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ILIAS and the World's Underground Laboratories

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This is a brief review and comparison of the status of the underground laboratories in Europe and the world, covering in generic fashion the key important comparison issues and motivations for the infrastructures now and in the future.

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1. Introduction

The very deep underground laboratories of the world offer access to the best in quiet environments. Quiet from cosmic-ray muon flux but also, for increasing numbers of experiments, from vibration noise, electrical noise, natural radiation, radon gas and even biological contamination. Realisation of this diversity of use and benefit is starting to generate a revolution of development. Large new experiments are planned for particle astrophysics with many laboratories pushing expansion schemes and new deep laboratories being built. However, there is also a new generation of experiments outside the field of physics starting up. The discipline of Underground Particle Astrophysics is transforming into a divers field, becoming a sub-topic of a field called Underground Science.

2. The World's Deep Laboratories

As an illustration of the situation shown in Figure 1 is a table comparing characteristics of the world's current and up-coming most well known deep underground sites and in Figure 2 an overview table of the experimental activity and status of expansion plans where known (see also [1] and [2] and related sources). Of most interest to users is often the depth as this is related to the level of cosmic ray shielding provided by the rock. Traditionally this is given in m.w.e. (meters water equivalent), the depth normalised to the density of water. However, a better comparison, which naturally accounts for the averaging of the rock cover, is to use the muon flux. It should be noted here that there are a much larger number of underground laboratories at shallower depth not shown here, for instance as covered in Europe by the organisation CELLAR [3] and [4]. In general these are less than 200m deep and are used for low background measurements of materials.

There is a significant range of characteristics observed here that reflect not just the needs of the science but also constraints due to geographic and local economic factors and the need usually to piggyback off an existing underground infrastructure, such as road tunnel or deep mine. This situation introduces challenges for the laboratories such as the need to cooperate closely with the host owners. These factors have partly limited the number of sites and the scope sites have for expansion. Recognising this there has been a trend in recent years toward better coordination between laboratories to improve efficiency, including moves toward better coordination in allocation of space. An example of the need for this is with dark matter experiments. Efforts will be needed to move next generation dark matter experiments to sites with the necessary depth, while other classes of experiment, such as liquid argon for use in proton decay, may be able to function at shallower depths [5]. It will be important to allocate such experiments space at the appropriate depth in order to use available space most efficiently.

In Europe the laboratory coordination is run first by the highly successful organisation ILIAS (Integrated Large Infrastructures for Astroparticle Science) [6], funded by the European Union. ILIAS involves over 20 institutes representing around 1500 scientists with interest in underground physics and gravitational waves. ILIAS comprises six networks, three joint research projects and a trans-national access programme (TA). A specific laboratory network has produced joint safety training and policy activity and, through regular meetings between senior representatives, progress toward coordinating science policy.

