SNOLAB

MINING FOR KNOWLEDGE

CREUSER POUR TROUVER... L'EXCELLENCE

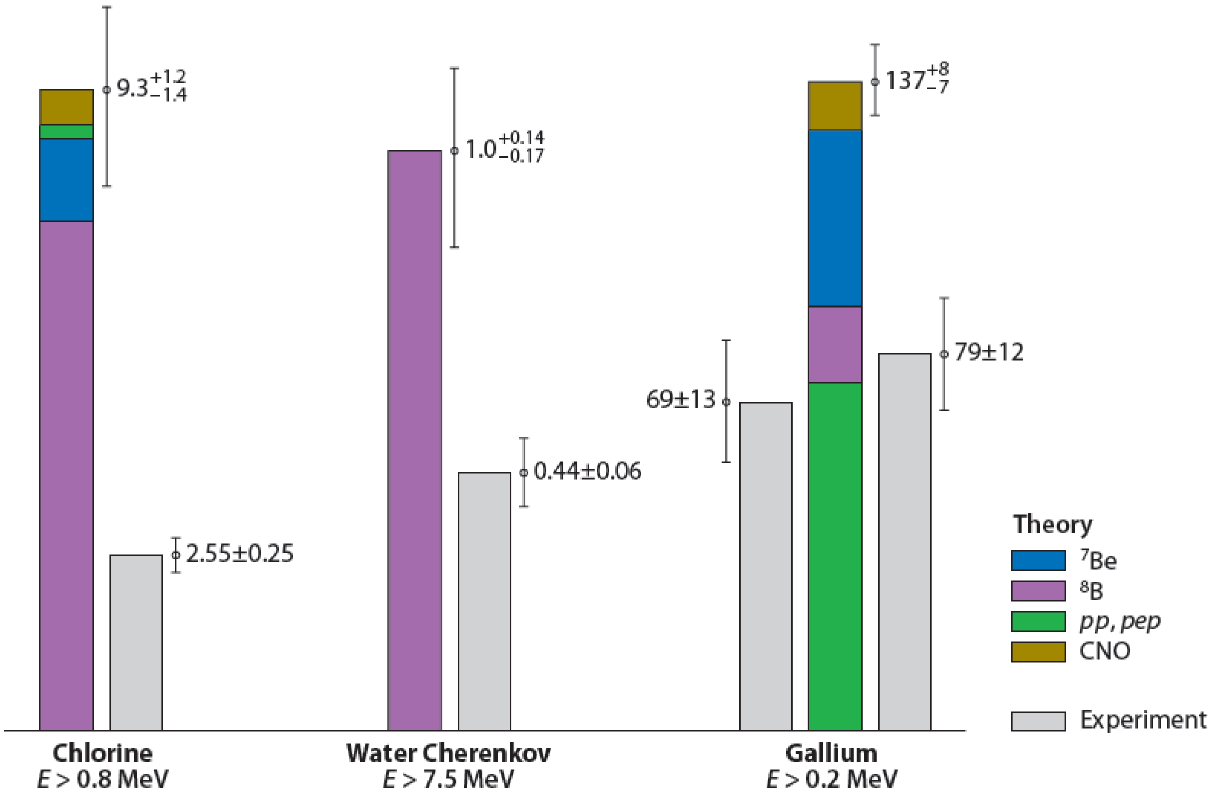
An International Facility for Underground Physics

Outline:

- SNO
- SNOLAB
  - Surface & Underground Facilities
  - Construction Status and Schedule
- Experimental Program
  - SNO+
  - HALO
  - Dark Matter Program (briefly)

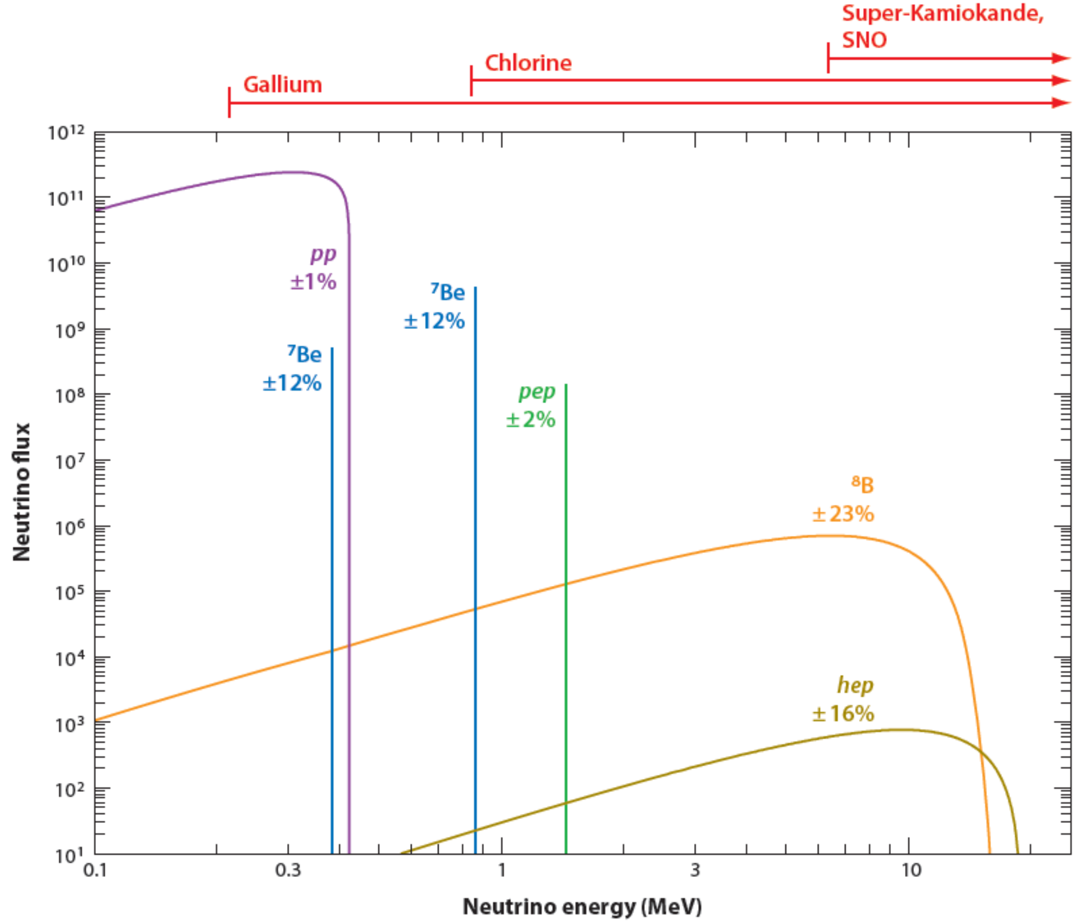
It all started with the solar neutrino problem…

- To show that the Sun's luminosity is provided by nuclear fusion in the core
- Solar models by John Bahcall
- Pioneering radiochemical experiment by Raymond Davis, Jr.
- Follow-on experiments in Japan, Italy and Russia
- Discrepancy established at many σ



Expectations - the Standard Solar Model

- Solar calculations correct?
- Experiments correct? ~ consistent but difficult; not measuring same thing → speculation including neutrino oscillations, MSW resonant flavour changes
- Need new idea
  - Herb Chen, UCI



The Sudbury Neutrino Observatory

- Deuterium target (1kT D_2O) → 3 reactions
- Herb's idea (1984)… NC is the key
- But np weakly bound in D
  - Deep mine to avoid cosmic rays
  - attention to Low Energy backgrounds
- D_2O + mine → Canada (Sudbury)
- 1989 Collaboration and proposal
- 1990 Funding, start of construction
- 1999-2006 data (3 phases)
- 2001 first results
- 2009-10 last results (25 years later)

$$\nu_e + d \rightarrow p + p + e^- - 1.44\,\mathrm{MeV}\,(\mathrm{CC}),$$

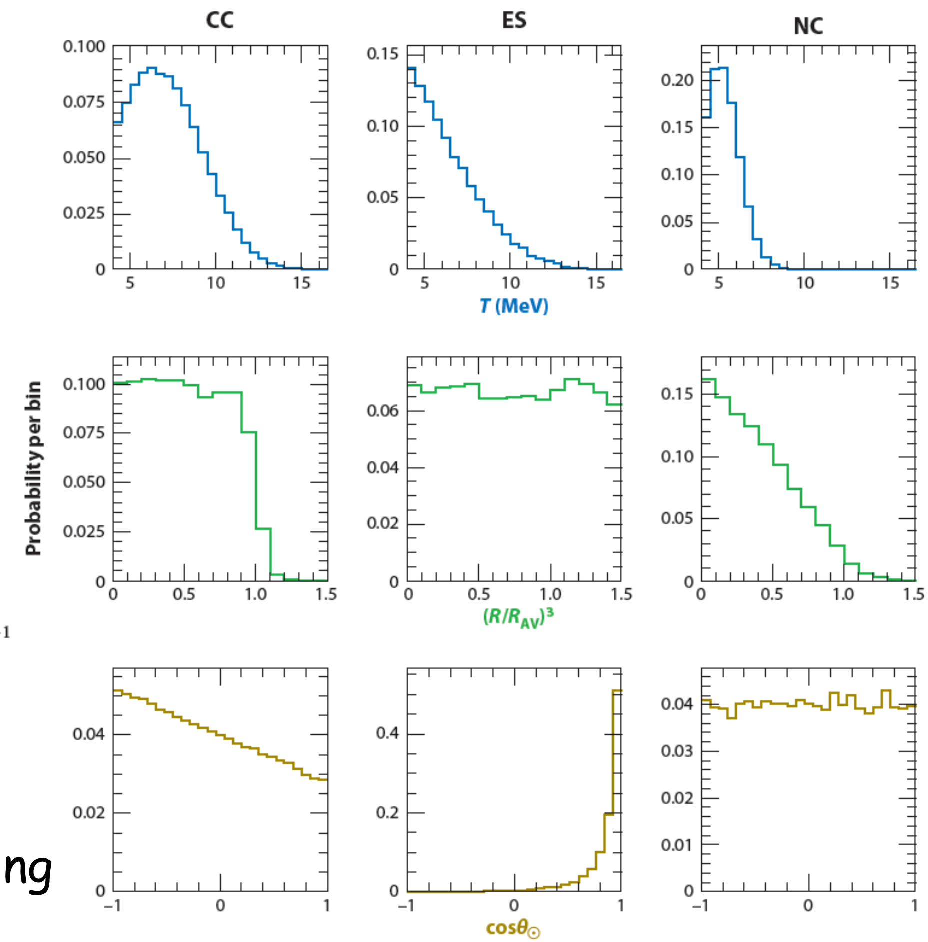
$$\nu_x + d \rightarrow p + n + \nu_x - 2.22\,\mathrm{MeV}\,(\mathrm{NC}),$$

$$\nu_x + e^- \rightarrow \nu_x + e^-\,(\mathrm{ES}),$$

Phase I - pure D_2O (2001)

- NC neutrons detected by capture on d
  n + d → t + γ (6.25 MeV)
- Close to analysis threshold of 5.5MeV
- Extract NC/CC ratio from ES and CC rates ignoring NC rate
- Signal extraction by maximum likelihood based on pdf's of Energy, Radial Distribution, angular distribution
- Huge emphasis on calibration to understand detector (~300K calibration constants tracked as function of time – requiring ~20% of livetime dedicated to calibration)

Phys. Rev. Lett. 87, 071301 (2001)



$$\phi_{CC}^{SNO}(\nu_e) = 1.75 \pm 0.07\,(\text{stat.})^{+0.12}_{-0.11}\,(\text{syst.}) \pm 0.05\,(\text{theor.}) \times 10^6\ \text{cm}^{-2}\,\text{s}^{-1}$$

