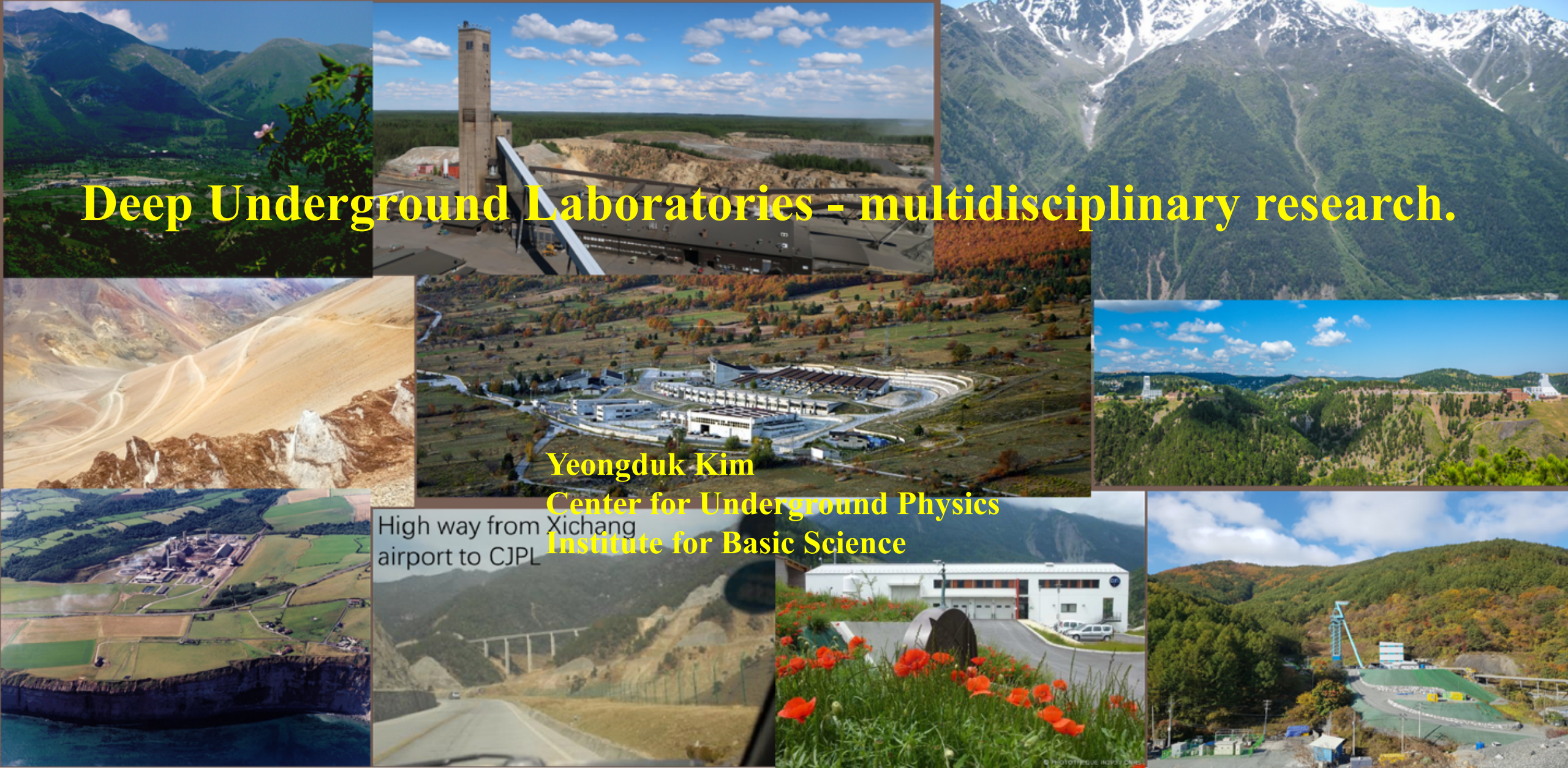
Deep Underground Laboratories - multidisciplinary research.



Yeongduk Kim
Center for Underground Physics
Institute for Basic Science

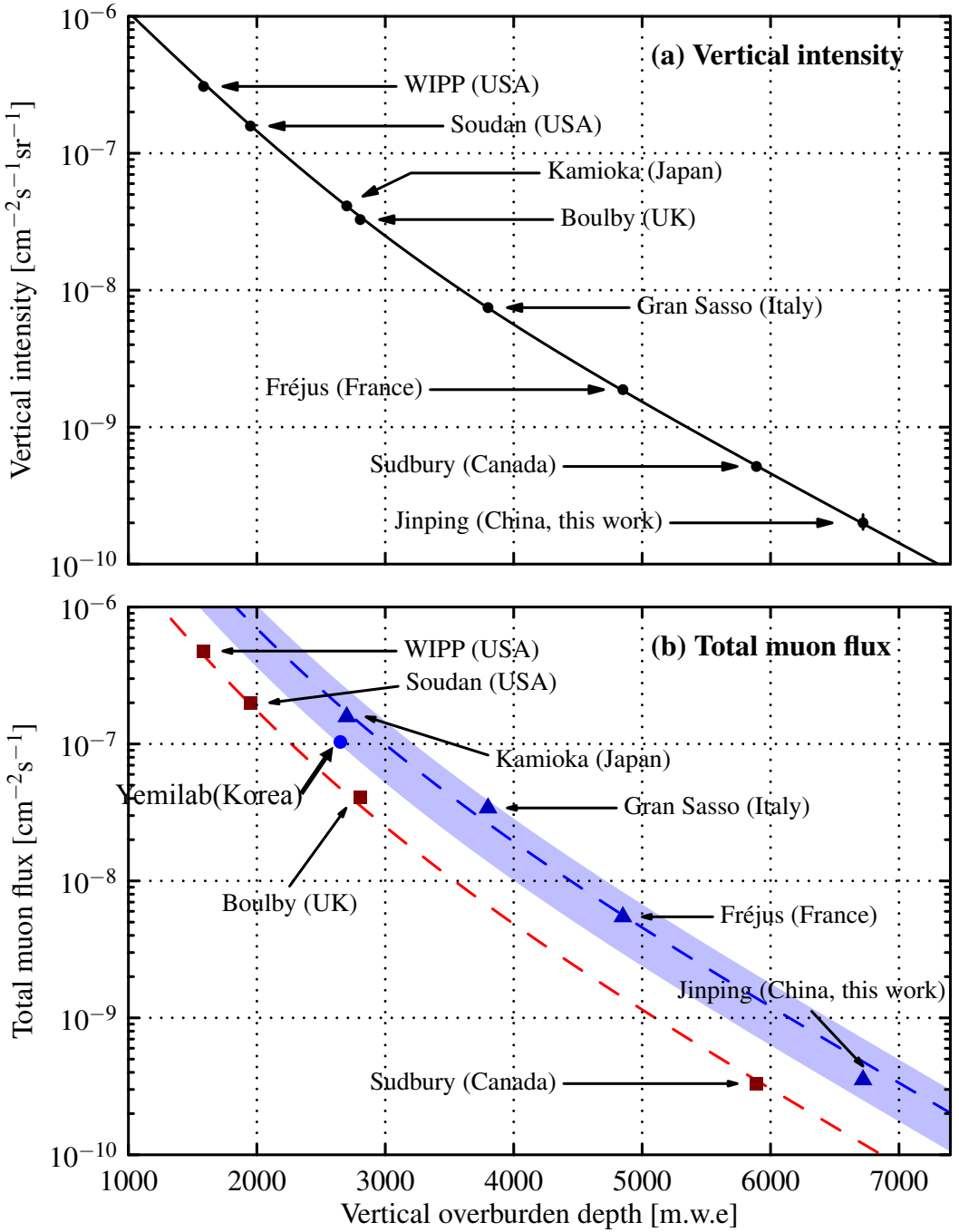
2023. 9. 1.

TAUP 2023, Vienna

Underground Research Facility

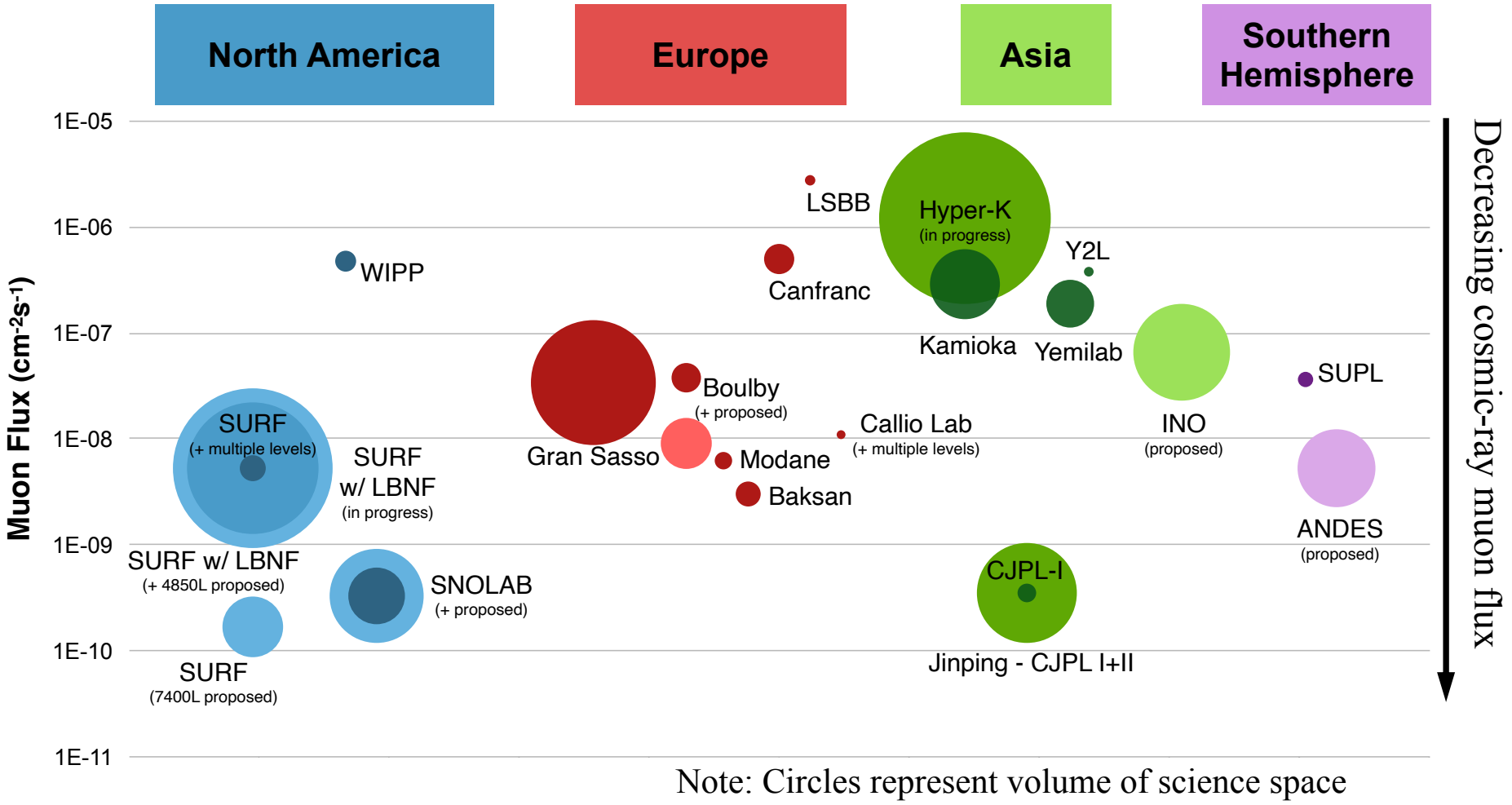
Muon flux

- Vertical flux is in linear with vertical depth.
- Total muon flux depends on geological profile.
- Updated from a**rXiv:2007.15925**



Worldwide Underground Facilities

From Jaret Heise's plot



- For last years, 5 new underground laboratories are completed or under construction in Asia.
- CJPL-II, HK, JUNO, Yemilab, SUPL

Radiopurity for Ultra-low background

For the ultimate backgrounds required for next generation experiments, we need to improve both the mitigation and the assay for the materials.

