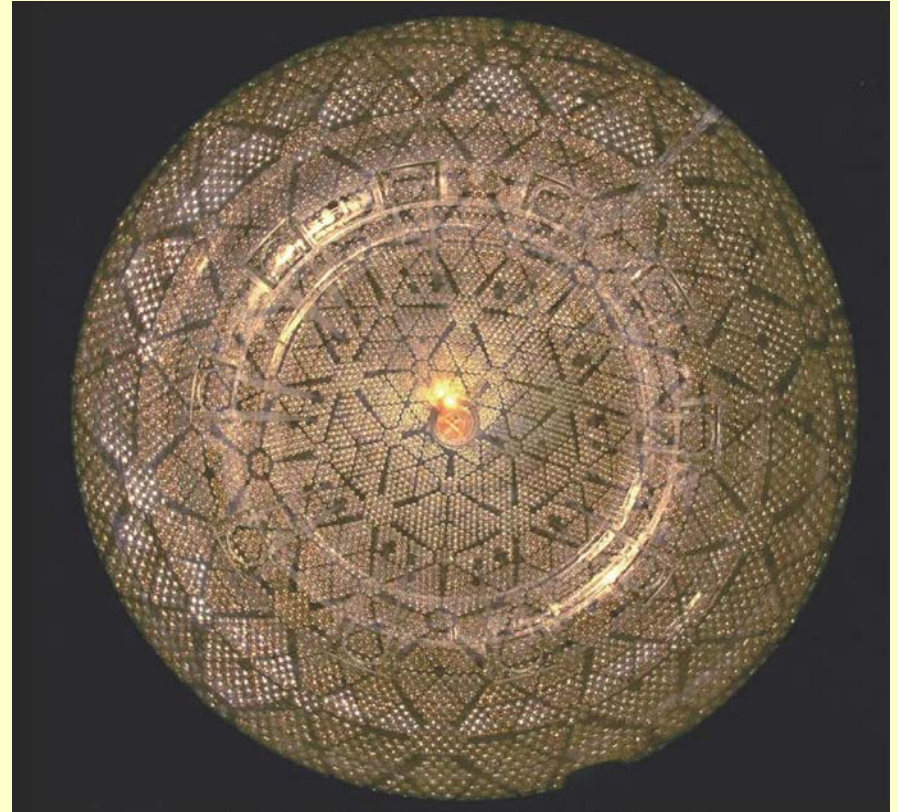
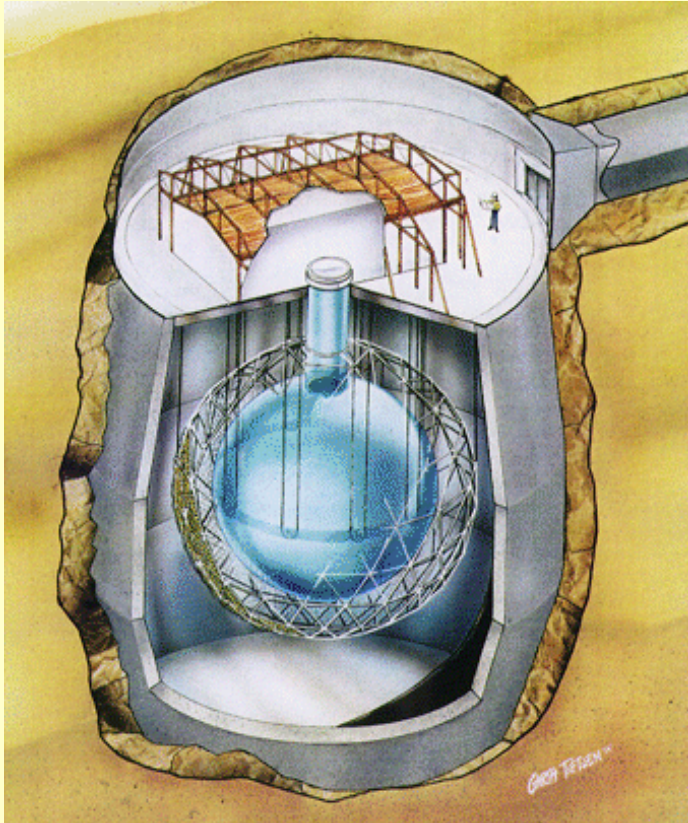
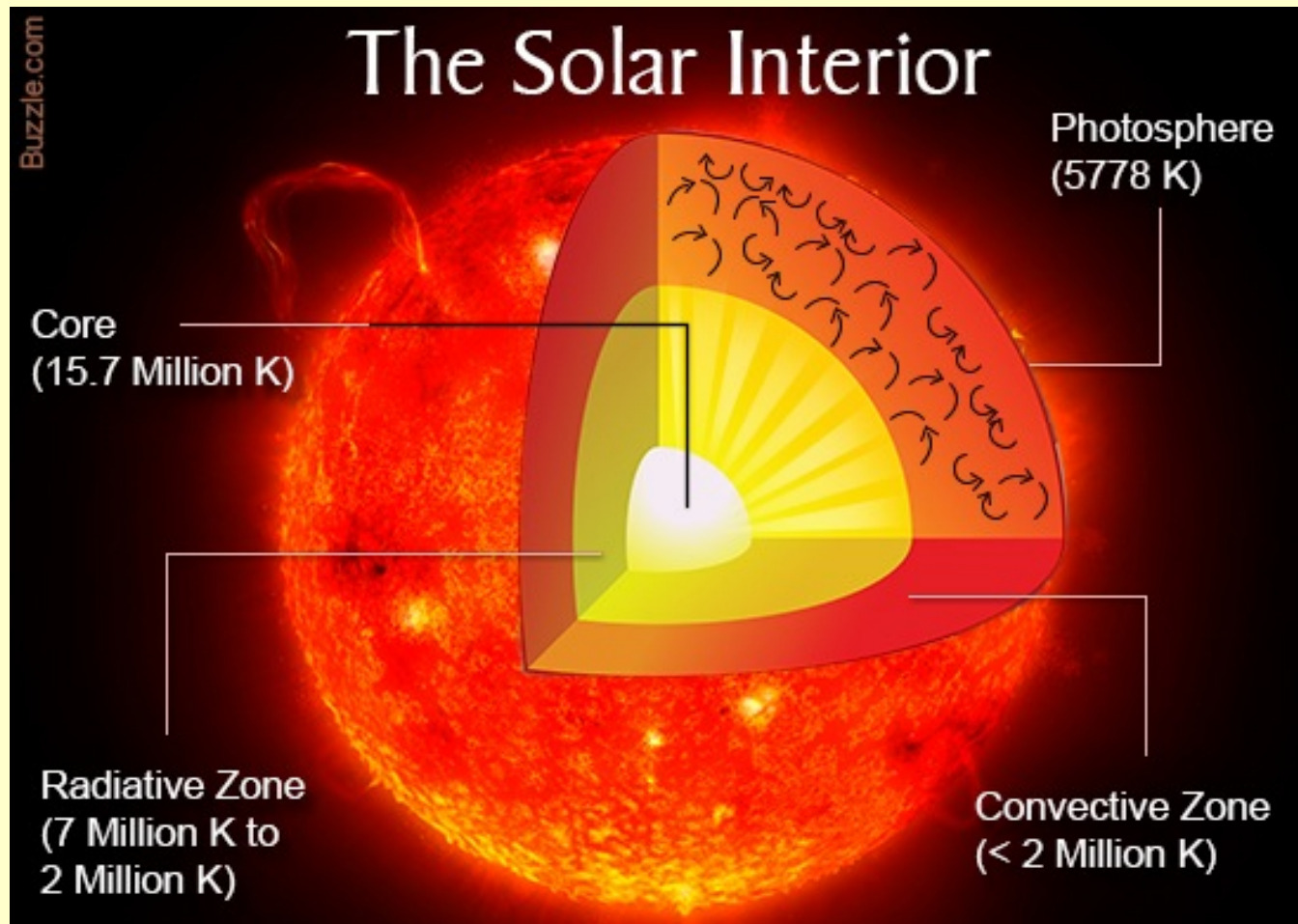


The Sudbury Neutrino Observatory: Observation of Flavor Change for Solar Neutrinos.



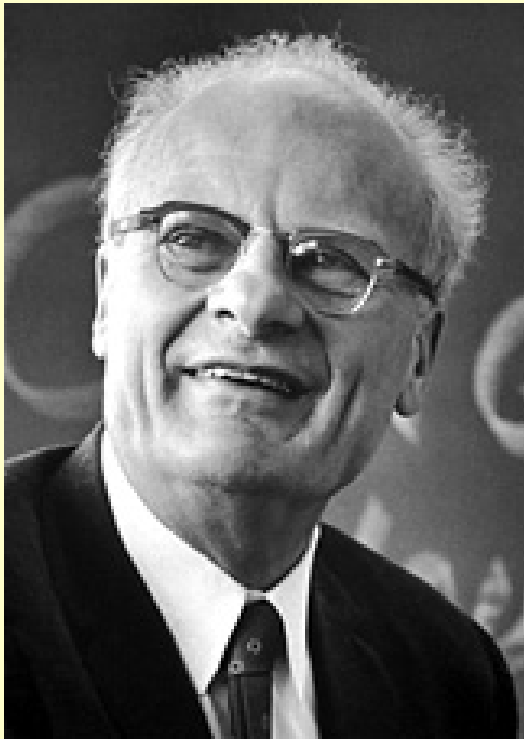
Art McDonald, Professor Emeritus
Queen's University, Kingston, Ontario, Canada

Neutrinos from the Sun

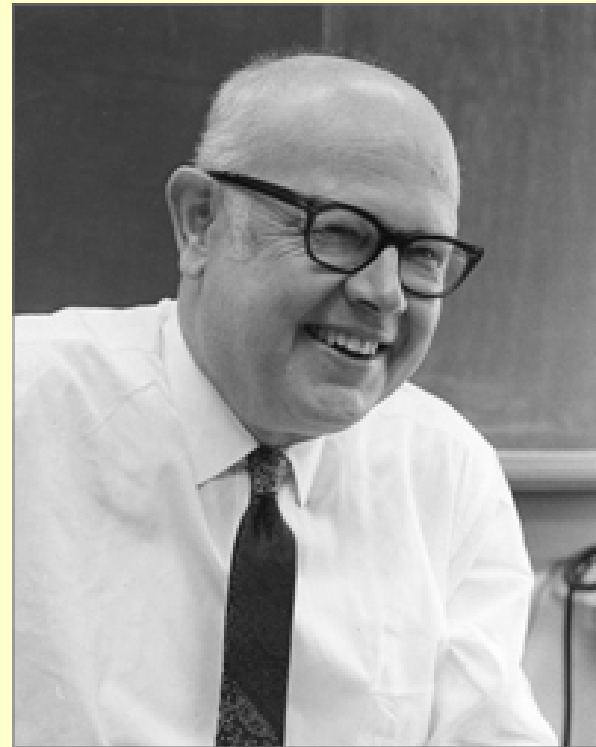


The middle of the sun is so hot that the centers of the atoms (nuclei) fuse together, giving off lots of energy and neutrinos. The neutrinos penetrate easily through the dense material in the Sun and reach the earth.

