Sean Paling
STFC Boulby Underground Science Facility

Astroparticle physics & ultra low background studies

The search for Dark Matter & beyond

Earth and environmental science, Astrobiology and planetary exploration

Boulby Underground Laboratory:

The UK's deep underground science facility. Status, plans and opportunities for growth

Underground lab @ Boulby

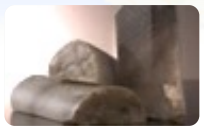
Science and Technology Facilities Council
Boulby Underground Laboratory

Boulby Underground Laboratory

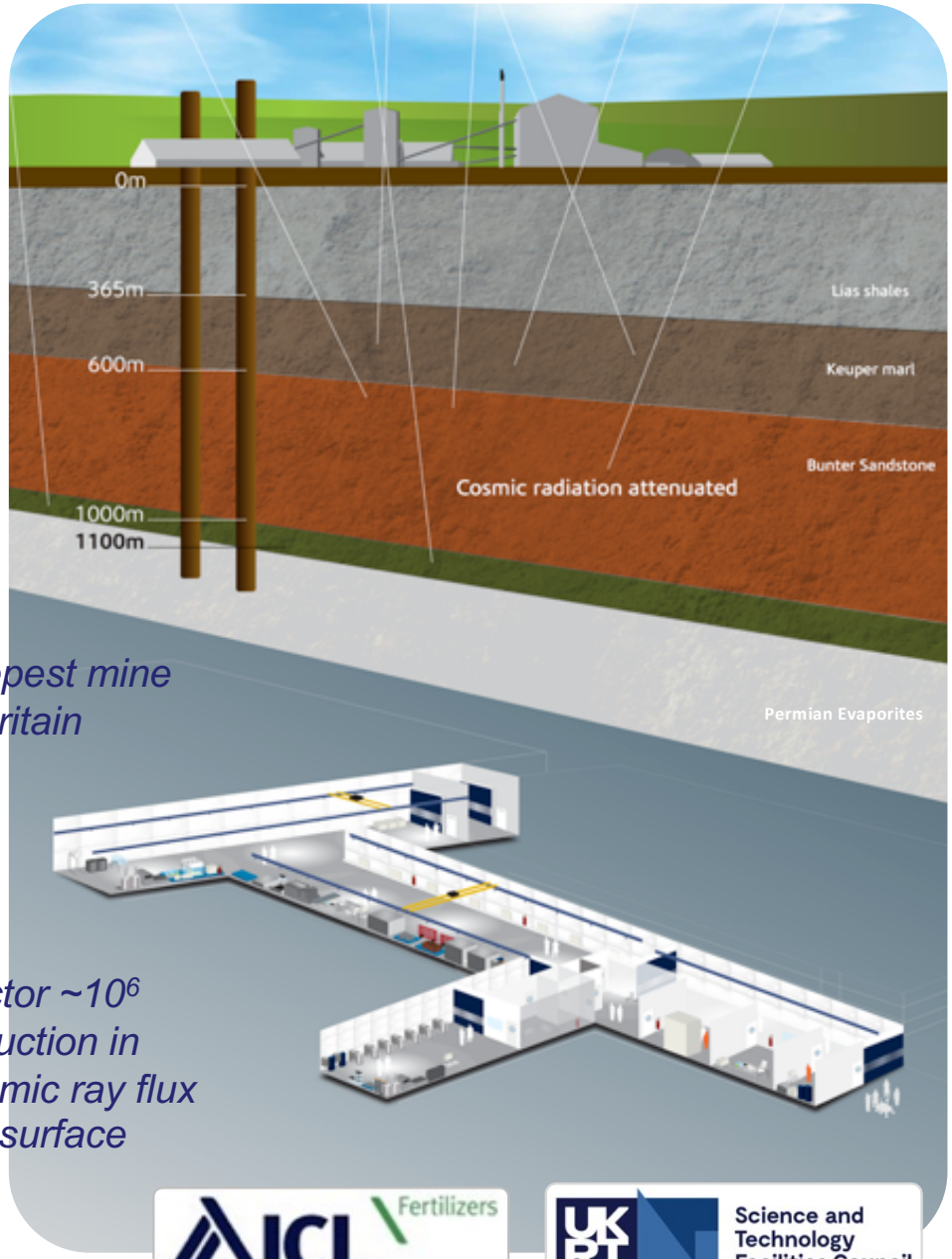
The UK's deep underground science facility operating in a working polyhalite & salt mine.

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 ~10^6 reduction in cosmic ray flux vs. surface

A QUIET place in the Universe

ICL Fertilizers

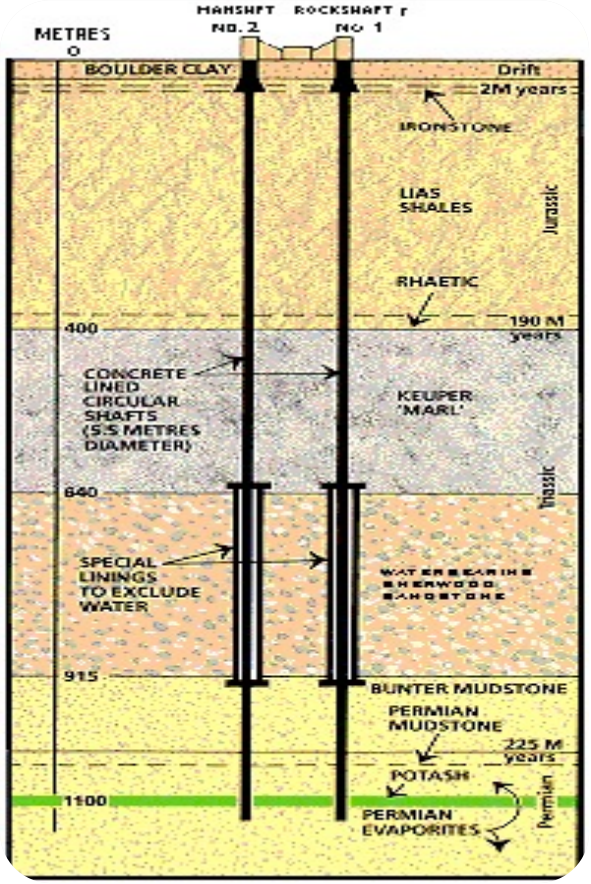
Science and Technology Facilities Council

Science and Technology Facilities Council
Boulby Underground Laboratory

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

Mine Shafts

New Lab (2017)

ICL Fertilizers

Science and Technology Facilities Council

Surface support and staging building

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

3000m^3 Outside Experimentation Area

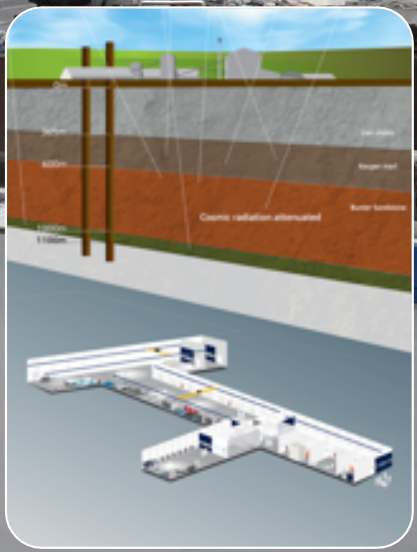
BUGS+ Material screening

Boulby Underground Lab Facilities 2020:

>4000m^3 class 1k & 10k clean room lab space

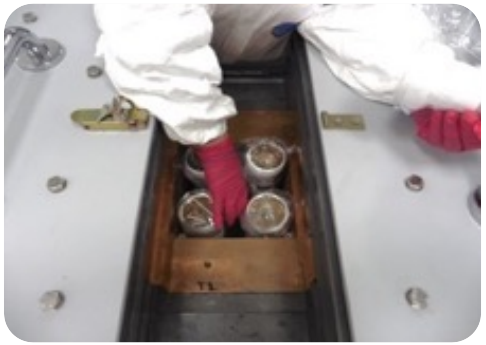
100Mb Internet AC, Air filtration, 5T & 10T lifting, LN generation, fume hood & clean prep

3000m^3 Outside Expt. Area. Power & internet



Underground Science @ Boulby Mine

- DRIFT/CYGNUS: Directional Dark Matter
- Spherical Proportional Counters (NEWS-G) R&D
- BUGS: Ultra-low background material screening
- AWE(Ge): Atmospheric gamma spectroscopy
- RESOURCE: Salt cavity energy storage study
- Deep Carbon: Muon tomography for CCS+
- AIT-NEO: Neutrino detection for nuclear security
- BISAL: Geo-microbiology / Astrobiology studies
- MINAR: Space Exploration Tech. Development
- Etc... (More to come).



