Nigel Smith
Director, SNOLAB

# Deep underground physics: facility and experiment developments at SNOLAB


- The Dark Matter puzzle
- How do you detect Dark Matter?
- Why go underground?
- Underground labs around the world
- SNOLAB update and programme

# Weighing a Galaxy

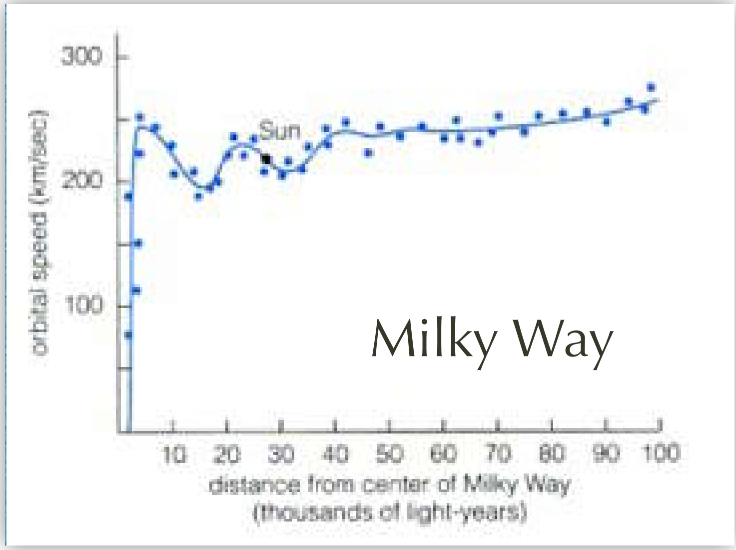
- Scale 10kPc (30 000 light years)
- Uses Doppler shift of light from star in spiral galaxy to give velocity (red shift)
- Expect velocity to fall off with distance from centre

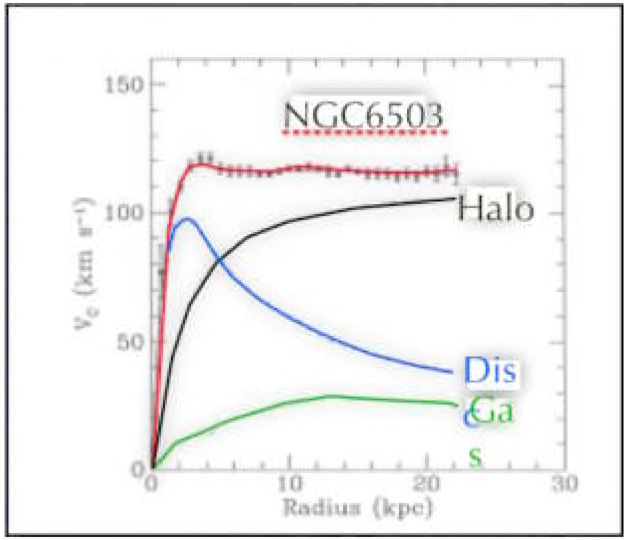
$$v_c^2 = G_N \, M_{vis}/r$$

$$M_{tot}(r) = v_c^2 r / G_N$$

...but it doesn't

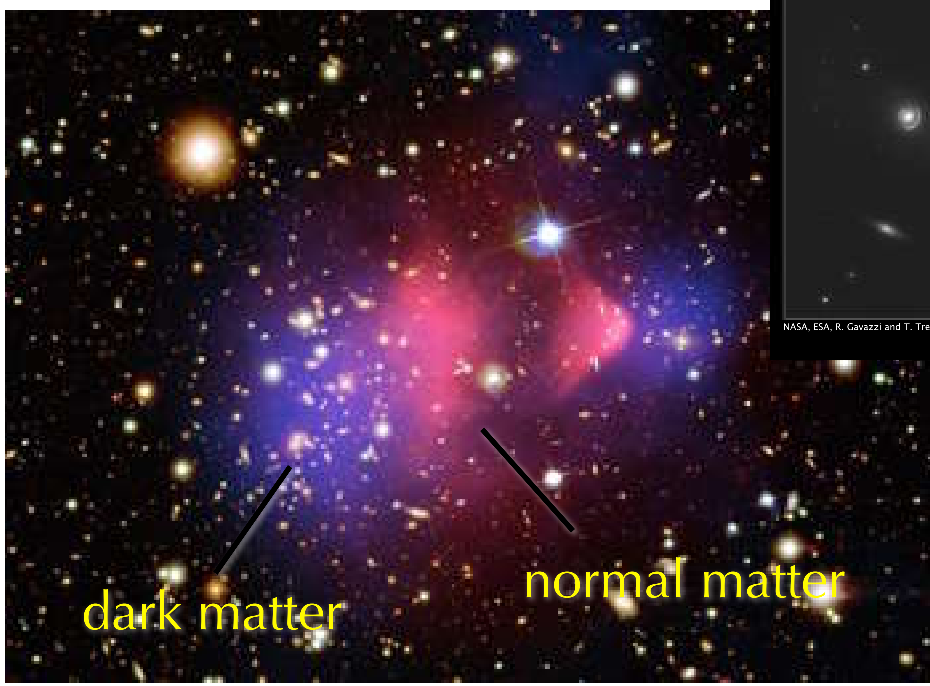
... $\rho_{dm} \approx 0.3$ GeV/cc



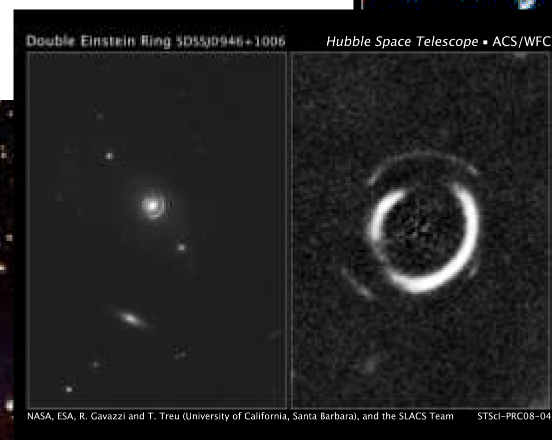



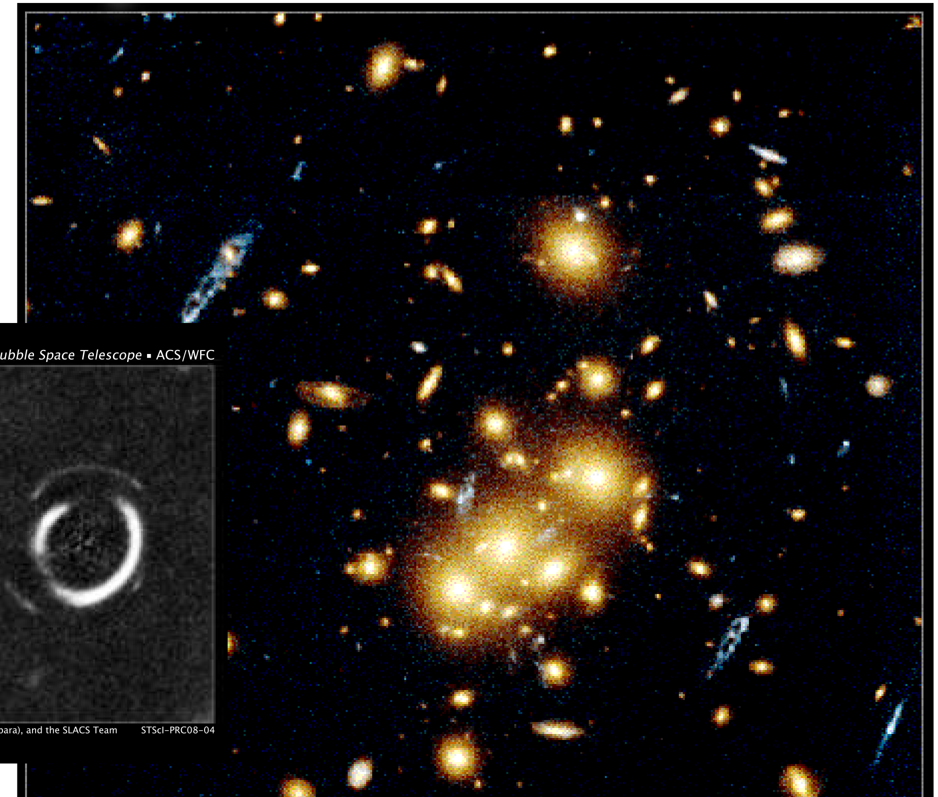

# Weighing Galaxy Clusters

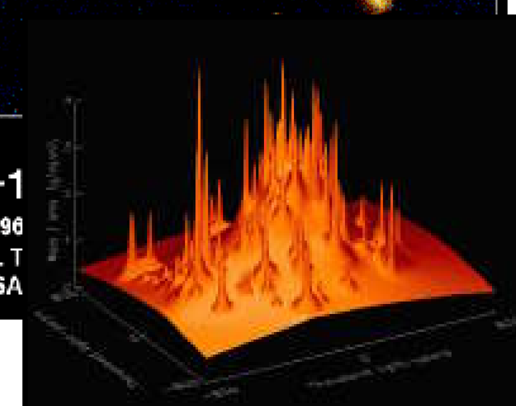
- Scale 1 Mpc  (3M l.y.)
- Use gravitational lensing of quasars or galaxies by galaxy clusters.




Bullet cluster (interacting galaxies)
gravitational lensing compared to Xray images



Wise: Kavli Institute

# Mass of the Universe

Describe with a cosmological mass density:

$$- \Omega_m (\Omega_{cdm} + \Omega_{hdm} + \Omega_b) + \Omega_\lambda + \Omega_\kappa$$

Total density: $\Omega_T = 1.02 \pm 0.02$

(which is what we want for BB inflation)

Energy density: $\Omega_\Lambda = 0.73 \pm 0.04$

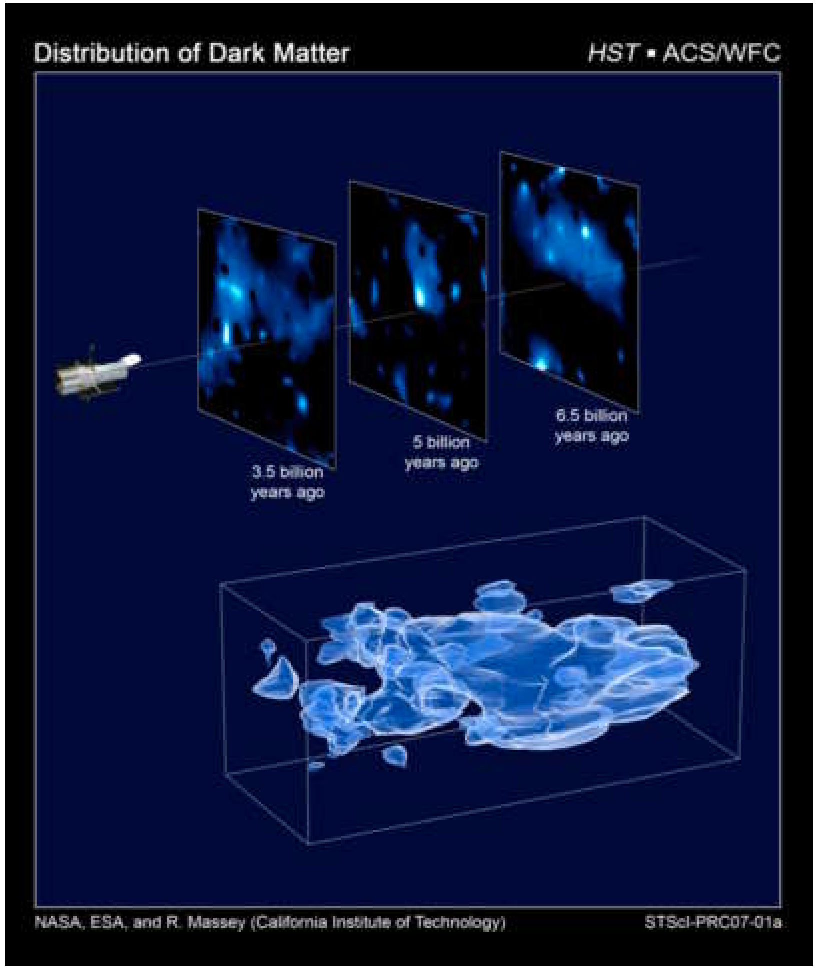
Matter density: $\Omega_m = 0.27 \pm 0.04$

