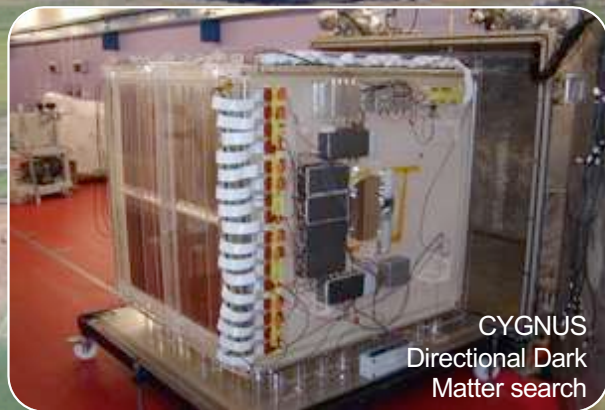




Sean Paling  
STFC Boulby Underground Science Facility

Astroparticle Physics: the search for Dark Matter & beyond



CYGNUS  
Directional Dark Matter search



Earth and environmental science, Astrobiology and planetary exploration

# Deep Science at Boulby Underground Laboratory:

Subterranean studies at the UK's deep underground science facility

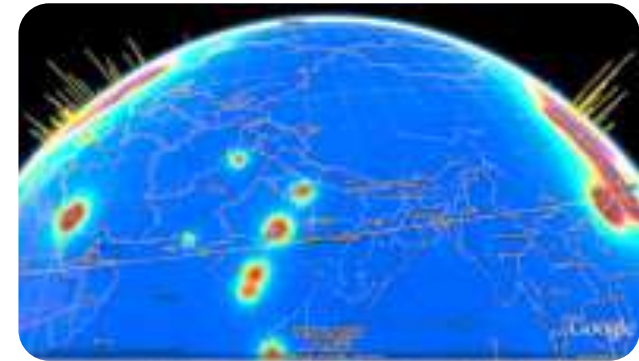


Underground lab @ Boulby



# AIT-NEO (WATCHMAN)

World  
antineutrino  
flux levels



## A WATER Cherenkov Monitor of ANtineutrinos

Design,  
excavation,  
installation &  
operation 2019  
to 2026(+)

### HARTLEPOOL REACTORS

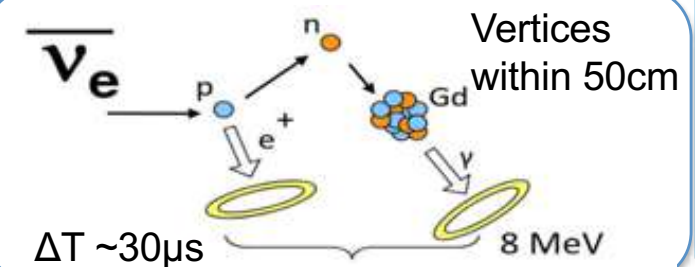
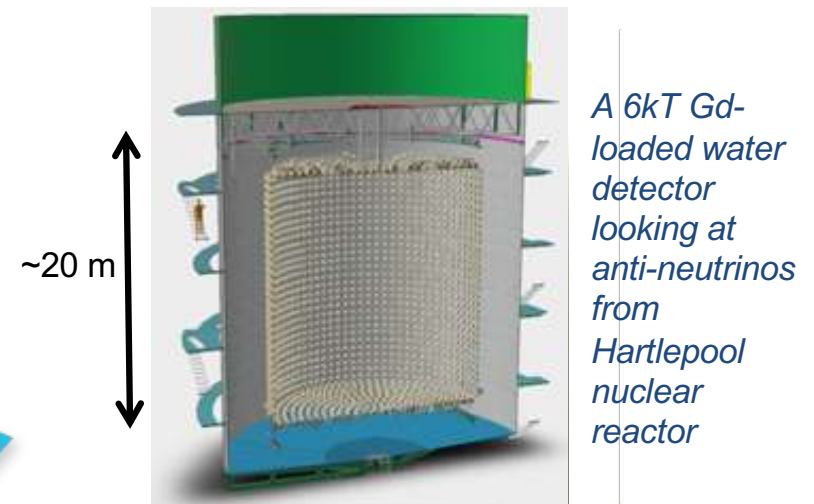


- 2 cores
- 1570 MWt per core
- 25 km standoff



Funding: US (>\$70M), UK (~£10M)  
confirmed in 2017 & 2018 respectively

### WATCHMAN detector at the Boulby mine



**NEW** 6kT prototype detector: R&D for anti-neutrino monitoring of nuclear reactors for global nuclear non-proliferation purposes & more



# Deep Science @ Boulby Underground Laboratory...

- 1) About Boulby Mine and Boulby Underground Lab
- 2) Boulby Science Overview:
  - Astroparticle Physics & Low Background Science
  - Earth & Environmental Science
  - Astrobiology & Planetary Exploration Studies
- 3) The future: inc. AIT-NEO (WATCHMAN)

Find out more:

@BoulbyLab

[www.stfc.ac.uk/boulby](http://www.stfc.ac.uk/boulby)



Science and  
Technology  
Facilities Council





# Boulby Underground Laboratory

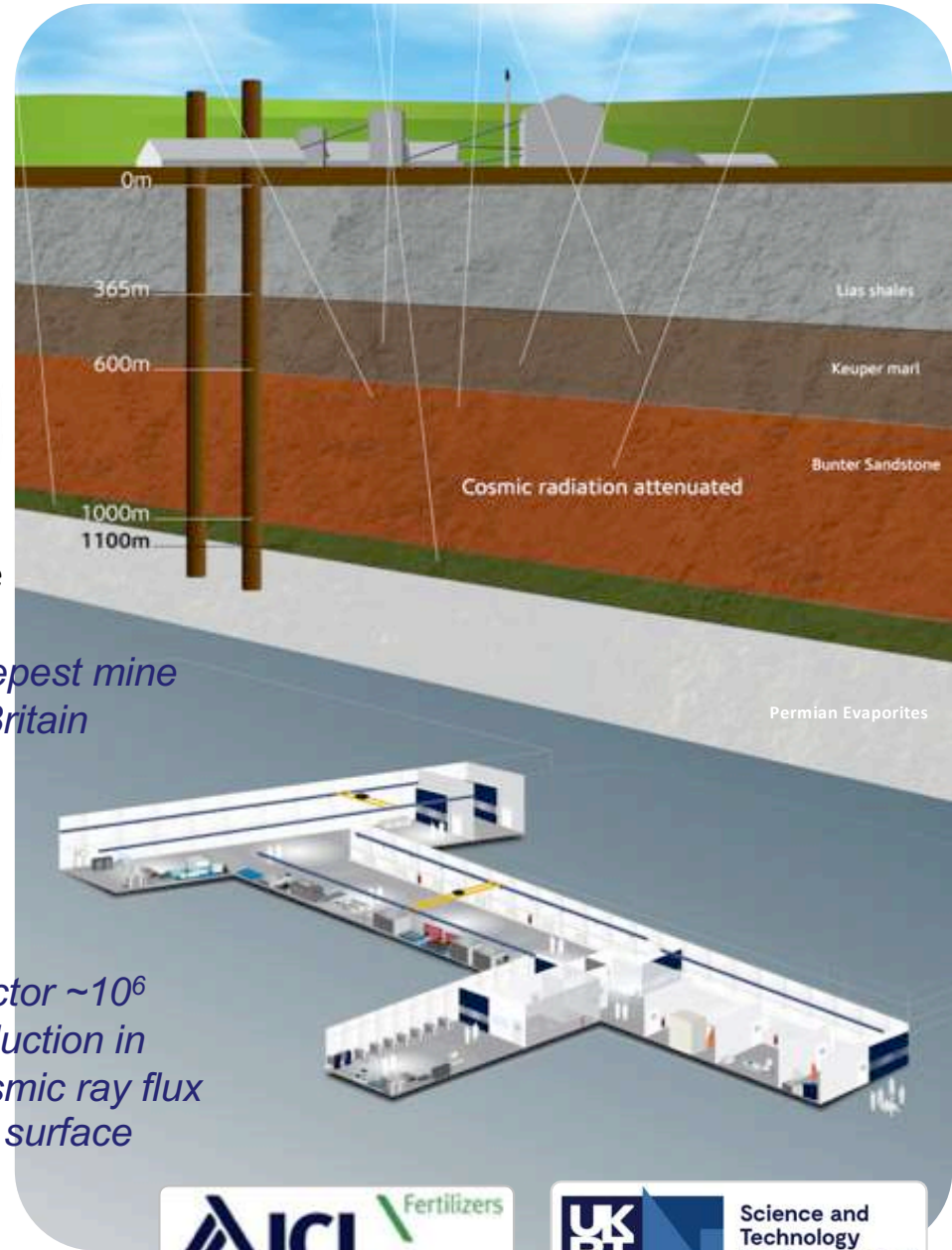
The UK's deep underground science facility operating in a working polyhalite & salt mine.

