# Underground Laboratories

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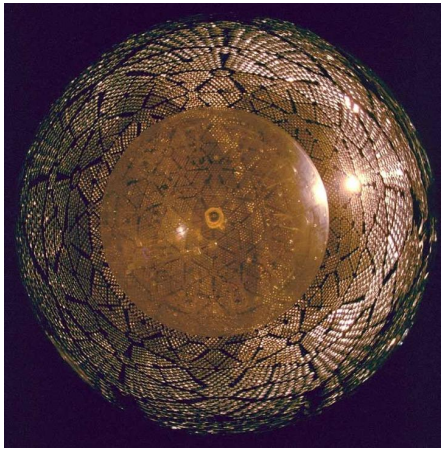
October 2022



# Outline

- Introduction and Overview of Underground Laboratories - Progress and Promise
  - Why go Underground?
  - The past 20 years
  - Opportunities for the coming 20 years
- A Partial Survey of Existing Facilities
  - Essential Laboratory Attributes
- Conclusions Regarding Yemilab

# Why Go Underground?

Physics - Special Environment, Low Backgrounds, Stable, Primarily Rare-search Experiments

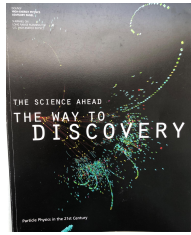
Biology - Origins of Life, Life in Extremes, New Life

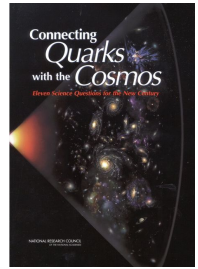
Geology - Coupled Processes (Thermal, Hydrological, Chemical, Mechanical), Resource Identification & Extraction, Earthquakes, Transparent Earth

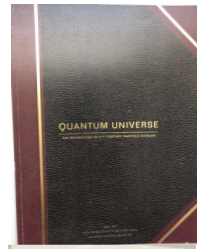
Engineering - Properties of Rock, Societal Needs, Technologies

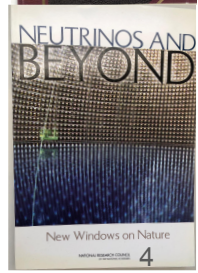
# Why Go Underground?

- Rich Literature on this topic:
  - 2000 - Nuclear Physics Long Range Plan Meeting, *Institute of Nuclear Theory Seattle*
    - Primarily Neutrinos
  - 2001 - Underground Science *Institute of Nuclear Theory Study (Bahcall Report)*
    - Underground facility, Neutrinos, Proton Decay, Nuclear Astrophysics, Geoscience, Bio, Materials, …
  - 2001 - The Science Ahead: The Way to Discovery *HEPAP Study*
    - Lepton-Flavor Physics (SNO, Super-K, Borexino, KamLAND results expected)
    - Early Discussion of Accelerator-based neutrino beams (JPARC, BNL, FNAL)
    - US-based ILC dominated the report
  - 2003 - Connecting Quarks with the Cosmos *National Academies Report*
    - Dark Matter, Neutrinos, Proton Decay, Gravity, Cosmic Rays, Nuclear Astrophysics
  - 2003 - Quantum Universe *HEPAP Study*
    - Dark Matter, CP-violation, Neutrino Oscillation, Strings, Supersymmetry
  - 2003 - Neutrinos and Beyond *NRC*
    - ICE3 and Underground Laboratory
    - Neutrino Properties with Solar and Long Baseline neutrinos, Dark matter, Proton Decay, Double Beta Decay



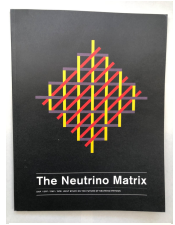



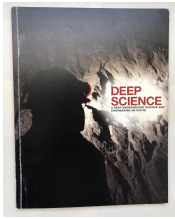



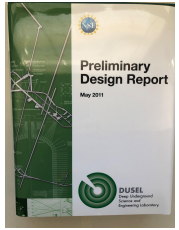
# Why Go Underground?

- Rich Literature on this topic:
  - 2004 - The Neutrino Matrix *Joint APS Study*
    - Approx. dozen neutrino experiments presented, beta decay, 0νββ, neutrinos: LBL, solar, reactor
    - Neutrino mixing, sterile, CP-violation
  - 2005 - Discovering the Quantum Universe *HEPAP Study*
    - Role of Particle Colliders - Supersymmetry, Dark Matter,
  - 2005 - Deep Science *NSF report*
    - Companion to Facility Proposals - DUSEL
      - Multidisciplinary Science
      - Strong need for underground space
      - Universe's building blocks, Dark matter, Neutrinos, CP violation, Proton Decay,
      - Dark Live, Geosciences, Engineering (ground truth)
  - 2011 - DUSEL Preliminary Design Report
    - Multidisciplinary Science Program
      - Geo, Eng, Bio, Physics



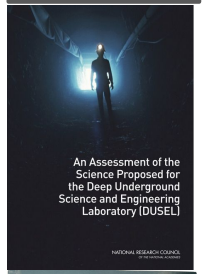


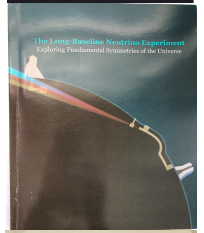


# Why Go Underground?

- Rich Literature on this topic:
  - 2011 - Review of Options for Underground Science *DOE Report (Marx report)*
    - Long Baseline Neutrinos, Third Generation Dark Matter, Ton-scale Double-Beta Decay,
  - 2012 - An Assessment of the Science Proposed for the Deep Underground Science and Engineering Laboratory *NRC*
    - Dark Matter, Neutrino Oscillations, 0νββ, Proton Decay, Supernovae neutrinos, Nuclear Astrophysics, Engineering, Geosciences, Biology, Importance of co-location
  - 2014 - The Long-Baseline Neutrino Experiment
    - BNL-FNAL Report on Physics Opportunities with LBNE
  - 2014 - Strategic Plan for US Particle Physics in the Global Context (P5)
    - Dark Matter G2 and G3, Short and Long-Baseline Neutrinos, PIP upgrades, LBNF
  - 2022 - HEPAP Long Range Plan *Snowmass* In process
    - LBNE/DUNE, G3 Dark Matter, Neutrinoless Double-Beta Decay