Baryon density: $\Omega_b = 0.044 \pm 0.004$

Neutrinos (HDM): $\Omega_\nu < \sim 0.015$

Non-baryonic Cold Dark Matter

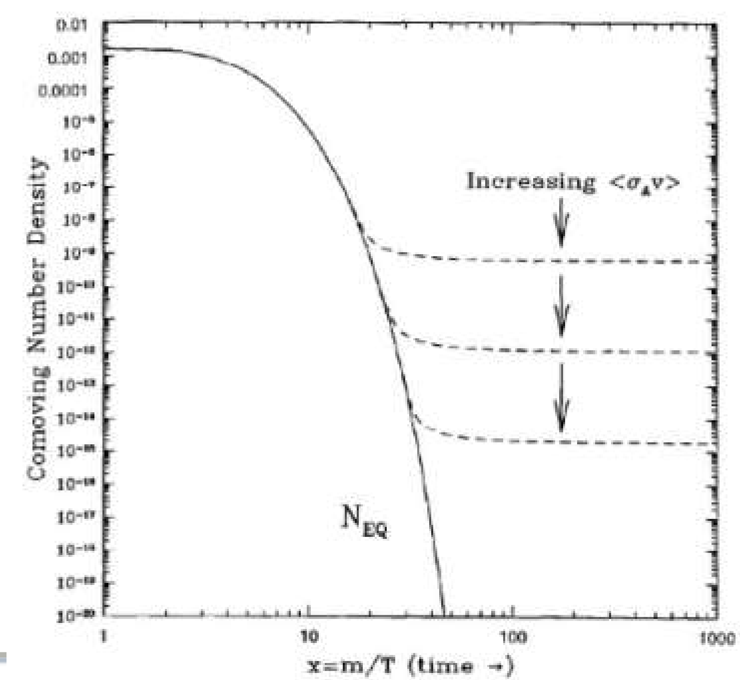
$\Omega_d = \Omega_m - \Omega_b = 0.22$




95% of what makes up the Universe is unknown — the concordance…

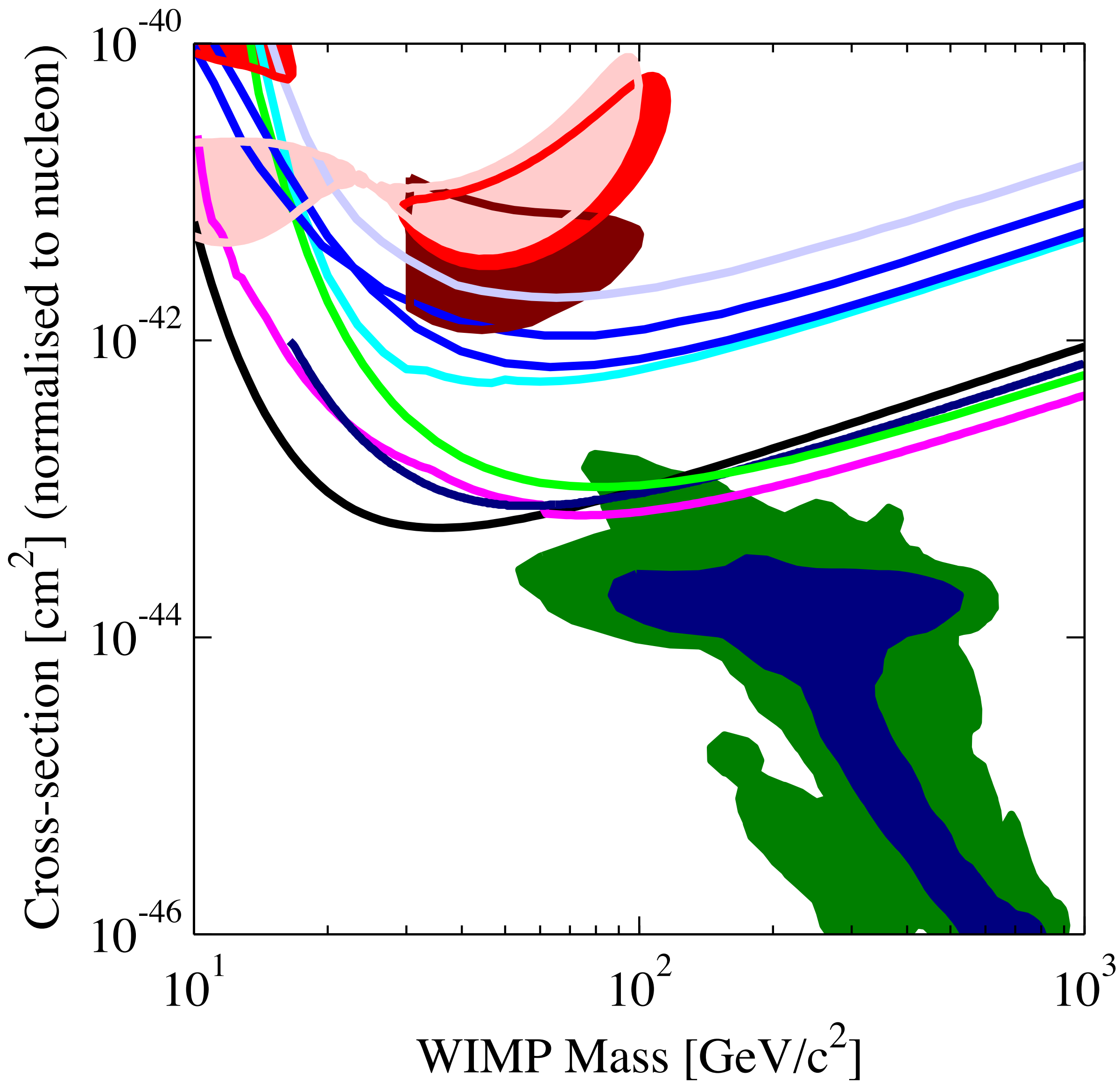
# The WIMP solution

- SUSY models
  - Hierarchy problem $M_W << M_P$
  - CMSSM parameters
    - Higgs vacuum expectation value ratio: tan β
    - Gaugino masses: $m_{1/2}$ (assume same @ GUT scale)
    - Scalar masses: $m_0$ (assume same @ GUT scale)
    - Higgs mixing: μ
- Produced in early Universe
  - In thermal equilibrium $T > m\chi$
  - Production stalled when $T < m\chi$
  - Freeze out if expansion>annihilation
- Four neutralinos: WIMPs
  - χ, lightest SUSY particle (LSP)
  - 50 GeV < $m\chi$ < 300 TeV (expt.)
  - $10^{-12}$pb < $\sigma\chi$ < $10^{-8}$pb (theory)

# Current S.I. Limits

- ‘Canonical’ halo model
  - Spin independent interaction
  - normalised to nucleon
- Different statistical methods adopted dependent on technique




DATA listed top to bottom on plot
DAMA/LIBRA 2008 3sigma, with ion channeling
DAMA/LIBRA 2008 3sigma, no ion channeling
KIMS 2007 - 3409 kg-days CsI
DAMA 2000 58k kg-days NaI Ann. Mod. 3sigma w/DAMA 1996
ZEPLIN I (2005)
ZEPLIN II (Jan 2007) result
CRESST 2007 60 kg-day CaWO4
Edelweiss II first result, 144 kg-days interleaved Ge
ZEPLIN III (Dec 2008) result
CDMS: 2009 Ge
XENON10 2007, measured Leff from Xe cube
Trotta et al 2008, CMSSM Bayesian: 68% contour
Trotta et al 2008, CMSSM Bayesian: 95% contour

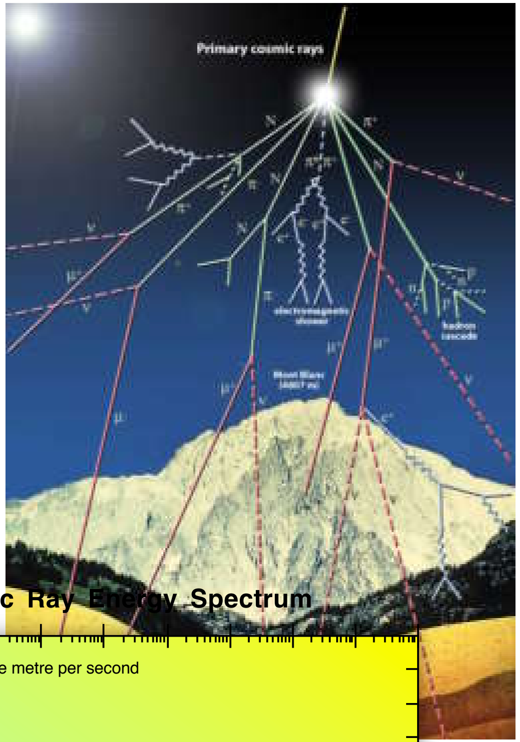
http://dmtools.berkeley.edu/limitplots/ Gaitskell/Mandic

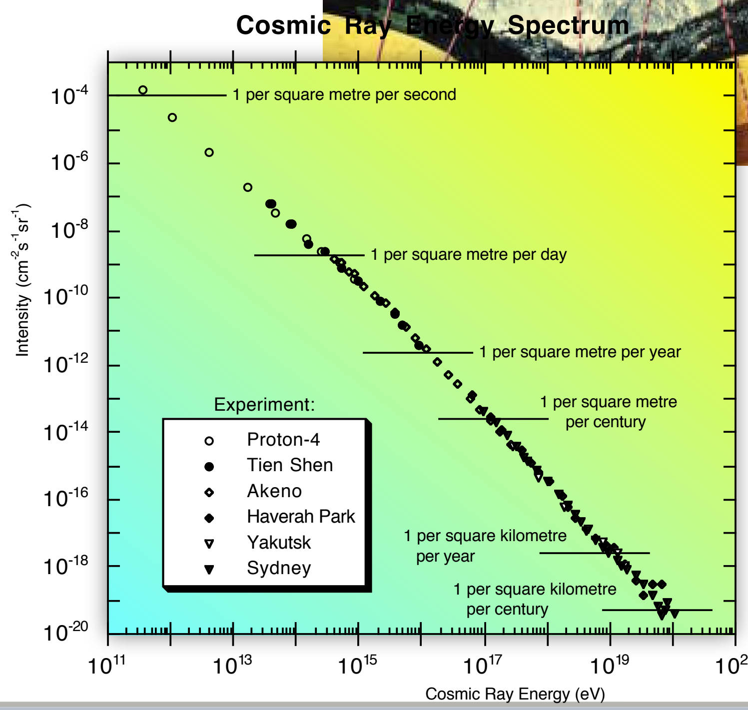
# Experimental Challenge

- WIMP nuclear recoil signal is:
  - Low rate ($1 - 10^{-5}$ events/kg/day)
  - Small energy (1-100keV actual: observed is less)
  - Similar observed exponential spectrum to many background signals (PMT, $\gamma$, etc.)
- Detection technique must be:
  - Low background
    - Gamma, beta: from U/Th/Co/Pb/etc radio-impurities
    - Neutron: from U/Th radio-impurities and c.r. $\mu$ spallation
  - Low threshold
    - To minimise form factor, maximise spectrum
  - Discriminating - Position sensitivity
    - Difference between WIMPs/n and $\gamma/\beta$, background rejection, directionality
  - Large mass (ultimately to reach $10^{-10}$ pb)

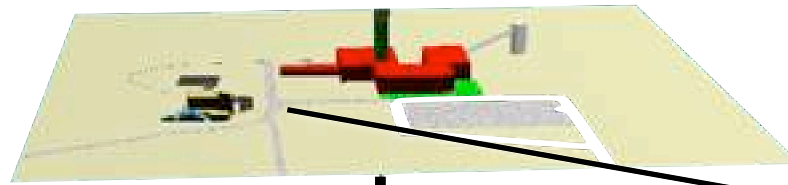
# Go underground!

- Studies for rare events, either decays (eg proton or $0\nu\beta\beta$), low $\sigma$ measurements or weak interactions (dark matter, natural or generated neutrino), require very radio-quiet environments to undertake searches
- Deep underground facilities provide significant rock overburden and commensurate reduction in c.r. flux, and c.r.-spallation induced neutrons
- Reduction in gamma backgrounds from reduction in c.r.s and neutrons
  - Additional science programmes possible with such infrastructure - extreme biosystems, geology, geophysics, gravitational waves...



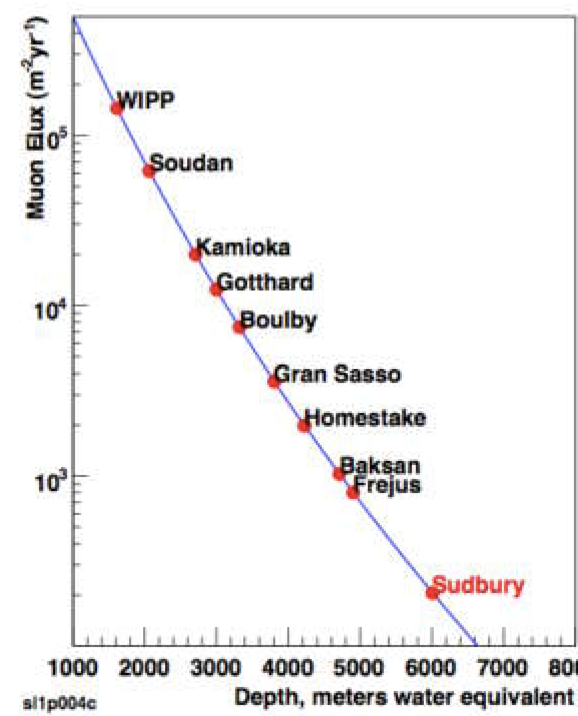
# Muon backgrounds

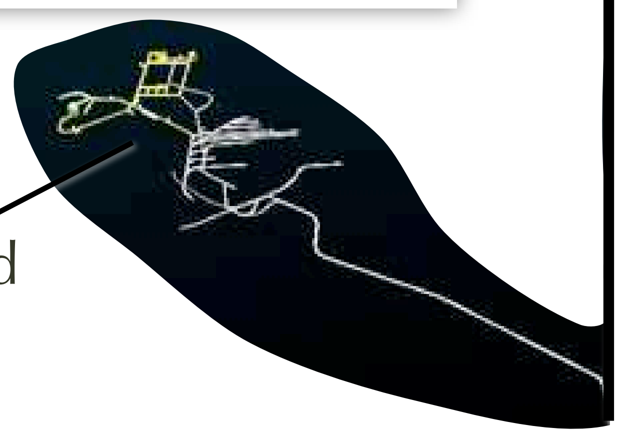


2km rock overburden (6000mwe)

Surface Facility

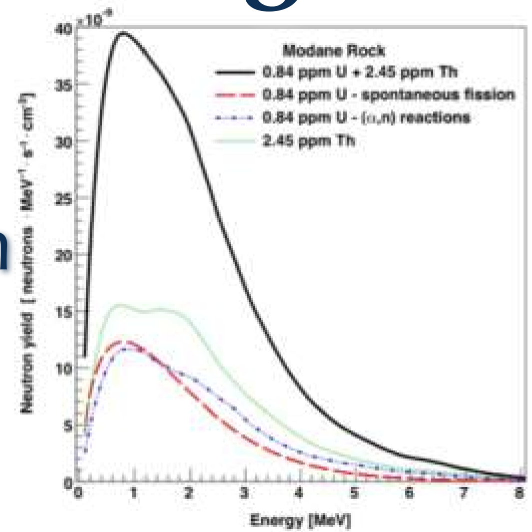

Muon Flux = 0.27/m$^2$/day

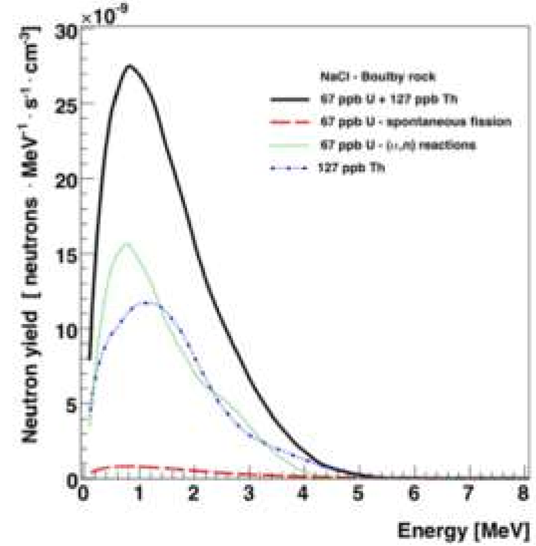


Underground Laboratory

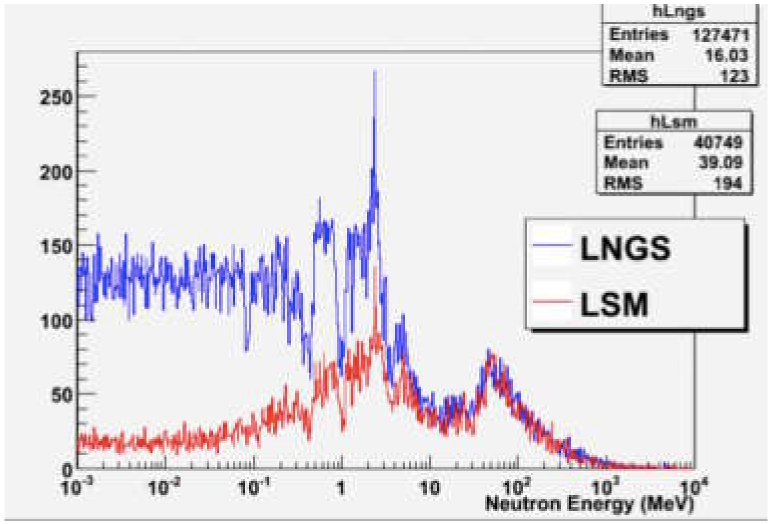
# Neutron backgrounds




Kudryavtsev

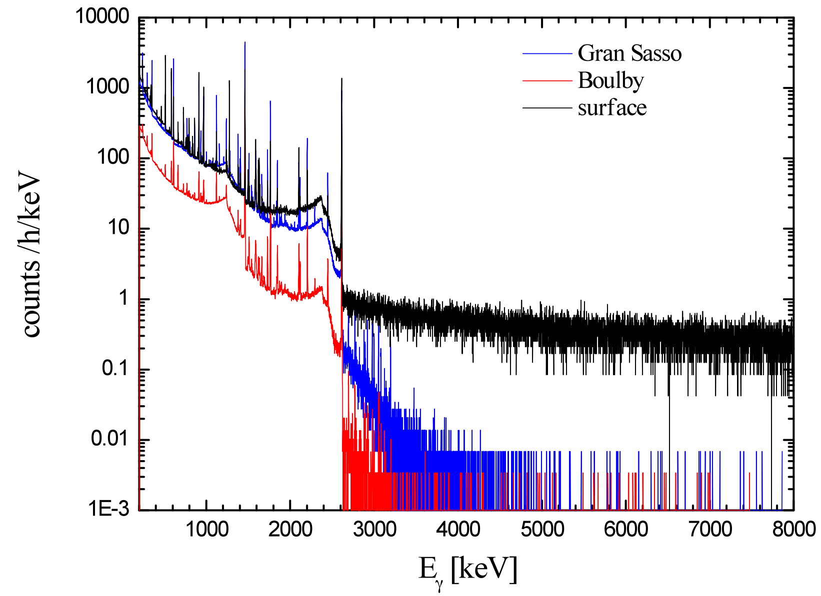
- Neutron production from
  - c.r. muon spallation
  - U/Th fission
  - α, n reactions
- Spectrum in laboratory depends on local geology (rock composition)
  - both for fast and thermal neutrons
  - U/Th + moderators
  - muons + moderators
  - small levels of high neutron cross-section make a big difference