1.1km depth (2805 mwe). With low background surrounding rock-salt

Operated by the UK's Science & Technology Facilities Council (STFC) in partnership with the mine operators ICL



Polyhalite



*Deepest mine in Britain*

*Factor ~10<sup>6</sup> reduction in cosmic ray flux vs. surface*



A **QUIET** place in the Universe

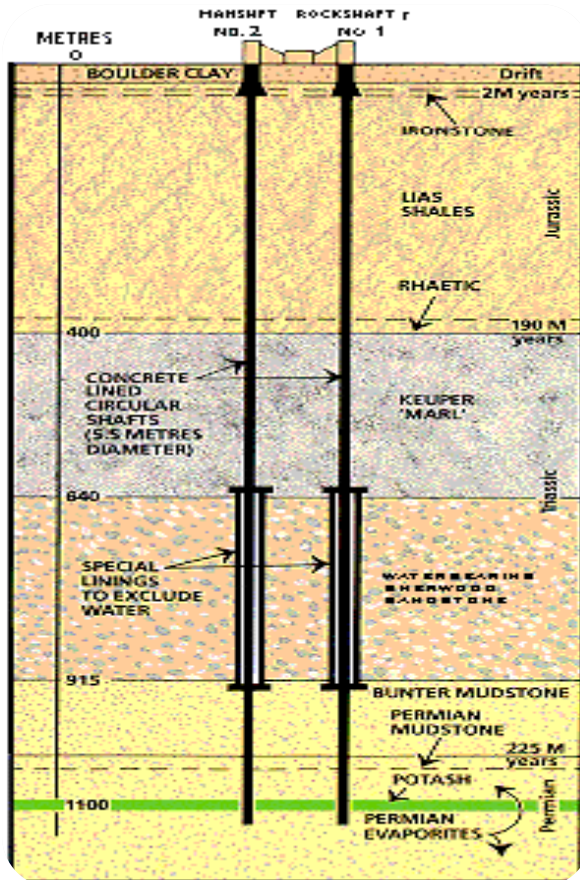






# Boulby Geology & Mining

Major local employer. Open since 1968.  
 Originally mining potash (KCl) for fertiliser.  
 Now first and only producers of polyhalite  
 Excavations are in Salt (NaCl) & Potash (KCl) Permian evaporite layers left over from the Zechstein Sea.



Boulby Geology

Potash



KCl

Rock-Salt



NaCl

Polyhalite



$K_2Ca_2Mg(SO_4)_4 \cdot 2H_2O$



Typical Boulby Salt Roadway

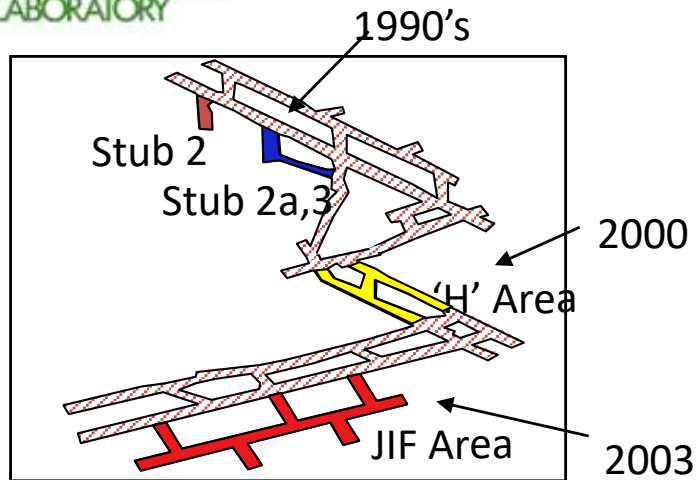


Zechstein Sea



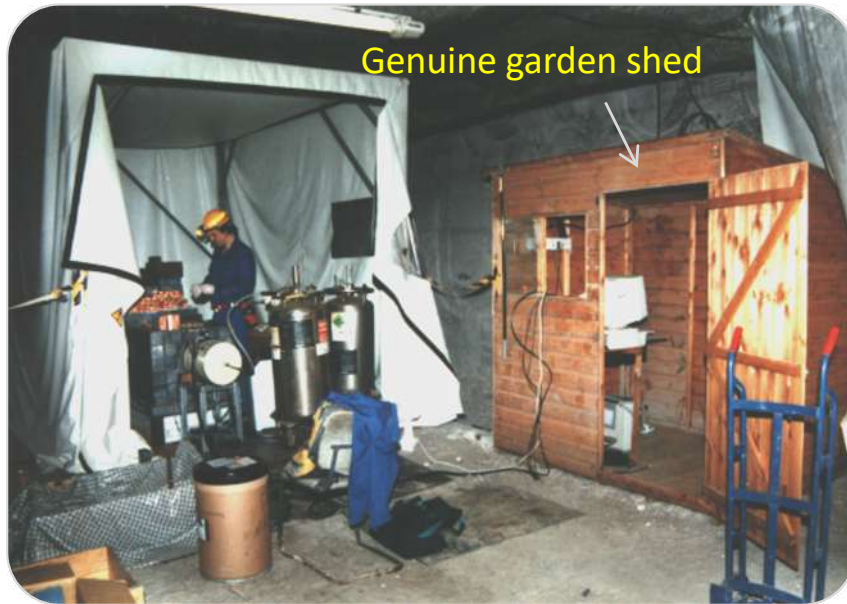


# Boulby Infrastructure Evolution



Map of the Dark Matter research areas

JIF Area  
2003-2015





Surface support and staging building

Office space, chemistry & clean prep lab, storage and staging space, IT room, conference room,

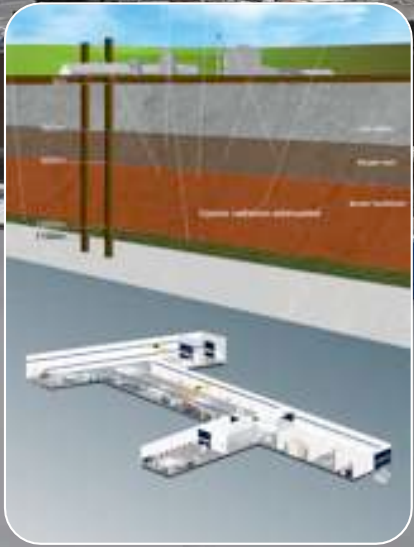


3000m³ Outside Experimentation Area



BUGS+ Material screening

**Boulby Underground Lab Facilities 2020:**  
>4000m³ class 1k & 10k clean room lab space  
100Mb Internet AC, Air filtration, 5T & 10T lifting, LN generation, fume hood & clean prep  
3000m³ Outside Expt. Area. Power & internet

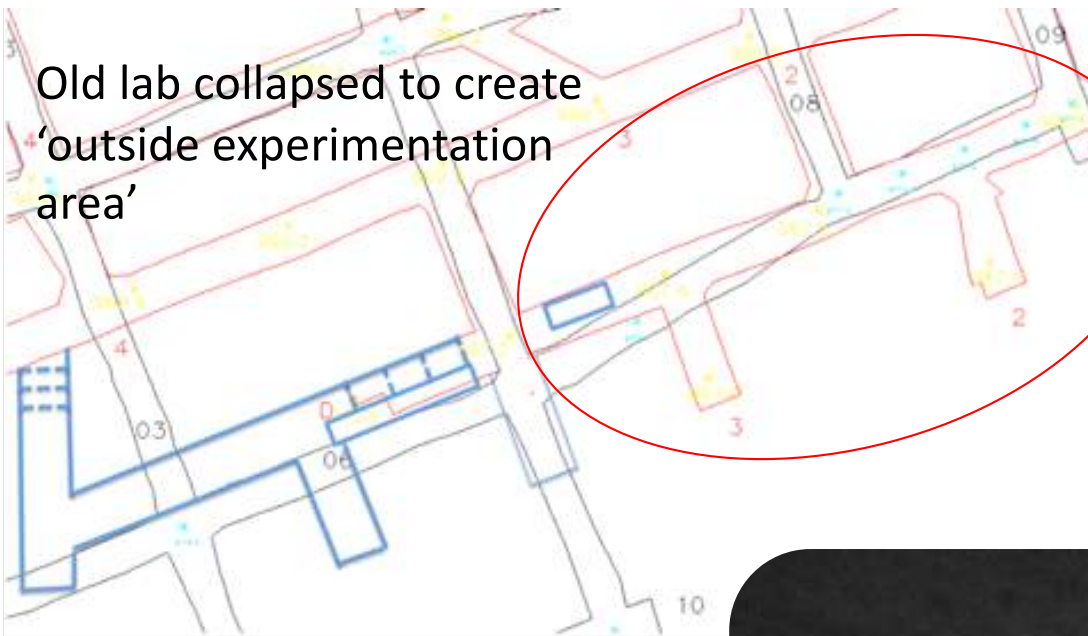






# Outside Expt Area (OEA)

Old lab collapsed to create 'outside experimentation area'



Work yet to do: Install lighting, 240/110V power, Internet. Ventilation, doors, MINAR Hut



'Outside Science': Geology / Geophysics studies. Astrobiology, MINAR, Mars Analogue space



OEA/MINAR Control Hut

Outside Experimentation / MINAR Area:



# Underground Science @ Boulby Mine



- DRIFT/CYGNUS: Directional Dark Matter
- Spherical Proportional Counters (NEWS-G) R&D
- BUGS: Ultra-low background material screening (for LUX-ZEPLIN and Super-K-Gd and more)
- AWE(Ge): Atmospheric gamma spectroscopy
- RESOURCE: Salt cavity energy storage study
- BISAL: Geo-microbiology / Astrobiology studies
- MINAR: Space Exploration Tech. Development
- Misc. Low Background & Geoscience...
- Etc... (More to come).



