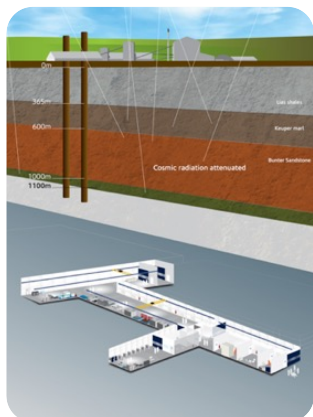


Overview of Deep Underground Science Facilities

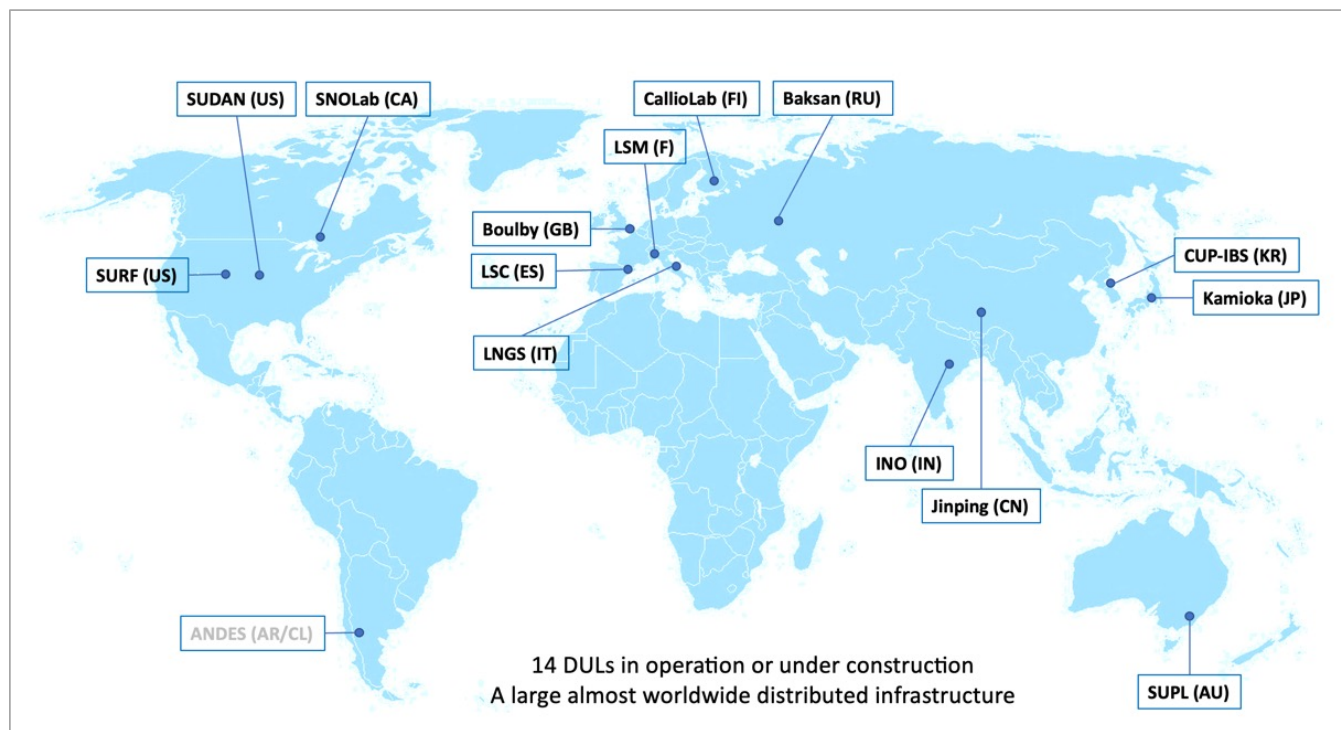
World Underground Labs



Boulby Underground Laboratory (UK)



Gran Sasso National Laboratory LNGS (Italy)



Sean Paling – STFC Boulby Underground Laboratory
European Laboratory Directors Group Meeting – July 2023

Why go underground?

Deep Underground Science Themes

Low Background Particle / Astroparticle Physics

- Direct dark matter searches
- Atmospheric, solar & supernova neutrinos
- Reactor and accelerator neutrinos
- Neutrino-less double beta decay
- Nuclear astrophysics / stellar reactions
- Misc. rare-decay processes

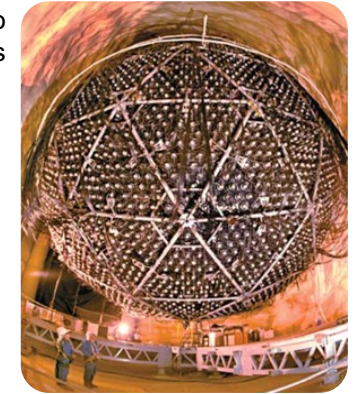
Other 'Multi-disciplinary' studies

- Pure and applied cosmic ray studies,
- Misc. low background studies, Gamma spectroscopy
- Misc. Earth and Environmental Sciences
- Geo-microbiology & life in extreme environs
- Astrobiology and planetary exploration
- Quantum sensors, quantum computing
- Etc...

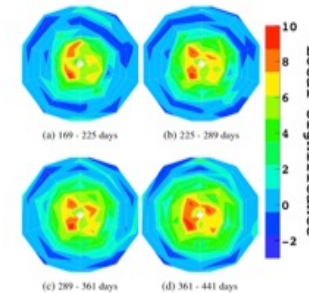
Dark Matter Studies



Neutrino Studies

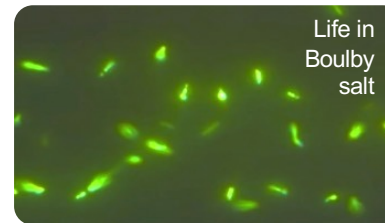


Geology & geophysics



ULB Gamma spectroscopy

Biology, astrobiology and more.



Life in Boulby salt



Boulby Underground Laboratory

What's needed from an underground lab? (1)

Experimental Space with... Low Backgrounds...

Cosmic ray Muons...

- Deep underground facilities provide rock overburden & commensurate reduction in c.r. flux & spallation induced products (neutrons)

Go underground...

Neutrons...

Production from

- c.r. muon spallation
- U/Th fission
- α , n reactions

Radon....

