

Background Characterisation for BUTTON-30

A Technology Testbed for Kiloton-Scale Antineutrino Monitoring

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On behalf of the BUTTON Collaboration



BUTTON-30: A Technology Testbed

Physical design:

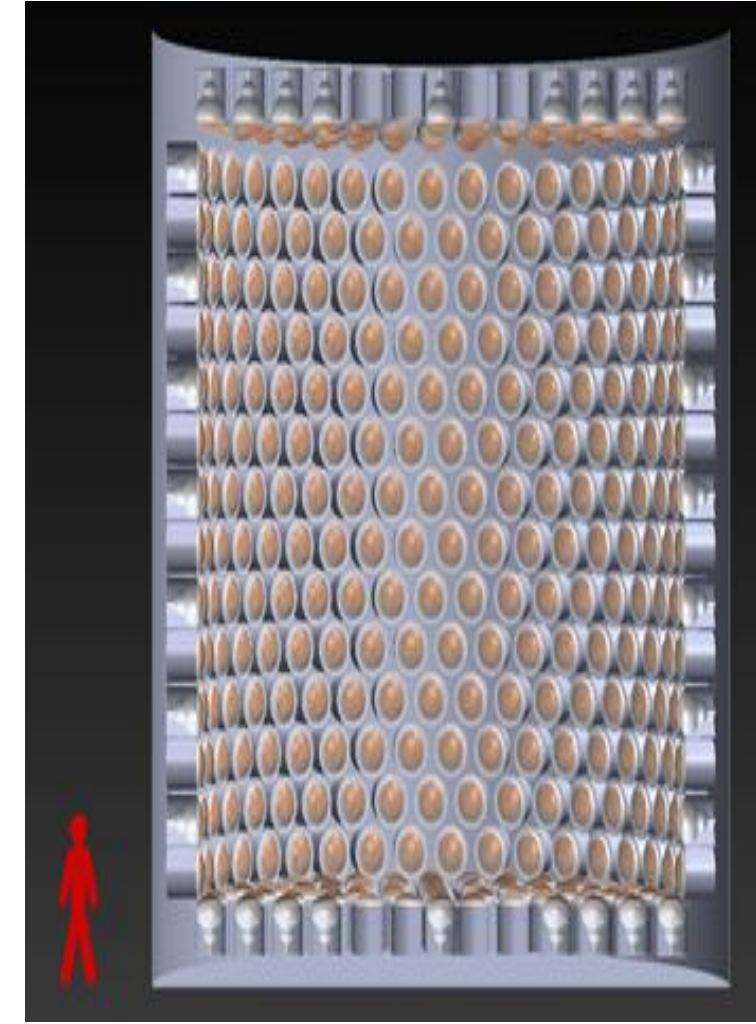
- 30-tonne cylindrical tank
- 3.6 m diameter × 3.2 m height
- 316L stainless steel (low-activity)

BUTTON is a hybrid antineutrino detector:

- Hybrid: Cherenkov + scintillation light
- Gadolinium-loaded for enhanced neutron tagging
- First underground Gd-WbLS detector

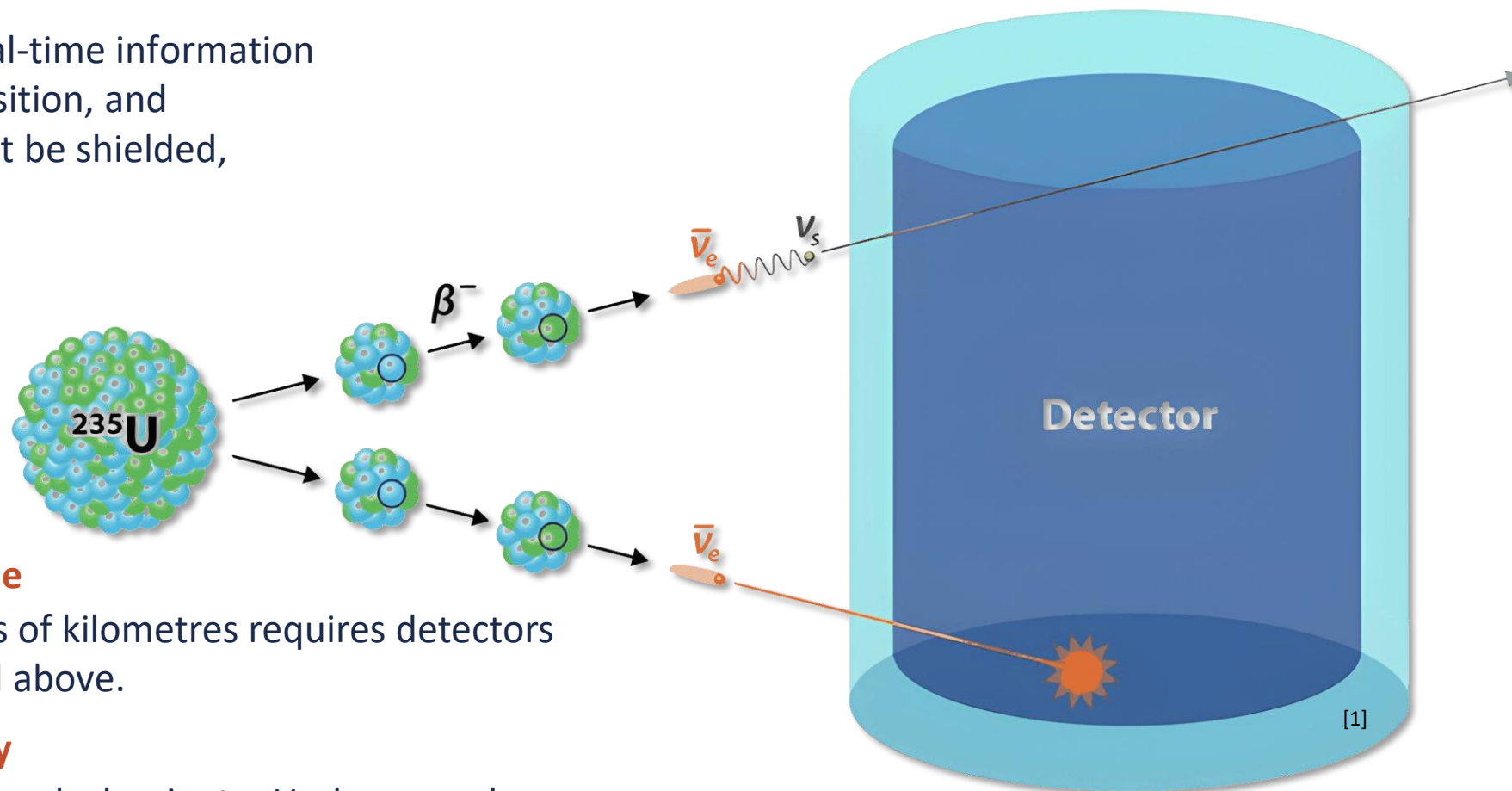
BUTTON is a Technology Testbed:

- 96 Hamamatsu R7081 10" photomultipliers
- Modular design enables testing next-generation photodetectors



A unique probe

Reactor antineutrinos carry real-time information about core power, fuel composition, and operational status. They cannot be shielded, spoofed, or switched off.



Remote monitoring needs scale

Monitoring at tens to hundreds of kilometres requires detectors at the tens-of-tonnes scale and above.

Backgrounds set the sensitivity

The signal is weak and backgrounds dominate. Underground antineutrino detection lives or dies on the ability to control them.



