Canadian Neutrino Program
A History of SNO and SNOLAB
BNO-50
David Sinclair

- It is a great pleasure to join with you in celebrating the 50th anniversary of the world's first, purpose built underground laboratory
- This laboratory has been the home of many pioneering studies in fundamental physics and several of these have been critical in the development of the Canadian program.
- Examples are SAGE which showed that the problem of missing solar neutrinos was not just a high energy problem; and the pioneering work of Pomansky in developing the search for 2 neutrino- and neutrinoless- double beta decay

Outline of this talk

- Address the history of SNO and SNOLAB
- Include some discussion of Dark Matter searches along with the neutrino physics
- Look at the current and near term physics program at SNOLAB
- Will not cover T2K which is an important follow-on to SNO but not one I have been involved with.

The Early Days

- The underground, neutrino program in Canada started with John Simpson, working in a salt mine
- Looked for double beta decay in germanium detectors
- Loaded Ge and Si detectors with tritium and looked for endpoint distortion

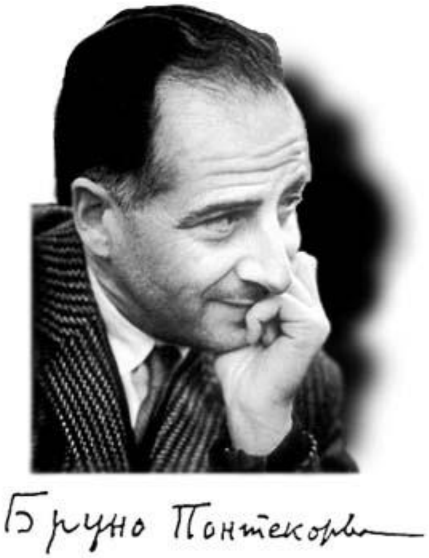
SNO

- The neutrino program took off with the start of SNO
- The following is a very brief history

Ray Davis and his Chlorine based Detector

Pontecorvo Questions Neutrino

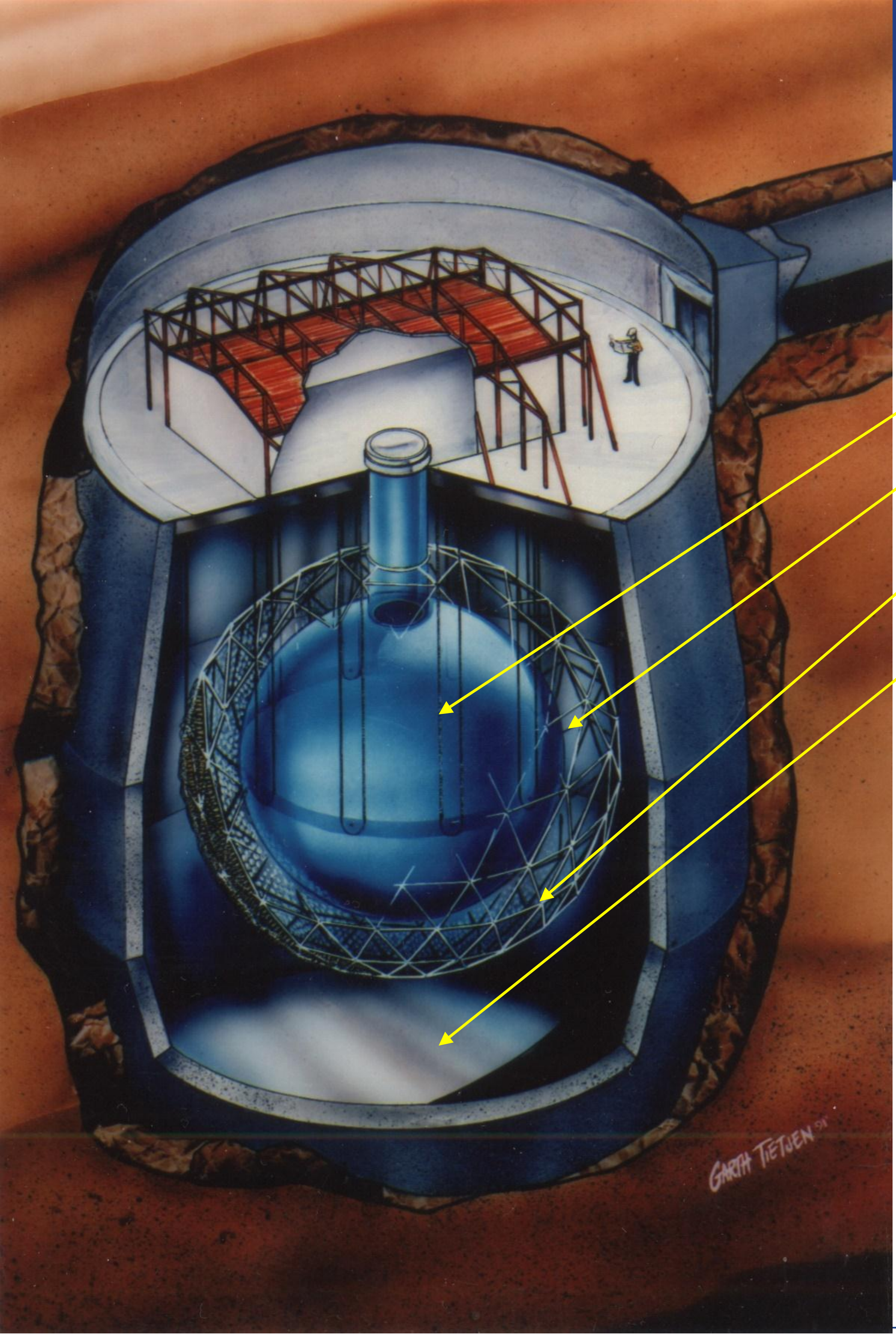
- Perhaps neutrinos ‘oscillate’
- Idea was not generally accepted
- Required large mixing of neutrinos and this went against accepted wisdom
- Strong incentive for Gallium experiments



Bruno Pontecorvo

Background to SNO (cont)

- 1984 Herb Chen proposes a heavy water solar neutrino detector with Neutral Current detection capability
- 1985 Mikheyev and Smirnov develop theory or resonant oscillations
- Suddenly the ‘World’ believes in neutrino oscillations
- Single set of parameters solves SNP with small vacuum mixing, dark matter and supernova!!!
- 1990 SAGE shows greatly suppressed Ga rate
- 1990 Start of construction of SNO



- 1000 Tonnes of D_2O
- 12 M Acrylic vessel
- 10,000 phototubes
- 8000 Tonnes of pure light water
- 2000 m deep in Mine
- World's largest deep cavern
- All materials very pure

Physics with SNO

Look for events in heavy water that could be attributed to neutrinos

3 reactions

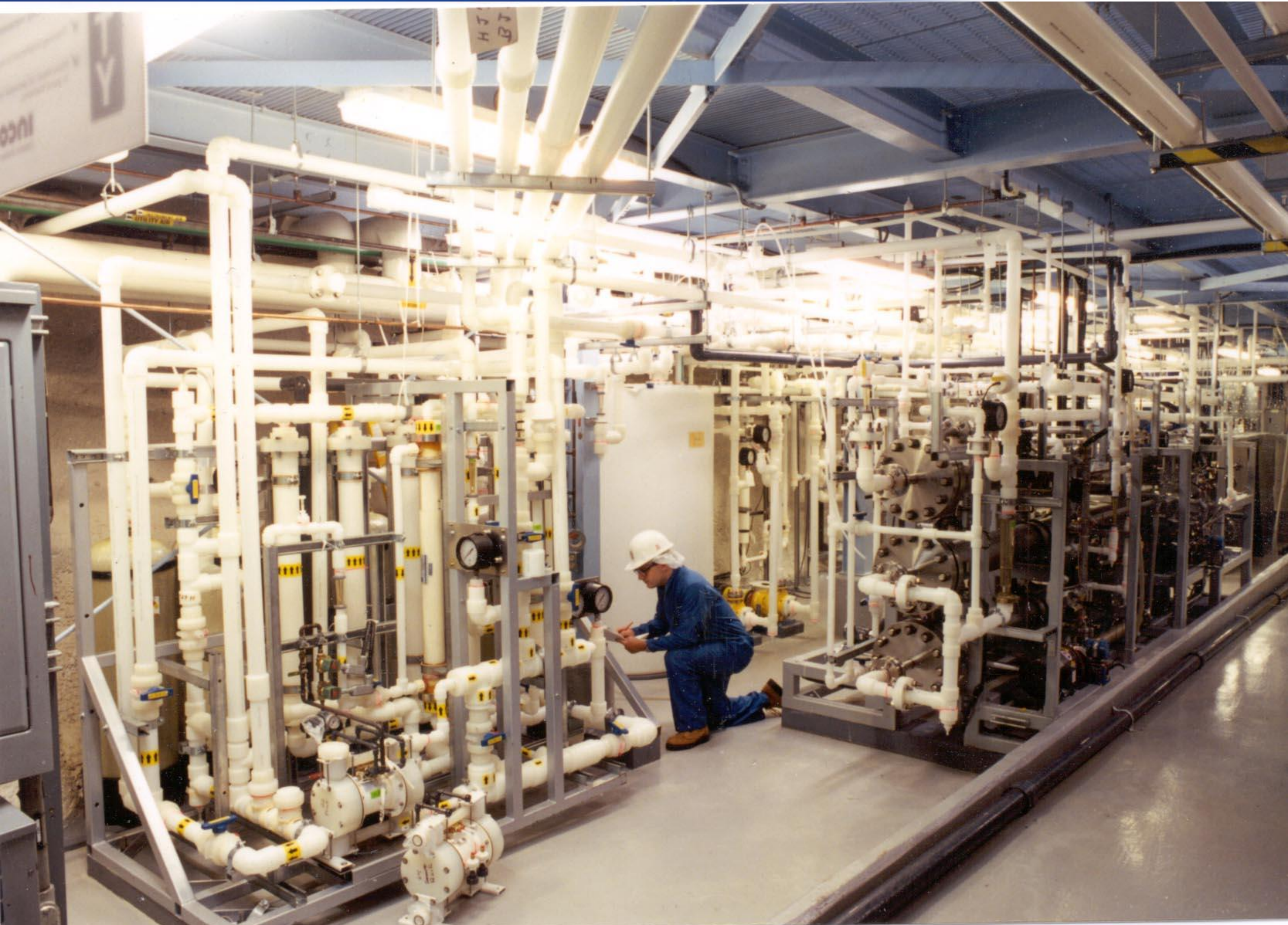
charged current – measures the ν – e flux