ULB screening of LZ PMTs

Astrobiology & planetary exploration

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

Science and Technology Facilities Council
Boulby Underground Laboratory

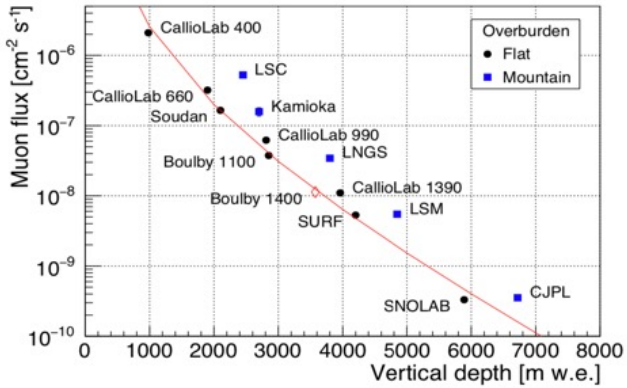
Science and Technology Facilities Council
Boulby Underground Laboratory

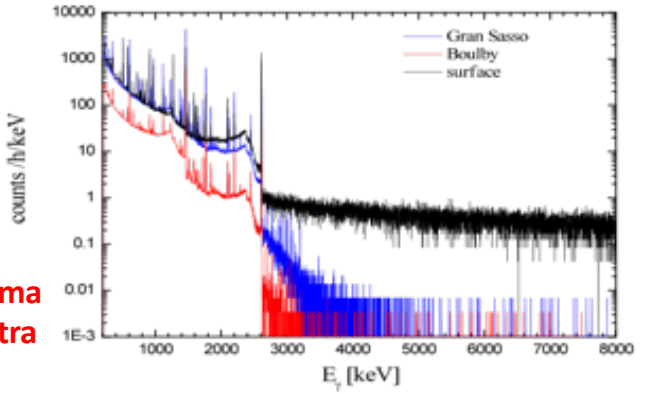
Boulby Facility Details…

BOULBY UNDERGROUND LABORATORY

- The UK's deep underground science facility. One of 4 in Europe, <15 in the world.
- Supports work of >10 collaborative projects (astrophysics to climate, geology, environment etc), >40 institutions, >170 scientists & students.
- Facility funded and operated by the Science & Technology Facilities Council (STFC).
- Operations, H&S & science programme managed by 10 (+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^3)
- Diverse science programme.
- Science and Industry partnership



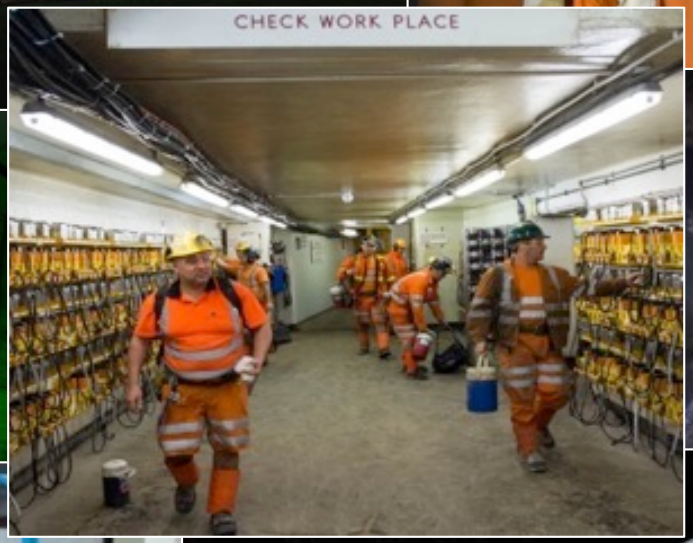


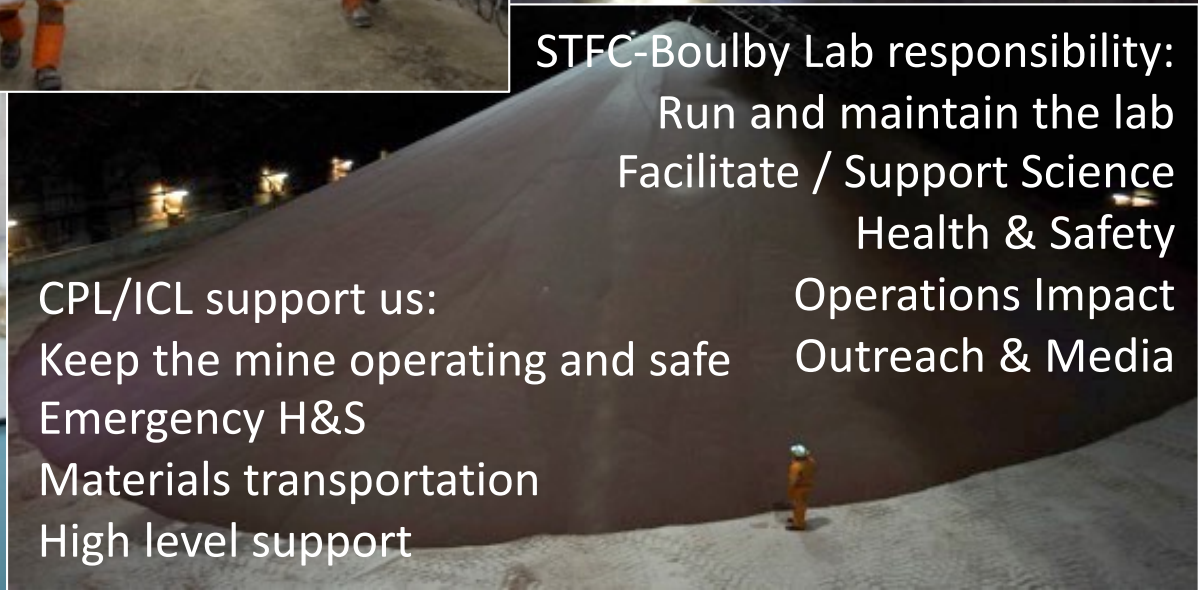
Gamma Spectra

Science and Technology Facilities Council

ICL Fertilizers

Working alongside mining at Boulby…





STFC-Boulby Lab responsibility:
Run and maintain the lab
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 and Technology Facilities Council
Boulby Underground Laboratory

Science Programme Status & Plans.

- Astroparticle & Low Background Science
- Earth & Environmental Science
- Astrobiology & Planetary Exploration Studies
- Outreach & Education

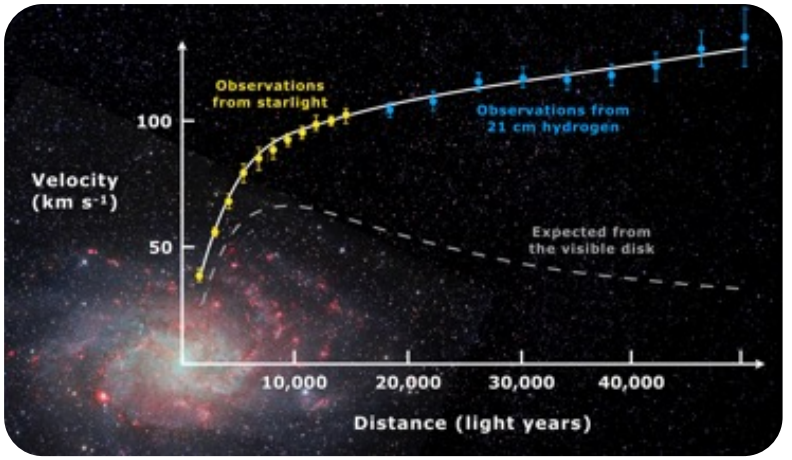
Find out more:
@BoulbyLab
www.stfc.ac.uk/boulby

Science and Technology Facilities Council
Boulby Underground Laboratory

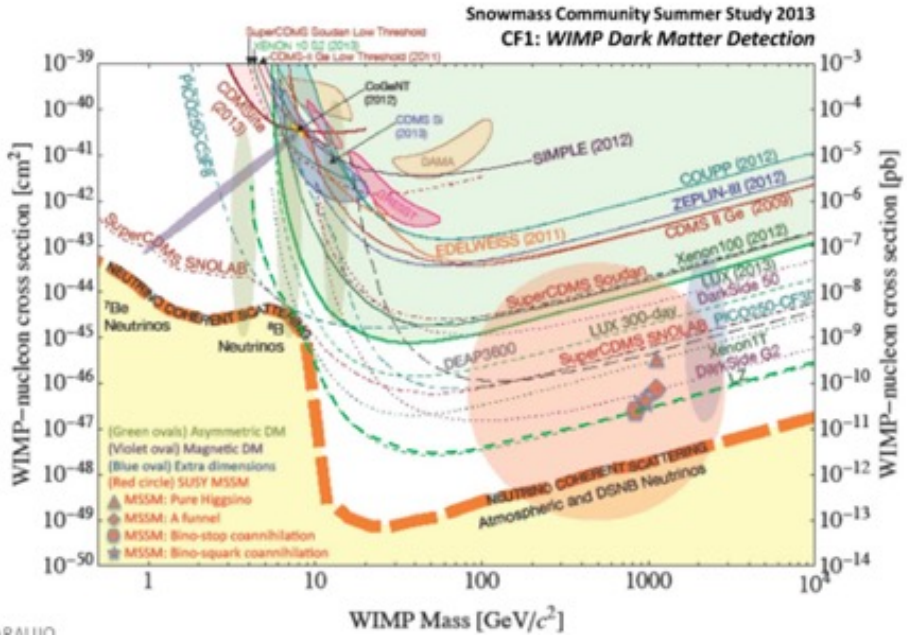
Boulby Dark Matter Studies…

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

Boulby now hosts CYGNUS directional DM programme, NEWS-G/Dark-Sphere R&D and providing ULB material screening for other studies, inc **LUX-ZEPLIN (LZ)**



