History of the SNO Experiment

Art McDonald
Gray Chair in Particle Astrophysics, Emeritus
Queen's University, Kingston

- **The first SNO Collaboration meeting took place in 1984. According to the minutes:**
- **On September 27, 1984 there was the first meeting at NRC Ottawa that led to the formation of the SNO Collaboration with George Ewan and Herb Chen as spokespersons. Attendees were:**
  - **Davis Earle (Chalk River), Doug Hallman (Laurentian U),**
  - **George T. Ewan, Hay-Boon Mak, W. McLatchie, B. C. Robertson,** Alec Stewart **(Queen's),**
  - **Herb Chen (UC Irvine), Art McDonald (Princeton U),**
  - **C.K. Hargrove, D. Hanna, W.F. Davidson, K.W. Geiger, W.R. Dixon, R.S. Storey, D.C. Santry (NRC Ottawa),**
  - **John Simpson, P. Jagam (U Guelph),**
  - A.E. Litherland, George Luste, Kenneth Okron (U Toronto)
  - J.K.P. Lee, R.B. Moore, D. Ryan (McGill).

- **Prior to this, starting in 1983, George Ewan, Walter Davidson, Pierre Depomier and others, including Ken Lande from U. Penn explored the possibility of an underground site for a proton decay experiment and identified possible sites in the Sudbury area, including the eventual SNO site. They had developed a good relationship with INCO and local politicians but funding was not obtained from NSERC.**

- **In March 1984, Herb Chen had toured the Sudbury site as part of that discussion and in early June, contacted Cliff Hargrove at NRC Ottawa to ask if it could be possible to borrow enough heavy water to look for solar neutrinos.**

- **Cliff phoned Geoff Hanna, Director of Physics Division, AECL, Chalk River, and got a positive response (in principle) that he relayed to Herb the next day.**
- **Note: Geoff Hanna had worked with Bruno Pontecorvo and Ted Hincks at Chalk River in the late 1940's and measured the tritium beta spectrum with a proportional counter and set a limit of ~ 0.5 KeV for neutrino mass that was the best limit for a number of years.**

- **Ted Litherland reviewed the field of underground physics at the CAP conference at Sherbrooke, mentioned the solar neutrino possibilities and got interest from a number of physicists who met at the end of June and developed plans for the first SNO meeting in Sept.**

- **For a detailed account of the many political meetings leading to the establishment of SNO, see the articles by Walter Davidson and George Ewan in Physics in Canada Nov/Dec 2005.**

SNO Collaboration Meeting, Chalk River, 1986

PROPOSAL TO BUILD A NEUTRINO OBSERVATORY IN SUDBURY, CANADA (presented by David Sinclair in 1985)
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)

16 scientists in the original collaboration in 1985

- **Herb Chen published two papers for solar neutrino detection with heavy water: in 1985: Charged current detection and 1986: adding neutral current reaction.**

- **David Sinclair took a sabbatical at NRC from Oxford Jan to Sept. 1985 and then brought the Oxford group into SNO with Neil Tanner.**

- **There were several attempts for funding in Canada and in 1986, Universities in the US and Canada chipped in $350 k to excavate further and verify the SNO site in the Creighton Mine after the NSERC GSC said no.**

- **The collaboration continued the design, leading to the 1987 SNO "White Book" that was submitted to the agencies for funding.**

- **The site was chosen as the 6800 ft level of INCO's Creighton mine near Sudbury and that site was subsequently verified by a series of geological studies following the extension of the existing mine drift to near the site. VP Research of INCO, Walter Curlook helped to obtain final INCO approval.**

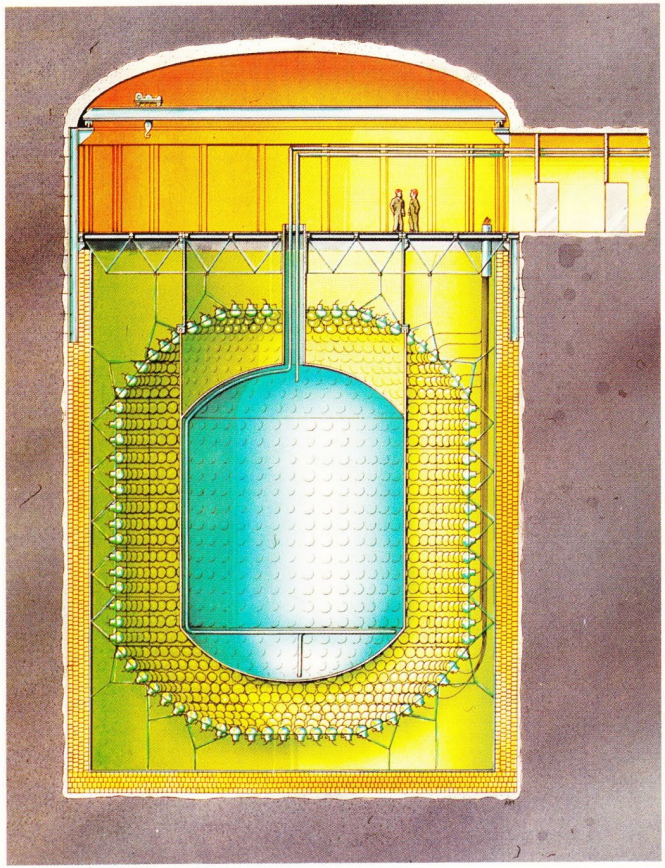
- **Ontario Hydro confirmed willingness to exchange heavy water with AECL to provide pure water uncontaminated by tritium.**

SNO Proposal 1987:

The White Book

SUDBURY NEUTRINO OBSERVATORY

Proposal



Participating Institutions

Queen's University
University of California at Irvine
Oxford University
National Research Council of Canada
Chalk River Nuclear Laboratories
University of Guelph
Laurentian University
Princeton University
Carleton University

SNO-87-12
1987 October

- **Sadly Herb Chen passed away from Leukemia in 1887, one month after the White Book was completed.**

- **Art McDonald became US Spokesman, (joined in 1988 by Gene Beier from U. Penn). Art took a year's sabbatical at Queen's to work on SNO in 1988 and moved to Queen's in August 1989. David Sinclair moved from Oxford to NRC Ottawa in 1989 to work full time on SNO.**

- **In 1989, Art McDonald became SNO Director with David Sinclair and Davis Earle as Associate Directors and the SNO Institute was formed.**

- **A joint US/Canada DOE-style full review occurred in late 1989, chaired by Ed Temple, leading to full funding in January 1990, with country responsibilities and budgets presented in the review.**

- **At that point, NRC got a new President who decided that the High Energy Physics group would be disbanded (later became CRPP at Carleton); AECL decided not to accept a contract for Engineering Design and Project Management and so an RFQ was put out to four companies, won by MONENCO with a team that had just completed building a CANDU nuclear power plant in Korea.**

Author page for the White Book SNO-87-12

SUDBURY NEUTRINO OBSERVATORY PROPOSAL

G.T. Ewan, H.C. Evans, H.W. Lee, J.R. Leslie, H.-B. Mak,
W. McLatchie, B.C. Robertson, P. Skensved
Queen's University at Kingston

R.C. Allen, G. Bühler, H.H. Chen, P.J. Doe
University of California at Irvine

D. Sinclair, N.W. Tanner
University of Oxford

J.D. Anglin, M. Bercovitch, W.F. Davidson,
C.K. Hargrove, H. Mes, R.S. Storey
National Research Council of Canada

E.D. Earle, G.M. Milton
Chalk River Nuclear Laboratories, Atomic Energy of Canada Ltd.

P. Jagam, J.J. Simpson
University of Guelph

A.B. McDonald
Princeton University

E.D. Hallman
Laurentian University

A.L. Carter, D. Kessler
Carleton University

October 1987

Additions to the author list in a later re-issue of the White Book

As of January 15, 1988 the Collaboration was expanded and included the following additional members and institutions:

University of Pennsylvania: E.W. Beier, W. Frati, F.M. Newcommer, R. Van Berg

Princeton University: R.T. Kouzes, M.M. Lowry, R.M. Key

Queen's University: J.D. MacArthur

Laurentian University: R.U. Haq

As of November 1, 1988 the Collaboration has been expanded and includes the following additional members and institutions:

Los Alamos National Laboratory: R.G.H. Robertson, T. Bowles, B. Cleveland, S. Elliot, M. Fowler, D. Vieira, D. Wark, J. Wilhelmy, J. Wilkerson, J. Wouters

→ To U. Washington, Seattle, 1994

University of British Columbia: C. Waltham

TRIUMF: Rich Helmer, 1994

Chalk River Nuclear Laboratories: E.T.H. Clifford

Carleton University: B. Hollebone

University of Oxford: N. Jelley, P. Trent, J. Barton

As of March 9, 1989 the Collaboration has been expanded and includes the following additional institution and members:

Lawrence Berkeley Laboratory: E. Norman, K. Lesko, B. Sur, A. Smith, R. Fulton

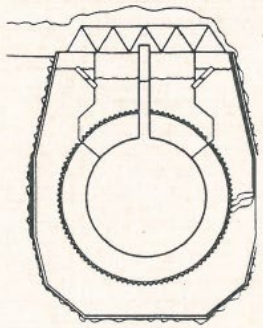
The Design for the final project review of the SNO Project in 1989 (Temple Review) was done by the Plant Design Division at Chalk River, led by Ken McFarlane, who later became the principal engineer for the SNO water systems with David Sinclair and later the Head of the Engineering team at SNOLAB

ATOMIC ENERGY OF CANADA LIMITED

ÉNERGIE ATOMIQUE DU CANADA LIMITÉE

SUDBURY NEUTRINO OBSERVATORY
Mk II ENGINEERING PROPOSAL

PSD-TM-12
Revision P2



Edited by
K.M. McFARLANE

Prepared by
CRNL Plant Design Division
Spectrum Engineering Corporation Limited
and
The SNO Collaboration

Plant Design Division
Chalk River Nuclear Laboratories
Chalk River, Ontario K0J 1J0
1989 September

Sudbury Neutrino Observatory (SNO)

The final detector was very similar to the design presented for the 1989 review with a spherical vessel and PMTs with light collectors.

