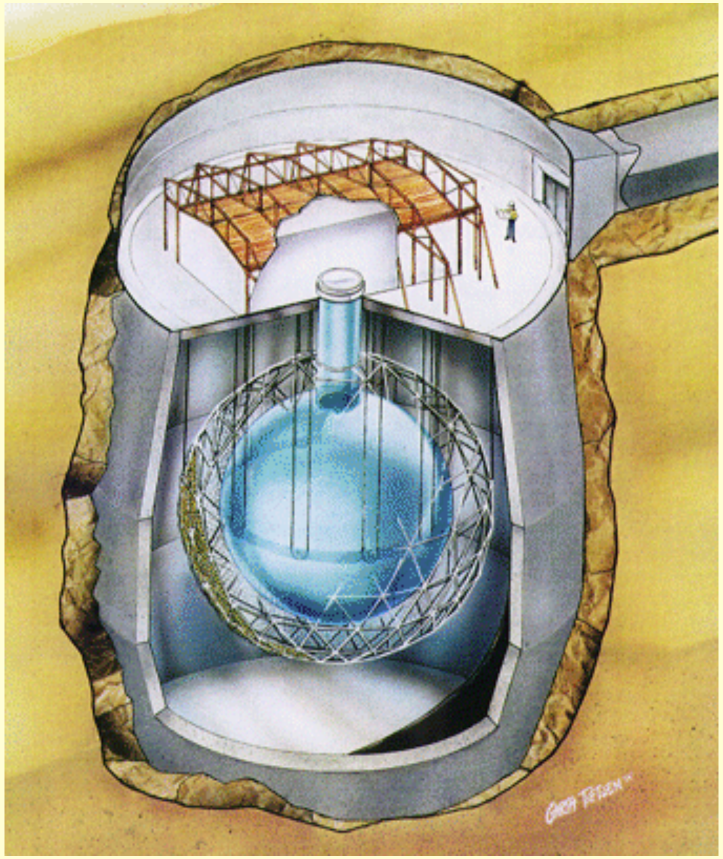
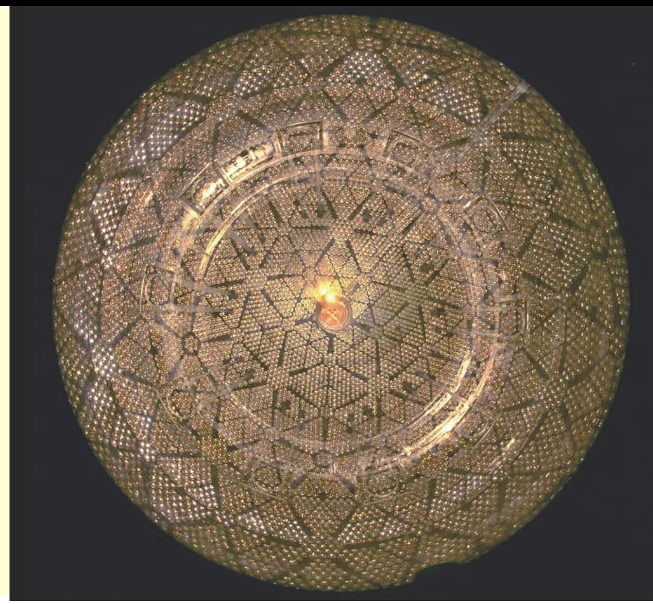
The Sudbury Neutrino Observatory: Observation of Flavor Change for Solar Neutrinos.



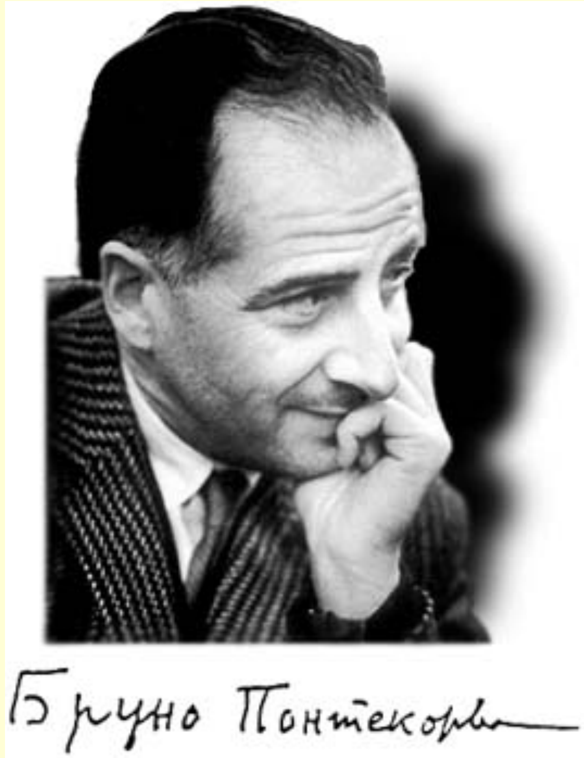


Art McDonald,
Gray Chair in Particle Astrophysics, Emeritus
Queen's University, Kingston, Ontario, Canada
For the SNO Collaboration

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

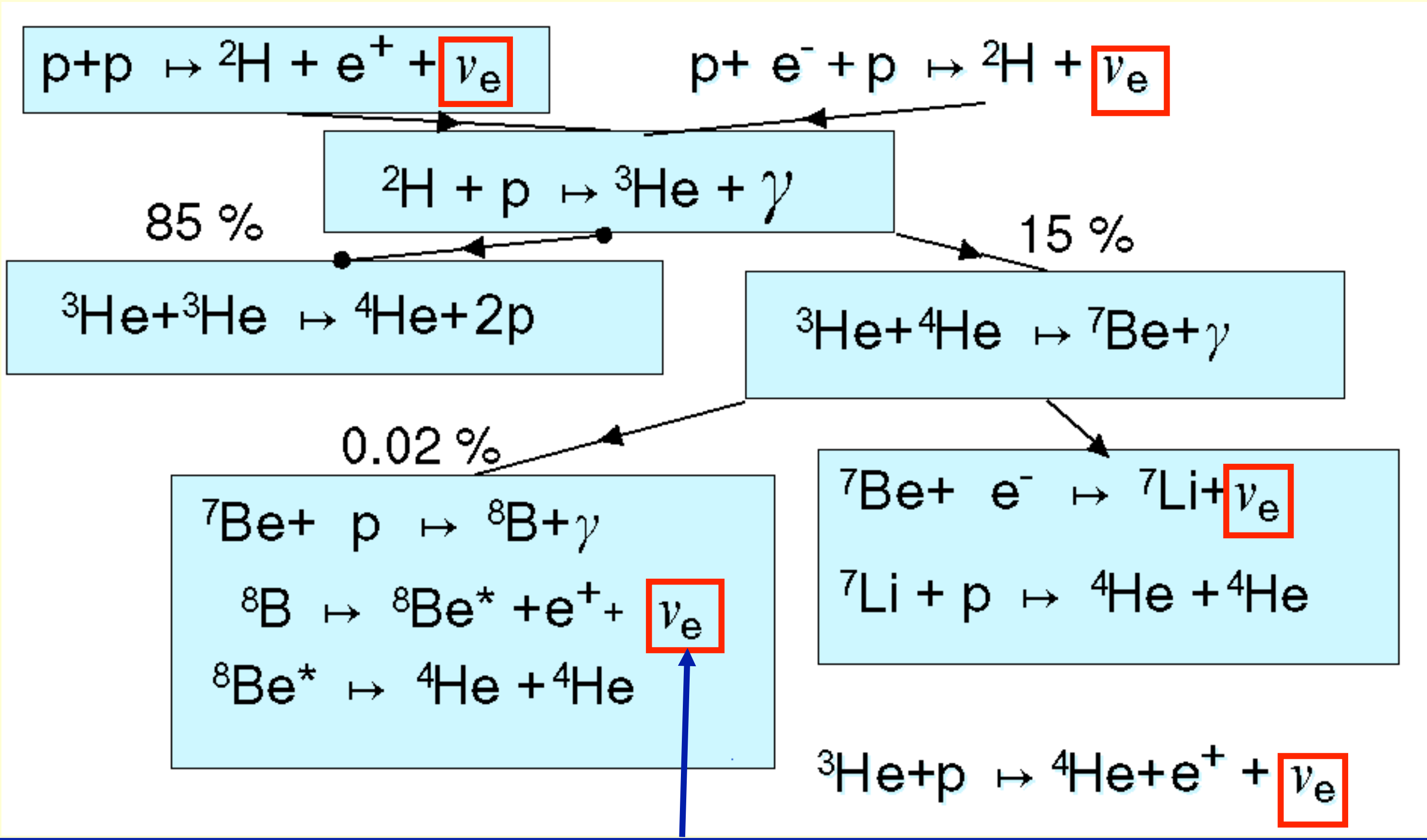
1968: Davis' Measurements of electron neutrinos with Chlorine-based detector show 3 times fewer than Bahcall's calculations.

Ray Davis: Nobel Laureate 2002

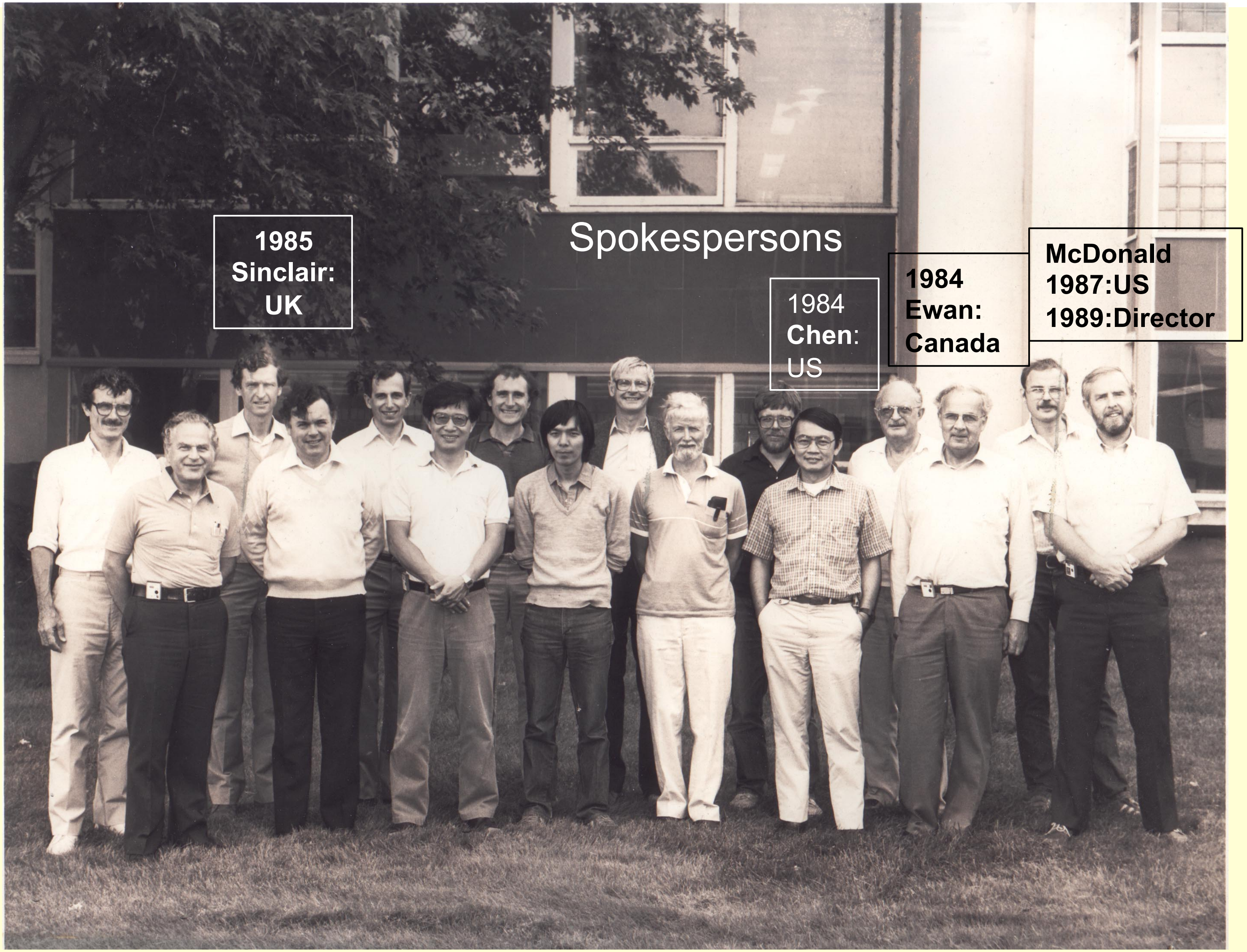


1968: Gribov and Pontecorvo suggest flavor change (oscillation) of electron neutrinos to muon neutrinos as a possible reason.

SOLAR FUSION CHAIN



1984: Herb 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 is created with Chen and George Ewan as Spokesmen.



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)

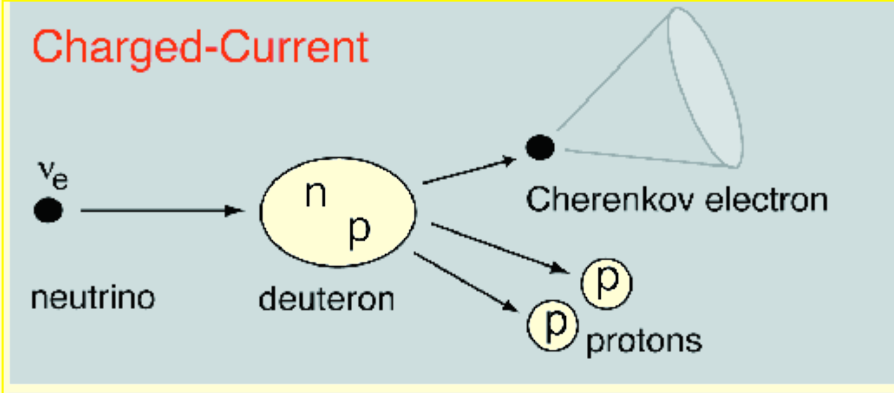
Unique Signatures in SNO (D_2O)

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

Electron Neutrinos (CC)

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

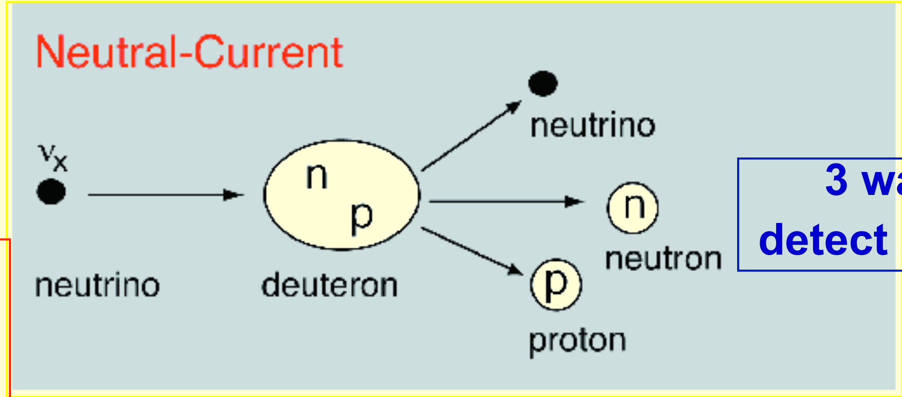
$E_{thresh} = 1.4$ MeV



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.

