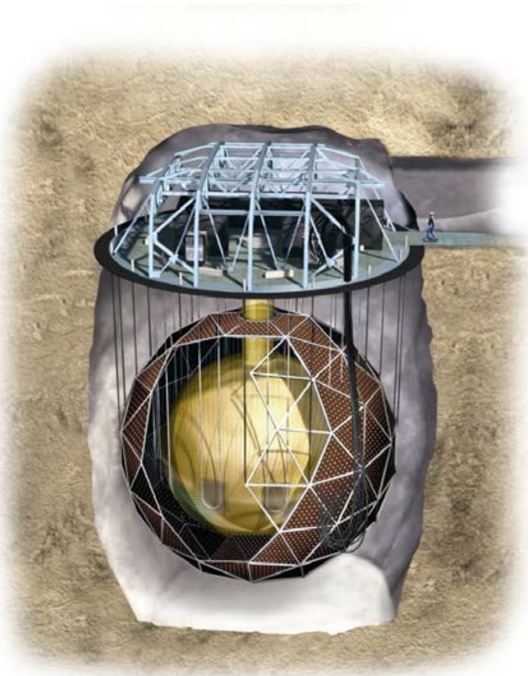
Sudbury Neutrino Observatory



2015 Nobel Prize
for Physics
2016 Breakthrough Prize
For Fundamental Physics

Robin Ollerhead, Professor Emeritus
Department of Physics, University of Guelph
Member of the SNO collaboration

Summer Lectures Club   May 19, 2016

What are neutrinos?

- Particles postulated by Pauli in 1930 to explain “missing energy” in beta decay, in which electrons are emitted from radioactive nuclei.
- These particles must be electrically neutral and of very small, perhaps zero, mass.
- Later named “neutrinos” – little neutral ones – by Italian physicist Enrico Fermi.
- Now known to come in three varieties, or “flavours”, each associated with a type of particle: electron (e), muon (μ), or tau (τ).
- Symbol ν (Greek letter nu) ν_e ν_μ ν_τ
- Pass easily through matter

Where do neutrinos come from?

- Beta decay, as described earlier   e.g.bananas

- Nuclear reactions; in particular, fusion reactions in the core of the sun (or any other star); nucleosynthesis

- The “Big Bang” – creation of the universe

Some Nuclear Physics

Nuclear Physics! WHY?

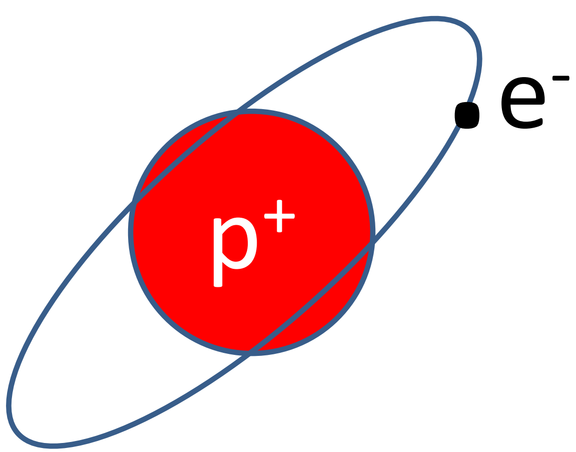
- To understand where so many neutrinos come from
- To understand why heavy water is essential to the experiment
- To understand why the experiment is considered to be so important

Hydrogen

$_1H^1$

Simplest atom

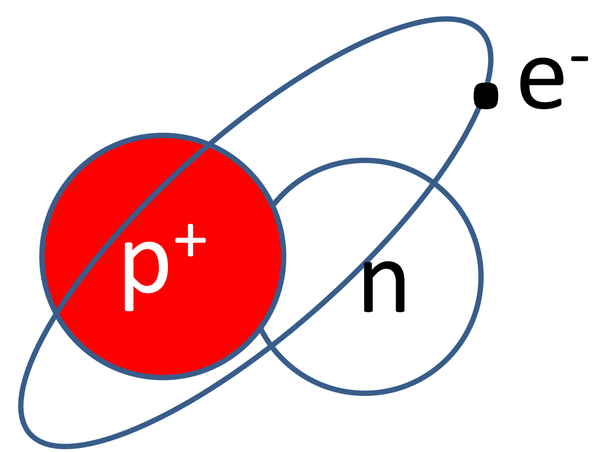
- Atomic number 1 – one proton in nucleus
- Mass number 1 – one nucleon in the nucleus
- Symbol for nucleus: p



Deuterium: $_1H^2$ or D

Isotope of hydrogen

- Atomic number 1 – identifies hydrogen
- Mass number 2 – added neutron in nucleus
- Symbol for nucleus: d (deuteron)



Other elements

- Atomic number 2- Helium: $_2He^3$ $_2He^4$
- Atomic number 3 – Lithium: $_3Li^6$ $_3Li^7$
- Atomic number 6 – Carbon: $_6C^{12}$
- Atomic number 8 _ Oxygen: $_8O^{16}$

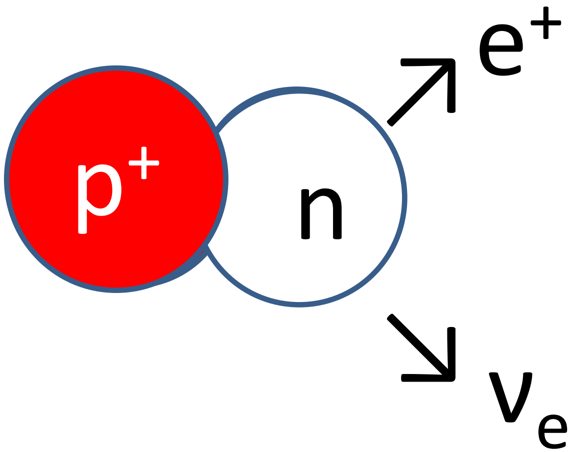
Water and Heavy Water

- Ordinary water - H_2O
- Heavy water – D_2O
  - deuterium in place of ordinary hydrogen
  - 11% heavier
  - Natural abundance 0.022 ppm
  - Chemically the same as water; difficult to separate
  - 1000 tonnes has a value of $300 million

Fusion

$$p + p \rightarrow d + e^{+} + \nu_e$$

$$_1H^1 + {}_1H^1 \rightarrow {}_1H^2 + e^{+} + \nu_e$$



Proton-Proton Chain

(a$_1$) ${}^1_1H + {}^1_1H \rightarrow {}^2_1H + e^+ + \nu$
(b$_1$) ${}^2_1H + {}^1_1H \rightarrow {}^3_2He + \gamma$
(c$_1$) ${}^3_2He + {}^3_2He \rightarrow {}^4_2He + 2{}^1_1H$

or (c$_2$) ${}^3_2He + {}^4_2He \rightarrow {}^7_4Be + \gamma$
(d$_2$) ${}^7_4Be + e^- \rightarrow {}^7_3Li + \nu$
(e$_2$) ${}^7_3Li + {}^1_1H \rightarrow 2{}^4_2He$

or (d$_3$) ${}^7_4Be + {}^1_1H \rightarrow {}^8_5B + \gamma$
(e$_3$) ${}^8_5B \rightarrow {}^8_4Be + e^+ + \nu$
(f$_3$) ${}^8_4Be \rightarrow 2{}^4_2He$

- Origin of neutrinos from the sun (all stars)
- Conversion of hydrogen to helium
- Creation of new elements: nucleosynthesis

Nucleosynthesis

Through a series of nuclear reactions, other elements are created:

- Carbon: $3\ {}_2He^4 \rightarrow {}_6C^{12}$
- Oxygen: $4\ {}_2He^4 \rightarrow {}_8O^{16}$, etc.
- Understanding of neutrinos is essential to our understanding of the source of energy in our sun, evolution of stars, and creation of elements!