1. Mitigation
   - Radon free air supplying system : Increasing demand.
     - LNGS, LSM, LSC, Yemilab, Kamioka, …
   - Clean Rooms – Class 1-10000, Dust free & Rn-free clean rooms, rapidly increasing.
     - NOA(LNGS), Boulby,
   - Chemical purification - Recrystallization, Ion exchange, Distillation, …
   - Electroformed copper, New material
     - SURF, LSC, ECuME (SNOLAB), HAMMER (LNGS)
   - Surface cleaning - Electropolishing, Nitric acid
   - Shielding materials - Water tank, LN2 tank, Cu, Roman Pb shielding, Rock Argon
     - ARIA(Italy), CJPL, LXe detectors,

Radiopurity for Ultra-low background

2. Radioassay

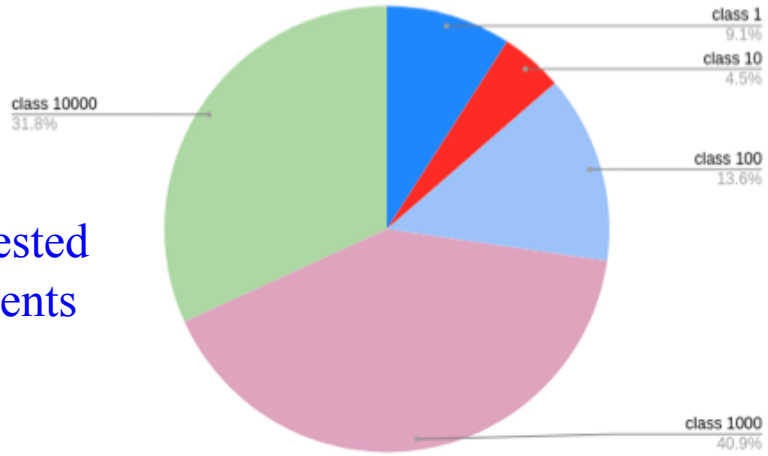
- HPGe Spectroscopy (Daughters of ^{226}Ra ^{228}Ra, ^{40}K …)
  - Down to ~10 μBq/kg sensitivity for GeMPI. Typically ~ 1mBq/kg sensitivity.
  - ~100 HPGe detectors at underground
  - Large facility (~ 10 HPGe): BUGS(Boulby), BHUC(SURF), DURF(CJPL), STELLA(LNGS), …
- Alpha Screening - UltraLo-1800 (XIA), Si Spectrometers becoming a standard at DUL
  - ~ 10^{-4} $alphas/(cm^2\ hour)$
- Radon Emanation Assays - Rn emanation from construction materials is critical to DM searches.
  - ~ 0.2 mBq of sensitivity with Rn Chamber.
  - UCL, Boulby, SNOLAB, SURF, …
- Mass Spectrometry – Dedicated machines increasing. Sensitivity reaches down to 0.01 ppt
  - HR ICP-MS (LNGS), QQQ-ICP-MS (PNNL, LSC), Kamioka, SNOLAB, CUP(IBS), CJPL…
- NAA – Plastic materials
  - ~0.1 ppt for both ^{238}U & ^{232}Th reaches PTFE, Acrylic (JUNO)

- More laboratories install the above equipment as standards at UL.
- Need to develop Solid Phase Extraction followed by alpha measurements with low temperature detector, liquid scintillator, well-type HPGe etc. for < 10 μBq/kg

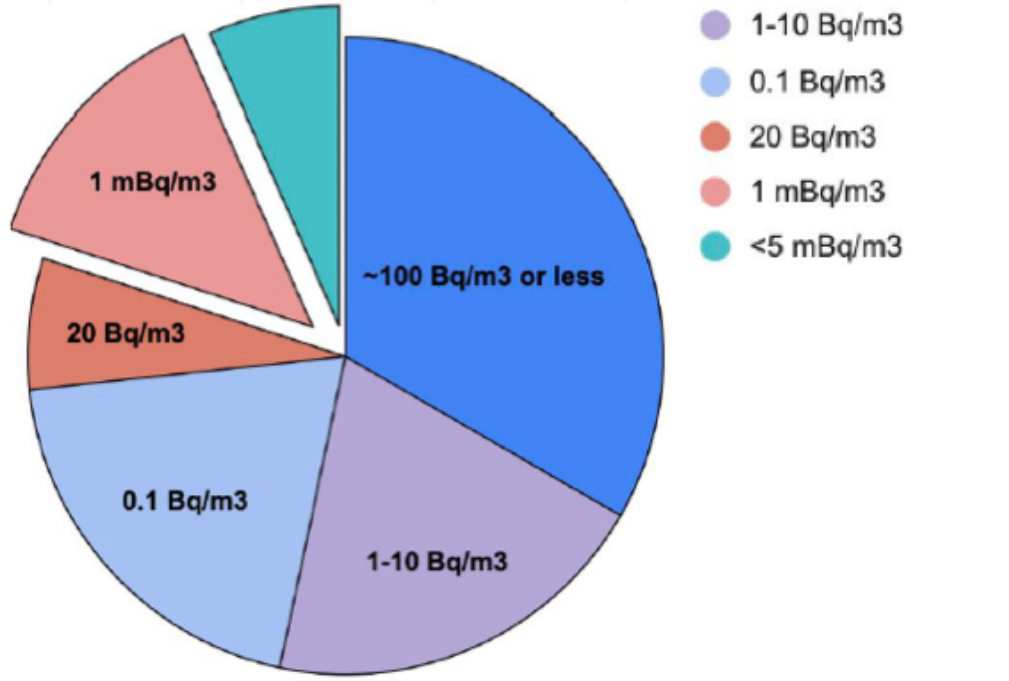
Clean room

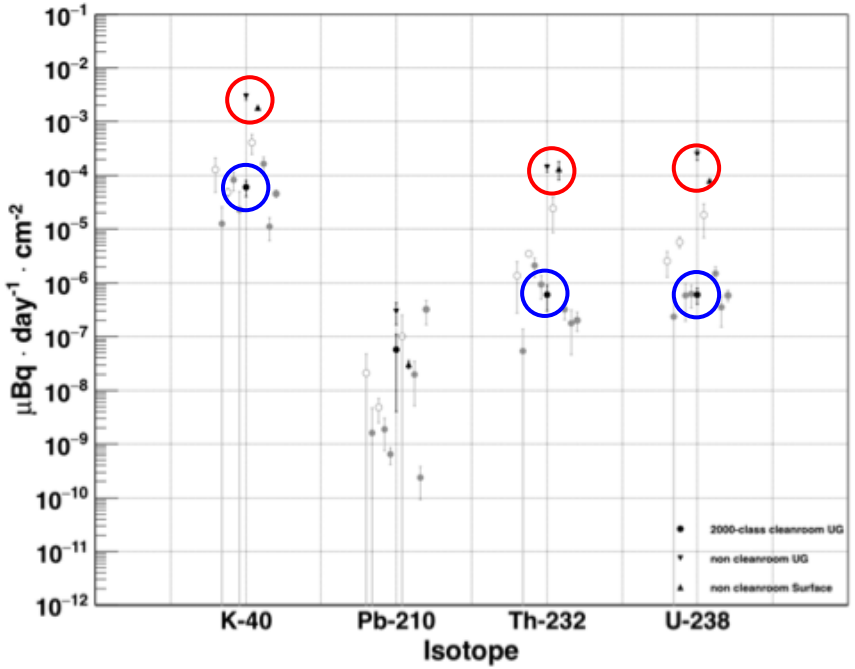
Increasing demand for clean room with 1-10000 class, and Radon reduced clean room is also demand fo r future experiments. (snowmass report "Supporting Capabilities for Underground Facilities")

Cleanroom class requested by future UG experiments



Radon reduced space needs for future experiments





Dust fall-out
2 orders lower in 2000 Class room
$\sim 10^{-6} \mu Bq/(day\ cm^2)$

Nucl.Instrum.Meth.A 994 (2021) 165051

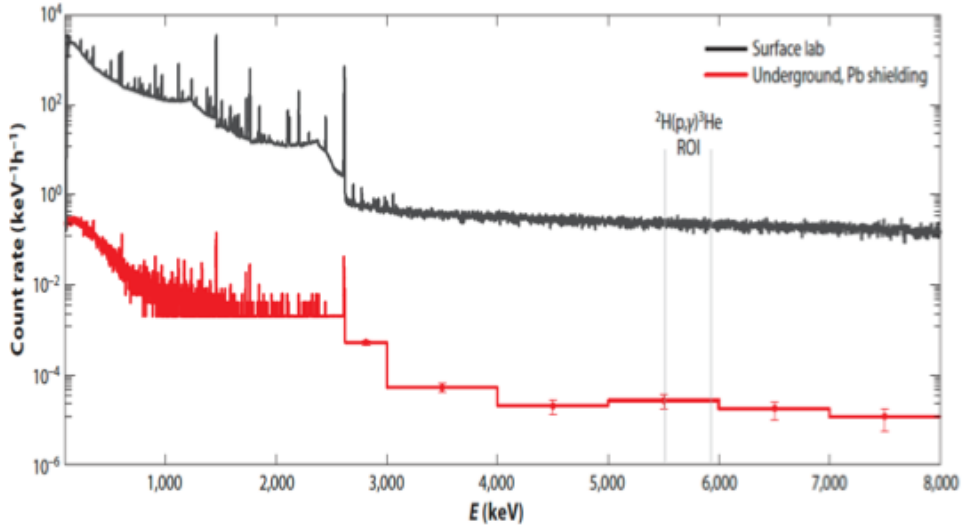
Multidisciplinary Research @ Underground

- Nuclear Astrophysics -
- Biology
- Quantum Computing
- Geology, Engineering
- Radiation Monitoring
- Etc.

Ref. "Snowmass 2021: Underground Facilities & Infrastructure, Topical Report on Synergies in Research at Underground Facilities", Curceanu et al., arXiv:2210.03145

Nuclear Astrophysics

M. Aliotta et al., Annu. Rev. Nucl. Part. Sci. 72, 177 (2022)



In the energy range of stellar burning, the reaction cross-sections of interest are extremely small.

At ground, the heavy shielding produce 2ndary radiation from cosmic ray, which is absent at deep underground.

4 underground labs.

Facility	Location	Begin	Depth	Accelerator	E	Ben intensity
			mwe		keV	Proton, alpha (emA)
LUNA-400	LNGS	2001	3800	Cockcroft–Walton	400	1 mA, 0.5mA
LUNA-MV	LNGS	2022	3800	Cockcroft–Walton	3500	1 mA, 0.5mA
CASPAR	SURF	2017	4300	Van de Graaff	1100	0.25 mA
JUNA	CJPL	2020	7620		400	12 emA, 6 emA
Felsenkeller	Felsenkeller	2019	110	Pelletron Tandem	5000	~ 0.01 mA

S. Zavatarelli's slide

	motivation
^{14}N(p,γ)^{15}O	Solar Neutrino and core and sh ell H-burning
^{19}F(p,γ)^{20}Ne ^{19}F(p,γ)^{16}O	NeNa cycle in AGB
^{24}Mg(p,γ)^{25}Al	Mg-Al cycle in AGB
^{10}B(α,p or d)	First generation stars
^{6,7}Li(α,γ)^{10,11}B	First generation stars

Biology @ DUL

- Underground Microbial Research
  - ~99% of microbes in nature are unknown.
  - Huge microbial diversity at extreme conditions, such as deep underground, to be discovered.

- Low radiation backgrounds Effect.
  - Long-term impact of low dose radiation on living systems.

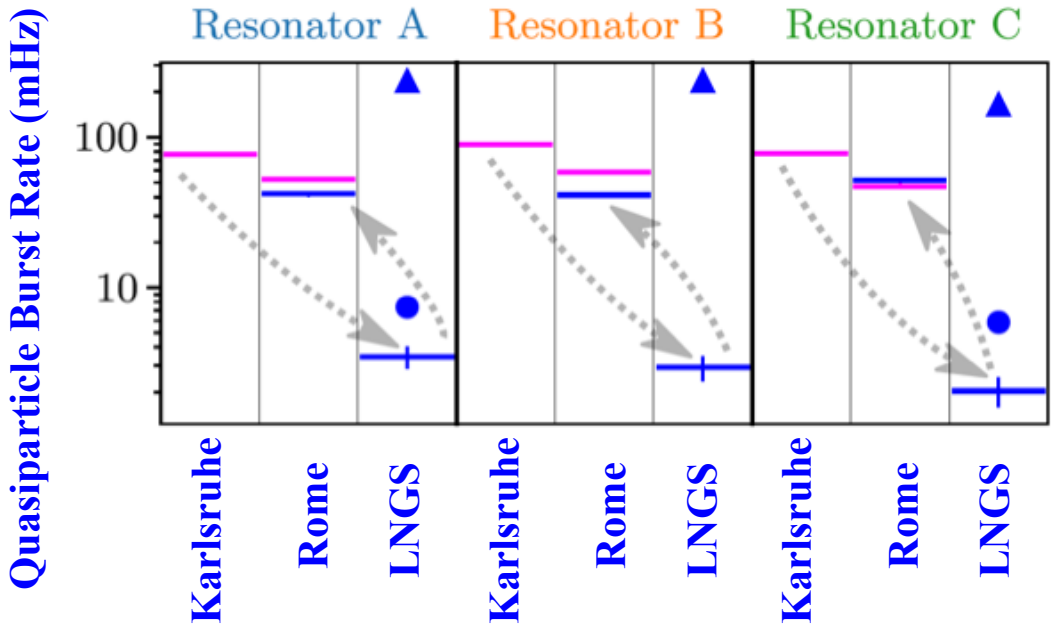
- DULIA(Deep Underground Laboratories Integrated Activity)-Bio workshops are held in 2015, 2019 : Aldo Ianni

- LNGS, SURF, Boulby, LSC, LSM, SNOLAB

Quantum Computing

- To make the quantum computing viable, the qubits must exhibit long coherence times.
- Coherence for superconducting qubits can be spoiled by an excess density of quasi-particles.
- One contribution to quasi-particle poisoning appears due to ionizing background radiation.
- Qbit backgrounds = Dark matter backgrounds → Low Energy Excess (from Jeter Hall)
- DUL can be a good environment for the studies.