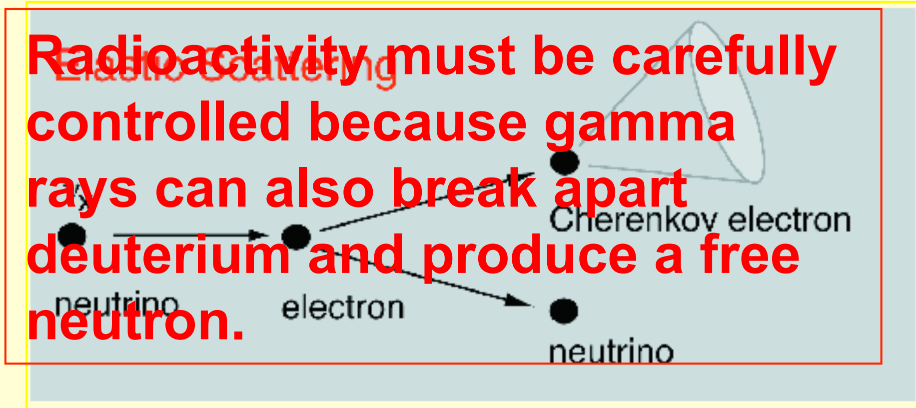
Elastic Scattering from Electrons

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

ν_x, but enhanced for ν_e x 6

10 times lower count rate

Points away from the Sun



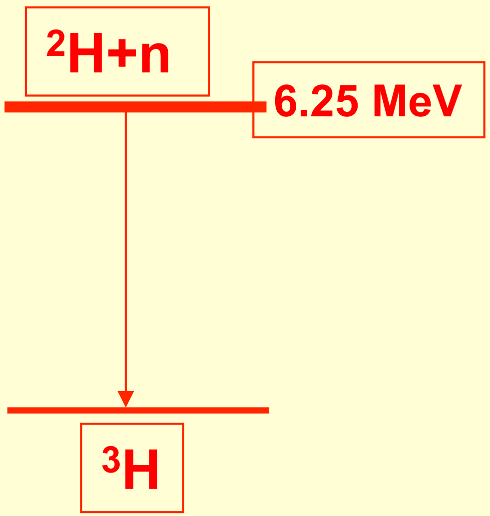
Radioactivity must be carefully controlled because gamma rays can also break apart deuterium and produce a free neutron.

3 neutron (NC) detection methods (systematically different)

Phase I (D_2O)

Nov. 99 - May 01

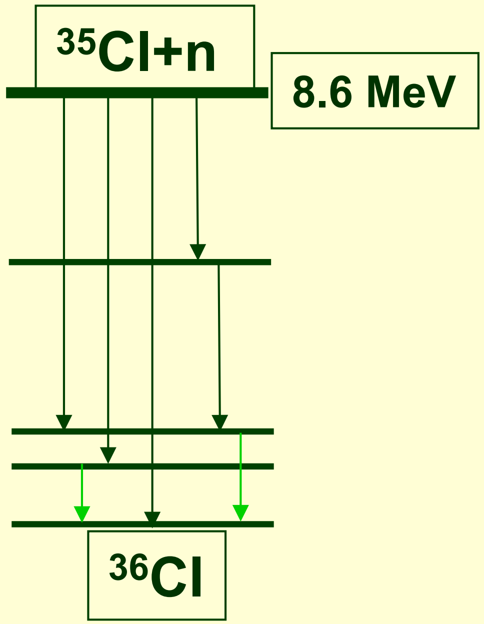
n captures on
$^2H(n, \gamma)^3H$
Effc. ~14.4%
NC and CC separation by energy, radial, and directional distributions



Phase II (salt)

July 01 - Sep. 03

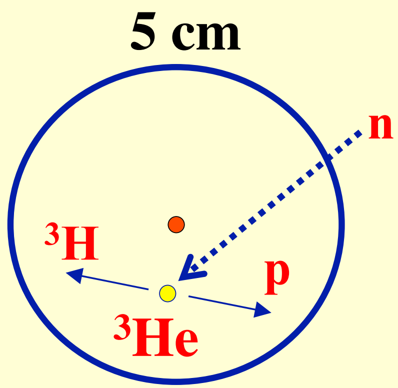
2 tonnes of NaCl
n captures on
$^{35}Cl(n, \gamma)^{36}Cl$
Effc. ~40%
NC and CC separation by event isotropy



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.

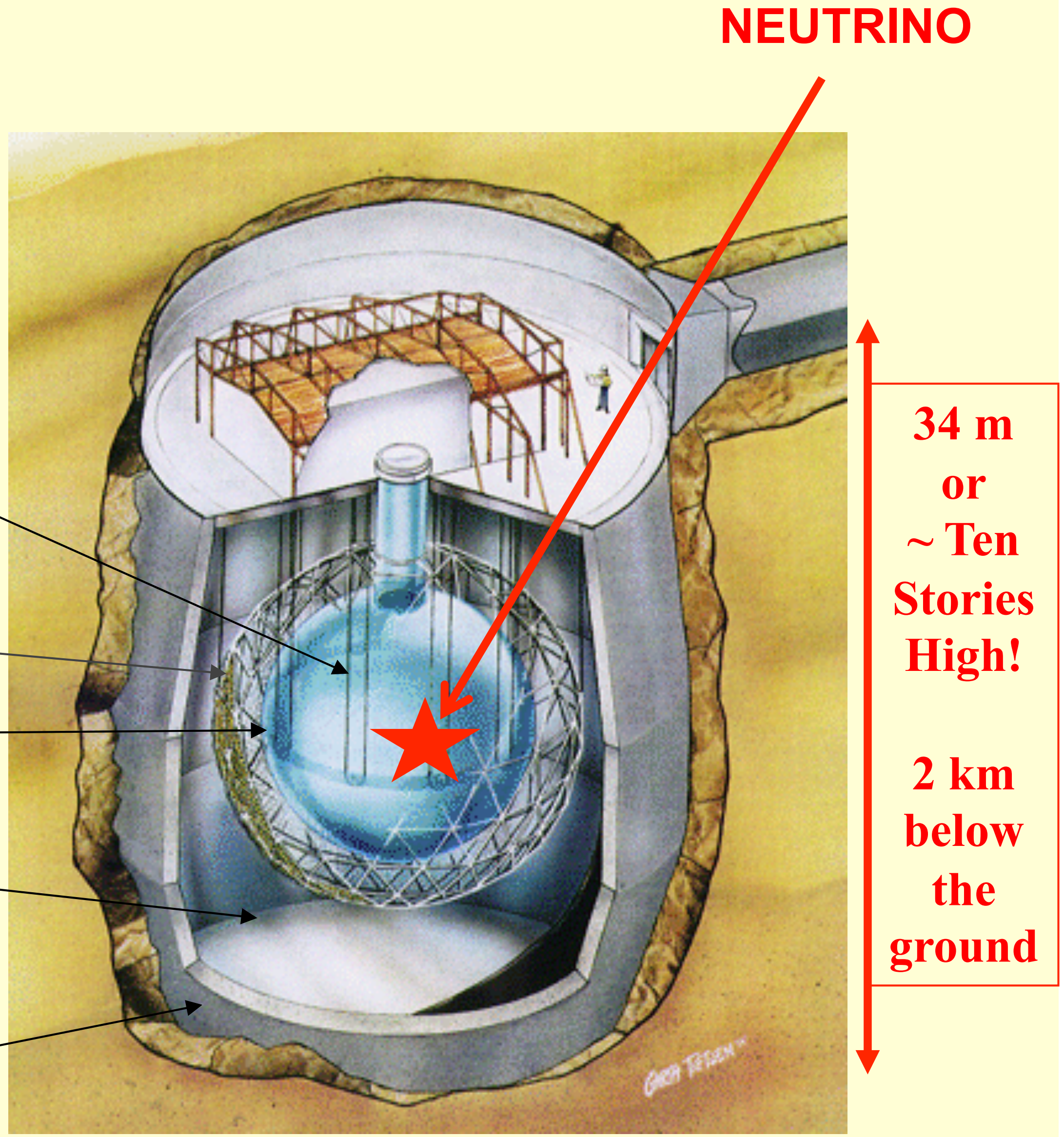
1000 tonnes of heavy water: D_2O
$ 300 million on Loan for $1.00

9500 light sensors

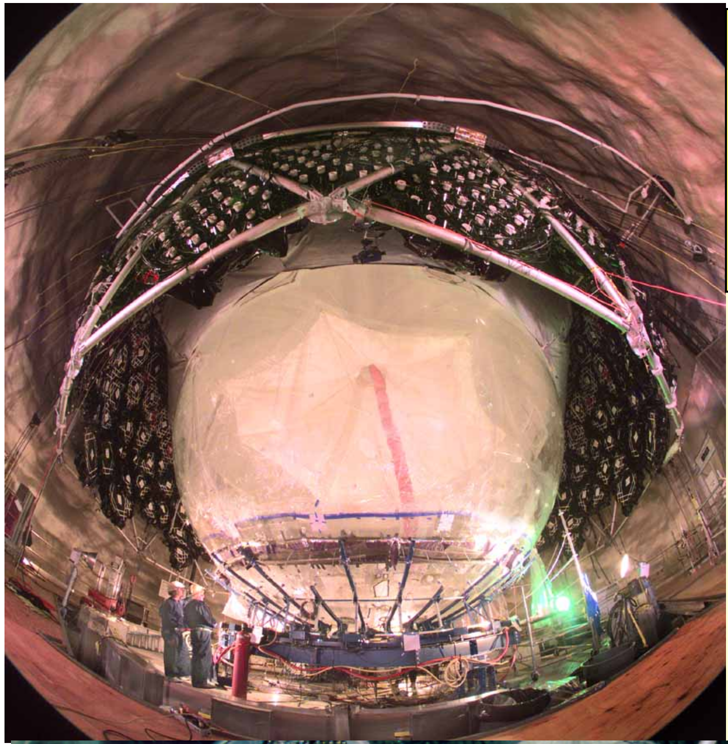
12 m Diameter Acrylic Container

Ultra-pure Water: H_2O.

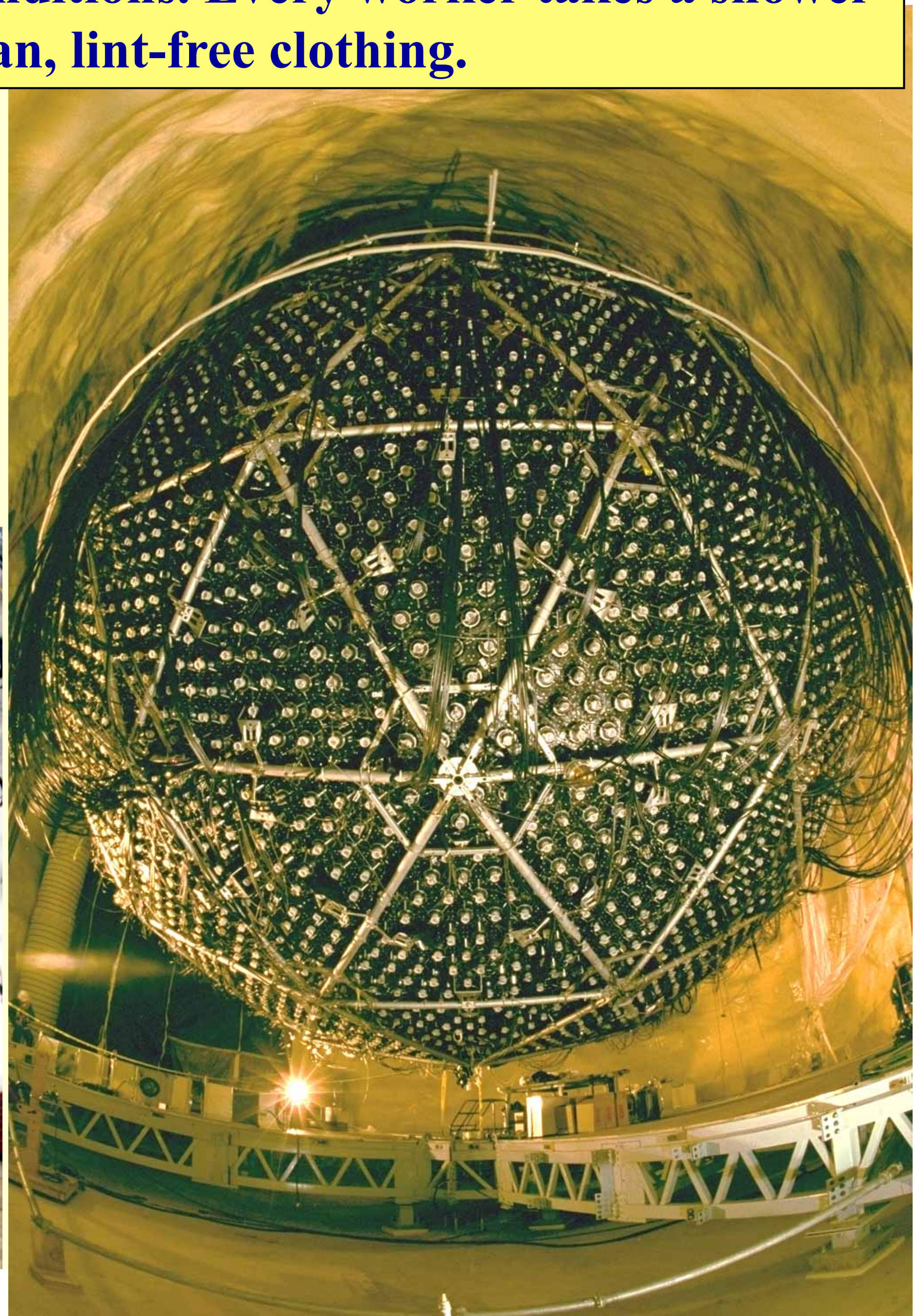
Urylon Liner and Radon Seal



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.



