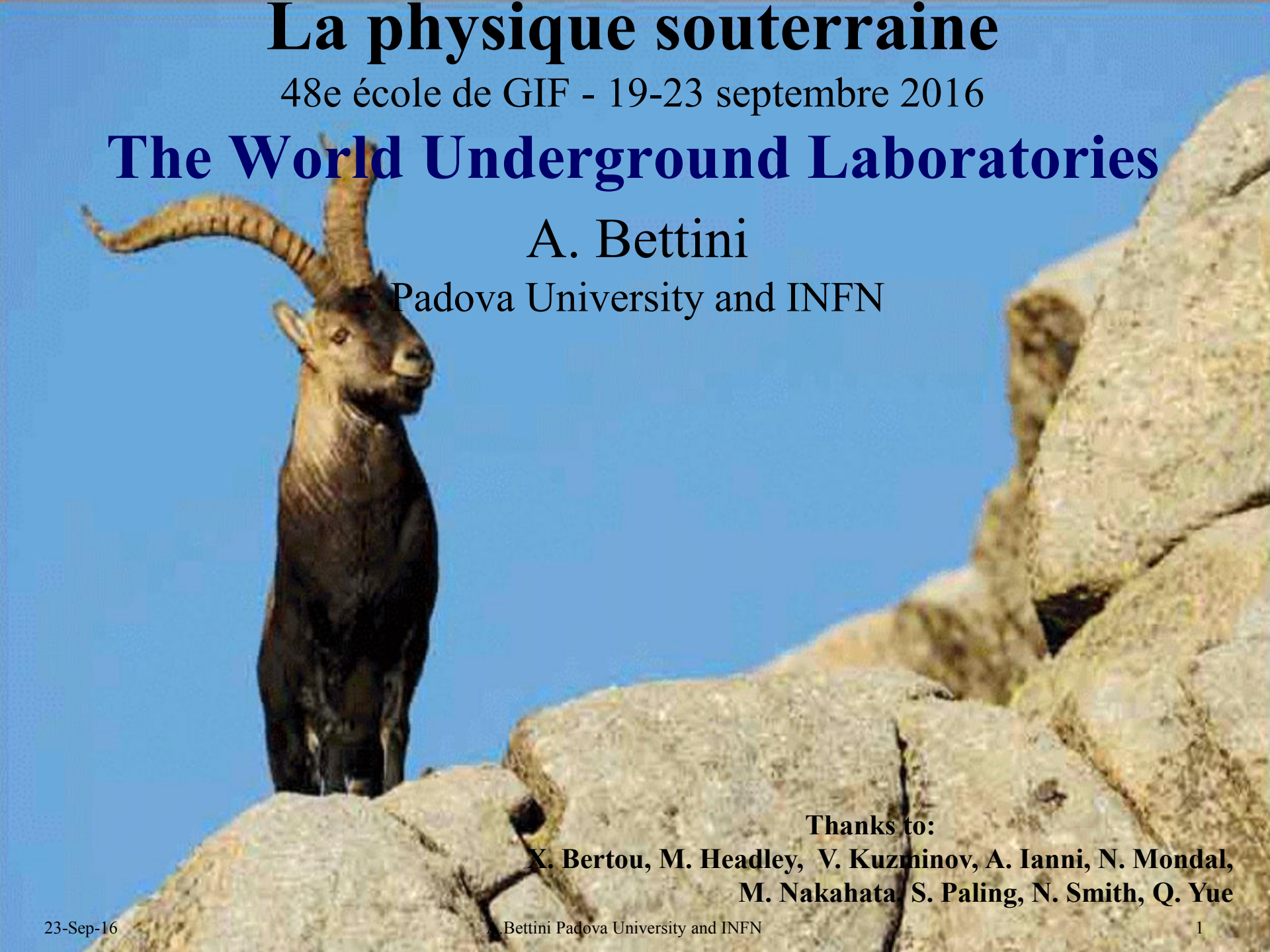
La physique souterraine

48e école de GIF - 19-23 septembre 2016

The World Underground Laboratories

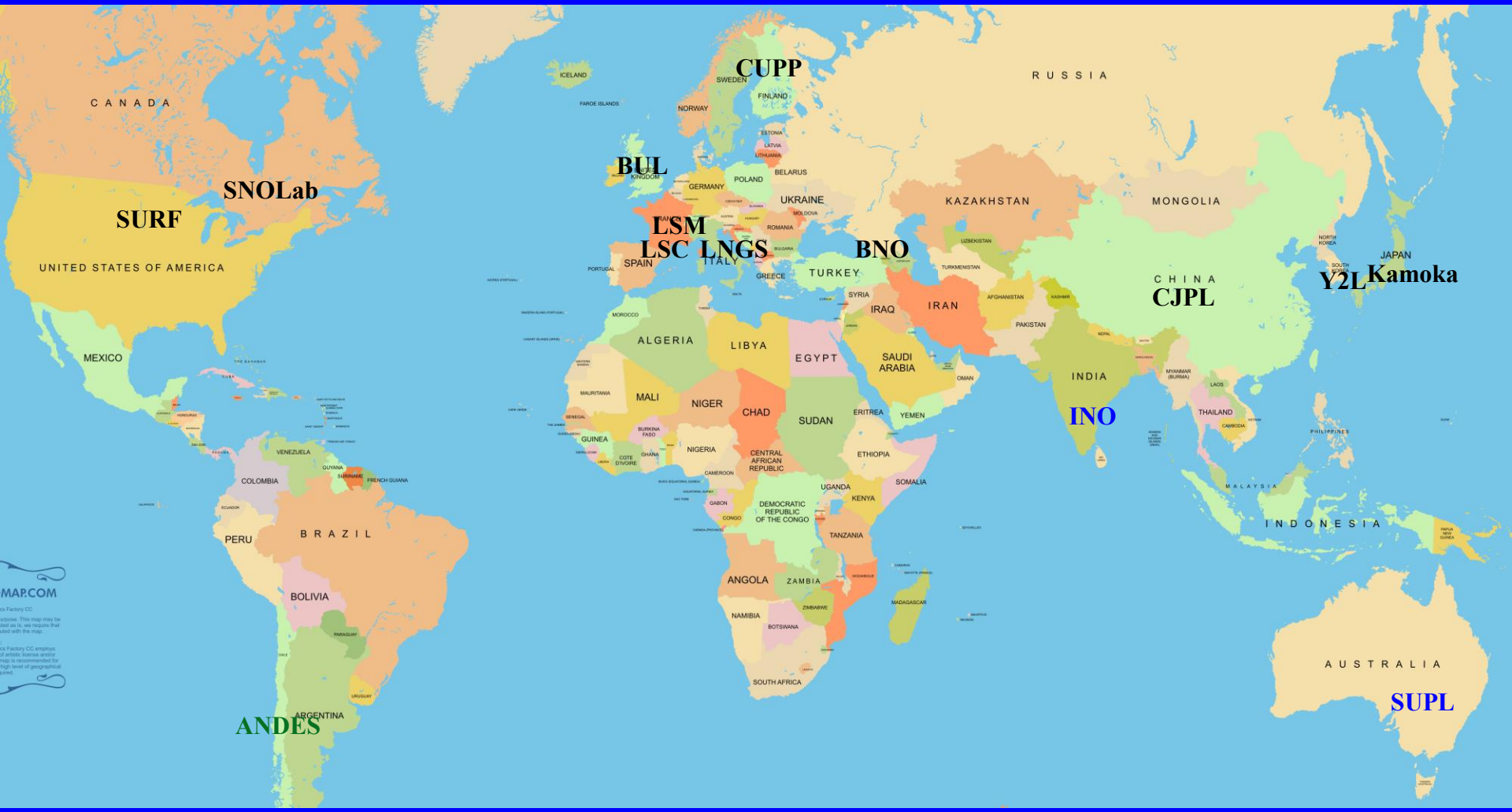
A. Bettini

Padova University and INFN



Thanks to:
X. Bertou, M. Headley, V. Kuzminov, A. Ianni, N. Mondal, M. Nakahata, S. Paling, N. Smith, Q. Yue

The sites



Shall not discuss infrastructures dedicated to host far detectors for neutrino beams from proton accelerators or nuclear reactors

Characteristics

- **A laboratory is not a mine**
  - Excavation technique different
  - Services to experiments needed
- **Depth (μ flux, spallation *n* fluence)**
  - Determines only a fraction of the background sources
  - μs are useful or calibration
- **Diameter & height of the halls**
  - Limits the thickness of the shields (e. g. water shield 10-12 m diameter)
  - Maximum hall span depends on rock quality and depth (see CJPL)
- **Horizontal vs. vertical access** (life much easier if H access)
- **Distance from accelerator**
- **Support infrastructures, personnel** (quantity and quality)
- **Underground area allocation policy, turnover of experiments**
  - Laboratory vs. observatory
  - Scientific Committee: international vs. local (or national)
- **Degree of internationality of the community**
- **Other science** (geology, biology, engineering, etc.)
- **Management issues**
  - Budget, funding of the experiments, accountability policy
  - Safety and security policy
  - Environmental policy

Costs

a. Civil works installation costs. Not strongly dependent on volume. Higher in a mine
b. Costs for excavation proportional to the volume.
c. Costs for rock support proportional to the surface. Increasing with depth. Same level as b)
d. Costs for outfitting. Level of a+b

Total $\simeq$ 4b+a

LNGS. 190 000 m^3, horizontal access through freeway; no access construction costs
Construction cost 330 €2015/outfitted m^3 (tot 63 M€)

SNOLab. 47 000 m^3, vertical access through a modern working mine; no access construction expenses
Construction cost 1500 $Can/outfitted m^3 $\simeq$1000 €/outfitted m^3 (tot 30 M$Can)

SURF (Old, dismissed mine). Construction costs difficult to evaluate in the design phases
E.g.: costs for access only: rehabilitation of one of the two shaft = 30 M$US + second shaft + maintenance of the old ones over several years. Total on the order of a complete LNGS

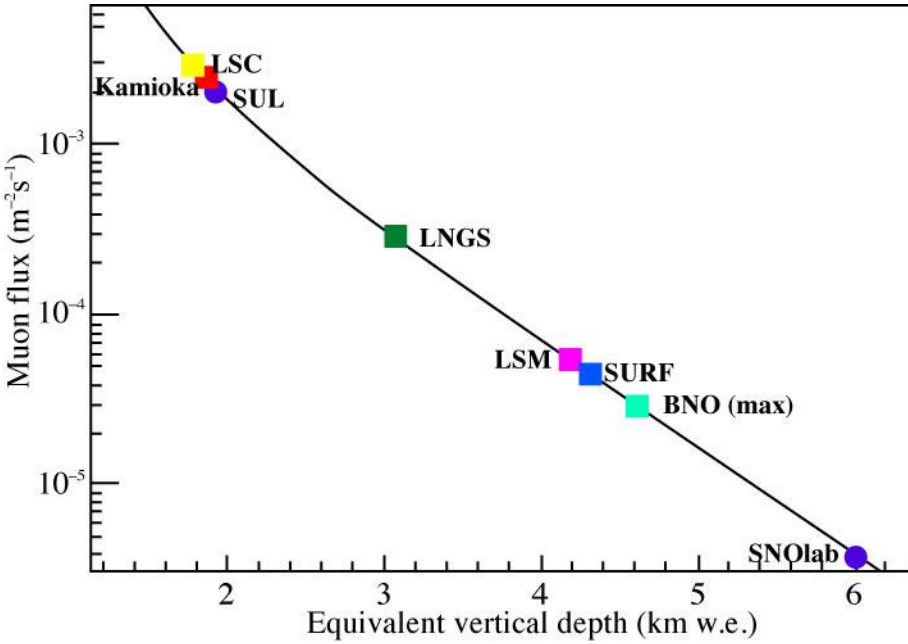
Different decisions

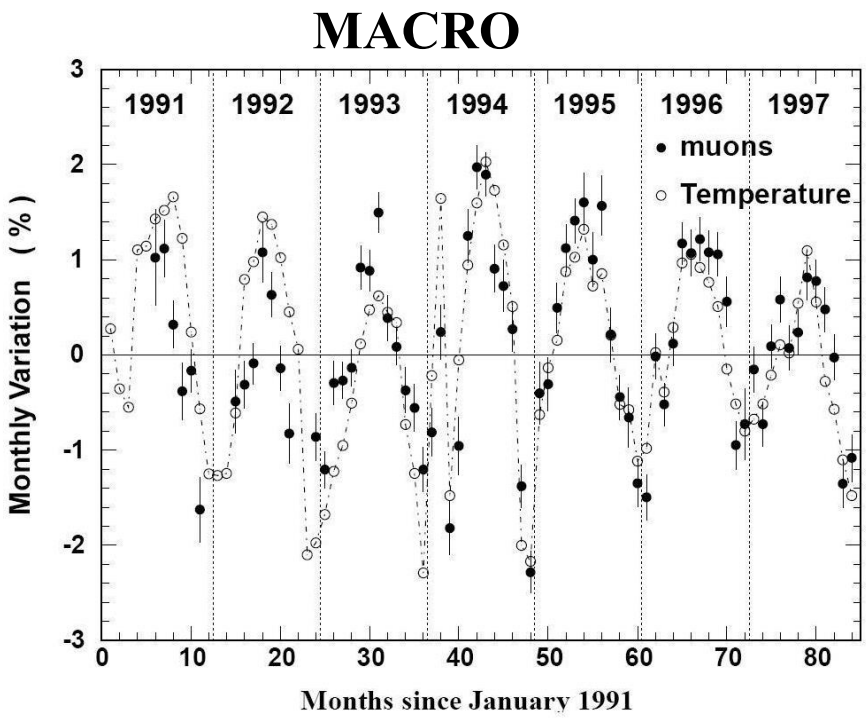
- BNO built (1966) with a dedicated access tunnel
  - In general 2nd (smaller) one advisable for safety
- LNGS (the largest), LSC, LSM, (ANDES): close to a free way; construction must be in phase
  - Reduce construction & running costs. Drive-in to experiments
- Kamioka: similar, drive-in in a working mine, no interference
- CJPL, CUNPA. Hydroelectric power station infrastructures offer similar opportunities
- LNGS, LSC, ….built general purpose experimental halls, turnover of experiments
- SNOLab (the deepest), built in a working mine (pros and cons)
- Kamioka, SNOLab: build experiment specific halls
- SURF in an dismissed mine. Rehabilitation costs are high and need high contingencies due to the high risk

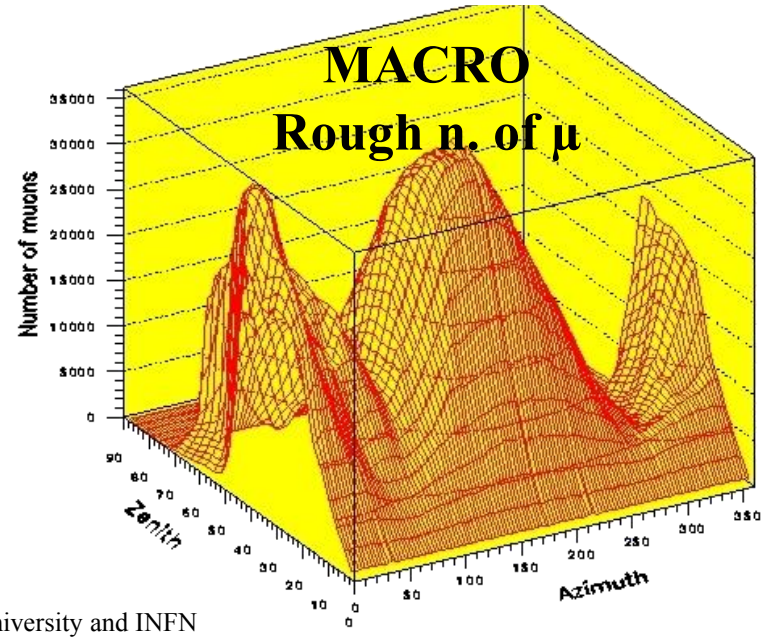
Muons

Equivalent vertical depth = depth for the same μ flux under horizontal surface

- μ flux decreases with increasing overburden
  - can be suppressed by anticoincidence
- cosmogenic background does not contribute substantially to the budget at depth > 1500 m
- with a few exceptions (^{11}C in scintillator detectors
- angular dependence of the μ flux
- seasonal variations of the μ flux and of their spallation neutrons







Neutrons

- **From (α,*n*) and fission** (U/Th) in the rocks and concrete at lower energies (< 8 MeV)
  - not difficult to shield, energy spectrum must be known
  - dependent on geology and on the concrete (few-several $10^{-2}m^{-2}s^{-1}$)
    - Reduced to $2.3 \cdot 10^{-3}$ $m^{-2}s^{-1}$ at BNO
  - independent of depth @> 100 m's
- **Interactions of μs in the rocks**
  - higher neutron energies (several GeV), thicker shields needed
  - flux is time dependent (seasonal variations)
  - flux depends on depth
  - flux 3-4 orders of magnitude smaller than thermal
- **Interactions of μs in the shields & in the detector**
  - cannot be shielded
  - decreases with increasing depth
  - **induced <u>prompt</u> background can be reduced by anticoincidence**
    - 4 orders of magnitude in BOREXINO
  - **metastable nuclides more difficult, can be reduced by depth**
    - **experiment dependent, more severe for high-Z materials**

μ-induced backgrounds

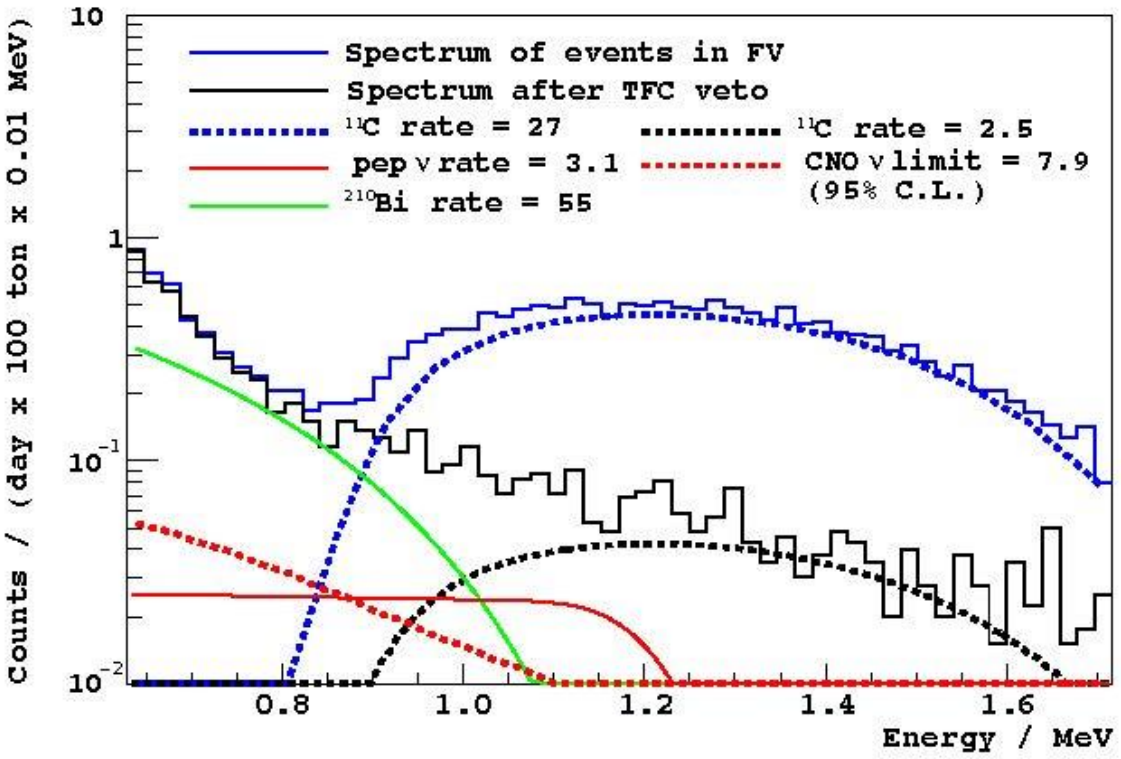
Residual μ induced backgrounds are of two types

Prompt. Can be suppressed by almost two orders of magnitudes by anticoincidence

Delayed. Can be suppressed by delayed coincidence and geometrical cuts if delay is not too much

At about 1500 m rock overburden μ induced background are already negligible

Exception 11C in liquid scintillator detectors

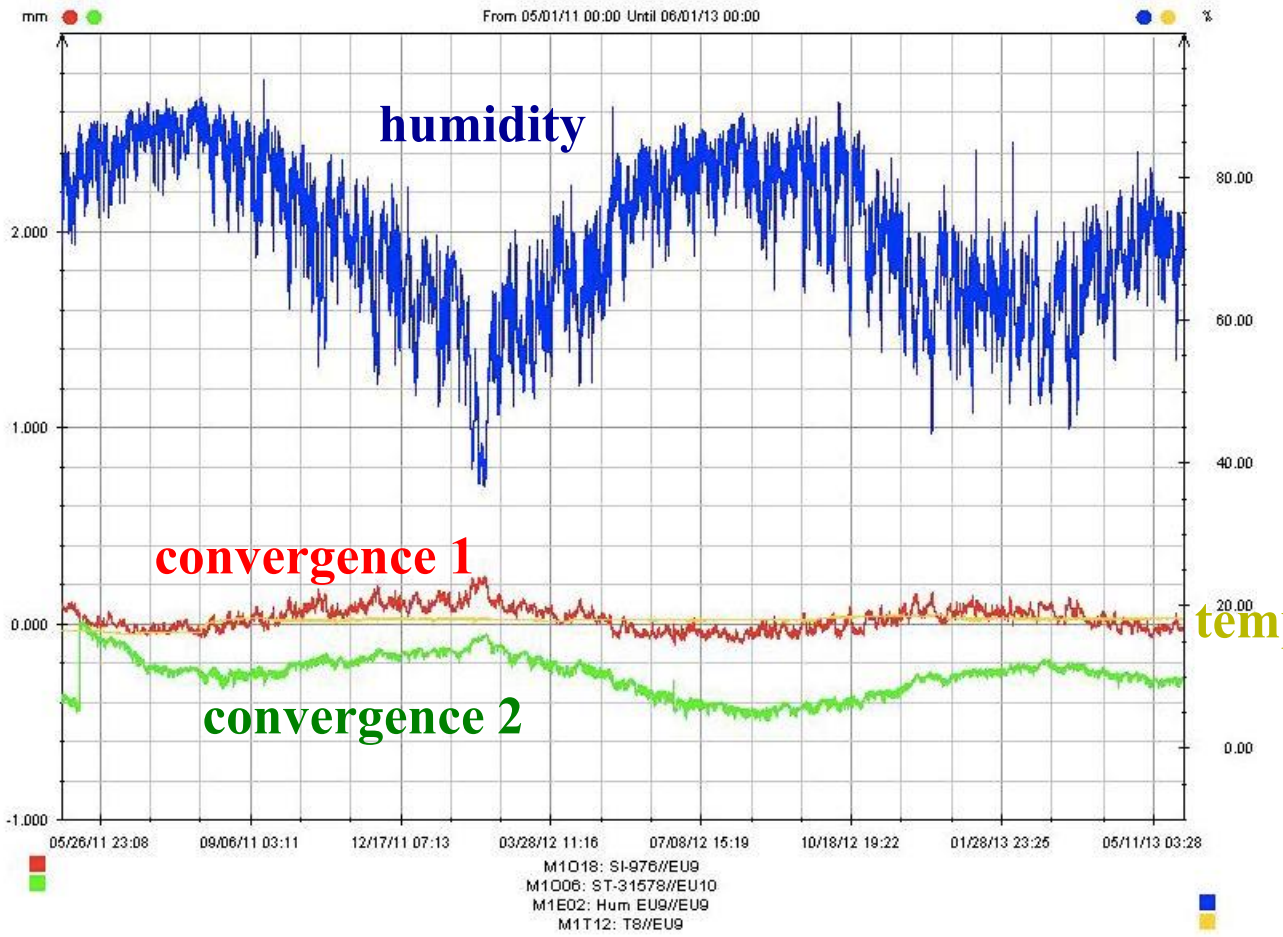


BOREXINO @ LNGS

Monitoring environment changes

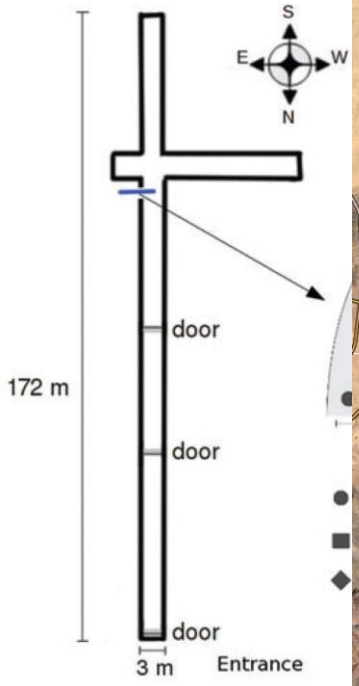
- convergence of the caves
- seasonal variations of the μ flux
- seasonal variations of the *n* flux
- seasonal dependence of humidity (temperature is about constant)
- seasonal and aperiodic variation of the Rn activity in the air
- ……..