Understanding How the Sun Burns



Hans Bethe
Basic Theory 1939
Nobel Laureate 1967



Willy Fowler
Theory, Experiments 1950's, 60's
Nobel Laureate 1983

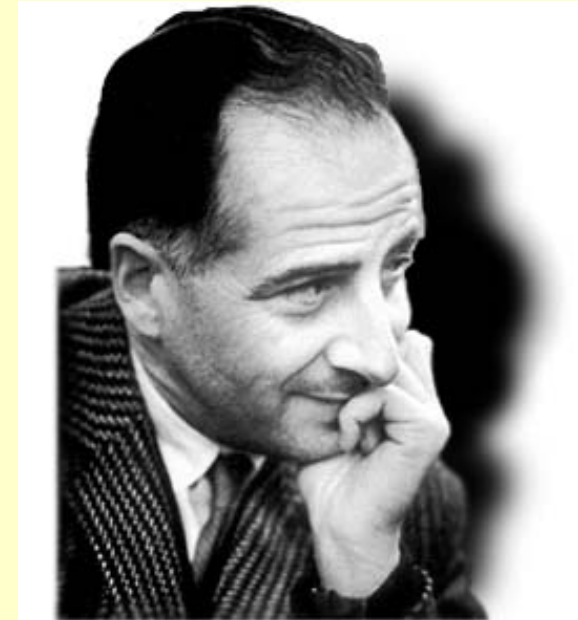
We stand on the Shoulders of Giants

Pioneers of Solar Neutrino Physics: Davis, Bahcall, Pontecorvo & Gribov



1968: Davis' Measurements with Chlorine-based detector show 3 times fewer than Bahcall's calculations.

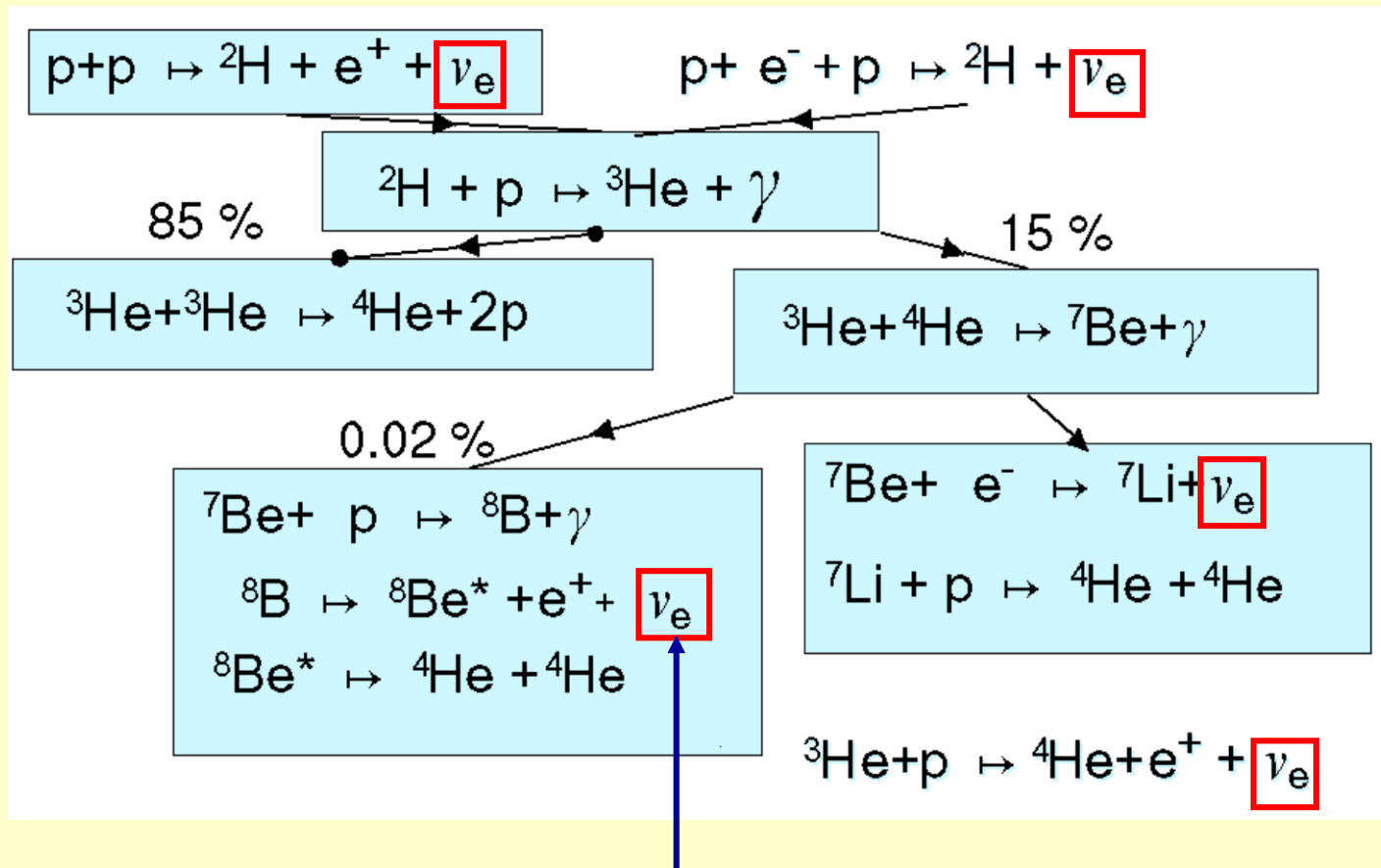
Ray Davis: Nobel Laureate 2002



Бруно Понтекорво

1968: Gribov and Pontecorvo suggest flavor change (oscillation) of electron neutrinos to muon neutrinos as a possible reason.

SOLAR FUSION CHAIN



1984: Chen proposes **heavy water** to search for direct evidence of flavor transformation for neutrinos from ${}^8\text{B}$ 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?

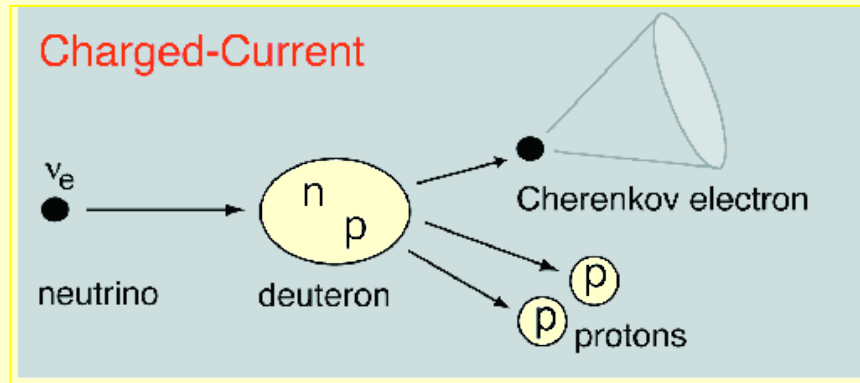
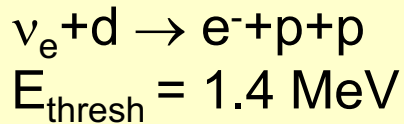


Billions of them stream out every second from the nuclear reactions powering the Sun and strike our detector. Once an hour they make a burst of light that we can detect.

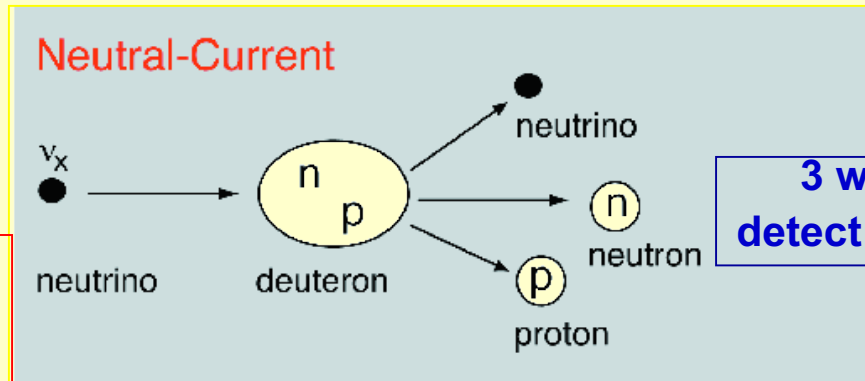
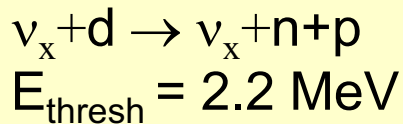
Unique Signatures in SNO (D₂O)

(1 in 6400 molecules in ordinary water are D₂O. We used >99.75% D₂O)

Electron Neutrinos (CC)



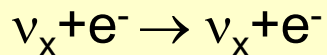
Equal Sensitivity All Types (NC)



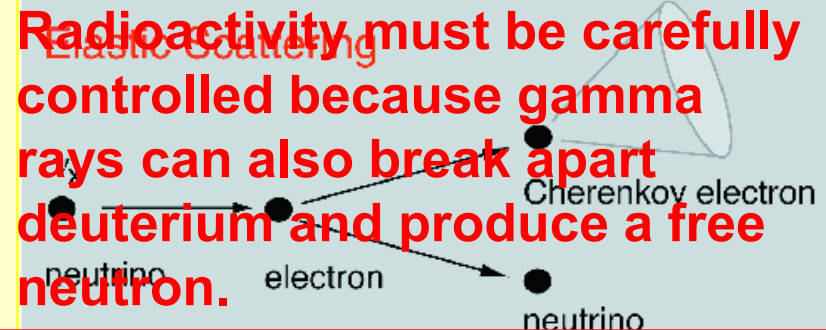
3 ways to
detect neutrons

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

Elastic Scattering from Electrons



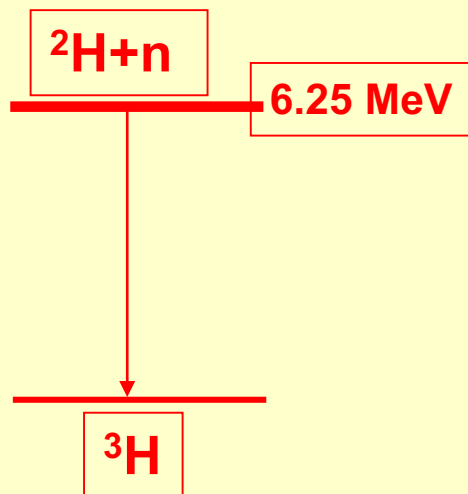
ν_x , but enhanced for ν_e x 6
10 times lower count rate
Points away from the Sun



3 neutron (NC) detection methods (systematically different)

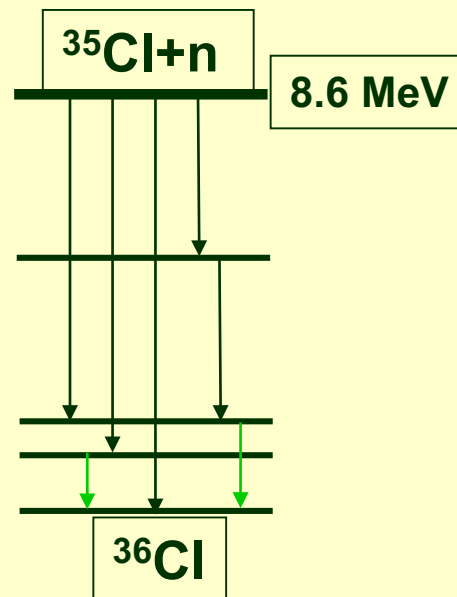
Phase I (D_2O)
Nov. 99 - May 01

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



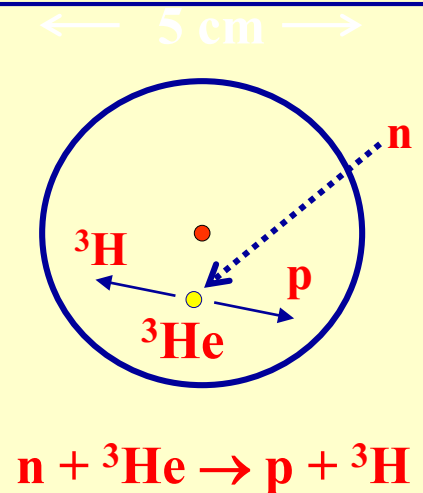
Phase II (salt)
July 01 - Sep. 03

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



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

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



Sudbury Neutrino Observatory (SNO)