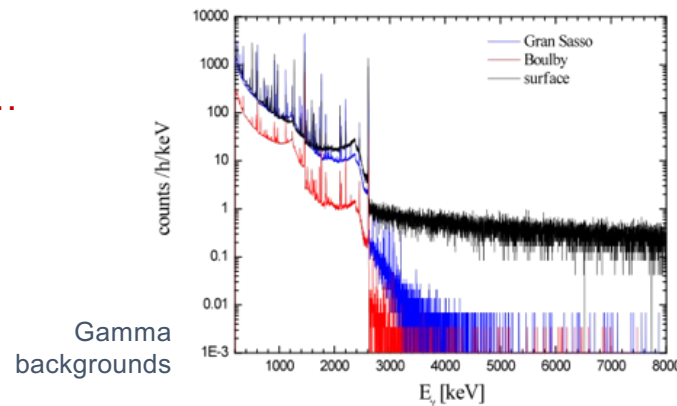
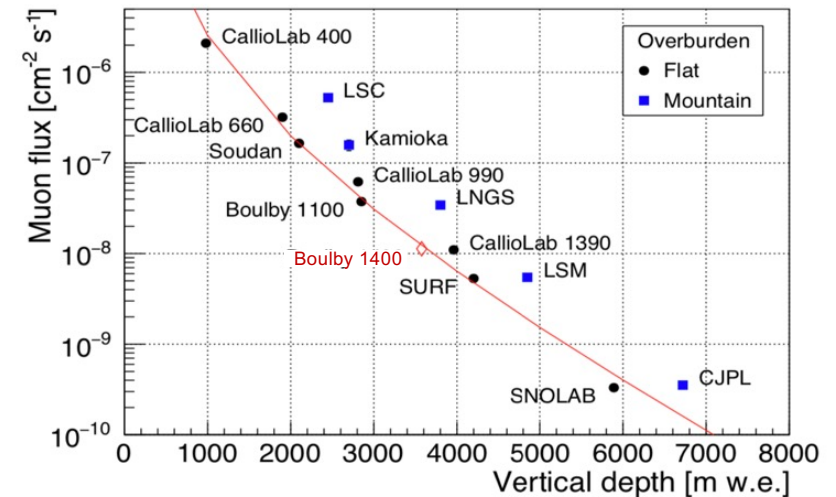
- Dependent on local geology & ventilation

Choose low background rock...

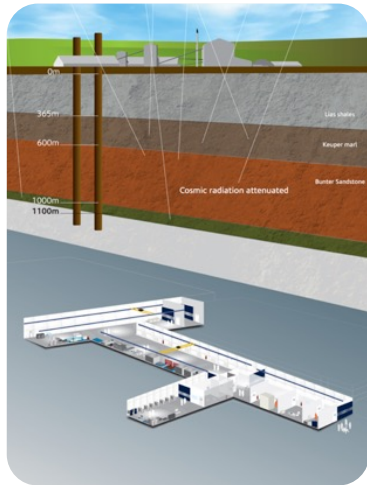
Gammas....

- Reduction in γ -ray background at higher energies from c.r. and neutron reduction
- Below 3.5MeV dependent on local geology

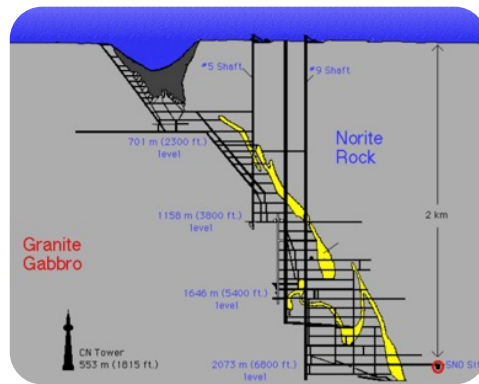
Muon Flux vs. Depth



Underground Labs around the world....

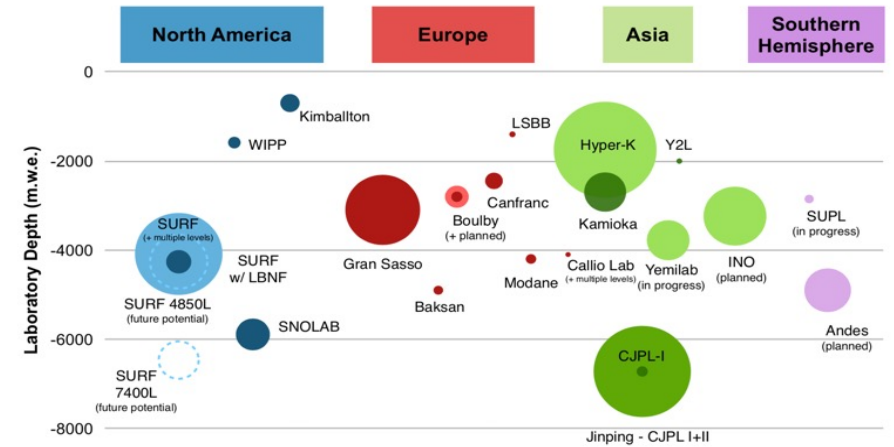


Boulby

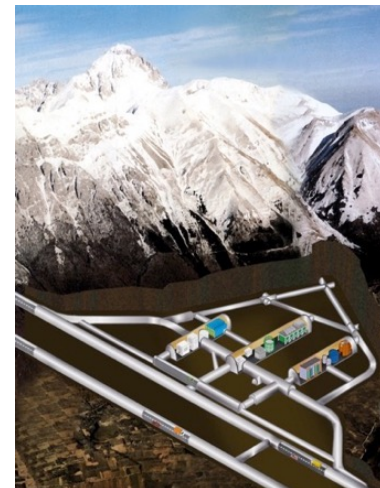


SNOLAB

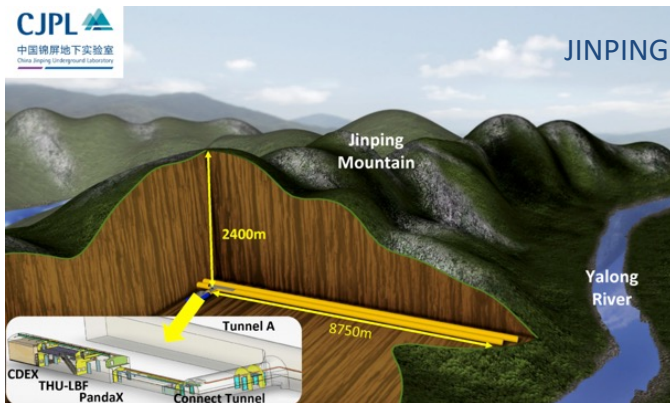
In mines and under mountains



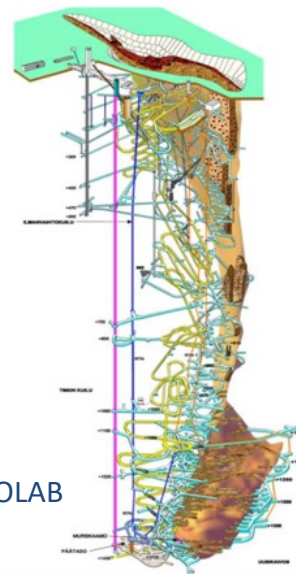
LNGS



SURF



JINPING



CALLIOLAB

What's needed from an underground lab? (2)

