THE SOLAR NEUTRINO RESULTS OF SNO

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ON BEHALF OF THE SNO COLLABORATION

RECONTRES DU VIETNAM: NEUTRINOS
QUI NHON, JULY 18, 2017

THE SNO COLLABORATION

August 2008 meeting @ SNOLAB

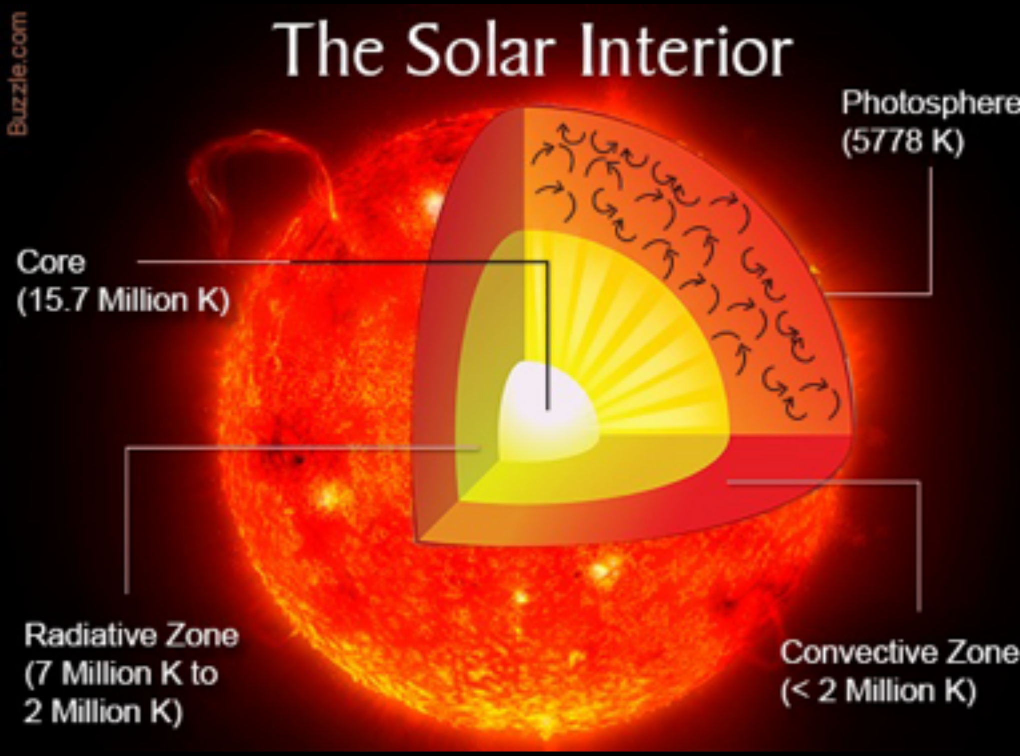
dedicated to

Fraser Duncan, Davis Earle, Cliff Hargrove, John Simpson

SOLAR NEUTRINOS

THE SUN AS A NEUTRINO SOURCE

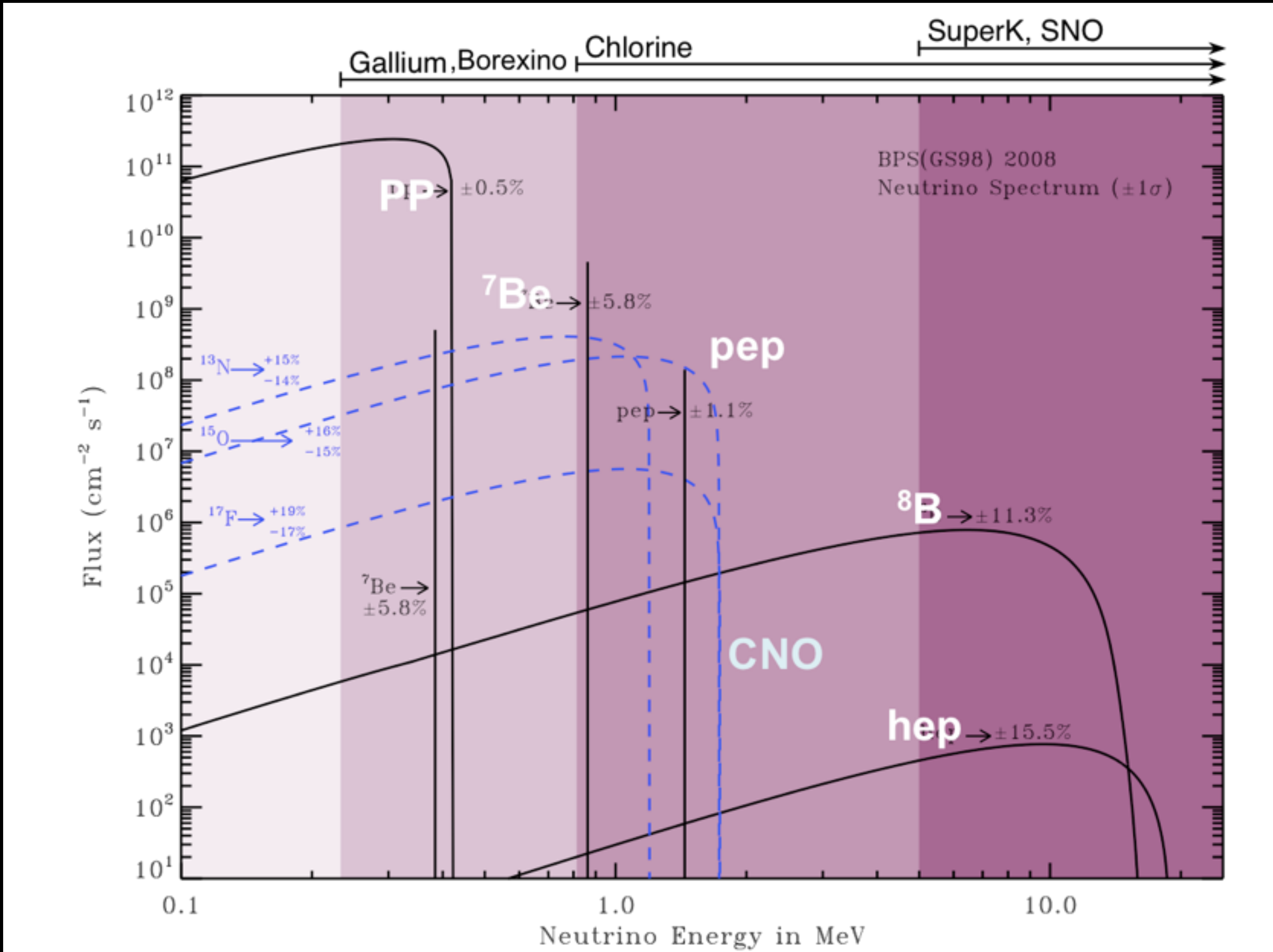
- Nuclear fusion reactions recognized early on as the only viable source of stellar energy production
- Hans Bethe (1930's): first solar model based on nuclear reactions



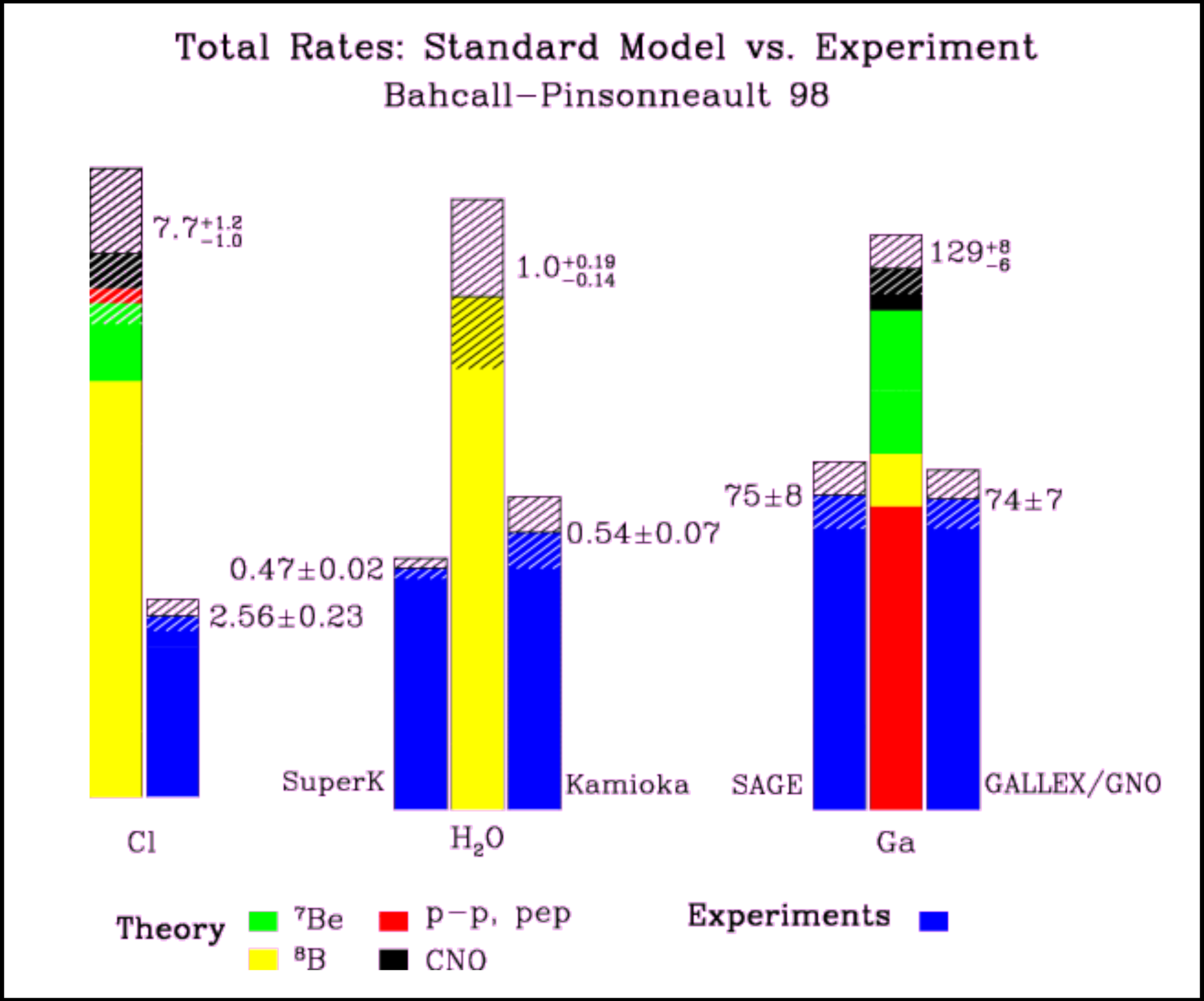
- John Bahcall: increasingly detailed solar model calculations of the solar neutrino fluxes, since the 60's

- Ray Davis@Homestake: pioneering radiochemical measurements of solar neutrino captures on chlorine.
- Measured flux consistently 1/3 of Bahcall's predictions

SOLAR NEUTRINO SPECTRUM



THE SOLAR NEUTRINO PROBLEM



Gribov and Pontecorvo suggested (1968) flavor change from electron to muon neutrinos

EARLY DAYS OF SNO

VOLUME 55, NUMBER 14 PHYSICAL REVIEW LETTERS

Direct Approach to Resolve the Solar-Neutrino Problem

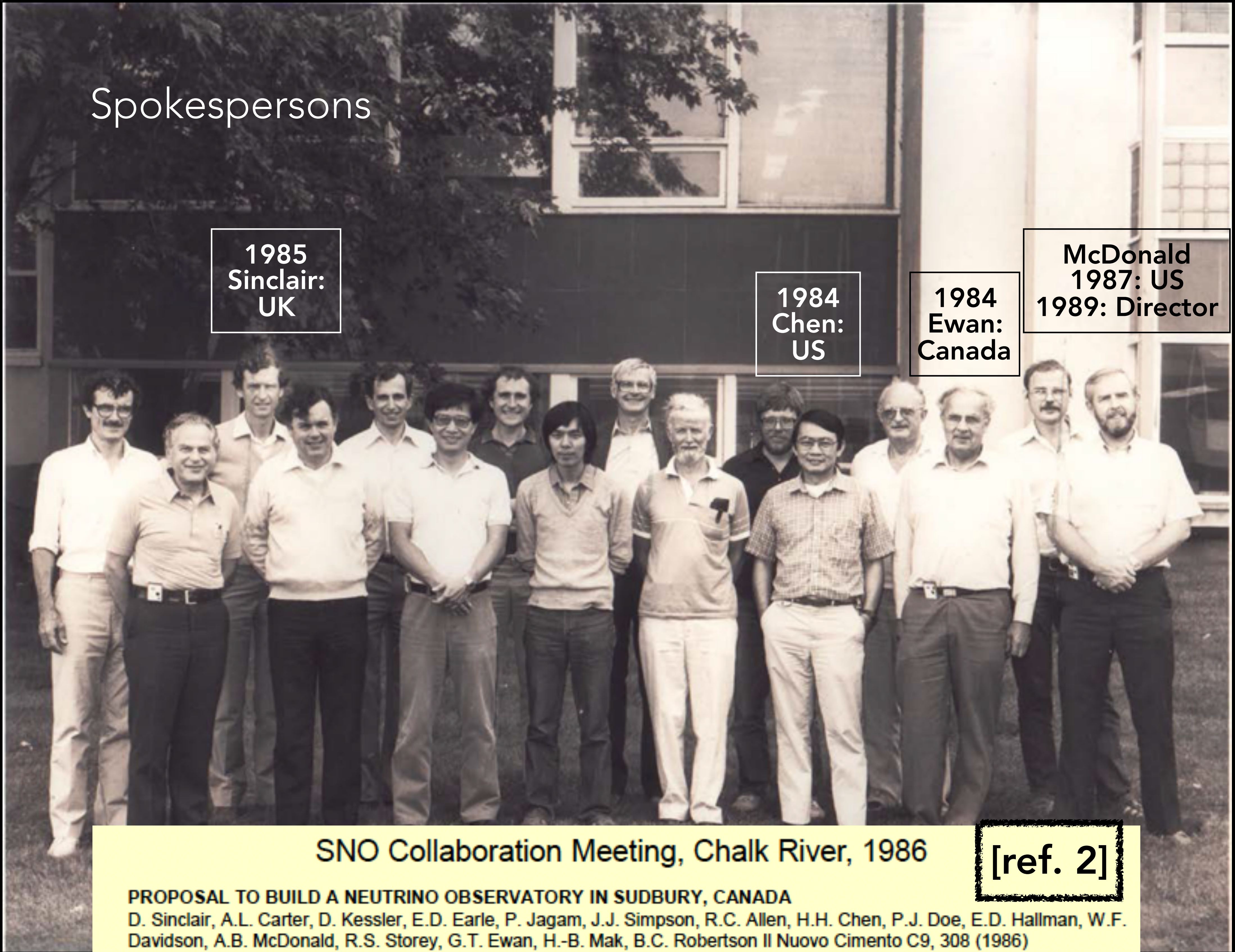
[ref. 1]