Some questions answered

- Where do neutrinos come from?

-Billions are created every second in the core of the sun (and all other stars)

- Why are they important?

-messengers directly from the core of the sun

-can confirm (or not!) our understanding of how energy is produced in stars, how elements are created, evolution of stars, cosmology

How do we detect neutrinos from the sun?

- Experiments by Raymond Davis (1968-79) used a large tank of perchloroethylene (C_2Cl_4) 1.5 km underground in the Homestake gold mine.
- Inverse beta-decay: $\nu_e + {}_{17}Cl^{37} \rightarrow {}_{18}Ar^{37} + e^-$
- Collected and counted argon atoms
- Result: Only about 1/3 of the number expected from theoretical calculations were detected.

The Solar Neutrino Problem

- Either: the models of the sun are wrong

-we don’t know the composition of the sun

-we don’t understand nuclear reactions in the sun

-we don’t understand creation of the elements

- Or: our knowledge of neutrinos is incomplete

-is it possible that neutrinos can “oscillate” between types i.e. change “flavours”?

SNO was designed to resolve the "Solar Neutrino Problem"

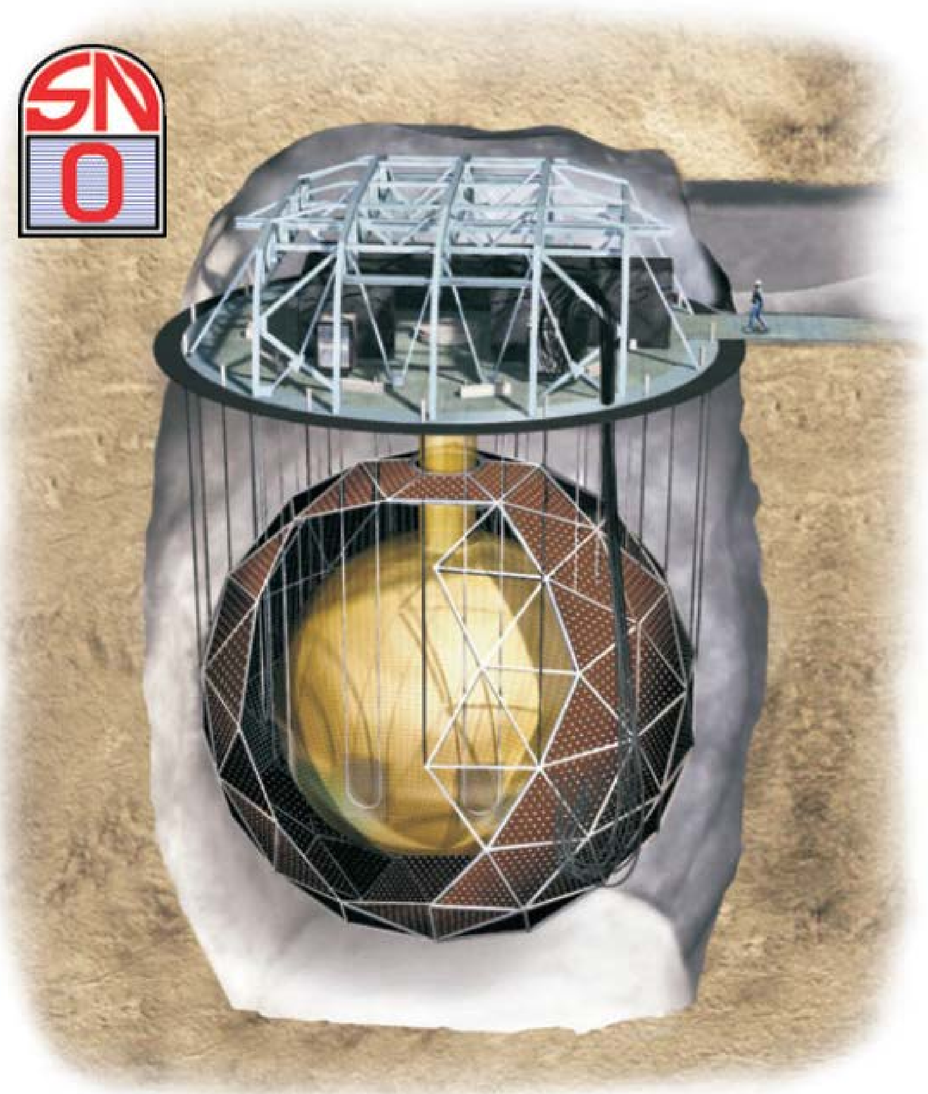
- energetic solar neutrinos, one way or another, transfer energy to an electron which emits Cherenkov light

CC $$\nu_e + d \Rightarrow p + p + e^-$$

NC $$\nu_x + d \Rightarrow p + n + \nu_x$$

ES $$\nu_x + e^- \Rightarrow \nu_x + e^-$$

- the photomultiplier tubes (PMTs) are sensitive enough to detect single photons of light
- from a few hit PMTs we can reconstruct the energy, position and direction of the electron



Three ν Reactions in SNO

ν Reaction	Detection

CC $\nu_e + d \rightarrow p + p + e$

- Good measurement of ν_e energy spectrum
- Weak directional sensitivity $\propto$ 1-1/3cos(θ)
- **ν_e only : what the Sun produces !**

- cone of Cherenkov light from e

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

- Measure total ^{8}B ν flux from the sun.
- Equal sensitivity to all ν types ν_e, ν_μ and ν_τ

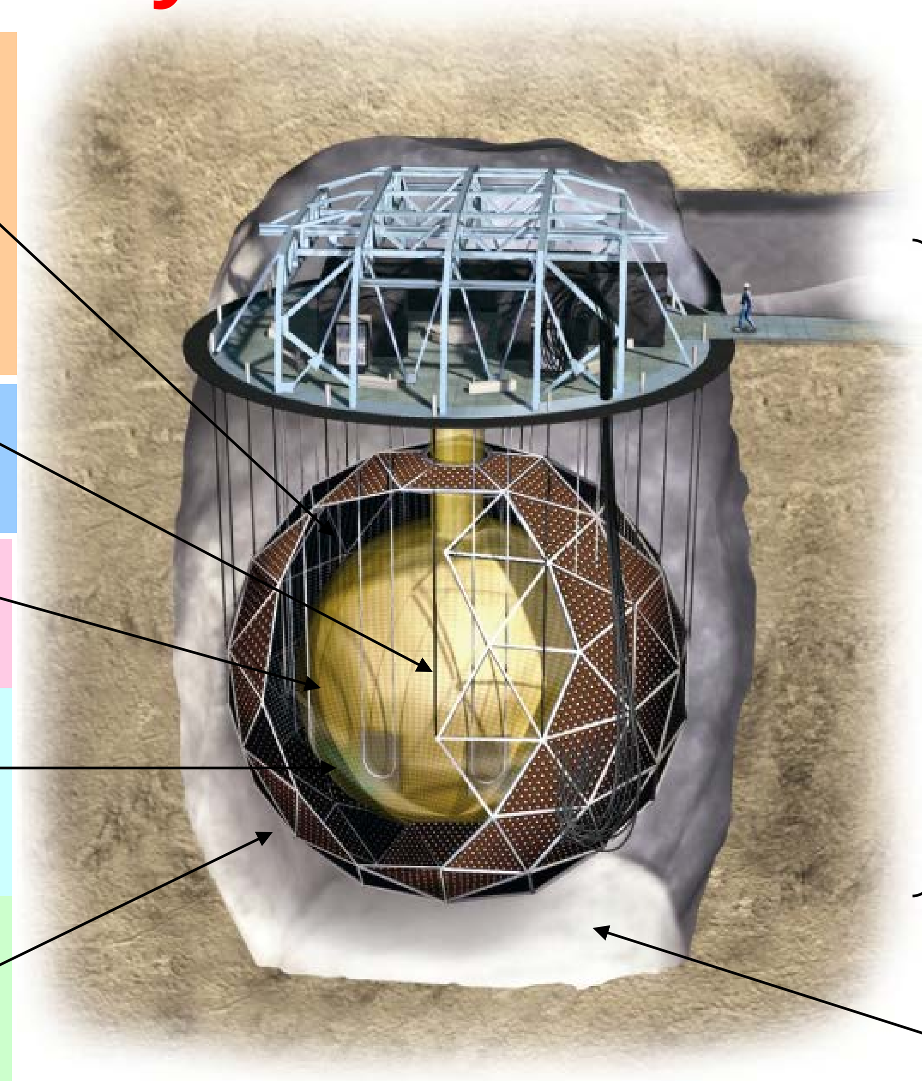
- n captures and produces gamma ray/s
- gamma/s knock off electrons
- electrons produce Cherenkov light