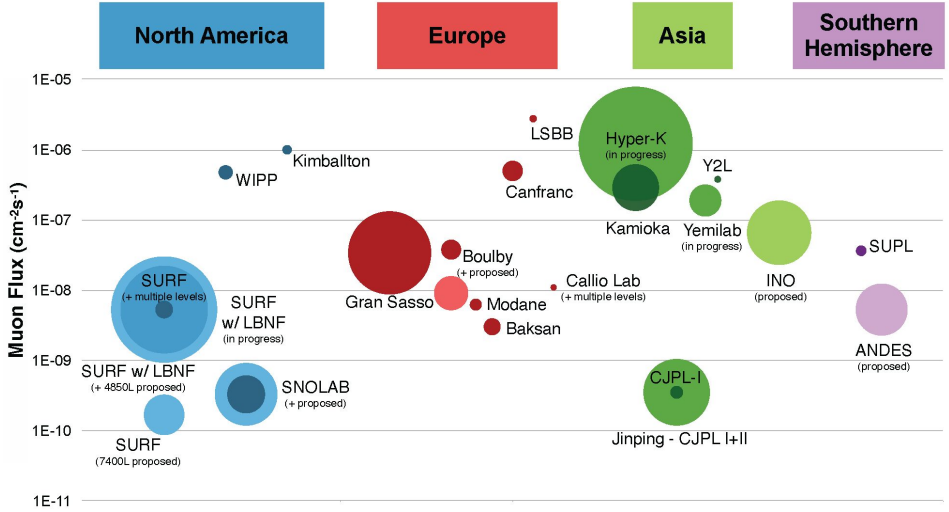

# Two Decades of Building and Discovery

## Underground Laboratories

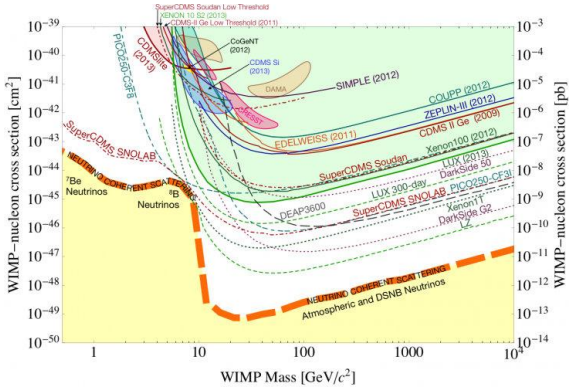
Homestake (1965), IMB (1979), Kamioka (1982), Gran Sasso (1985), SNO (1999), SNOLAB (2009), Jinping (2011, 2014), SURF Davis Campus (2012, 2025), Y2L (2003, 2014) Yemilab (2022)

## Current Situation

General expansions proposed for SURF, SNOLAB, & Boulby



# Two Decades of Building and Discovery



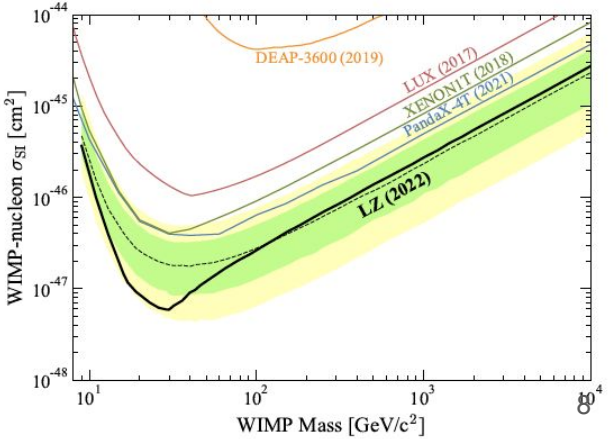

## Dark Matter Experiments

**Dark Matter Completed:** LUX, Xenon10,Xenon100, Xenon1T, PandaX, PandaX-II, DEAP-3600, Darkside10, CDMS, CDMS II, CDMS-Si, SuperCDMS Soudan, XMASS, EDELWEISS-III, COGENT, DAMA, COUPP, PICASSO, CREST, COSINE-100, DM-Ice17, CDEX, MiniClean

**Dark Matter Running:** LZ, XenonNT, PandaX-4T, Darkside50, DAMIC, SENSEI

**Dark Matter Constructing/Commissioning:** SuperCDMS SNOLAB, Darkside20k, PICO, DEAP-3600, NEWS-G SABRE, COSINE-200

Dark Matter Planning: XLZD, TESSERACT, Low Mass Dark Matter, DarkSide-20K@LNGS, ARGO@SNOLAB



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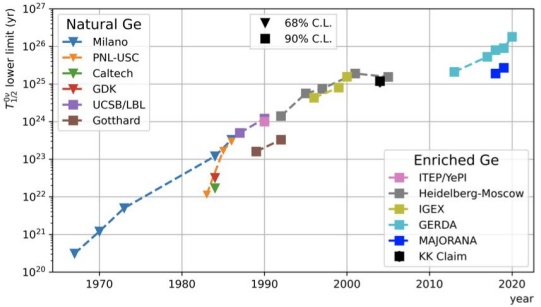


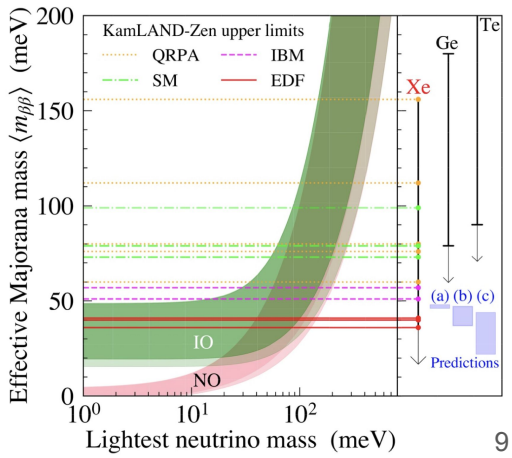

## Neutrinoless Double-Beta Decay

**0νββ Completed:** Majorana Demonstrator, EXO-200, NEMO, GERDA, KamLAND-Zen 400, Cuoricino, CUORE-0, CUPID-0, COBRA, AMoRE

**0νββ Running:** CUORE, KamLAND-Zen 800, CUPID-Mo

**0νββ Constructing/Commissioning:** Legend-200, SNO+, nEXO, AMoRE

**0νββ Planning:** NEXT, KamLAND2-Zen, LEGENDE 1k, PANDAX 1k



# Two Decades of Building and Discovery

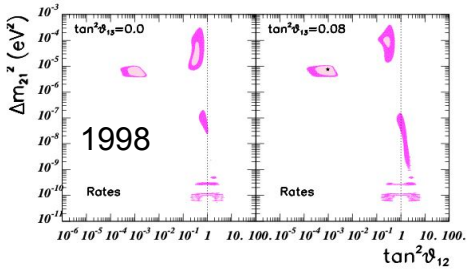
## Neutrino Oscillations

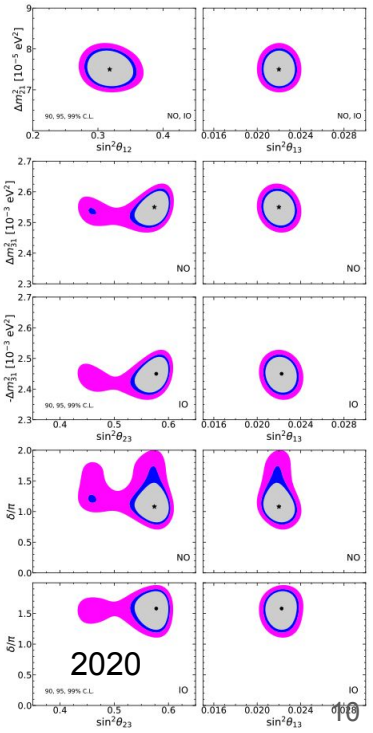
**ν Oscillation Completed:** Homestake, IMB, LSND, Kamioka, SuperK, Bugey, KARMEN, Palo Verde, Double Chooz, SNO, OPERA, Borexino, K2K, Minos, Daya Bay