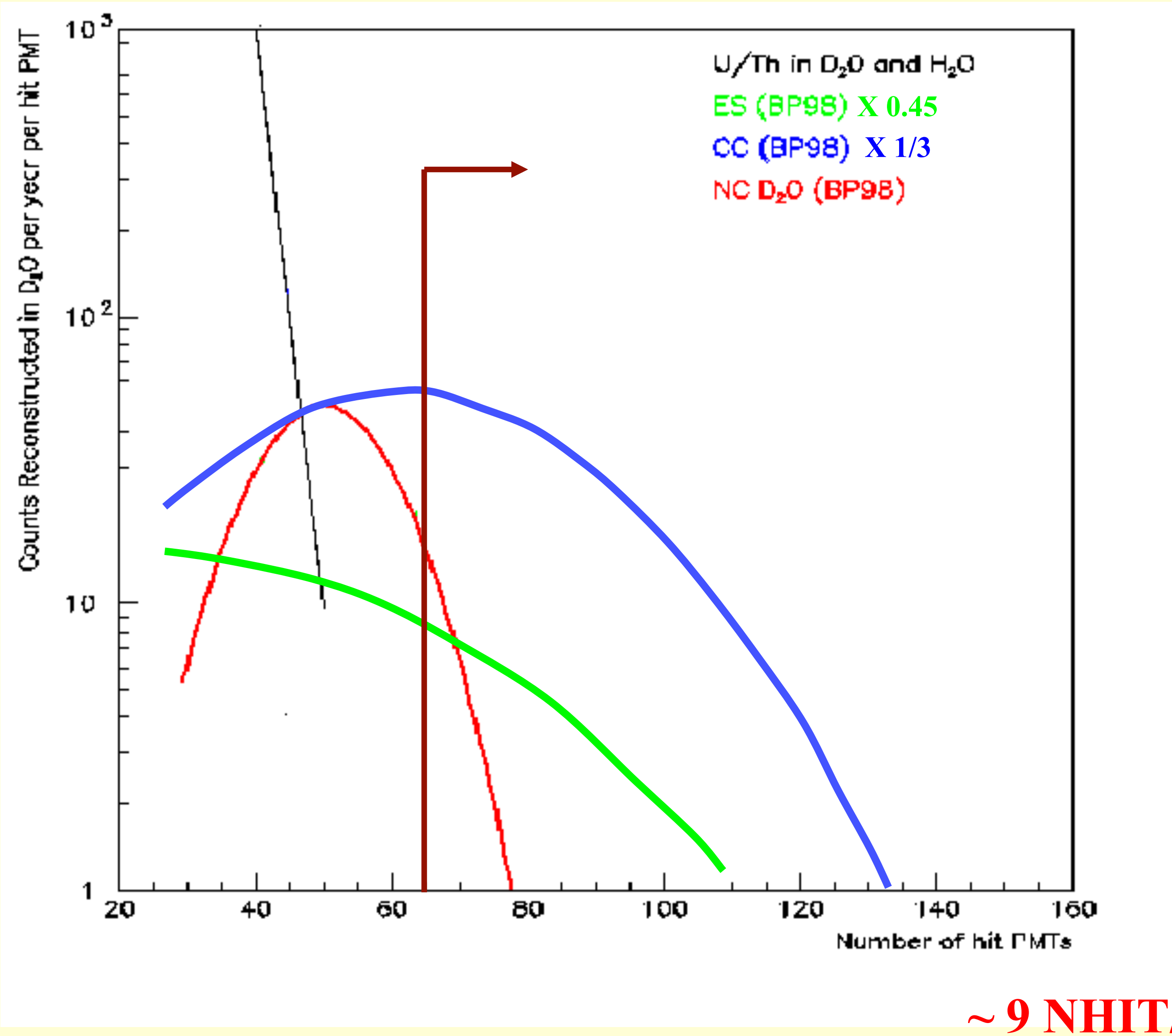
70,000 showers during the course of the SNO project



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

Signals in SNO (Monte Carlo, Renormalized)

Pure D_2O



First Analysis:

High Threshold,

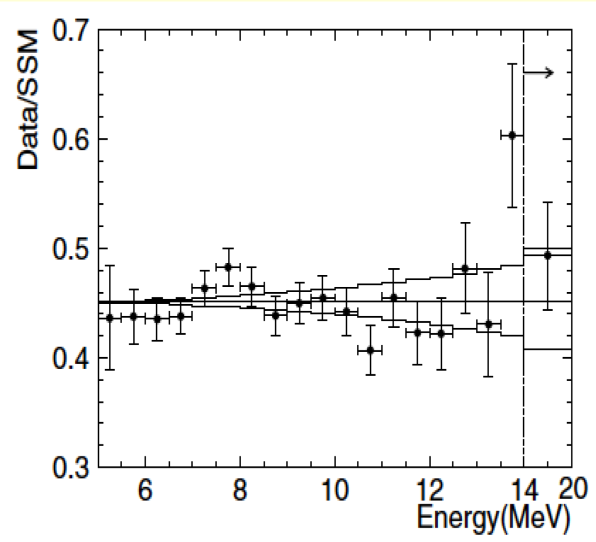
CC, ES only

Jun 2001 PRL 87, 071301

~ 9 NHIT/MEV

As of 2001, beautiful solar data from SuperKamiokande but no indication of energy distortion or day/night effect.

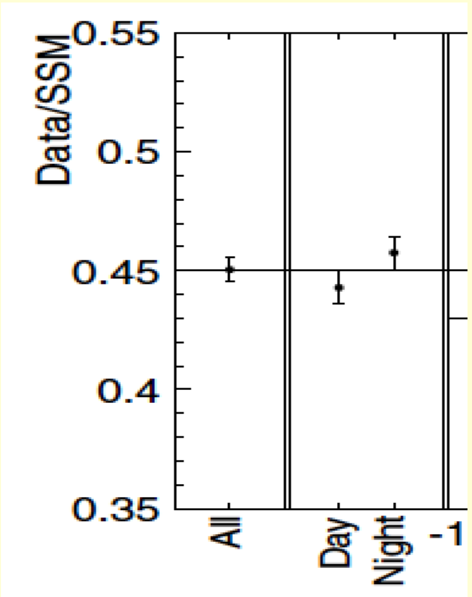
The first SNO paper in 2001 measures the CC reaction accurately enough to show a 3.3 σ difference with the SK elastic scattering flux that has a ~15% sensitivity to neutral current events.

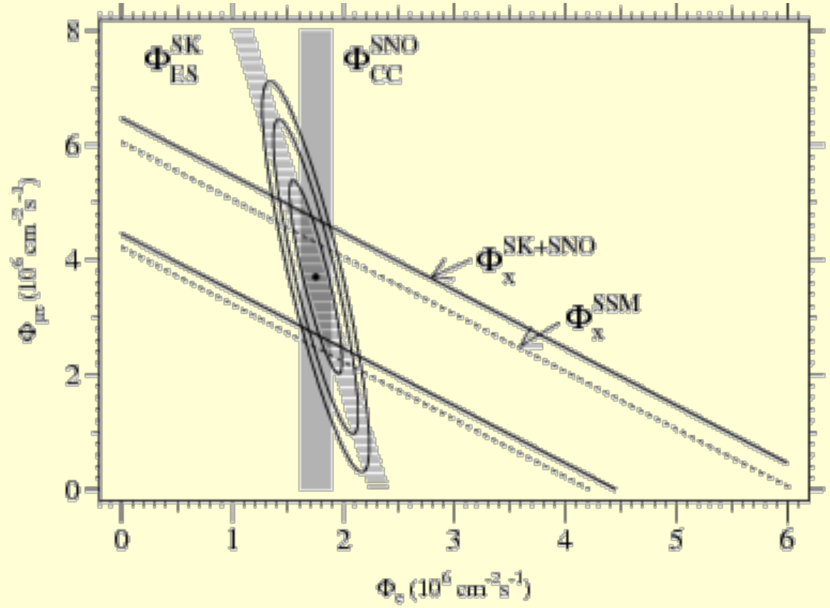


$$\phi_{\rm SNO}^{\rm CC}(\nu_e) = 1.75 \pm 0.07\ ({\rm stat.})^{+0.12}_{-0.11}\ ({\rm sys.}) \pm 0.05\ ({\rm theor.}) \times 10^6\ {\rm cm}^{-2}{\rm s}^{-1}$$

$$\phi_{\rm SK}^{\rm ES}(\nu_x) = 2.32 \pm 0.03\ ({\rm stat.})^{+0.08}_{-0.07}\ ({\rm sys.}) \times 10^6\ {\rm cm}^{-2}{\rm s}^{-1}.$$

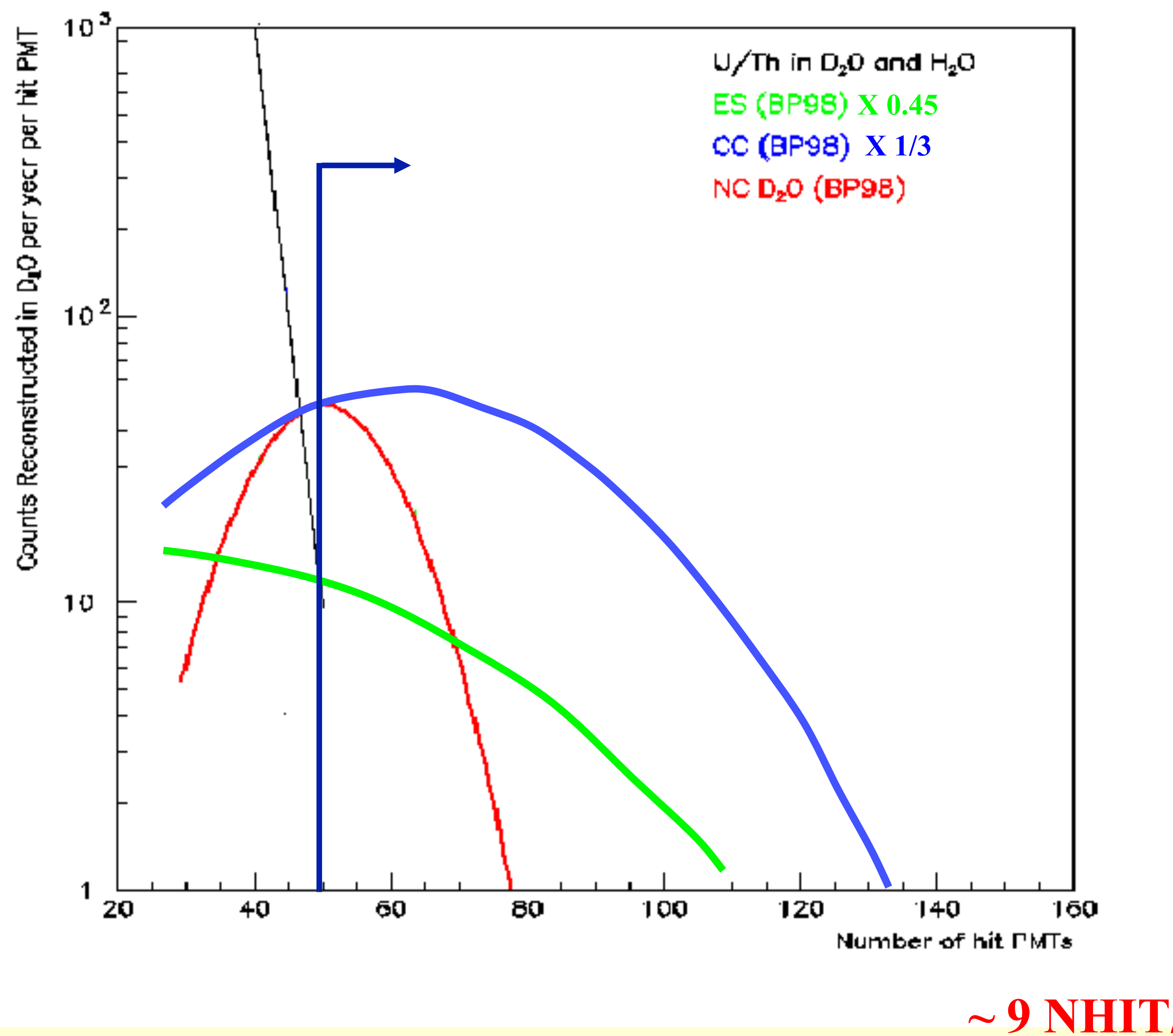
The difference between the flux $\phi^{\rm ES}(\nu_x)$ measured by Super-Kamiokande via the ES reaction and the $\phi^{CC}(\nu_e)$ flux measured by SNO via the CC reaction is $0.57 \pm 0.17 \times 10^6\ {\rm cm}^{-2}{\rm s}^{-1}$, or 3.3σ [15].