Other Factors:

Science and operations support:

- Good surface & underground infrastructure & support facilities
- Reliable utilities: power, ventilation, heat management, water, gases/liquids
- Good Health & Safety and security systems for underground use
- Scientific support personnel: design, construction, operation/analysis
- Infrastructure support and personnel: workshops, chemical labs, IT etc.
- Good ancillary science support facilities: low background assay, clean rooms etc...

'A hole in the ground is not a facility!'



Other Facility Characteristics:

- Size (monolithic or distributed; Space available)
- Ease of Access (vertical or horizontal); Max installation size limitations
- Location (neutrino flux from beam/reactor, Earth, ease of access, quality of life)
- Cleanliness and radiological interference
- Suitable geology

Non lab-based things are very important too.



Local Politics & funding: multi-year budgets, solid host nation support, local support /engagement in the facility and the science. Science community networking.

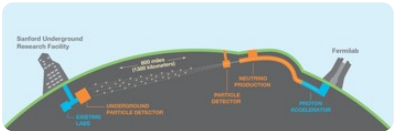


Boulby Underground Laboratory

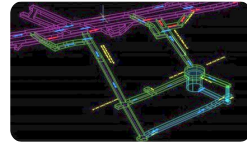
World deep underground laboratories...



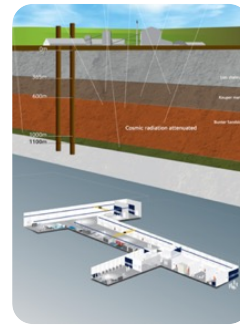
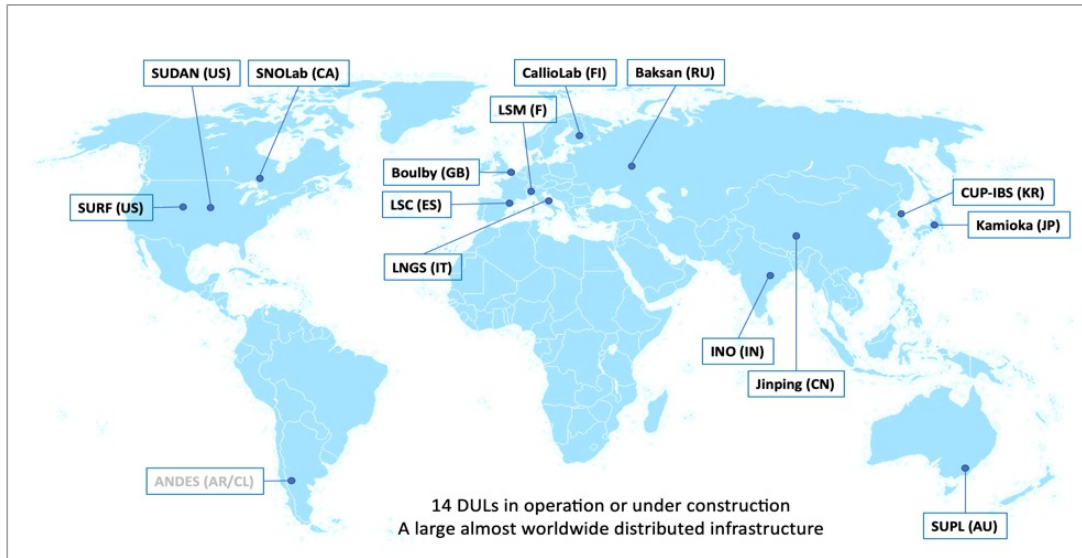
SNOLAB (Canada)
 Active Mine, 5890 mwe
 Current vol: 30,000m³
 SNO+, SuperCDMS, Deep3600,
 PICO, Next Gen 0vBB (to come?)



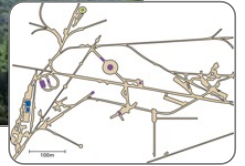
SURF Laboratory (USA)
 Disused Mine, 4200 mwe
 Current vol: 7,100m³
 LZ, MJD, DUNE (to come)



World Underground Labs



Gran Sasso National Laboratory
 LNGS (Italy)
 Under mountain, 3800 mwe
 Current vol: 180,000m³
 Borexino, Xenon, DarkSide +



Kamioka (Japan)
 Active Mine, 2700 mwe
 Current vol: 150,000m³
 Super-K, XMAS, Kamland-Zen +
 Hyper-K (nearby, to come)