- Threshold: 1.8 MeV

Prompt-delayed coincidence

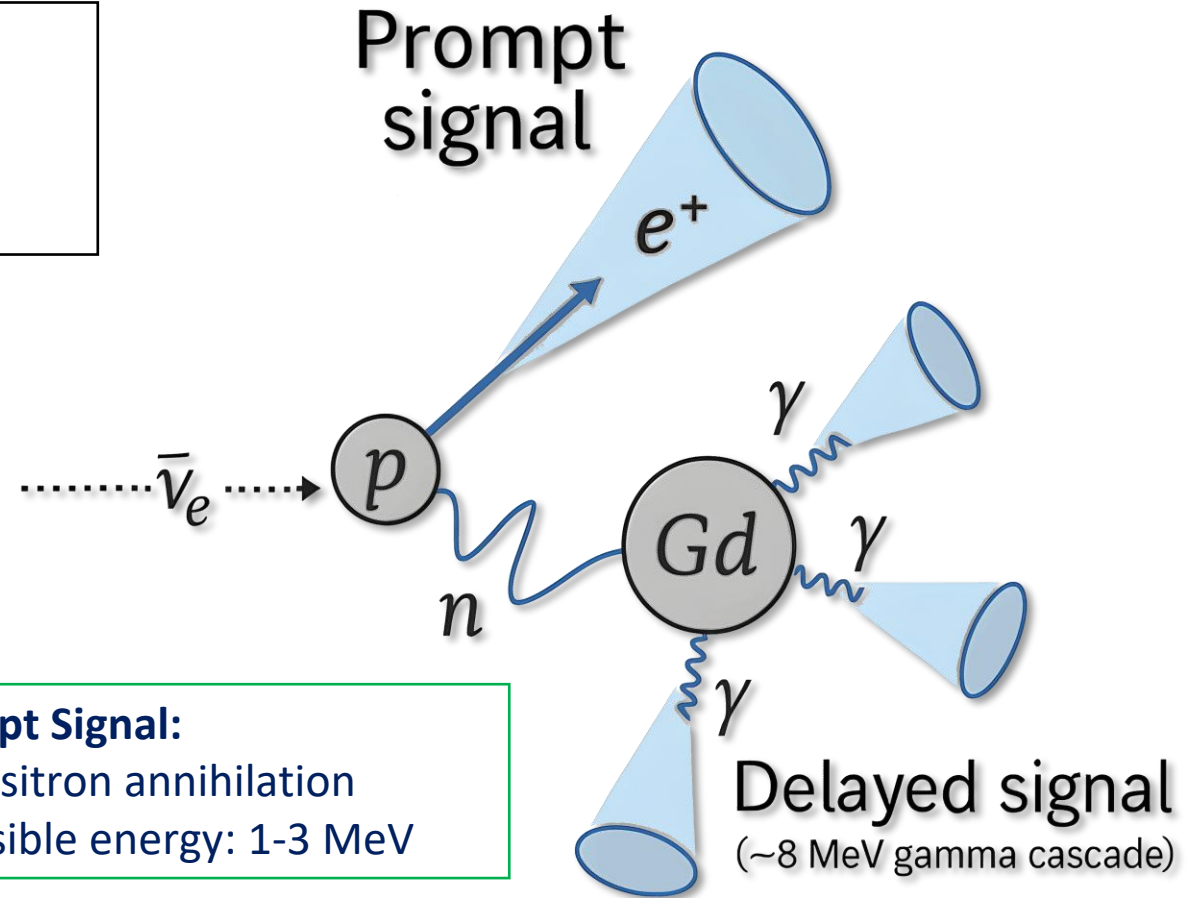
Inverse beta decay produces a positron and a neutron that thermalises and captures on Gd.

Neutrons can mimic the delayed signal

Ambient neutrons from (α, n) reactions and muon spallation capture on Gd identically to IBD neutrons.

Accidentals break the measurement

Spatial correlation cuts are the primary tool for rejection, requiring accurate knowledge of background rates and positions.



Prompt Signal:

- Positron annihilation
- Visible energy: 1-3 MeV

Delayed Signal:

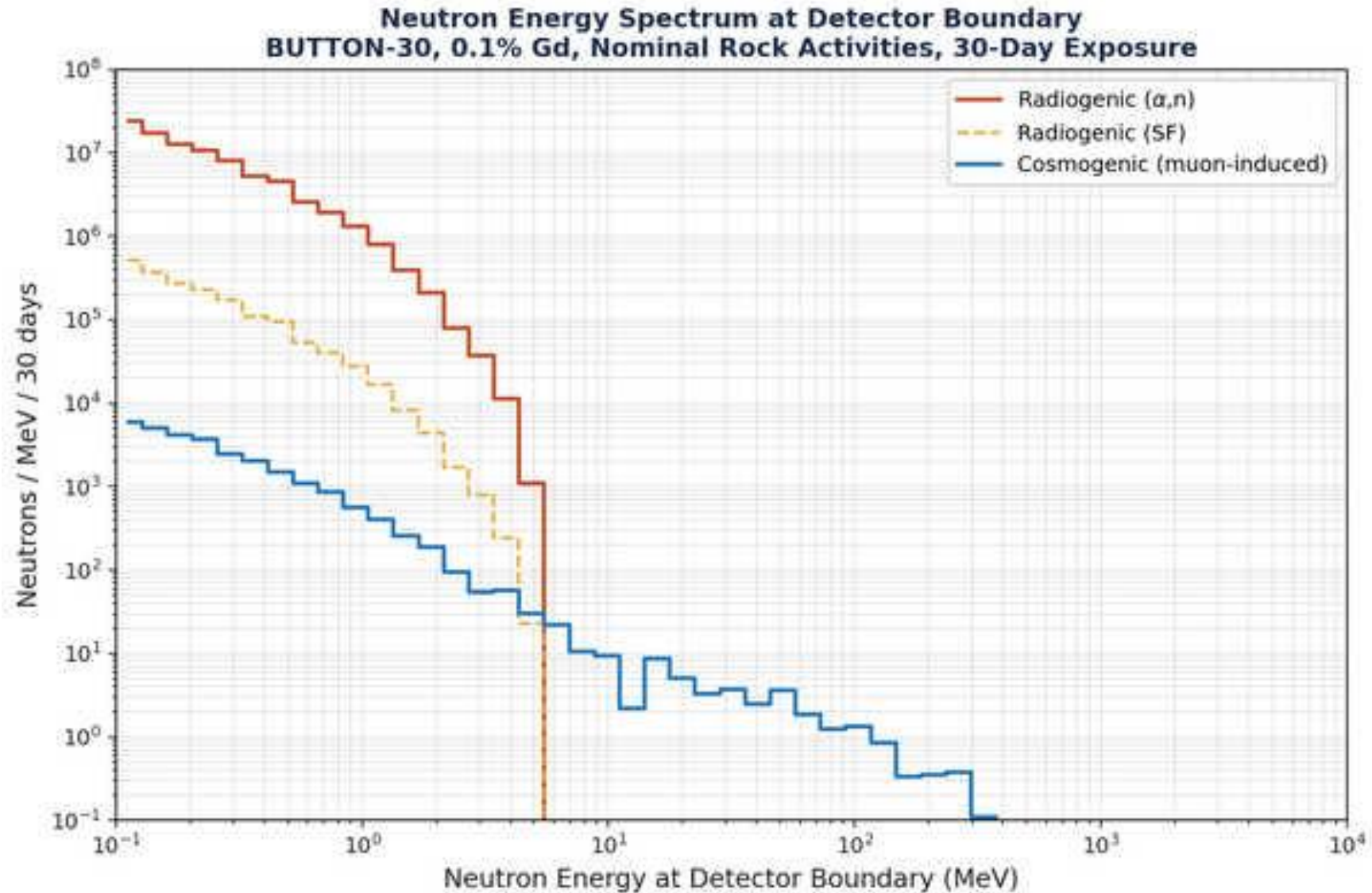
- ~30 μ s with Gd
- $n + Gd \rightarrow 8$ MeV γ cascade