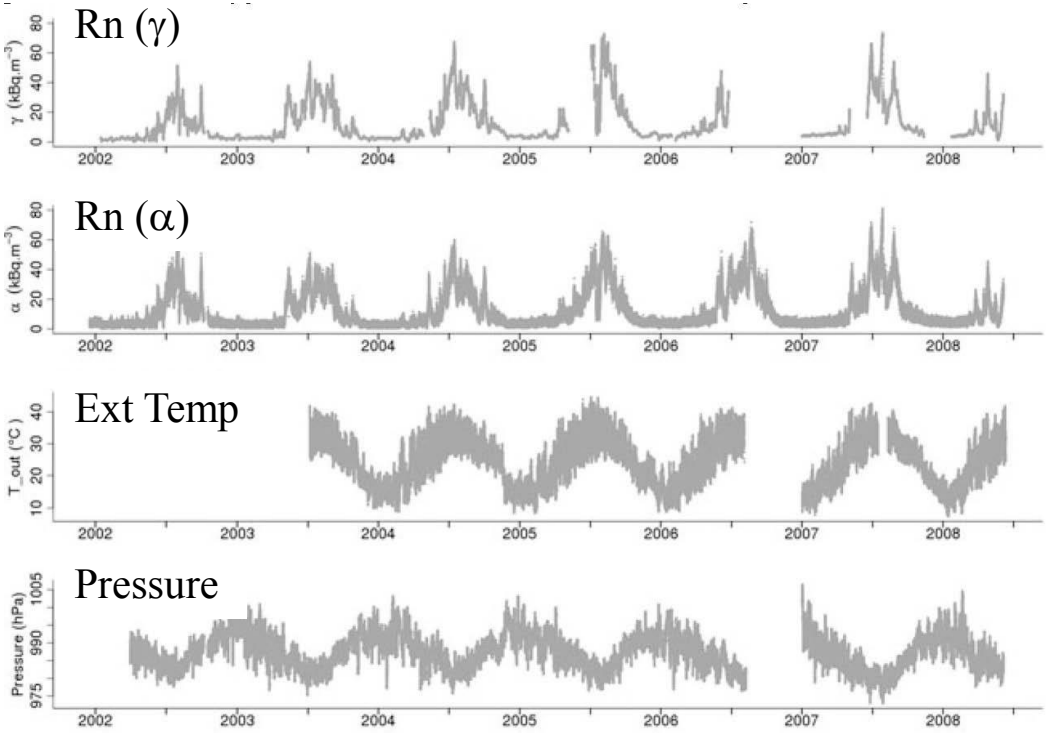
LSC optical fibres monitor



Rn seasonal variations in Amran tunnel

S. M. Barbosa et al. Geoph Journ. Internaz. **182** (2010) 829





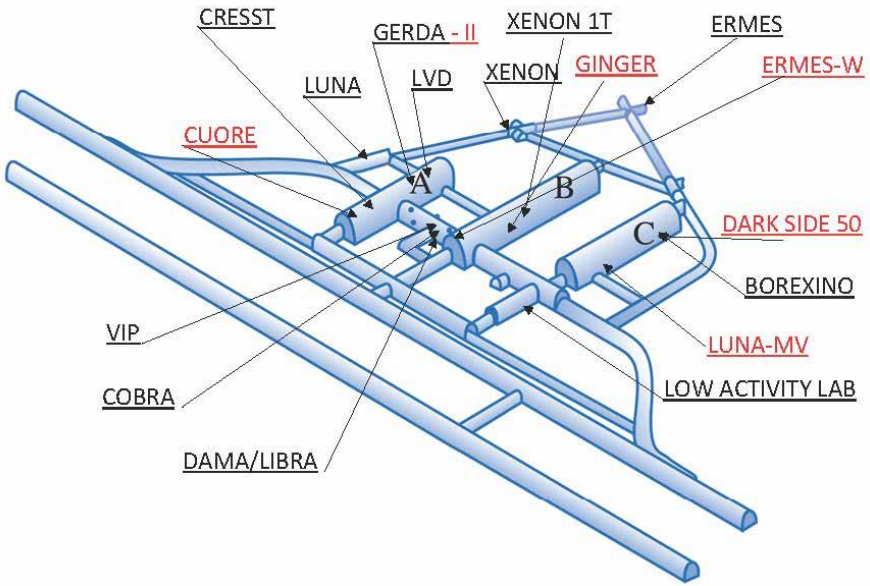
Originally escavated for Gravitational Waves antenna
Now used as underground geophysics observatory

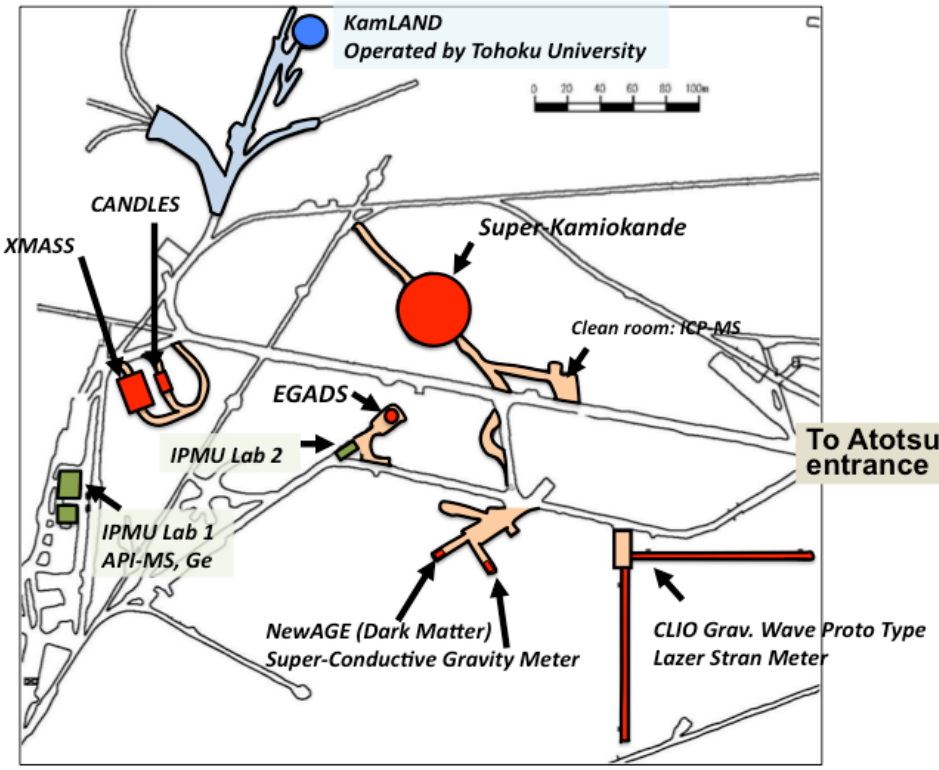
At LSC much smaller modulation observed

Different design concepts

Gran Sasso Laboratory designed with general purpose large halls. Majority of experiments approved for a number of years

Kamioka Observatory in a mine with easy horizontal access. Many existing tunnels allow building new halls for new approved experiments

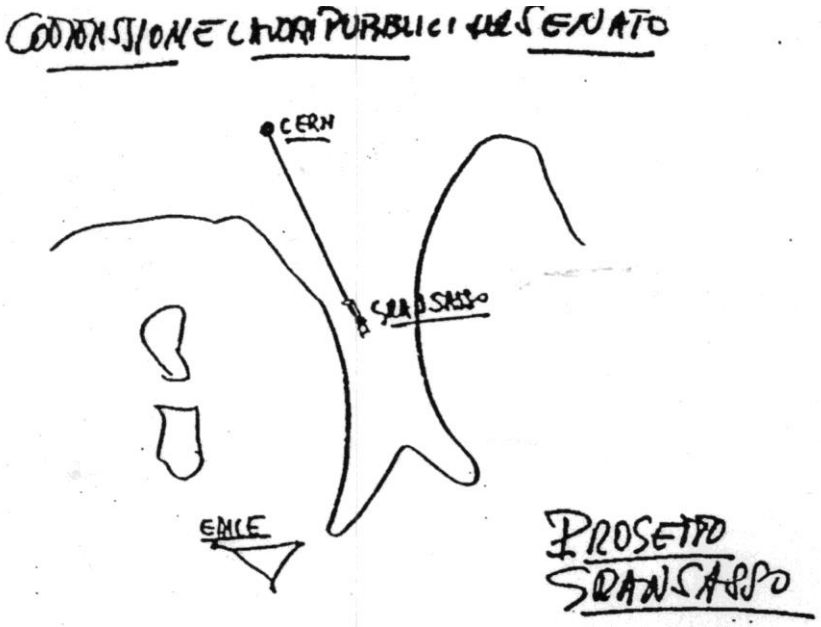


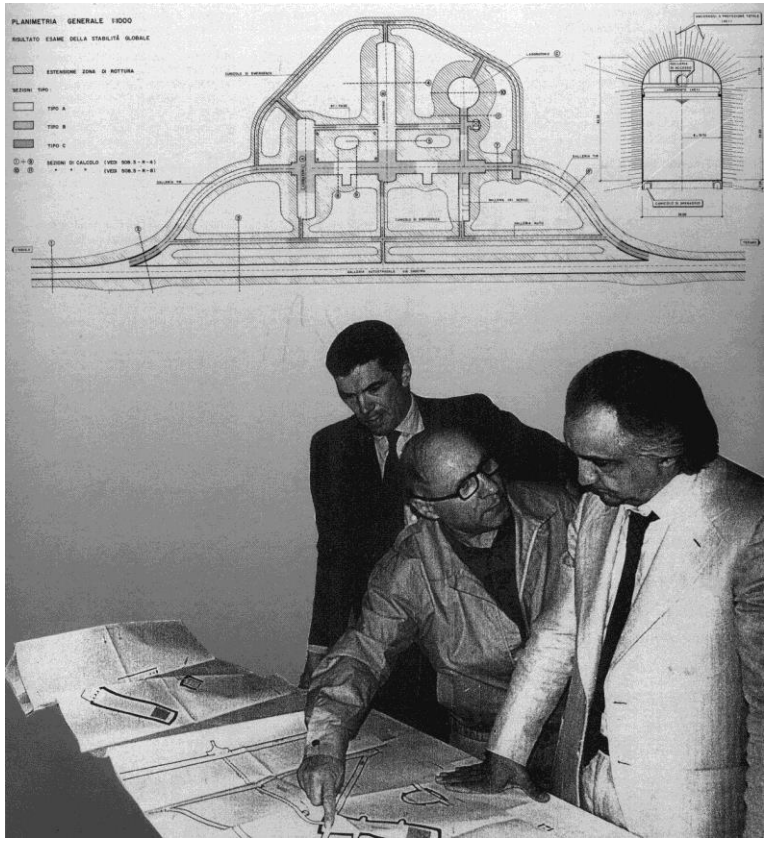


INFN Laboratori Nazionali del Gran Sasso

1979 A. Zichichi proposes to the Parliament to build a large underground laboratory close to the Gran Sasso freeway tunnel, under construction

1982 the Parliament approves the construction, finished in **1987**





http://www.lngs.infn.it/

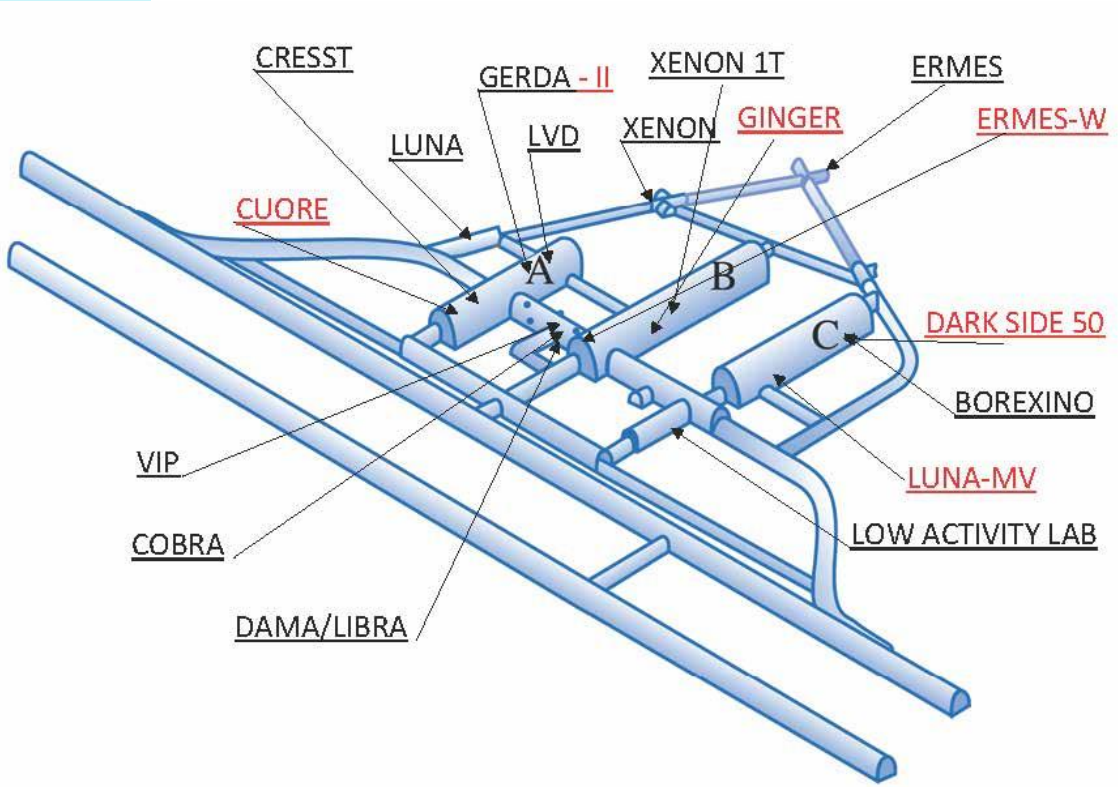
LNGS of INFN

L. Votano (2012) EPJ-p 127:109

- 1400 m rock overburden (3.2 km w.e.)
- n flux = $3.8 \pm 0.3\ 10^{-2}\ m^{-2}s^{-1}$ (spectrum measured)
- μ flux = $3 \times 10^{-4}\ m^{-2}s^{-1}$ (angular dependence measured)
- γ flux= $1 \times 10^{-4}\ m^{-2}s^{-1}$
- Volume 180 000 m^3, area 17 300 m^2
- Radon in air 50-80 Bq/m^3
- Drive in to the experiments
- Personnel on site = 110. Users=950 from 29 Countries

LNG. Science and Services

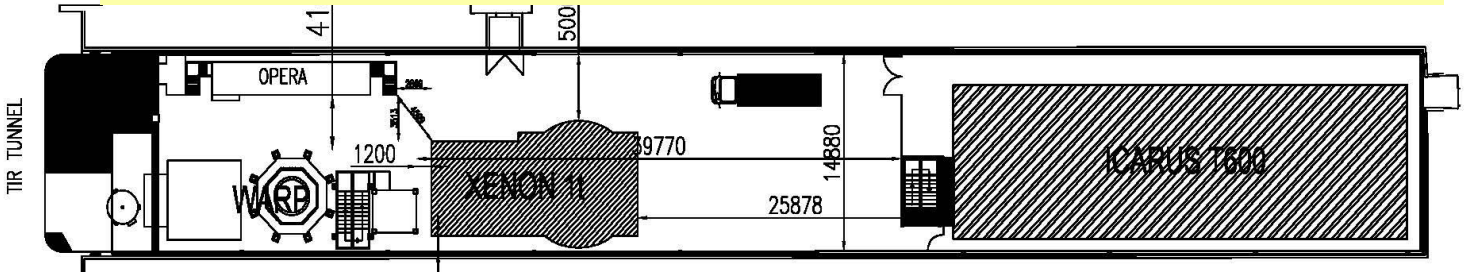
Administration
Public relationships support
Secretariats (visa, work permissions, etc.)
Outreach
Environment protection
Prevention, safety, security
General, safety, electrical plants
Civil works
Chemistry
Cryogenics
Low activity measurements
Mechanical shop
Electronics
Computing and networks
Offices
Assembly halls
Lab & storage spaces
Library
Conference rooms
Canteen



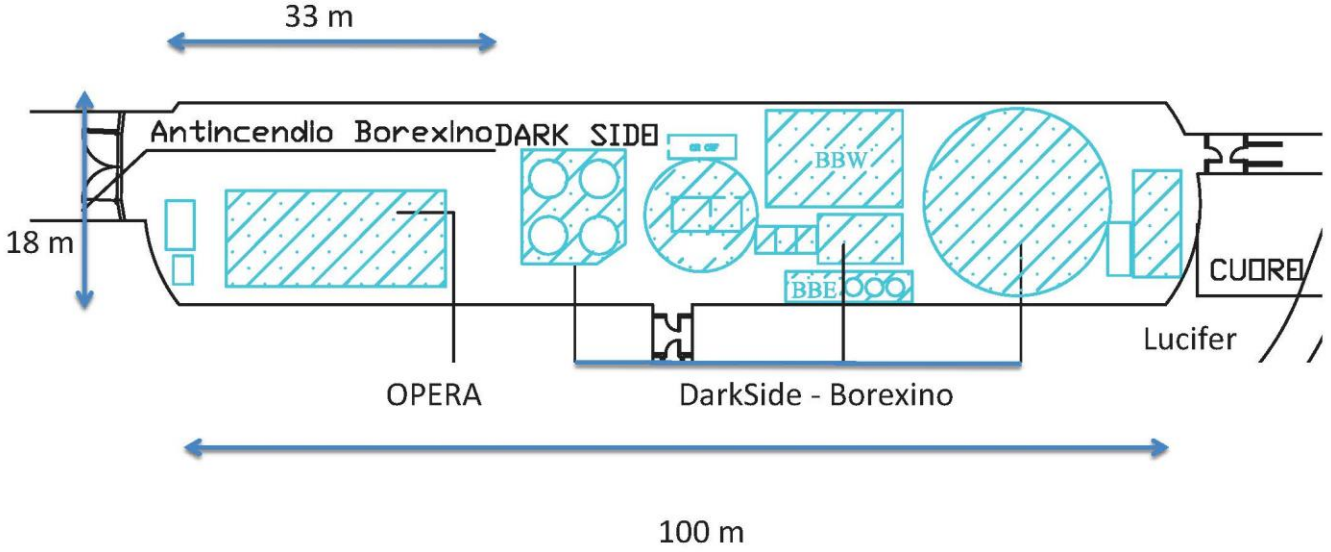
LNGS

End of the CNGS programme + termination of WARP ,
ICARUS, OPERA and WARP decommissioned

Hall B. Available in 2015, 100 m minus XENON 1 t space

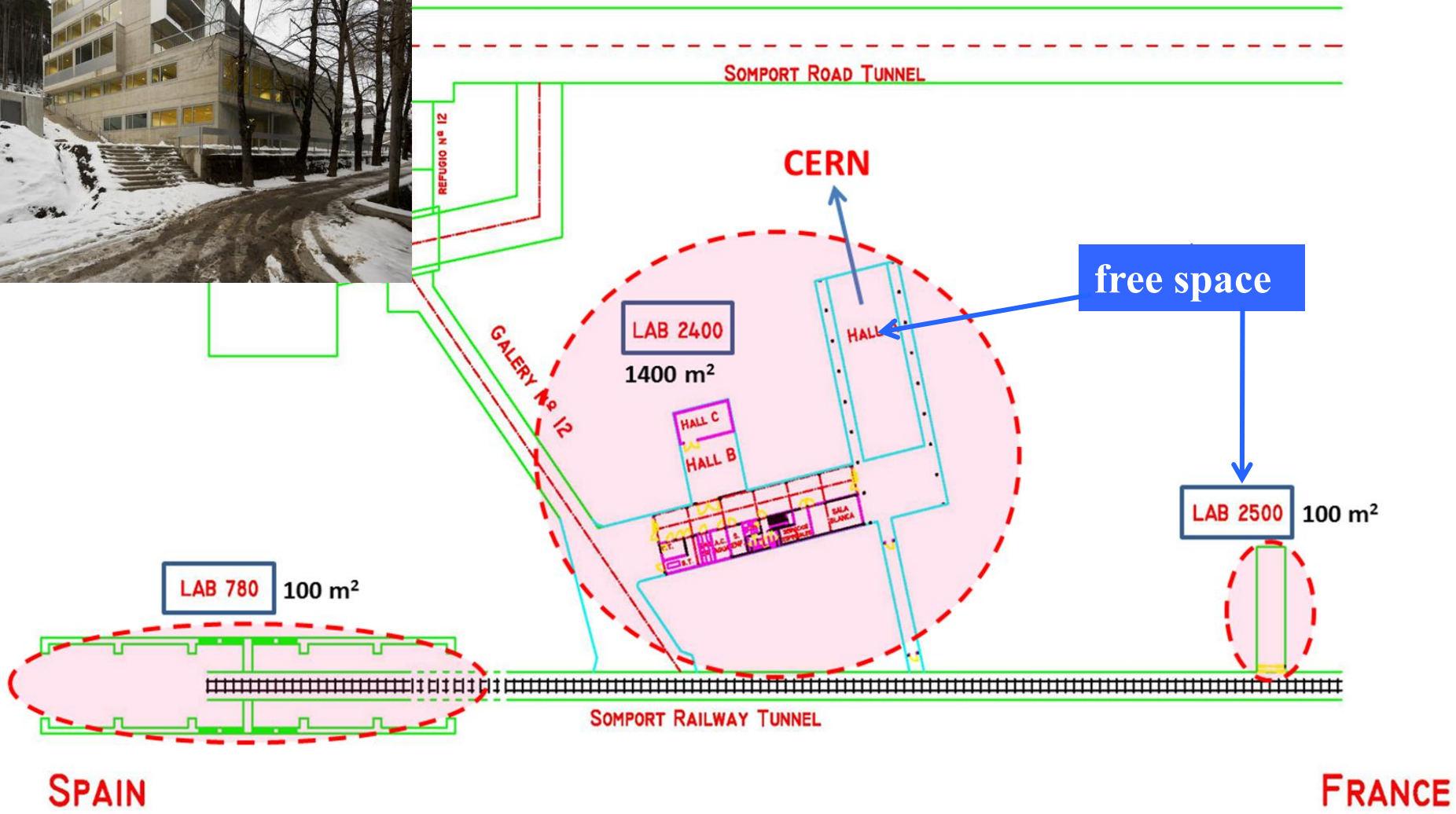


Hall C. Available in 2017



LSC

Total area 1560 m^2
Total volume 10500 m^3
Max coverage 850 m

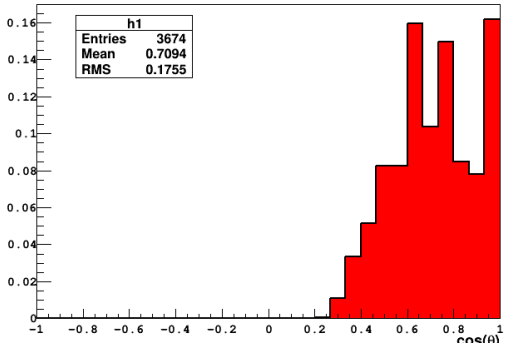


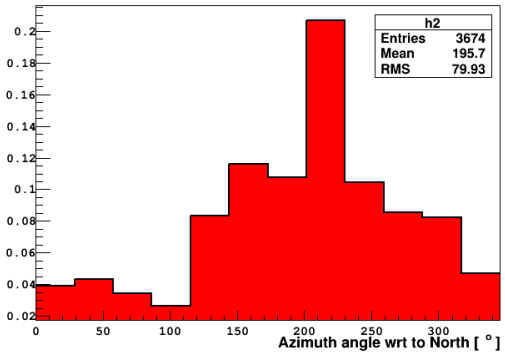
A. Bettini (2012) EPJ-p 127:112

http://www.lsc-canfranc.es/en/

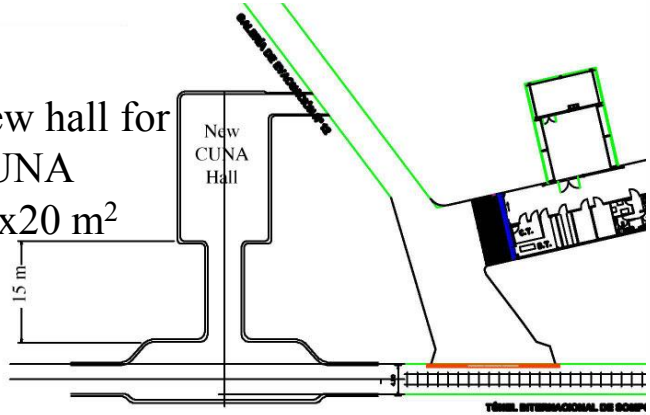
LSC

Muon flux monitor vs angles



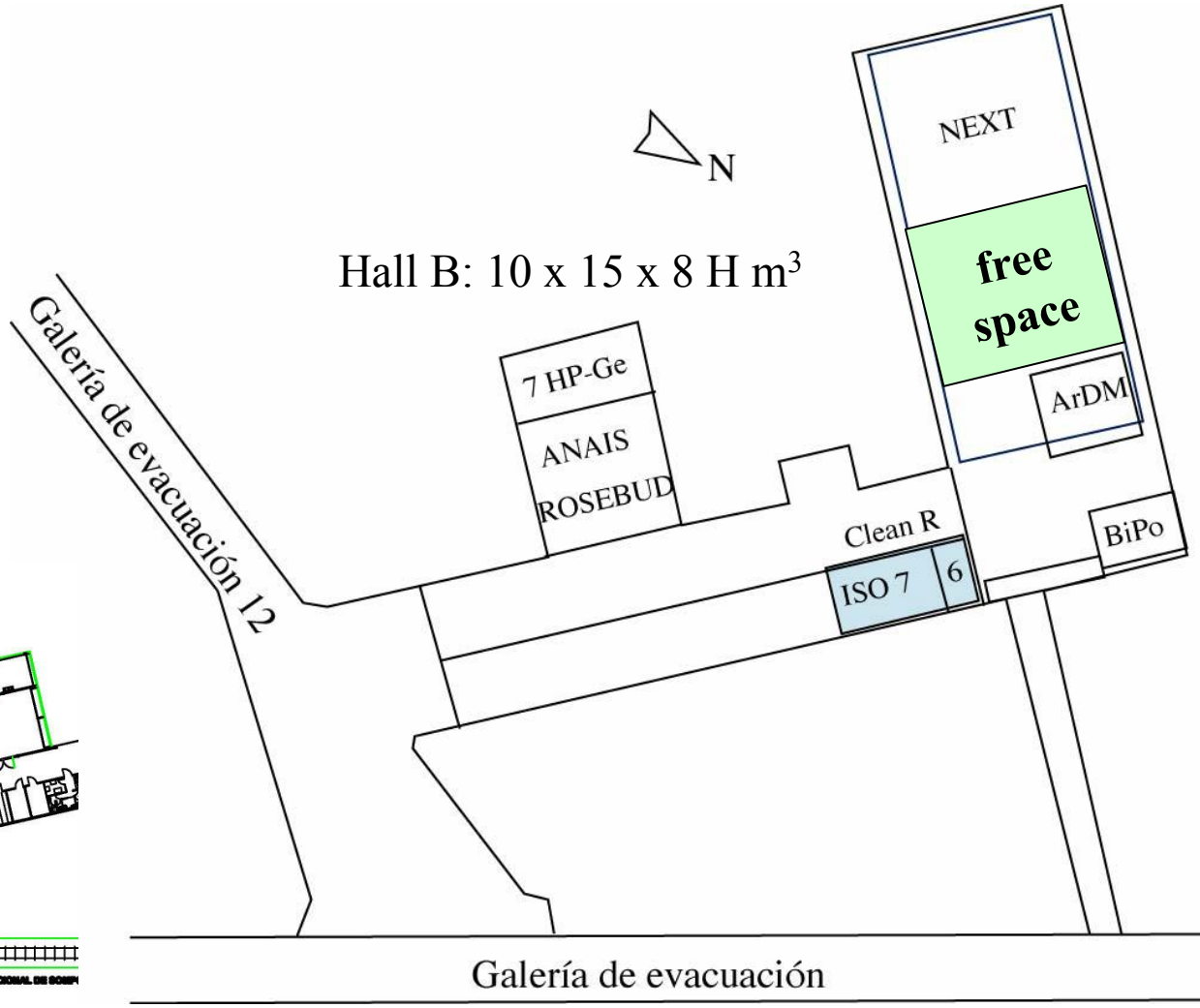


New hall for CUNA 12x20 m^2



Hall A: 14.5 x 40 x 10 H m^3

Hall B: 10 x 15 x 8 H m^3



LSC. Services

- **Screening** HpGe underground laboratory
  - 8 detectors. Sensitivity, assuming secular equilibrium and 10% efficiency:
    $^{238}U \sim 10 – 100$ ppt
    $^{232}Th \sim 50 – 330$ ppt
    $^{40}K \sim 10 – 100$ ppb
- **Underground Clean room**
  - Class 6 and 7
- **Radon abatement system**
  - provides 220 m^3/h radon-free air
- **Radon detector (mBq/m^3)** being installed
- **Chemistry laboratory (**on surface**)** with Cu electro-forming facility
- **Workshop (**on surface and underground**)**