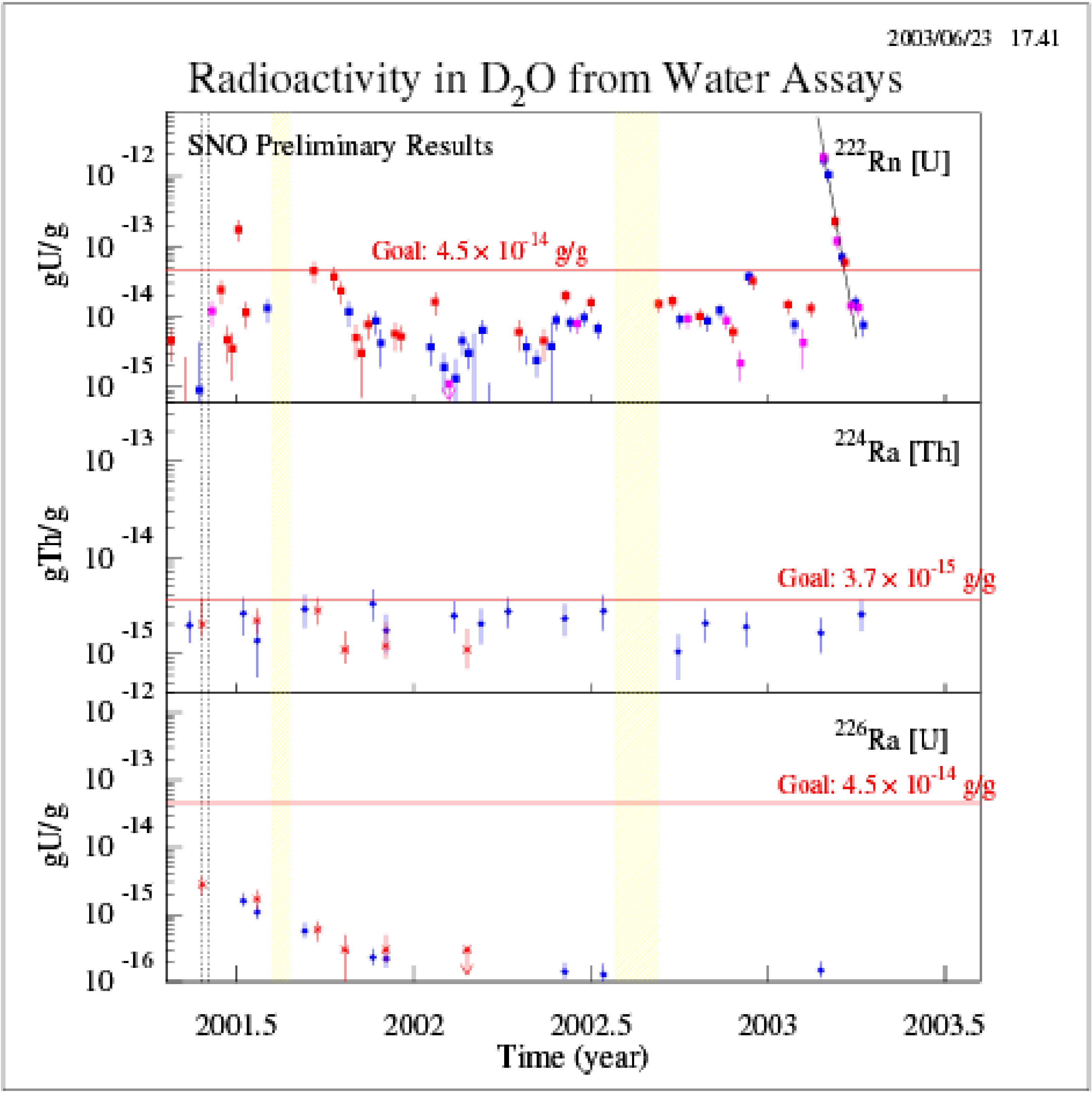
elastic scattering – mix of electron and total neutrino flux sensitivity

neutral current – measures total neutrino flux

Run in 3 phases

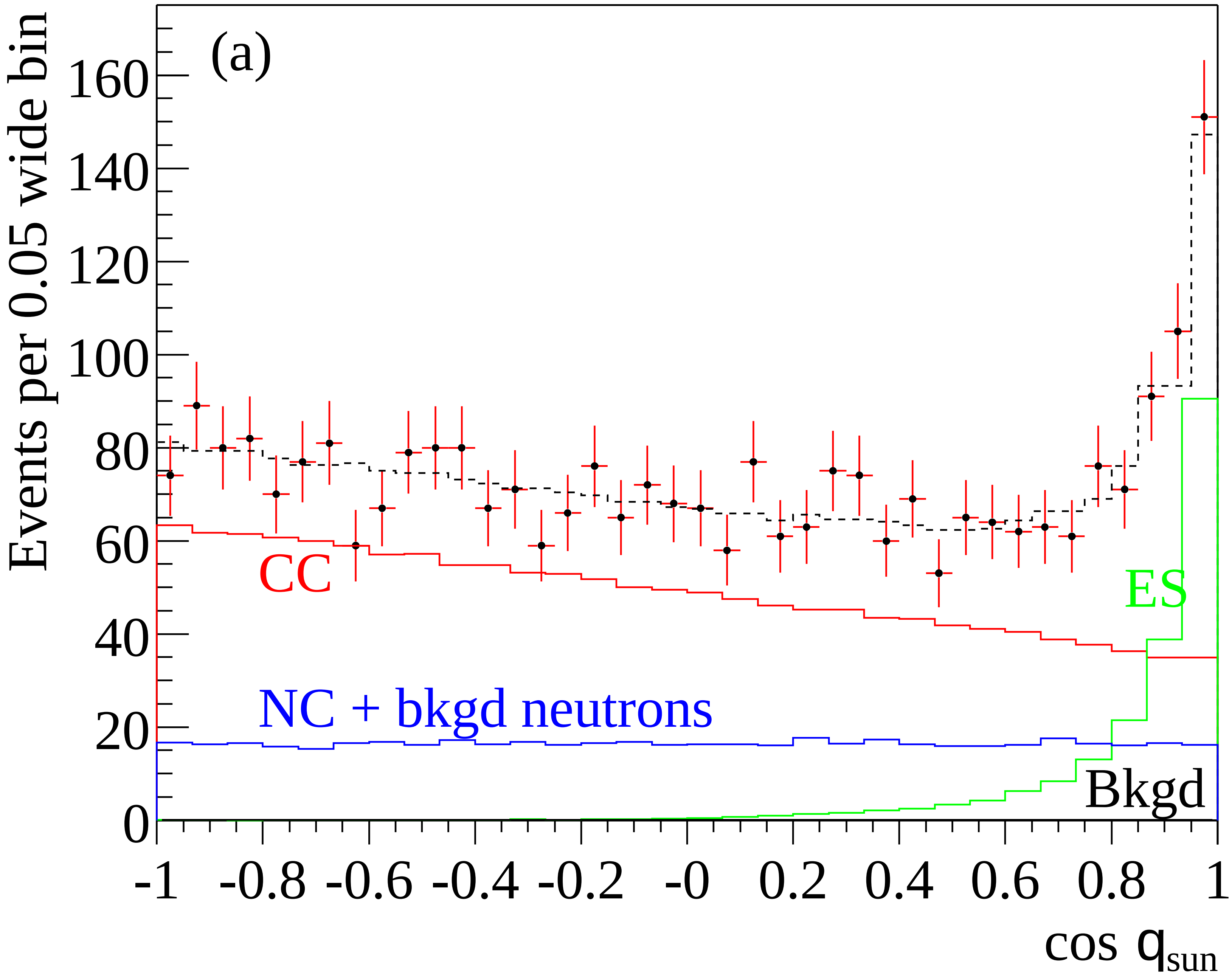
- 1) Run with pure Heavy Water
- 2) Add 0.2% NaCl to enhance NC detection
- 3) Remove NaCl, add Neutral Current Detectors (NCDs)
- Each phase is approx. 2 years

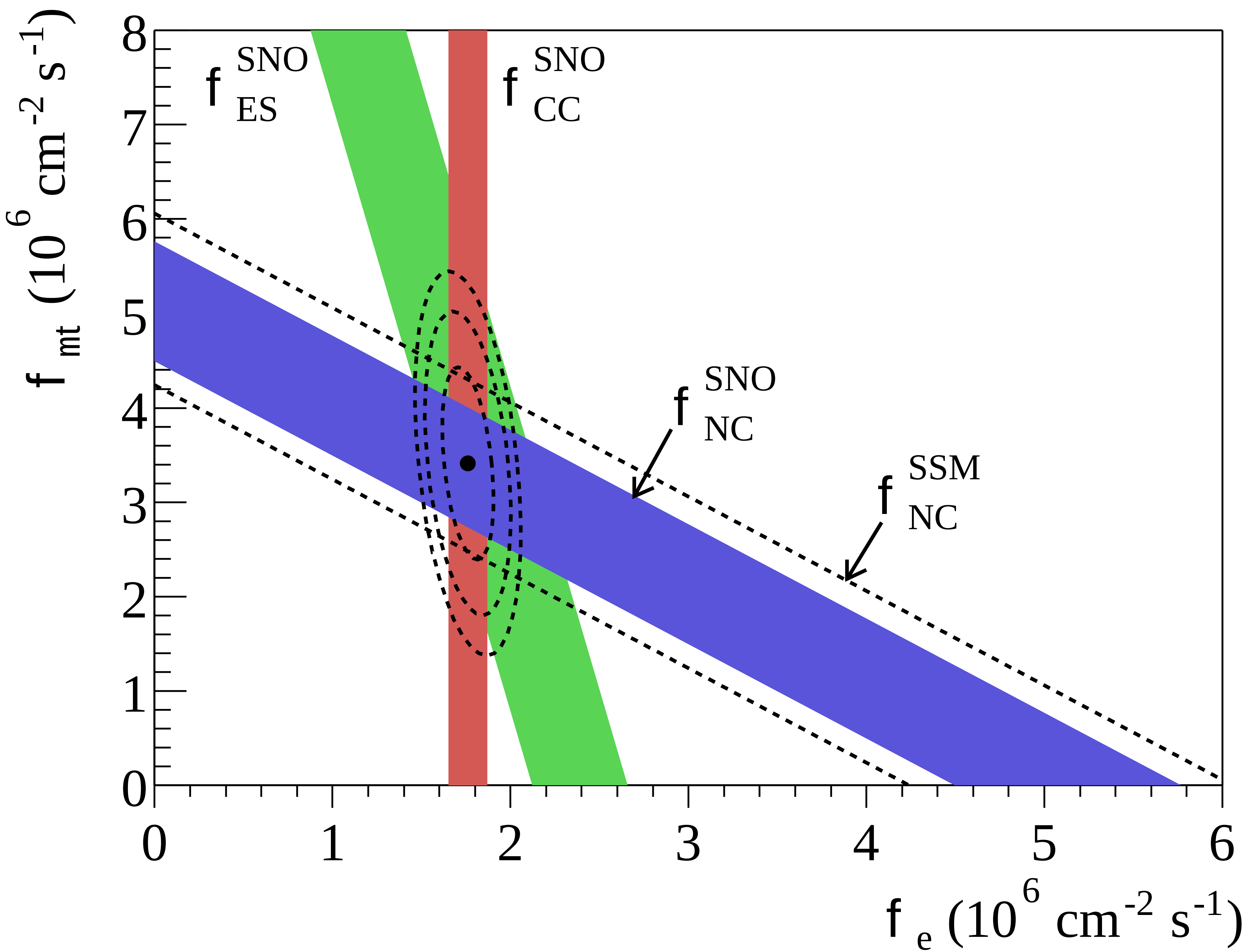




2003/06/23 17.41
Radioactivity in D_2O from Water Assays
SNO Preliminary Results
^{222}Rn [U]
Goal: 4.5×10^{-14} g/g
gU/g
^{224}Ra [Th]
Goal: 3.7×10^{-15} g/g
gTh/g
^{226}Ra [U]
Goal: 4.5×10^{-14} g/g
gU/g
2001.5
2002
2002.5
2003
2003.5
Time (year)