L. Cardani et al., Nature Comm. 12, 2733 (2021). LNGS tests



w/o shielding

w/ ThO_2 source

w/ shielding

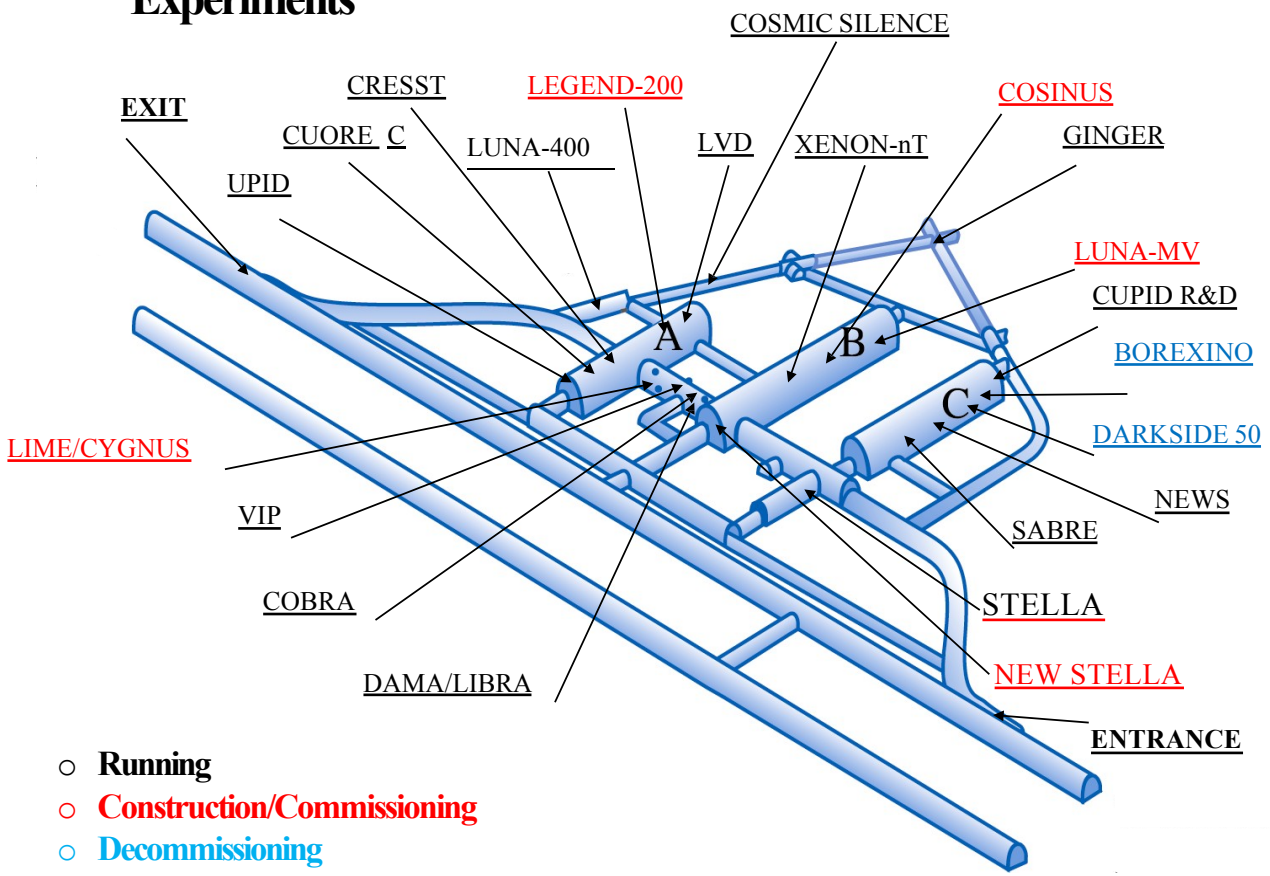
- LNGS, SURF, Boulby, LSC, …

Updates of Underground Labs

LNGS

- Radon ~100 Bq/m3 with 5-8 air changes/day
- 3 main experimental halls: 100 m x 20 m (W) x 18 m (H) (Vol = 180,000m^3)
- 22 experiments data taking or under construction
- Laboratory for very low radioactivity measurements

Experiments



- **Running**
- **Construction/Commissioning**
- **Decommissioning**

Dark Matter :
XENON-nT, COBRA, COSINUS, CRESST, DAMA, DARKSIDE-20k, LEGEND-200, LEGEND-1000, NEWS-DM, SABRE, VIP
Neutrinoless DBD:
CUORE, CUPID
Multidisciplinary:
LUNA-400, LUNA-MV…

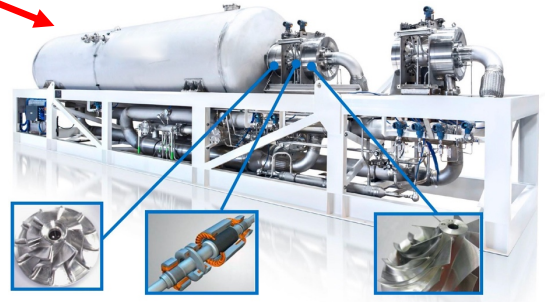
Multidisciplinary

- Gravitation and General Physics
  - Precision measurements
  - Tests in highly reduced seismic noise environment
- Material science – Ultrapure crystals for DM and DBD
- Geophysics and geology
  - Underground water, trace radioactivity
  - Antineutrinos from the earth
- Quantum Computing – Low background studies
- Biology – Effects of very low doses on living organism

Updates

- STELLA upgrade for low background measurement.
  - New GeMPI will be installed.
- NOA: new large clean room(ISO6), Dark side sensor assembly
  - All packaging, bonding machines
  - Rn-free air system will be installed.
- HAMMER the new additive manufacturing Lab
- LNGS-FUTURE program to upgrade LNGS infrastructures.

- Nitrogen liquefier to support DarkSide-20k and other underground projects.
- Helium liquefier (Underground) to support the LHe-bathbased Dilution Refrigerators.
- Cryogenic Platform (CRYO-P): 2 dilution refrigerators at underground to test cryogenic detectors and perform low background tests.
- Advance Cryogenic Lab (ACryL): Above-ground dilution refrigerators to develop, test, and characterize cryogenic components.

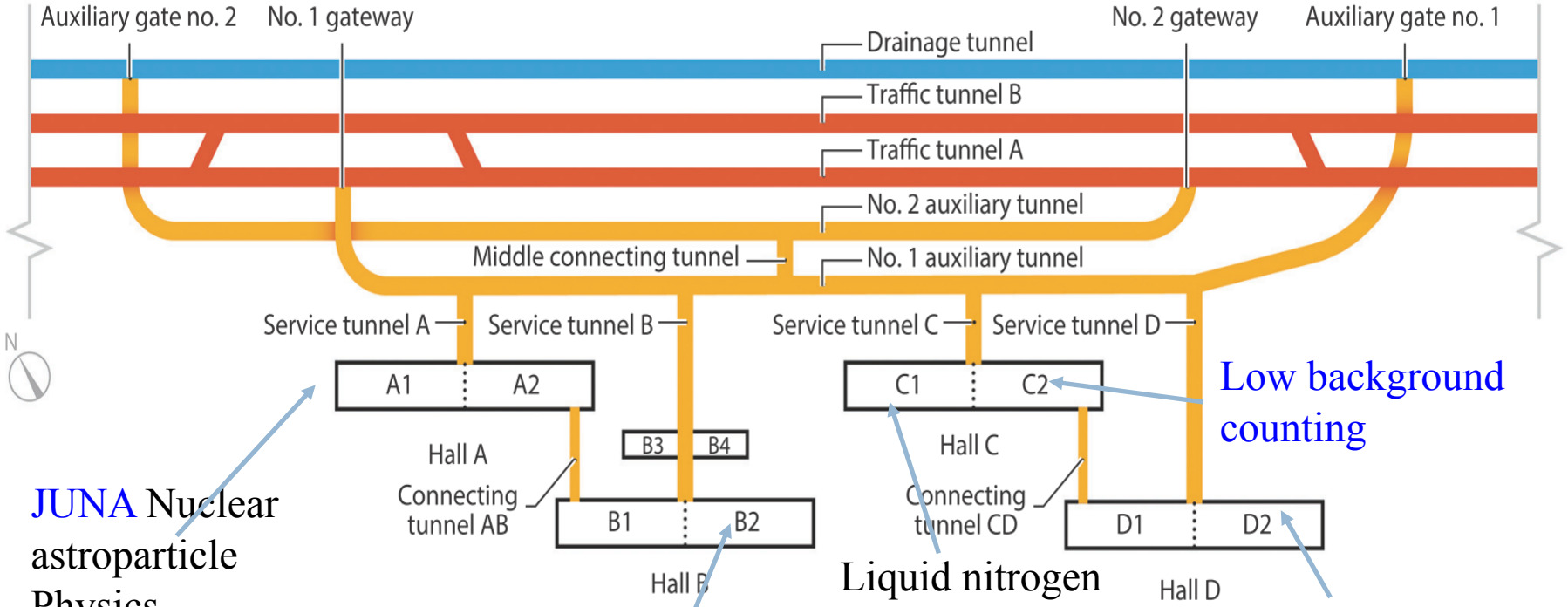


CJPL

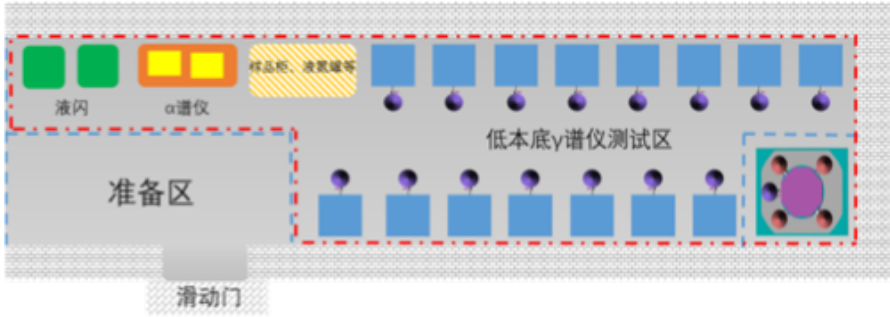
- World's deepest underground lab: 2400m rock overburden;
- Constructed by Tsinghua U. and Yalong Hydropower Company in 2009-2010
  - CJPL-II : 300k m^3 with 4 main halls of 14m x14m x130m
    - 2015: excavation of Halls complete
    - 2016: expansion and ventilation

- CJPL-1 : 4k m^3,
  - Two DM exp.
    - CDEX, PandaX
  - LBF(radio-assay)

Dark Matter :
PandaX, PandaX-xT, CDEX, CDEX-300, CDEX-1T,
Neutrinoless DBD:
CDEX-DBD, NuDEx(^{82}Se), CUPID-CJPL
Neutrino:
Jinping Neutrino Exp
Multidisciplinary:
JUNA, Microbial, SER(QC), GeoDEX(Geology)



DURF project



- National Major Science &Technology infrastructure of China
  - Based on CJPL-II
  - Feasibility report approved in 2018.12
  - Formal start in the end of 2020
- DURF (Deep Underground and ultra-low Radiation background Facility for frontier physics experiments)
  - Shielding setup
    - LN2、 Pure water Tank
  - Low background counting & materials
    - Material screening
    - Underground copper production
  - Surface lab. in Xichang city
  - Will be finished by the end of 2024