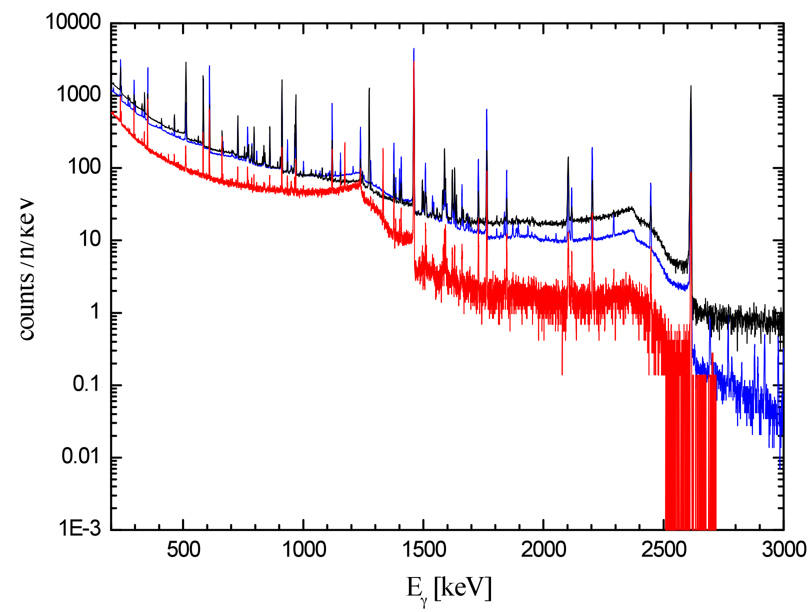



Persiani / Selvi

# Gamma Backgrounds

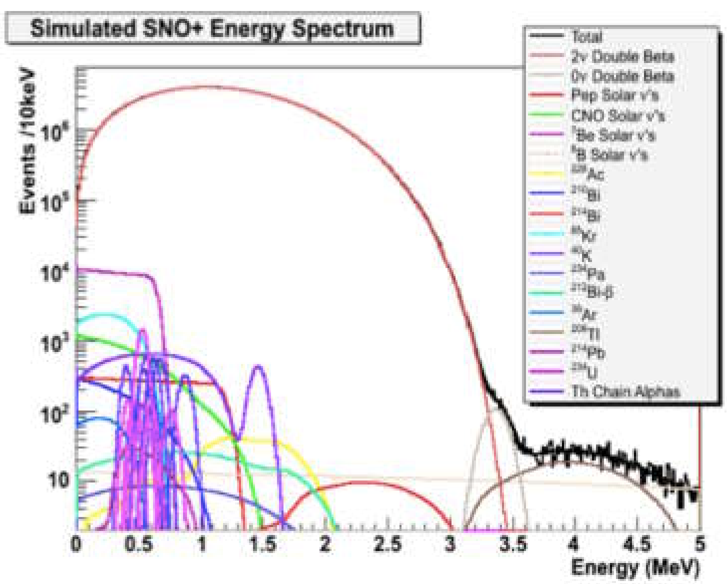
- Reduction in gamma background at higher energies from c.r. and neutron reduction
- Below 3.5MeV dependent on local geology and rock material
  - Boulby (red)
  - Gran Sasso (blue)
  - surface (black)



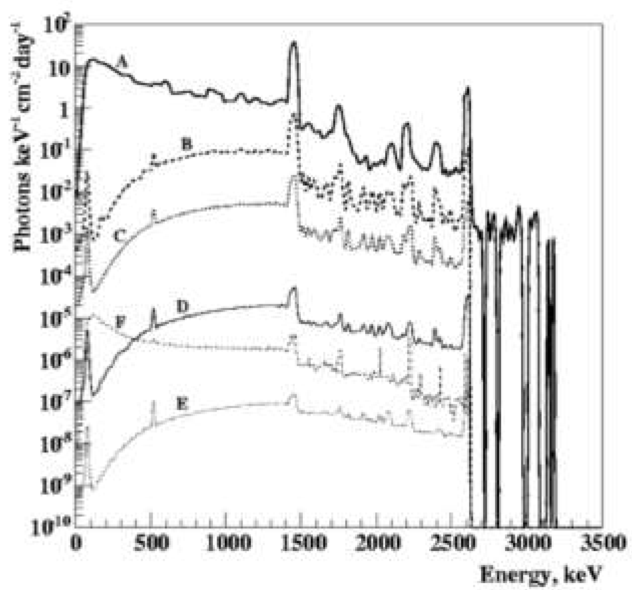



# Background Suppression

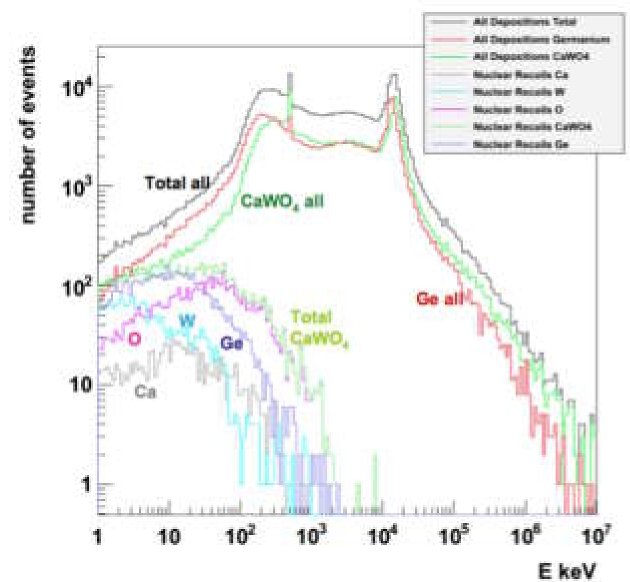
- c.r. μ and n spallation (depth, μ veto, self veto)
- γ,β (traditional gamma shielding or gamma blind)
- radon (clean room operations, atmospheric and material selection and radon suppression)
- U/Th (α,n) in rock and detector materials (shield, veto)
- Cosmogenics (underground fabrication)
- gravitational gradient (massive rock bed, away from surface)




SNO+ @ SNOLAB




γ in Pb @ Boulby (Carson)




EURECA @ LSM (Kudryavtsev)

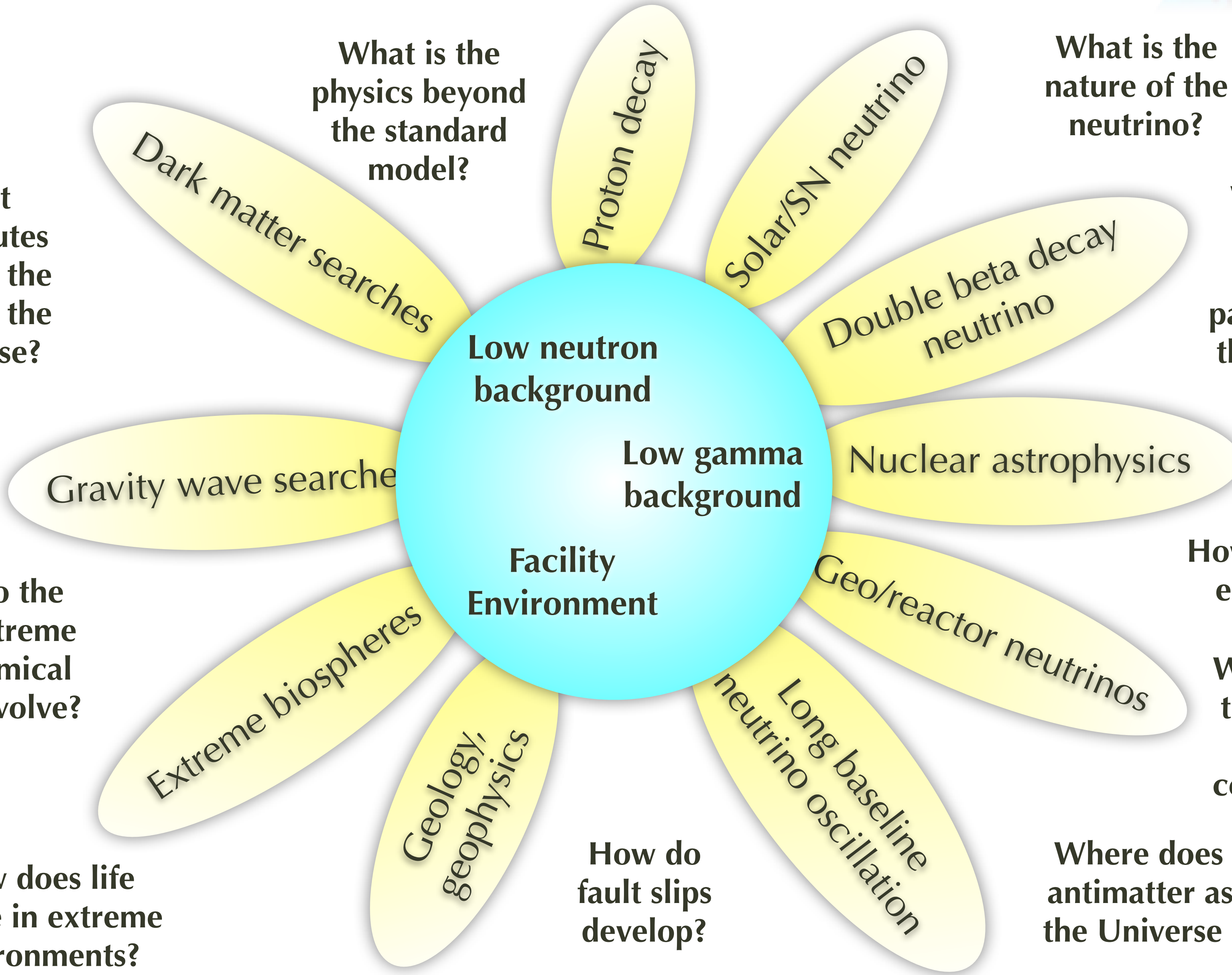
# Science questions...

What is the physics beyond the standard model?

What is the nature of the neutrino?

What constitutes most of the mass of the Universe?

What is the mass, and mixing parameters, of the neutrino?




How do stars burn?

How do they explode?

How do the most extreme astronomical events evolve?

Where does the heat of the Earth come from?

How does life evolve in extreme environments?

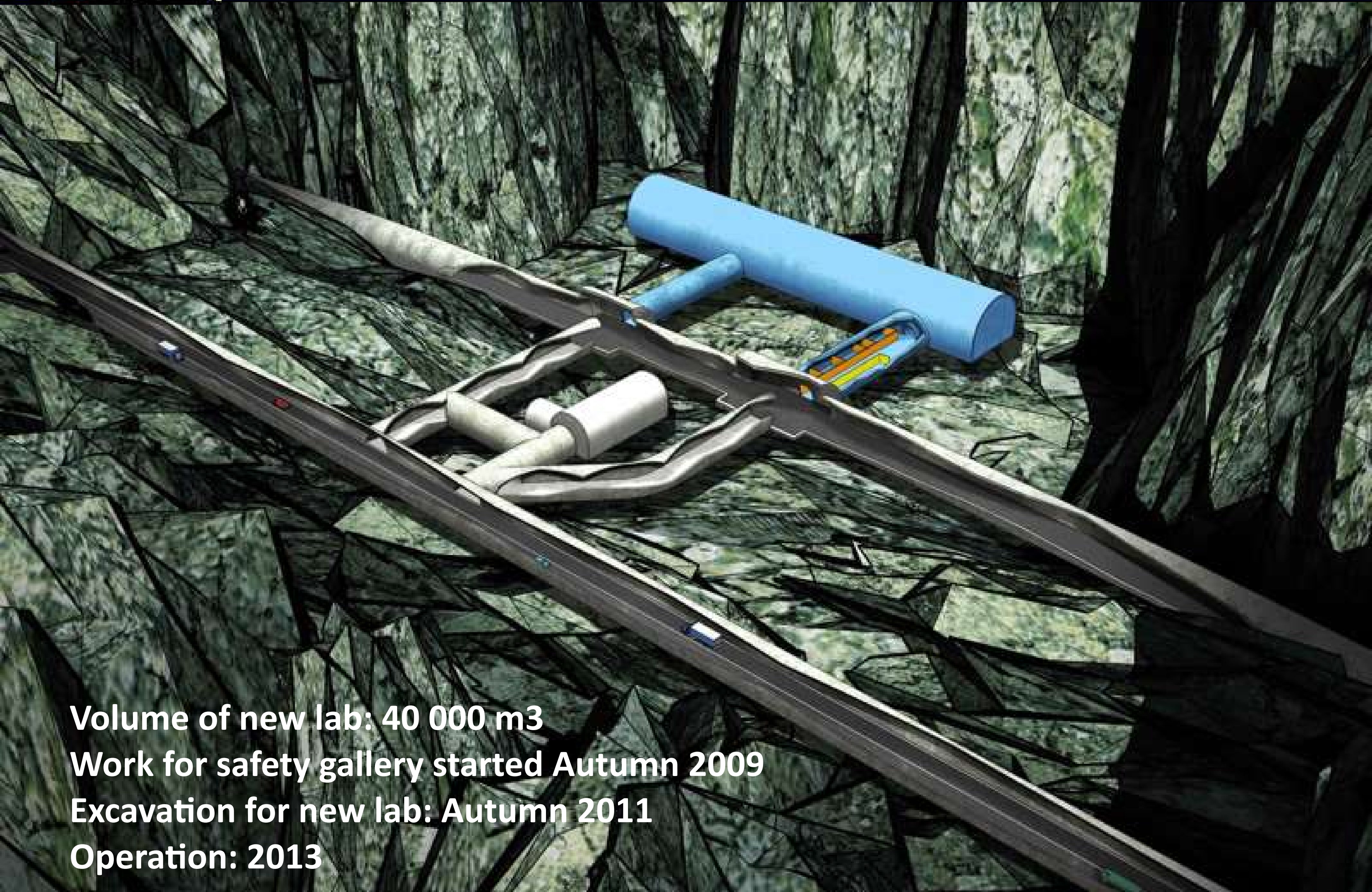
How do fault slips develop?

Where does the matter-antimatter asymmetry in the Universe come from?

