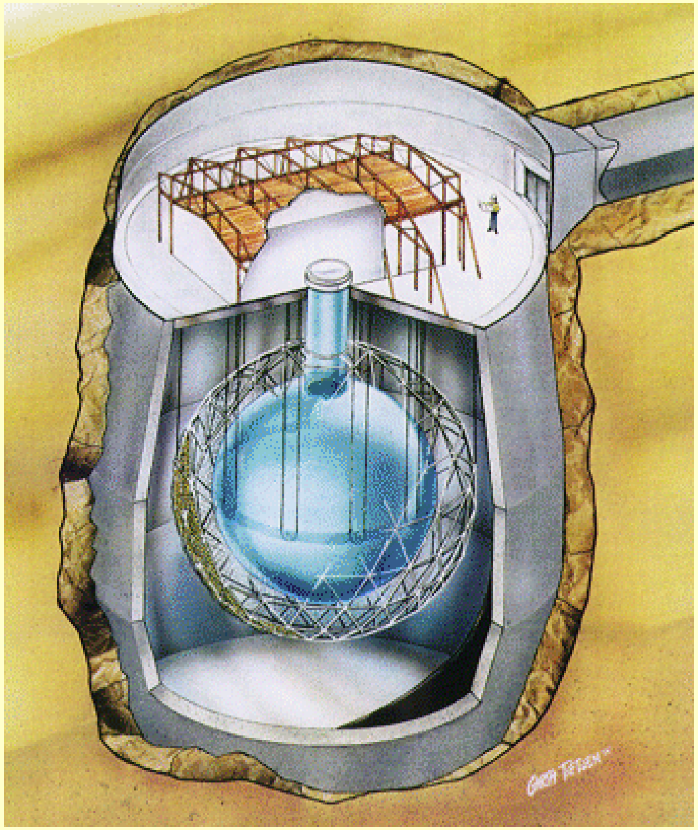
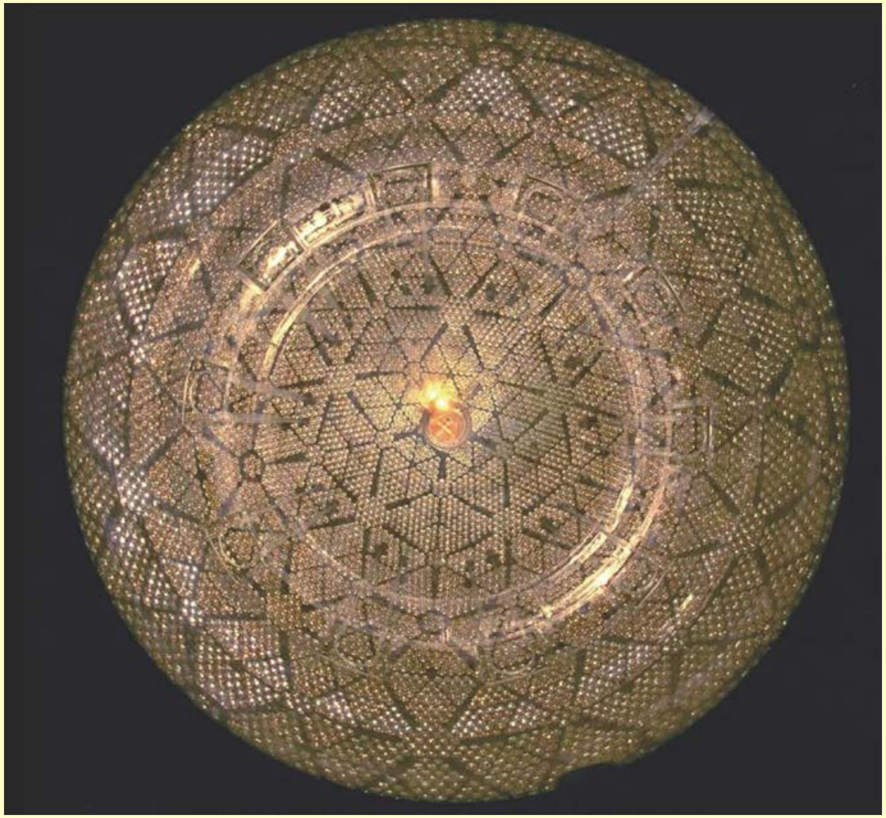
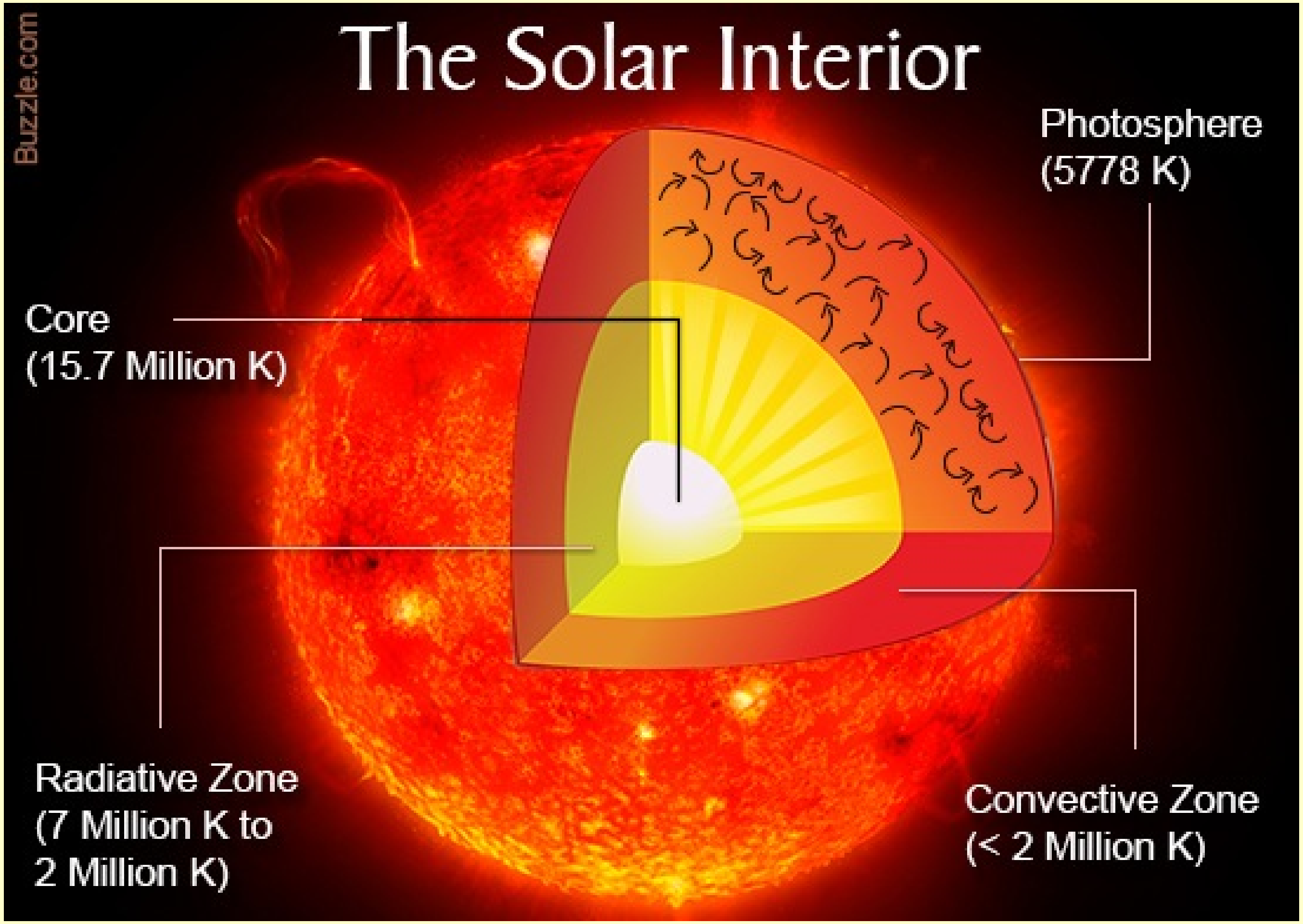
The Sudbury Neutrino Observatory: Observation of Flavor Change for Solar Neutrinos.





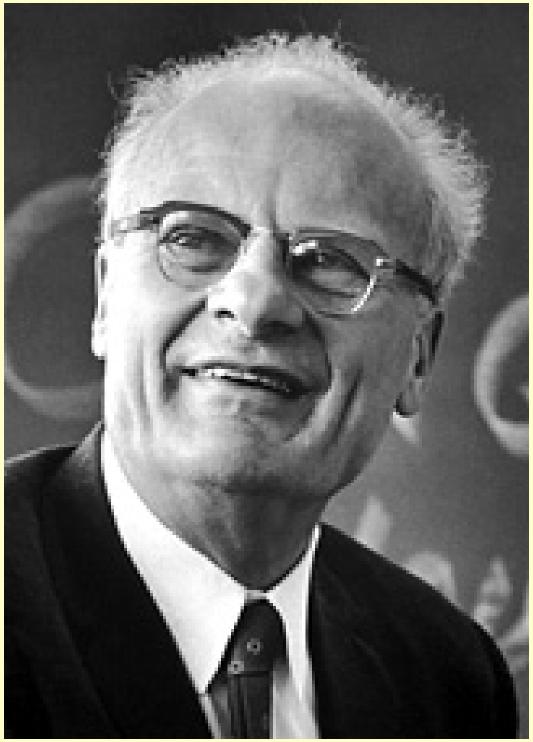
Art McDonald, Professor Emeritus
Queen's University, Kingston, Ontario, Canada

Neutrinos from the Sun

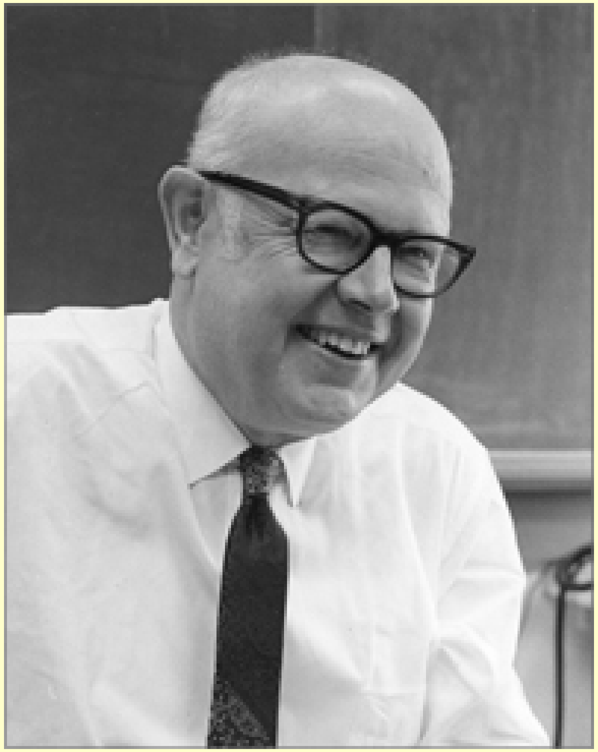


The middle of the sun is so hot that the centers of the atoms (nuclei) fuse together, giving off lots of energy and neutrinos. The neutrinos penetrate easily through the dense material in the Sun and reach the earth.