ES $\nu_x + e \rightarrow \nu_x + e$

- Low Statistics
- Mainly sensitive to ν_e : less to ν_μ and ν_τ
- Strong directional sensitivity

- cone of Cherenkov light from e

The Sudbury Neutrino Observatory



18 m diameter Support Structure for 9456 light sensors

1000 tonnes D_2O

12 m diameter Acrylic Vessel

1700 tonnes Inner shielding H_2O

5300 tonnes Outer shielding H_2O

Deepest cavern (of its size) in the world Inco/Vale - SNO

Clean Room Construction *

Ultra-low Activity Components *

Ultra-Pure Water

Plastic Liner & Radon Seal

Partnerships - SNO institutions/scientists, engineers, development companies $\rightarrow$ ***spin offs***

More answers

- Why use heavy water?

-every molecule contains two deuterons (d), essential to detection of neutrinos in SNO

- Why 2 km underground?

-to shield out cosmic rays from space which would interfere with detection of neutrinos

- Why in Canada?

-availability of 1000 tonnes of pure heavy water from AECL, valued at $300 million

-deepest accessible location in North America at INCO’s Creighton mine

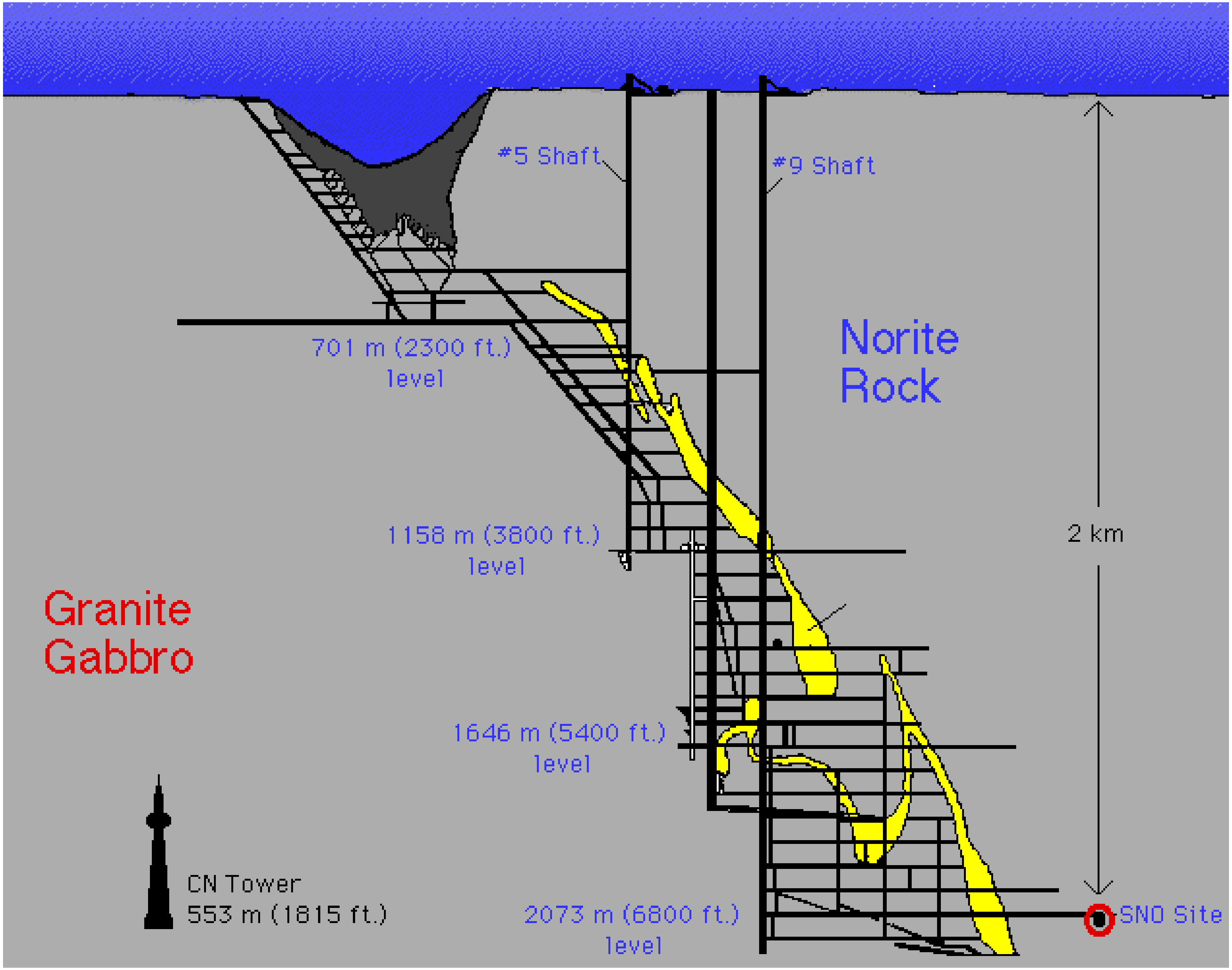
A brief history of SNO

- 1984 – SNO collaboration founded
- 1987 – detailed proposal submitted to funding agencies
- 1989 – Art McDonald moved to Queen’s University to become Director of the SNO project
- 1990 – capital funding obtained; excavation begins
- 1994 – cavity finished; assembly of detector begins
- 1998 – water fill begins; official opening with Stephen Hawking
- 1999 – start of taking data
- 2006 – end of taking data
- 2017 – heavy water removed