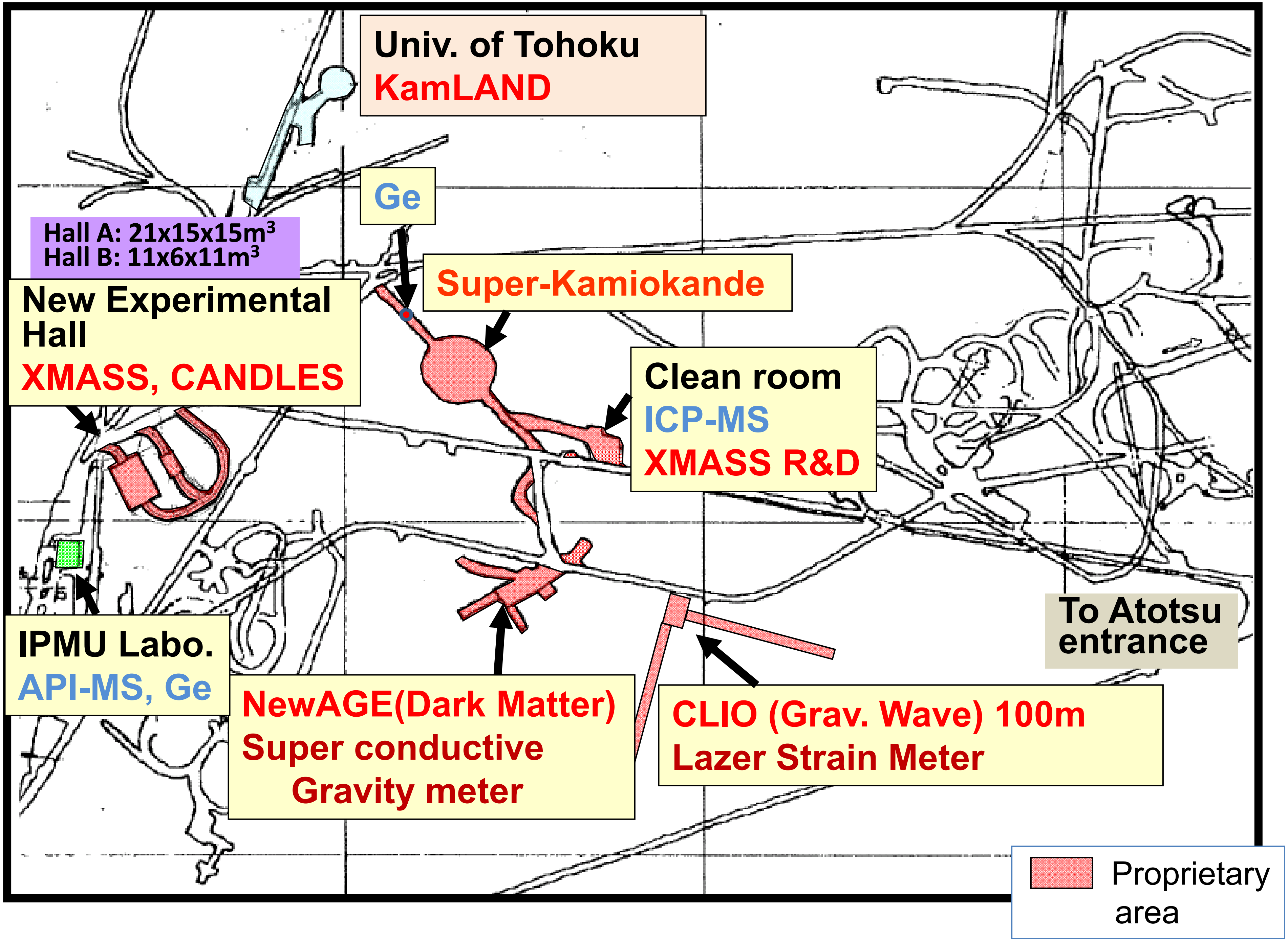
# World status

- Many underground laboratories exist around the world
  - Europe: mountain road tunnels, mines
  - Asia: mines and hydro-electric plants
  - North America: mines
- Expansion underway at several to provide space for the underground physics field
  - Highlighted France, Japan, China, U.S.A.
- Different scale experiments being developed
  - Megatonne neutrino beam/proton decay
  - Kilotonne dark matter/neutrinoless double beta decay

# LSM and Extension

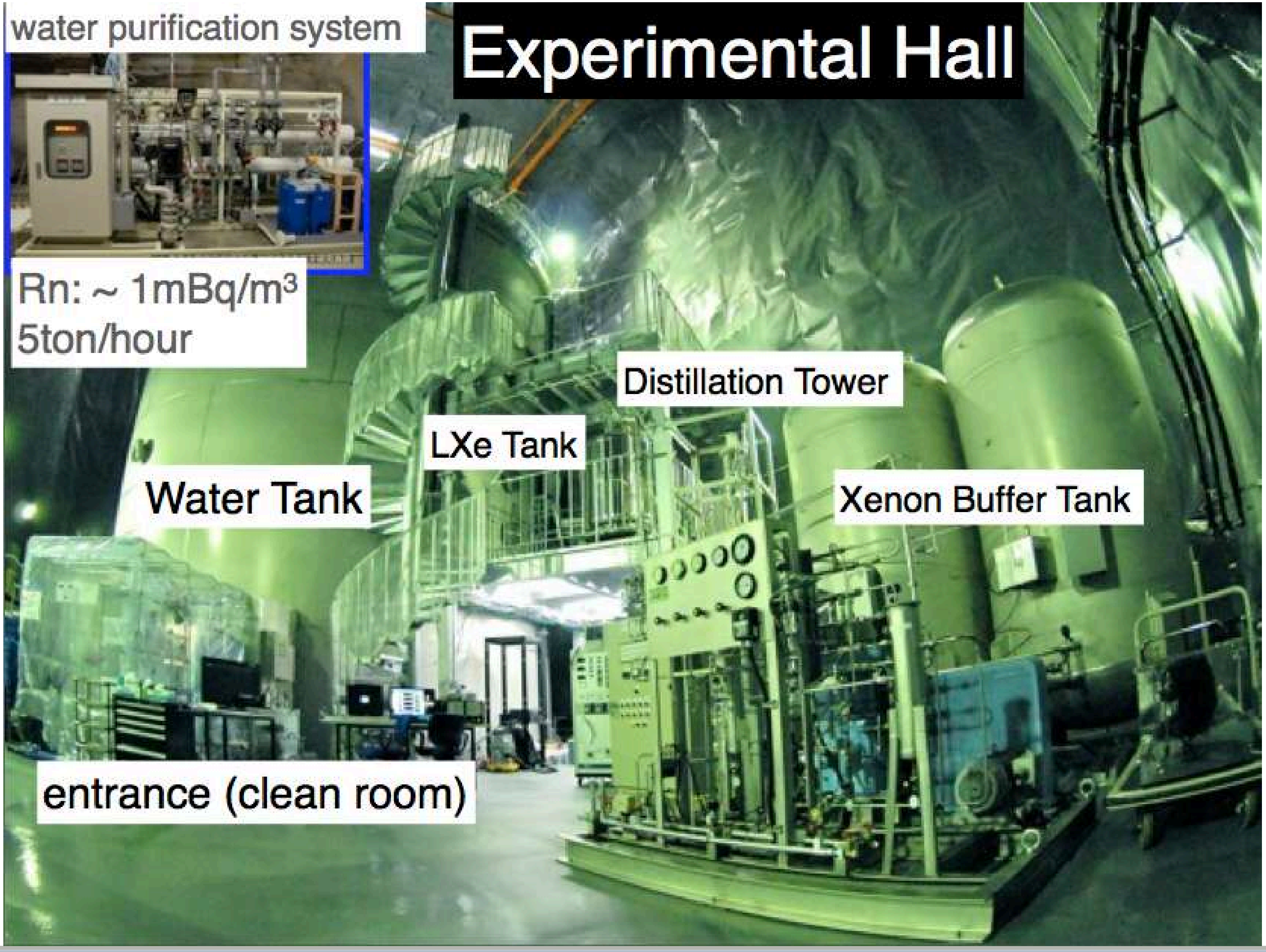


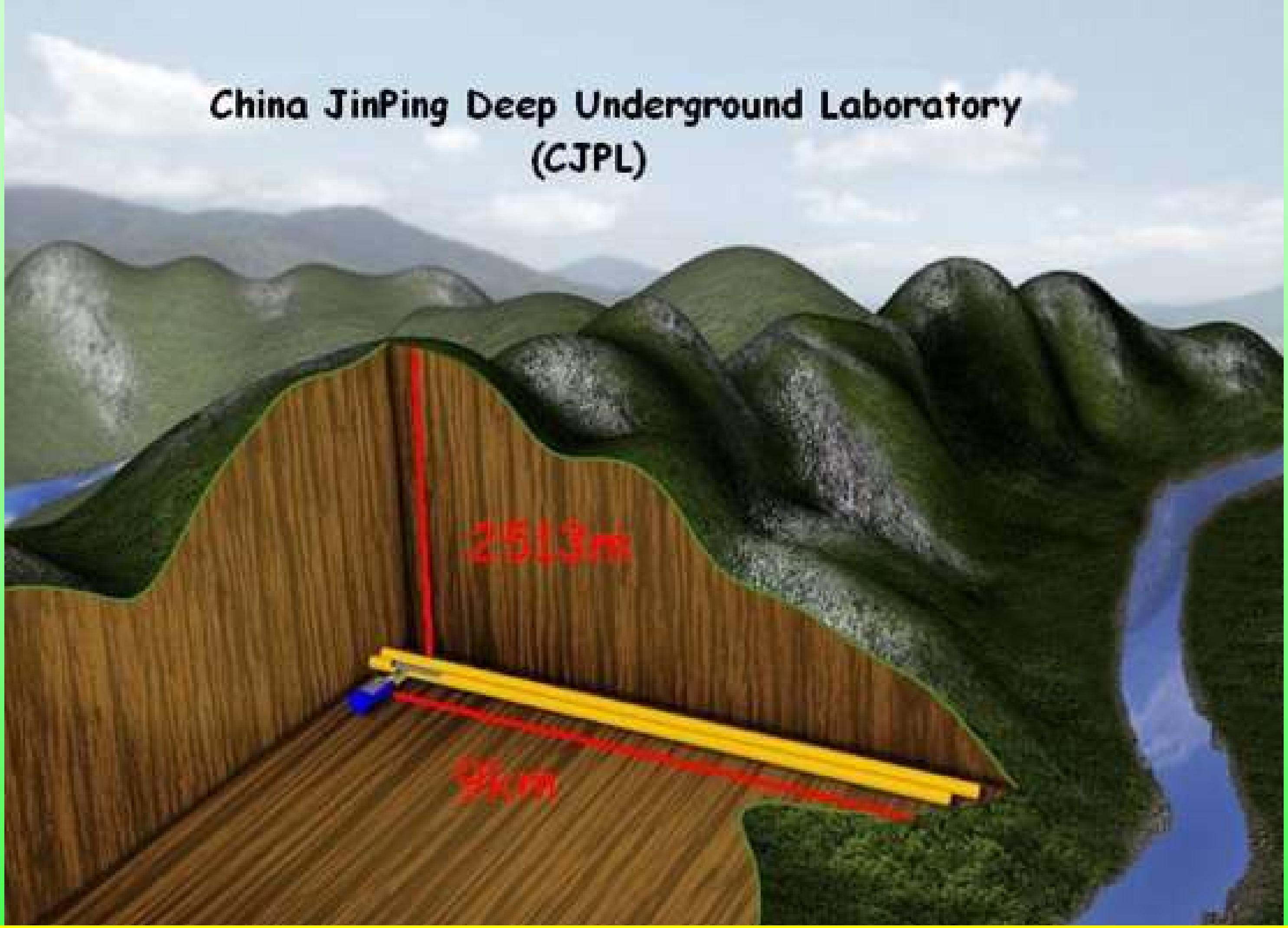
Volume of new lab: 40 000 m3
Work for safety gallery started Autumn 2009
Excavation for new lab: Autumn 2011
Operation: 2013



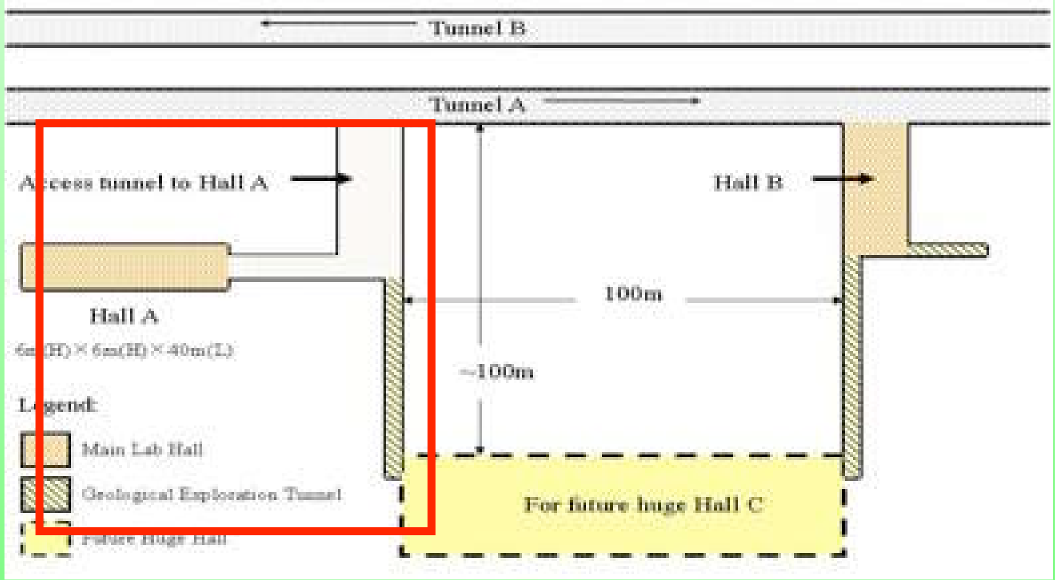
Univ. of Tohoku
KamLAND
Ge
Hall A: 21x15x15m³
Hall B: 11x6x11m³
Super-Kamiokande
New Experimental Hall
XMASS, CANDLES
Clean room
ICP-MS
XMASS R&D
IPMU Labo.
API-MS, Ge
NewAGE(Dark Matter)
Super conductive
Gravity meter
CLIO (Grav. Wave) 100m
Lazer Strain Meter
To Atotsu entrance
Proprietary area

# XMASS 800kg Status



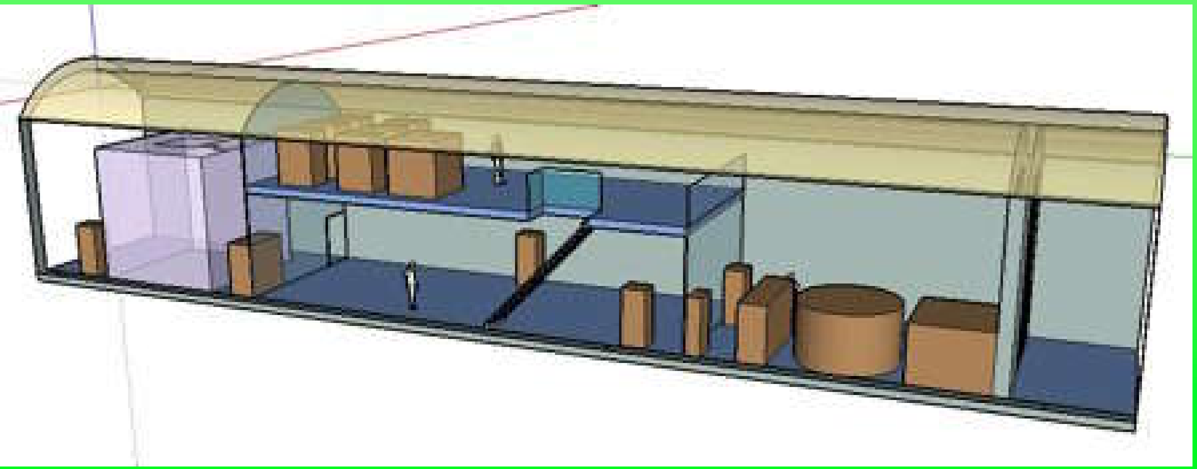



- Jinping Mountain Peak：4193m
- Maximum rock overburden: ~2500m
- Length of Jinping transportation tunnel: 17.5km
- Rock cover larger than 1500m:>70%




Layout of CJPL and
its Phase-I space (red square)

2009, Hall-A cavity OK!

