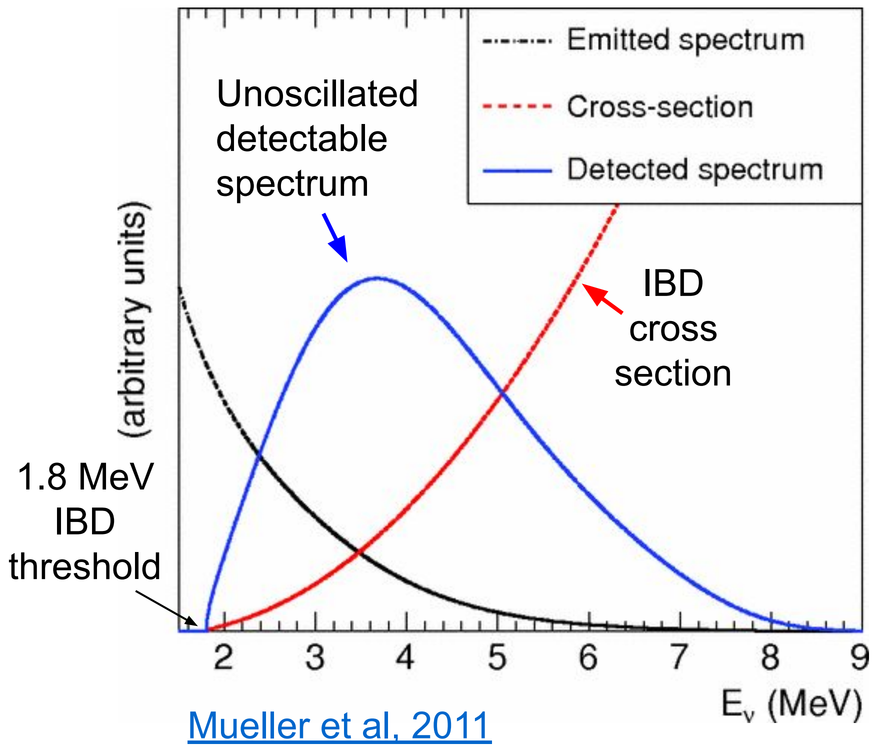
Detector configurations:
22m tank / 9m inner-PMT radius / 4600 PMTs.
16m tank / 5.7m inner-PMT radius / 1824 PMTs.
(15% photocoverage.)

Reactor monitoring with antineutrino detection

Reactor antineutrino flux is unshieldable, so ideal for reactor monitoring for non-proliferation.



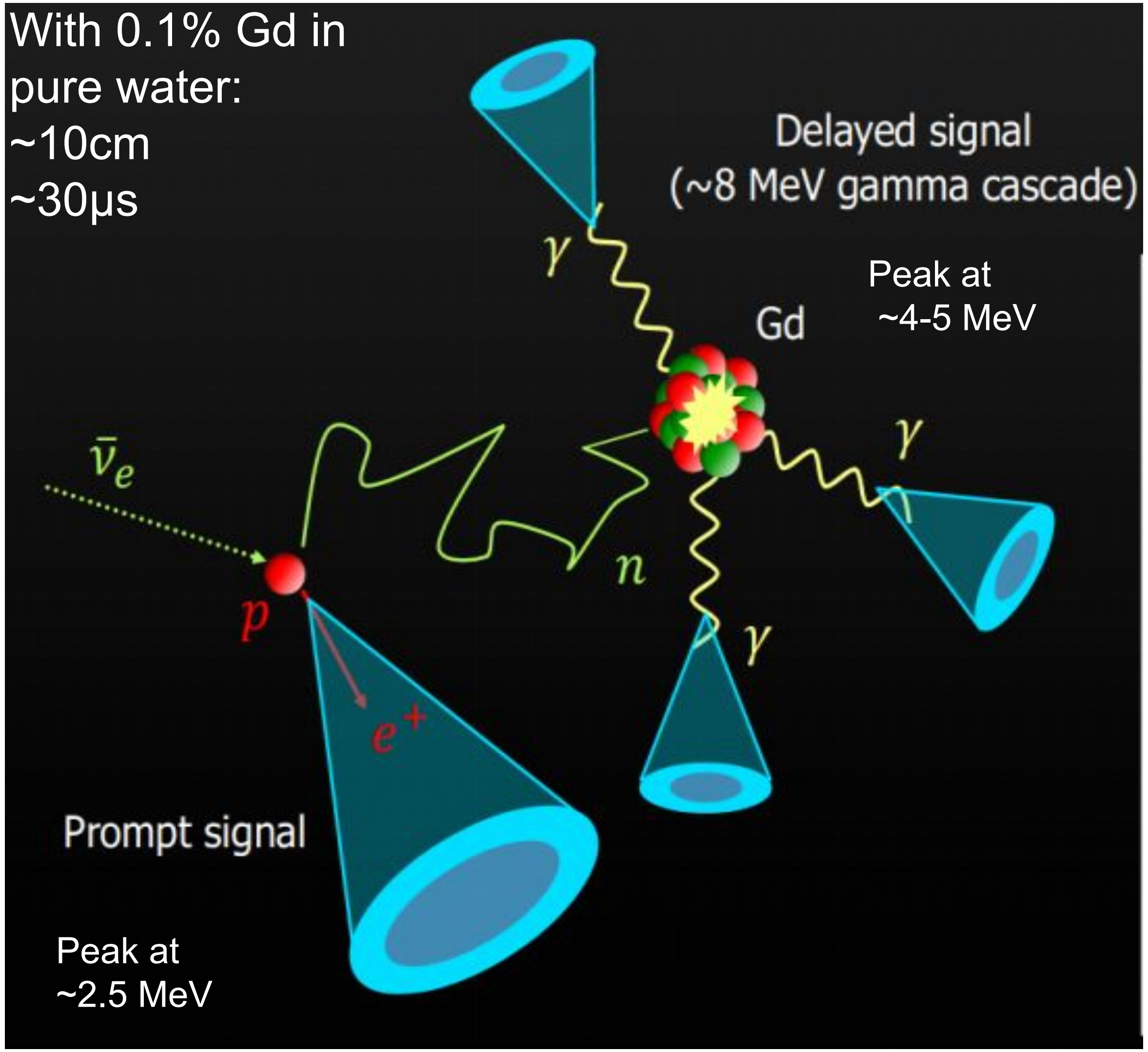
APS/Alan Stonebraker



Mueller et al, 2011
https://journals.aps.org/prc/abstract/10.1103/PhysRevC.83.054615

Anti-neutrinos from a 3GW$_{th}$ reactor complexes investigated in this study:
10^{22} per second isotropic emission (10^{21} fissions per second).

AIT-NEO gadolinium-doped Cherenkov



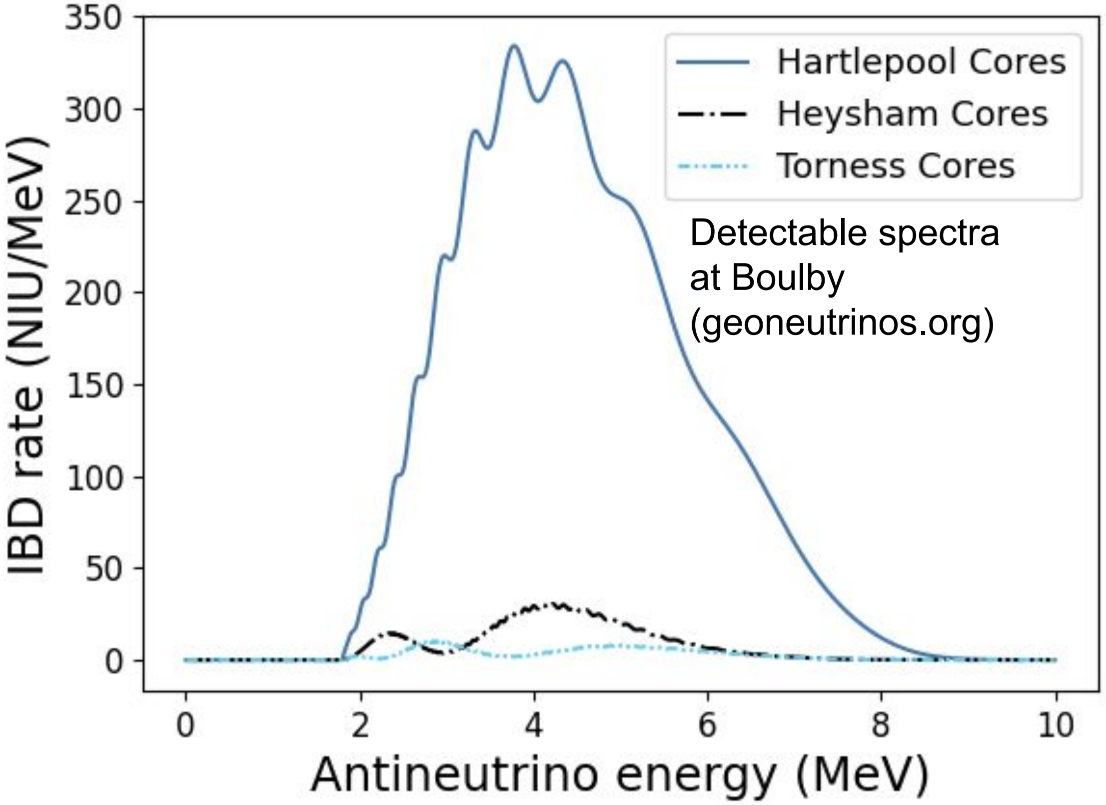
Gadolinium (Gd) loading: inverse beta decay (IBD) heartbeat for low-energy reactor antineutrino detection.

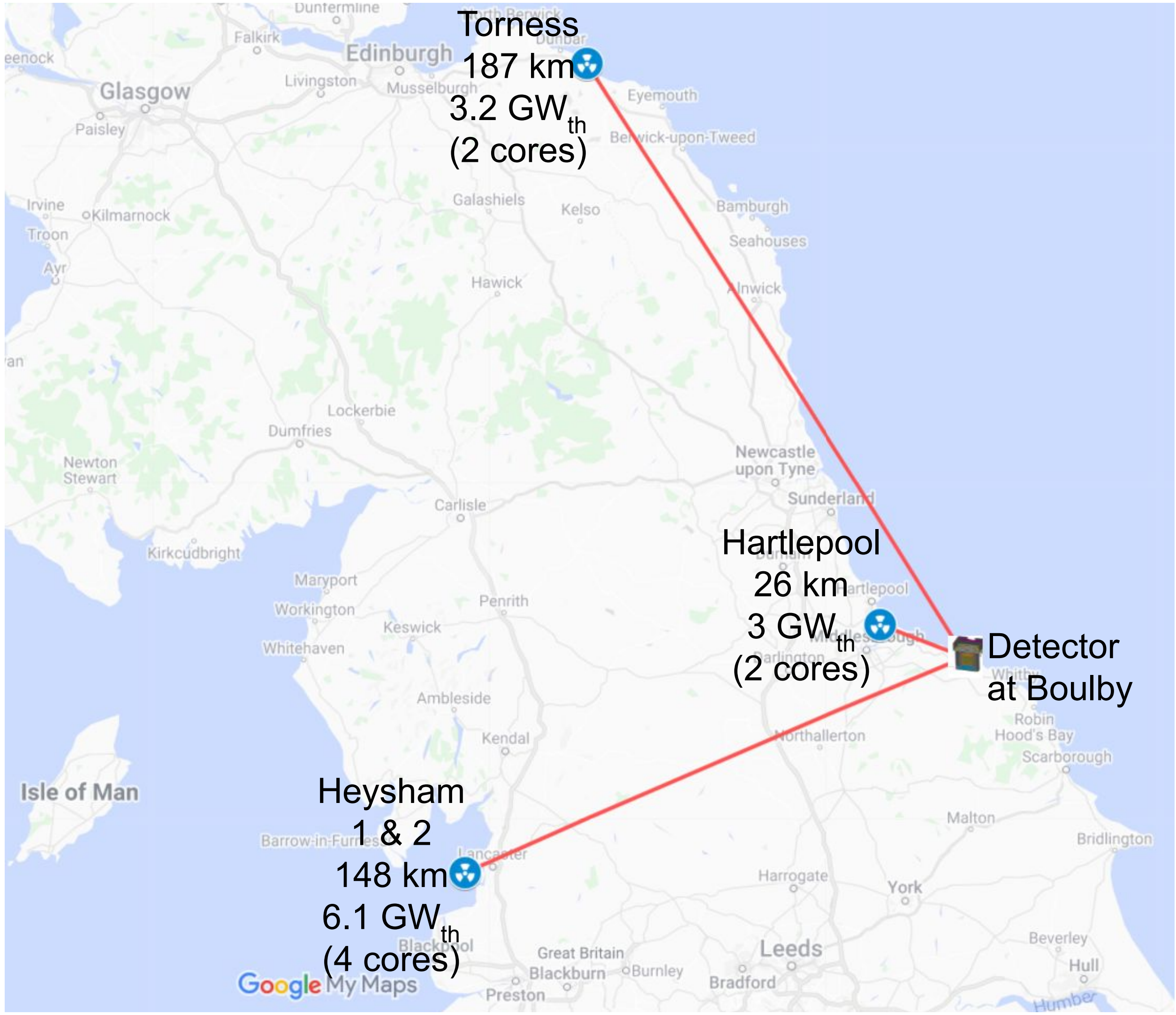
Coincident (close in space and time) signal pair enhances signal sensitivity and helps background rejection.