Galactic rotation curves



World DM particle search limits and future projections

ZEPLIN-II & III: *The world's first 2-phase Xenon dark matter detectors (Finished 2011)*

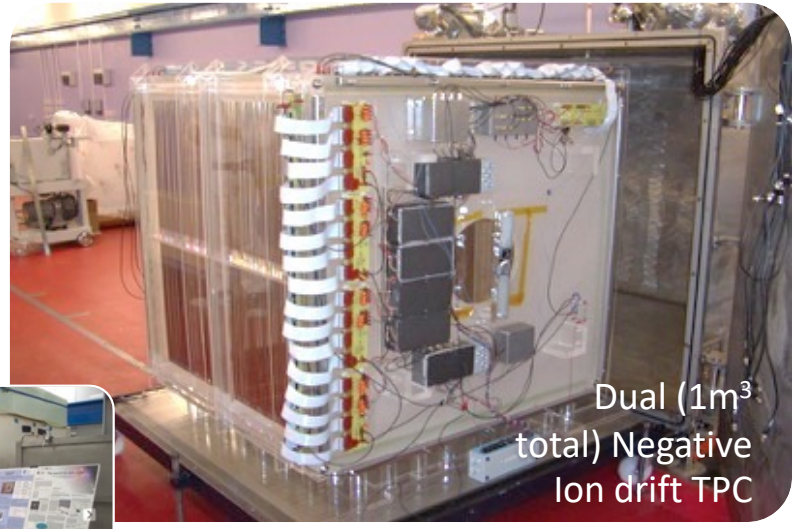
ZEPLIN-III @ Boulby

Science and Technology Facilities Council
Boulby Underground Laboratory

Boulby Dark Matter Studies…

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**).

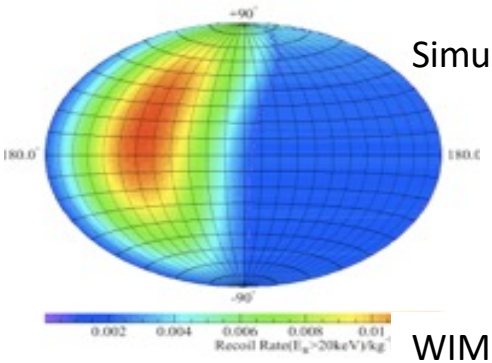


DRIFT-IId @ Boulby

NEWS-G @Boulby Uni. B'ham & NEWS-G collab

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

Directional detection



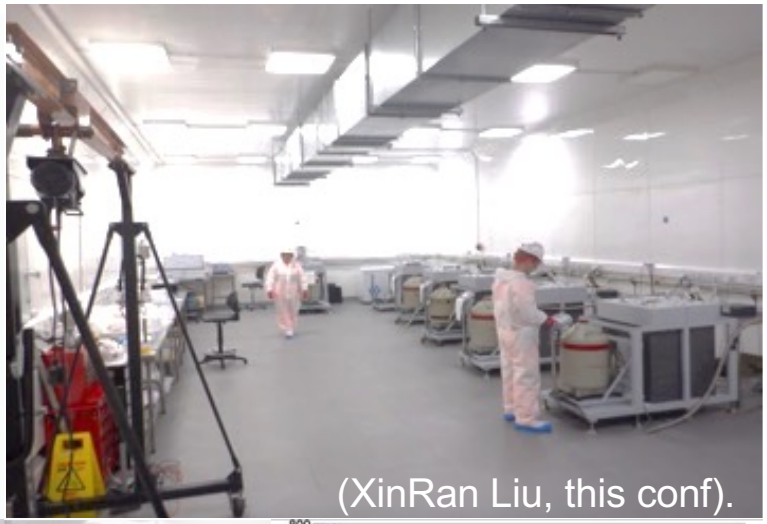
Simulated data

WIMP flux

NEWS-G: Spherical gas TPC: Low mass (0.1-10 GeV) DM detection & neutron spectrometry

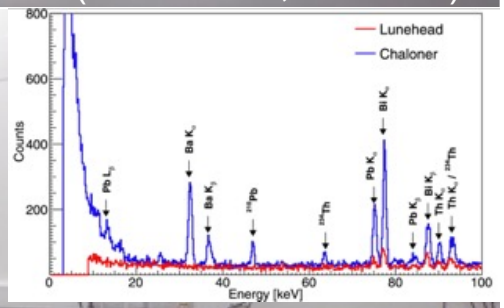
Directional DM detection providing the most powerful direct detection signature

XIA alpha particle counter

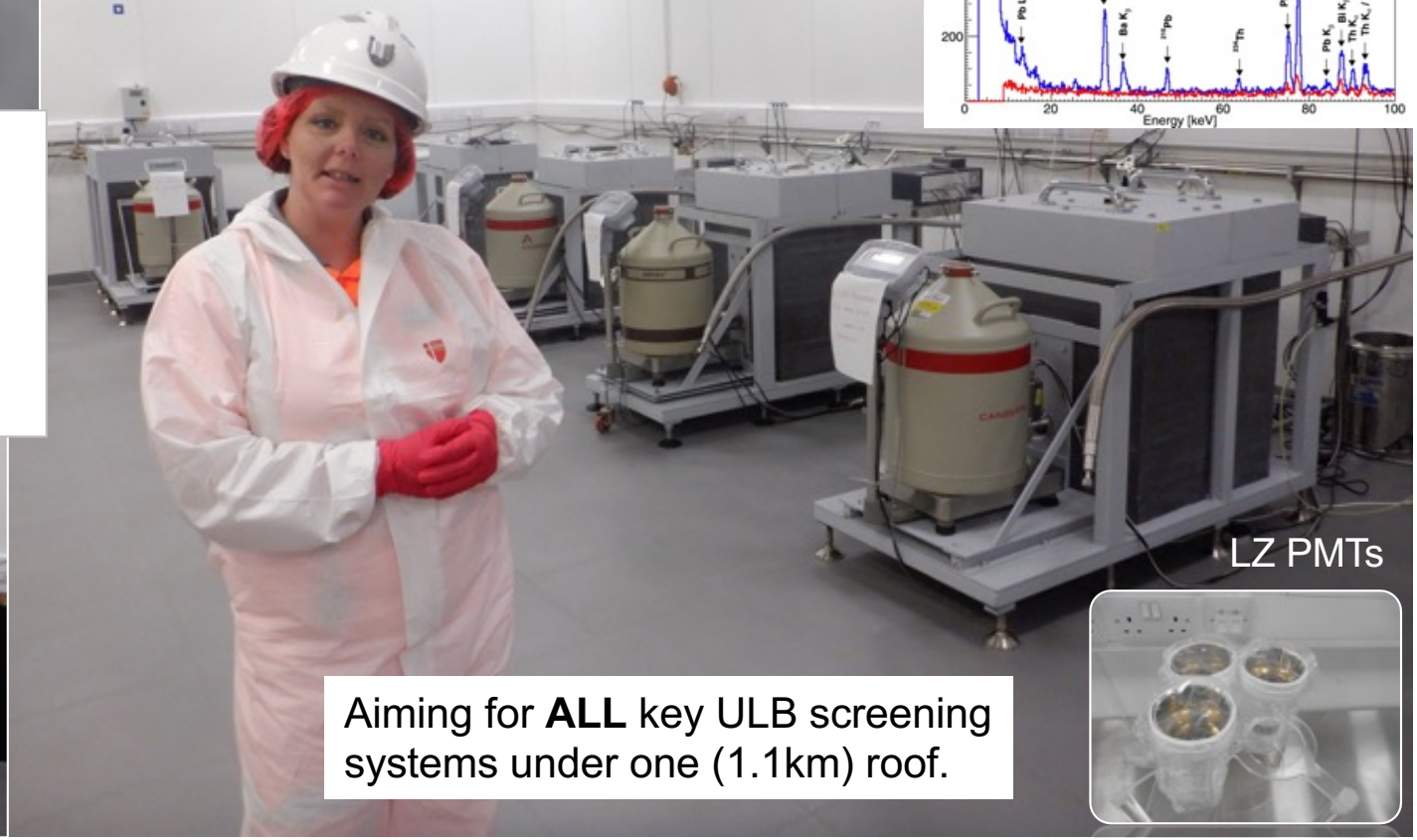


(XinRan Liu, this conf).

8 ULB Ge detector systems, 2 XIA alpha counters, Rn emanation, ICPMS to come



BUGS (Boulby UnderGround Screeening). World-class material screening for current and future ULB experiments. Towards PPT sensitivity for G3 DM and Neutrino experiments



LZ PMTs

Aiming for **ALL** key ULB screening systems under one (1.1km) roof.