Herbert H. Chen
Department of Physics, University of California, Irvine, California 92717
(Received 27 June 1985)

George Ewan (Queen's University, Canada)
First co-spokesman of SNO, together with Herb Chen

- **Herb Chen:** neutral current reaction on deuterium can measure the total flux in all flavors, regardless of oscillations
- **George Ewan** brings the Canadian side: availability of large quantities of heavy water, and deep mines
- **Art McDonald:** SNO director since 1990, for the construction, operation, and data analysis phases
    - 2015 Nobel Prize in Physics

1986 SNO MEETING



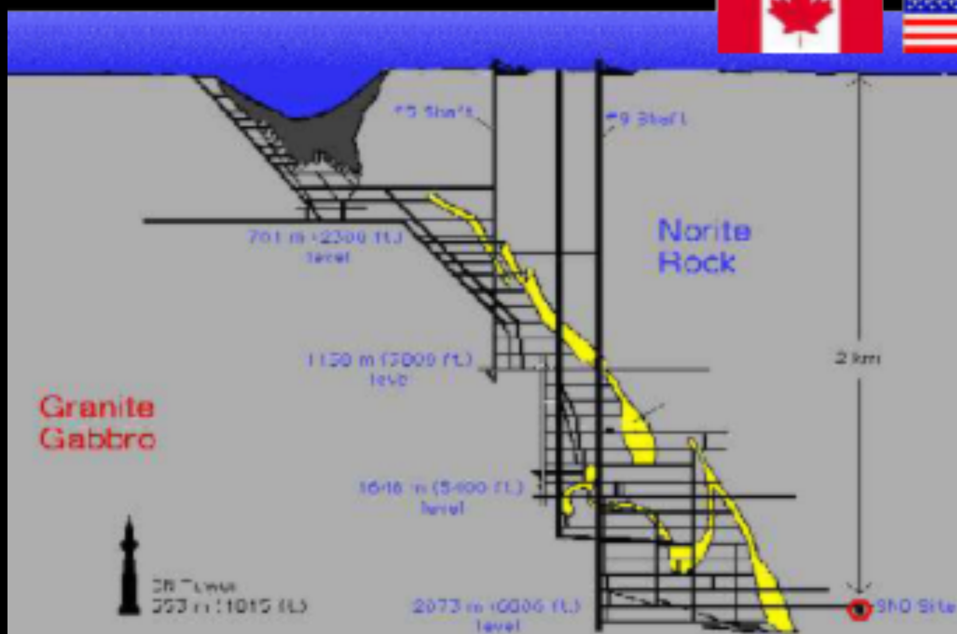
SNO Collaboration Meeting, Chalk River, 1986

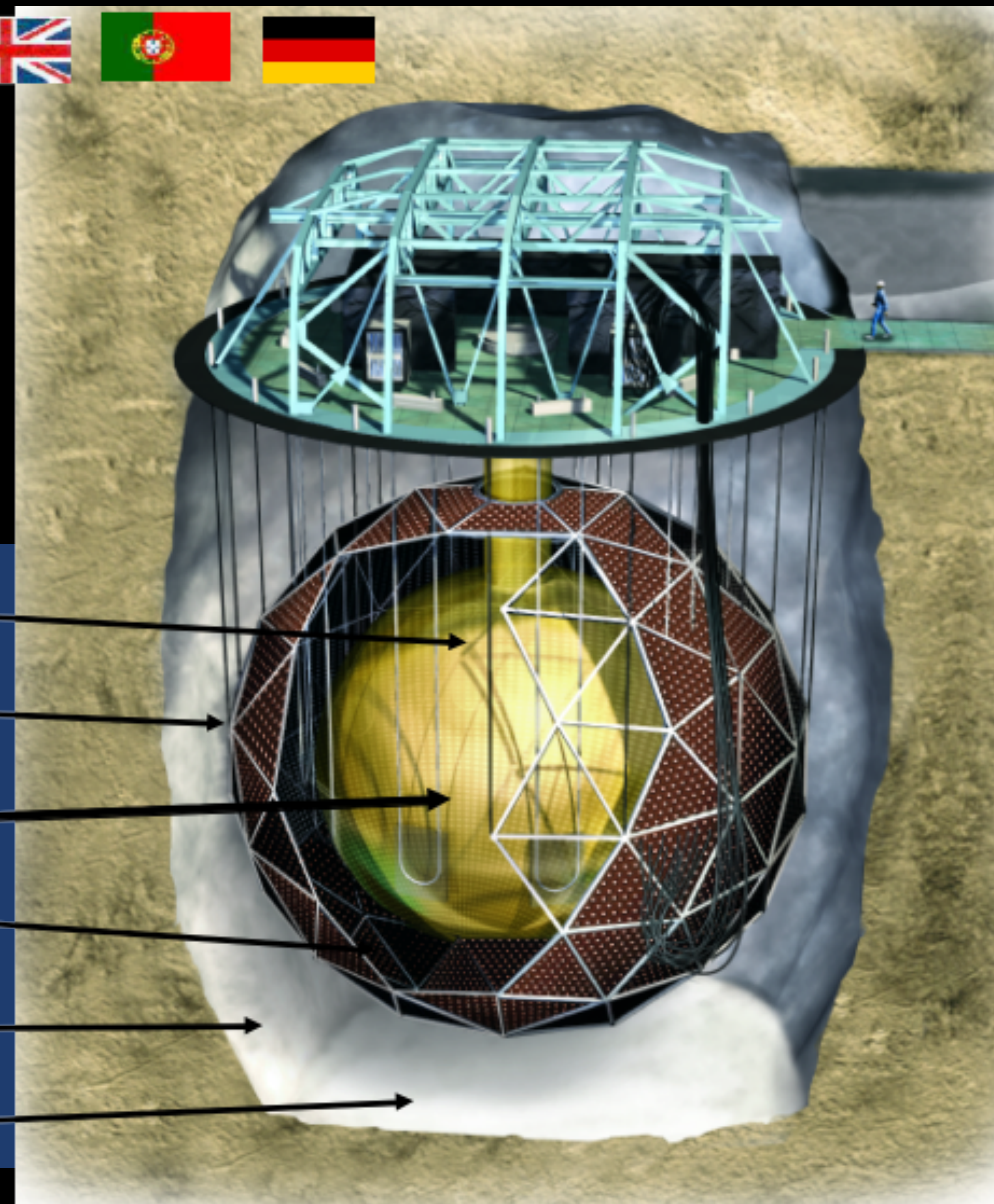
[ref. 2]

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)

SUDBURY NEUTRINO OBSERVATORY CONSTRUCTION AND EXPERIMENTAL ASPECTS

THE SUDBURY NEUTRINO OBSERVATORY (SNO)





- D_2O (heavy water) : 1000 ton
- PMT Support structure: 9500 PMTs
- Acrylic Sphere: 12 m diameter
- Internal H_2O layer: 1700 ton
- External H_2O layer: 5300 ton
- Urylon liner: Radon seal

[ref. 3]

CONSTRUCTION

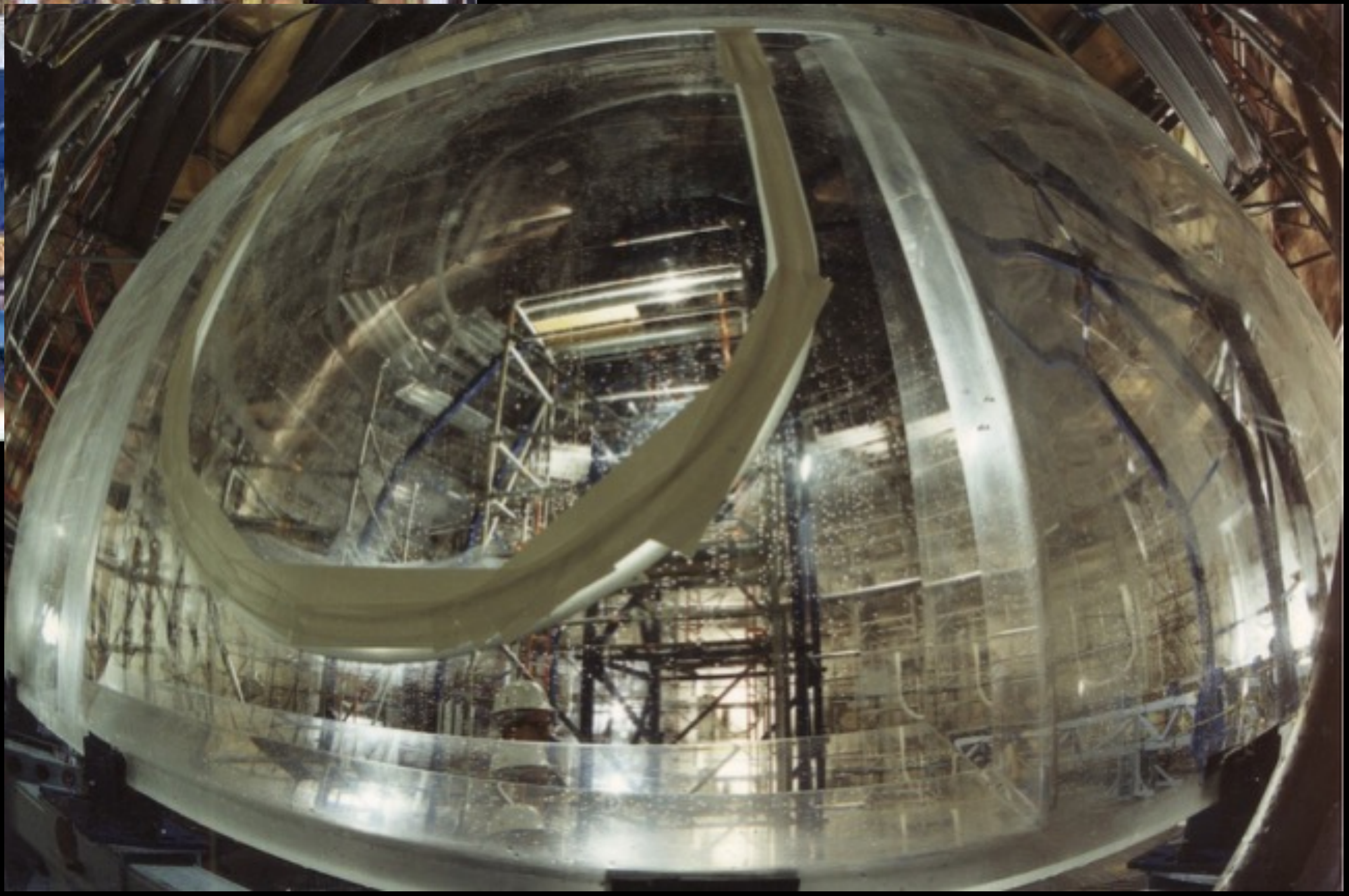
- SNO was built in the active Creighton mine (INCO, now VALE), close to Sudbury, Ontario
- The experimental cavities were dug on purpose for SNO, at 6800 ft (2 km) depth

CONSTRUCTION OF SNO

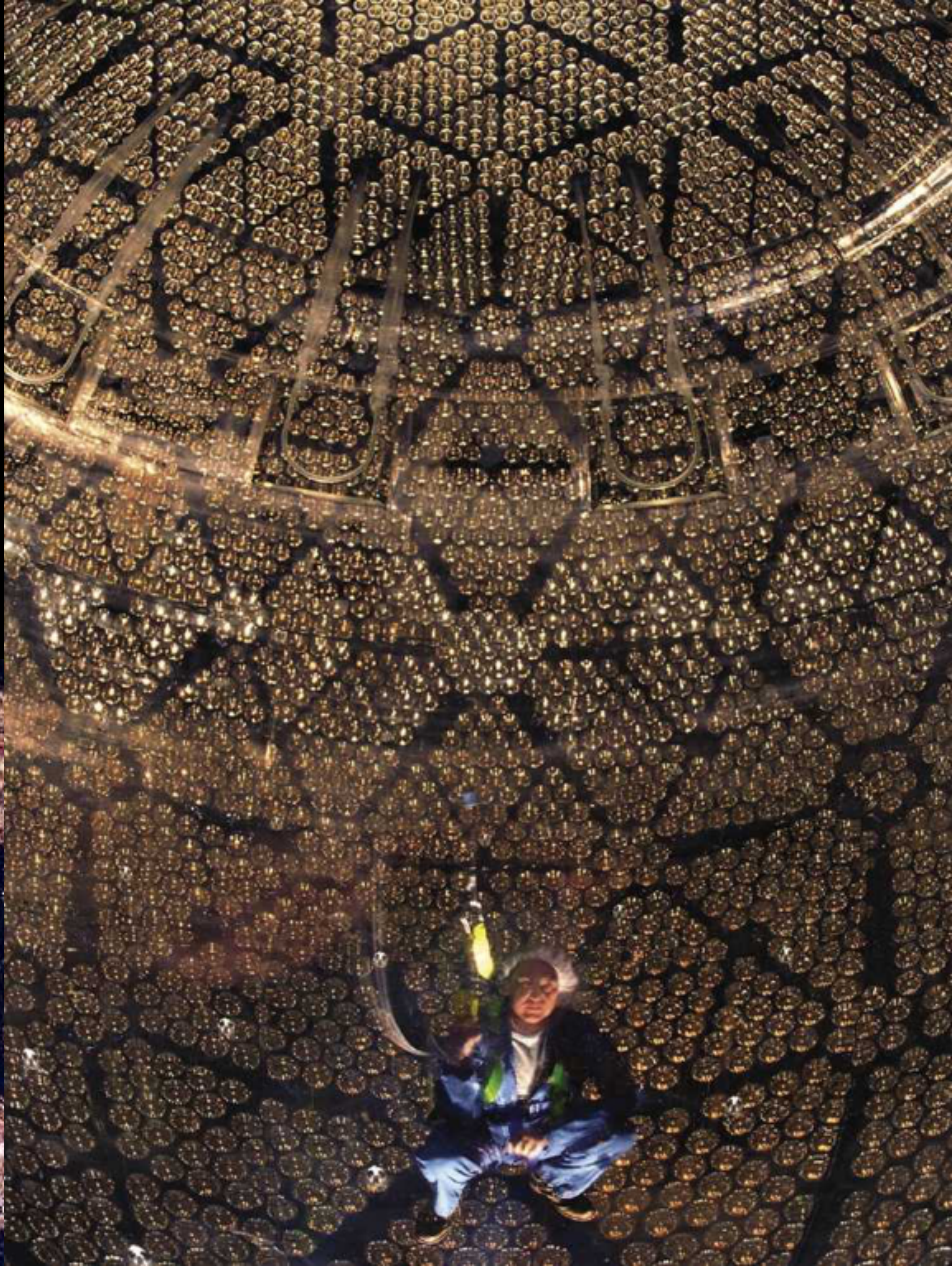
ACRYLIC VESSEL (AV)

Made of 5 cm thick pre-curved tiles.