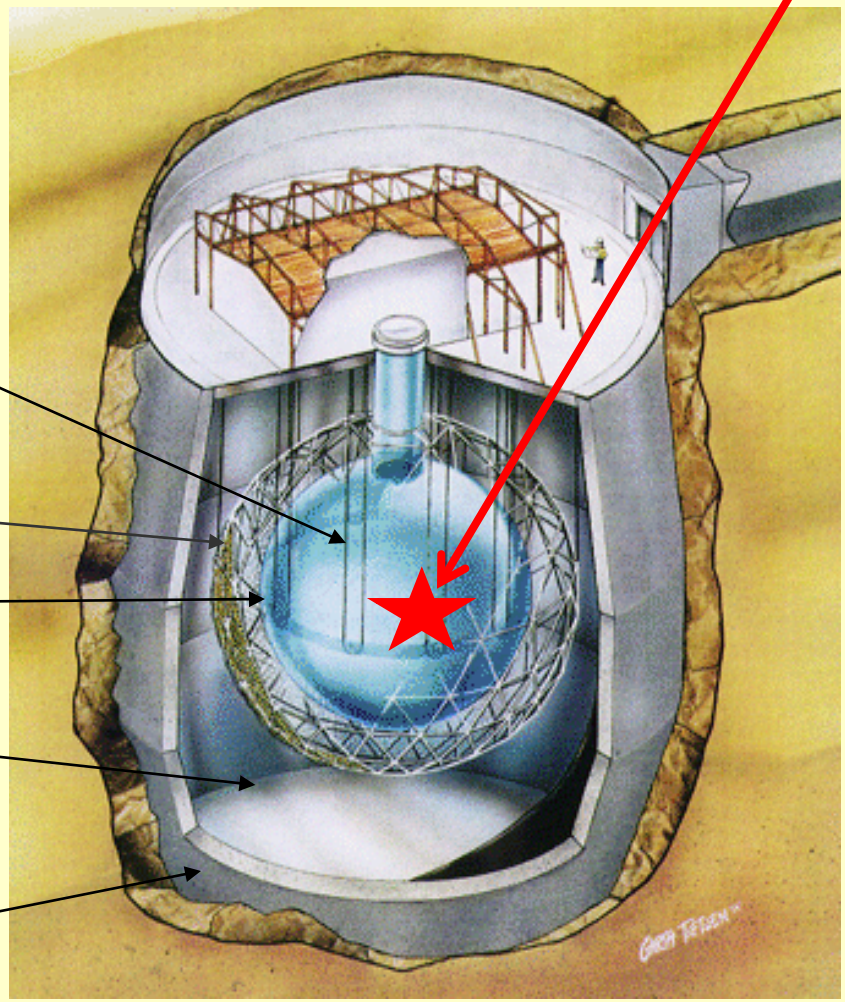
1000 tonnes of heavy water: D_2O
$ 300 million on Loan for $1.00

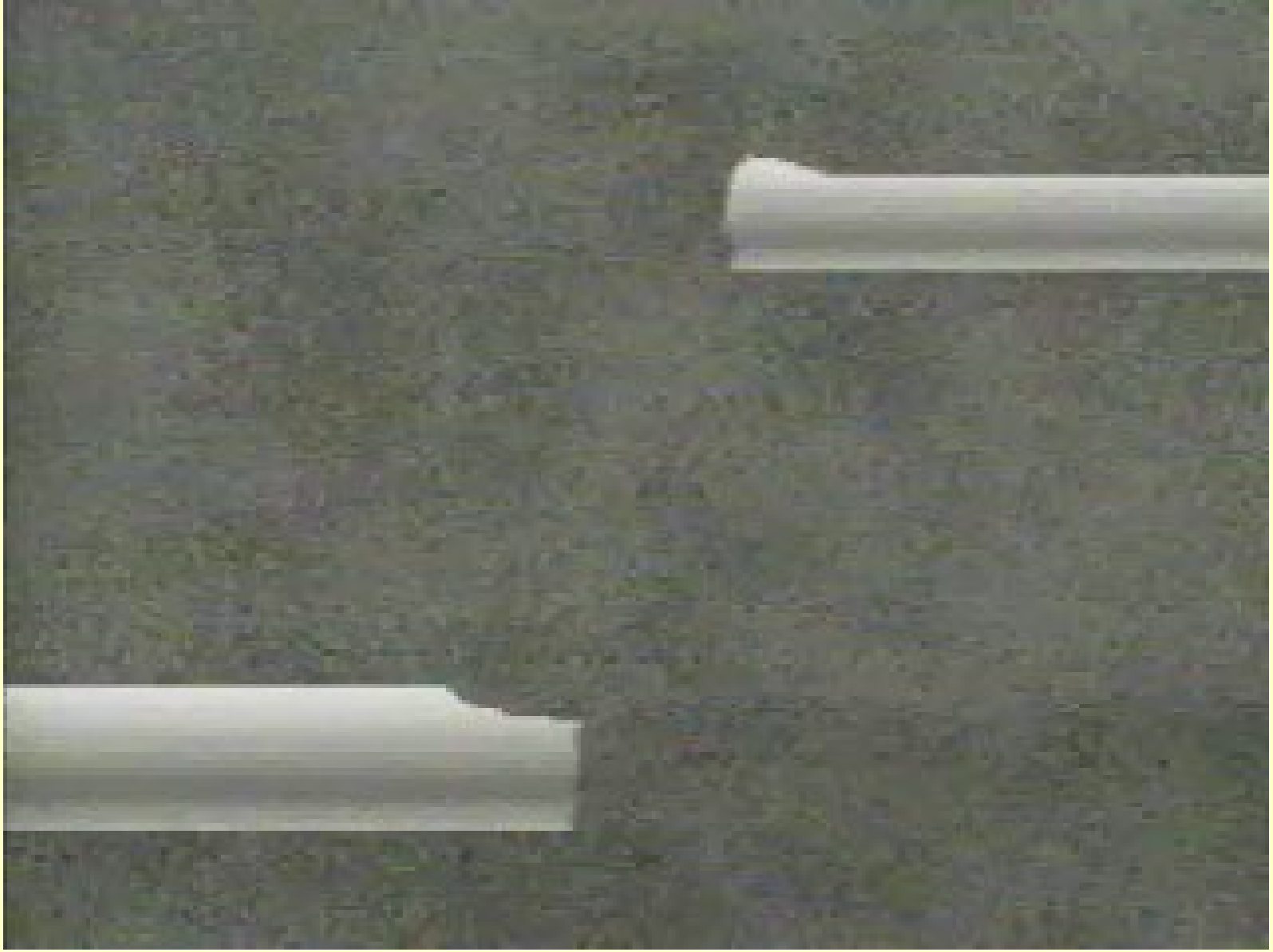
9500 light sensors

12 m Diameter Acrylic Container

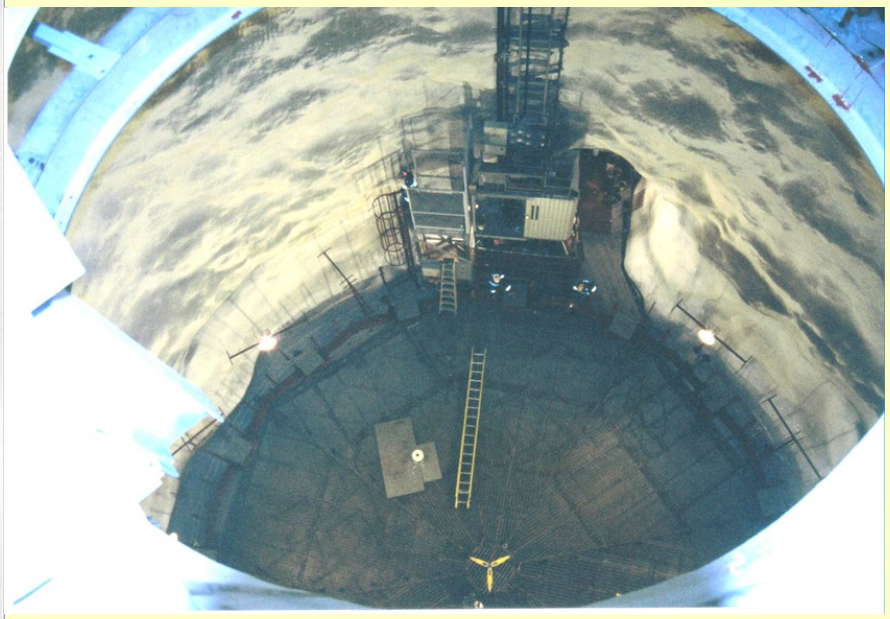
Ultra-pure Water: H_2O.