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

NEUTRINO

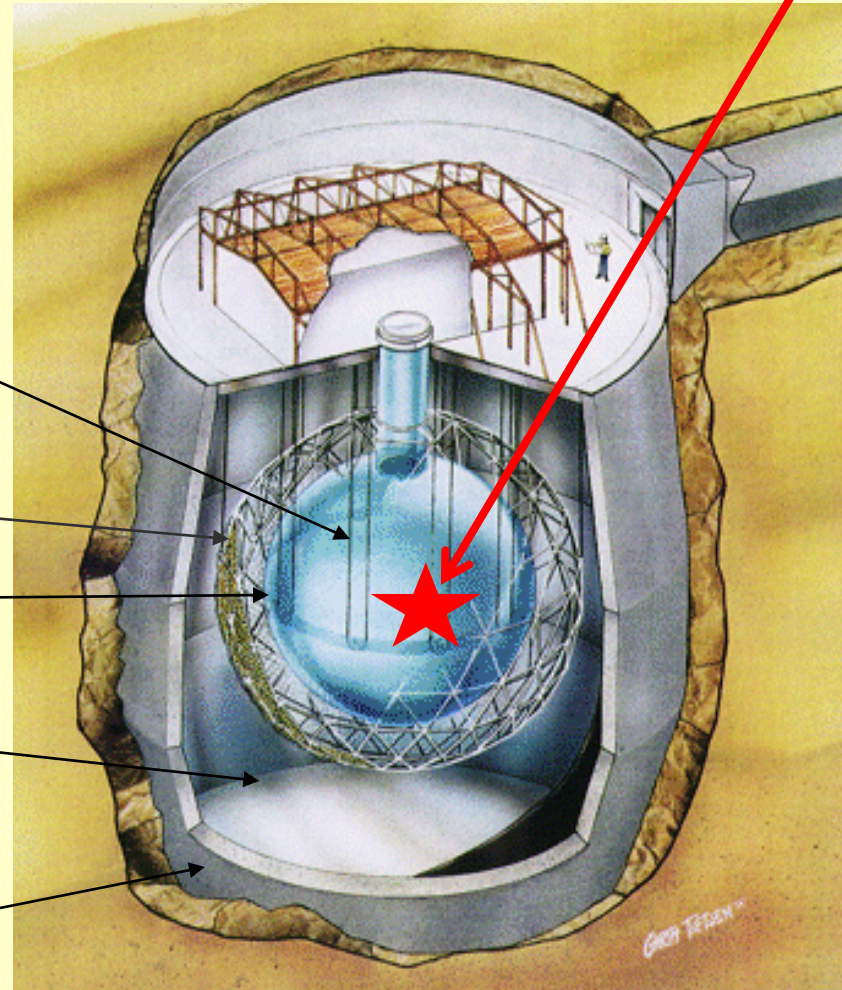
1000 tonnes of heavy water: D_2O
\$ 300 million on Loan for \$1.00

9500 light sensors

12 m Diameter Acrylic Container

Ultra-pure Water: H_2O .

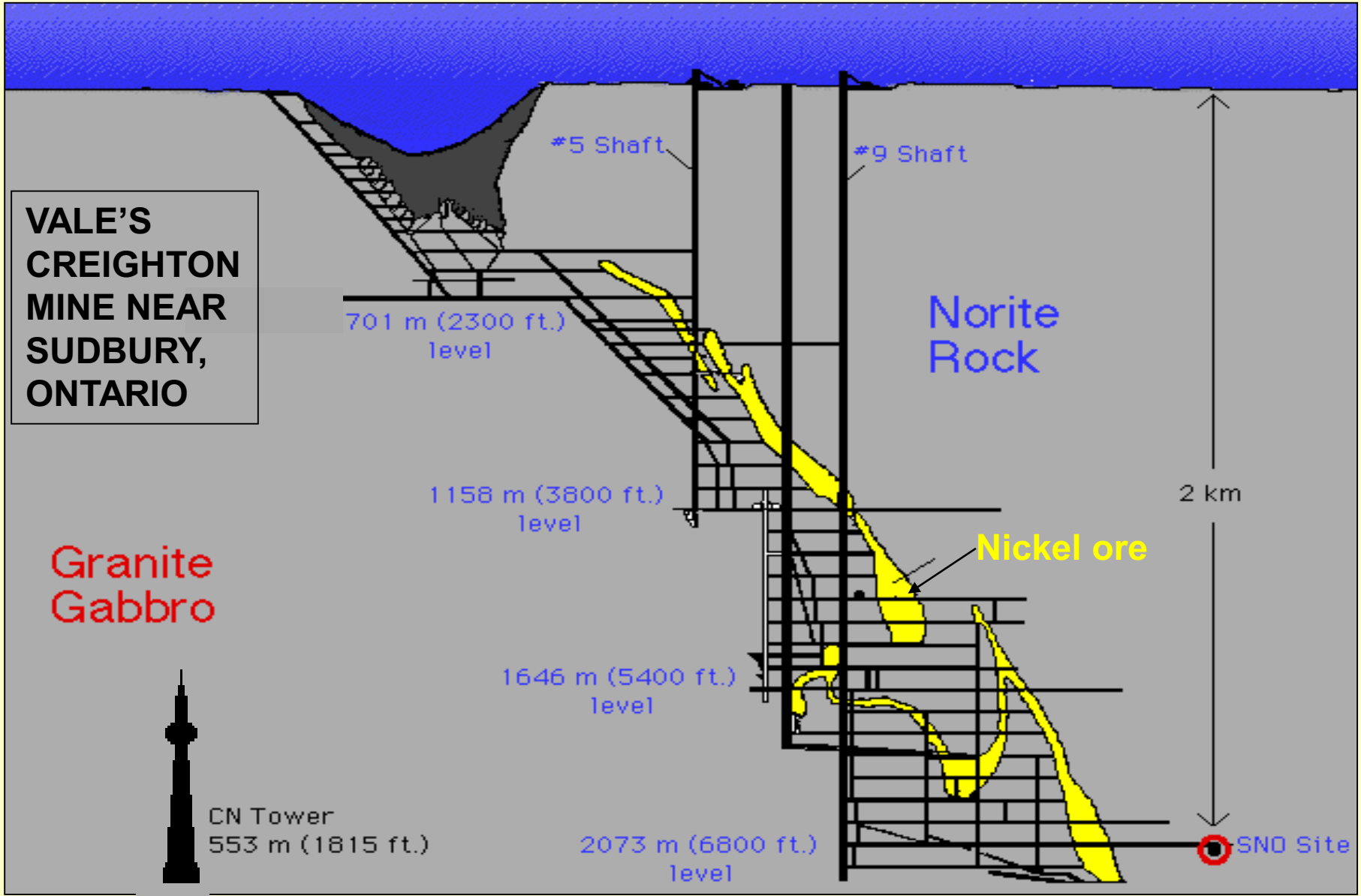
Urylon Liner and Radon Seal

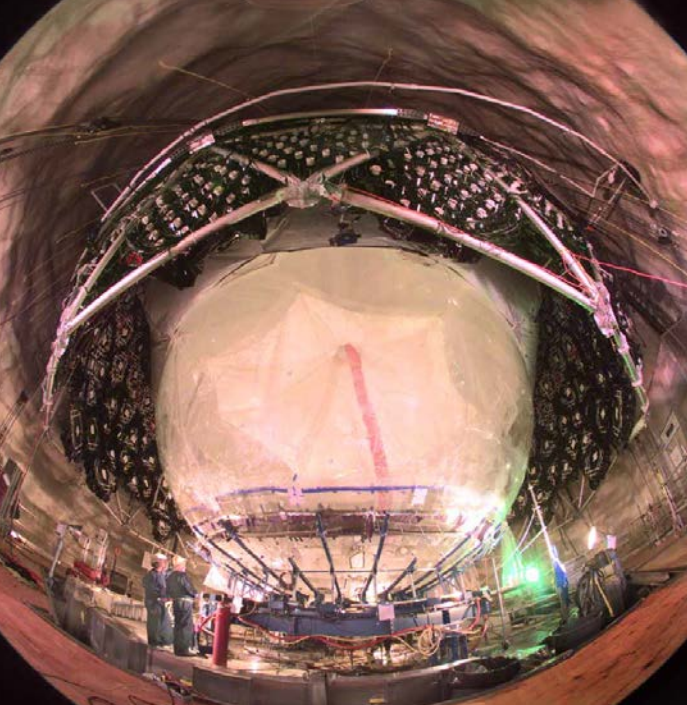


34 m
or
~ Ten
Stories
High!

2 km
below
the
ground

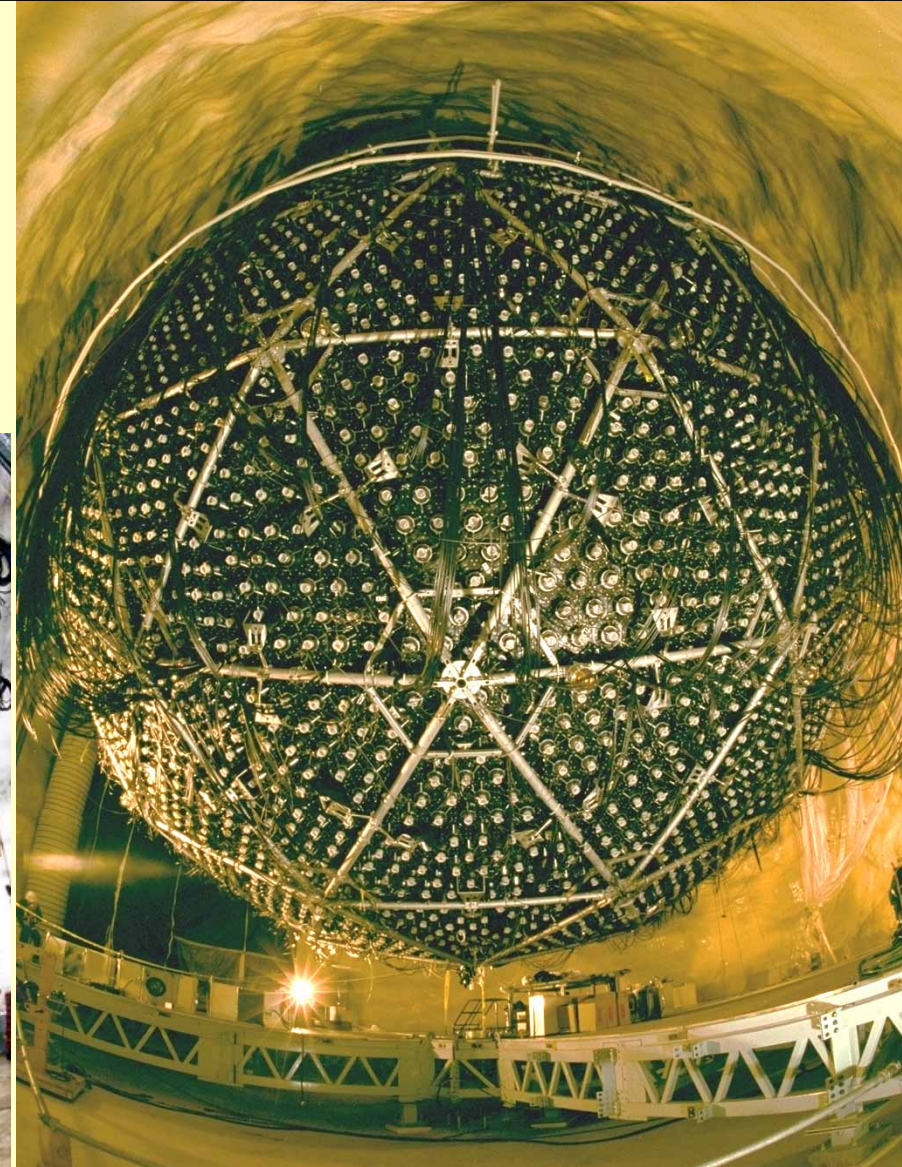
To study Neutrinos with little radioactive background, we went 2 km underground to reduce cosmic rays and built an ultra-clean detector: SNO