Bonding the joints in-situ was a big challenge.



PMTS



REACTIONS ON DEUTERIUM

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

Charged Current reaction

W boson exchange

Only electron neutrinos

Detect electron in final state

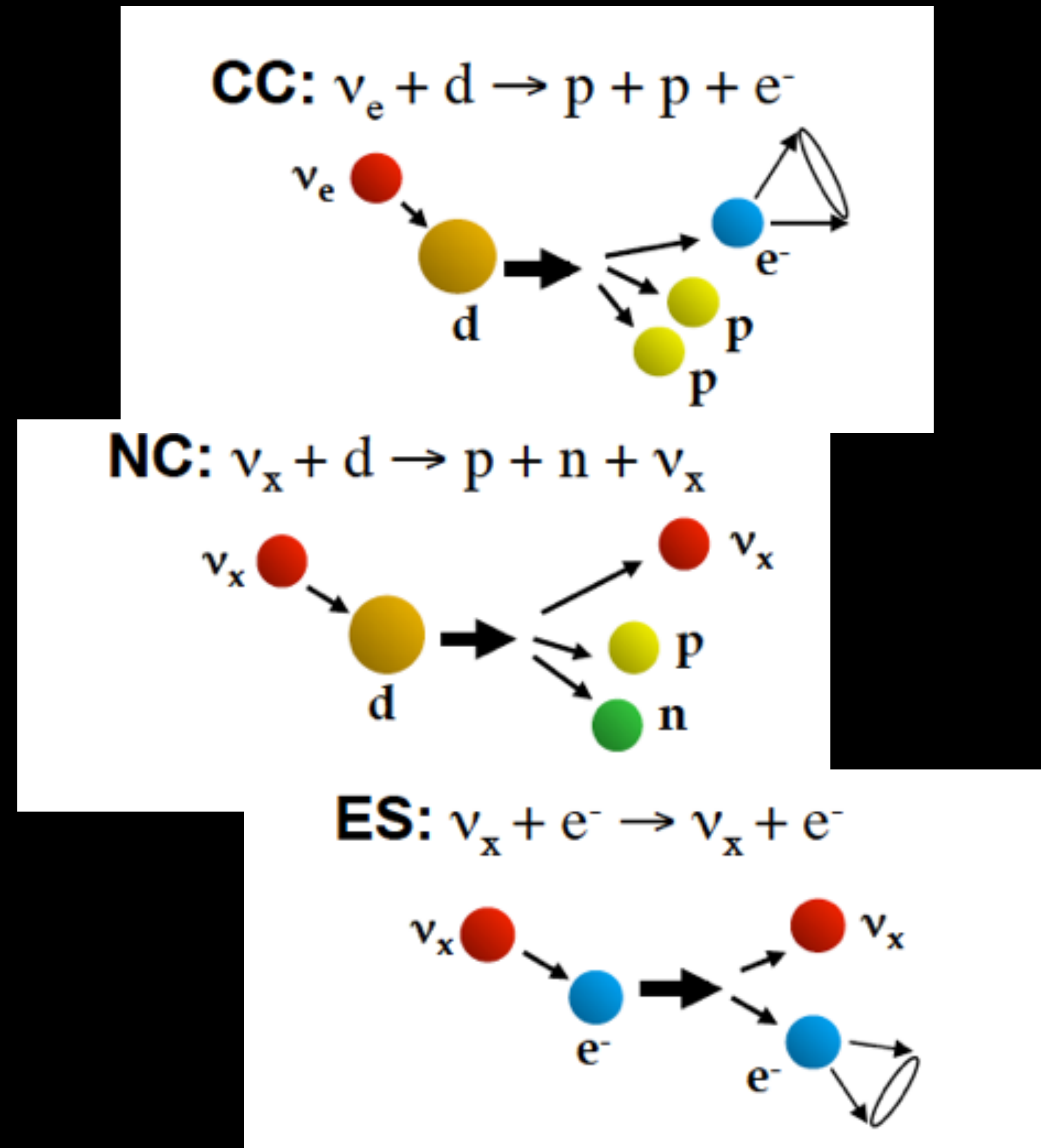
$$\nu_x + d \Rightarrow p + n + \nu_x$$

Neutral Current reaction

Z boson exchange

All neutrino flavors

Detect neutron in final state



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

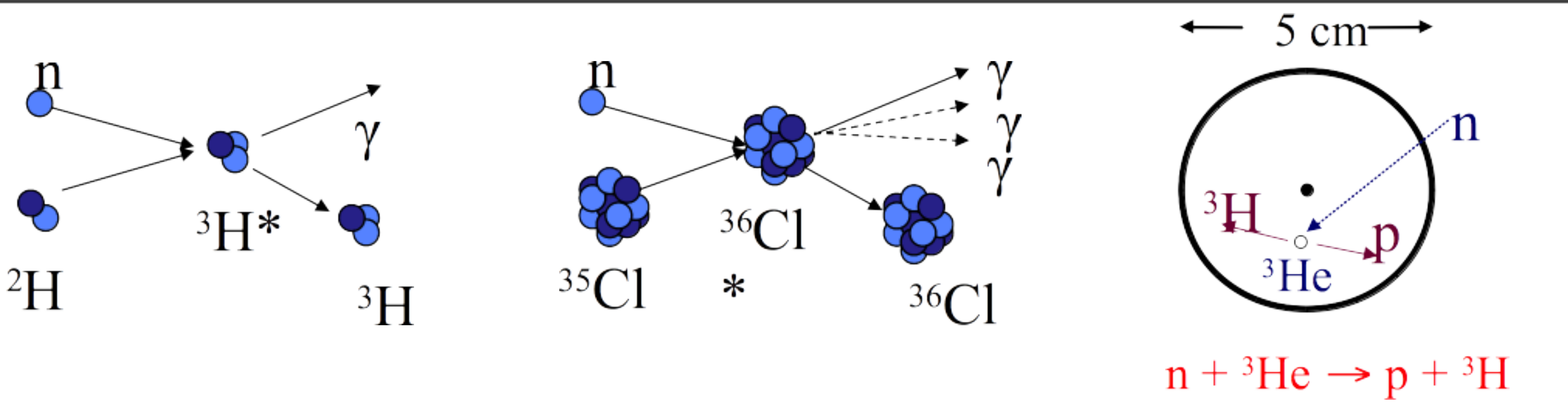
Elastic Scattering reaction

Directional, lower statistics

Less sensitive to ν_μ, ν_τ

THE 3 PHASES OF SNO

Phase I (D_2O)	Phase II (salt)	Phase III (NCD)
Nov. 99 - May 2001	July 2001 - Sept. 2003	Nov. 2004 - Dec. 2006

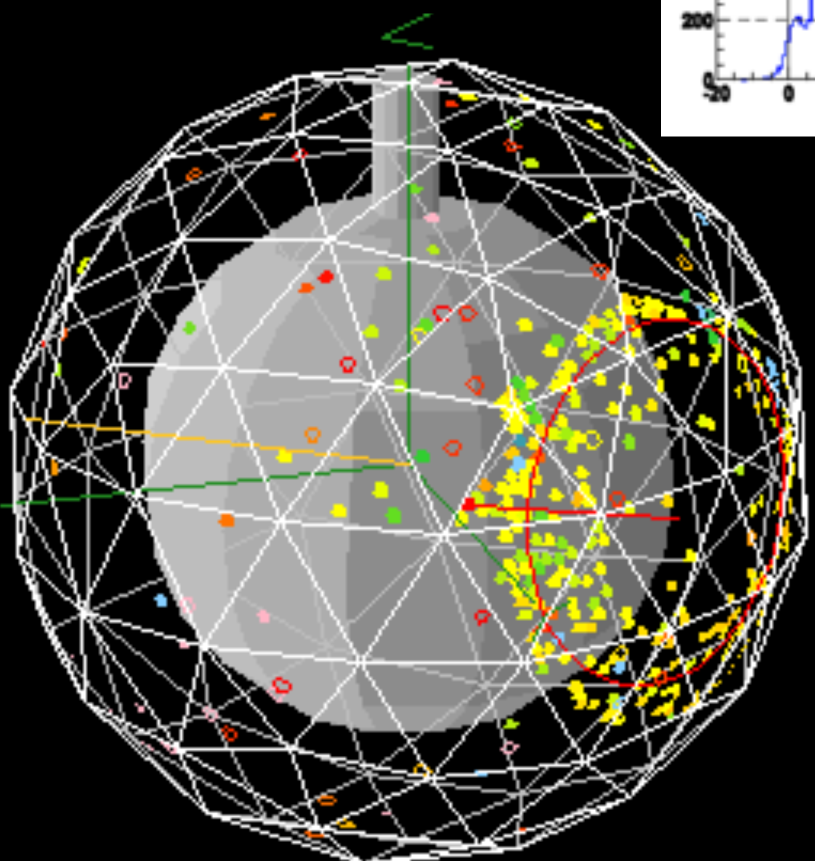


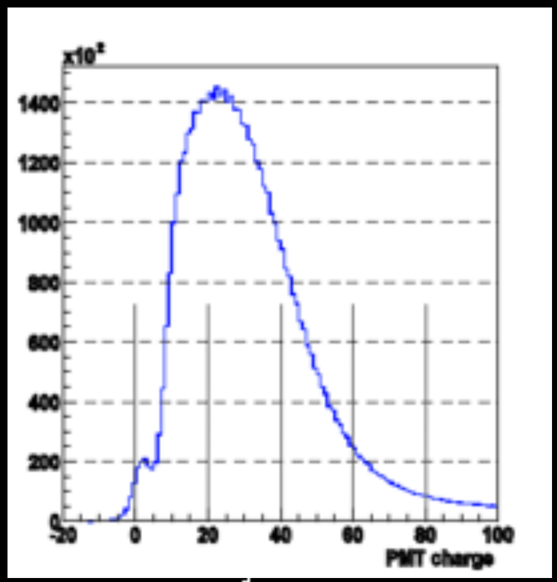
neutrons captured by deuterons	neutrons captured by chlorine	neutrons captured by ^{3}He
$E(\gamma) = 6.25$ MeV	$\Sigma(E(\gamma)) = 8.6$ MeV	array of 40 proportional counters

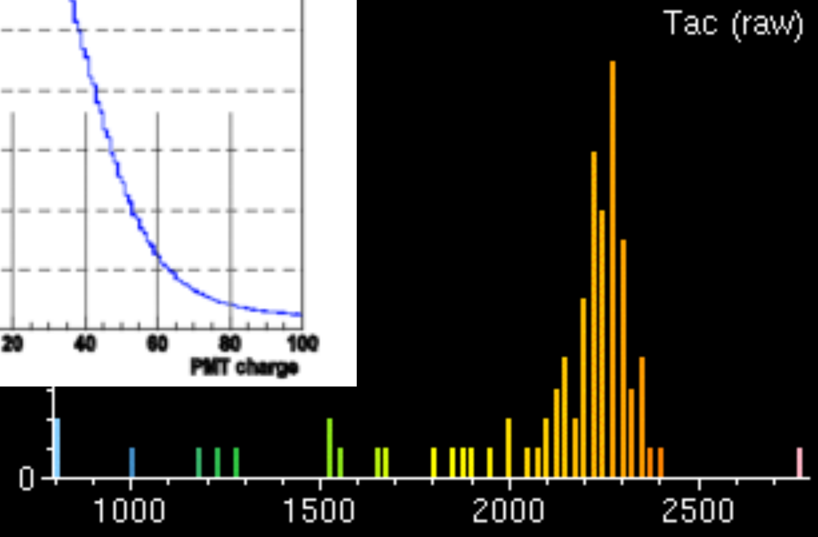
EXPERIMENTAL OBSERVABLES

hit PMTs:

- position
- time
- charge

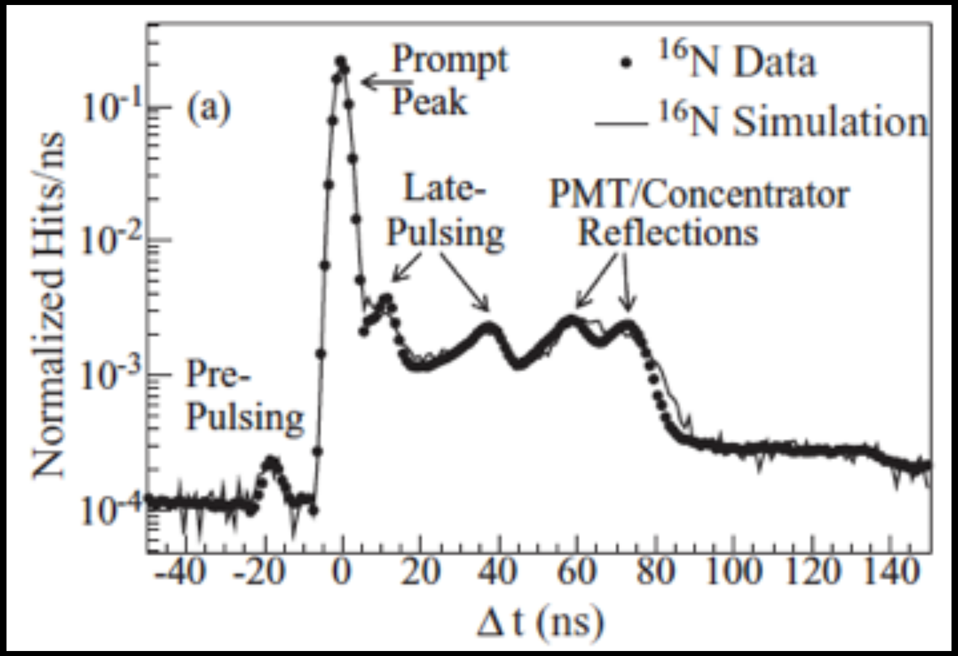






From these we calculate:

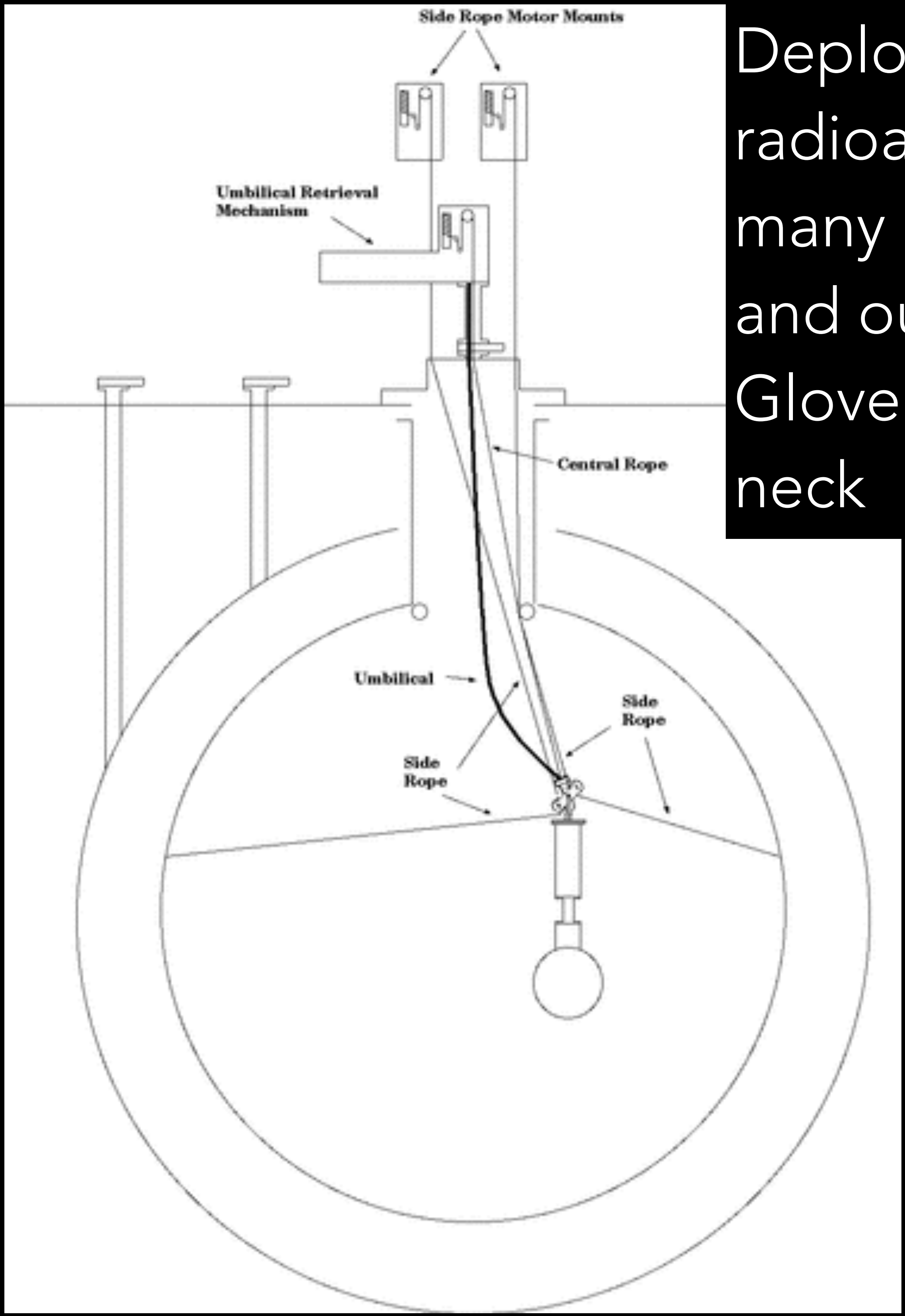
- event position
- direction
- energy
- isotropy



SNO used extensive calibrations to tune response models and determine systematics

CALIBRATIONS

[refs. 4-8]



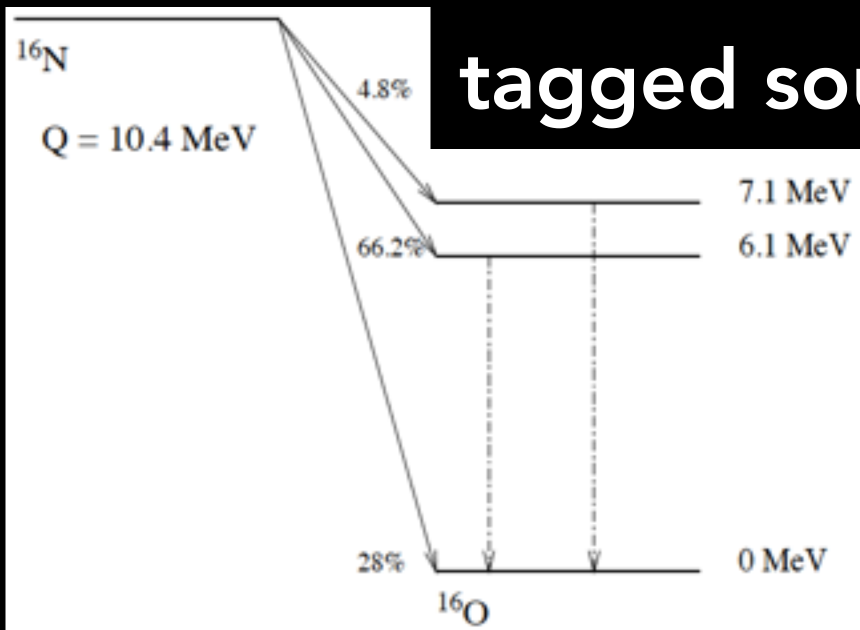
Deploy optical and radioactive sources in many positions inside and outside the AV

Glove box on top of AV neck

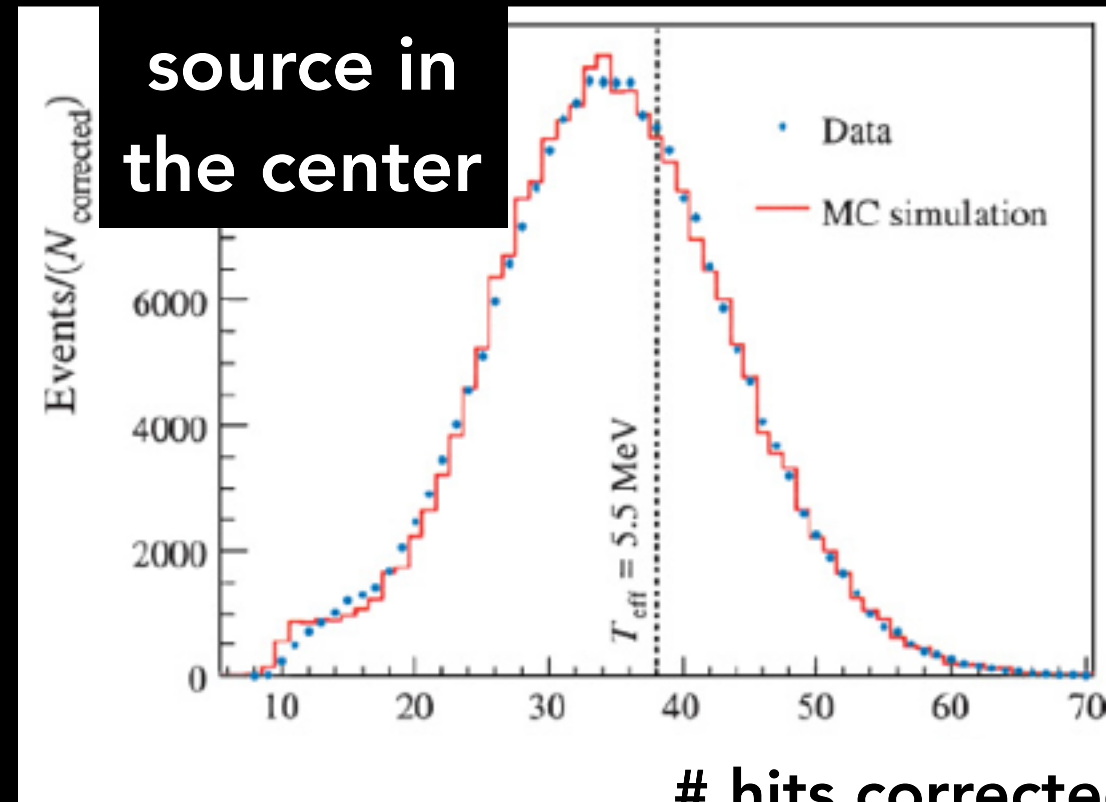
Also: radioactivity spikes uniformly distributed in the heavy water: ^{222}Rn, ^{24}Na

N16 ENERGY CALIBRATION

6.13 MeV γ tagged source

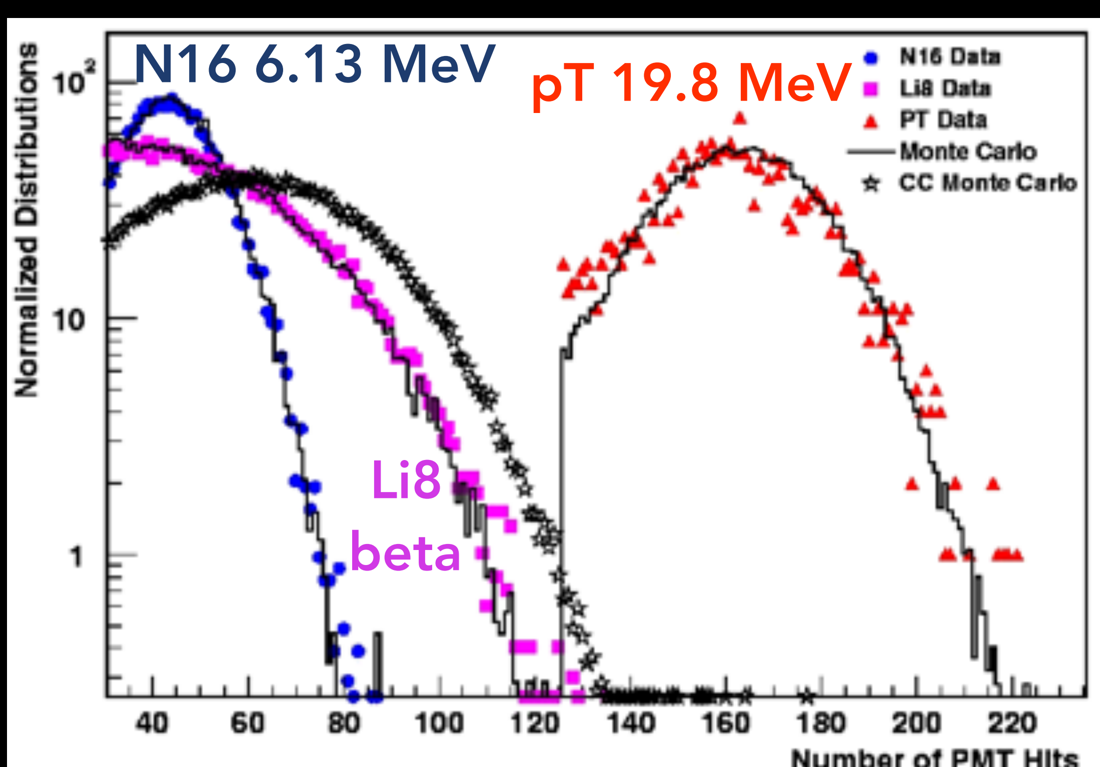


source in the center



 # hits corrected for optical response

Other sources used to validate higher energies

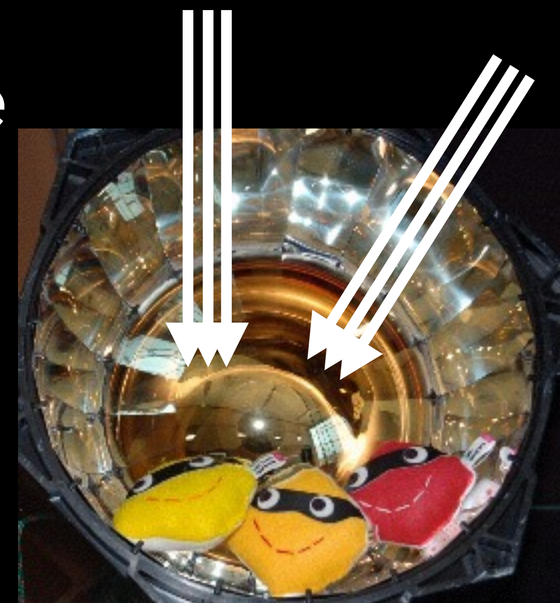


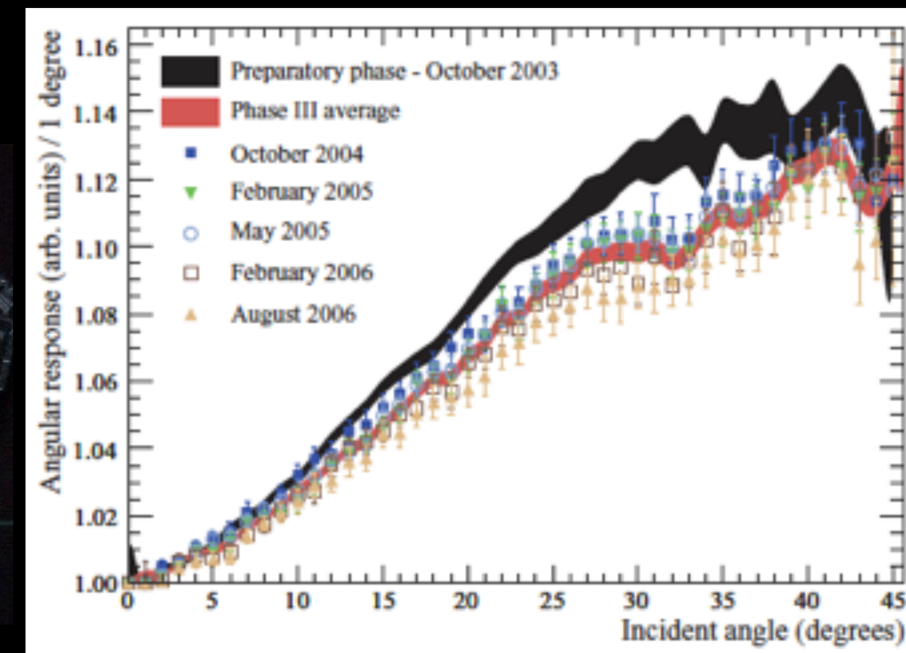
- Energy estimator using number of prompt hits
  - later using all PMT hits, including late times
- # of detected PMT hits varies with event position by up to 8% due to PMT angular response, attenuation in heavy and light water, and acrylic
  - Need to measure the optical properties *in-situ* -> optical calibration