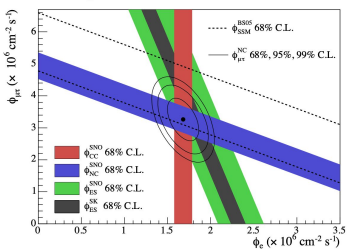
**ν Oscillation Running:** T2K, NOVA, BNB

**ν Oscillation Constructing/Commissioning:** Juno, HyperK, DUNE Phase I

**ν Oscillation Planning:** DUNE Phase II, LSC



# Two Decades of Building and Discovery

**Nuclear Astrophysics**

**Operating Facilities:**

LUNA 400kV, LUNA MV – INFN

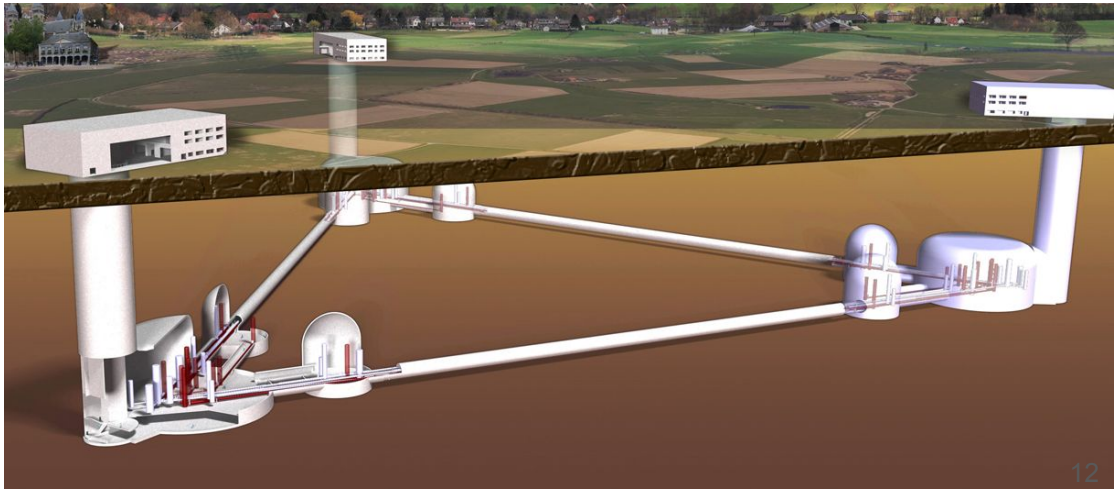
CASPAR 1MV – SURF

# Two Decades of Building and Discovery

**Gravity Wave Detection**

**Operating:** KAGRA (Kamioka), CLIO (Kamioka)

**Proposed:** Dutch next-generation Einstein Telescope



# Summary of Two Decades of Building and Discovery

**Low Background Assay, Rn-reduced Air, Contamination Control**

**Existing HPGe:** BHUC (SURF), BUGS(Boulby), STELLA (INFN), SNOLAB, Y2L

**Building/Commissioning:** Yemilab

**Rn-Reduced Air:** SURF, Y2L, *Kamioka*, *SNOLAB*

**DUST Control:** Opportunity for Significantly Reduced Surface Contamination and Rn emanation

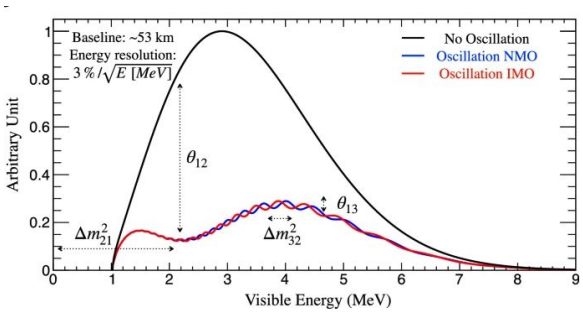
# Looking to the Future

## Neutrinos

**Confirmed:** MSW Neutrino Oscillations & Solar Model

**Just Won't Die:** Sterile Neutrinos

**Remaining:** CP-violation, Lepton-number Violation, Absolute Neutrino Mass Scale, Dirac or Majorana Neutrinos, Observe Neutrinoless Double-Beta Decay

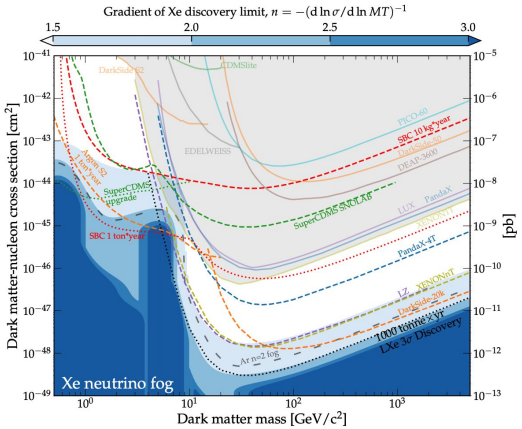



## Dark Matter

**Confirmed:** Theorists Prefer Light Dark Matter over WIMPs 7 to 1

**Confirmed:** Theorists were wrong every step of the way to discovering Neutrino Oscillations

**Remaining:** WIMPs down to the Neutrino fog, New Lighter DM Models, Discover Particle Dark Matter!



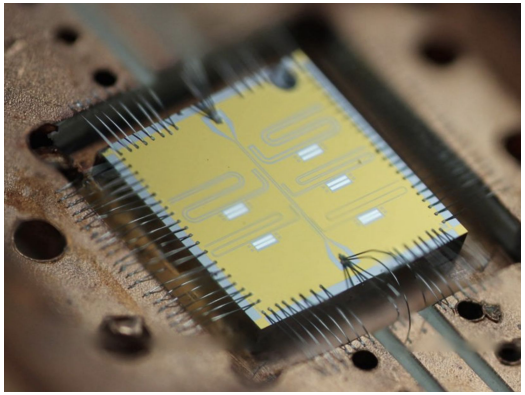
# Looking to the Future

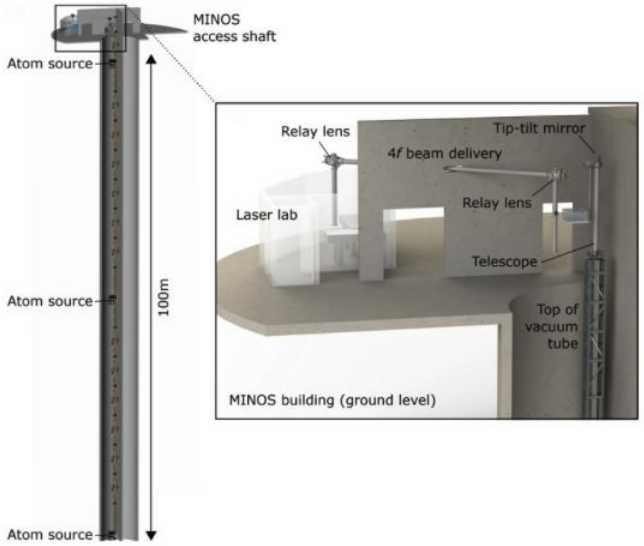
**Recent/New Applications**

QIS

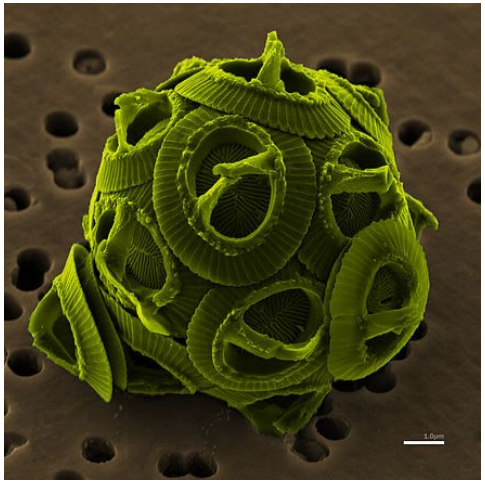
Atomic Interferometry

Industrial User(s)