Urylon Liner and Radon Seal

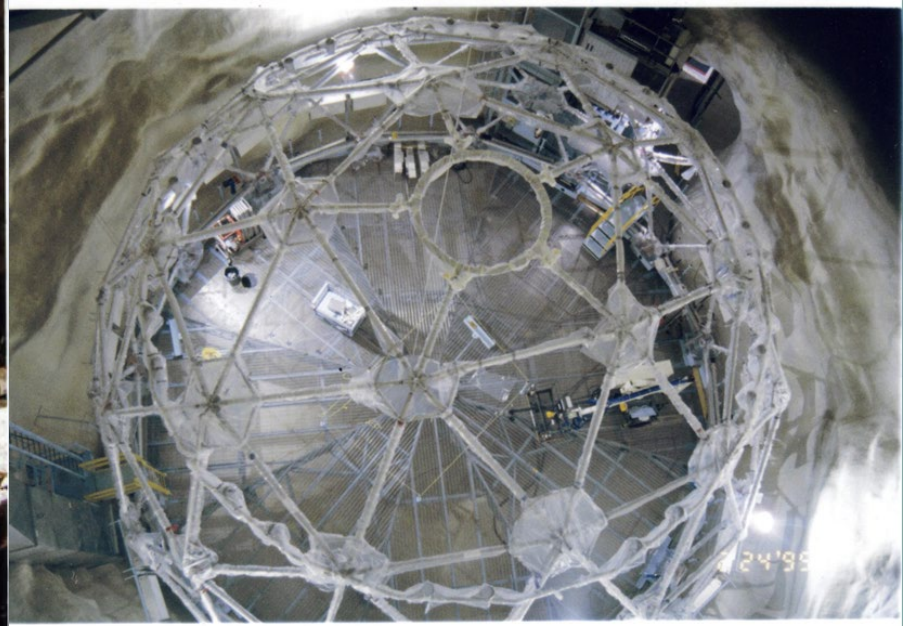


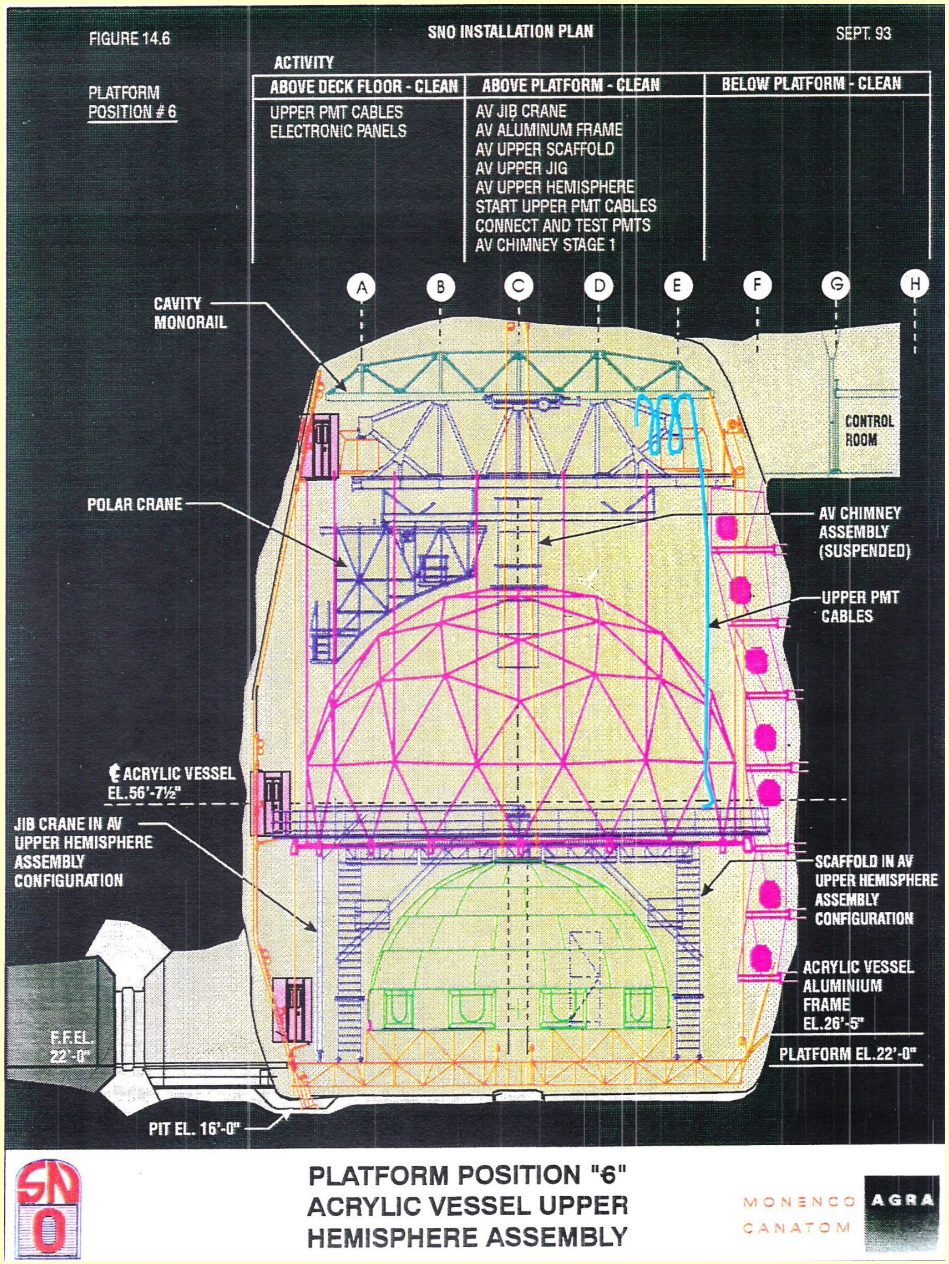


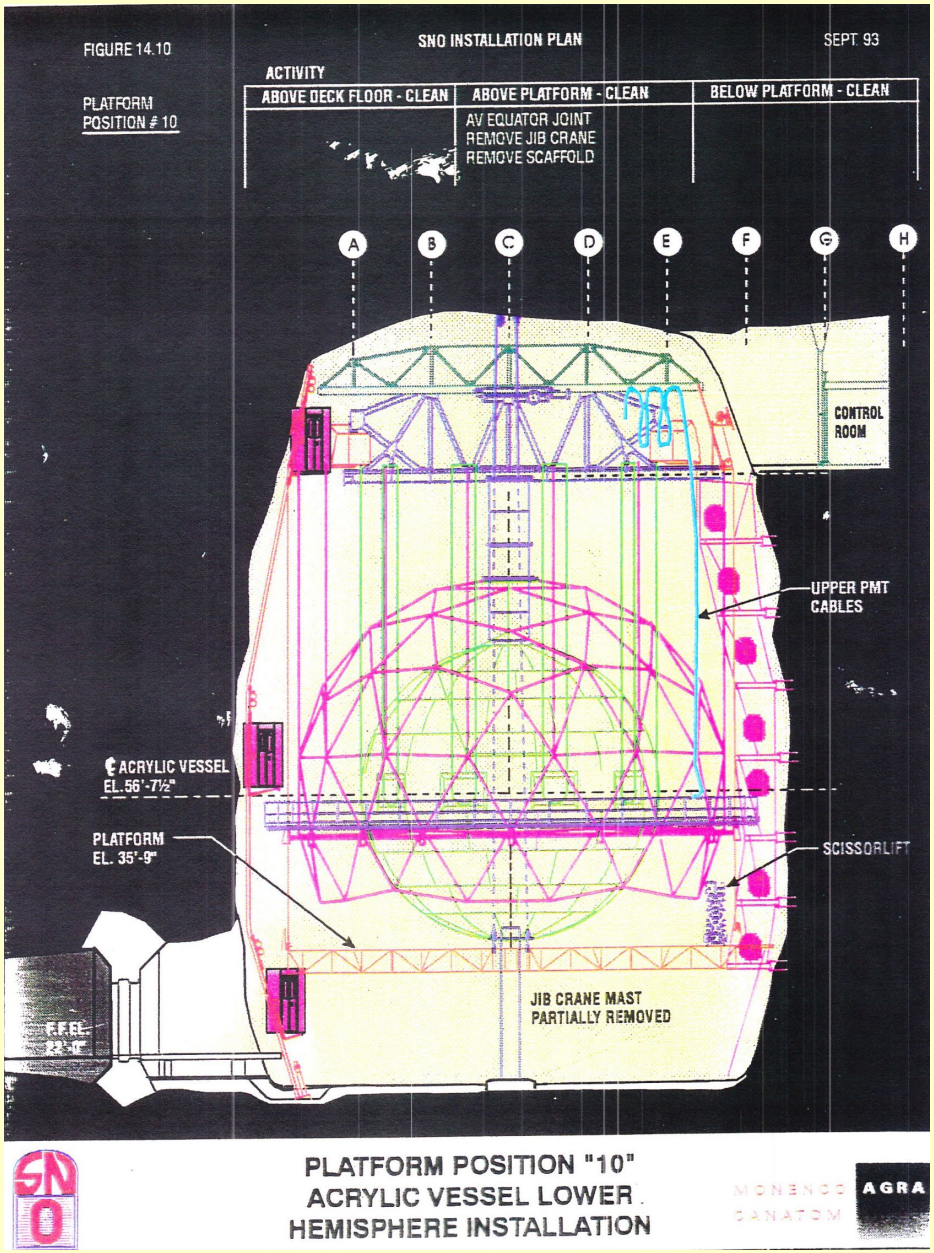
Urylon wall coating completed



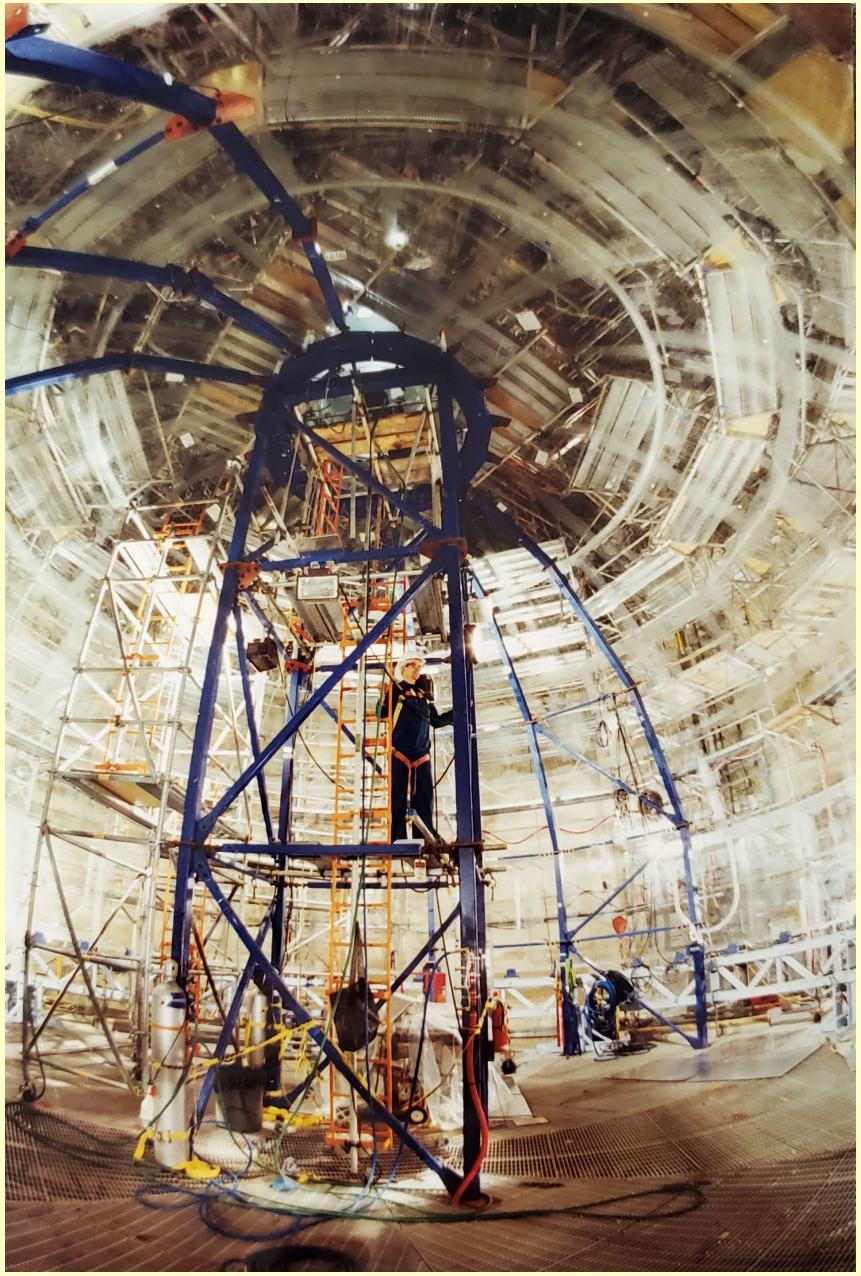
Start of construction of PMT support