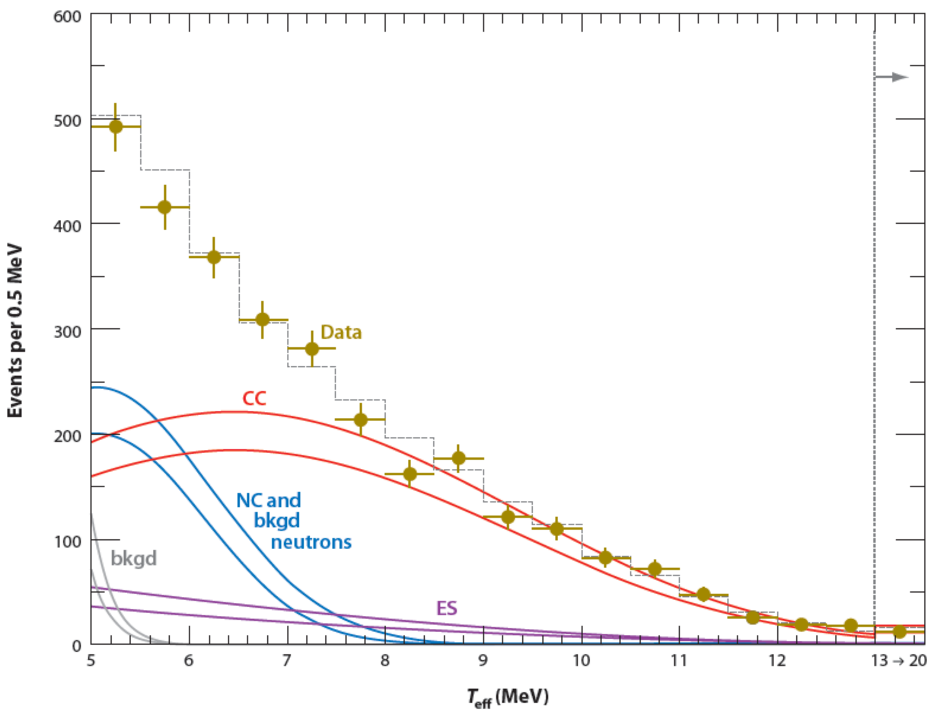
$$\phi_{ES}^{SNO}(\nu_x) = 2.39 \pm 0.34\,(\text{stat.})^{+0.16}_{-0.14}\,(\text{syst.}) \times 10^6\ \text{cm}^{-2}\,\text{s}^{-1}.$$

$$\phi_{ES}^{SK}(\nu_x) = 2.32 \pm 0.03\,(\text{stat.})^{+0.08}_{-0.07}\,(\text{syst.}) \times 10^6\ \text{cm}^{-2}\,\text{s}^{-1}$$

CC exceeds ES flux by 3.3σ indicating presence of non-electron flavours

Phase I - pure D_2O (2001)

- Measurement in background free window in Energy
- Level of neutron background (photodisintegration) not assessed at this point
- Potential exists to measure shape of CC energy spectrum and extract P_{ee} survival probability
- Errors on fluxes from full 3D maximum likelihood fit

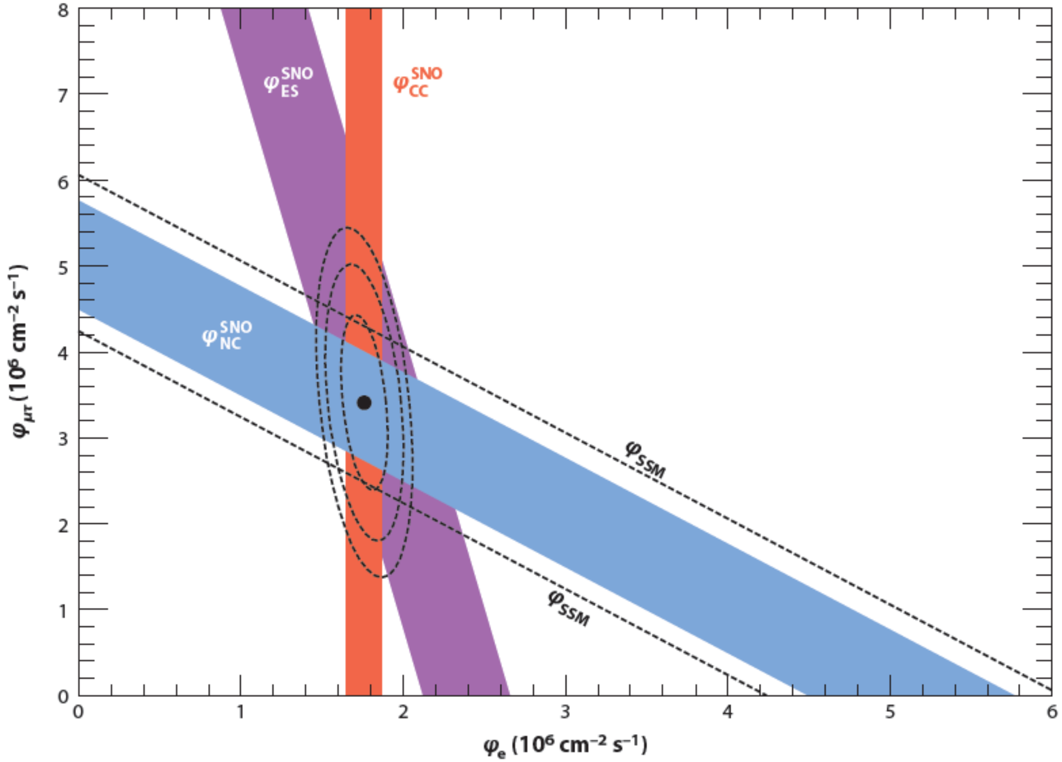


Phase I - pure D_2O (2002)

- Accumulate more statistics
- Lower analysis energy threshold to 5.0 MeV
- Assess disintegration backgrounds and refit

Phys. Rev. Lett. 89 011301 (2002)

5.3 σ determination of non-electron neutrino flavour presence



$$\phi_{CC} = 1.76^{+0.06}_{-0.05}\,(\text{stat.})^{+0.09}_{-0.09}\,(\text{syst.}),$$

$$\phi_{ES} = 2.39^{+0.24}_{-0.23}\,(\text{stat.})^{+0.12}_{-0.12}\,(\text{syst.}),$$

$$\phi_{NC} = 5.09^{+0.44}_{-0.43}\,(\text{stat.})^{+0.46}_{-0.43}\,(\text{syst.}).$$

$$\phi_{\nu_e} = 1.76^{+0.05}_{-0.05}\,(\text{stat.})^{+0.09}_{-0.09}\,(\text{syst.})$$

$$\phi_{\nu_{\mu\tau}} = 3.41^{+0.45}_{-0.45}\,(\text{stat.})^{+0.48}_{-0.45}\,(\text{syst.}),$$

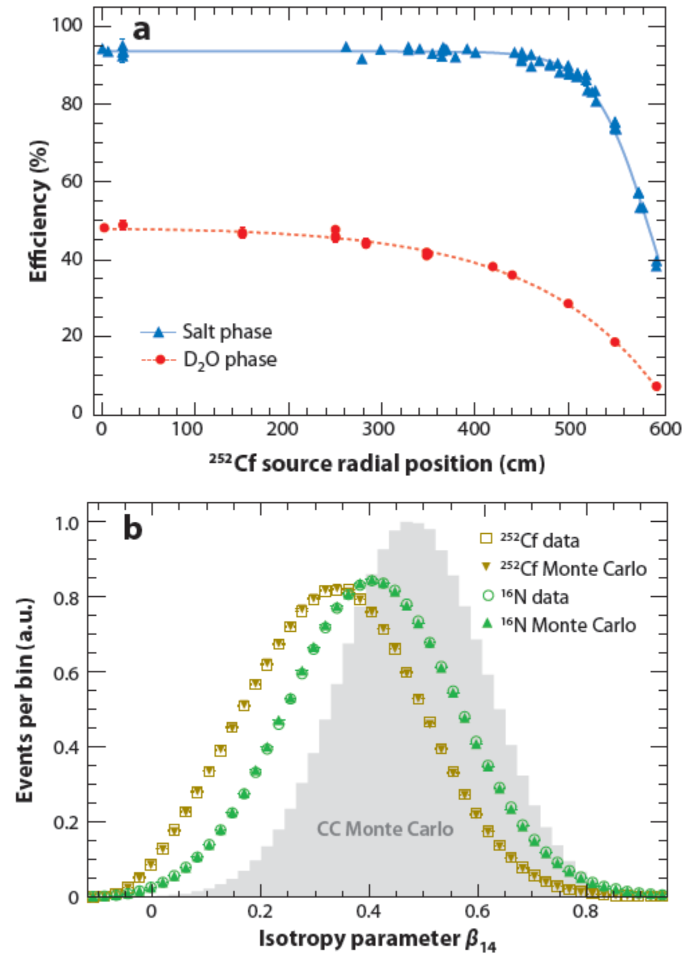
Phase II
(because we didn't think a priori that Phase I would produce a significant measurement)

- Added 1 tonne of NaCl to the D_2O to enhance neutron capture and increase energy

  $n + {}^{35}Cl \rightarrow {}^{36}Cl + \gamma$'s (8.6 MeV)

- Multiple gammas makes the neutron capture events more isotropic than the Cherenkov events
- Radial spectrum of CC and NC now very similar so less separation power
- Isotropy parameter, β_{14}, introduced

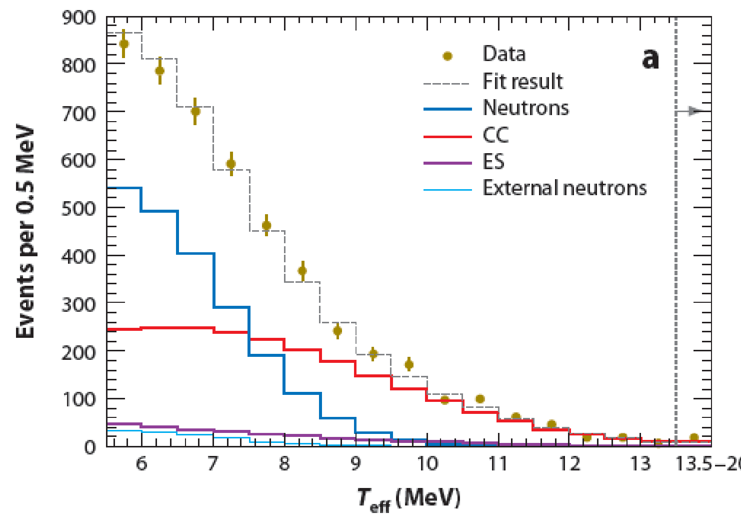
Note role of calibration and simulation in precision understanding of detector response!