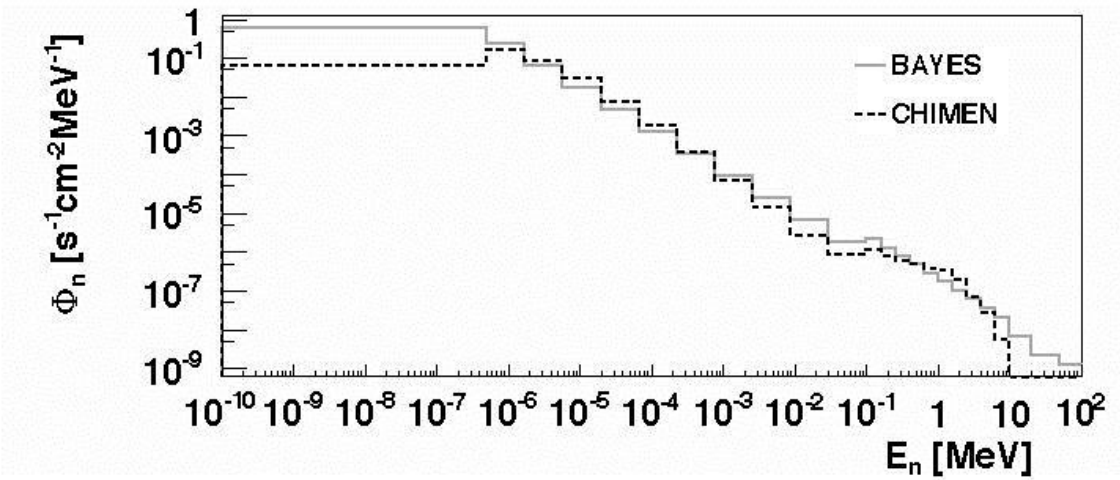
LSC. Electroforming

	U [ppt]	Th [ppt]
OFHC*	0.2±0.01	1±0.06
Electro-formed**	< 1	< 1

* measurement at PNNL
** measurement at LNGS

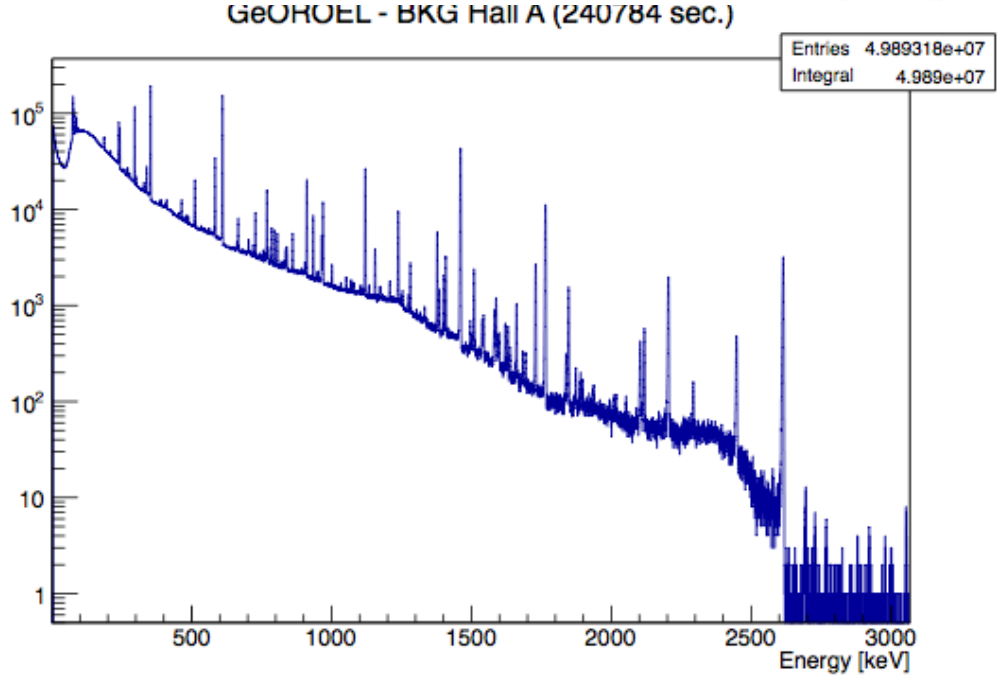
Energy spectra n and γ

Largely independent on depth, dependent on geology and construction materials (n)



LSC as an example

$\Phi_{\text{Hall-A}} = (3.47\pm0.35)\times10^{-2}$ m^{-2}s^{-1}



Hall A

^{40}K: 0.17±0.03 cm^{-2}s^{-1}

^{232}Th: 0.38 ±0.02 cm^{-2}s^{-1}

^{238}U: 0.68 ±0.17 cm^{-2}s^{-1}

Tot: 1.23±0.17 cm^{-2}s^{-1}

LSC. Science

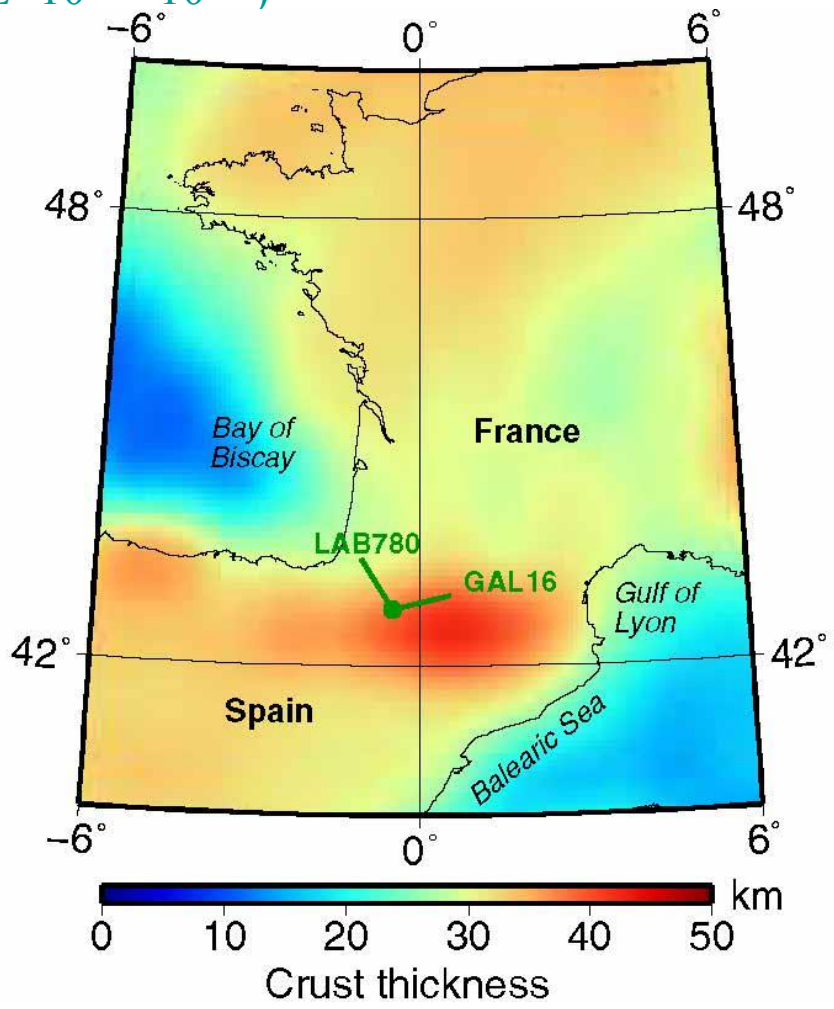
✓	**ANAIS**	DarkMater (NaI(Tl)), Annual modulation	construction
✓	**ArDM**	DarkMatter (2phase LAr TPC)	1st physics run completed
✓	**NEXT**	0ν2β (Enr ^{136}Xe gas TPC)	commissioning demonstr.
✓	BiPo-3	0ν2β (surface purityfor SuperNEMO)	operational
✓	Muons	cosmic rays monitoring	operational
✓	SuperK-Gd	screening for SuperK-Gd	operational
✓	GEODYN	Geodynamics	operational
✓	GOLLUM	life in extreme environment	operational

Expressions of Interest under review

- ✓CUNA Nuclear astrophysics (new excavation, max 300 m^2)
- ✓ Direct Dark Matter with CLYC scintillators
- ✓ Ultra-sensitive force sensor for short range interactions
- ✓ Low mass WIMP search with Micromegas-based TPC

LSC. GEODYN

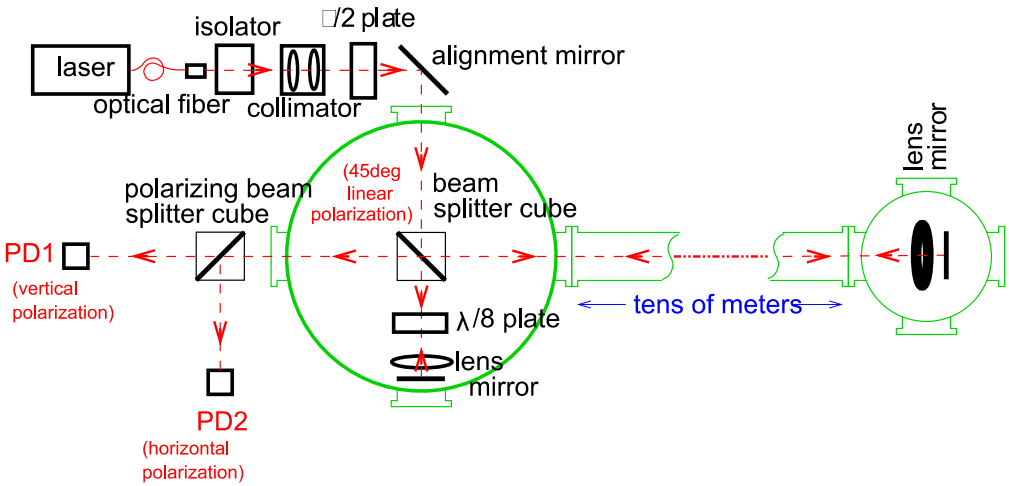
- LSC is located underground in one seismically very active areas in Europe
- Ideal position for an advanced geodynamic observatory with
  - two perpendicular LASER strainmeters ($\Delta L/L=10^{-8}$ - 10^{-12})
  - borad-band and strong motion seismometers
  - CGPS stations on the surface
- Integrate in the TOPO-IBERIA project
- Local phenomena
  - measure seismic phase velocity
  - Slow earthquakes
  - Strain seasonal changes
  - Tectonic deformation
- Global phenomena
  - Siesmic core modes
  - Free oscillations of the Earth
  - Free core nutation



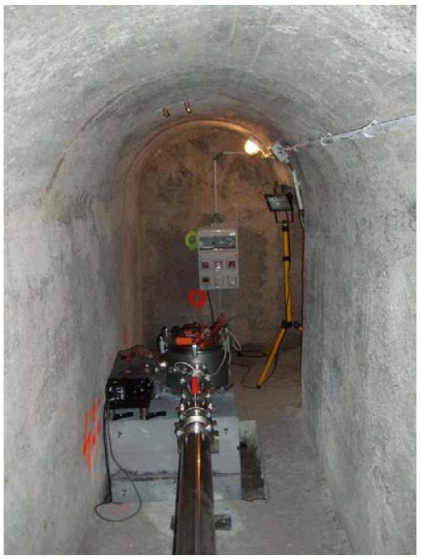
LSC. GEODYN

Seismic station installed inside the Lab780 gallery,

On left, detail of the Titan accelerometer and the Trillium 240s seismometer.

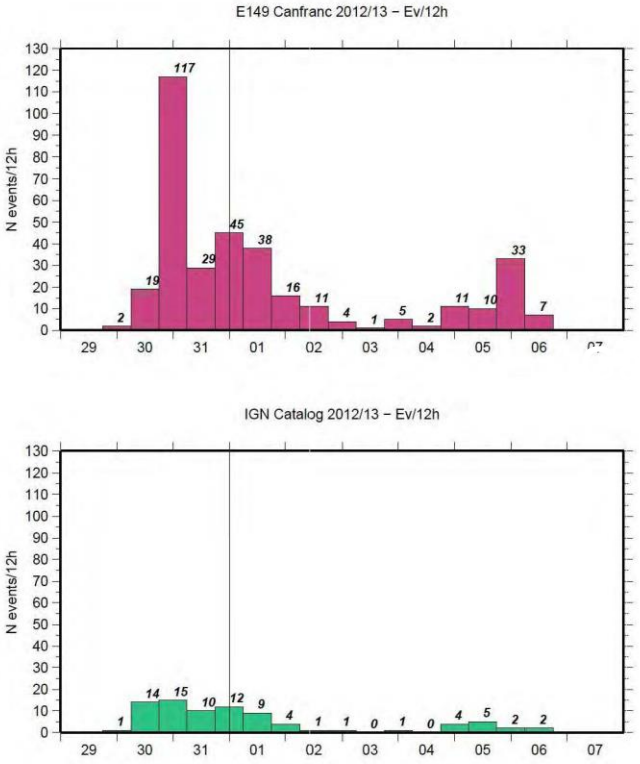


Simplified schema (up) and views of the two ends of the installed strainmeters.



GEODYN. Accelerometer

Strong reduction of the environmental noise allows detection of many more events in a seismic sequence



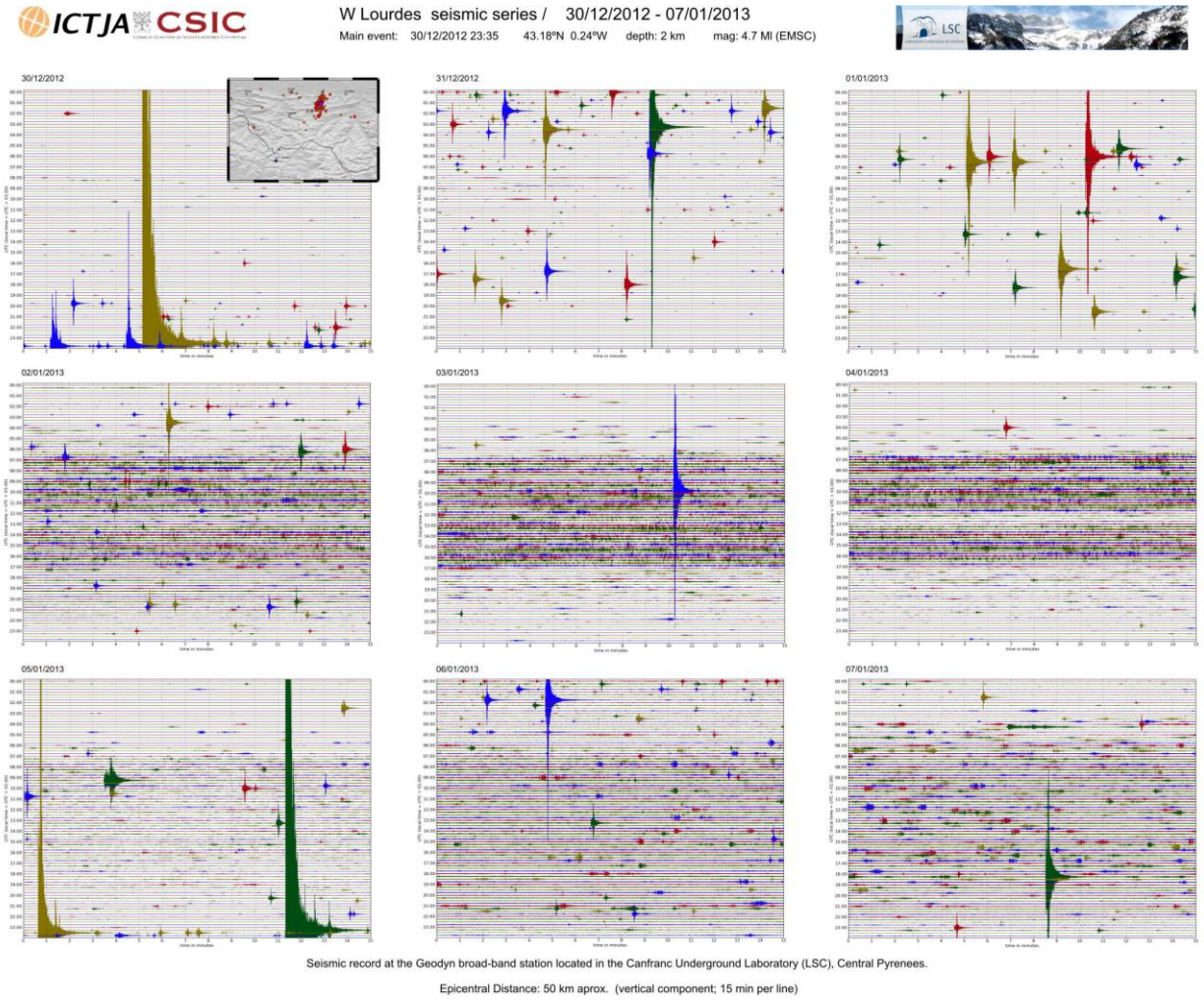
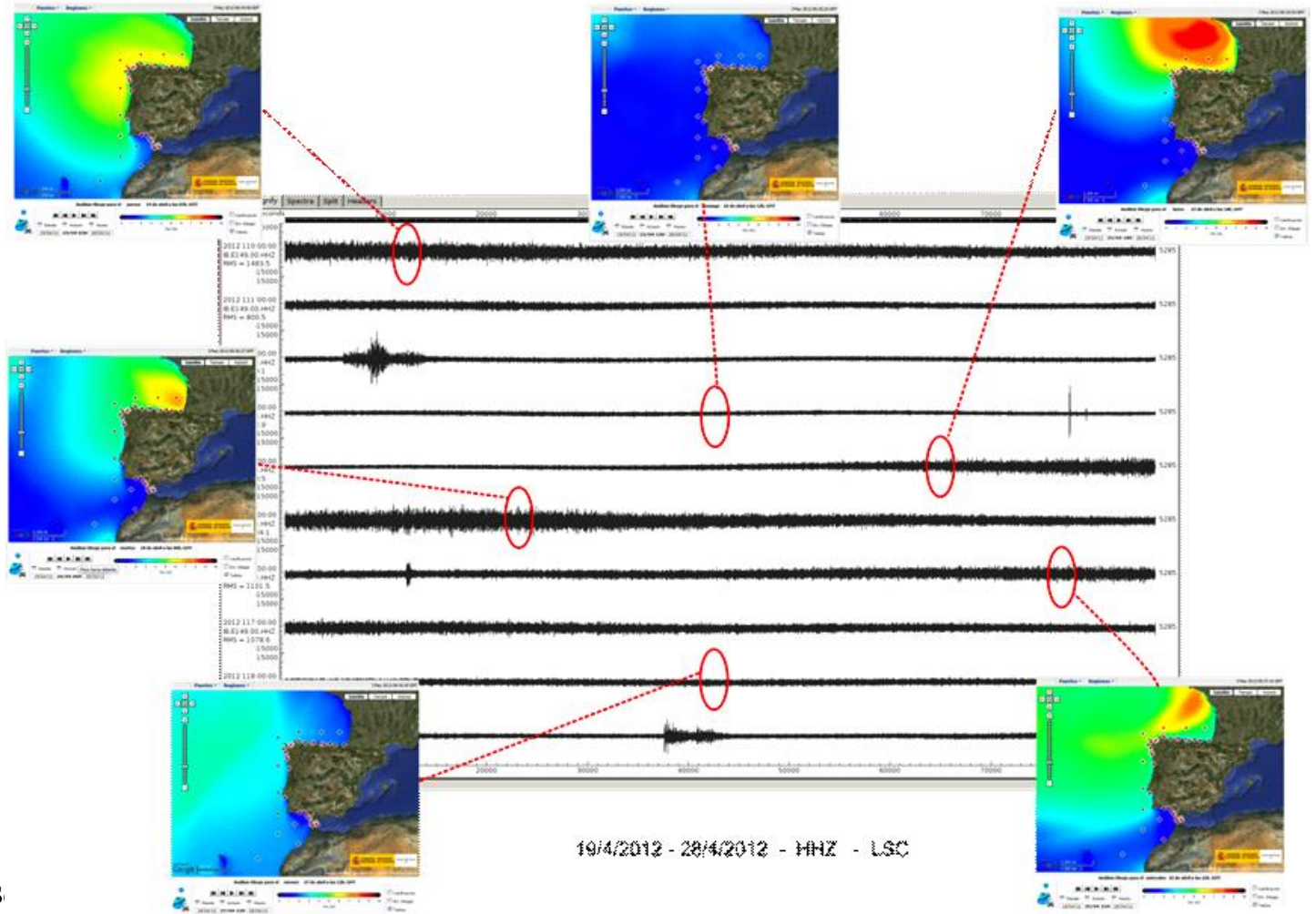


Figure 5. Histograms of events detected at Canfranc site during the seismic crisis (upper panel) versus the events reported on the official IGN catalogue from Spanish permanent network (lower panel).

