Title: Art McDonald: A Deeper Understanding of the Universe from 2 km Underground

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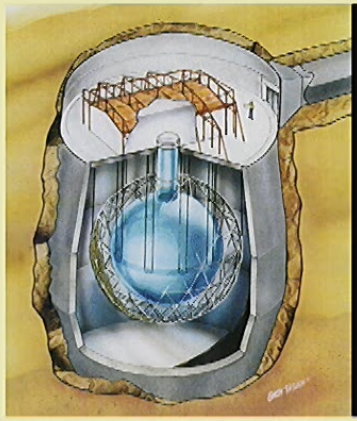
Abstract: By creating an ultra-clean underground location with a highly reduced radioactive background, otherwise impossible measurements can be performed to study fundamental physics, astrophysics and cosmology. The Sudbury Neutrino Observatory (SNO) was a 1,000 tonne heavy-water-based neutrino detector created 2 km underground in a mine near Sudbury, Canada. SNO has used neutrinos from 8B decay in the Sun to observe one neutrino reaction sensitive only to solar electron neutrinos and others sensitive to all active neutrino flavors. It found clear evidence for neutrino flavor change that also requires that neutrinos have non-zero mass. This requires modification of the Standard Model for Elementary Particles and confirms solar model calculations with great accuracy. The 2015 Nobel Prize in Physics and the 2016 Breakthrough Prize in Fundamental Physics were awarded for these measurements. Future measurements at the expanded SNOLAB facility will search for Dark Matter particles thought to make up 26% of our Universe and rare forms of radioactivity that can tell us further fundamental properties of neutrinos potentially related to the origin of our matter-dominated Universe.

A Deeper Understanding of the Universe from 2 km Underground

Sudbury Neutrino Observatory



Art McDonald,
Professor Emeritus
Queen's University, Kingston, Ontario

With our laboratory 2 km underground we have created the lowest radioactivity location in the world where we study some of the most basic scientific questions:

- **How do stars like our Sun burn and create the elements from which we are made?**

- **What are the basic Laws of Physics for the smallest fundamental particles?**

- **What is the composition of our Universe and how has it evolved to the present ?**

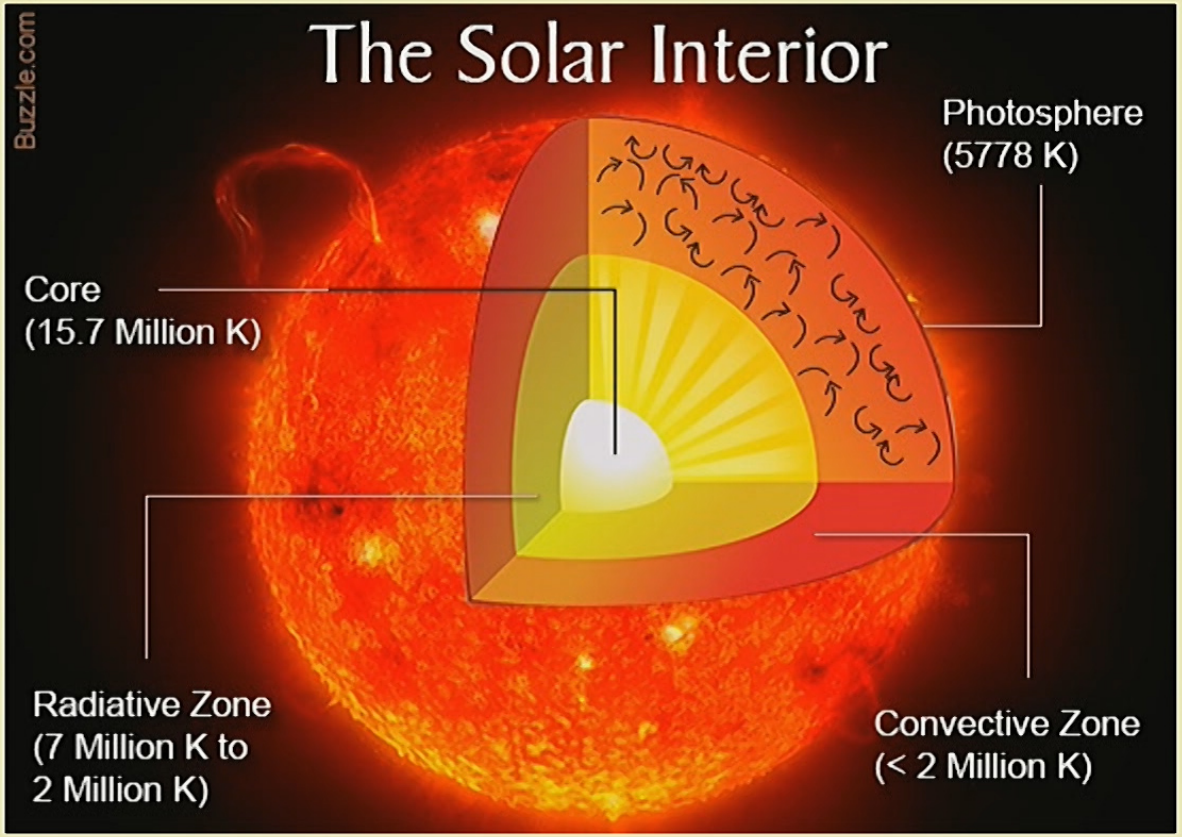
How do you make measurements that can provide answers to enormous questions like these?

Answers:

1: Measure elusive particles called NEUTRINOS that come from the deepest reaches of the Sun where the energy is generated.

2: Measure fundamental particles (DARK MATTER) that are left over from the original formation of the Universe.

3. Measure rare forms of radioactivity (DOUBLE BETA DECAY) that can tell us more about fundamental laws of physics.



The middle of the sun is so hot that the centers of the atoms (nuclei) fuse together, giving off lots of energy and particles called neutrinos.

Neutrino facts:

• Neutrinos, along with electrons and quarks, are basic particles of nature that we do not know how to sub-divide further.

• Neutrinos come in three "flavours" (electron, mu, tau) as described in The Standard Model of Elementary Particles, a fundamental theory of microscopic particle physics.

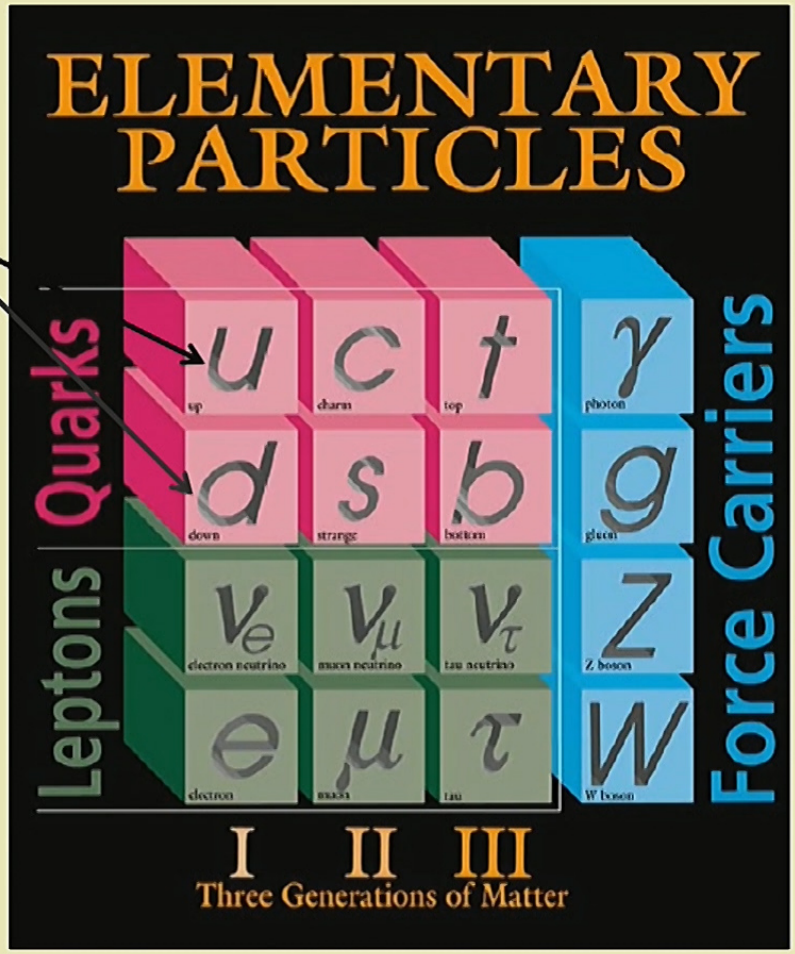
•They only stop if they hit the nucleus of an atom or an electron head-on and can pass through a million billion kilometers of lead without stopping. They only feel the Weak Force.

• Therefore they are very difficult to detect and their properties have been the least known among the basic particles.

• The Standard Model said that they should not change their flavor. If they do, it means that they have a mass greater than zero.

- Three up and/or down Quarks are combined to make a proton or neutron.

- An atom is composed of electrons circling a nucleus containing protons and neutrons.

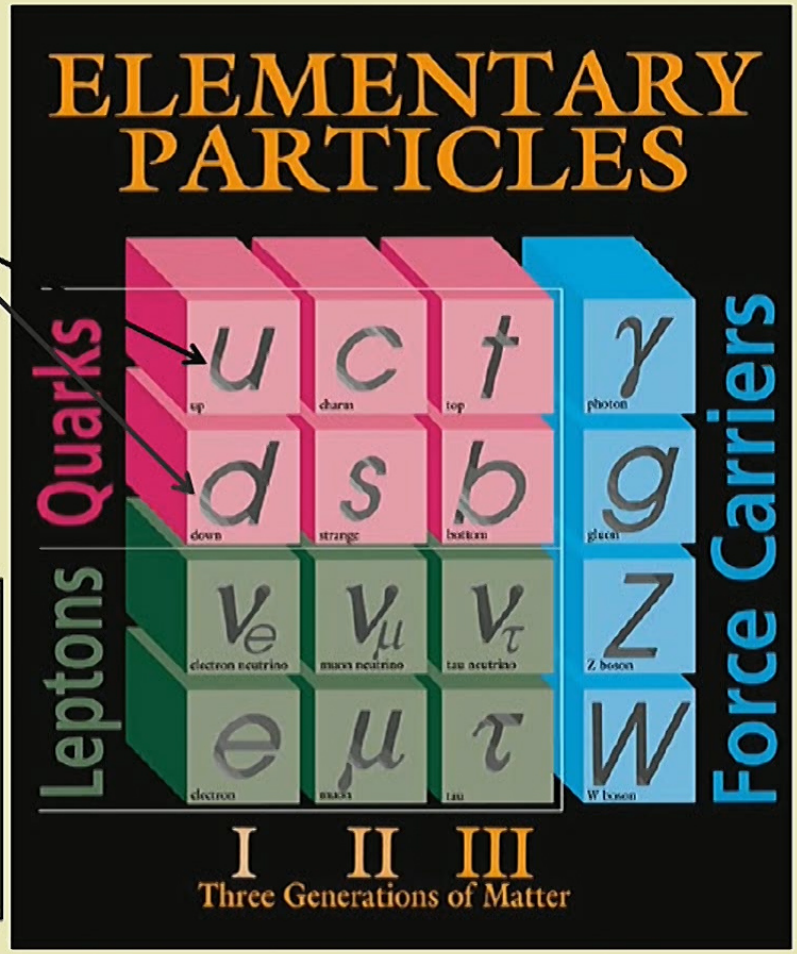


+
Higgs
Boson
+
Graviton

- Three up and/or down Quarks are combined to make a proton or neutron.