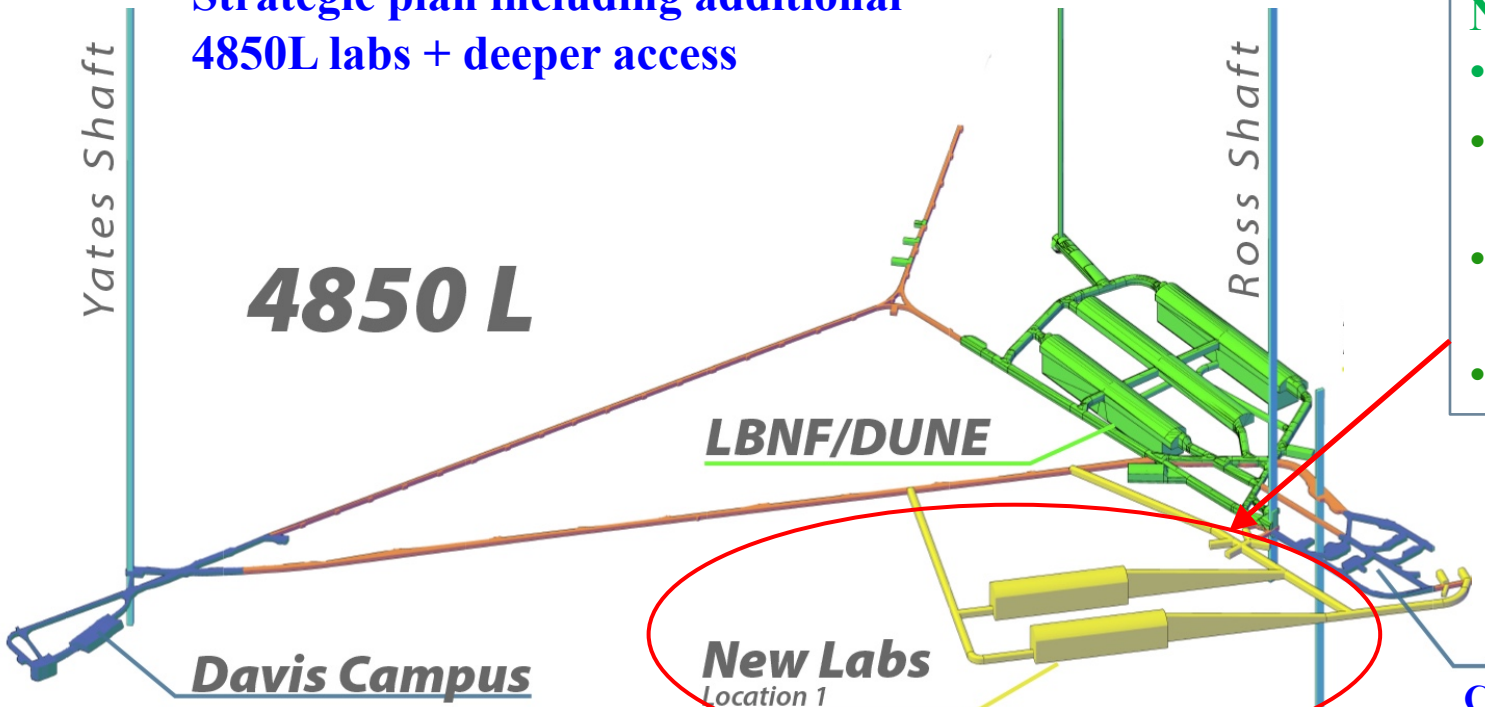
- 15 HPGe detectors
  - 10 x coaxial p-type
  - 2 x coaxial n-type
  - 2 x well-type
  - 1 x ultra-low energy
- Low-radon air purging
- MDA: <1.0 mBq/kg

Hall

Service tunnel

SURF - Current & Future Plan

Strategic plan including additional 4850L labs + deeper access



New Labs for future experiments

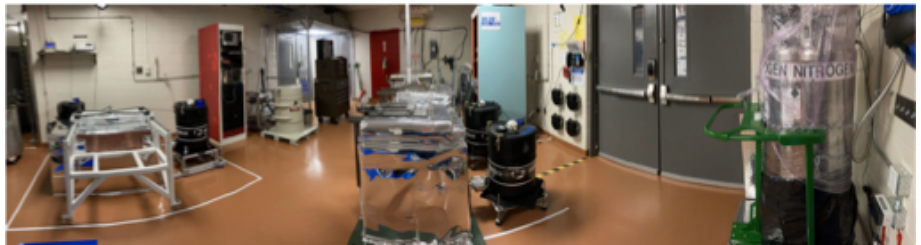
- **South Dakota approved $13M (phase1)**
- Initial design underway to support excavation in early 2024
- 4850L: Up to 2 new caverns (phase 2 100M$)
  100m L x 20m W x 24m H, Each
- availability proposed starting in ~2030

SURF whitepaper https://arxiv.org/abs/2203.08293

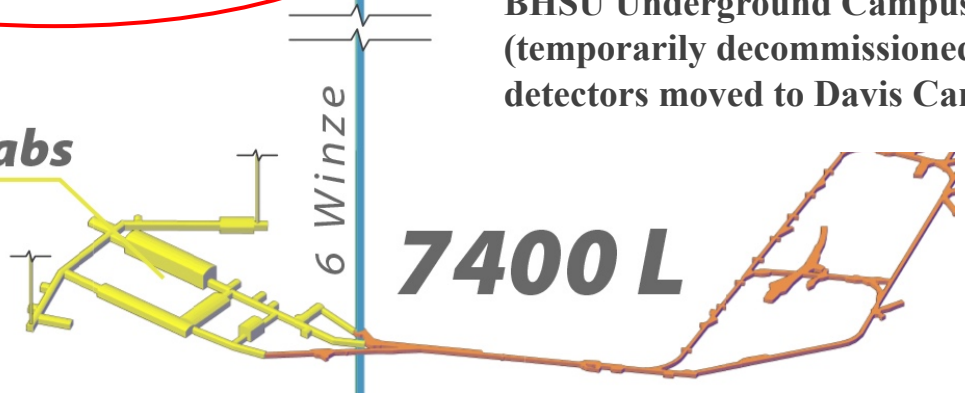
LUX-ZEPLIN (LZ)

MAJORANA DEMONSTRATOR (MJD), incl Copper Electroforming

BHSU Underground Campus, incl Low-Background Counting



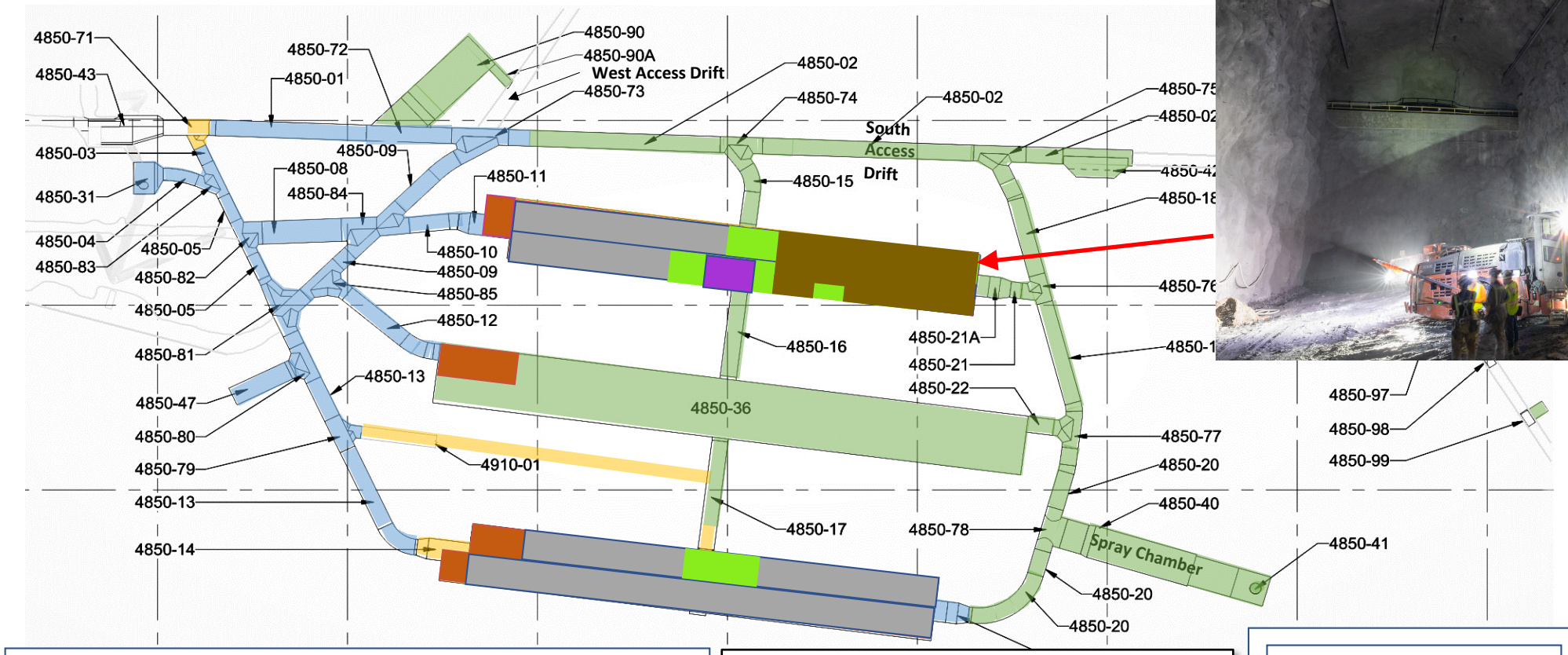
CASPAR (temporarily mothballed Spring 2021)
BHSU Underground Campus
(temporarily decommissioned Summer 2020, detectors moved to Davis Campus)



7400L: Caverns (nominal)
75m L x 15m W x 15m H
schedule TBD

LBNF/DUNE Excavation Progress

77% completed by volume. Excavation phase continues through mid-2024.



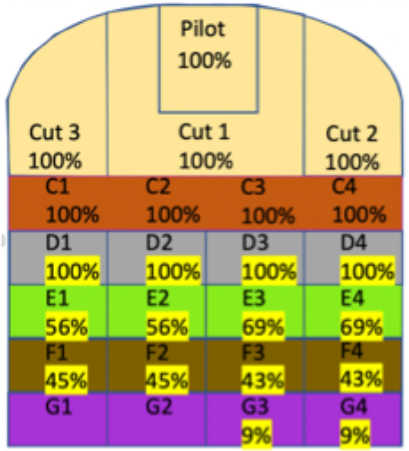
- 4850L Excavation Completed
- Excavation and Ground Support Complete and Accepted
- Concrete Complete

2x Detector Caverns:
145m L x 20m W x 28m H

1x Utility Cavern:
190m L x 20m W x 11m H

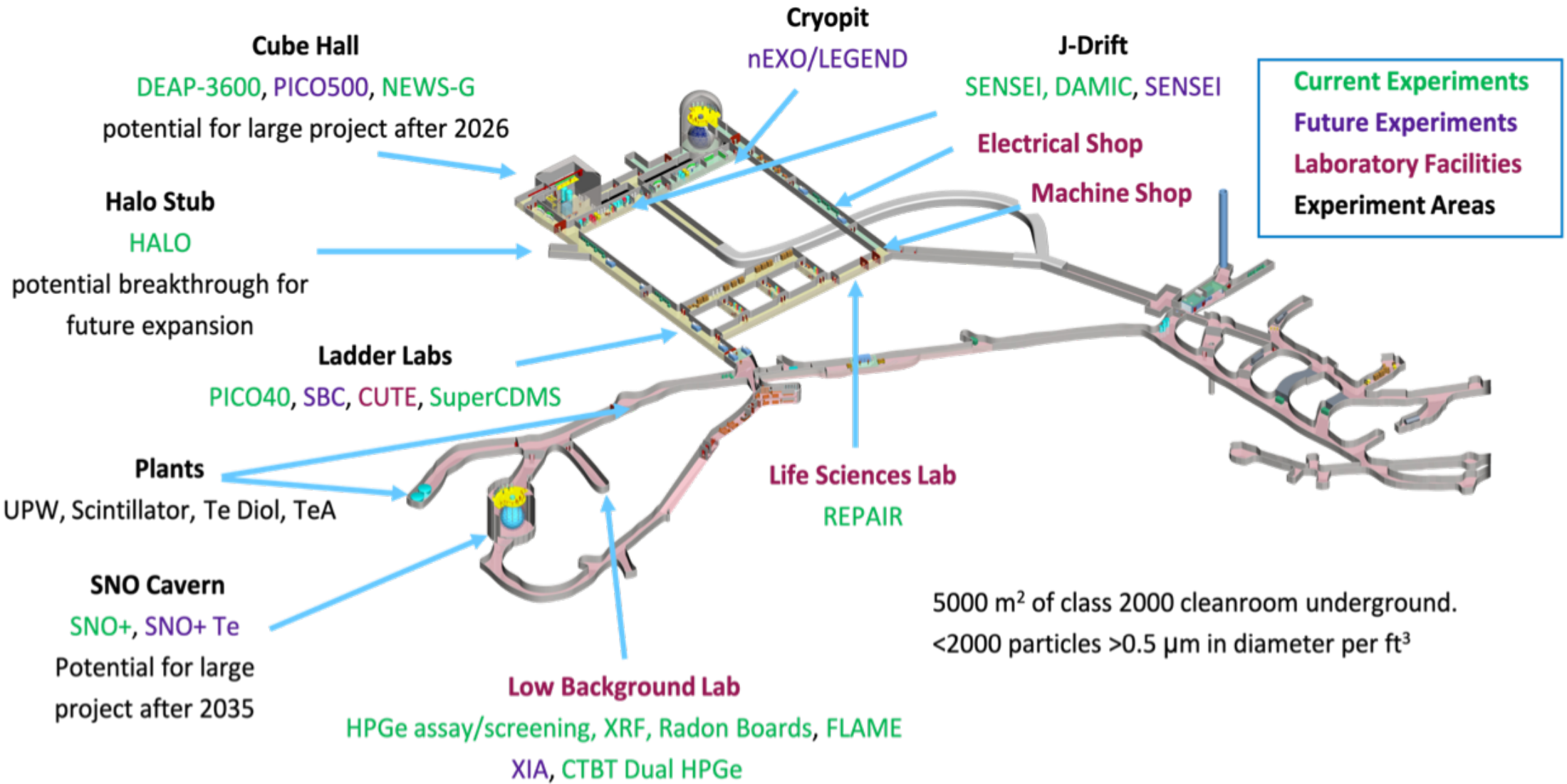
Benching 4850L – 4910L

- Bench C
- Bench D
- Bench E
- Bench F
- Bench G



SNOLAB

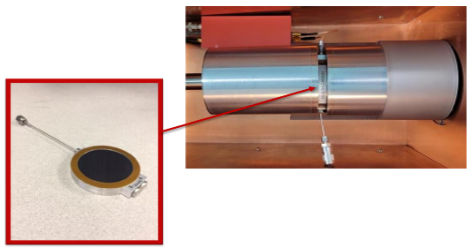
- SNOLAB is operated jointly by University of Alberta, Carleton University, Laurentian University, University of Montreal, and Queen's University and are funded by the Province of Ontario, and the Canada Foundation for Innovation.