ULB screening of LZ PMTs



Life in Boulby salt...



Astrobiology & planetary exploration

**A busy & growing multi-disciplinary science programme:**  
Astrophysics and Low Background science, Earth and Environmental Science, Astrobiology and Planetary Exploration.





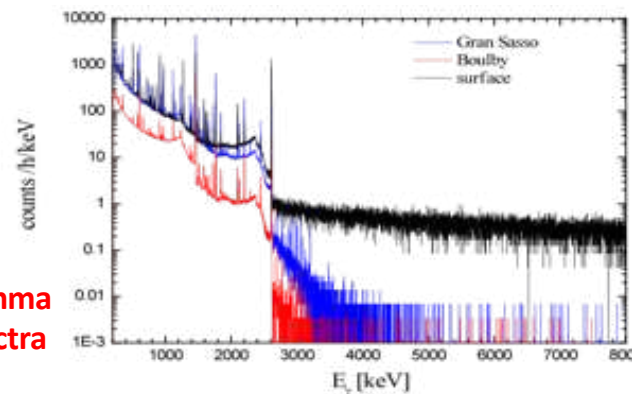
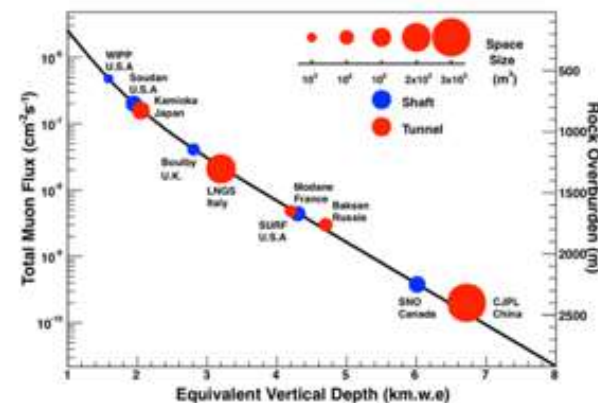
# Boulby Facility Details...

- The UK's deep underground science facility. One of 4 in EU. >10 in the world.
- Supports work of 10 collaborative projects (astrophysics to climate, geology, environment etc), >40 institutions, >170 scientists and students.
- Facility funded and operated by the Science & Technology Facilities Council (STFC).
- Operations, H&S & science programme managed by 8 (+2) onsite staff and supported by Rutherford Appleton Lab (PPD).
- Mine operators ICL-UK provide wide-ranging operational & high level support.



**How does Boulby Compare?**

- Low Radon levels (3 Bq/m<sup>3</sup>)
- Diverse science programme.
- Science and Industry partnership

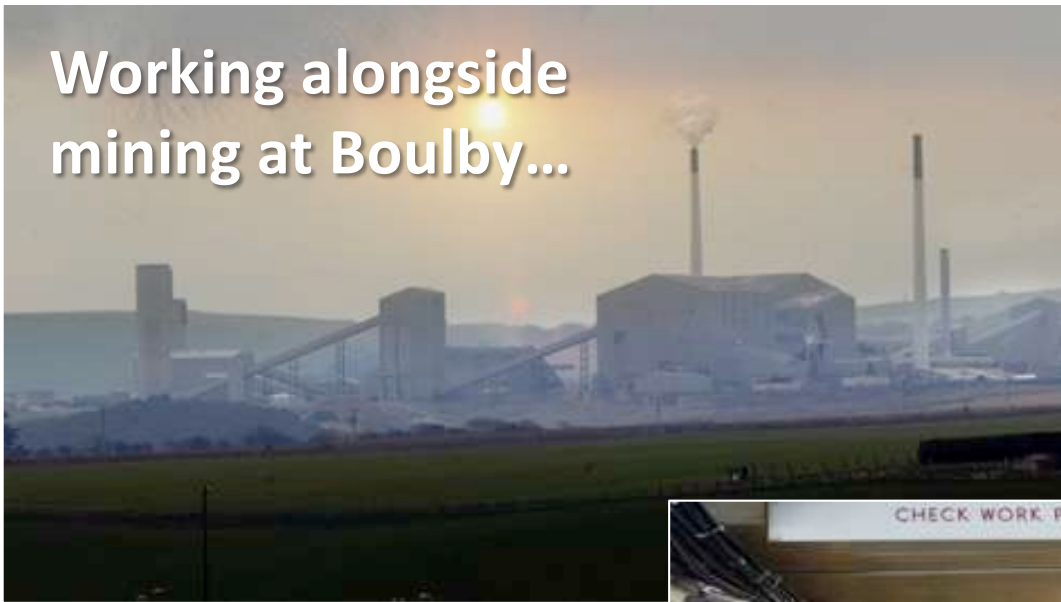


Gamma Spectra





# Working alongside mining at Boulby...



STFC-Boulby Lab responsibility:  
Facilitate / Support Science  
Health & Safety  
Operations Impact  
Outreach & Media

CPL/ICL support us:  
Keep the mine operating and safe  
Emergency H&S  
Materials transportation  
High level support



# Science Programme Status & Plans.

- Astroparticle Physics & Low Background Science
- Earth & Environmental Science
- Astrobiology & Planetary Exploration Studies
- The Future: inc. AIT-NEO (WATCHMAN)

Find out more:

@BoulbyLab

[www.stfc.ac.uk/boulby](http://www.stfc.ac.uk/boulby)



Science and  
Technology  
Facilities Council





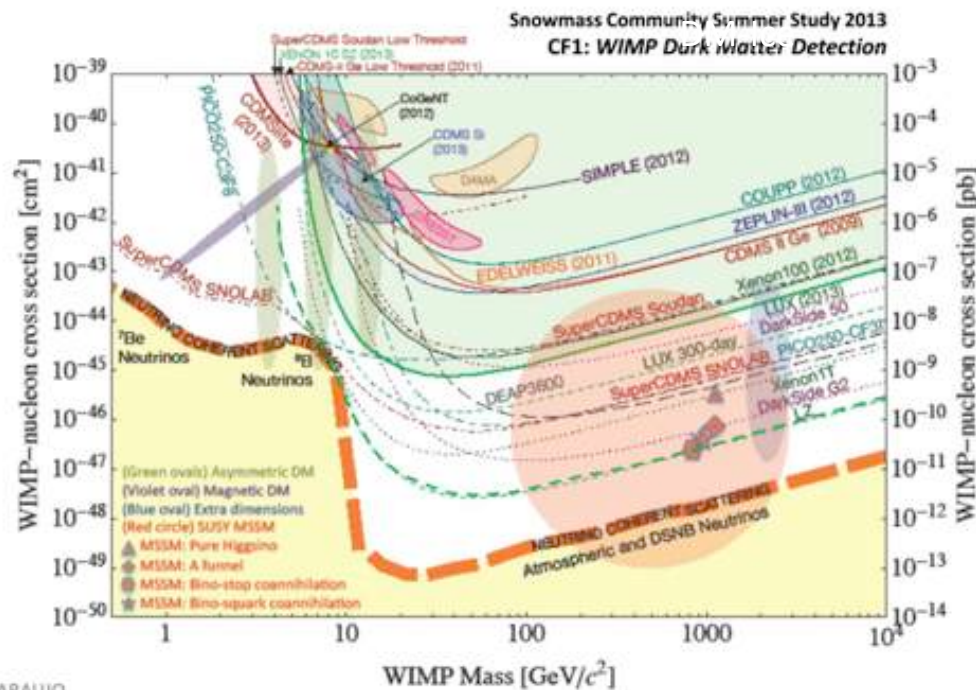
# Boulby Dark Matter Studies...

Boulby has hosted **Dark Matter search** studies for two decades. Including the **NAIAD, DRIFT & ZEPLIN** experiment programmes.

Boulby now hosts DRIFT Directional DM programme, doing R&D for CYGNUS & providing ULB material screening for other studies, inc **LUX-ZEPLIN (LZ)**



ZEPLIN-III @ Boulby



**ZEPLIN:** The world's first 2-phase Xenon dark matter detector (Finished 2011)



Current limits & future projections



# Dark Matter Studies @ Boulby.

## DRIFT/CYGNUS: R&D for DIRECTIONAL Dark Matter detection.

**STATUS:** Programme operating at Boulby since 2001. Currently limit-setting and conducting system performance & scale-up R&D. Plans for further R&D & expansion / collaboration (**CYGNUS**).