- An atom is composed of electrons circling a nucleus containing protons and neutrons.

- Neutrinos feel only the weak force (and gravity) and are produced in some forms of radioactivity or in nuclear or particle reactions involving the transformation of quarks.



+ Higgs Boson + Graviton

The original Standard Model included neutrinos with zero mass and never changing from one type to another. We and others have shown that this is not correct.

Why is it important for us to know these details about the sun & neutrinos?

1. **The Sun**: Most of the elements from which we are made **(H, C, N, O)** were **produced** in the nuclear processes in the center of stars like the sun.

2. **Neutrinos** are an essential part of the production of all the elements heavier than iron in collapsing stars called **supernovae.**

3. **The Sun**: People are trying to reproduce the sun's energy generation here on earth, confined by magnetic fields instead of gravity. It is called a **fusion power source**. We have proven that calculations of sun are very accurate, and they are very similar to the calculations needed for **fusion power here on earth.**

4. **Neutrinos**: Neutrinos are produced extensively in the Big Bang and depending on their mass, canhave a significant influence on **how the Universe evolves**.

5. **Neutrino Astronomy** can be used to study far distant parts of our Universe.

So our measurements help with our understanding of the Universe large and small as well as providing practical information for new energy systems here on earth.

The major scientific question that SNO set out to answer

• THE NUCLEAR REACTIONS WHICH POWER THE SUN MAKE ENORMOUS NUMBERS OF NEUTRINOS.

• HOWEVER, DAVIS' NEUTRINO MEASUREMENTS 1967-84 OBSERVED TOO FEW OF THE ELECTRON FLAVOUR NEUTRINOS PRODUCED IN THE SUN, COMPARED TO SOLAR MODEL CALCULATIONS

(The Solar Neutrino Problem).

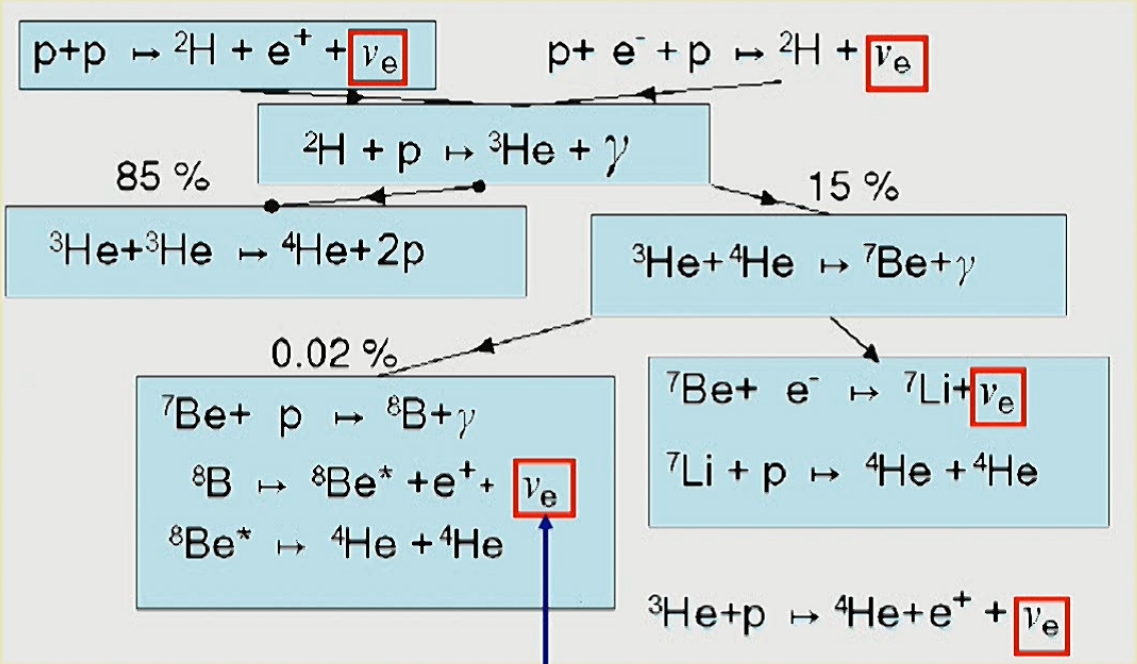
• **EITHER :**

1. THE SOLAR MODEL CALCULATIONS WERE INCOMPLETE OR INCORRECT

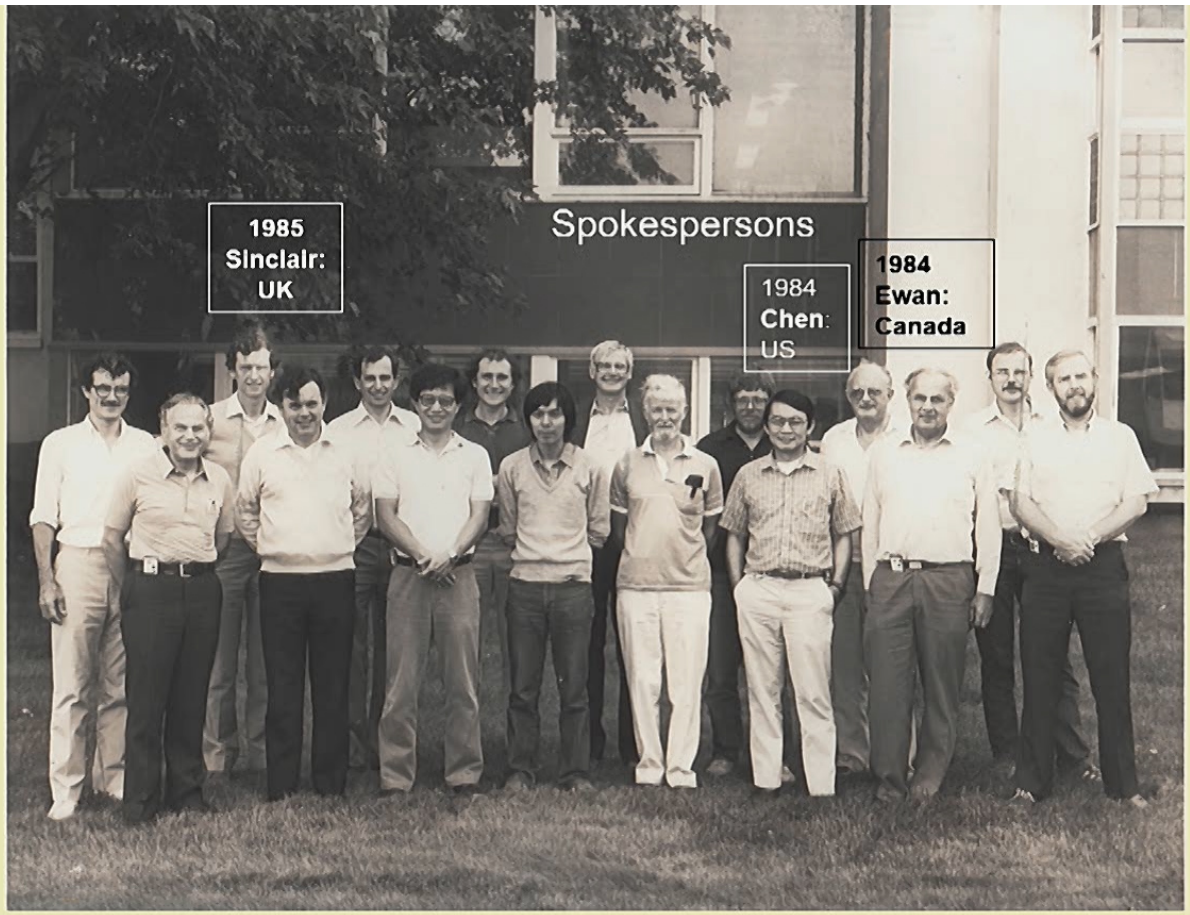
OR

2.THE ELECTRON NEUTRINOS CREATED IN THE SUN ARE CHANGING TO ANOTHER FLAVOUR AND ELUDING THE PAST EXPERIMENTS THAT WERE SENSITIVE ALMOST EXCLUSIVELY TO ELECTRON NEUTRINOS.

SOLAR FUSION CHAIN



1984:Herb Chen proposes heavy water to search for direct evidence of flavor transformation for neutrinos from ^{8}B decay in the Sun. Electron neutrinos and all active neutrinos are measured separately to show flavor change independent of solar model calculations.



SNO Collaboration Meeting, Chalk River, 1986

PROPOSAL TO BUILD A NEUTRINO OBSERVATORY IN SUDBURY, CANADA
D. Sinclair, A.L. Carter, D. Kessler, E.D. Earle, P. Jagam, J.J. Simpson, R.C. Allen, H.H. Chen, P.J. Doe, E.D. Hallman, W.F. Davidson, A.B. McDonald, R.S. Storey, G.T. Ewan, H.-B. Mak, B.C. Robertson Il Nuovo Cimento C9, 308 (1986)

How does SNO detect neutrinos from the Sun?

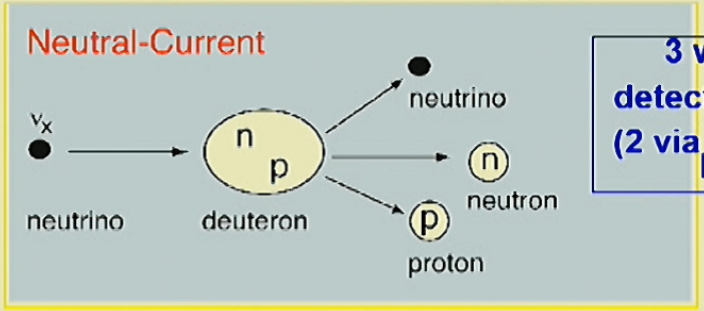
Billions of them stream out every second from the nuclear reactions powering the Sun and strike our detector. Once an hour they make a burst of light that we can detect.

Unique Signatures in SNO (D_2O)

(1 in 6400 molecules in ordinary water are D_2O. We used >99.75% D_2O)

Equal Sensitivity All Types

$\nu_x + d \rightarrow \nu_x + n + p$



3 ways to detect neutrons (2 via a Burst of light)

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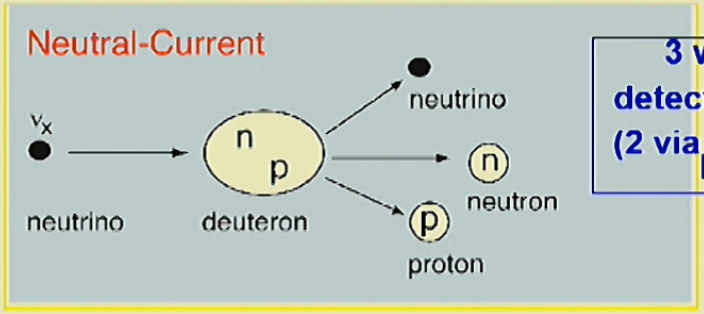
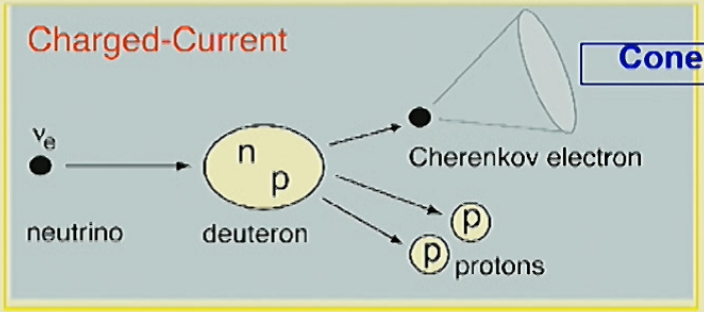


3 ways to detect neutrons (2 via a Burst of light)

Electron Neutrinos

$\nu_e + d \rightarrow e^- + p + p$



Cone of Light

Comparing these two reactions tells if electron neutrinos have changed their type.