# Looking to the Future



**Opportunities**

Biology - Limits of Life, New Life, Origins of Life

Geology - Coupled processes, Resources, Earthquakes, Transparent Earth

Engineering - Properties of Rock, Societal Needs

Long-term Access, Extended Scale Access, Deep Access, Dedicated Access

# (Partial) Survey of Facilities

Sanford Underground Research Facility (SURF) - US*

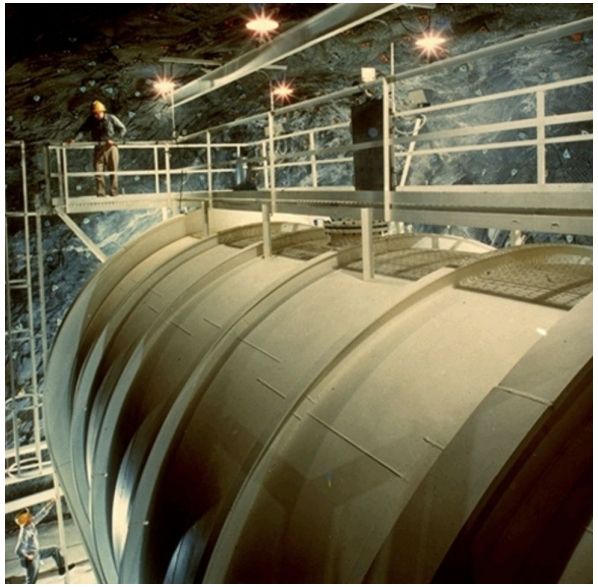
SNOLAB - Canada*

BOULBY - United Kingdom*

Kamioka Observatory - Japan*

*INFN Gran Sasso - Italy*

YemiLAB - Korea*



* Responded to Snowmass Request for information, otherwise google

# Sanford Underground Research Facility (SURF)

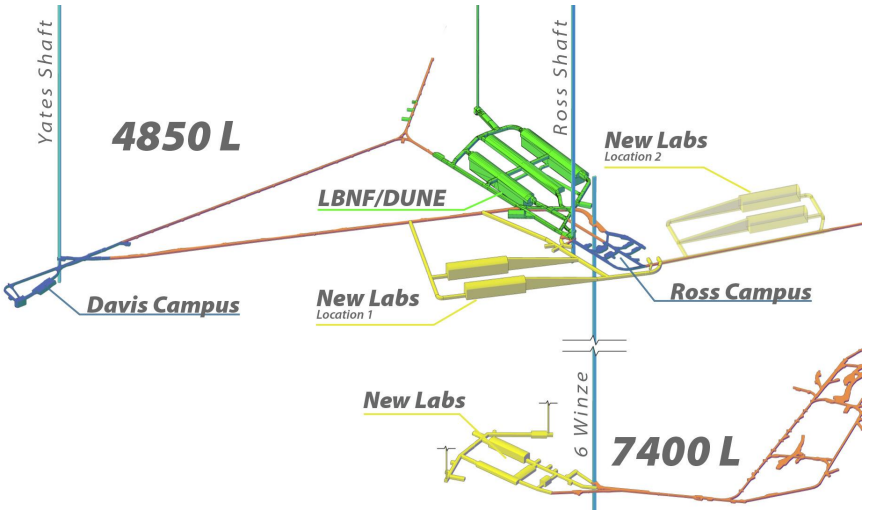
Former Homestake Gold Mine, multiple drifts and access - surface to 4850’ (8000)

Past Experiments - Davis Solar Neutrino Experiment, LUX, Majorana Demonstrator

Current Program - LZ, MJ-$^{180}$Ta, CASPAR, BHUC, Geomicrobiology, Geoengineering, E&O

Under Construction - LBNE/DUNE (DUNE excavations ~ 35% complete, FY24)

Expansions proposed - 4850 (BO ~ FY27) and 7400 L



# Sanford Underground Research Facility (SURF)

Oversight Agency - US DOE

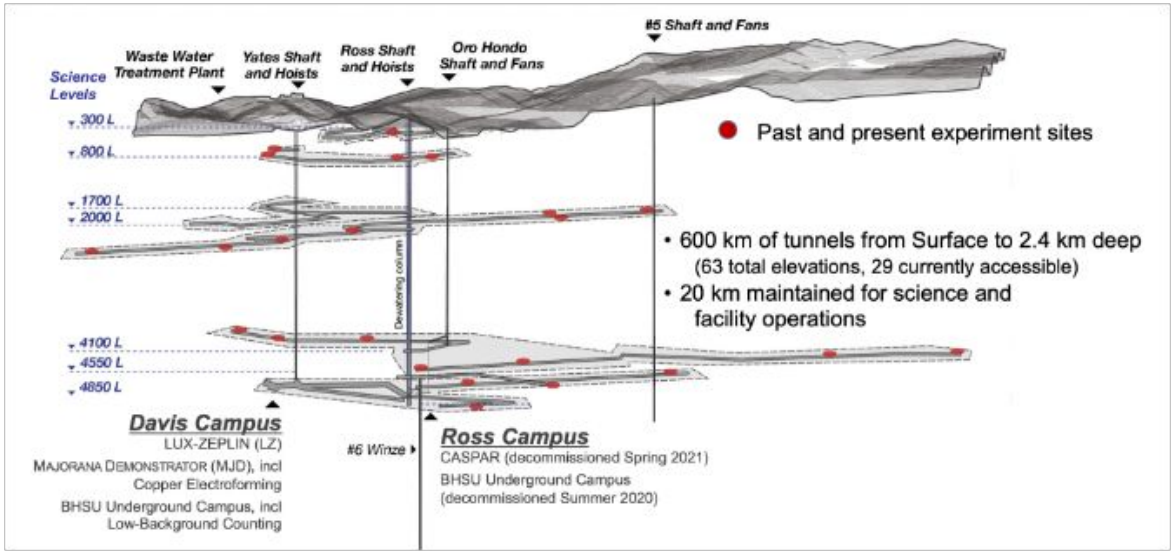
AHJ: South Dakota Office of Risk Management