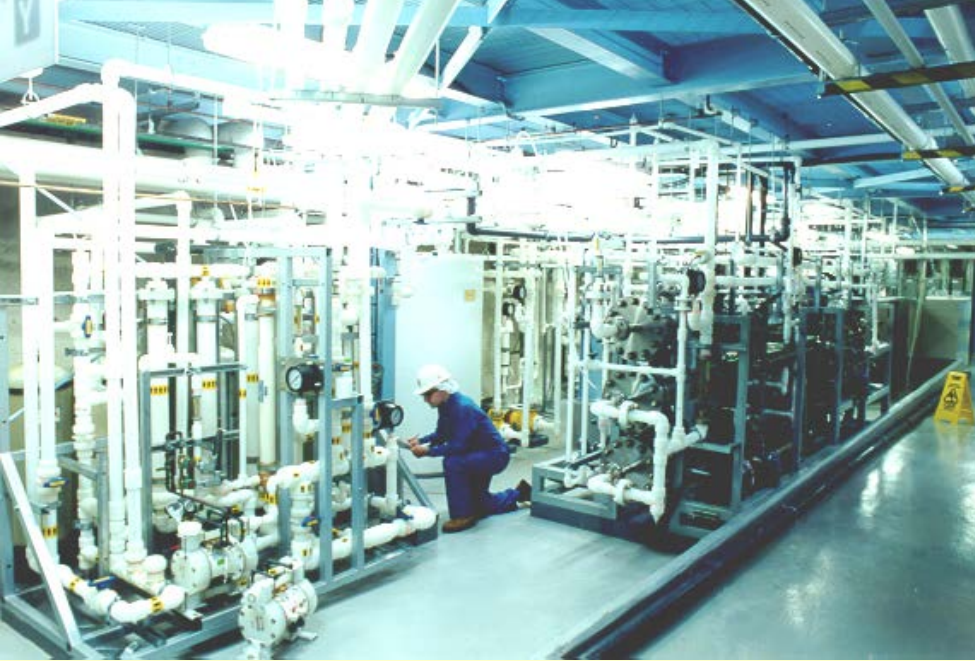




SNO: One million pieces transported down in the 3 m x 3 m x 4 m mine cage and re-assembled under ultra-clean conditions. Every worker takes a shower and wears clean, lint-free clothing.

70,000
showers
during the
course of the
SNO project



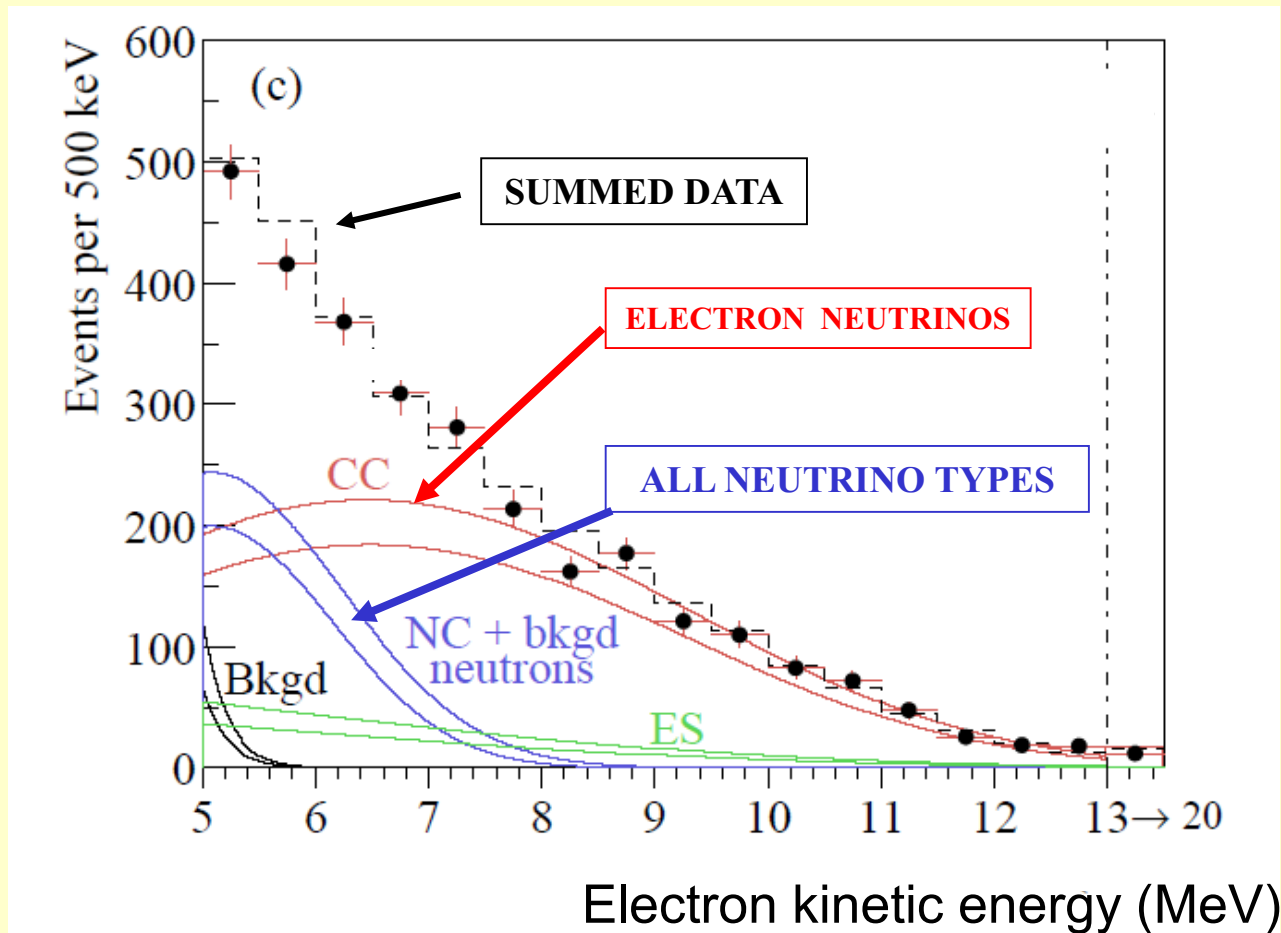


Water systems were developed to provide low radioactivity water and heavy water: 1 billion times better than tap water. Less than one radioactive decay per day per ton of water!!

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



WE OBSERVED NEUTRINOS FROM THE SUN WITH ALMOST NO RADIOACTIVE BACKGROUND



**After Calibration:
ELECTRON
NEUTRINOS
AT EARTH ARE
ONLY 1/3
OF ALL
NEUTRINOS**

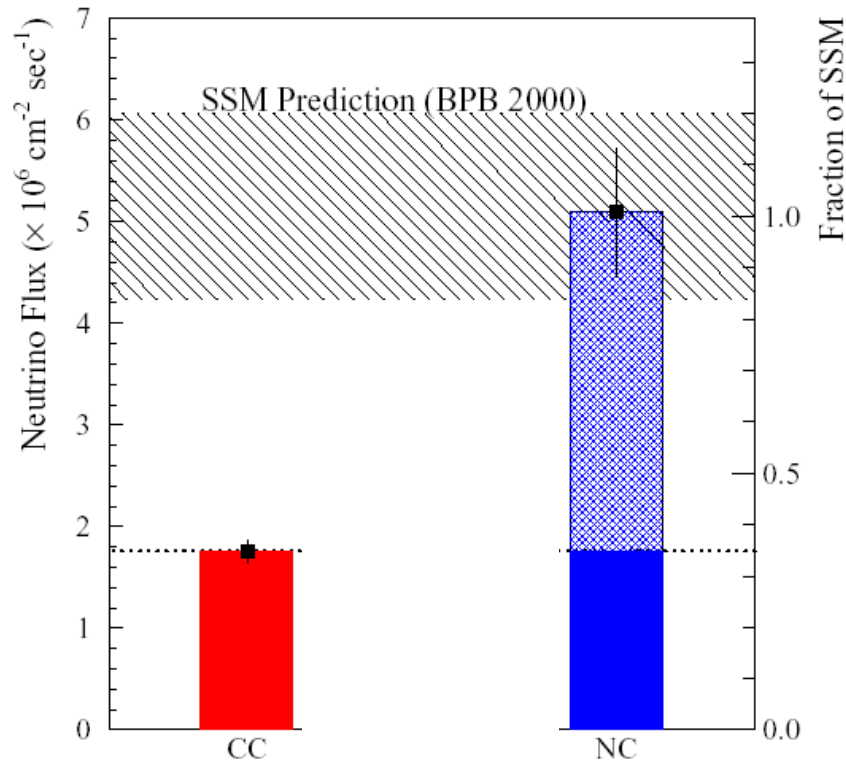
Data from Pure Heavy Water Phase in 2002