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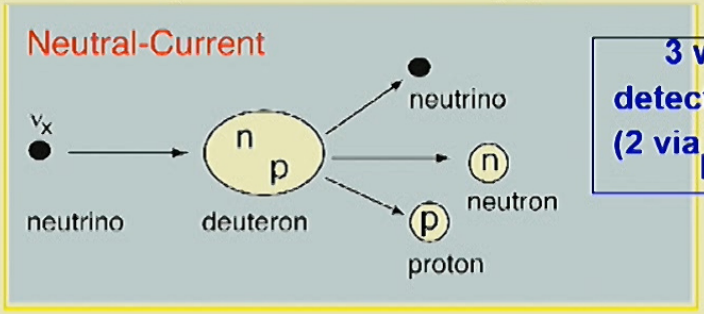

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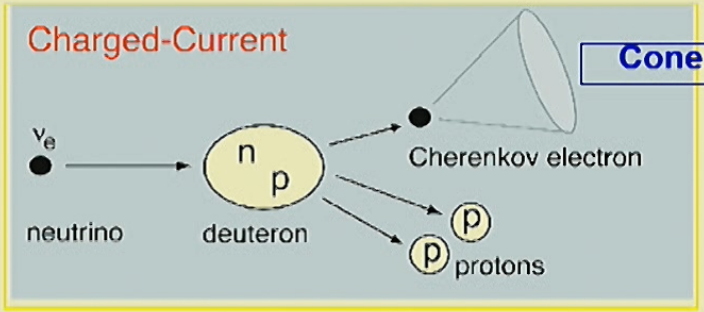
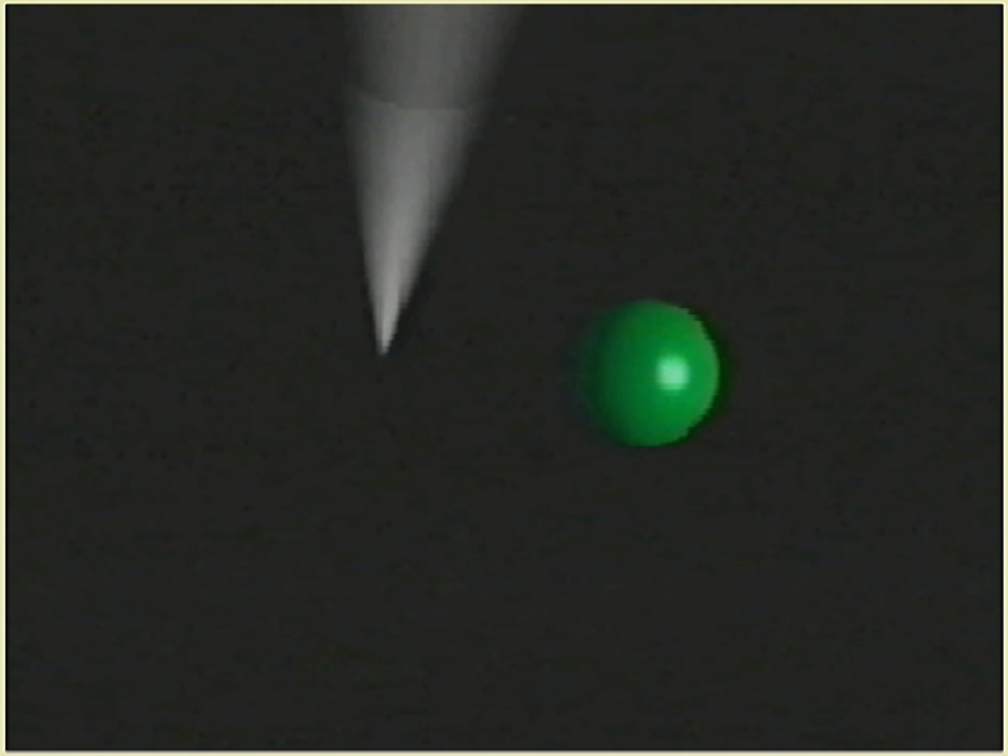


Cone of Light

Comparing these two reactions tells if electron neutrinos have changed their type.

Radioactivity must be carefully controlled because gamma rays can also break apart deuterium and produce a free neutron.

Two different bursts of light occur when a neutrino strikes heavy water.



White = Oxygen
Green = Proton
Blue = Neutron
Red = Electron

Heavy water has an extra neutron (blue) in the hydrogen nucleus. 1 in 6400 water molecules are like this.

The first type of burst is sensitive to all flavours of neutrinos: electron, mu and tau neutrinos

Sudbury Neutrino Observatory (SNO)

Neutrinos are very difficult to detect so our detector had to be very big with low radioactivity deep underground.

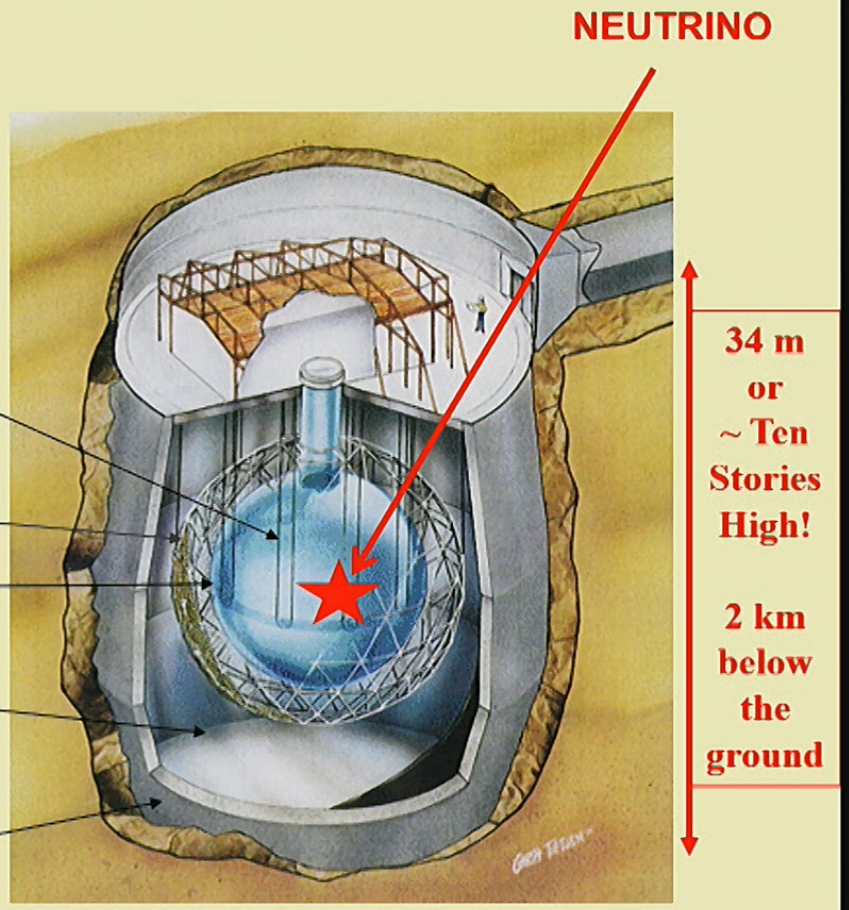
1000 tonnes of heavy water: D_2O
$ 300 million on Loan for $1.00

9500 light sensors

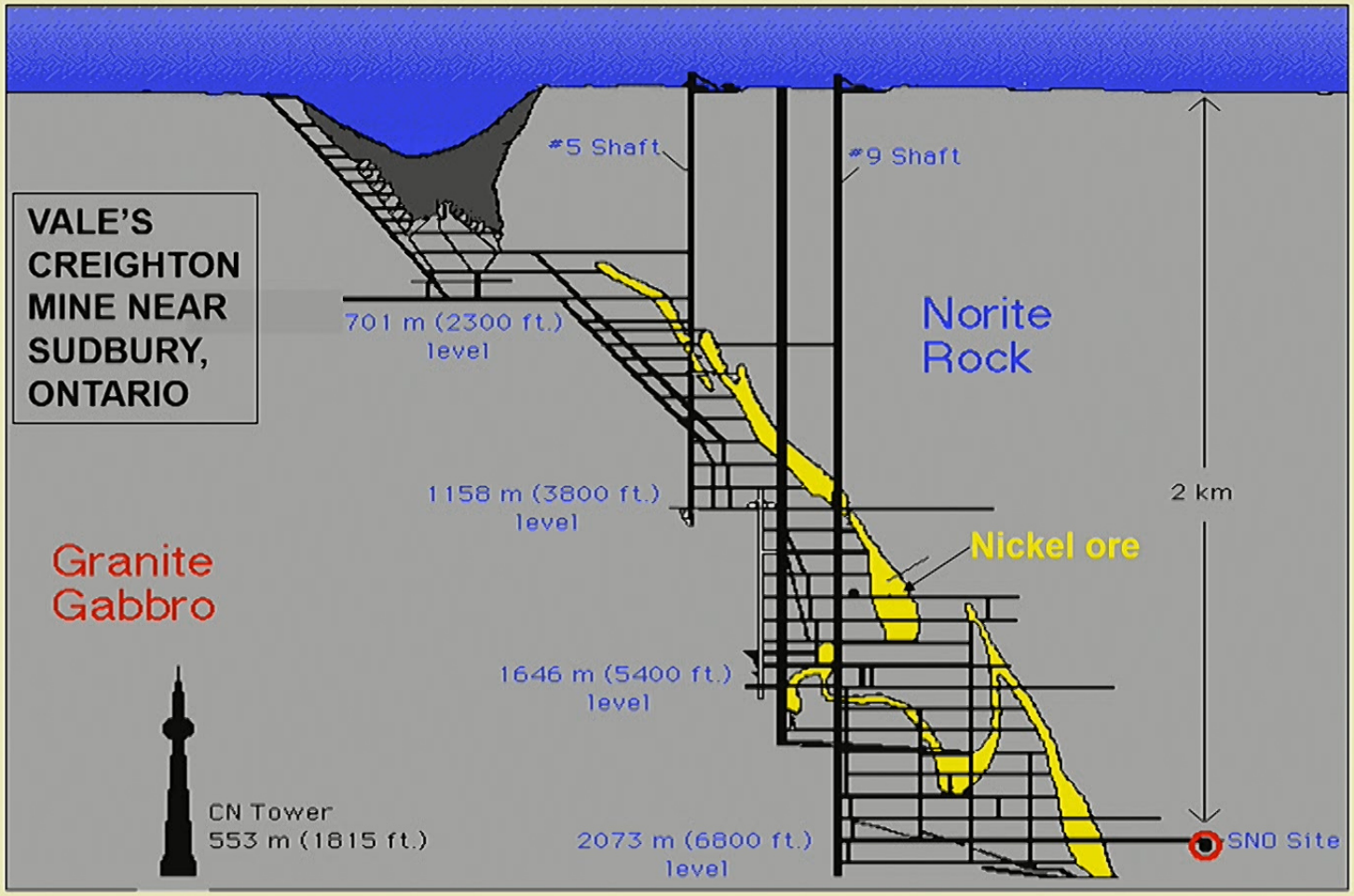
12 m Diameter Acrylic Container

Ultra-pure Water: H_2O.