Understanding How the Sun Burns



Hans Bethe
Basic Theory 1939
Nobel Laureate 1967



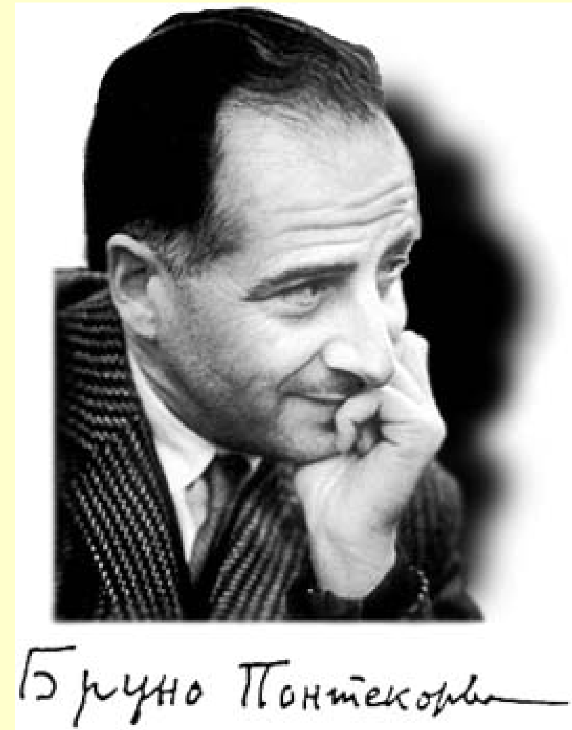
Willy Fowler
Theory, Experiments 1950's, 60's
Nobel Laureate 1983

We stand on the Shoulders of Giants

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

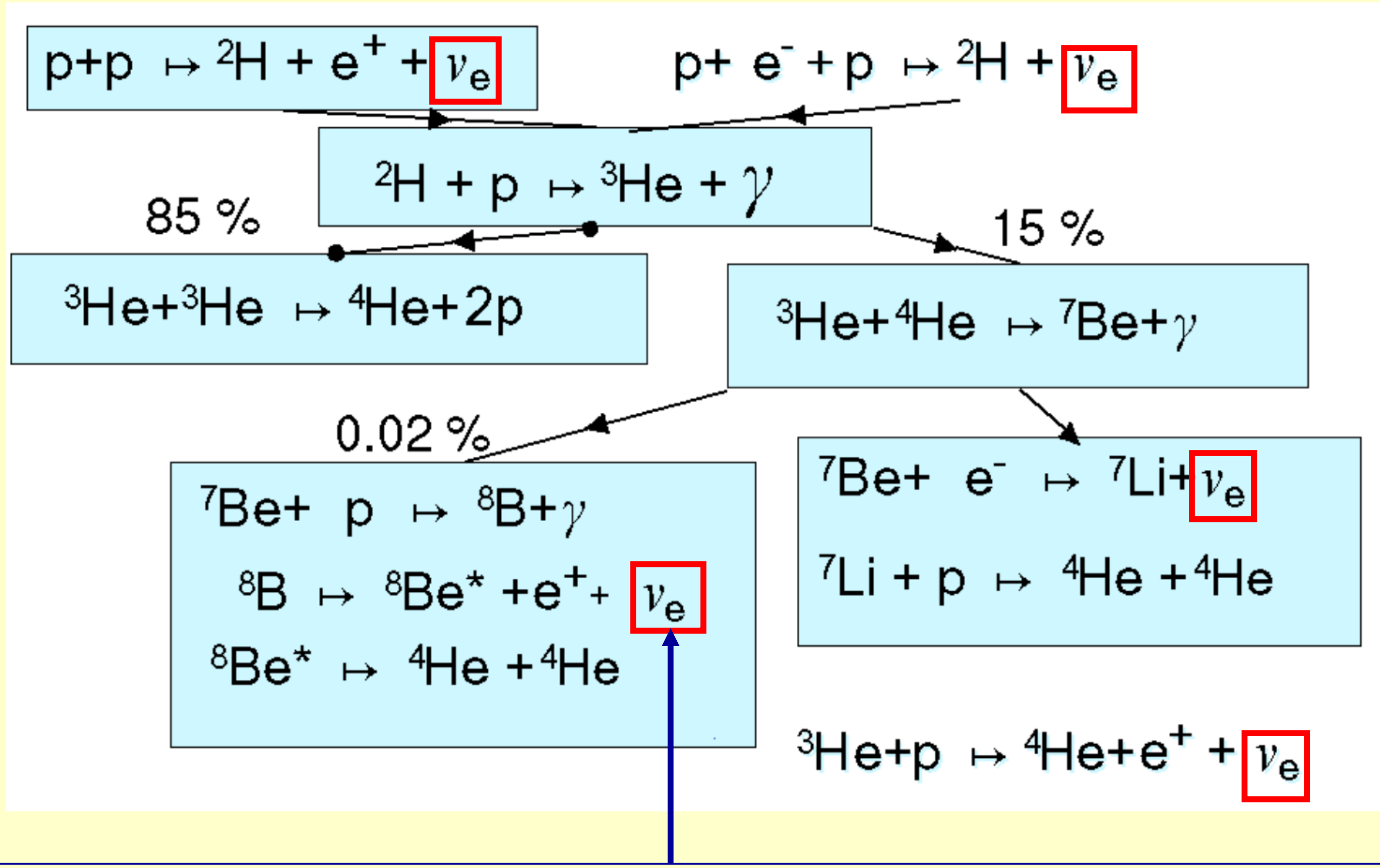
1968: Davis' Measurements with Chlorine-based detector show 3 times fewer than Bahcall's calculations.

Ray Davis: Nobel Laureate 2002



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

SOLAR FUSION CHAIN



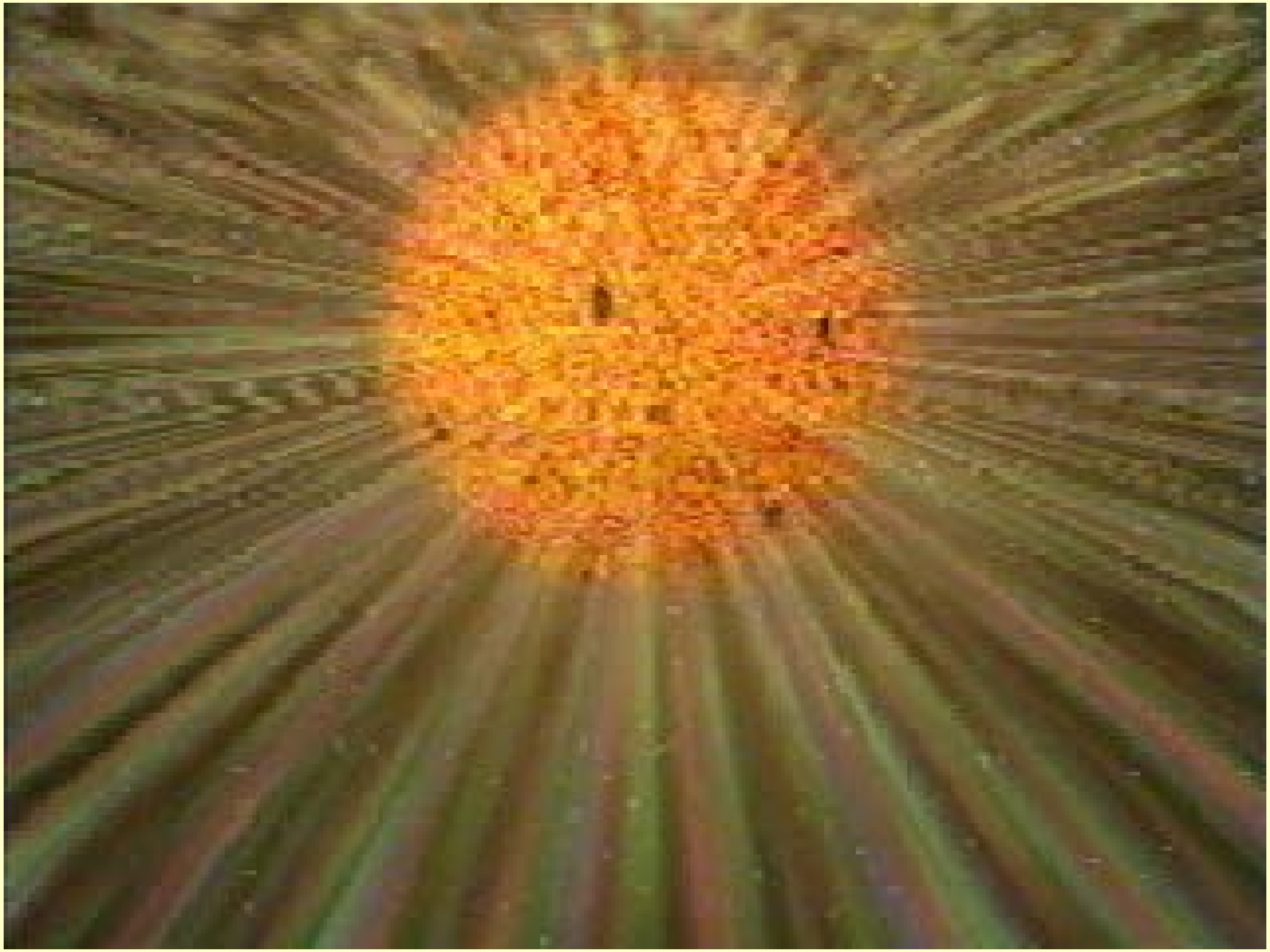
1984: Chen proposes heavy water to search for direct evidence of flavor transformation for neutrinos from ^8B decay in the Sun.

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.

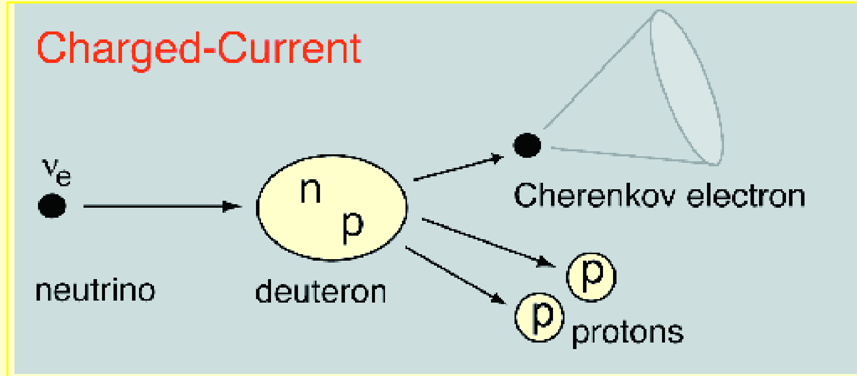
Unique Signatures in SNO (D_2O)

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

Electron Neutrinos (CC)

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

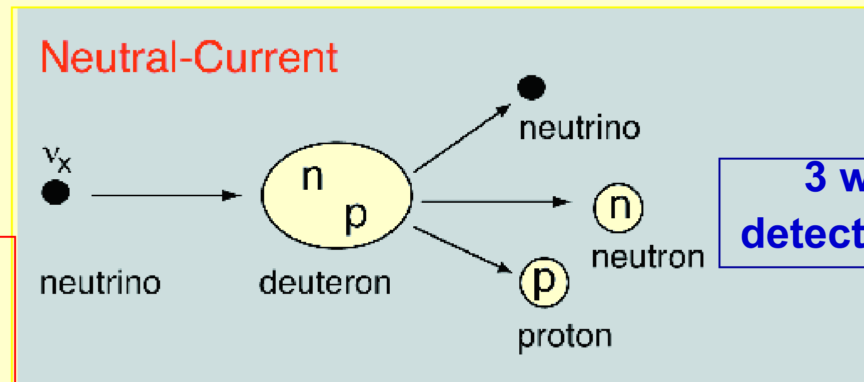
$E_{thresh} = 1.4$ MeV



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.