Data plotted as function of Direction to Sun – Pure D_2O




f^{SNO}_{ES}
f^{SNO}_{CC}
f^{SNO}_{NC}
f^{SSM}_{NC}
f_{mt} $(10^6\ cm^{-2}\ s^{-1})$
f_e $(10^6\ cm^{-2}\ s^{-1})$
0
1
2
3
4
5
6
7
8

Results of Salt Phase

$$\phi_{CC}^{SNO} = 1.59^{+0.08}_{-0.07}(\text{stat})^{+0.06}_{-0.08}(\text{syst})$$
$$\phi_{ES}^{SNO} = 2.21^{+0.31}_{-0.26}(\text{stat}) \pm 0.10\,(\text{syst})$$
$$\phi_{NC}^{SNO} = 5.21 \pm 0.27\,(\text{stat}) \pm 0.38\,(\text{syst})$$

As total neutrino flux is much greater than electron neutrino flux neutrinos must oscillate, neutrinos must mix and neutrinos must have mass

SNO Recognition

The Nobel Prize in Physics 2015

Photo: A. Mahmoud
Takaaki Kajita
Prize share: 1/2

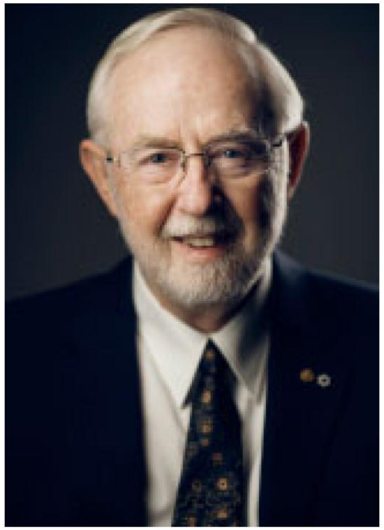


Photo: A. Mahmoud
Arthur B. McDonald
Prize share: 1/2

The Nobel Prize in Physics 2015 was awarded jointly to Takaaki Kajita and Arthur B. McDonald *"for the discovery of neutrino oscillations, which shows that neutrinos have mass"*

Where do we go from here

- Where do neutrino masses come from and can we get a more direct measure of the masses? Can detection of double beta decay help?
- Neutrinos cannot make up a large fraction of the Dark Matter. Can we find what does?
- We have done a precision measurement on high energy solar neutrinos – can we go lower?
- These questions follow from the success of SNO
- Attempted solutions build on the technology developed to make SNO possible

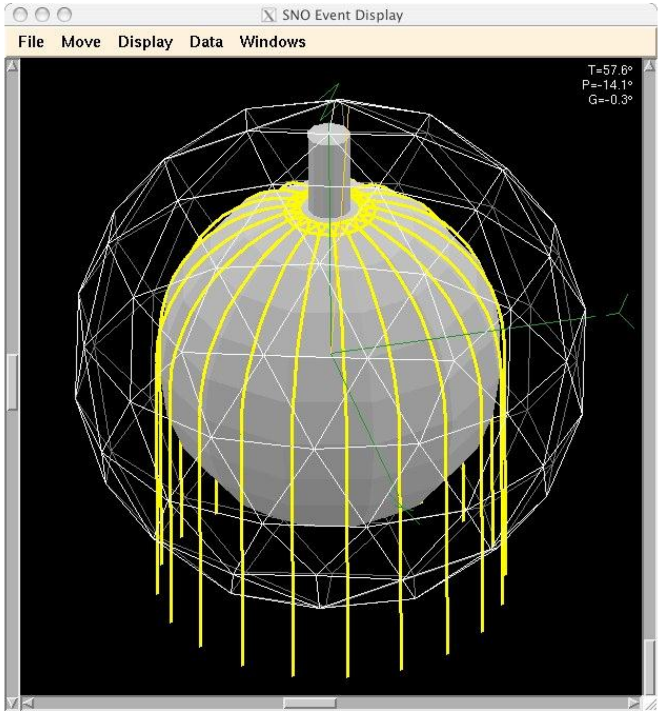
SNOLAB

- SNOLAB is a facility that provides a basic infrastructure in which to mount ultra-low background experiments
- It has been established as an International Facility for Underground Science
- Continues the vision of Baksan but will not focus on cosmic ray physics

Double Beta Searches

- SNO+
  - Convert SNO to liquid scintillator
  - Use of LAB scintillator
  - Load with Tellurium to search for double beta decay

  - Status - Currently filled with light water to commission detector

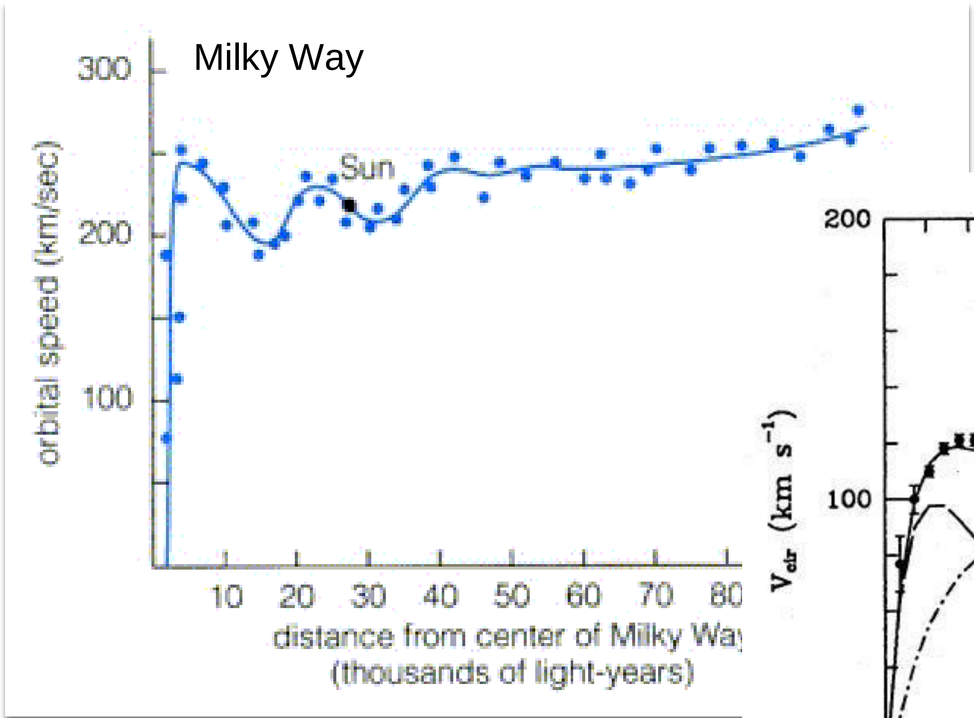


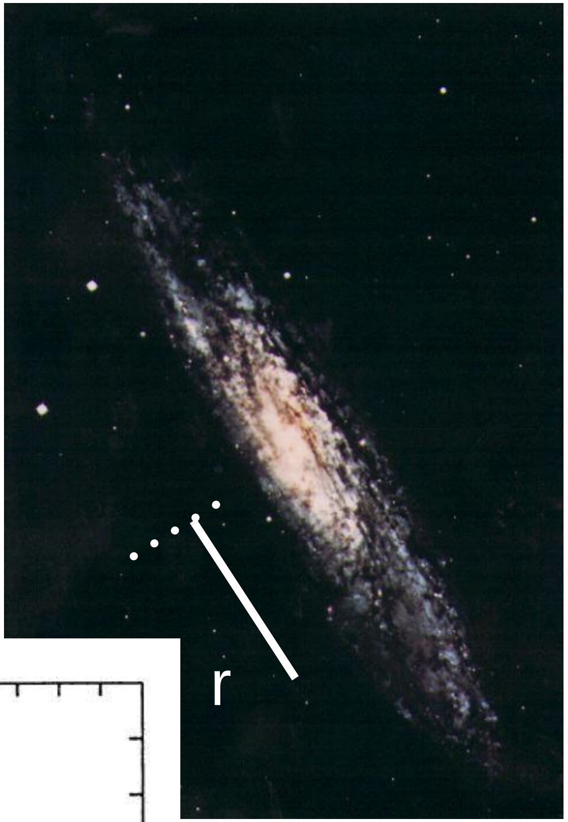
Future double beta

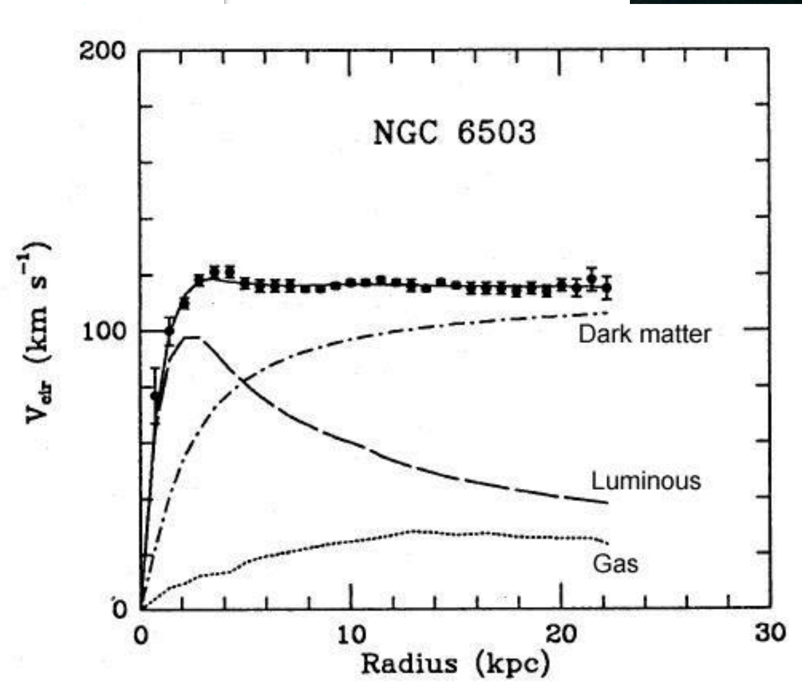
- Possible large double beta decay experiment with xenon (See Vladimir’s talk)
- Possible germanium detector
- Large hall (Cryopit) available
- Decision will follow US downselect process

What is the dark matter puzzle?