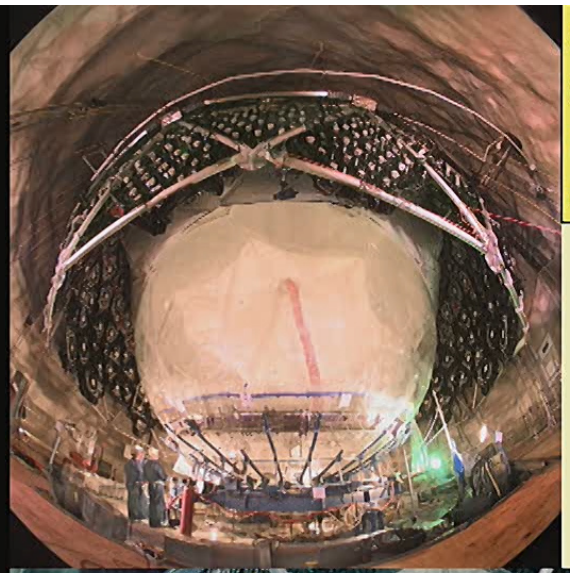
Urylon Liner and Radon Seal



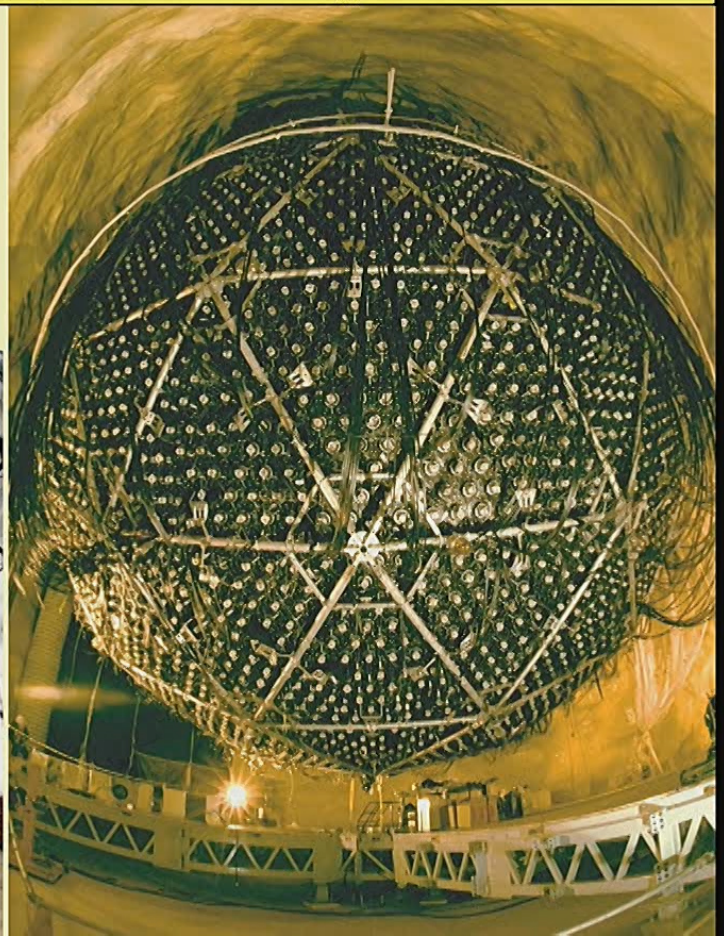
To study Neutrinos with little radioactive background, we went 2 km underground to reduce cosmic rays and built an ultra-clean detector: SNO

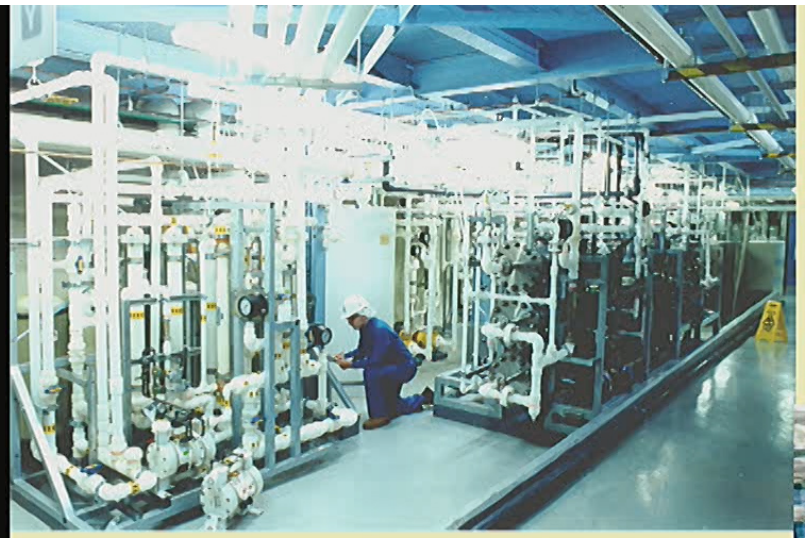


SNO: One million pieces transported down in the 3 m x 3 m x 4 m mine cage and re-assembled under ultra-clean conditions. Every worker takes a shower and wears clean, lint-free clothing.



70,000 showers during the course of the SNO project

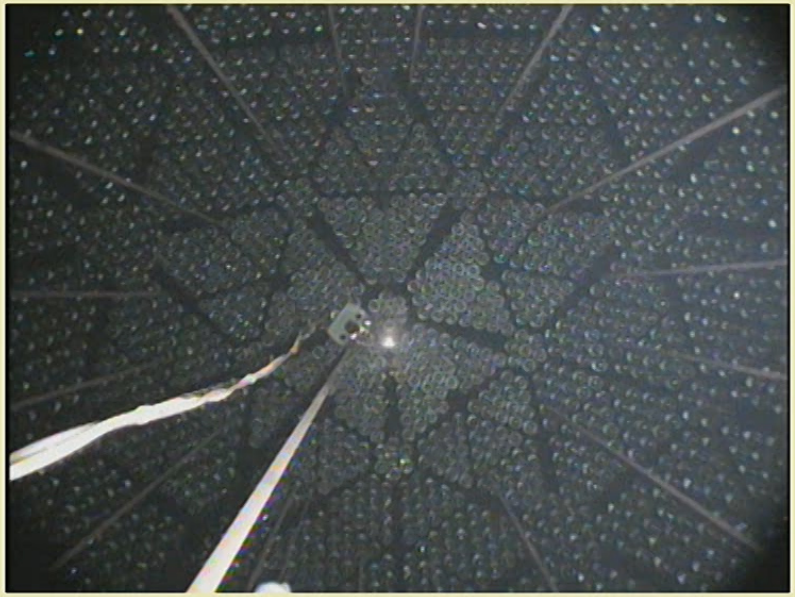


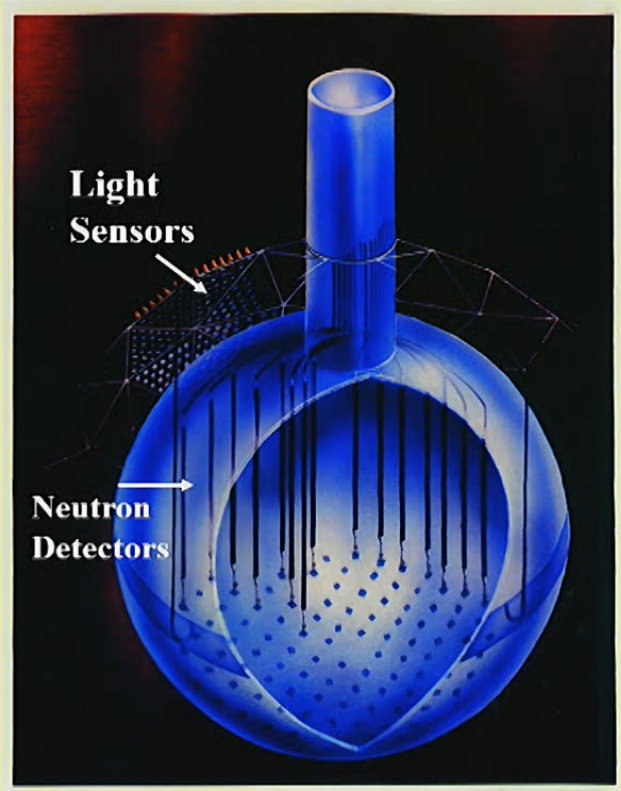


Water systems were developed to provide low radioactivity water and heavy water: 1 billion times better than tap water. Less than one radioactive decay per day per ton of water!!

Steven Hawking's Visit Posed some special Challenges – INCO Designed a special Rail car for him. (Stainless steel with Lots of nickel, of course)

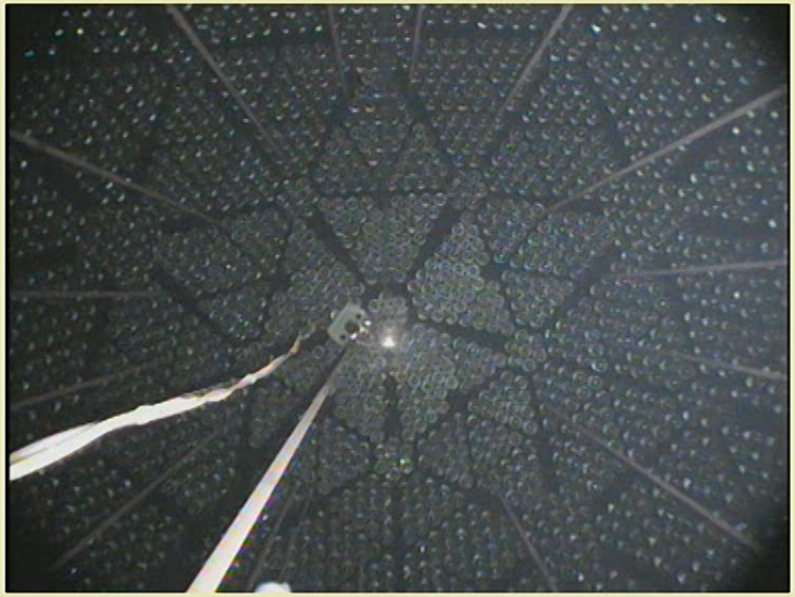
Phase 3: 400 m of Ultra Low Background Neutron Counters installed in the heavy water by a remotely controlled submarine

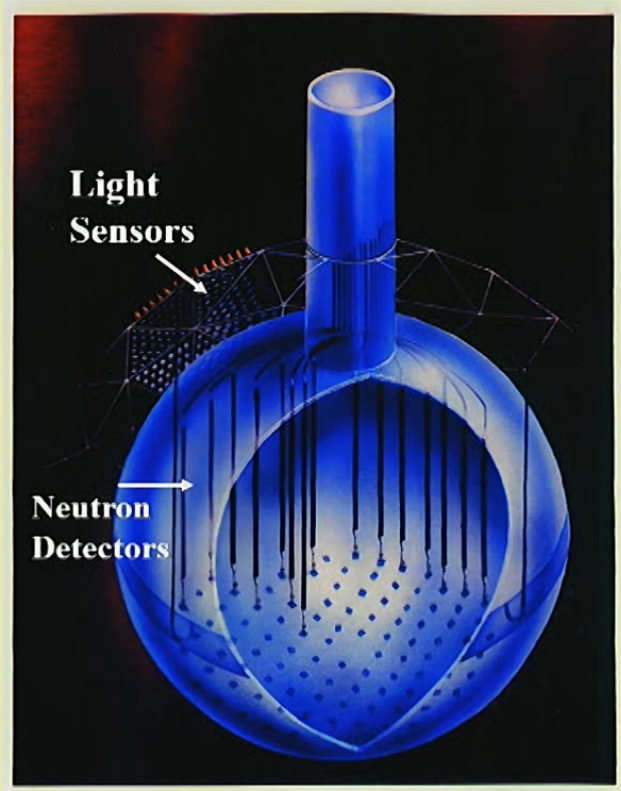


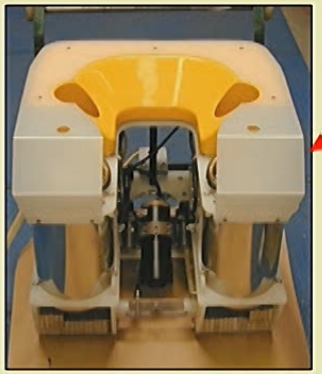


The Neutron Counters were a great success (after a lot of hard work by the SNO collaboration development team).

