Deep underground physics: facility and experiment developments at SNOLAB

Nigel Smith
Director, 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

\[ v_c^2 = G_N \frac{M_{\text{vis}}}{r} \]

\[ M_{\text{tot}}(r) = \frac{v_c^2 r}{G_N} \]

...but it doesn’t

... \( \rho_{\text{dm}} \approx 0.3 \text{ GeV/cc} \)

Milky Way
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:

\[-\Omega_m (\Omega_{\text{cdm}} + \Omega_{\text{hdm}} + \Omega_{\text{b}}) + \Omega_{\Lambda} + \Omega_{\kappa}\]

Total density: \(\Omega_T = 1.02\pm0.02\)
(which is what we want for BB inflation)

Energy density: \(\Omega_\Lambda = 0.73\pm0.04\)

Matter density: \(\Omega_m = 0.27\pm0.04\)

Baryon density: \(\Omega_b = 0.044\pm0.004\)

Neutrinos (HDM): \(\Omega_\nu < \sim0.015\)

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: $\tan \beta$
    - Gaugino masses: $m_{1/2}$ (assume same @ GUT scale)
    - Scalar masses: $m_0$ (assume same @ GUT scale)
    - Higgs mixing: $\mu$

- **Produced in early Universe**
  - In thermal equilibrium $T > m_\chi$
  - Production stalled when $T < m_\chi$
  - Freeze out if expansion > annihilation

- **Four neutralinos: WIMPs**
  - $\chi$, lightest SUSY particle (LSP)
  - $50 \text{ GeV} < m_\chi < 300 \text{ TeV}$ (expt.)
  - $10^{-12} \text{ pb} < \sigma_\chi < 10^{-8} \text{ pb}$ (theory)
Current S.I. Limits

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

![Graph depicting cross-section vs. WIMP mass for various experiments and methods.](http://dmtools.berkeley.edu/limitplots/Gaitskell/Mandic)

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
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, γ, 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. μ spallation
  - **Low threshold**
    - To minimise form factor, maximise spectrum
  - **Discriminating** - Position sensitivity
    - Difference between WIMPs/n and γ/β, background rejection, directionality
  - **Large mass** (ultimately to reach 10^{-10} pb)
Go underground!

- Studies for rare events, either decays (e.g., 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...

Cosmic Ray Energy Spectrum

- Cosmic Ray Energy (eV)
- Intensity ($\text{cm}^{-2} \text{s}^{-1} \text{sr}^{-1}$)

- Proton-4
- Tien Shen
- Akeno
- Haverah Park
- Yakutsk
- Sydney

- 1 per square metre per second
- 1 per square metre per day
- 1 per square metre per year
- 1 per square kilometre per year
- 1 per square metre per century
- 1 per square kilometre per century
Muon backgrounds

2km rock overburden (6000mwe)

Muon Flux = 0.27/m²/day

Surface Facility

Underground Laboratory

Muon Flux = 0.27/m²/day

at various locations around the world, such as WIPP, Soudan, Kamioka, Gotthard, Boulby, Gran Sasso, Homestake, Baksan, Frejus, and Sudbury.
Neutron backgrounds

- Neutron production from:
  - c.r. muon spallation
  - U/Th fission
  - $\alpha$, 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
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)
Science questions...

Low neutron background

Low gamma background

What is the physics beyond the standard model?

Dark matter searches

Gravity wave searches

What constitutes most of the mass of the Universe?

Proton decay

Solar/SN neutrino

What is the nature of the neutrino?

Double beta decay neutrino

Nuclear astrophysics

How do stars burn?

Geo/reactor neutrinos

How do they explode?

Facility

Environment

Long baseline neutrino oscillation

Where does the heat of the Earth come from?

How do fault slips develop?

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

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

What do the most extreme astronomical events evolve?

Extreme biospheres

Geology, geophysics

How does life evolve in extreme environments?
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
Volume of new lab: 40 000 m³
Work for safety gallery started Autumn 2009
Excavation for new lab: Autumn 2011
Operation: 2013
XMASS 800kg Status

water purification system

Experimental Hall

Rn: \( \sim 1 \text{ mBq/m}^3 \)
5ton/hour

Distillation Tower

LXe Tank

Water Tank

Xenon Buffer Tank

entrance (clean room)
- 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)

6.5m*6.5m*40m main hall A

2009, Hall-A cavity OK!

● 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.
• **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

- Cube Hall
- Cryopit
- Halo Stub
- Utility Drift
- Ladder Labs
- Personnel facilities
- South Drift
- SNO Cavern
Laboratory Space

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

<table>
<thead>
<tr>
<th></th>
<th>Excavation</th>
<th>Clean Room</th>
<th>Laboratory</th>
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<td>7220</td>
<td>46650</td>
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SNO Access Drift
Cryopit Access
Cryopit

[Image of Cryopit]
The Cube Hall Goes Clean
Unsealing door to Ladder Labs 5th Aug
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.
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.
- Cryopit: prepare and paint.
- Renovation of old Personnel Area (reclaim for experiments or infrastructure).
## Experimental Programme

<table>
<thead>
<tr>
<th>Experiment</th>
<th>Solar nu</th>
<th>0nuBB</th>
<th>Dark Matter</th>
<th>SuperNovae</th>
<th>Geo nu</th>
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<td>PUPS (Seismicity)</td>
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<th>2009+</th>
<th>DEAP-3600, MiniCLEAN, PICASSO-III (Dark Matter)</th>
<th>SNO+, HALO, (Neutrino)</th>
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<th>2010+</th>
<th>SuperCDMS, COUPP, DarkSide (Dark Matter)</th>
<th>Exo-Gas (Neutrino)</th>
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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)

2009+ DEAP-3600, MiniCLEAN, PICASSO-III (Dark Matter)
2010+ SuperCDMS, COUPP, DarkSide (Dark Matter)

Current: PICASSO-II, DEAP-I (Dark Matter)
PUPS (Seismicity)

DEAP-3600 MiniCLEAN
Cube Hall

Cryopit
EXO?, CLEAN?

SuperCDMS

DEAP-I
PUPS
PICASSO-III
PICASSO-II

SNO Cavern
South Drift

Personnel facilities

Halo
Stub

Utility Drift
Ladder Labs

COUPP-60

COUPP-4

DarkSide

EXO?, CLEAN?
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=43.5 cm, 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
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
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
COUPP

- Bubble chamber approach using CF$_3$I
- ‘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

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

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

Degenerate hierarchy:
$$m_1 \approx m_2 \approx m_3$$
$0\nu\beta\beta$ at SNOLAB

- **SNO+**: $^{150}\text{Nd} \rightarrow ^{150}\text{Sm} + e^- + e^-$
  - Uses existing SNO detector. Heavy water replaced by scintillator loaded with $^{150}\text{Nd}$. 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**: $^{136}\text{Xe} \rightarrow ^{136}\text{Ba}^{++} + e^- + e^-$
  - 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
Measuring the SNO+ Acrylic Vessel
Measuring the SNO+ Acrylic Vessel
Excavating a larger space in the SNO+ Utility room to
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.
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