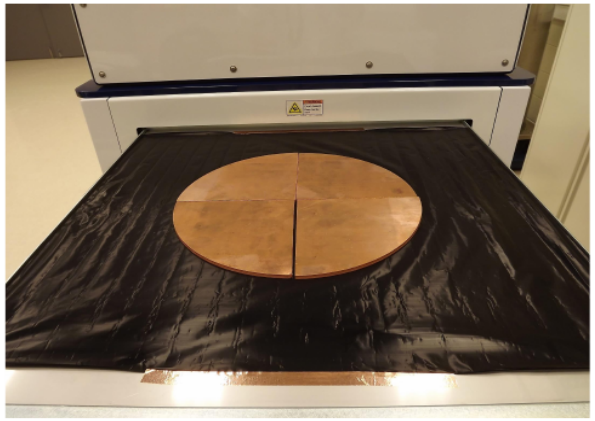


Updates of SNOLAB

- Radon Emanation Assay :

  Background goal of ^{222}Rn counts : <1/week. (Cf. Best detectors currently at ~4/day.)
- Underground Background Measurements
  - Radon (Durridge RAD7 continuous monitoring)
  - Neutron Backgrounds (Bubble Technology BDS System - 144 detectors at 6 thresholds)
  - Gamma Backgrounds: (2 NaI Detectors – Detailed spectra up to 3 MeV)
  - EMI Backgrounds: (RIGOL Spectrum Analyzer – 9 kHz to 7.5 GHz)
- Cryogenic operation
  - Underground liquid nitrogen production since 2022 (supplies most of the lab needs)
  - CUTE (shielded dilution refrigerator) has been operational since 2020, can run for weeks unattended. Tests for SuperCDMS
- Dust measurements of actual radioactive fallout successfully guiding operations.
- New ICPMS, HPGe counters, XIA alpha counters





Kamioka, Super-K

SK-VI (0.01%Gd)results and SK-VII (0.03%Gd) performance

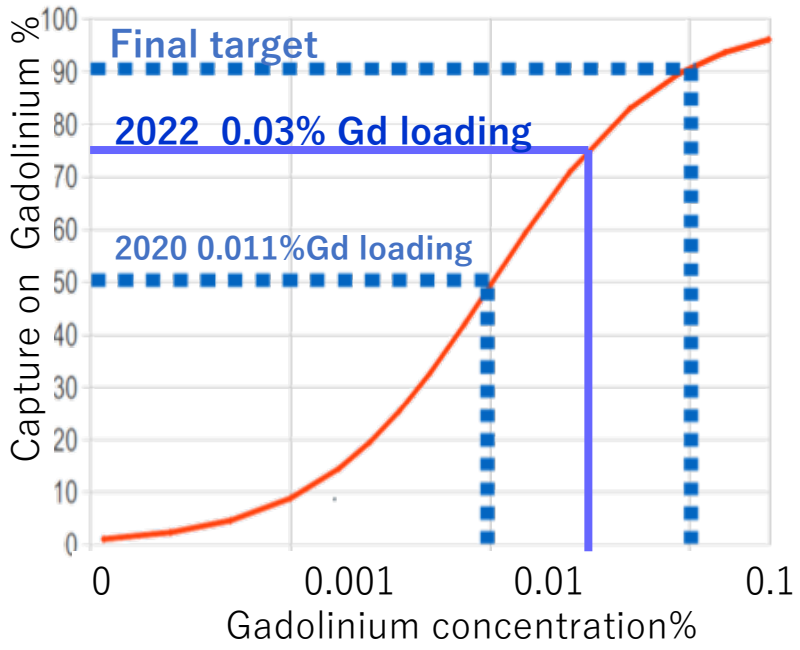
Gd-loading to SK

Significantly enhances detection capability of neutrons from $\bar{\nu}_e$ interactions

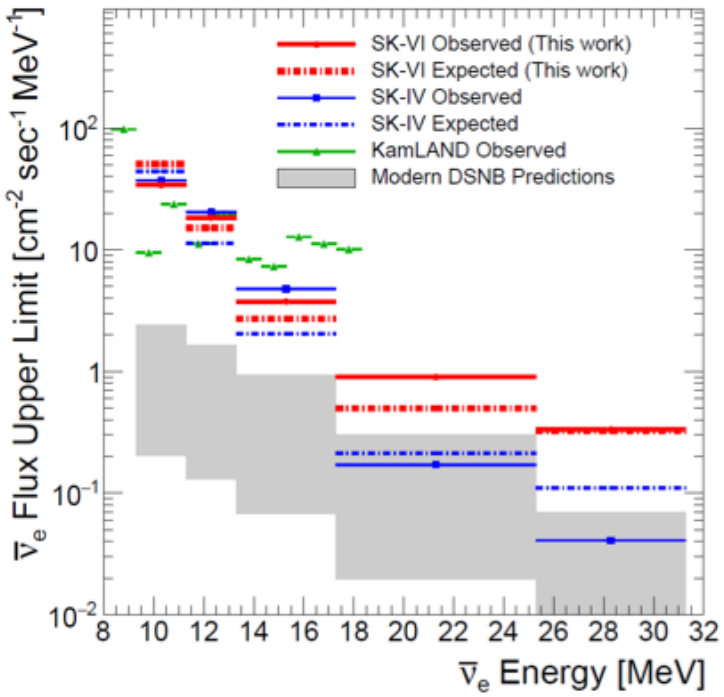
Physics targets:

- **Detect the world's first Diffuse Supernova Neutrino Background (DSNB)**
- **Improve pointing accuracy for supernova**
- **Early warning of nearby supernova from pre-burst signal (silicon burning)**
- **Enhance ν or $\bar{\nu}$ discrimination in atmospheric ν & T2K analysis**
- **Reduce backgrounds in proton decay search**

2nd loading in June-July 2022
0.033% Gd (SK-VII)

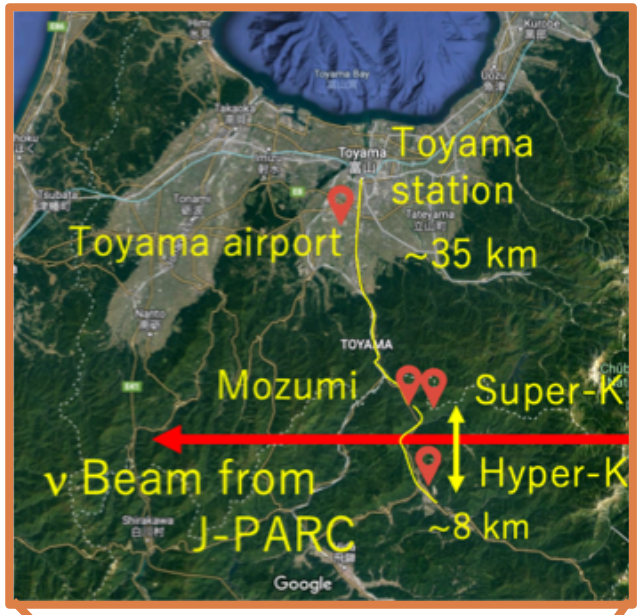


Astrophysical Journal Letters 951 L27 (2023)



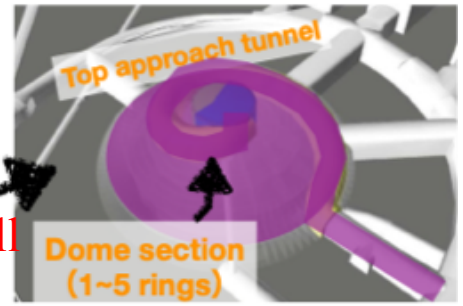
Comparable to the World's highest sensitivity by pure water phase SK-IV (2970 days)

Hyper-Kamiokande

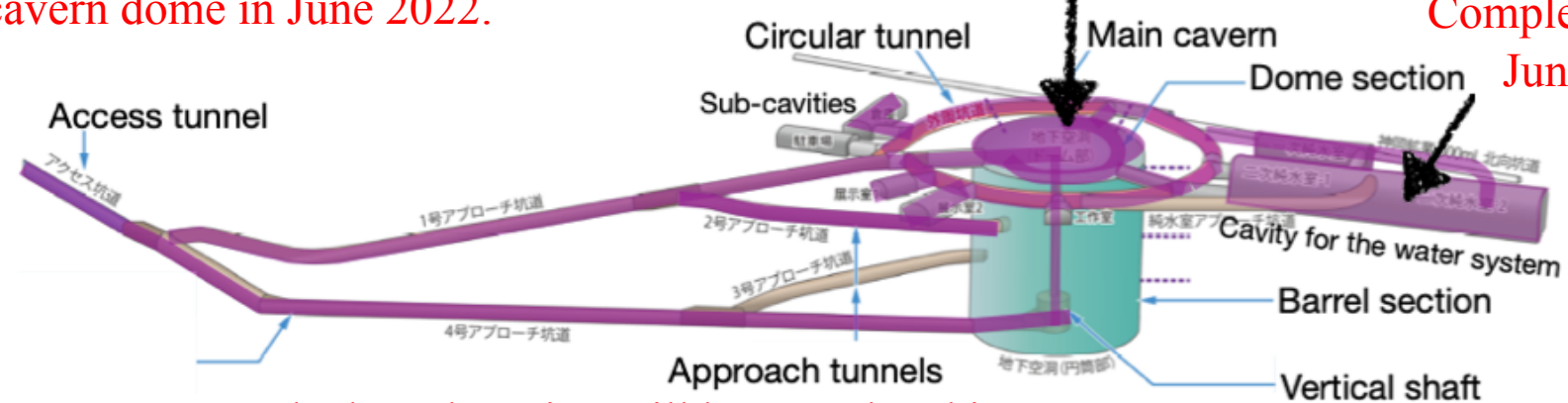


Excavation started in May 2021.
The tunnel reached the center of the cavern dome in June 2022.

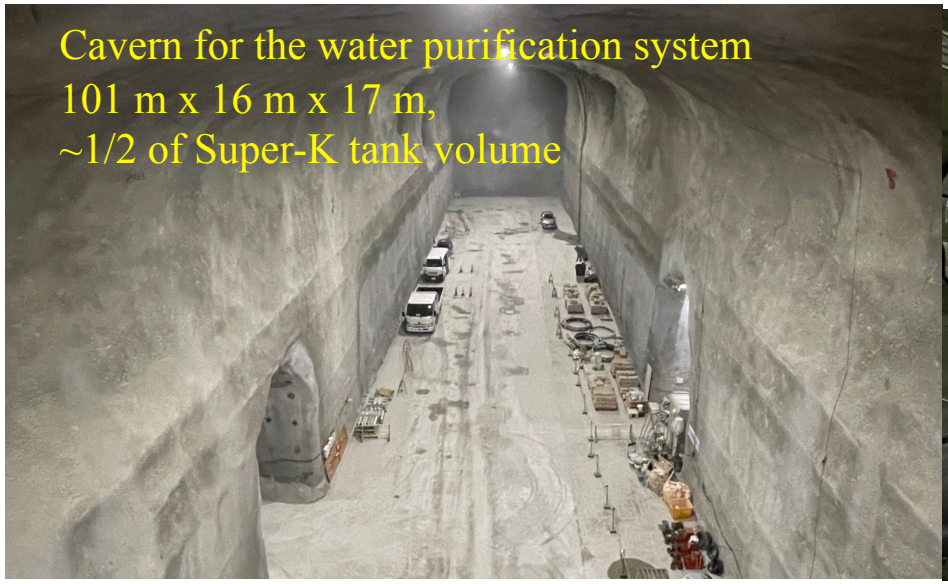
Excavation of the dome, the highlight of the excavation, will be completed in Oct. 2023.