Phase 3: 400 m of Ultra Low Background Neutron Counters installed in the heavy water by a remotely controlled submarine







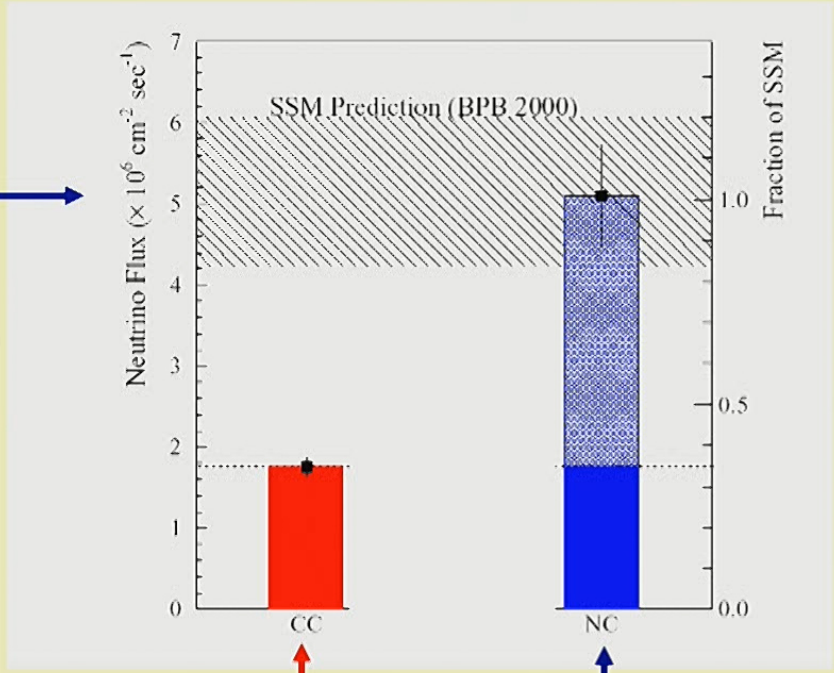
The original Submarine …

Yellow, of course!

Well, maybe not!

The yellow paint was much too radioactive

SOLAR MODEL



Excellent Agreement With the Solar Model Calculations

SNO USED HEAVY WATER TO MEASURE TWO SEPARATE THINGS

LESS THAN ONE CHANCE IN 10 MILLION FOR "NO CHANGE IN NEUTRINO TYPE"

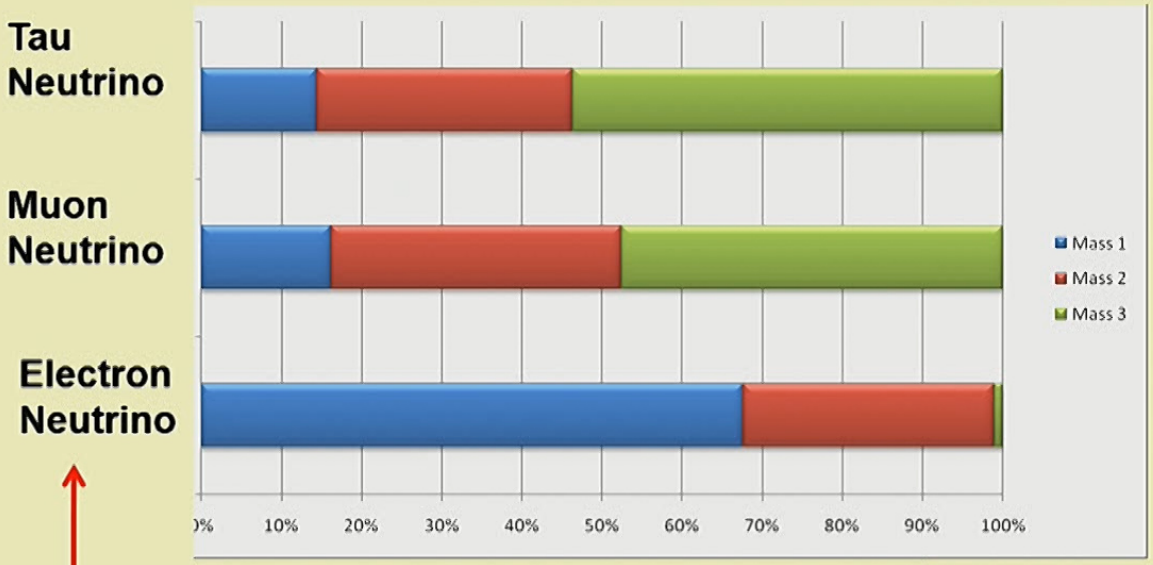
ELECTRON NEUTRINOS

ALL NEUTRINO TYPES

A CLEAR DEMONSTRATION NEUTRINOS CHANGE THEIR TYPE: 2/3 OF THE ELECTRON NEUTRINOS HAVE CHANGED TO MU, TAU NEUTRINOS ON THE WAY FROM THE SOLAR CORE TO EARTH. THIS REQUIRES THAT THEY HAVE A FINITE MASS.

NEUTRINO OSCILLATIONS AND NEUTRINO MASS

Neutrino Flavors (Electron, Muon, Tau) can be expressed as combinations of Masses (1,2,3)



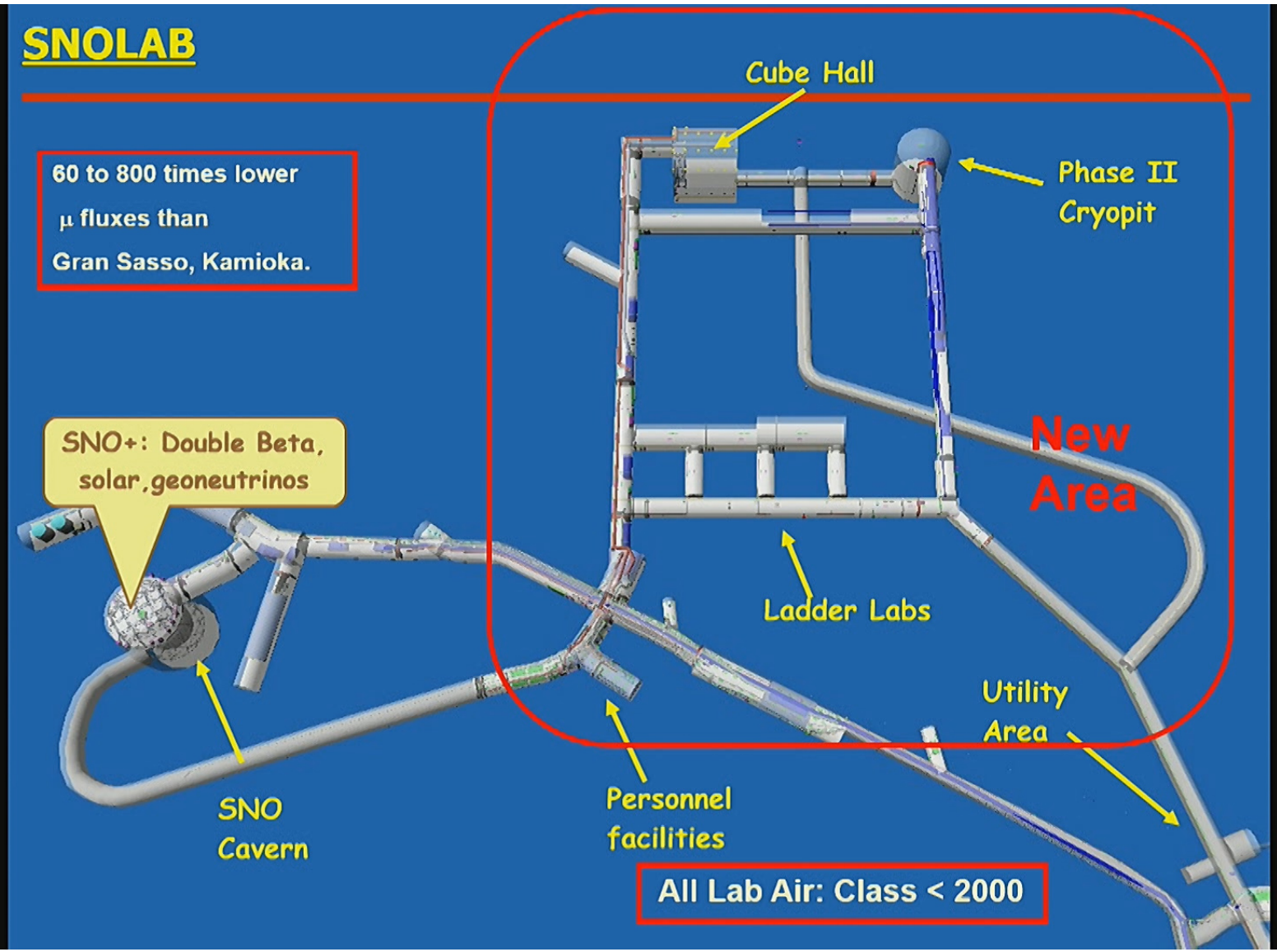
Quantum mechanics states

Created in a unique Flavor State

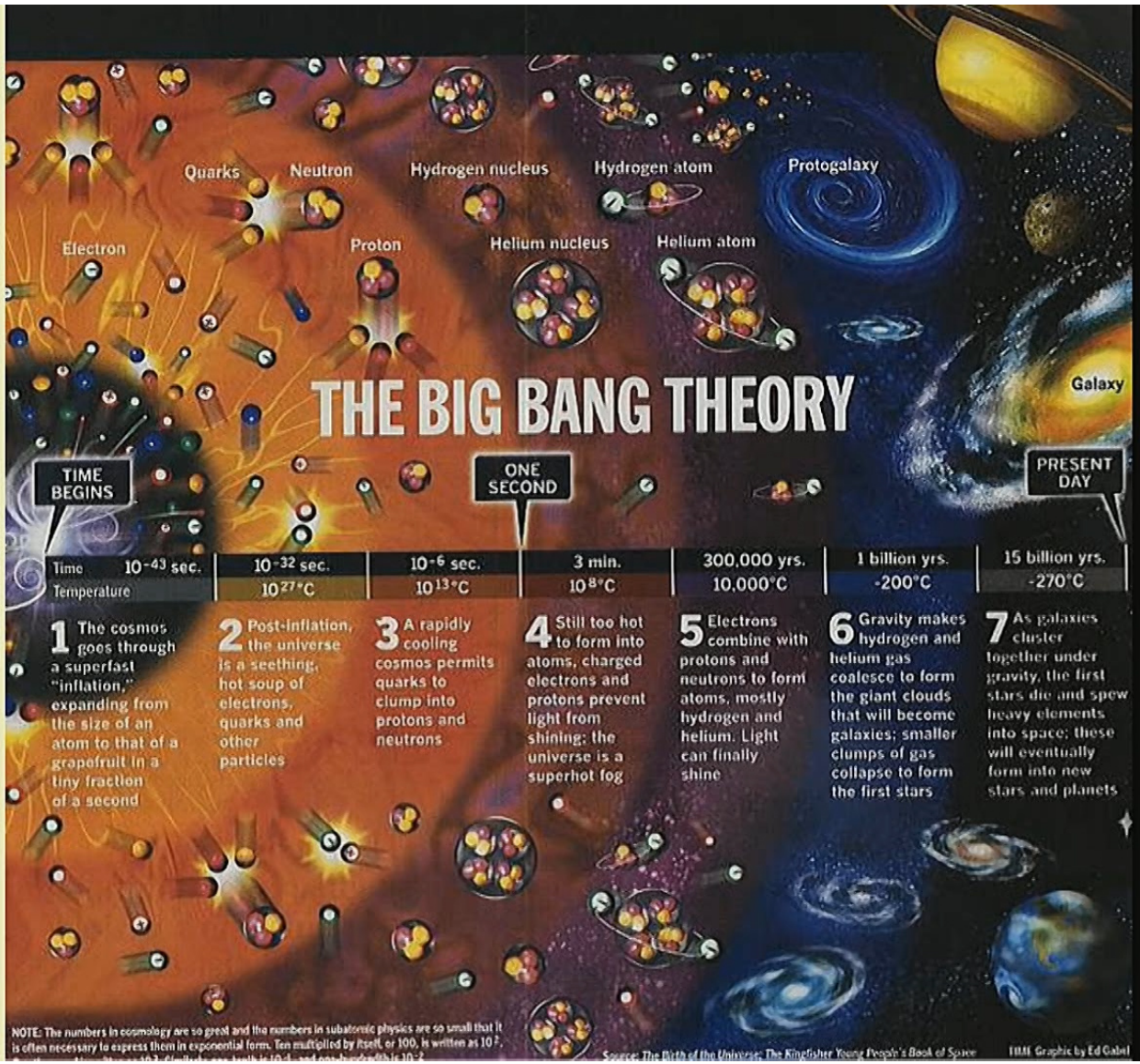
The mass fractions change as the neutrino travels