OPTICAL CALIBRATION

- PMT + reflector response versus incidence angle
- reflectivity degraded over time

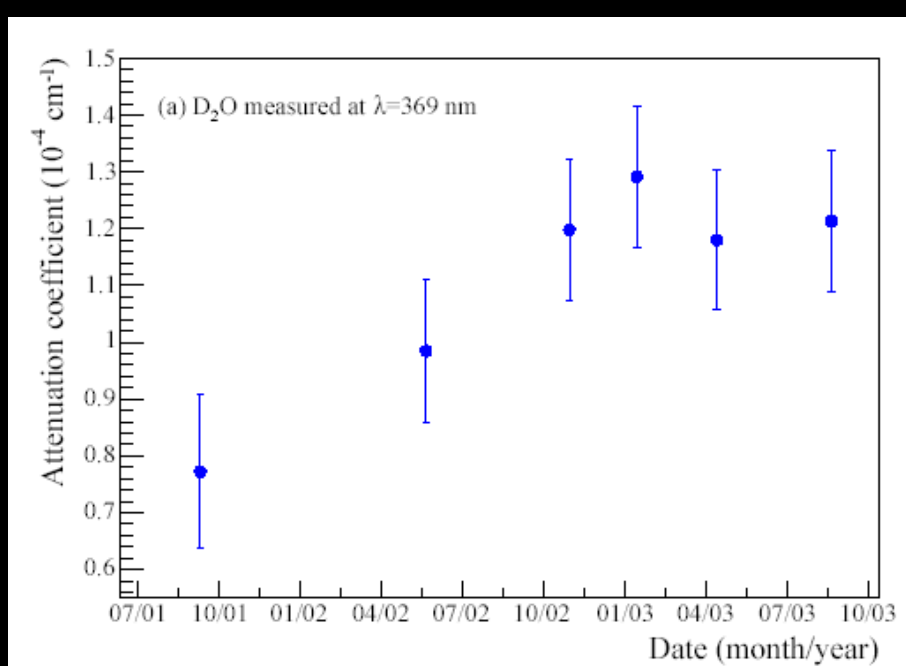
[refs. 7, 14, 17]



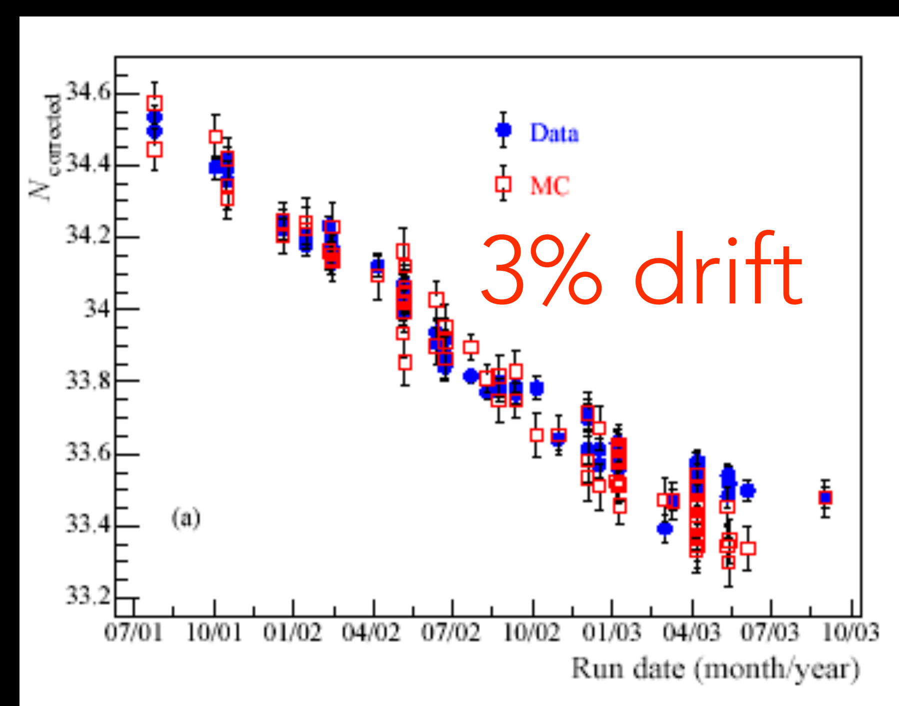


- In salt phase, a drift in energy response was identified as caused by increasing attenuation of heavy water

Heavy water attenuation



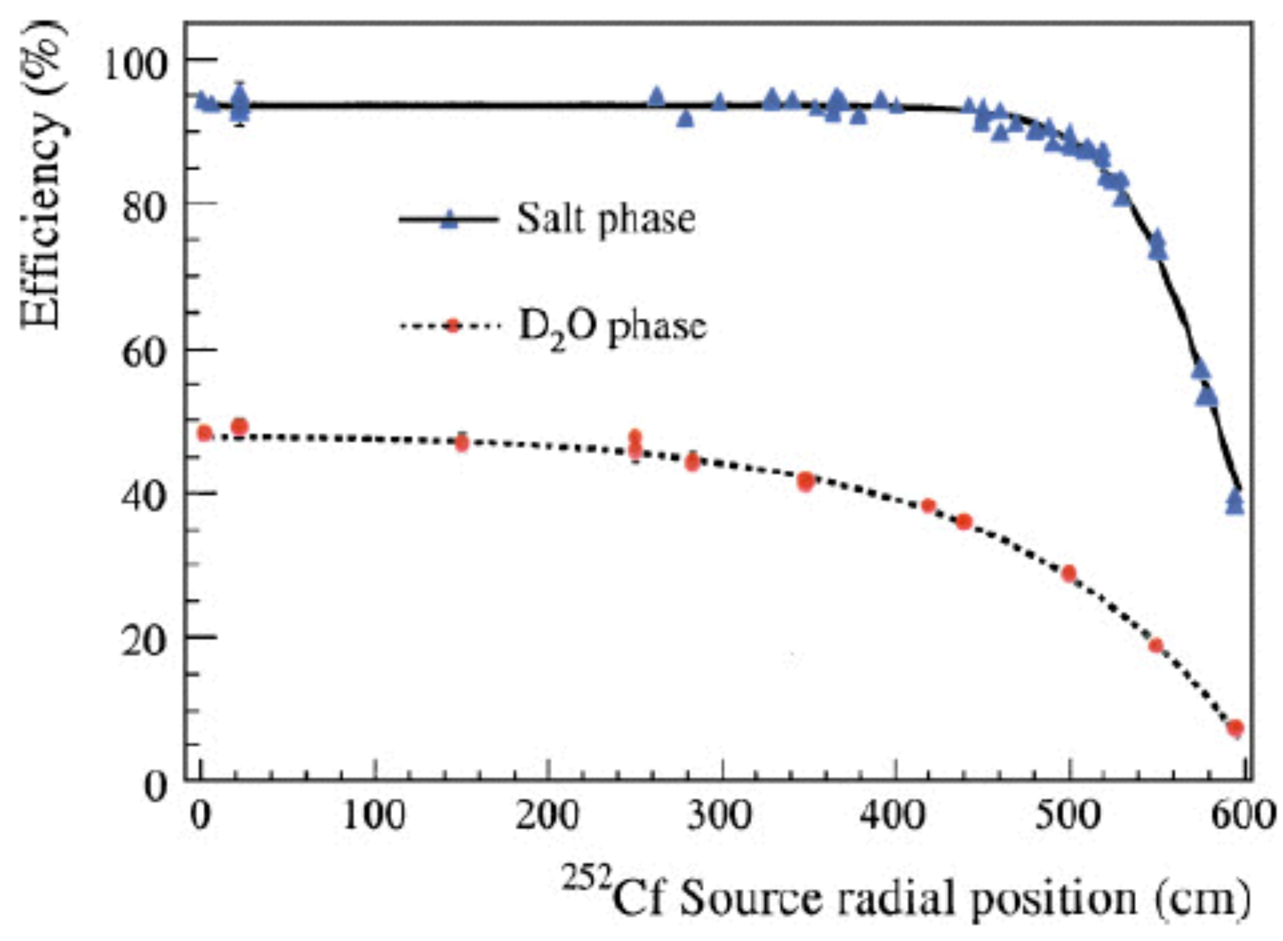
Number of PMT hits

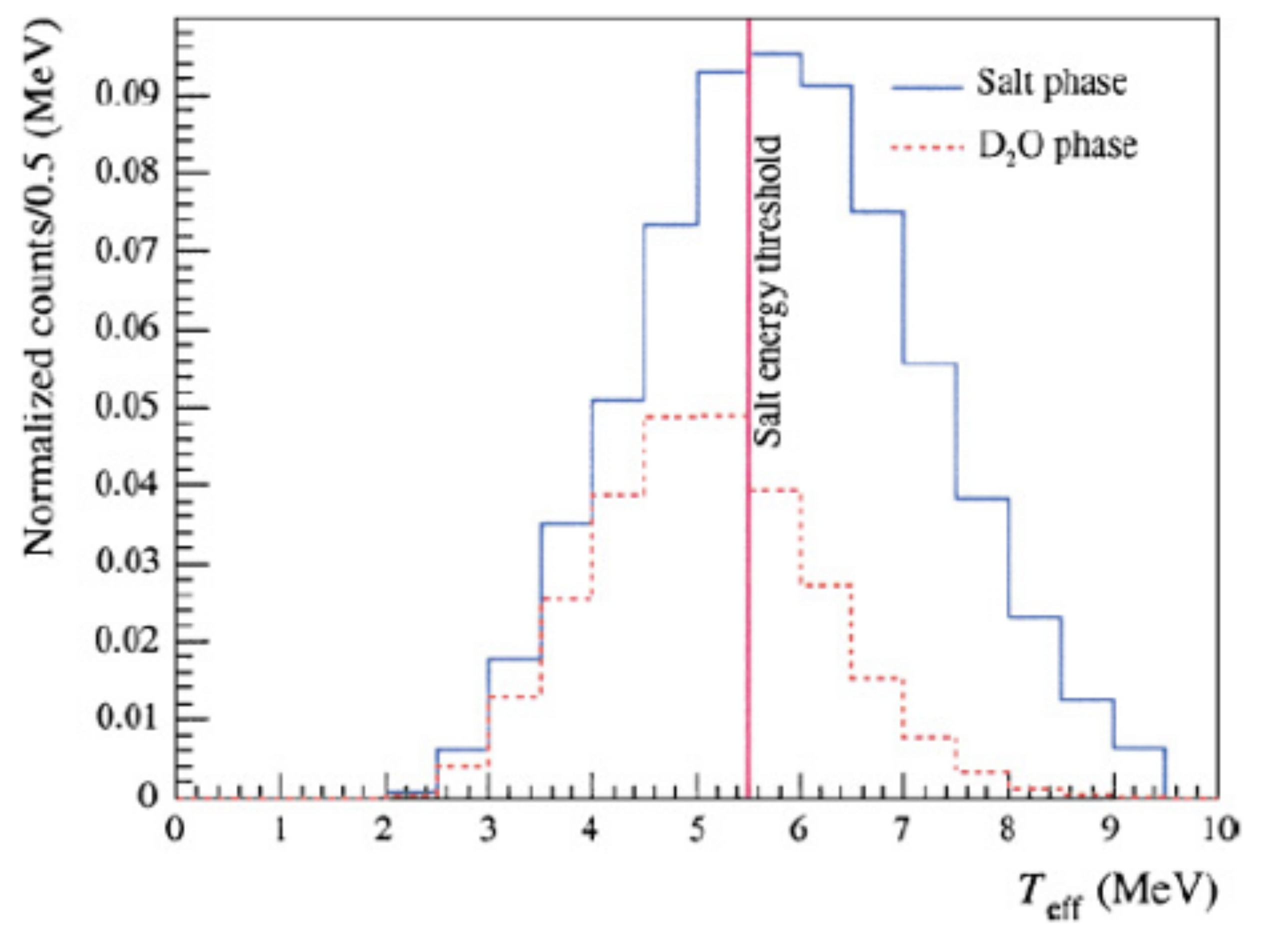


After all corrections, energy scale systematics were < 0.6%

NEUTRON CALIBRATION

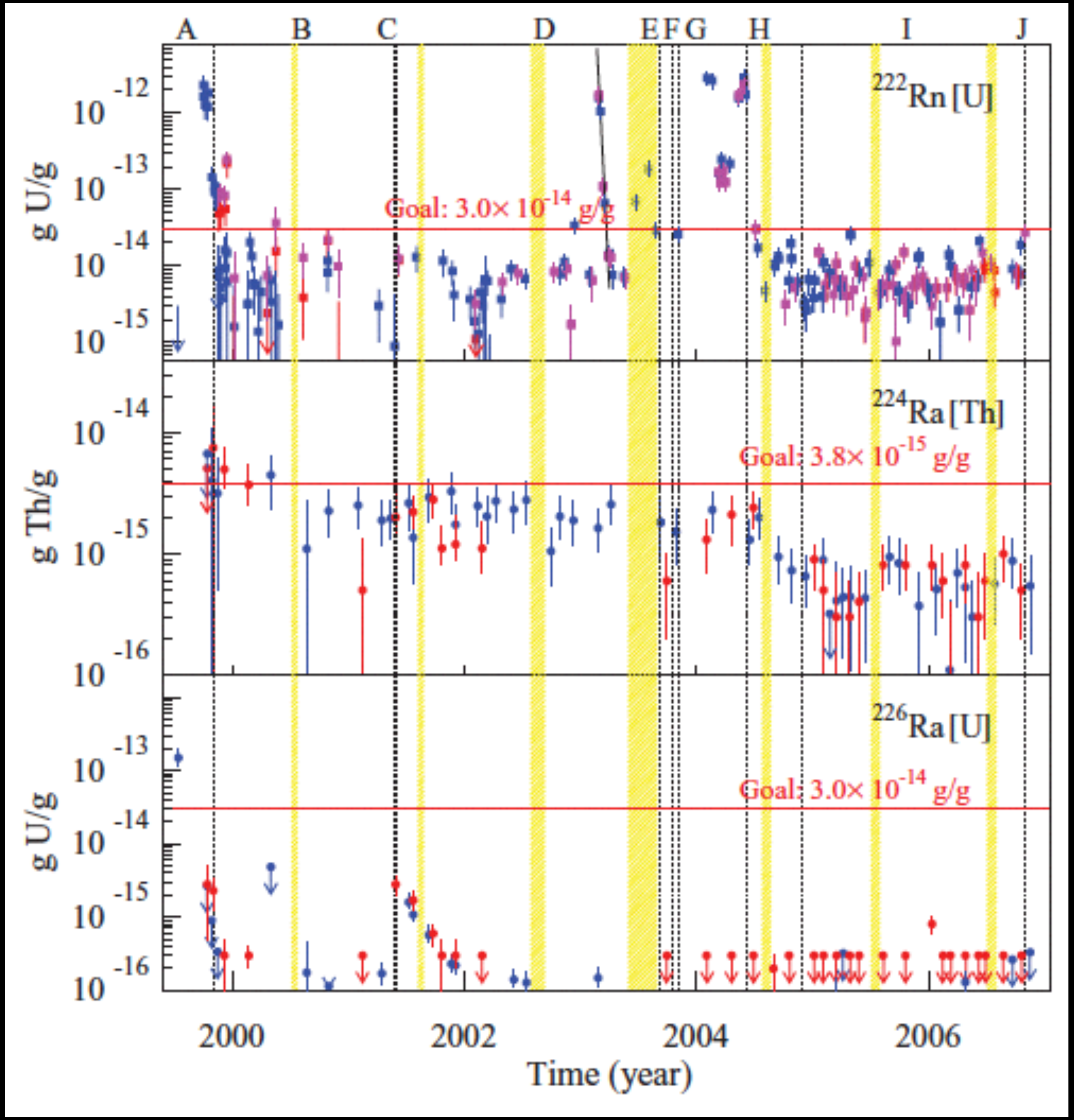
- AmBe and ^{252}Cf point sources
- Adding salt improved capture and detection efficiencies