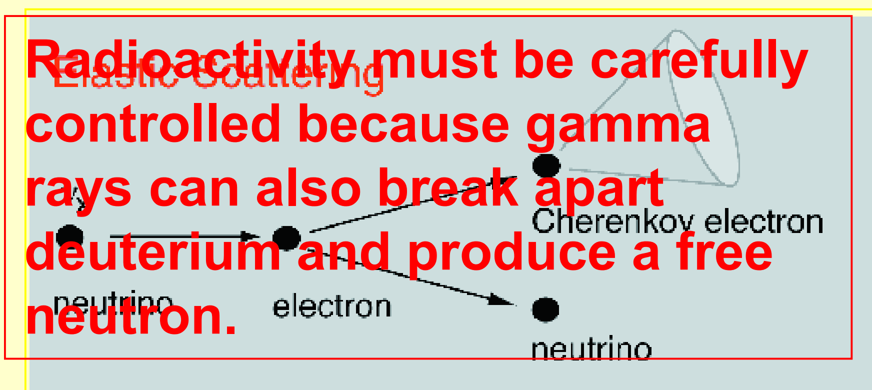
Elastic Scattering from Electrons

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

ν_x, but enhanced for ν_e x 6

10 times lower count rate

Points away from the Sun

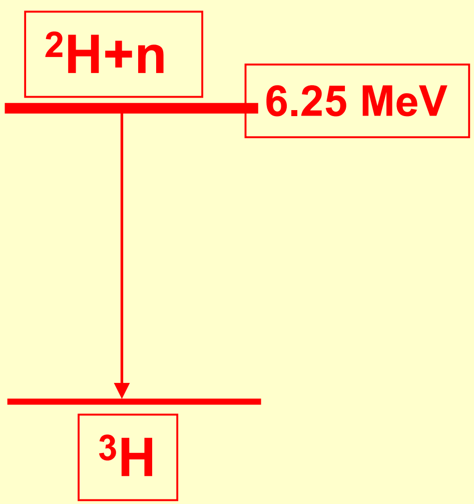


Radioactivity must be carefully controlled because gamma rays can also break apart deuterium and produce a free neutron.

3 neutron (NC) detection methods (systematically different)

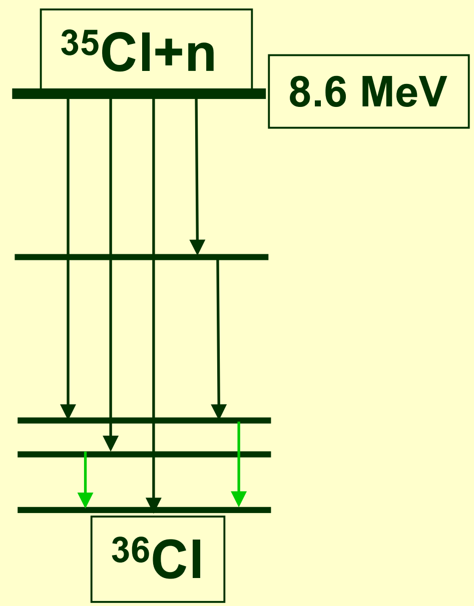
Phase I (D_2O)
Nov. 99 - May 01

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



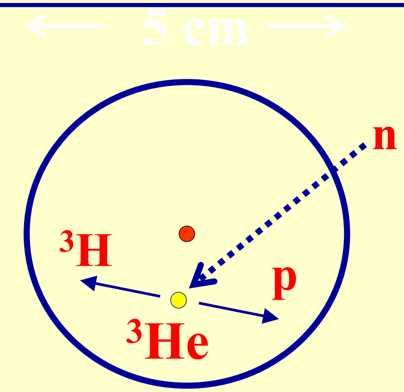
Phase II (salt)
July 01 - Sep. 03

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 seperate detection system.



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

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

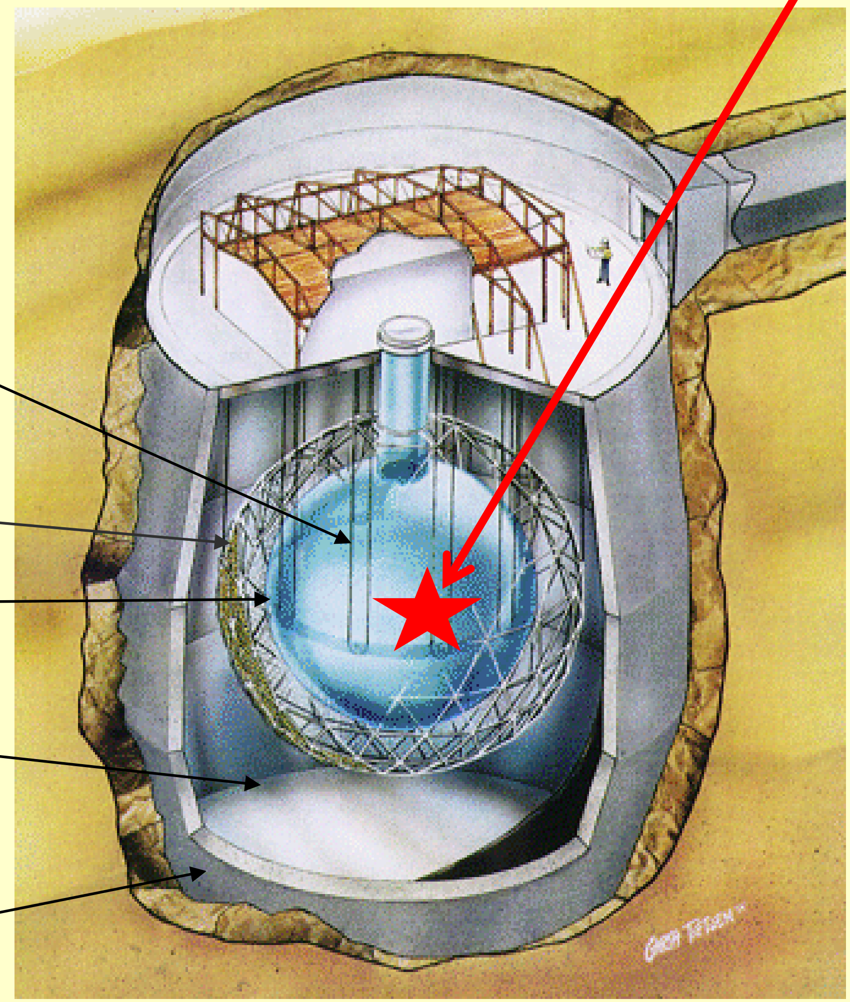
9500 light sensors

12 m Diameter Acrylic Container

Ultra-pure Water: H_2O.

Urylon Liner and Radon Seal

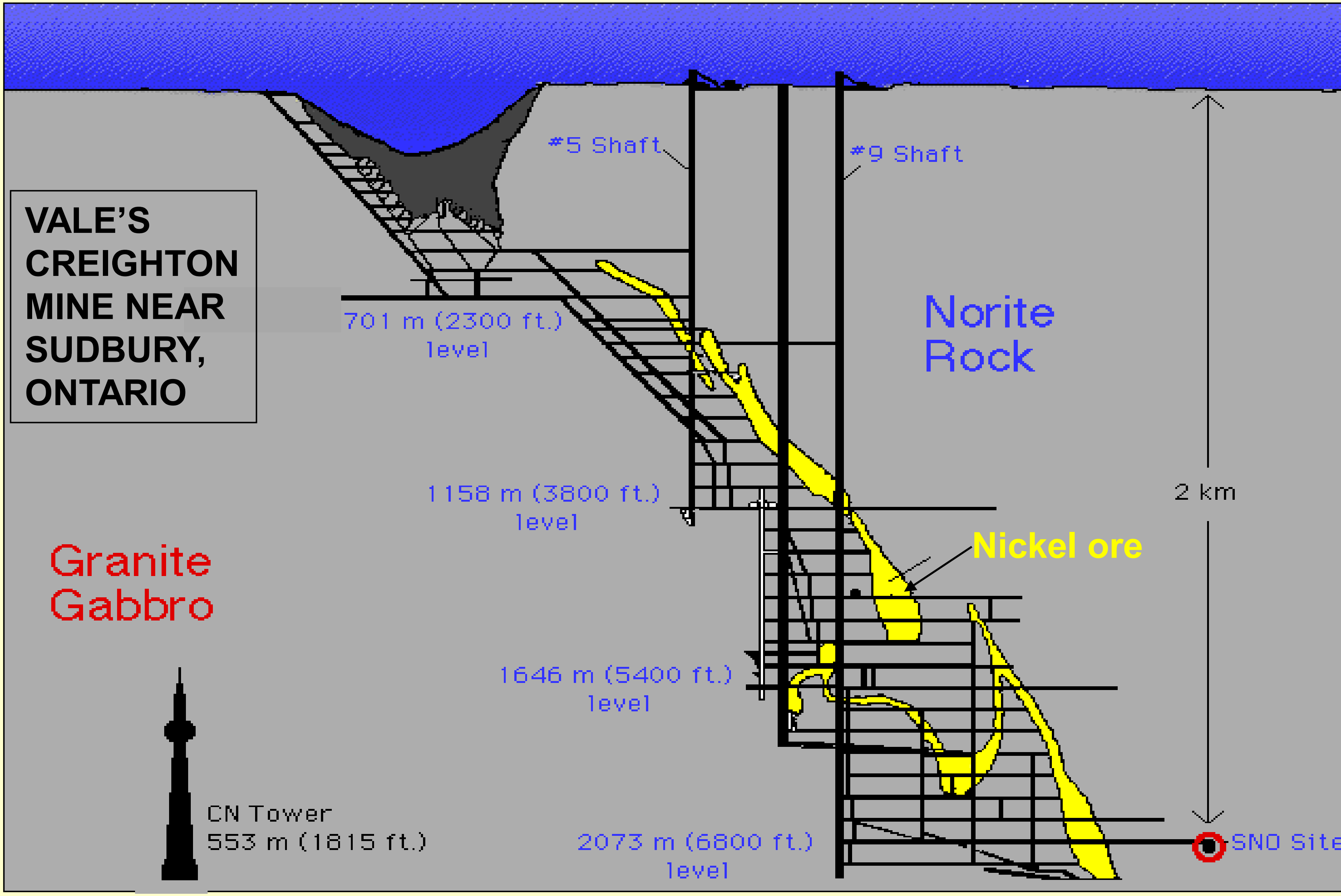
NEUTRINO



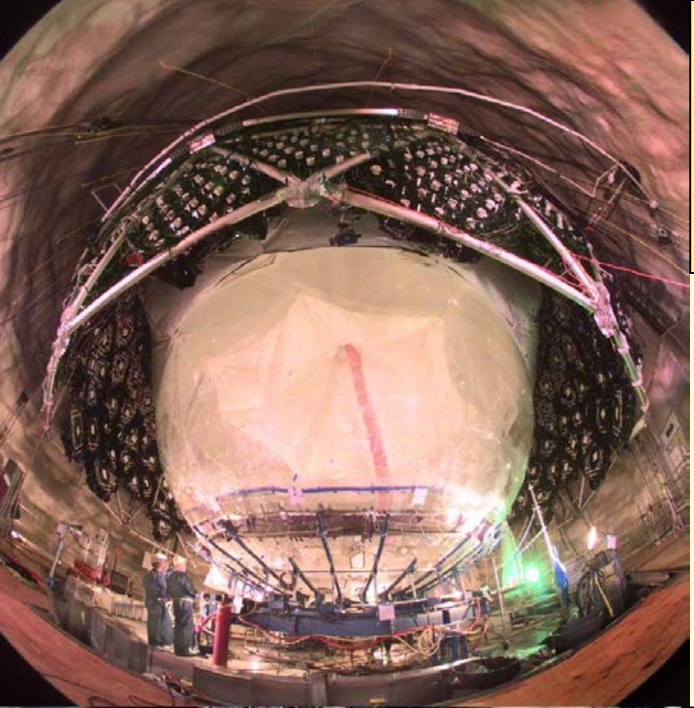
34 m or ~ Ten Stories High!