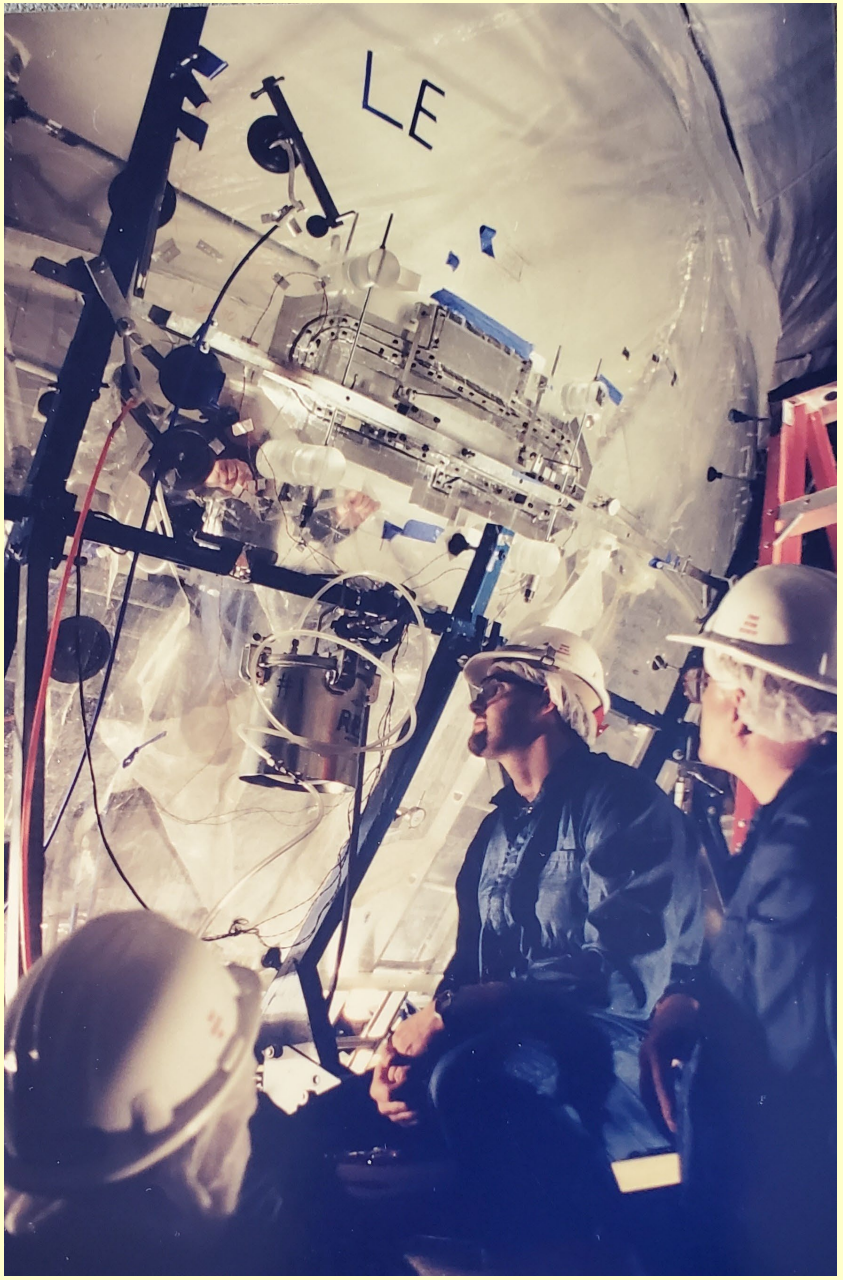




Construction Sequence



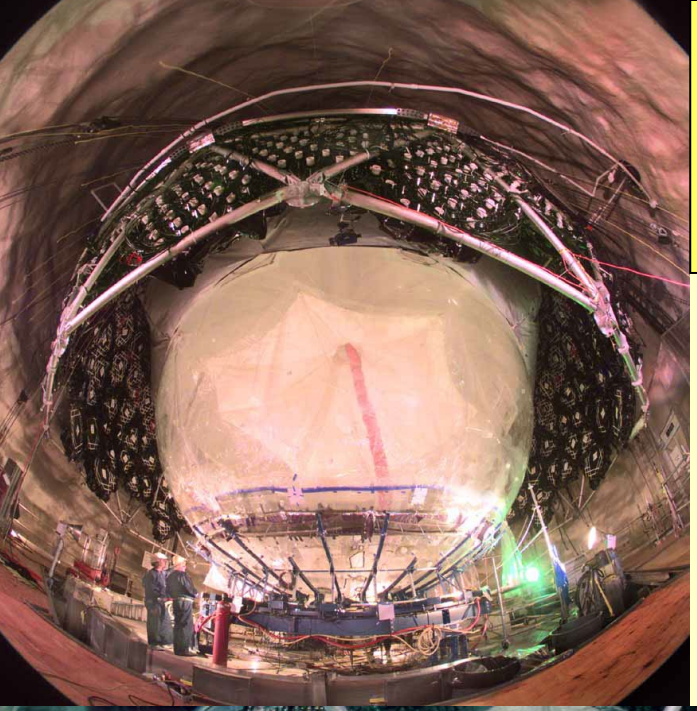
Bonding the upper AV hemisphere



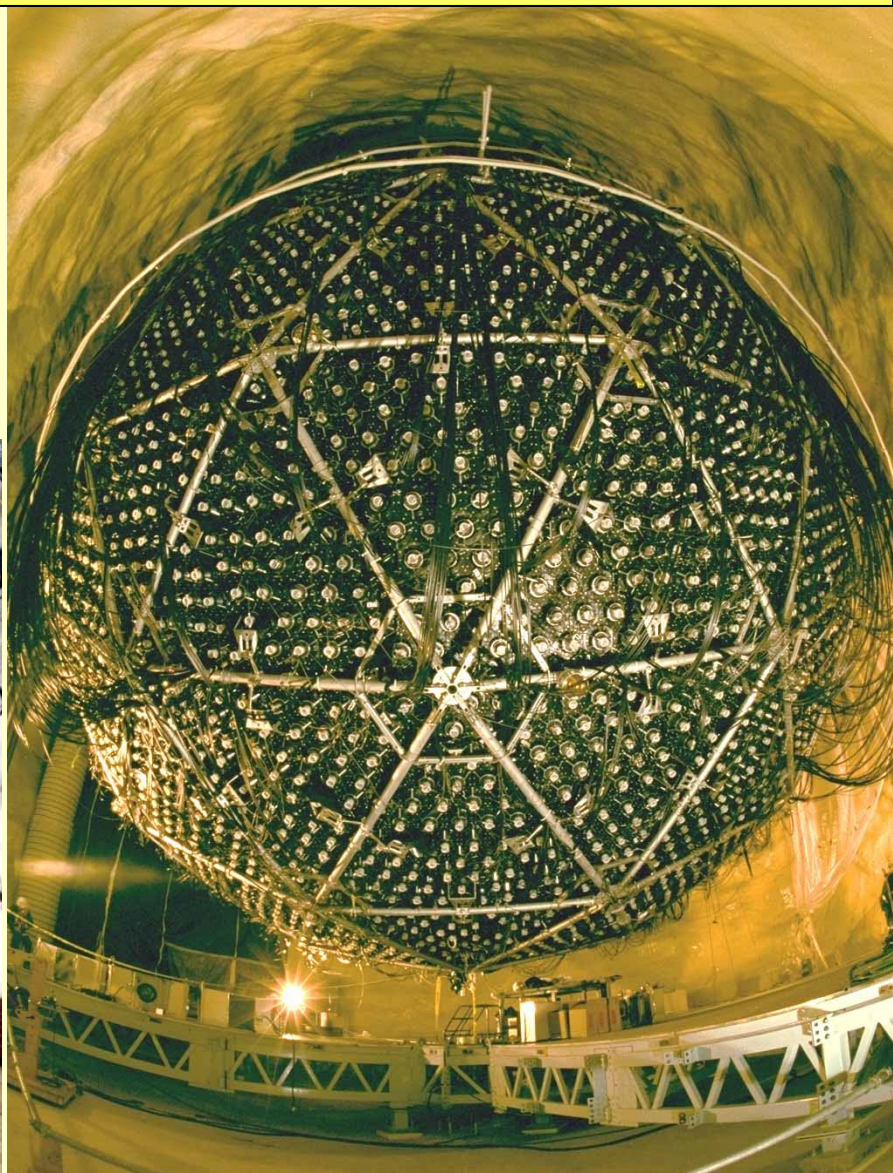
Repairing one of the flaws

Over 1 kilometer of successful bonds. About 5 meters requiring repairs.