GEODYN

Seismic noise and perturbations over the North Atlantic

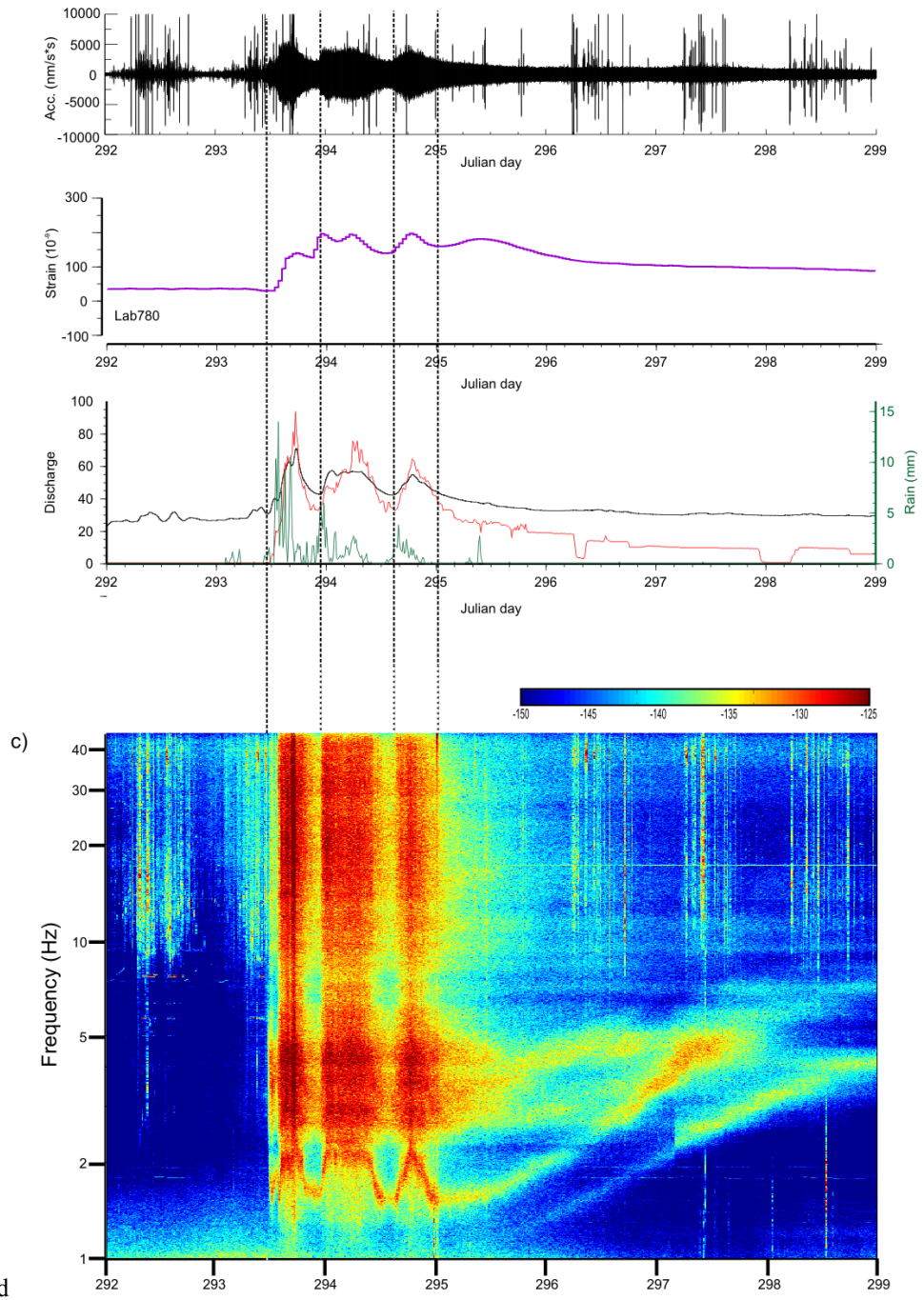
Seismic noise in the band 0.05-1.0 Hz is dominated by oceanic swell. This allows using seismic records to track large perturbations over the ocean. 10 days records during the passage of the Petra explosive cyclogenesis in April 2012



GEODYN

Hydrogeological signals

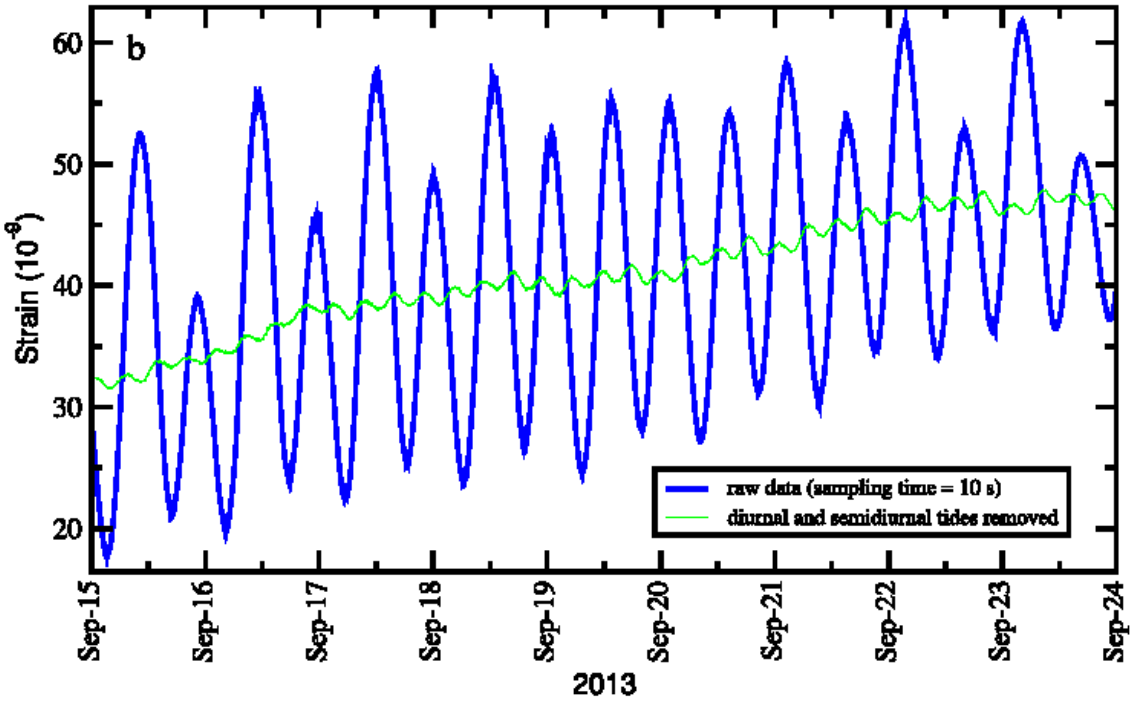
Vertical seismic and strain data, comparison between discharge rate (red), rainfall (green) and seismic envelope (black) and spectrogram of the vertical seismic component during the large storm and flood on October 2012. (time scale in Julian days, 2012)



GEODYN. Earth tides

Amoruso and Crescentini (2016), Nonlinear and minor ocean tides in the Bay of Biscay from the strain tides observed by two geodetic laser strainmeters at Canfranc (Spain), J.Geophys. Res. Oceans, 121

Strain data example, Lab780



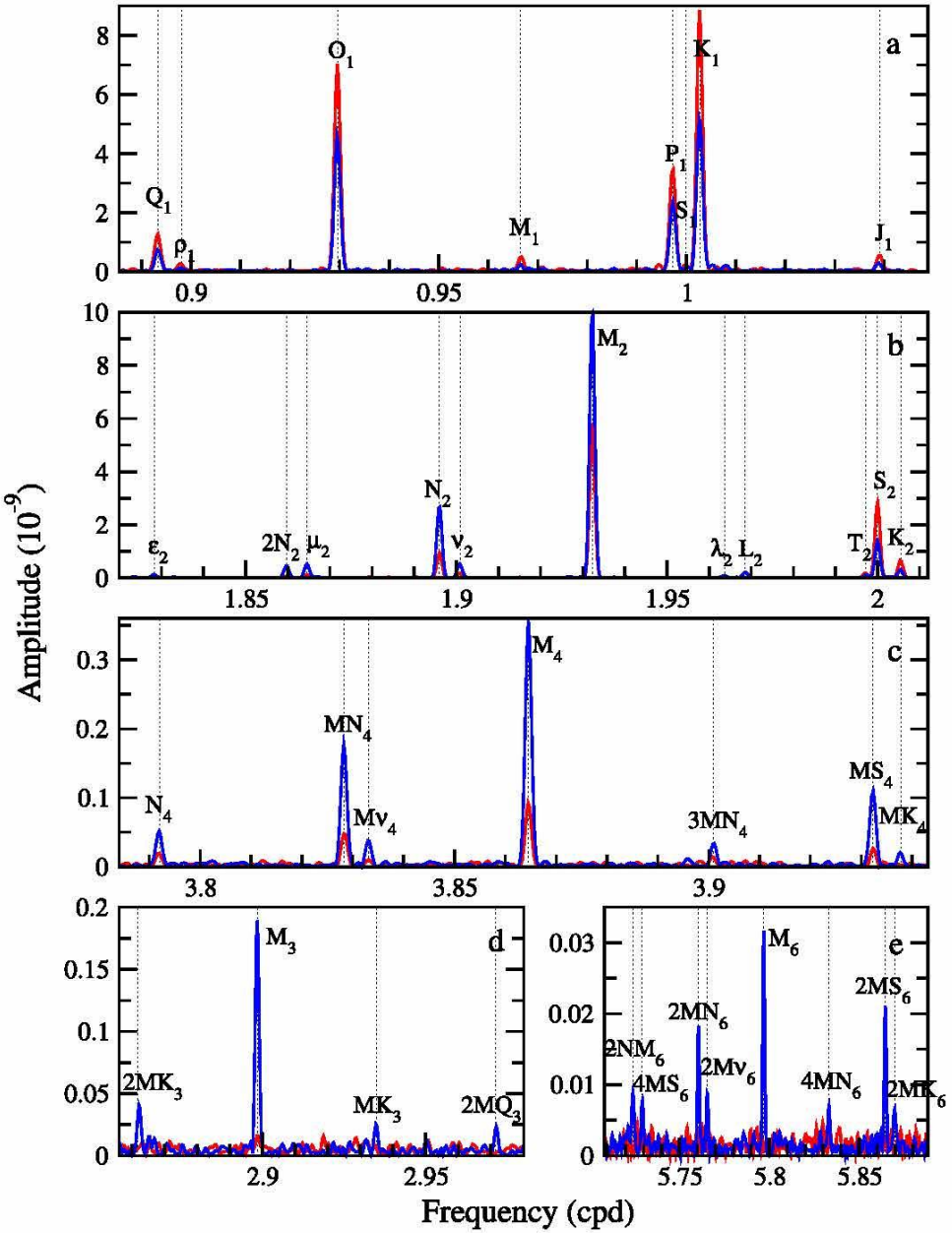
Blu = data
Green = data after subtraction of the main diurnal and semidiurnal signal
Higher frequency components are clearly seen

Earth tides are due to two causes

1. Deformation of the solid earth
2. Variation of the Ocean bottom load due to the sea tides

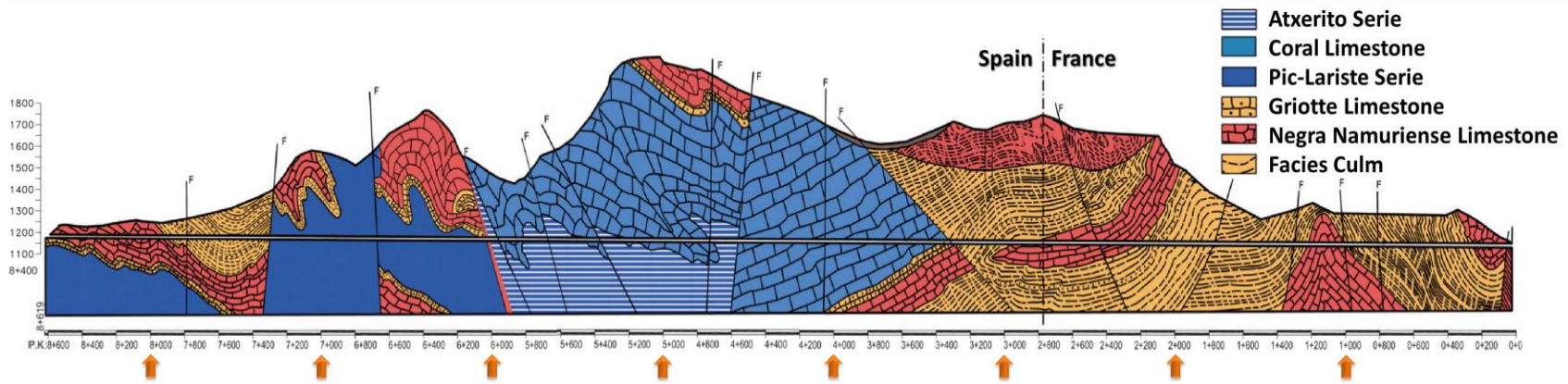
Data allow checking the Oceanic models

GEODYN. Earth tides



Fourier transforms of 2.5 years data in different frequency intervals
Blue: Lab780, red: Gal16
Model calculations agree with data both in amplitude and phase for diurnal and semidurnal data, need improvement for higher frequency bands

LSC. GOLLUM



Main objective is the identification and characterization of the microbial communities living in a range of different rocks throughout the length of the Somport tunnel, from the surface to the maximum depth

Rock samples will be taken at 500 meters intervals, crashed through a 14 t press, DNA extracted with a specific kit and subjected to high-throughput sequencing.

This will be accomplished through 16S amplicon sequencing, allowing characterization of the taxonomic diversity of prokaryotic communities; as well as with metagenomics, or sequencing of the combined genomes in a given sample.

These procedures will allow determining precision the microbial composition at different depths and on different mineral substrates

LSC. GOLLUM

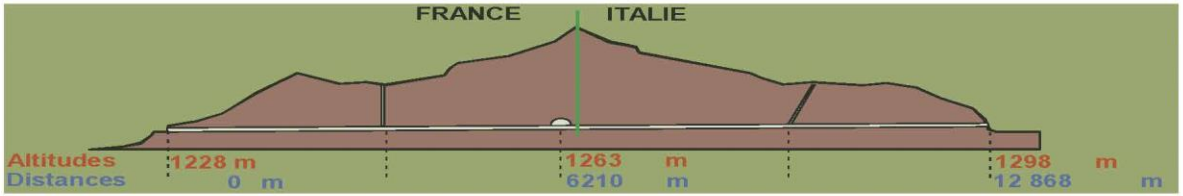
May 2016, 14 cores (50 to 100 cm long) located @ 1500, 2000), 2500, 3000, 3500.
Sterilized water tanks for cooling. Samples taken to monitor possible water contamination; show no bacterial contamination in water
Cores stored in cold stainless steel cylinders, quickly placed in a refrigerated van at 0 ºC and shipped to Valencia. Samples stored in –20 ºC and –50 ºC refrigerators.

June and July, DNA extraction from rocks. DNA found in most of the samples, ranging from 0.3 to 2 nanograms of DNA in 10 grams samples (Samples from the surface rock in the tunnel have1000 times more DNA)

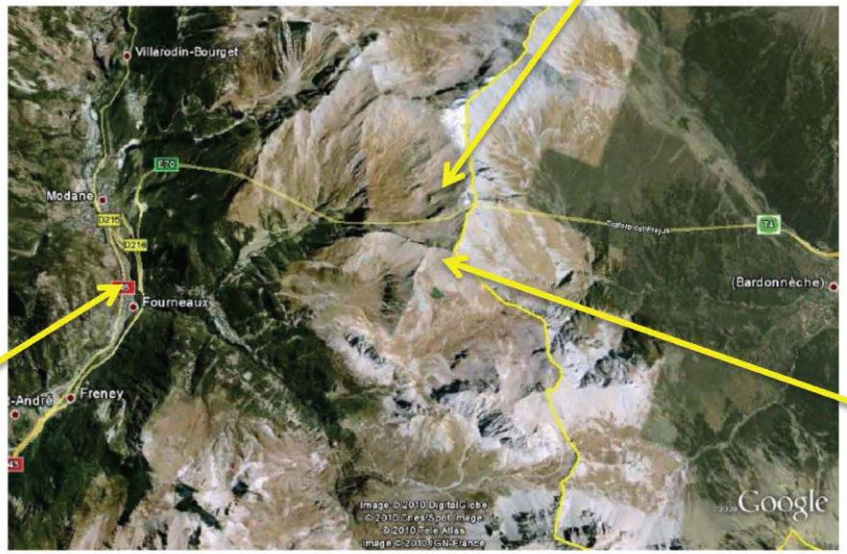
DNA samples are now in hands of a sequencing company. First science results in November. First sequencing results DNA being from bacteria and archaea

Laboratoire Subterrain de Modane. LSM

Fréjus roadway tunnel



Surface facility @ Modane



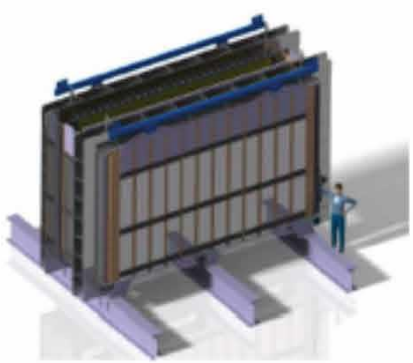
Underground site

F. Piquemal (2012) EPJ-p 127:110

LSM

Fundamental physics:

- Neutrino: double beta decay (SuperNEMO), EcHo (ν mass)
- Dark matter (EDELWEISS, LUMINEU, SEDINE, MIMAC)
- Nuclear structure (TGV, SHIN)
- General Relativity test with
- Optical atomic clock



SupernEMO demonstrator installation in progress

Sedine

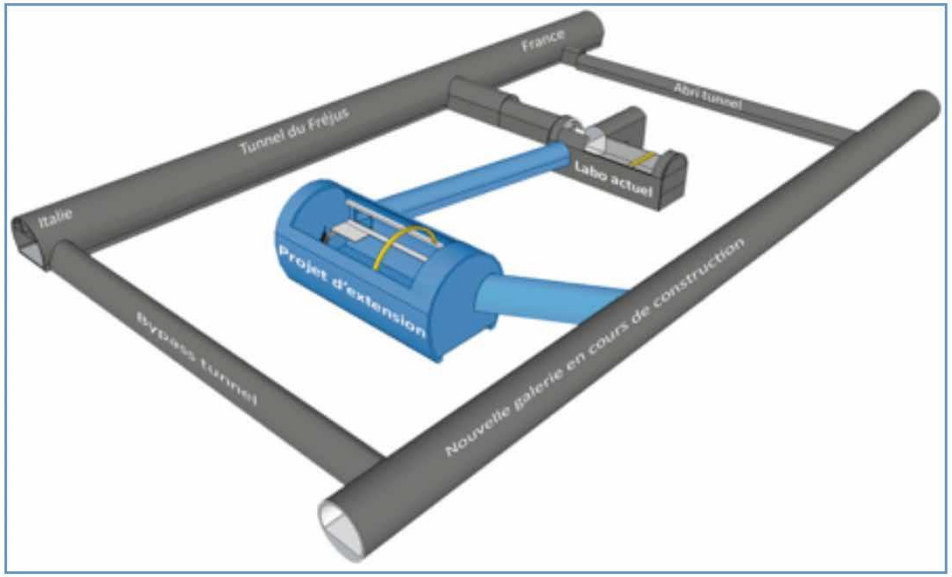
Gamma spectrometer (16)

Multidisciplinary activities

- **Ultra low radioactivity measurements**
  Environmental sciences, applications, expertises
- **Logical test failures in nano/micro-électronics**
- **Biology**

LSM DOMUS

DOMUS extension project 14 000 m^3 (X4 present LSM)



Cavity: Length 40 m,width18 m, height 16 m

BUL. Boulby Underground Laboratory

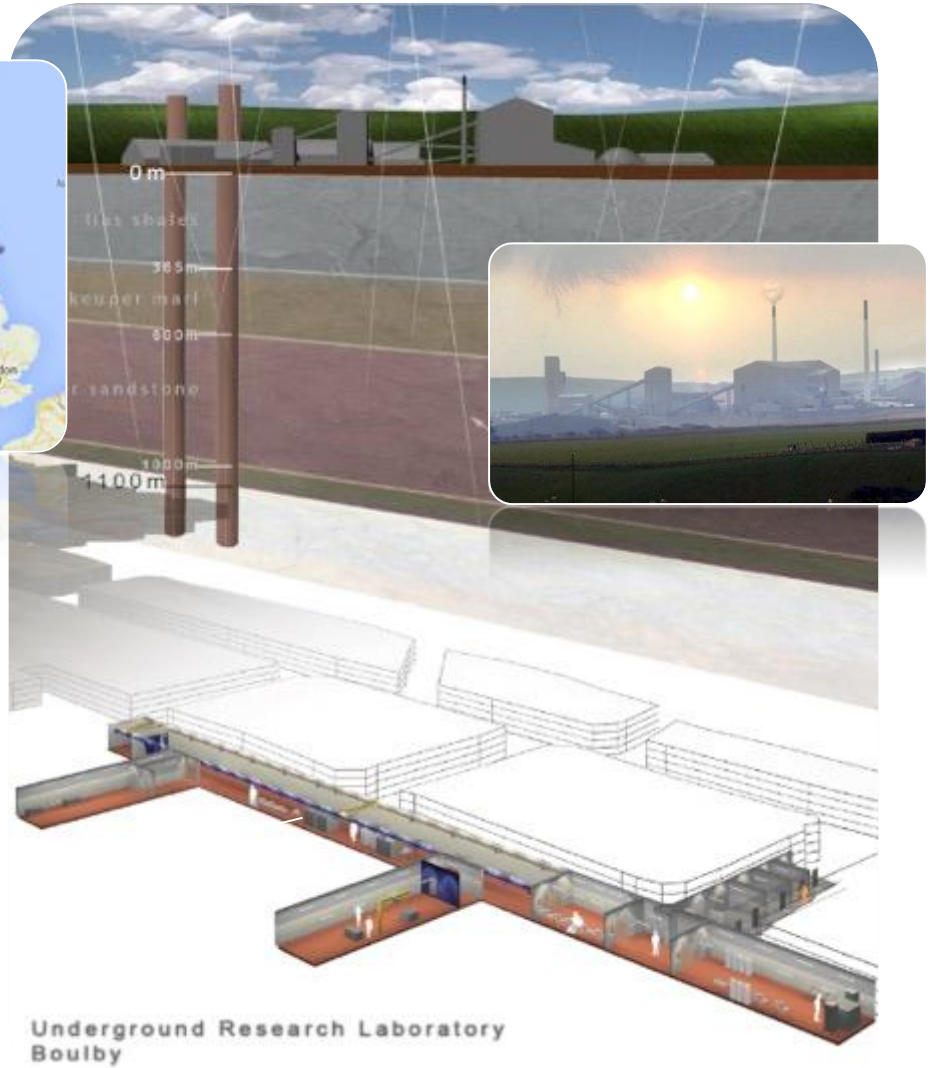
Hosted in an operating in a working potash and salt mine

Operated by the UK's Science & Technology Facilities Council (STFC) in partnership with the mine operators ICL

1.1 km depth. With low background surrounding rock-salt

Low gamma background

Very Low Rn activity <3 Bq/m^3



BUL. Science

- DRIFT: Directional Dark Matter Search
- DM Ice: NaI(TI) Dark Matter detector
- Ultra-low background material screening (5 Ge detectors)
- Deep Carbon: Muon Tomography for CCS (etc)
- ERSaB: Environmental gamma spectroscopy
- BISAL: Geomicrobiology / Astrobiology studies
- MINAR: Space Exploration Tech. Development
- Misc. Geology / Geoscience
- Misc. Low-background support projects

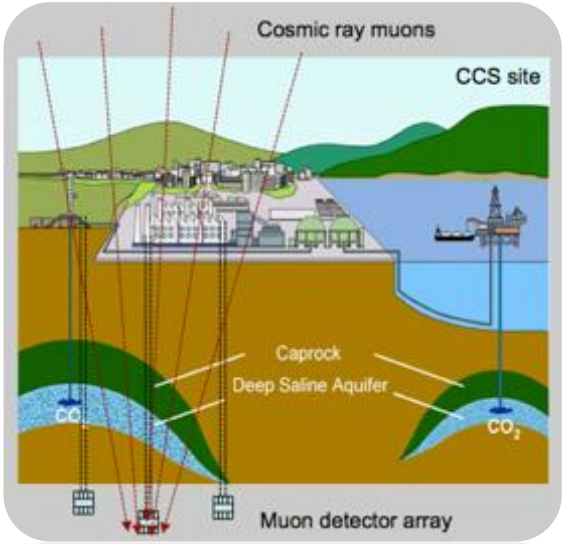
BUL. Multi-Disciplinary

ERSaB: Gamma spectroscopy & low background counting environmental radioactivity studies

Boulby, Scottish Universities Env. Research Ctr (SUERC)

DEEP-Carbon: Muon Tomography for deep geological mapping applications including CCS

Boulby, Durham, Sheffield, Bath, Premier Oil, CPL.



From astrophysics to climate, geology, the environment, life on Earth & beyond...

MINAR: Space Technology Development

Boulby, Edinburgh, NASA, DLR, CPL etc.

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

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

sean.paling@stfc.ac.uk

BUL. Astrobiology & Mars Analogue

Sampling life in Boulby Brine

Subsurface Astrobiology Laboratory

BISAL
Boulby International Subsurface Astrobiology Lab

A base for studies of life in Boulby rock – studies of limits of life on earth and on other planets

ALSO: An important 'Mars Analogue site' – with geology & conditions to allow explorations & astrobiology technique & instrumentation development

Led by Edinburgh, UKCA

MINAR
Mine Analogue Research

Mining & extraplanetary exploration instrumentation development

sean.paling@stfc.ac.uk

Boulby and Instrumentation for Earth and Space Exploration

BUL. Misc Geology / Geoscience

Improved mining technologies

E.g. enhanced extraction but reduced subsidence?

Rock deformation studies

E.g. salt deformation and oil reservoirs?

Seismology

E.g. how does stress change induce earthquakes?

Carbon Capture & Storage

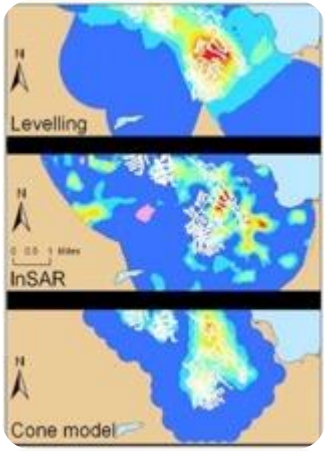
E.g. The effect of fractures on the sealant properties of anhydrite for CCS

Geochemistry

E.g. how does fluid (oil) move through rock masses?