Science and Technology Facilities Council
Boulby Underground Laboratory

Multi-Disciplinary Studies

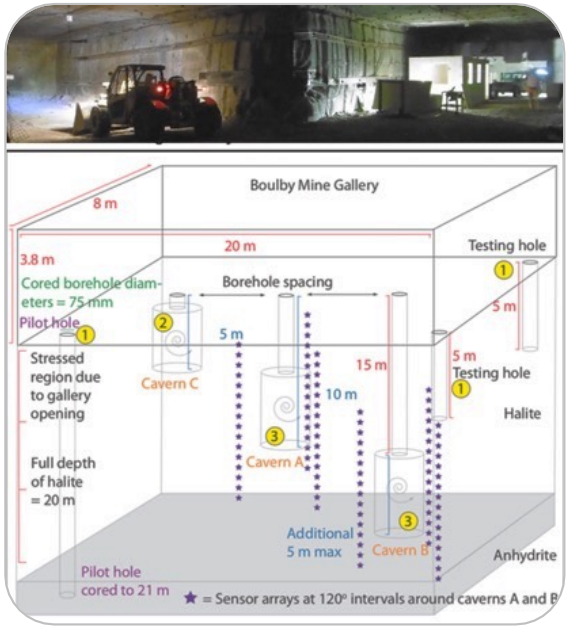
BOULBY UNDERGROUND LABORATORY

ERSaB: Gamma spectroscopy & low background counting environmental radioactivity studies

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

RESOURCE: Rock engineering feasibility study of salt cavity compressed gas sustainable energy storage

Boulby, British Geology Survey (BGS), Cambridge, Manchester.



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

MINAR: Space Technology Development

Boulby, Edinburgh, NASA, York, ICL etc.

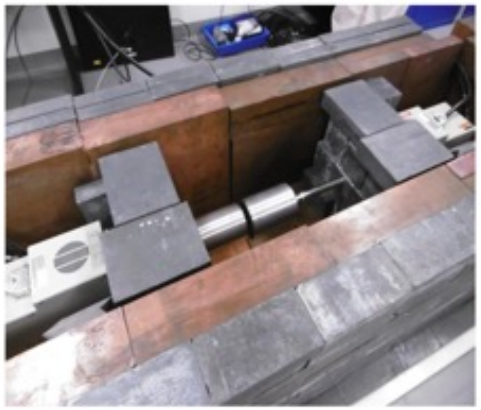
Plus Misc. Geology & Geoscience (& more to come)...

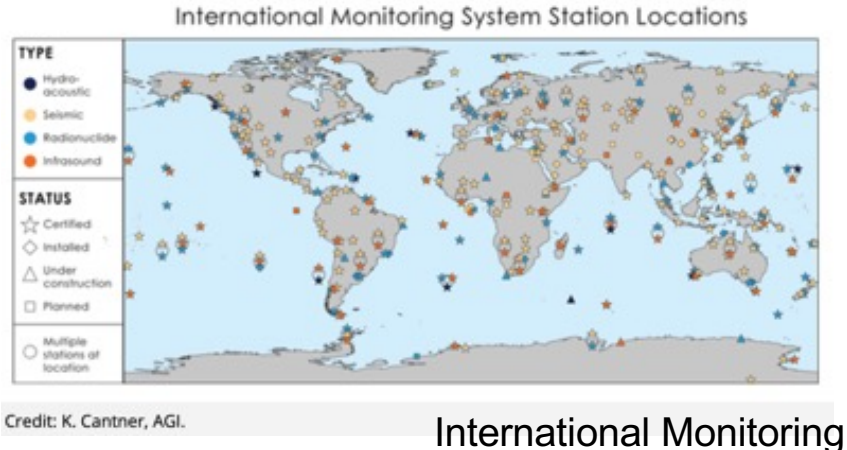
BISAL: Astrobiology / Geo-microbiology. Studies of life in salt, life on Earth & beyond

AWE-Ge: CTBT Atmospheric Radionuclide Monitoring

Improving the sensitivity of Nuclear Test Monitoring

A V Davies, R Britton
AWE, Aldermaston, Reading, Berkshire, RG7 4PR

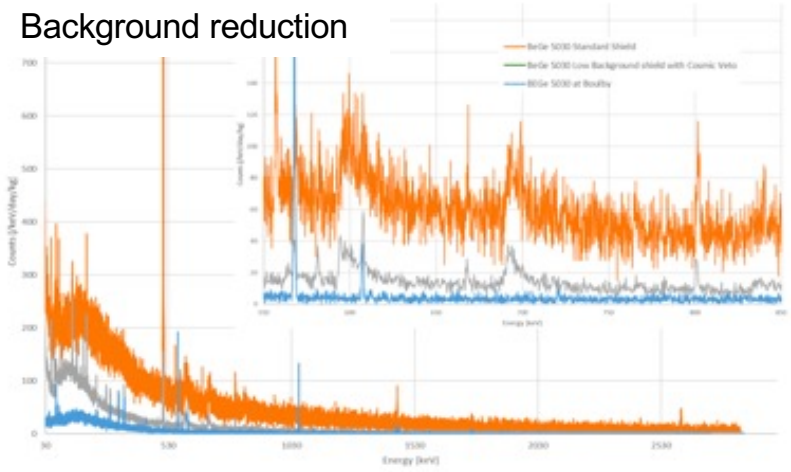




International Monitoring System Sites

Improving the accuracy & sensitivity of atmospheric radionuclide monitoring for international Comprehensive Test Ban Treaty (CTBT) verification

Background reduction



Nuclide	Singles MDA Bq/m3	Gate Energy	Projected Peak	RIMMER Factor	Background Counts (projected)	Lc Currie	Lc Poisson	MDA Currie	MDA Poisson	Ratio to singles
CS-134	3.38E-07	604.721	796.00	2.02E-03	2	9	6		4.85E-08	0.143
BA-133	4.41E-07	30.625	356.00	7.10E-01	54	37	49	8.47E-10		0.002
AG-108m	4.76E-07	24.013	434.00	2.37E-04	61	39	75	2.68E-06		5.632
CO-60	5.14E-07	1173.23	1330.00	8.73E-04	1	7	3		5.61E-08	0.109
AG-110m	4.33E-07	657.76	885.00	1.04E-03	3	11	7		1.09E-07	0.253
EU-152	8.23E-07	40.118	245.00	2.08E-02	40	32	52	2.52E-08		0.031
SB-125	1.99E-06	27.202	408.00	9.01E-03	34	30	45	5.40E-08		0.027
SC-46	4.71E-07	889.277	1120.00	1.31E-03	1	7	3		3.73E-08	0.079
RH-102	1.08E-06	21.836	475.00	1.64E-04	30	28	41	2.81E-06		2.603
FE-59	9.00E-07	192.343	1100.00	1.81E-04	9	17	16		1.44E-06	1.600
LA-140	1.15E-06	328.762	487.00	1.08E-03	11	18	18		2.71E-07	0.235
CS-136	1.30E-06	31.817	1240.00	1.82E-03	7	15	13		1.16E-07	0.090
SB-126	1.01E-06	414.7	666.00	1.81E-03	5	13	10		8.99E-08	0.089

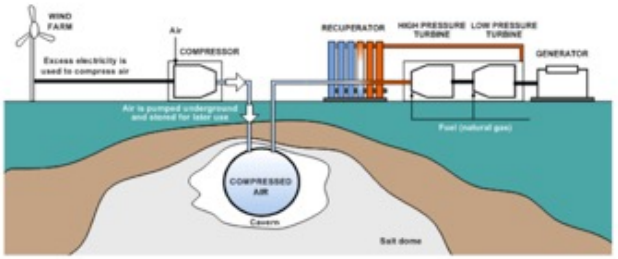
Renewable Energy StOrage in UndeRground CavErns *(RESOURCE)*

STFC Boulby Mine, BGS and the University of Cambridge

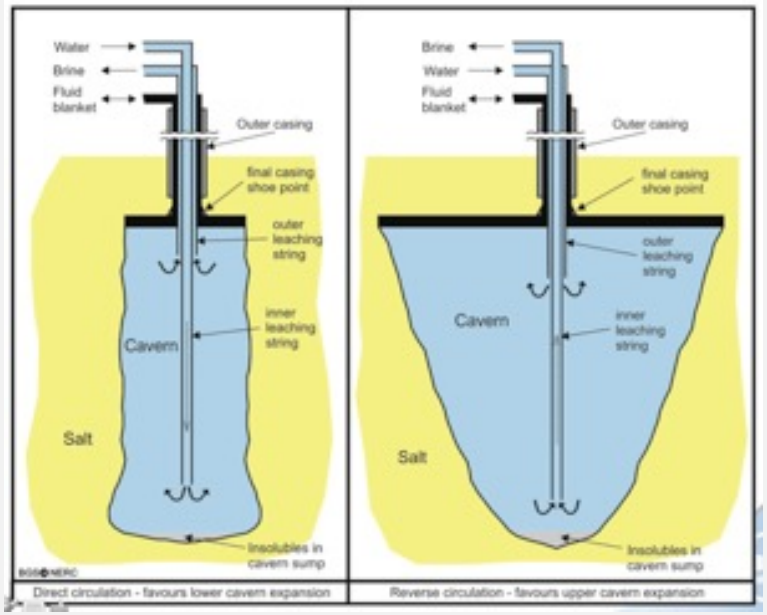
NERC Grant Proposal 2020

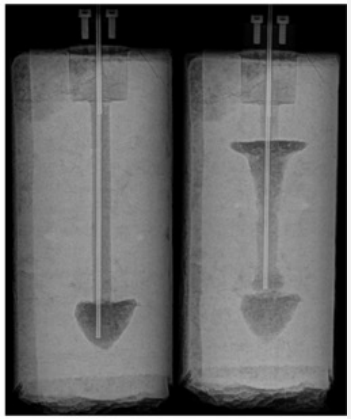
British Geological Survey
Boulby Underground Lab
U.Cambridge & U.Manchester