After traveling there is a finite probability to be detected as a different flavor type

262 SNO Physics Paper Authors: Adam Cox, Aksel L. Hallin, Alain Bellerive, Alan Smith, Alan Poon, Alexander Wright, Allan Myers, Alysia Marino, André Krüger, André Roberge, Andre Krumins, Andrew Ferraris, Andrew Hime, Anett Schülke, Anthony Noble, Araz Hamian, Arthur McDonald, Aubra Anthony, Azriel Goldschmidt, Barry Robertson, Bassam Aharmim, Bei Cai, Benjamin Monreal, Bernard Nickel, Berta Beltran, Bhaskar Sur, Blair Jamieson, Brandon Wall, Brent VanDevender, Brian Morissette, Bruce Cleveland, Bryan Fulsom, Bryce Moffat, Carsten Krauss, Catherine Mifflin, Charles Currat, Charles Duba, Charlotte Sims, Christian Nally, Christian Ouellet, Christine Kraus, Christopher Kyba, Christopher Howard, Christopher Jillings, Christopher Tunnell, Christopher Waltham, Clarence Virtue, Colin Okada, Darren Grant, David Anglin, David Sinclair, David Waller, David Wark, Davis Earle, Diane Reitzner, Dimpal Chauhan, Doug Hallman,D ouglas Cowen, Douglas McDonald, Duncan Hepburn, Ed Frank, Edward Clifford, Michael Dragowsky, Emmanuel Bonvin, Eric Norman, Erik Saettler, Etienne Rollin, Eugene Guillian, Eugene Beier, Fabrice Fleurot, Feng Zhang, Ferenc Dalnoki-Veress, Fraser Duncan, Gabriel D. Orebi Gann, Geoffrey Miller, George Doucas, George Ewan, Gerhard Bühler, Gersende Prior, Gordana Tešić, Gordon,McGregor, Gregory Harper, Guy Jonkmans, Gwen Milton, Hadi Fergani, Hamish Robertson, Hans Bichsel, Hans Mes, Hardy Seifert, Hay Boon Mak, Heidi Munn, Helen M. O'Keeffe, Hendrick Labranche, Henry Lee, Hok Seum Wan Chan Tseung, Huaizhang Deng, Hugh Evans, Hui-Siong Ng, Ian Lawson, Ilan Levine, Ira Blevis,Jacques Farine, James Cameron, James Hall, James Loach, James Leslie, Jaret Heise, Jason Detwiler, Jason Hewett, Jason Pun, Jason Goon, Jeanne Wilson, Jeffrey Secrest, Jeremy Lyon, Jerry Wilhelmy, Jessica Dunmore, Jian-Xiong Wang, Jimmy Law, Jocelyn Monroe, John Amsbaugh, John Boger, John Orrell, John Simpson, John Wilkerson, Jon Hykawy, Jose Maneira, Joseph Formaggio, Joseph Banar, Joseph Germani, Joshua Klein, Juergen Wendland, Kai Zuber, Kara Keeter, Kareem Kazkaz, Karsten Heeger, Katherine Frame, Kathryn Schaffer, Keith Rielage, Kennneth McFarlane, Kevin Graham, Kevin Lesko, Kevin McBryde, Khalil Boudjemline, Klaus Kirch, Laura Kormos, Laura Stonehill, Laurel Sinclair, Louise Heelan, Malcolm Fowler, Manuel Anaya, Marc Bergevin, Marcus Thomson, Maria Isaac, Marie DiMarco, Mark Boulay, Mark Chen, Mark Howe, Mark Kos, Mark Neubauer, Martin Moorhead, Masa Omori, Melin Huang, Melissa Jerkins, Michael Bowler, Michael Browne, Michael Lay, Michael Lowry, Michael Miller, Michael Thorman, Michal Shatkay, Mike Schwendener, Miles Smith, Minfang Yeh, Miriam Diamond, Mitchell Newcomer, Monica Dunford, Morley O'Neill, Mort Bercovitch, Myung Chol Chon, Naeem Ahmed, Nathaniel Tagg, Neil McCauley, Nicholas Jelley, Nicholas West, Nikolai Starinsky, Nikolai Tolich, Noah Oblath, Noel Gagnon, Nuno Barros, Olivier Simard, Patrick Tsang, Paul Keener, Peter Wittich, Peter Doe, Peter Watson, Peter Skensved, Peter Thornewell, Philip Harvey, Pierre Luc Drouin, Pillalamarr Jagam, Ranpal Dosanjh, Reda Tafirout, Reena Meijer Drees, Reyco Henning, Richard Allen, Richard Ford, Richard Helmer, Richard Hemingway, Richard Kouzes, Richard Hahn, Richard Lange, Richard Ott, Richard Taplin, Richard Van Berg, Richard Van de Water, Rizwan Haq, Robert Black, Robert Boardman, Robert Stokstad, Robert Heaton, Robert Komar, Robin Ollerhead, Rushdy Ahmad, Ryan MacLellan, Ryan Martin, Ryuta Hazama, Salvador Gil, Sarah Rosendahl, Scott Oser, Sean McGee, Shahnoor Habib, Sherry Majerus, Simon Peeters, Stanley Seibert, Steffon Luoma, Steven Elliott, Steven Bille, Steven Brice, Teresa Spreitzer, Thomas Andersen, Thomas J. Radcliffe, Thomas J. Bowles, Thomas Kutter, Thomas Sonley, Thomas Steiger, Timothy Van Wechel, Tom Burritt, Tudor Costin, Tyron Tsui, Vadim Rusu, Vladimir Novikov, Walter Davidson, William Frati, William Handler, William Heintzelman, William Locke, William McLatchie, Xin Chen, Xin Dai, Yaroslav Tserkovnyak, Yasuo Takeuchi, Yekaterina Opachich, Yuen-Dat Chan **And 11 who have passed away:** Herbert Chen, John C. Barton, John Cowan, Andre Hamer, Clifford Hargrove, Barry C. Knox, Jan Wouters, Peter Trent, Robert Storey, Keith Rowley and Neil Tanner


SNOLAB
60 to 800 times lower
μ fluxes than
Gran Sasso, Kamioka.
Cube Hall
Phase II
Cryopit
New
Area
SNO+: Double Beta,
solar, geoneutrinos
Ladder Labs
Utility
Area
SNO
Cavern
Personnel
facilities
All Lab Air: Class < 2000

Impact of Future SNOLAB experiments



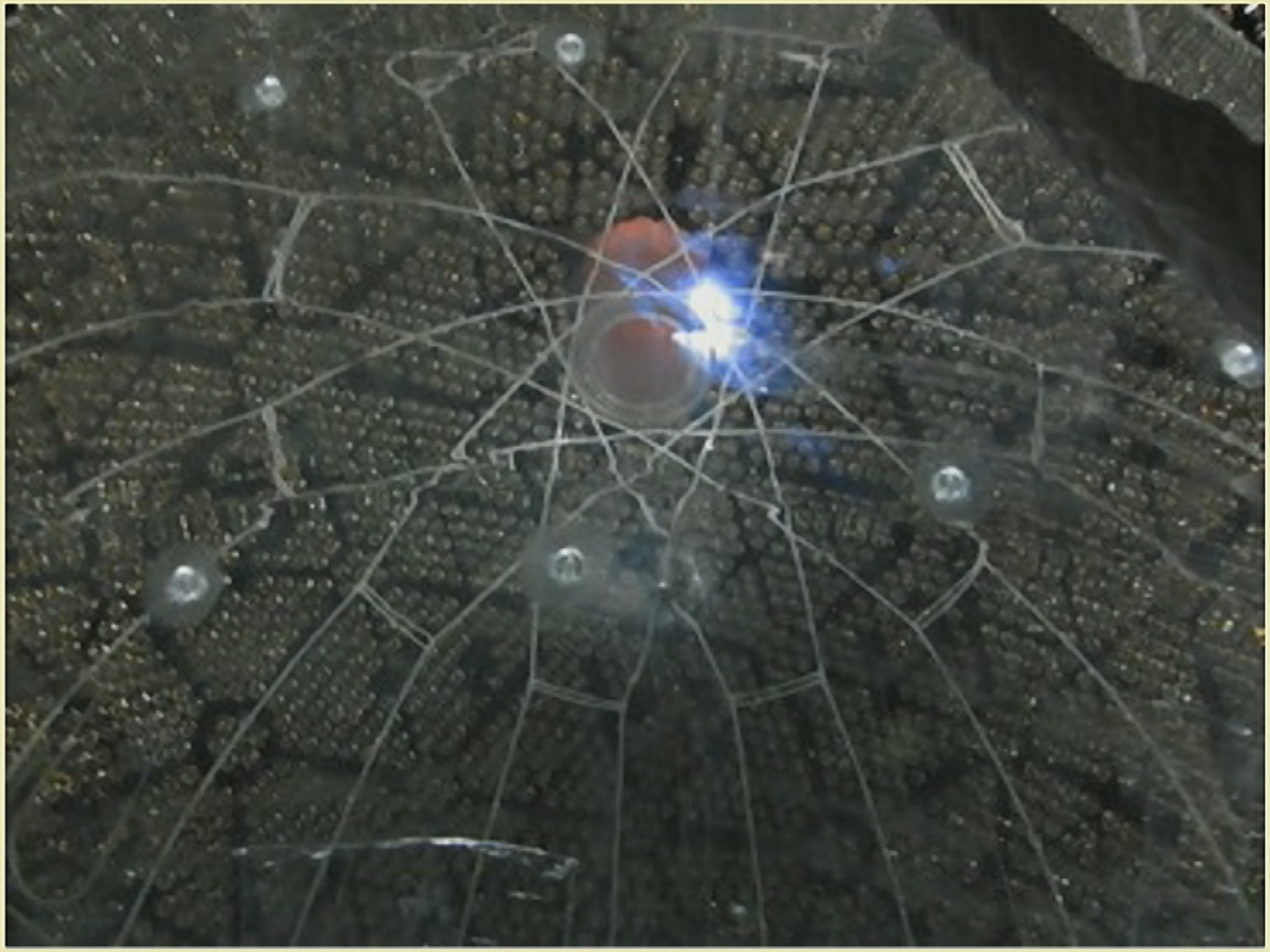
Experiments at SNOLAB

NEUTRINOS:

- **SNO+: An experiment is in construction (called SNO+) to replace the heavy water with an organic liquid (Linear Alkyl Benzene:LAB) loaded with 4 tons of Tellurium-organic compound.**

- **Tellurium is an ideal element to observe "neutrino-less double beta decay" a very rare radioactive process that will test whether neutrinos are their own anti-particles and if so, could tell us the absolute mass of all neutrino types. This is relevant to theories where neutrinos have a strong role in the conversion of anti-matter to matter in the early Universe.**

- **SNO+ will be among the most sensitive international experiments for neutrino-less double beta decay. SNO+ will also provide a sensitive measurement of neutrinos from the Earth, lower energy neutrinos from the Sun and from Supernovae.**



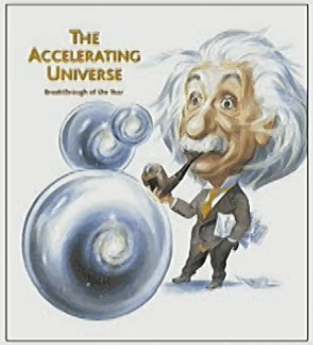
Hold-down ropes installed, now filling with pure water.