Vale's Creighton Mine

near Lively

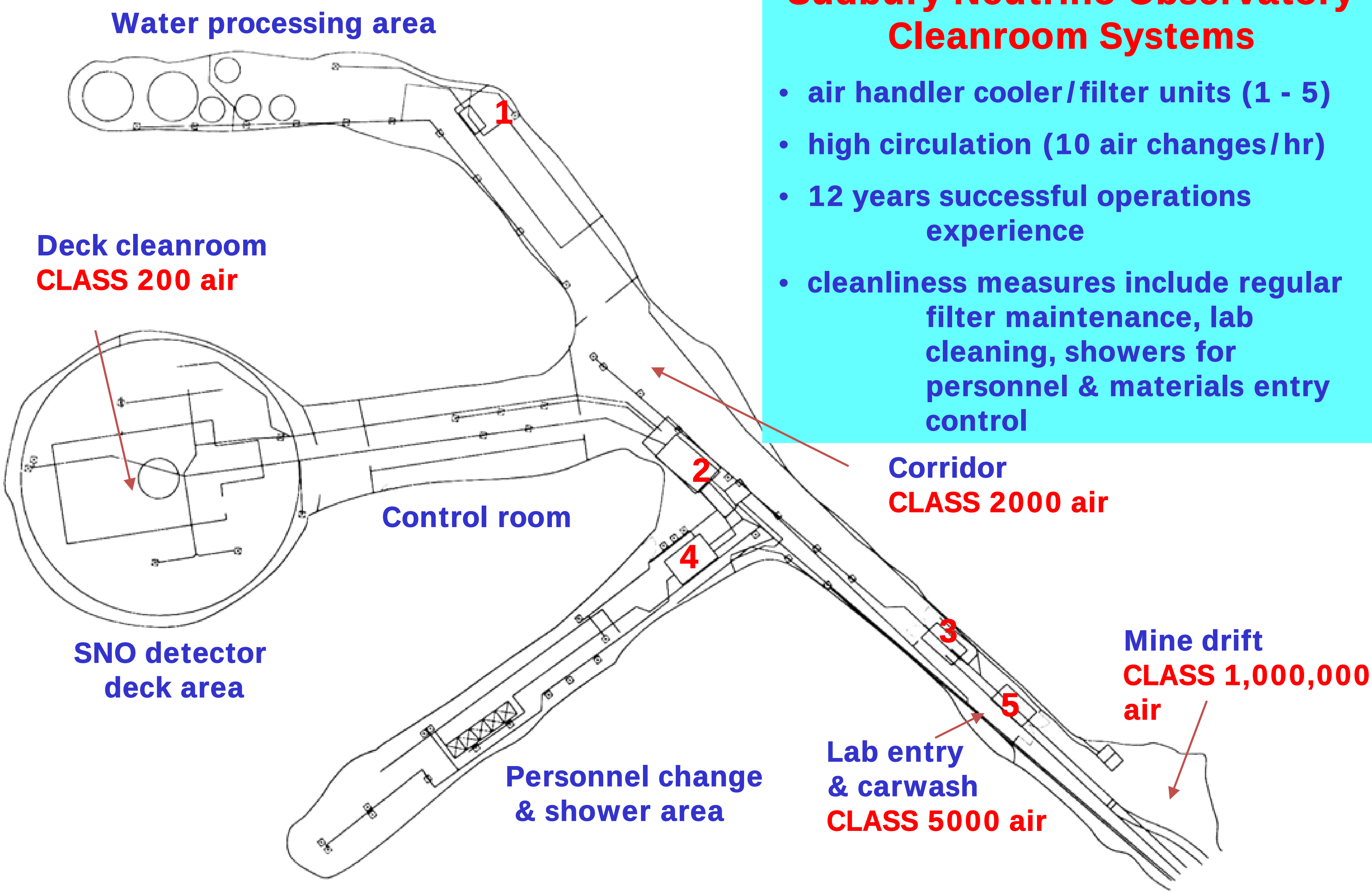
deepest and best site in North America



Vale Creighton Mine

Sudbury Neutrino Observatory Cleanroom Systems

- air handler cooler/filter units (1 - 5)
- high circulation (10 air changes/hr)
- 12 years successful operations experience
- cleanliness measures include regular filter maintenance, lab cleaning, showers for personnel & materials entry control