Geomicrobiology

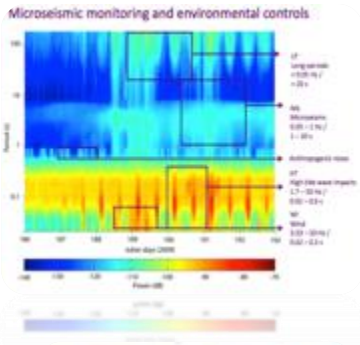
E.g. What effect do microbes of rock stuctural integrity (cliff, geological repositories)



Subsidence mapping

Durham, Imperial College, Boulby, Edinburgh British Geological Survey (BGS)

Micro-seismic monitoring



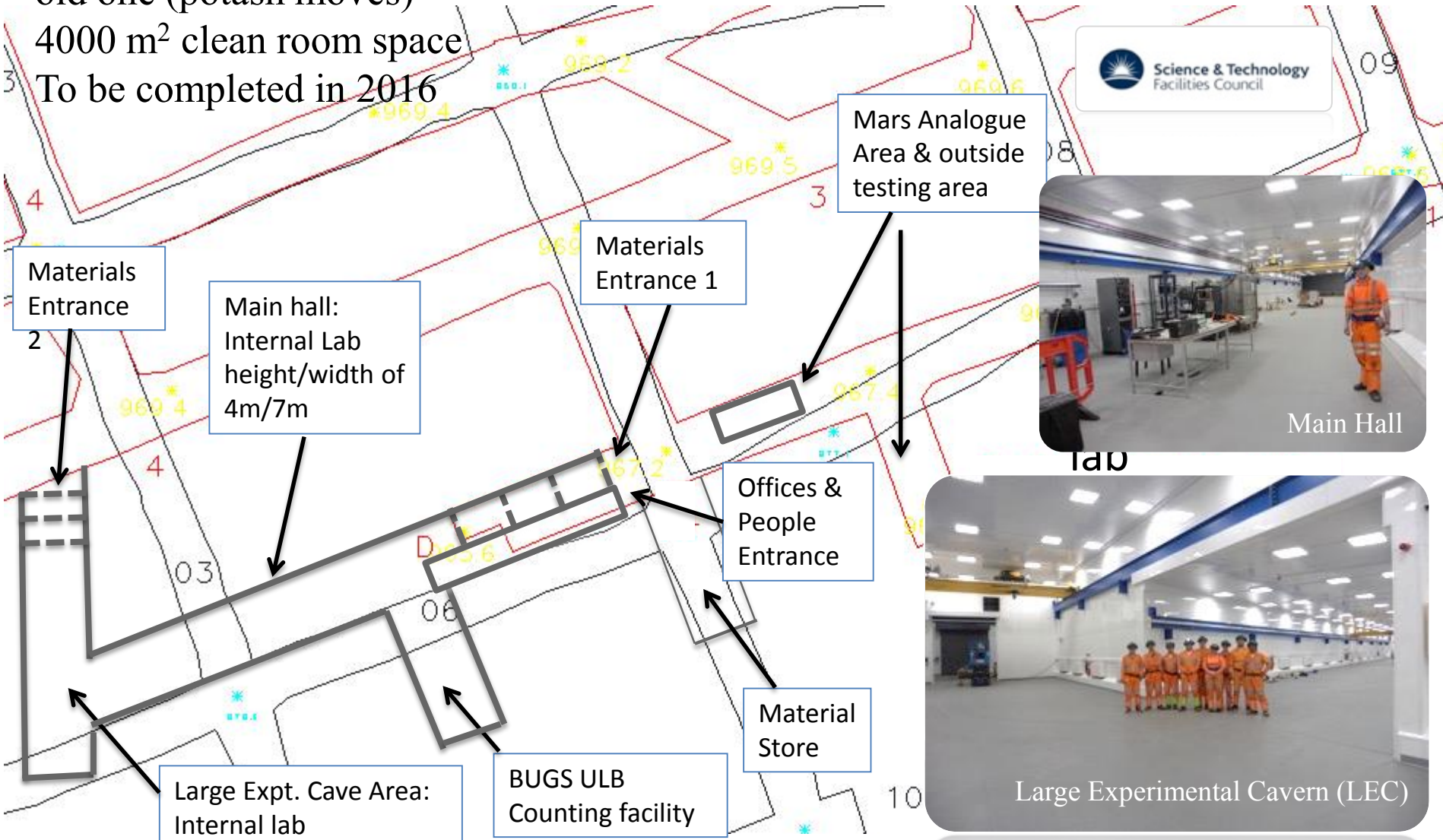
Geochemistry

Cliff erosion mapping

Anhydrite mechanical properties

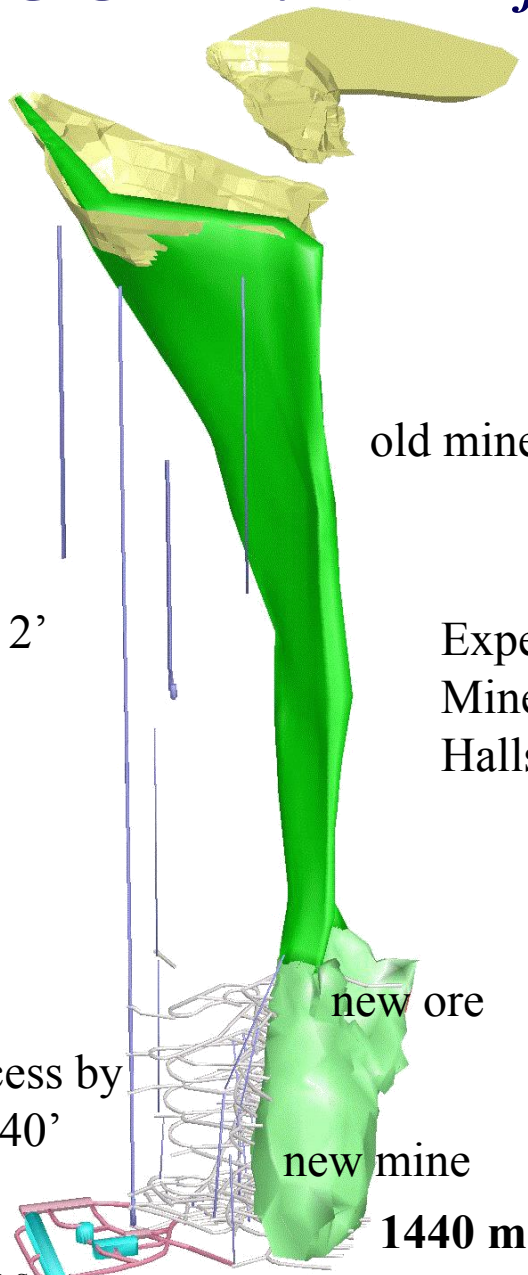
BUL New

New lab under construction t replace old one (potash moves)
4000 m^2 clean room space
To be completed in 2016



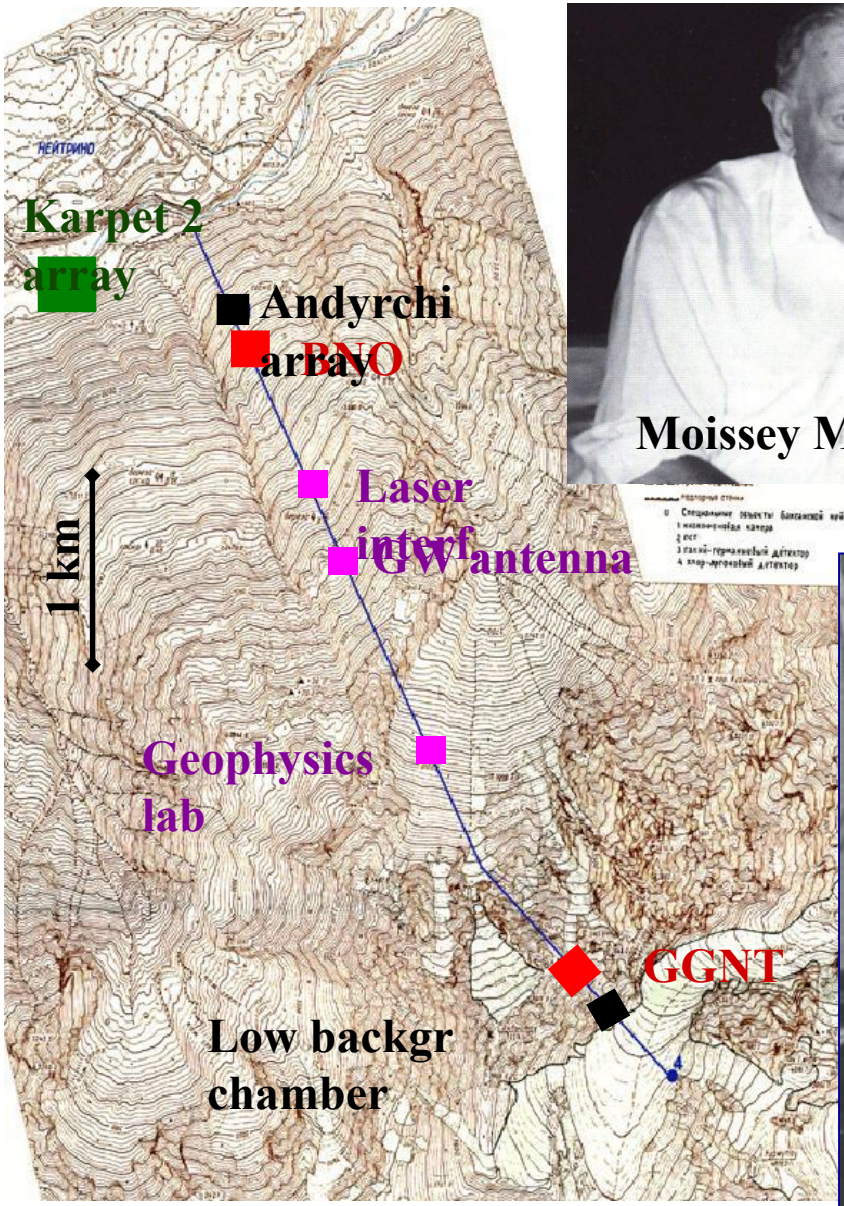
CUPP. *Centre for Underground Physics in Pyhäsalmi*

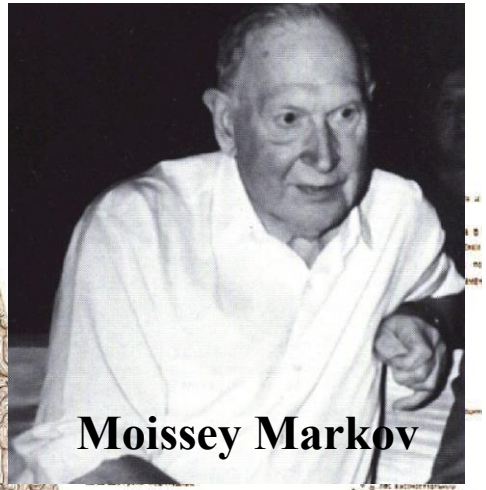
http://www.cupp.fi/



Experiment EMMA on cosmic rays at shallow depth
Mine is expected to close around 2019
Halls, with infrastructures, may be available then for experiments.

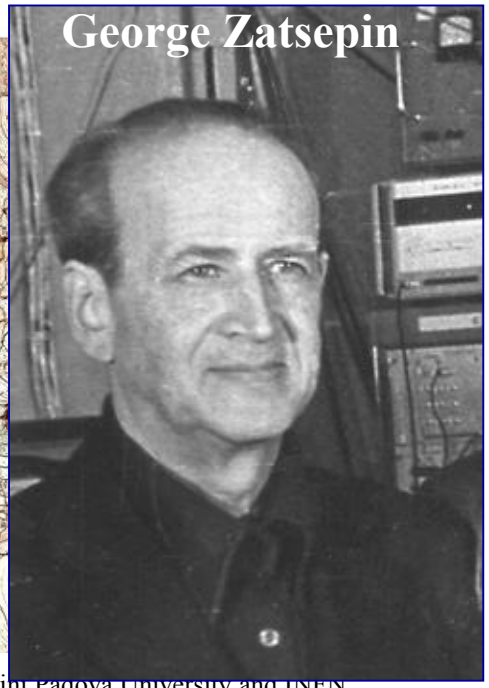
Baksan Neutrino Observatory. INR-RAS




Moissey Markov

1966. Under the action of M. Markov, Head of the Physics Division, the Academy of Sciences of the USSR obtains a Decree of the Soviet Government for the construction of the underground and surface facilities (Neutrino village)

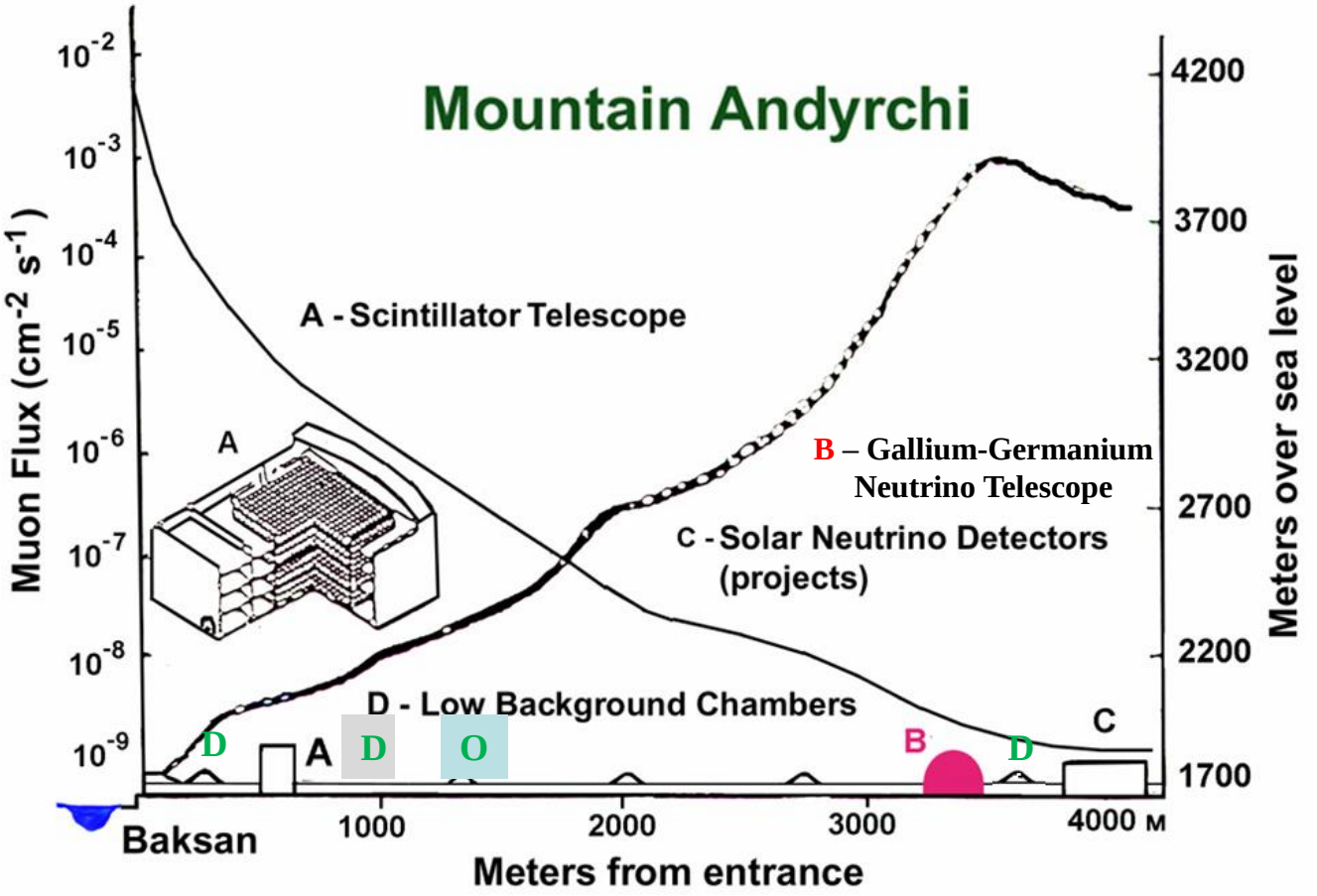
Scientific activity started under the leadership of


George Zatsepin

and

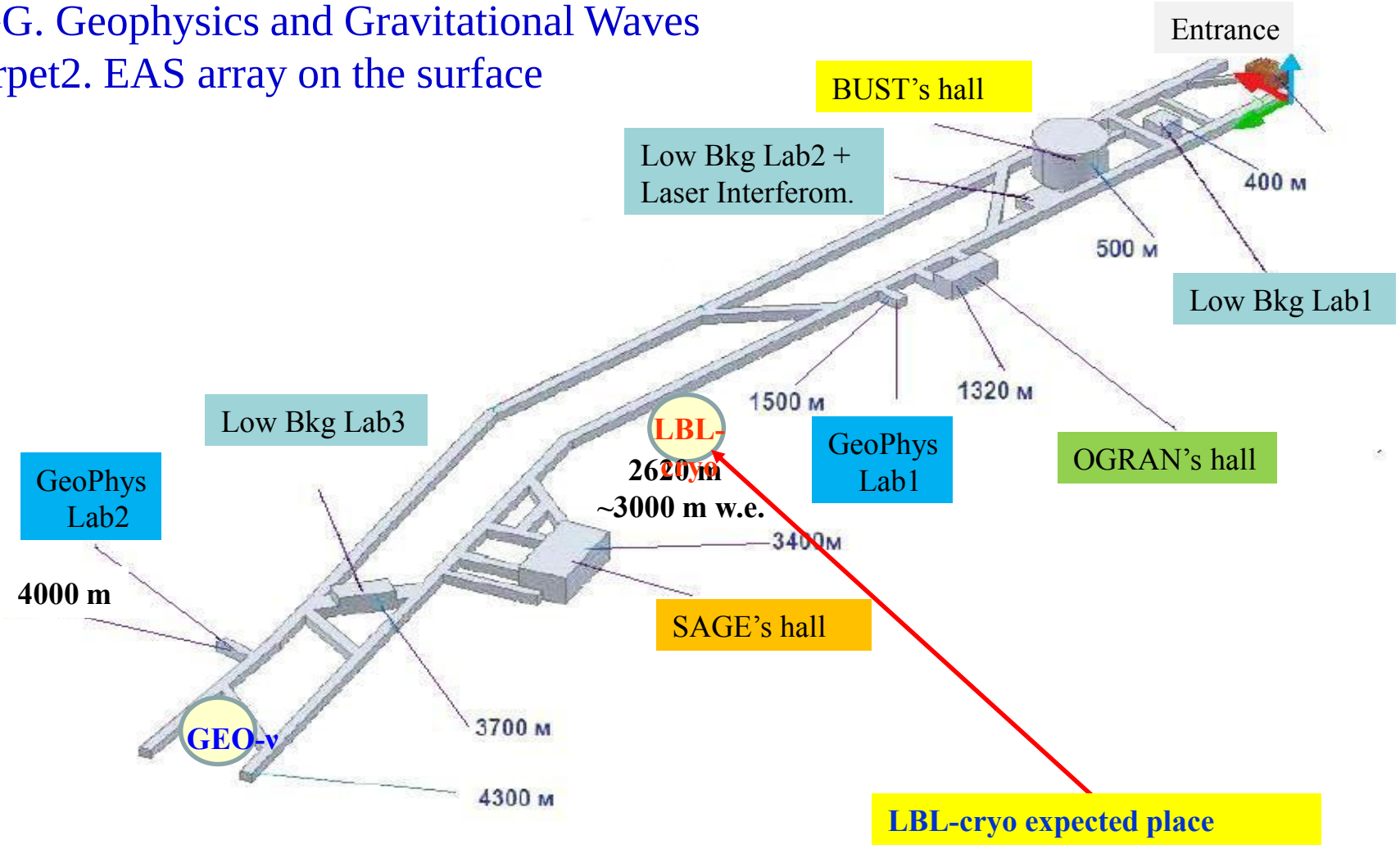
Alexander Chudakov

Baksan Neutrino Observatory – INS-RAS



BNO. Operational

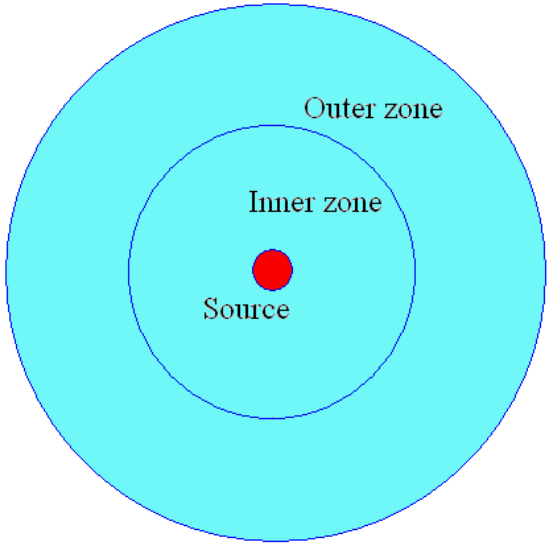
BUST-Baksan Underground Scintillation Telescope - Cosmic rays and neutrinos
GGNT (former SAGE)-Gallium Neutrino Telescope – Solar neutrinos
Low Bkgrnd searches (double beta mainly)
LGG. Geophysics and Gravitational Waves
Carpet2. EAS array on the surface



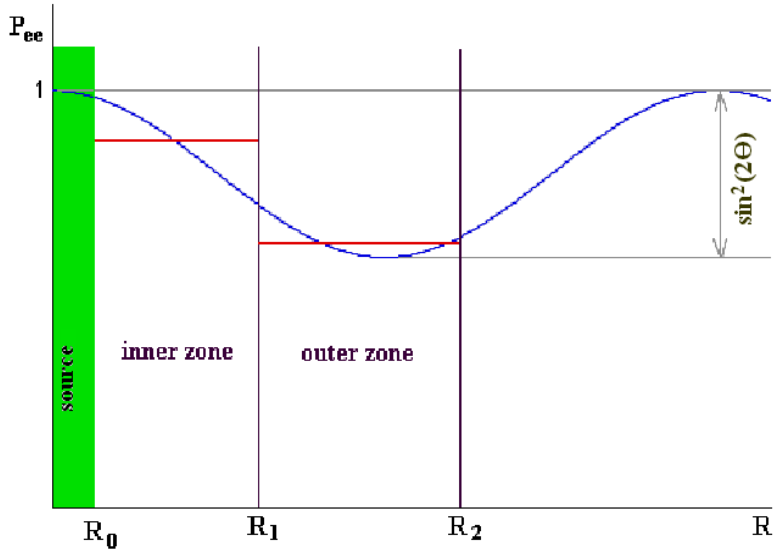
BNO. Projects

New Ga source experiment

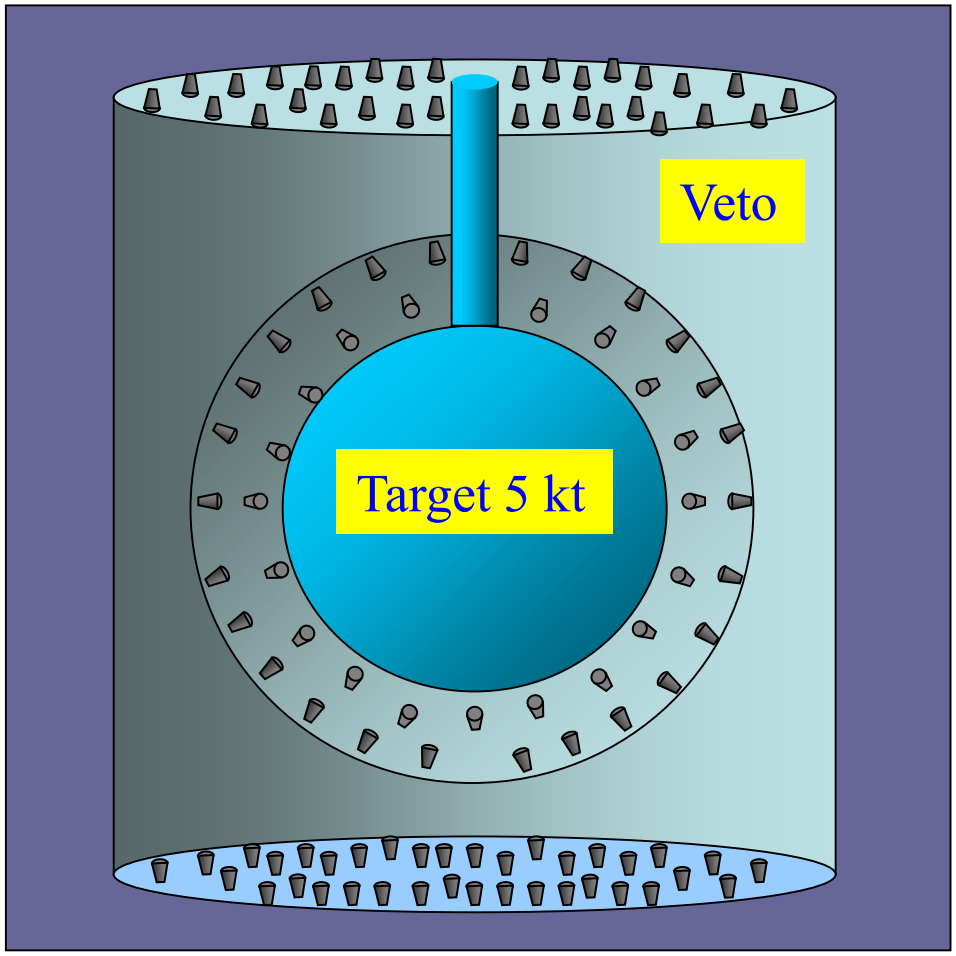
"BEST"– Baksan Experiment on Sterile Transitions



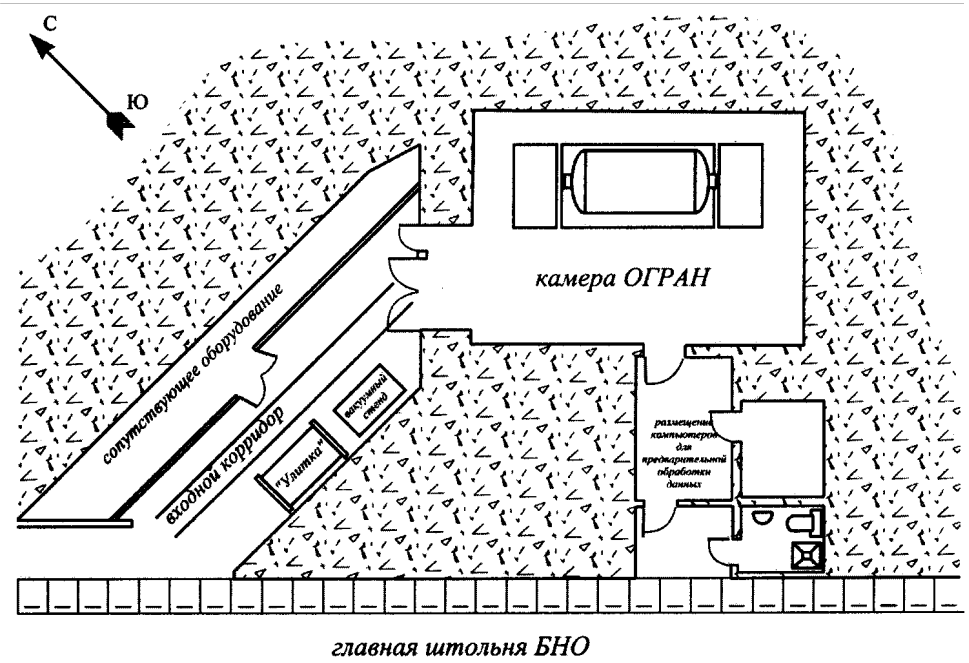
- (Almost) monochromatic pure ν_e (0.75 MeV)
- Known neutrino flux
- Small size of source (several cm)
- Negligible backgrounds
- High density of ν_e interactions in Ga metal
- Seeking funding for enrichment of 3.5 kg ^{50}Cr & for producing of 3 MCi ^{51}Cr source



BNO. Proposal
Geo-Neutrino Liquid Scintillator detector



BNO. Proposal
Optical-Acoustical Gravitational Antenna-ORGAN



New hall at 3500 m from entrance

Sensitivity: 10^{-18}

Kamioka Observatory

In 1983 M. Koshiba established the Kamioka Underground Observatory to host KamiokaNDE (**NDE=Nucelon Decay Experiment later = Neutrino Detection Experiment**)

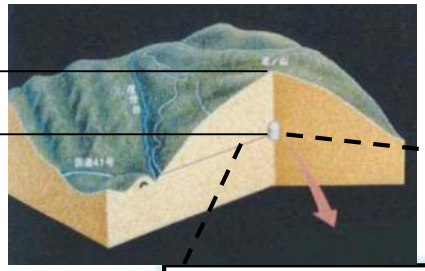
The present facilities of the Kamioka Observatory have been designed for Super-Kamiokande

Recently a process of enlargement has started

- Overburden 1000 m ≈ 2.7 km w.e.
- Horizontal access
- μ flux: $\phi_\mu = 3 \times 10^{-3}$ m^{-2}s^{-1}
- Radon: few Bq/m^3 (with ventilation)
- Neutrons: thermal $= 8.25 \pm 0.58 \times 10^{-2}$ m^{-2} s^{-1}
  non thermal $= 11.5 \pm 1.2 \times 10^{-2}$ m^{-2} s^{-1}

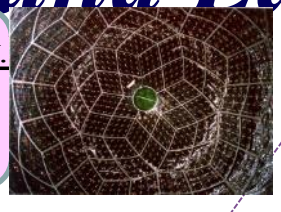
- Users >200+KAMland
- Building for offices and computer facilities on the surface

Kamioka Underground Laboratories



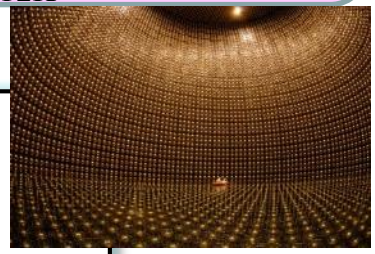
KamLAND (Tohoku Univ.