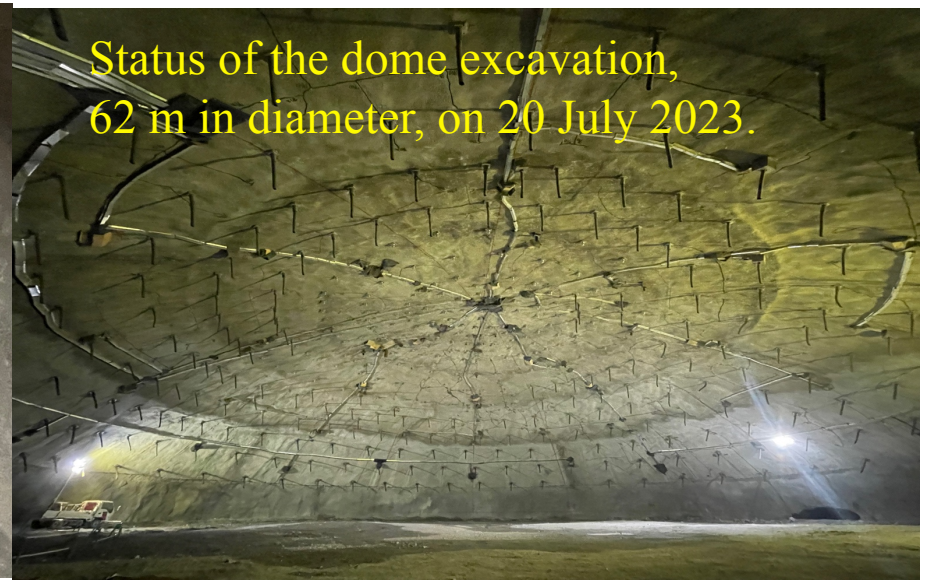


Completed in June 2023



The barrel section will be completed in 2024.





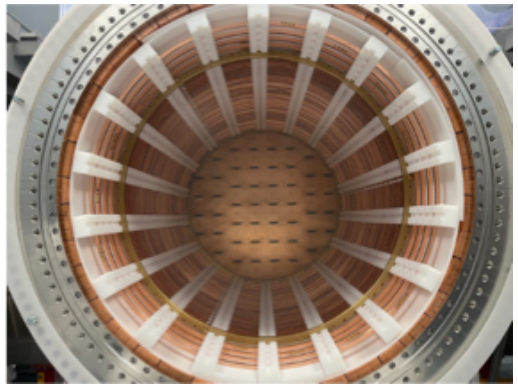
LSC - updates

x2 increase in budget, people on site and experiments

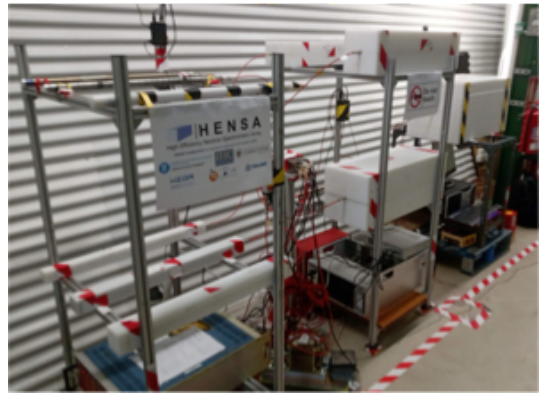
HPGe detector GeRysy

ICPMS-QQQ

ANAIS Experiment.



NEXT-100 interior



High Efficiency Neutron Spectrometry Array (HENSA)

GeRysy: **New** lowest background world **record** in **HPGe** gamma screening with **µBq/kg sensitivity** (led by **G. Zuzel**).

ICPMS-QQQ: New, placed in Class ISO5 clean room underground: **2 (20) ppq** sensitivity in ^{238}**U(**^{232}**Th).** Improving on ^{40}**K.**

ANAIS experiment: Modulation excluded at 3 sigma. Started **last (7th) year** of data taking **to reach 5 sigma** exclusion.

NEXT-100 experiment: Most **elements in place**. TPC installed. Detector to be **completed** by **November 30, 2023**.

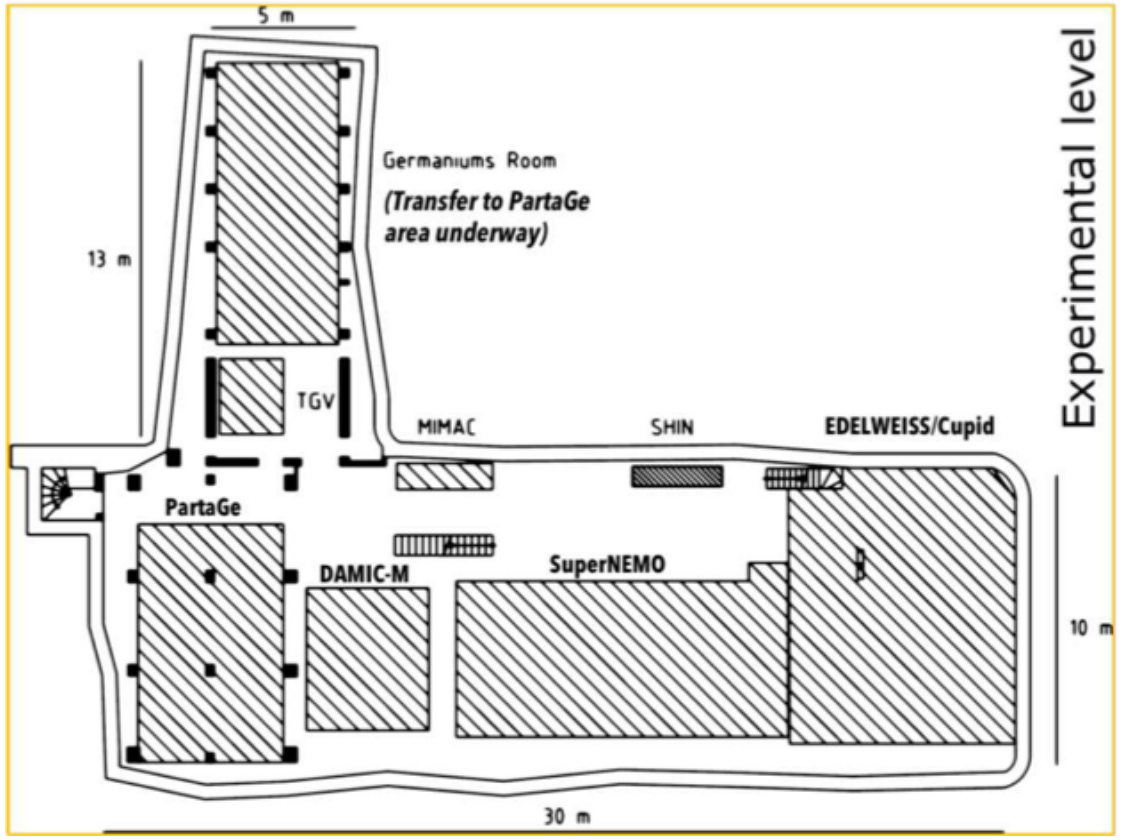
HyperKamiokande: Coordination of the Spanish contribution to the construction of HK (PMT covers, ventilation and geomagnetic compensation systems, electronic components, calibration sources, …).

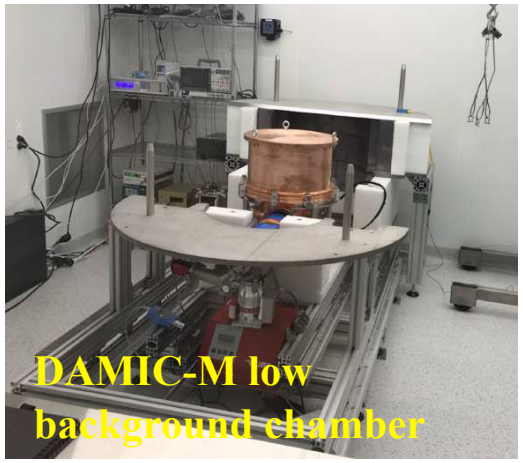
A dedicated facility for biology is built underground at LSC, becoming leader on biology for ULs

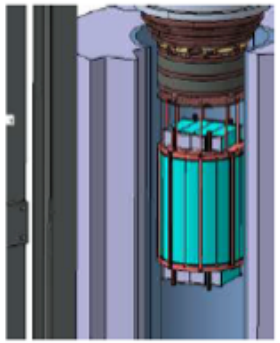
LSM

- Tight occupation of available 400 m²
- Plans to install 180 m² mezzanine level (over the crane access) above expt. Level
- Current conversion of EDELWEISS area for BINGO + DAMIC-M + future expts
- **Priority topics → Light Dark Matter, R&D for 0nDBD**

Dark Matter :
NEWS-G, Edelweiss, DAMIC-M
Neutrinoless DBD:
CUPID-Mo, SuperNEMO, BINGO
Multidisciplinary:







BINGO cryostat @LSM

^{100}Mo + ^{130}Te scintillating targets

BGO internal shelding

Multidisciplinary

Pluri-disciplinary program open to academic & industrial users + partners

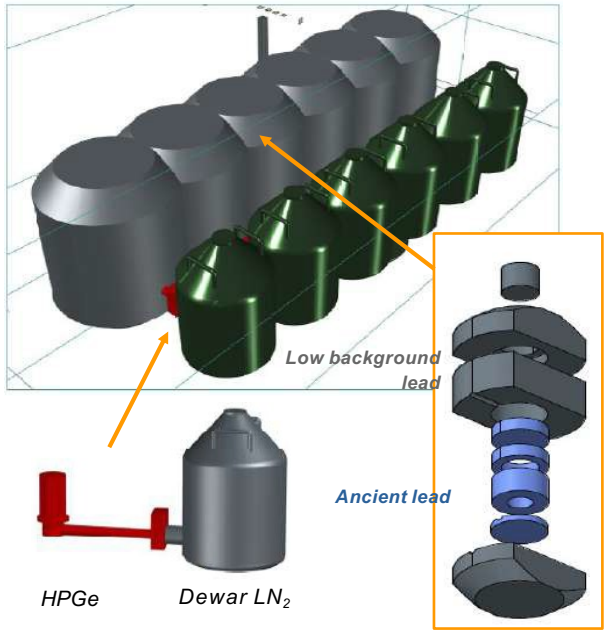
- France: IRSN, CEA, CENBG, IP2I, LSCE (Université Paris-Saclay, CEA, CNRS), EDYTEM (CNRS, U. Savoie Mont-Blanc),
- International: JINR Dubna (Russia), UTEF Prague and SURO (Czech Republic)
- *LSM provides possibility to cover the very lowest-rate end of their measurements*

^{137}Cs used for river sediment dating

^{137}Cs in Sahara sand dust in Alps glaciers

Current Ge facility upgrade: PARTAGe

- More efficient use of space (room for up to 22 HPGe)
- Shielding optimisation
- Ease of operation (LN_2 refill)



11 HPGe transferred so far

Boulby Laboratory

Dark Matter :
DRIFT, NEWS-G, CYGNUS, DarkSPHERE
Multidisciplinary:
RESOURCE, BUTTON, BISAL, MINAR, Deep Carbon, CTBT
Assay:
BUGS

- 4000 m^3 class 1000 and 10000 clean room lab space.
  - Radio-purity assay, LN generation, 5T and 10T lifting
  - **Low radon level environment ~3 Bq/m^3**
- 3000 m^3 outside experimental area
- Future plans to build a new much larger underground facility from 2030+ aimin to host next generation DM and DBD experiments

Direction of R&D at Boulby

- Instrumentation development for NEWS-G at SNOLAB
  - Multi-anode sensor
  - Gas filtration
  - Rate effect studies
- Neutron spectroscopy (N_2)
  - Neutron BG surveys
  - Industrial applications
- **Towards scaled-up detector at Boulby, 3m diam. 5 Bar He-CH_4H_{10}: DarkSPHERE**

BUGS (Boulby UnderGround Screeening). World-class material screening facility towards PPT sensitivity for G3 DM and Neutrino experiments.

- Aiming for **ALL** key ULB screening systems under one (1.1km) roof.
- 8 ULB Ge detector systems, 2 XIA alpha counters, Rn emanation, ICPMS to come

Science and Technology Facilities Council
Boulby Underground Laboratory

Multi-Disciplinary Studies

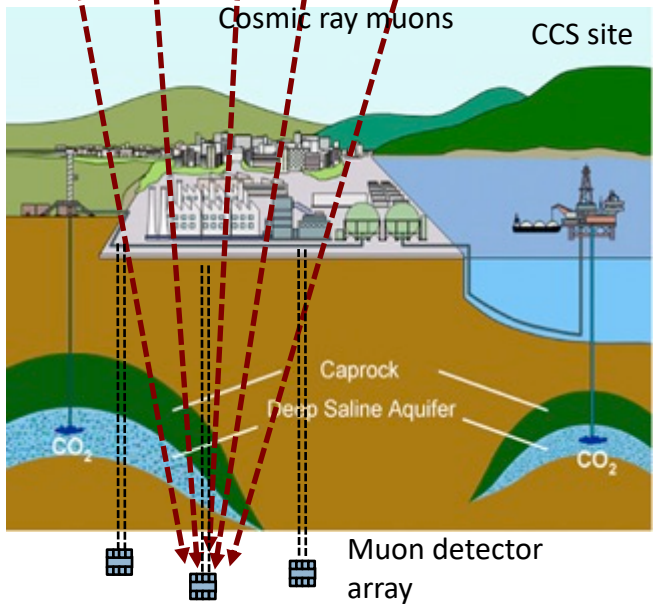
Diverse programme: astroparticle physics, Earth and Environmental Science, Astro Biology and Planetary exploration.