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Site	**Location and access**	**Current space**	**Depth and muon flux (μ m^{-2} s^{-1})**	**Rock and radon (Bq m^{-3})**	**Neutrons (m^{-2} s^{-1})**
			Europe		
BNO	Andyrchi, Russia; independent tunnel	3 halls: 24×24×16 m^3; 60×10×12m^3; 40,000 m^3	850 m.w.e. and 4700 m.w.e. (SAGE area); $3.03 \pm 0.19 \times 10^{-5}$	40 norite rock	1.4×10^{-3} (>1 MeV); 6.28×10^{-4} (>3 MeV)
BUL	Boulby mine, UK; vertical	1,500 m^2	2800 m.w.e. under flat surface; $4.5 \pm 0.1 \times 10^{-4}$	1-5 salt	1.7×10^{-2} (>0.5 MeV)
CUPP	Pyhasalmi mine, Finland; vertical	>1000 m^2 spaces no longer used by the mine	down to 1400 m	- pyrite ore, zinc ore	-
LNGS	Gran Sasso, Italy; road tunnel	3 halls plus tunnels total 17,300 m^2; 180,000 m^3	3200 m.w.e., under mountain; 3×10^{-4}	50-120 $CaCO_3$ and $MgCO_3$	3.78×10^{-2} (total); 0.32×10^{-2} (>2.5MeV)
LSC	Canfranc, Spain; road tunnel	2 halls: 40×15×12m^3; 15×10×8m^3; tot 1000 m^2	2400 m.w.e., under mountain; 2×10^{-3} - 4×10^{-3}	50-80 limestone,	2×10^{-2}
LSM	Modane, France; road tunnel	1 hall and service areas: 400 m^2	4800 m.w.e. under mountain; 4.7×10^{-5}	15; (0.01 filtered) calcitic schists	5.6×10^{-2} (work in progress)
SLANIC	Prahova mine, Romania; vertical	70,000 m^2 average ht. 52-57 m	208 m, under flat surface	6 salt	-
SUNLAB	Sieroszowice mine, Poland; vertical	85×15×20 m^3	900-950 m (2200 m.w.e.) 650-700 m for large caverns	20 salt and copper ore	-
SUL (Uk)	Solotwina mine, Ukraine; vertical	25×18×8 m^3; 4 of 6×6×3 m^3; total area 1000 m^2	1000 m.w.e. under flat surface; 1.7×10^{-2}	33 salt	$<2.7 \times 10^{-2}$
			Asia		
INO (proposed)	Masinagudi, India; independent tunnel	2 halls: 26×135×25 m^3; 53×12×9 m^3	3500 m,w.e.	- compacted granite	-
Kamioka	Japan; independent horizontal	Hall SK 50 m dia; 40×4 &100×4 m wuth L-arm	2700 m.w.e. 3×10^{-3}	20-60 lead and zinc ore	$8.25 \pm 0.58 \times 10^{-2}$ (th); $11.5 \pm 1.2 \times 10^{-2}$ (fast)
Oto-cosmo	Tentsuji, Japan; Indep. horizontal	2 halls: 50 m^2; 33 m^2; total ~100 m^2	1400 m.w.e. 4×10^{-3}	10 (radon reduced) -	4×10^{-2}
Y2L	YangYang, S. Korea; horizontal	Current space: 100 m^2 Planned space: 800 m^2	~2000 m.w.e. 2.7×10^{-3}	40-150 -	8×10^{-3} (1.5-6.0 MeV)
			North America		
DUSEL (proposed)	Homestake, USA; vertical	7200, 4500, 100 m^2 at 1450, 2200, 2438 m dep	233, 4100, 6400, 7000 m.w.e. under flat surface	~40-200 (at 1478 m) metasedimentary	-
SNOLAB	Creighton mine, Canada; vertical	SNO ~200 m^2; main18× 15×15-19.5 m^3 ; ladders 6-7 m; total 46,648 m^3	6001 m.w.e. under flat surface 3×10^{-6}	120; norite, granite gabbro	4.7×10^{-2} (th) 4.6×10^{-2} (fast)
SUL (US)	Soudan mine, USA; ~vertical	2 halls: 72×14×14 m; 82 ×16×14 m; tot 2300 m^2	2000 m.w.e under flat surface 2×10^{-3}	300-700; Ely greenstone	2×10^{-2} (calc)
WIPP	Carlsbad, USA; vertical	500×8×6 m available	2000 m.w.e. 2×10^{-3} expected	< 7; salt	115+/-22 m^{-2}d^{-1} (th+ath)
Kimballton	Butt Mountain, USA; horizontal	30×11×6 m	1400 m.w.e	- Paleozoic dolomite	-

Figure 1: Summary characteristics of the world's deep underground laboratories.

3. Important Features of the Laboratories

Several particular features are worth noting when comparing the laboratories (Figure 1): Firstly, the geology of the site is critical. It determines the natural radiation background - gamma from the U, Th and K in the rock; neutron from rock fission and muons [7]. Extreme examples of note are sites in salt, such as WIPP, Boulby and Slanic, for which the natural rock background can be exceptionally low. In harder granite type rock, the background can be higher by 100 times or more. It is straightforward to measure these, using a Ge detector for instance, but more challenging to determine the fission and muon neutron background [8]. Interestingly, measurements confirm simulations showing that although salt provides significantly lower gamma background than for other rock, for neutrons the scattering process in salt means this background is not improved by nearly so much. Contamination by radon and its daughters is a major issue with widely different concentrations encountered in the different sites. Again salt wins here with levels typically of a few Bqm^{-3}, compared to 100-1000 times more in some other sites (see Figure 1). The rock type and situation,