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

Sensitivity to real signals at Boulby Mine

This talk focuses on the reactors at Heysham and Torness.



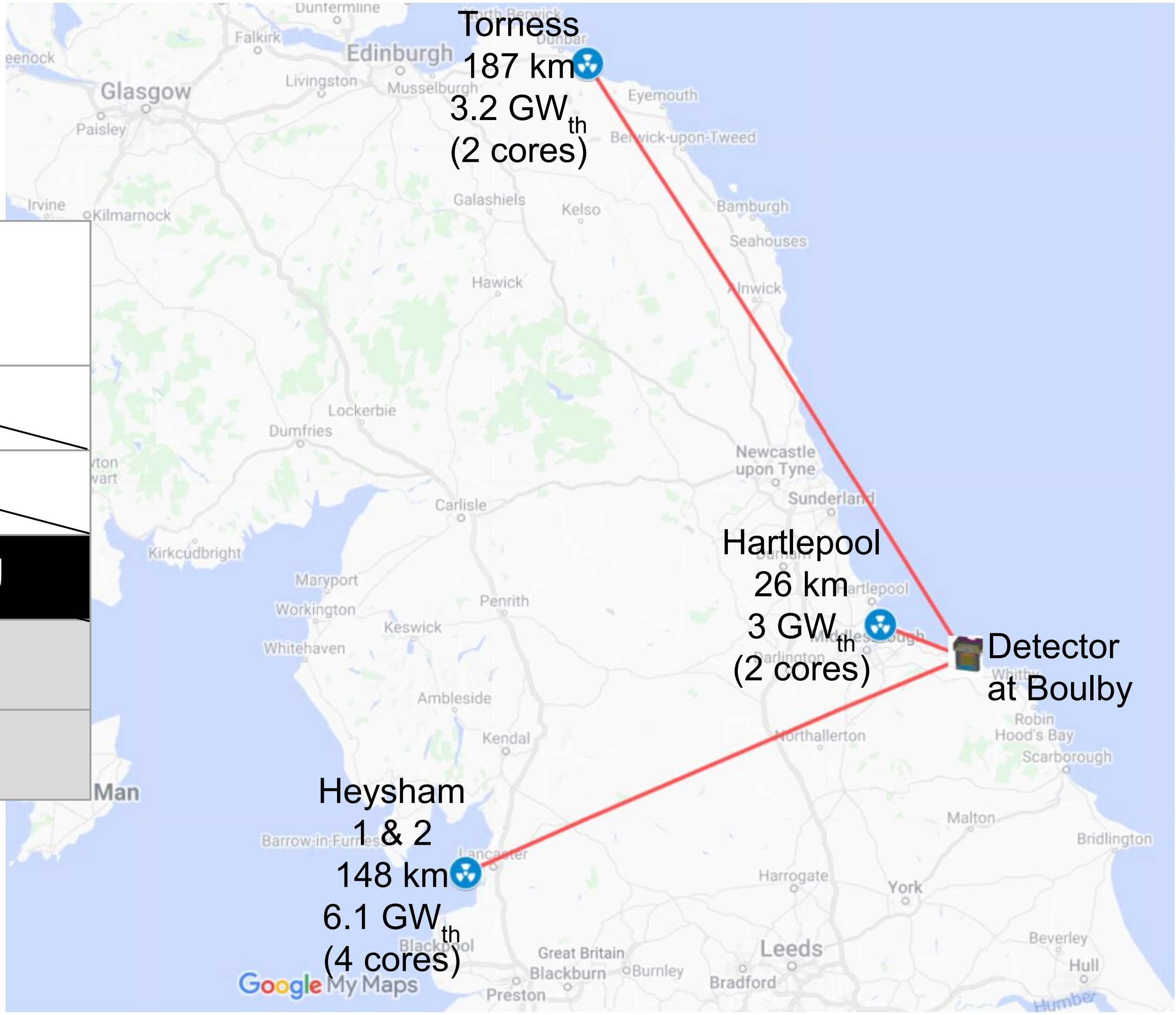


NIU (Neutrino Interactions Units) = interactions per 10^{32} targets (i.e. free protons for IBD) per year.

Signals from reactors over 100 km away

This talk focuses on the reactors at Heysham and Torness.

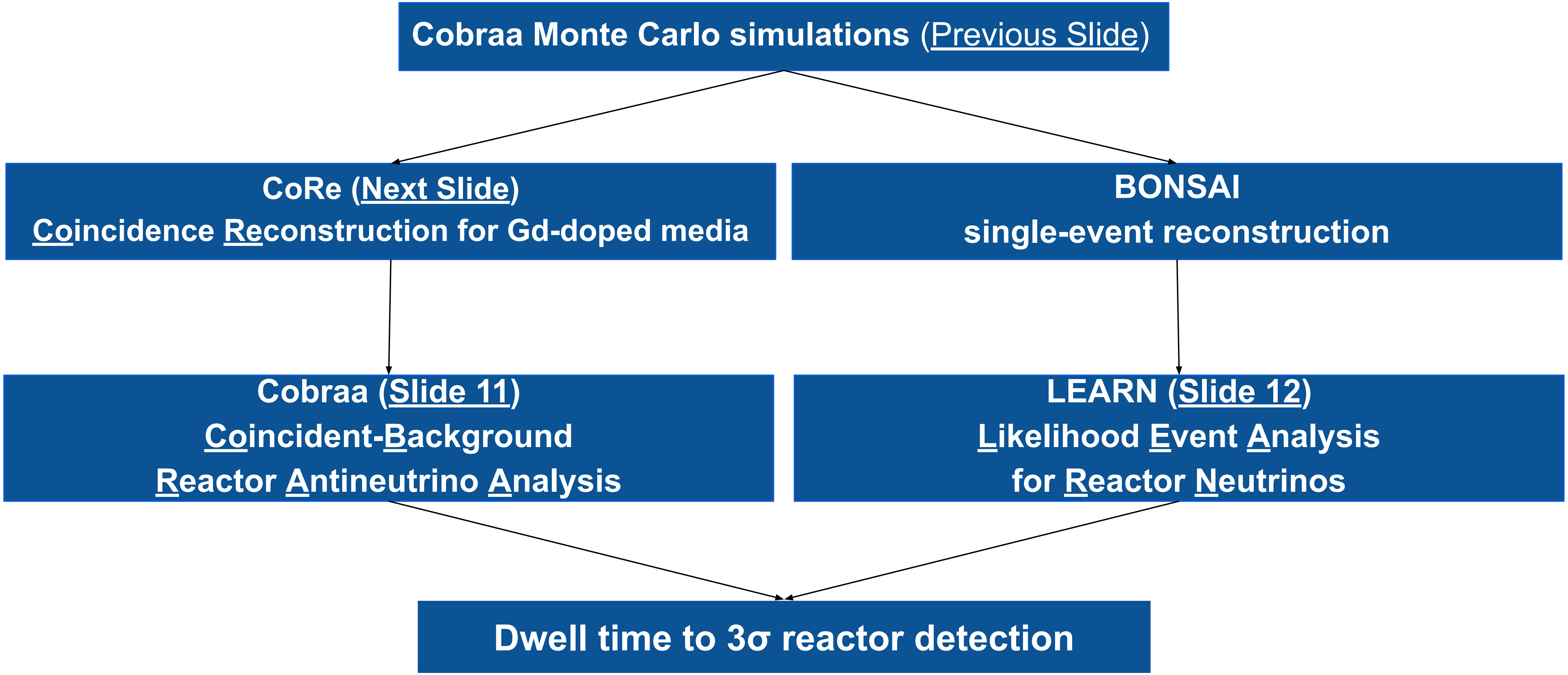
	Heysham 1&2	Heysham 2 +Torness	Heysham 2
Hartlepool			
Heysham 1	69.6 NIU		
Heysham 2	69.6 NIU	64.6 NIU	39.6 NIU
Torness	25 NIU	64.6 NIU	25 NIU
World reactors	161 NIU	161 NIU	161 NIU



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.

Cobraa and LEARN pathways



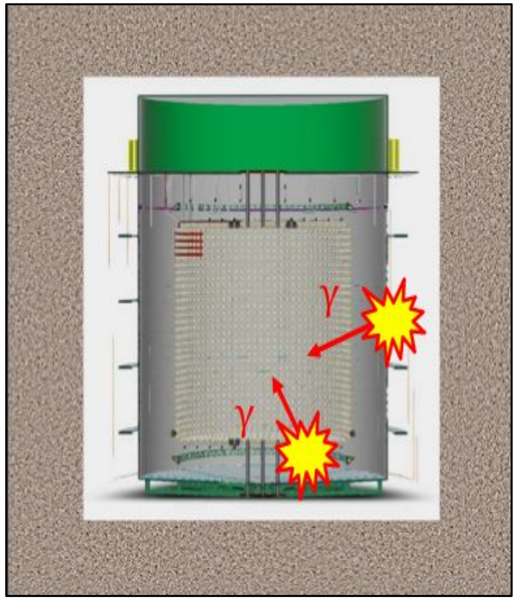
$$t_{dwell} = \frac{N_\sigma^2 \Sigma b_i}{s^2 - N_\sigma^2 \Sigma \sigma_{b_i,sys}^2}$$

Coincident signal and background simulations

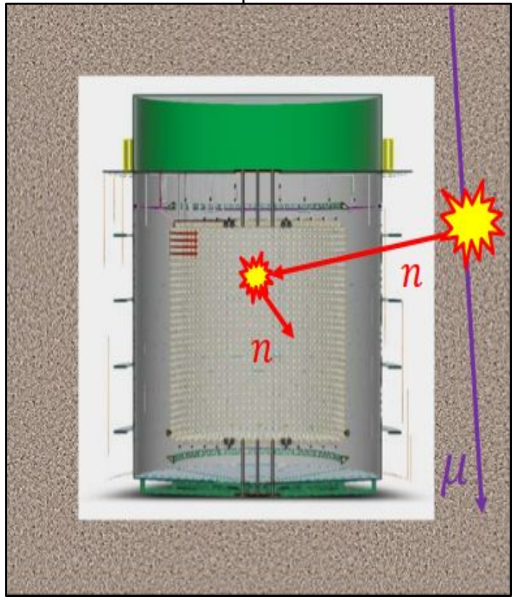
Both pathways use Cobraa MC simulations of coincident signal and backgrounds. These are:

False pairs - uncorrelated

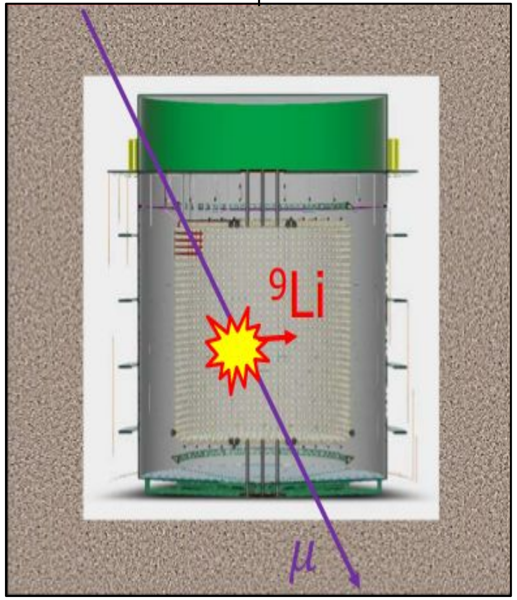
'True' pairs - correlated



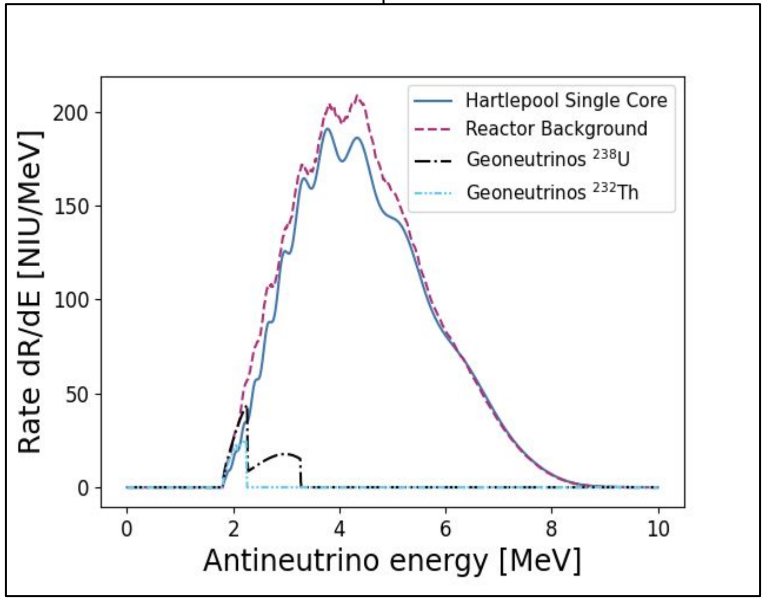
Radioactive decay *'accidental coincidences'*



Fast neutron pairs



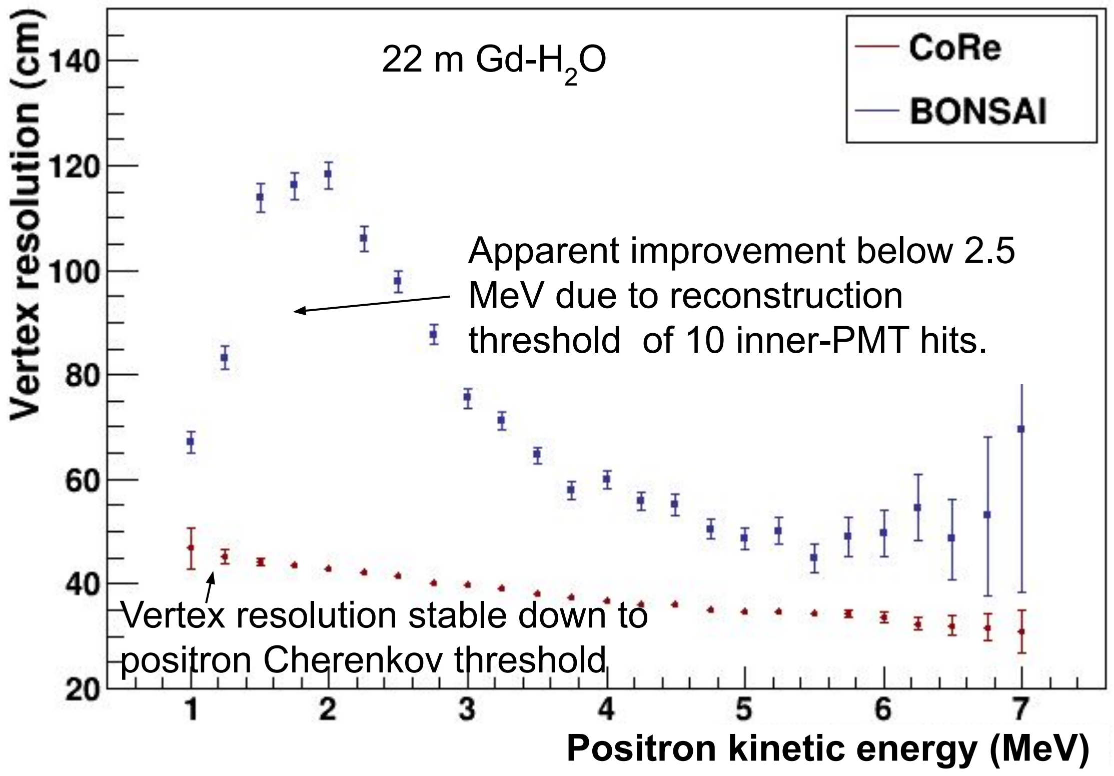
β-n decays



Antineutrino signal and backgrounds

CoRe - improved resolution

CoRe (BONSAI* extension) uses the light from both events and outputs a single, common vertex. The extra light from the neutron improves the vertex resolution.



Biggest improvement was for positrons in the Gd-H_2O detector where **vertex resolution improved by a factor of 2.4 at 2.5 MeV** - the peak of the positron signal.

*Low-energy fitter used in Super-K

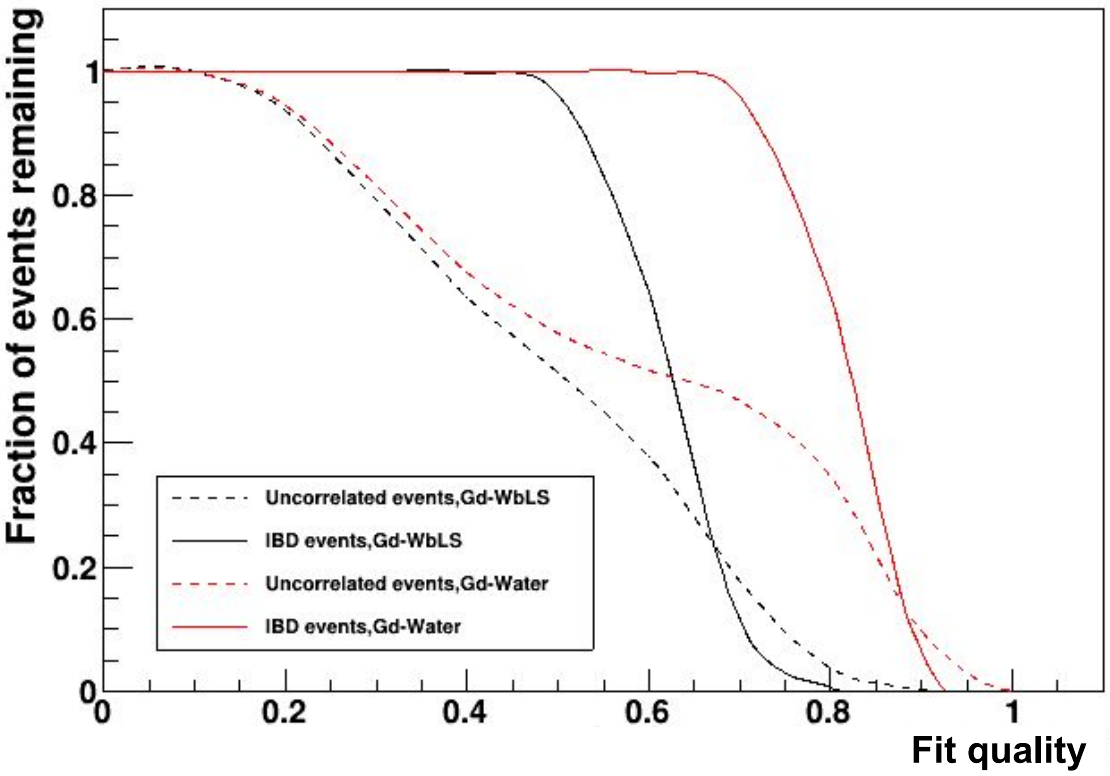
CoRe - improved resolution and bg rejection

CoRe (BONSAI* extension) uses the light from both events and outputs a single, common vertex. The extra light from the neutron improves the vertex resolution.

Powerful rejection of accidental coincidences of uncorrelated events (radioactive decays here).

Fit quality better for 'true' pairs than 'false' pairs in both media.

A cut on fit quality can reject ~50% of accidental coincidences while leaving the signal untouched.



*Low-energy fitter used in Super-K

Cobraa simulation/analysis toolchain

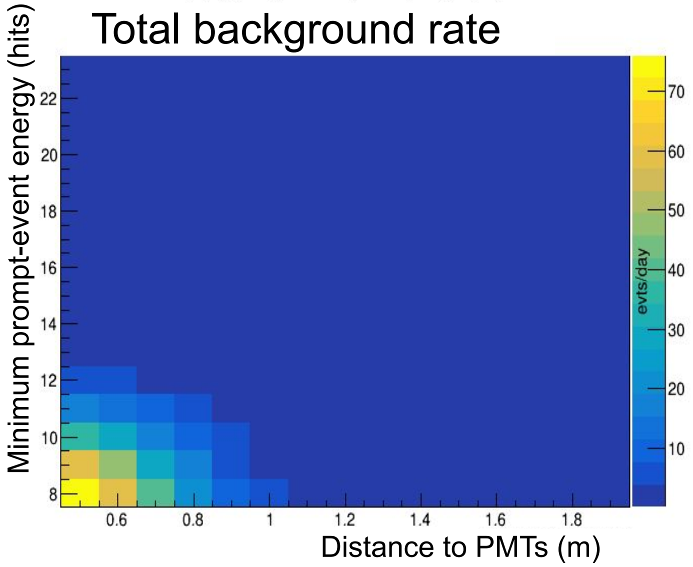
<u>Co</u>incident-<u>B</u>ackground <u>R</u>eactor <u>A</u>ntineutrino <u>A</u>nalysis

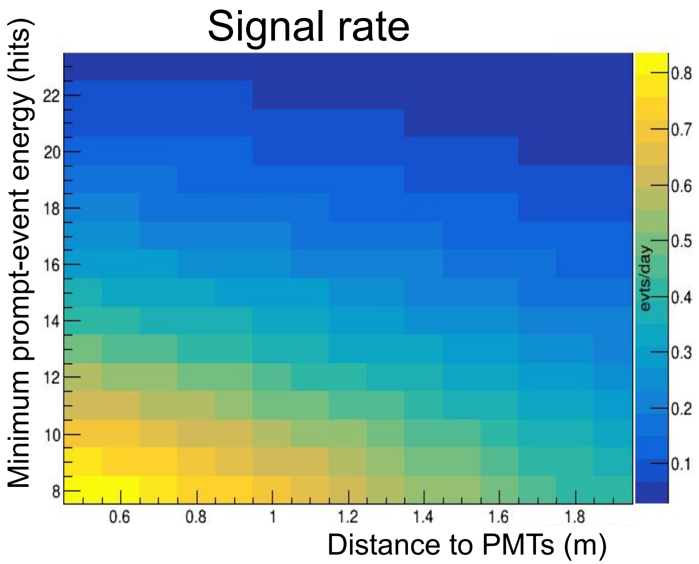
Step 1 (after CoRe):
Multiplicity cut for fast neutron rejection reduces fast neutron rate by >90%.