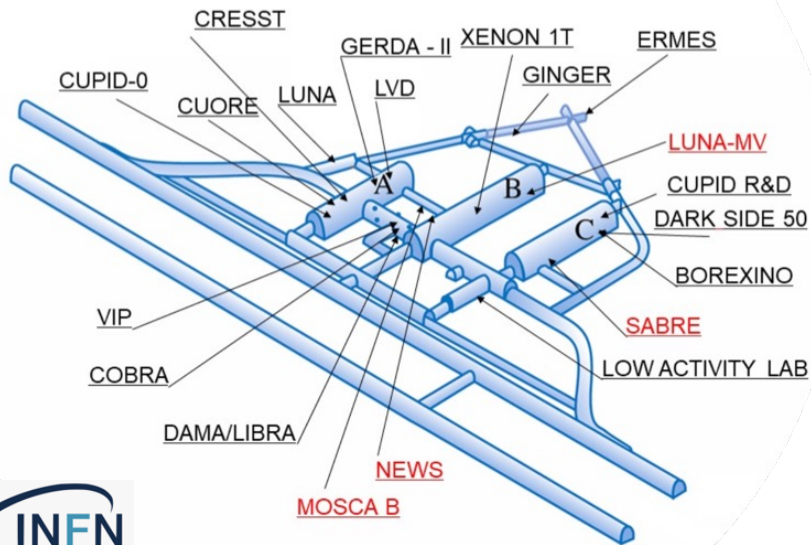
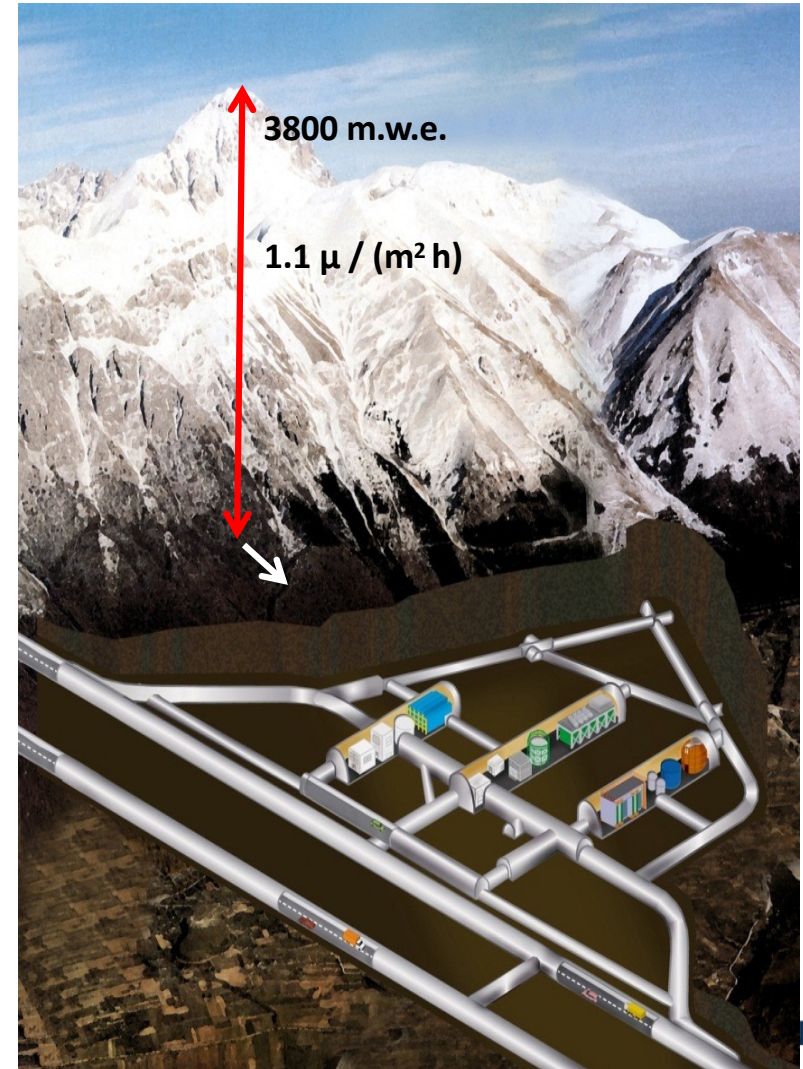
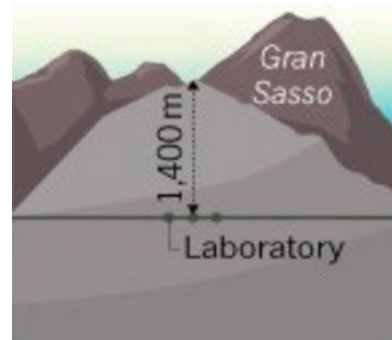


Boulby Underground Laboratory (UK)
 Working Mine, 2850 mwe
 Current vol: 7,200m³
 ZEPLIN+ (past), BUGs, News-G,
 RECON, Multi- sci, BUTTON (to come)

LNGS / Gran Sasso Deep Underground Lab

- Shielded by 1400 m (3800 m.w.e.) of rock (Gran Sasso Mountains)
- Total Muon flux $3 \cdot 10^{-8} \text{ cm}^{-2} \text{ s}^{-1}$
- Radon $\sim 100 \text{ Bq/m}^3$ with 5-8 air changes/day
- 3 main experimental halls:
100 m long, 20 m width and 18 m height
- 22 experiments data taking or under construction
- Laboratory for very low radioactivity measurements

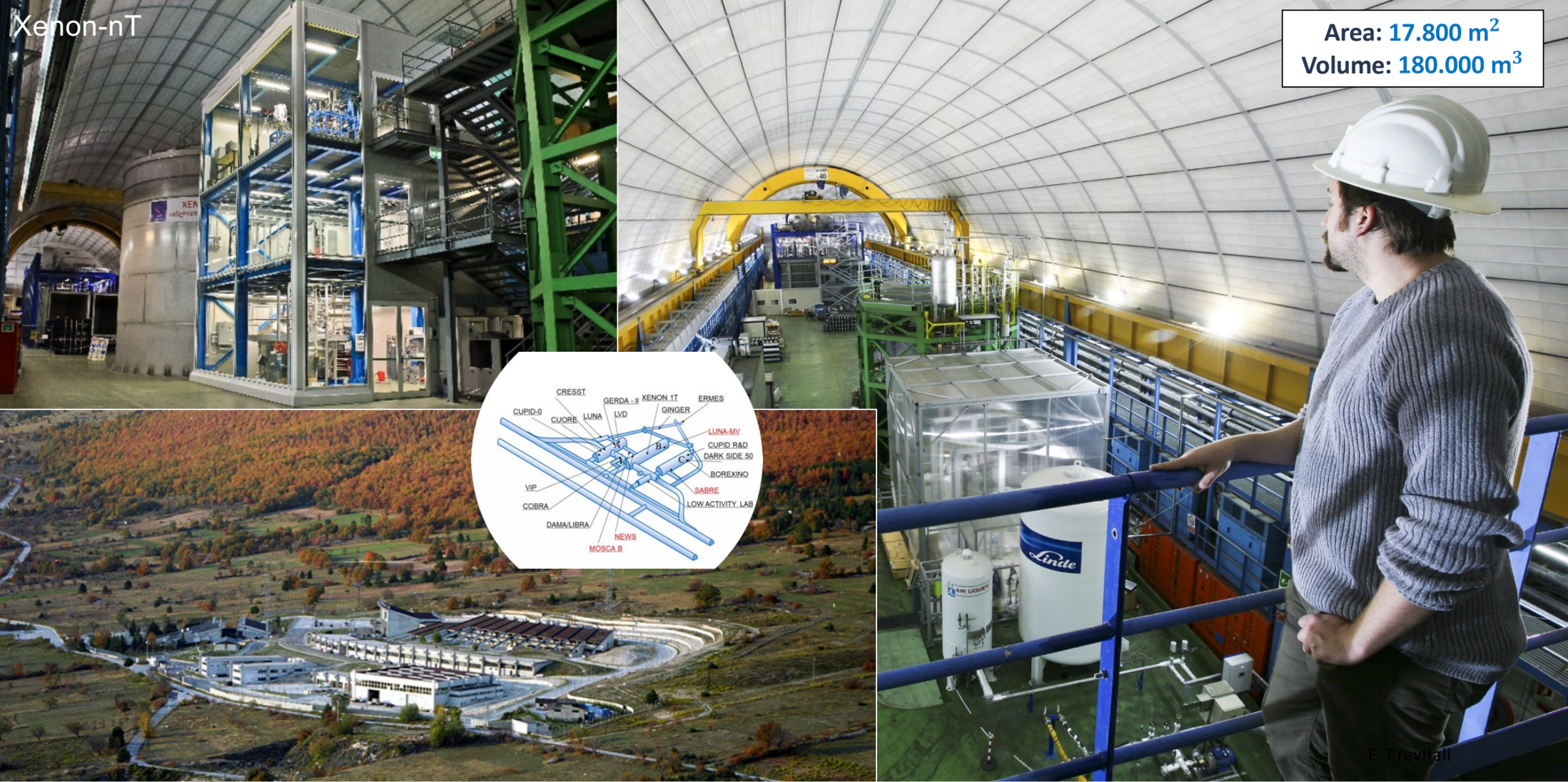
Area: **17.800 m²**
Volume: **180.000 m³**