[ref. 14]

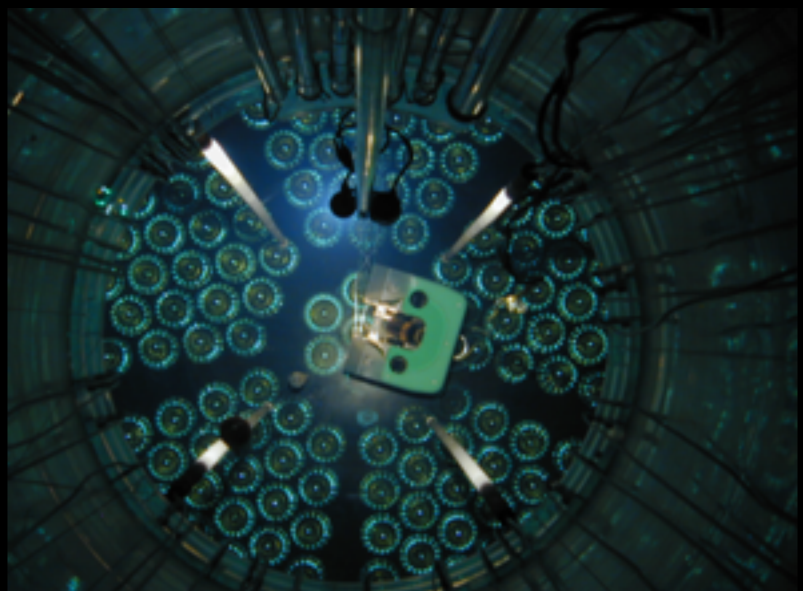
CHALLENGE: RADIOACTIVITY



Heavy and light water regularly purified and assayed.
Well below target levels.

[refs. 9-10, 17]

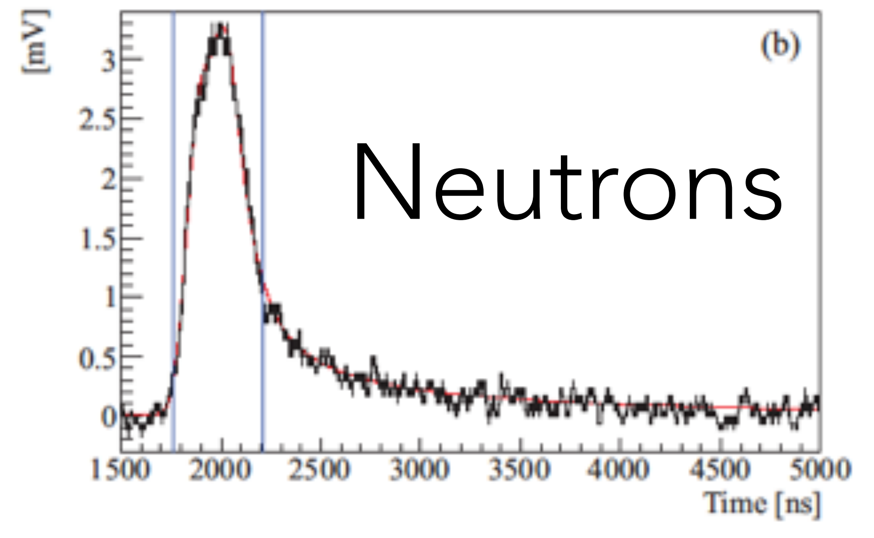
NEUTRAL CURRENT DETECTORS



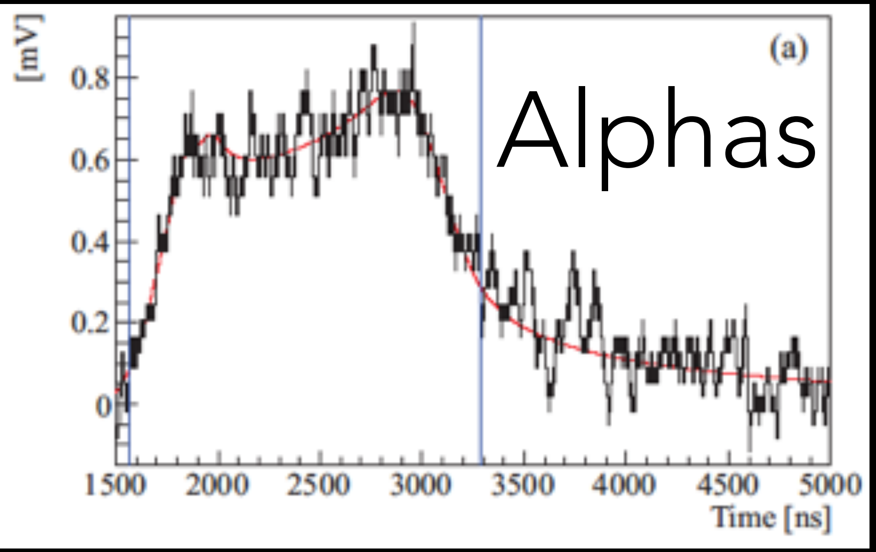
- Array of ^{3}He-filled proportional counters deployed in the AV

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

  - Neutron capture efficiency: 21.5%
- Pulse-shape allows background discrimination
  - neutron pulses, obtained from calibrations



  - alpha pulses, obtained from ^{4}He-filled counters

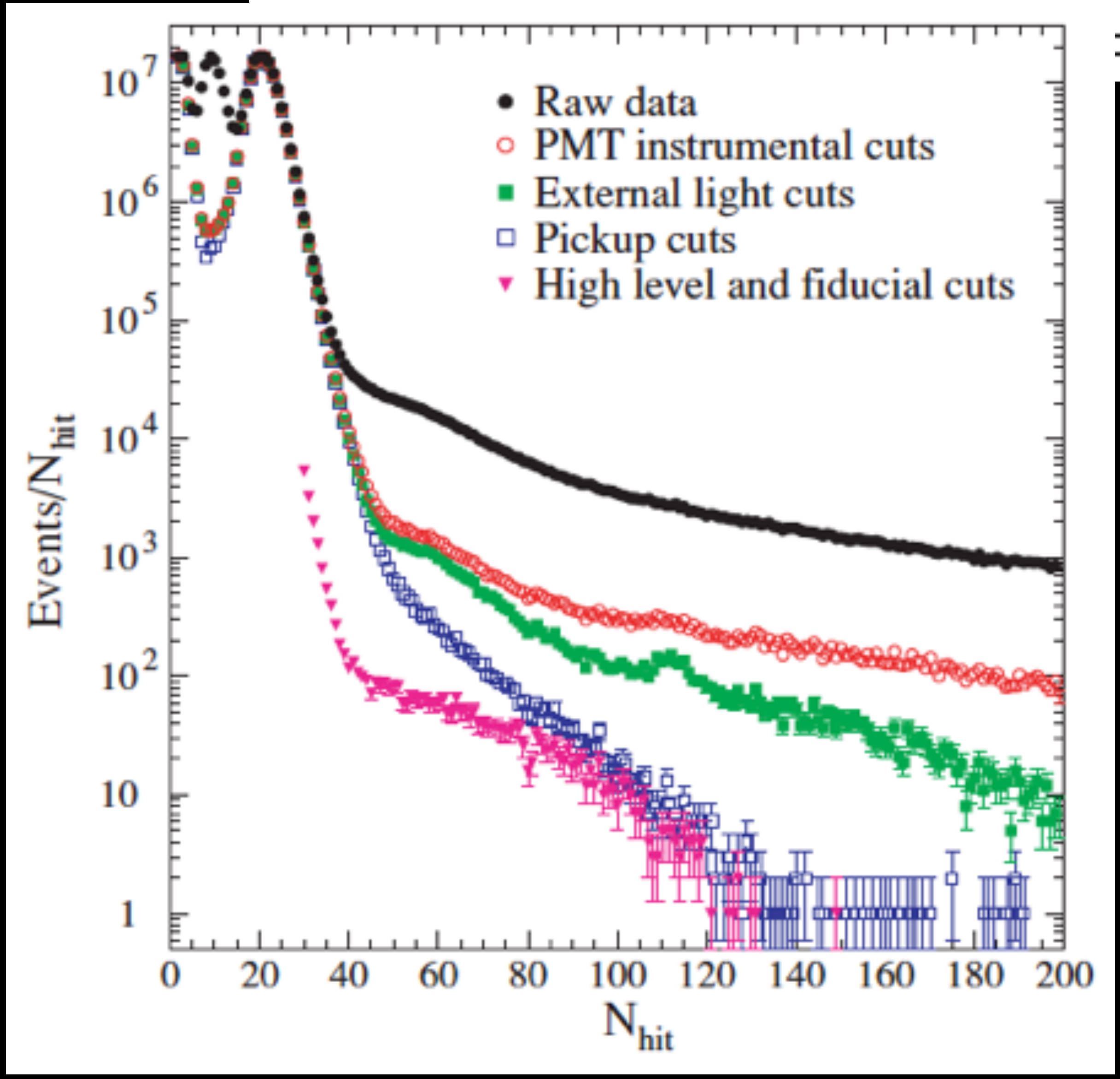


[refs. 11, 17,18]

SUDBURY NEUTRINO OBSERVATORY SOLAR NEUTRINO RESULTS

SNO DATA-TAKING

Phase	Start date	End date	Total time [days]	
			Day	Night
I	November 1999	May 2001	119.9	157.4
II	July 2001	August 2003	176.5	214.9
III	November 2004	November 2006	176.6	208.6



Large fraction of data-taking used in calibrations

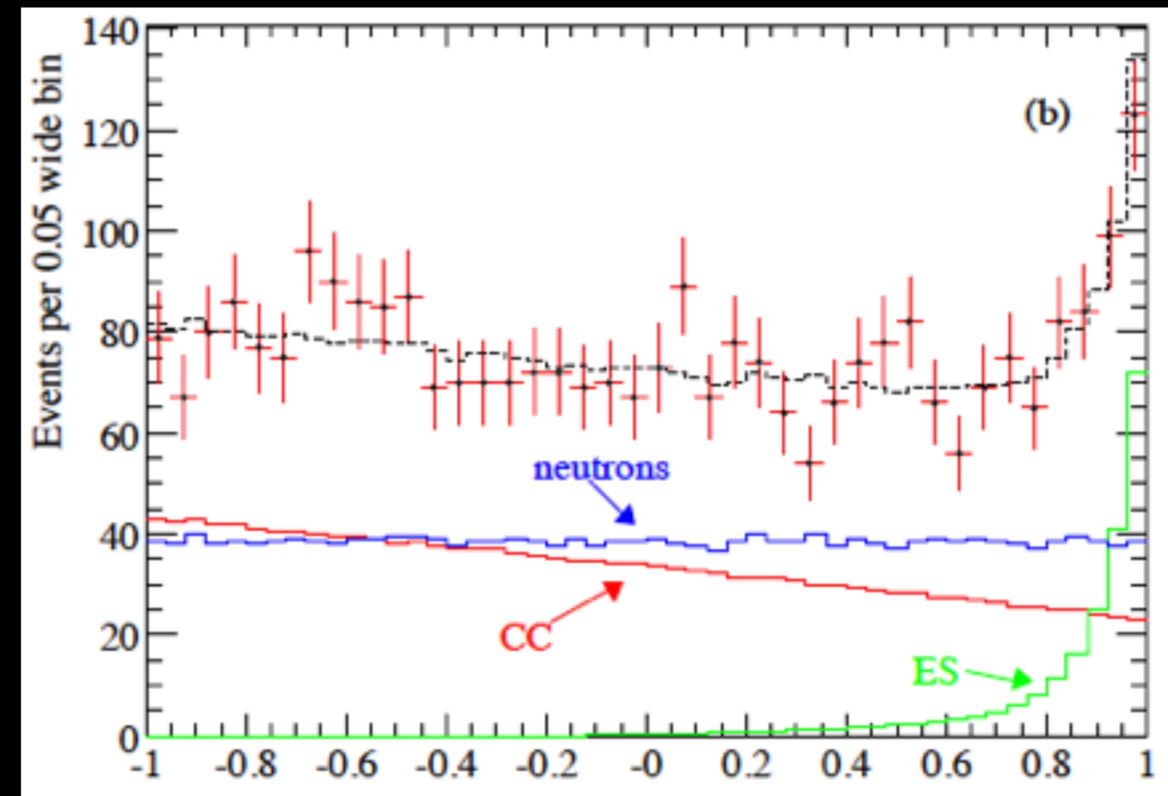
$$\text{CC:}\ \left(1.43^{+0.39}_{-0.21}\right)\%,$$
$$\text{ES:}\ \left(1.46^{+0.40}_{-0.21}\right)\%,$$
$$\text{neutrons:}\ \left(2.28^{+0.41}_{-0.23}\right)\%.$$