- There is more to a galaxy than meets the eye...
- Looking at the speed of a star in a rotating galaxy shows there is more material within than can be accounted for by stars, dust, etc.
- Material you can't see - dark matter

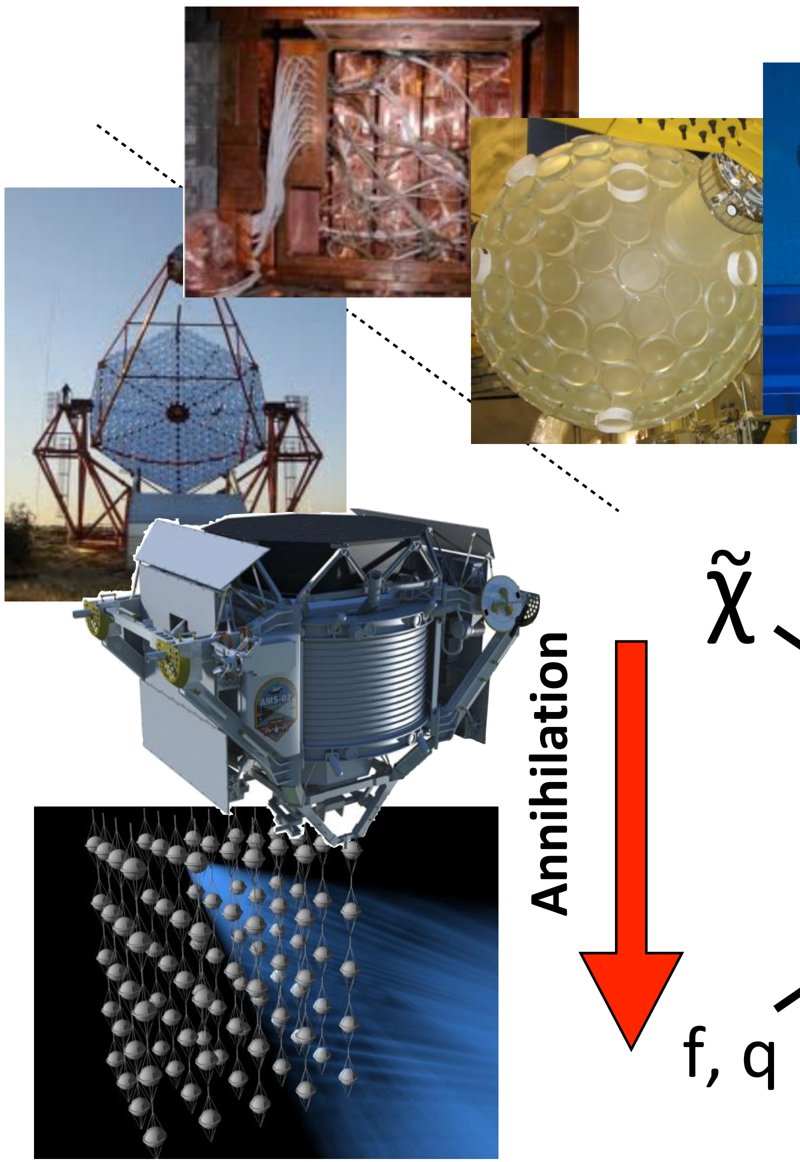


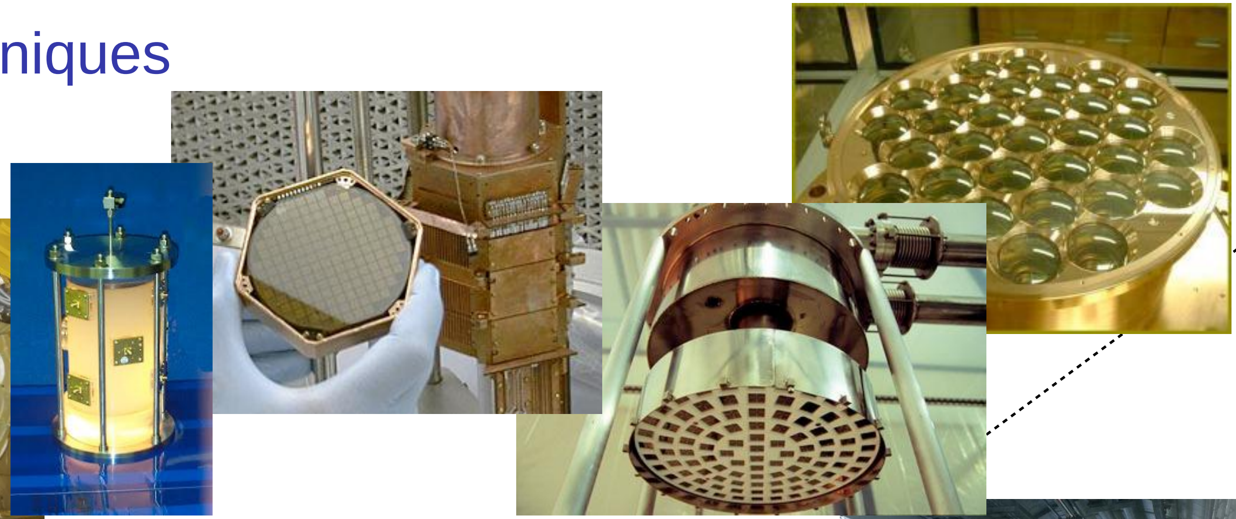


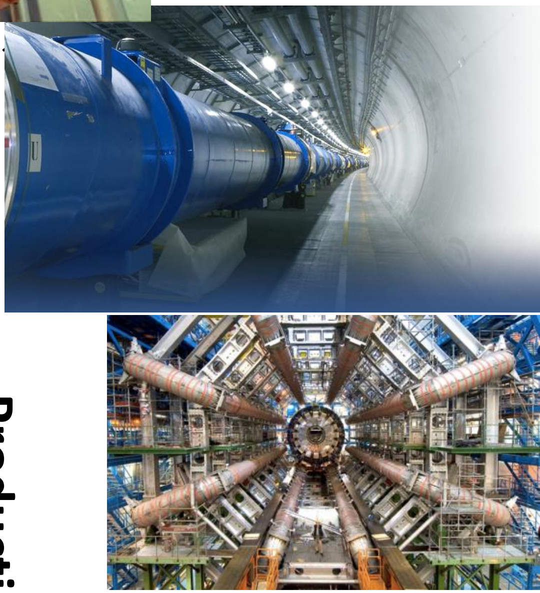


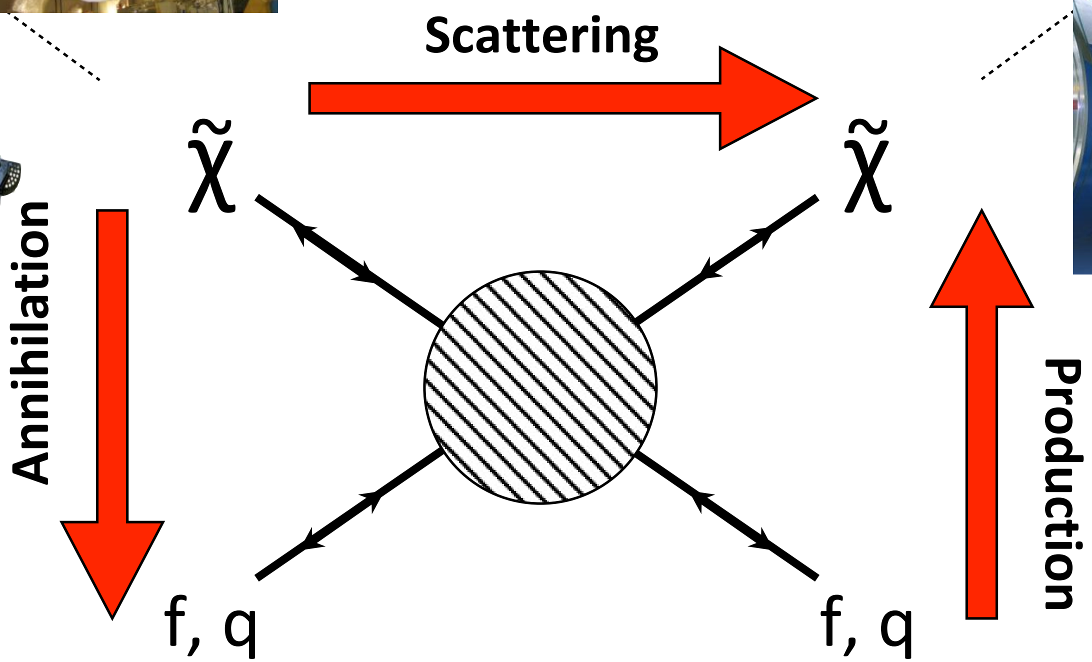
Dark Matter Experimental techniques

- Complementary techniques









Experimental Challenge

- WIMP nuclear recoil signal is:
  - Low rate (0.01 - 10^{-5} events/kg/day)
  - Small energy (1-100 keV actual: observed is less)

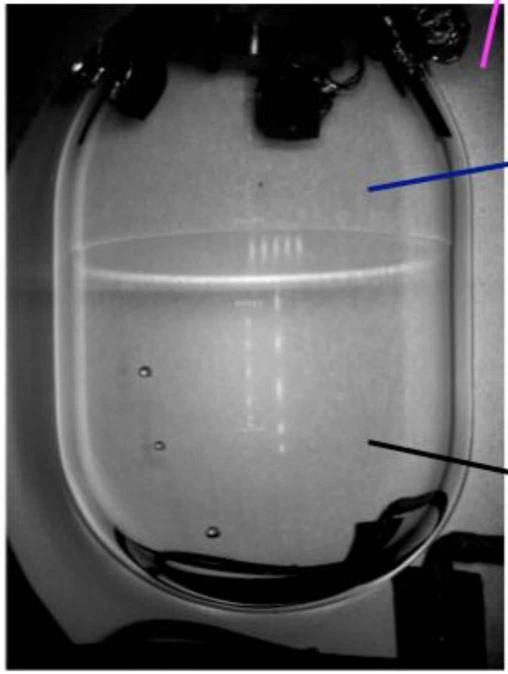
- Detection technique must be:
  - Low background
    - Gamma, beta: from U/Th/Co/Pb/etc radio-impurities
    - Neutron, nuclear: from U/Th radio-impurities, radon daughters and c.r. μ spallation
    - Go underground!
  - Low threshold
    - To minimise form factor, maximise spectrum
  - Discriminating - Position sensitivity
    - Difference between WIMPs/n and γ/β, background rejection, directionality
  - Large, massive
    - Provide enough target material for interactions

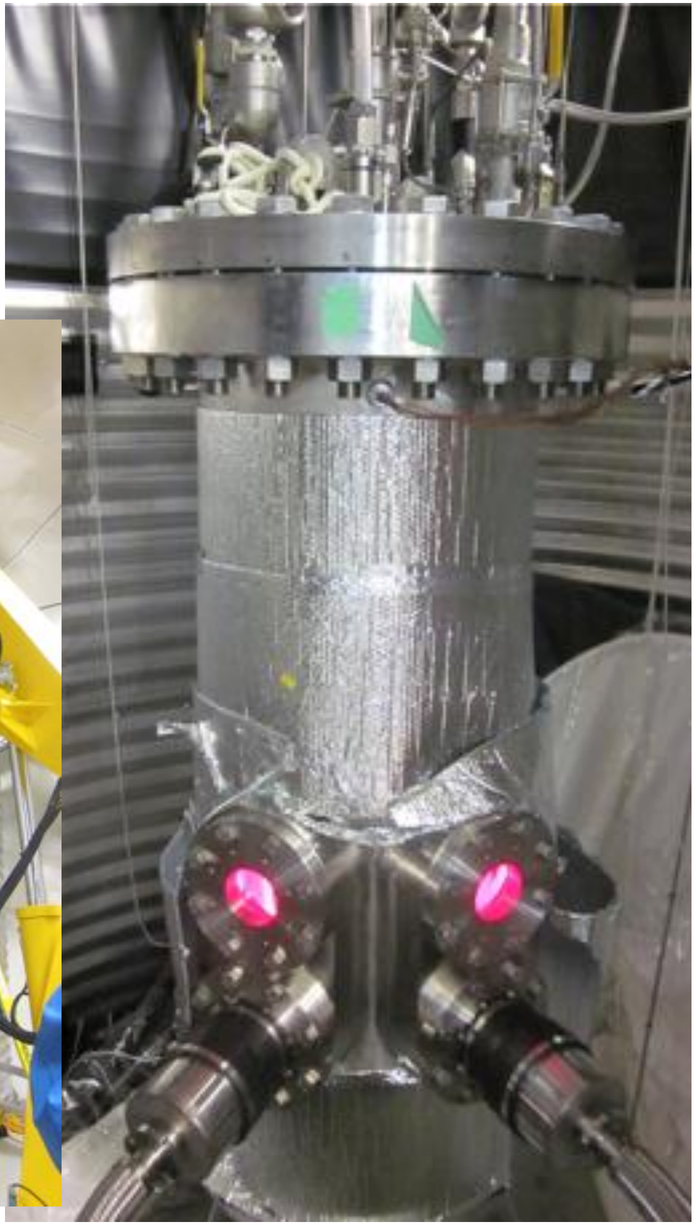
Current programme:
Dark Matter at SNOLAB