- unique XRF technique developed to monitor dust deposition and surfaces

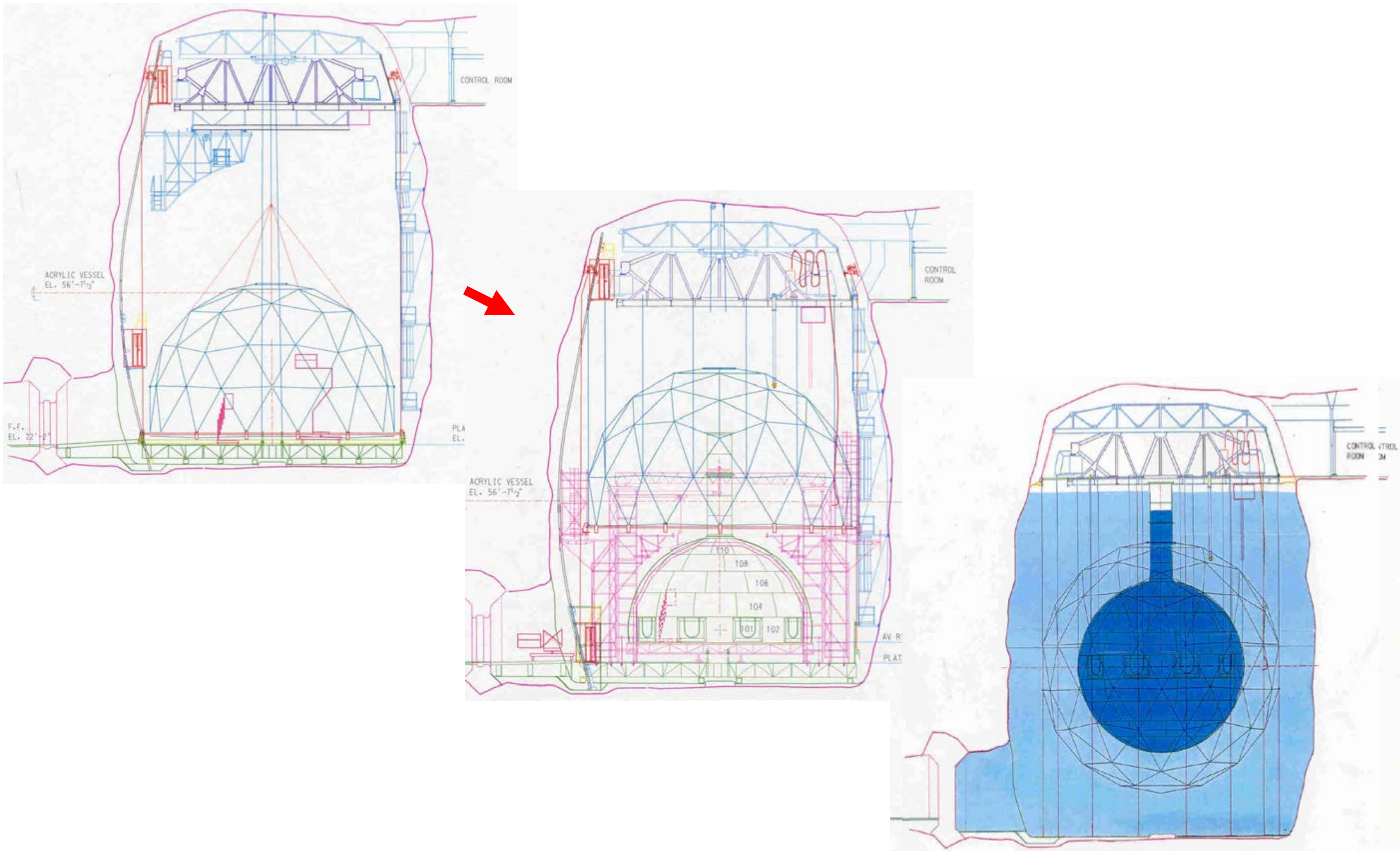
SNO surface building

Entrance to SNO drift

Outside entrance to lab area

Excavation of cavity

How the SNO Detector was Assembled



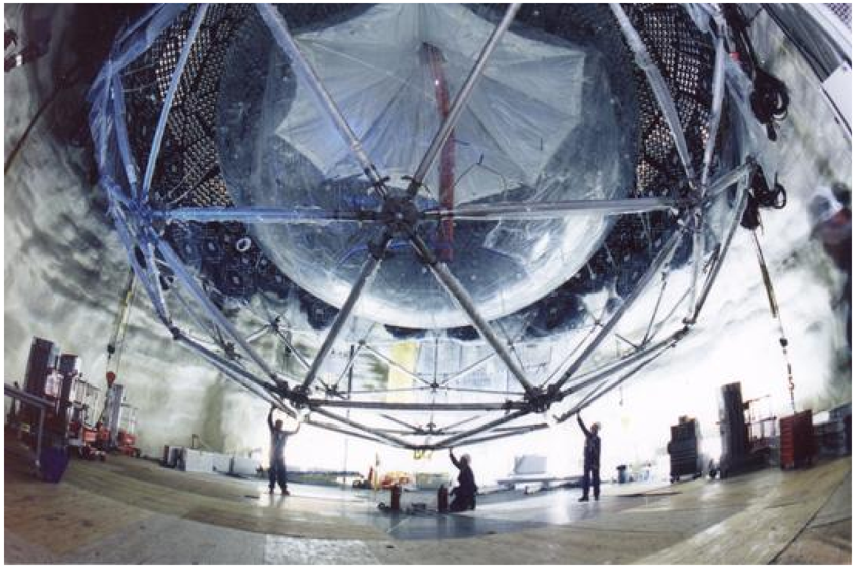
Acrylic panel to be installed

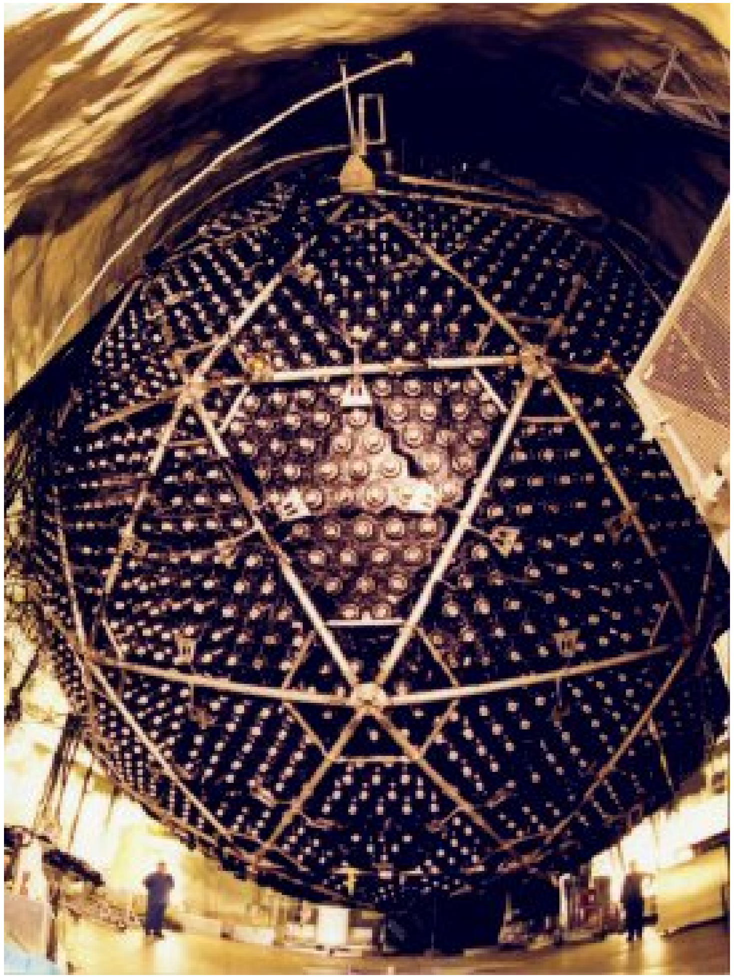
Upper hemisphere of AV

Inside upper hemisphere of AV

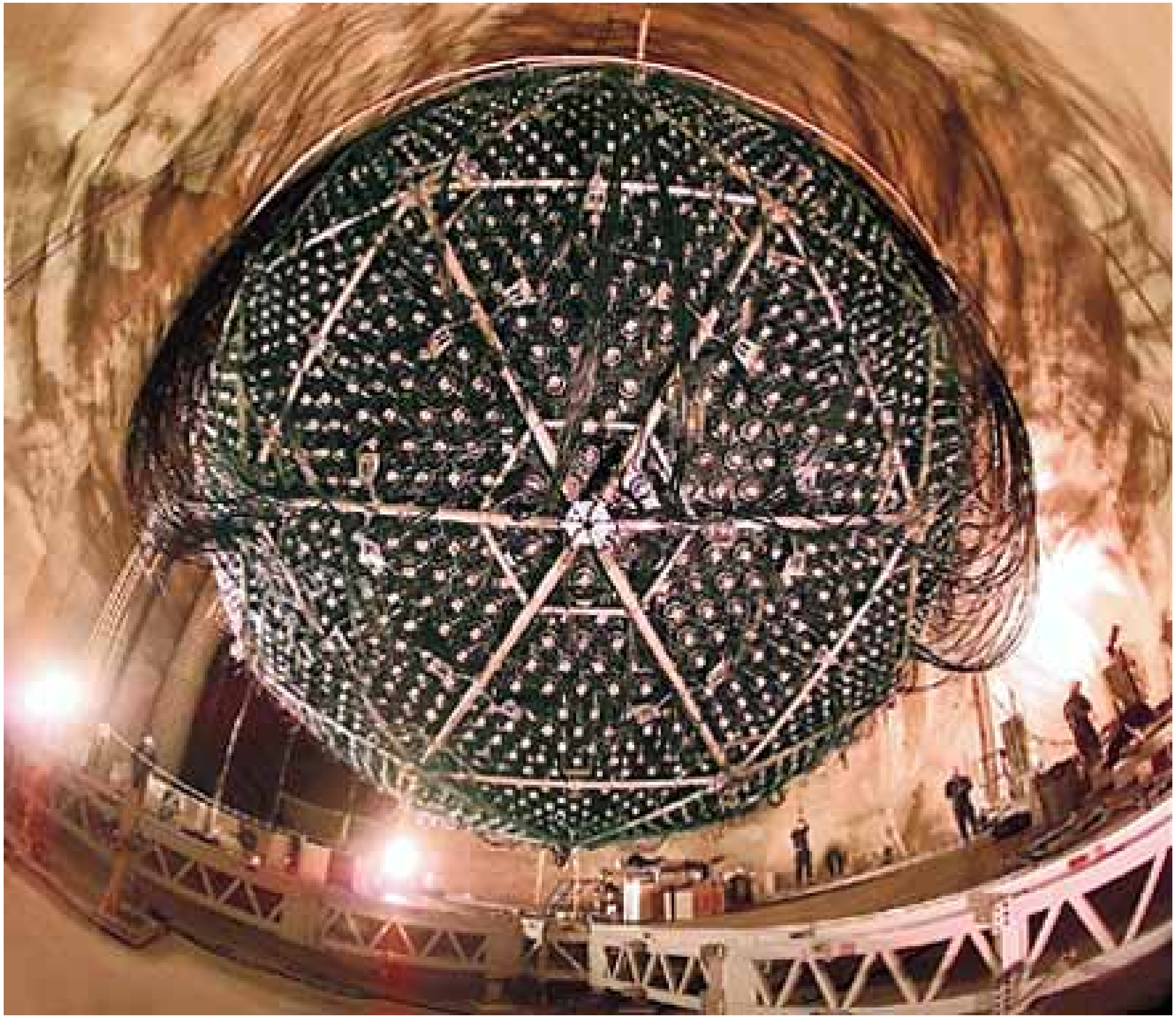
PSUP trial assembly at Berkeley

The SNO Detector during Construction

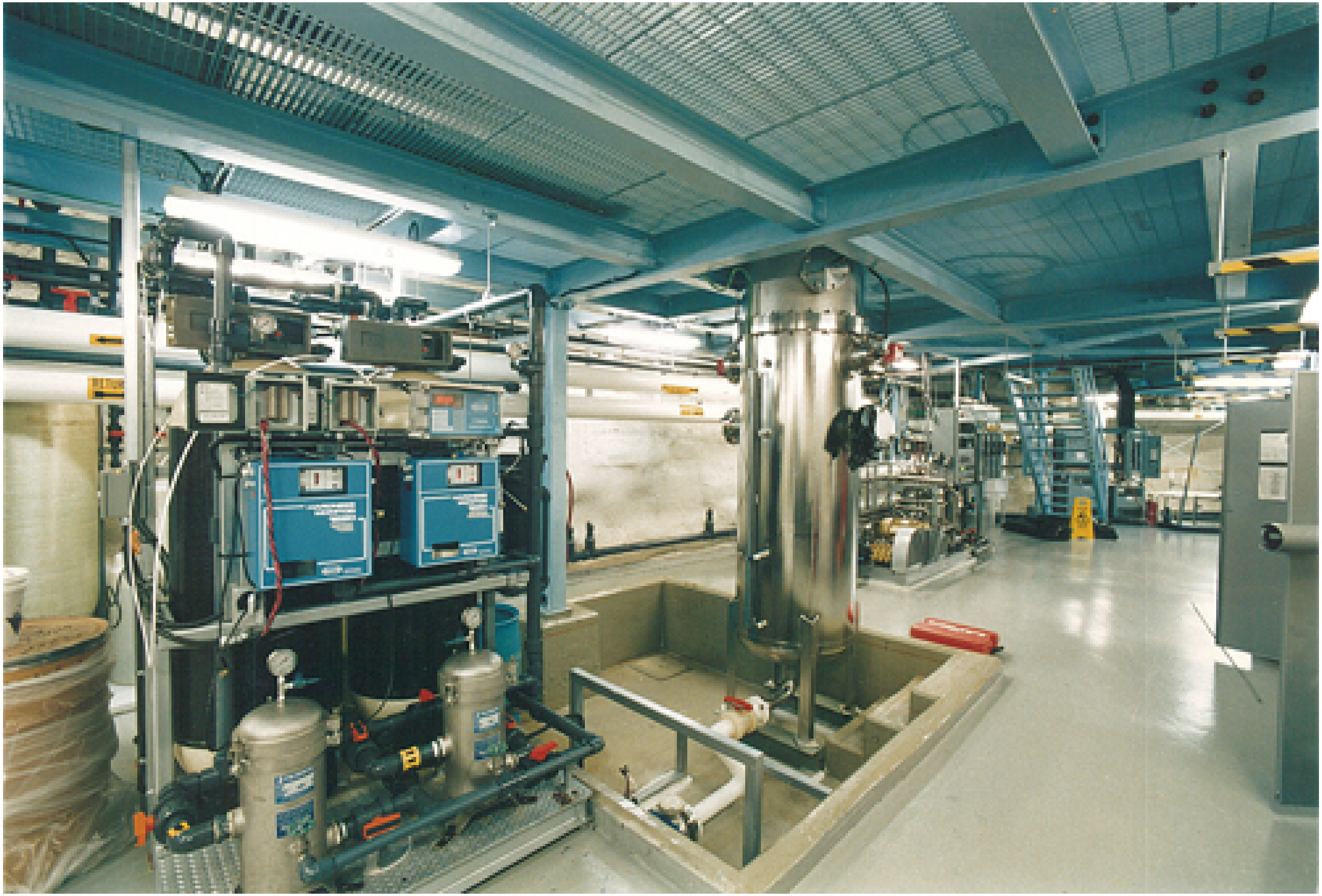




PSUP with PMTs and cables



Water treatment area



Group of physicists underground