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

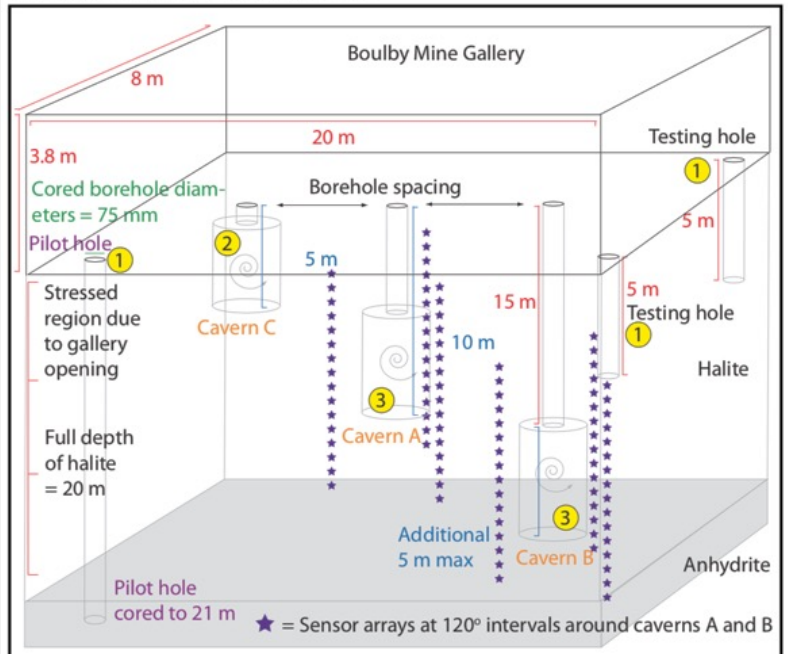




Above: Scoping lab-based dissolution tests of salt from Boulby Mine, giving insight into the solution mining process.

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

Plan for In-situ Testing at Boulby Mine

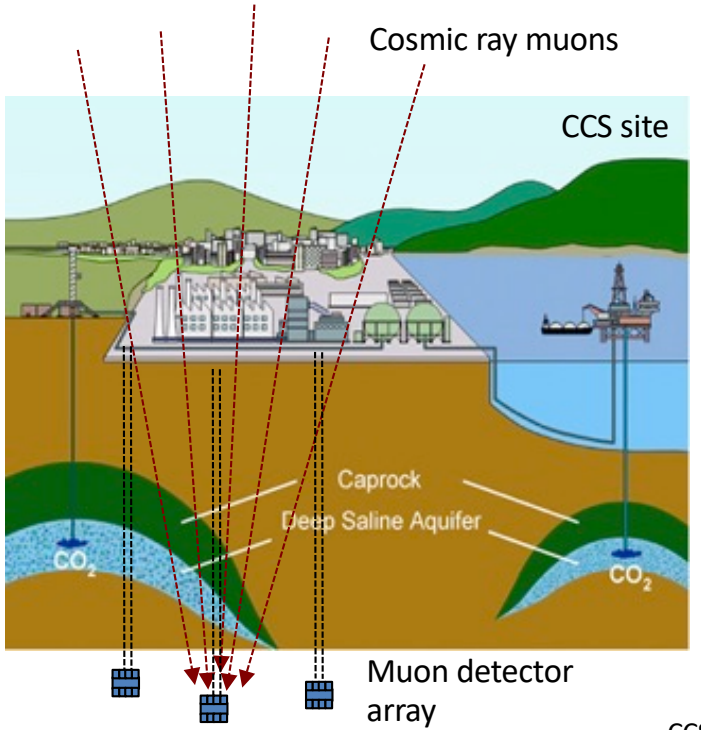


1. Drill and core pilot hole. Study fabric, chemistry and mechanical properties of core. Also drill and core testing holes. Study core and run dissolution tests.
2. Drill and core shallow hole to 5m. Case hole, cement casing and form solution-mined cavern.
3. Drill and core intermediate hole to 8m and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

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:

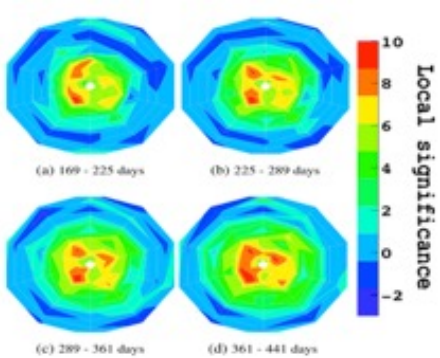
- Deep geological repository monitoring.
- Monitoring in Carbon Capture & Storage (CCS)

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

Astrobiology & Planetary Exploration

Sampling life in Boulby Brine

Subsurface Astrobiology Laboratory

BISAL
Boulby International Subsurface Astrobiology Lab

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

MINAR
Mine Analogue Research

Mining & extraplanetary exploration instrumentation development

Boulby and Instrumentation for Earth and Space Exploration

sean.paling@stfc.ac.uk

MINAR V. 9th to 20th 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.

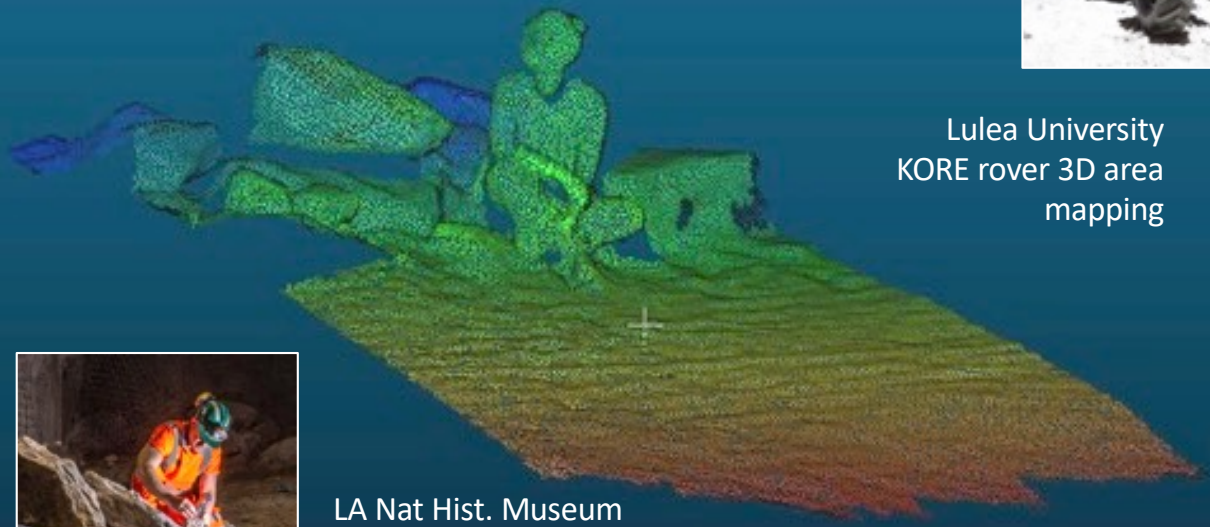
MINAR – Pac Man, HABIT & many more

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 VII & VIII.
2018 - 2020

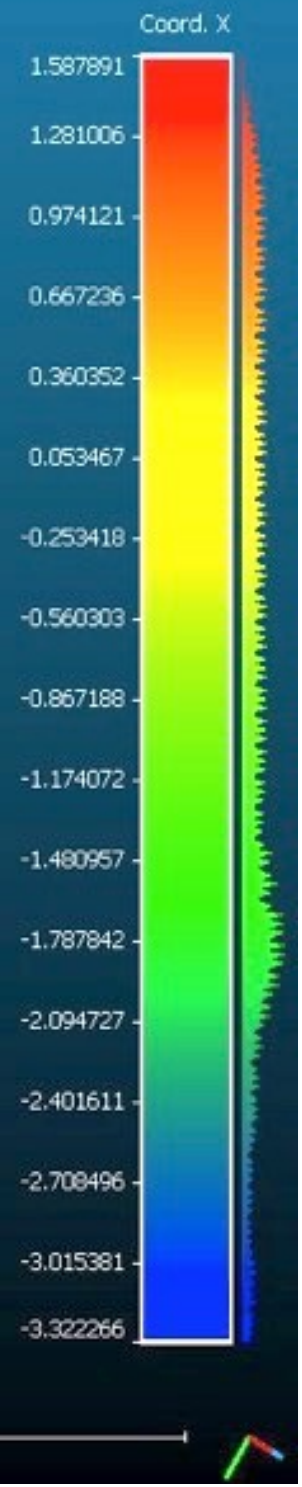
NASA-JPL
Signatures of life studies



Lulea University
KORE rover 3D area
mapping

LA Nat Hist. Museum
Fluid inclusions in salts

Edinburgh University
MUFFHINS water activity
monitoring payload



Science and Technology Facilities Council
Boulby Underground Laboratory

Boulby Growth Potential & Plans….

Develop as an internationally-important centre for astro-particle physics and pure and applied multi-disciplinary science.