- Noble Liquids: DEAP-I, MiniCLEAN, & DEAP-3600
  - Single Phase Liquid Argon using pulse shape discrimination
  - Prototype DEAP-I completed operation. Demonstration of PSD at 10^8.
  - DEAP-3600 operational - first commissioning and calibration data under analysis, MiniCLEAN currently filling with argon.
  - Will measure Spin Independent cross-section.
- Superheated Liquid / Bubble chamber: PICASSO, COUPP & PICO
  - Superheated droplet detectors and bubble chambers. Insensitive to MIPS radioactive background at operating temperature, threshold devices; alpha discrimination demonstrated;
  - PICO-60 (C_3F_8) in data taking; New chamber in construction to remove interface events (PICO-40);
  - Measure Spin Dependent cross-section primarily, some sensitivity to SI;
  - World leading spin-dependent sensitivity published in 2012, 2015, 2017.
- Solid State: DAMIC, SuperCDMS
  - State of the art CCD (DAMIC) Si / Ge crystals with ionisation / phonon readout (SuperCDMS).
  - DAMIC operational since 2012, 100g CCD operational; Upgrade planned to 1kg
  - SuperCDMS next phase will benefit from SNOLAB depth to reach desired sensitivity. Approved as a US DOE/NSF G2 experiment
  - Mostly sensitive to Spin Independent cross-section at low mass.

PICO-60 Recent Results

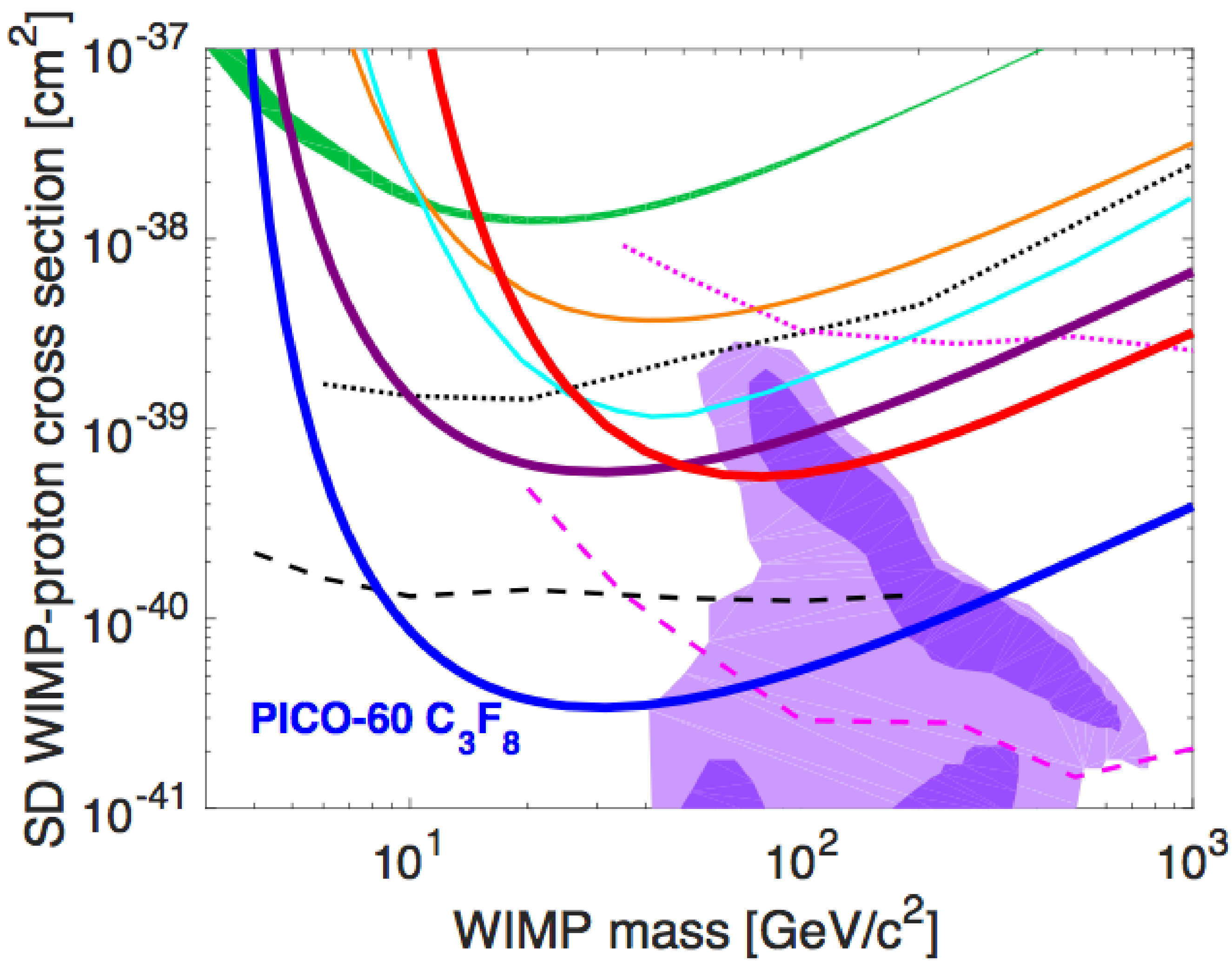
- Superheated fluid bubble chambers
- Particle interactions nucleate bubbles
  - Good discrimination against backgrounds
  - Alphas ’louder’
  - Gammas do not nucleate
- Visual and acoustic sensors





arXiv: 1702.07666

WIMP - Proton Exclusion

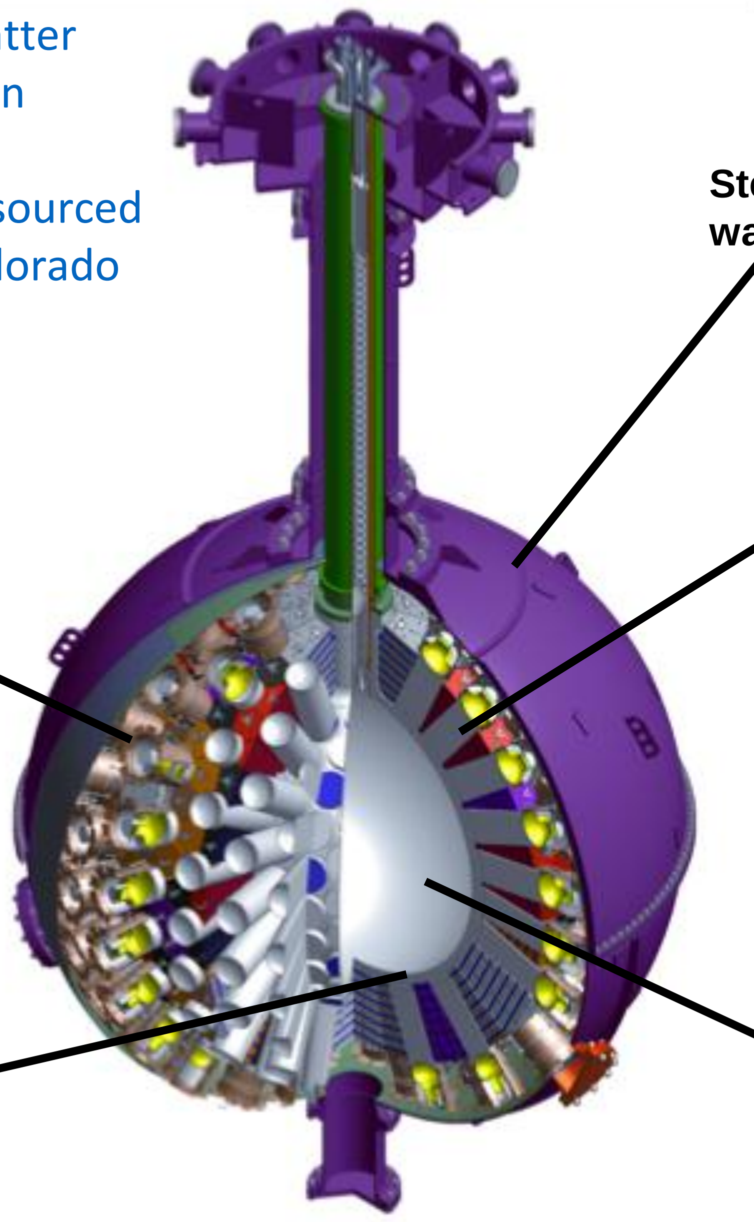


The 90% C.L. limit on the SD WIMP-proton cross section from PICO-60 C3F8 blue, along with limits from PICO-60 CF3I (red), PICO-2L (purple), PICASSO (green), SIMPLE (orange), PandaX-II (cyan), IceCube (dashed and dotted pink), and Super-K (dashed and dotted black)

DEAP-3600 Design

Uses liquid argon as a dark matter target with good discrimination

Low background argon being sourced from underground wells in Colorado



Steel Shell immersed in 8 m water shield at SNOLAB

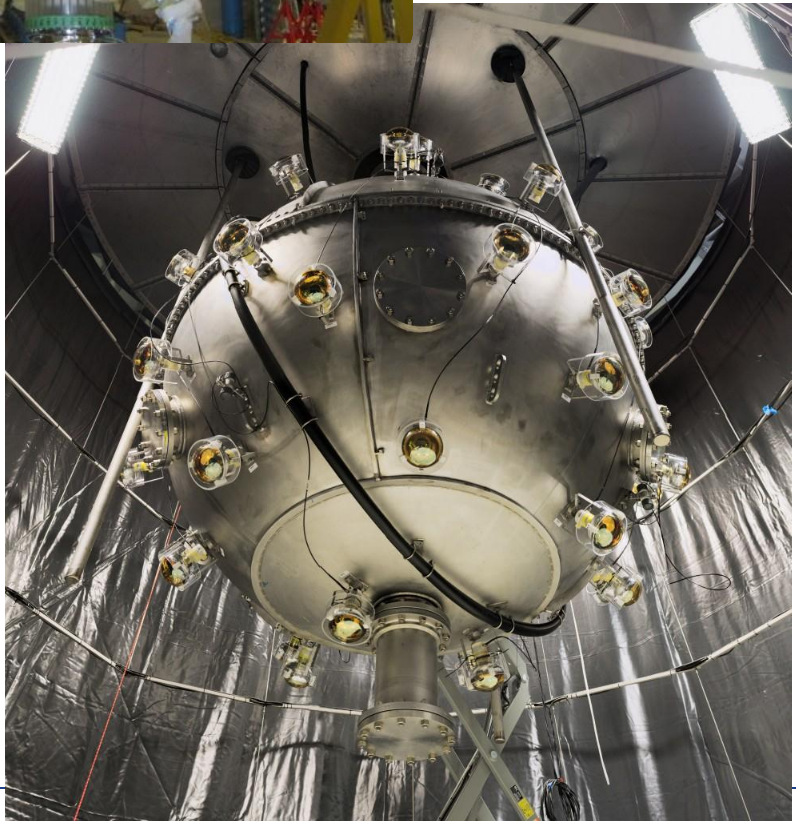
255 Light sensors
Hamamatsu R5912 HQE PMTs
8-inch (32% QE, 75% coverage)