Stephen Hawking at official opening April 28-29, 1998

Special car built for Stephen Hawking

Stephen Hawking in underground control room

Jeff Karn and Rob Hanson under the PMT array

Electronics rack

Control room (taking data)

Three phases of SNO measurements

Detection of neutrons from NC reaction

- Pure D_2O (Nov 1999 to May 2001)

-n detected by capture on deuterium, γ-ray, electron, Cherenkov radiation

- Salt (2 tons NaCl) added (July 2001 to August 2003)

-n capture on chlorine; γ-ray cascade, more electrons, more Cherenkov radiation

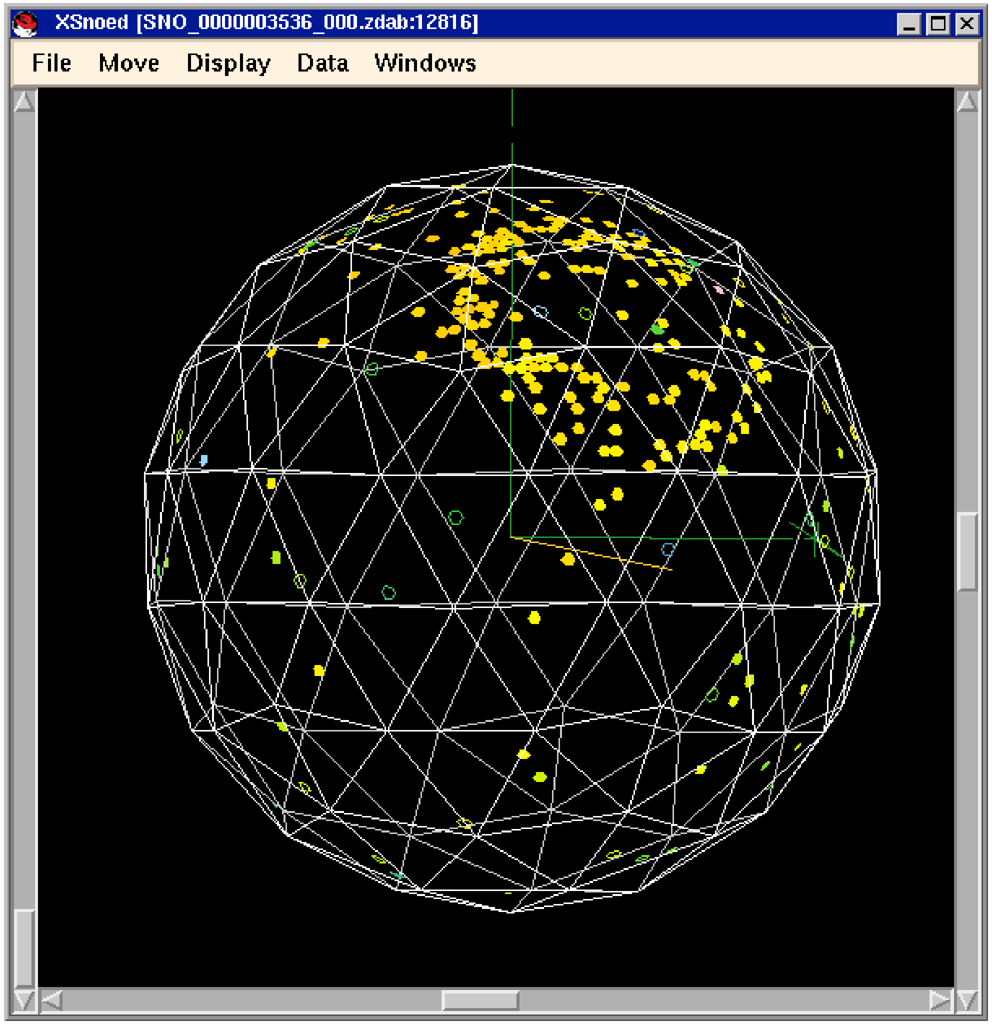
- Dedicated n detectors (Nov 2004 to Nov 2006)