1000t liquid scintillator detector
Rector, geo neutrinos
^{136}Xe double beta decay



Super-Kamiokande

50,000 t water Cherenkov detector
Atmospheric, solar, supernova neutrinos
Proton decay, indirect dark matter search
Far detector for T2K



CANDLES

CaF_2 scintillation detector for ^{48}Ca double beta decay

KamLAND
(old Kamiokande site)

Lab.A

Super-K dome

clean room

Gd test

water system

Gravitational-waves

CLIO : 100 m prototype
Geo-physics 100 m + 100m
Laser strainmeter

XNASS

Dark matter

100m

NEWAGE

Directional dark matter

Kamioka. Science

Tokyo University

Super-Kamiokande
- Atmospheric and solar neutrinos.
- T2K Neutrino beam from JPARK (up to 10 times present exposure: mass hierarchy, CP)
- Dissolve 0.1% Gd for anti-neutrino physics in future (relic SN neutrinos)

XMASS (Dark Matter: liq. Xenon single phase, 800 kg)
- 1st phase detector completed
- 2nd phase: 1500 kg, new low bkgrnd PMTs

CANDLES (Double beta)
- Commissioning

NewAGE (Dark Matter)
- Directionality

CLIO (prototype of KAGRA)

Geo-physics
- Laser strainmeter
- Superconductive gravity meter

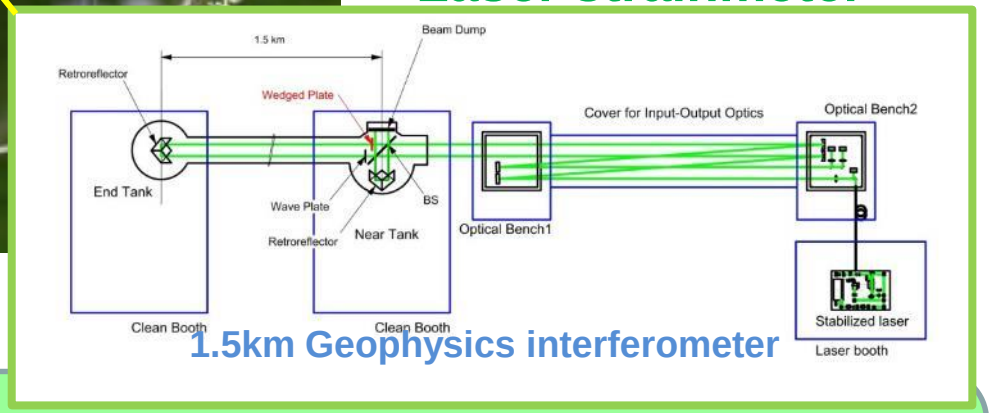
Tohoku University

KamLAND-ZEN
- Double beta decay of ^{136}Xe best present limit
- Double source mass to 800 kg. Expected starting this Autumn

Kamioka KAGRA (Tokyo University)

KAGRA center area

Laser strainmeter



1.5km Geophysics interferometer

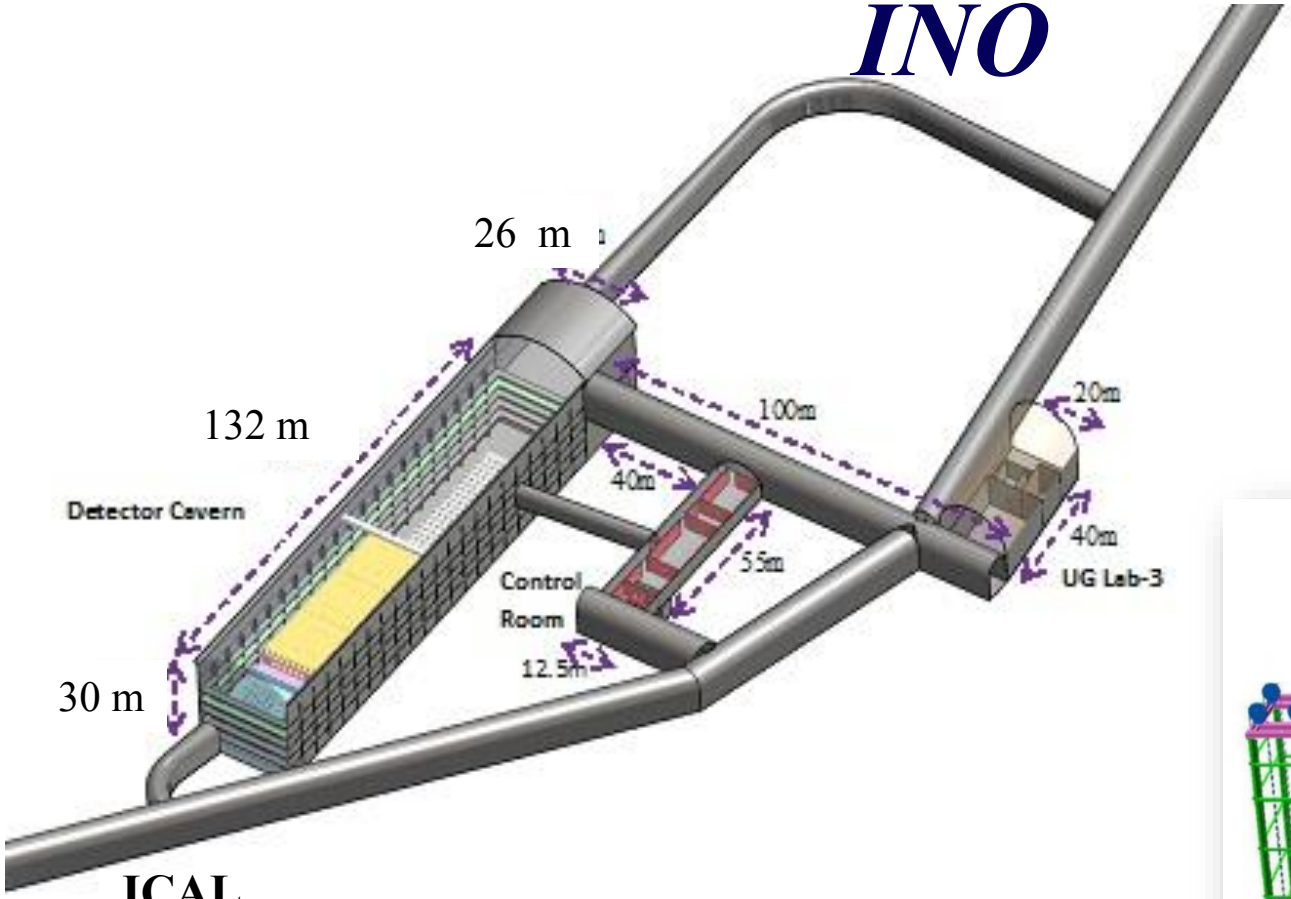
- Installation of the major equipment completed by March 2015.
- Normal temperature operation achieved at 2016 spring.
- Cryogenic operation from the end of FY2017.
- 3km KAGRA tunnel shared with 1.5km laser strainmeter for geophysics

INO India based Neutrino Observatory

Location: Pottipuran village, Tamin Nadu, India
Maximum overburden: 1480 m
Access through 2 km tunntel to be excavated
INO Collaboration: > 100 scientists from 23 institutions and universities in India
Project funded and approved by Federal Government
Waiting for OK by the Tamin Nadu

N. K. Mondal (2012) EPJ-p 127:106

INO



ICAL

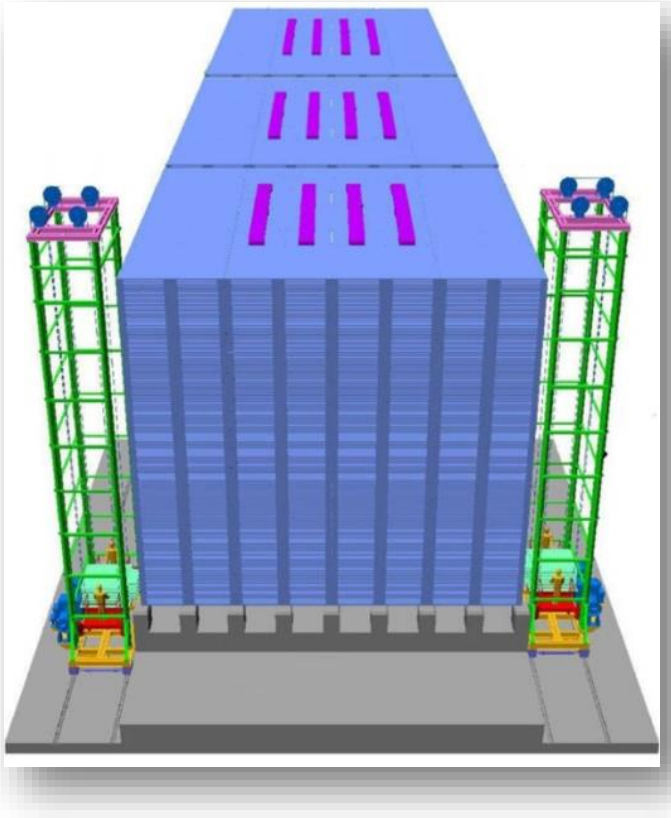
50 kt magnetized tracking calorimeter

Neutrino physics

"Large" θ_{13} allows determining mass order at 3 σ with 750 kg yr exposure

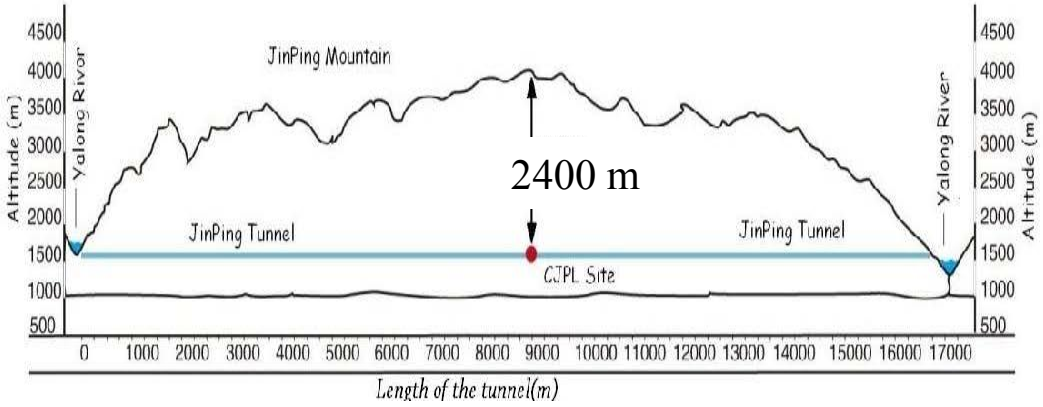
Space for 100 kt in main hall

Smaller halls for smaller experiments



China Jinping Laboratory. CJPL

CJPL-II

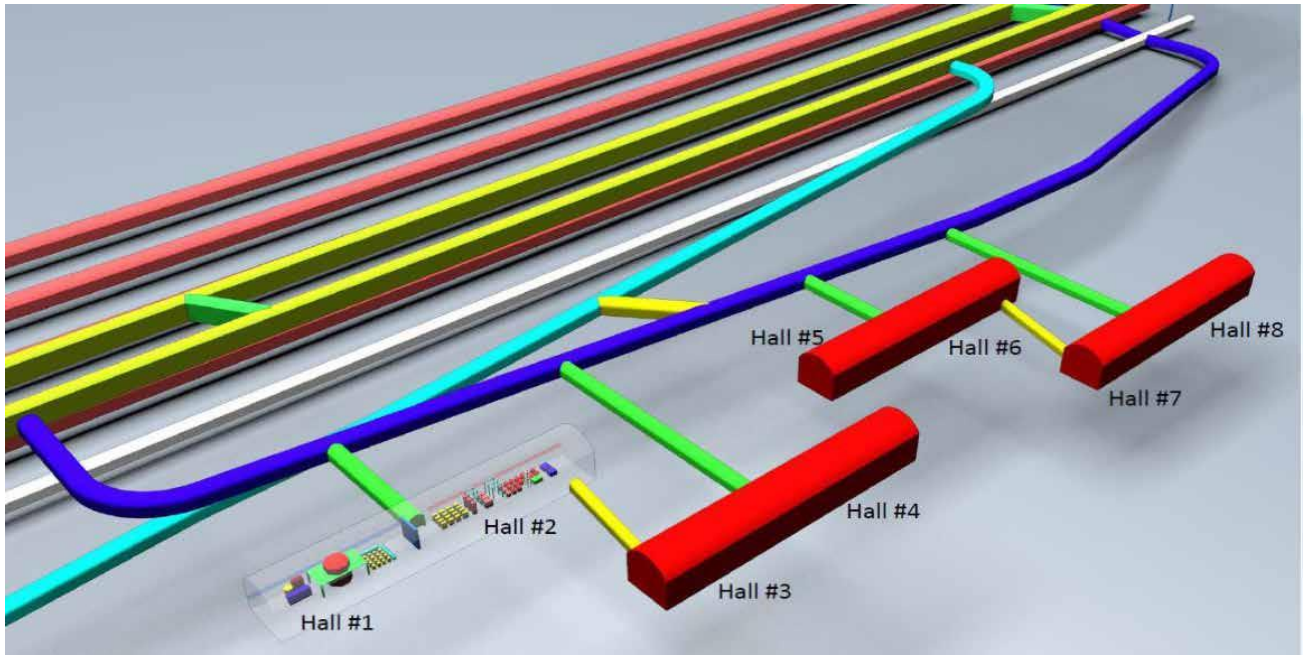


Deepest underground lab: 2400 m
μ flux = 60/(m^2 yr)=2 x 10^{-6}/(m^2 s)
Drive in to the halls
Tunnels (17km) for hydropower stations

CJPL-I
40x6x6 m^3 ready in 2011
PANDAX (Dark matter, Xe)
CDEX (Double Beta Ge)

H. Cheng (2012) EPJ-p 127:105

CJPL - II



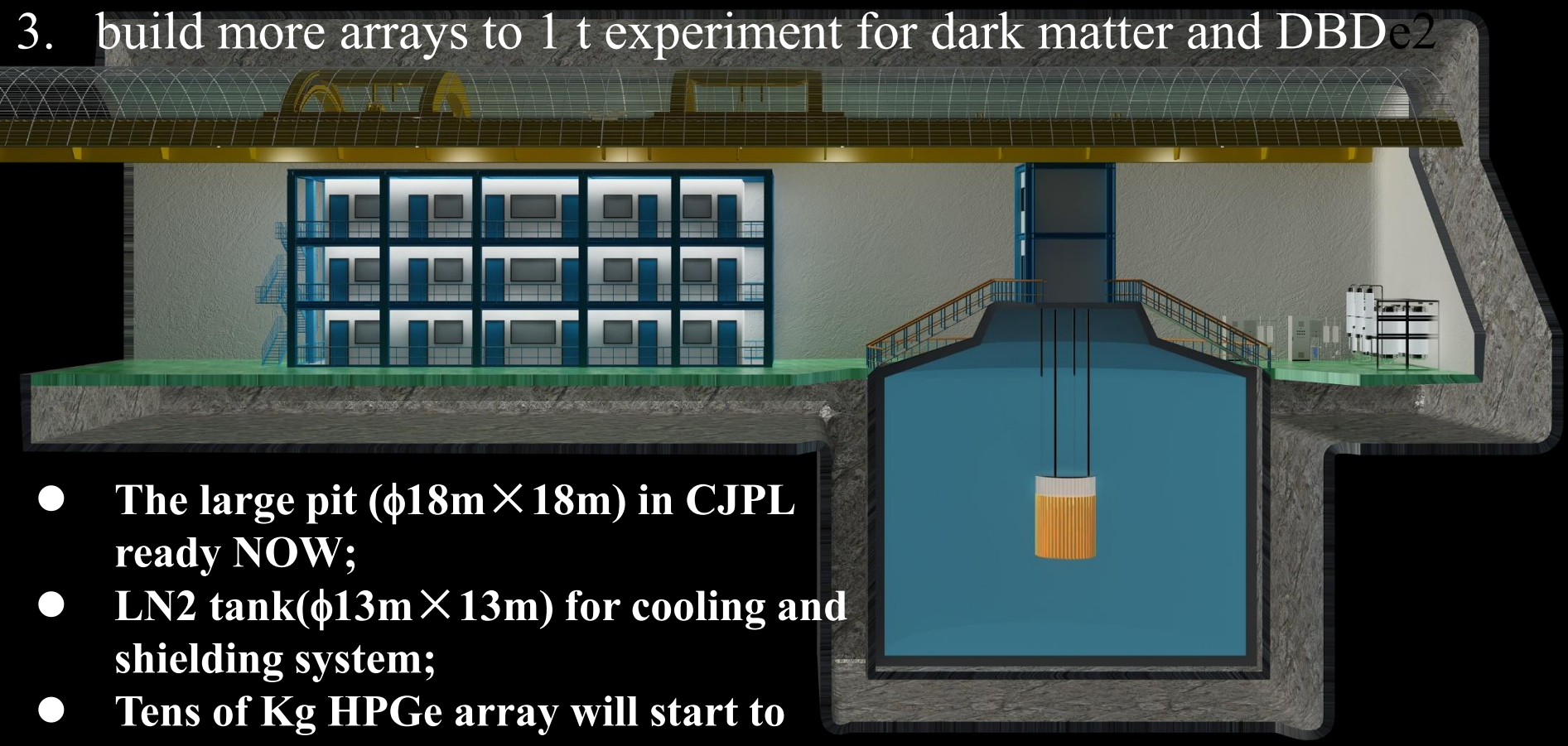
8 general purpose experimental halls, each 65 x 14 x 14 m^3, sharing a L 60 m W 8.2 m H 8.1m connecting tunnel, which leads to the main traffic tunnel of CJPL-II
Two safety tunnels connect H2 with H3 and H7 with H6 (emergency evacuation)
Total volume to excavate 130 000 m^3
Civil works started Dec. 2015, completed Nov. 2015
Expansion approved and started in Dec. 2015, with
Cylindrical pit 18 m diameter, 18 m deep (total height 32 m) in Hall 5. DONE
Pool L27 m, D 14 m (total: L 27 m, W 14 m, H 28 m) in Hall 4. DONE

CJPL II

CDEX-1T DM+DBD experiment

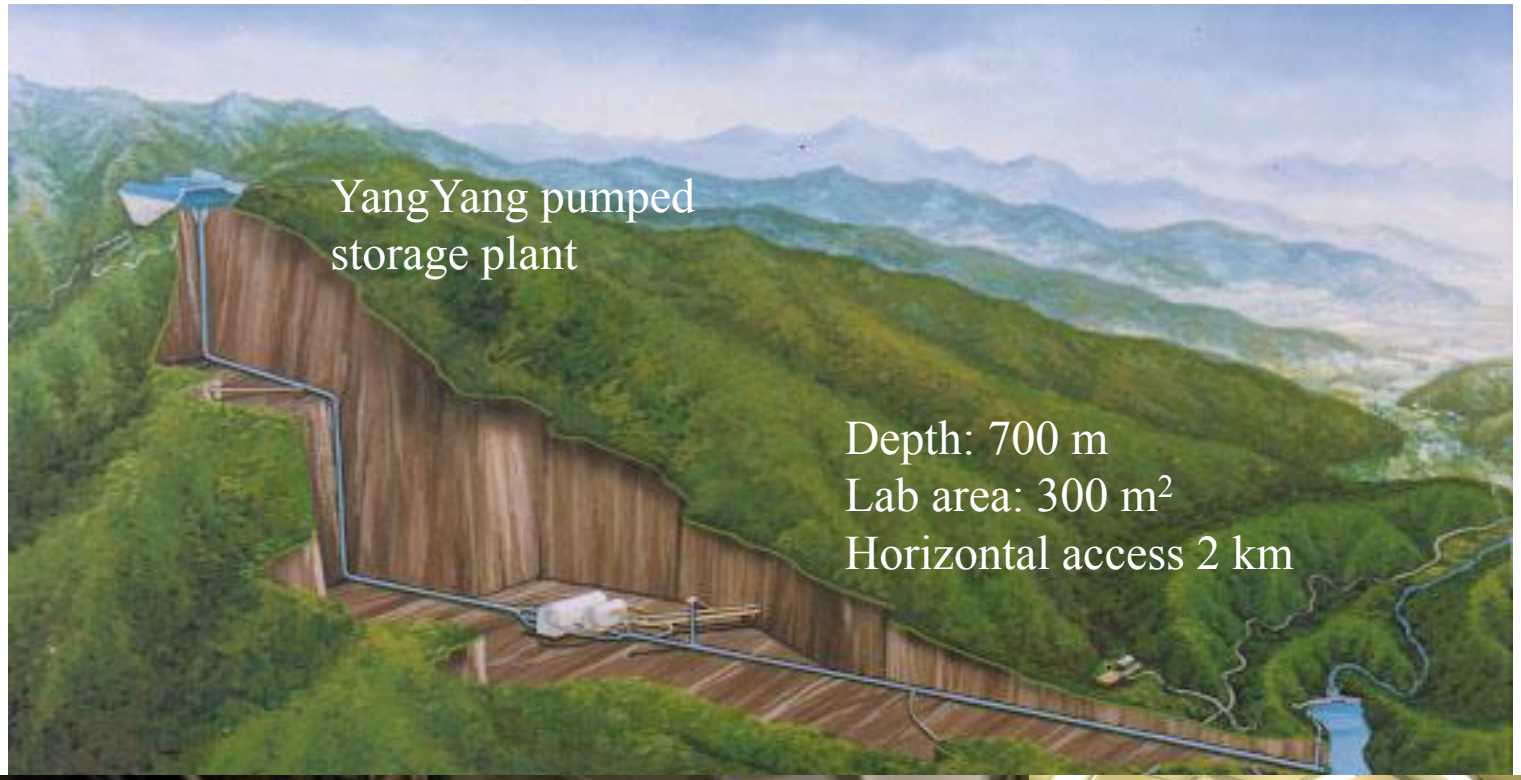
Staged programme to:

1. learn production of HPGe counters scalable to large masses
2. produce and operate a 10 crystal array
3. build more arrays to 1 t experiment for dark matter and DBDe^2



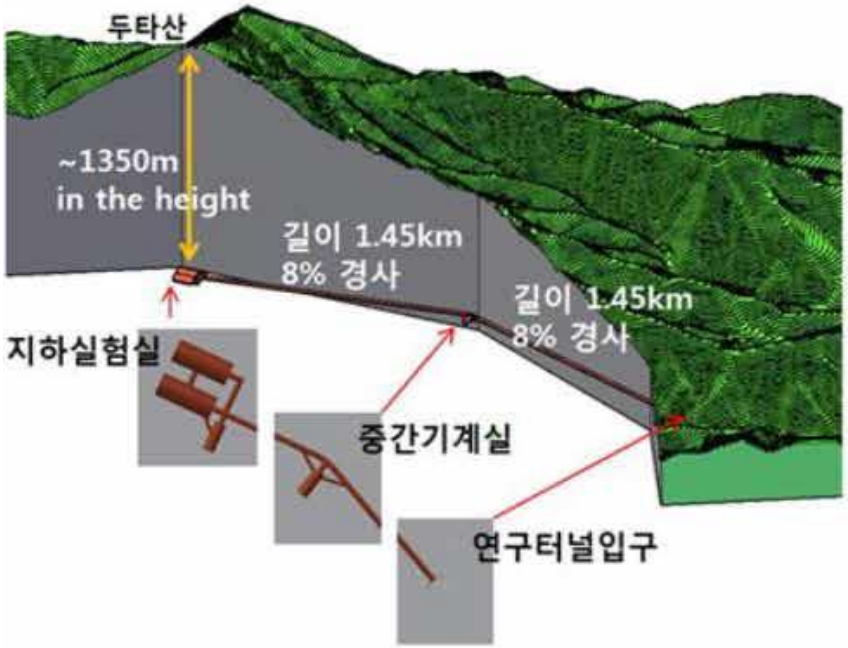
- **The large pit (ϕ18m×18m) in CJPL ready NOW;**
- **LN2 tank(ϕ13m×13m) for cooling and shielding system;**
- **Tens of Kg HPGe array will start to setup in several years.**