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



1998: Rich Helmer from TRIUMF discussing the data acquisition with a visitor

Water systems: Less than one U, Th decay per day per tonne of water (measured)

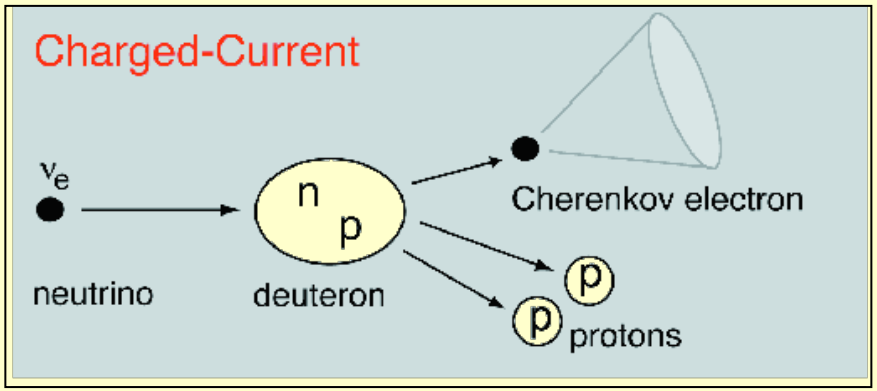
Unique Signatures in SNO (D_2O)

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

Electron Neutrinos (CC)

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

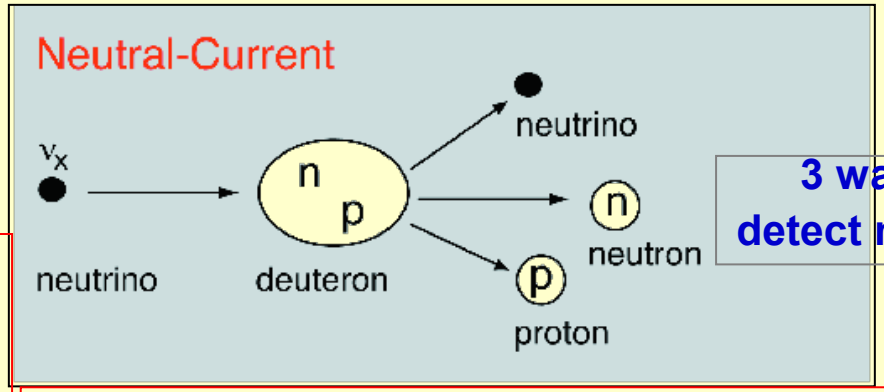
$E_{thresh} = 1.4$ MeV



Equal Sensitivity All Types (NC)

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

$E_{thresh} = 2.2$ MeV



3 ways to detect neutrons

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. Less than one decay per day per ton of water from U, Th required & measured

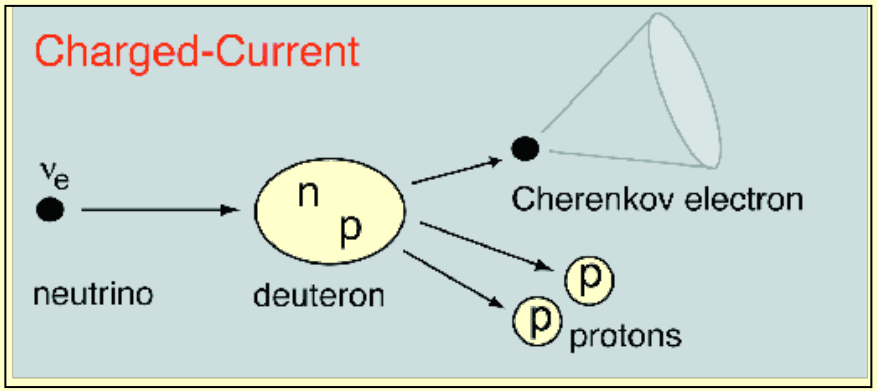
Unique Signatures in SNO (D_2O)

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

Electron Neutrinos (CC)

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

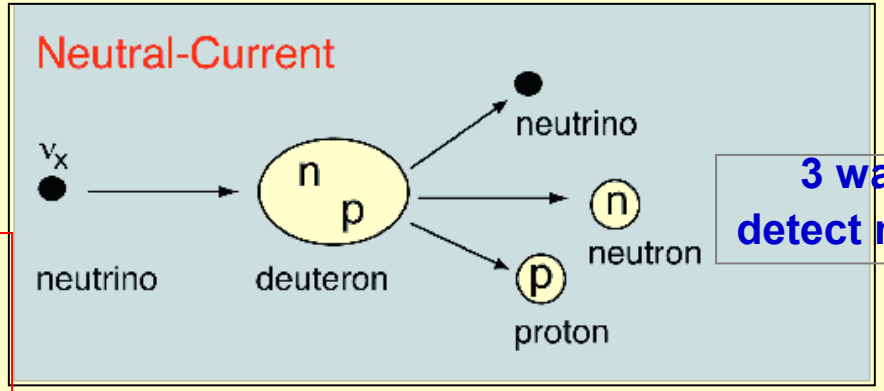
$E_{thresh} = 1.4$ MeV



Equal Sensitivity All Types (NC)

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

$E_{thresh} = 2.2$ MeV



3 ways to detect neutrons

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

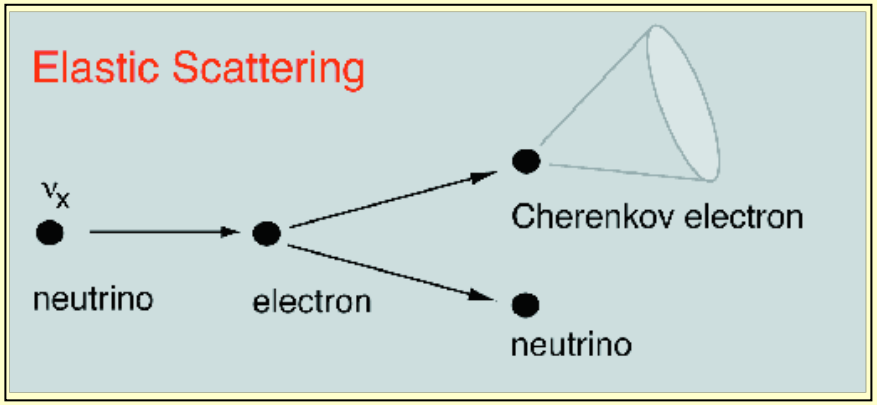
Elastic Scattering from Electrons

$\nu_x + e^- \rightarrow \nu_x + e^-$

ν_x NC: 15% vs ν_e: 85%

10 times lower total rate than CC

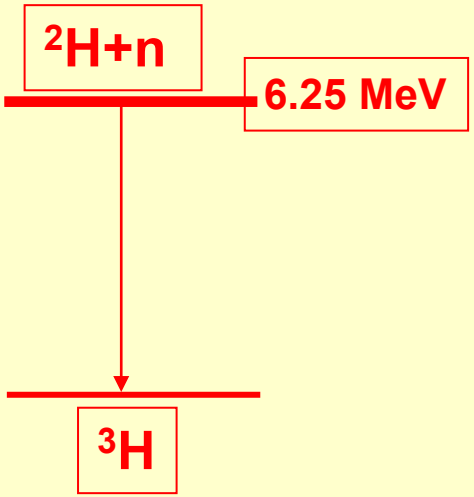
Points away from the Sun



3 neutron (NC) detection methods (systematically different)

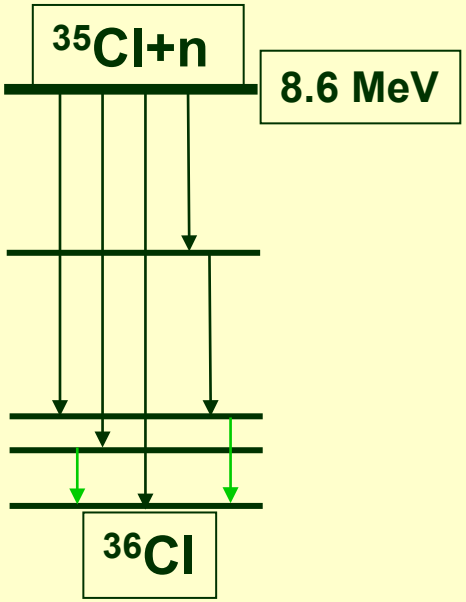
Phase I (D_2O)
Nov. 99 - May 01

n captures on
$^2H(n, \gamma)^3H$
Effc. ~14.4%
NC and CC separation by energy, radial, and directional distributions



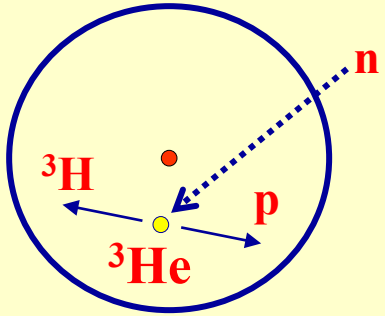
Phase II (salt)
July 01 - Sep. 03

2 tonnes of NaCl
n captures on
$^{35}Cl(n, \gamma)^{36}Cl$
Effc. ~40%
NC and CC separation by event isotropy



Phase III (^3He)
Nov. 04-Dec. 06

400 m of proportional counters
$^3He(n, p)^3H$
Effc. ~ 30% capture
Measure NC rate with entirely separate detection system.