Phase II (Salt Phase)

- Modified detector
- Modified analysis
- Blind analysis (as were Phase I analyses)
- Consistent results
- No sign of MSW upturn in P_{ee}, would be nice to see this as further evidence of MSW

Phys. Rev. Lett. 92, 181301 (2004)

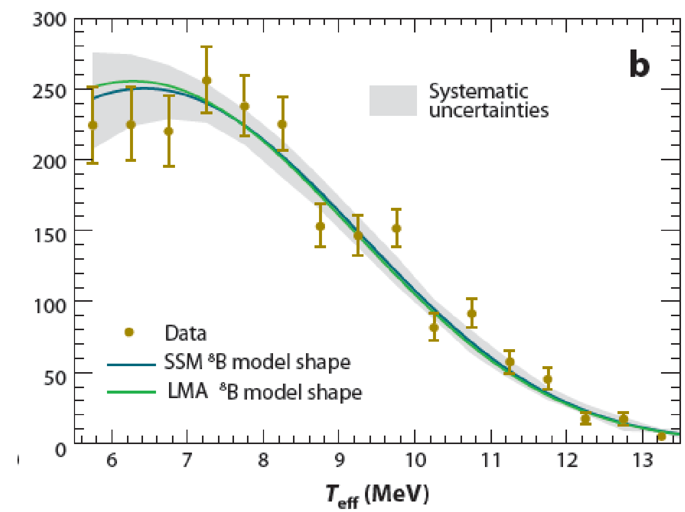


$$\phi_{CC} = 1.68^{+0.06}_{-0.06}\,(\text{stat.})^{+0.08}_{-0.09}\,(\text{syst.}),$$

$$\phi_{ES} = 2.35^{+0.22}_{-0.22}\,(\text{stat.})^{+0.15}_{-0.15}\,(\text{syst.}),$$

$$\phi_{NC} = 4.94^{+0.21}_{-0.21}\,(\text{stat.})^{+0.38}_{-0.34}\,(\text{syst.}),$$

$$\frac{\phi_{CC}}{\phi_{NC}} = 0.340^{+0.023}_{-0.023}\,(\text{stat.})^{+0.029}_{-0.031}\,(\text{syst.}).$$

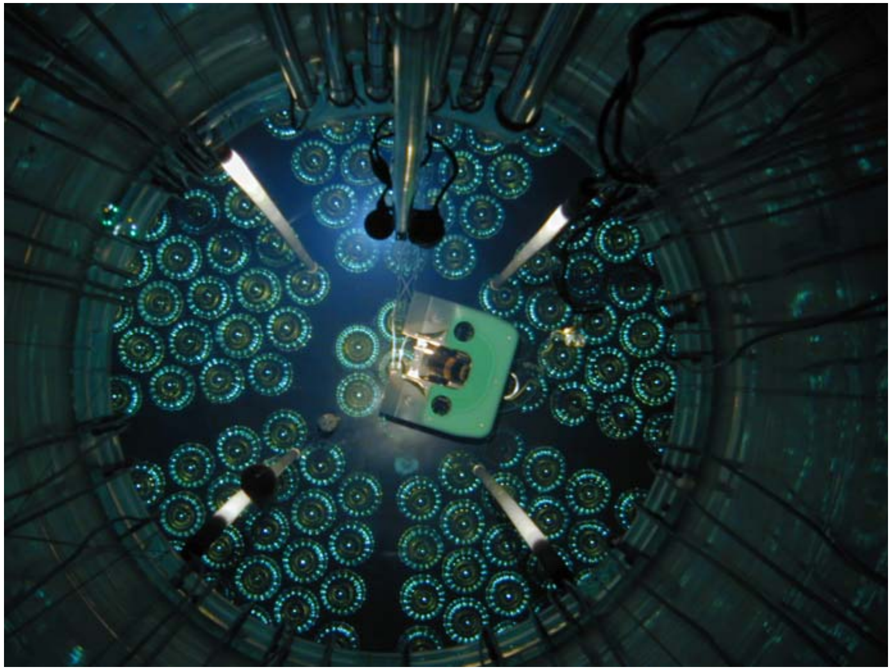


Phase III
(because we didn't think that "once" was enough)

- Deploy an array of ^3He neutron counters; 40 strings up to 11 m long on a 1m x 1m grid anchored to the bottom of the acrylic vessel
- Provides event by event detection of NC events → NCDs

$$n + {}^3He \rightarrow t + p \ (764 \text{ keV})$$

- Another independent and blind analysis



$$\left.\begin{aligned}
\phi_{CC} &= 1.67^{+0.05}_{-0.04}\,(\text{stat.})^{+0.07}_{-0.08}\,(\text{syst.}),\\
\phi_{ES} &= 1.77^{+0.24}_{-0.21}\,(\text{stat.})^{+0.09}_{-0.10}\,(\text{syst.}),\\
\phi_{NC} &= 5.54^{+0.33}_{-0.31}\,(\text{stat.})^{+0.36}_{-0.34}\,(\text{syst.}),
\end{aligned}\right\} \rightarrow \frac{\phi_{CC}}{\phi_{NC}} = 0.301 \pm 0.033\,(\text{total})$$

Phase I, II and III results

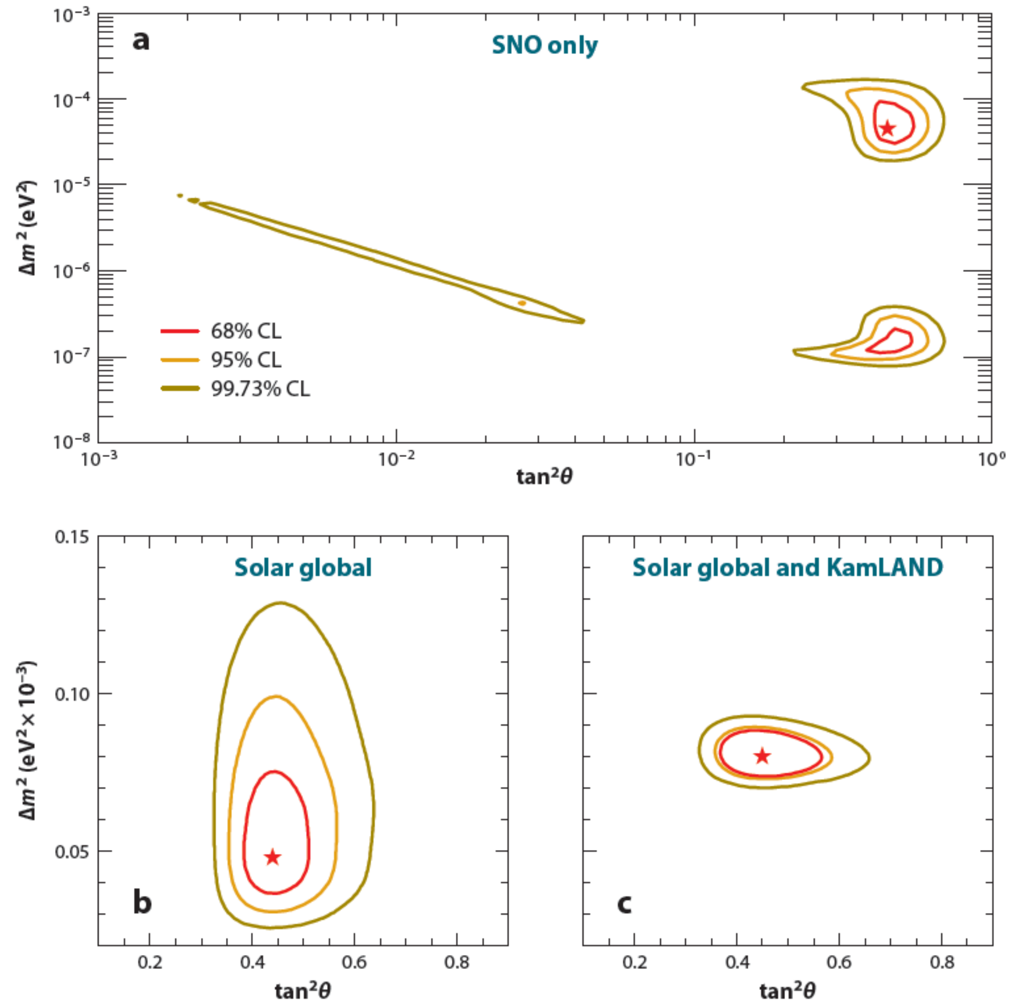
- Oscillation parameter analysis with individual SNO Phases

Phys. Rev. Lett. 101, 111301 (2008)

- Most recent result
  - Low Energy Threshold Analysis (LETA) (4.5 MeV)

arXiv:0910.2984v1 [nucl-ex]

  - Improves θ_{12} constraints by factor of 2
- Still to come…
  - Combined 3 phase analysis



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 & supernova experiments requiring depth and cleanliness.
- Large scale experiments (up to ktonne, not Mtonne)
  - → But also provide space for prototyping of future experiments.
- Commissioning goal has been to progressively create a significant new space for an active programme as early as possible.

Confirmed impact craters listed by size

Name	Location	Diameter (km)	Age (megayears)
Vredefort	Free State, South Africa	300	2020
Sudbury	Ontario, Canada	250	1850
Chicxulub	Yucatán, Mexico	170	65

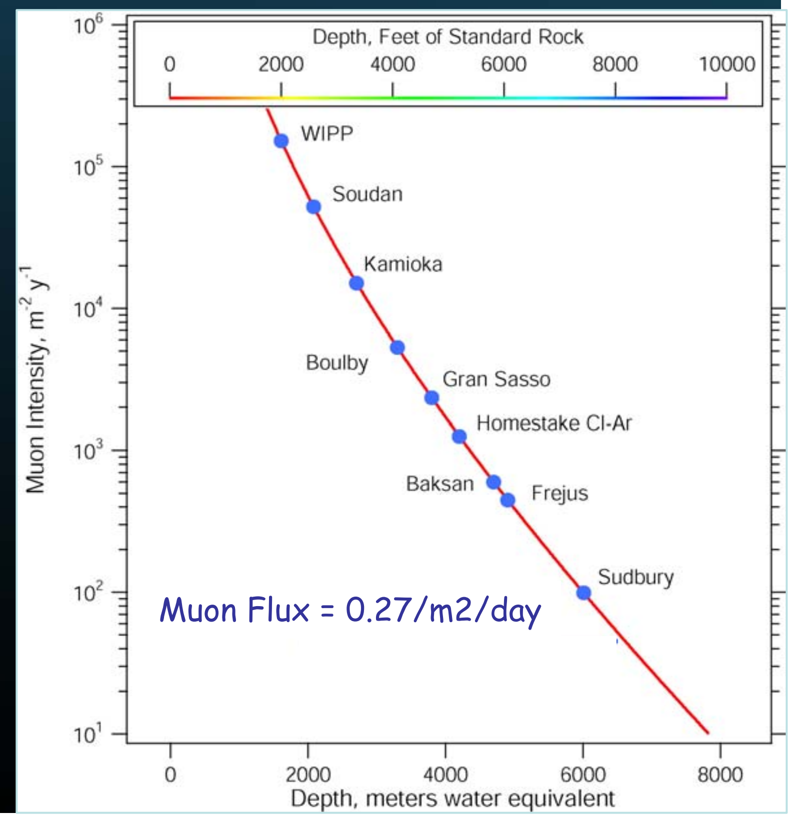
Orsay

200 km South

6700 km West

2km flat overburden (6000mwe)