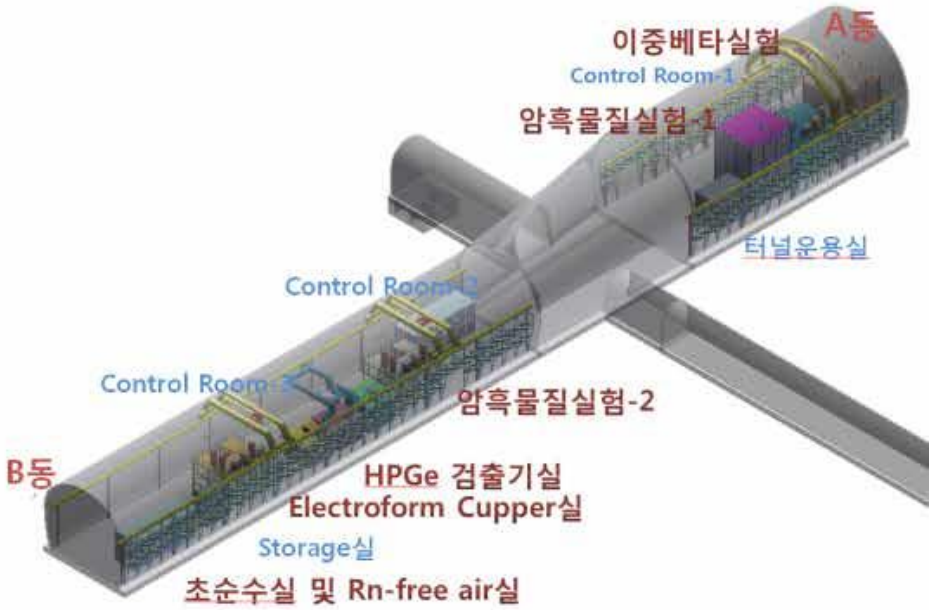
YangYang Lab. Y2L



Y2L. Extension project

- A new underground laboratory is under consideration at 1400m depth.
- since the expansion at Y2L seems to be not attractive compared to the new laboratory. – **Still need government approval.**

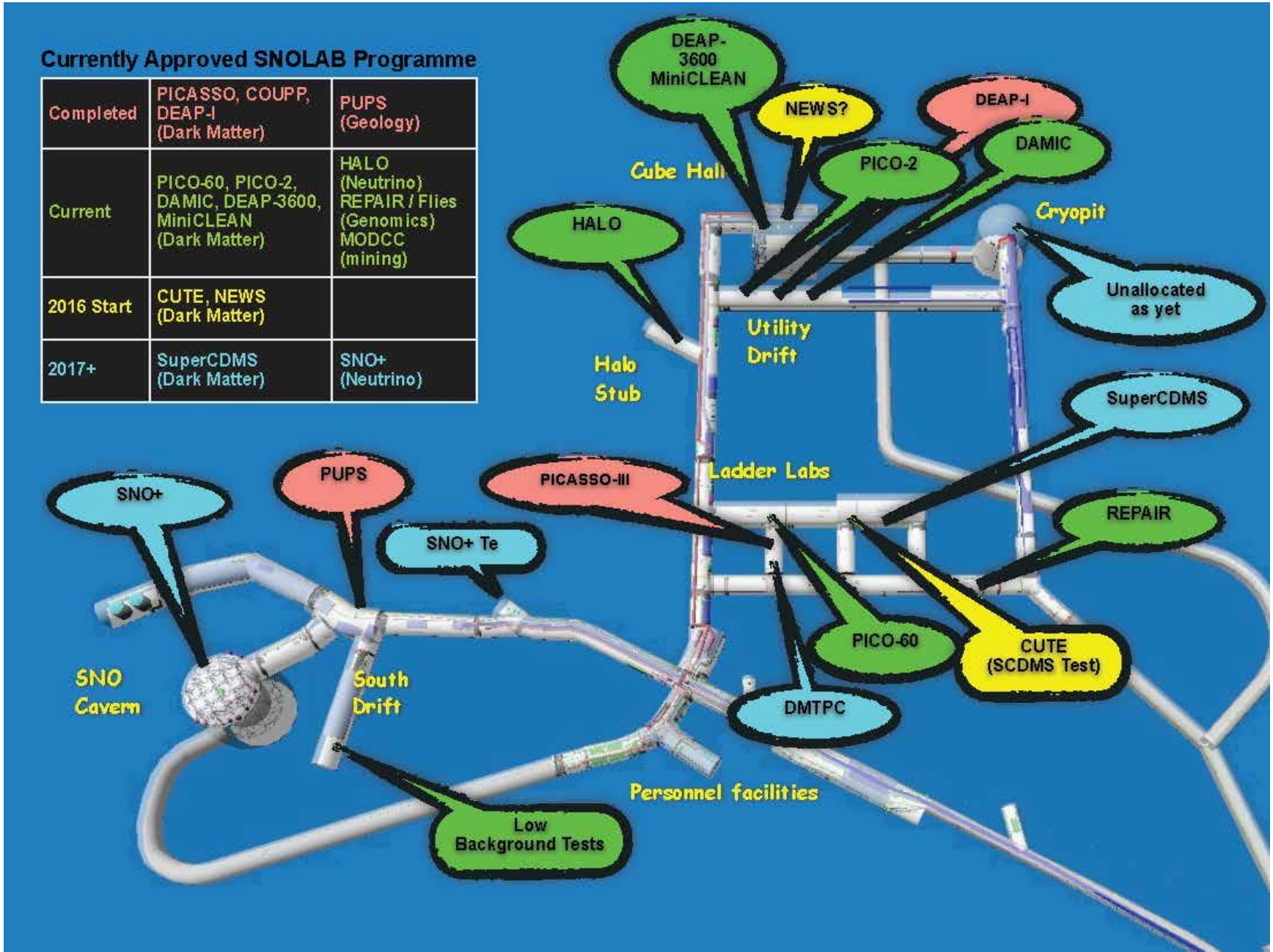




- 2000 m^2 lab area.
- 1400 m depth is similar to Gran Sasso Lab.
- Plan to finish until 2019.

N. Smith (2012) EPJ-p 127:108

SNOLab



SNOLab. Progress of the experiments

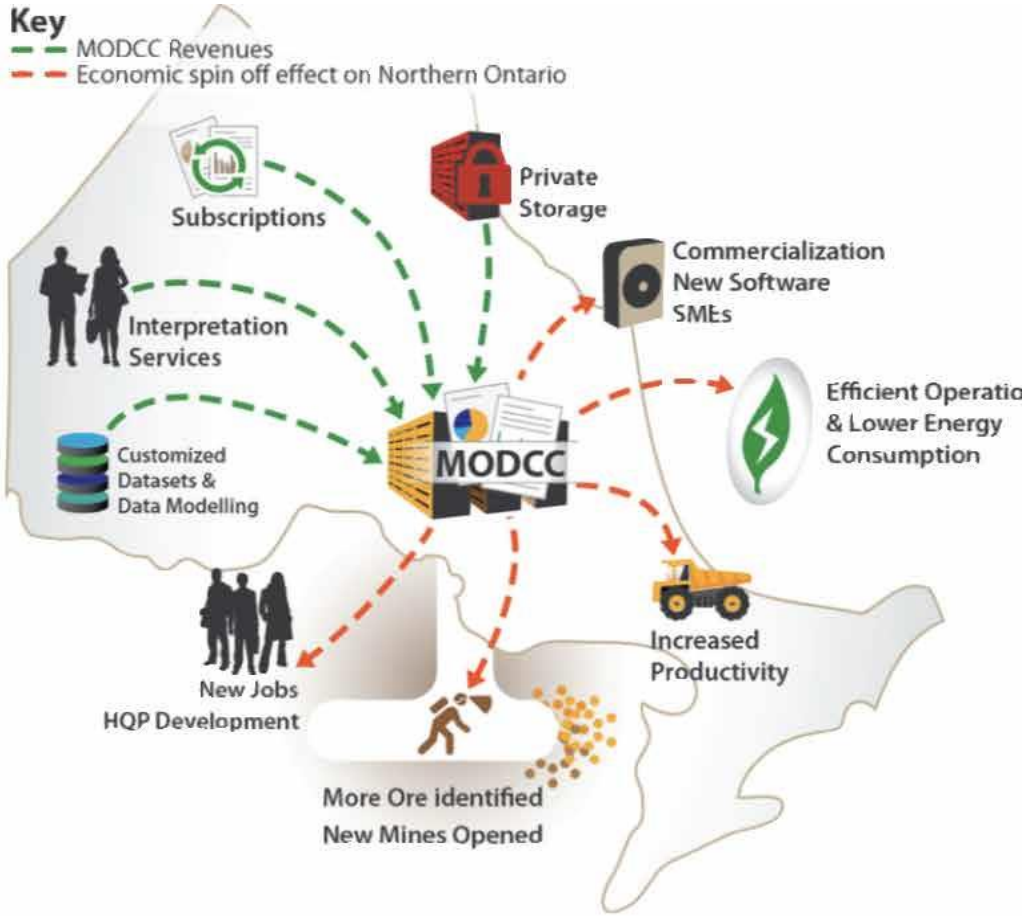
- SNO+: Uses existing SNO detector.
  - Heavy water replaced by scintillator loaded with ^{130}Te. Modest resolution compensated by high statistical accuracy. ($^{130}Te \rightarrow {}^{130}Xe + e^- + e^-$)
  - LAB process plant construction completed, commissioning underway. Cavity fill underway (again), Te plant in development.
- DEAP-3600: Single phase Liquid Argon using PSD
  - target construction complete, cooling underway, expect argon fill in the next few weeks. All ancillary systems complete.
- MiniCLEAN: Single Phase Liquid Argon using PSD
  - target construction complete, cool-down underway. Ancillary systems complete.
- SuperCDMS-SNOLAB: Dark matter Si / Ge crystals with ionisation / phonon readout
  - Planning well advanced for deployment, .
- PICO: Rapid expansion bubble chambers. Insensitive to MIPS at operating temperature, threshold devices; alpha discrimination proven;
  - PICO-60: New results posted (arXiv:1510.07754) New chamber and target fluid in deployment.
  - PICO-2: New science results posted (arXiv:1601.03729), background identified. New run underway.

SNOLab. Progress of the experiments

- DAMIC CCD based dark matter detector
  - Initial science run complete (arXiv:1510.02126), first 100g prototypes installed, upgrade underway.
- NEWS DM detector: high pressure spherical chamber; planning underway
- DMTPC DM directional detector: planning underway
- HALO Supernova neutrino detector
  - SNEWS connection made October 2015. Live to SN.
- MODCC Mining mining data
  - construction completed August 2015. Space is fully operational.
- Genomics:
  - Low radiation environment impact on mutations, NSERC funded project in development with NOSM;
  - Fruit fly metabolism tests complete with Laurentian. New tests planned.
- nEXO Double beta detector
  - engineering support to evaluate deployment at SNOLAB.

SNOLab. New Directions

- MODCC - mining data observatory using pp culture
  - Rock wall stresses are a major problem for mining groups as ore bodies go deeper
- Genomics projects underway
  - Metabolism in fruit flies in a mining environment
    - Intent to study stresses on miners and potential mitigation
  - Low radiation effect on cell mutation (LNT study)
    - Study effect of sub-background radiation levels and radiation type on cell mutation
    - introduce radiation species individually



Homestake mine

Physics Beyond the Standard Model started before the Standard Model itself, in a mine of South Dakota

For an historical recollection, read: J. Bahcall. Nucl. Phys. B (Proc. Suppl.), **118**, 77, astro-ph/0209080.

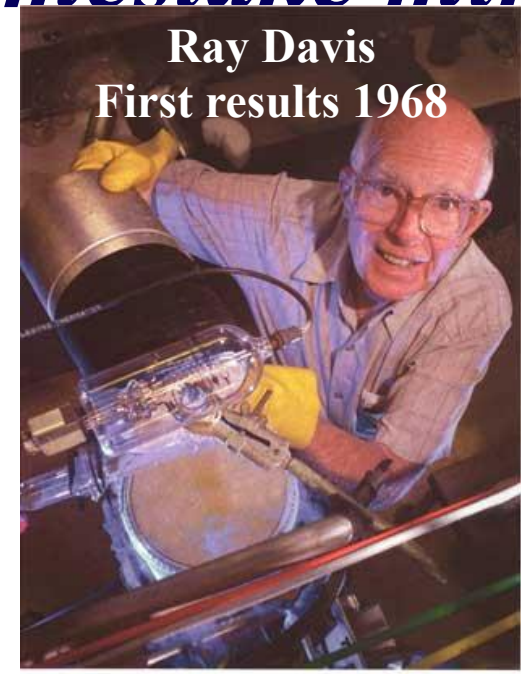
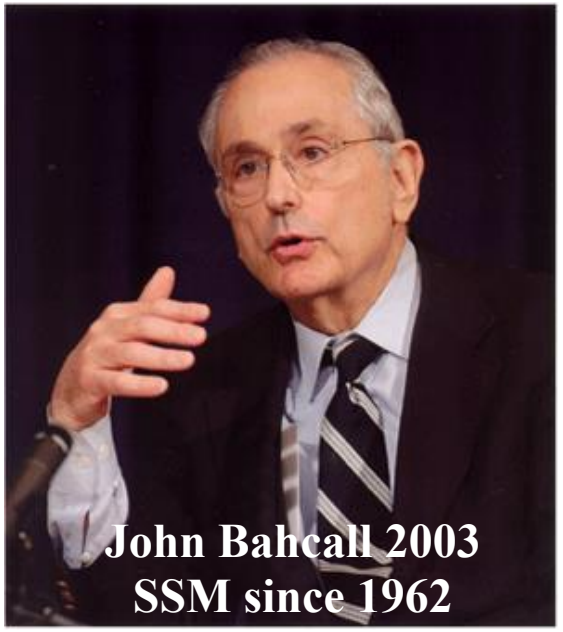
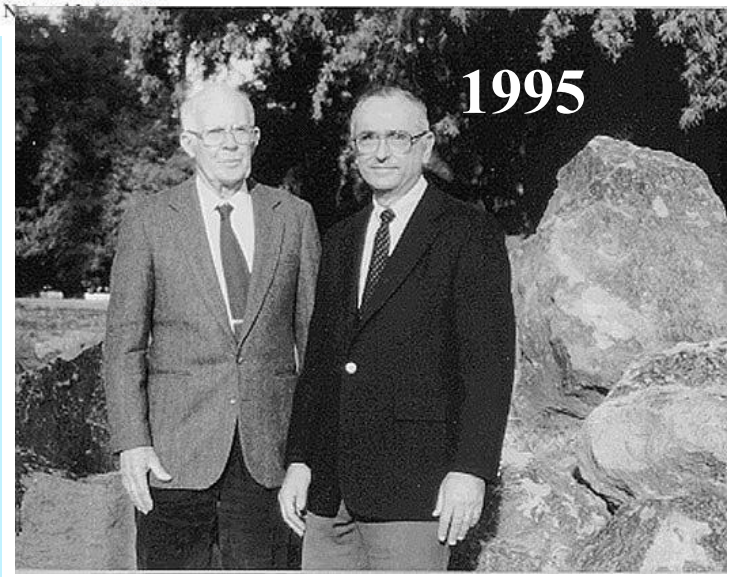


Photo courtesy of Brookhaven N

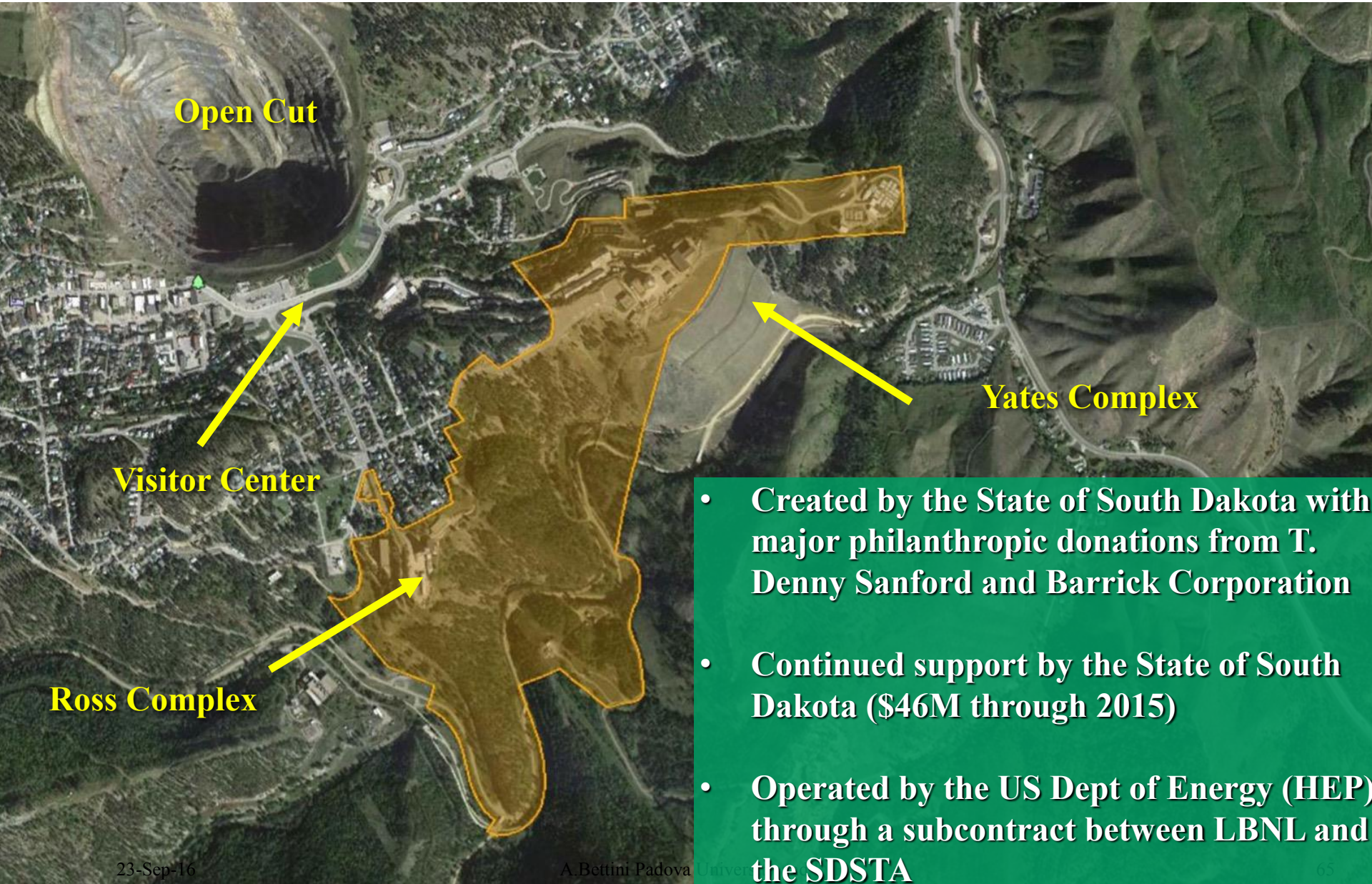


After a long and complex process, in spring 2007, NSF has selected amongst several proposals the Homestake mine as the site in which the Deep Underground Science (physics, biology, geology) and Engineering Laboratory should be designed

Presently it is a DoE laboratory: SURF=Sanford Underground Research Facility



Sanford Underground Research Facility

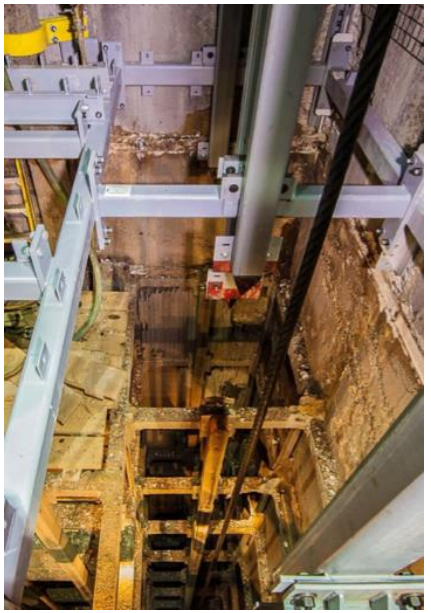


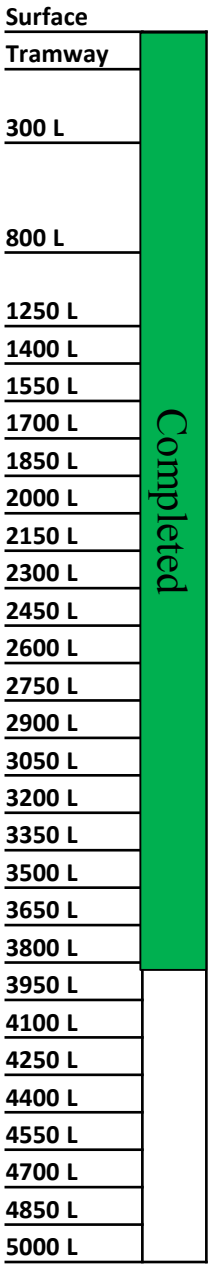
- Created by the State of South Dakota with major philanthropic donations from T. Denny Sanford and Barrick Corporation
- Continued support by the State of South Dakota ($46M through 2015)
- Operated by the US Dept of Energy (HEP) through a subcontract between LBNL and the SDSTA

SURF. Status

K/Lesko (2012) EPJ-p 127:107

- Facility Highlights
  - Deep (1480 m) underground facility dedicated for science, with significant capacity & expansion possibilities
  - Redundant safe access with 2 principal shafts
- Ross Shaft Rehabilitation
  - Strip and re-equip underway, new installation of steel and ground support ~77% complete
  - Total project ~$30M, on track for 2017 completion and transition to LBNF construction
  - Rehab completion scheduled for mid 2017
- Yates Shaft
  - Provides main access for personnel and materials
  - Maintenance ongoing, full rehabilitation after Ross Shaft Rehabilitation completed (TBD)
- Dewatering
  - Maintaining water level ~5700' below surface



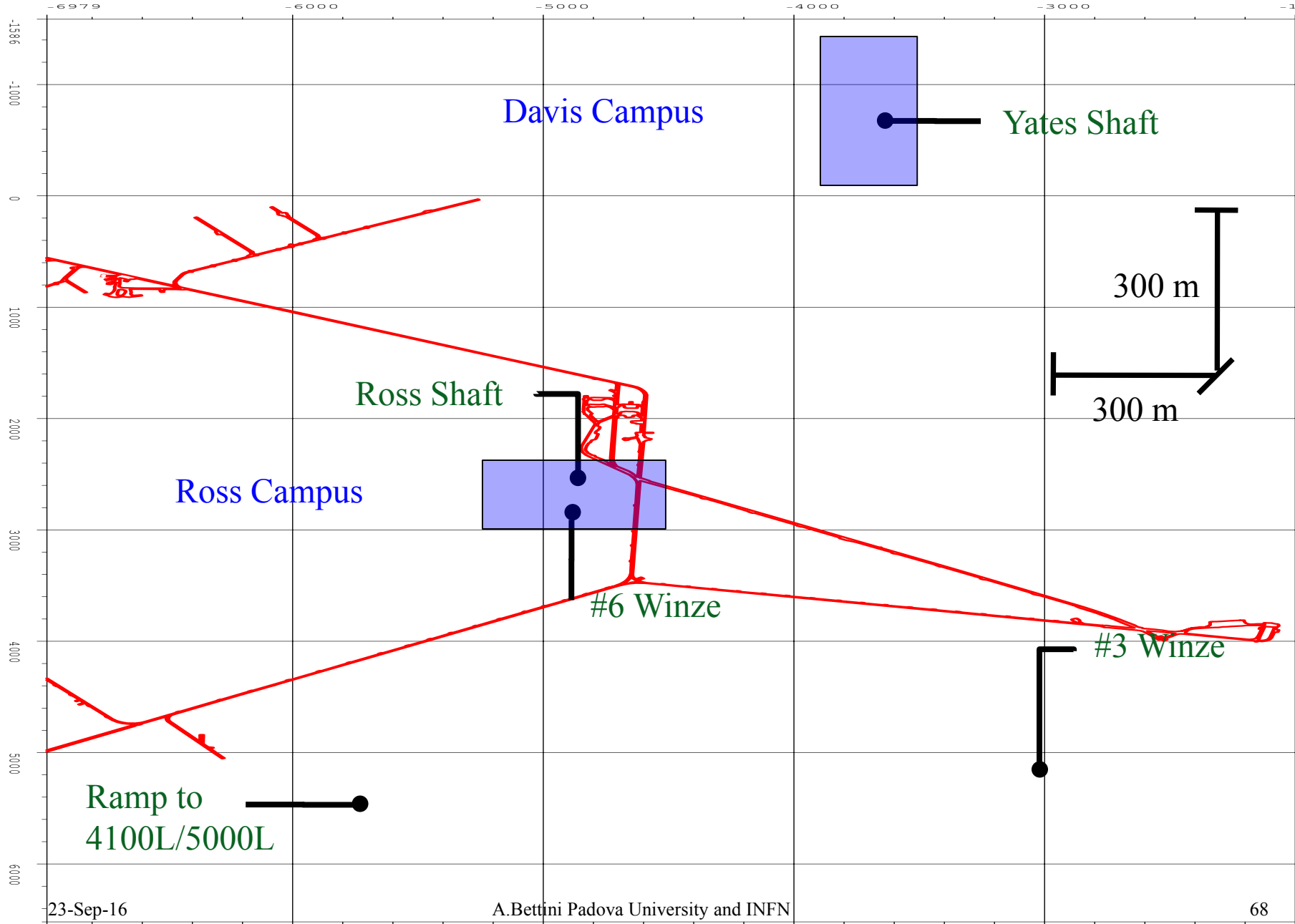


SURF. Science

- Physics
  - LUX (Dark Matter. LXe) – Running
  - MAJORANA Demonstrator (DBD. Enr Ge) – Running
  - CASPAR. Nuclear Astrophysics 1 MV accelerator – Ready
  - BHUC. Underground biology and physics laboratories
  - DUGGL. Characterization for Grav Wave detector
- Geology
  - GEOX. Optical fibers, tiltometer
  - Hydro Gravity (Local gravity for water table..)
  - Transparent earth (Seismic array)
  - klSMET (Rock simulation monitoring)
- Biology
  - Biodiversity, Biofuels, Lignocellulose, Syngas, Astrobiology with NASA
- Engineering
  - Chip error testing