Status: DRIFTII-d limit setting and R&D exploring issues and technologies for scale up - CYGNUS

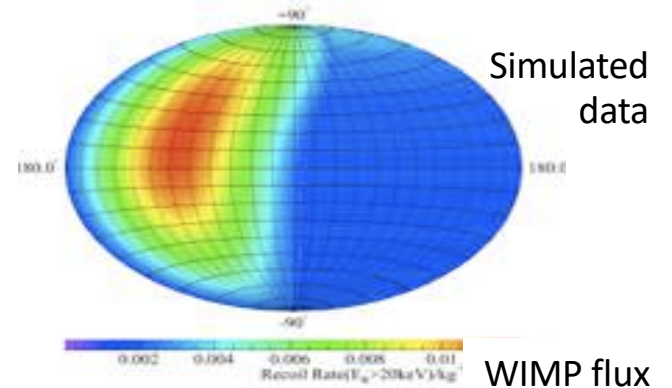


DRIFT-II-d @ Boulby

Dual (1m<sup>3</sup> total) Negative Ion DRIFT TPC

Directional detection

Occidental College,  
New Mexico,  
Colorado State,  
Hawaii, Wellesley,  
Sheffield,  
Edinburgh, Boulby

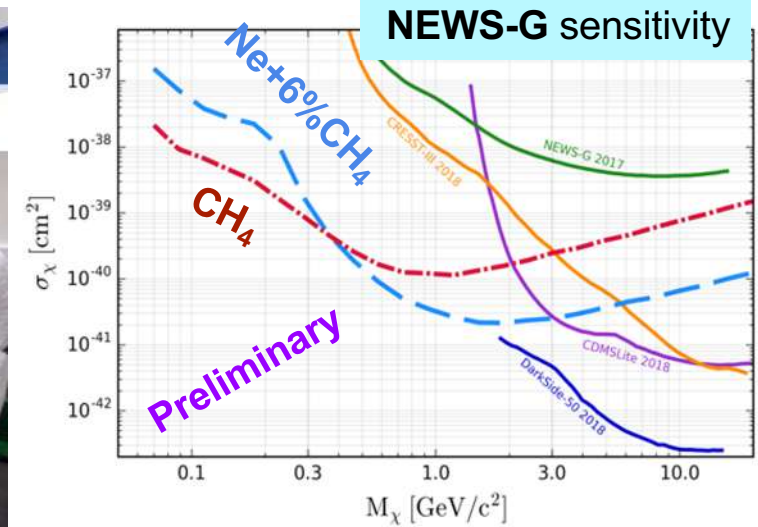


Directional DM detection – providing the most powerful direct detection signature



# Spherical Proportional Counters in Boulby

k. Nikolopoulos  
 I. Katsioulas  
 P. Knights  
 T. Need  
 R. Ward  
 University of Birmingham

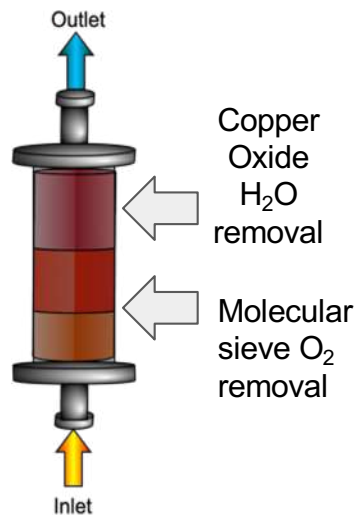


AI-S30 R&D Detector



Simulation study of neutron interactions in the S30 at Boulby

## Purpose-made gas filter

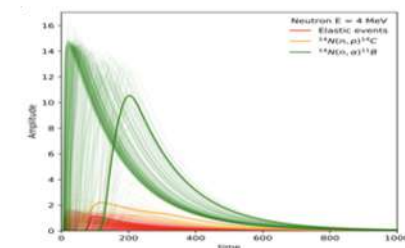
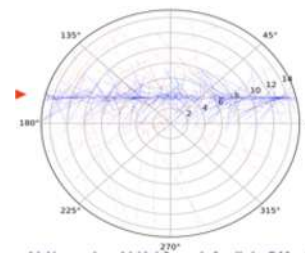


## 11-anode sensor



## Direction of R&D at Boulby

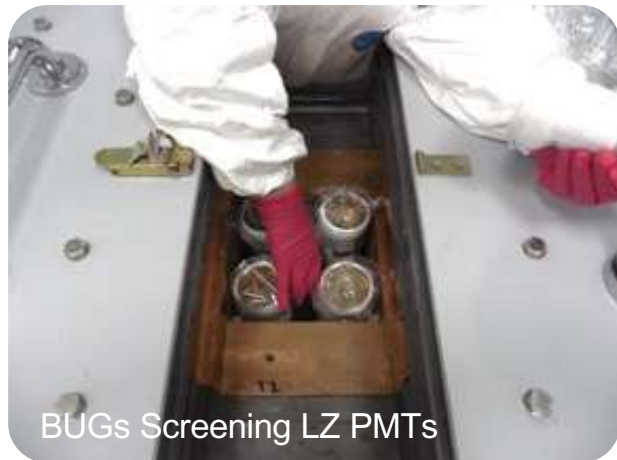
- Instrumentation development for NEWS-G at SNOLAB
  - Multi-anode sensor
  - Gas filtration
  - Rate effect studies
- Neutron spectroscopy N<sub>2</sub>-based
  - Neutron BG measurements for rare event searches
  - Industrial applications





# BUGS (+) Material Screening

Growing suite ('BUGS': Boulby Underground Germanium Suite) of Ultra-Low-Background (ULB) germanium detector systems to support Dark Matter & misc 'rare-event' studies...

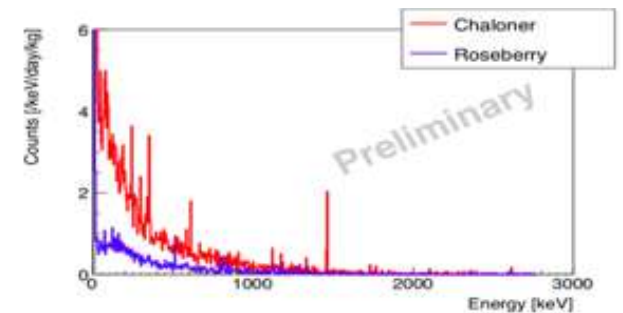
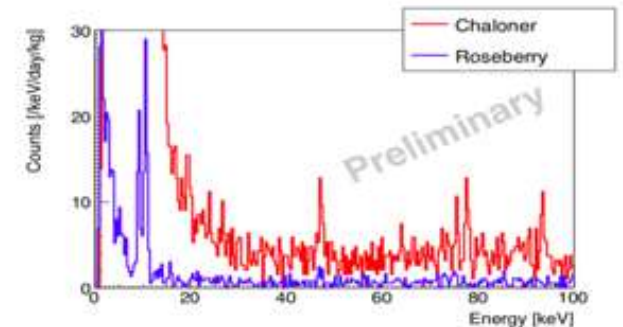


BUGs Screening LZ PMTs

Sensitivity down to **<50ppt** U/Th per sample, & improving

### Our Current Detectors;

- Ortec 1.8 kg (72%) p-type (ULB)
- Canberra 2.0 kg (112%) & 3.2 kg (171%) p-types (S-ULB)
- 2x Canberra BEGe detectors (5030 ULB, 6530 S-ULB)
- Canberra SAGe Well-type (S-ULB)

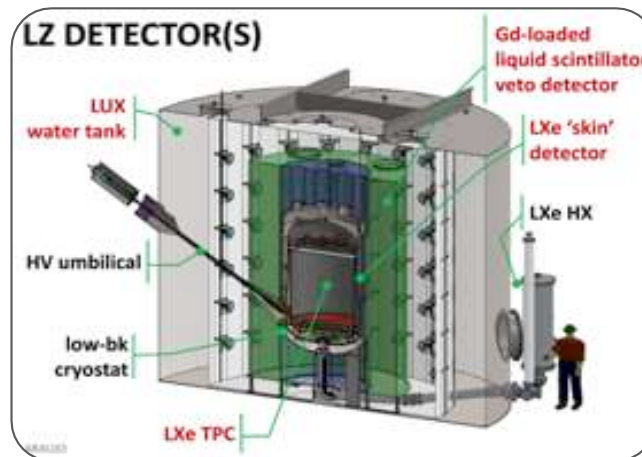


ULB counting studies supporting UK DM (**LZ**) and neutrino communities.

Now **EXPANDING** ULB counting capabilities. Inc. **XIA surface alpha counting**

In collaboration with UCL, DMUK, Sheffield & others.

Boulby undertaking major role in material selection for **LUX-ZEPLIN** and **Super-K-Gd**

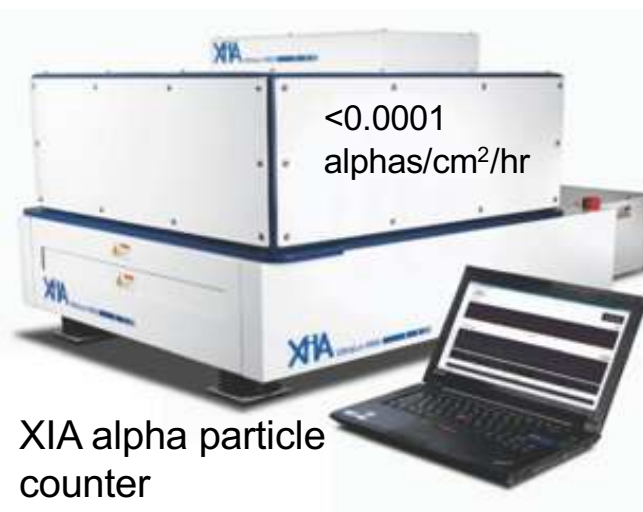


LUX-ZEPLIN



Now material Screening for Gd upgrade to Super-K / T2K





XIA alpha particle counter



**BUGS capabilities expanding** to support current and future ULB experiments. Working towards PPT sensitivity for G3 DM and Neutrino Expts.