50 cm light guides + polyethylene shielding provide neutron moderation

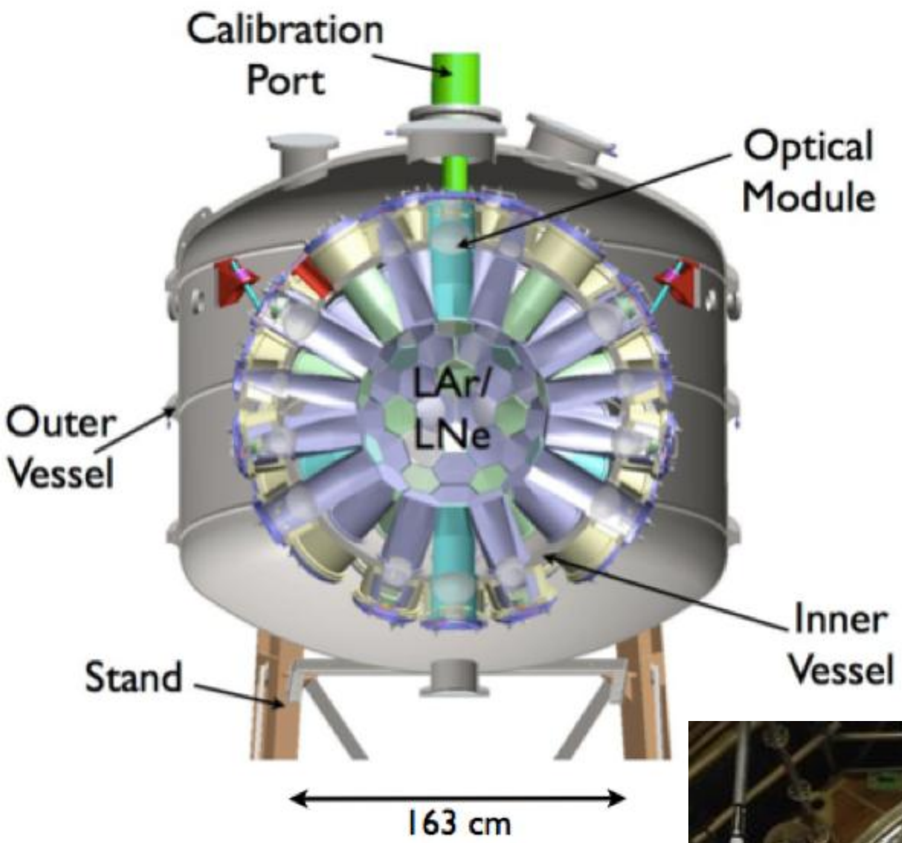
Vessel is "resurfaced" in-situ to remove deposited Rn daughters after construction

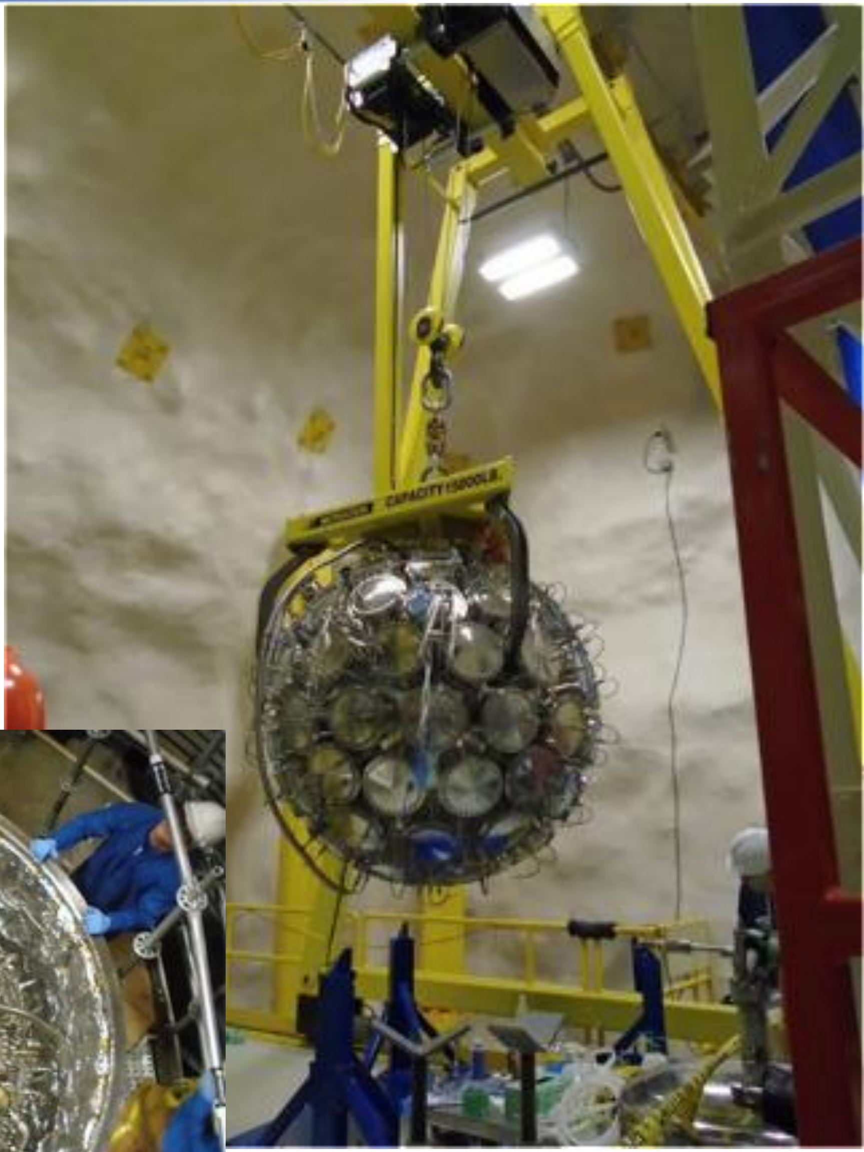
3600 kg argon target (1000 kg fiducial) in sealed ultra-clean Acrylic Vessel