Underground Laboratory



SNOLAB Overall Status

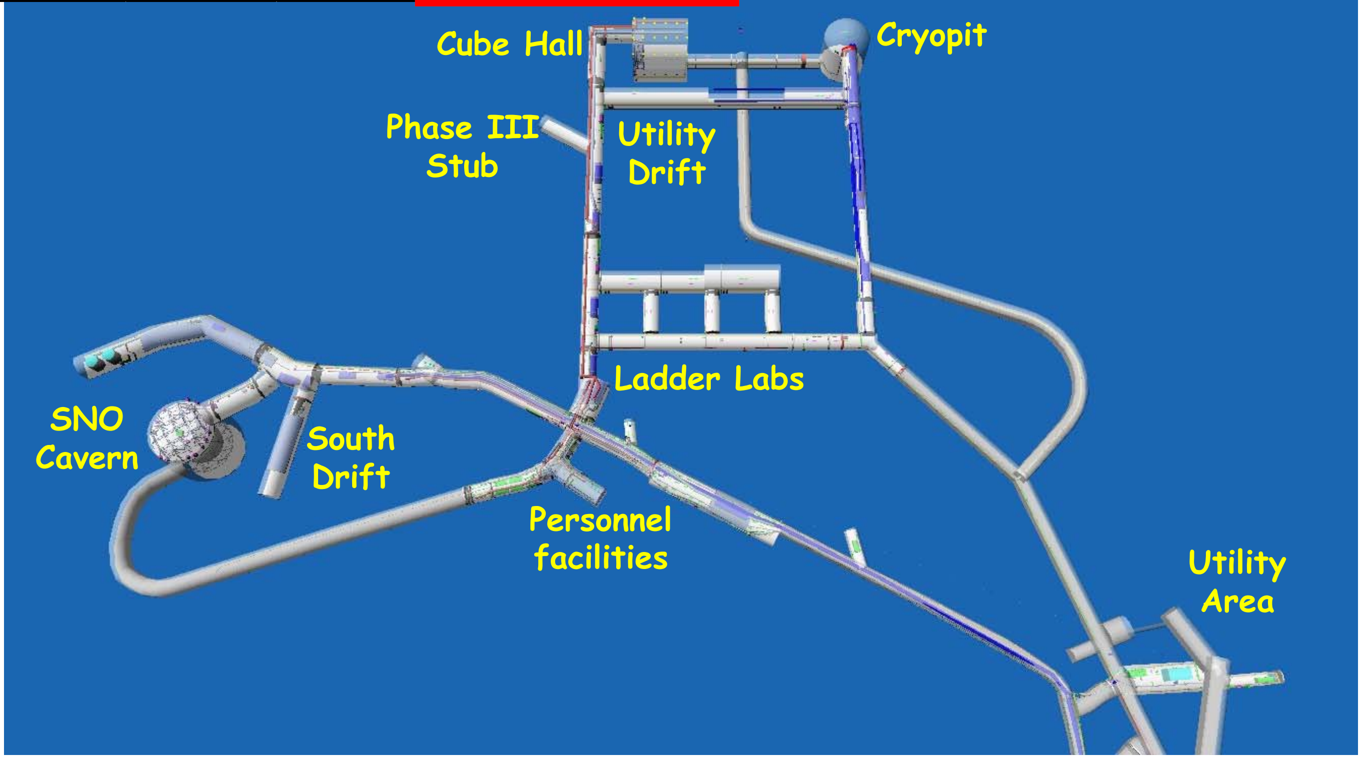
- Surface Facility
  - Operational from 2005.
  - Provides offices, conference room, dry, warehousing, IT servers, clean-room labs, detector construction labs, chemical + assay lab
- Underground Construction (Cube Hall, Cryopit, Ladder Labs, Lab Entrance)
  - Excavation complete and outfitting began June 2007.
  - General outfitting in Phase I areas almost complete + Cryopit 5T crane/access.
  - Final infrastructure (Chiller, MPC, HVAC, waste water plant) commissioned
  - First experimental infrastructure installation underway in Cube Hall
  - Ladder labs opened as clean areas, final clean underway
- Experimental Programme
  - Continued operation of DEAP-1 and PICASSO.
  - Current allocations to: PICASSO, DEAP-I, SNO+, DEAP-3600, MiniCLEAN, CDMS, HALO.
  - Anticipated or under discussion: EXOgas 200, COUPP, DarkSide, low background counters to measure 39Ar, future Cobra upgrade…


Surface Facilities
Control Rooms
IT Server Room
Clean Room Labs
Meeting Rooms

Underground Facilities

	Excavation		Clean Rm		Laboratory	
	Area	Volume	Area	Volume	Area	Volume
SNO	1,863 m^2	16,511 m^3	1,133 m^2	13,321 m^3	752 m^2	11,679 m^3
SNOLAB	7,215 m^2	46,648 m^3	4,942 m^2	37,241 m^3	3,055 m^2	29,555 m^3

All clean spaces to be operated as a Class 2000 clean room.




Lab
Entrance


Personnel
Facility


Galley/Ref
uge


Cryopit

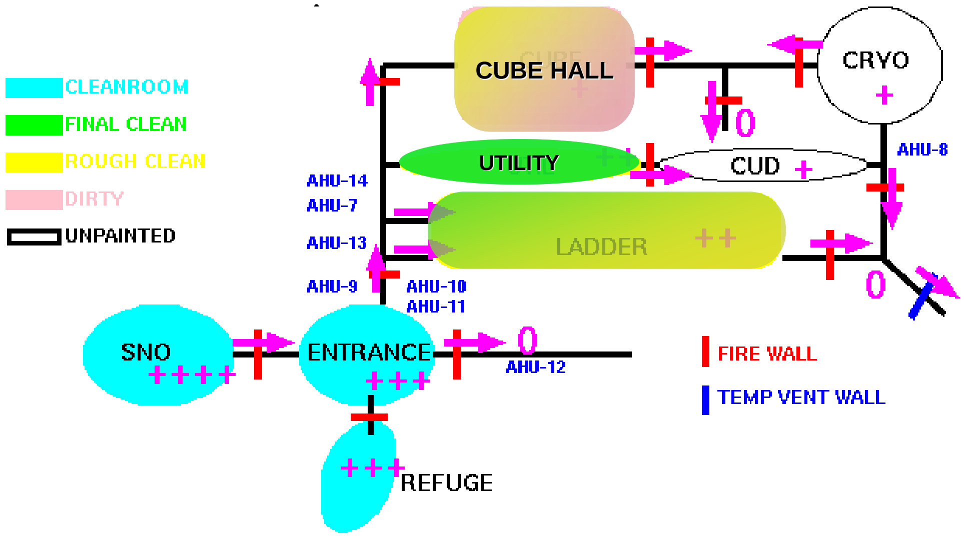

Cube
Hall

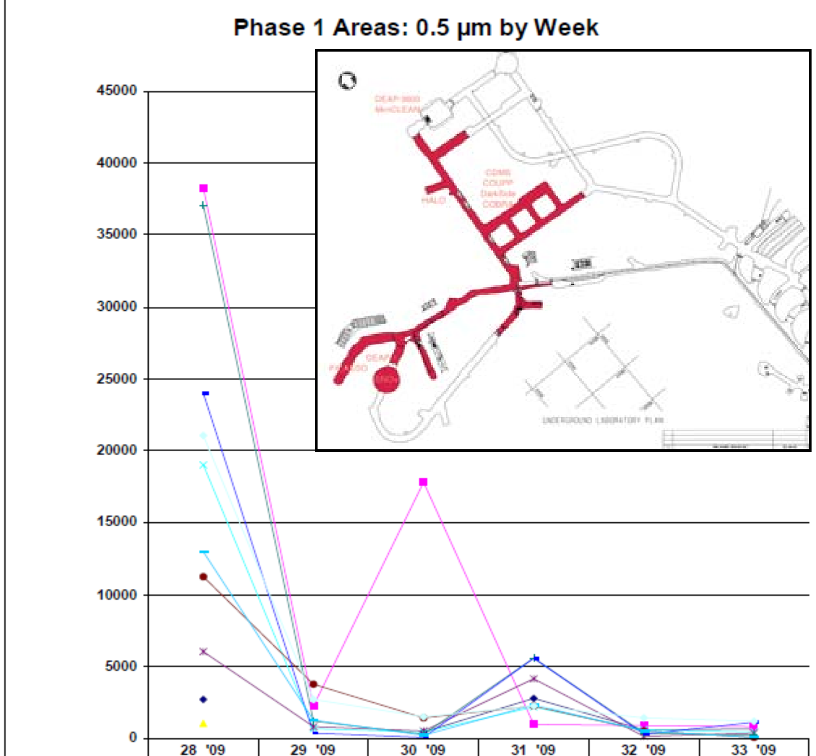
Unsealing door to Ladder Labs 5th Aug


Ladder
Labs

Construction Status

- With the "going clean" of the Ladder Labs there is now 3,700 m^2 of space inside the clean room boundary of the lab. For comparison the surface building is 3,000 m^2.
- Ladder Labs still require a "fine clean" to bring them to final clean



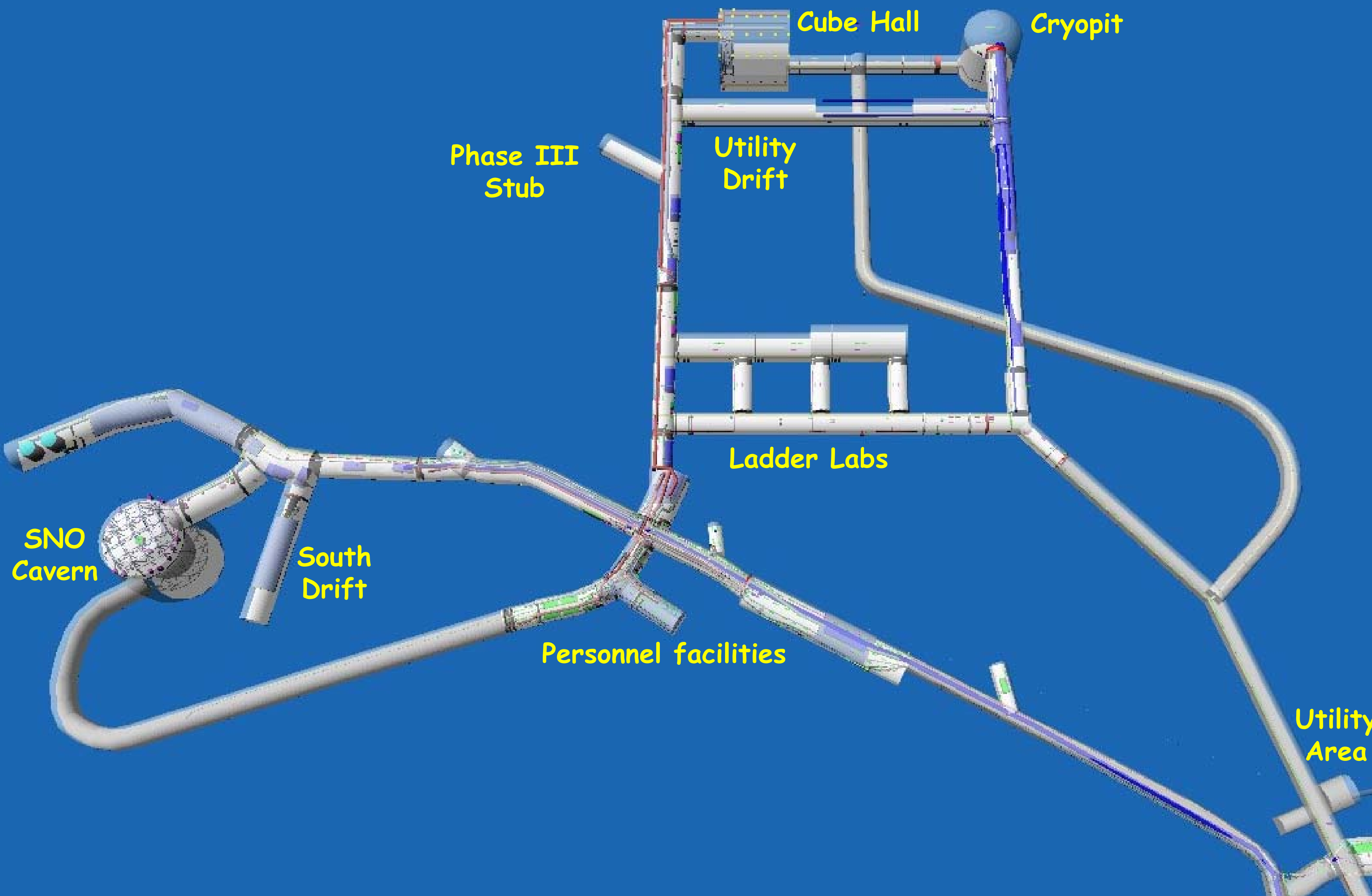


	28 '09	29 '09	30 '09	31 '09	32 '09	33 '09
Cube Util	2726.666667		450	2830	582.5	695
Cube Ctrl	38290	2290	17810	990	917.5	825
Cube Stage	1043.333333					
Drift N	19013.33333	670	420	2210	615	440
MHAD A	6033.333333	860	560	4170	137.5	345
MHAD B	11226.66667	3750	1400	2280	545	50
Room 125	37043.33333	1240	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