Signal-loss from cuts, phase I

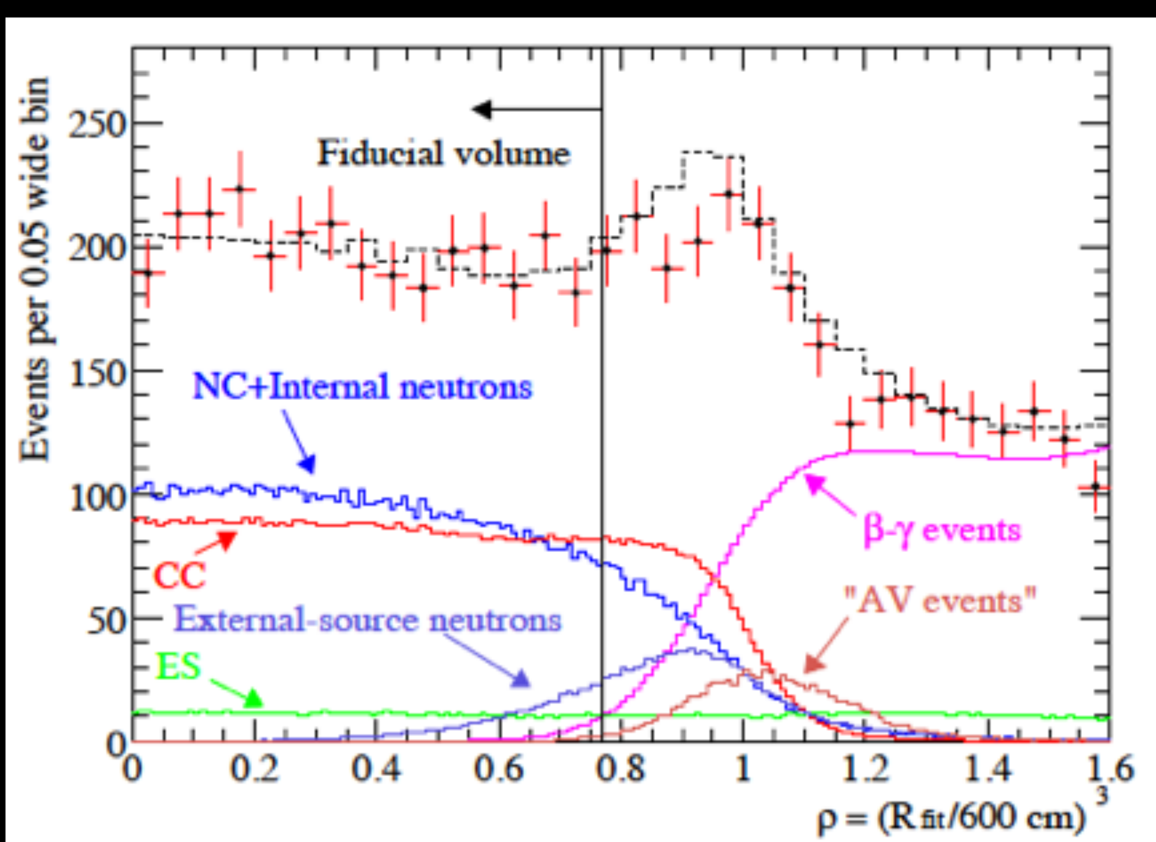
[ref. 15]

SIGNAL EXTRACTION

- Fit distributions of direction, position, isotropy
- Measure number of events and energy spectrum of CC, NC, ES
- (Energy fixed in phase I result)

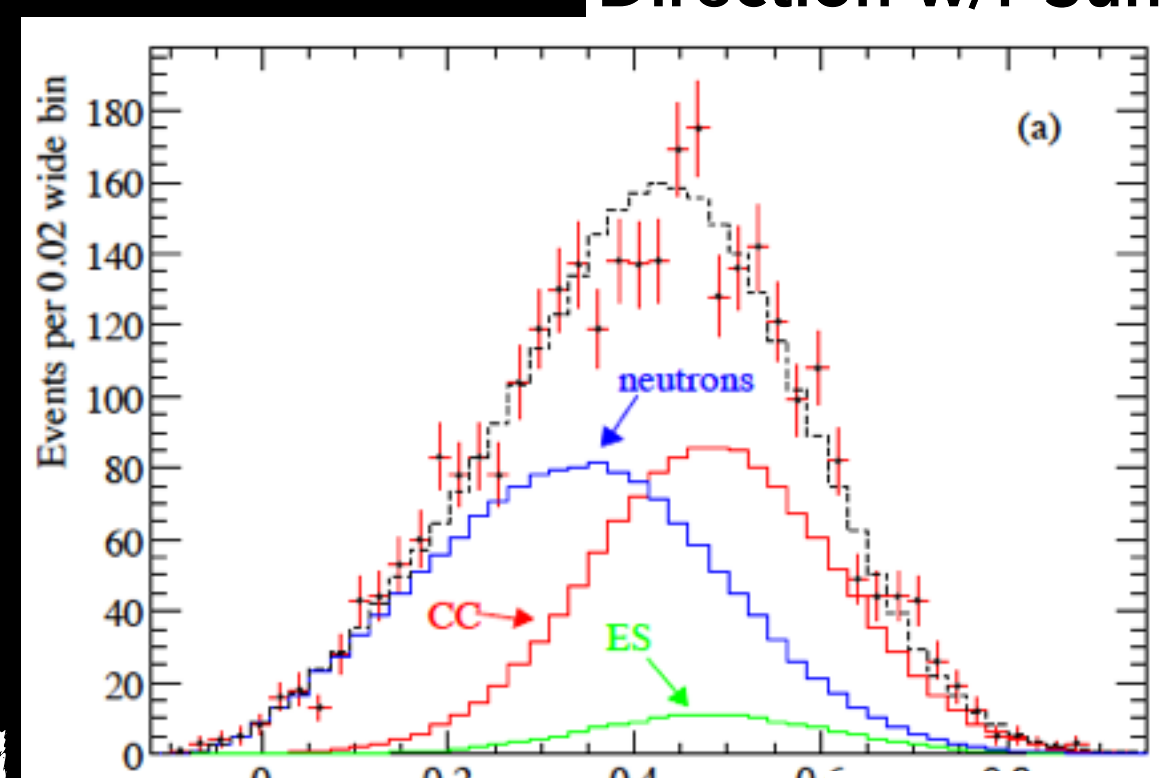


Direction w/r Sun



Radial position

[ref. 13]