**SOLAR
MODEL**

**SNO USED
HEAVY
WATER TO
MEASURE
TWO
SEPARATE
THINGS**

**ELECTRON
NEUTRINOS**

**ALL NEUTRINO
TYPES**



**Excellent
Agreement
With the
Solar Model
Calculations**

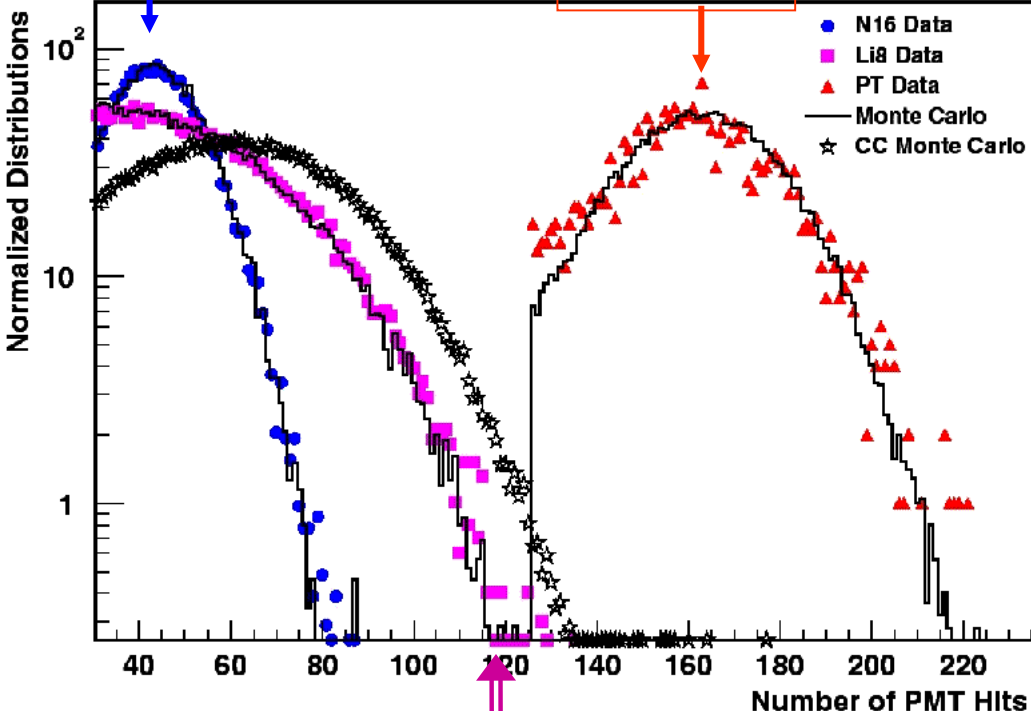
**LESS THAN ONE
CHANCE IN 10
MILLION
FOR “NO
CHANGE IN
NEUTRINO
TYPE”**

**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.**

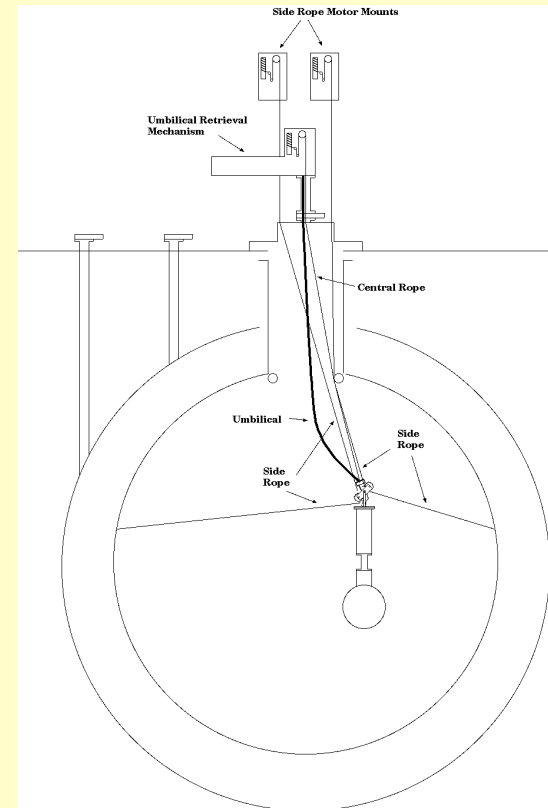
6.13 MeV

SNO Energy Calibrations

19.8 MeV

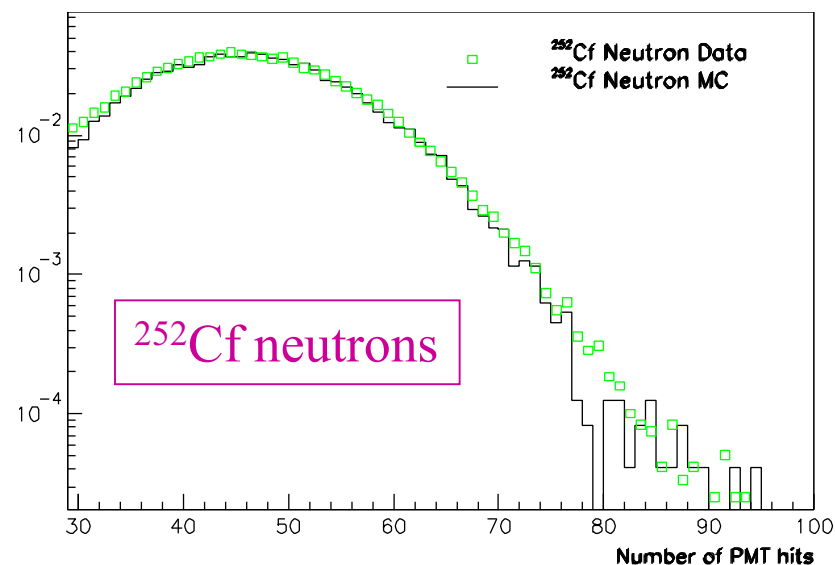


Detailed
Detector
Mapping
with
LaserBall,
 ^{16}N , ^{252}Cf ,
 ^{238}U , ^{232}Th



β 's from ^8Li
 γ 's from ^{16}N and $t(p,\gamma)^4\text{He}$

Radioactivity: Rn and
encapsulated U and Th



Measuring U/Th Content

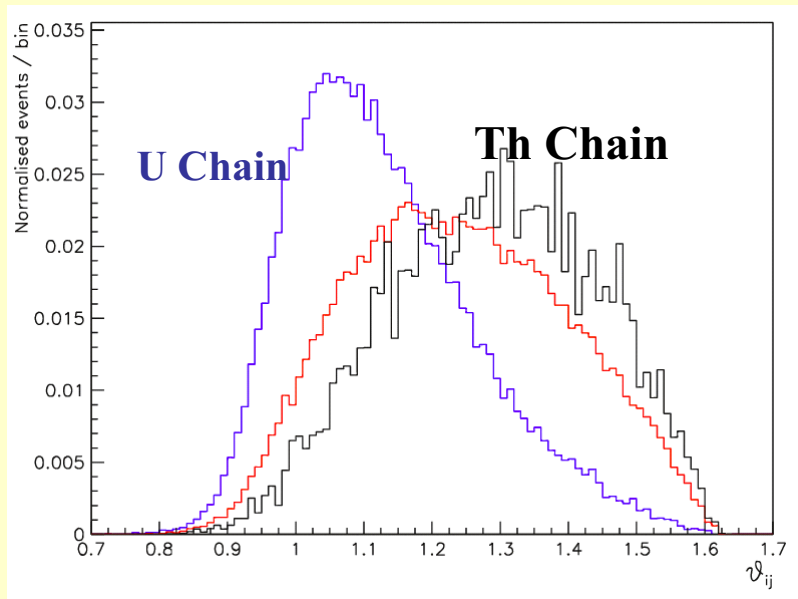
Ex-situ

- Ion exchange (^{224}Ra , ^{226}Ra)
- Membrane Degassing (^{222}Rn)
- count daughter product decays

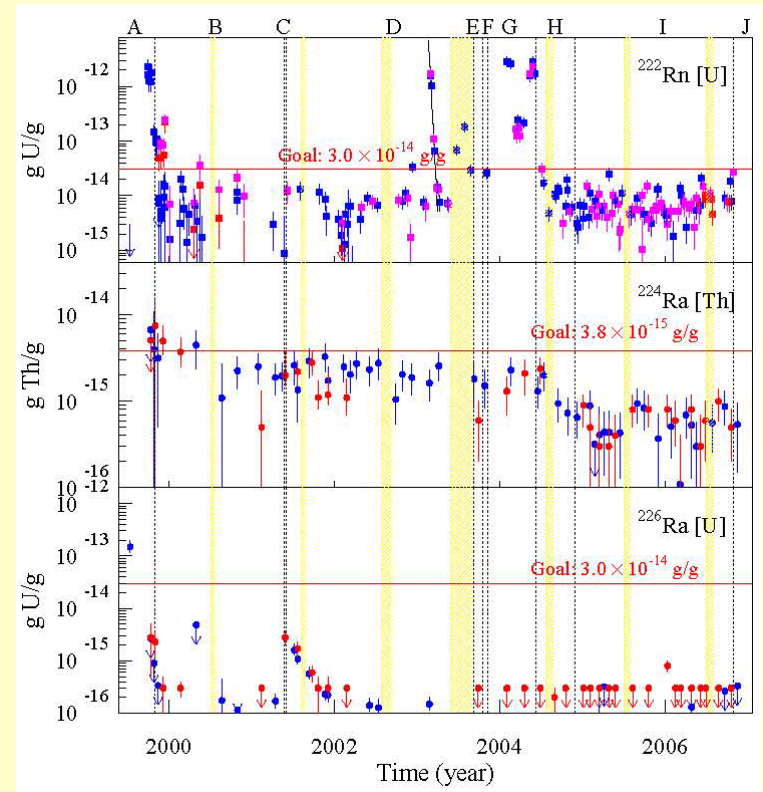
In-situ

- Low energy data analysis
- Separate U and Th Chains

Using Event isotropy

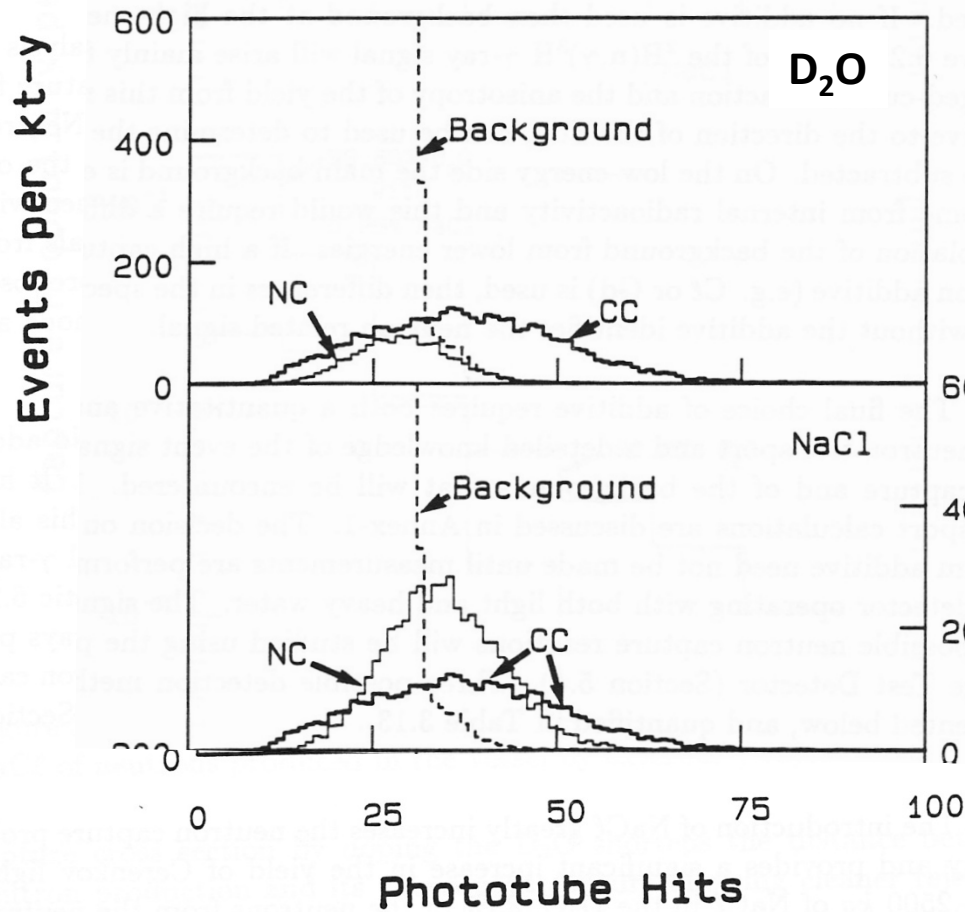


Isotropy

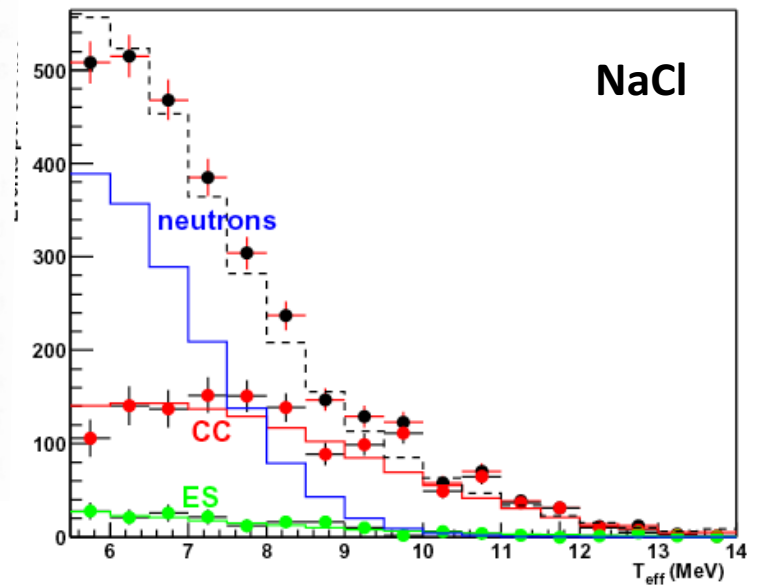
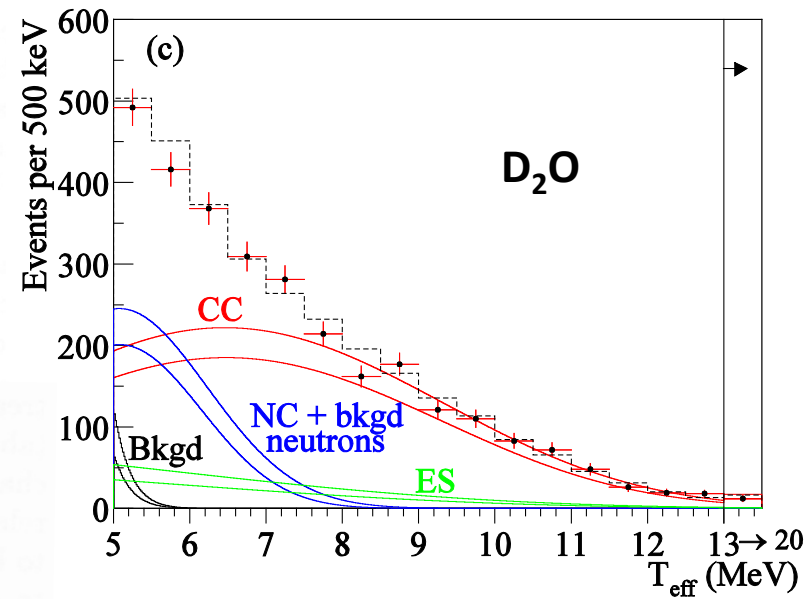


Numbers of background neutrons from gamma rays breaking apart deuterium are measured to be 3 times smaller than the signal. Uncertainty from this is less than 10% of the neutrino measurement.