Step 2:
6-way parallel optimisation:

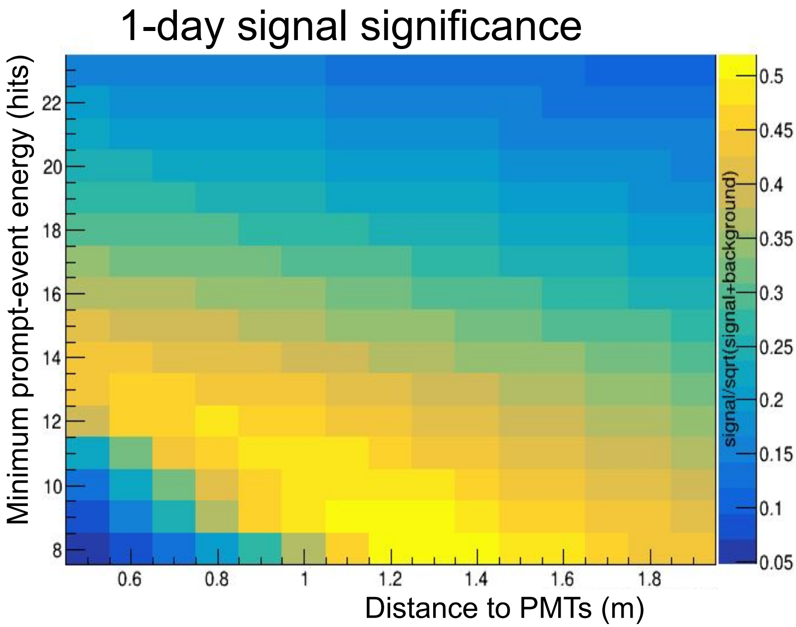
- threshold energy for prompt and delayed interaction (E_p and E_d),
- fiducial cut,
- time between events (dT),
- **fit quality - *'timing goodness'*,**
- **maximum E_p**

Step 3:
Analytical post-muon veto for radionuclide reduction



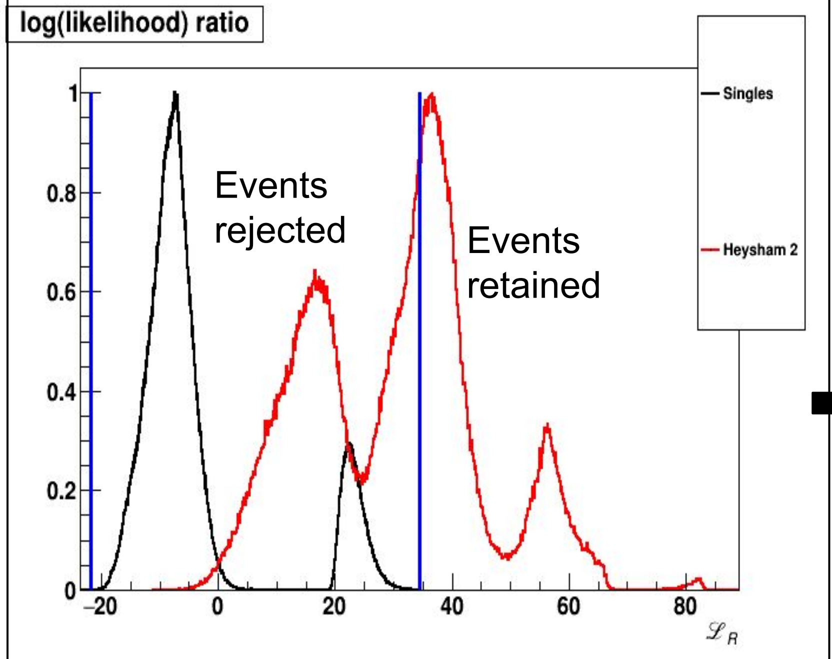


2D signal, total background and significance mapped for each value of dT, fit quality, E_d and maximum E_p.

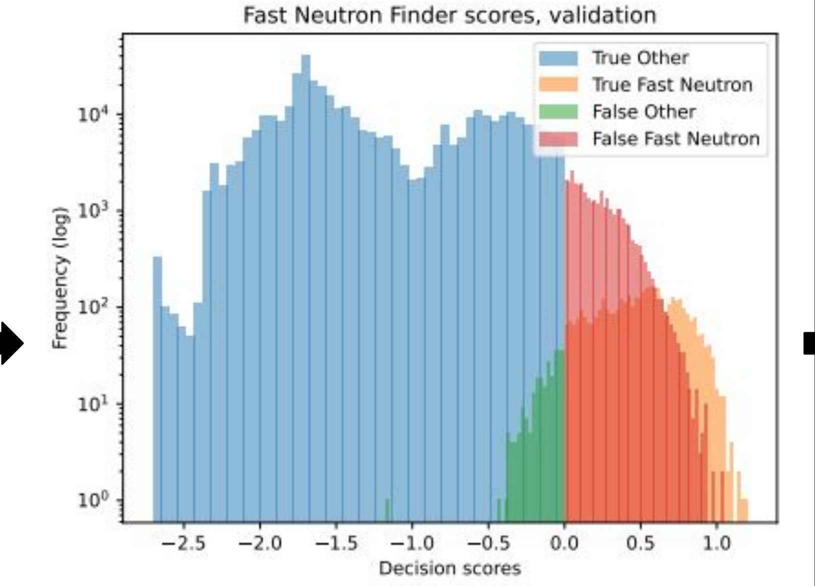


LEARN Likelihood Event Analysis for Reactor Neutrinos

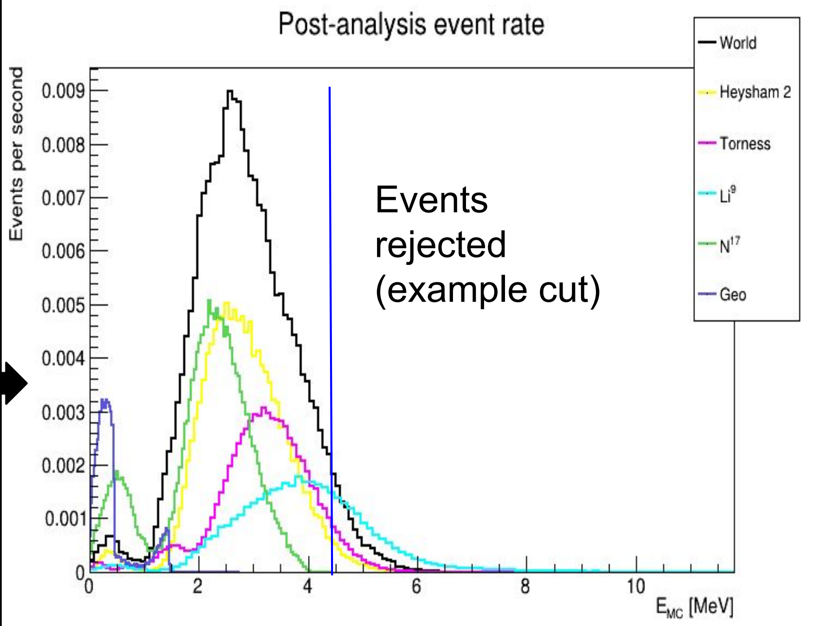
Likelihood Event Analysis for Reactor Neutrinos



Likelihood-based rejection of uncorrelated backgrounds due to radioactivity. (**James Armitage, U. of Sheffield**)

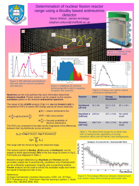


Multiplicity cut + machine learning for rejection of fast neutron backgrounds. (**Niamh Holland, U. of Sheffield**)



Example of energy cut and post-muon veto to deal with remaining fast neutrons and β-neutron decays.

Independent analysis: LEARN analysis process developed by **Steve Wilson, U. of Sheffield**



Talk to Steve Wilson for more info on LEARN at his poster:
‘Determination of nuclear fission reactor range using a Boulby-based antineutrino detector’.

Cobraa/LEARN comparison (Gd-WbLS)

Detector & analysis path	Heysham 1&2	Heysham-Torness	Heysham 2
16m Gd-H_2O Cobraa	2327	3448	8739
16 m Gd-WbLS Cobraa	738	1022	3589
16 m Gd-WbLS LEARN	1017	963	2968
22m Gd-H_2O Cobraa	241	232	985
22 m Gd-WbLS Cobraa	152	192	**647**
22 m Gd-WbLS LEARN	196	164	**577**

Dwell time in days to 3σ significance from Cobraa and LEARN.

Agreement of between 6% and 27% from the two independent analyses.

Could see single-site Heysham 2 reactor at a distance of ~150 km in less than two years of reactor operation.

Toolchain for reactor antineutrino detection

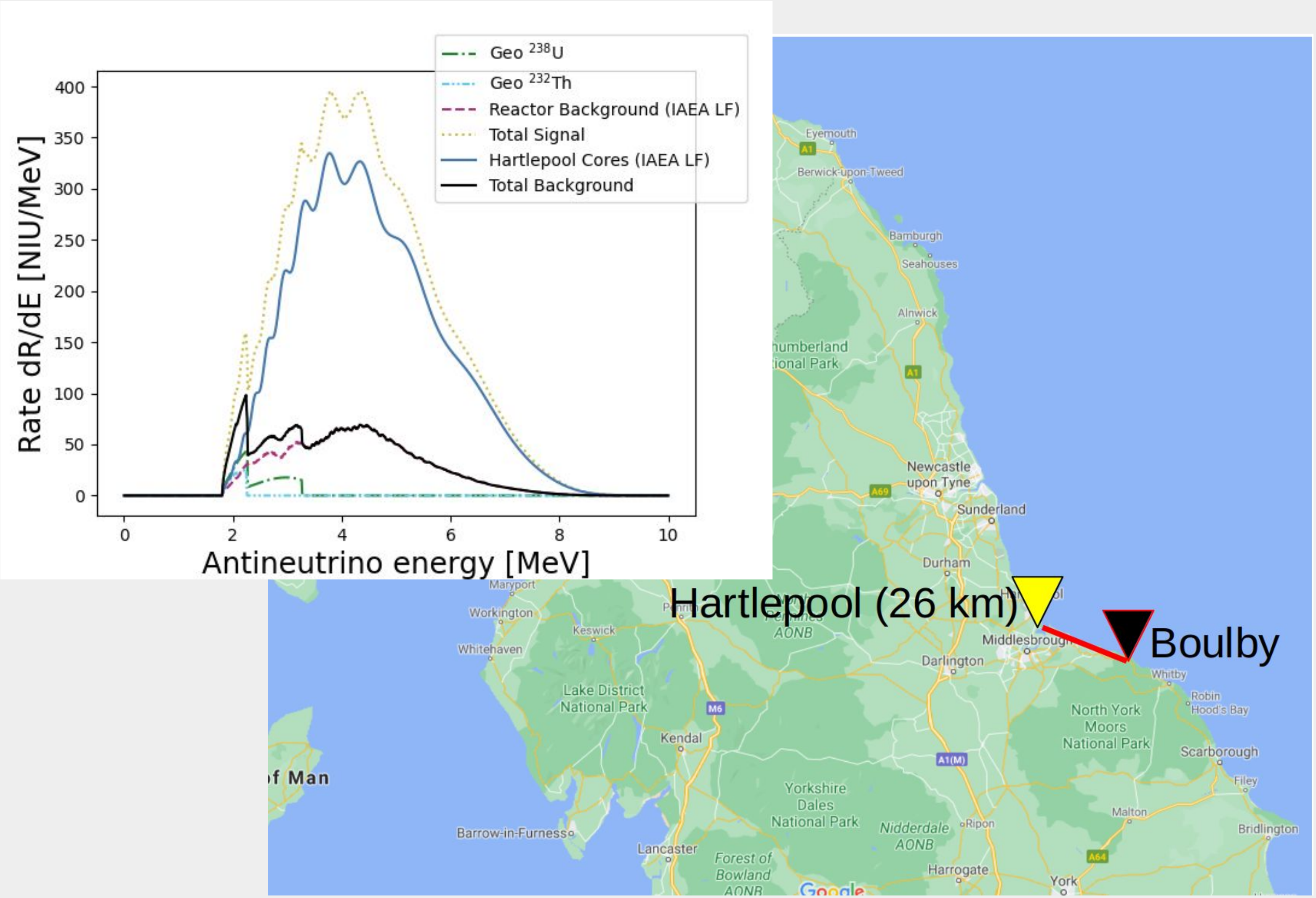
- **First evaluation of sensitivity to real reactor signals with realistic treatment of backgrounds for non-proliferation**.

