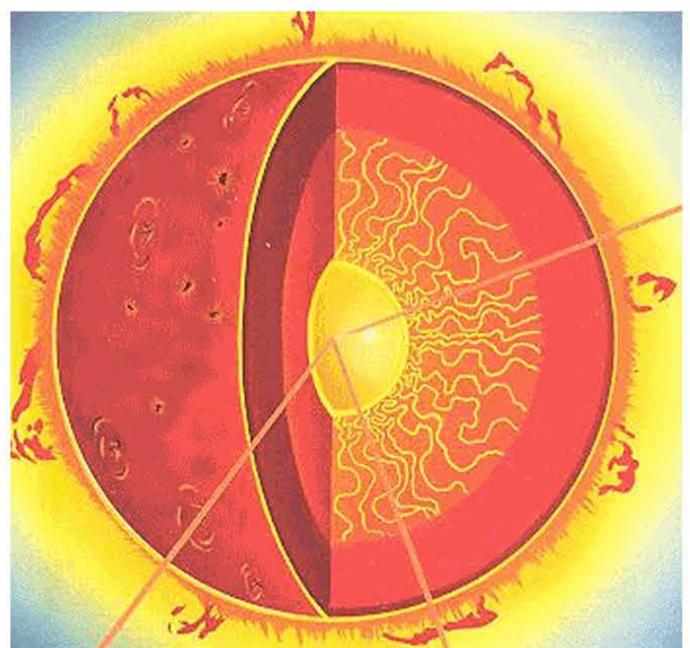
Neutrino Masses and Oscillations

Neutrinos may be the most abundant elementary particle in the universe. Chargeless, pointlike (as far as we know) and long thought to be massless, they should be the easiest particle to understand. However, in the early 1980s, all the available data on neutrinos just didn't fit together.

The Solar Neutrino Problem

In the 1950s and '60s progress in astro- and nuclear physics had advanced to the stage where models of the Sun's interior seemed solid, and theorists were confident in their predictions of the fluxes and spectra of neutrinos emanating from the solar core. It looked like solar neutrinos could be detected by large, sensitive detectors, placed deep underground to keep cosmic ray backgounds low.

However, by 1980, a long-running experiment by Ray Davis in a South Dakota mine persistently detected far too few solar neutrinos. A 1950 idea of Bruno Pontecorvo's was revived, suggesting that neutrinos – being chargeless – might oscillate quantum mechanically in flight from one state to another. It appeared that three types ("flavours") of neutrinos existed, and Davis' experiment was only sensitive to one type.



Hence if the neutrinos oscillated between the Sun and Earth, one might expect a reduced flux, detecting only the directly emitted "electron" neutrinos and missing those that oscillated to "mu" and "tau" flavours.

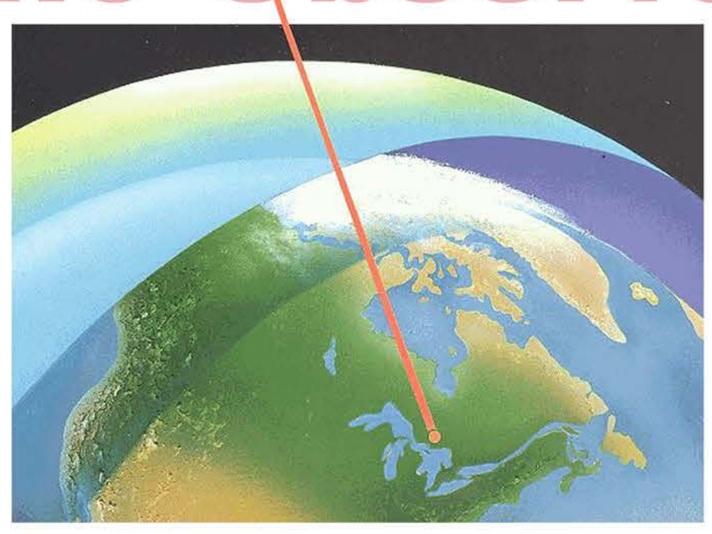
This much was no more than speculation. The idea also required the neutrino types to have small but differing masses, something that was not included in the existing "Standard Model" of particle physics. What was needed was an experiment that could measure the fluxes of all neutrino flavours. Enter the Sudbury Neutrino Observatory (SNO).