ERSaB: Gamma spectroscopy & low background counting environmental radioactivity studies

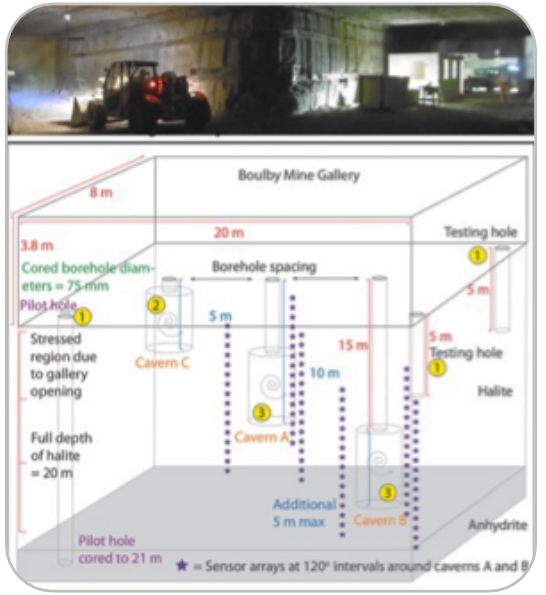
Mining & extraplanetary exploration instrumentation development

AWE-Ge: CTBT Atmospheric Radionuclide Monitoring
- Improving the accuracy & sensitivity of atmospheric radionuclide monitoring for international Comprehensive Test Ban Treaty (CTBT) verification

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



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

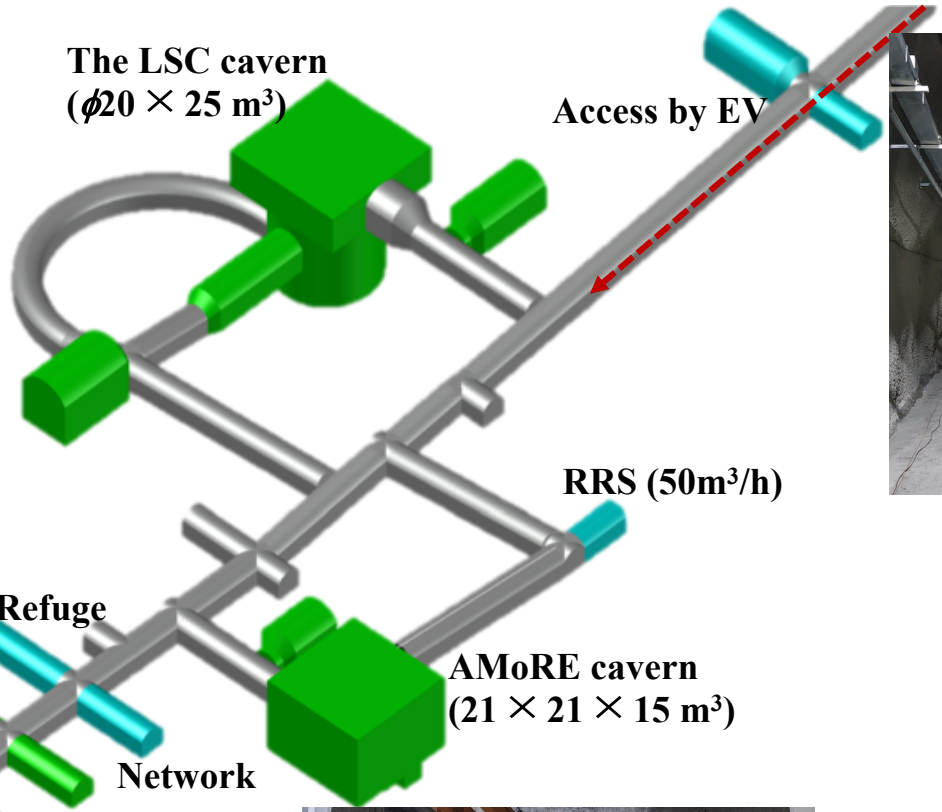


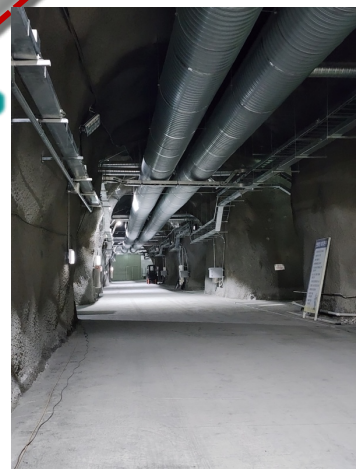
BISAL: Astrobiology / Geo-microbiology. Studies of life in salt, life on Earth & beyond

Yemilab

Dark Matter :
COSINE-100U, COSINE-200, lowmass DM
Neutrinoless DBD:
AMoRE-II
Neutrino:
IsoDAR
Multidisciplinary:
High sensitive Earthquate, Sea water monitoring

- IBS built a new underground laboratory in South Korea.
- ~ 1000 m depth, >3000 m^2 lab space.
- Two access ways, ramp-way and man-riding elevator are utilized.
- Open to other researchers than IBS.

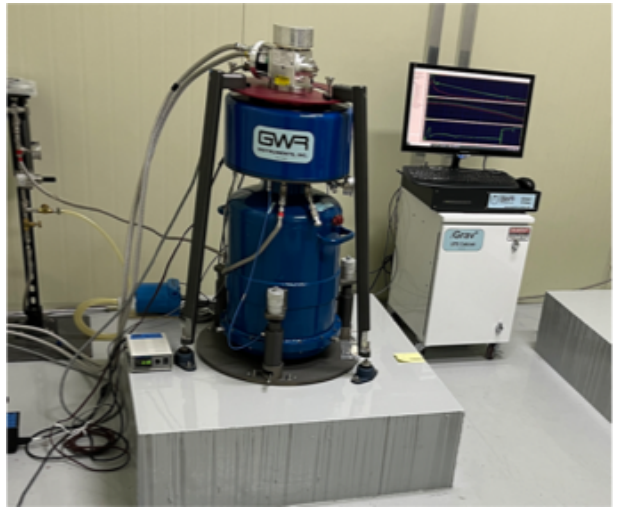




Radioassay & Multidisciplinary

Yemigo:

- A superconducting gravimeter (iGRAV#001) has been installed in the 1,005m (-120m below sea level) to measure the micro-gravity change underground
- Detecting prompt elasto-gravity signals (PEGS) before P-waves when the earthquake occurs.



iGRAV: Superconducting Gravimeter

- When an earthquake occurs, changes in gravity caused by the movement of tectonic plates with large masses propagate at the speed of light!

- **Muon rates: 1.0 × 10^{-7} μ/cm^2 sec**
- Radon reduction system (50 m^3/h, goal: 1/1,000 reduction) is operating.
  - 200m^3/h RRS is under consideration.
- LN2 generators(60L/day) for cryostats and HPGe.
- Dust proof doors
- Neutron backgrounds measured w/ bonner sphere.
- COSINE-100U & AMoRE-II begins in 2024.
- 2 DRs for general use of cryostat detector tests.

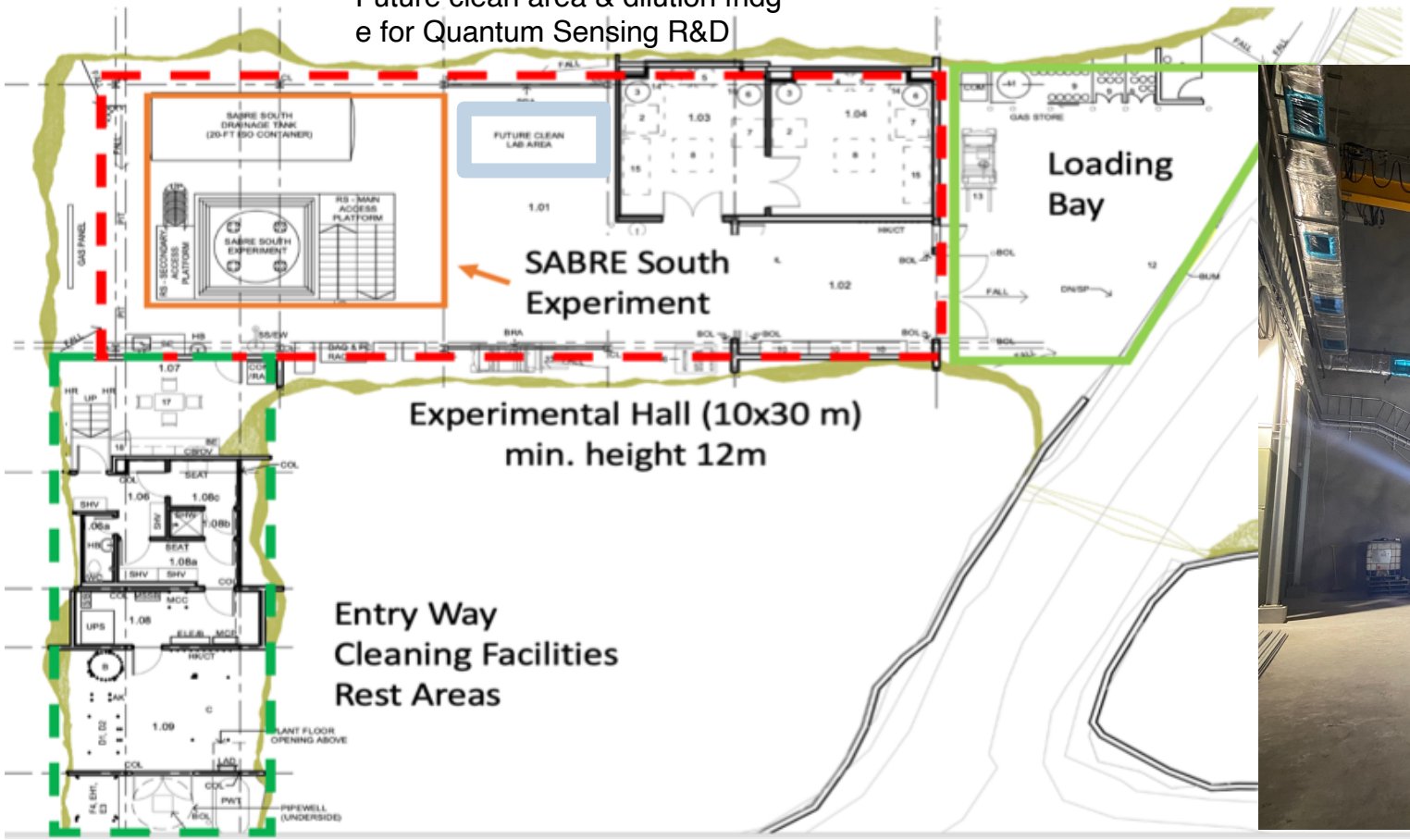
- Neutron detectors

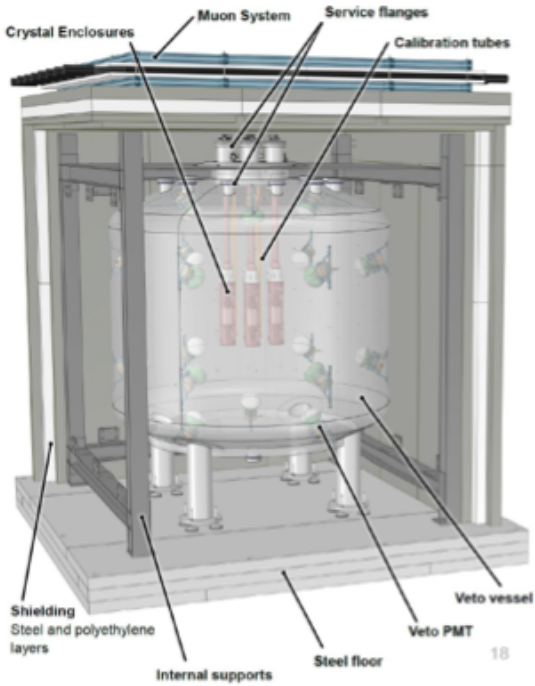
SUPL

- First deep underground laboratory in the Southern Hemisphere
  - 1025 m deep (2900 m water equivalent) with flat over burden
  - Helical drive access
  - Low background screening facilities