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Site	Users (approx)	Current experiments	Future plans
Europe			
BNO	Staff 50-60; Users 30-35	Neutrinos: BUST; SAGE	Uncertain
BUL	Staff 2; Users 30	Dark Matter: ZEPLIN II, ZEPLIN III, DRIFT II; Other: SKY, ongoing R&D, HPGe measurements, geophysics	Expansion to deeper hard rock underway; LAGUNA
CUPP	Staff 3-6; Users 10	Muons: EMMA	Expansion study; LAGUNA
LNGS	Staff: 64 + 23 Users: 750	Dark matter: LIBRA, CRESST2, XENON10, WARP; Double Beta Decay: COBRA, CUORICINO, GERDA; Solar/geo/SN/beam neutrinos: BOREXINO, LVD, OPERA, ICARUS; Nuclear astrophysics: LUNA2; Other: VIP, LISA, R&D, HPGe, geology, biology, environmental studies	MODULAr - new facility at shallow depth (1200 m.w.e.) proposed
LSC	Being defined	Being defined by open call. In old lab: ANAIS, Rosebud, R&D activity, 4 HPGe detectors	LAGUNA
LSM	Staff 8-9; Users 100	Dark Matter: EDELWEISS; Double beta Decay: NEMO, BiPo, TGV; Other: SHIN, HPGe detectors	ULISSE: 2 new halls: 100×24 m; 18×50 m (with water shield). MEMPHIS, LAGUNA
SUL (Uk)	Staff 14; Users 11+	Double Beta Decay: $^{116}CdWO_4$ scintillators, SuperNEMO R&D; R&D on: $CaWO_4$, $ZnWO_4$, $PbWO_4$, $CaMoO_4$, new molybdates	uncertain
SLANIC	Variable	MicroBq laboratory and whole body counting	HPGe spectrometry; nuclear astrophysics; LAGUNA
SUNLAB	Being defined	Being defined	LAGUNA
Asia			
INO (proposed)	Staff: 50-100	ICAL - 50 kt magnetized Fe tracking calorimeter for atmospheric and very long base-line accelerator neutrinos	Plans being prepared
Kamioka	Staff: 13+2 Users: >200	Neutrino astrohysics and beam: Super-Kamiokande, XMASS prototype, KAMLAND; Dark Matter: NEWAGE, XMASS; Gravity: CLIO; Double Beta Decay (proposed): CANDLE.	New halls: 15×21 m for XMASS 800 kg; 6×11 m for CANDLE; gravitational antenna LCGT request; Hyper-K study
Oto-cosmo	Users: ~ 20	Double Beta Decay, Dark Matter: ELEGANTV, MOON-1, CaF_2	uncertain
Y2L	Users: ~ 30	Dark Matter: KIMS; Double Beta Decay R&D; HPGe	Can be expanded as desired
North America			
DUSEL (proposed)	Staff: >80 Users:>200	First experiments through SUSEL inc. LUX (Dark Matter)	Expansion depends on approval
SNOLAB	Staff: ~30 Users: >100	Neutrino astrophysics/Double Beta Decay: SNO+; Dark Matter: DEAP/CLEAN, PICASSO; Letters being considered	SuperCDMS, EXO. Further site expansion limited by rock removal
SUL (US)	Staff: 9 Users: >200	Neutrino beam: MINOS; Dark Matter: CDMS II; low background	uncertain
WIPP	Staff: as needed	Double Beta Decay R&D: EXO, MEGA/SEGA, MAJORANA	Expansion to fill designated area
Kimballton	Staff: as needed	Neutrino astrophysics: LENS, R&D	Expansion to fill designated area

Figure 2: Deep underground experiments and plans.

including seismic activity, faulting, water ingress and other geology, also determines the form of cavern that can be constructed, notably the height. Salt, for instance, undergoes plastic flow which restricts the excavations at depth. However, at shallower depths, such as Slanic, this restriction relaxes. Here extraordinary caverns of 40-50m in height have been in use for over 100 years (see Figure 3). To create larger caverns at depth, harder rock, such as at Gran Sasso is essential.