How IBD Experiments Control Backgrounds

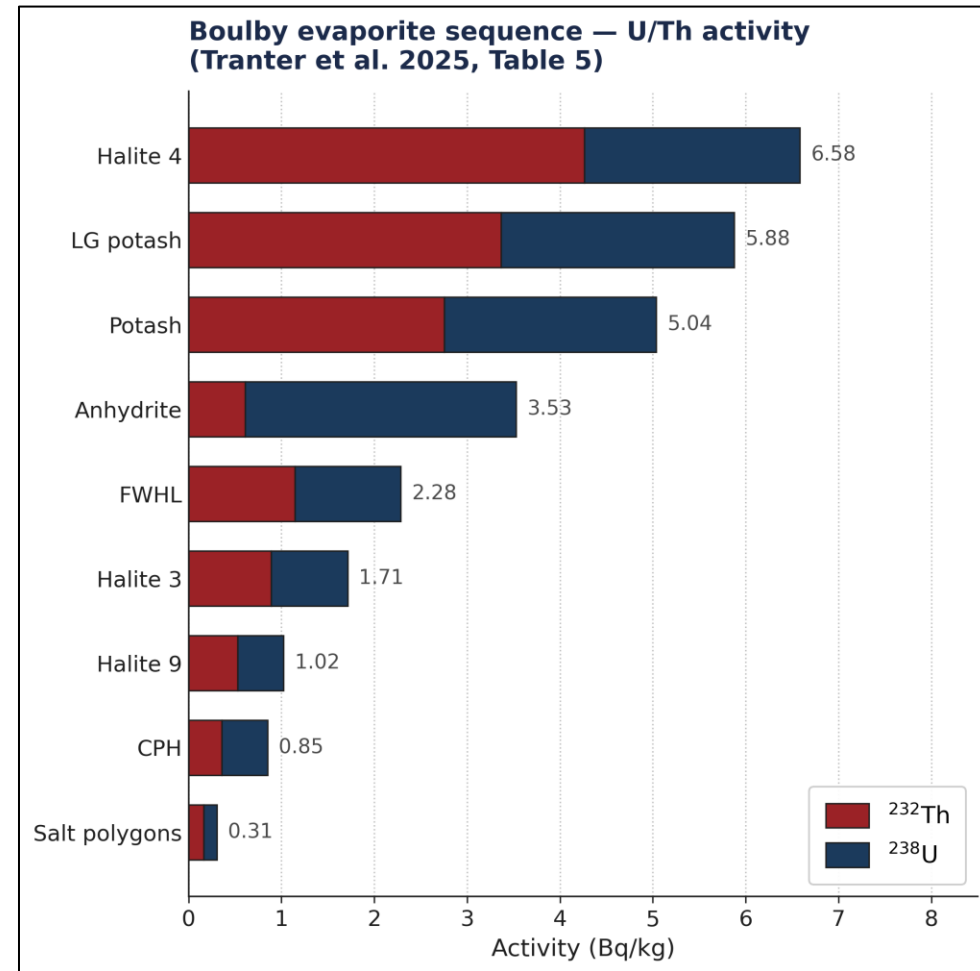
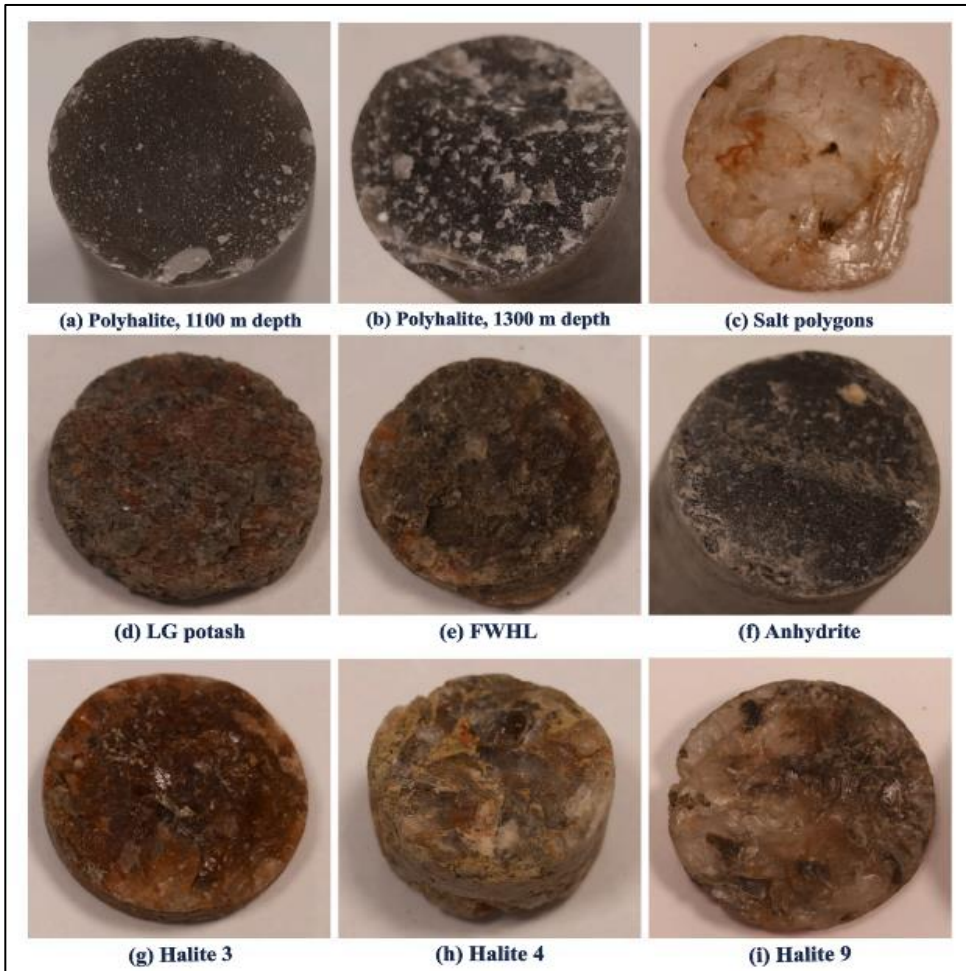
	Strategy	What it does	BUTTON
	1. Depth	Suppresses cosmogenic muon flux	
	2. Fiducial volume	Self-shielding at the detector core	
	3. Passive & active veto	External shield, muon tag	
	4. Coincidence timing	Narrow prompt-delayed window	
	5. Spatial topology	Prompt-delayed vertex correlation	

Simulation enables the cuts - BUTTON's strategies depend on accurate knowledge of the background rate and spatial distribution inside the detector.