Signals in SNO (Monte Carlo, Renormalized)

Pure D_2O



April 2002:

Further Analysis

NC/CC,

Day/Night

Nucl-ex/0204008
Nucl-ex/0204009

~ 9 NHIT/MEV

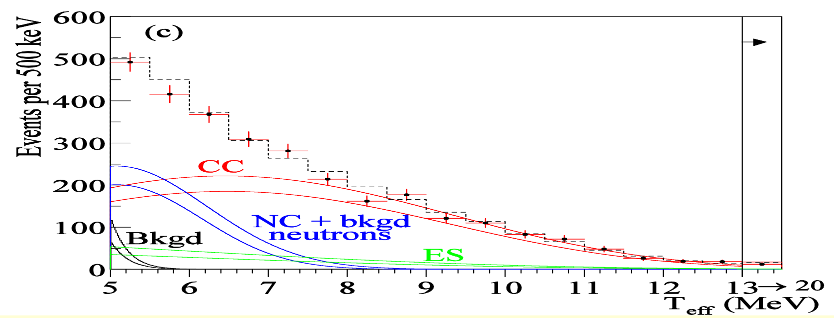
Second SNO paper, April 2002

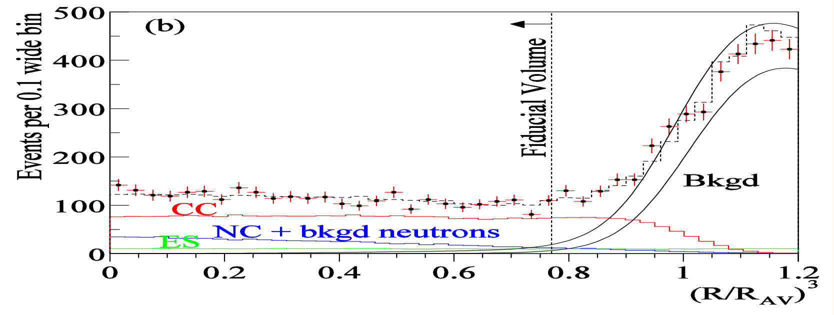
Hypothesis test of no flavor change: assume no MSW distortion of CC, do fit and use NC and CC rates to extract electron neutrino and other neutrino flux ($\times 10^{-6}$ cm^{-2} s^{-1})

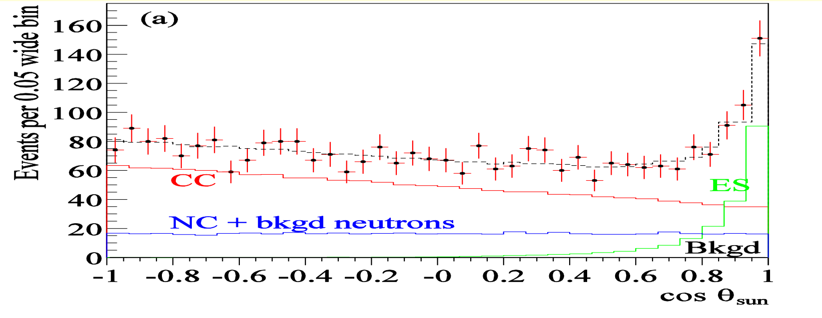
$$\phi_e = 1.76^{+0.05}_{-0.05}(\text{stat.})^{+0.09}_{-0.09}\ (\text{syst.})$$

$$\phi_{\mu\tau} = 3.41^{+0.45}_{-0.45}(\text{stat.})^{+0.48}_{-0.45}\ (\text{syst.})$$

5.3 σ confirmation of flavor change



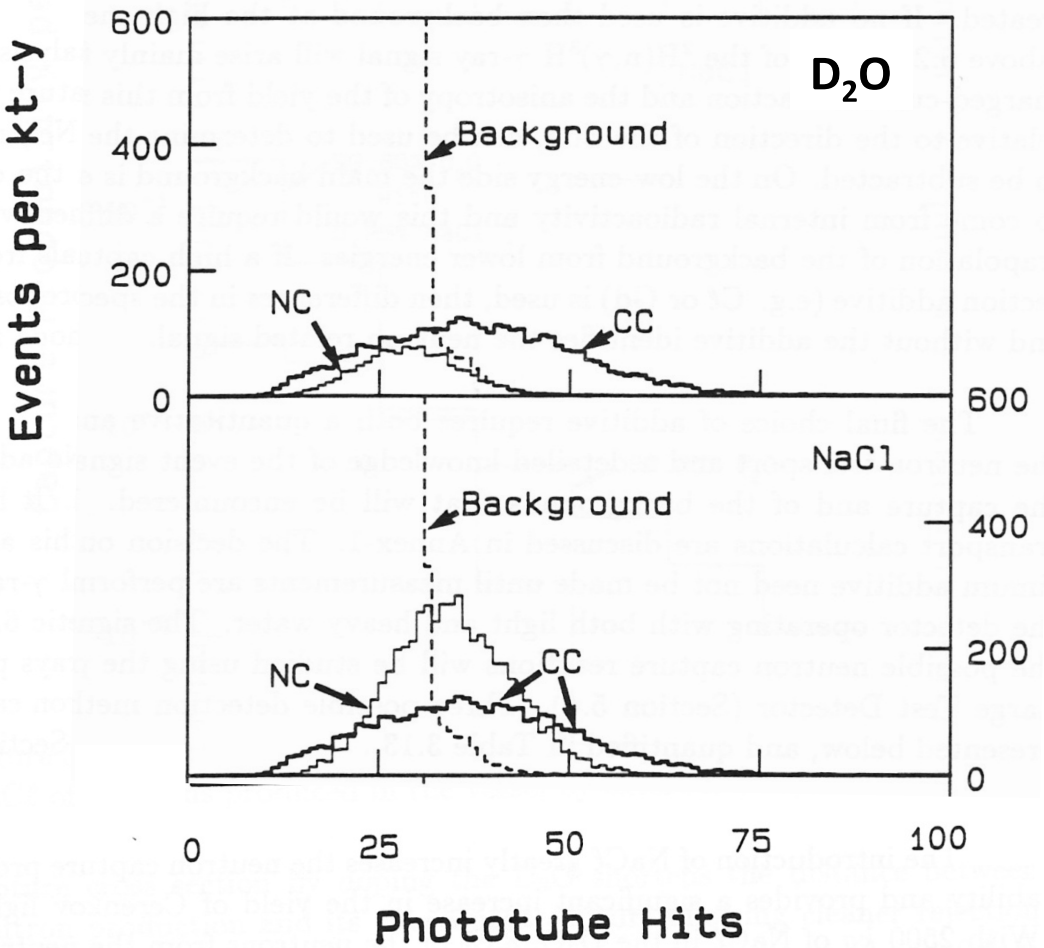




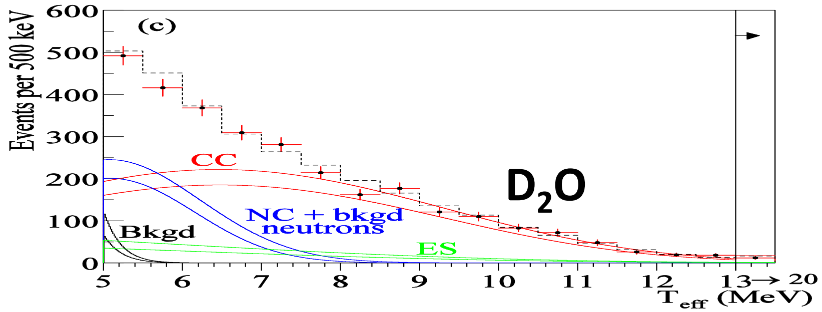
Next Phase: Add 2 tonnes of salt

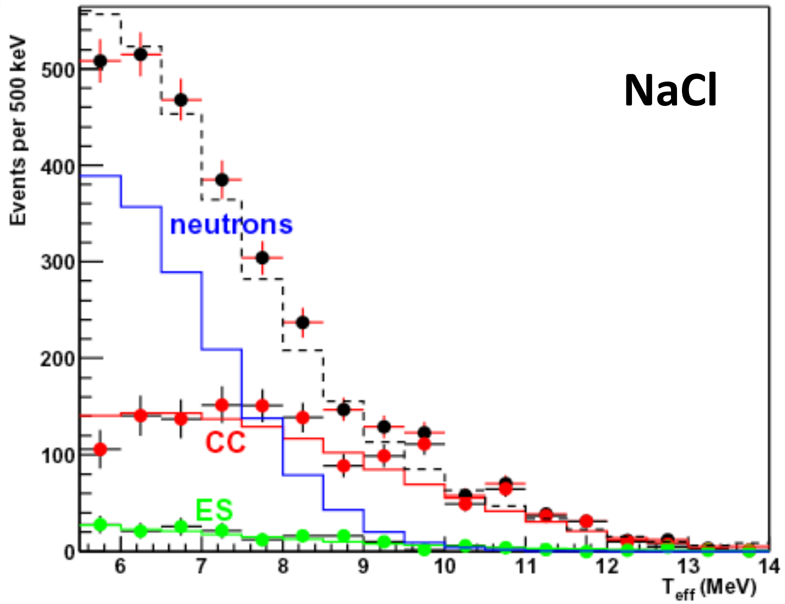
SNO "White Book"

As simulated in 1987

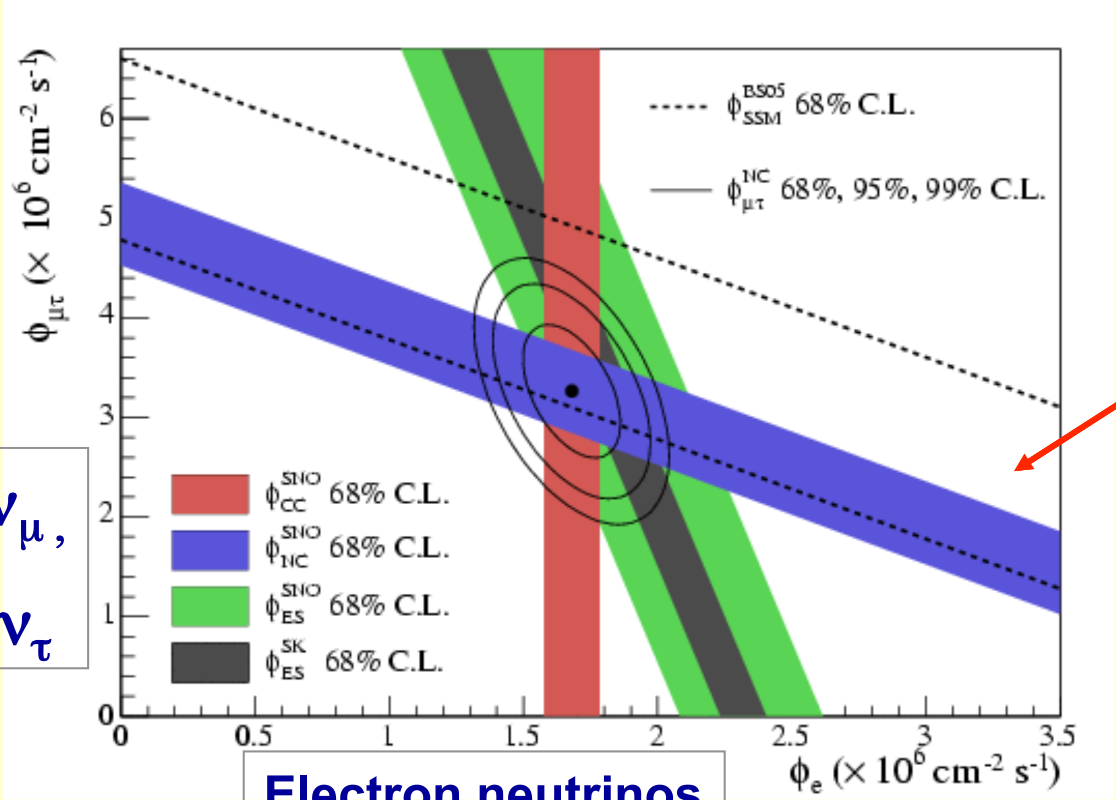


As measured 1999-2003





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 $10^6\,\text{cm}^{-2}\text{s}^{-1}$)

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

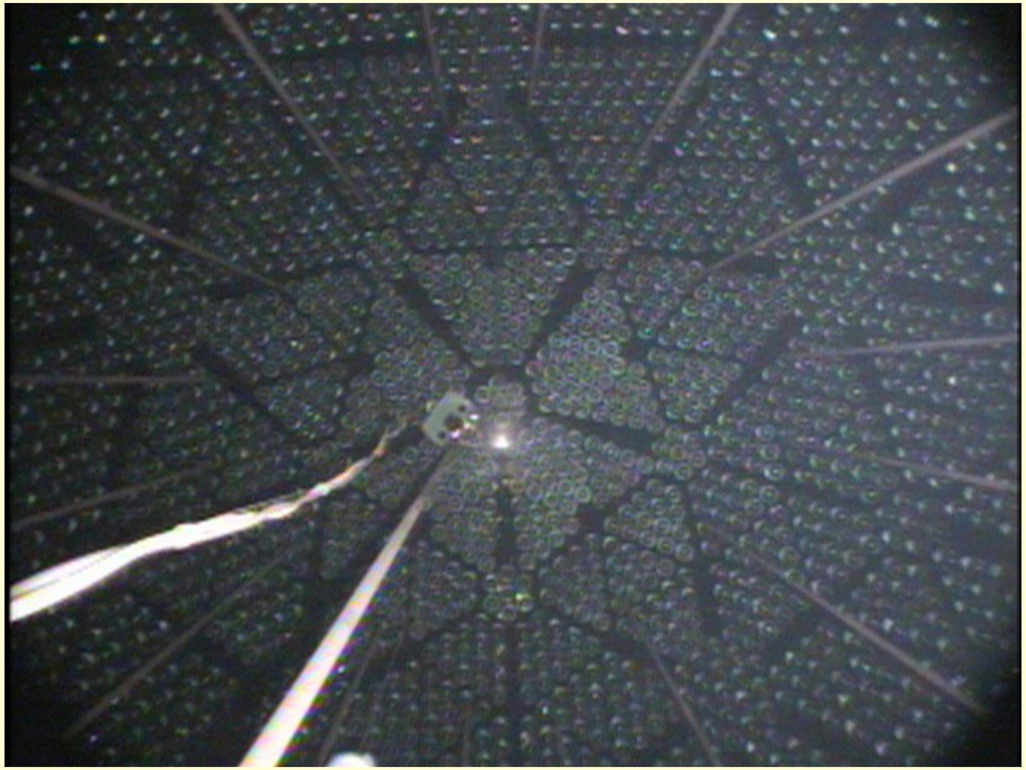
The Total Flux of Active Neutrinos is measured independently (NC) and agrees well with solar model Calculations:

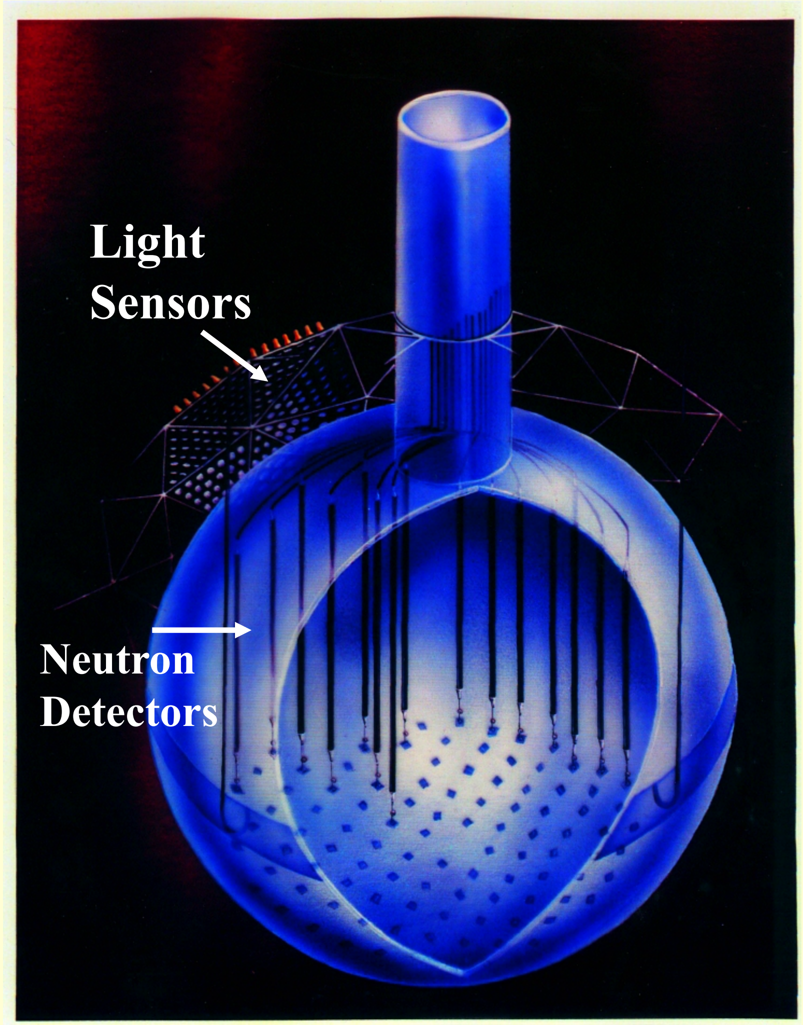
5.82 +- 1.3 (Bahcall et al),

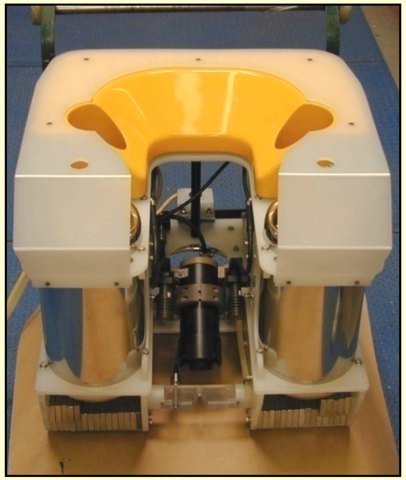
5.31 +- 0.6 (Turck-Chieze et al)

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



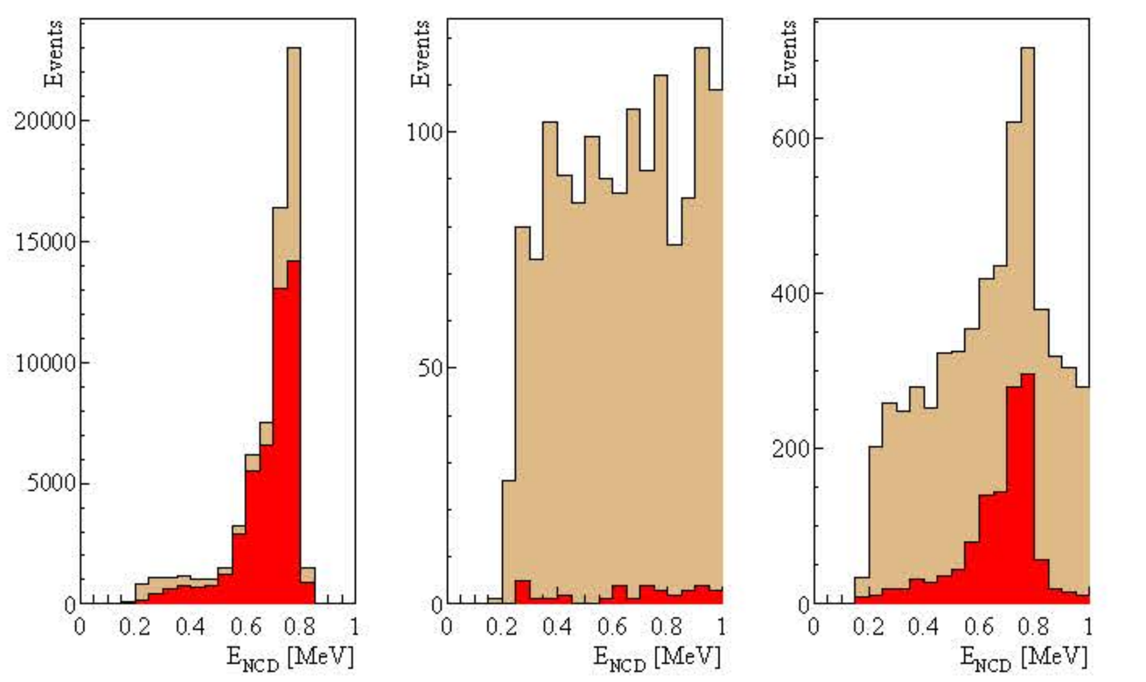




Final Complete Analysis of SNO solar data

The SNO Collaboration (B. Aharmim et al) Phys. Rev. C 88, 025501 (2013)

NCD pulse shape analysis to identify neutron events



^{3}He detectors: neutron source | **^{4}He detectors: alpha backgnd** | **^{3}He detectors: neutrino data**

$$CC/NC = 0.317 \pm 0.016(stat) \pm 0.009(syst)$$

implies flavor change at far more than 7 σ and shows that θ_{12} is non-maximal by more than 5 σ.

Full joint analysis of solar data from all three phases provides best sensitivity with all correlations, backgrounds, systematic uncertainties included.

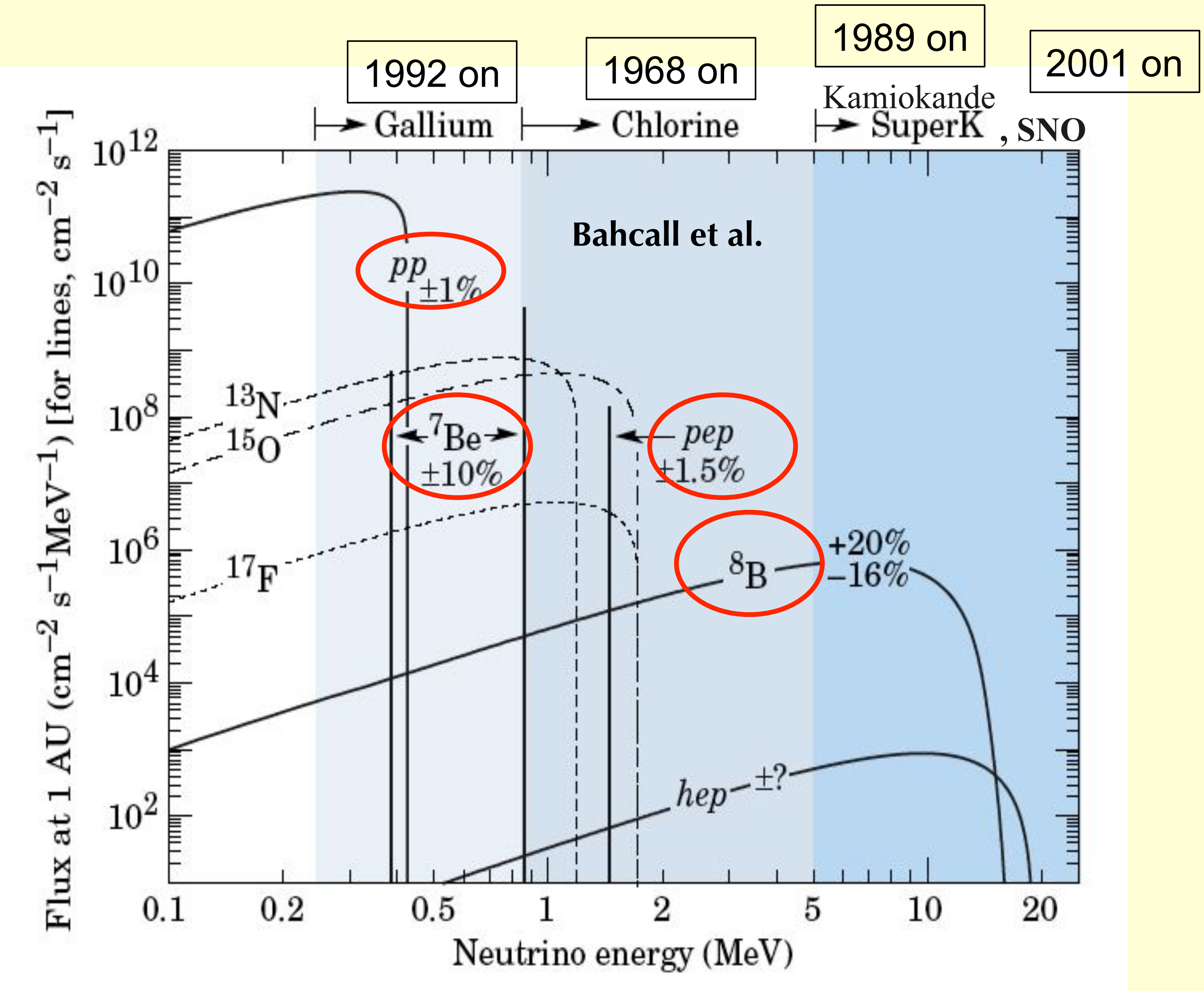
Individual results from all three phases are very consistent within uncertainties

$$\Phi_{^8B} = 5.25 \pm 0.16 \, {}^{+0.11}_{-0.13}$$

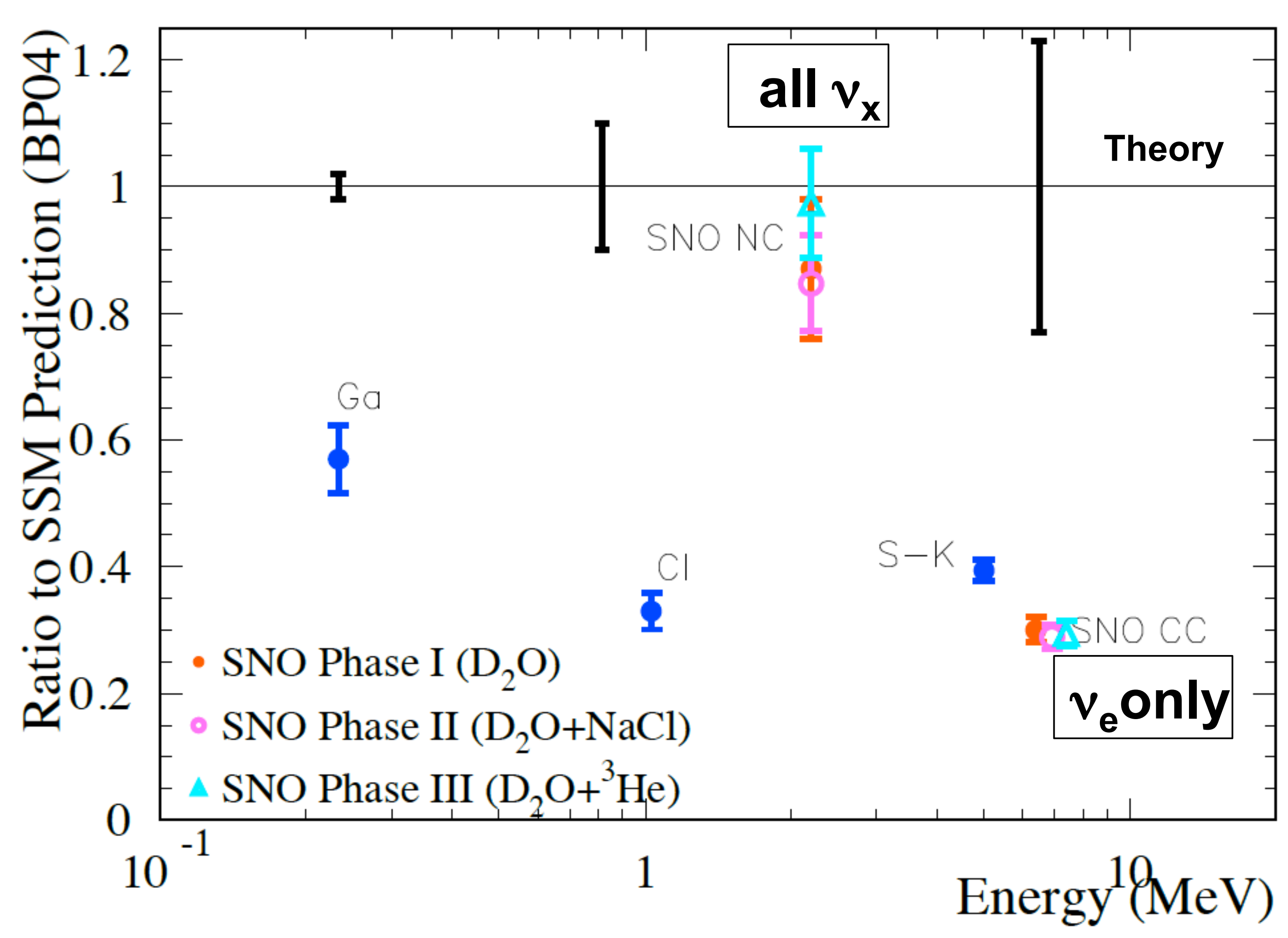
More accurate than current solar models and lying between the fluxes predicted for two values of metallicity in the sun