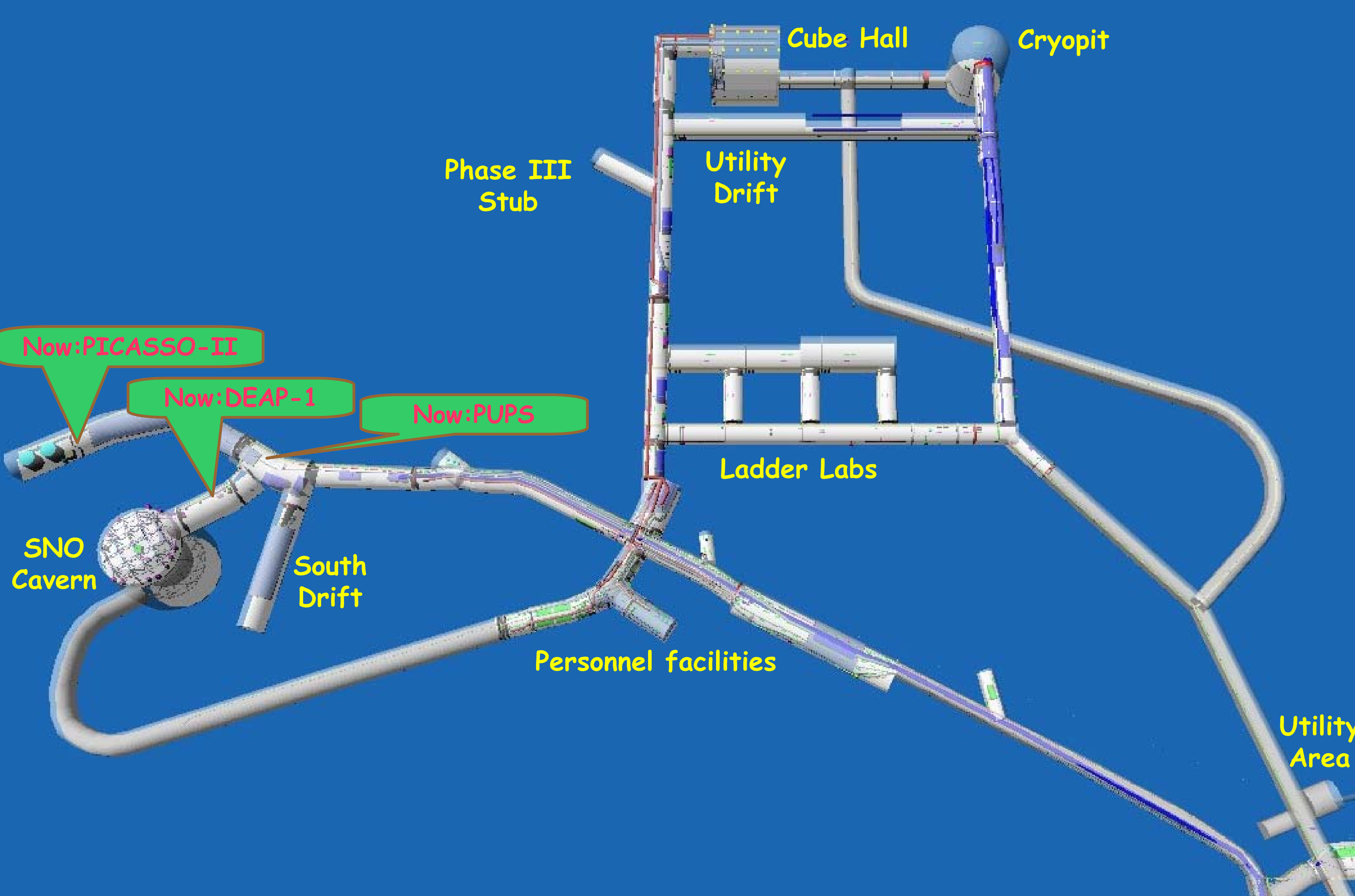
Facility Construction Schedule

- 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:
  - Fine cleaning of Ladder Labs
  - Installation of services (plumbing, electrical) in Ladder Labs and Cube Hall.
  - Cryopit: prepare and paint.
  - Renovation of old Personnel Area (reclaim for experiments or infrastructure).

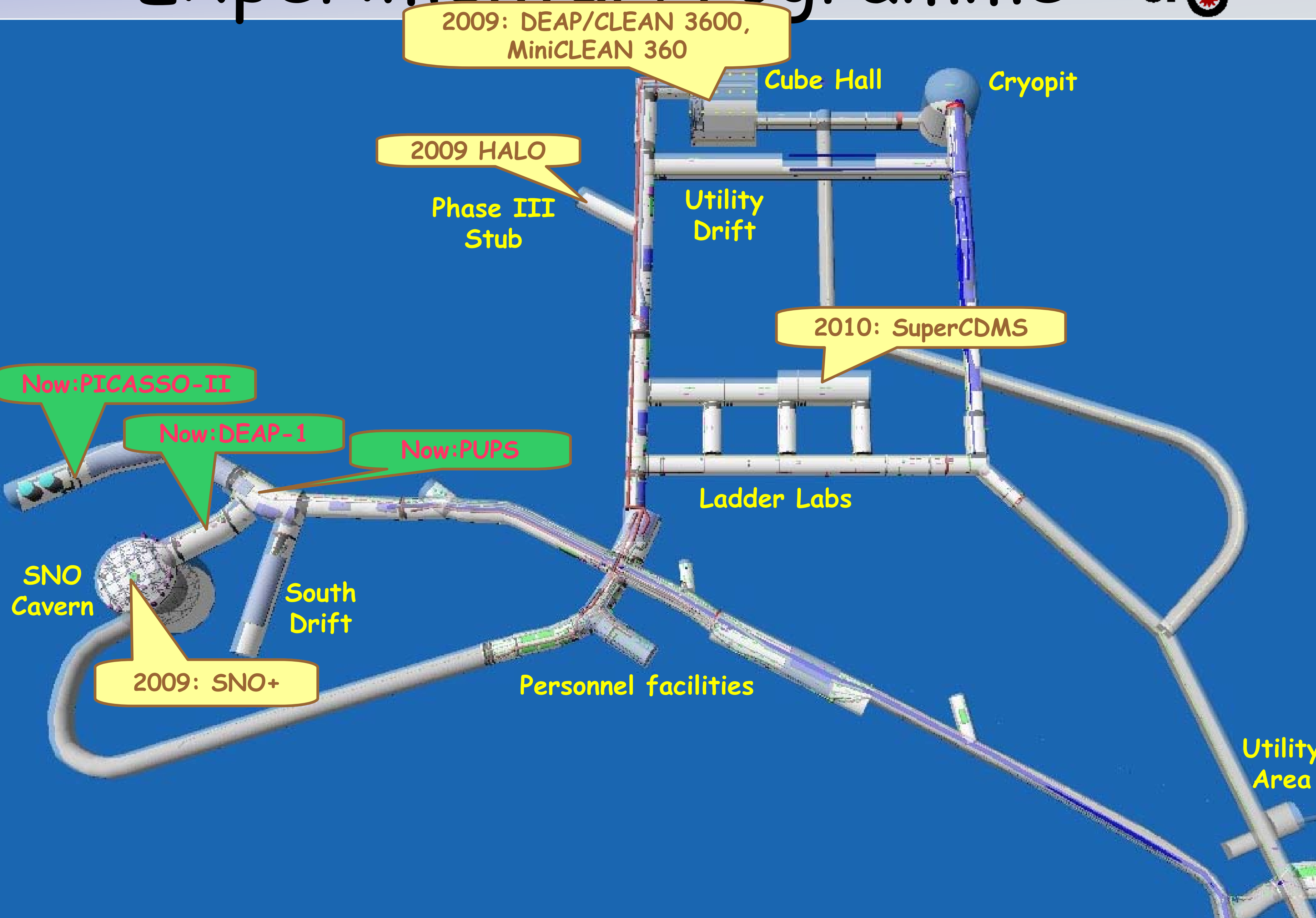
Experimental Programme



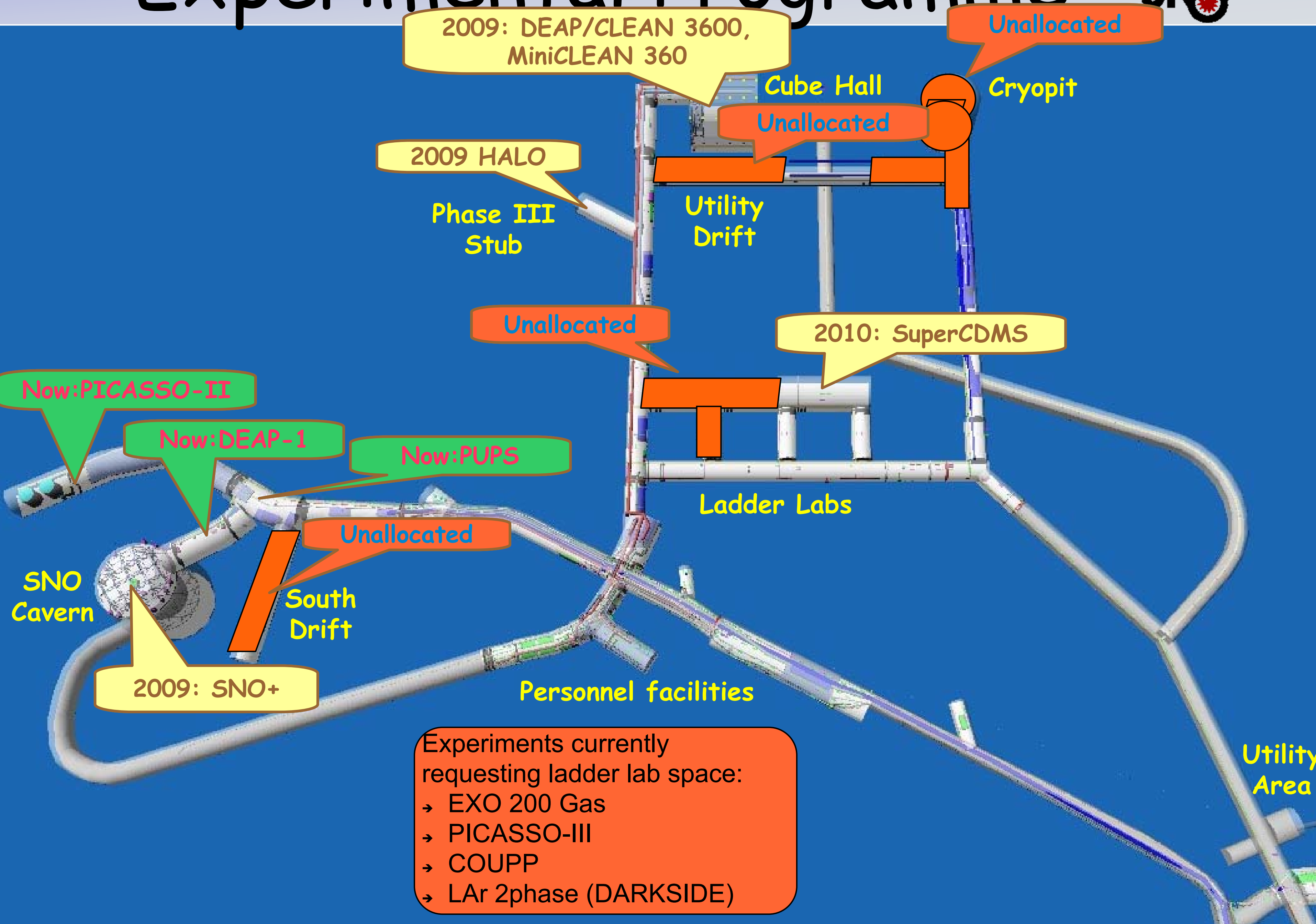
Experimental Programme



Experimental Programme



Experimental Programme



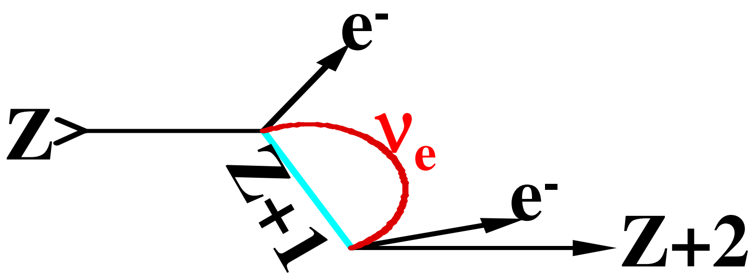
Experiments currently requesting ladder lab space:

- EXO 200 Gas
- PICASSO-III
- COUPP
- LAr 2phase (DARKSIDE)

Experimental Programme Summary

Experiment	Solar nu	0nuBB	Dark Matter	SuperNovae	Geo nu	Other	Space allocated	Status
SNO+	√	√		√	√		SNO Cavern	Underway
PICASSO			√				SNO Utility	Running
DEAP-1			√				SNO Control	Running
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	Request
DarkSide			√				Ladder Labs	Request
PICASSO-III			√				Ladder Labs	Planning

0νββ with SNO+



- 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.
    → 100 meV sensitivity to neutrino mass in 3 yrs of running starting in 2011
  - Capital funding received June 2009.