As simulated in 1987



As measured 1999-2003



SNO Results for Salt Phase

Flavor change determined by $> 7 \sigma$.

New physics beyond The Standard Model of Elementary Particles!

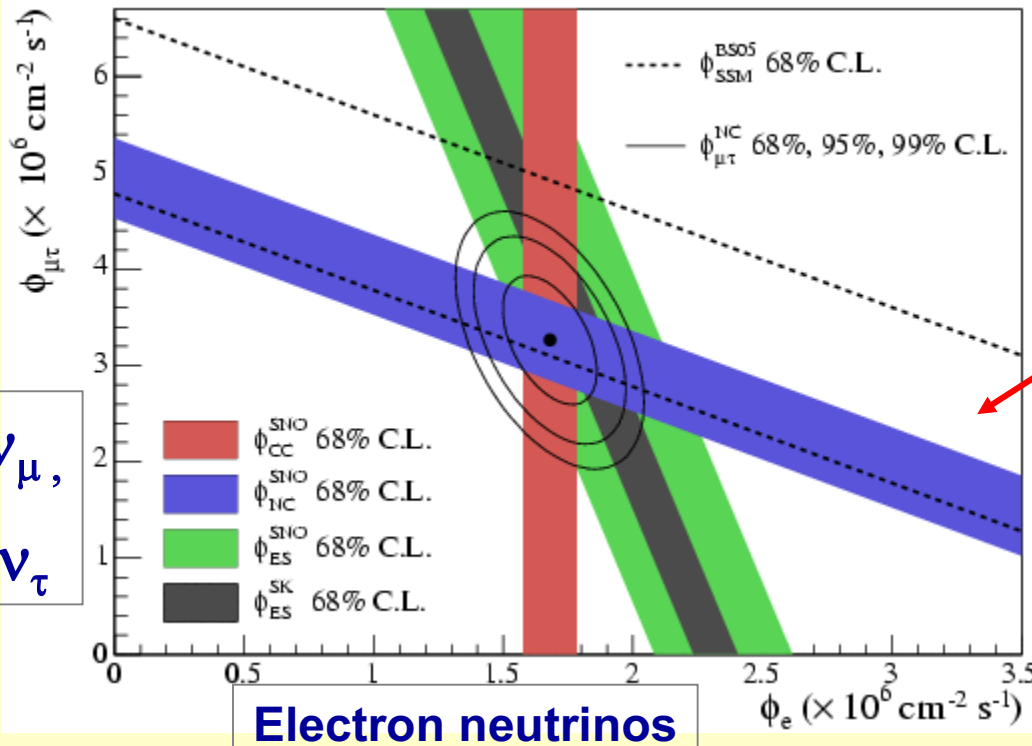
The Total Flux of Active Neutrinos is measured

independently (NC) and agrees well with solar model

Calculations:

5.82 $\pm$ 1.3 (Bahcall et al),

5.31 $\pm$ 0.6 (Turck-Chieze et al)



$$\phi_{CC} = 1.68^{+0.06}_{-0.06}(\text{stat.})^{+0.08}_{-0.09}(\text{syst.})$$

$$\phi_{NC} = 4.94^{+0.21}_{-0.21}(\text{stat.})^{+0.38}_{-0.34}(\text{syst.})$$

$$\phi_{ES} = 2.35^{+0.22}_{-0.22}(\text{stat.})^{+0.15}_{-0.15}(\text{syst.})$$

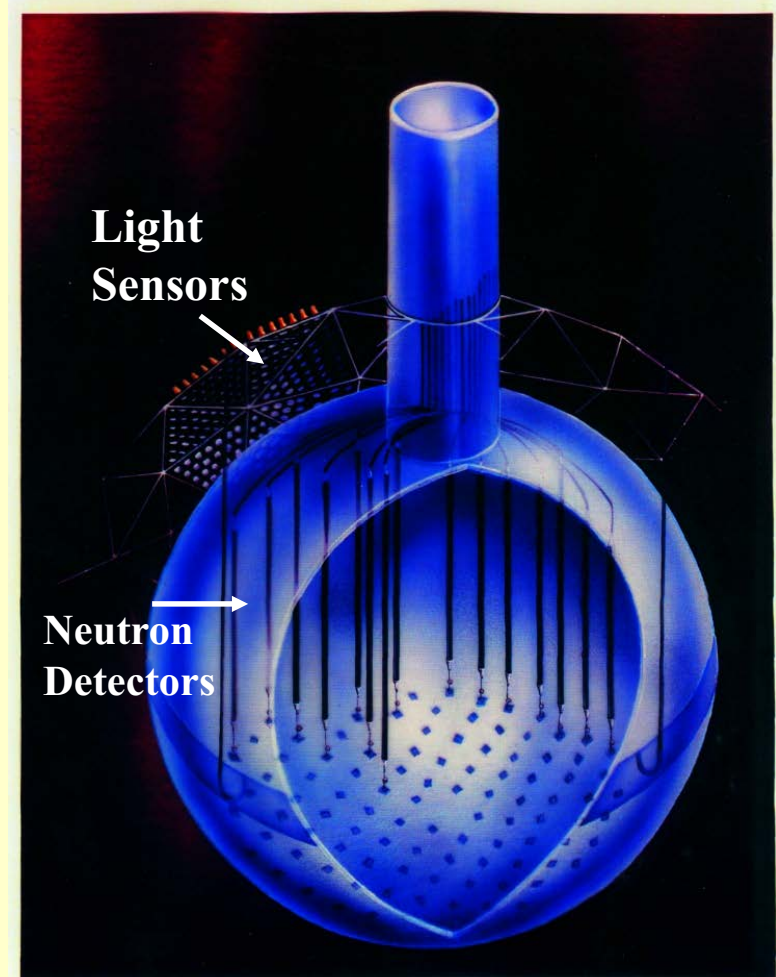
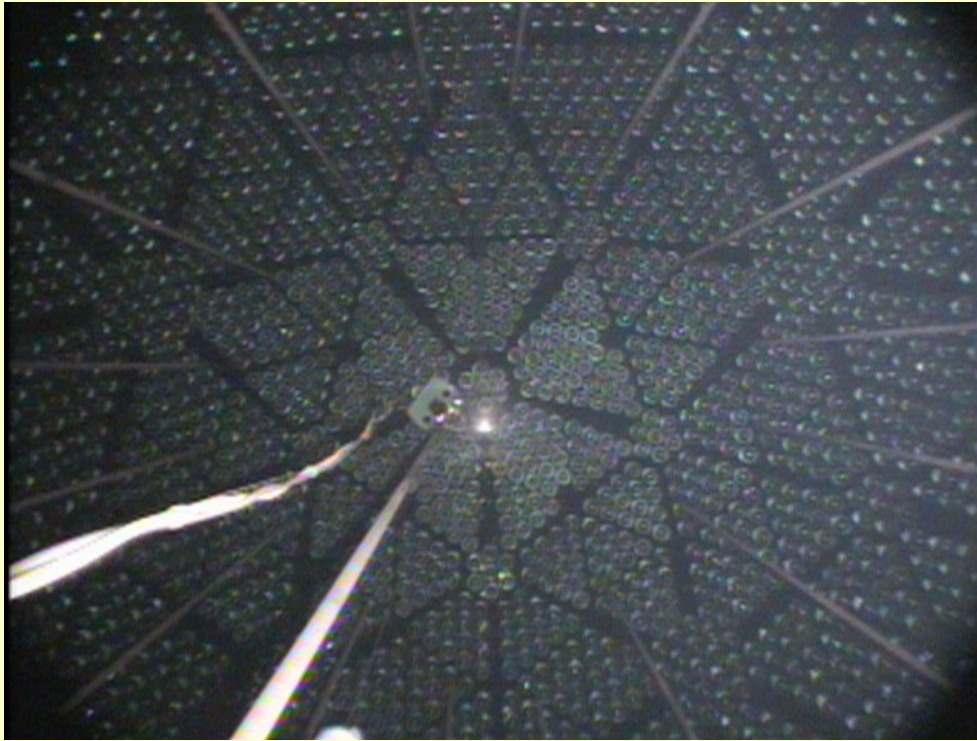
(In units of $10^6 \text{ cm}^{-2} \text{ s}^{-1}$)

$$\frac{\phi_{CC}}{\phi_{NC}} = 0.34 \pm 0.023(\text{stat.})^{+0.029}_{-0.031}$$

Electron Neutrinos are only 1/3 of Total



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 Hamish Robertson and his team).

The original Submarine...