Dedicated Science Facility

In-house Safety Training Program

**Staff**

8 Eng Staff, 6 Scientists, 2 EH&S, 178 total Staff (16 for science) modest additions planned



# Sanford Underground Research Facility (SURF)

**Environment**

Depth and Shielding 4300 mwe

5.3e-5 muons/$m^2$/s

Temperature 24/28°C

RH 42/79%

Rn 300 Bq/$m^3$

Neutrons 1.7e-2 n/$m^2$/s

Gammas 1.9 γ/$cm^2$/s

**Space**

Ross Campus Clean Room 12.1 x 6.1 x 2.4 m

Ross Campus Hall 30 x 3 x 2.8

Davis Detector Room 11 x (9.8 - 12.8) x 2.7

Davis Machine Shop 9.8 x 5.3 x 2.7

Davis Assay Room 7.3 x 5.6 x 2.7

Davis E-forming Room 6.3 x 8.7 x 2.7

Davis Campus 17 x 10 x 12

Surface Lab 6.6 x 5.6 x 2.7

Surface Lab Rn-reduced 6.6 x 8.4 x 3.3

Blue = available in next 10 years, Green = available now

# Sanford Underground Research Facility (SURF)

**Utilities**

Electrical Power 20,000 kW (15,000 kW available in FY27)

3 diesel generators backup

Chilled Water 246 kW (70 kW available)

Compressed air

20 Gbps, 100 Gbps planned

**Access**

Yates Shaft 1.39 x 3.77 x 2.58 m, 4.8 tonnes

Ross Shaft 1.40 x 3.70 x 3.62 m, 5.897 tonnes

Slung loads - to 10 m

Rail capacity 5.9 tonnes cars

# Sanford Underground Research Facility (SURF)

**Underground Assembly Support & Occupancy**

Multiple Clean Rooms

Rail Truck (flat and lowboy)

Low Background Assay (8 HPGe)

Underground Refuge 144 x 4 days (250 x 4 planned)

Peak 97 people/shift, Steadystate 67/shift

Multiple Cranes 2.7 tonnes

**Surface Facilities**

Limited Office Space

Surface Assembly Lab

Assembly Shop

Machine Shop

Storage and Warehouse

# SNOLAB

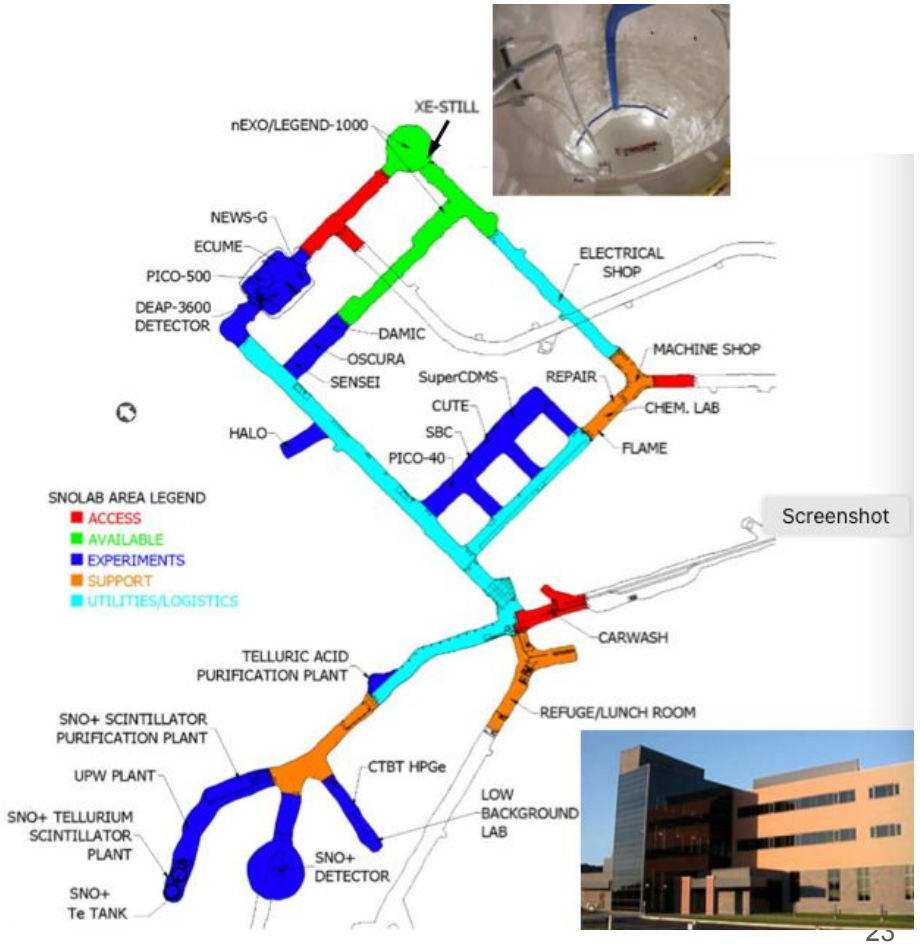
Active Nickel Mine - 6800’

Past Experiments - SNO, COUPP, DEAP1, DEAP-3600, miniCLEAN, NEWS-DM, PICASSO, PICO-2L, PICO-60

Current Program - SNO+(LS), PICO 40, CUTE, SENSEI, OSCURA, DAMIC, HALO

Constructing - SuperCDMS SNOLAB, DEAP-3600 II, PICO-500, ECUME, NEWS-G, SNO+(Te), SBC,

Expansions proposed - 6800 (?)



# SNOLAB

Oversight Agencies - CFI, NSERC, Ontario Opportunities Fund

AHJ: N/A (Suspect it is Vale and Canadian Ministry of Mines)

Shared with Vale Mining

Vale Training + SNOLAB Specific

**Staff**

60 Technical, 40 Science,
5 EH&S, 20 Admin

# SNOLAB

**Environment**

Depth and Shielding 6000 mwe

< 0.27 muons/$m^2$/day

Temperature 18/23°C

RH 30/50%

Rn 100 Bq/$m^3$

Neutrons 4.1 e3 n/$m^2$/day

Gammas 510 γ/$m^2$/d

**Space**

SNO Cavity 22m dia x 35 m tall - SNO+

Ladder Labs - Pico-40, SBC, CUTE, SuperCDMS, HALO, SENSEI, OSCURA, DAMIC, NEWS-G, additional labs