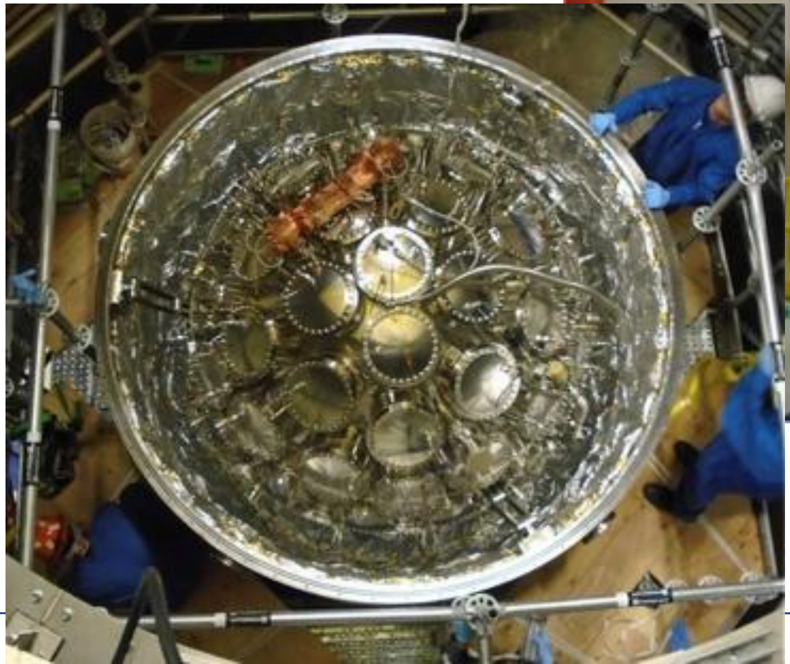
DEAP-3600 Construction



MiniCLEAN Design / Construction



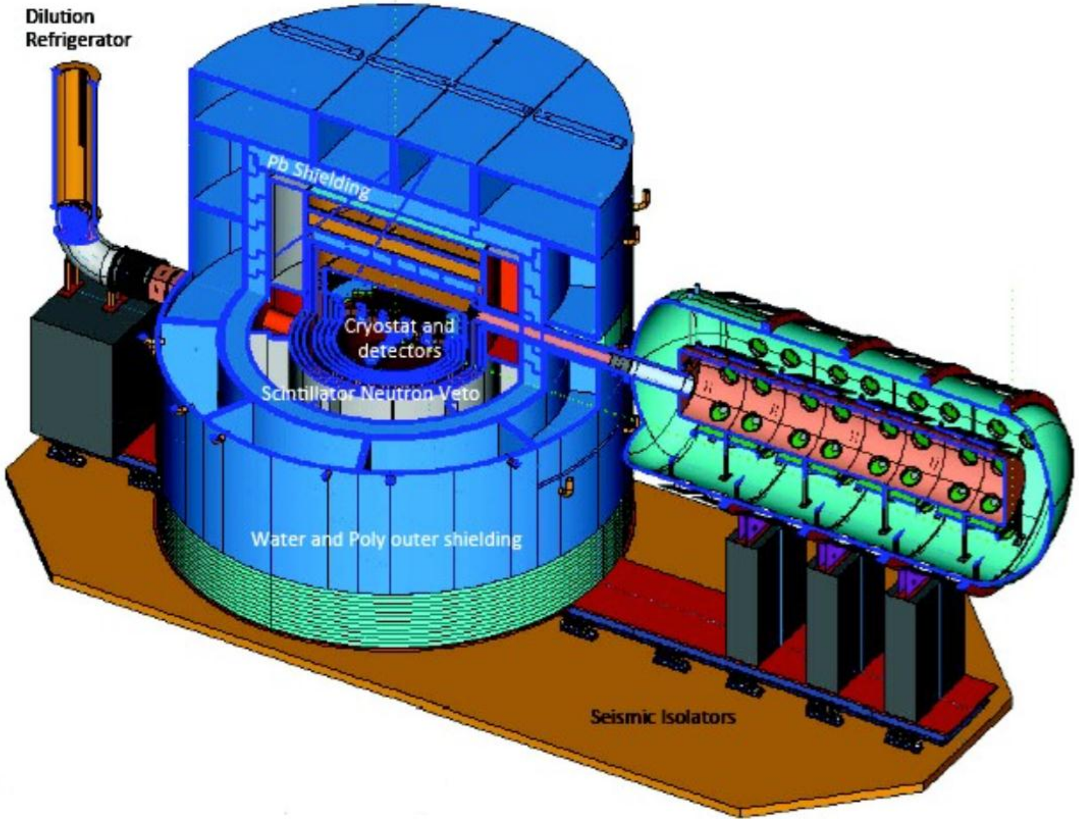




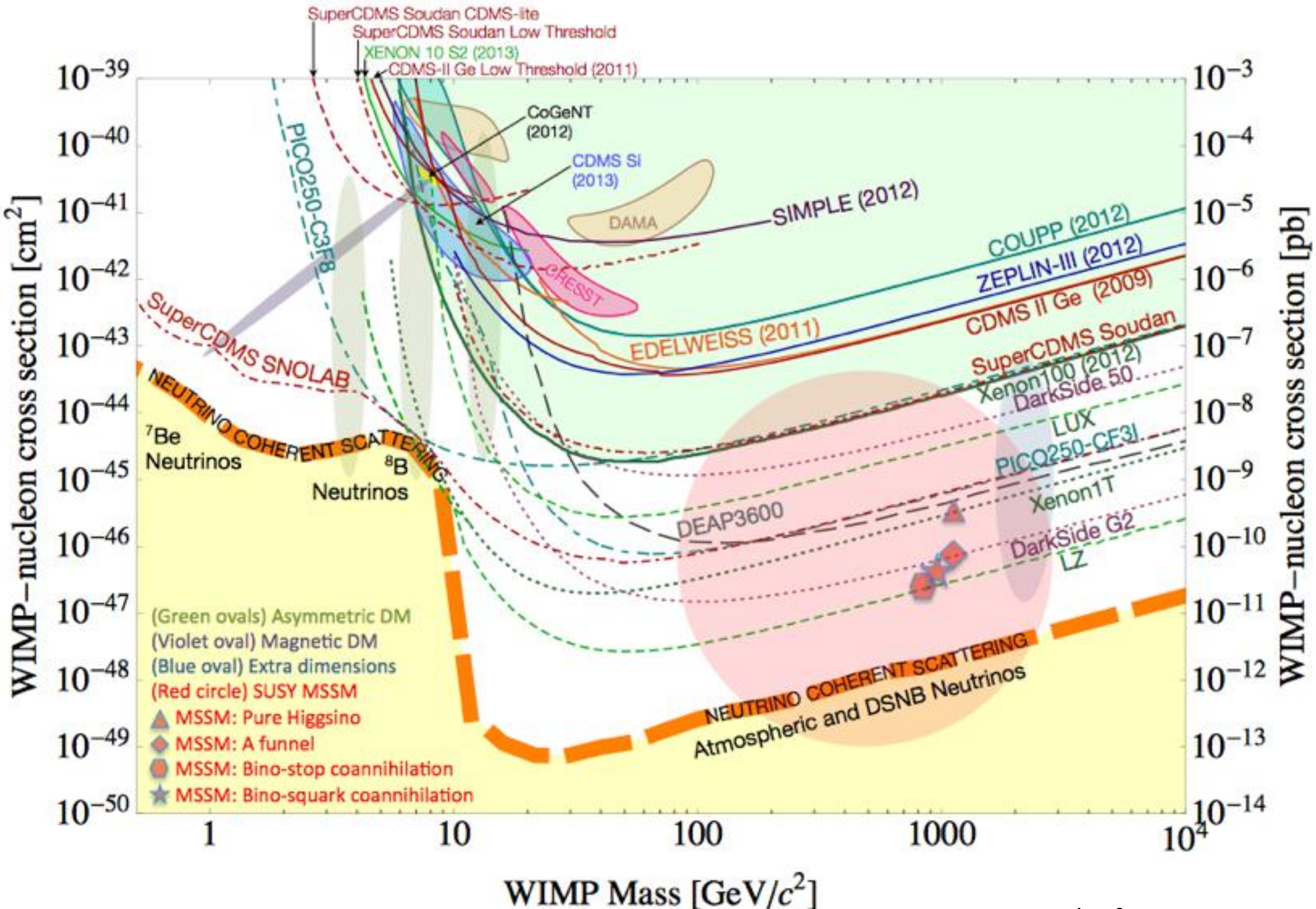
Cryogenic Detector Programme

- US G2 Down-select funded SuperCDMS-SNOLAB with emphasis on low energy WIMPS. Cryostat and system to accommodate full 400 kg capacity with ~25kg will be initially deployed.
  - Potential future international developments
- SNOLAB and SuperCDMS working to coordinate between funding agencies, laboratory and experiment, through the project lifecycle.