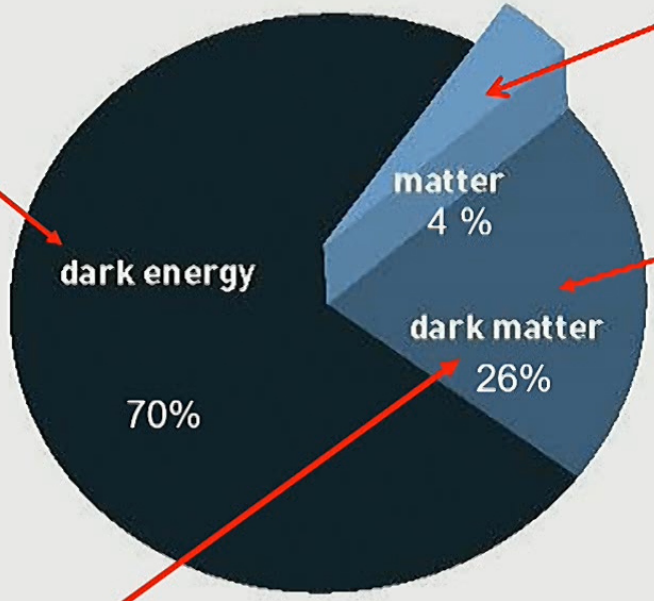
Composition of the Universe as we understand it today

(Very different than 20 years ago thanks to very sensitive astronomical and astrophysical experiments such as measurements of the cosmic microwave background, large scale structure and distant supernovae.)

US!!!

Responsible for accelerating the Universe's expansion



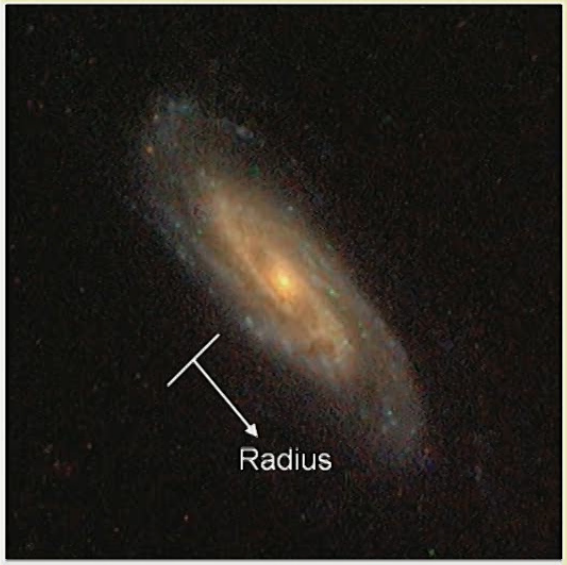


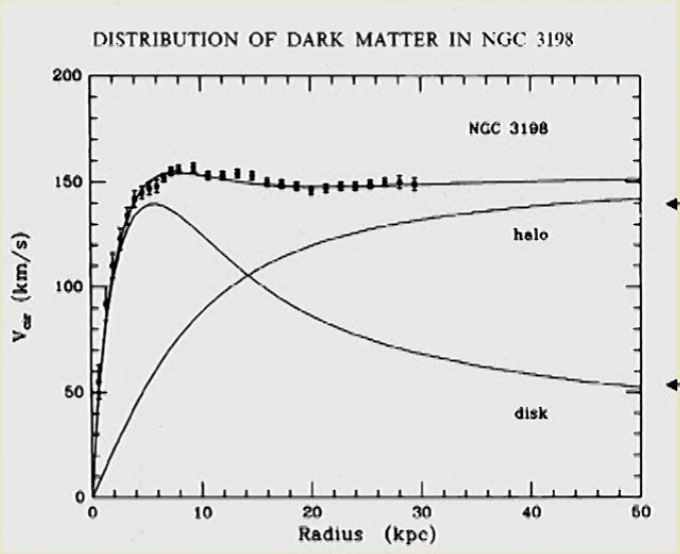
Neutrinos Are only a few %

With underground labs we look for Dark Matter particles left from the Big Bang, with ultra-low radioactive background.
We look for Weakly Interacting Massive Particles: "WIMPS"

The evidence for *dark matter* is strong from astrophysics measurements:

For example: SPIRAL GALAXIES WOULD FLY APART IF THEY ARE COMPOSED OF ONLY THE GLOWING MATTER





DARK MATTER

GLOWING MATTER

- **HOWEVER, WE DO NOT KNOW WHAT THE "WIMPS" ARE. THEY MUST BE STABLE ENOUGH TO SURVIVE 13 BILLION YEARS AND MUST BE SO MASSIVE THAT THE HIGHEST ENERGY ACCELERATORS HAVE NOT PRODUCED THEM YET.**

- **WE ARE LOOKING FOR THEM TO STRIKE OUR DETECTORS PRODUCING LIGHT. THE LARGE HADRON COLLIDER AT CERN, GENEVA IS TRYING TO PRODUCE THEM FOR THE FIRST TIME SINCE THE BIG BANG.**

Experiments at SNOLAB

- **DARK MATTER:**

A number of different techniques are being employed to detect Dark Matter particles left from the Big Bang:

Examples:

- DEAP-3600 (Liquid Argon),
- PICO (bubble detection in materials containing fluorine),
- SuperCDMS relocating to SNOLAB (Solid State Bolometers)

- **SUPERNOVA DETECTION**

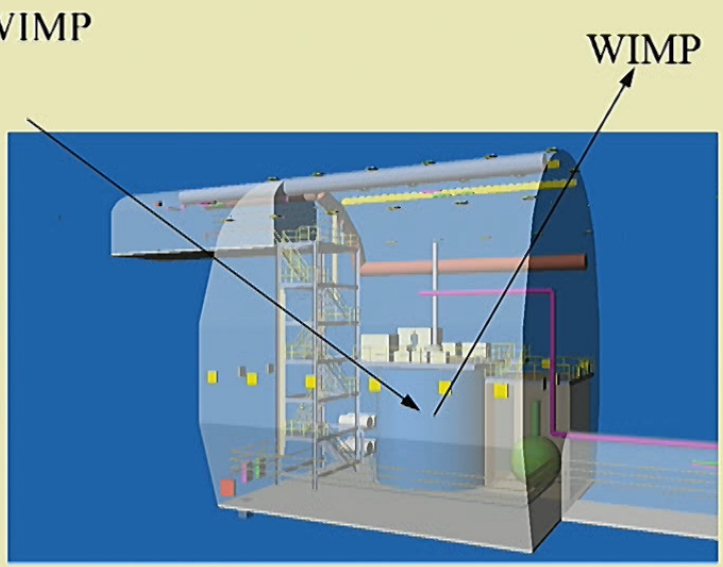
- HALO: A Supernova detector using Lead and the SNO ^{3}He detectors to emphasize electron neutrino detection for a galactic supernova.

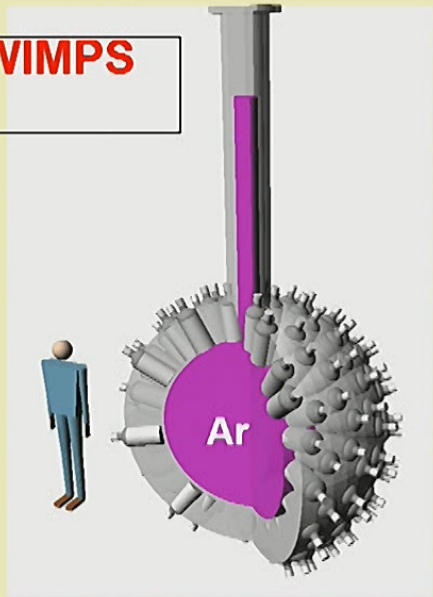
- SNO+: Observable even during operation to observe Neutrino-less Double Beta Decay.