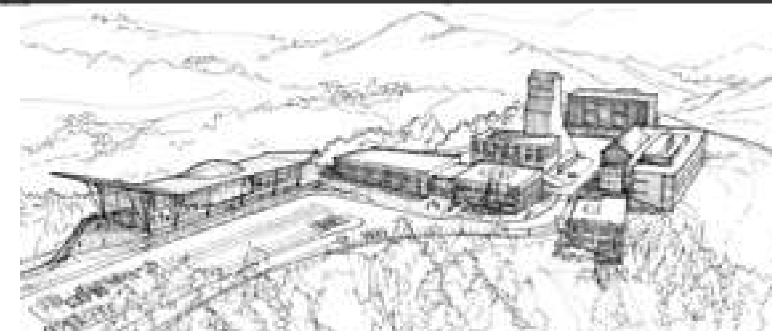


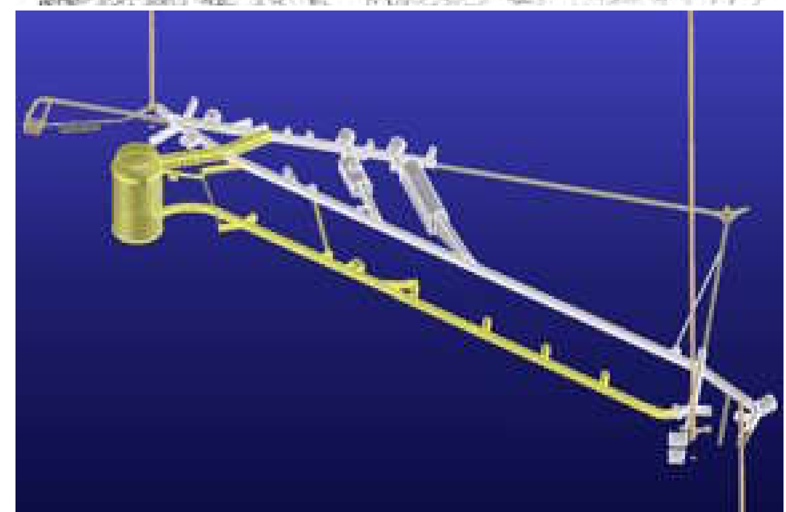
6.5m*6.5m*40m main hall A

- The construction of infrastructure of CJPL Phase-1 will be finished in April,2010.
- The Low background measurement facility will be established in Sept. 2010.

# DUSEL Facility Design Advancing Following Interactions with Agencies and Collaborations

- **World-Class Facility**
  - Research Campuses
    - Surface
    - 4850 (~4200 mwe)
    - 7400 (~7100 mwe)
    - Other Levels and Ramps
  - Dual Access to Research Campuses
  - Best-practices Life Safety Systems and Programs
  - Experimental Support Groups
  - Design Enabling Future Expansion
  - Project Enabling Participation by Other Agencies
- **Suite of Transformational Experiments**
  - Diverse and Compelling Suite
  - Integral Education and Outreach Efforts





# SNOLAB Objectives

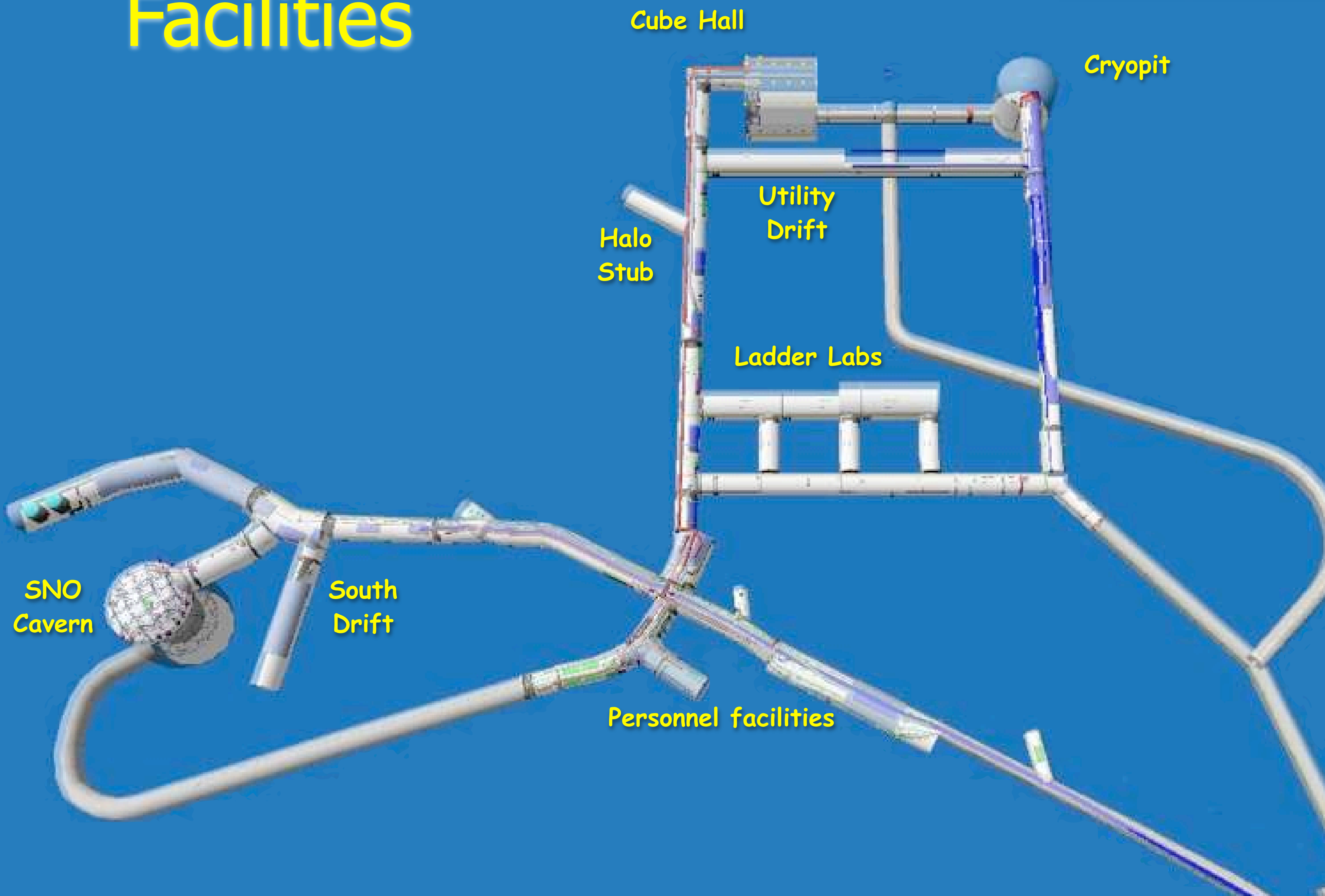
- To promote an International programme of Astroparticle Physics
- To provide a deep experimental laboratory to shield sensitive experiments from penetrating Cosmic Rays
- To provide a clean laboratory
  - Entire lab at class 2000, or better, to mitigate against background contamination of experiments.
- To provide infrastructure for, and support to, the experiments
- Focus on dark matter, double beta decay, solar & SN experiments requiring depth and cleanliness.
  - Also provide space for prototyping of future experiments.
- Large scale expt's (ktonne, not Mtonne)
- Goal has been to progressively create a significant amount of space for an active programme as early as possible.

# SNOLAB Overall Status

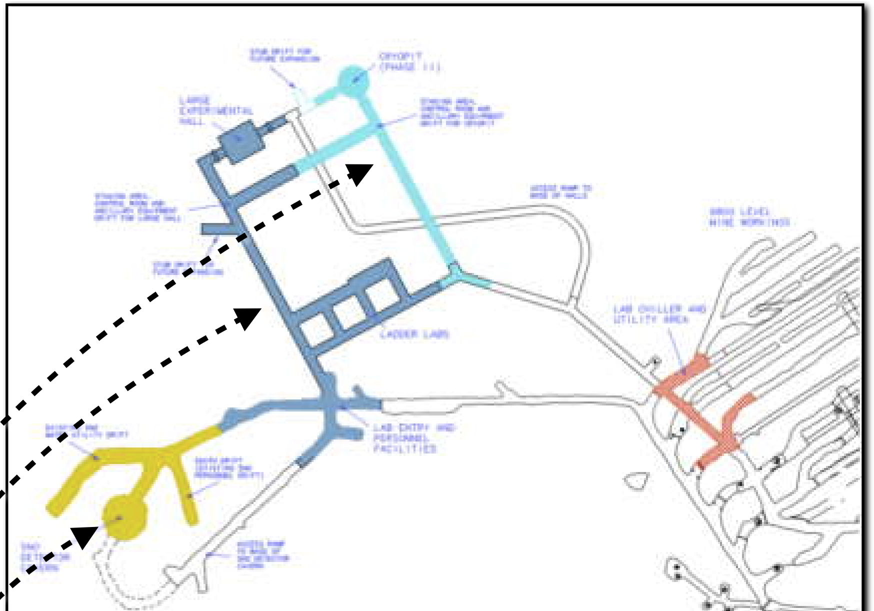
- Surface Facility
  - Operational from 2005.
  - Provides offices, conference room, dry, warehousing, IT servers, clean-room labs, detector construction labs, chemical + assay lab
- Underground Construction (Cube Hall, Cryopit, Ladder Labs, Lab Entrance)
  - Excavation complete and outfitting began June 2007.
  - General outfitting in Phase I areas complete + Cryopit 5T crane/access.
  - Cube Hall and Ladder Labs final cleaning complete, first experiments going in
  - Phase-II clean by Spring 2011
- Experimental Programme
  - Relocation and continued operation of DEAP-1 and PICASSO.
  - Current allocations to: PICASSO-III, DEAP-I, SNO+, DEAP-3600, MiniCLEAN, SuperCDMS TF, SuperCDMS, COUPP, HALO.
  - Anticipated or under discussion: EXO-gas, DarkSide, low background counters to measure $^{39}Ar$, future Cobra upgrade, B.G.E., additional low background assay
- Operational funding currently secured to 2013

# Surface Facilities

# Underground Facilities



# Laboratory Space



All clean spaces will be operated as Class2000 clean rooms (or better).

| | Excavation | | Clean Room | | Laboratory | |
|---|---|---|---|---|---|---|
| | Area (m$^2$) | Volume (m$^3$) | Area (m$^2$) | Volume (m$^3$) | Area (m$^2$) | Volume (m$^3$) |
| Original SNO Areas | 1860 | 16500 | 1130 | 13300 | 750 | 11700 |
| Phase I | 6070 | 38750 | 3900 | 29750 | 2430 | 23700 |
| Phase II | 7220 | 46650 | 4940 | 37250 | 3060 | 29550 |


Chiller


Chiller


Lab Entry


Lab
Entrance


Personnel
Facility


SNO Access Drift

# Facilities 3 Feb 2009


Galley/
Refuge


Meeting
Room


Cryopit
Access


Cryopit


Cryopit


Cube
Hall


Cube
Hall


Cube
Hall

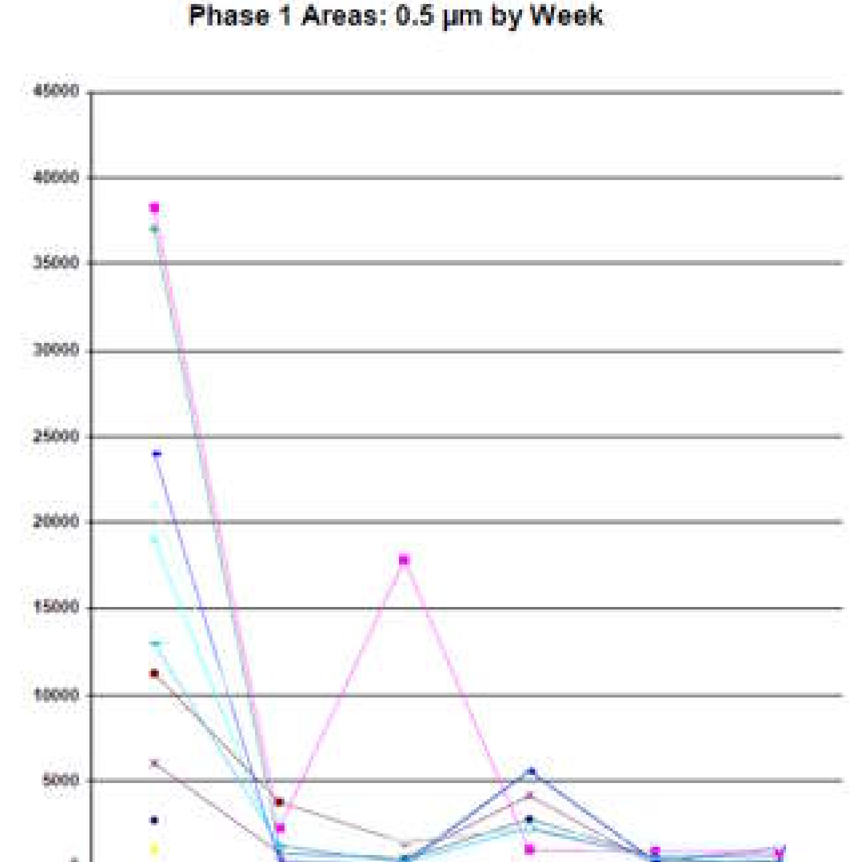
# The Cube Hall Goes Clean

Unsealing door to Ladder Labs 5th Aug


Ladder
Labs

# Construction Status

- With the final cleaning of the Ladder Labs there is now 40,000 ft2 (3,700 m2) of space inside the clean room boundary of the lab. For comparison the surface building is 32,000 ft2.
- Cube Hall still requires a “fine clean” to bring it to final clean room conditions.




| | 28 '09 | 29 '09 | 30 '09 | 31 '09 | 32 '09 | 33 '09 |
|---|---|---|---|---|---|---|
| Cube Util | 2726.666667 | | 450 | 2830 | 582.5 | 695 |
| Cube Ctrl | 38290 | 2290 | 17810 | 990 | 917.5 | 825 |
| Cube Stage | 1043.333333 | | | | | |
| Drift N | 19013.33333 | 670 | 420 | 2210 | 615 | 440 |
| MHAD A | 6033.333333 | 860 | 560 | 4170 | 137.5 | 345 |
| MHAD B | 11226.66667 | 3750 | 1400 | 2280 | 545 | 50 |
| Room 125 | 37043.33333 | 1240 | 310 | 5570 | 362.5 | 240 |
| Room 127 | 24026.66667 | 370 | 110 | 5610 | 275 | 1165 |
| Room 131 | 12960 | 1320 | 220 | 2330 | 562.5 | 70 |
| Room 132 | 21083.33333 | 2710 | 1530 | 2270 | 1430 | 1205 |

# Facility Construction Schedule

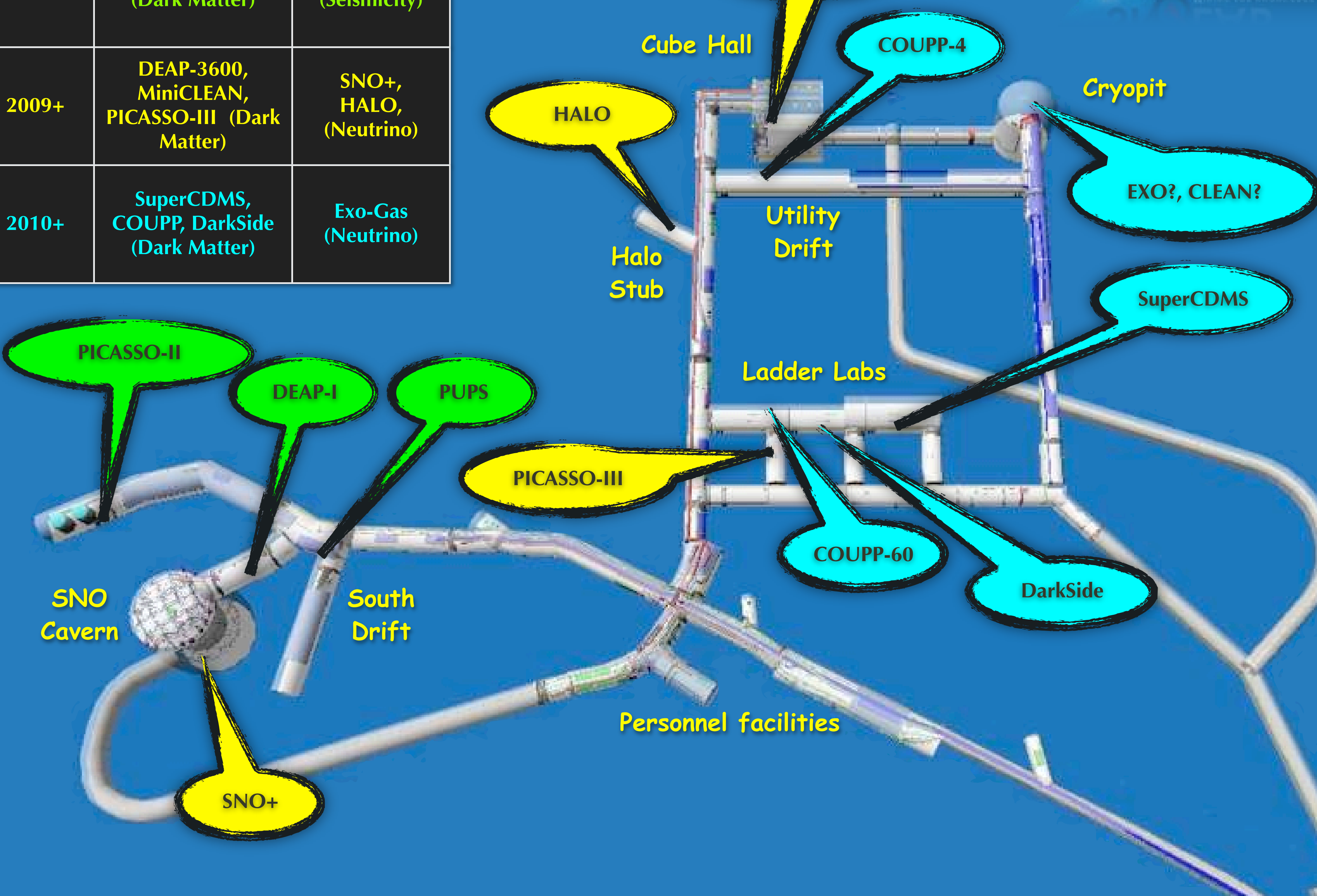
- Contractor work almost done (still some "building automation" and fire alarm tasks).
- Remaining work will be done primarily by SNOLAB personnel (with contractors as necessary).
- Next facility construction activities:
  - Installation of final services (plumbing, electrical) in Ladder Labs and Cube Hall.
    - experiment driven
  - Cryopit: prepare and paint.
  - Renovation of old Personnel Area (reclaim for experiments or infrastructure).