4. Geographic Issues

A second issue is the division between tunnel-based and mine-based sites. The advantages held by the former are often cited, for instance the benefits of horizontal access. However, while horizontal access may be an advantage during experiment construction, for the user vertical, walk-in, lift access, can be more convenient. Meanwhile, mine companies, such as INCO at SNOLAB or CPL at Boulby, are anyway well used to transporting large items down shafts and fabricating underground. One concern is safety. This is key to both but particularly for tunnels because of the presence of the general public, in contrast with a mine where access for everyone is strictly

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Figure 3: The Slanic site in Romania - a relatively shallow site but with exceptionally large caverns excavated in salt (thanks to Romulus Margineanu).

controlled. This control may make mine sites more suitable for future experiments requiring unusual or potentially dangerous materials. There is also ready prospect for new excavation to allow interdisciplinary science through access to fresh, uncontaminated rock.

The geographic location is a further point to note. All current deep laboratories are located in relatively remote, rural areas with limited transport and accommodation options. These are challenges for the laboratory directors but arguably worse are the environmental challenges, particularly in Europe where all four deep sites are in national parks. This has, for instance, restricted surface laboratory development at Boulby, and at Gran Sasso has halted expansion plans in part due to the environmental impact on the local water table. More importantly, site location is vital to certain science activity, notably neutrino physics. Here, if the best neutrino oscillation physics is to be extracted then the distance to a potential next generation neutrino beam or factory needs to be optimised, depending on the beam energy. Long baselines favor better separation of matter effects from CP violation and provide a richer neutrino physics, including determining the MNSP matrix elements [9]. Thus, for instance, the proximity of Frejus to CERN (130 km) may disfavour this site in certain scenarios. The relative remoteness of a site like Phyasalmi, away from commercial nuclear energy reactors is also a consideration. The anti-neutrino background from these is, for instance, a limiting factor for new experiments seeking to observe the background neutrino flux from past supernova or geo-neutrinos [10] and [11].

5. Science and Expansion

Figure 2 lists most of the current activity underground. The recent success of Borexino at Gran Sasso is a particular milestone, not just for successfully observing ^{7}Be solar neutrinos in real time but because this experiment has demonstrated the feasibility of achieving backgrounds in a large (87.9 ton, fiducial) active medium, liquid scintillator in this case, at the exceptional level of 7×10^{-18} g/g ^{323}Th. Such progress points the way to building much larger detectors at depth, notably a 100-1000 Kton experiment to push proton decay sensitivity by one to two orders. Such a detector could also measure the relic neutrino flux from past supernovae and, with a suitable beam, unravel lepton CP violation. The LAGUNA collaboration, now part-funded by the European Commission, will study three potential technologies in this area, water cherenkov, liquid argon and

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liquid scintillator, and investigate options for a new underground laboratory at Boulby (UK), Canfranc (Spain), Frejus (France), in Italy, Phyasalmi (Finland), Slanic (Romania) or Sunlab (Poland). In Japan, similar plans are well advanced with detailed rock studies in the region of Kamioka mine already completed [12] and [13].

The development of LAGUNA is evidence of the vibrancy in underground science in general, with new sites emerging, such as the Indian Neutrino Observatory (INO), and many expansions underway (see Figure 2). In particular, the fields of dark matter and neutrino physics are maturing and will need a new generation of larger, multi-tonne, experiments. The Canfranc halls have recently been built with this in mind and at Frejus, ULISSE is well advanced to establish two new halls totalling >3000 m^2, including an integrated water shield. Meanwhile, at Boulby, there are prospects new areas and at Phyasalmi, now the deepest mine in Europe at 1400 m, engineers are proposing a new facility separated from the main mining activity. Worldwide, the best know expansion activities are at SNOLAB and DUSEL. The former includes the new Cryopit Laboratory that will be the world's first underground site dedicated specifically to liquid noble gas experiments.

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