2 km below the ground

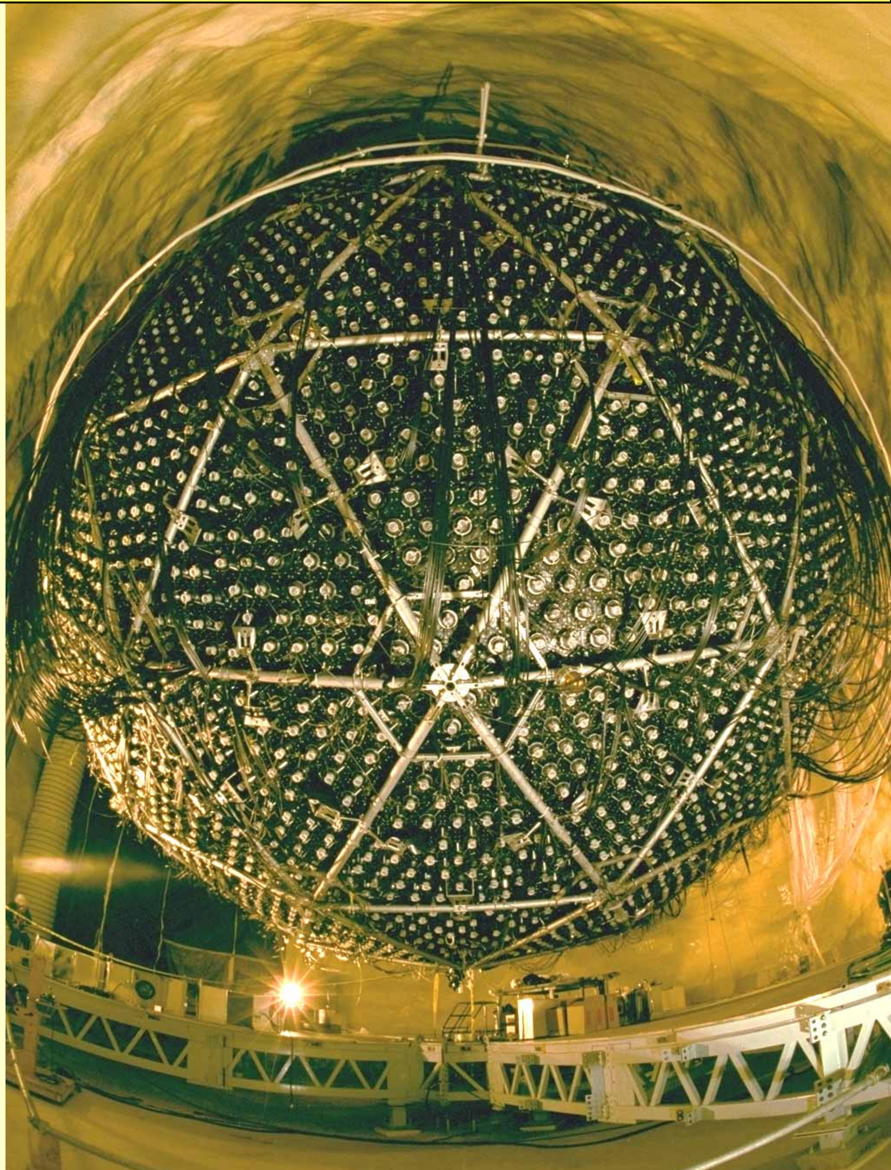
To study Neutrinos with little radioactive background, we went 2 km underground to reduce cosmic rays and built an ultra-clean detector: SNO

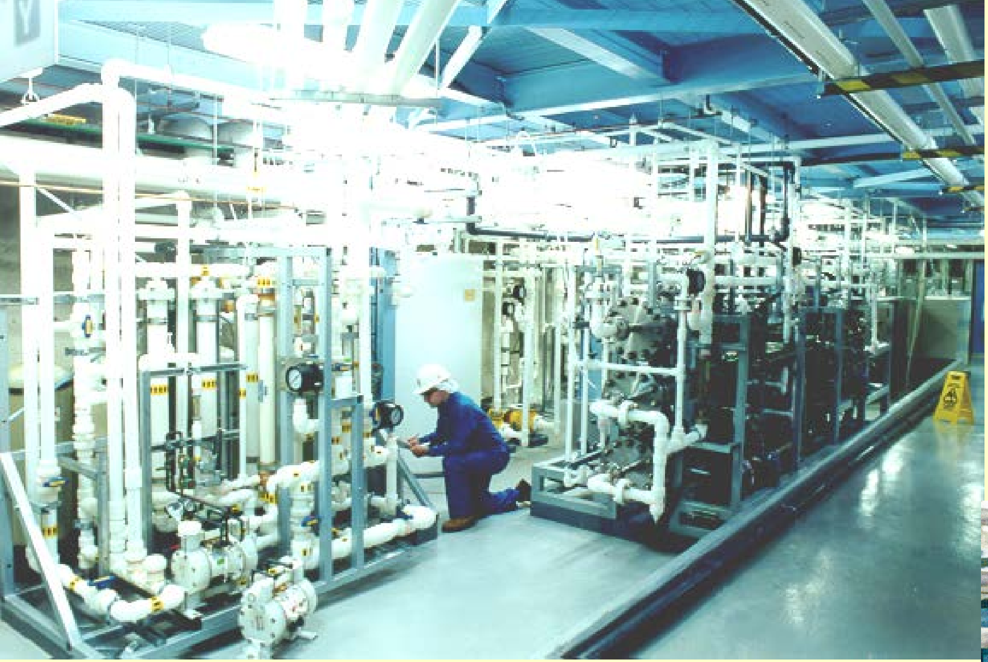


SNO: One million pieces transported down in the 3 m x 3 m x 4 m mine cage and re-assembled under ultra-clean conditions. Every worker takes a shower and wears clean, lint-free clothing.



70,000 showers during the course of the SNO project

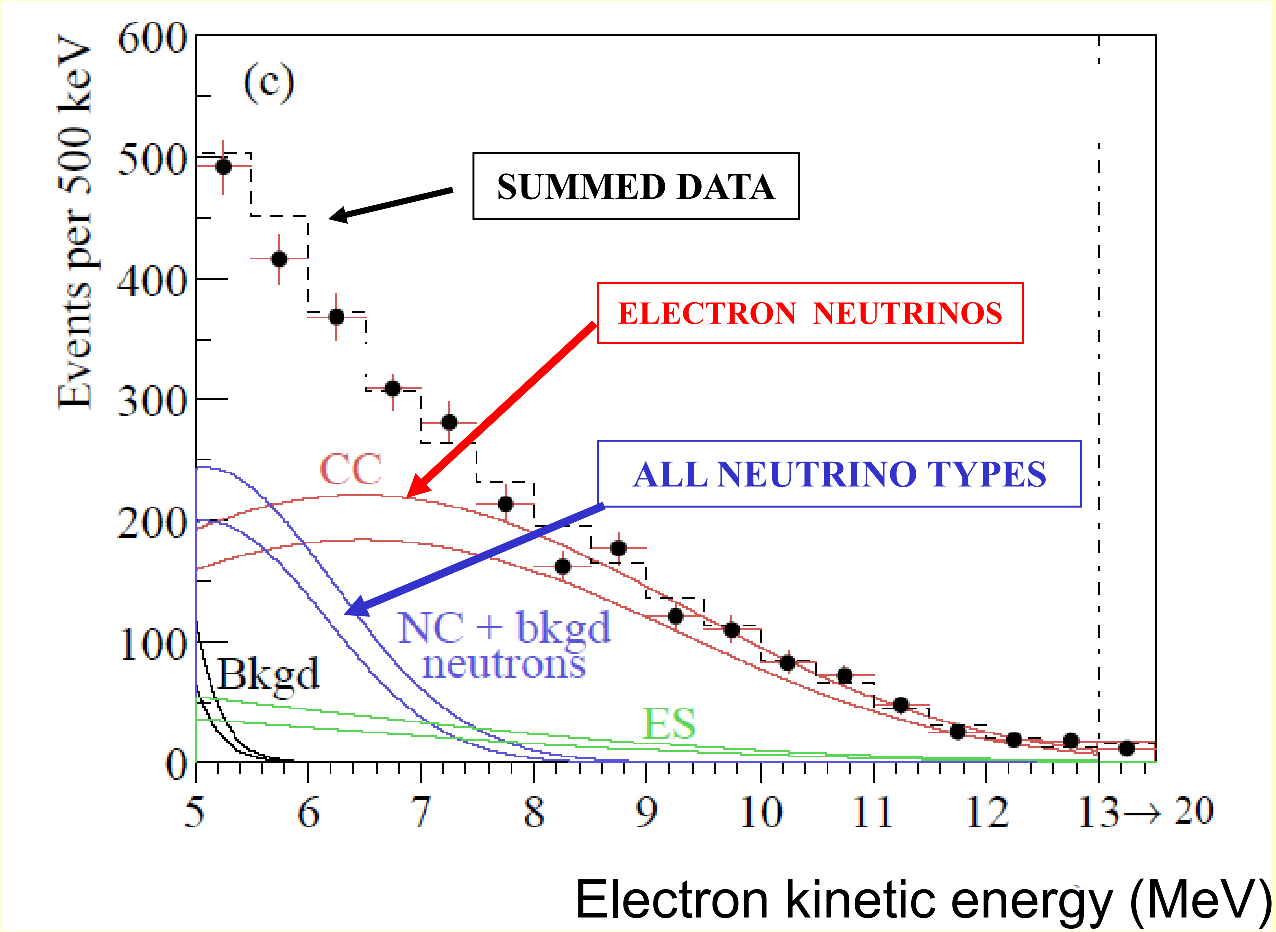




Water systems were developed to provide low radioactivity water and heavy water: 1 billion times better than tap water. Less than one radioactive decay per day per ton of water!!