Cosmogenic and Radiogenic Neutron Energy Spectrum



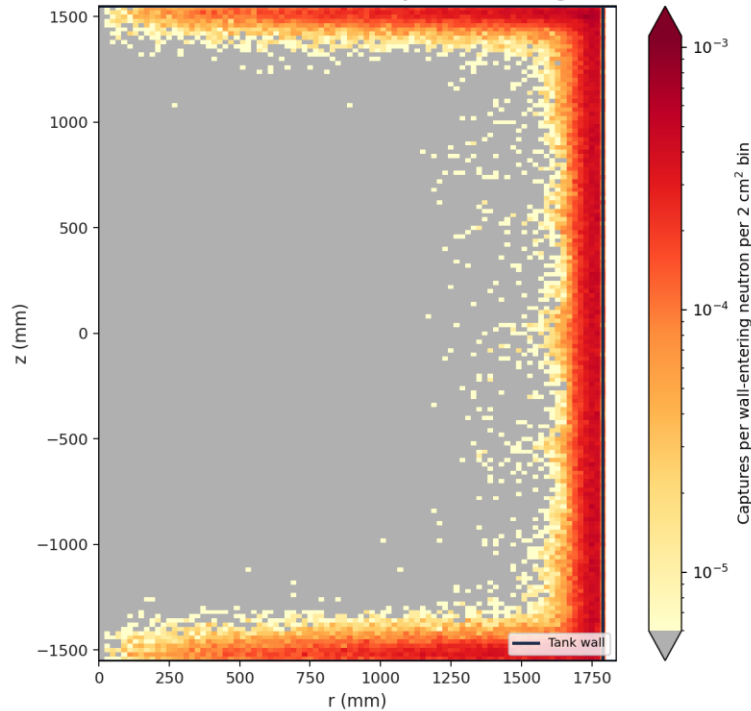
The Rock is Heterogeneous



Halite activity spans a factor of ~20 across the 1100 m level. Strata undulate horizontally over hundreds of metres; no direct measurement exists at the BUTTON location. The nominal rock activities for this work are taken from in-situ wall measurements: **Th = 1.88, U = 1.63 Bq/kg** (Malczewski 2013, via Tranter 2025 §3.3).

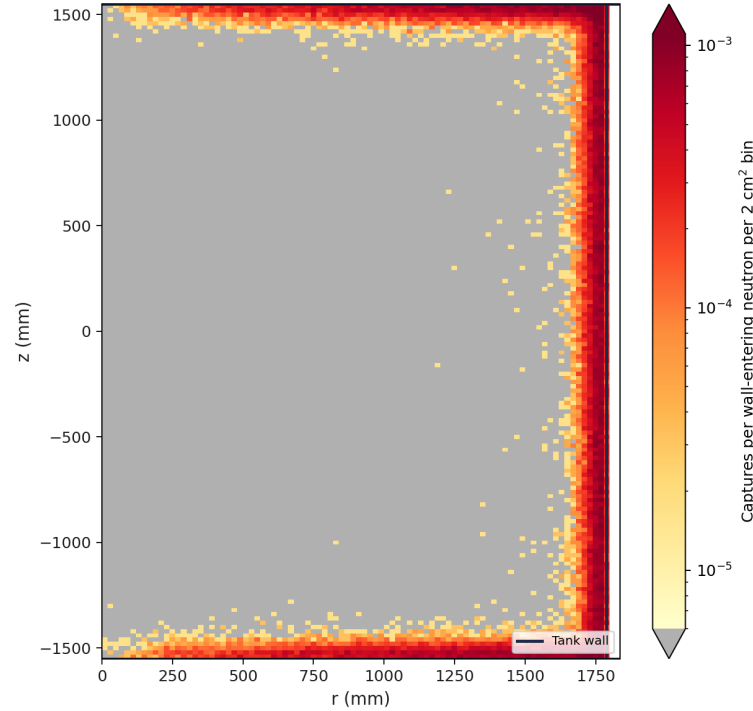
Gd Localises the Radiogenic Capture Distribution

Neutron capture heatmap, log scale
0% Gd (Pure water), nominal rock, per wall-entering neutron



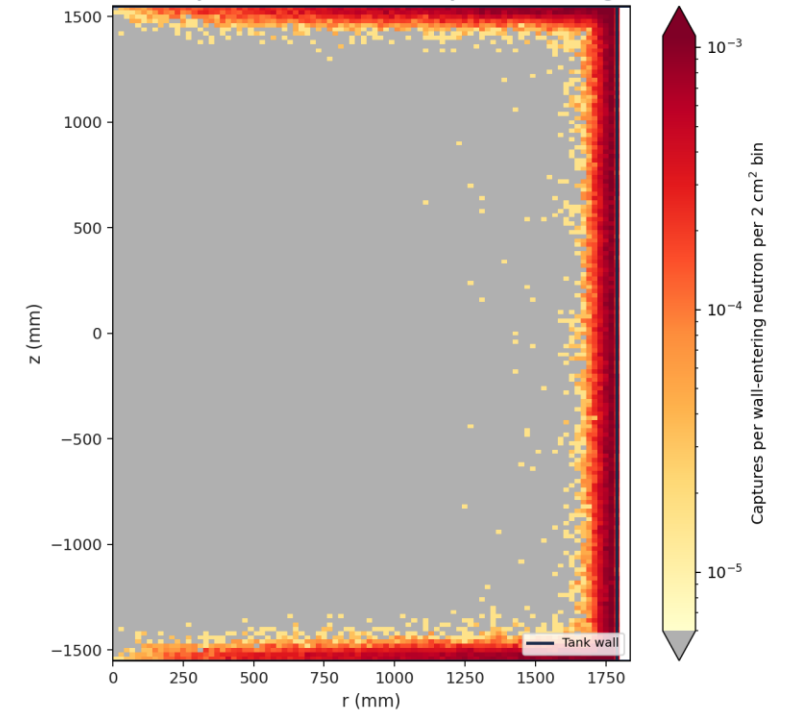
0% Gd+Water

Neutron capture heatmap, log scale
0.1% Gd (Gd-doped water), nominal rock, per wall-entering neutron