Ladder labs – SuperCDMS / CUTE location



Spin independent results summary



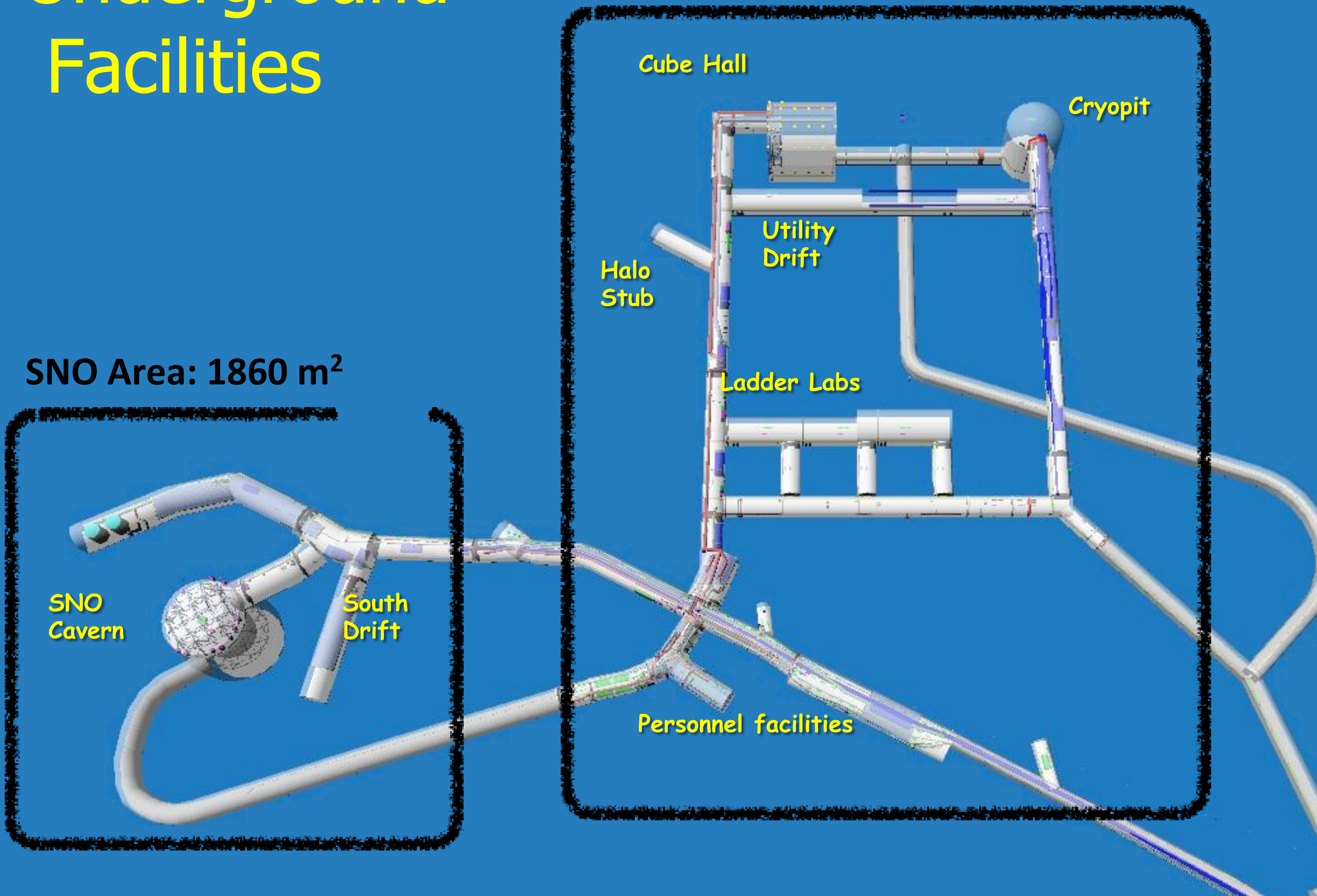
Plot from SNOMASS Review

Surface Facilities

Underground Facilities

SNOLAB Area: 5360 m^2

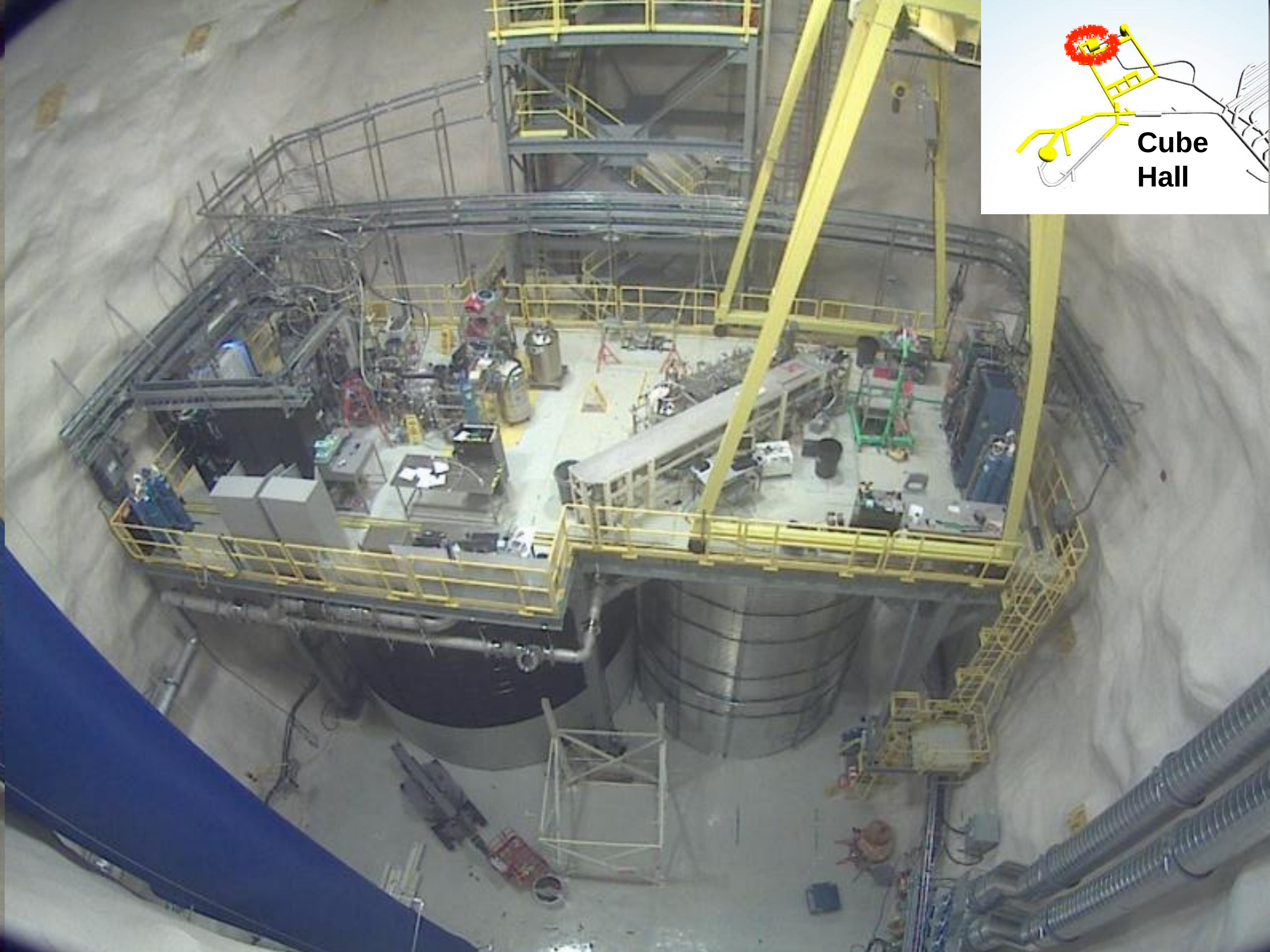
SNO Area: 1860 m^2




Lab Entry
6800


Lab
Entrance

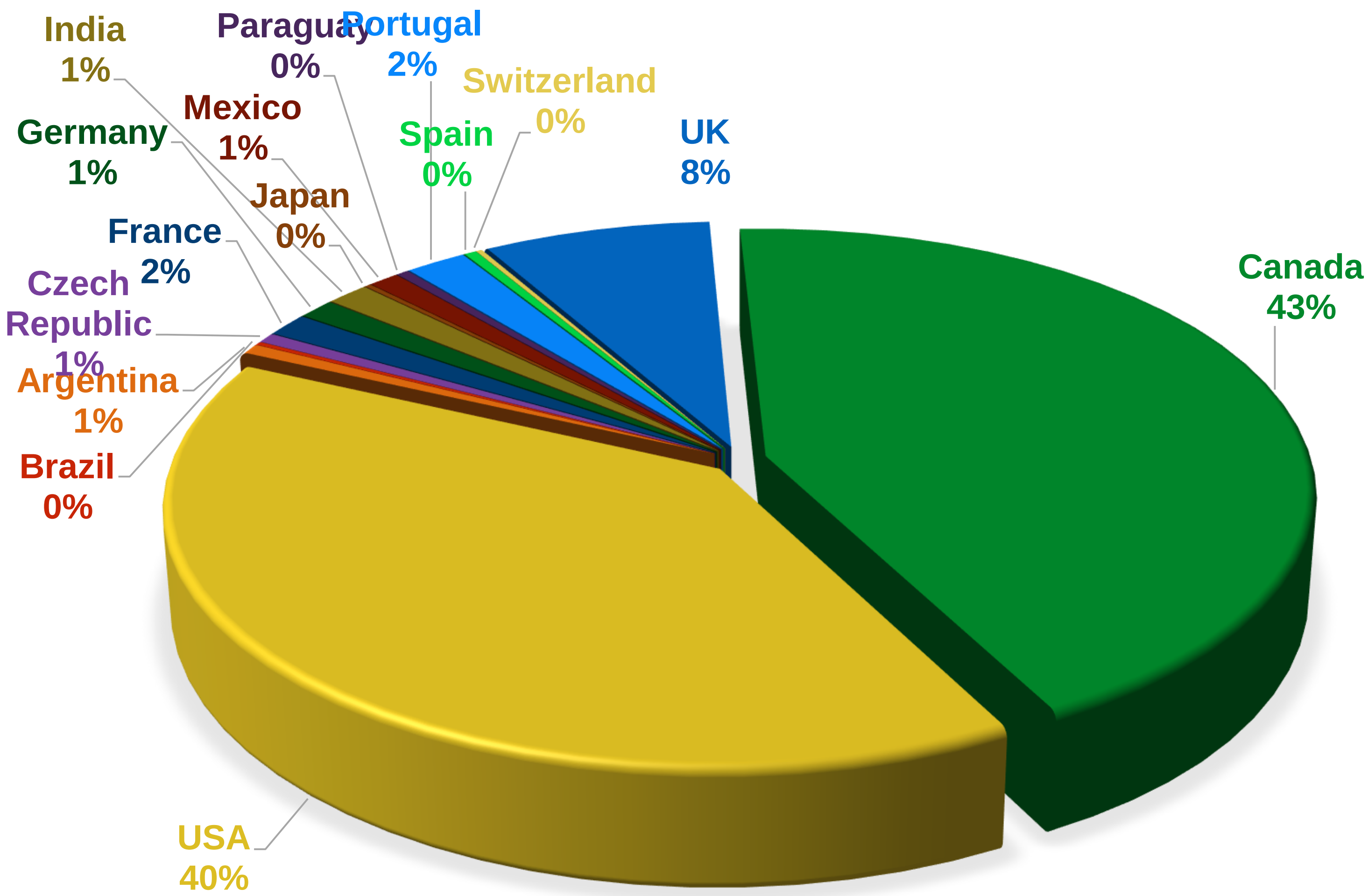

Cryopit


Cube
Hall

Community supported

- 164 faculty researchers from 78 institutions over 15 countries
  - ~25% of faculty are Canadian
- ~500 faculty, highly qualified personnel and technical support
- ~11,000 underground person-shifts per year (~50/dayshift)

Users by Country



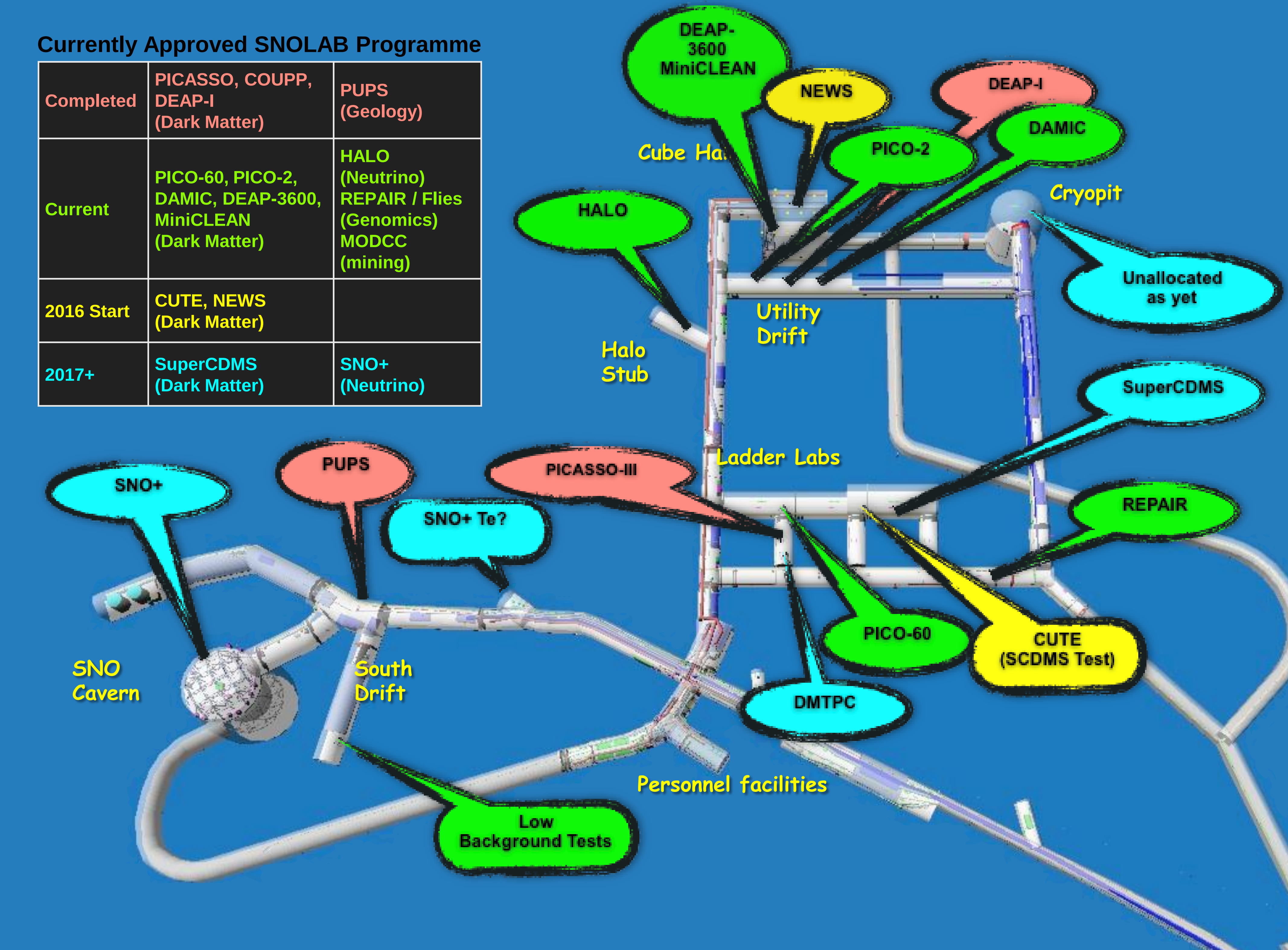
Total Number of Users - 488

Current programme

Experiment	Neutrino	Dark Matter	Status	Collaboration Demographics
CUTE		√	In Preparation	Canada, US, UK, France, India, Spain
DAMIC		√	Operational	Canada, US, Argentina, Brazil, Mexico, Paraguay, Switzerland
DEAP-3600		√	Operational	Canada, US, UK
DEAP-50T/CLEAN		√	Letter of Intent	Canada, US, UK
DMTPC		√	Concept Phase	US, UK,
DUST			Letter of Intent	Canada
FLAME			Operational	Canada
Ge-1T	√		Letter of Intent	Canada, US
nEXO	√		Concept Phase	Canada, US
HALO	√		Operational	Canada, US, UK, France, Germany, Japan
MiniCLEAN		√	Commissioning	Canada, US
MODCC			Operational	Canada
NEWS		√	In Preparation	Canada, US, France
PICO-60		√	Operational	Canada, US, Czech Republic, India, Mexico
PICO-500		√	Letter of Intent	Canada, US, Czech Republic, India, Mexico
REPAIR			Operational	Canada
SuperCDMS		√	In Preparation	Canada, US, UK, France, India, Spain
SNO+	√		Commissioning	Canada, US, UK, Germany, Mexico, Portugal

Currently Approved SNOLAB Programme

Completed	PICASSO, COUPP, DEAP-I (Dark Matter)	PUPS (Geology)
Current	PICO-60, PICO-2, DAMIC, DEAP-3600, MiniCLEAN (Dark Matter)	HALO (Neutrino) REPAIR / Flies (Genomics) MODCC (mining)
2016 Start	CUTE, NEWS (Dark Matter)	
2017+	SuperCDMS (Dark Matter)	SNO+ (Neutrino)



Summary

- Deep underground research facilities provide the ultra-quiet radioactive background environments for rare or low energy interactions
- SNOLAB has developed from the initial SNO solar neutrino detector to support a wide range of projects:
  - Direct Galactic dark matter searches
  - Neutrino intrinsic physics properties
  - Natural neutrino sources
  - Genomics
  - Mining innovation
- The initial science programme has already delivered new results, with the larger experiments coming on line imminently
  - PICO-60 new results in 2017
  - Next major results anticipated from DEAP-3600 detector in time for TAUP
  - SNO+ being commissioned with water, first scintillator on site