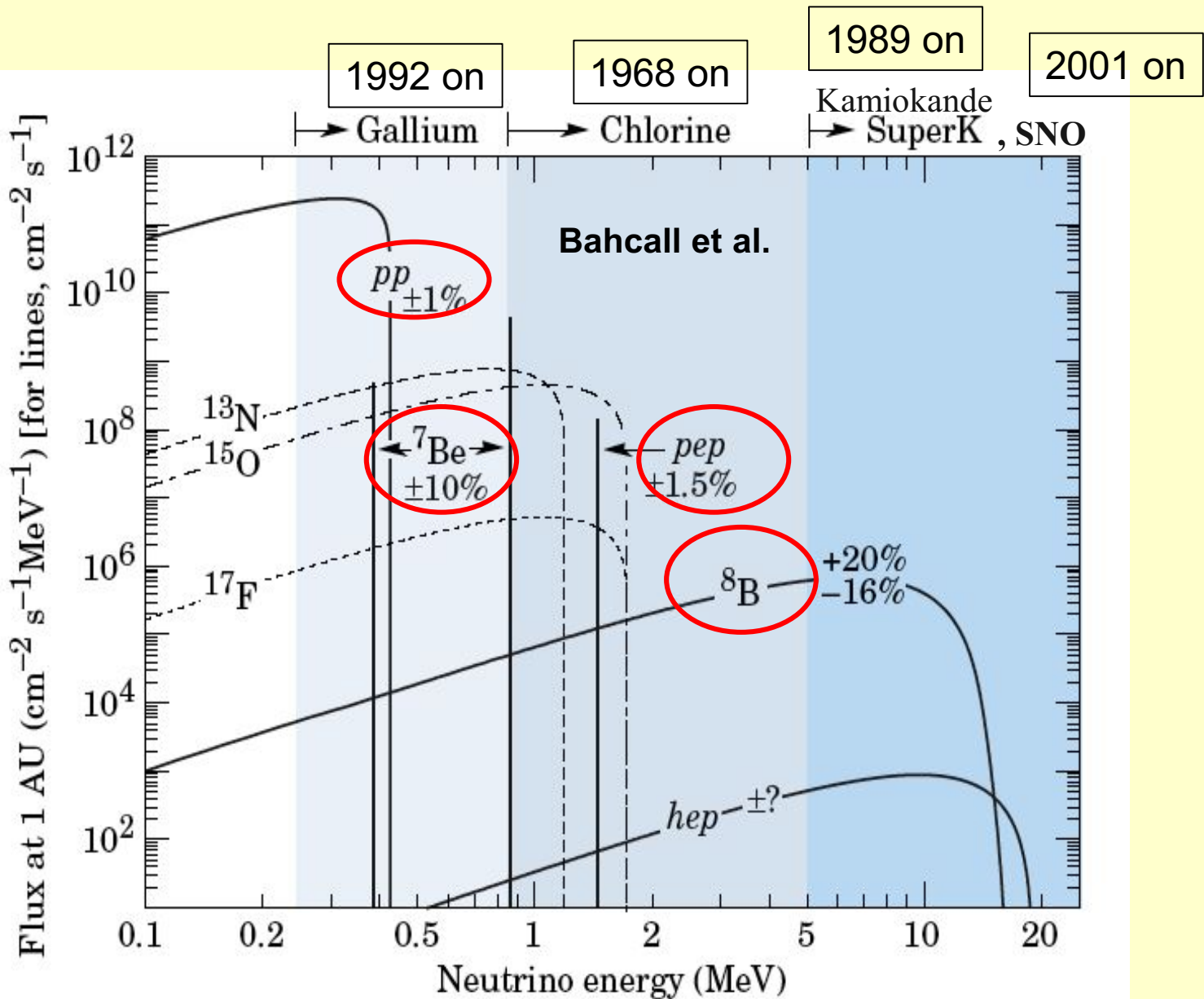
Yellow, of course!

Well, maybe not!