- A 22 m detector with Gd-WbLS would be sensitive to 3σ detection of a 3.1 GW_{th} reactor ~150 km away within two years of reactor operation.
- Cobraa+CoRe is a comprehensive simulation-reconstruction-analysis package for remote reactor detection which can be readily adapted to other site/signal configurations.
- The CoRe reconstruction was specially designed for Gd-doping, and is to be refactored for open-source use.
- Likelihood analysis and more modern machine learning classification help to reject accidentals and fast neutrons in the LEARN pathway.
- Results from independent pathways agree by between 6% and 27% for all configurations.

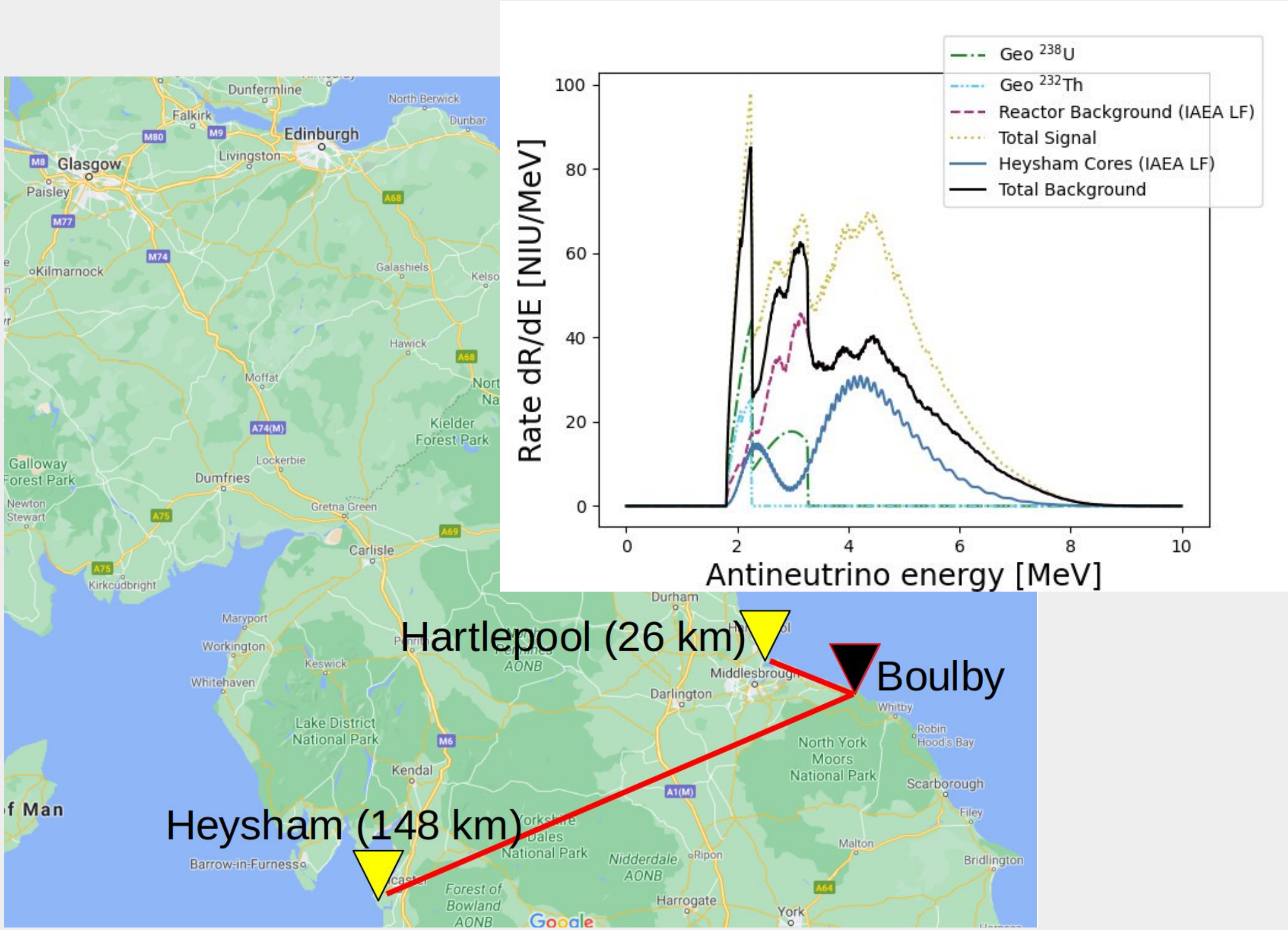
Backups

including breakdown of results

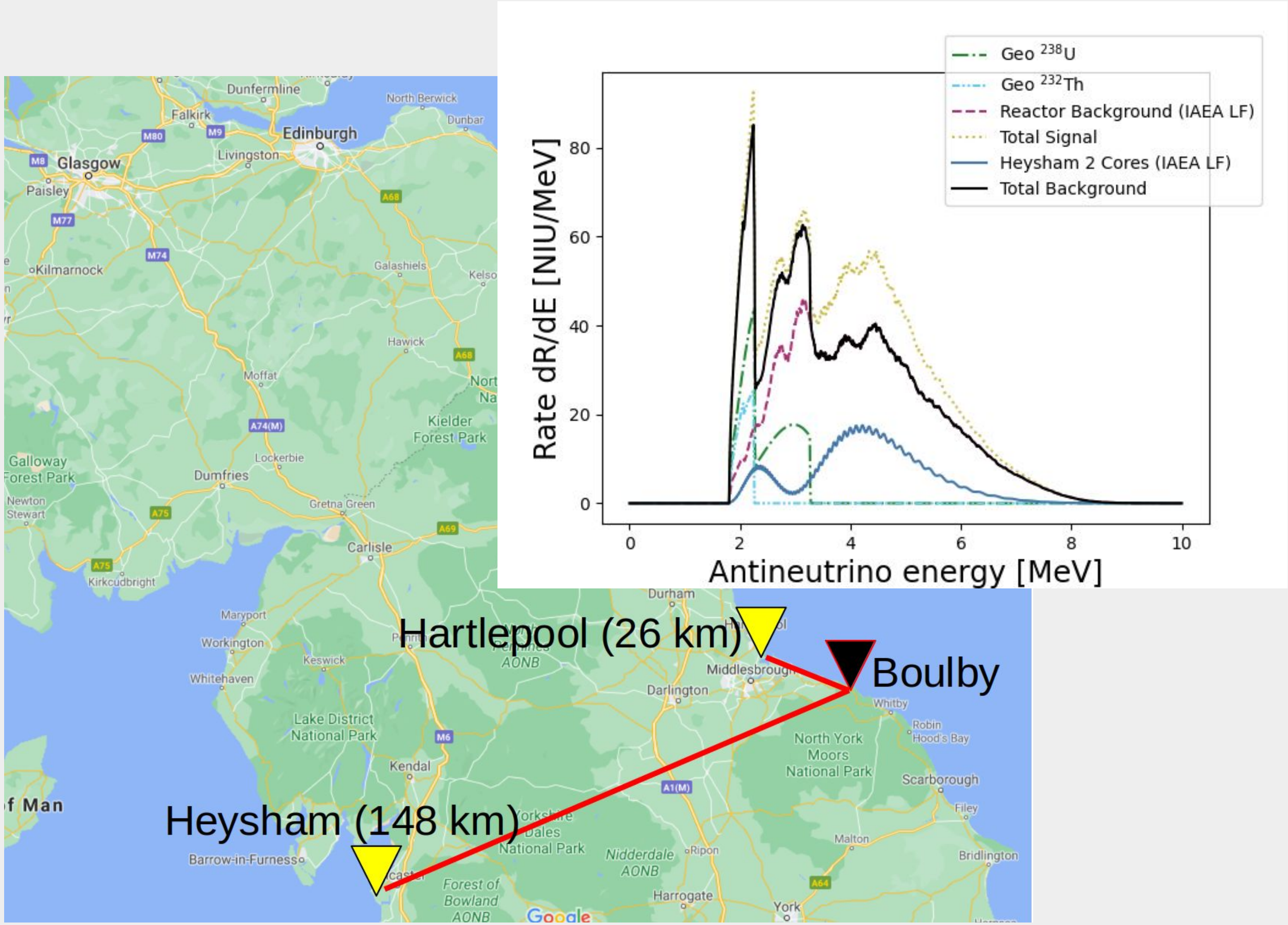
Hartlepool


Geo ^{238}U
Geo ^{232}Th
Reactor Background (IAEA LF)
Total Signal
Hartlepool Cores (IAEA LF)
Total Background
Rate dR/dE [NIU/MeV]
Antineutrino energy [MeV]
400
350
300
250
200
150
100
50
0
0
2
4
6
8
10
Hartlepool (26 km)
Boulby
Eyemouth
Berwick-upon-Tweed
Bamburgh
Seahouses
Alnwick
Newcastle upon Tyne
Sunderland
Durham
Middlesbrough
Darlington
Whitby
Robin Hood's Bay
North York Moors National Park
Scarborough
Filey
Malton
Bridlington
York
Harrogate
Ripon
Nidderdale AONB
Yorkshire Dales National Park
Forest of Bowland AONB
Lancaster
Kendal
Lake District National Park
Barrow-in-Furness
Keswick
Workington
Whitehaven
Maryport
Google