CUBE Hall: DEAP-3600, ECUME, PICO-500

Cryo-pit - tonne scale DBD

Blue = available in next 10 years, Green = available now

# SNOLAB

**Utilities**

Electrical Power 3 MW

Standby Generator 3MW

Chilled Water 320 tons

Waste heat 1.5 MW

150 CFM compressed air

10  Gbps

**Access**

Cage 54” x 144” x 68” 5500 lbs

2 x 10 shifts/day, 5 days/week

Mine Shutdown 2 weeks/year

Shaft work 2023-2025 to limit u/g access

# SNOLAB

**Underground Assembly Support & Occupancy**

Laboratory Clean Room Class 2000

Rail Truck

Low Background Assay

Peak 120 people/shift, Steadystate 50/shift

Multiple Cranes: 2., 2., 10.  tonnes

**Surface Facilities**

Significant Office Space 34k sf

4700 sf clean room labs

Assembly Shop

Machine Shop

Storage and Warehouse

Chemistry Labs

# BOULBY


Active Potash Mine - 2850 mwe

Past Experiments - ZEPLIN, DRIFT, NAIAD

Current Program - CYGNUS, Low Background Assay, NEWS-G/Dark Sphere R&D

Planning - DarkSPHERE, LXe-G3

Expansions proposed - 25m x 25m tall cavity, 14,000 $m^3$ Rooms

# BOULBY

Oversight Agencies - STFC/UKRI

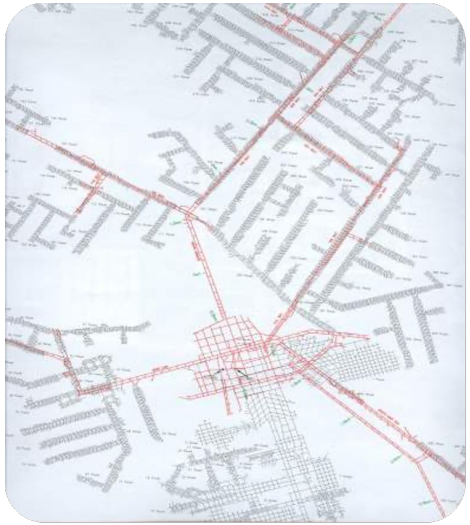
AHJ: STFC/ICL-UK

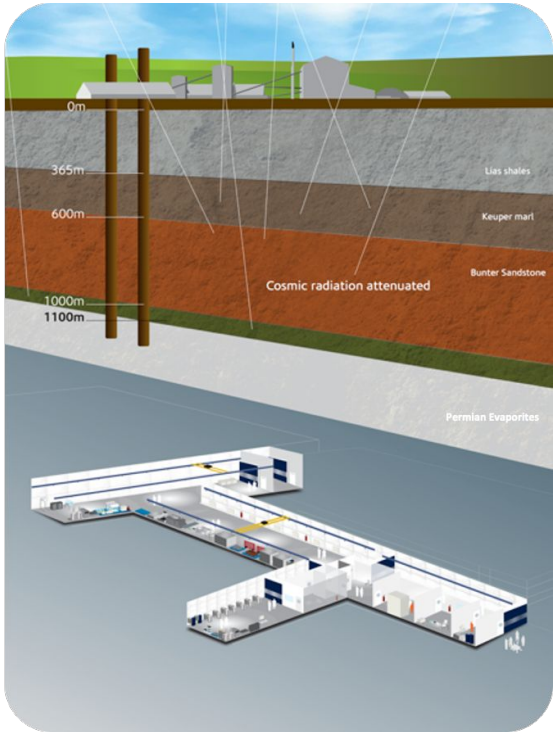
Shared with ICL-UK

Safety STFC Site Specific

**Staff**

5 Technical, 5 Science,
2 EH&S, 2 Admin





# BOULBY

**Environment**

Depth and Shielding 2850 mwe

4e-8/$cm^2$/s

Temperature 21°C

RH 40/50%

Rn 2.5 Bq/$m^3$

Neutrons 4.1 e-6 n/$cm^2$/s

Gammas 0.13 γ/$cm^2$/s

**Space**

Main Hall: 60 x 6 x 3.8 m 10k CR

BUGS: 20 x 6 x 3.8 1k CR

LEC: 10 x 6 x 6 10k CR

Outside: 20 x 6 x 3.8

Discussion of Major New Excavations 25m dia x 25 m tall

Blue = available in next 10 years, Green = available now

# BOULBY


BUGS+ Material screening

**Utilities**

Electrical Power 100 kW

Standby Generator N/A

Chilled Water N/A

Waste heat N/A

Compressed air Yes

2 x 40 Gb to surface 1 Gb offsite

**Access**

Cage 2m x 2m  5500 lbs

3 shifts/day

15 science/cage, 3-4 cages / shift

Peak 30, Steady-state 10,
Refuge 30, expected to increase
to 60/50/100

# BOULBY

**Underground Assembly Support & Occupancy**

4000$m^3$ Class 10k, 1800$m^3$ Class 1k

Rn-reduced Air

Low Background Assay

Peak 120 people/shift, Steadystate 50/shift

Multiple Cranes: 5, 10  tonnes

**Surface Facilities**

Some Office Space, planning for 2600$m^2$

Assembly Shop N/A

Machine Shop N/A

Storage and Warehouse

Chemistry Labs N/A

# Kamioka Observatory

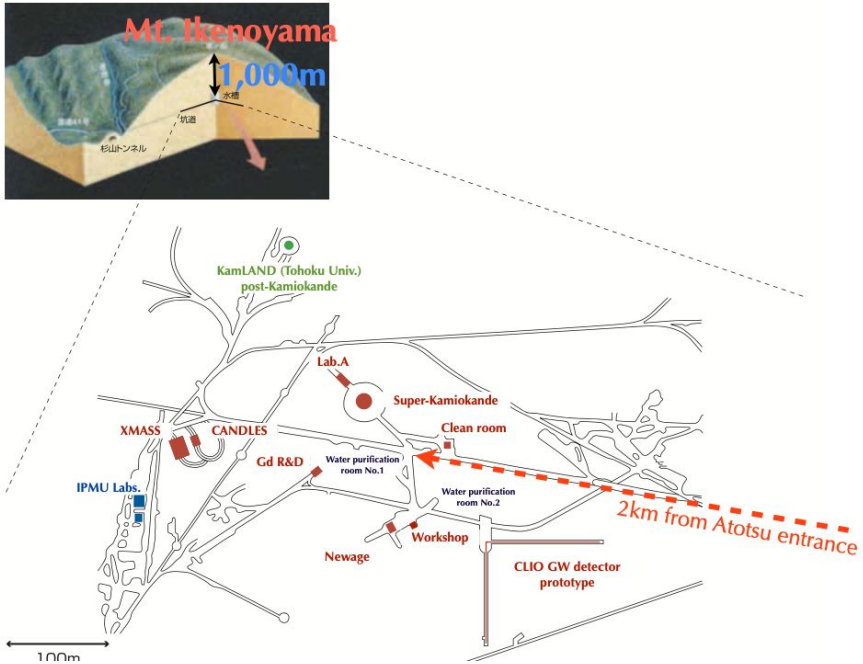
Former Mine - 2700 mwe

Horizontal Access - roadway

Past Experiments - KamiokaNDE I, II, III
K2K, XMASS, KamLAND

Current Program - SuperK, T2K,