LNGS / Gran Sasso Deep Underground Lab

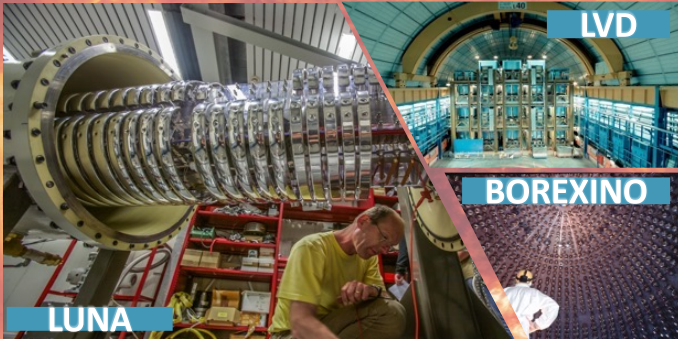
Xenon-nT

Area: 17.800 m²
Volume: 180.000 m³



Gran Sasso Science

Neutrino Astrophysics



Nuclear Astrophysics

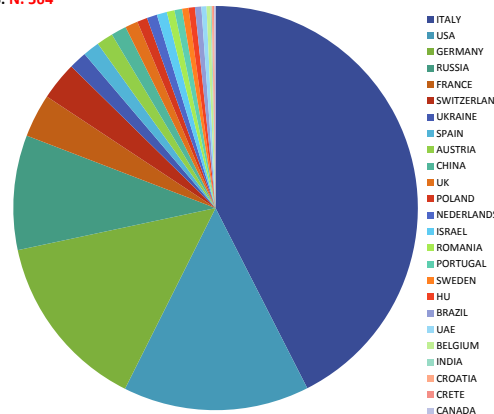
Dark Matter Search



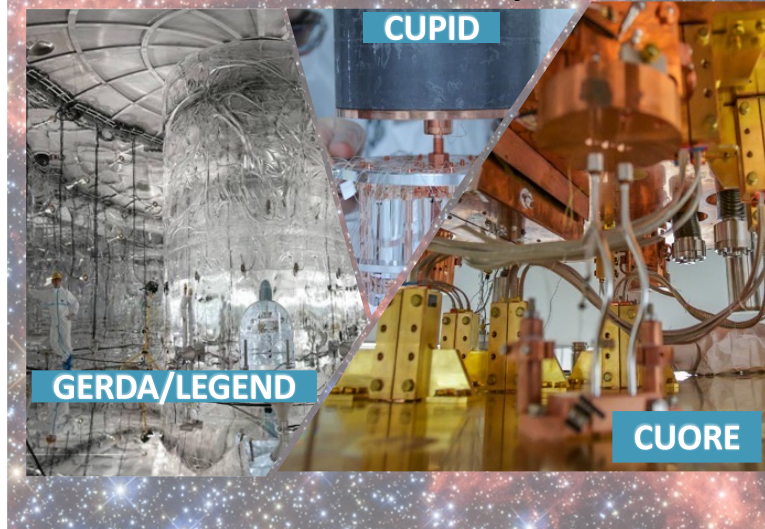
TAUP2021, 26 August – 3 September 2021



TOTAL USERS: N. 981
 ITALIAN USERS: N. 417
 FOREIGN USERS: N. 564



Neutrinoless Double Beta Decay



..... but also

- **Test on quantum mechanics**
 - Study on Planck invariance
 - Electron decay
- **Radiobiology**
- **Geophysics**
 - Earthquake monitoring and study
 - Analysis of water resources
- **Ultra Trace elemental analysis**
 - Low radioactivity tests and measurements
 - Cultural Heritage analysis
 - Advanced additive manufacturing

E. Previtali

Boulby Underground Laboratory (UK)



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 $\sim 10^6$ 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.

Typical Boulby Salt Roadway

Mine Shafts

New Lab (2017)

Potash (KCl)

Rock-Salt (NaCl)

Polyhalite ($K_2Ca_2Mg(SO_4)_6 \cdot 2H_2O$)

Boulby Science Now & Future

Particle physics and ultra-low background studies

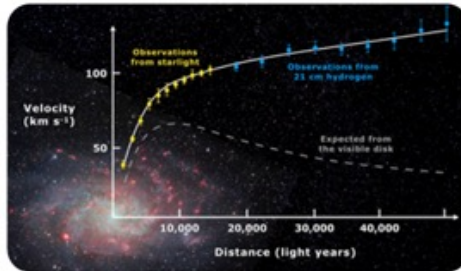


Boulby Dark Matter Studies...

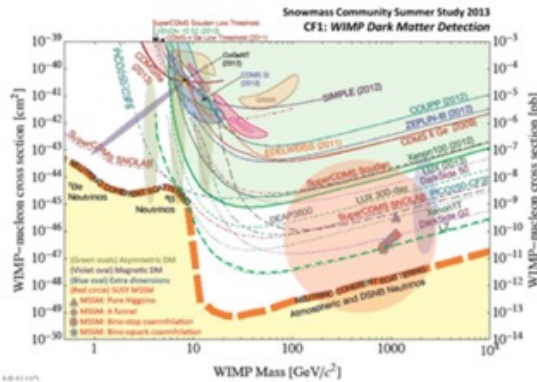


Boulby has hosted **Dark Matter search** studies for over two decades. Including the **NAIAD**, **DRIFT** & **ZEPLIN** experiment programmes.