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

Including other solar neutrino measurements

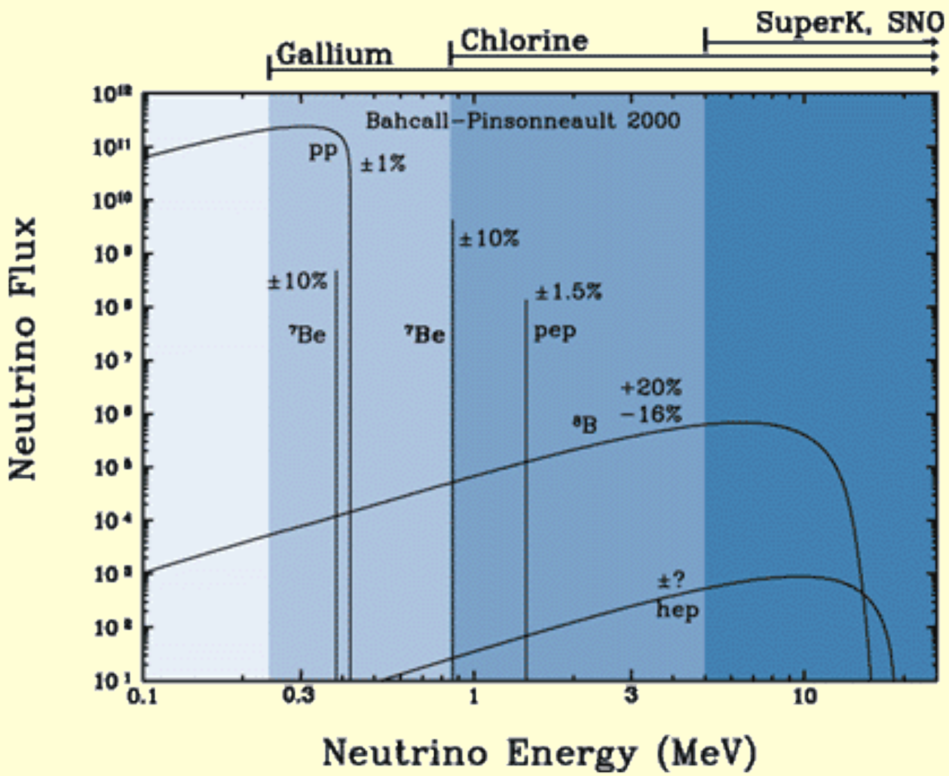


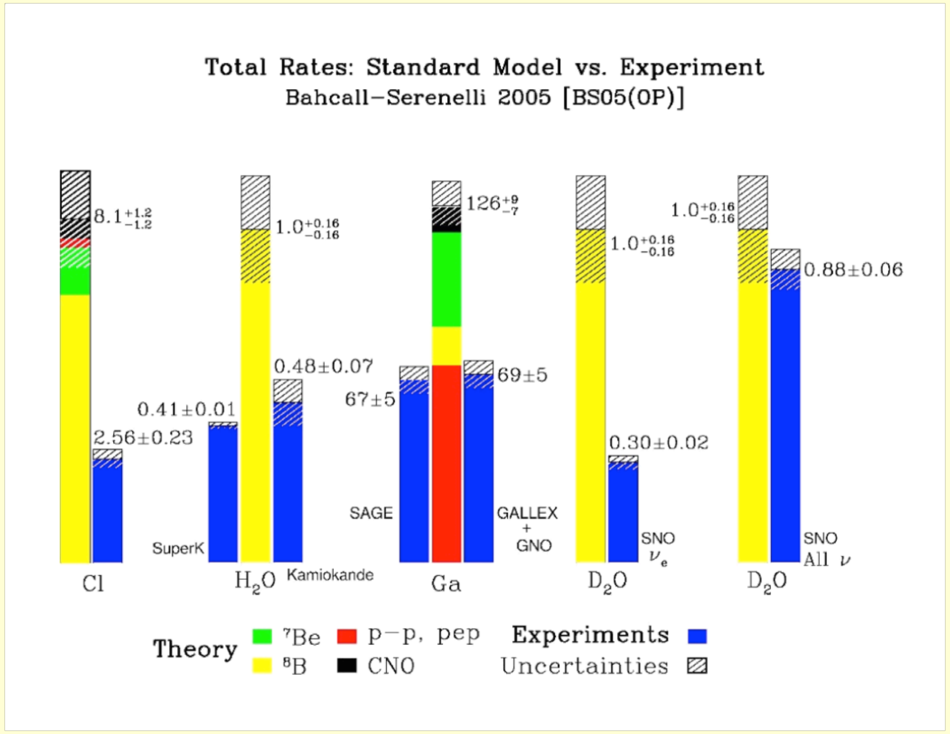
Solar Neutrino Problem Resolved



Combining SNO with other solar measurements

Solar Fluxes: Bahcall et al | **Experiment vs Solar Models**

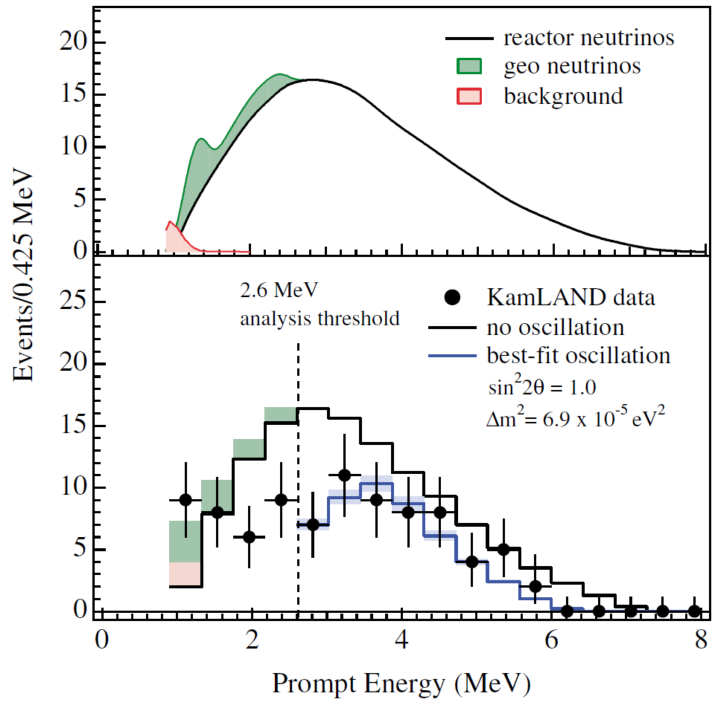


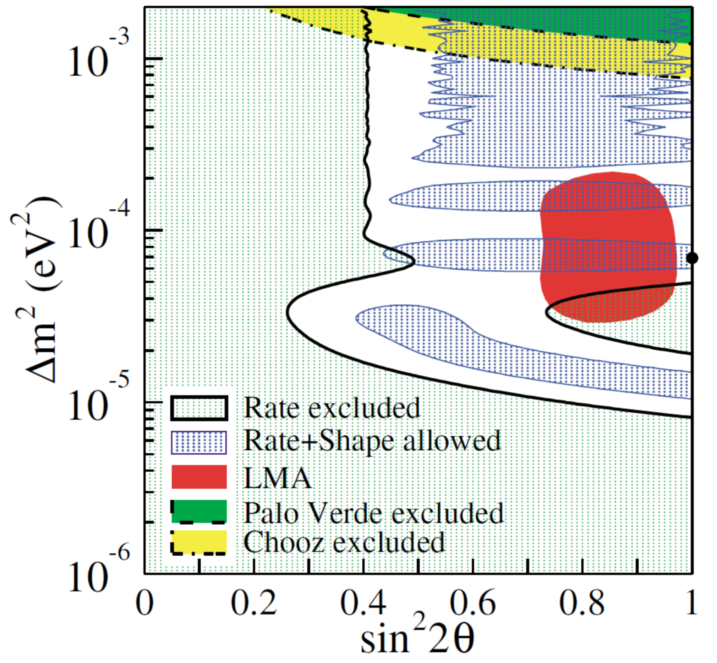


The analysis concludes that the electron neutrinos are converted by interaction with the dense electrons in the sun via the Mikheyev-Smirnov-Wolfenstein (MSW) adiabatic effect. This interaction determines that Mass 2 is greater than Mass 1 as well as determining Δm_{12}^2 and the mixing parameter θ_{12}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

The Kamland experiment provided further confirmation for Flavor Change for electron (anti-)neutrinos and overlapped the LMA region for the 1,2 parameters using anti-neutrinos from all the reactors in Japan. Excellent resolution on Δm^2_{12}

K. Eguchi et al, Physical Review Letters, 90 (2003) 021802.





Current Situation of the SK solar neutrino measurement

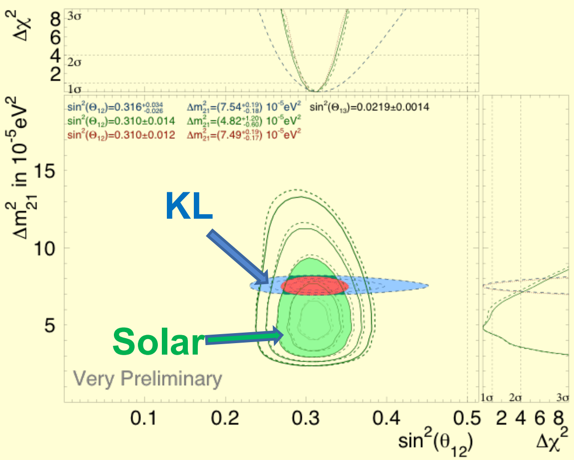
High statistics: ~94,000 solar neutrino events (till May, 18)

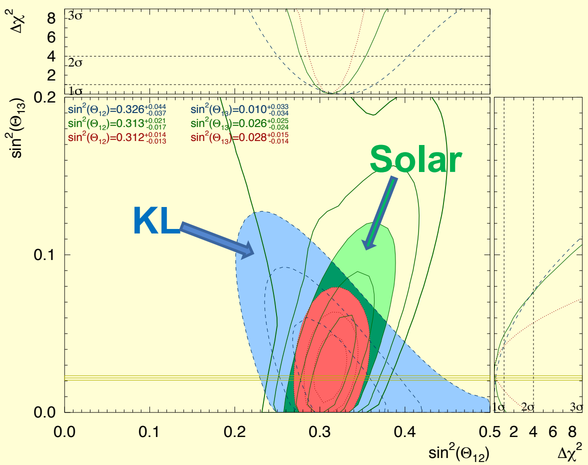
1. **Precise determination** of the oscillation parameters

   ➔ solar global analysis
   - all solar flux (SK+Ga+Cl), spectrum, time variation (seasonal, D/N)
   - SNO + SK (spectrum, time variation) [w/o solar flux calculation]

- The stress between KL and solar result is persistent

	Thre. (MeV)	# solar ν ev.	Live days
SK-I (96.04~01.07)	4.5	22,404	1496
SK-II (02.10~05.10)	6.5	7,212	791
SK-III (06.07~08.08)	4.5	8,147	548
SK-IV (08.09~18.05)	3.5	55,792	2860
Total	-----	93,555	5480





1. Constraint: $\sin\theta_{13}$=0.0219± 0.0014

Solar: $\sin^2\theta_{12}=0.310\pm0.014$, $\Delta m^2_{12}=4.82^{+1.20}_{-0.60}$

KL: $\sin^2\theta_{12}=0.316^{+0.034}_{-0.026}$, $\Delta m^2_{12}=7.54^{+0.19}_{-0.18}$

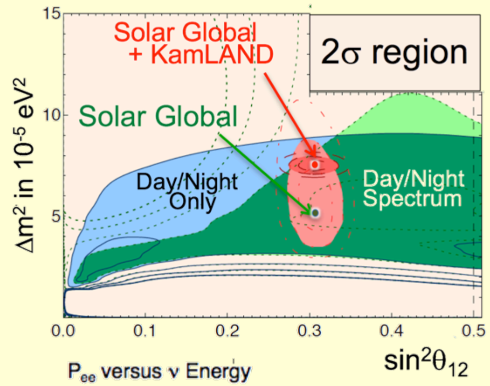
Conv: $\sin^2\theta_{12}=0.310\pm0.012$, $\Delta m^2_{12}=7.49^{+0.19}_{-0.17}$

2. no constraint on $\sin\theta_{13}$

Solar: $\sin^2\theta_{12}=0.313^{+0.021}_{-0.017}$, $\sin^2\theta_{13}=0.026^{+0.025}_{-0.024}$

KL: $\sin^2\theta_{12}=0.326^{+0.044}_{-0.037}$, $\sin^2\theta_{13}=0.010^{+0.033}_{-0.034}$

Current Situation of the SK solar neutrino measurement

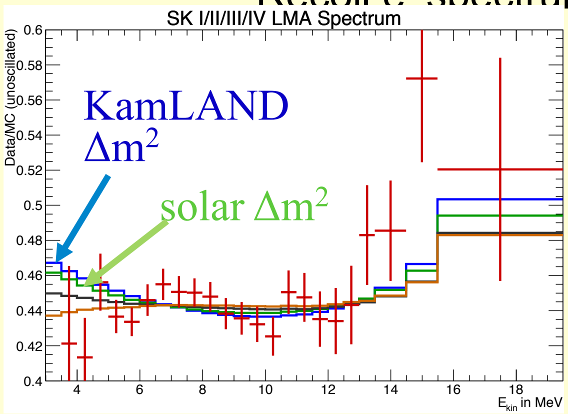


2. Day/Night

- **Matter Effect of the oscillation through the earth → 2.6 σ**
- Flux independent evidence of LMA
  - Oscillation parameter det. only by D/N:
    ⇔ consistent with the results of solar Global
- Need to increase statistics

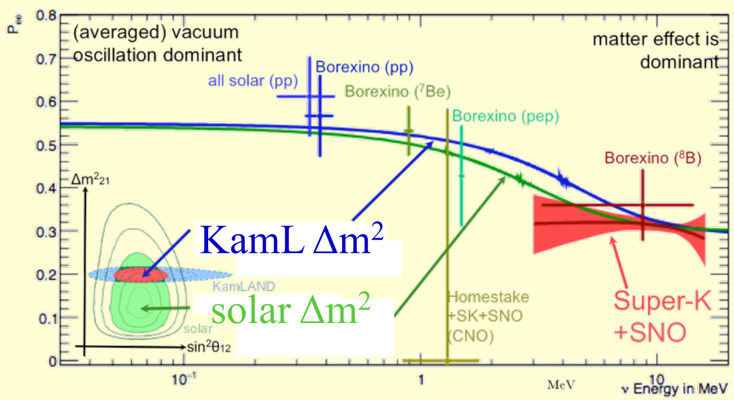
3. Upturn

- Recoil e⁻ spectrum using all the data from SK-I~IV (5480 days)