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

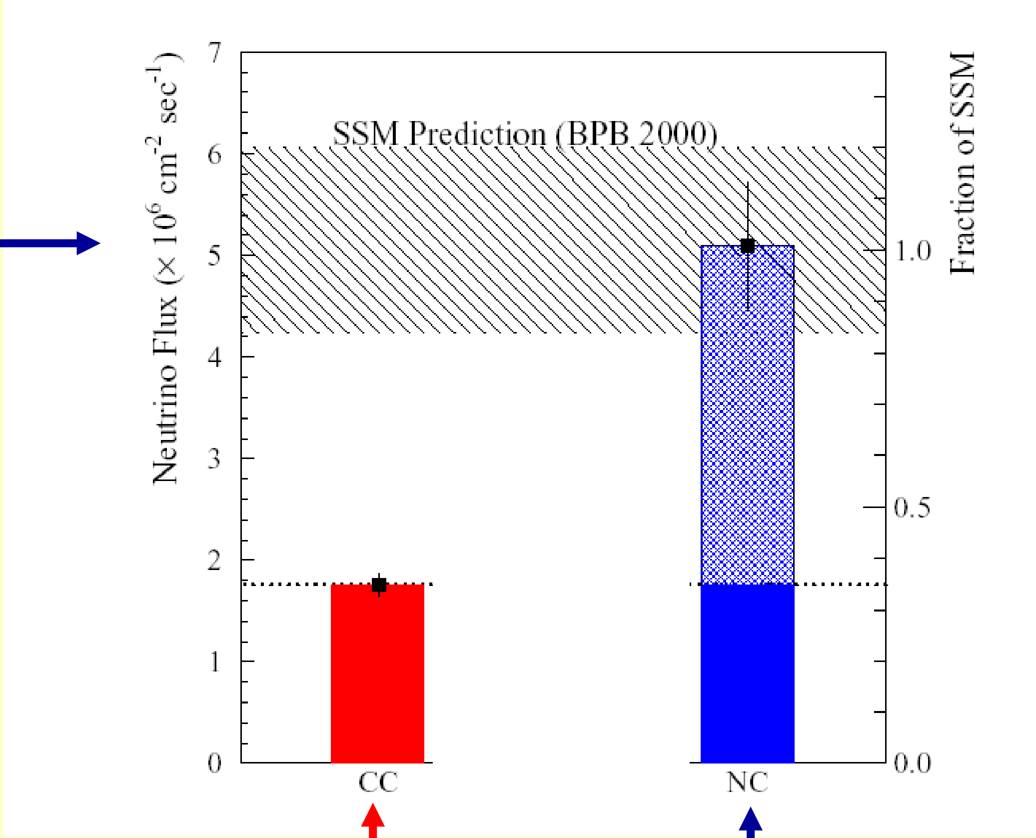
WE OBSERVED NEUTRINOS FROM THE SUN WITH ALMOST NO RADIOACTIVE BACKGROUND



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

Data from Pure Heavy Water Phase in 2002

SOLAR MODEL



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

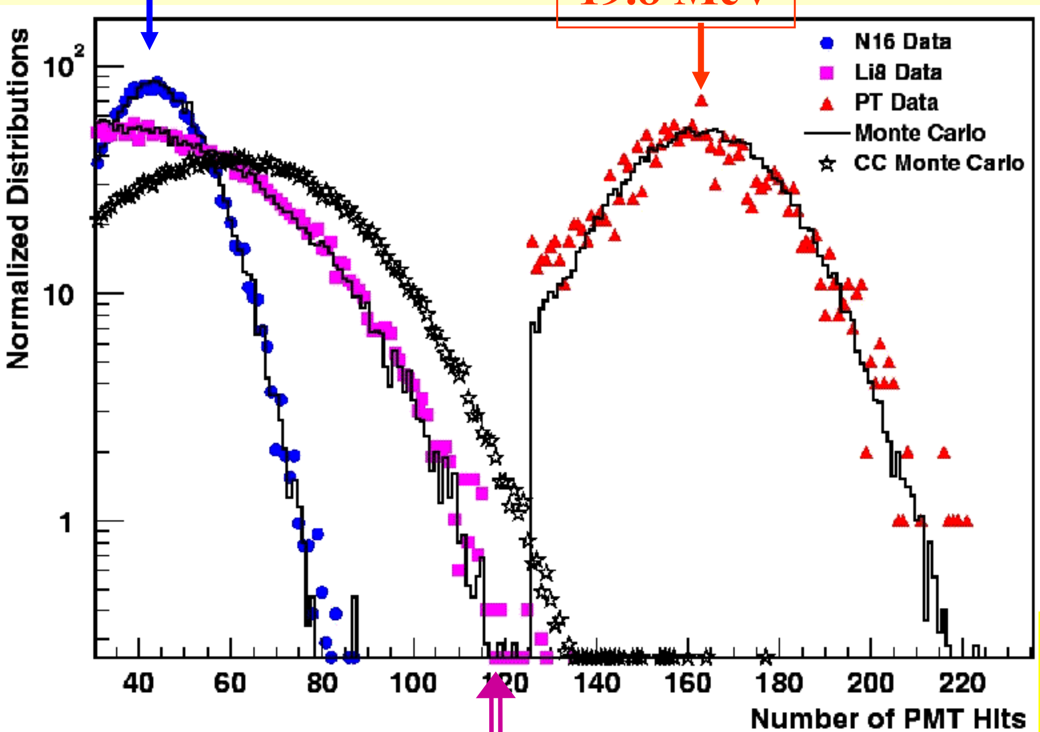
ALL NEUTRINO TYPES

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.

SNO Energy Calibrations

6.13 MeV

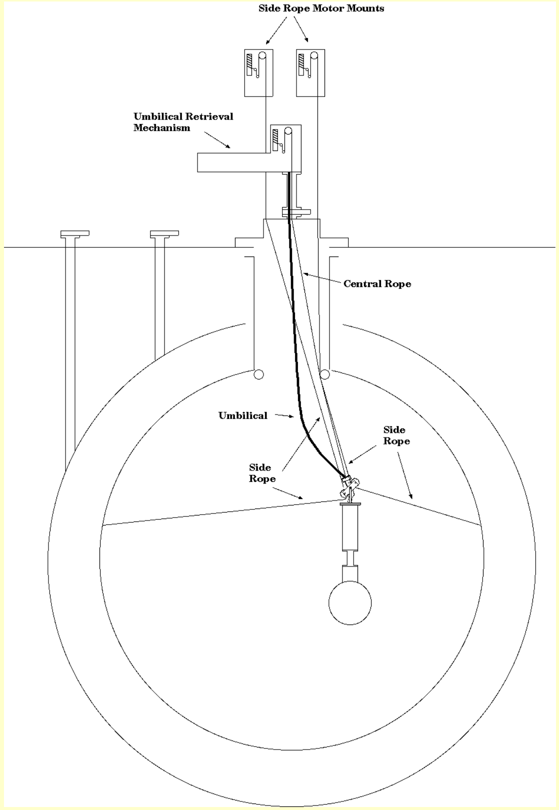
19.8 MeV

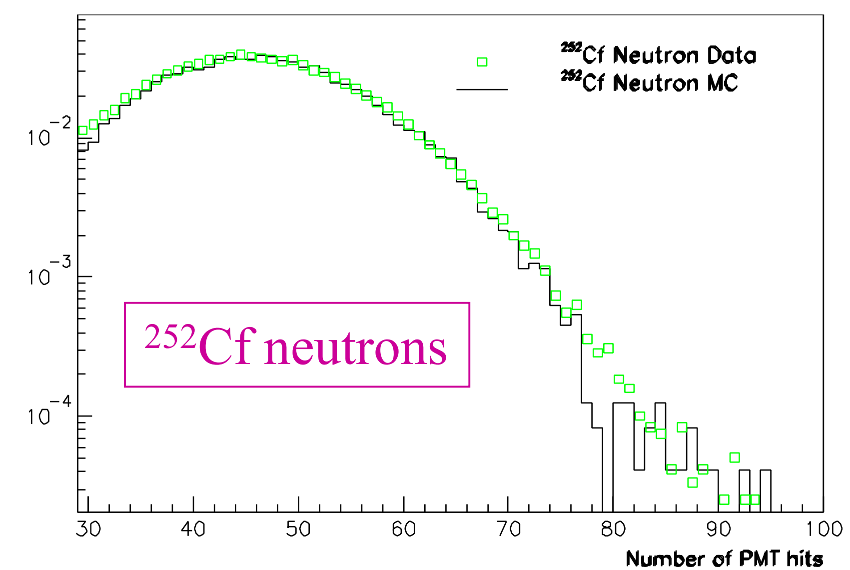


β's from ^{8}Li
γ's from ^{16}N and t(p,γ)^{4}He

Radioactivity: Rn and encapsulated U and Th

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





^{252}Cf neutrons

Measuring U/Th Content

Ex-situ

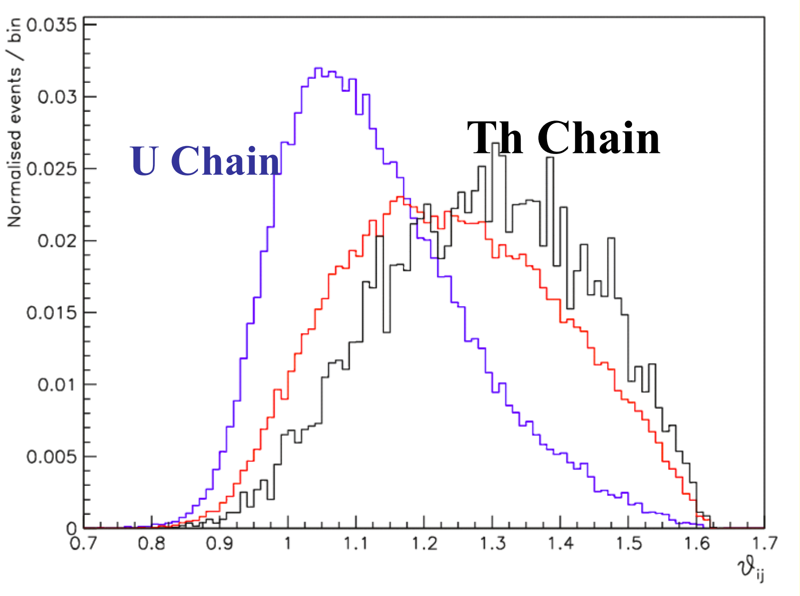
- **Ion exchange (^{224}Ra, ^{226}Ra)**
- **Membrane Degassing (^{222}Rn)**