- **Expand in all current science theme areas:**
  - Astro-particle Physics & Low Background Science
  - Earth & Environmental Science
  - Astrobiology & Planetary Exploration Studies

- **For Astro-particle Physics & Low Background Science:**
  - Develop BUGS to give world-class support for future ULB projects
  - Host/support new medium-scale projects: (BOLEYN, DarkSPHERE+)
  - **EXPAND to host Next Generation Dark Matter & Rare Event Studies & more.**

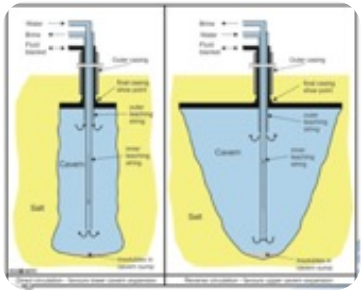
Find out more:
@BoulbyLab
www.stfc.ac.uk/boulby

Future Science...

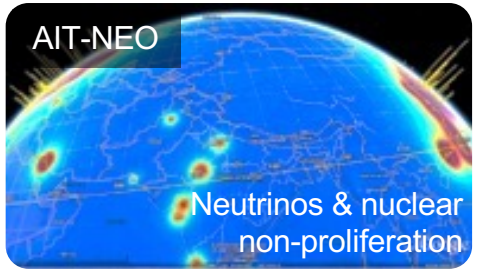
Continue current studies, PLUS…

- Expanded **MINAR** & **Planetary exploration technology** development**.** Links to mining / industry, **Robotics.**
- **RESOURCE+:** Advanced salt cavity test facility for studies of compressed gas energy storage.
- Misc. Geoscience R&D: **geological repositories / waste containment, geothermal energy** and more.
- **BUGS+:** Expanding ultra low background material screening and environmental gamma spectroscopy.
- Misc. applied low background studies: **AWE-Ge/RECON, Muon Tomography, QCLB** (Quantum Computing)
- Misc: medium scale astro-particle studies: **DarkSPHERE, AION, LEGEND, AIT-NEO / BOLEYN,**
- Large scale EXPANSION: **Next Gen DM / 0vBB decay +**

Robotics



RESOURCE: Salt cavity energy storage



Develop as a truly multi-disciplinary facility for **Astrophysics and Low Background** science, **Earth and Environmental Science**, **Astrobiology and Planetary Exploration Technology Development**.

BOULBY UNDERGROUND LABORATORY

AIT-NEO (WATCHMAN)

A WATer CHerenkov Monitor of ANtineutrinos

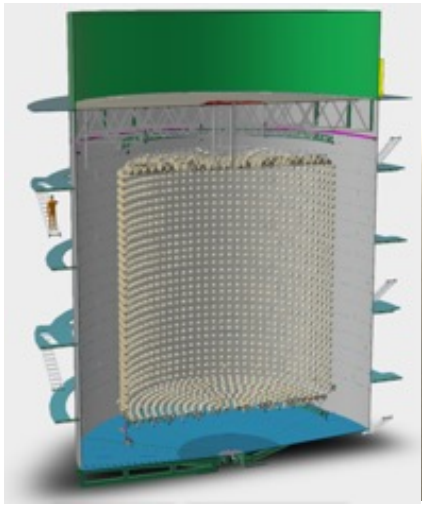
World antineutrino flux levels

Design, excavation, installation & operation 2019 to 2027(+)

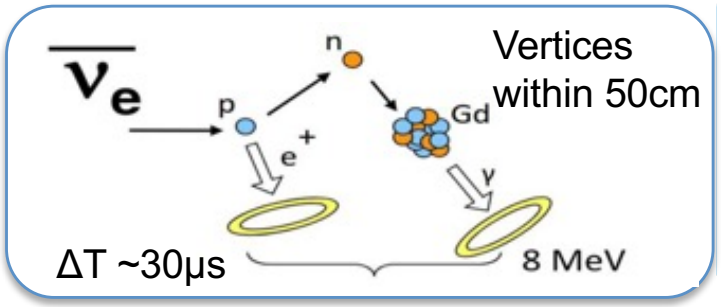
HARTLEPOOL REACTORS

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

WATCHMAN detector at the Boulby mine



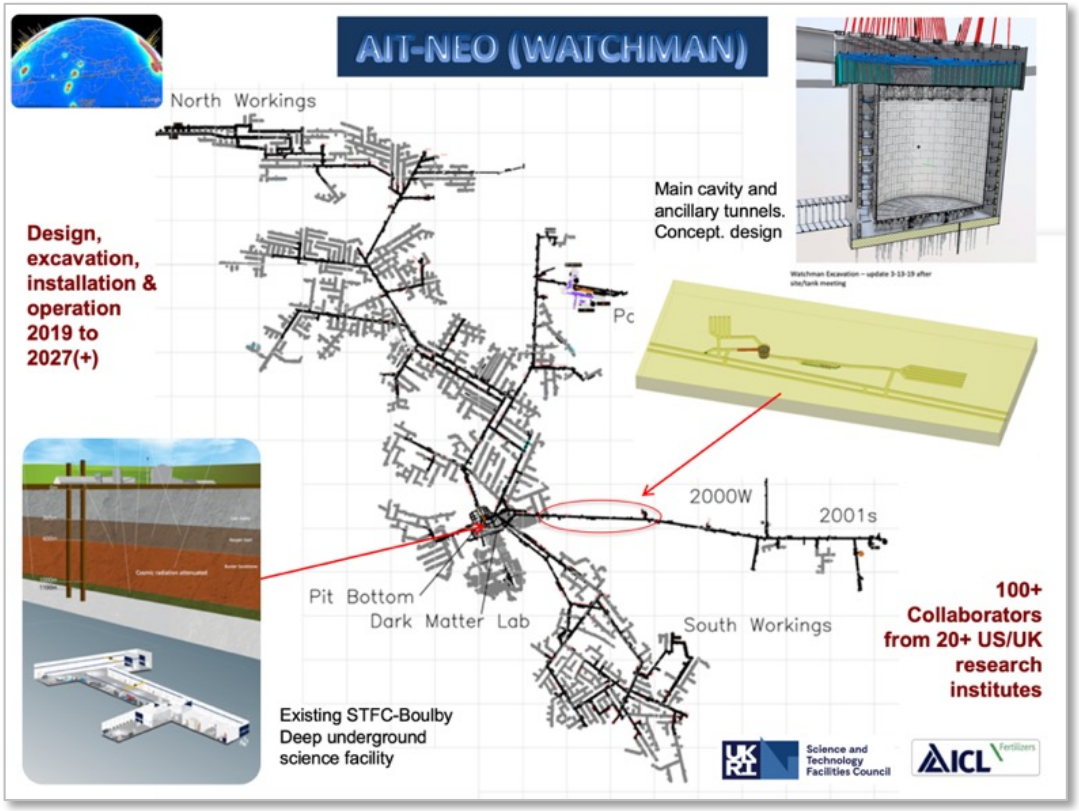
A ~6kT Gd-loaded water (& WBLS) detector looking at anti-neutrinos from nearby nuclear reactors



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

Science and Technology Facilities Council
Boulby Underground Laboratory

AIT-NEO (WATCHMAN) Status…



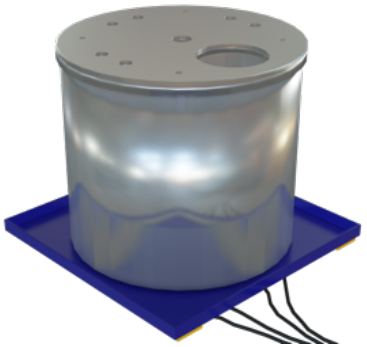
AIT-NEO recent happenings:

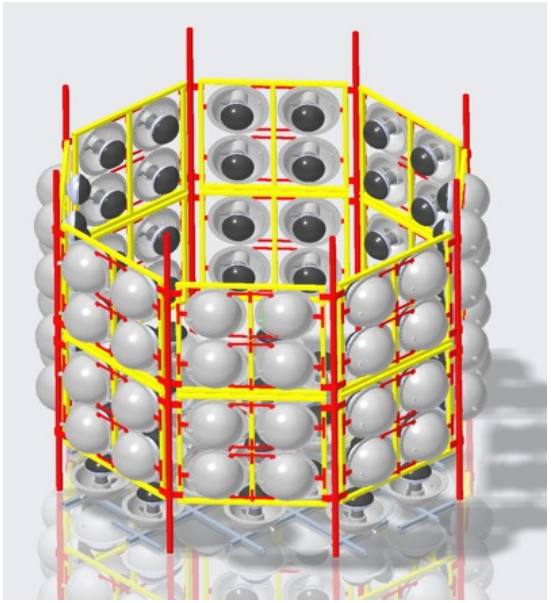
- **2018-Present**: Detector design and performance studies. Studies of new site location, geology, designs, costs and schedule
- **June 2021:** NEW news from EDF of **Hartlepool closure in 2024** due to new understanding of aging rates.
- **December 2021:** News of **early closure (2028) of next nearest power stations** (Heysham 2 and Torness).

Status & Next Steps

- Full AIT-NEO now not likely to go ahead at Boulby
- Continued collaborative (US/UK) work undertaken on technology demonstrators – inc 30T system @ Boulby
- '**BOLEYN":** Boulby antineutrino detection technology testbed. Engineering, operation, technology, fill medium and low-background studies.
- Installation –> operation @ Boulby: 2022-2024

BOLEYN.
~30T antineutrino technology testbed.