The yellow paint was much too radioactive

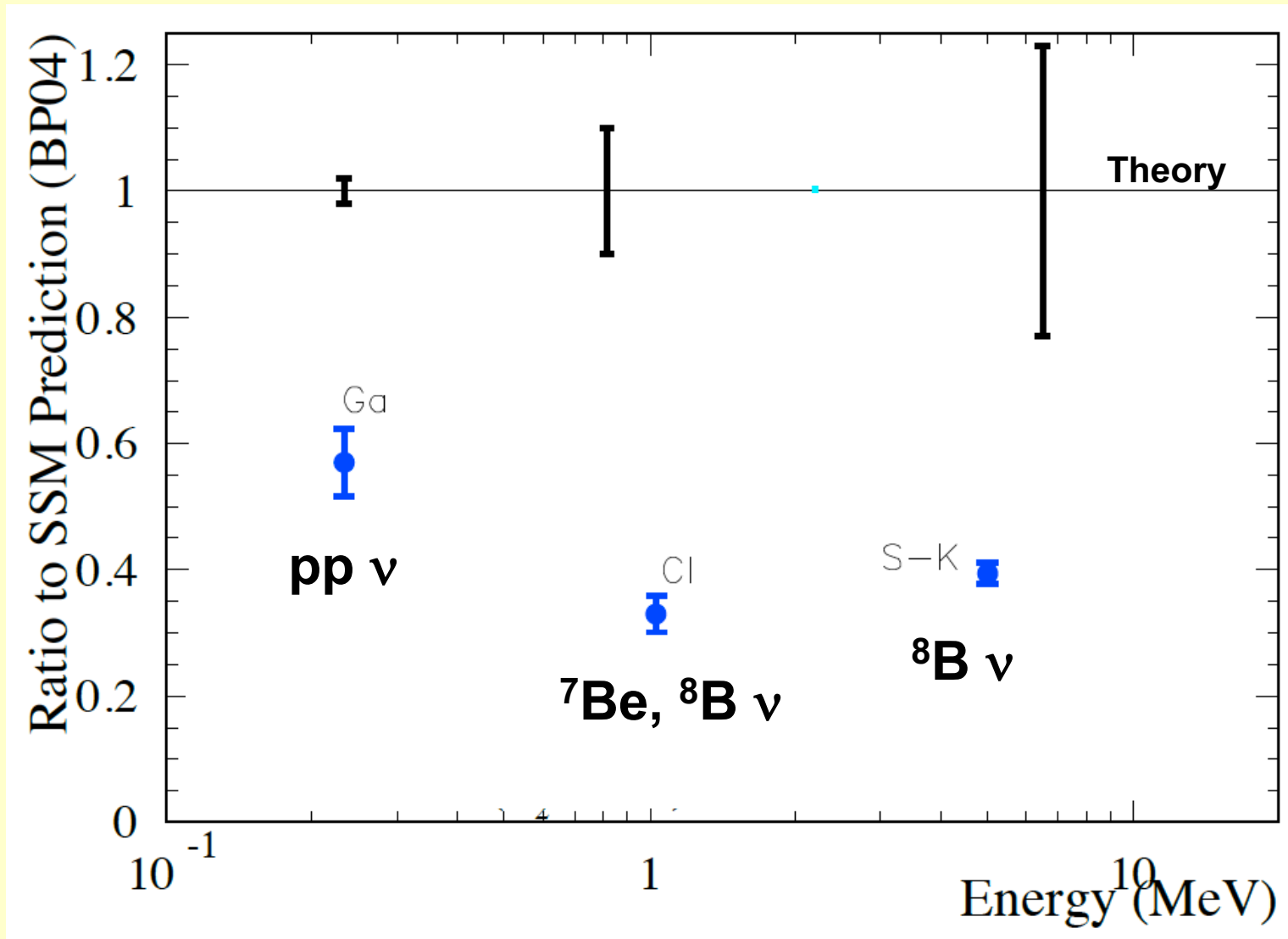


Including other solar neutrino measurements

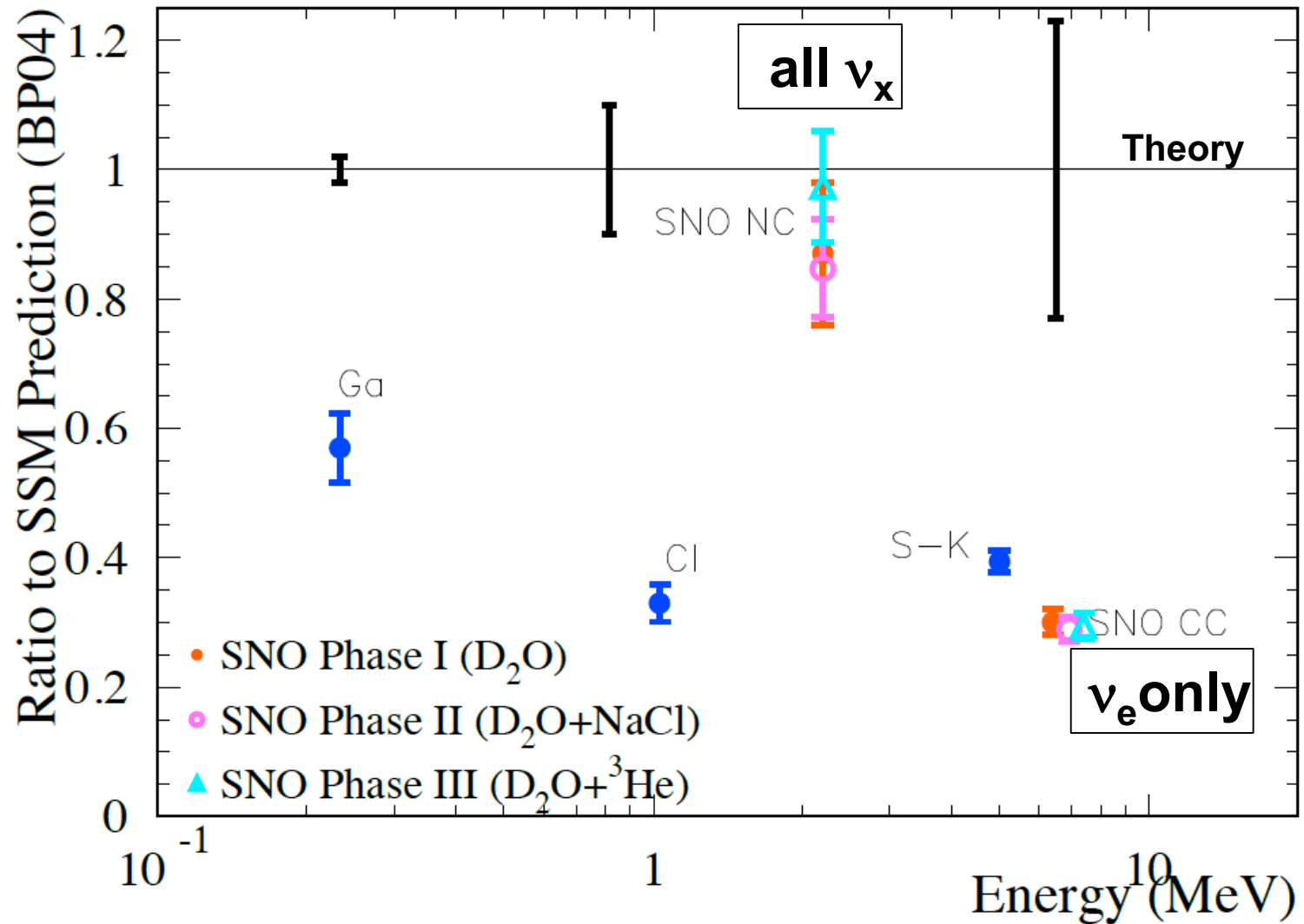


Solar Neutrino Problem

Year 2000 Experimental sensitivity: primarily or exclusively electron neutrinos

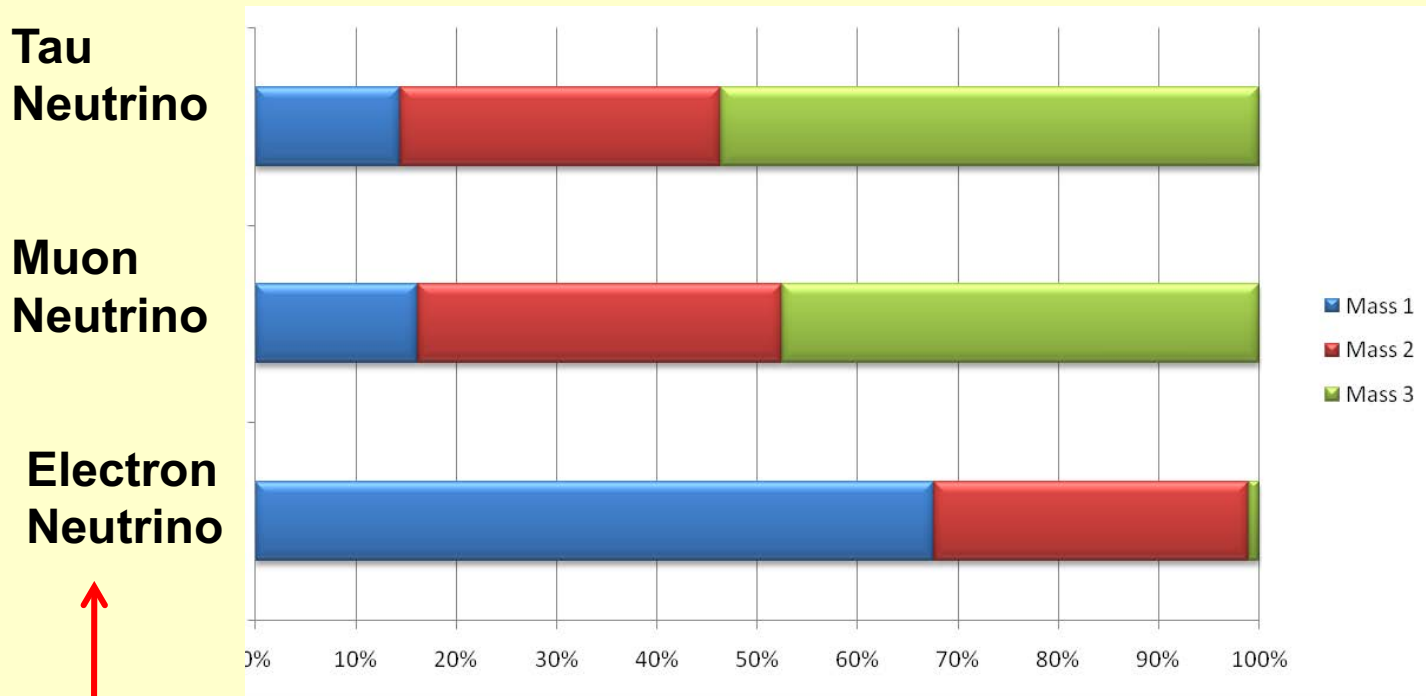


Solar Neutrino Problem Resolved



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

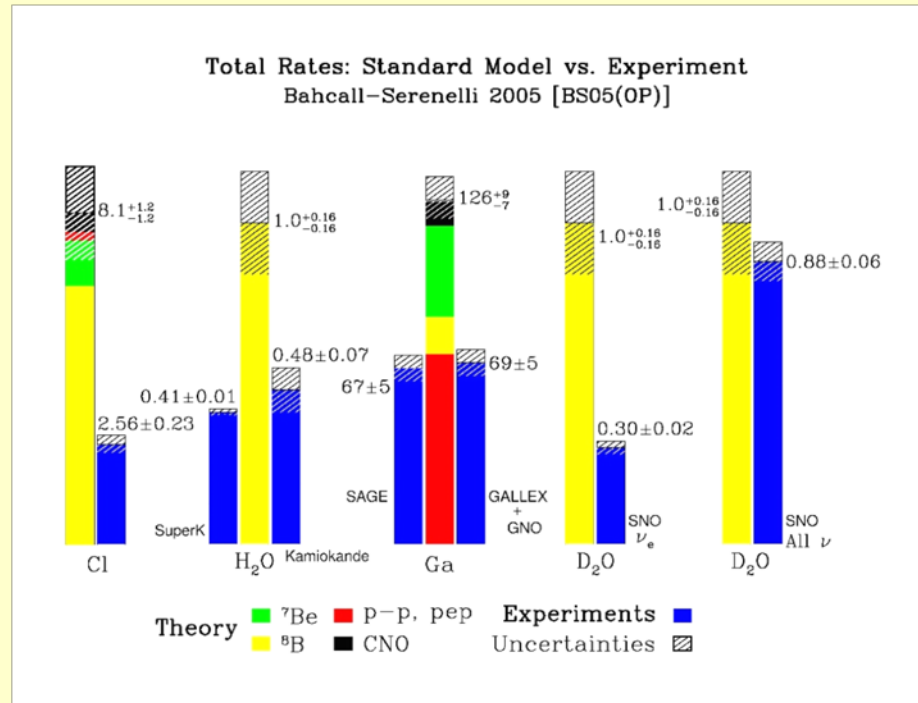
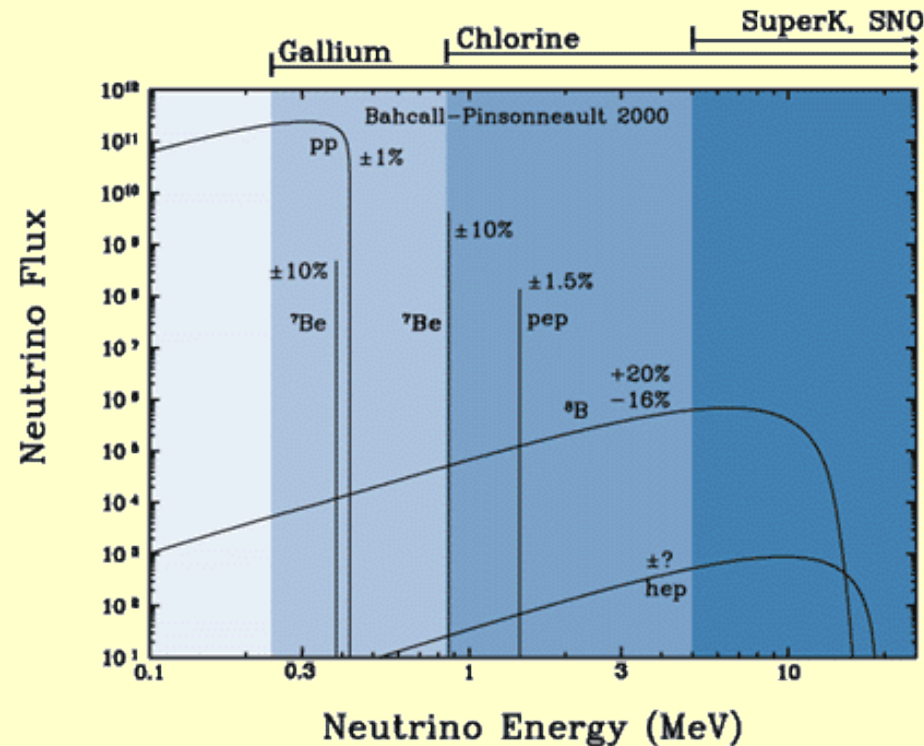
The mass fractions change as the neutrino travels

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

Combining SNO with other solar measurements

Solar Fluxes: Bahcall et al

Experiment vs Solar Models



The analysis concludes that the electron neutrinos are converted to a pure Mass 2 state by interaction with the dense electrons in the sun via the Mikheyev-Smirnov-Wolfenstein (MSW) effect. This interaction determines that Mass 2 is greater than Mass 1 as well as determining Δm_{12}^2 and the mixing parameter θ_{12}

The Future: SNO

DEAP/CLEAN 3600 kg Ar,
MiniCLEAN 500 kg Ar, Ne:
Dark Matter

Cube Hall

New large scale
project.

60 to 800 times lower
 μ fluxes than
Gran Sasso, Kamioka.

HALO
SuperNovae

Phase II
Cryopit

Now: PICO-2L,
DAMIC: Dark Matter

Now: PICO-60: Dark Matter

2016: SuperCDMS Dark Matter

New
Area

SNO+: Double Beta,
solar, geoneutrinos

Low Background
counting facility

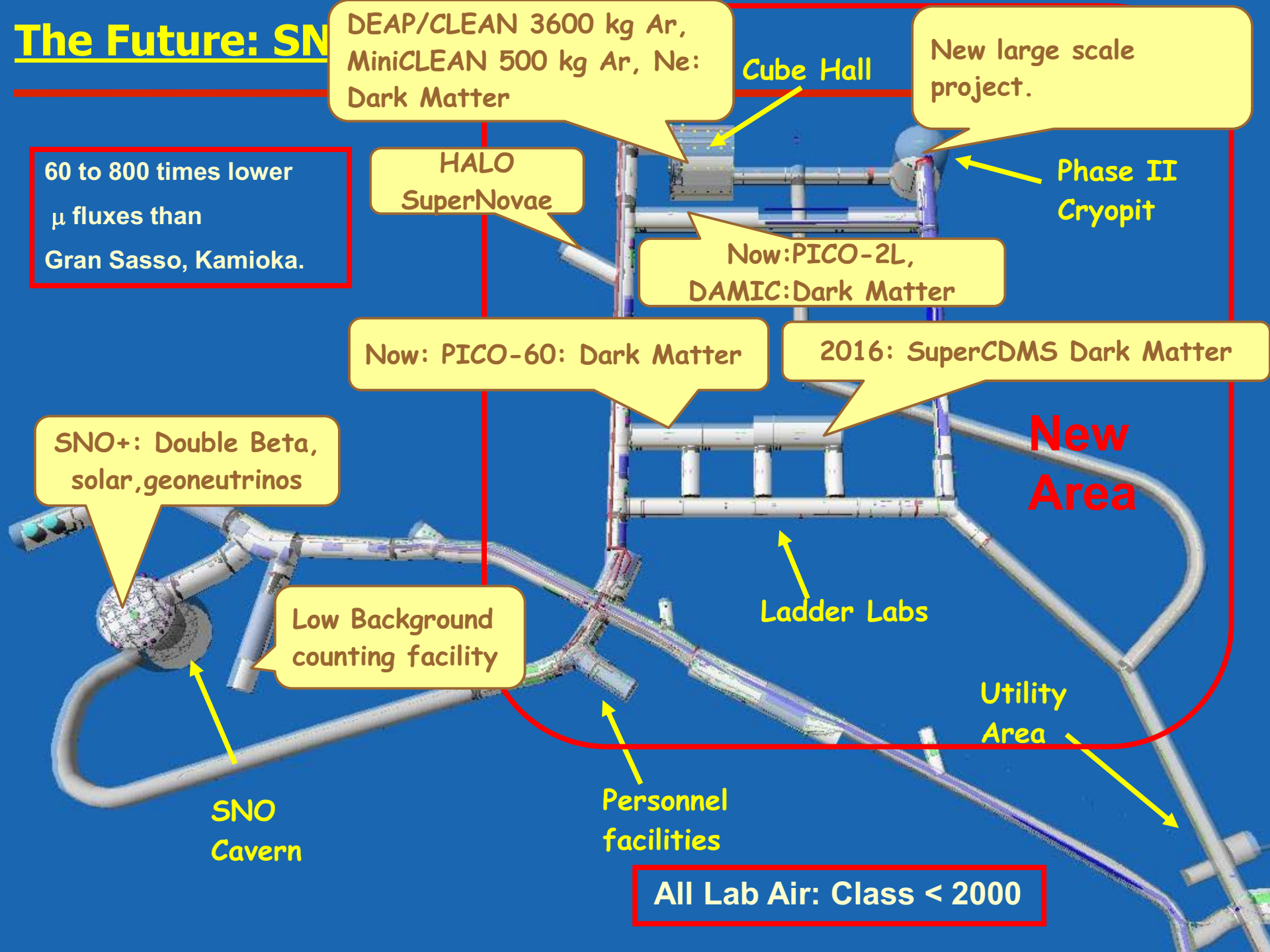
Ladder Labs

Utility
Area

Personnel
facilities

SNO
Cavern

All Lab Air: Class < 2000



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 over 2 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.**

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

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

- DEAP and MiniClean (Liquid Argon), PICO (bubble detection in materials containing fluorine), DAMIC (Highly Pixelated solid state detectors) and SuperCDMS relocating to SNOLAB (Solid State Bolometers)

The Sudbury Neutrino Observatory

Funding Agencies, Other Support for SNO

CANADA:

- NSERC
- NRC
- Industry Canada
- Northern Ontario Heritage Fund Corp.
- INCO
- AECL
- Ontario Power Generation
- Nortel

Institutions:

Canada

University of Alberta (since 2005)

Chalk River Labs (until 1992)

Carleton University

University of Guelph

Laurentian University

NRC (until 1992)

Queen's University

University of British

Columbia

UK

Oxford

Portugal

LIP Lisbon

(since 2005)

USA:

- US Department of Energy

UK:

- Particle Physics and Astronomy Research Council

USA

Brookhaven National Lab

Princeton University (until 1992)

University of Texas at Austin (2002- 2008)

Los Alamos National Lab

Lawrence Berkeley National Lab

University of Pennsylvania

University of Washington

UC Irvine (until 1989)

Louisiana State University (since 2005)

MIT (since 2005)



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, 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, 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