0.1% Gd+Water

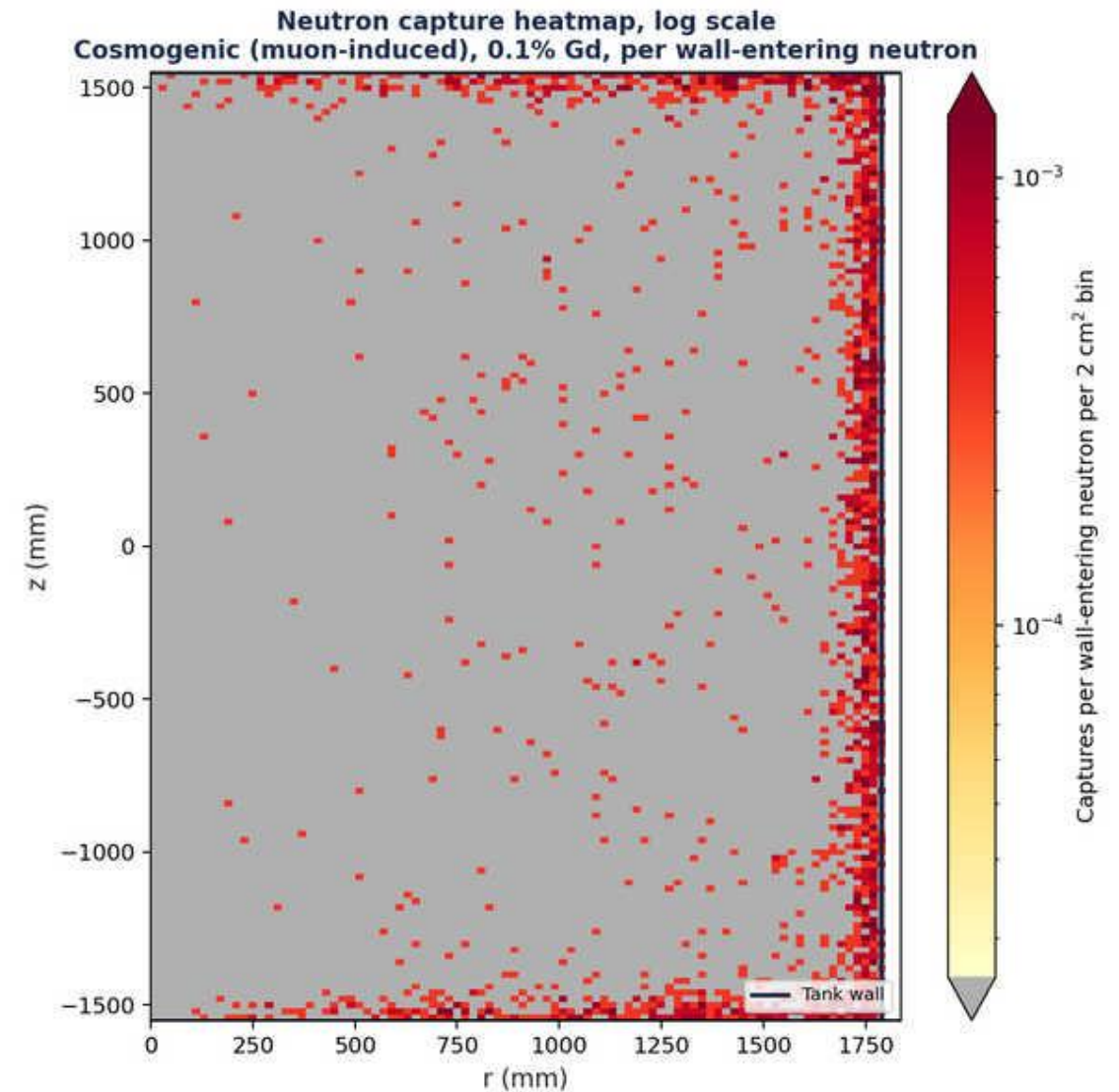
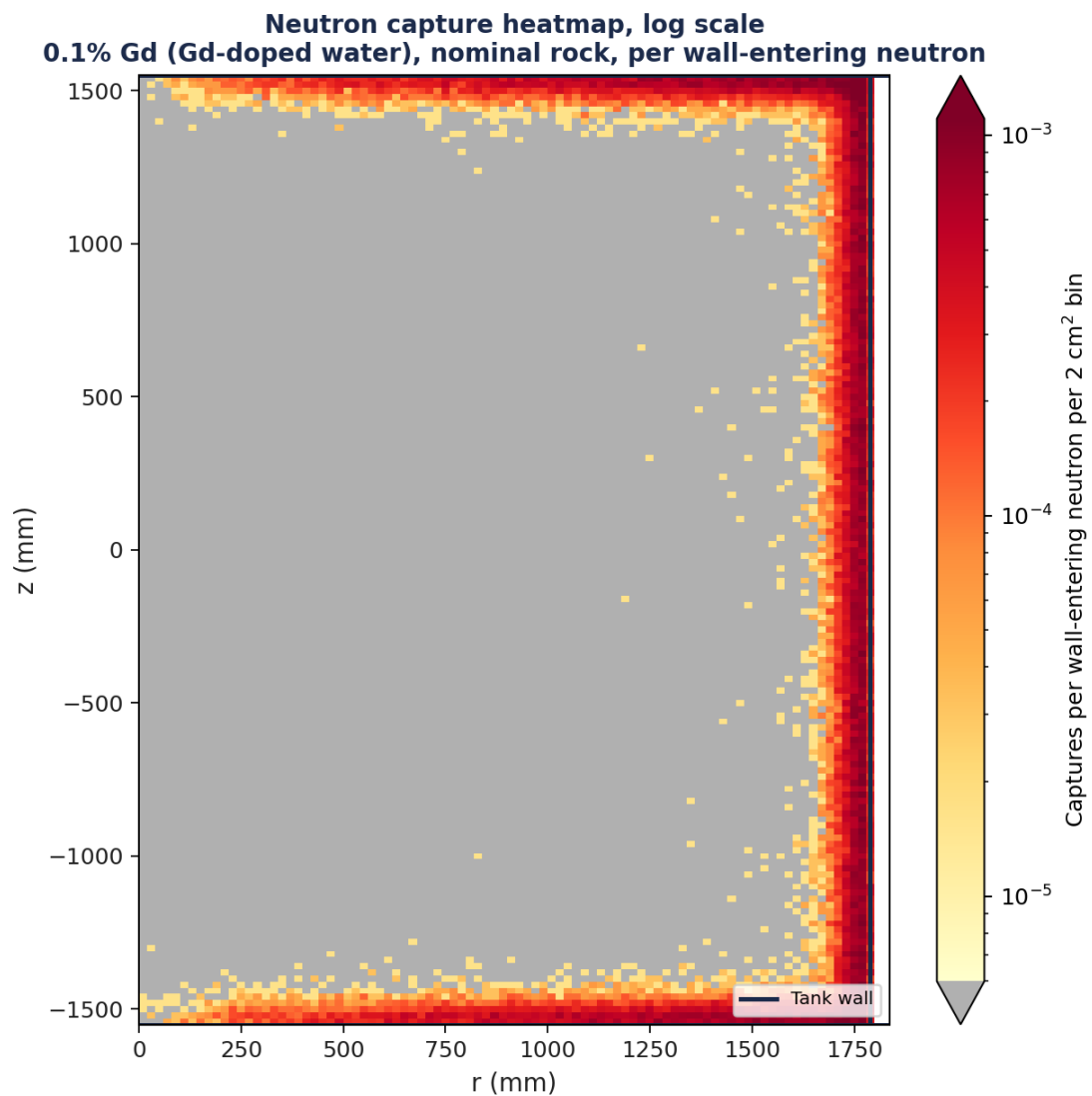
Neutron capture heatmap, log scale
0.2% Gd (Gd-doped water), nominal rock, per wall-entering neutron