LZ and SK-Gd sample testing underway. XIA surface alpha screening system commissioned.





# Boulby Multi-Disciplinary Studies



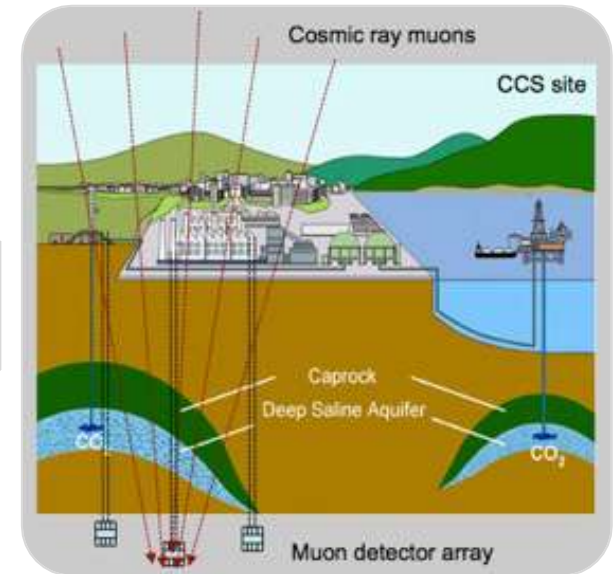
**ERSaB:** Gamma spectroscopy & low background counting environmental radioactivity studies

*Boulby, Scottish Universities Env. Research Ctr (SUERC), Atomic Weapons Estab. (AWE)*

**DEEP-Carbon:** Muon Tomography for deep geological mapping applications including CCS



*Boulby, Durham, Sheffield, Bath, Premier Oil, CPL.*



**Low Background Science, Earth & Environment Science, Astrobiology & Planetary Exploration...**



**MINAR:** Space Technology Development

*Boulby, Edinburgh, NASA, York, ICL etc.*

**Plus** Misc. Geology & Geoscience (& more to come)...

Life in Boulby Salt...



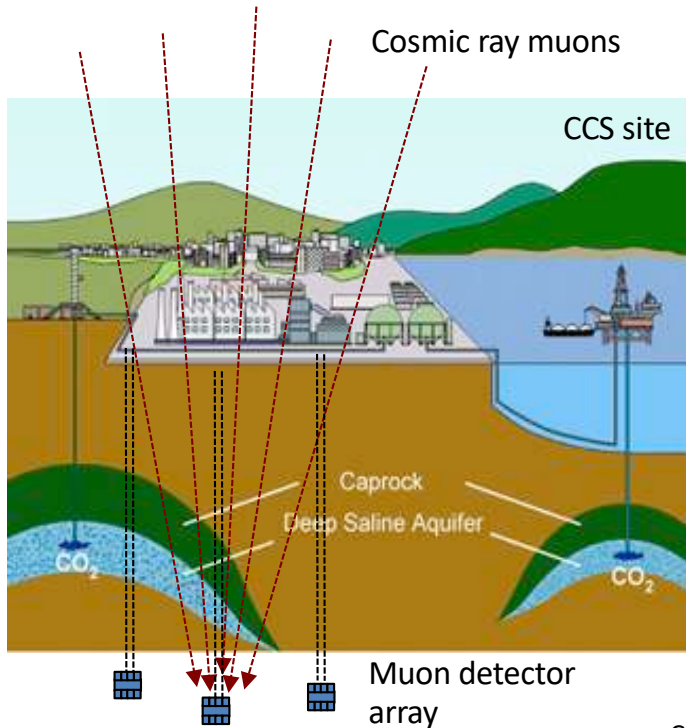
**BISAL:** Astrobiology / Geo-microbiology. Studies of life in salt, life on Earth & beyond



# Muon Tomography / Geo-survey

Development of a **Muon Tomography** techniques for deep 3D geological surveying - inc Carbon Capture @ Storage (CCS)

STFC-Boulby,  
Durham, Sheffield,  
Bath, NASA



**Potential for cheap, reliable, practical, real-time long-term monitoring of deep structures. Potential applications:**

- Deep geological repository monitoring.
- **Monitoring in Carbon Capture & Storage (CCS)**



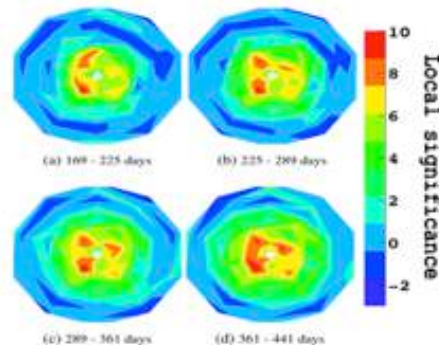
Muon-tides detector development



Bore hole detector installation

**Status:** Project phase 1 complete. Spin-out company for Muon Tomog applications created (Sheffield, Durham).  
**Next:** UK-Japan proposed study of Muon Tomography for Tsunami early warning (2020)

CCS site simulation



**Deep-Carbon Project: £1.4M funding from UK Dept of Energy & Climate change (DECC) & Premier Oil:**

- Bore-hole detector development & testing
- Muon-Tides technology demonstrator
- Simulations of technique performance in CCS

# Renewable Energy StOrage in UndergrounD CavErns (RESOURCE)

STFC Boulby Mine, BGS and the University of Cambridge

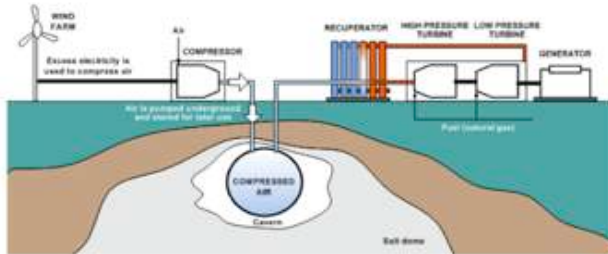
NERC Grant Proposal 2020

British Geological Survey

Boulby Underground Lab

U.Cambridge & U.Manchester

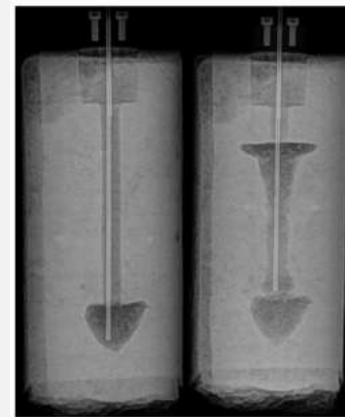
## Low Carbon Technologies



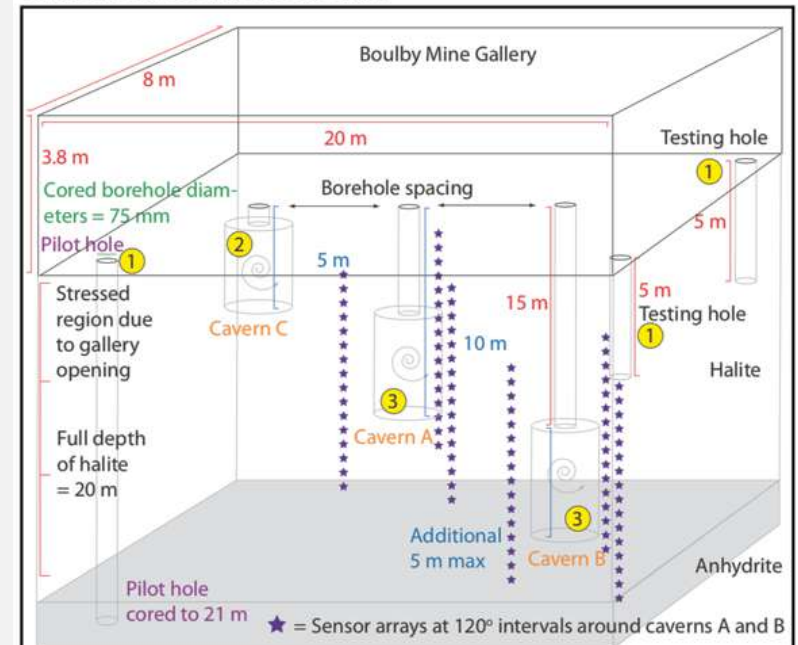
- Engineering solutions have been devised to store energy whilst production is high and feed it into the grid when production is low (e.g. CAES, hydrogen storage)
- Helps to regulate the production of renewable energy



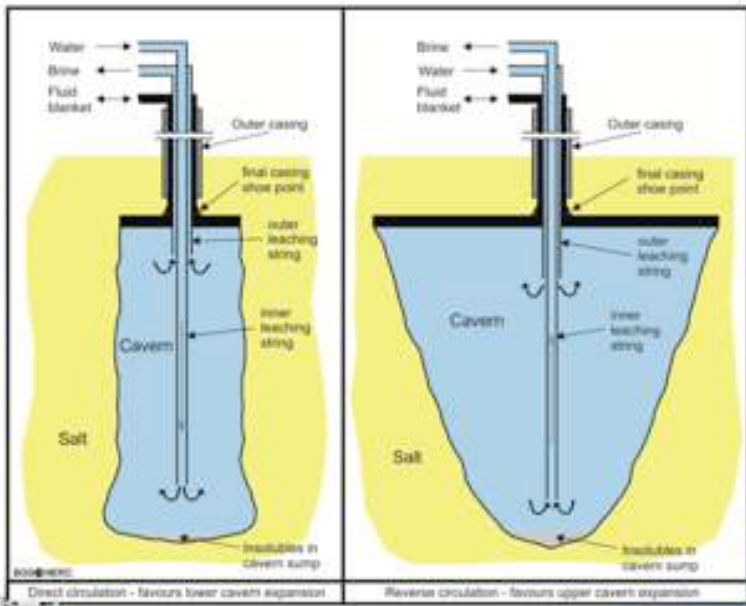
Plan for In-situ Testing at Boulby Mine



Above: Scoping lab-based dissolution tests of salt from Boulby Mine, giving insight into the solution mining process.