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



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

World DM particle
search limits and
future projections



ZEPLIN-III @ Boulby

XIA alpha particle counter
<math><0.0001</math> alphas/cm²/hr

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

(XinRan Liu, this conf)

BUGS (Boulby UnderGround Screening). 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.

NEWS-G
Spherical Proportional Counter (SPC) studies @ Boulby

k. Nikolopoulos, I. Katsioulas, P. Knights, T. Need, R. Ward
University of Birmingham
And wider NEWS-G Collab.

Purpose-made gas filter
Copper Oxide H₂O removal
Molecular air sieve O₂ removal

11-anode sensor

SPC concept: Variable target Low E_{th}, Low mass sensitivity

Simulation study of neutron interactions in the S30 at Boulby


SPC Sensitivities

Direction of R&D at Boulby

- Instrumentation development for NEWS-G at SNOLAB
 - Multi-anode sensor
 - Gas filtration
 - Rate effect studies
- Neutron spectroscopy (N₂)
 - Neutron BG surveys
 - Industrial applications
- Towards scaled-up detector at Boulby, 3m diam. 5 Bar He-CH₄H₁₂: **DarkSPHERE**


Multidisciplinary Science


Applied low background particle physics, Earth and Environmental science, Astrobiology & Planetary Exploration Technology Development.

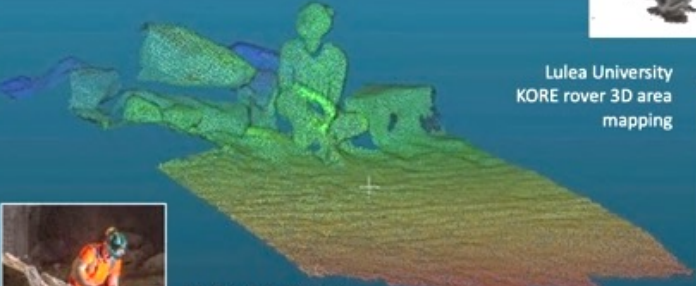


NASA-JPL
Signatures of life studies


MINAR VII & VIII.
2018 - 2020









Lulea University
KORE rover 3D area mapping




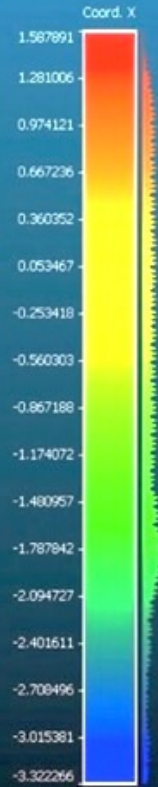
LA Nat Hist. Museum
Fluid inclusions in salts



Edinburgh University
MUFFHINS water activity monitoring payload







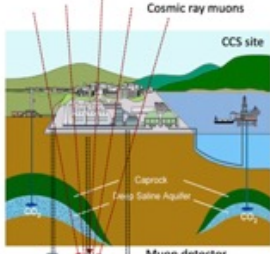
Coord. X

1.587891
1.281006
0.974121
0.667236
0.360352
0.053467
-0.253418
-0.560303
-0.867188
-1.174072
-1.480957
-1.787842
-2.094727
-2.401611
-2.708496
-3.015381
-3.322266

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




Cosmic ray muons
CCS site
Caprock
Deep Saline Aquifer
CO₂
Muons detector array

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)**



Muons-tides detector development



Bore hole detector installation

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

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

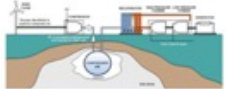
- Bore-hole detector development & testing
- Muon-Tides technology demonstrator
- Simulations of technique performance in CCS

Renewable Energy StOrage in UndeRground CavErns (RESOURCE)


STFC Boulby Mine, BGS and the University of Cambridge

RESOURCE Collaboration:
British Geological Survey
Boulby Underground Lab
U.Cambridge & U.Manchester

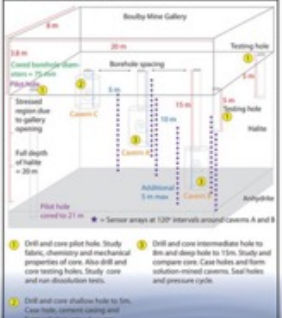
Low Carbon Technologies



- 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 trials, Boulby Mine



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

- 1 Drill and core pilot hole. Study fabric, chemistry and mechanical properties of rock. Also drill and core testing holes. Study core and rock dissolution levels.
- 2 Drill and core shallow hole to 5m. Core hole cement casing and form solution-mineral cavern.
- 3 Drill and core intermediate hole to 8m and deep hole to 13m. Study and compare core. Core holes and form solution-mineral caverns. Seal holes and pressure cycles.
- 4 Drill and core shallow hole to 5m. Core hole cement casing and form solution-mineral cavern.

Boulby Activities Now and Potential Future

Now	
Current Projects	Status
CYGNUS - DM R&D	E/P
News-G - DM R&D	A
BUGS: Ge, XIA, RnEm - Material Screening	A
RECON - Nuclear Security R&D	A
BUTTON – Nuclear security R&D	A
Muon Tomog – CCS & undersea Geoimaging R&D	A
RESOURCE – Energy store R&D	A
Seismology/AION R&D	A
BISAL – Biology/Astrobiology	A
MINAR – Planetary Exploration Tech development	A
Misc. Other. SELLR, C14, Adrok, BIO-SPHERE...	A/P
Outreach/ Education - Misc events, progs, Remote3...	A

Status: A = Active, P = Paused, E = End, I = Interest confirmed

2023-2030

Medium Term (Current Lab + mods)	Status
BUGS: Ge, XIA, RnEm, ICPMS - Material Screening	A/P
BUTTON-30 – Nuclear security R&D	P
RECON+ - Nuclear Security R&D	A/P
DarkSPHERE – DM Search	I
DATUM – Neutrino Tech R&D	I
SoLAr, SOLAIRE – DM/Neutrino R&D	I
AION-100 & 1000 R&D	I
Seismology Array – Geosurvey R&D	I
RESOURCE+ – Energy store R&D	A/I
Muon Tomog – CCS & undersea Geoimaging R&D	A/I
BISAL+ – Biology/Astrobiology	A/I
MINAR+ – Planetary Exploration Tech development	A/I
Misc. Other. Quantum Computing Tech R&D	-
Outreach/ Education: General Public, Schools +	A