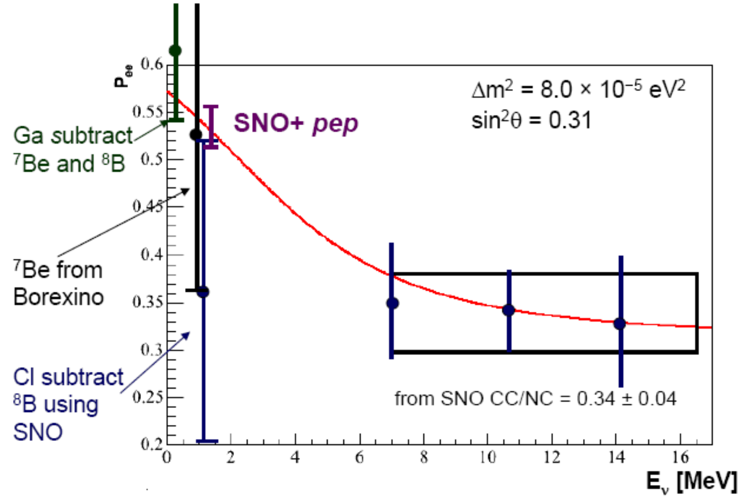
Other Physics

- Low energy solar neutrinos
- Geo-neutrinos
- Reactor neutrino oscillations
- Supernova neutrino detection

Other SNO+ Physics

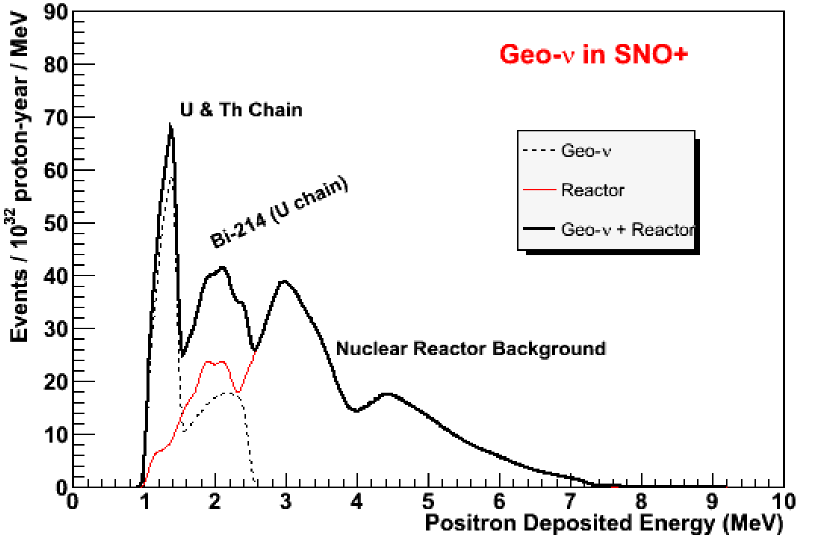
Low Energy Solar

→ exploit pep solar neutrinos for precision studies of neutrino-matter couplings
- pep allows for it to be precision
- SNOLAB depths allows for us to do it
- MSW is the most sensitive probe of neutrino-matter couplings (e.g. non-standard interactions) and could reveal new physics



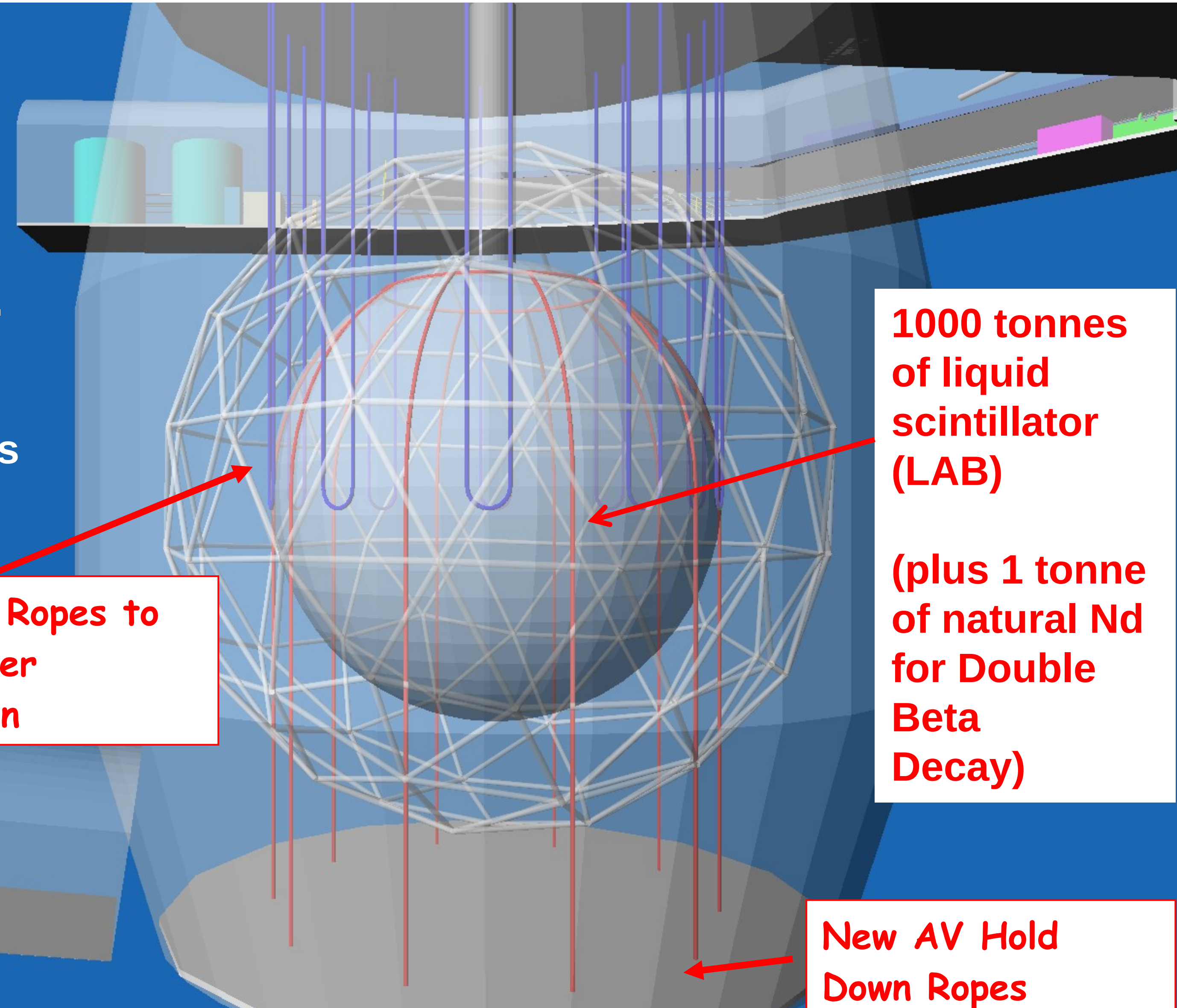
Geo-neutrino & Reactor antineutrino

- four times smaller reactor background in the geo-neutrino region than in KamLAND
- test competing models of the composition of the continents
- exceptionally well characterized local geology enables residuals to probe the U and Th content of the deep Earth
- reactor spectrum "dip" confirms L/E behaviour for neutrino oscillations; helps constrain Δm^2 and θ_{12}



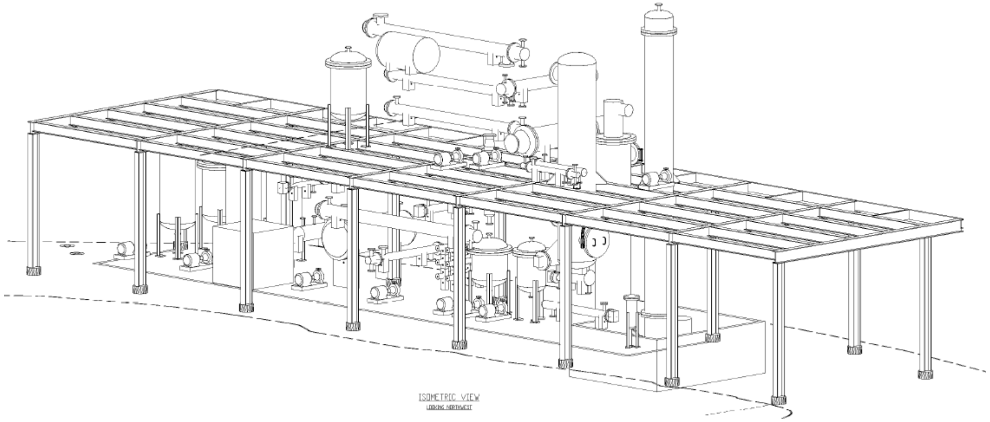
The organic liquid is lighter than water so the Acrylic Vessel must be held down.

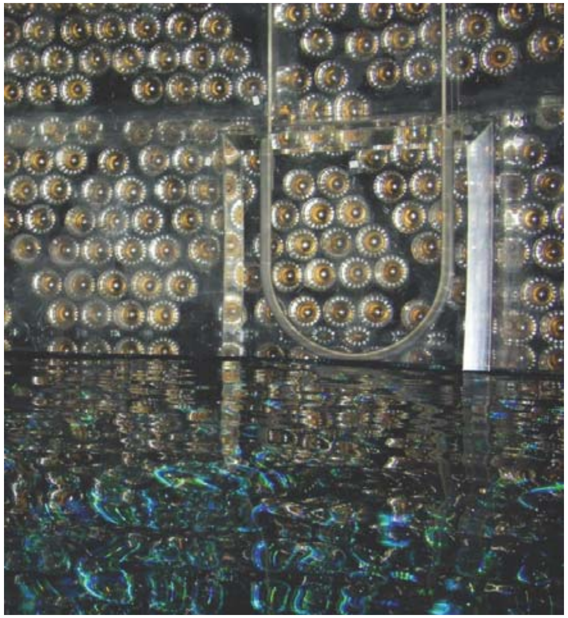
New scintillator purification systems are required.