# Experimental Programme

| Experiment | Solar nu | 0nuBB | Dark Matter | SuperNovae | Geo nu | Other | Space allocated | Status |
|---|---|---|---|---|---|---|---|---|
| SNO+ | √ | √ | | √ | √ | | SNO Cavern | Underway |
| PICASSO-III | | | √ | | | | Ladders Labs | Underway |
| DEAP-1 | | | √ | | | | J'-Drift | Underway |
| DEAP-3600 | | | √ | | | | Cube Hall | Underway |
| MiniCLEAN | | | √ | | | | Cube Hall | Underway |
| HALO | | | | √ | | | Halo Stub | Underway |
| PUPS | | | | | | Seismicity | Various | Completed |
| SuperCDMS | | | √ | | | | Ladder Labs | Request |
| EXO-gas | | √ | | | | | Ladder Labs | Request |
| COUPP | | | √ | | | | Ladder Labs | Underway |
| DarkSide | | | √ | | | | Ladder Labs | Request |
| COBRA | | √ | | | | | Ladder Labs | Request |

SNOLAB
MINING FOR KNOWLEDGE
CREUSER POUR TROUVER... L'EXCELLENCE

| | | |
|---|---|---|
| Current | PICASSO-II, DEAP-I (Dark Matter) | PUPS (Seismicity) |
| 2009+ | DEAP-3600, MiniCLEAN, PICASSO-III (Dark Matter) | SNO+, HALO, (Neutrino) |
| 2010+ | SuperCDMS, COUPP, DarkSide (Dark Matter) | Exo-Gas (Neutrino) |

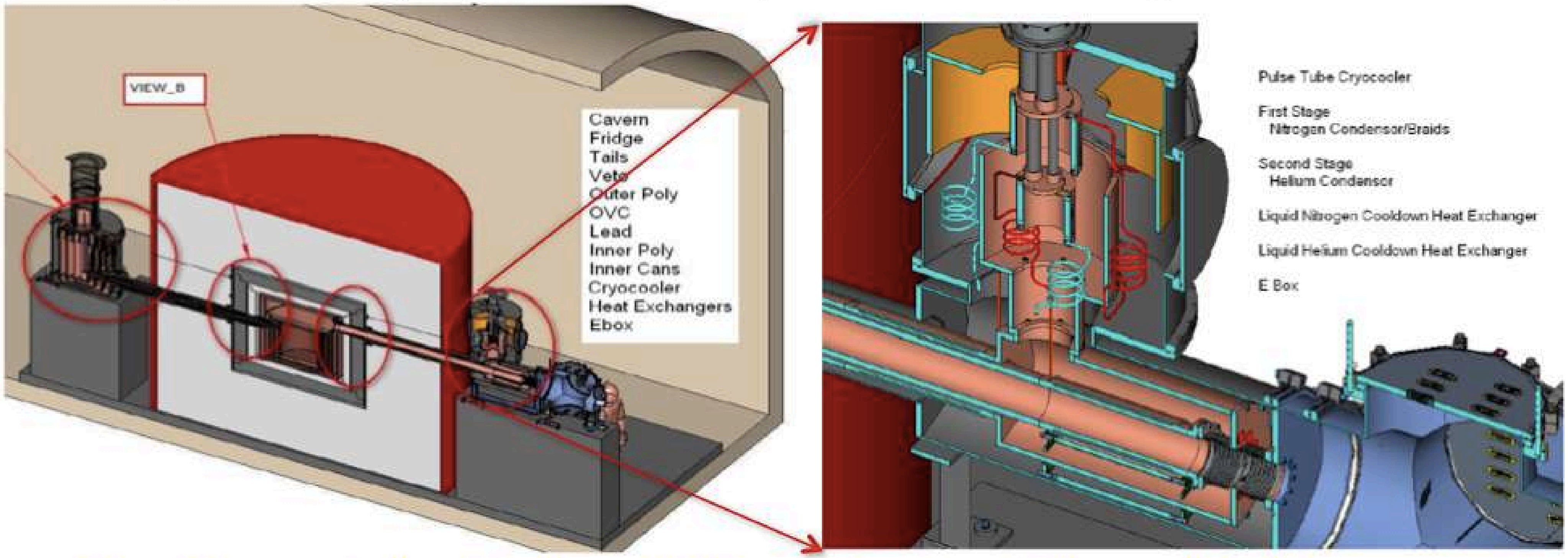


# Dark Matter at SNOLAB

- Noble Liquids:  DEAP-I, MiniCLEAN, & DEAP-3600, DarkSide
  - Single Phase Liquid Argon uses pulse shape discrimination. Two-phase (DarkSide)
  - Prototype DEAP-I operational in SNOLAB now. Successful demonstration of PSD and test bench for DEAP/CLEAN design/operations.
  - Construction for DEAP-3600 and MiniCLEAN underway. Full DEAP-3600 capital funding granted (with SNO+), expected turn-on Fall 2010
  - Will measure Spin Independent cross-section.
- Superheated Liquid / Bubble chamber:  PICASSO, COUPP
  - Superheated droplet detectors and bubble chambers. Insensitive to MIPS radioactive background at operating temperature, threshold devices
  - PICASSO currently operational in SNOLAB, demonstration of alpha rejection and test bench for scale-up of detector volumes.
  - COUPP-4kg deployment completed, 60kg early next year.
  - Will measure Spin Dependent cross-section primarily, COUPP has SI sensitivity
- Solid State:  SuperCDMS
  - State of the art Ge crystals with ionisation and phonon readout.
  - Currently operational in Soudan. Next phase will benefit from SNOLAB depth to reach desired sensitivity. Test facility in Ladder Labs under development.
  - Mostly sensitive to Spin Independent cross-section.

# SuperCDMS

Planning to submit proposal 2011. Expected reach 0.3 zepto-barnes.




- Need deeper site than Soudan > 4000 mwe. Need new fridge and shield.
  - New fridge and shield design work in progress at FNAL.
- Select iZIP detector technology ~ 1 kg each.
  - Detector fabrication at Stanford/SLAC (baseline).
  - Direct readout of all electrical channels, similar to CDMS II.

Brink DM2010

# DEAP3600/miniCLEAN

85 cm radius acrylic sphere contains 3600 kg LAr
(55 cm, 1000 kg fiducial)

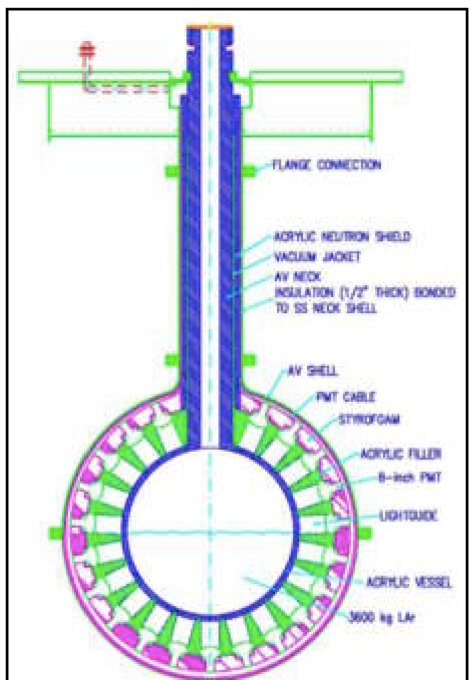
266 8" PMTs (warm)

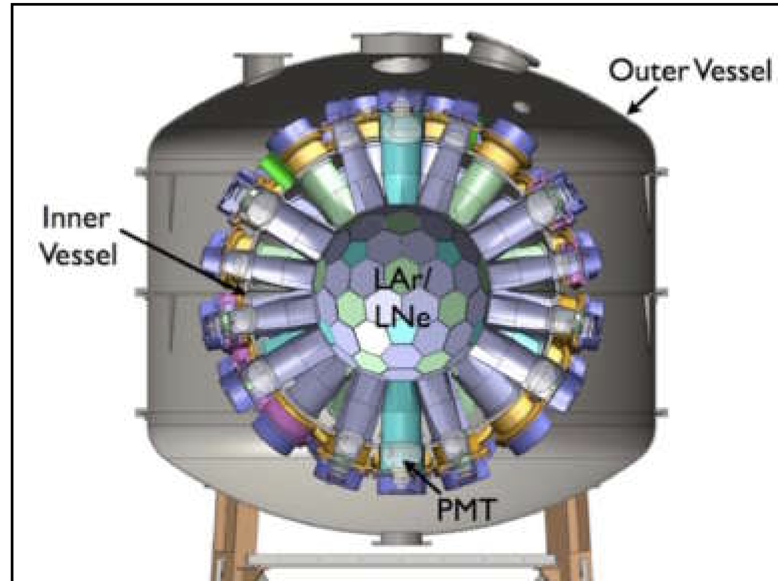
50 cm acrylic light guides and fillers for neutron shielding (from PMTs)

Steel shell for safety to prevent cryogen/water mixing (AV failure)

Only LAr, acrylic, and WLS (10 g) inside of neutron shield

8.5 m diameter water shielding tank




~150 kg fiducial volume (wavelength shifter at R=43.5cm, fiducial volume at R=30.5 cm)

PMTs - R5912-02MOD operating in cryogenic liquid

Liquid cryogen can be argon or neon

Cryogen, PMTs and wavelength shifters contained in stainless steel Inner Vessel (IV)

IV is surrounded by stainless steel Outer Vessel with vacuum insulation and thermal blanket

PMT and wavelength shifter on acrylic plate are part of modular optical cassette

91 optical cassettes, plus one port used for calibrations

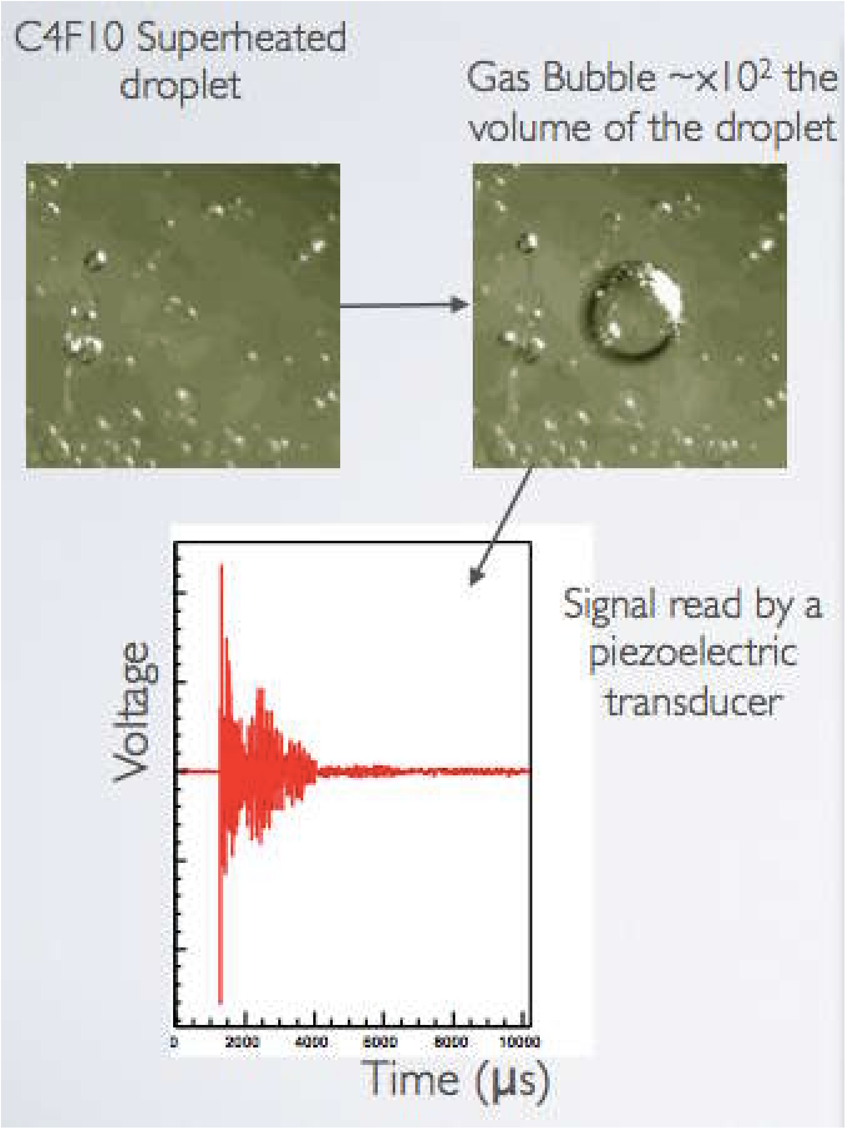
# CubeHall - DEAP/ miniCLEAN


DEAP-3600 Director
Mark Boulay
standing at the location of the
DEAP-3600 Shield tank.