KamLAND-Zen, CLIO, KAGRA,
NEWAGE, CANDLES

Constructing - Hyper-Kamiokande



# Kamioka Observatory

Oversight Agencies - MEXT

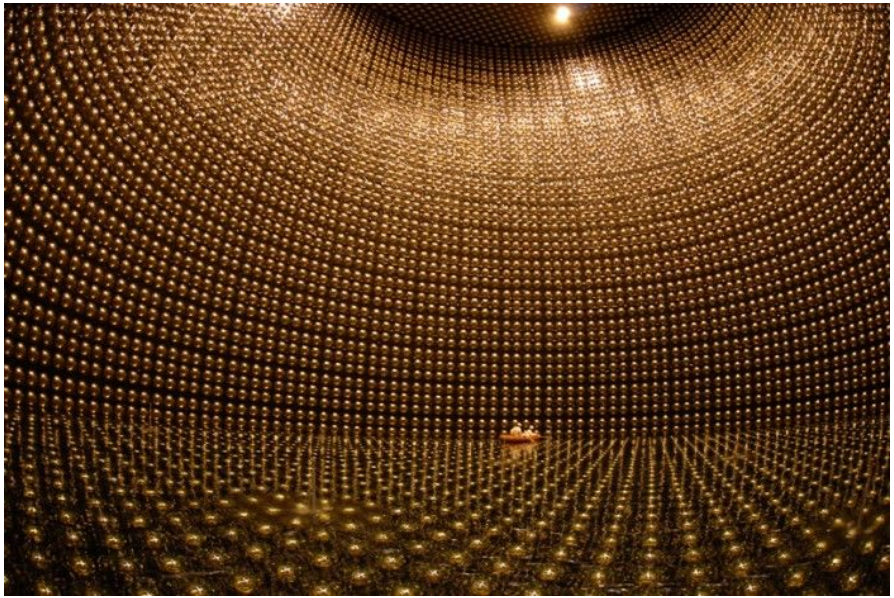
AHJ: Labour Standard Inspection Office

Shared with Kamioka Mining & Smelting

Mine Safety Training, University Safety Training

**Staff**

3 Technical, 26 Science,
0 EH&S, 8 Admin



# Kamioka Observatory

**Environment**

Depth and Shielding 2700 mwe

1.5e-7/$cm^2$/s 273 GeV

Temperature 13/13°C

RH 100% (?)

Rn 64 $Bq/m^3$

Thermal Neutrons 12.5 e-5 $n/cm^2/s$

Gammas 2.7e-6 $\gamma/cm^2/sr/s$

**Space**

Super-K: 39.3 dia x 41.4 m

Hyper-K: 68 dia x 71 m

KamLAND: 29 dia x 32m

Lab C 20 x 15 x 15

Lab D 14 x 7 x 11

Lab E 15 x 10 x 9

Lab G 50 x 8 x 7

Blue = available in next 10 years, Green = available now

# Kamioka Observatory

**Utilities**

Electrical Power N/A

Standby Generator N/A

Chilled Water N/A

Waste heat N/A

Compressed air N/A

XX  Gb

Surface Air ~ 70 Bq/$m^3$

Rn-free 36$m^3$/hour

**Access**

Horizontal Access

Open 24/7/365

Road 3.2m tall x 4.5 wide

Rail 2.5m x 3

10 tonne truck

Peak 100, Steady-state 2,
Refuge N/A

# Kamioka

**Underground Assembly Support & Occupancy**

100$m^2$ room Class 10, 50$m^2$ Class 200k

Rn-reduced Air, Rn-free Air

Low Background Assay

Peak 100 people/shift, Steadystate 2/shift

Multiple Cranes: 1, 2  tonnes

**Surface Facilities**

Office Space for 50

6 Meeting Rooms

Assembly Shop N/A

Machine Shop N/A

Storage and Warehouse

Multiple Surface Labs

Low Background Assay

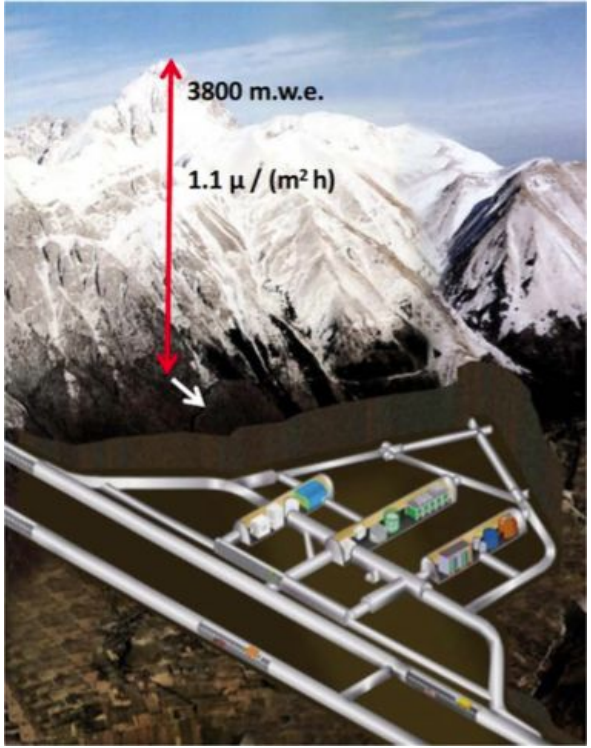
# INFN - Gran Sasso

Dedicated Physics Laboratory - 2800 mwe

Horizontal Access (Highway Tunnel)

Past Experiments - Borexino, OPERA, MACRO, GALLEX, Icarus, Warp

Current Program - COBRA, COSINUS, CRESST, CUORE, CUPID-0, CUPID, DAMA, DARKSIDE, ERMES, GERDA, GINGER, LUNA, LVD, NEWS-DM, SABRE, VIP, XENON



# INFN - Gran Sasso

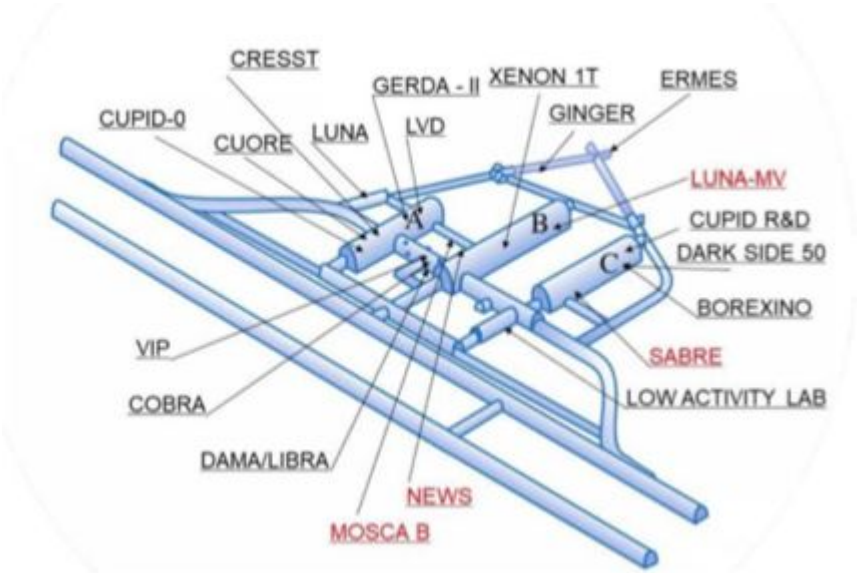
Operations Agency - INFN

Separate Environmental oversight

Issues with Chemical u/g

**Staff**

60 Technical, 60 Science



# INFN - Gran Sasso

**Environment**

Depth and Shielding 2800 mwe

TBD ~ 1.e-4/$cm^2$/s

Temperature 15-26°C

RH 30 - 90%

Rn 20 - 80 Bq/$m^3$

Thermal Neutrons <4.6e-6 n/$cm^2$/s

Gammas 0.3-0.4 γ/$cm^2$/s

**Space**

3 halls each 100 x 20 x 18 m

Total volume 180,000 $m^3$

Blue = available in next 10 years, Green = available now

# INFN - Gran Sasso

**Utilities**

Electrical Power N/A

Standby Generator N/A

Chilled Water N/A

Waste heat N/A

Compressed air N/A

N/A  Gbps

Rn 20 - 80 Bq/$m^3$

**Access**

Highway Tunnel

20 tonnes (guess)