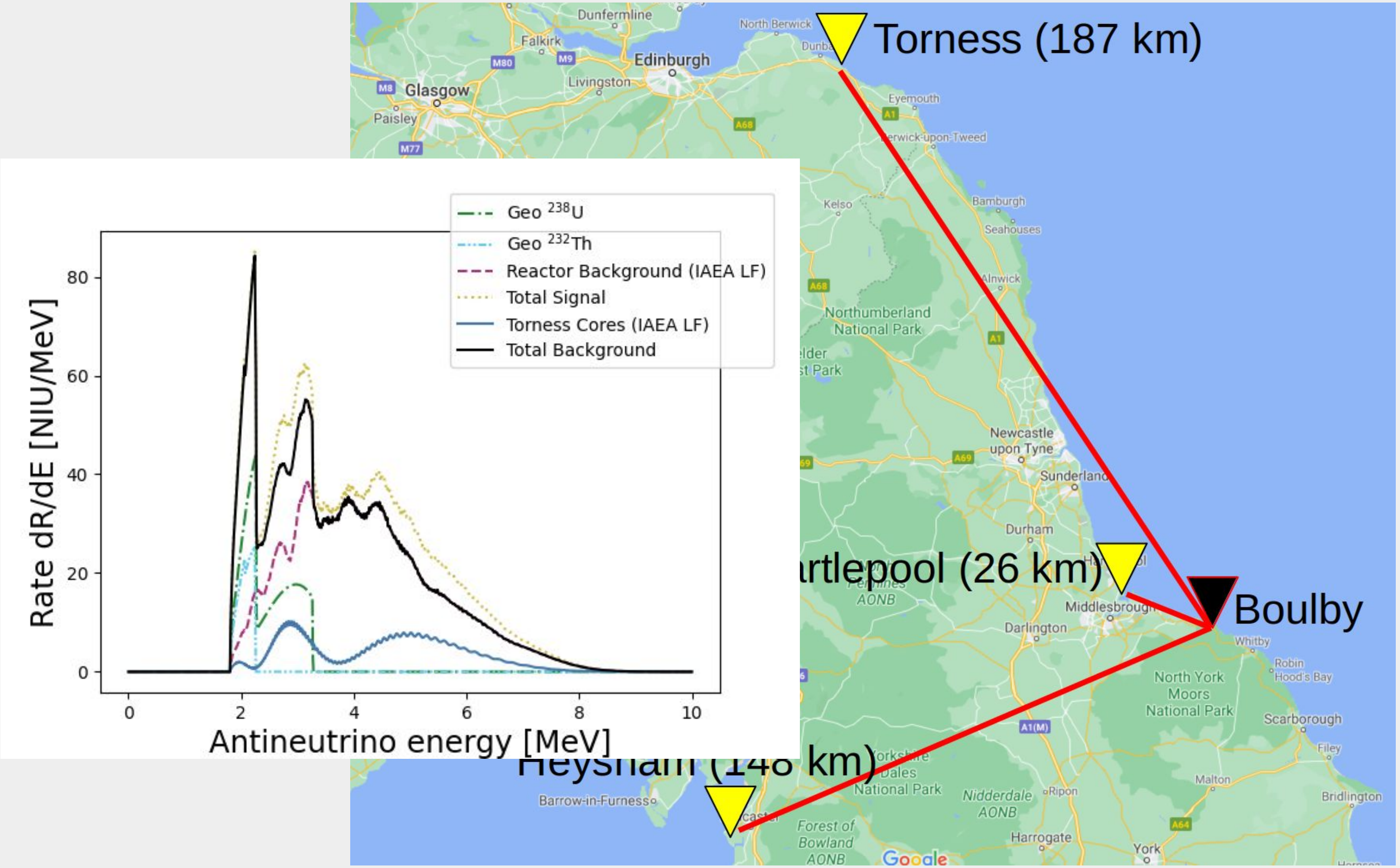
Heysham


Geo ^{238}U
Geo ^{232}Th
Reactor Background (IAEA LF)
Total Signal
Heysham Cores (IAEA LF)
Total Background
Rate dR/dE [NIU/MeV]
Antineutrino energy [MeV]
0
20
40
60
80
100
0
2
4
6
8
10
Hartlepool (26 km)
Boulby
Heysham (148 km)
Glasgow
Edinburgh
Dunfermline
Falkirk
Livingston
Paisley
Kilmarnock
Galashiels
Hawick
Moffat
Kielder Forest Park
Lockerbie
Dumfries
Gretna Green
Carlisle
Galloway Forest Park
Newton Stewart
Kirkcudbright
Maryport
Workington
Whitehaven
Keswick
Lake District National Park
Kendal
Barrow-in-Furness
Durham
Middlesbrough
Darlington
Whitby
Robin Hood's Bay
North York Moors National Park
Scarborough
Filey
Malton
Bridlington
Yorkshire Dales National Park
Nidderdale AONB
Ripon
Harrogate
York
Forest of Bowland AONB
North Berwick
Dunbar

Heysham 2


Geo ^{238}U
Geo ^{232}Th
Reactor Background (IAEA LF)
Total Signal
Heysham 2 Cores (IAEA LF)
Total Background
Rate dR/dE [NIU/MeV]
Antineutrino energy [MeV]
0
2
4
6
8
10
20
40
60
80
Hartlepool (26 km)
Boulby
Heysham (148 km)

Torness


Torness (187 km)
artlepool (26 km)
Boulby
Heysham (148 km)
Dunfermline
Falkirk
Edinburgh
Livingston
Glasgow
Paisley
North Berwick
Eyemouth
Berwick-upon-Tweed
Bamburgh
Seahouses
Kelso
Alnwick
Northumberland National Park
Newcastle upon Tyne
Sunderland
Durham
Middlesbrough
Darlington
Whitby
Robin Hood's Bay
North York Moors National Park
Scarborough
Filey
Yorkshire Dales National Park
Nidderdale AONB
Ripon
Malton
Bridlington
Barrow-in-Furness
Forest of Bowland AONB
Harrogate
York
Google
Geo ^{238}U
Geo ^{232}Th
Reactor Background (IAEA LF)
Total Signal
Torness Cores (IAEA LF)
Total Background
Rate dR/dE [NIU/MeV]
0
20
40
60
80
0
2
4
6
8
10
Antineutrino energy [MeV]

CoRe - background rejection power

Thanks to better reconstruction of correlated events:

a measure of fit quality can be used to help select true correlated events and reject false pairs.

BONSAI fit quality (*timing goodness*)

$$g(\boldsymbol{x}) = \frac{\sum_{\mathrm{hits}} w_i e^{-0.5\left(\frac{\Delta t_i(\boldsymbol{x})}{\sigma}\right)^2}}{\sum_{\mathrm{hits}} w_i}$$

where w_i are weights calculated using a wider Gaussian distribution.

(σ = 4 ns and σ_w = 50 ns)

Sensitivity metrics.

Anomaly measurement (known backgrounds, unknown reactor cycle):

1. Dwell time from Gaussian significance with Gaussian uncertainties on background

$$t_{dwell} = \frac{N_\sigma^2 \Sigma b_i}{s^2 - N_\sigma^2 \Sigma \sigma_{b_i,sys}^2}$$

b_i is the rate of the i^{th} background,
s is the signal rate and
N_σ is the required significance

2. Dwell time from Poisson significance with Poisson uncertainty on background
3. Dwell time from Poisson significance with Gaussian uncertainty on background

Reactor measurement (unknown backgrounds and reactor cycle):

1. Dwell time from Knoll [3] derivation for 3σ detection at the 95% confidence level
2. Dwell time from Knoll significance for 2σ detection at the 90% confidence level

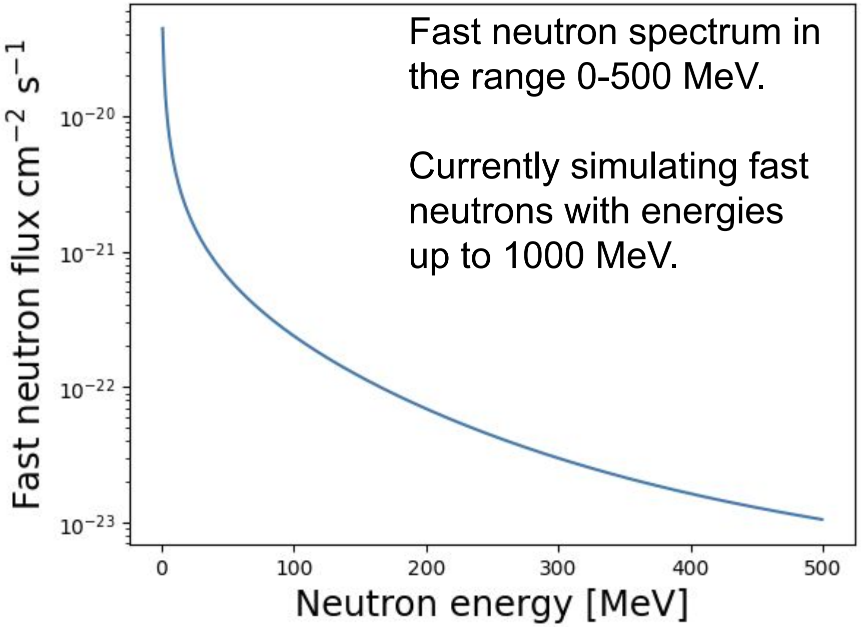
[3] G. F Knoll, Radiation Detection and Measurement John Wiley & Sons, Inc, 2000.

Systematic uncertainties on backgrounds

- Includes rates per day of backgrounds at the Poisson 95% UCL where coincidences were evaluated to zero.

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

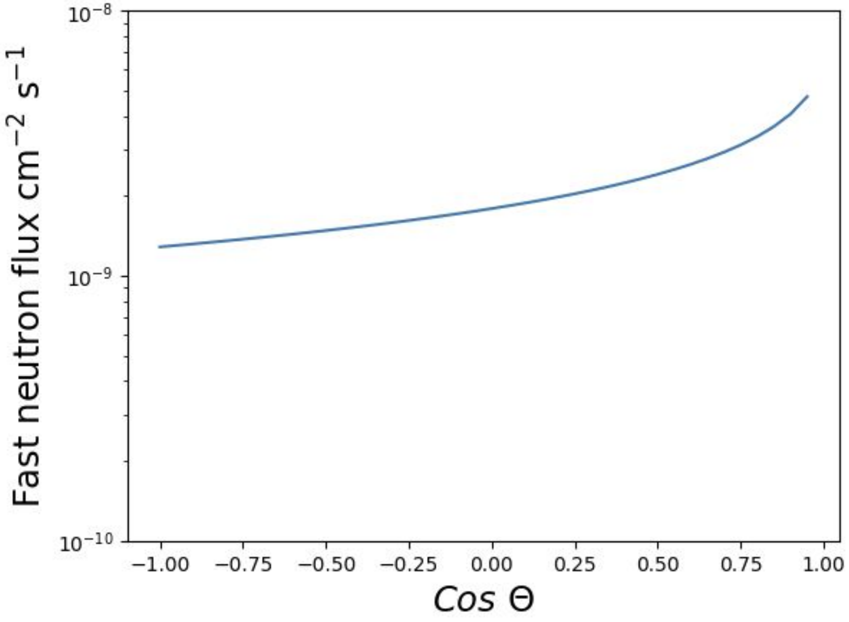
Fast neutrons



The mean fast neutron energy at Boulby is 88 MeV.

Fast neutrons below 10 MeV are unlikely to penetrate into the detector.

Boulby rate (>10 MeV) in a detector: 1.11 $\times10^{-9}$cm^{-2}s^{-1} x cavern surface

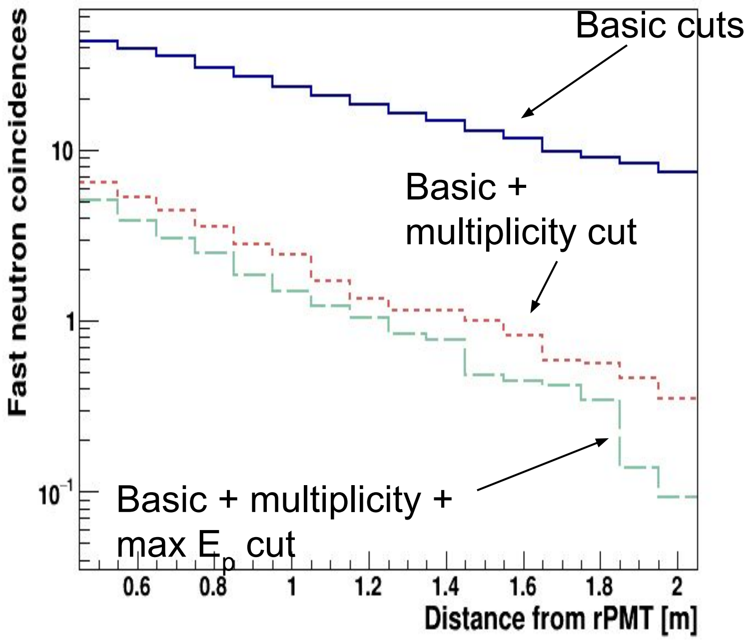


Highest-energy fast neutrons parallel to the muon direction.

Secondary neutrons are isotropic and least likely to be rejected by muon veto.

Asymmetric fiducial cut probably not useful if un-vetoed fast neutrons are largely isotropic.

Total fast neutron rejection



Cut on maximum prompt energy E_p (at n9<40 here*) is particularly effective as we move towards the centre of the detector (16m detector, Gd-water).

* Optimised value n9<25-30 for this configuration

What's new? Post-muon veto.

Analytical post-muon veto for radionuclide reduction:

$$\mathrm{R_i} = \left(1 - \epsilon + \epsilon \frac{\int_{\mathrm{t_{veto}}}^{\infty} \mathrm{e}^{-\ln(2)\mathrm{t}/\mathrm{t}_{1/2}}\mathrm{dt}}{\int_{0}^{\infty} \mathrm{e}^{-\ln(2)\mathrm{t}/\mathrm{t}_{1/2}}\mathrm{dt}}\right) \mathrm{R_{i,tot}}.$$

Assumptions:

- Muon tracking →detector deadtime negligible.
- 95% muon-detection efficiency ϵ in fiducial volume (reduction to allow for technical issues and muons that skim the edge of the fiducial).