count daughter product decays

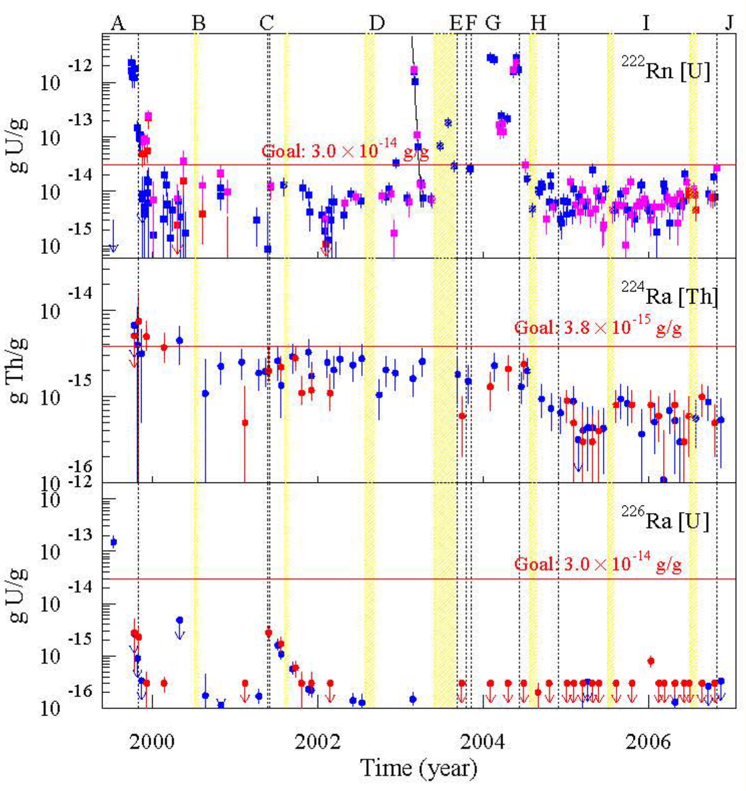
In-situ

- **Low energy data analysis**
- **Separate U and Th Chains**

Using Event isotropy

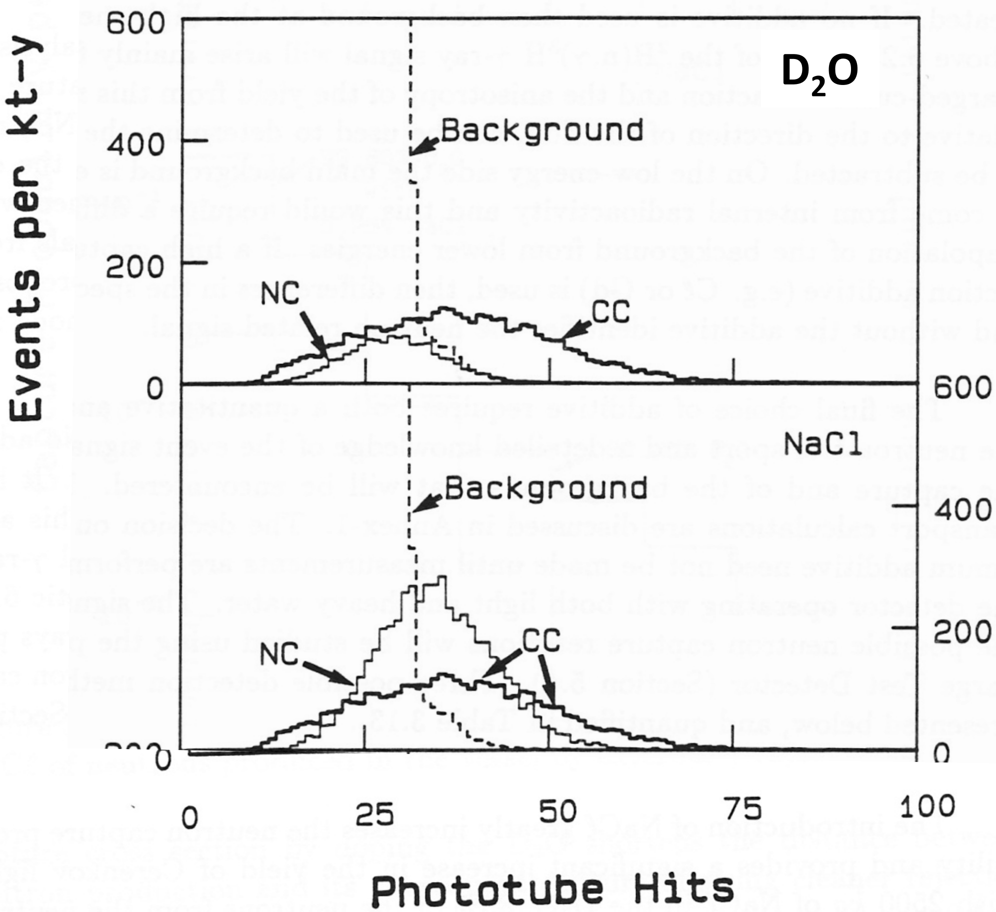


Isotropy

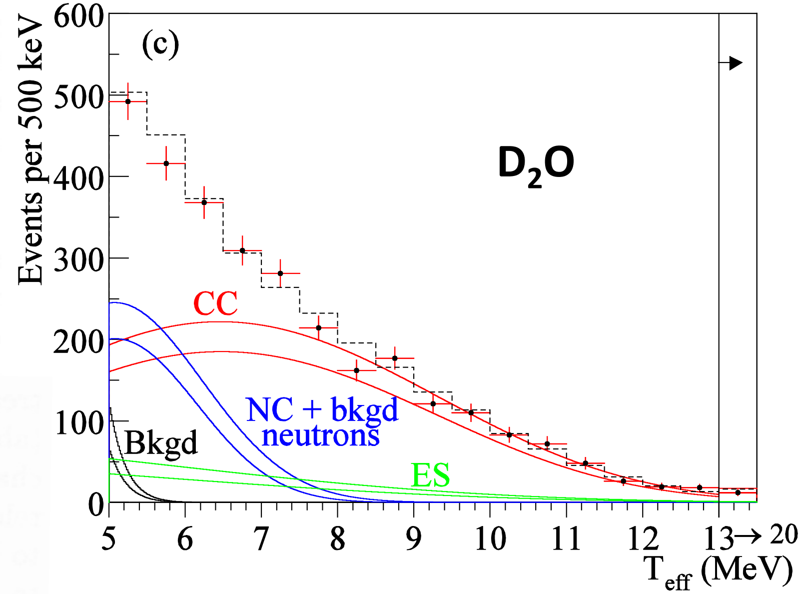


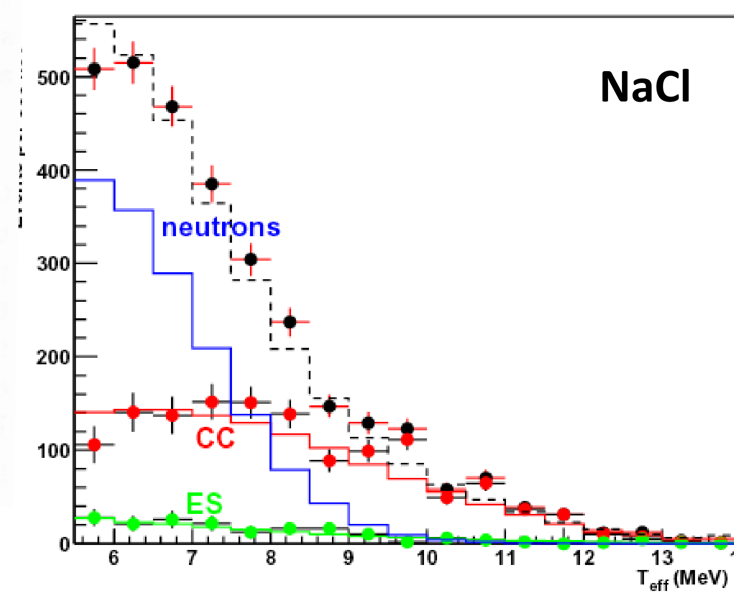
Numbers of background neutrons from gamma rays breaking apart deuterium are measured to be 3 times smaller than the signal. Uncertainty from this is less than 10% of the neutrino measurement.

As simulated in 1987

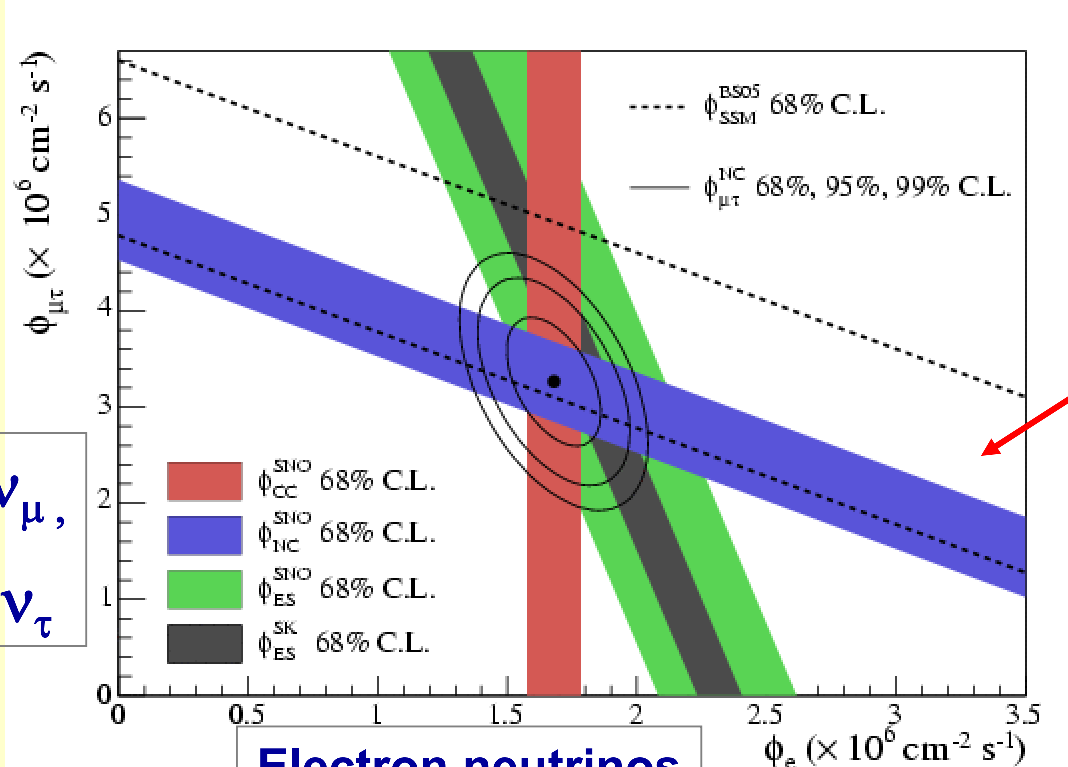


As measured 1999-2003





SNO Results for Salt Phase



ν_μ, ν_τ

Electron neutrinos

Flavor change determined by > 7 σ.

New physics beyond The Standard Model of Elementary Particles!

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

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

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

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

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

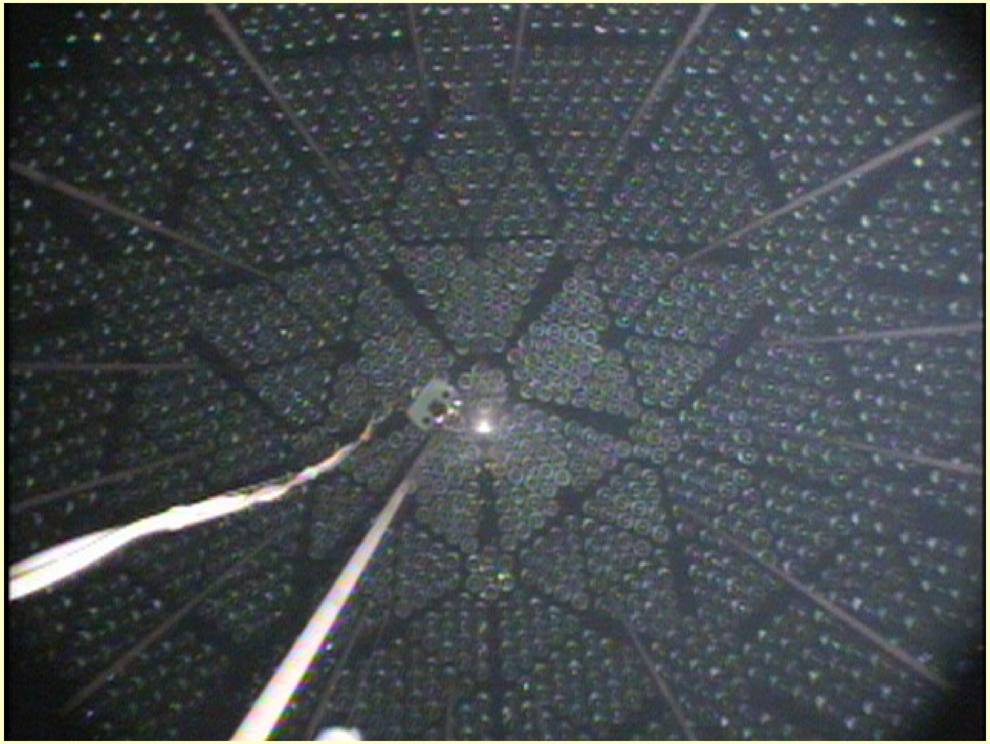
The Total Flux of Active Neutrinos is measured independently (NC) and agrees well with solar model Calculations:

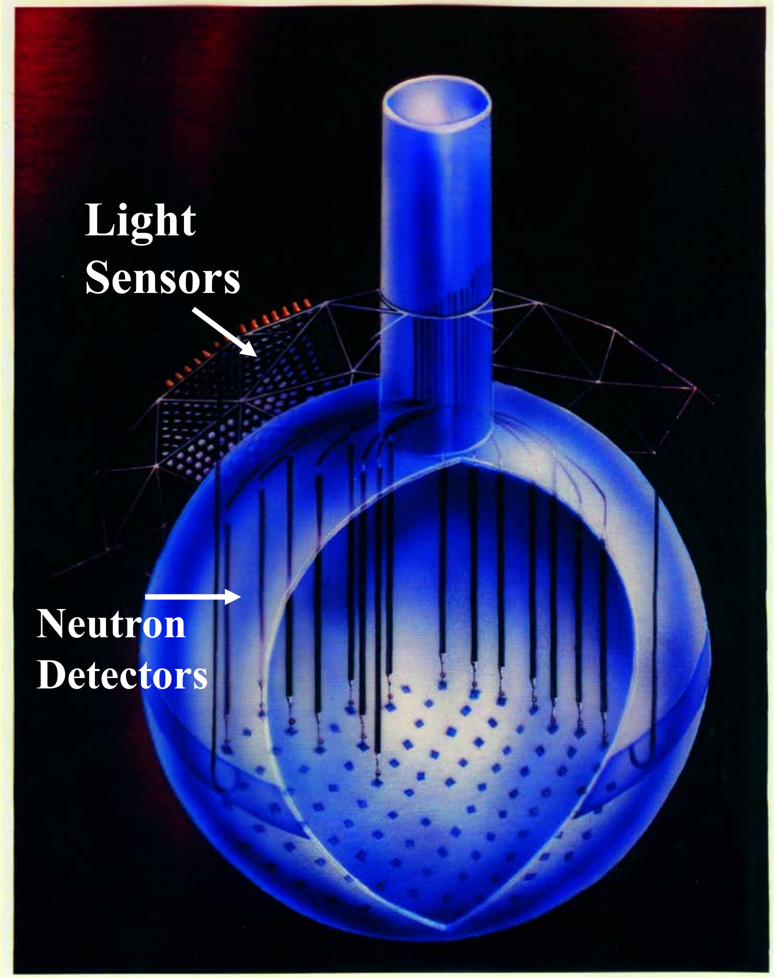
5.82 +- 1.3 (Bahcall et al),

5.31 +- 0.6 (Turck-Chieze et al)