0.2% Gd+Water

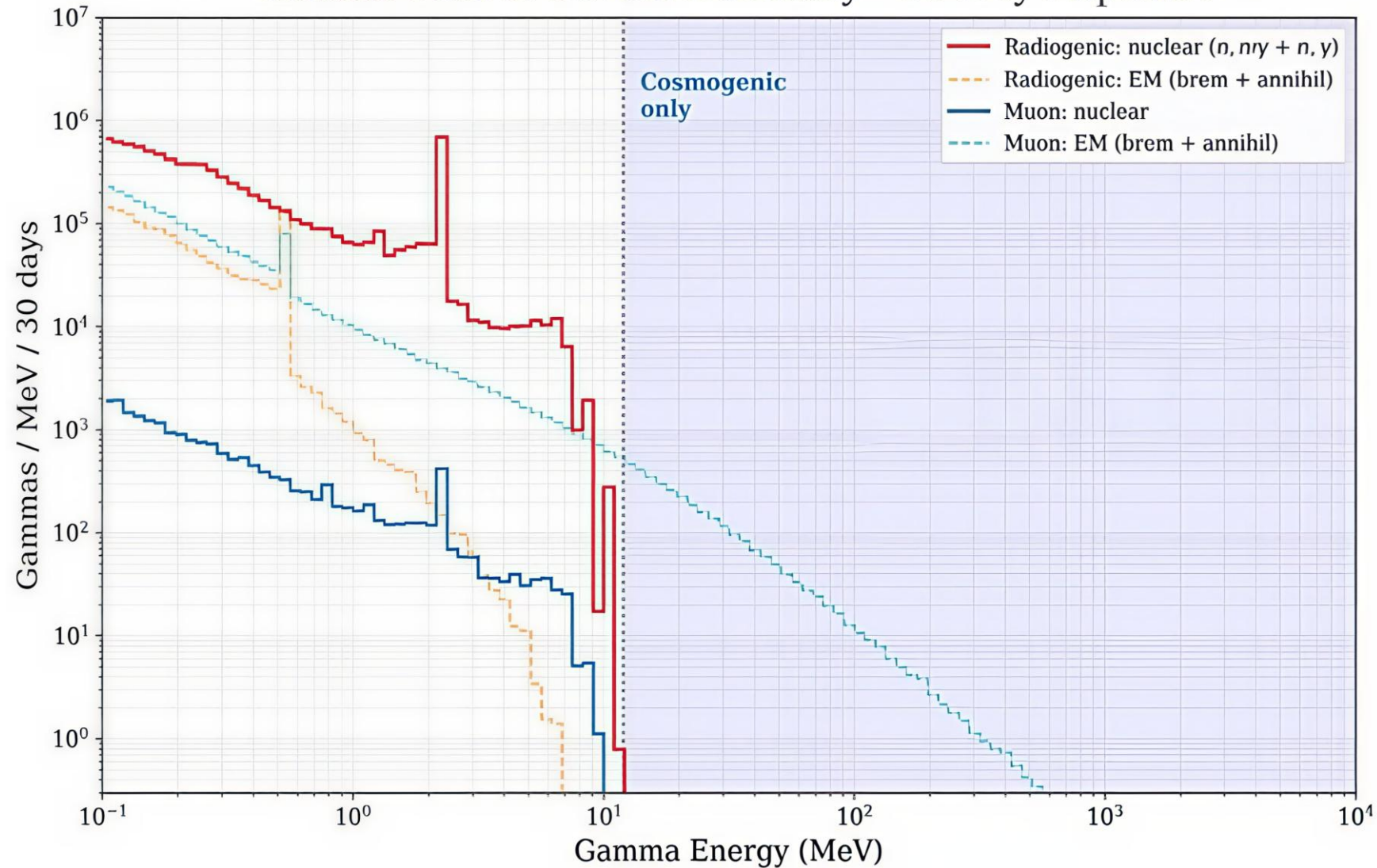
At 0.1% Gd, captures concentrate in a thin wall shell set by the Gd capture mean free path.
Without Gd, captures diffuse throughout the volume.
The wall-localised population is removable by spatial cuts; **the volume-distributed component is not.**

Cosmogenic Capture Distribution



Radiogenic and Cosmogenic Gamma Flux

Gamma Flux at Cavern Boundary - 30-Day Exposure



The Scale of the Problem

Entering Laboratory 6.5×10^7 /day

Entering detector 6.5×10^5 /day

Captured in Gd+Water 4.4×10^5 /day



Signal	NIU	30 t (IBD/yr)	1 kt (IBD/yr)
Hartlepool 1&2	1041	20.9	696
Heysham 1&2	70	1.4	47
Heysham 2 only	40	0.8	27
Torness	65	1.3	43

NIU = IBD interactions per 10³² free protons per year.
1 kt H₂O = 6.686 × 10³¹ free protons. Raw interaction rates, before efficiency or cuts
IBD signal rates at Boulby (Kneale 2023, Table III)

* Kneale et al., Phys. Rev. Applied 20, 034073 (2023), Table III. Rates scaled to BUTTON-30 (30 t) and 1 kt H₂O.

Summary: BUTTON-30

What this work is:

- Complete radiogenic and cosmogenic background prediction for BUTTON-30
- Rock-composition systematic bracketed from the literature

What we've shown:

- Radiogenic captures dominate; Gd localises them near the walls
- Cosmogenics subdominant but spatially irreducible above 12 MeV

Impact:

- Quantifies the background systematic for dwell-time calculations
- Constrains the background floor the kiloton inherits
- Reducing the rock composition uncertainty is the highest-impact next step for BUTTON's background understanding.

1 PREPARED FOR SUBMISSION TO JINST

2 **The BUTTON-30 detector at Boulby**

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BUTTON Collaboration and Support



UK Institutions:

University of Liverpool (lead)
 University of Sheffield
 University of Edinburgh
 University of Warwick
 University of Glasgow
 STFC Boulby Underground Laboratory
 UK National Nuclear Laboratory
 AWE Aldermaston

US Institutions:

Brookhaven National Laboratory
 Lawrence Livermore National Laboratory
 UC Berkeley / LBNL
 UC Davis
 University of Michigan
 University of Pennsylvania
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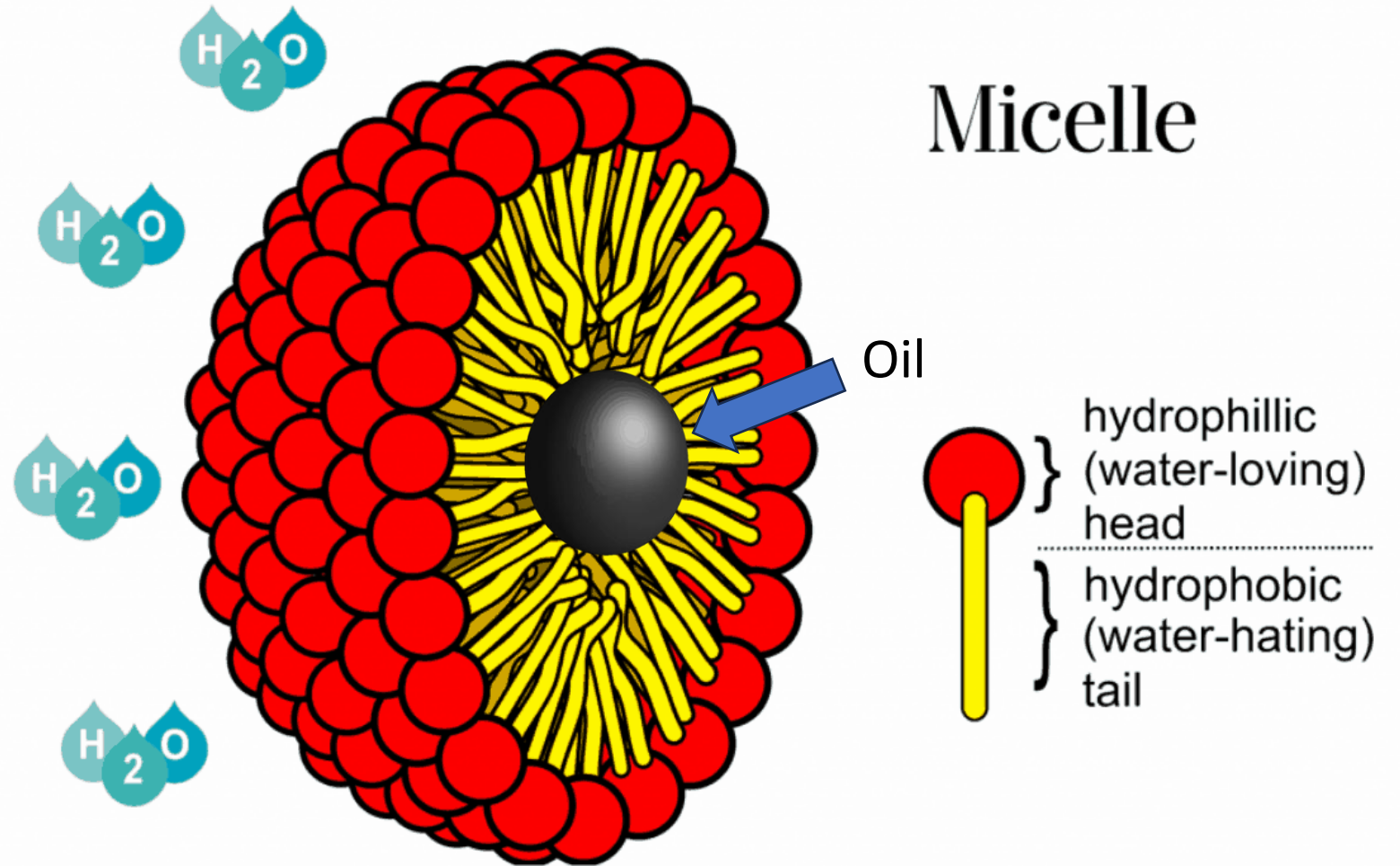
Water-based Liquid Scintillator (WbLS)