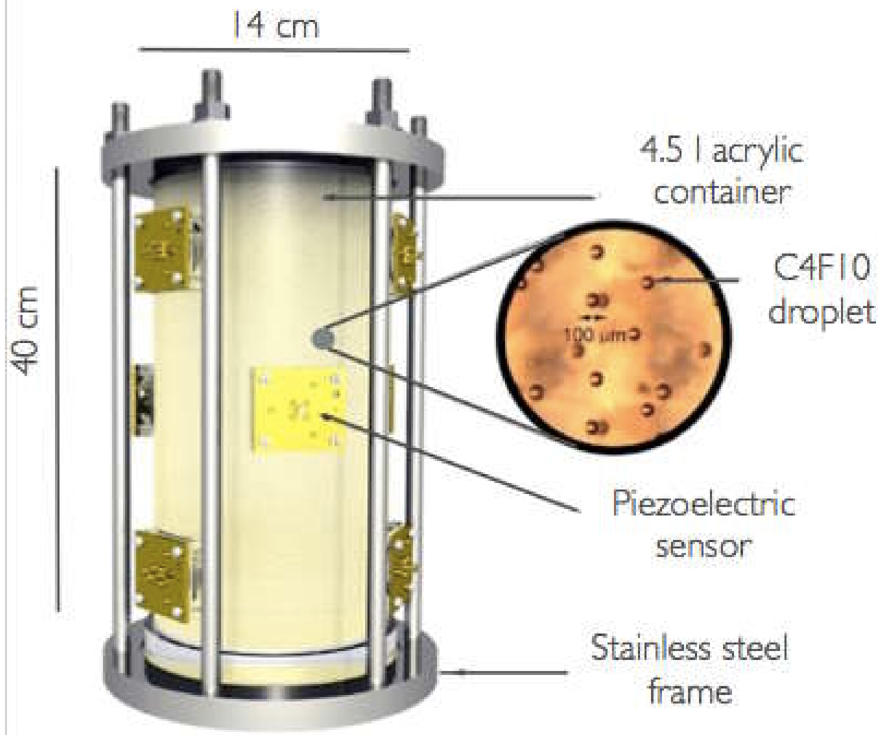
Nigel Smith with DEAP-3600 Director Mark Boulay standing at the location of the DEAP-3600 experiment.

Acceptance testing of the MiniCLEAN Vacuum Vessel.

# The PICASSO detector




- Superheated droplet detectors; acoustic pickup
- alpha-n discrimination demonstrated; run gamma blind as threshold detector
- 32 detector array relocated to new area within SNOLAB



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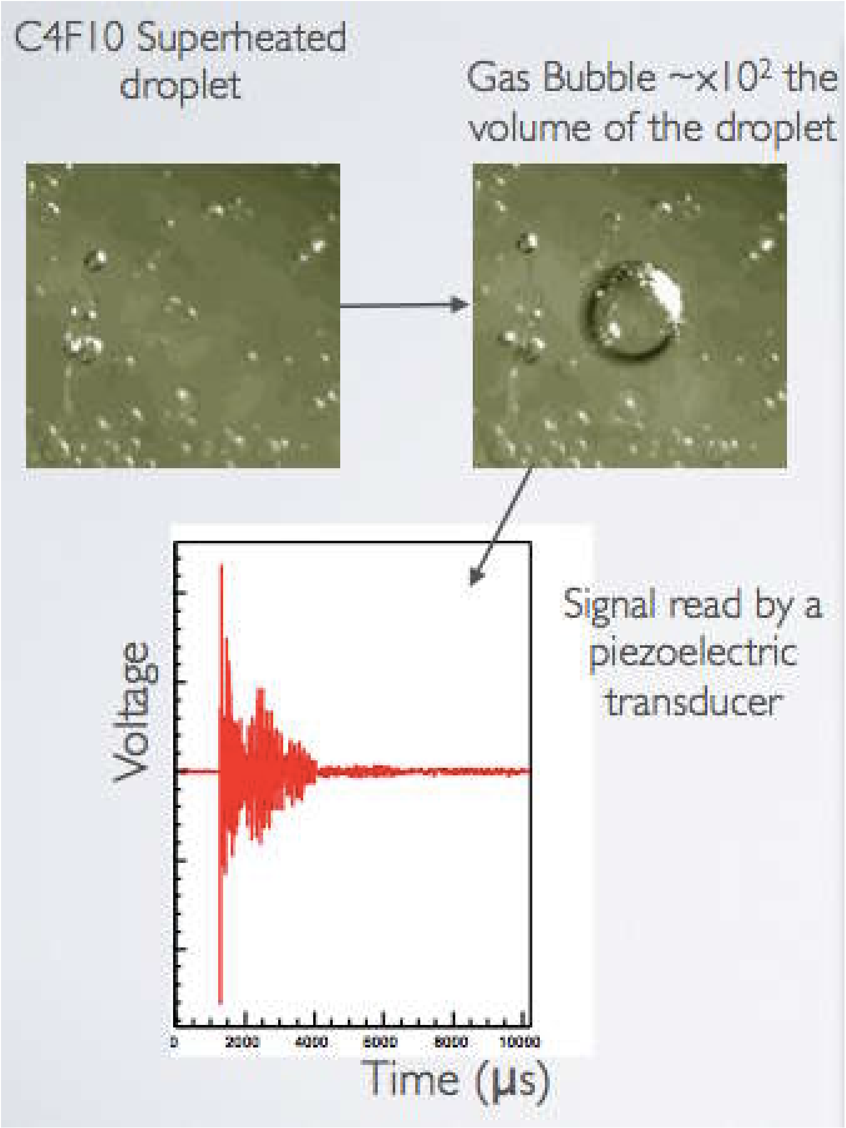
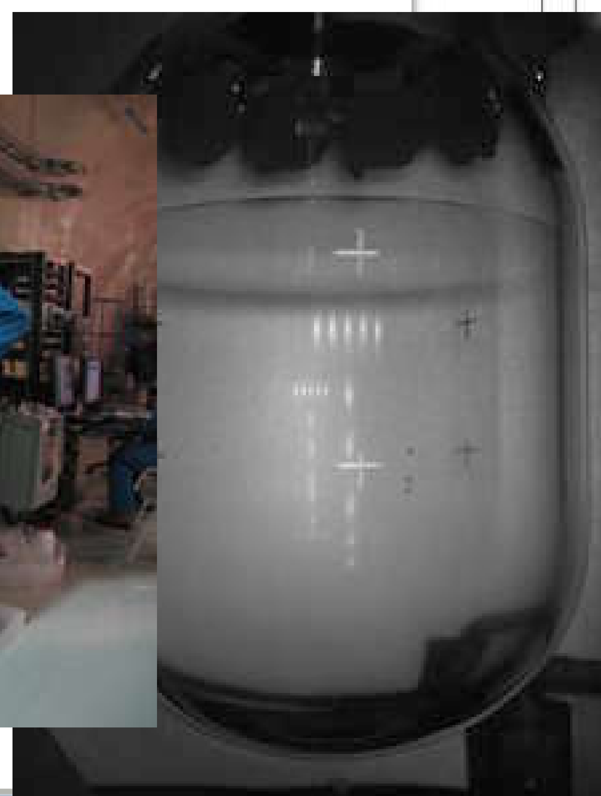
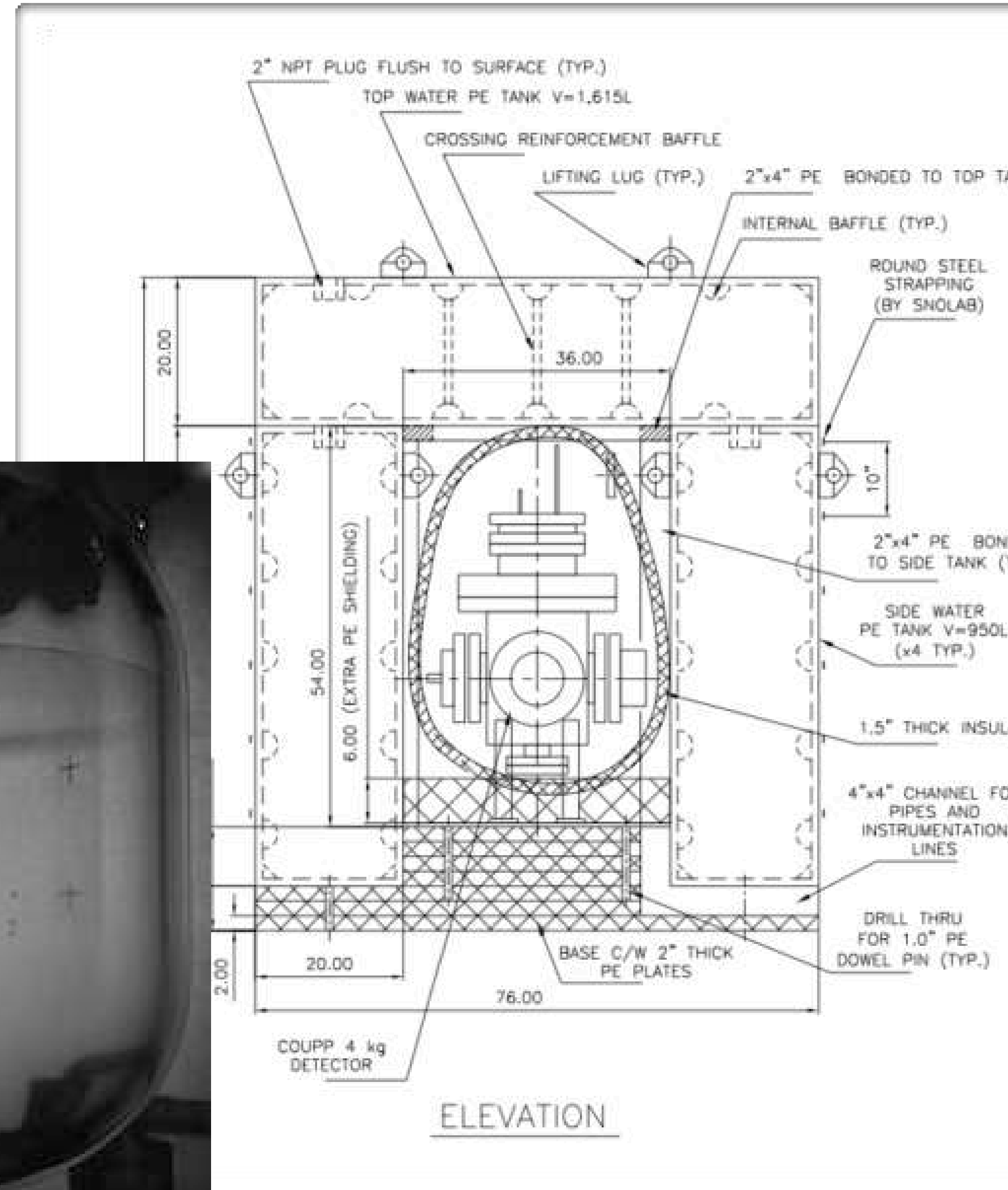



# COUPP

- Bubble chamber approach using $CF_3I$
- 'Rapid deployment' of COUPP-4kg completed at SNOLAB
- COUPP-60kg to follow early next year

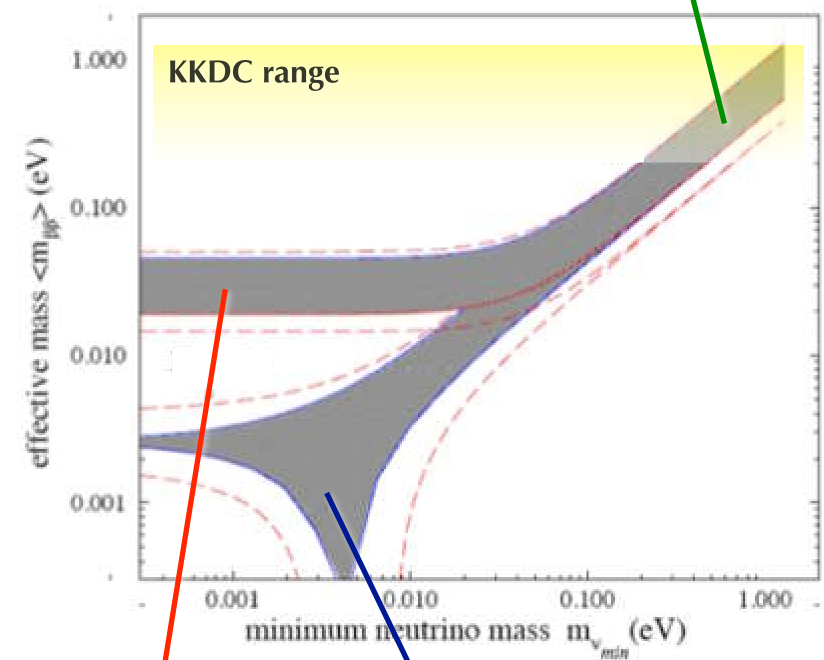




# Double beta decay

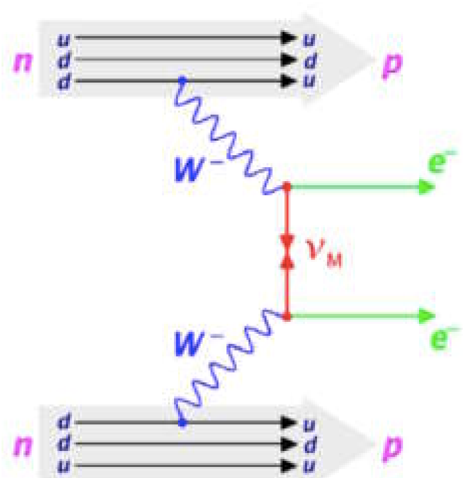
- $2\nu\beta\beta$ expected in SM
  - half life > $10^{19}$ years
- $0\nu\beta\beta$ forbidden in SM ($\Delta L=2$)
  - allowed in BSM models
  - half life > $10^{25}$ years
  - requires $\nu$ mass
  - requires Majorana nature

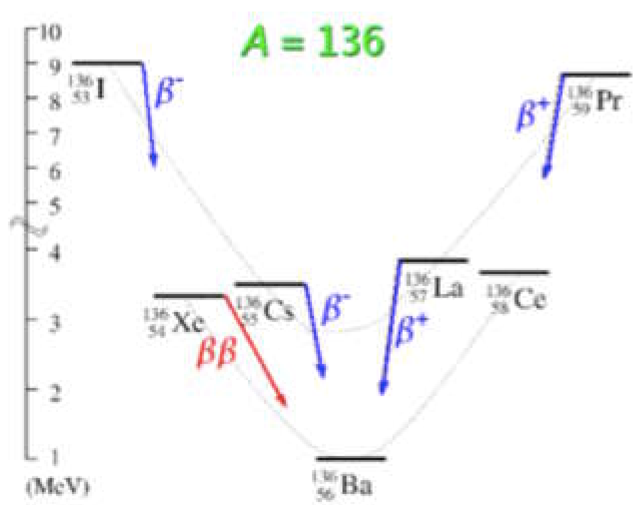
Degenerate hierarchy:
$m_1 \approx m_2 \approx m_3$