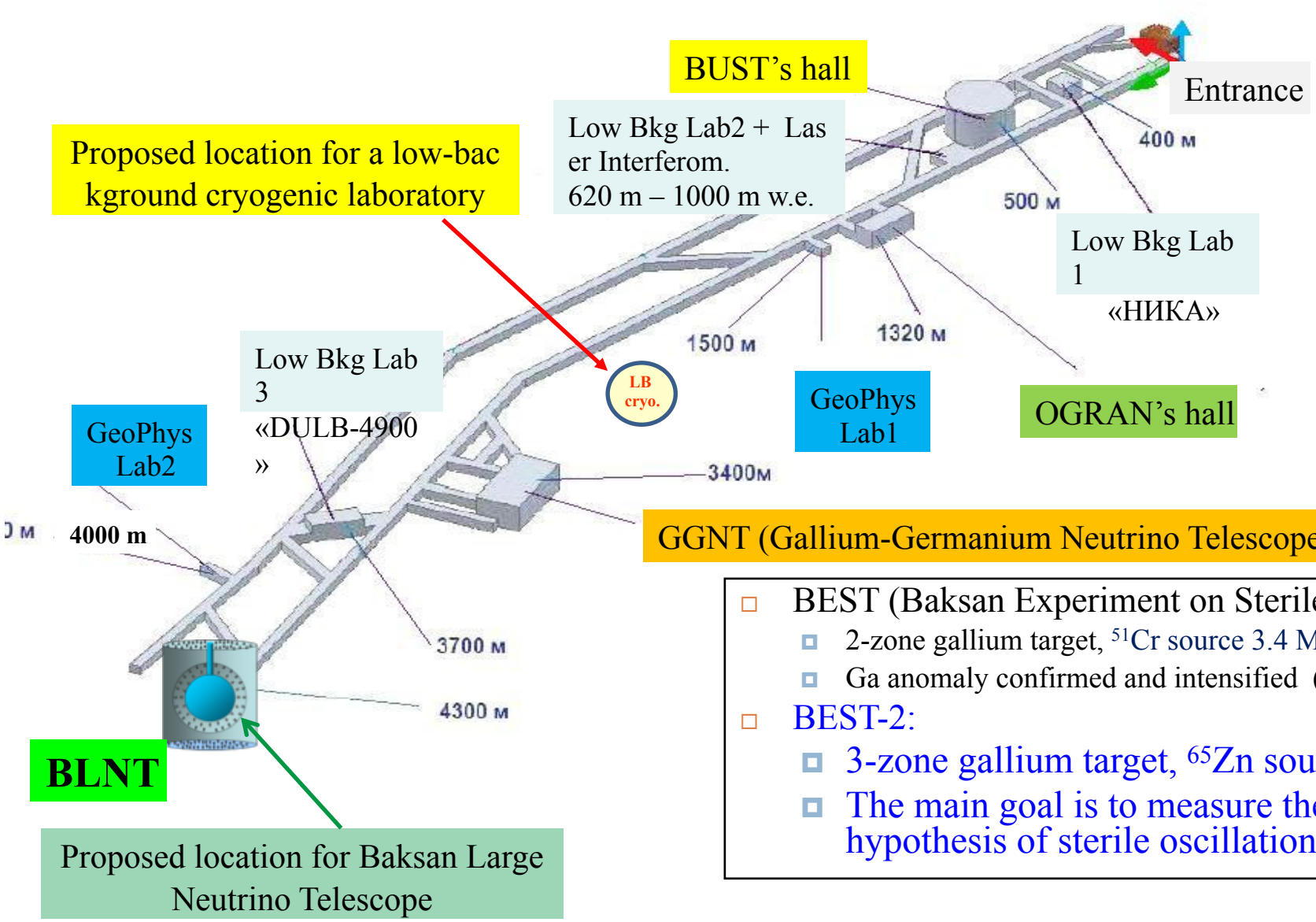
Dark Matter :
SABRE-South
Multidisciplinary:
QC

https://www.supl.org.au





Underground Laboratories of the BNO INR RAS



- BEST (Baksan Experiment on Sterile Transitions):
  - 2-zone gallium target, ^{51}Cr source 3.4 MCi
  - Ga anomaly confirmed and intensified ($R_0 = 0.80 \pm 0.05$, 4 σ)
- BEST-2:
  - 3-zone gallium target, ^{65}Zn source (E_ν increases by 1.8 times).
  - The main goal is to measure the parameter Δm^2 in the hypothesis of sterile oscillations

Callio Lab

Basic information:

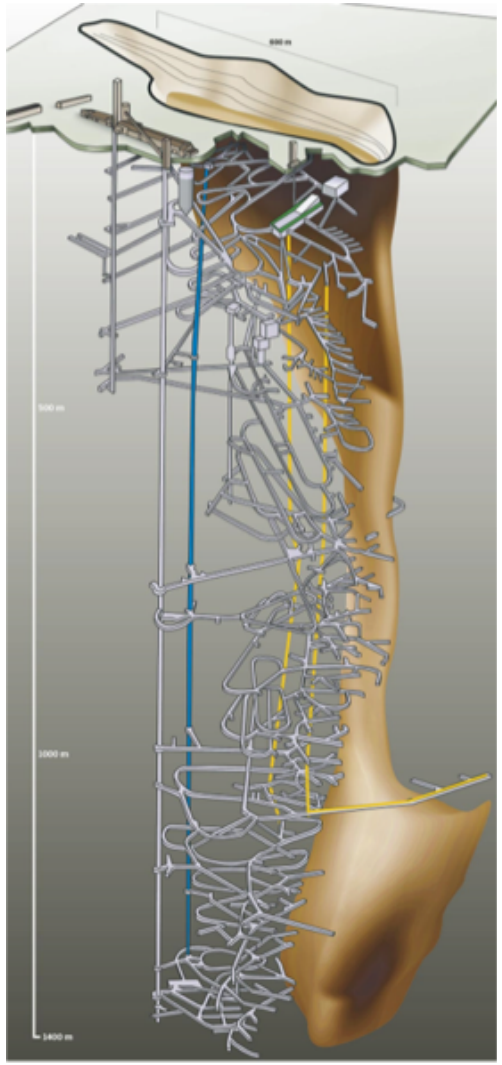
- Maximum depth at 1430 meters (~4000 m.w.e.), incline tunnel and elevator access, main level and support facilities at 1410 meters
- Member of DULIA network and collaborating with CELLAR network

New developments at Pyhäsalmi mine:

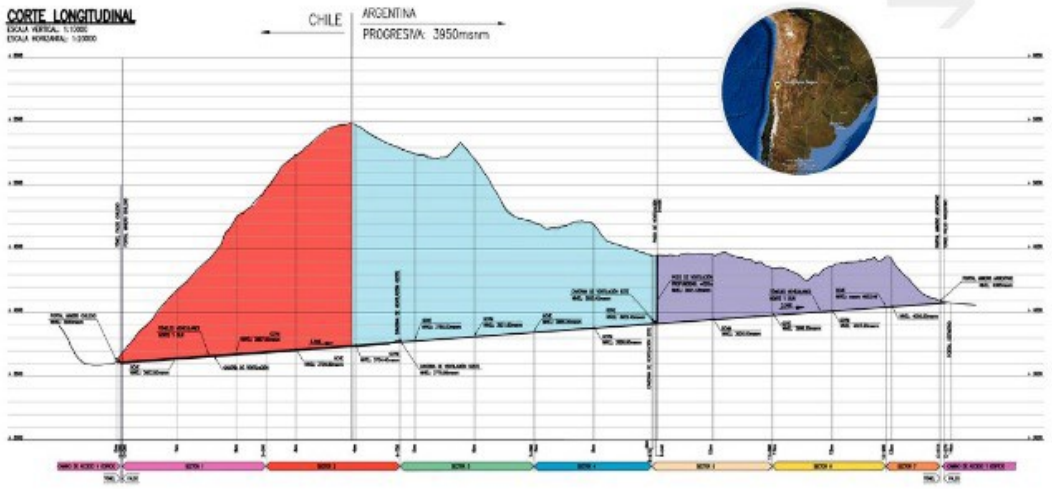
- **Underground mining ended after 60 years (1962-2022)**
- **Proposal : New use for underground mine as pumped hydro storage (2024-2074)**

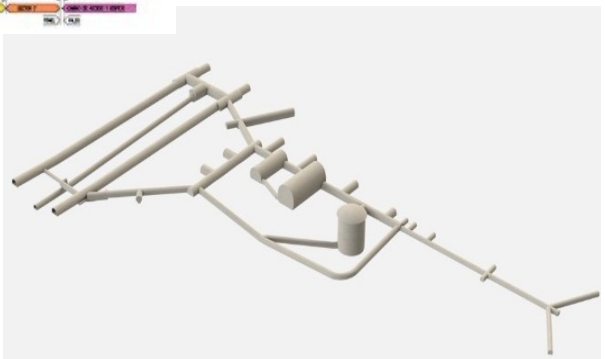
NEMESIS 1.4 DM-experiment:

- DM-like anomalies in neutron multiplicity spectra collected underground with Pb targets by three independent experiments: NEMESIS (at 210 m.w.e.) NMDS (at 583 m.w.e.), and ZEPLIN-II (at 2850 m.w.e.)
- New analysis shows small but persistent anomalies at high neutron multiplicities
- Upgraded setup moved to main level at 3900 m.w.e.



ANDES - not yet





Deep: 1750 m rock overburden La
rge: 4000 m^2, 70000 m^3
Planned as an **international laboratory** run by a **consortium**

Agua Negra tunnel situation on hold

Was financed by IDB, financing is now on hold

Argentina strongly supporting the tunnel, Chile not really

Paarl Africa Underground Lab. (PAUL)

- A tunnel laboratory is proposed near Cape Town.
- ~ 800 m overburden.
- 600 m^2, 3000 m^3
- Apply for Horizon-EU funding (2023)
- Unique underground lab in Africa.

Paarl

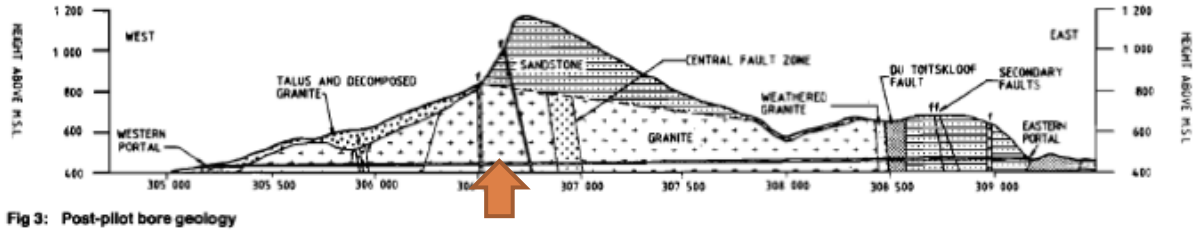
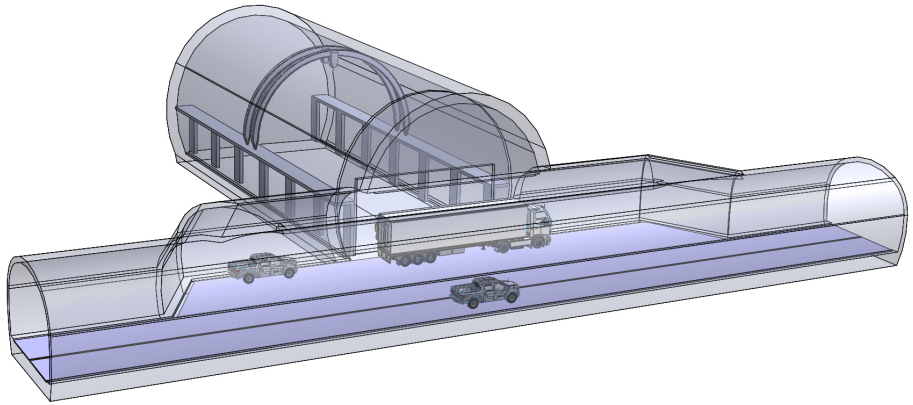


Fig 3: Post-pilot bore geology

176 THE CIVIL ENGINEER in South Africa — April 1988



- Ultra-low background gamma-ray spectrometry
- Dark Matter search
- Biological science
- Anti-neutrino monitoring (Koeberg Nuclear Power Station)

Integration Efforts

- CELLARS
  - European underground physics community

- Radiopurity Database maintained by SNOLAB and PNNL people, : https://radiopurity.org
  - Need contributions from all of us.

- Discussing about agreements for sharing resources, equipment etc.

Medium, Shallow Depth Laboratories

- Jadugoda Underground Laboratory (JUDL, 550m) - India
- Janossy Underground Laboratory (30m) - Hungary
- Felsenkeller Underground Laboratory (45m) – Nuclear Astrophysics

Thanks for the updates !

Qian Yue (CJPL), Shigetaka Moriyama (Kamioka), Elisabetta Barberio (SUPL), Jungho So (Yemilab), Sean Paling (BOULBY), Carlos Peña Garay (LSC), Jules GASCON (LSM), Julia Puputti (Callio), Paolo Gorla (LNGS), Valery Petkov (Baksan), Jaret Heise (SURF), Jeter Hall, Jodi Cooley (SNOLAB), Xavier Bertou (ANDES)

Summary

- Deep underground laboratories are expanding and new ones are emerging.
- Multidisciplinary researches are expanding too.
- Radiation Assay and Mitigation continue to improve the limits and levels with advanced technologies and equipment, such as, dedicated cryogenic detector system for detector tests, a large size clean room with a large number of low background HPGe detectors.
- We should continue to improve the sensitivities of radioassay and mitigation of the radioactivities to reach the ultimate low backgrounds required for next generation dark matter and neutrinoless double beta decay experiments.