1s veto reduces rates significantly:

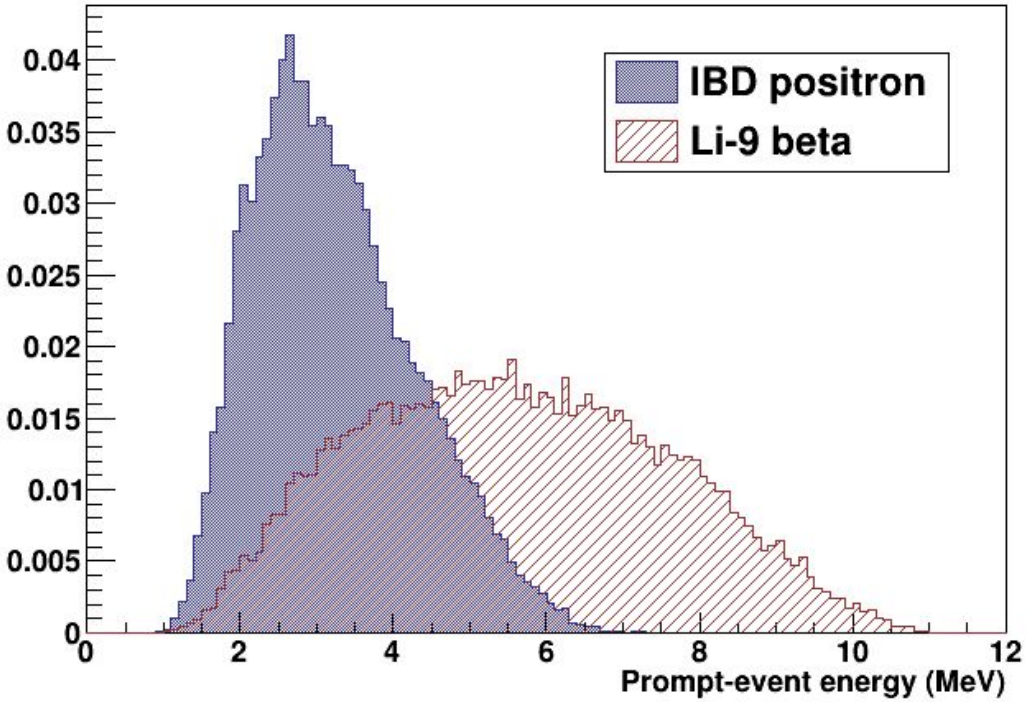
$$\mathrm{R}_{^9\mathrm{Li,veto}} = 0.069\ R_{^9Li,tot}$$

$$\mathrm{R}_{^8\mathrm{He,veto}} = 0.053\ R_{^8He,tot}$$

$$\mathrm{R}_{^{17}\mathrm{N,veto}} = 0.85\ R_{^{17}N,tot}$$

Prompt-energy cut-off

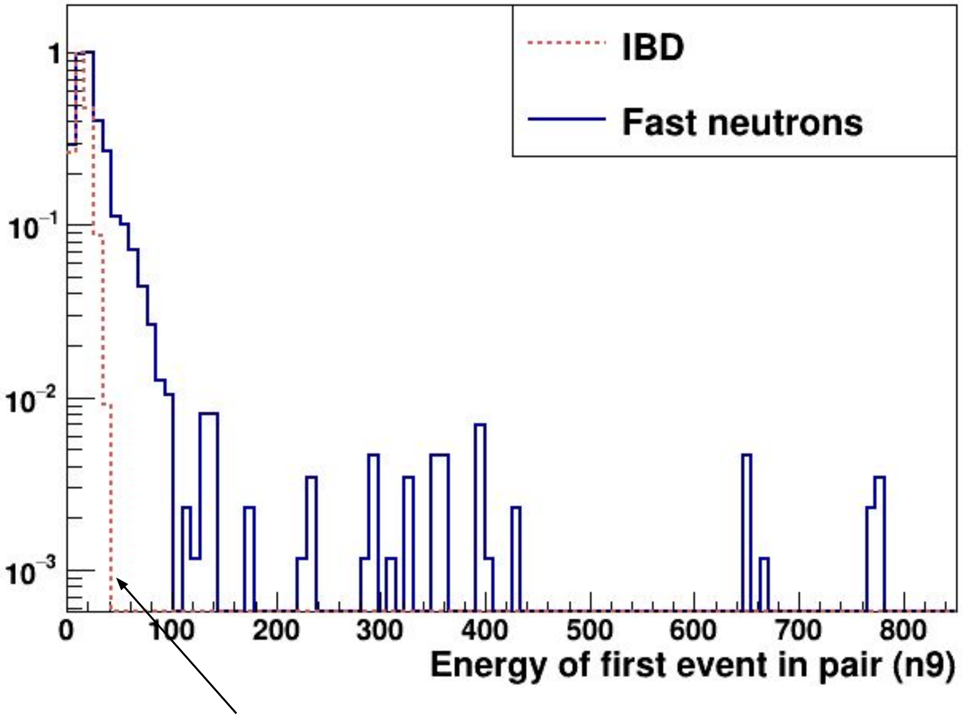
Radionuclide rejection



Peak positron energy ~2.5 MeV

^{9}Li β endpoint energies 11.2 MeV (29%) and 10.8 MeV (10.8%)

Fast neutron rejection



Maximum positron 'energy' (n9) is ~40 hits (60 total inner PMT hits).

Radioactive backgrounds

Radioactive backgrounds handled as part of likelihood analysis (LEARN - Likelihood Event Analysis of Reactor Neutrinos)

Likelihoods based on:

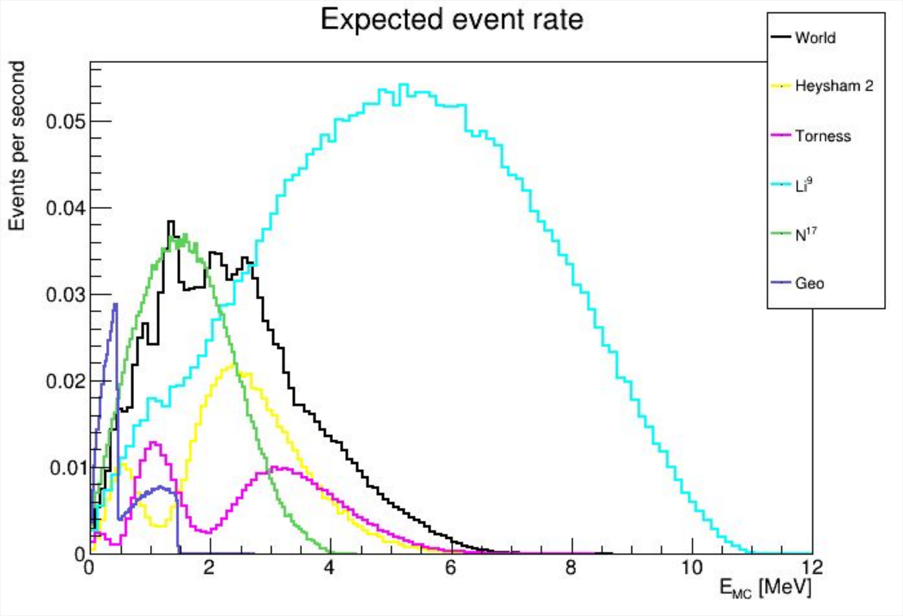
- Energy (n100, n100_prev)
- Time between events (dt_prev_us)
- Position between events (drPrevr)
- Absolute position (closestPMT)

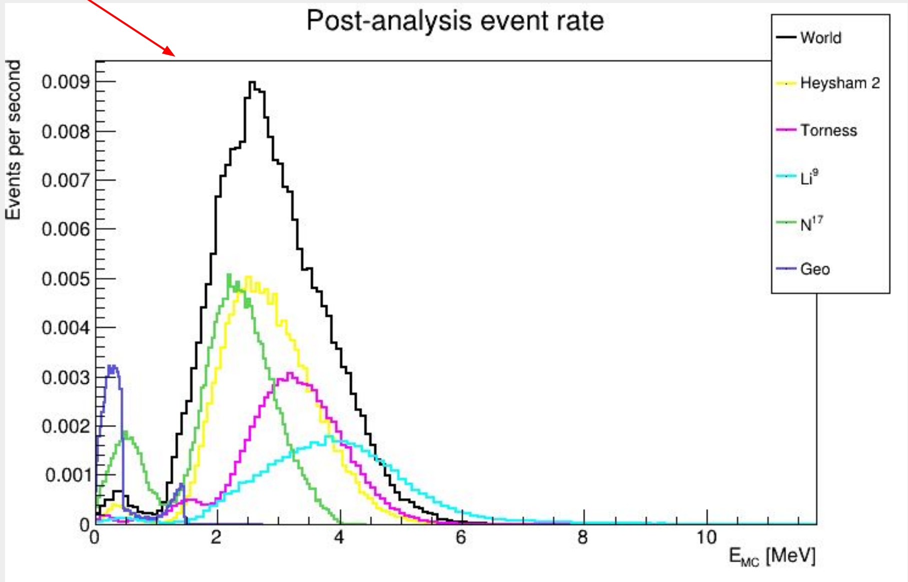
Likelihood ratio test used to remove singles

- Cut on ratio of signal likelihood to background likelihood optimised to remove singles events from radioactive backgrounds