Blue line: KamLAND Δm^2_{21}
Green line: solar Δm^2_{21}

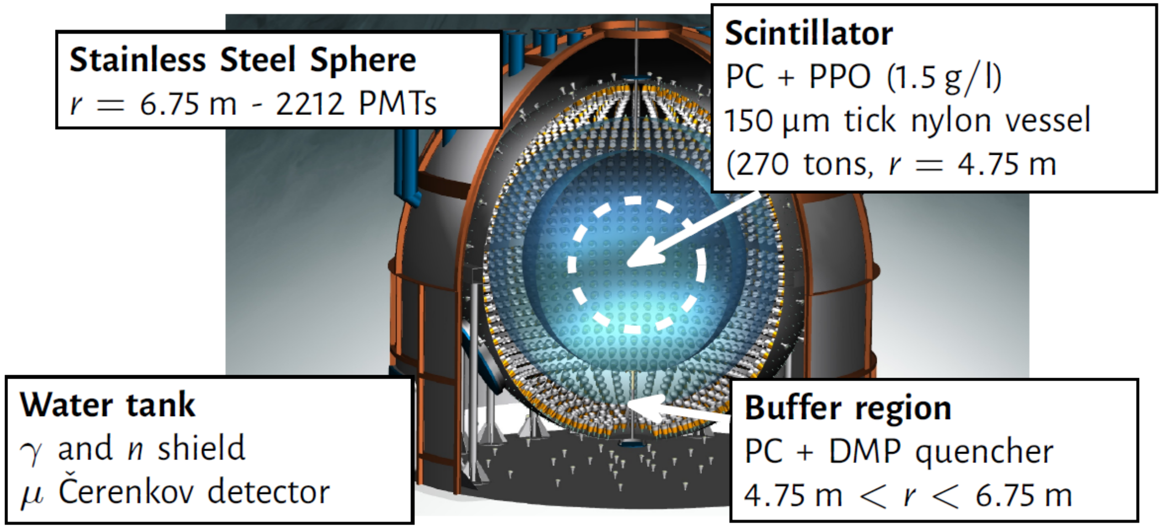
- data: consistent with solar best fit Δm^2 within 1σ, but ~2σ for the KamLAND measurement
- Need to lower the energy threshold
- Achieved 3.5 MeV (K.E.) so far
  → next goal: 3.0 MeV

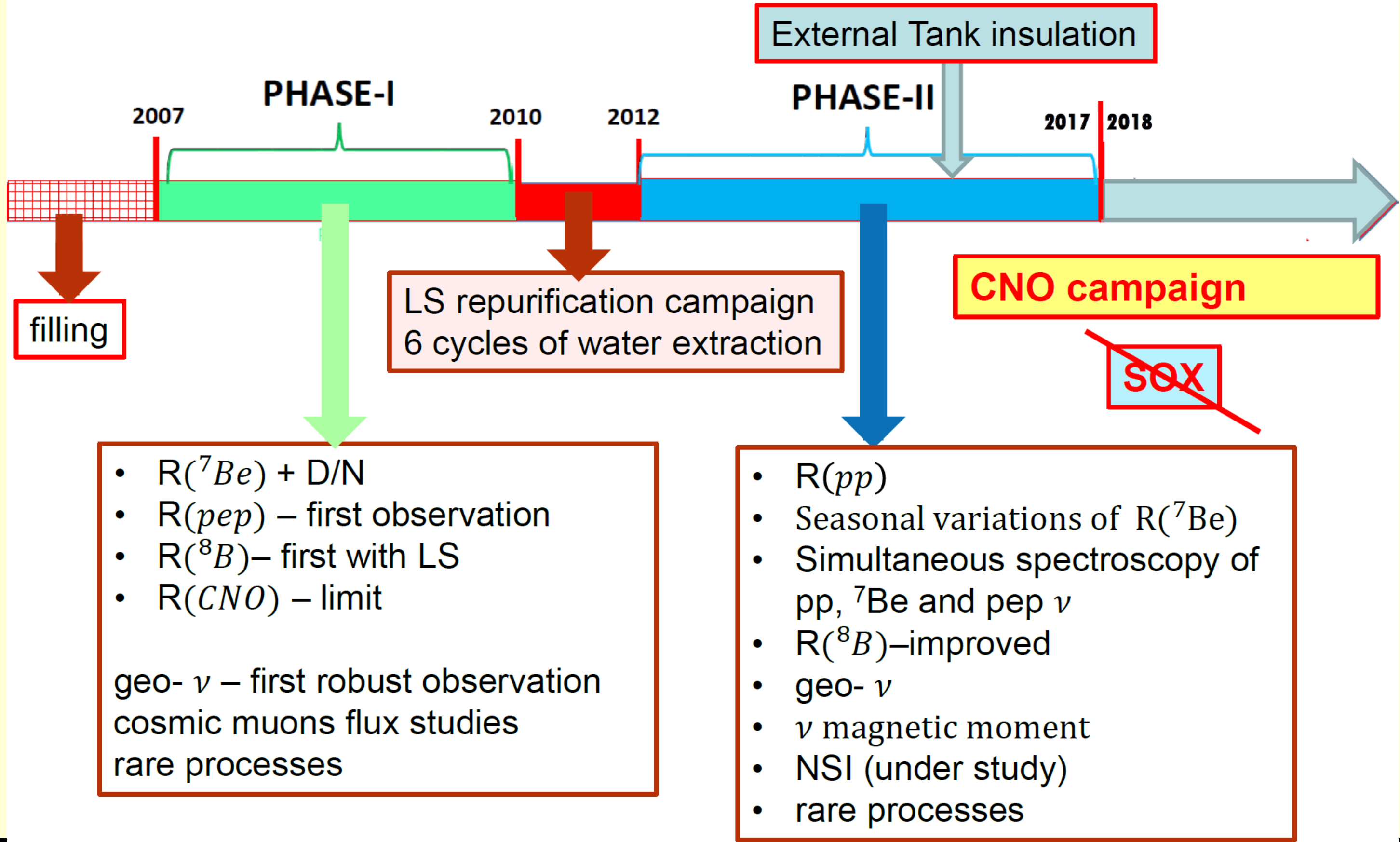


SK now shut down to install Gd for relic supernova neutrino detection.

Borexino is an **ultrapure liquid scintillator** experiment installed at the Gran Sasso National Laboratories of the Italian National Institute of Nuclear Physics

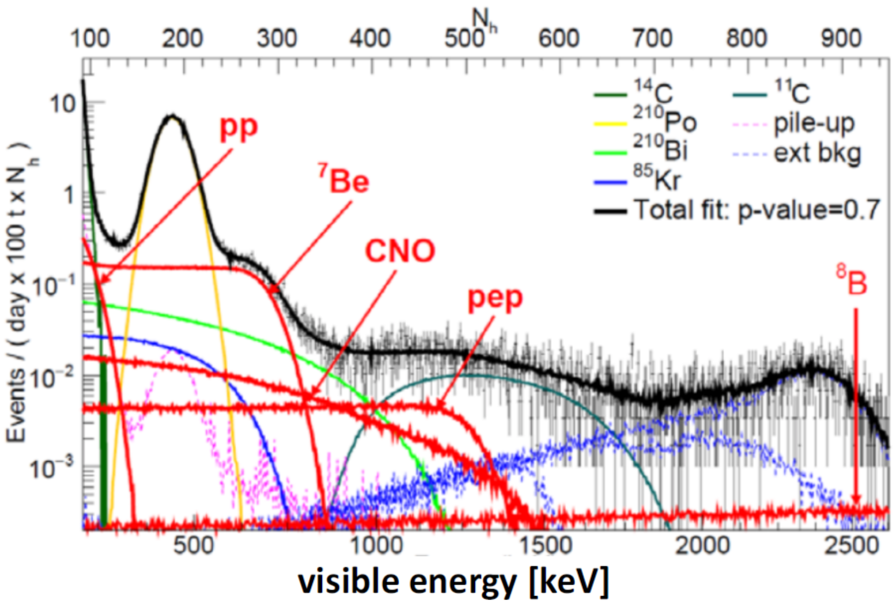
↑ 1400 m of rock ↑



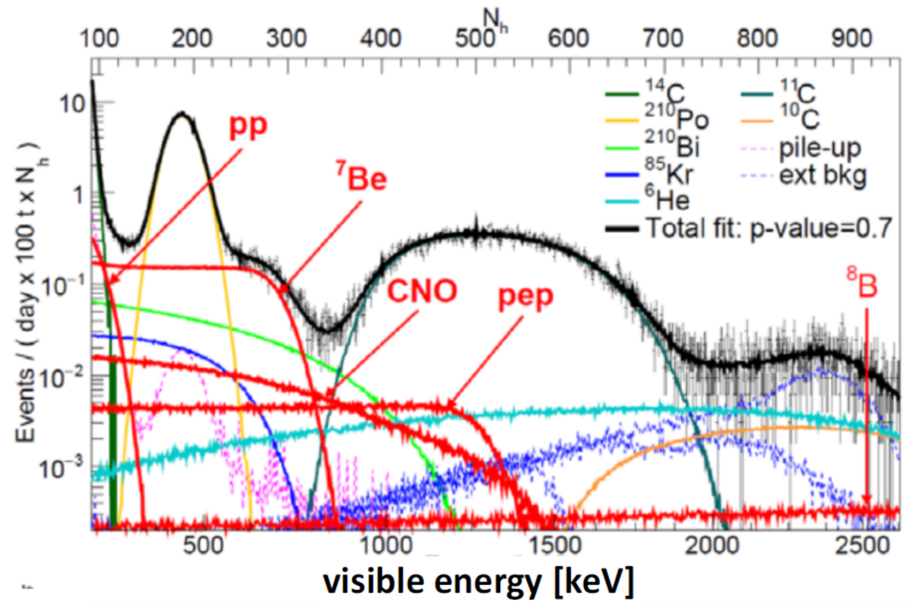


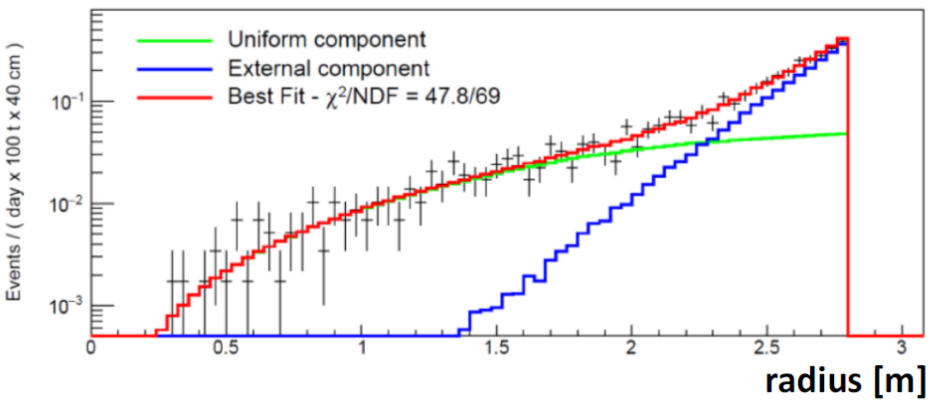
Multivariate fit example

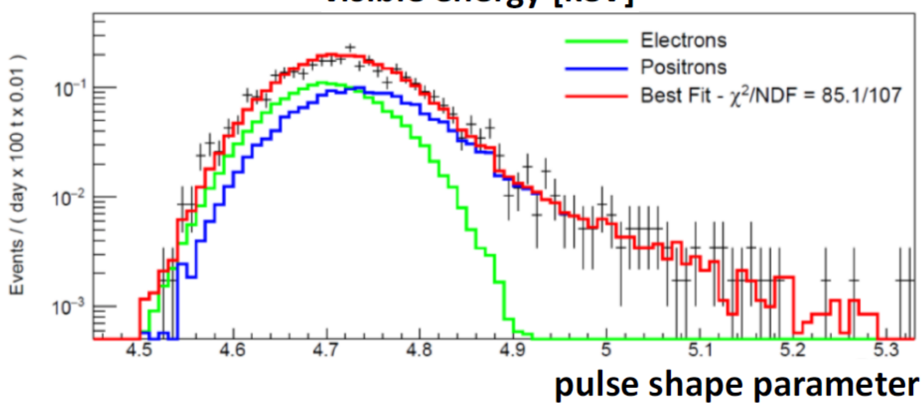
^{11}C-depleted data sample



^{11}C-enriched data sample







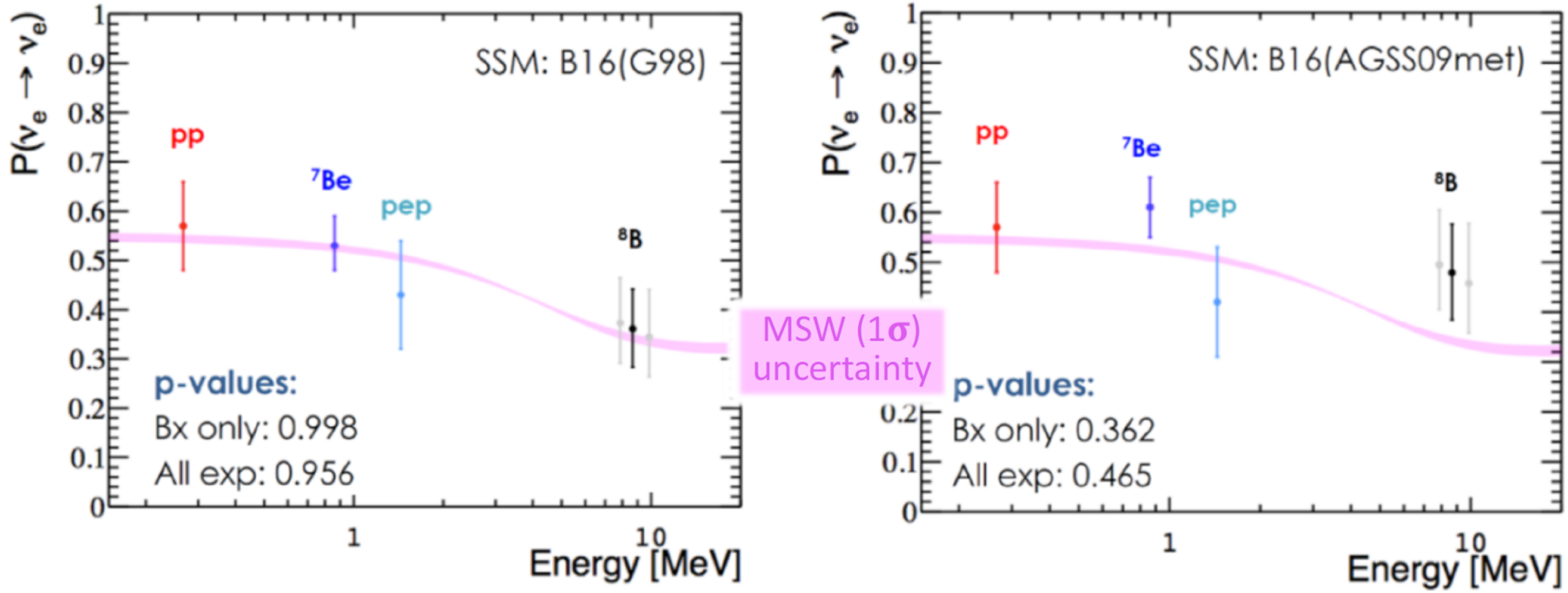
radial event distribution

e^+/e^- discrimination

Testing MSW-LMA oscillation probabilities

JG|U

High metallicity SSM   Low metallicity SSM



Uncertainties in the determination of $P_{ee}(E)$

- **pp and pep neutrinos:** small uncertainty on flux prediction (~1%)
  → experimental errors (11% resp. 16%) dominate
- **^{7}Be and ^{8}B neutrinos:** very accurate measuerements (~3%)
  → SSM uncertainties dominate