- 1 Drill and core pilot hole. Study fabric, chemistry and mechanical properties of core. Also drill and core testing holes. Study core and run dissolution tests.
- 2 Drill and core shallow hole to 5m. Case hole, cement casing and form solution-mined cavern.
- 3 Drill and core intermediate hole to 8m and deep hole to 15m. Study and compare core. Case holes and form solution-mined caverns. Seal holes and pressure cycle.



Mid-scale rock engineering tests of gas containment in salt cavities for energy storage





# Astrobiology & Planetary Exploration



Sampling life in Boulby Brine



Subsurface Astrobiology Laboratory



A base for studies of life in Boulby rock – studies of limits of life on earth and on other planets



**ALSO: An important 'Mars Analogue site'** – with geology & conditions to allow explorations & astrobiology technique & instrumentation development

Led by Edinburgh, UKCA



Mining & extraplanetary instrumentation development

Boulby and Instrumentation for Earth and Space Exploration





# MINAR V. 9<sup>th</sup> to 20<sup>th</sup> October 2017

## MINAR 5

### Overall objectives:

- To test instruments and methods for the subsurface exploration of the Moon and Mars.
- To develop new educational material.

MINAR – Pac Man, HABIT & many more

### Main accomplishments:

- Testing of life detection equipment and planetary exploration instruments from: NASA JPL, NASA Ames, University of Leicester, Space-X Institution, University of Newcastle, University of Edinburgh, Luleå University of Technology.
- Development of education materials on planetary exploration at primary and secondary school level.
- Training of ESA Astronaut, Matthias Maurer.
- Life links from Boulby with up to 38,000 views.
- Live link with Kalam Centre, India



MINAR - SPLIT



MINAR - Pancam



Boulby Underground Laboratory shared UK Centre for Astrobiology's live video. Published by Emma Meehan [?] · 17 October ·

14,955 Views

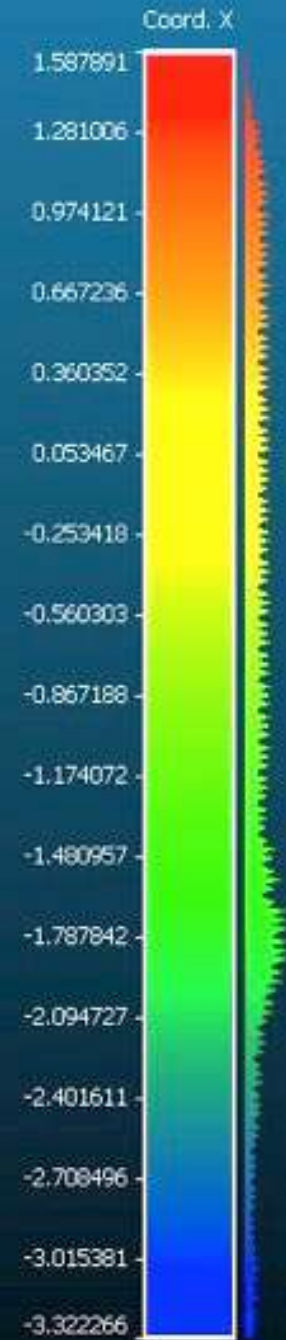
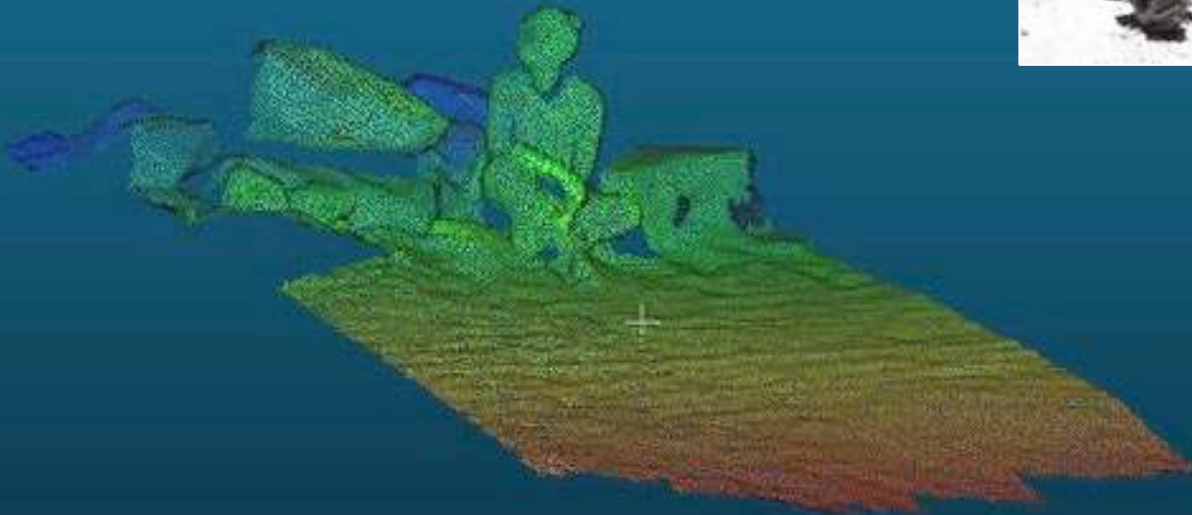
UK Centre for Astrobiology was live.





# MINAR VI. 10<sup>th</sup>-20<sup>th</sup> September 2018

Lulea University  
KORE rover 3D area mapping



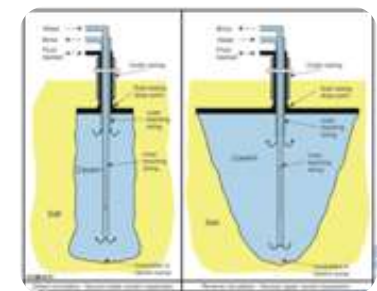
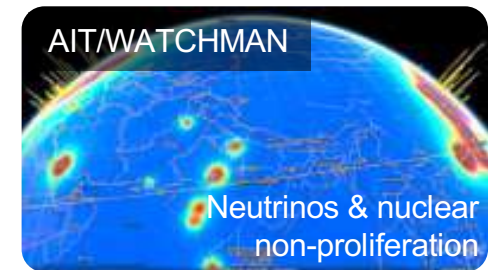
Edinburgh University  
MUFFHINS water activity  
monitoring payload



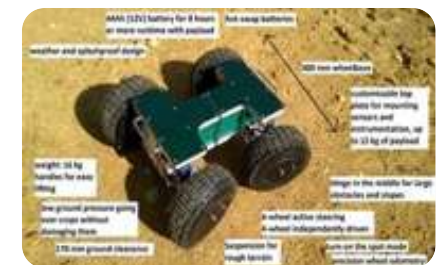
# Future Science...

Continue current studies, PLUS...

- **BUGS:** Expanding ULB material screening and environmental gamma spectroscopy.
- Expanding **Astrobiology**, **MINAR** & wider **Robotics**
- **RESOURCE** study (NERC): Salt cavity test facility for studies of compressed gas energy storage?
- Misc Others... Inc. supporting **NEWS-G**, **DAMIC**, **AION**...
- **'BOULBY-FS'**: STFC funded feasibility study for Boulby hosting next generation **Dark Matter**, **Neutrino** and **Neutrino-less Double beta decay** studies...
- **AIT-NEO (WATCHMAN)**: 6kT Water-based neutrino detector for nuclear non-proliferation purposes & more...