Access 24/7

N/A people/shift peak

# INFN - Gran Sasso

**Underground Assembly Support & Occupancy**

No common CR

Low Background Assay

225 people average

Cranes: 5  tonnes

**Surface Facilities**

*Substantial Surface Support*
*17000 $m^2$*

Chemistry Lab

ULB Lab

# Yemilab

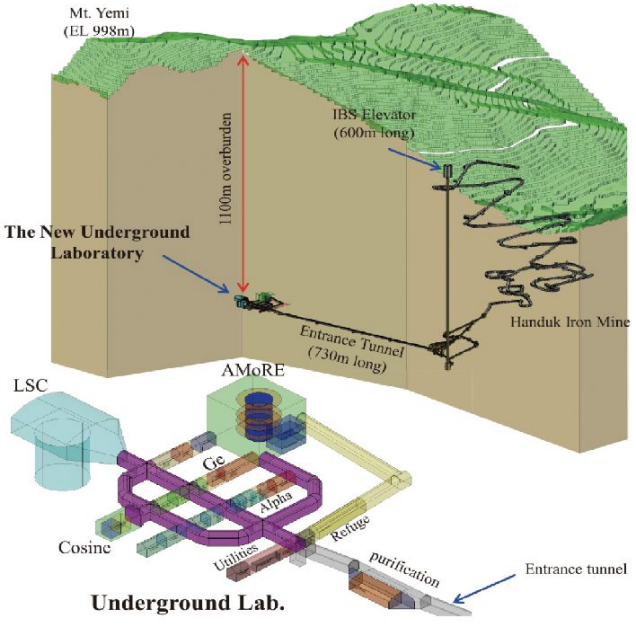
Active Mine - 2500 mwe

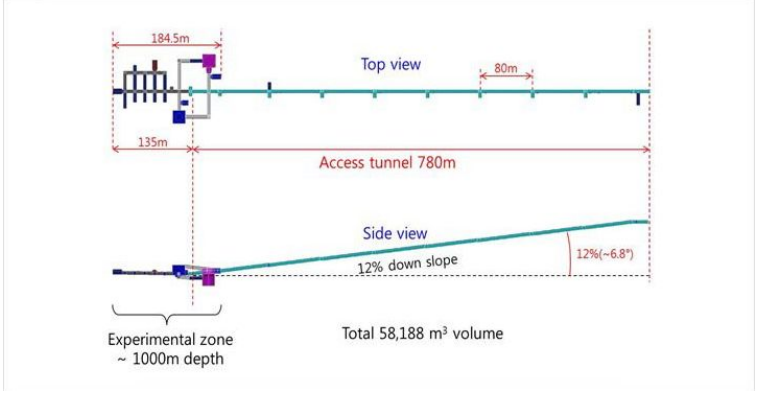
Vertical Access, Dedicated Access Drift

Past Experiments - none, new laboratory!

Current Program - Establishing Research Program

Constructing - COSINE, AMoRE, LSC, IsoDAR, KNU, KIGAM, Low Background Counting



# Yemilab


Operations Agency - Center for Underground Physics in IBS

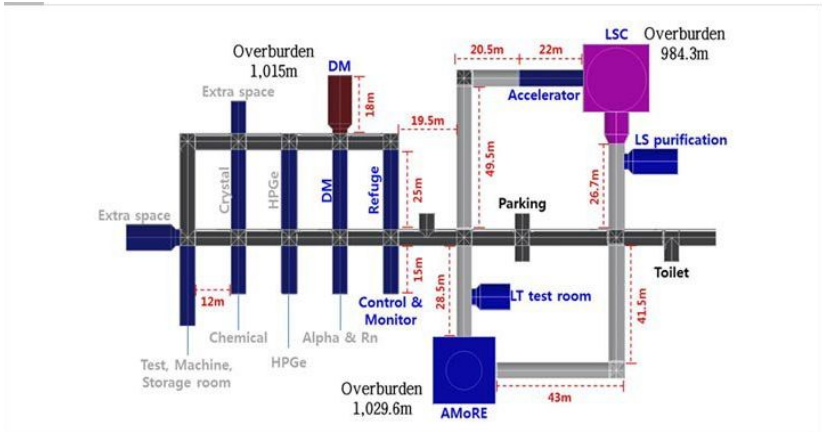
Oversight Agencies - Ministry of Science and ICT

Shared with SM Handeok Iron-Mine & Construction

Mine Safety Training, Yemilab Safety Training

**Staff**

7 Technical, 5 Science
Expansion anticipated to:
10 Technical, 8 Science
1 EH&S, 2 Admin



# Yemilab

**Environment**

Depth and Shielding 2500 mwe

TBD ~ 1.e-6/$cm^2$/s

Temperature 25°C

RH TBD%

Rn 20 - 2000 Bq/$m^3$

Thermal Neutrons TBD n/$cm^2$/s

Gammas 516 γ/s

**Space**

Operations: 15 x 5 x 5 m

LSC 22 x 22 x 8 + 20 dia x 20 h

Purification: 15 x 7 x 7

AMoRE 21 x 21 x 16 + 13 x 8 x 8

COSINE 15 x 15 x 8 + 25 x 5 x 5

KNU 15 x 8 x 8

KIGAM 15 x 8 x 8

IsoDAR 15 x 12 x 10, 20 x 7 x 7

Open 25 x 5 x 5, 3x(12 x 5 x 5)

Blue = available in next 10 years, Green = available now

# Yemilab

**Utilities**

Electrical Power 1800kW

Standby Generator 1800kW

Chilled Water 15 kW (35kW by 2023)

Waste heat 180 kW

Compressed air N/A

10  Gbps

Rn TBD ~ 20 - 2000 Bq/$m^3$

**Access**

Vertical Access 2.8 x 1.5 x 3.5 m

1.5 tonnes

Access TBD 3 shift/day 24 hr monitoring

40 people/shift peak

40 people refuge

# Yemilab

**Underground Assembly Support & Occupancy**

No common CR

Rn-reduced Air 50 CMH

Low Background Assay

Peak 40 people/shift, Steadystate TBD/shift

Multiple Cranes: 5  tonnes

**Surface Facilities**

*2500* $m^2$ Office Space

*64* $m^2$ Clean Room

*64* $m^2$ Assembly Shop

*32* $m^2$ Machine Shop

*64* $m^2$ Storage and Warehouse

*64* $m^2$ Chemistry Labs

*64* $m^2$ Low Background Assay

# Conclusions

I am very excited to see the commissioning of Yemilab and a new suite of experiments taking place in a well shielded laboratory

In comparison with other and well established laboratories you have integrated essential infrastructure elements and have those that are essential for a successful world-class science program

Some of your planned experiments and unique and will provide critical new information on high profile science questions

Congratulations on making Yemilab a reality.  I look forward to your upcoming publications