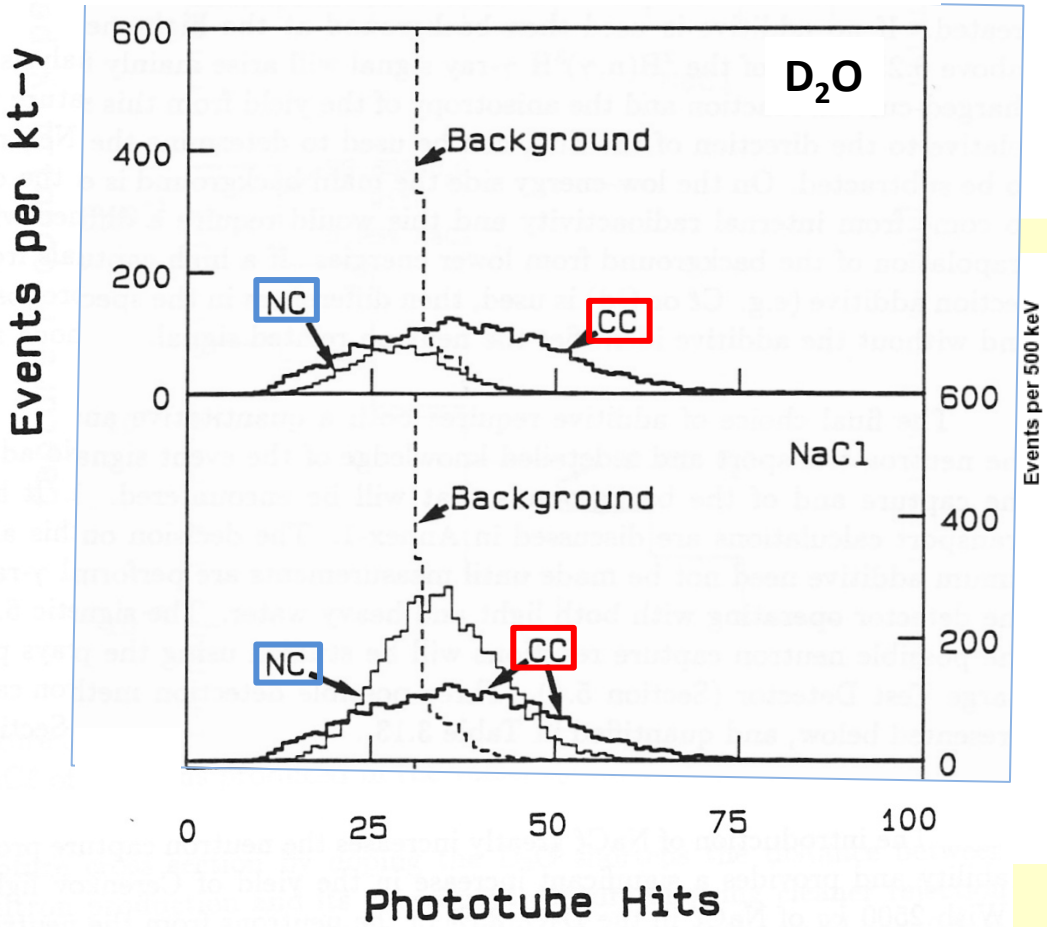


$n + {}^3He \rightarrow p + {}^3H$

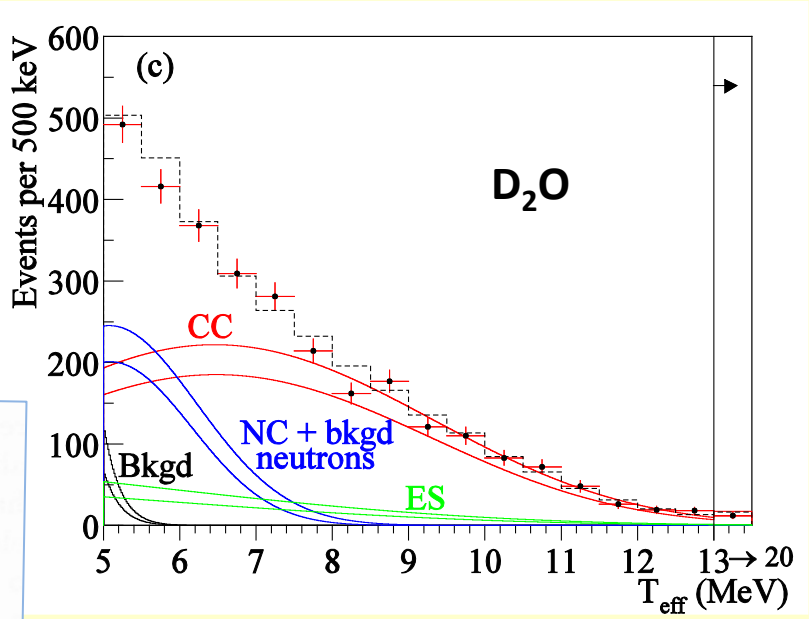
Salt Phase: Add 2 tonnes of NaCl

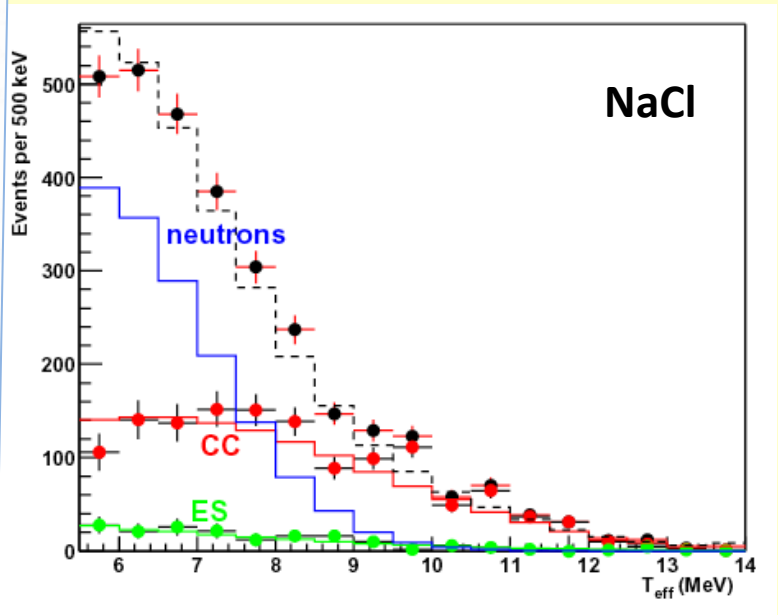
SNO "White Book"