2030-2040+

Long Term (Current lab plus major new lab)
<p>Particle Physics and Low Background Science:</p> <p>Dark Matter: Major Next Gen Experiments:</p> <ul style="list-style-type: none"> Xenon (XLZD) Argon (DarkSideLM+) Gas (DarkSPHERE+) <p>Neutrinos:</p> <ul style="list-style-type: none"> BUTTON-100+ DATUM (LEGEND Support), SoLAr / SOLAIRE+ <p>Mat screening & LB Techniques: A world's best facility:</p> <ul style="list-style-type: none"> Ge, XIA, RnEm, ICPMS, Cleanliness & Engineering R&D <p>Misc Other:</p> <ul style="list-style-type: none"> AION-100 AION 1000 Nuclear Security Gamma spec Quantum Computing Tech R&D & Operation
<p>Earth & Environmental Science:</p> <ul style="list-style-type: none"> Sustainable Energy R&D Seismology Observatory Geological Repositories R&D Misc geology / Geophysics R&D
<p>Astrobiology & Planetary Exploration:</p> <ul style="list-style-type: none"> Extremophile R&D Astrobiology / life beyond Earth R&D Human habitation R&D Planetary exploration technology development Robotics and AI Mining and industry application development.
<p>Outreach and Education:</p> <ul style="list-style-type: none"> A National Centre for Science and technology outreach and education.

Target projects for a major new UK underground facility / campus

Boulby Facility Expansion Plans

Submitted to STFC June 2021

FINAL REPORT

FEASIBILITY STUDY
FOR DEVELOPING THE BOULBY UNDERGROUND LABORATORY
INTO A FACILITY FOR FUTURE MAJOR
INTERNATIONAL PROJECTS

Supported by the STFC Opportunities Call 2019

H M Araújo¹, J Dobson², C Ghag², S Greenwood³, V A Kudryavtsev⁴, P Majewski⁵, S M Paing⁶, V Péc¹, R Saakyan⁷, P R Scovell⁸, N Smith⁹, and T J Sumner^{1*}

¹Imperial College London, UK
²University College London, UK
³STFC Rutherford Appleton Laboratory, UK
⁴University of Sheffield, UK
⁵STFC Boulby Underground Laboratory, UK
⁶SNOLAB, CA
*Corresponding author (t.sumner@imperial.ac.uk)

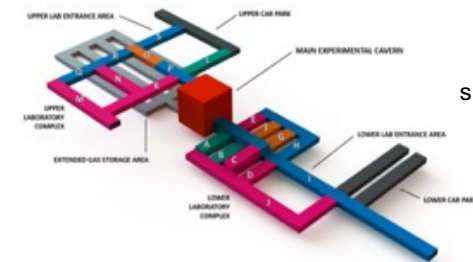
June 25, 2021
Issue v1.0

OFFICIAL-SENSITIVE [COMMERCIAL]

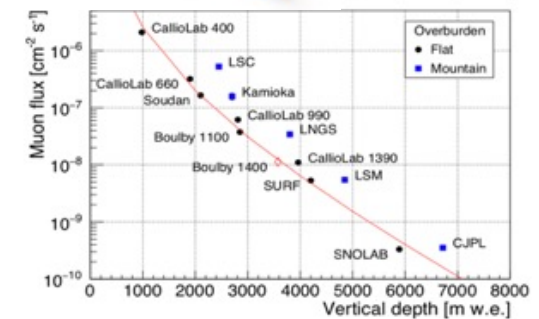
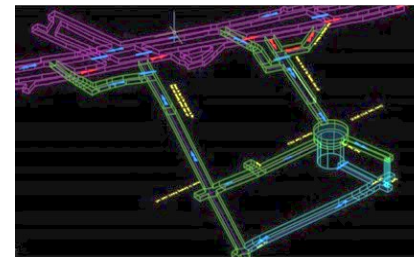
Boulby-FS (2020-21) Overview:

- Community-led study of motivation, context and practicalities of creating a major new deep underground science facility in UK
- Infrastructure specifications for potential projects (Dark Matter, Neutrinos & more).
- Conceptual designs for excavations and outfitting laboratories in 1.1km (Salt) and 1.4km (Polyhalite) layers
- Staffing and surface facility needs.
- Detailed costs and schedules.

LZ @ SURF.
Next generation
in the UK?



New lab specifications & designs



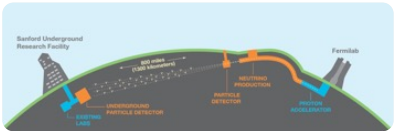
Government 'fit': Levelling Up, Strength in Places, Build Back Better, UK Science Superpower...

Boulby Now looking to EXPLAND to host next generation astro-particle physics projects from 2030+

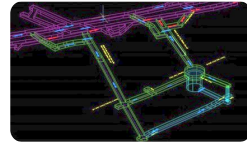
World deep underground laboratories...



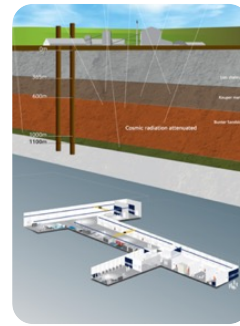
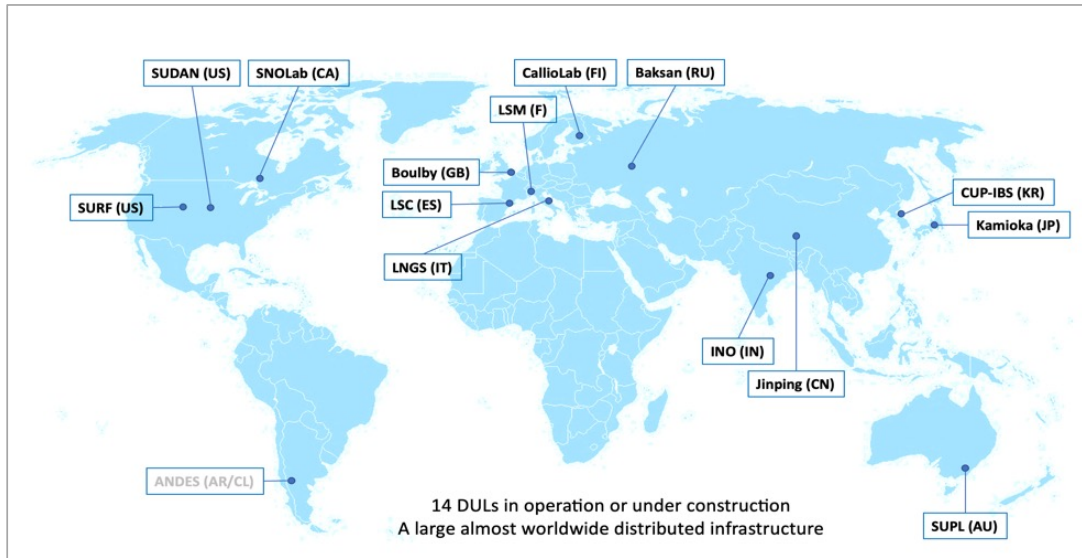
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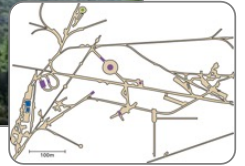
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 Current vol: 150,000m³
 Super-K, XMAS, Kamland-Zen +.
 Hyper-K (nearby, to come)