Inverted hierarchy:
$m_3 << m_1 \approx m_2$

Normal hierarchy:
$m_1 << m_2 \approx m_3$

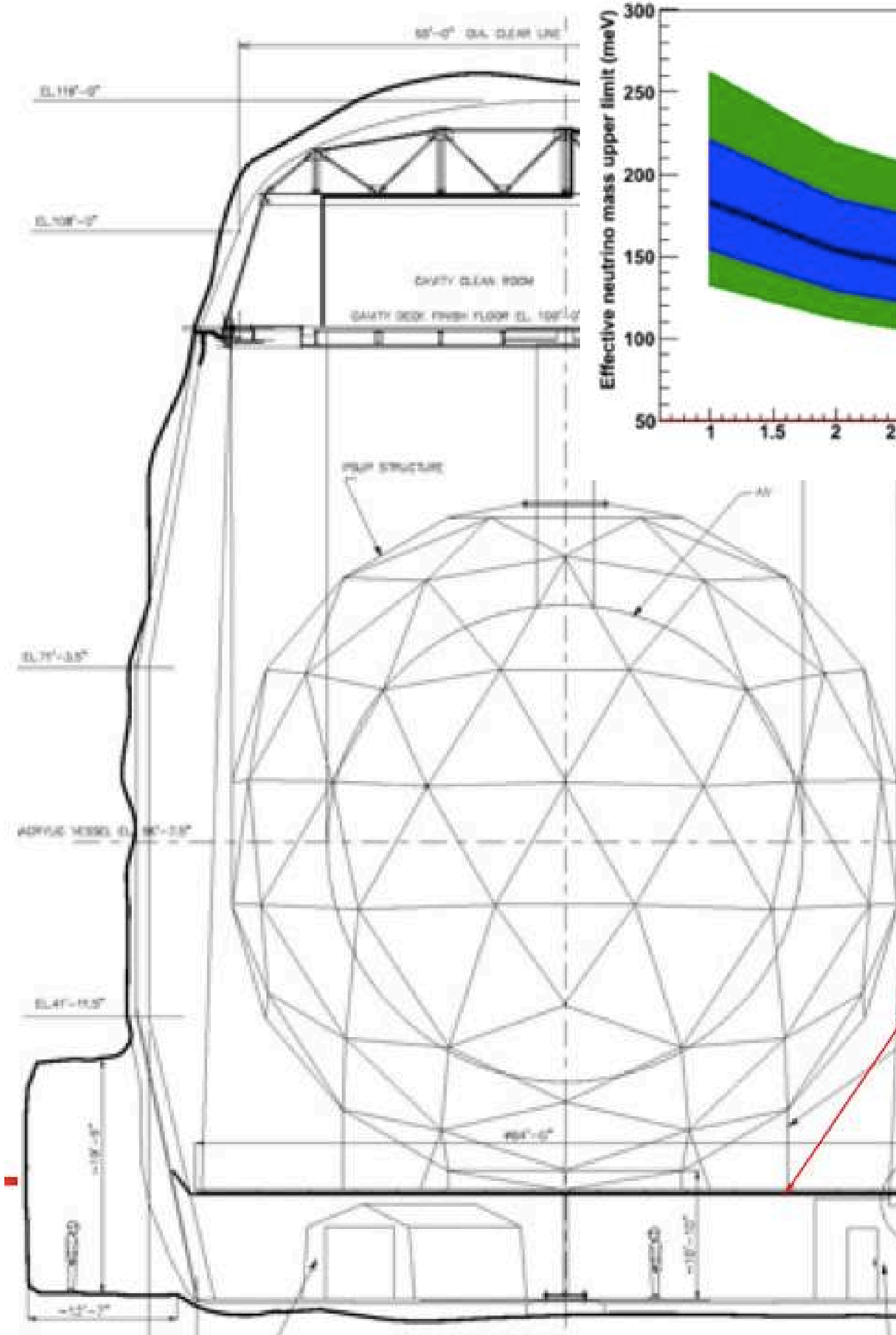


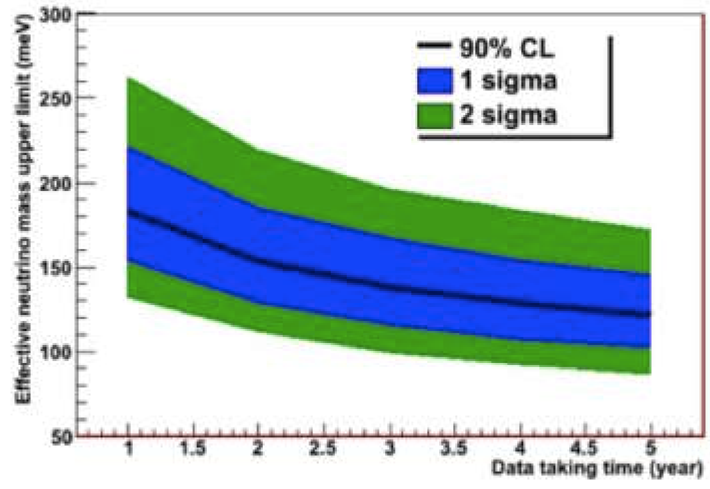



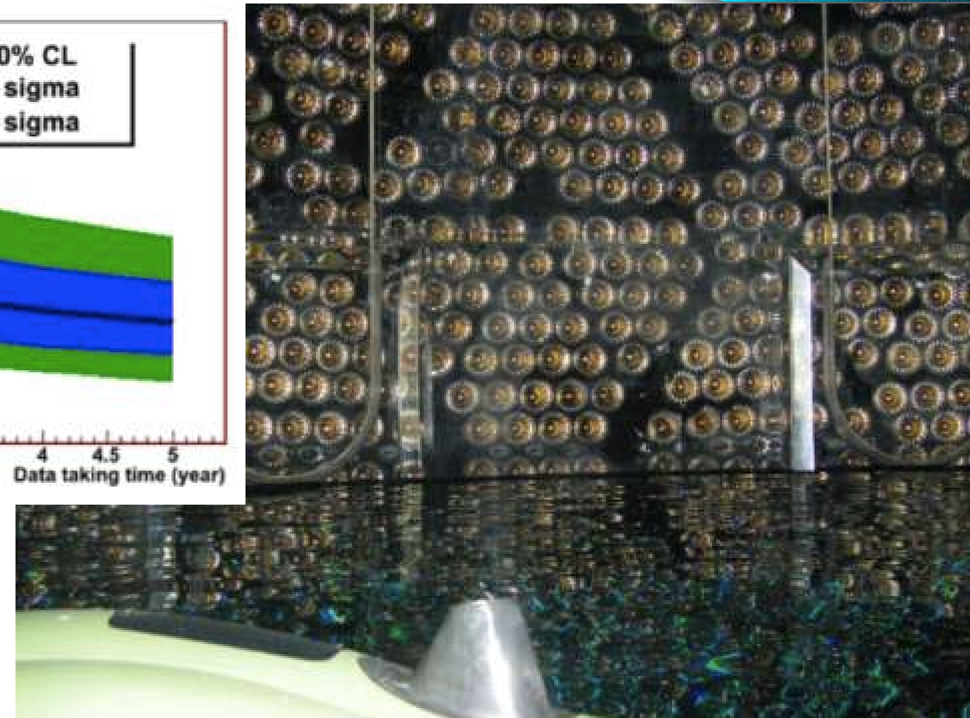
# $0\nu\beta\beta$ at SNOLAB

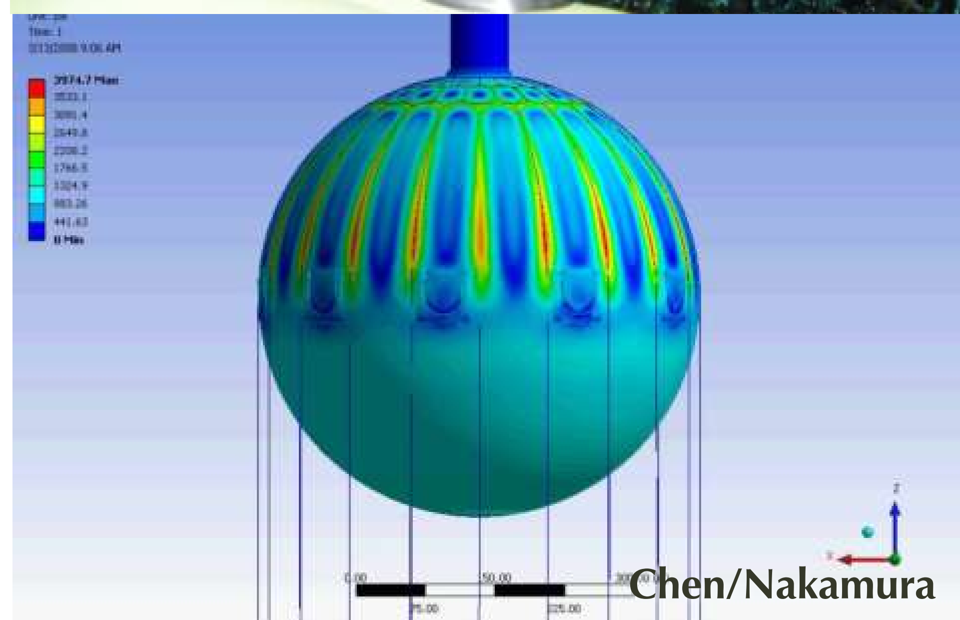
- SNO+ : $^{150}Nd \rightarrow {}^{150}Sm + e^- + e^-$
  - Uses existing SNO detector. Heavy water replaced by scintillator loaded with $^{150}$Nd. Modest resolution compensated by high statistical accuracy.
  - Requires engineering for acrylic vessel hold down and purification plant. Technologies already developed.
    - SNO Cavity: repairs to cavity liner and modification of detector support to hold down the Acrylic Vessel for liquid scintillator.
    - SNO Utility Room: Excavation of pit for liquid scintillator purification system.
  - Capital funding received June 2009, turn on fall 2010.
- EXO-gas : $^{136}Xe \rightarrow {}^{136}Ba^{++} + e^- + e^-$
  - Ultimate detector aim = large volume Xe Gas TPC
  - Developing technique to tag Ba daughter. Electron tracking capability.
  - Development work at SNOLAB surface facility

# The SNO+ detector



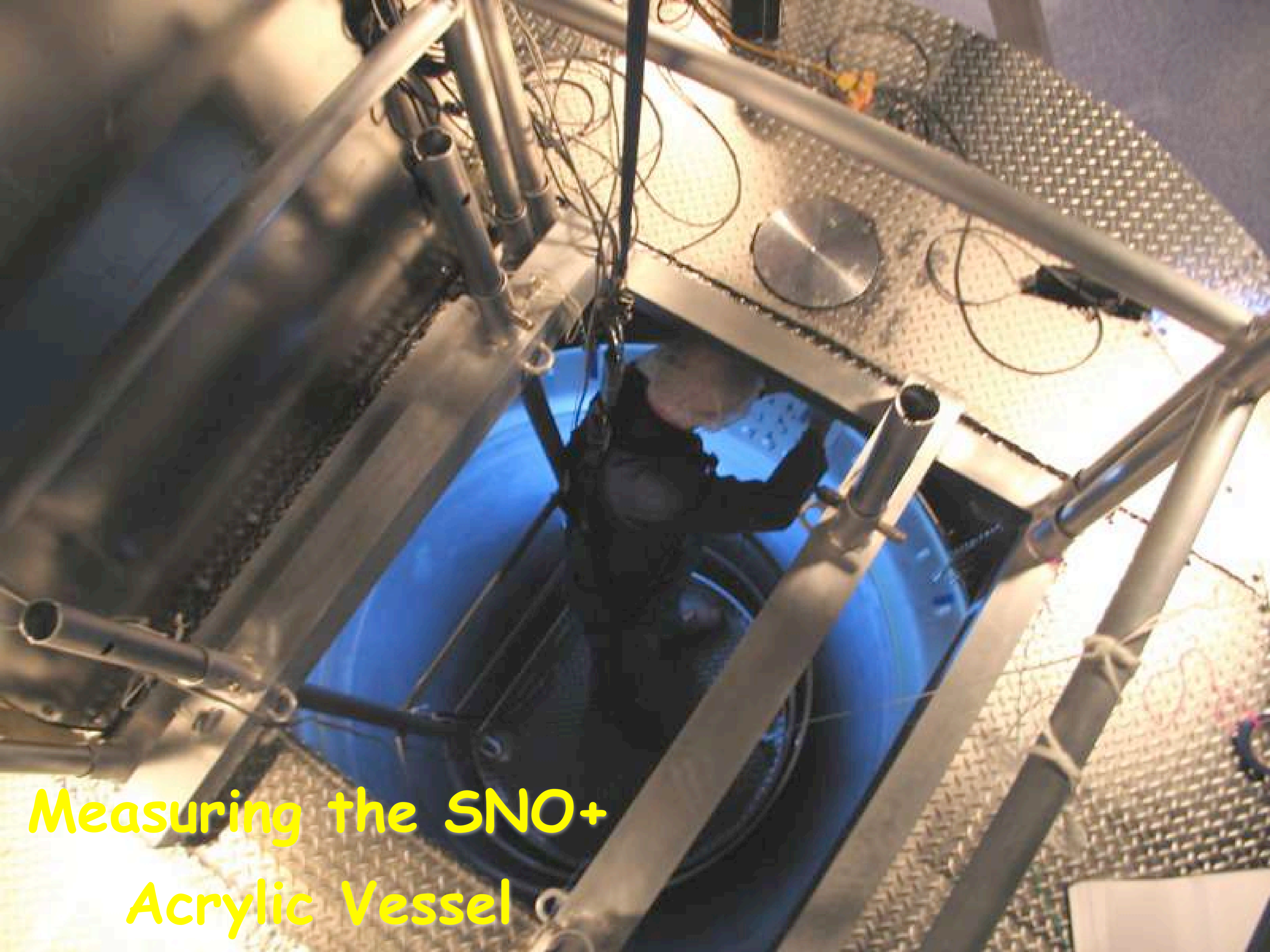




Chen/Nakamura


Measuring the SNO+
Acrylic Vessel


Measuring the SNO+
Acrylic Vessel

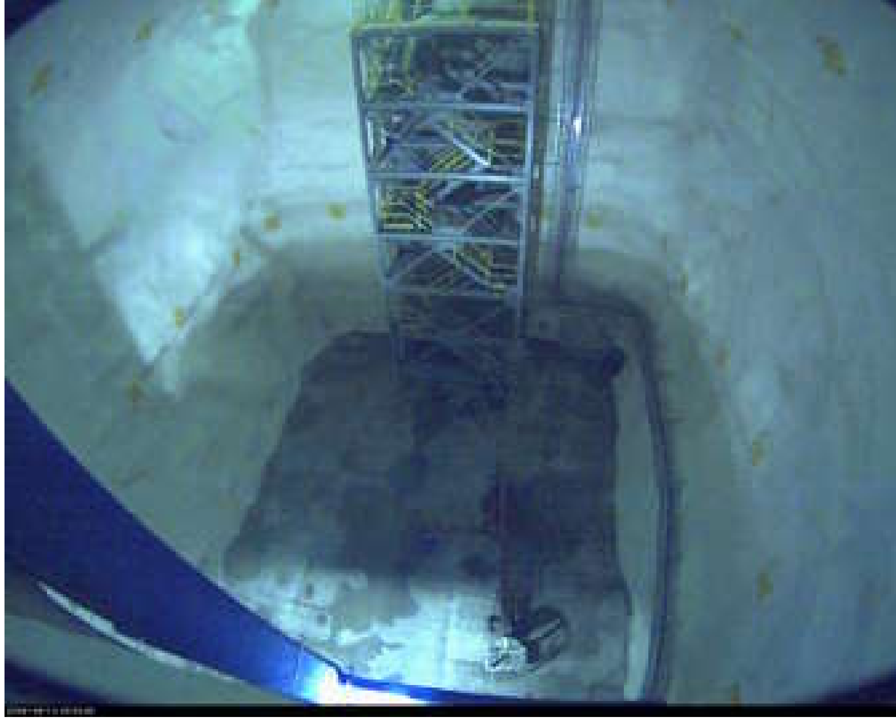

Excavating a larger
space in the

# Supernova neutrinos ++

- SNO+ :
  - Will also measure solar neutrino pep, geo-neutrinos, supernovae bursts and reactor neutrinos.
- HALO: Dedicated Supernova watch experiment
  - Charged/neutral current interactions in lead
  - Re-use of detectors (NCD/DAQ) and material (Pb)
  - Installation underway
  - Completion by end 2010.

$$\nu_e + {}^{208}\mathrm{Pb} \rightarrow {}^{207}\mathrm{Bi} + n + e^-$$
$$\nu_e + {}^{208}\mathrm{Pb} \rightarrow {}^{206}\mathrm{Bi} + 2n + e^-$$
$$\nu_x + {}^{208}\mathrm{Pb} \rightarrow {}^{207}\mathrm{Pb} + n$$
$$\nu_x + {}^{208}\mathrm{Pb} \rightarrow {}^{206}\mathrm{Pb} + 2n$$

# SNOLAB Conclusions



- SNOLAB facility completing final phase of 'going clean'
- Surface building complete
- All major infrastructure in place
- Facility is now in transition to experimental programme
  - Deployment of support systems for first experiments underway (SNO+, DEAP-3600, MiniCLEAN, HALO)
  - Smaller scale experiments underway or being relocated (COUPP-4, DEAP-I, PICASSO-III)
  - Infrastructure requirements for additional systems being developed (COUPP, CDMS, DarkSide)
- SNOLAB is looking forwards to contributing to the world programme of underground science