As simulated in 1987

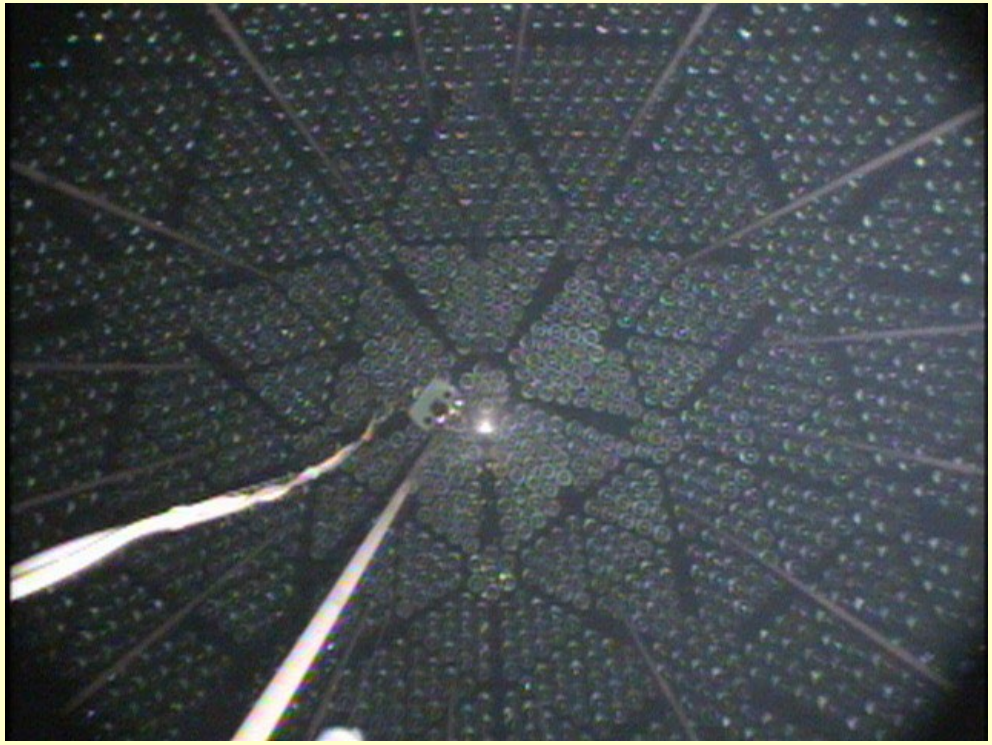


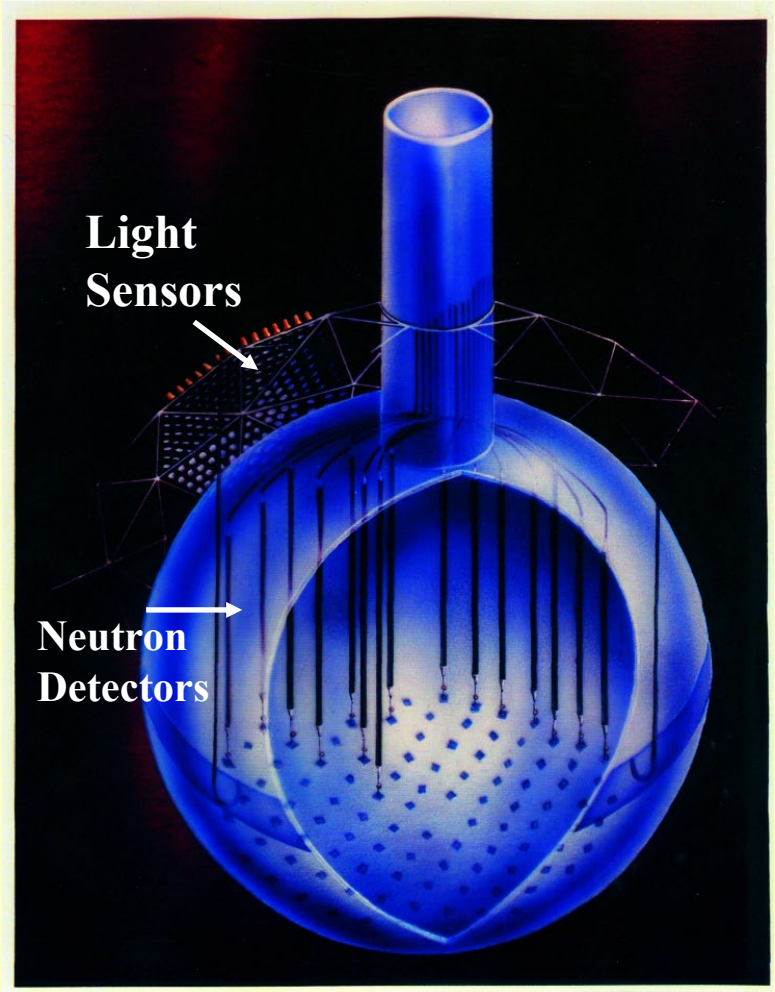
As measured 1999-2003

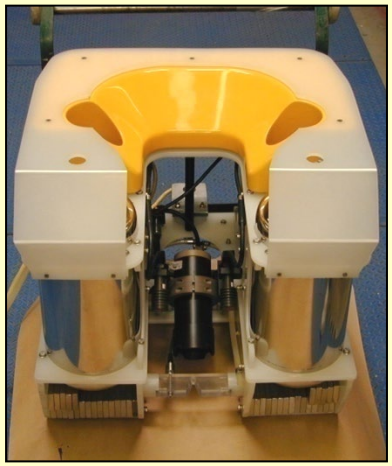




Phase 3: 400 m of Ultra Low Background Neutron Counters installed in the heavy water by a remotely controlled submarine



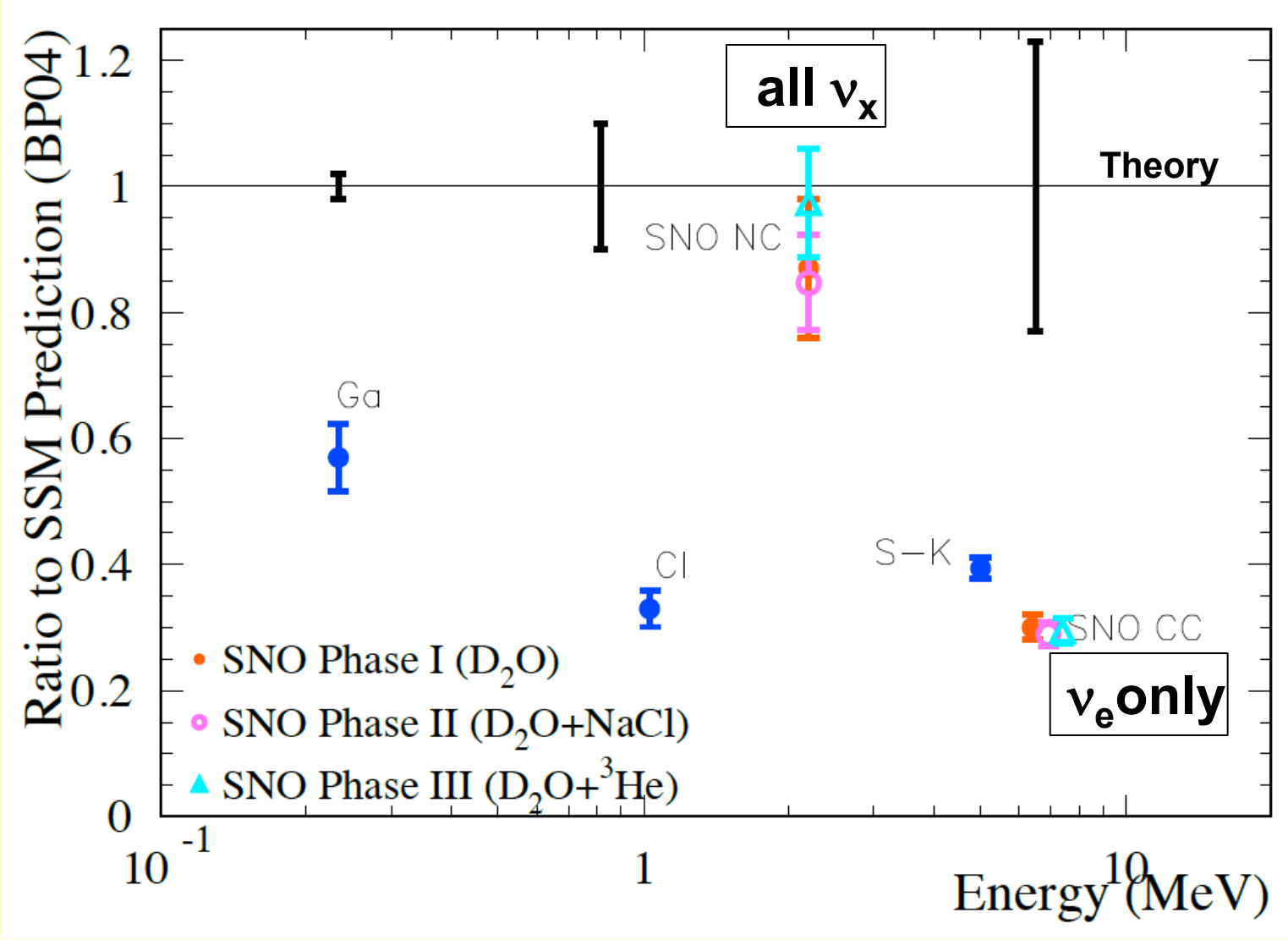


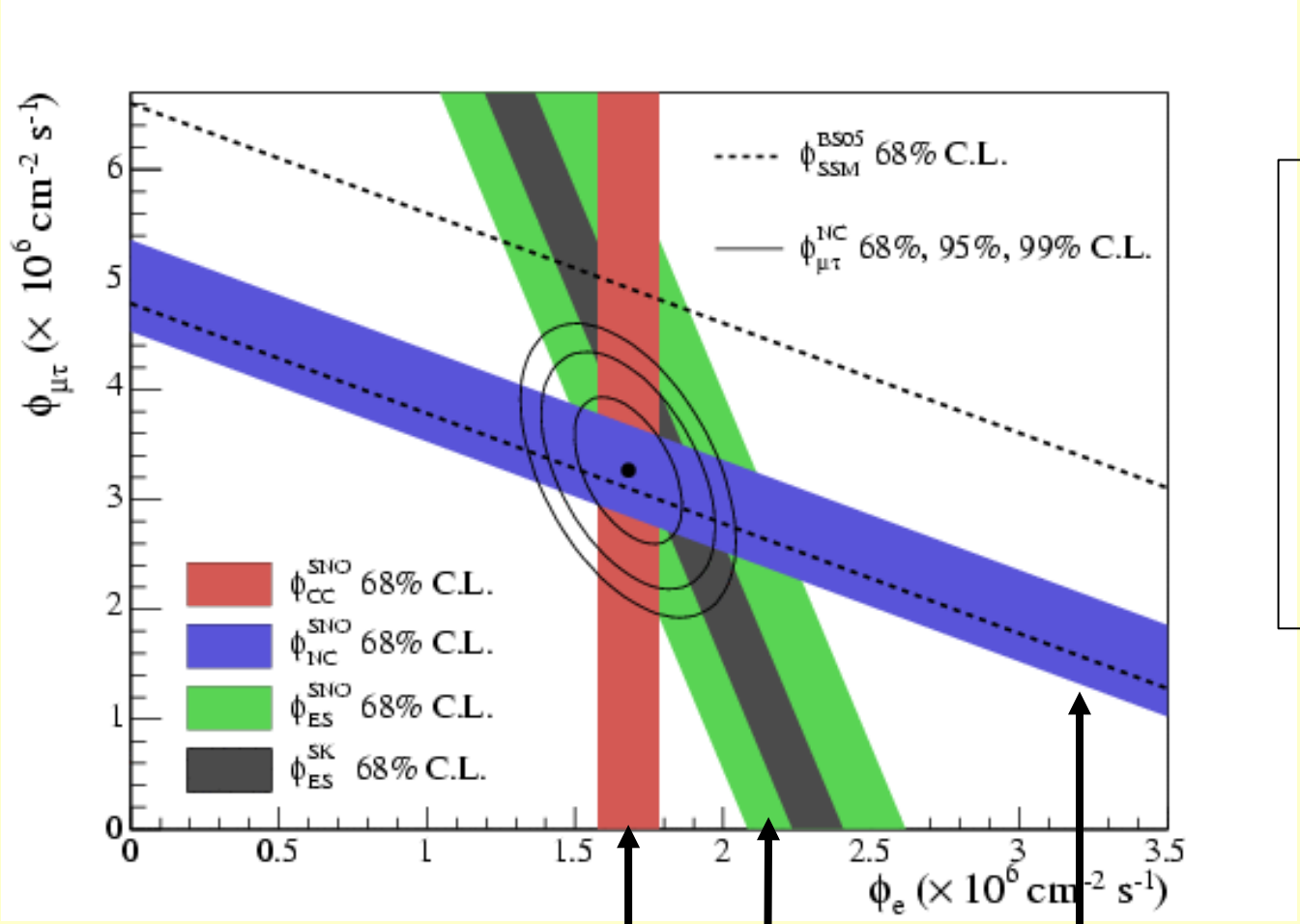


Original
Submarine

Solar Neutrino Problem Resolved:

- Solar Model Calculations are accurate
- About 2/3 of the electron neutrinos have changed to other flavours in transit from the core of the sun.