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 original Submarine…

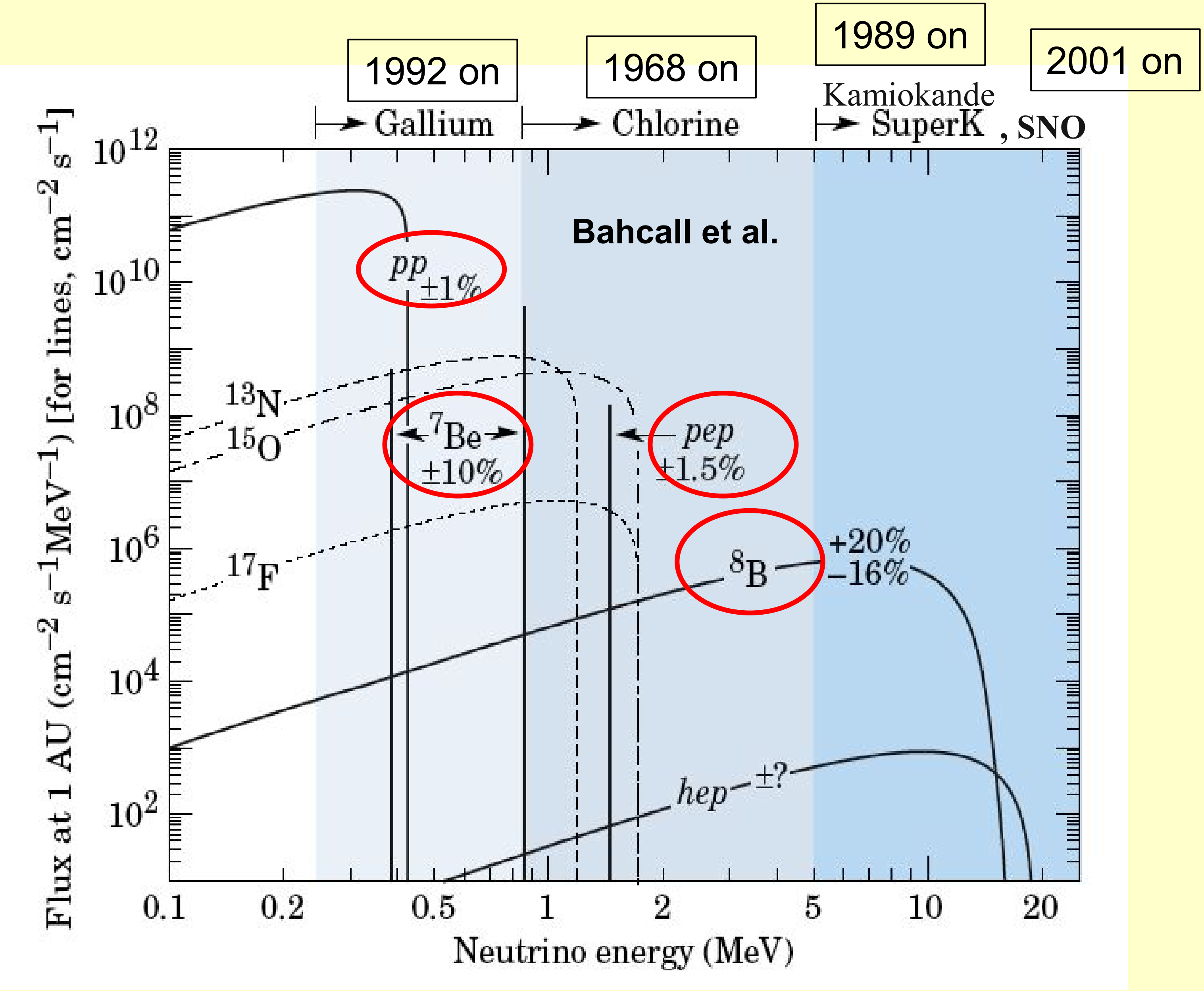
Yellow, of course!

Well, maybe not!

The yellow paint was much too radioactive

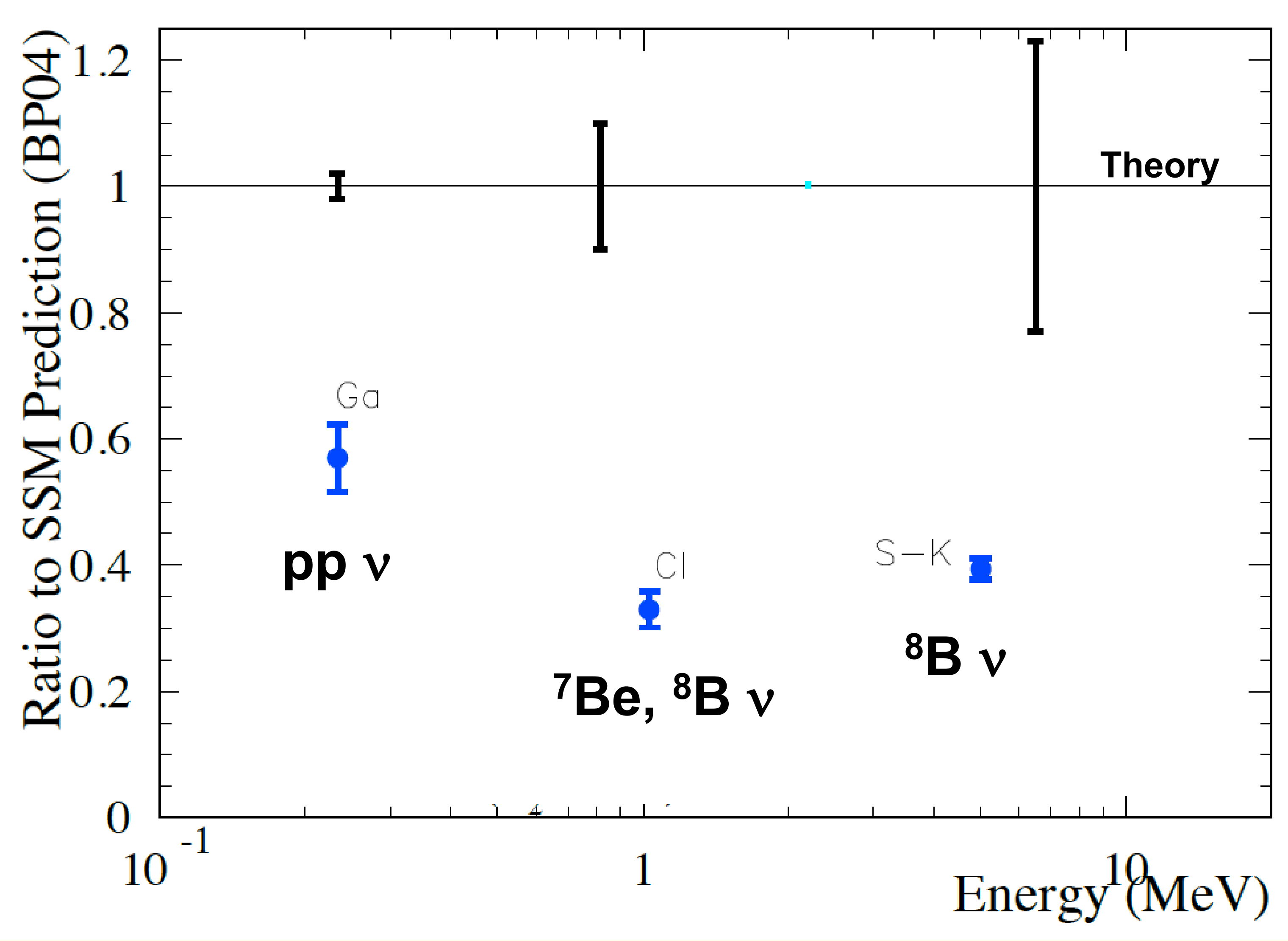
The Neutron Counters were a great success (after a lot of hard work by Hamish Robertson and his team).