RESOURCE: Salt cavity energy storage



Robotics

Continue / increase hosting **core STFC science projects** & wider **multidisciplinary studies** addressing RCUK (UKRI) priority themes



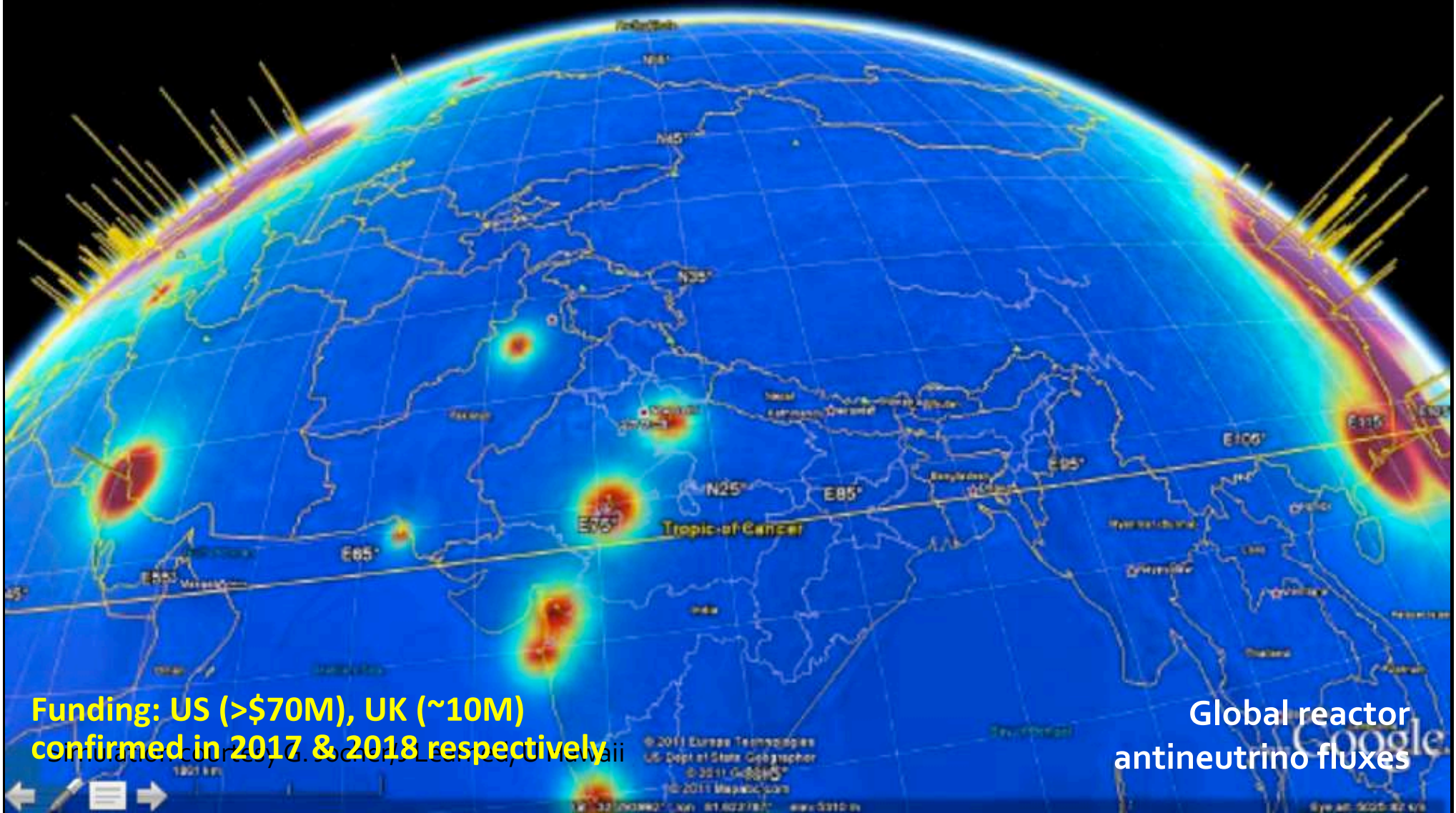


# AIT-NEO (WATCHMAN)



Advanced Instrumentation Testbed  
WATER Cherenkov Monitoring of Anti-Neutrinos

US-UK project to demonstrate & develop particle physics detector technology for nuclear security & fundamental science



Funding: US (>\$70M), UK (~10M)  
confirmed in 2017 & 2018 respectively

Global reactor  
antineutrino fluxes

# AIT-NEO (WATCHMAN)

World  
antineutrino  
flux levels



## A WATER Cherenkov Monitor of ANtineutrinos

Design,  
excavation,  
installation &  
operation 2019  
to 2026(+)

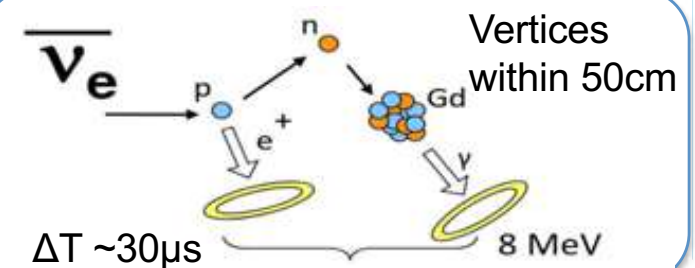
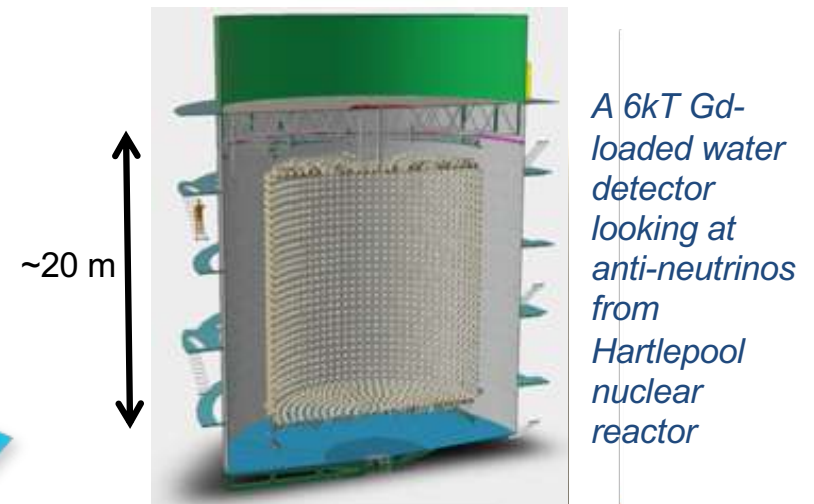
### HARTLEPOOL REACTORS



- 2 cores
- 1570 MWt per core
- 25 km standoff



### WATCHMAN detector at the Boulby mine



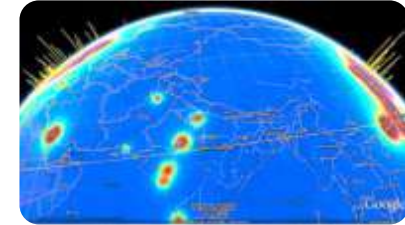
Funding: US (>\$70M), UK (~£10M)  
confirmed in 2017 & 2018 respectively

**NEW** 6kT prototype detector: R&D for anti-neutrino monitoring of nuclear reactors for global nuclear non-proliferation purposes & more





# AIT-NEO (WATCHMAN) Technology & Science



## 1) Reactor Monitoring for Nuclear Non-proliferation

A prototype detector for proof-of-principle and R&D for remote monitoring of distant nuclear reactors



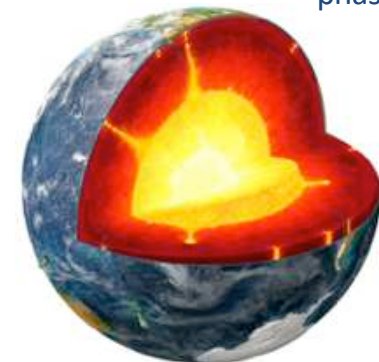
## 2) Technology Development & Fundamental Science

A world-class research detector for technology development and fundamental neutrino science R&D

Supernovae Neutrinos: Studies of exploding stars (immediate capability)



Geo-neutrinos: Studies of the Earth's centre (possible with later AIT phases)