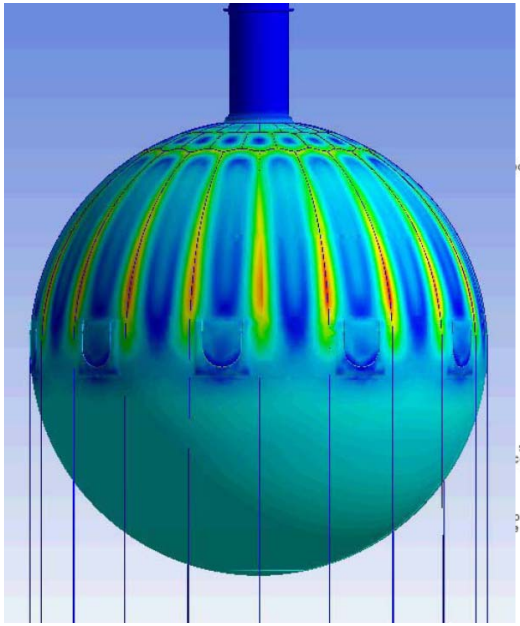


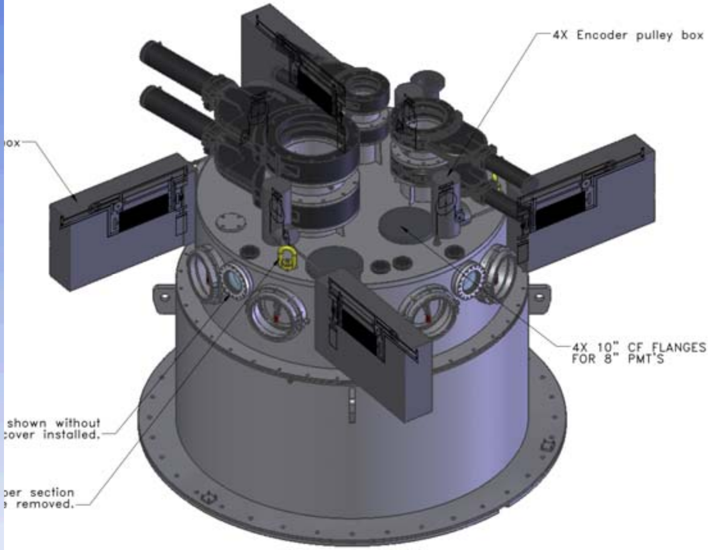
Otherwise, the existing detector, electronics etc. are reusable.

SNO+ Underway





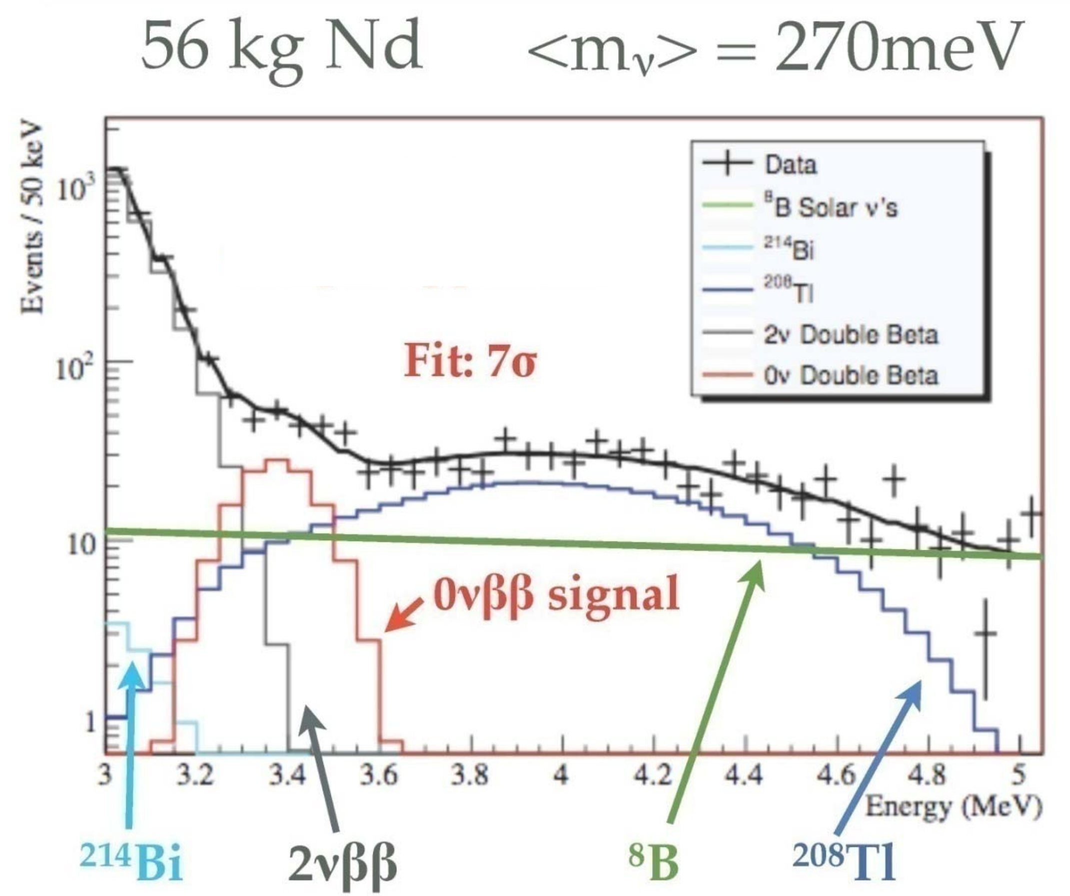




SNO+ (^{150}Nd ν - less Double Beta Decay)

SNO+ Sensitivity Limits with ~0.1 % natural Nd (3 yrs starting in 2011):

$m_{\nu\beta\beta}$ ~ 0.1 eV



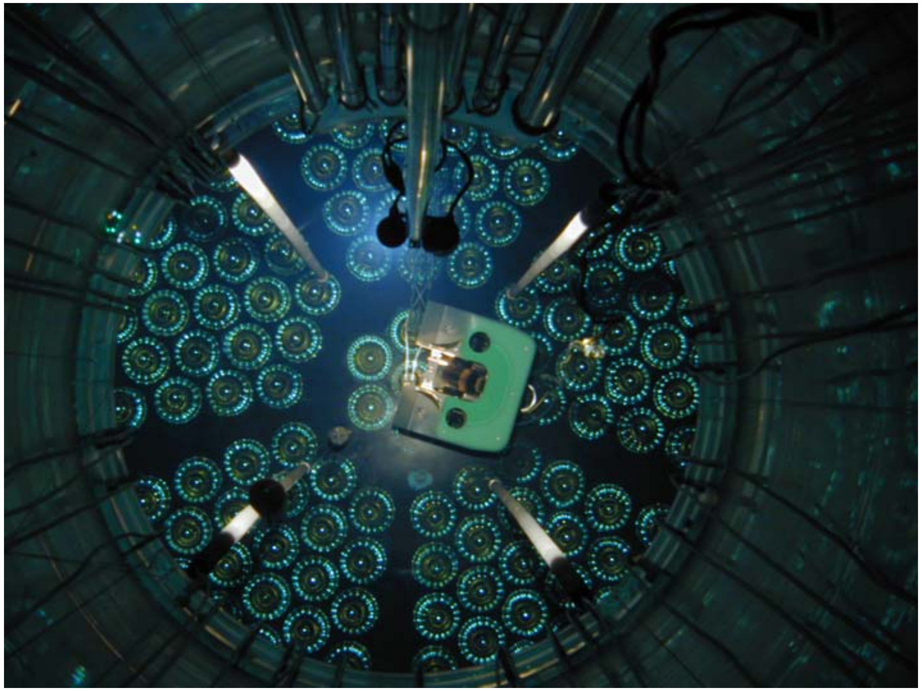
2νββ half life measured: (9.7 +/- 0.7 +/- 1.0) 10^{18} yr (NEMO III) (favourable value)

HALO - Design Overview

Philosophy - to produce a

- Very low cost
- Low maintenance
- Low impact in terms of lab resources (space)
- Long-term, high livetime

dedicated supernova detector



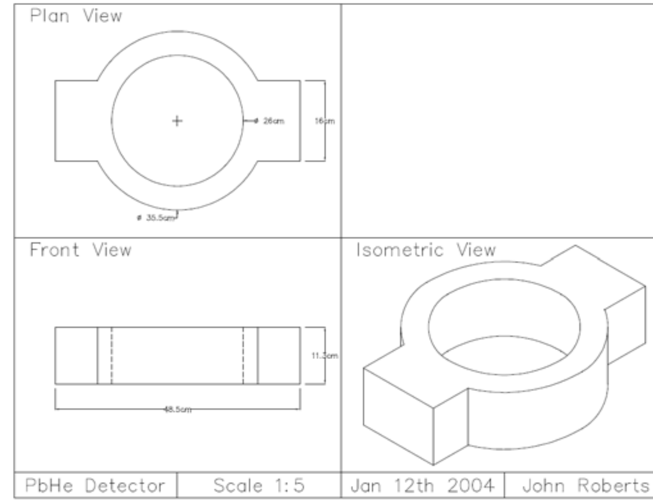
"Helium" – because of the availability of the ^{3}He neutron detectors from SNO

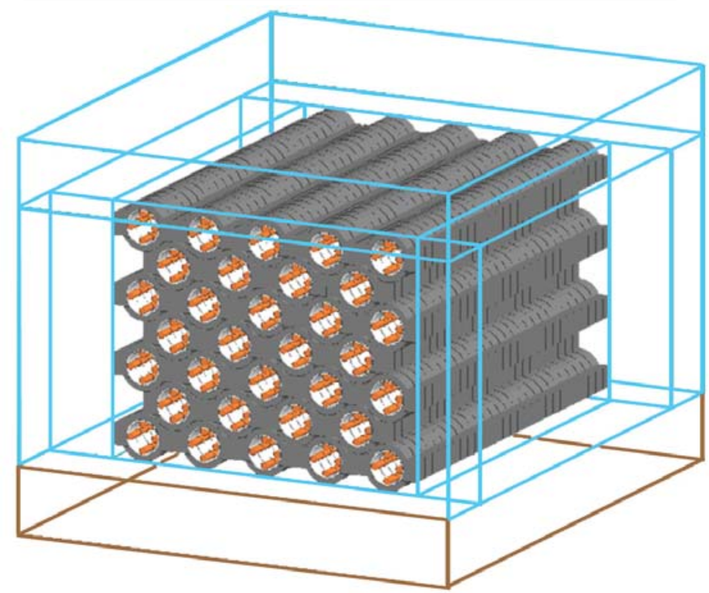
+

"Lead" – because of high ν-Pb cross-sections, low n-capture cross-sections, sensitivity to ν_e (dominantly) and ν_x complementing water Cerenkov and liquid scintillator detectors

HALO - Design Overview

- Lead Array
  - 32 three meter long columns of annular Lead blocks
  - 76 tonnes total lead mass (864 blocks)
- Neutron detectors
  - Four 3 meter ^{3}He detectors per column
  - 384 meters total length
- Moderator
  - ~250mm Ø schedule 40 PP tubing
- Reflector and Shielding
  - ~15 cm thick graphite blocks
  - 1' of water (boxes) on 5 sides