Salt Results on Neutrino Flavor change

Sensitive only to electron neutrinos

Partially sensitive to all neutrino types

Equally sensitive to all neutrino types

SNO PAPERS

- MEASUREMENT OF THE RATE OF ν_e + d to p + p + e^- PRODUCED BY ^{8}B SOLAR NEUTRINOS AT THE SUDBURY NEUTRINO OBSERVATORY, PRL 87 **(2001)** 07301 **(3.3 sigma flavour transformation of solar neutrinos)**

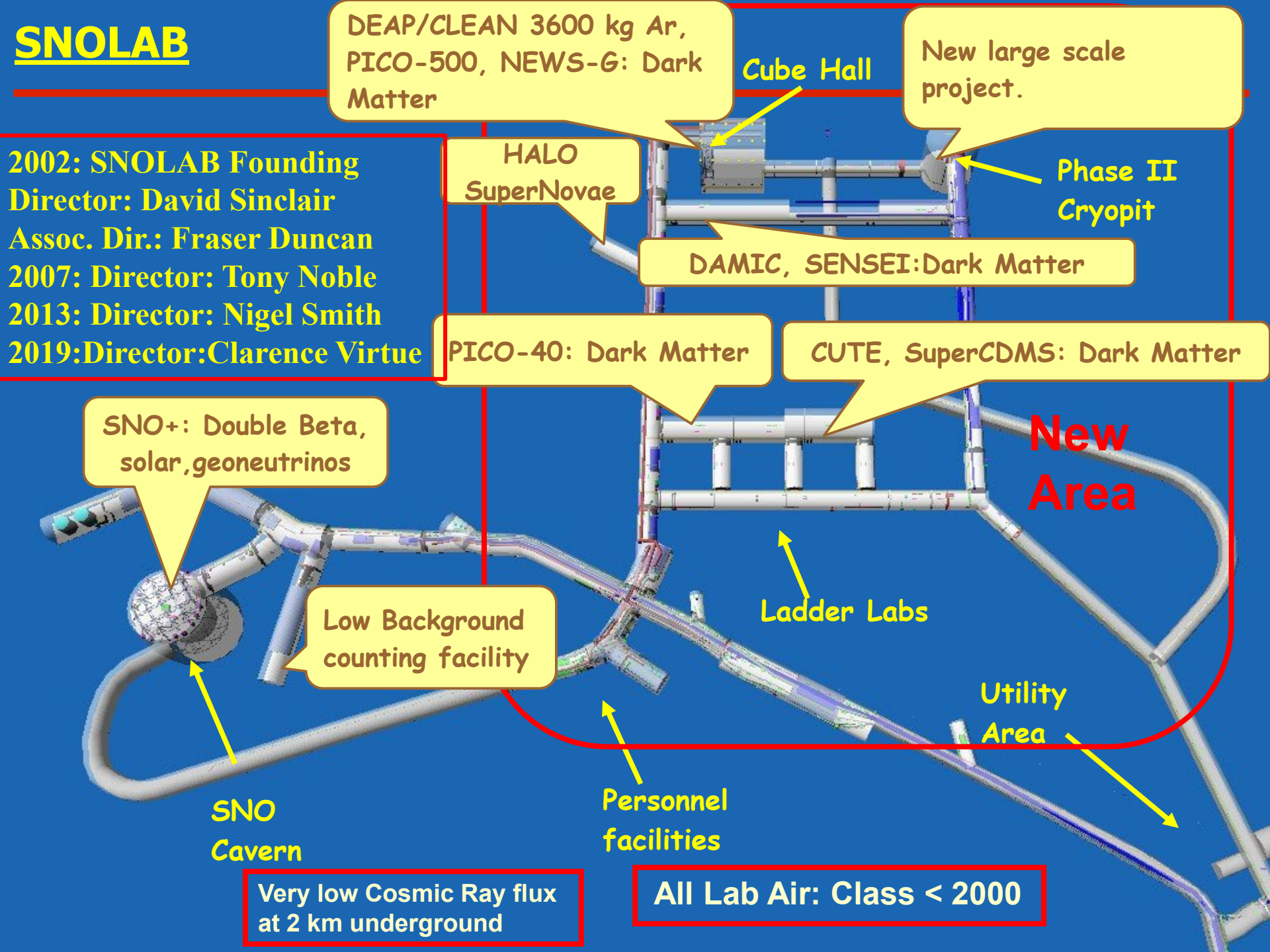
- DIRECT EVIDENCE FOR NEUTRINO FLAVOR TRANSFORMATION FROM NEUTRAL CURRENT INTERACTIONS IN THE SUDBURY NEUTRINO OBSERVATORY PRL 89 **(2002)** 011301 **(5.3 sigma flavour transformation)**
- MEASUREMENT OF **DAY AND NIGHT** NEUTRINO SPECTRA AT SNO AND CONSTRAINTS ON NEUTRINO MIXING PARAMETERS, PRL 89 **(2002)** 011306

- MEASUREMENT OF THE TOTAL ACTIVE ^{8}B SOLAR NEUTRINO FLUX AT THE SUDBURY NEUTRINO OBSERVATORY WITH ENHANCED NEUTRAL CURRENT SENSITIVITY, PRL 92 **(2004)** 181301 **(First salt)**
- AN INDEPENDENT MEASUREMENT OF THE TOTAL ACTIVE ^{8}B SOLAR NEUTRINO FLUX USING AN ARRAY OF ^{3}HE PROPORTIONAL COUNTERS AT SNO, PRL 101 **(2008)** 111301 **(First ^{3}He neutron detector measurement)**
- **COMBINED ANALYSIS OF ALL THREE PHASES OF SOLAR NEUTRINO** DATA FROM SNO, PRC 88 **(2013)** 025501

- **ELECTRON ANTINEUTRINO SEARCH** AT THE SUDBURY NEUTRINO OBSERVATORY, PRD70 **(2004)** 093014
- CONSTRAINTS ON **NUCLEON DECAY VIA "INVISIBLE" DECAY MODES** FROM SNO, PRL 92 **(2004)** 102004.
- SNEWS: THE **SUPERNOVA** EARLY WARNING SYSTEM (SNO+Others) New Journal of Physics, 6 **(2004)** 114.
- A SEARCH FOR **PERIODICITIES** IN THE ^{8}B SOLAR NEUTRINO FLUX MEASURED BY THE SUDBURY NEUTRINO OBSERVATORY, PRD 72 **(2005)** 052010.
- A SEARCH FOR NEUTRINOS FROM THE **SOLAR HEP** REACTION AND THE **DIFFUSE SUPERNOVA** BACKGROUND WITH THE SUDBURY NEUTRINO OBSERVATORY, Astrophysical Journal 653 **(2006)** 1545.
- MEASUREMENT OF THE **COSMIC RAY AND NEUTRINO-INDUCED MUON FLUX** AT THE SUDBURY NEUTRINO OBSERVATORY, PRD 80 **(2009)** 012001.
- A SEARCH FOR ASTROPHYSICAL **BURST** SIGNALS AT THE SNO, Astroparticle Phys. 55 **(2013)** 1.
- THE SEARCH FOR **NEUTRON-ANTINEUTRON OSCILLATIONS** AT SNO, PRD 96 **(2017)** 092005.
- TESTS OF **LORENTZ INVARIANCE** AT SNO, PRD 98 **(2018)** 112013.
- CONSTRAINTS ON **NEUTRINO LIFETIME** FROM SNO. PRD 99 **(2019)** 032013.
- A SEARCH FOR **HEP** SOLAR NEUTRINOS AND THE **DIFFUSE SUPERNOVA NEUTRINO** BACKGROUND USING ALL THREE PHASES OF SNO, PRD 102 **(2020)** 062006.

273 SNO Physics Paper Authors and 2016 Breakthrough Prize Winners: 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, Diane Reitzner, Dimpal Chauhan, Doug Hallman, Douglas 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, 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, 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 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 Biller, 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 15 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, Hugh Evans, Fraser Duncan, Davis Earle, Richard Hahn and Neil Tanner

SNOLAB


DEAP/CLEAN 3600 kg Ar, PICO-500, NEWS-G: Dark Matter
Cube Hall
New large scale project.
2002: SNOLAB Founding Director: David Sinclair
Assoc. Dir.: Fraser Duncan
2007: Director: Tony Noble
2013: Director: Nigel Smith
2019:Director:Clarence Virtue
HALO SuperNovae
Phase II Cryopit
DAMIC, SENSEI:Dark Matter
PICO-40: Dark Matter
CUTE, SuperCDMS: Dark Matter
New Area
SNO+: Double Beta, solar,geoneutrinos
Low Background counting facility
Ladder Labs
Utility Area
SNO Cavern
Personnel facilities
Very low Cosmic Ray flux at 2 km underground
All Lab Air: Class < 2000

AND ON TO THE FUTURE!