-array of specially designed detector tubes installed

- Three independent measurements of NC reaction

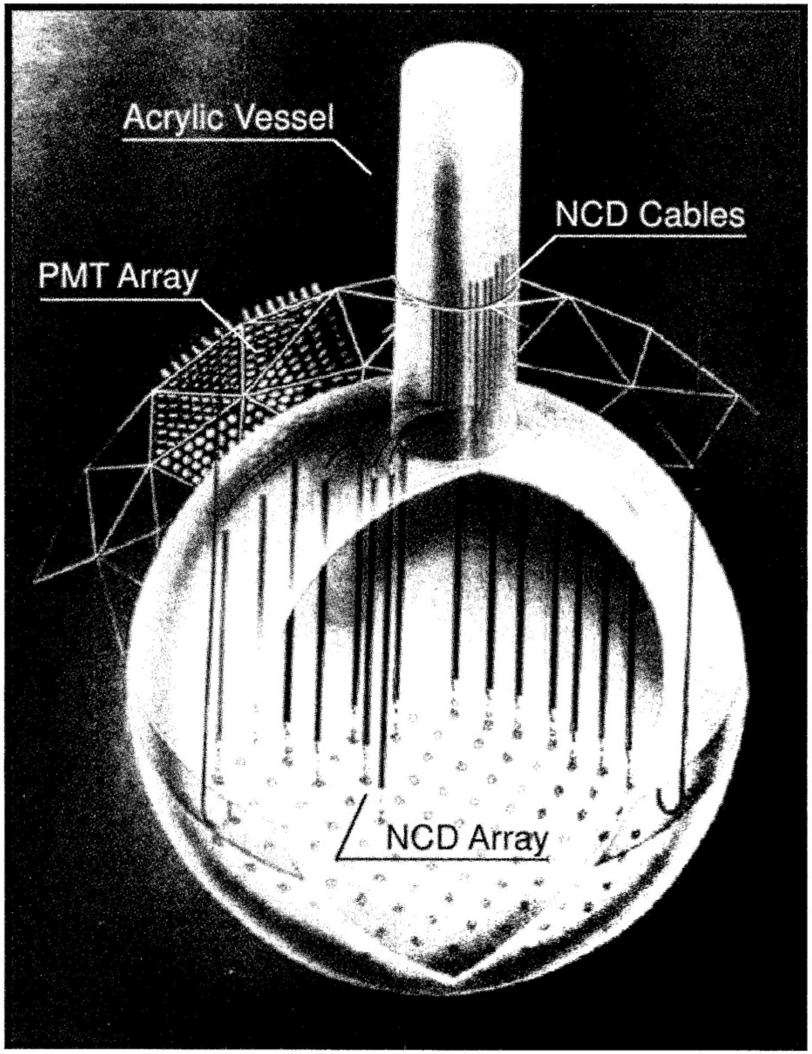
Cherenkov light yields the information

- energy is proportional to number of photons detected (requires calibration)
- position can be calculated from photon arrival times at each PMT (requires calibration)
- direction comes from fitting the axis of the Cherenkov cone



Neutrino candidate event

Neutron detectors in NCD array



Results

Measured flux of neutrinos coming from the sun in units of millions of neutrinos per square centimetre per second (an average of different measurements):

- Electron neutrinos only (from the "charged current reaction"): 1.7
- All "flavours" of neutrinos (from the "neutral current reaction"): 5.2
- Electron neutrinos make up only 1/3 of the total neutrino flux from the sun!

Direct Evidence for Neutrino Flavor Transformation from Neutral-Current Interactions in the Sudbury Neutrino Observatory

Q.R. Ahmad,[17] R.C. Allen,[4] T.C. Andersen,[6] J.D. Anglin,[10] J.C. Barton,[11,*] E.W. Beier,[12] M. Bercovitch,[10] J. Bigu,[7] S.D. Biller,[11] R.A. Black,[11] I. Blevis,[5] R.J. Boardman,[11] J. Boger,[3] E. Bonvin,[14] M.G. Boulay,[9,14] M.G. Bowler,[11] T.J. Bowles,[9] S.J. Brice,[9,11] M.C. Browne,[17,9] T.V. Bullard,[17] G. Bühler,[4] J. Cameron,[11] Y.D. Chan,[8] H.H. Chen,[4,†] M. Chen,[14] X. Chen,[8,11] B.T. Cleveland,[11] E.T.H. Clifford,[14] J.H.M. Cowan,[7] D.F. Cowen,[12] G.A. Cox,[17] X. Dai,[11] F. Dalnoki-Veress,[5] W.F. Davidson,[10] P.J. Doe,[17,9,4] G. Doucas,[11] M.R. Dragowsky,[9,8] C.A. Duba,[17] F.A. Duncan,[14] M. Dunford,[12] J.A. Dunmore,[11] E.D. Earle,[14,1] S.R. Elliott,[17,9] H.C. Evans,[14] G.T. Ewan,[14] J. Farine,[7,5] H. Fergani,[11] A.P. Ferraris,[11] R.J. Ford,[14] J.A. Formaggio,[17] M.M. Fowler,[9] K. Frame,[11] E.D. Frank,[12] W. Frati,[12] N. Gagnon,[11,9,8,17] J.V. Germani,[17] S. Gil,[2] K. Graham,[14] D.R. Grant,[5] R.L. Hahn,[3] A.L. Hallin,[14] E.D. Hallman,[7] A.S. Hamer,[9,14] A.A. Hamian,[17] W.B. Handler,[14] R.U. Haq,[7] C.K. Hargrove,[5] P.J. Harvey,[14] R. Hazama,[17] K.M. Heeger,[17] W.J. Heintzelman,[12] J. Heise,[2,9] R.L. Helmer,[16,2] J.D. Hepburn,[14] H. Heron,[11] J. Hewett,[7] A. Hime,[9] J.G. Hykawy,[7] M.C.P. Isaac,[8] P. Jagam,[6] N.A. Jelley,[11] C. Jillings,[14] G. Jonkmans,[7,1] K. Kazkaz,[17] P.T. Keener,[12] J.R. Klein,[12] A.B. Knox,[11] R.J. Komar,[2] R. Kouzes,[13] T. Kutter,[2] C.C.M. Kyba,[12] J. Law,[6] I.T. Lawson,[6] M. Lay,[11] H.W. Lee,[14] K.T. Lesko,[8] J.R. Leslie,[14] I. Levine,[5] W. Locke,[11] S. Luoma,[7] J. Lyon,[11] S. Majerus,[11] H.B. Mak,[14] J. Maneira,[14] J. Manor,[17] A.D. Marino,[8] N. McCauley,[12,11] D.S. McDonald,[12] A.B. McDonald,[14,13] K. McFarlane,[5] G. McGregor,[11] R. Meijer Drees,[17] C. Mifflin,[5] G.G. Miller,[9] G. Milton,[1] B.A. Moffat,[14] M. Moorhead,[11] C.W. Nally,[2] M.S. Neubauer,[12] F.M. Newcomer,[12] H.S. Ng,[2] A.J. Noble,[16,5] E.B. Norman,[8] V.M. Novikov,[5] M. O'Neill,[5] C.E. Okada,[8] R.W. Ollerhead,[6] M. Omori,[11] J.L. Orrell,[17] S.M. Oser,[12] A.W.P. Poon,[8,17,2,9] T.J. Radcliffe,[14] A. Roberge,[7] B.C. Robertson,[14] R.G.H. Robertson,[17,9] S.S.E. Rosendahl,[8] J.K. Rowley,[3] V.L. Rusu,[12] E. Saettler,[7] K.K. Schaffer,[17] M.H. Schwendener,[7] A. Schülke,[8] H. Seifert,[7,17,9] M. Shatkay,[5] J.J. Simpson,[6] C.J. Sims,[11] D. Sinclair,[5] P. Skensved,[14] A.R. Smith,[8] M.W.E. Smith,[17] T. Spreitzer,[12] N. Starinsky,[5] T.D. Steiger,[17] R.G. Stokstad,[8] L.C. Stonehill,[17] R.S. Storey,[10,†] B. Sur,[1,14] R. Tafirout,[7] N. Tagg,[6,11] N.W. Tanner,[11] R.K. Taplin,[11] M. Thorman,[11] P.M. Thornewell,[11] P.T. Trent,[11] Y.I. Tserkovnyak,[2] R. Van Berg,[12] R.G. Van de Water,[9,12] C.J. Virtue,[7] C.E. Waltham,[2] J.-X. Wang,[6] D.L. Wark,[15,11,9] N. West,[11] J.B. Wilhelmy,[9] J.F. Wilkerson,[17,9] J.R. Wilson,[11] P. Wittich,[12] J.M. Wouters,[9] and M. Yeh[3]