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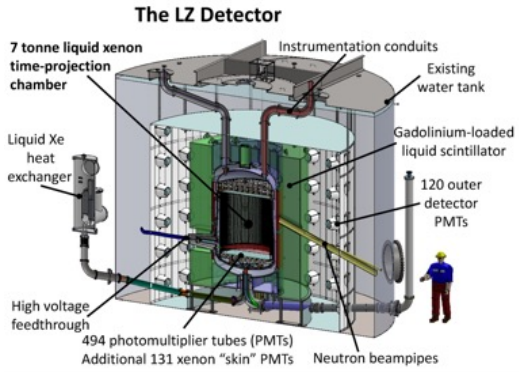
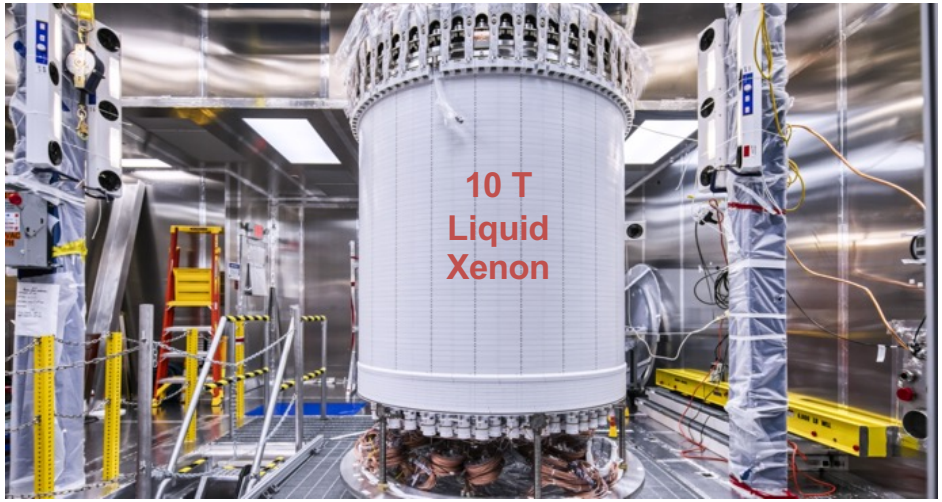
Next Generation Rare Event Studies @ Boulby

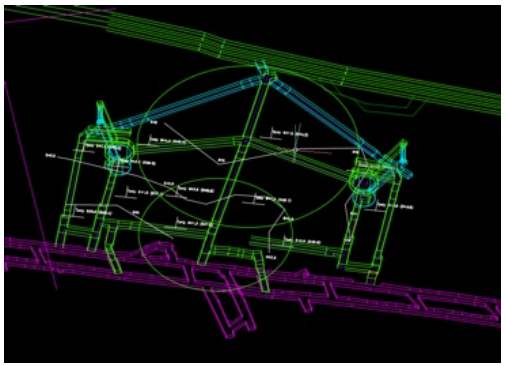
Towards EXPANDING Boulby to host MAJOR international Dark Matter, neutrino & fundamental science projects from 2028+





LZ Detector, SURF. USA

Boulby-FS study: Infrastructure design, feasibility & costing studies for next generation Dark Matter and/or 0vBB detectors **Study undertaken 2020-2021**



Next Generation @ Boulby?

- HIGH-impact, world-leading science
- LARGE multi-national collaborations
- BIG fundamental science questions
- MAJOR local & national investment, impact and visibility

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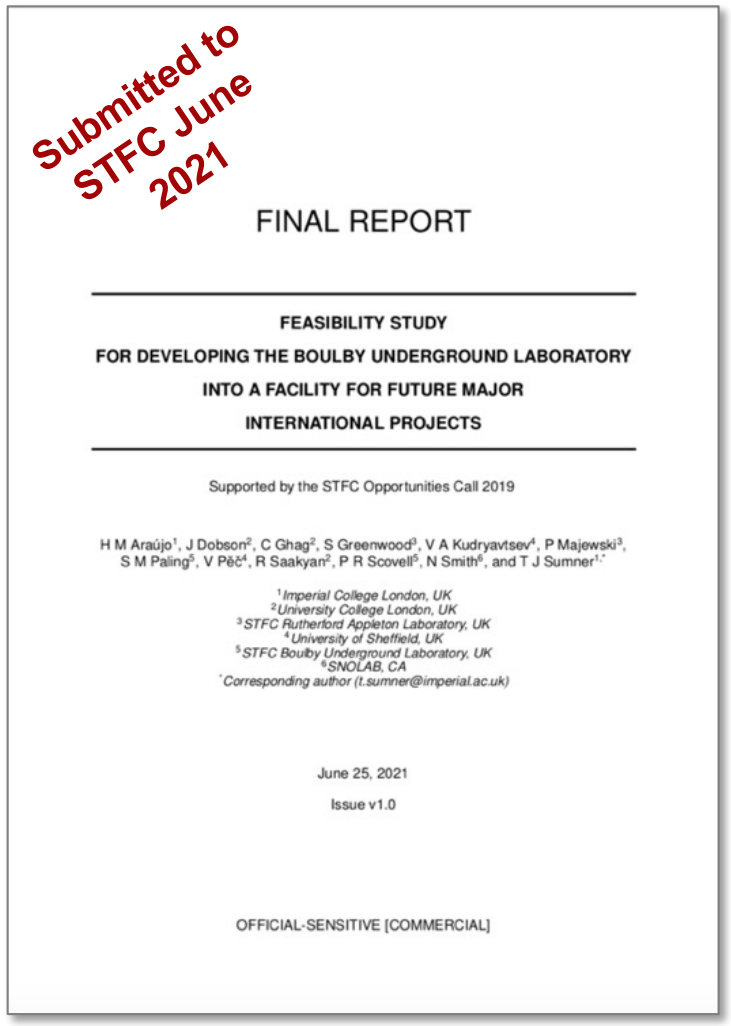
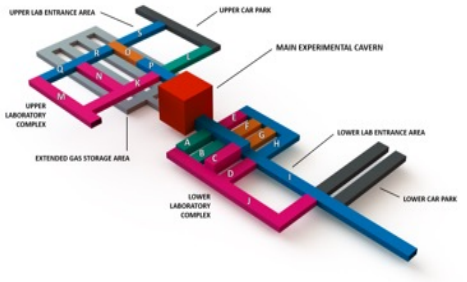
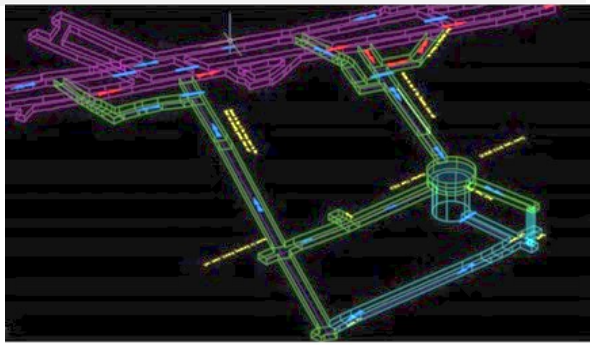
Boulby Feasibility Study (Boulby-FS)

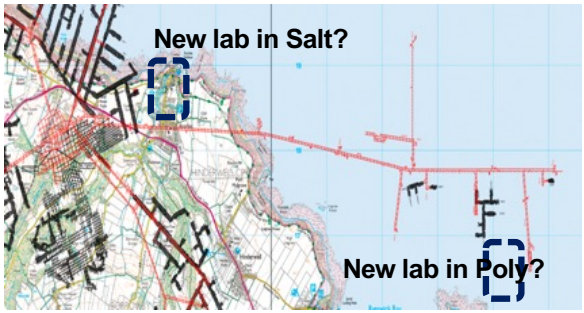


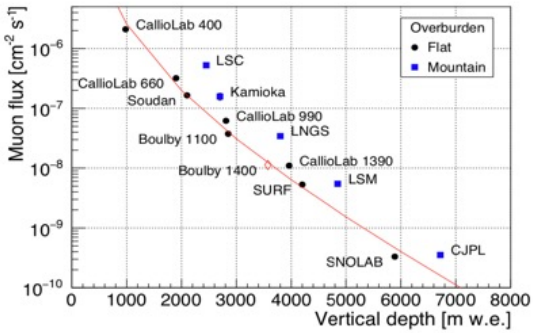
Boulby-FS Study Overview:

- Context and need: Dark Matter (DM), Neutrinoless Double Beta Decay (0vBB)
- Infrastructure specifications for potential projects (LXe & LAr DM, Ge 0vBB, and more)).
- Conceptual designs for excavations and outfitted labs – in 1.1km (Salt) and 1.4km (Polyhalite) layers
- Staffing and surface facility needs.
- Detailed costs and schedules.