The Sudbury Neutrino Observatory

In 1984 a paper by Herb Chen at UC Irvine pointed out that 1000 tonnes of heavy water (D_2O) could be used detect both the solar electron neutrino flux and the total solar neutrino flux, via the following reactions:

$$\nu_e + D \rightarrow p + p + e^-$$
$$\nu_{e,\mu,\tau} + D \rightarrow p + n + \nu_{e,\mu,\tau}$$

The charged electrons and strongly-interacting neutrons (in red) can be used to generate detectable signals. A discrepancy in the neutrino flux measured by these two reactions would be *prima facie* evidence for neutrino oscillations. Now all that was needed was the heavy water (nominal cost of $300K per tonne) and all the detectors, computing and technical infrastructure that goes with a major particle physics experiment - and a deep mineshaft to put it in.



Fortunately, two large pieces of the puzzle already existed in Canada; the heavy water was available from the nuclear power industry, which was in the doldrums, and the INCO nickel mine in Sudbury possessed a suitable site 2km underground. In the mid-1980s physicists at Carleton, Guelph, Queen's and the National Research Council formed the SNO collaboration and proved the experiment was feasible, physically, technically and geologically.

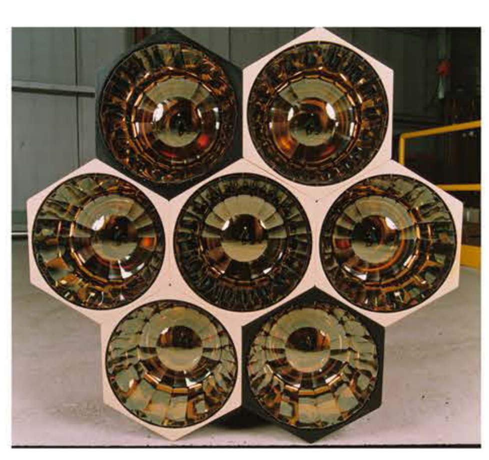
In 1988 the collaboration was joined by Chris Waltham and his group at UBC, and also by groups from the UK and USA.

UBC group in 1996 outside the Sudbury TraveLodge with the iconic INCO superstack in the background.
L-R: Christian Nally, Chris Waltham, Rich Helmer (TRIUMF), Rob Komar, Siong Ng, Jaret Heise and Alan Poon.

Building and running SNO

In a nutshell the problem was to build a very large neutrino detector in an environment of exceptional radiopurity in a dirty mine cavity with high levels of radon gas.

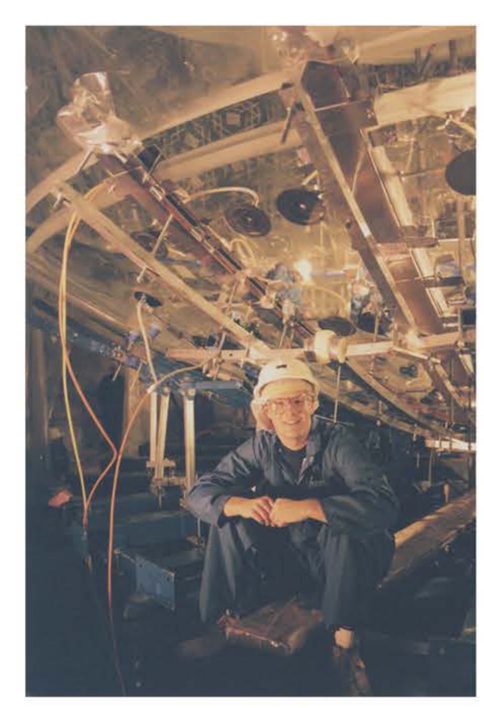
The view from novelist and cartoonist Rachel Hartman, whose husband is SNO physicist Scott Oser, who came to UBC from the UPenn SNO group in 2002.