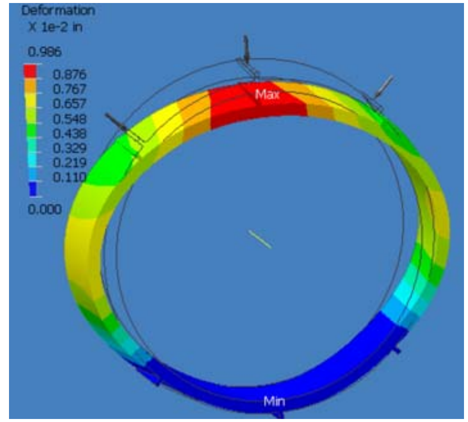
HALO - SN neutrino signal – Phase 1

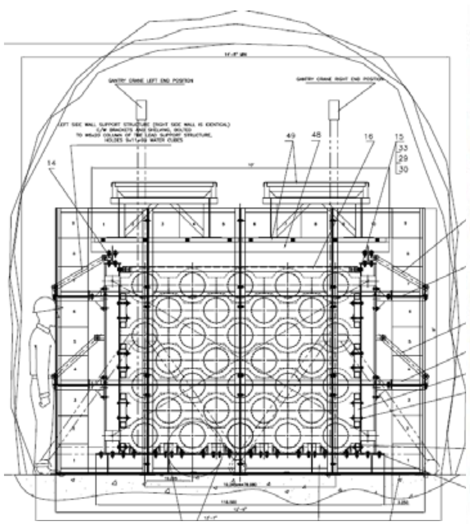
- In 76 tonnes of lead for a SN @ 10kpc†, MSW oscillated
  - Assuming FD distribution around T=8 MeV for ν_μ's, ν_τ's.
  - 65 neutrons through ν_e charged current channels
    - 29 single neutrons
    - 18 double neutrons (36 total)
  - 20 neutrons through ν_x neutral current channels
    - 8 single neutrons
    - 6 double neutrons (12 total)

~ 85 neutrons liberated; ie. 1.1 n/tonne

†- Engel, McLaughlin, Volpe, Phys. Rev. D 67, 013005 (2003)

HALO Underway

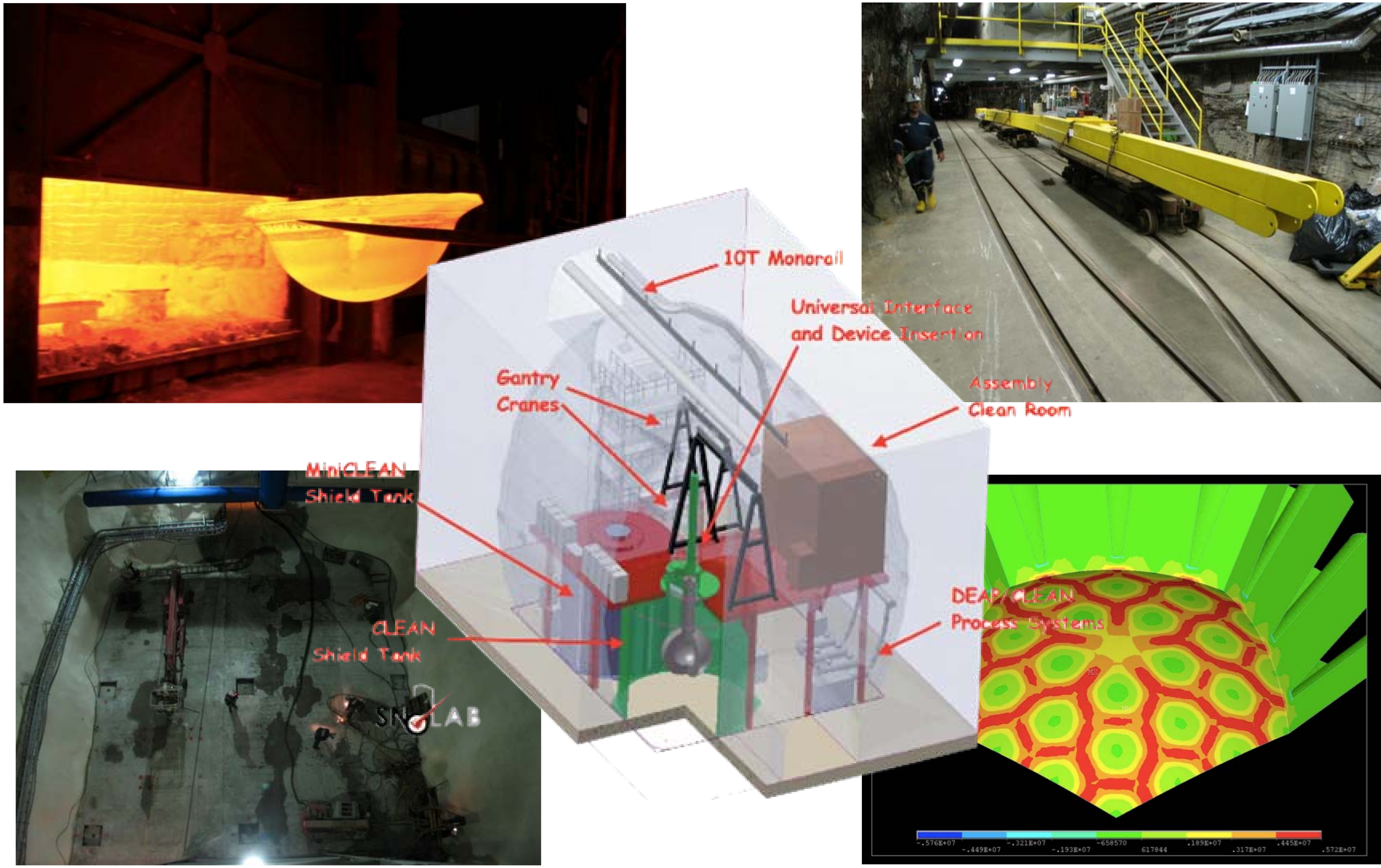


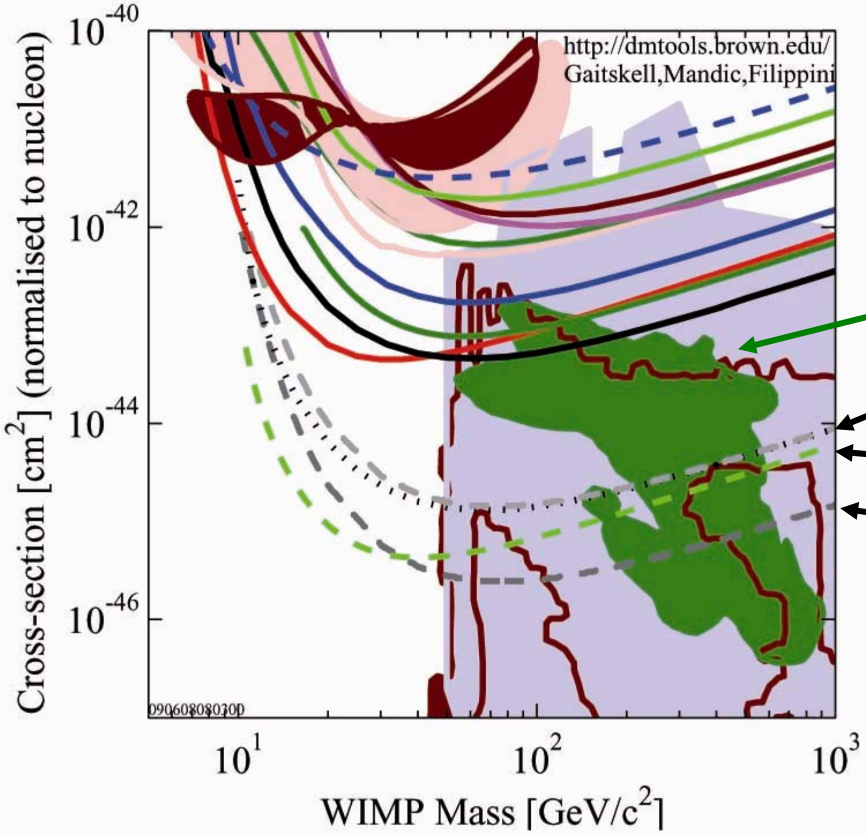


Dark Matter at SNOLAB

- 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. DEAP-3600 capital funding granted (CA$26M with SNO+)
  - Will measure Spin Independent cross-section.
- Superheated Liquids: PICASSO (COUPP)
  - Superheated droplet detectors. 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
  - Will measure Spin Dependent cross-section.
- 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 discussion
  - Most sensitivity to Spin Independent cross-section.

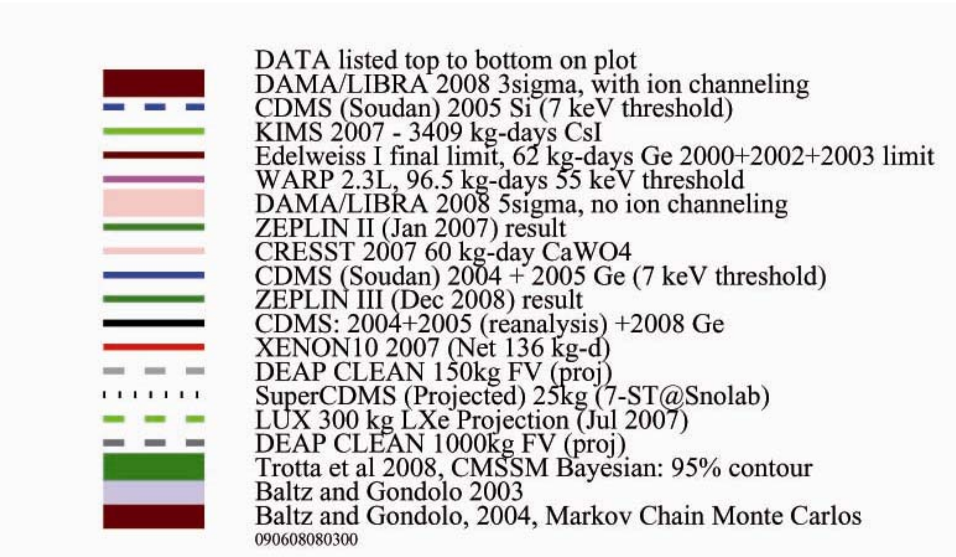
DEAP-3600/MiniCLEAN Underway





Predictions:
Minimal Super-Symmetric Models

SuperCDMS, MiniClean @ SNOLAB
LUX @ Sanford LAB
Deap 3600 @ SNOLAB



Physics Reach:

Spin-Independent Interactions

Status of SNOLAB

- SNOLAB Phase I infrastructure complete
  - Surface facility, Cube Hall, Ladder Labs
  - Final outfitting and cleaning underway
- Facility is now in transition to experimental programme
  - Deployment of support systems for first experiments underway (SNO+, DEAP-3600, MiniCLEAN, HALO)
  - Smaller scale experiments continue operations (DEAP-I, PICASSO)
  - Design/discussions on additional systems advanced (COUPP, CDMS, DarkSide)
- Additional space available, especially when Phase II (Cryopit) completed
- SNOLAB is looking forwards to contributing to the world programme of underground research facilities

end

Detailed Space

	Experimental Space		Length (ft)	Width (ft)	Height Shoulder/Back	Area (sq ft)
Existing	SNO Cavern	Cavern	70(dia)		85'/100'	3848
		Utility Drift	187	23		4300
		Control Room	57	20		1140
	South Drift	Drift	106	17	10'/16'	1802
Phase I	Ladder Labs	Drift C1	105	20	12'/19'	2100
		Drift C2	75	25	17'/25'	1875
		Drift B&D	360	15	10'/15'	5400
	Rectangular Hall	Hall	60	50	50'/65'	3000
		Utility Drift	115	20	10'/17'	2300
		Staging Area	45	16	10'/15'	720
		Control Room	62	18	10'/16'	992
Phase II	Cryopit	Cavern	50(dia)		50'/65'	1963
		Utility Drift	141	20	10'/17'	2820
		Staging Area	66	16	10'/15'	1056
		Control Room	64	16	10'/15'	1024
					Existing SNO	11090
					Phase I	27477
					Phase II	34340