Liquid Scintillator

- Limits size of detector
- Not miscible in water
- Destroys Cherenkov signal
- Expensive at scale

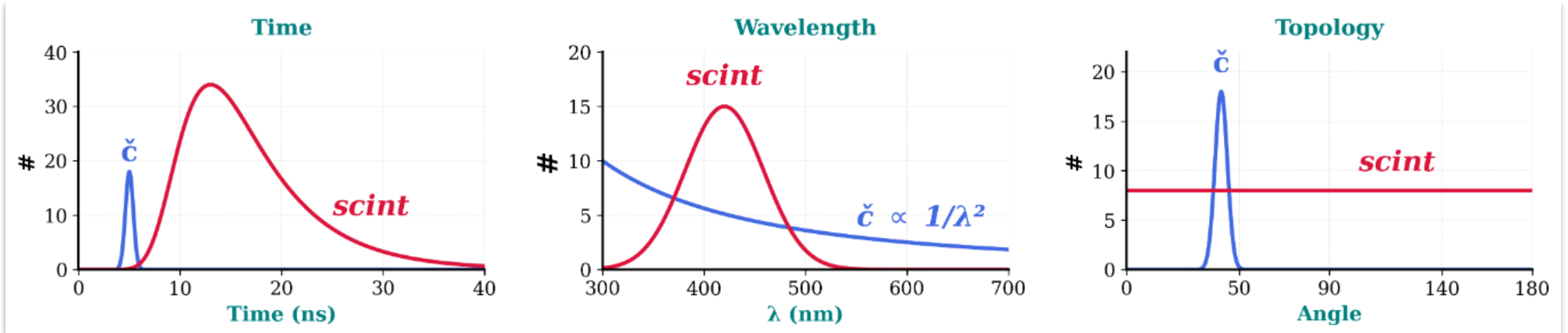
WbLS

- Miscible in water
- Lower attenuation -> larger volumes
- Higher light yield than pure water → better energy resolution
- Preserves Cherenkov directionality at low concentrations



The Hybrid Detection Challenge

Hybrid detectors combine Cherenkov and scintillation - but they must be distinguishable



Three discrimination methods:

- Time: Cherenkov light (**blue**) arrives promptly; scintillation (**red**) is delayed
- Wavelength: Cherenkov peaks in UV; scintillation peaks at ~420 nm
- Topology: Cherenkov is directional; scintillation is isotropic

BUTTON's challenge:

- Higher scintillator improves light yield but degrades discrimination - BUTTON finds the optimal trade-off.
- Pure water: excellent separation, but only ~300 photons/MeV
- Pure scintillator: ~10,000 photons/MeV, but no Cherenkov discrimination

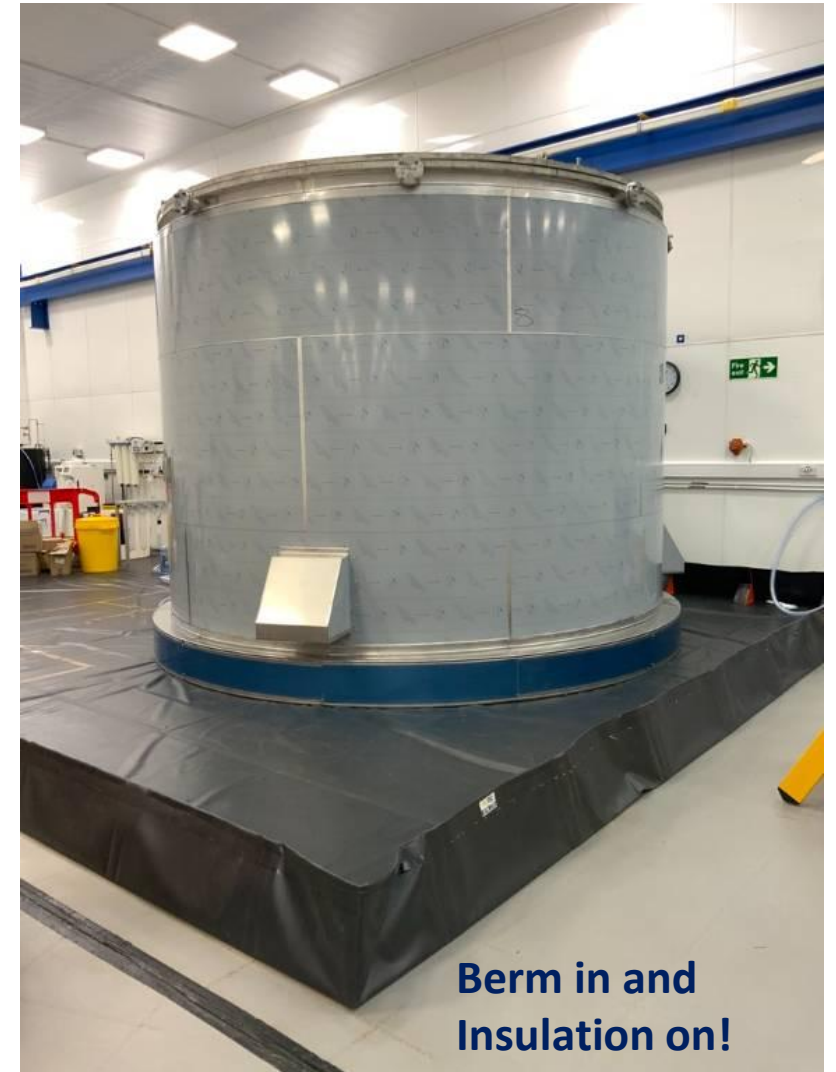
Tank Construction began Jan 2024



Before



During Construction

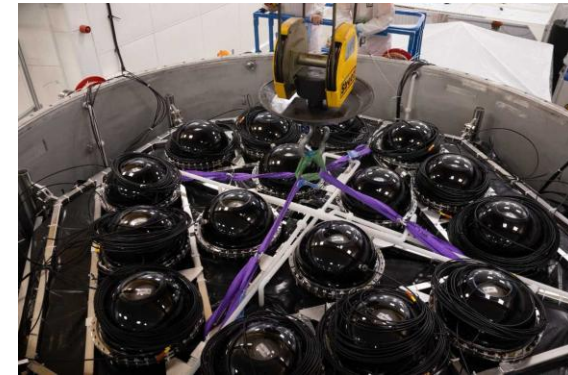
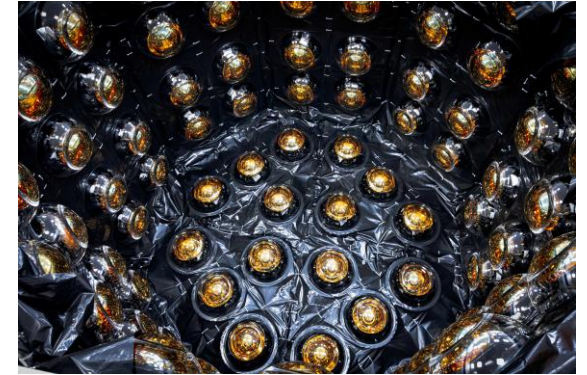
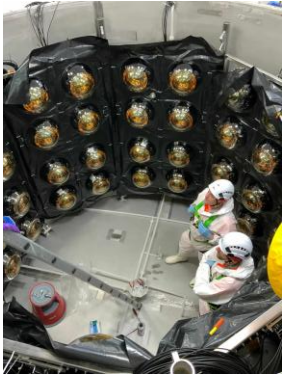
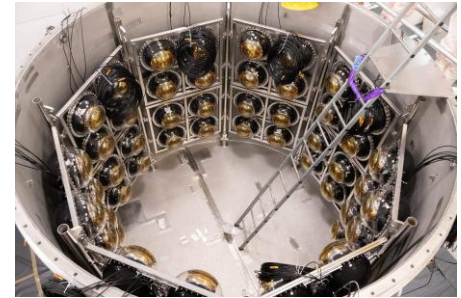
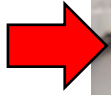