(SNO Collaboration)

[1] *Atomic Energy of Canada, Limited, Chalk River Laboratories, Chalk River, ON K0J 1J0, Canada*
[2] *Department of Physics and Astronomy, University of British Columbia, Vancouver, BC V6T 1Z1 Canada*
[3] *Chemistry Department, Brookhaven National Laboratory, Upton, NY 11973-5000*
[4] *Department of Physics, University of California, Irvine, CA 92717*
[5] *Carleton University, Ottawa, Ontario K1S 5B6 Canada*
[6] *Physics Department, University of Guelph, Guelph, Ontario N1G 2W1 Canada*
[7] *Department of Physics and Astronomy, Laurentian University, Sudbury, Ontario P3E 2C6 Canada*
[8] *Institute for Nuclear and Particle Astrophysics and Nuclear Science Division, Lawrence Berkeley National Laboratory, Berkeley, CA 94720*
[9] *Los Alamos National Laboratory, Los Alamos, NM 87545*
[10] *National Research Council of Canada, Ottawa, ON K1A 0R6, Canada*
[11] *Department of Physics, University of Oxford, Denys Wilkinson Building, Keble Road, Oxford, OX1 3RH, UK*
[12] *Department of Physics and Astronomy, University of Pennsylvania, Philadelphia, PA 19104-6396*
[13] *Department of Physics, Princeton University, Princeton, NJ 08544*
[14] *Department of Physics, Queen's University, Kingston, Ontario K7L 3N6 Canada*
[15] *Rutherford Appleton Laboratory, Chilton, Didcot, Oxon, OX11 0QX, and University of Sussex, Physics and Astronomy Department, Brighton BN1 9QH, UK*
[16] *TRIUMF, 4004 Wesbrook Mall, Vancouver, BC V6T 2A3, Canada*
[17] *Center for Experimental Nuclear Physics and Astrophysics, and Department of Physics, University of Washington, Seattle, WA 98195*

(Dated: 19 April 2002)

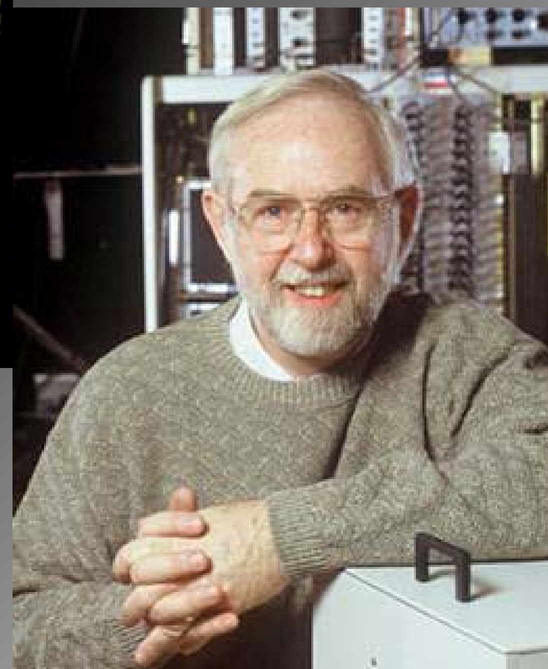
Observations of neutral-current ν interactions on deuterium in the Sudbury Neutrino Observatory are reported. Using the neutral current, elastic scattering, and charged current reactions and assuming the standard ^{8}B shape, the ν_e component of the ^{8}B solar flux is $\phi_e = 1.76^{+0.05}_{-0.05}(\text{stat.})^{+0.09}_{-0.09}$ (syst.) $\times 10^6$ cm^{-2}s^{-1} for a kinetic energy threshold of 5 MeV. The non-ν_e component is $\phi_{\mu\tau} = 3.41^{+0.45}_{-0.45}(\text{stat.})^{+0.48}_{-0.45}$ (syst.) $\times 10^6$ cm^{-2}s^{-1}, 5.3σ greater than zero, providing

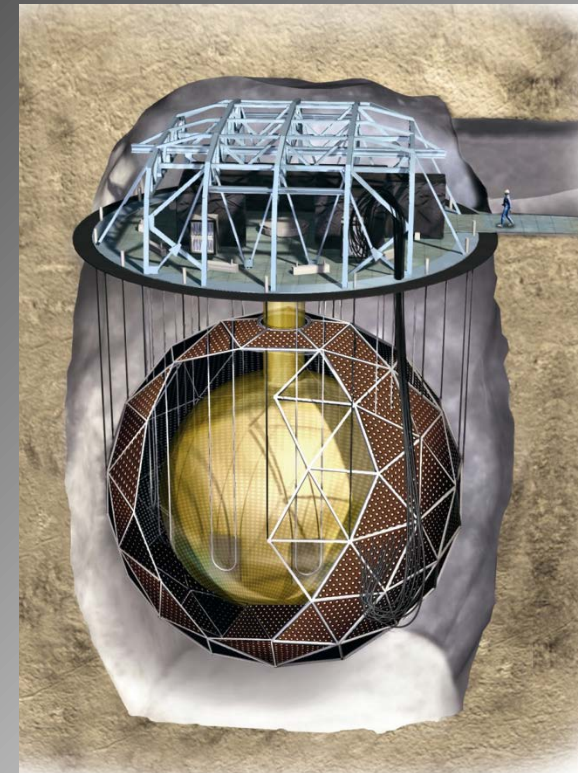
Phys. Rev. Lett. 89 No. 1 (2002)

SNO's Bottom Line

- With SNO's unique sensitivity to ALL neutrino flavours, SNO found neutrinos which were undetected by measurements at other laboratories.
- 2/3 of the original electron neutrinos from the sun's core have transformed into the other two flavours of neutrinos on their way to earth. Neutrinos thus have a tiny mass.
- When all neutrinos flavours are included, the total flux agrees with the value predicted by solar theories – SNO has solved the 30 year missing solar neutrino problem.
- SNO's results have provided strong constraints on neutrino properties and guide theoretical work seeking to obtain revisions to the Standard Model of particles and fields.

The SNO Project





- Polanyi prize 2006
- Nobel prize 2015
- Breakthrough prize 2016
- Recognition in House of Commons March 8, 2016

SNOLAB plan view