Stephen Hawking and fans observing the CRYOPIT area in September 2012

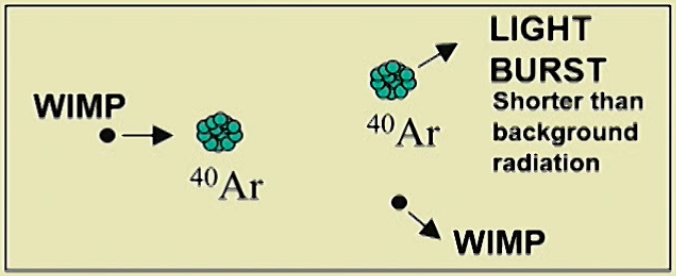
The DEAP-3600 Experiment

Search for WIMPS at SNOLAB





DEAP-3600: ~ 4 TONS OF LIQUID ARGON

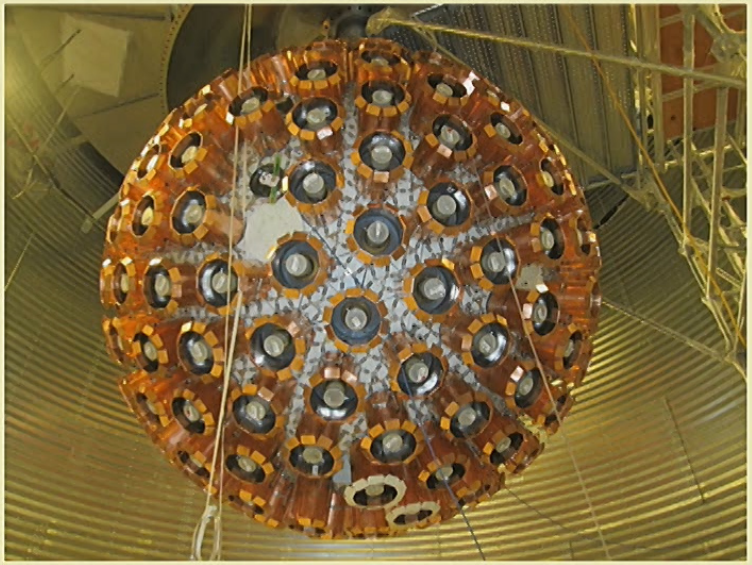


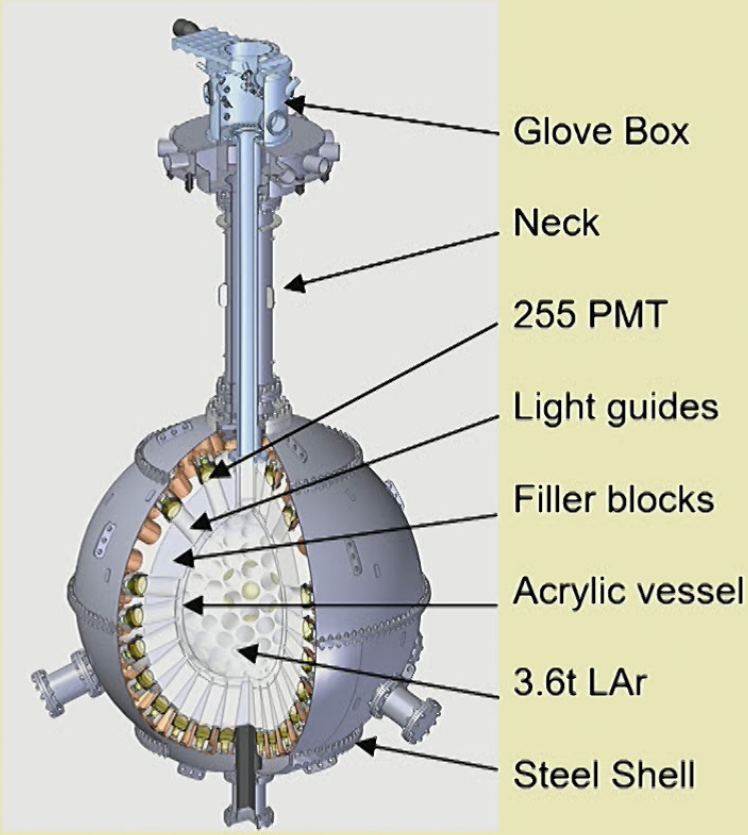
Nuclear recoil events from Dark Matter are very short (10 nanosecs) other radioactivity events are about 10 microsecs. Discrimination against background has been demonstrated to be a factor of10^8. Other radioactivity: <1 event/ 3 years.

This experiment will have sensitivity up to 10 times better than present ones for Dark Matter particles.

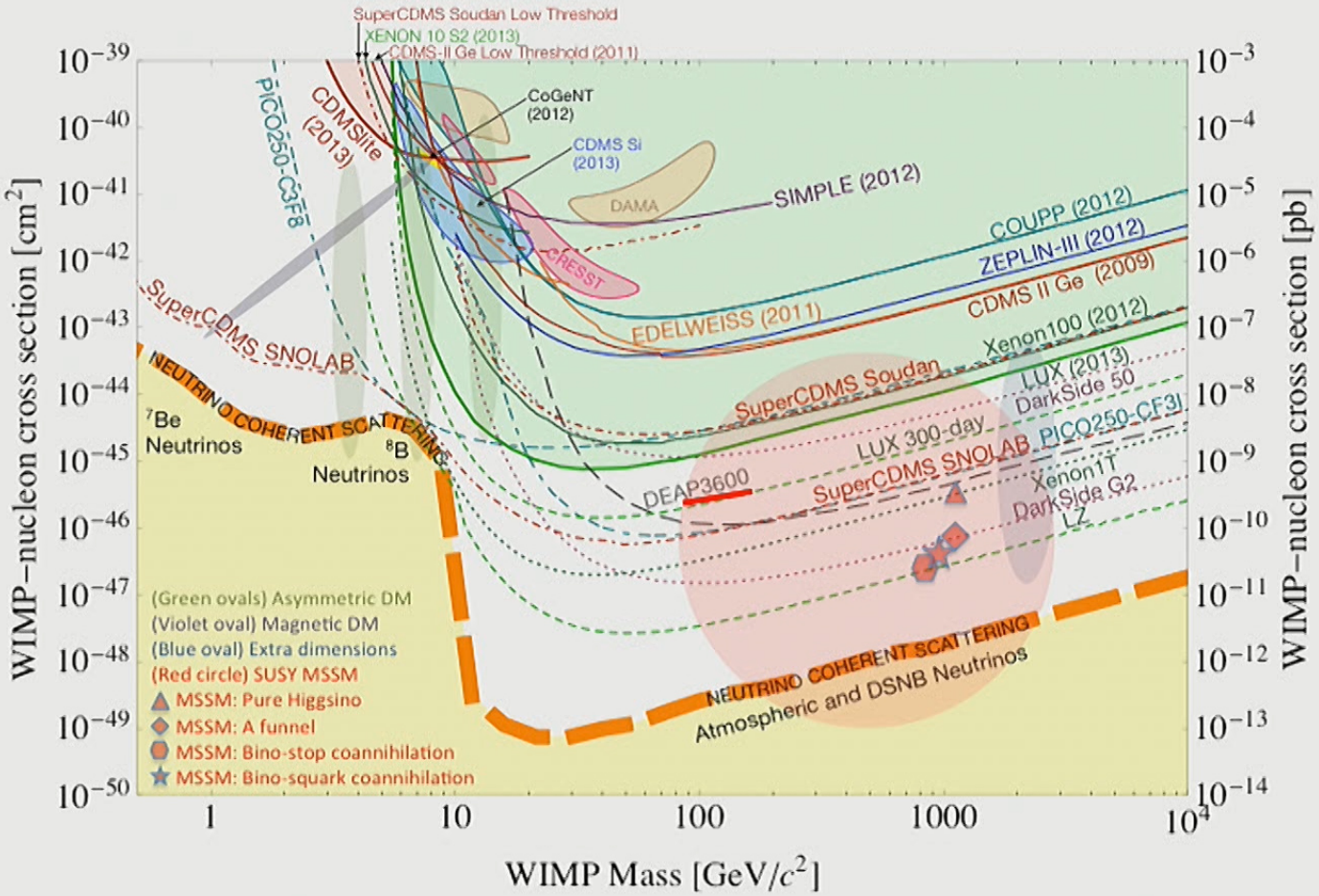
DEAP3600 detector

Now filled with Ar gas and cooling down over the next month. Exciting times.





Spin-Independent Limits



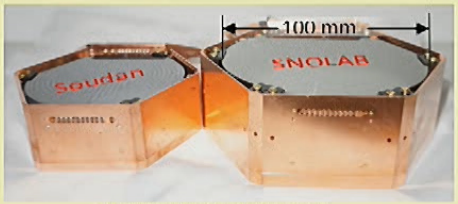
SuperCMDS @ SNOLAB – Basics

Two types of cryogenic semiconductor detectors:

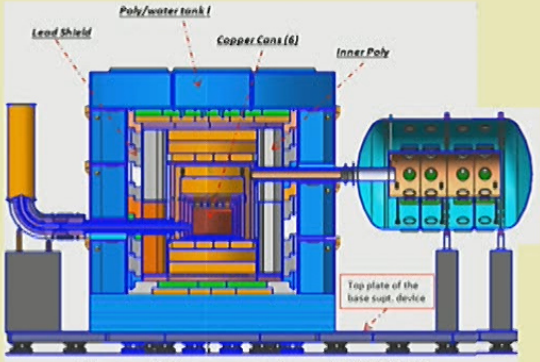
- iZIP: excellent background discrimination, optimal for 5-10 GeV, will reach neutrino limit
- HV detectors: extremely low threshold, optimal for ~0.5-5 GeV WIMPs.

Initial installation: ~30-40 detectors (mixed payload)
Long-term goal: reach neutrino floor down to 0.5 GeV

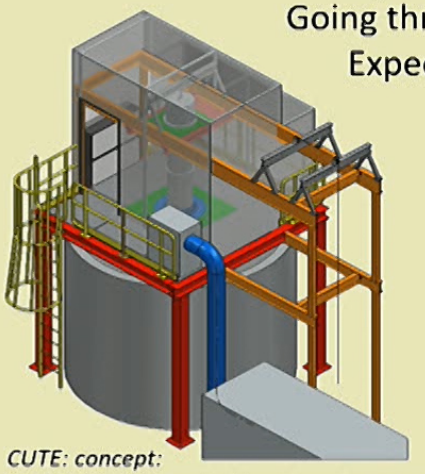
Funded by DOE/NSF/CFI (total ~ $35M)
Going through CD Review process
Expected start of operation in 2020



SuperCDMS Detectors



Concept for new setup at SNOLAB



CUTE: concept:
cryostat in water shield tank underground

Queen's initiative:
Cryogenic Underground TEst facility (CUTE):
Shielded facility to test detector performance and backgrounds; support effort to integrate EURECA detectors into SuperCDMS.

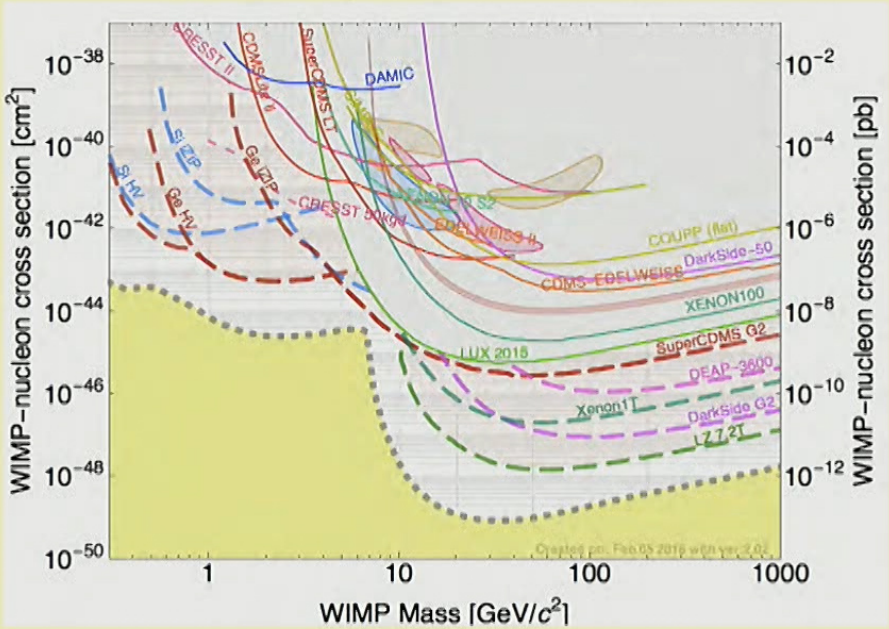
SuperCMDS @ SNOLAB – Expected Performance

Limiting Backgrounds:

- Lowest masses: cosmogenic ^{3}H, ^{32}Si (exposure during detector production, raw materials)
- Intermediate masses (~10 GeV): solar neutrinos (coherent neutrino-nucleus scattering)
- High masses: radiogenic neutrons (contamination in setup)

Choice of targets:

- Ge: higher cross section for standard interactions
- Si: better sensitivity at lowest masses, test of non-standard interactions



Main assumptions for estimating sensitivity:

5 yrs at 80% duty cycle
Ge iZIP: 200 kg-yr
Si iZIP: 15 kg-yr
Ge HV: 22 kg-yr
Si HV: 5 kg-yr

In Summary:

- **The Sudbury Neutrino Experiment (SNO) created the lowest radioactivity environment in the world and determined that solar neutrinos change their flavour, thereby showing that they have a finite mass.**

- **SNOLAB has an array of experiments that are seeking direct detection of WIMPS via the observation of nuclear recoils.**

- **There are a variety of techniques to eliminate background that are sensitive to both spin-independent and spin-dependent interactions.**

- **The upcoming generation of experiments will push sensitivity for Dark Matter particles by at least a factor of 10 in the next couple of years.**