$$\Lambda(x) = \frac{\mathcal{L}(x|\theta_s)}{\mathcal{L}(x|\theta_b)}$$

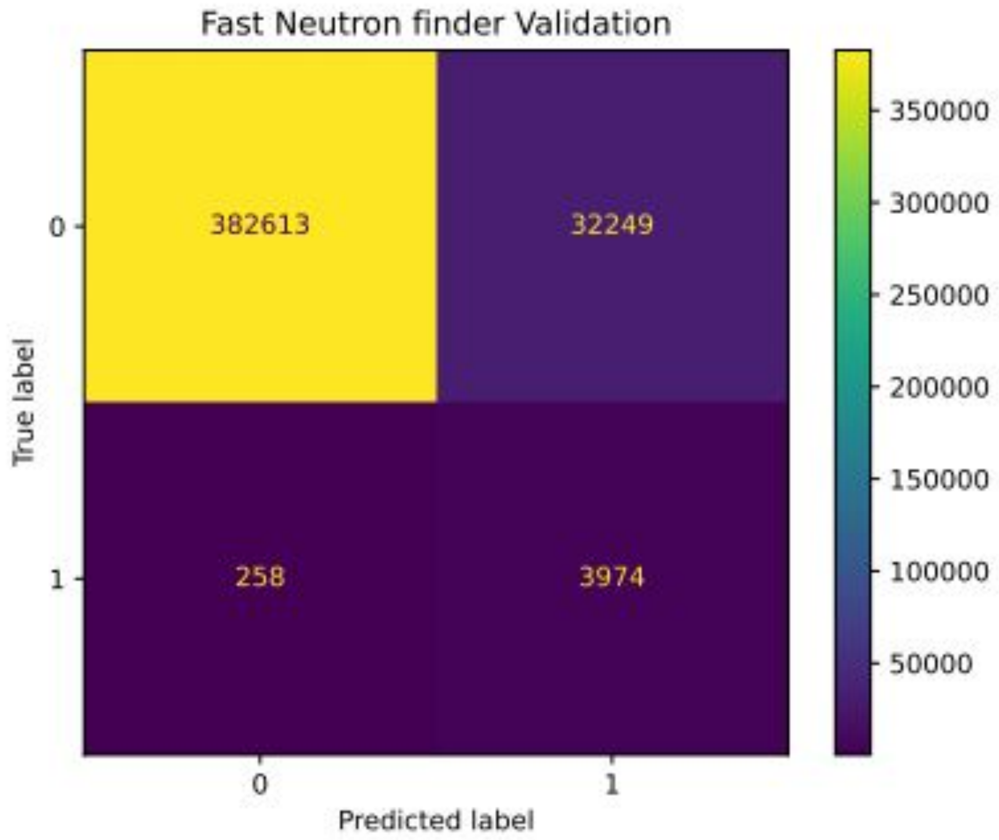
22 m Gd-WbLS

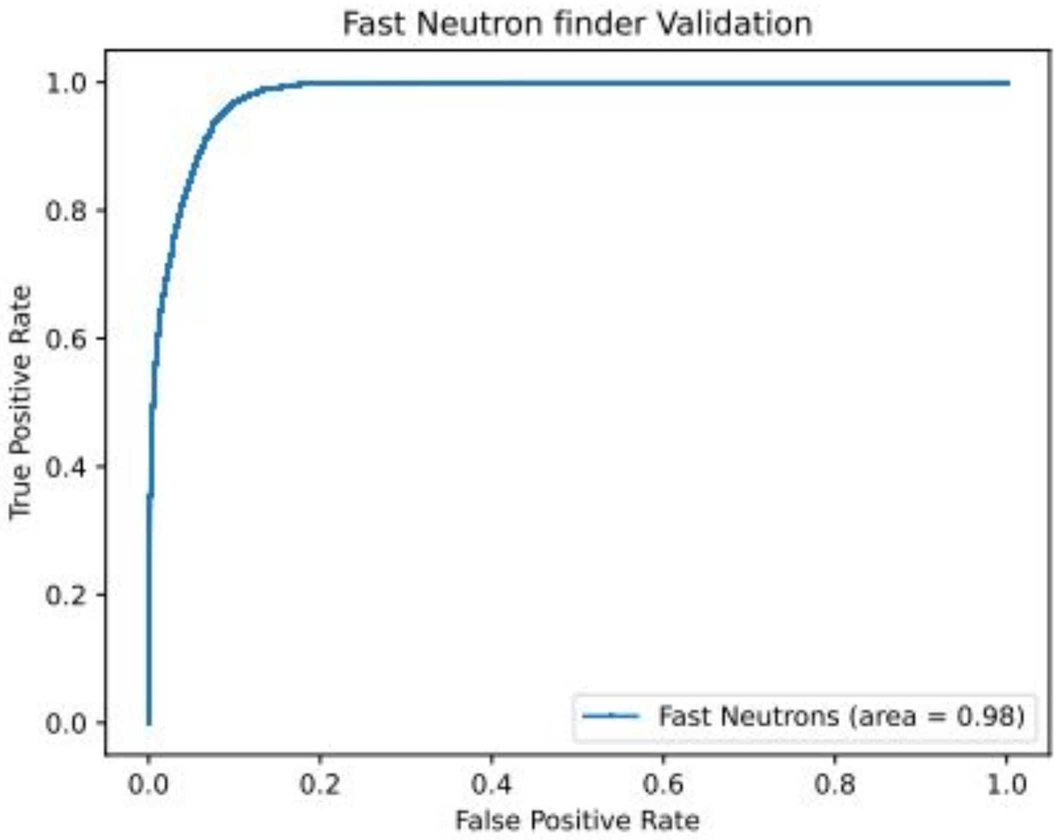

Expected event rate
Events per second
0.05
0.04
0.03
0.02
0.01
0
0
2
4
6
8
10
12
E_MC [MeV]
World
Heysham 2
Torness
Li9
N17
Geo


Post-analysis event rate
Events per second
0.009
0.008
0.007
0.006
0.005
0.004
0.003
0.002
0.001
0
0
2
4
6
8
10
E_MC [MeV]
World
Heysham 2
Torness
Li9
N17
Geo

AdaBoost for fast neutron rejection

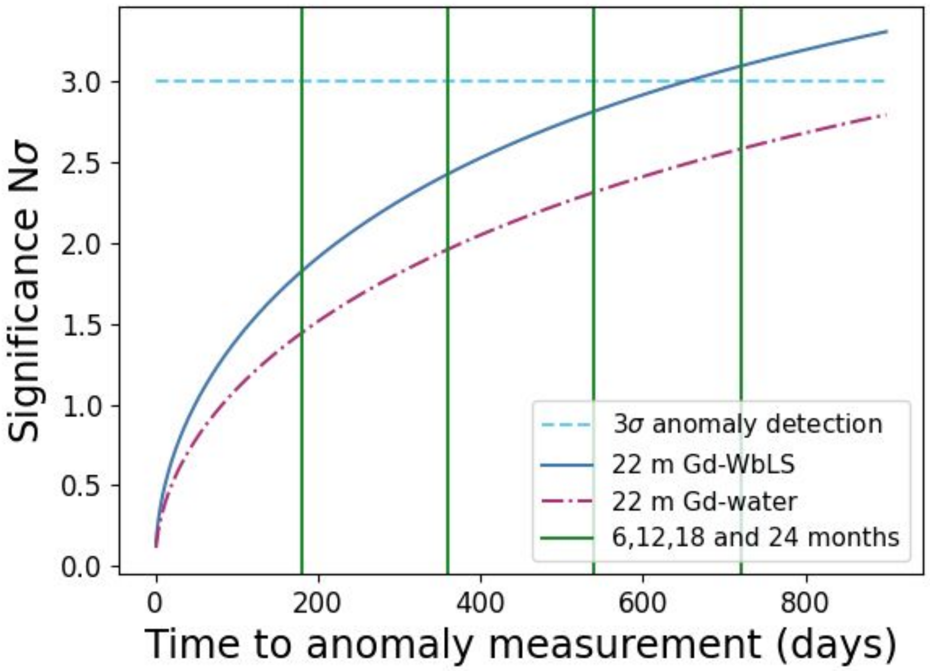
Steve Wilson/Niamh Holland, University of Sheffield





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**

Cobraa results breakdown for Gd-water*

16 m	s	Σb_i	^9Li & ^{17}N	Fast n	$IBD_{reactor}$	$\Sigma \sigma_{bi}$
Hartlepool 1	$3.0x10^{-1}$	$4.5x10^{-1}$	$2.5x10^{-2}$	$1.2x10^{-1}$	$3.1x10^{-1}$	$3.7x10^{-2}$
Heysham	$1.5x10^{-2}$	$3.9x10^{-2}$	$9.8x10^{-3}$	$9.7x10^{-3}$	$2.0x10^{-2}$	$2.9x10^{-3}$
Heysham-Torness	$6.0x10^{-3}$	$1.4x10^{-2}$	$4.8x10^{-3}$	$2.7x10^{-9}$	$9.0x10^{-3}$	$5.4x10^{-4}$
Heysham 2	$4.0x10^{-3}$	$1.5x10^{-2}$	$4.8x10^{-3}$	$2.7x10^{-9}$	$1.0x10^{-2}$	$6.1x10^{-4}$
22 m	s	Σb_i	^9Li & ^{17}N	Fast n	$IBD_{reactor}$	$\Sigma \sigma_{bi}$
Hartlepool 1	1.4	2.0	$1.2x10^{-1}$	$3.3x10^{-1}$	1.6	$1.3x10^{-1}$
Heysham	$1.0x10^{-1}$	$2.6x10^{-1}$	$6.9x10^{-2}$	$1.1x10^{-2}$	$1.8x10^{-1}$	$1.1x10^{-2}$
Heysham-Torness	$1.0x10^{-1}$	$2.4x10^{-1}$	$7.4x10^{-2}$	$1.1x10^{-2}$	$1.5x10^{-1}$	$9.6x10^{-3}$
Heysham 2	$5.9x10^{-2}$	$2.6x10^{-1}$	$6.9x10^{-2}$	$1.1x10^{-2}$	$1.8x10^{-1}$	$1.1x10^{-2}$

*Subdominant radioactivity and geoneutrino backgrounds omitted.

Cobraa results breakdown for Gd-Wbls*

16 m	s	Σb_i	^{9}Li & ^{17}N	Fast n	$IBD_{reactor}$	$\Sigma\sigma_{bi}$
Hartlepool 1	4.5×10^{-1}	6.2×10^{-1}	4.9×10^{-2}	7.4×10^{-2}	4.9×10^{-1}	3.6×10^{-2}
Heysham	3.8×10^{-2}	9.7×10^{-2}	2.5×10^{-2}	1.4×10^{-2}	5.9×10^{-2}	5.2×10^{-3}
Heysham-Torness	3.1×10^{-2}	8.8×10^{-2}	2.5×10^{-2}	1.4×10^{-2}	4.9×10^{-2}	4.8×10^{-3}
Heysham 2	1.5×10^{-2}	6.4×10^{-2}	1.6×10^{-2}	4.9×10^{-3}	4.3×10^{-2}	2.9×10^{-3}
22 m	s	Σb_i	^{9}Li & ^{17}N	Fast n	$IBD_{reactor}$	$\Sigma\sigma_{bi}$
Hartlepool 1	2.2	3.2	2.7×10^{-1}	5.4×10^{-1}	2.4	2.0×10^{-1}
Heysham	1.8×10^{-1}	4.8×10^{-1}	1.3×10^{-1}	4.4×10^{-2}	3.0×10^{-1}	2.1×10^{-2}
Heysham-Torness	1.3×10^{-1}	3.3×10^{-1}	8.5×10^{-2}	3.8×10^{-2}	2.1×10^{-1}	1.6×10^{-2}
Heysham 2	9.1×10^{-2}	3.9×10^{-1}	9.7×10^{-2}	3.4×10^{-2}	2.6×10^{-1}	1.8×10^{-2}

*Subdominant radioactivity and geoneutrino backgrounds omitted.

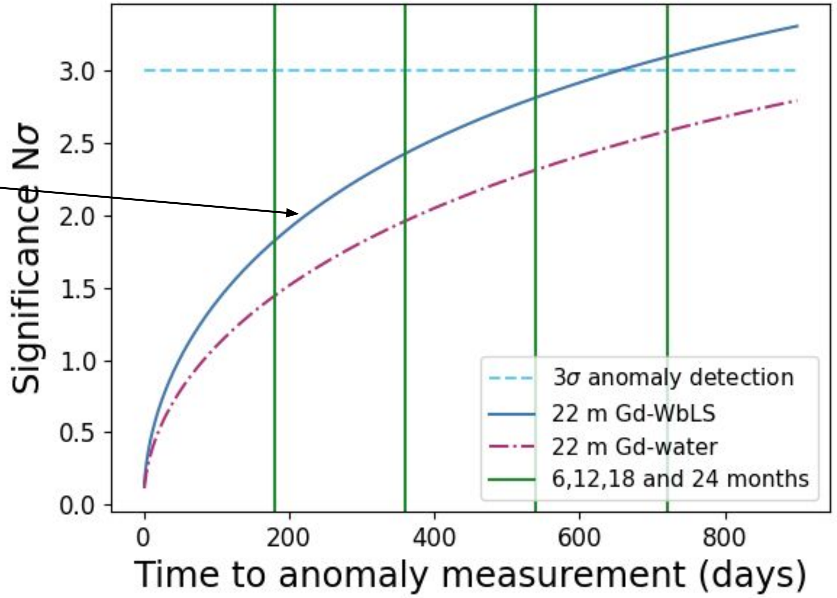
Cobraa/LEARN comparison (Gd-WbLS)

Agreement between 6% and 27% for the two independent analyses

Detector & analysis path	Heysham 1&2	H	
16m Gd-H_2O Cobraa	2327	3	
16 m Gd-WbLS Cobraa	738	1	
16 m Gd-WbLS LEARN	1017	963	2968
22m Gd-H_2O Cobraa	241	232	985
22 m Gd-WbLS Cobraa	152	192	**647**
22 m Gd-WbLS LEARN	196	164	**577**

2σ detection in 12 months or less.
Could be sufficient if combined with other monitoring methods

Dwell time in days to 3σ measurement from the Cobraa and LEARN analyses.



Significance of anomaly measurement sensitivity to Heysham 2 reactor complex with 22 m detector from Cobraa.

Could see single-site Heysham 2 reactor at a distance of ~150 km in less than two years of reactor operation.