Including other solar neutrino measurements

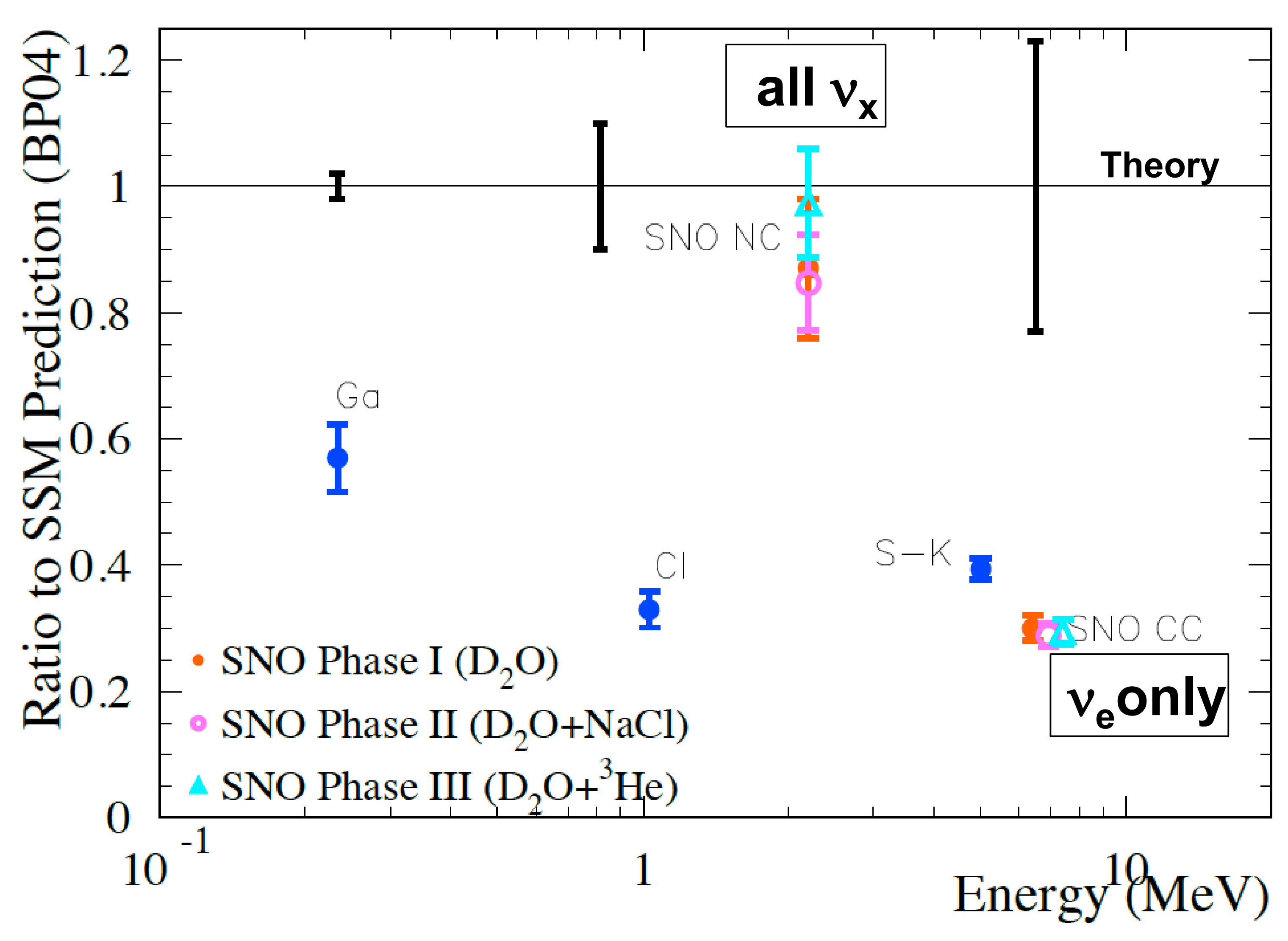


Solar Neutrino Problem

Year 2000 Experimental sensitivity: primarily or exclusively electron neutrinos



Solar Neutrino Problem Resolved



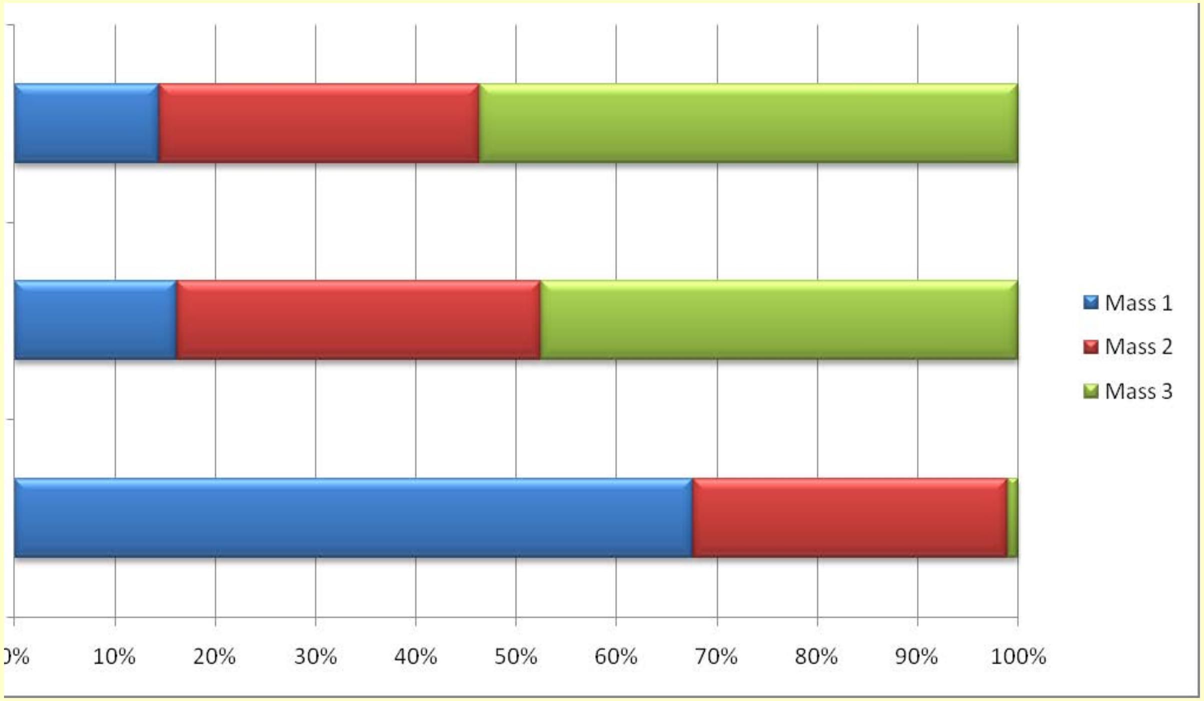
NEUTRINO OSCILLATIONS AND NEUTRINO MASS

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

Tau Neutrino

Muon Neutrino

Electron Neutrino



Quantum mechanics states

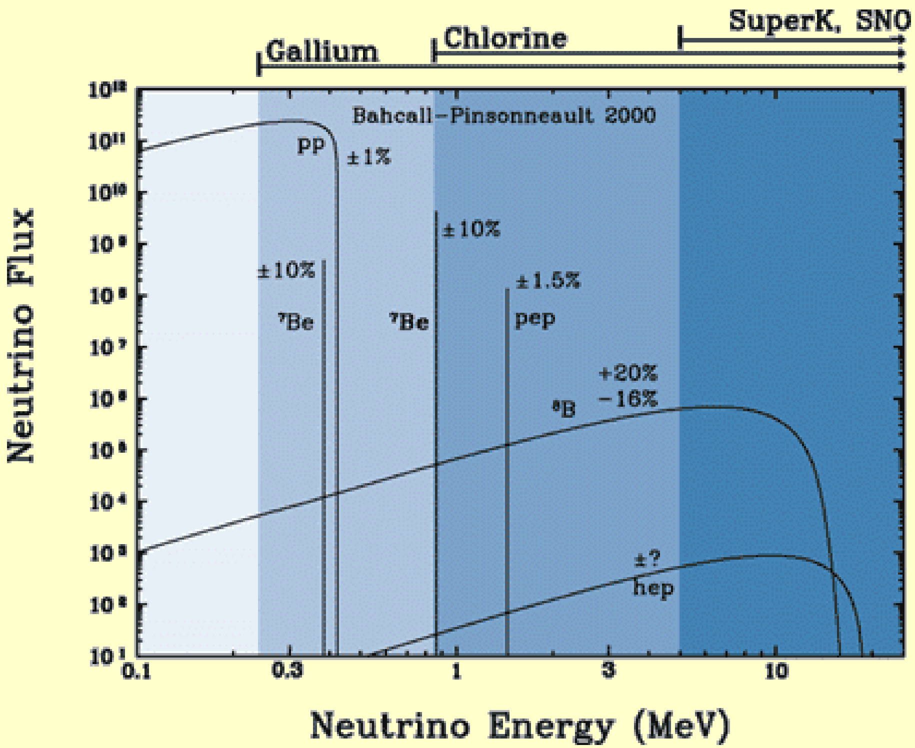
Created in a unique Flavor State

The mass fractions change as the neutrino travels

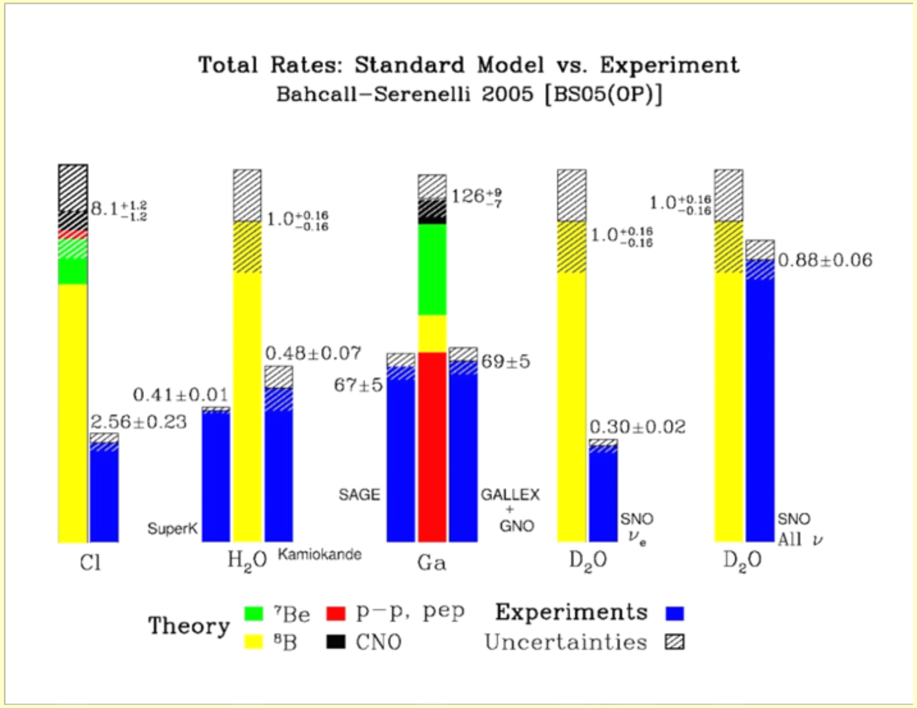
After traveling there is a finite probability to be detected as a different flavor type

Combining SNO with other solar measurements

Solar Fluxes: Bahcall et al



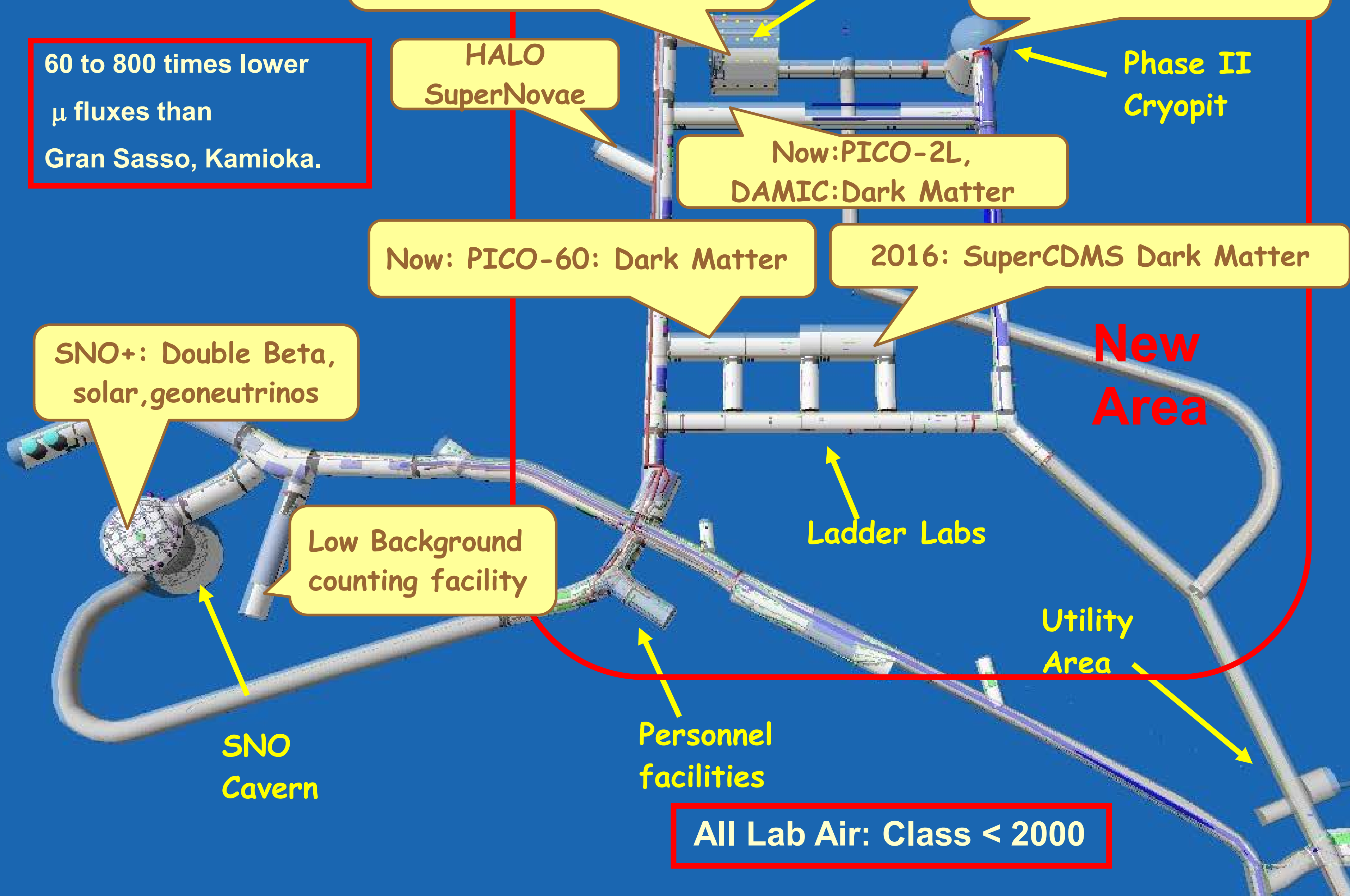
Experiment vs Solar Models



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: SN

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



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

USA:

- US Department of Energy

UK:

- Particle Physics and Astronomy Research Council

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

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)

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