Total Active = 22 groups
(32 Total Groups Since 2007)

SURF. Current 4850L

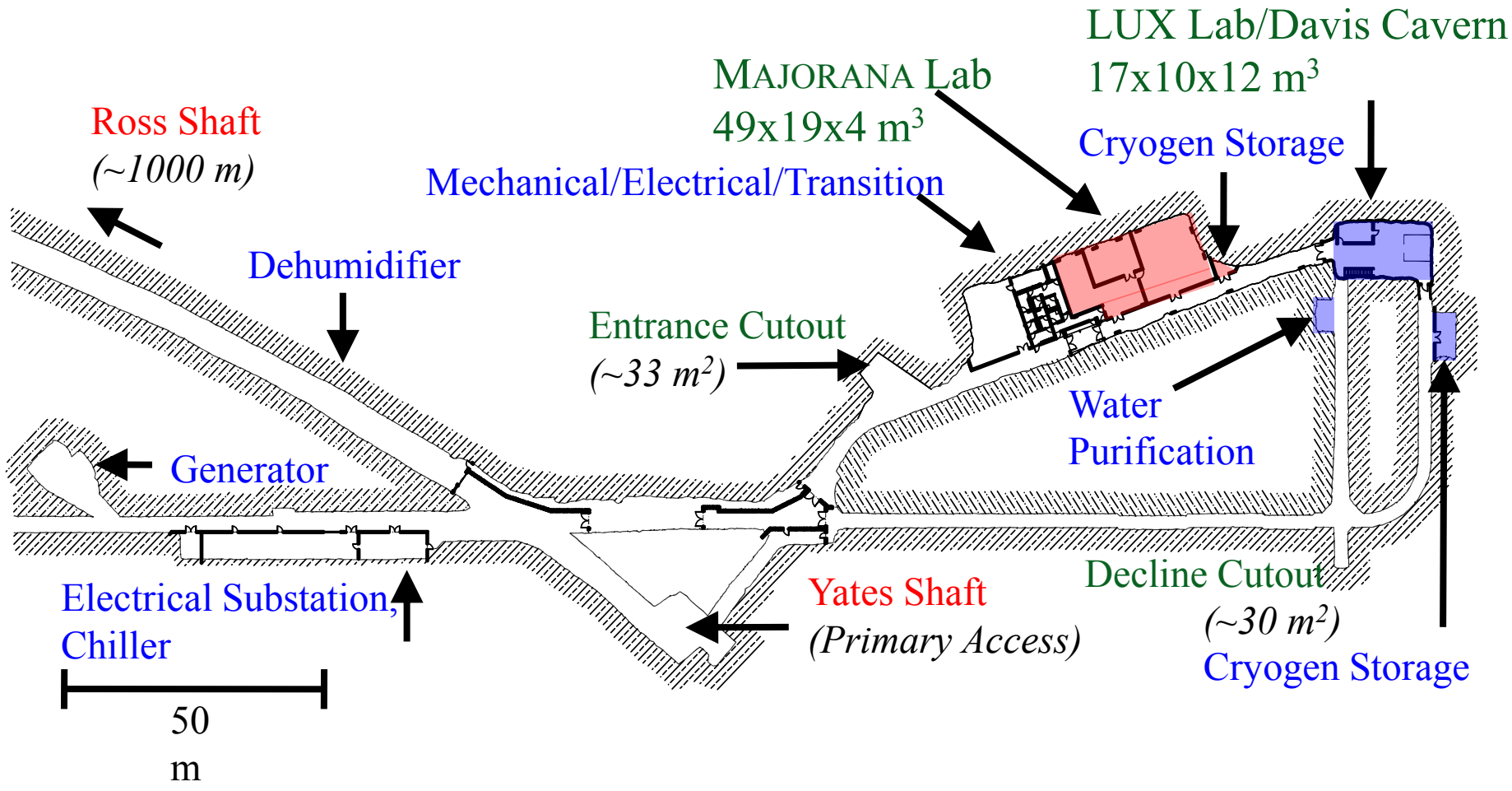


SURF. 4850L

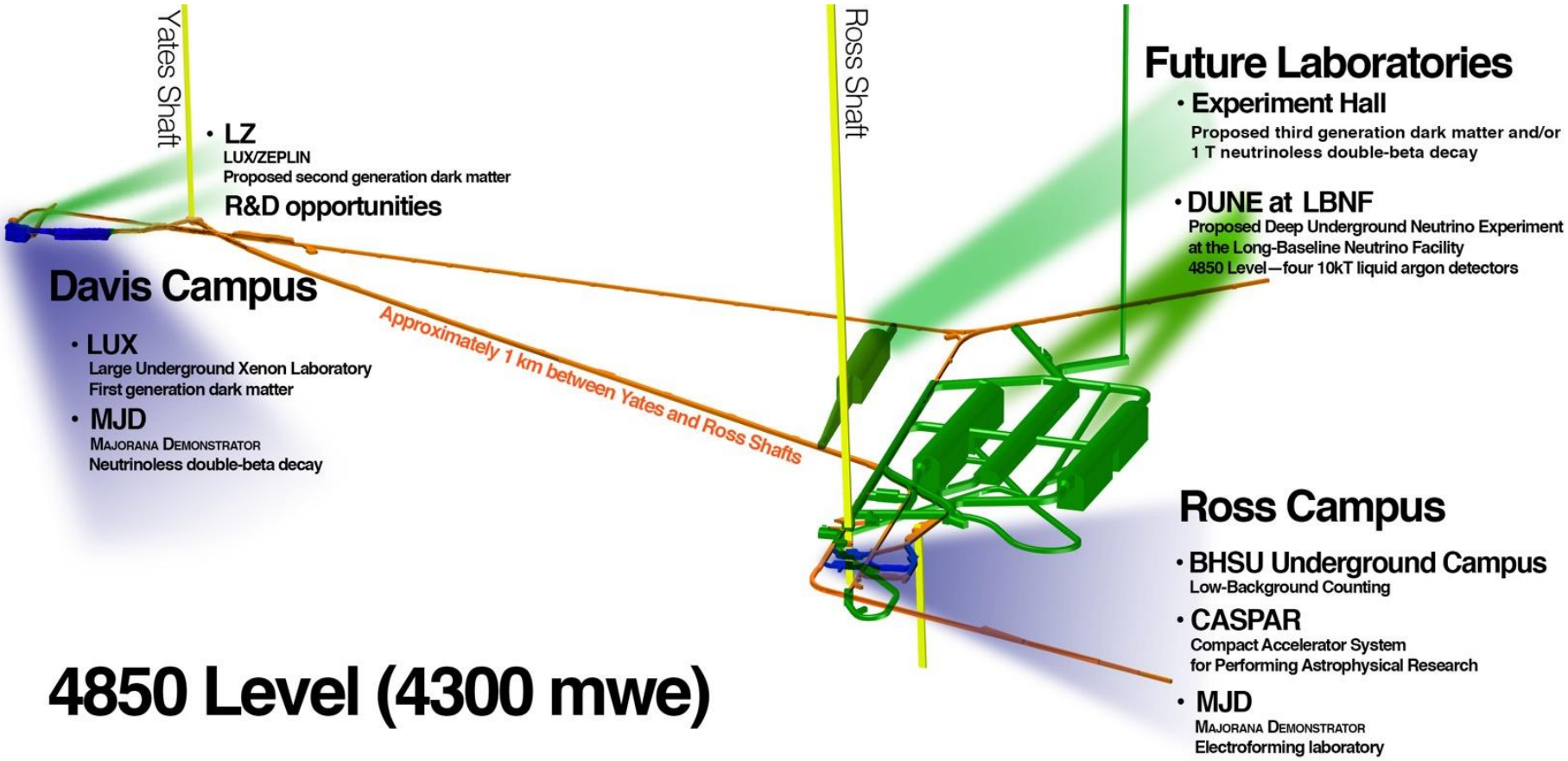
K. Lesko (2012) EPJ-p 127:107

Depth 1480 m

Surface: 3015 m^2 (total)/1015 m^2 (science) + Davis Campus + New excavations



SURF. Current & Future



Existing Facilities

Future Facilities

Heise, J. Phys, Conf **606** 012015 (2015),
also arXiv:1503.01112 (2015)
Lesko, Phys Procedia **61** 542 (2015)

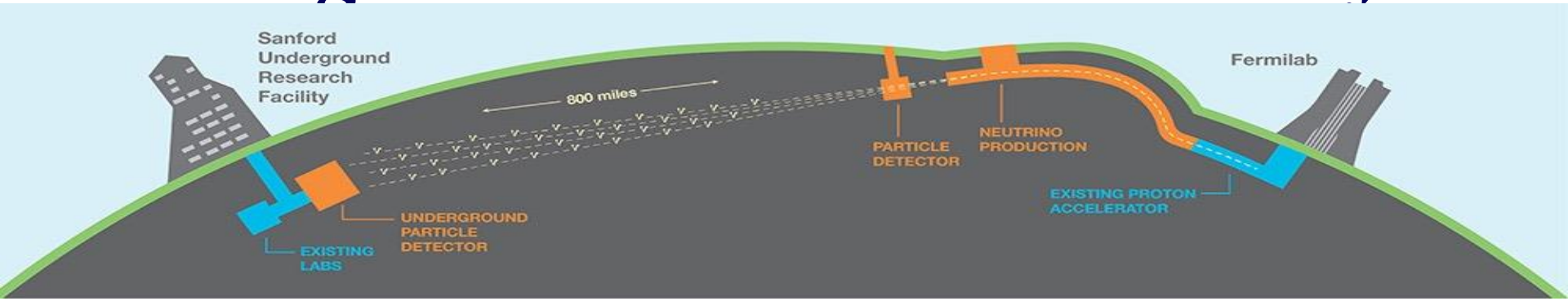
SURF. Services

- Operations
- Environment, safety and health
- Engineering
- Business, finance and human resources
- Education and outreach
- Low background assay (5 counters)
- Clean room underground
- Electroforming underground (MJD)

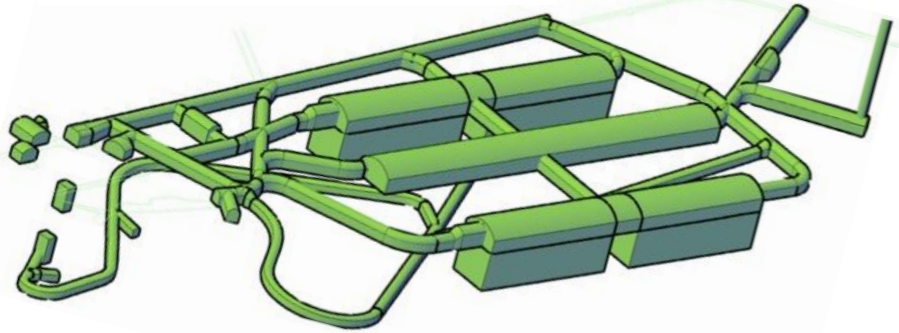
SURF. CASPAR

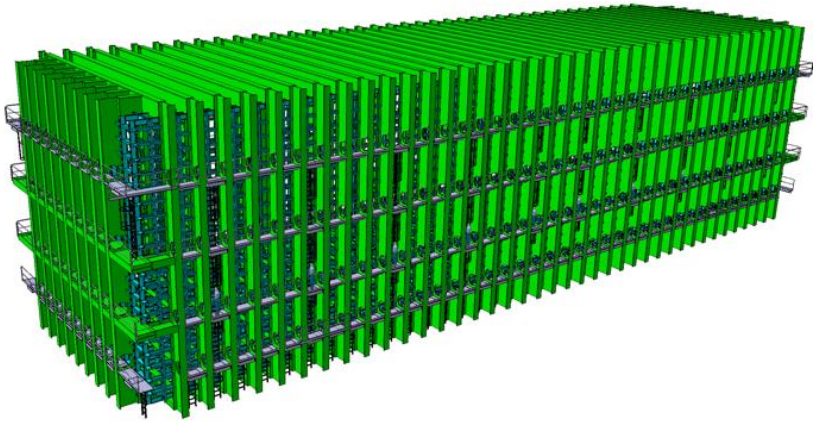
Compact Accelerator System for Performing Astrophysical Research

Long Base Line Neutrino Facility



- LBNF is DOE project led by FNAL, leading design for SD facilities
- 2 caverns on 4850L will accommodate 70 kT (total) / 40 kT (fiducial) Lar
- Geotechnical studies completed 2014, test blast program completed spring 2016
- Dec 2015, proposed appropriations support FY17 start of construction in SD
- Excavation start 2018, ~3 year duration
- 4 chambers 70 x 20 x 49 (H) m^3 halls, each hosting one 10 kt module

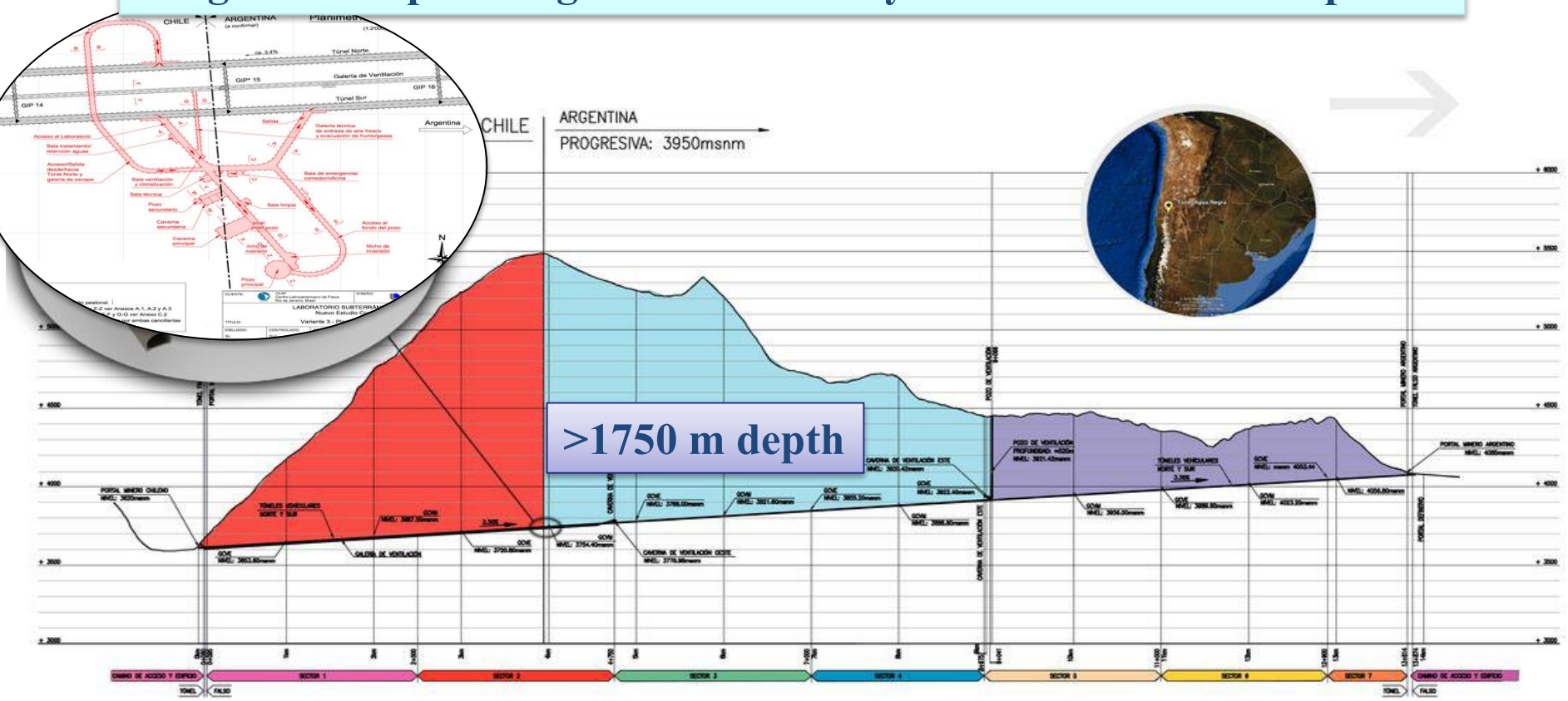




ANDES. *Agua Negra Deep Underground Laboratory*

- Agua Negra tunnel between Argentina and Chile, linking MERCOSUR to Asia
- Tunnel financed by Inter-American Development Bank; construction: 2017-2024
- Horizontal access, size of ~ 4 000 m^2 and ~ 70 000 m^3 in 8 halls and pits

Large and deep underground laboratory in the southern hemisphere



ANDES. Science

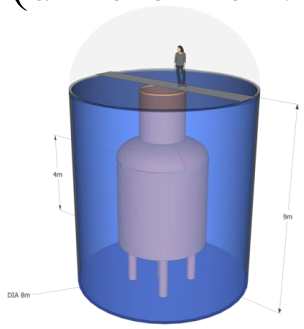
Neutrino physics, astrophysics, geology

- Large Latin America Neutrino Detector (BOREXINO technology)
- Supernova neutrinos (triangulation with Northern detectors)
- Double beta decay

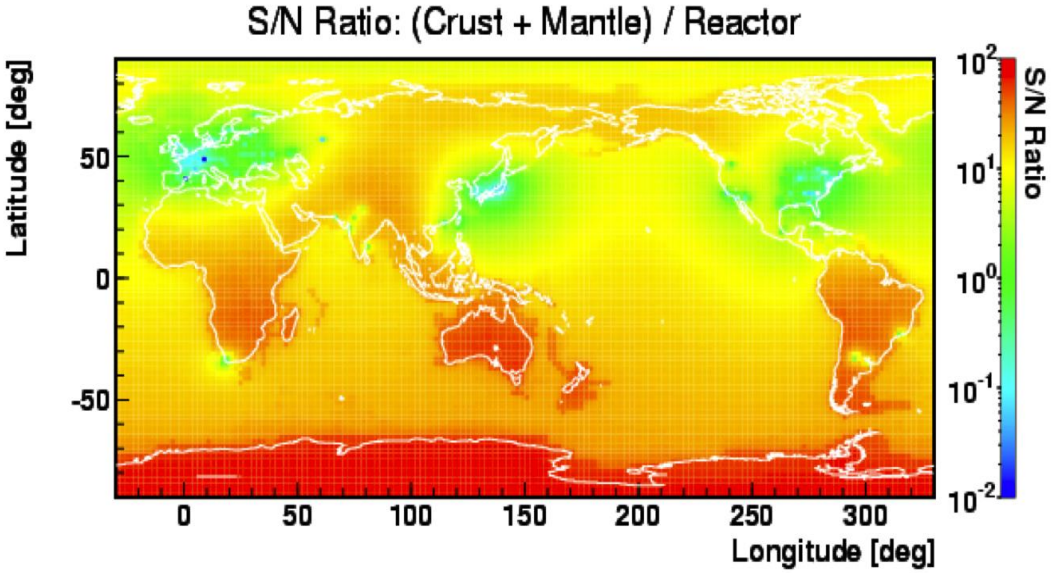
Dark matter

- Exploit modulation (different environmental phases)
- New technologies

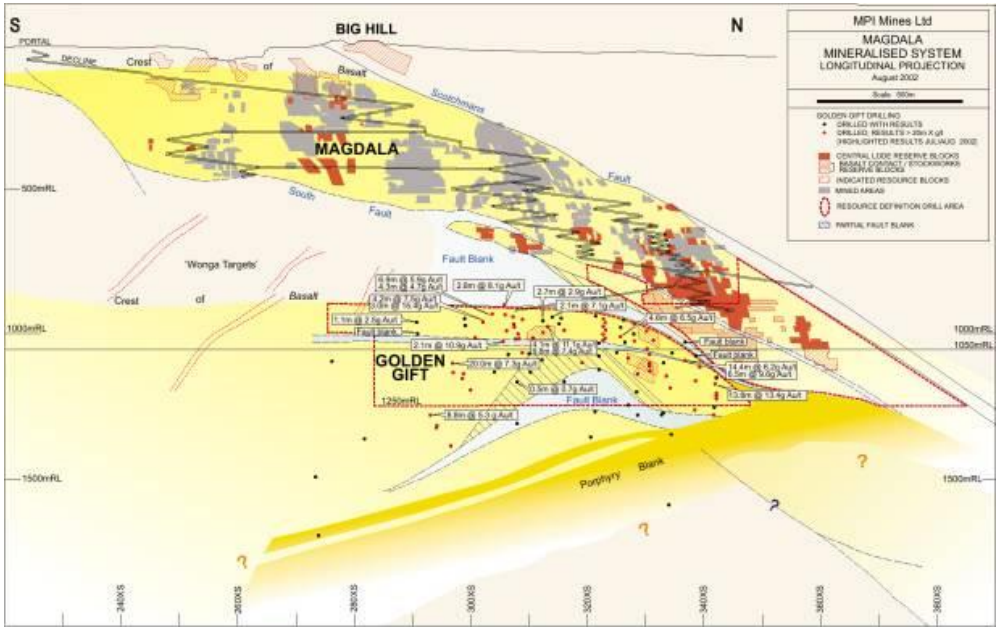
Ultra-low radiation pit



- Geophysics (Nazca plate, subduction)
  - Integrate underground nodes into Argentina and Chile surface seismic networks
- Biology underground
- Low background measurements
- Nuclear astrophysics



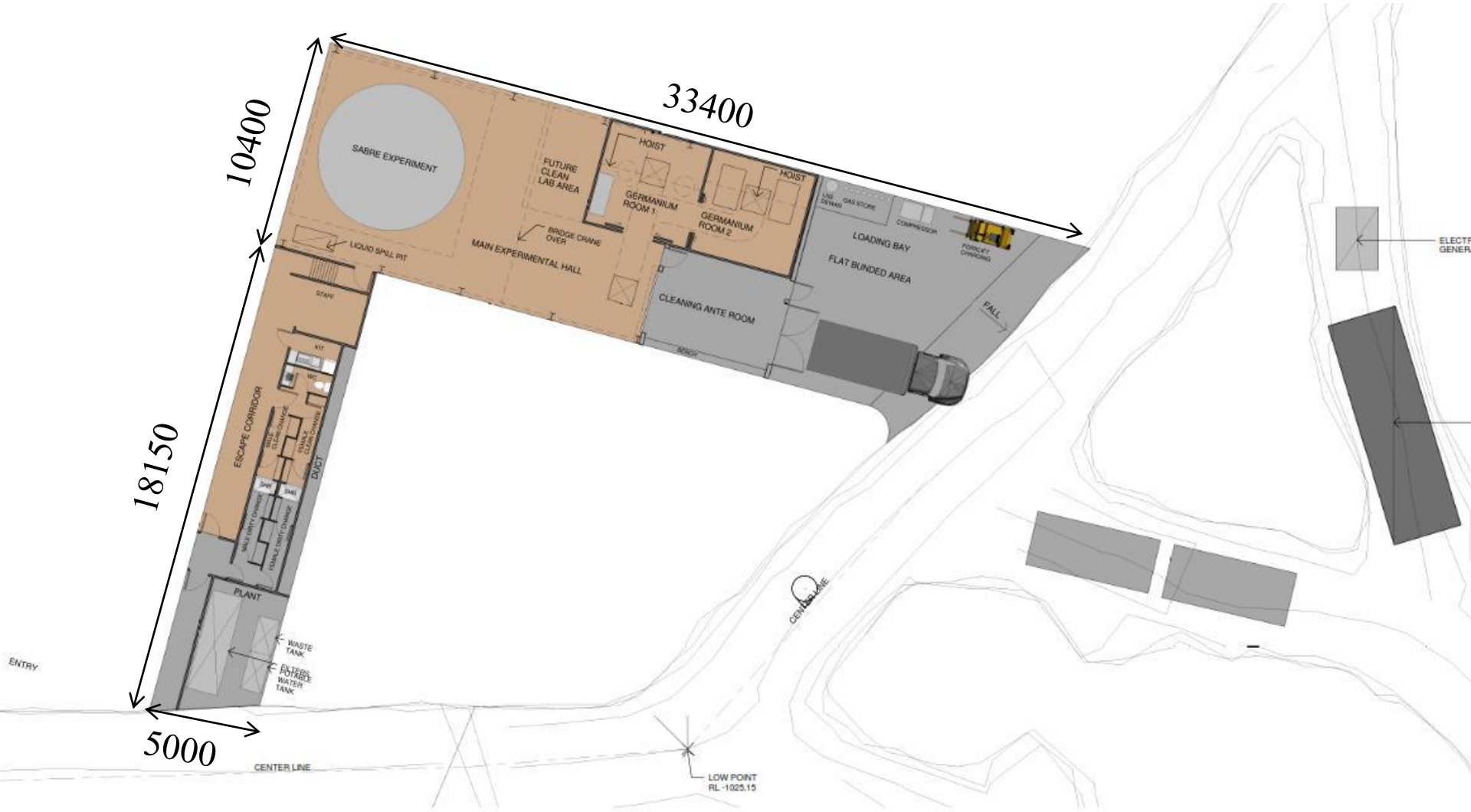
Stawel Underground Physics Laboratory. SUPL



To be hosted in the Stawell operational gold mine about 240 km NW Melbourne Vic.
Vertical access through road
1020 m depth
Funded for 3.5 M$Aus
Requested additional 3 MM$Aus
Will be the first (small) DUL in Southern Hemisphere

Will host SABRE a NaI(Tl) very low background experiment designed to test DAMA/LIBRA result. 2 copies in the two hemispheres at LNGS and SUPL

SUPL
Ground floor plan



Conclusions

- **Physics beyond the Standard Model is discovery of Underground Laboratories (solar and atmospheric neutrinos)**
- **The physics programme for the next decades appears extremely rich and challenging**
- **The interest of the scientific community is increasing (also in consideration of the disappearance of several accelerator facilities)**
- **Several facilities, but only a few are managed as structures for the international community with full-scale services and turnover of the experiments**
- **New laboratories and upgrades of existing ones, are being created along these lines. Will provide very good working conditions in the next decades**
- **Cost, e. g., for ton-scale DBD or 10 ton-scale DM > cost of a lab to host them**
- **Decisions in the different countries are sensitive to geo-political arguments**
- **Geology and biology may become important (but limited) elements of the programme**

Title