Government 'fit': Levelling Up, Strength in Places, Build Back Better

Results: It IS feasible, well motivated and timely.
Outfitted facility: £100m+ (Inc contingency, VAT)

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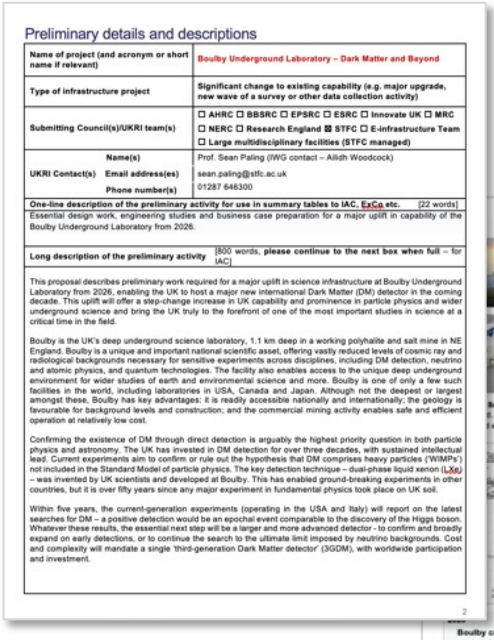
Next Generation Dark Matter(+) @ Boulby?

Status & Next Steps

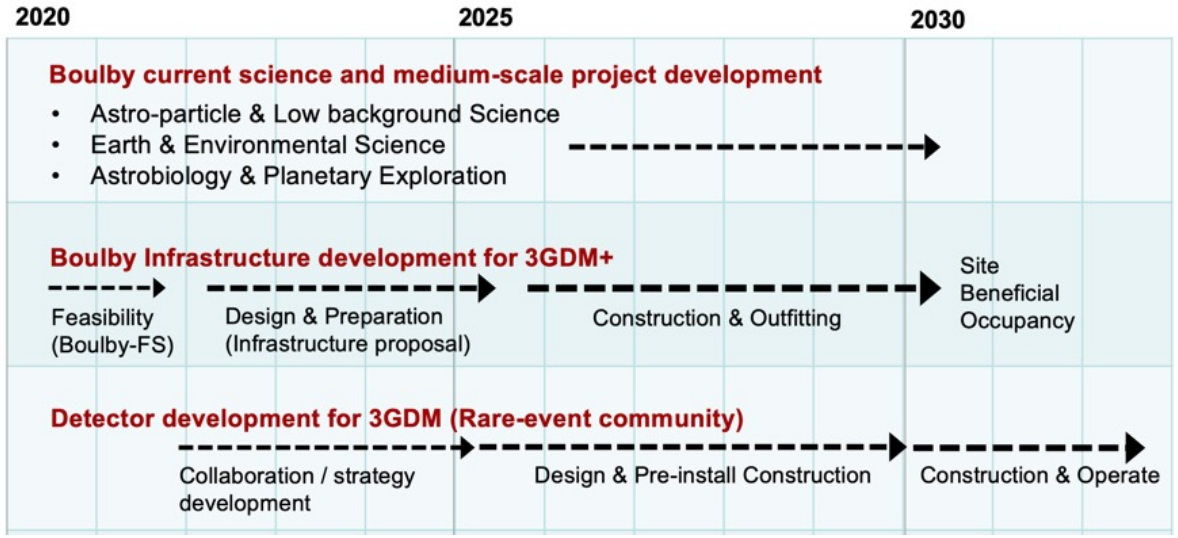
- Next steps **funding request** submitted to UKRI in 2021.
- Future (3 year) work includes:
  - Next step facility conceptual designs (1.1km & 1.4km)
  - Scoping, networking, community engagement.
  - Business case, economic impact studies, risks → **Submission to BEIS**



Preliminary details and descriptions

Name of project (and acronym or short name if relevant)	Boulby Underground Laboratory – Dark Matter and Beyond
Type of infrastructure project	Significant change to existing capability (e.g. major upgrade, new wave of a survey or other data collection activity)
Submitting Council(s)/UKRI team(s)	☐ AHRC ☐ BBSRC ☐ EPSRC ☐ ESRC ☐ Innovate UK ☐ MRC ☐ NERC ☐ Research England ☒ STFC ☐ E-infrastructure Team ☐ Large multidisciplinary facilities (STFC managed)
UKRI Contact(s) Name(s)	Prof. Sean Paling (IWG contact – Allidh Woodcock)
UKRI Contact(s) Email address(es)	sean.paling@stfc.ac.uk
UKRI Contact(s) Phone number(s)	01287 646300
One-line description of the preliminary activity for use in summary tables to IAC, ExCo etc. [22 words]	Essential design work, engineering studies and business case preparation for a major uplift in capability of the Boulby Underground Laboratory from 2026.
Long description of the preliminary activity [800 words, please continue to the next box when full – for IAC]	This proposal describes preliminary work required for a major uplift in science infrastructure at Boulby Underground Laboratory from 2026, enabling the UK to host a major new international Dark Matter (DM) detector in the coming decade. This uplift will offer a step-change increase in UK capability and prominence in particle physics and wider underground science and bring the UK truly to the forefront of one of the most important studies in science at a critical time in the field. Boulby is the UK's deep underground science laboratory, 1.1 km deep in a working polyhalite and salt mine in NE England. Boulby is a unique and important national scientific asset, offering vastly reduced levels of cosmic ray and radiological backgrounds necessary for sensitive experiments across disciplines, including DM detection, neutrino and atomic physics, and quantum technologies. The facility also enables access to the unique deep underground environment for wider studies of earth and environmental science and more. Boulby is one of only a few such facilities in the world, including laboratories in USA, Canada and Japan. Although not the deepest or largest amongst these, Boulby has key advantages: it is readily accessible nationally and internationally; the geology is favourable for background levels and construction; and the commercial mining activity enables safe and efficient operation at relatively low cost. Confirming the existence of DM through direct detection is arguably the highest priority question in both particle physics and astronomy. The UK has invested in DM detection for over three decades, with sustained intellectual lead. Current experiments aim to confirm or rule out the hypothesis that DM comprises heavy particles ('WIMPs') not included in the Standard Model of particle physics. The key detection technique – dual-phase liquid xenon (LXe) – was invented by UK scientists and developed at Boulby. This has enabled ground-breaking experiments in other countries, but it is over fifty years since any major experiment in fundamental physics took place on UK soil. Within five years, the current-generation experiments (operating in the USA and Italy) will report on the latest searches for DM – a positive detection would be an epochal event comparable to the discovery of the Higgs boson. Whatever these results, the essential next step will be a larger and more advanced detector - to confirm and broadly expand on early detections, or to continue the search to the ultimate limit imposed by neutrino backgrounds. Cost and complexity will mandate a single 'third-generation Dark Matter detector' (3GDM), with worldwide participation and investment.

Boulby Future: UKRI Bid

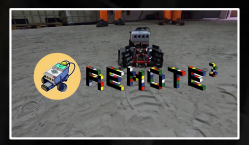


Now seeking community:

- Attention / understanding
- Support..
- Collaboration & involvement...

Thank You….

Science and Technology Facilities Council
Boulby Underground Laboratory



Sean Paling
STFC Boulby Underground Laboratory

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Facebook: Boulby Underground Laboratory

You Tube: Boulby Underground Laboratory

Boulby Underground Lab Backgrounds

Cosmic ray muon backgrounds:

Measured as $(3.79 \pm 0.04(stat) \pm 0.11\ (sys)) \times 10^{-8}\ cm^{-2}.\ s^{-1}$ (2850 ± 20 mwe)

H. Araujo, et al., Astroparticle Physics 29 (2008) 471–481.

Radon:

Measured as 2.5 +/- 1.6 $Bq.m^{-3}$ (year round)

Internal reports (JIF Lab 2015)

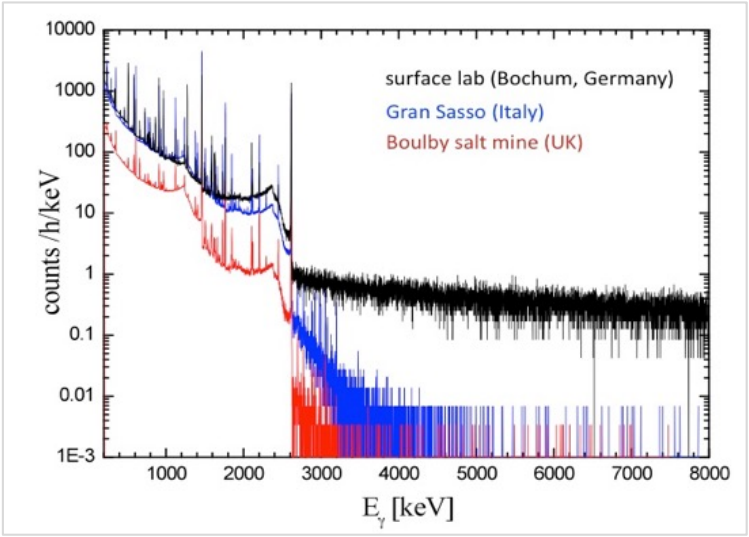
Neutrons:

Simulations based on U/Th content:
1.2×10^{-6} neutrons.$cm^{-2}s^{-1}$ (>500keV @rock/cavern bndry).

M.J. Carson et al., Astrop. Phys 21 (2004) 667.

Measured as: $(1.72 \pm 0.61(stat) \pm 0.38(sys)) \times 10^{-6}\ cm^{-2}s^{-1}$

M.J. Tziaferi et al., Astrop. Phys 27 (2007) 326-338.



Gammas:

Germanium detector survey of Boulby JIF Lab Area
Flux = 0.128 $cm^{-2}s^{-1}$

D. Malczewski et al. J. Radioanal. Nucl. Chem. 298 (2013) 1483-1489.

Sean Paling, Paul Scovell - 2021