Berm in and
Insulation on!

Slide courtesy of James Gooding, Liverpool University

PMT installation storyboard

Jan 2025



Slide courtesy of James Gooding, Liverpool University

April 2025

WbLS-Compatible PMT Encapsulation

The challenge:

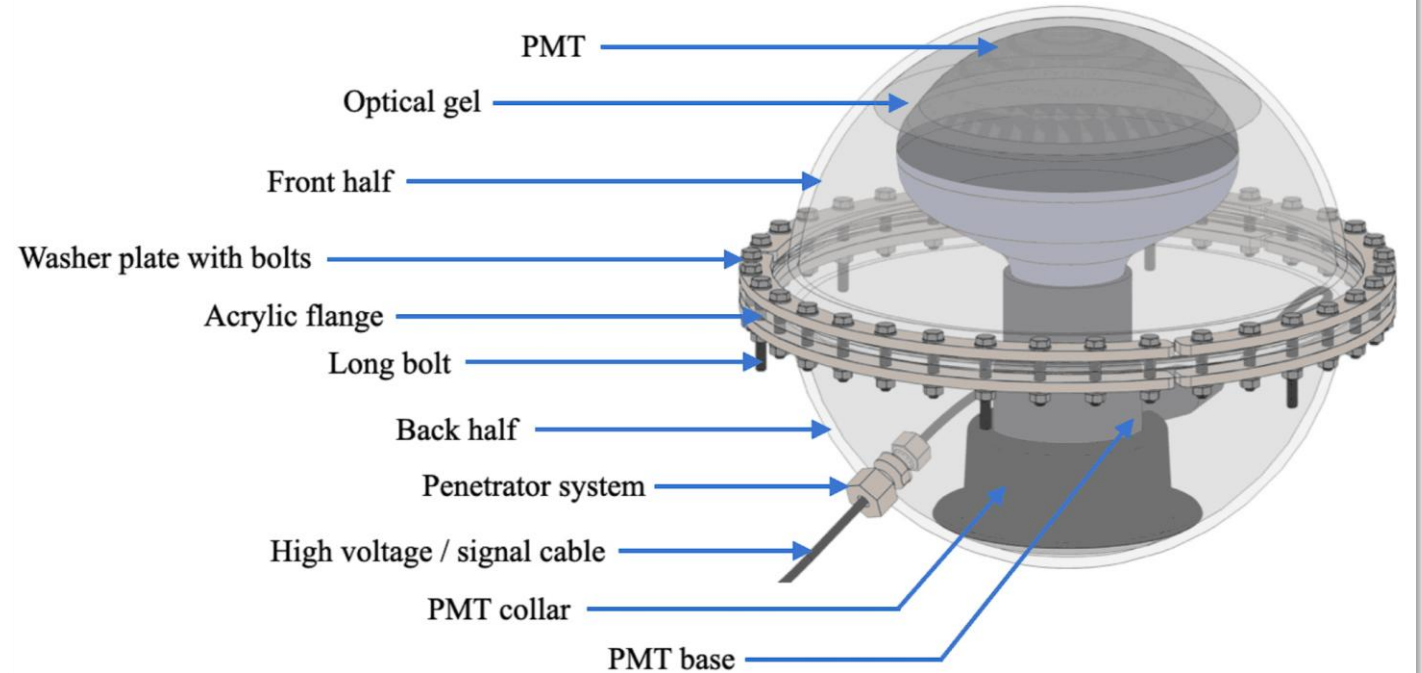
- Standard PMT bases incompatible with WbLS
- Material leaching degrades optical quality
- Need flexibility to test multiple fill media

The solution:

- 96 custom acrylic housings fabricated
- Watertight spherical design (blow-moulded)
- UV-transparent front hemisphere
- 4-month production campaign
- Rigorous QA: pressure tests, immersion, dark counts

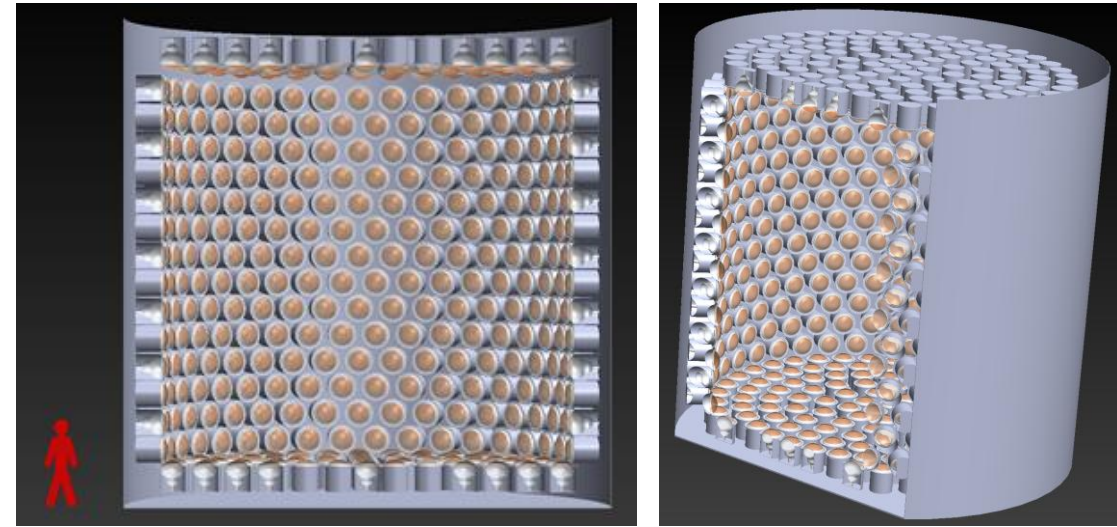
Engineering validation:

- First demonstration of WbLS-compatible PMT deployment at scale.
- 98% first-attempt success rate proves reproducibility.
- Validates materials, procedures, and QA protocols for kiloton-class detectors.



Future Plans BUTON 1kT

- Focussing on the a 10.5x10.5m, 15-20+% photo coverage tank
- Simulating reactor IBDs in tank (seeing IBDs)
- Need to understand backgrounds (this is still being updated and BUTON running will help)
- From current simulation work confident a 1kT tank will be able to detector reactor neutrinos



Expansion of Boulby gives us a unique opportunity to for growth

Physics goals:

- Reactor neutrino studies
- Diffuse Supernove neutrinos
- Dark matter experiments
- Neutrinoless double beta decay
- Full at scale deployment of WbLS