How to improve?

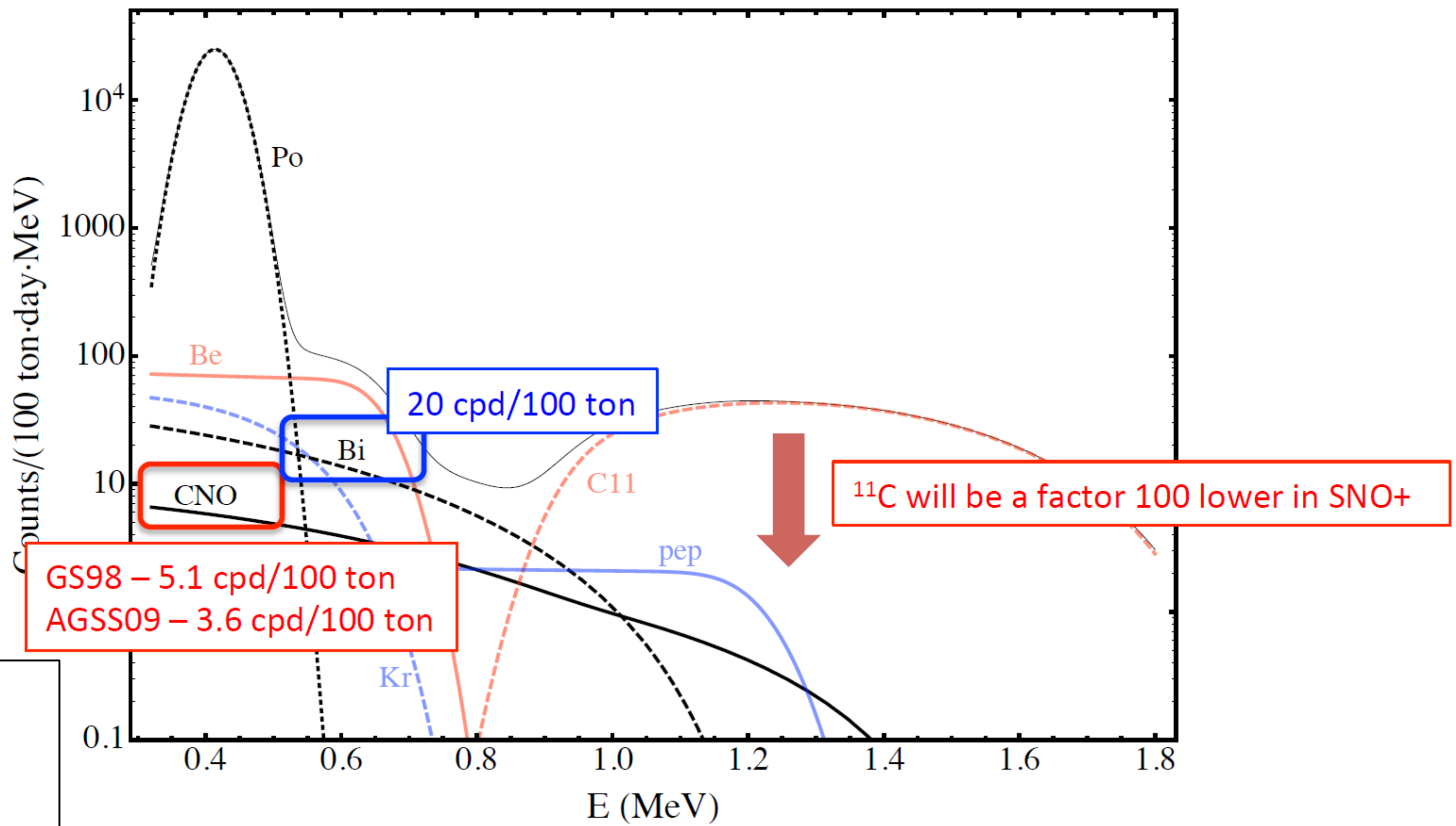
CNO: Villante Dresden 2018

Increase the detector depth → reduction of cosmogenic ^{11}C background

Consider larger detectors → Stat. uncertainties scales as $1/M^{1/2}$

SNO+ (1 kton), LENA (50 kton)

Event spectrum in ultrapure liquid scintillators (Borexino-like)

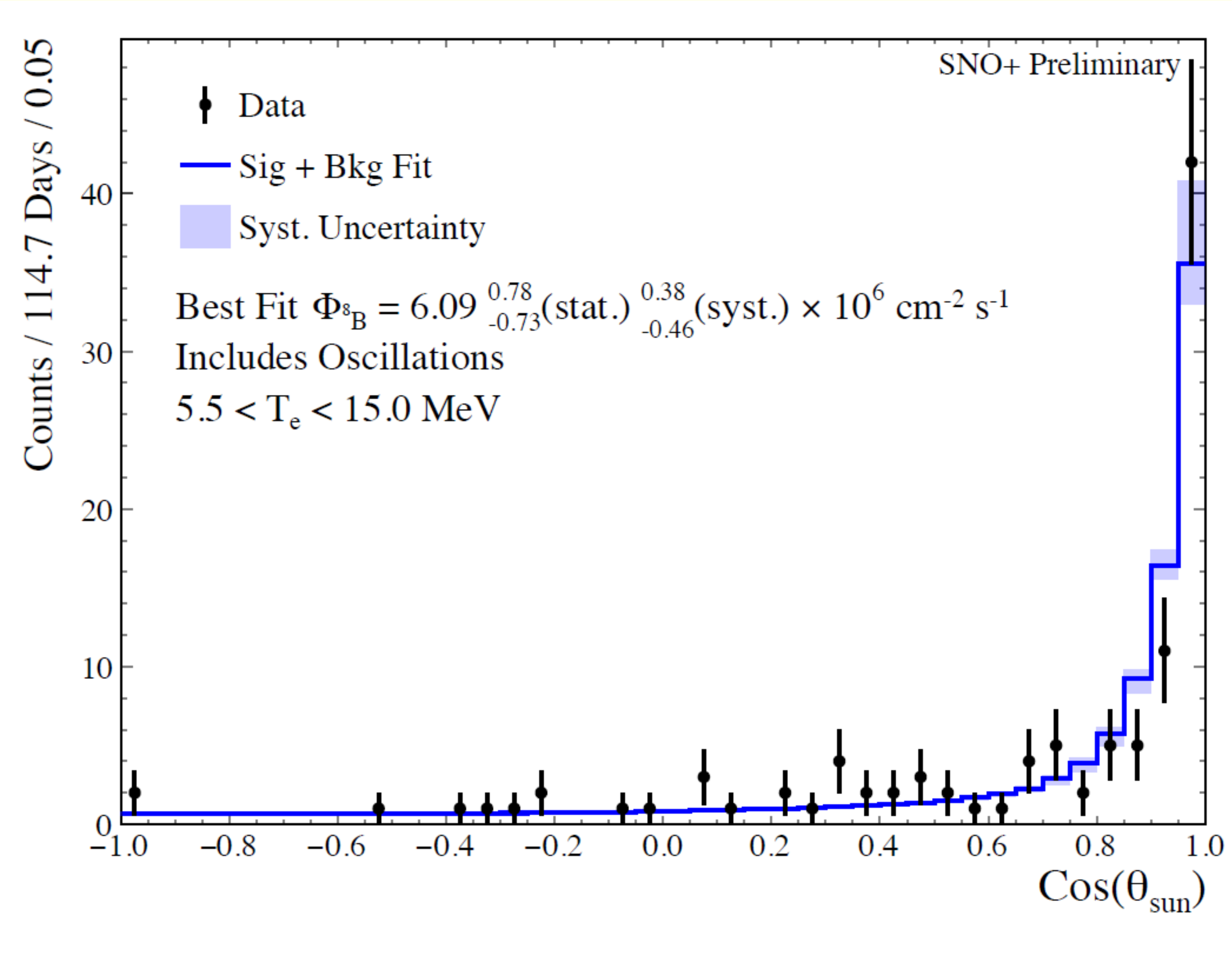


CNO could resolve the metallicity question

The final accuracy depends, however, on the internal background (^{210}Bi)

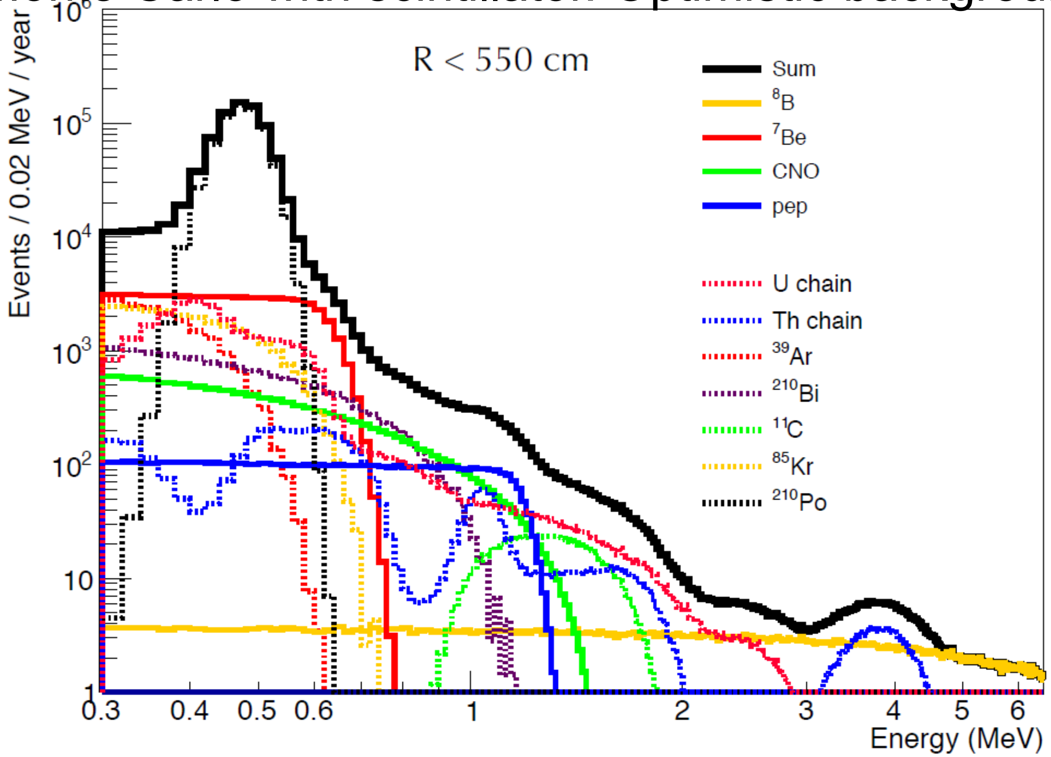
Borexino: 20cpd/100 ton → 150 nuclei / 100 ton

Currently running with H_2O. Scintillator about to be installed.



^8B from ES reaction on electrons in H_2O

Monte Carlo with scintillator. Optimistic background assumptions on Bi, Po



Assumptions:

- 400 Nhits/MeV light yield
- FV = 50%
- 95% reduction of ^{214}Bi via delayed coincidence
- 95% reduction of ^{210}Po and ^{214}Po via alpha tagging
- 50% constraint on ^{85}Kr
- 25% on ^{232}Th-chain
- 7% on ^{238}U chain

Low ^{11}C background

	6 months	1 yr
^{8}B	10,0%	7,1%
^{7}Be	5,1%	3,3%
pep	13,0%	8,9%
CNO + Bi	6,5%	4,4%

Te to be installed when ready in 2019 for 0νββ

2018 Conclusions re solar neutrinos

- Nature has been kind. Following up on Ray Davis' and John Bahcall's pioneering work has enabled us to learn about new neutrino properties and about the sun itself in considerable detail.

- The work with SNO has been strongly complimented by other very beautiful measurements of solar neutrinos (see Till's talk, SK and Borexino) and by Kamland's excellent work on reactor neutrinos.

- We are now at a point where future solar neutrino measurements can be helpful for solar models (CNO: metallicity) and for further limitations on neutrino effects (non-standard interactions…)

- Many of the planned large scale detectors (HyperK… Liquid argon…) will have solar capabilities as secondary objectives.

- Stay tuned.