Boulby Underground Laboratory (UK)
 Working Mine, 2850 mwe
 Current vol: 7,200m³
 ZEPLIN+ (past), BUGs, News-G,
 RECON, Multi- sci, BUTTON (to come)

Upcoming and Future Underground Science Projects

Particle / Astroparticle Physics

- Direct dark matter searches
- Atmospheric, solar and supernova neutrinos
- Reactor and accelerator neutrinos
- Neutrino-less double beta decay
- Nuclear astrophysics / stellar reactions
- Misc. rare-decay processes

Other 'Multi-disciplinary' studies

- Pure and applied cosmic ray studies,
- ULB Gamma spectroscopy
- Earth & Environmental Sciences
- Biology / Geo-microbiology
- Astrobiology and planetary exploration
- Quantum sensors, quantum computing
- Etc...

Projects are varied, technologically innovative, challenging, impactful, exciting & GROWING.

Super-Kamiokande
Kamioka, Japan
50kT $Gd-H_2O$
Solar, Atmospheric &
SN Neutrinos
1996 – now.



Lux-ZEPLIN (LZ)
SURF, USA
10T (7T) LXe
Dark Matter search
2022 - now



Upcoming and Future Underground Science Projects

Selected Astroparticle Physics Projects...

Operating:

LZ: DM, LXe - SURF, USA.

Super-K: Neutrinos, Gd-H₂O - Kamioka, Japan

KamLAND: Neutrinos, LS - Kamioka, Japan

CUORE: 0vBB, HPGe – LNGS, Italy

PandaX: DM, LXe – CJPL, China

CDEX: DM, HPGe – CJPL, China

LEGEND-200: 0vBB, HPGe – LNGS, Italy

XENON-nT: DM, LXe – LNGS, Italy

SNO+: 0vBB, Te-LS – SNOLAB, Canada

Under construction:

DarkSide-20k: DM, Lar – LNGS, Italy

SuperCDMS: DM, HPGe - SNOLAB, Canada

NEXT-100: 0vBB, Xe – LSC, Spain

JUNO: Neutrinos, LS – Jiangmen, China

DUNE: Neutrinos, Lar, SURF, USA

HyperK: Neutrinos, Gd-H₂O - Kamioka, Japan

Selected Nuclear astrophysics Projects

LUNA: 400kV Accelerator – LNGS, Italy

JUNA: 400kV Accelerator – CJPL, China

CASPAR: 1MV Accelerator – SURF, USA

Selected Future Projects

LEGEND-1000: 0vBB, 1000kg HPGe

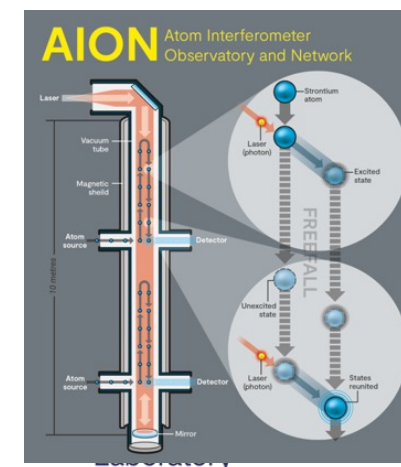
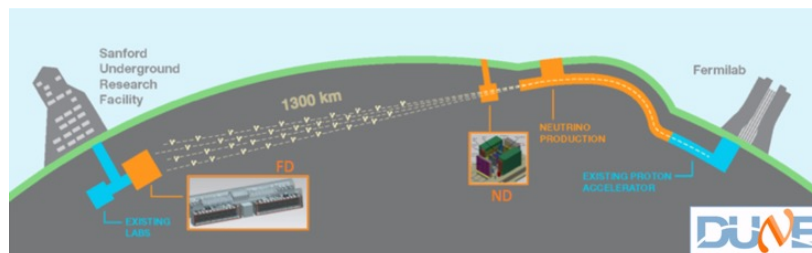
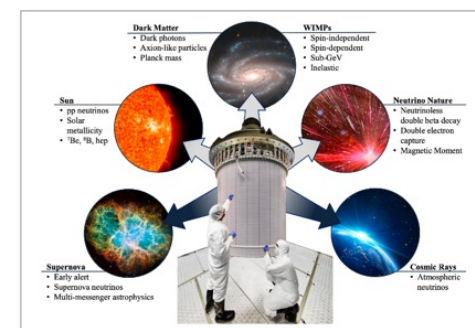
nEXO: DBD, 0vBB, 5000kg Xe

CUPID: 0vBB, 250kg Li₂MoO₄

XLZD: DM, 40-100T Lxe

ARGO: DM, 300T, Lar

AION 100 & 1000: DM & Grav. Waves,
Atomic Interferometer.



Summary & Some QUESTIONS...

Summary:

The world's underground laboratories are numerous and varied. These are special places for pure and applied science, innovation, outreach and education.

The underground science projects hosted by these laboratories are varied, technologically innovative, challenging, impactful, exciting, busy - and GROWING

QUESTIONS:

1) How can we make best use of the current underground science facilities – to serve the world science communities most effectively:

- Inter-laboratory communication and cooperation -> sharing practices?
- Some central coordination of facilities?
 - Available facility experimental space?
 - Available facility support services? E.g: Low background material screening.

2) Are underground science laboratories interacting sufficiently with national or international SURFACE facilities:

- Are they getting support they need from surface labs?
- Are their services being effectively/widely exploited by surface lab or wider community?
- Are underground facilities sufficiently visible?