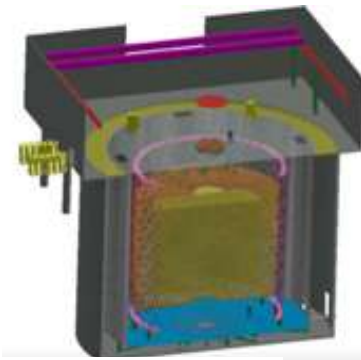


**A world-class pure & applied  
neutrino science project**

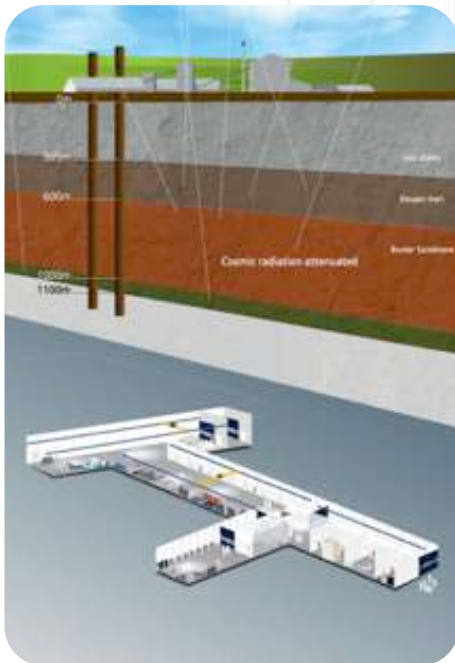
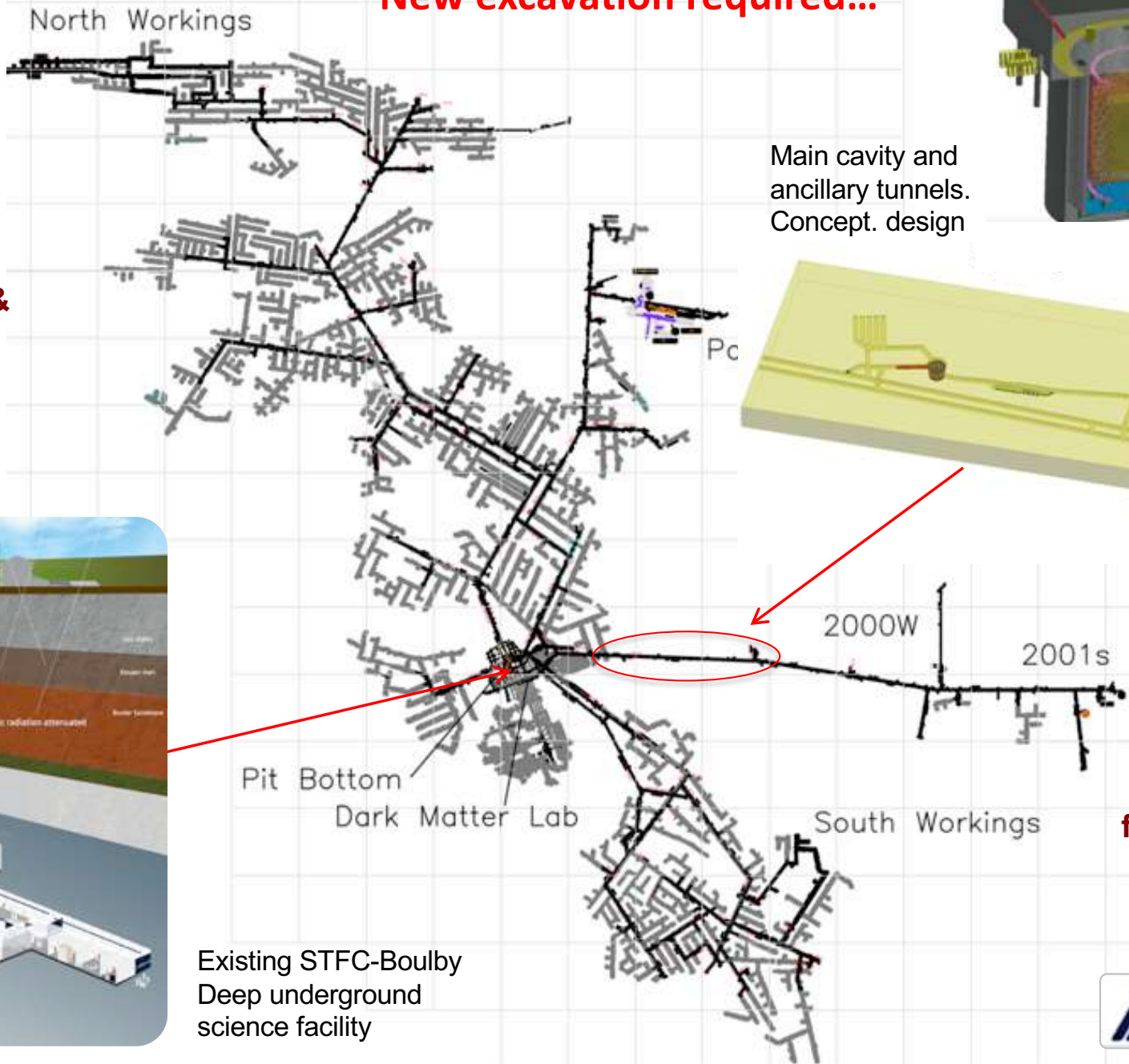
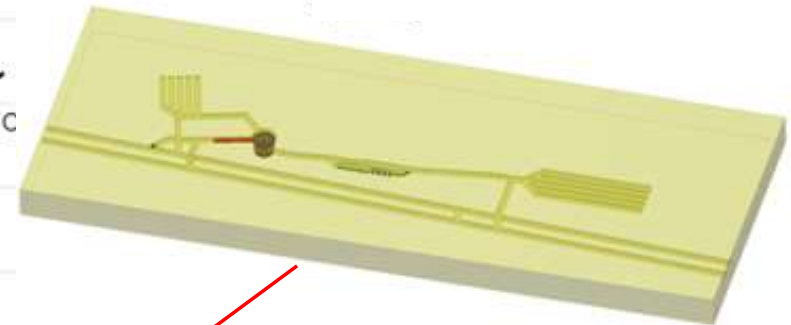


# New excavation required...

Design, excavation, installation & operation 2019 to 2026(+)



Main cavity and ancillary tunnels. Concept. design



Existing STFC-Boulby Deep underground science facility

100+ Collaborators from 20+ US/UK research institutes





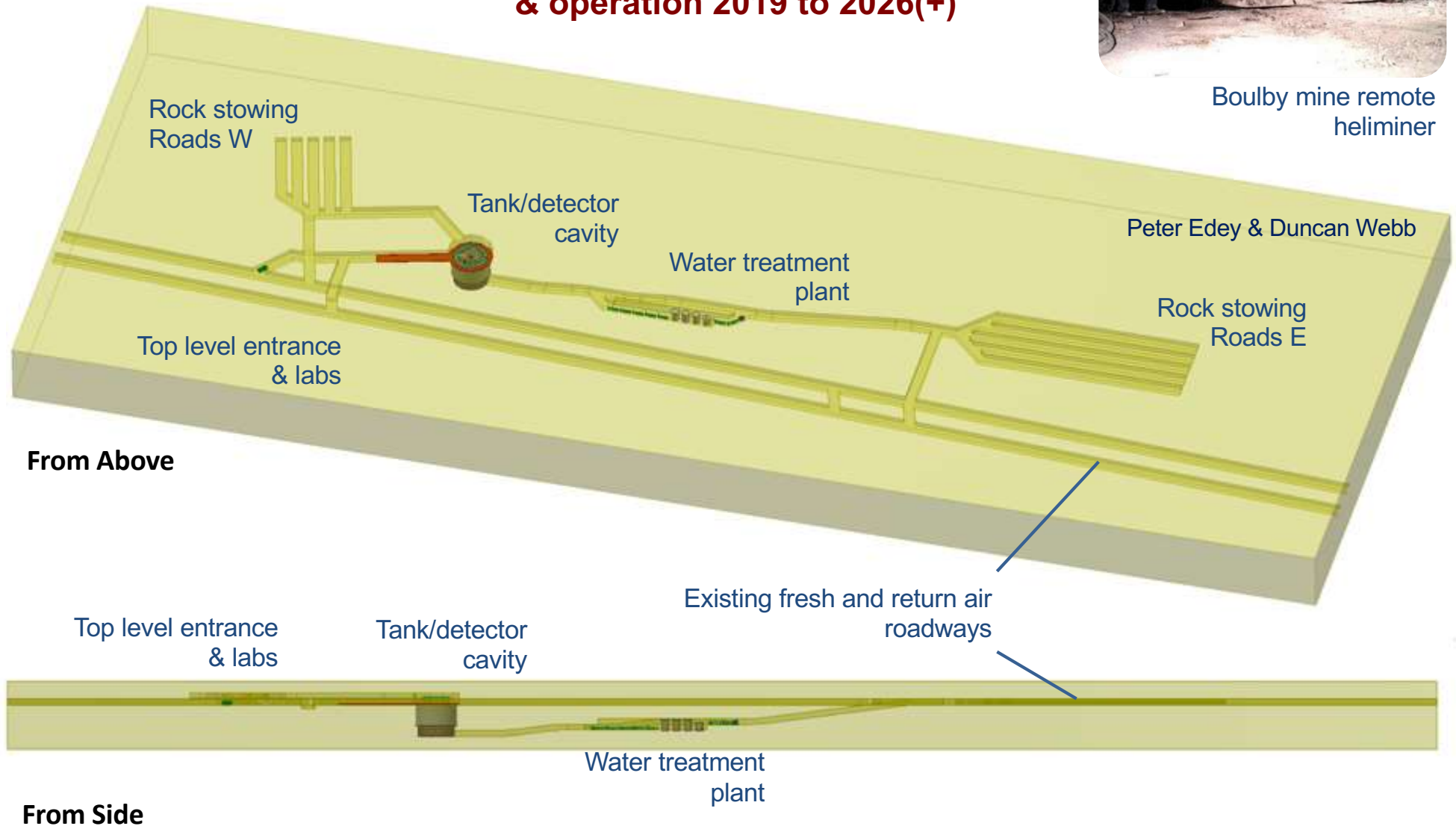
**DRAFT Excavation Design (Mar 20)**  
**Pete Edey & Duncan Webb (ICL)**

Spade (Heliminer etc)  
planned to first hit  
rock 2022



Boulby mine remote  
heliminer

**Design, excavation, installation  
& operation 2019 to 2026(+)**





# Thank You....



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STFC Boulby Underground Laboratory

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