Seven of the 9600 photomultiplier tubes and light concentrators that detected the photons emitted by the neutrino interactions. The UBC and Oxford groups designed and built the concentrators.

Thirty thousand tonnes of rock were removed to make the 30 x 22 x 22 m^3 cavity – big enough to hold the Hebb Tower.

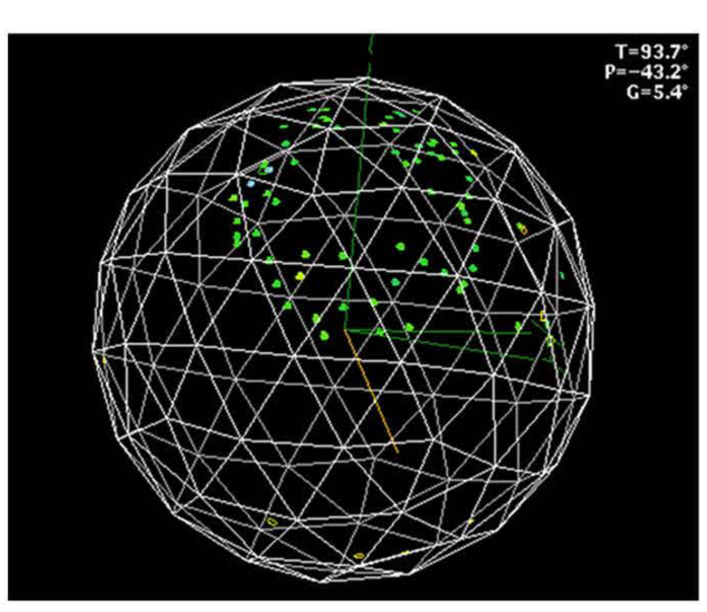
Filling the detector with 1000 tonnes of heavy water, 1999: Chris Waltham and a two 3-tonne railcar.



UBC graduate student Jaret Heise, in clean-room gear, building the 12 m diameter 35 tonne heavy water vessel, made from ultra-low radioactivity acrylic.

UBC graduate student Alan Poon and postdoc Rob Komar going underground during the acrylic vessel assembly phase in 1996.

SNO results and impact



A very clean solar neutrino event. The coloured hexagons represent photons detected in individual photomultiplier tubes. Most events required sophisticated pattern recognition code to distinguish. SNO saw one solar neutrino for every 10^8 event triggers; analysis was a major computational challenge.

By 2001 SNO produced hard evidence for a solar electron neutrino deficit. By 2003 SNO data definitively showed that the reason was indeed quantum mechanical oscillation, and that neutrinos had nonzero masses. The mass difference between the two lightest neutrinos is ~0.01 eV/c^2, a fifty-millionth of an electron mass.

Neutrino masses and mixing are now firmly established and the Standard Model of particle physics has had to accommodate this fact. The masses are too small to explain "Dark Matter", a fact which deepened that mystery.

It also remains a mystery why neutrinos have the particular masses and mixing angles that they do.

The SNO collaboration has produced many scientific and technical papers, three of which have earned more than 1000 citations (in 2013), with one paper (below) having more than 2000 citations:

VOLUME 89, NUMBER 1 PHYSICAL REVIEW LETTERS 1 JULY 2002

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] M. Howe,[17] 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] A.B. McDonald,[14,13] D.S. McDonald,[12] 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]

Poster prepared by Theresa Liao and Chris Waltham, 2013

100 Years of Physics at UBC
http://phas.ubc.ca

a place of mind
THE UNIVERSITY OF BRITISH COLUMBIA

UBC DEPARTMENT OF PHYSICS ASTRONOMY