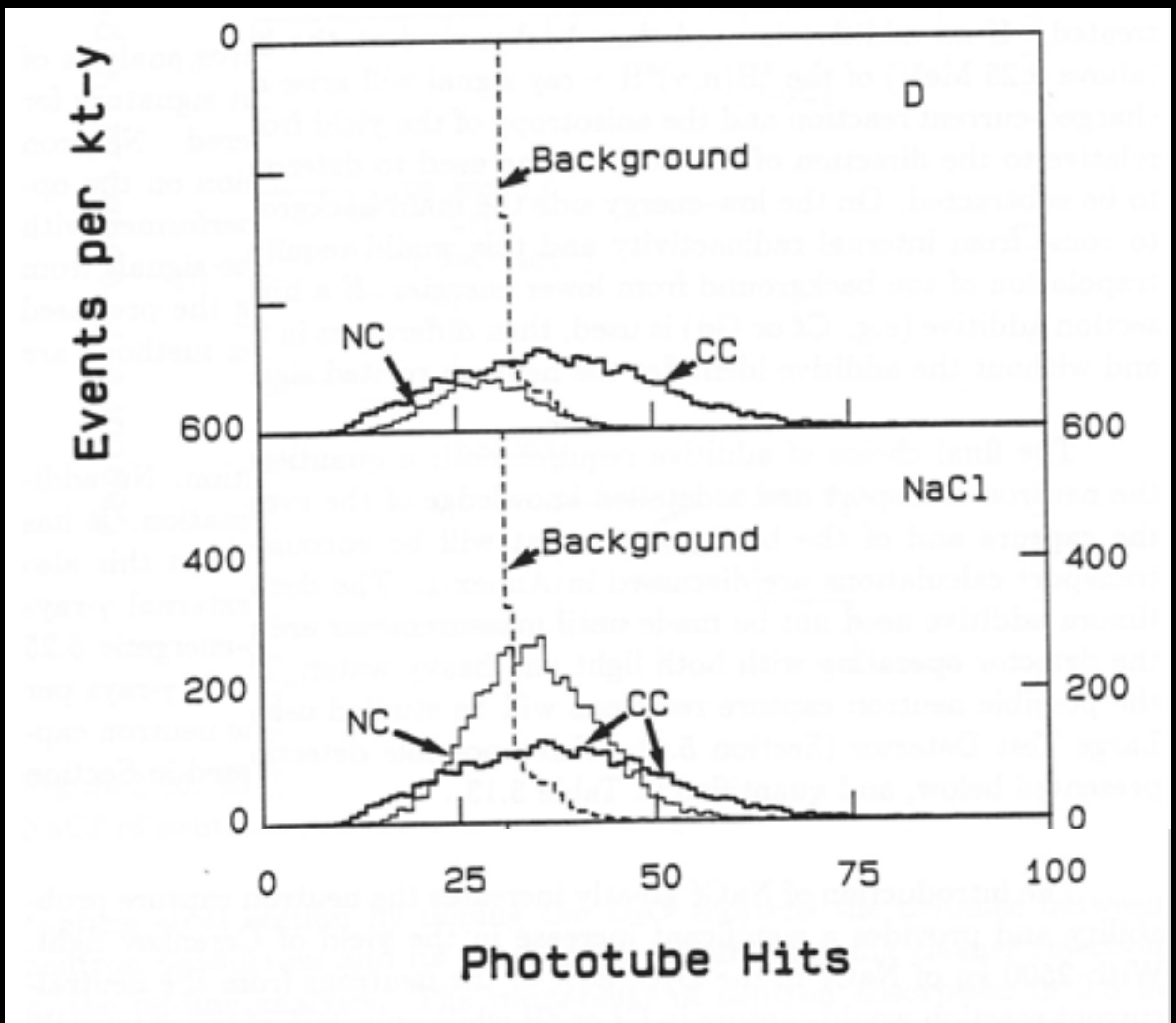


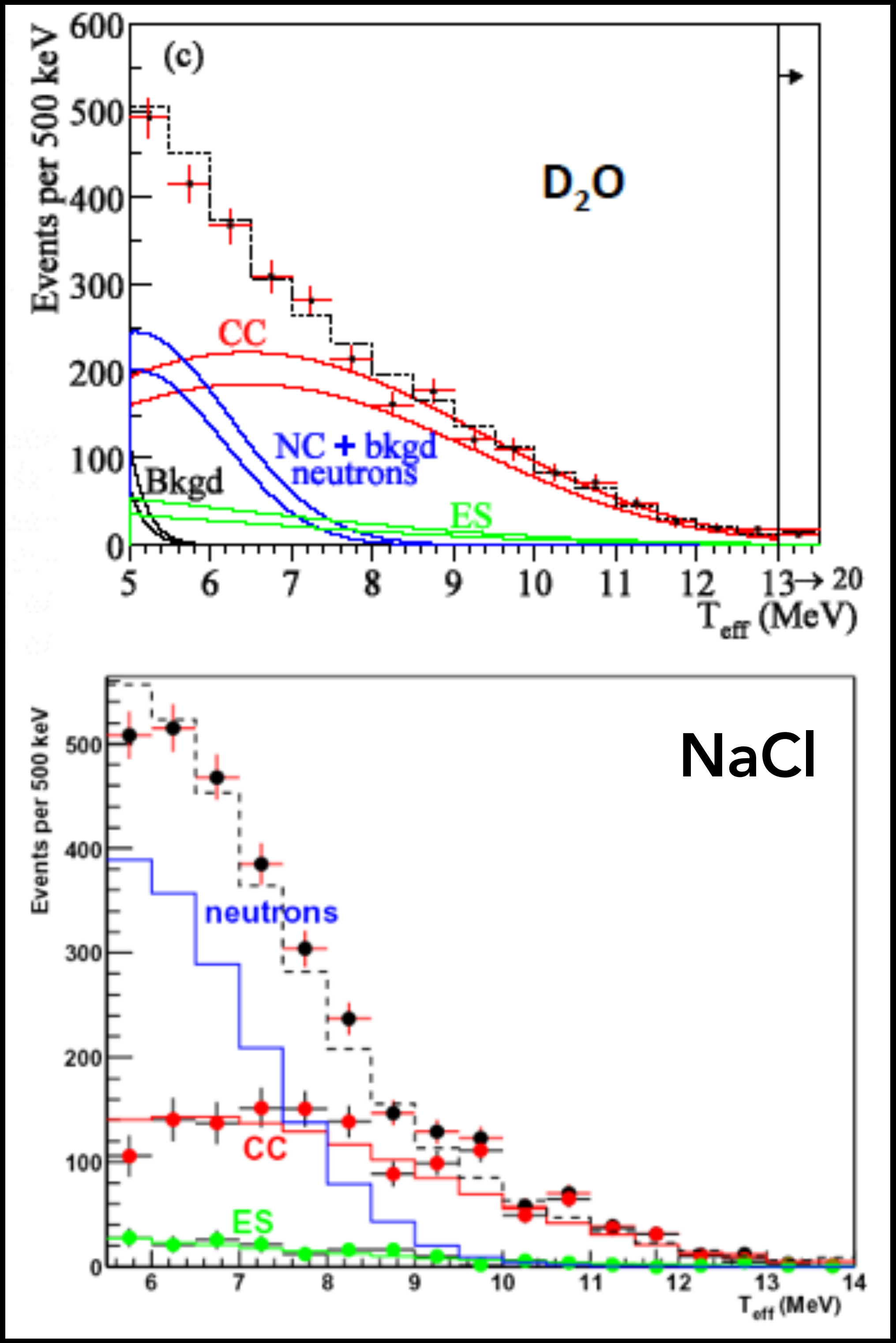
Isotropy

RESULTS, D20 AND SALT

measured 1999-2003

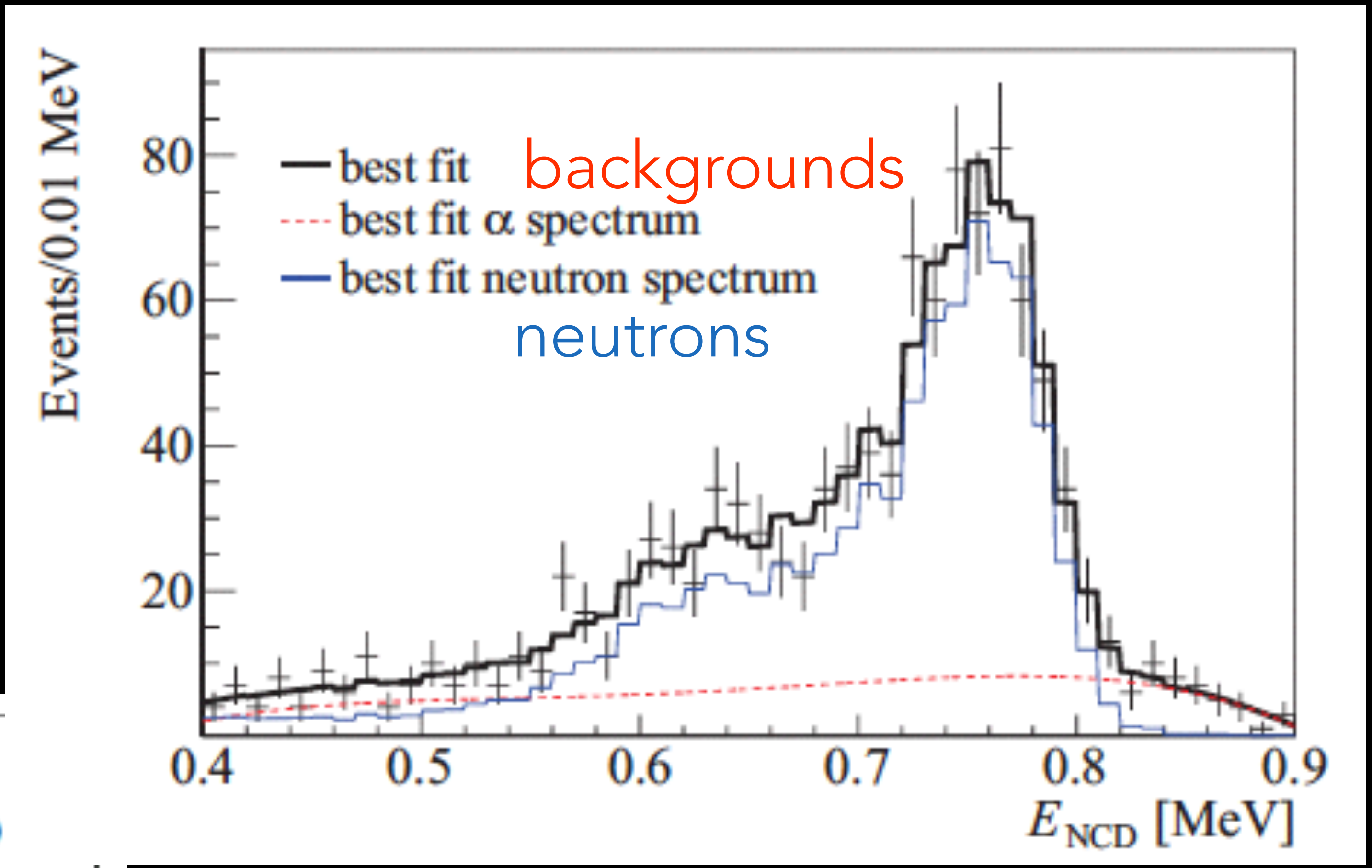
simulated in 1987

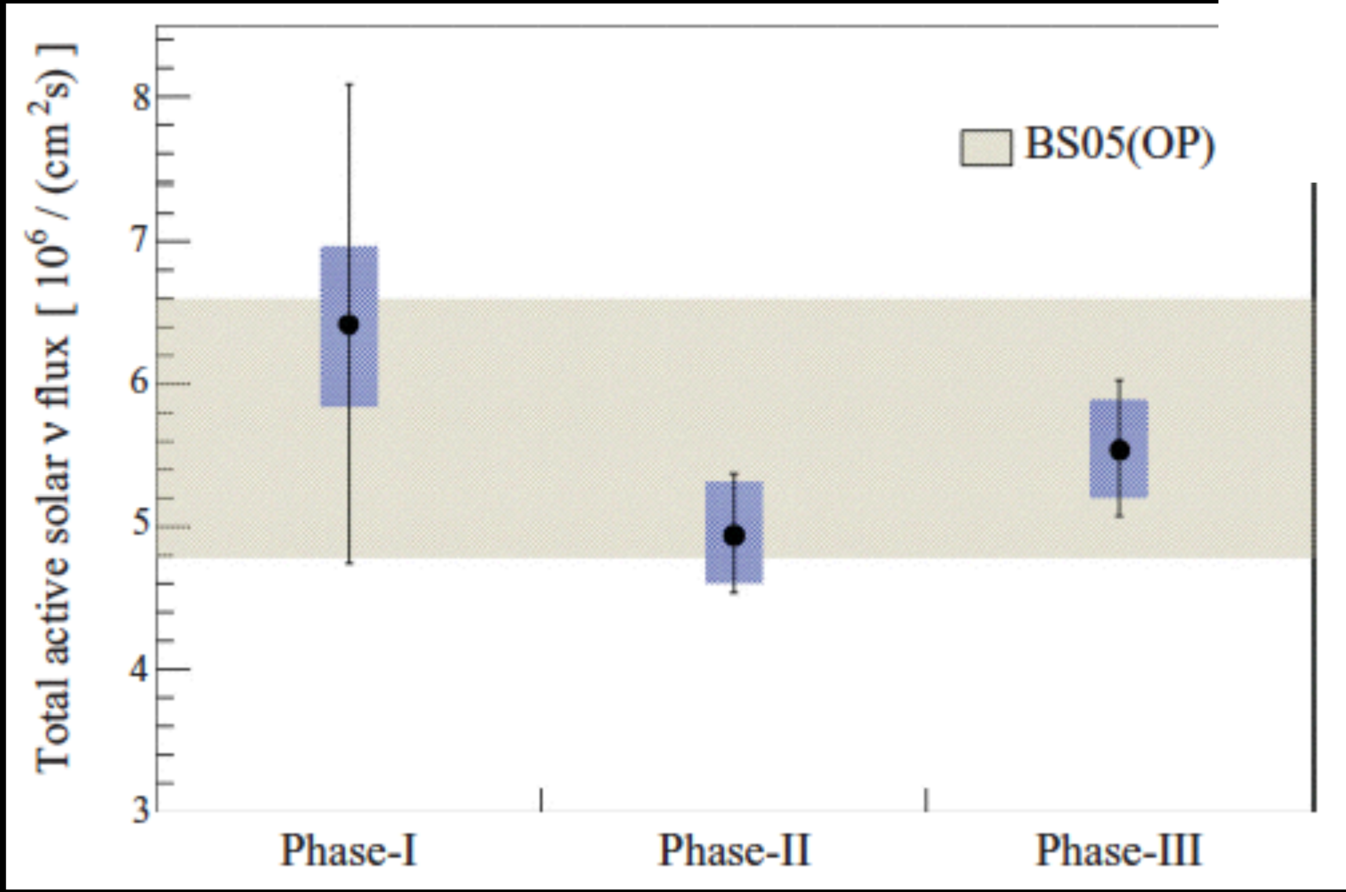




[refs. 12,13]

RESULTS, PHASE III

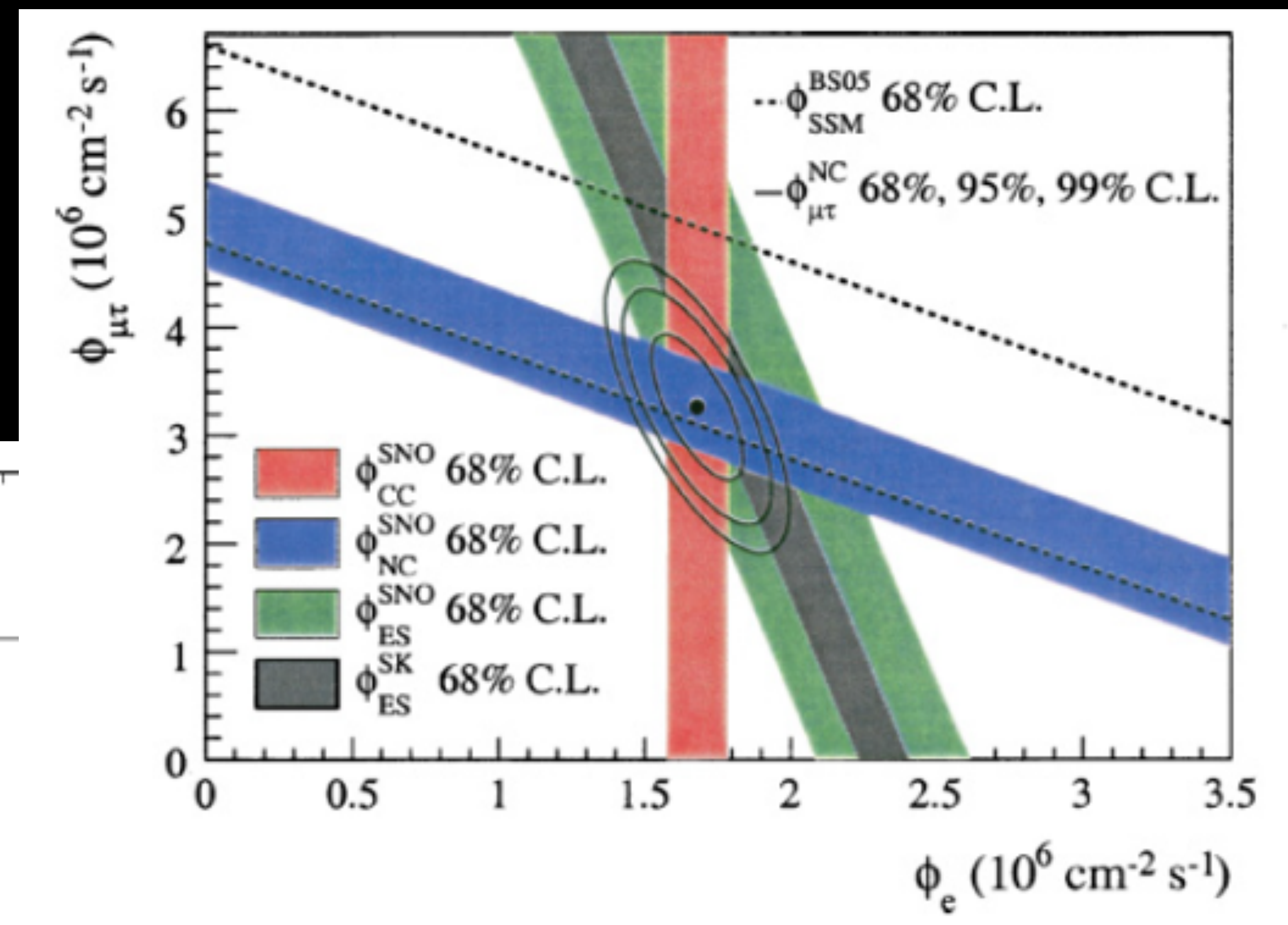


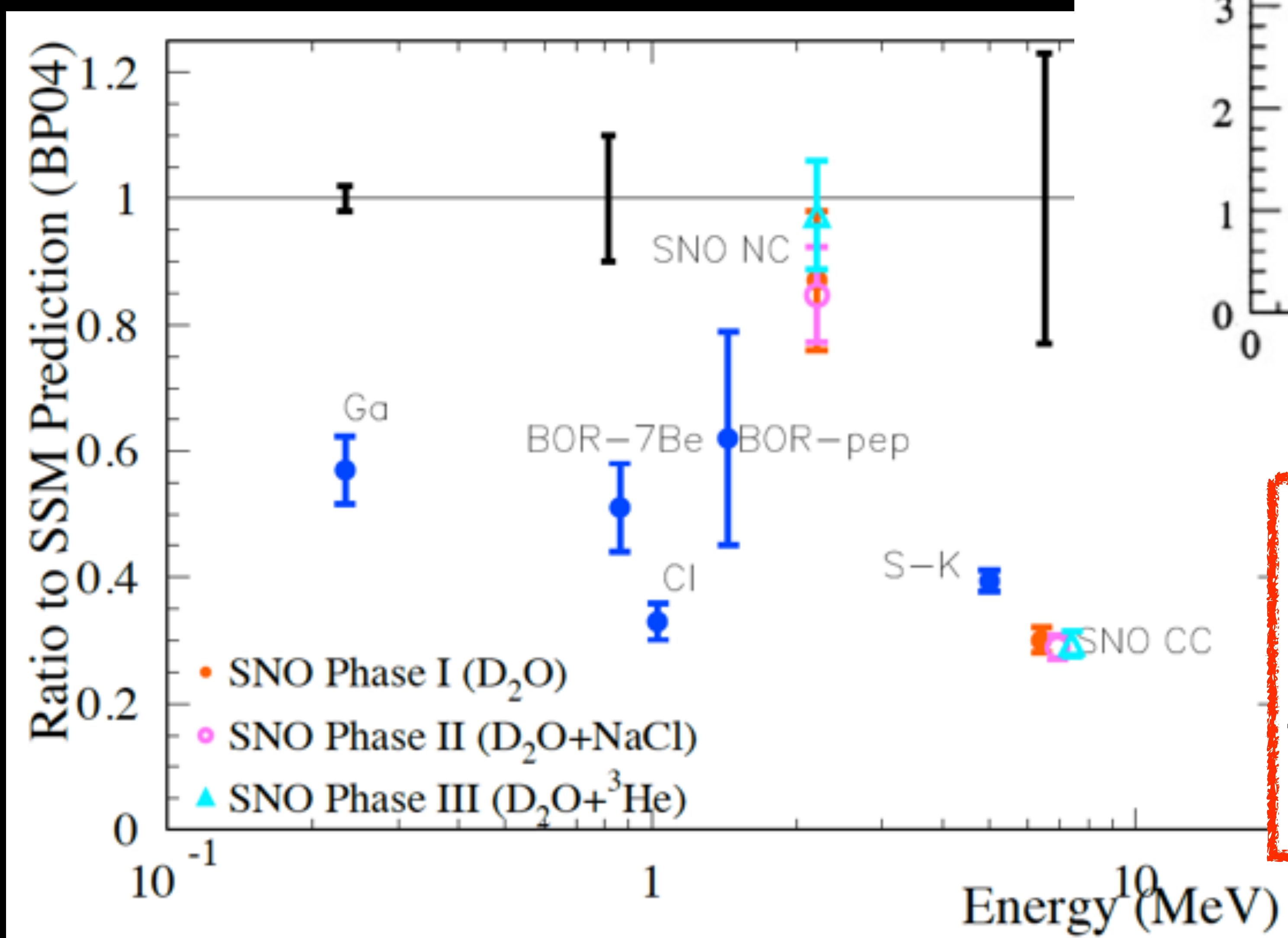


Results of all 3 phases compatible

[ref. 17, 18]

SOLAR NEUTRINO PROBLEM, SOLVED!





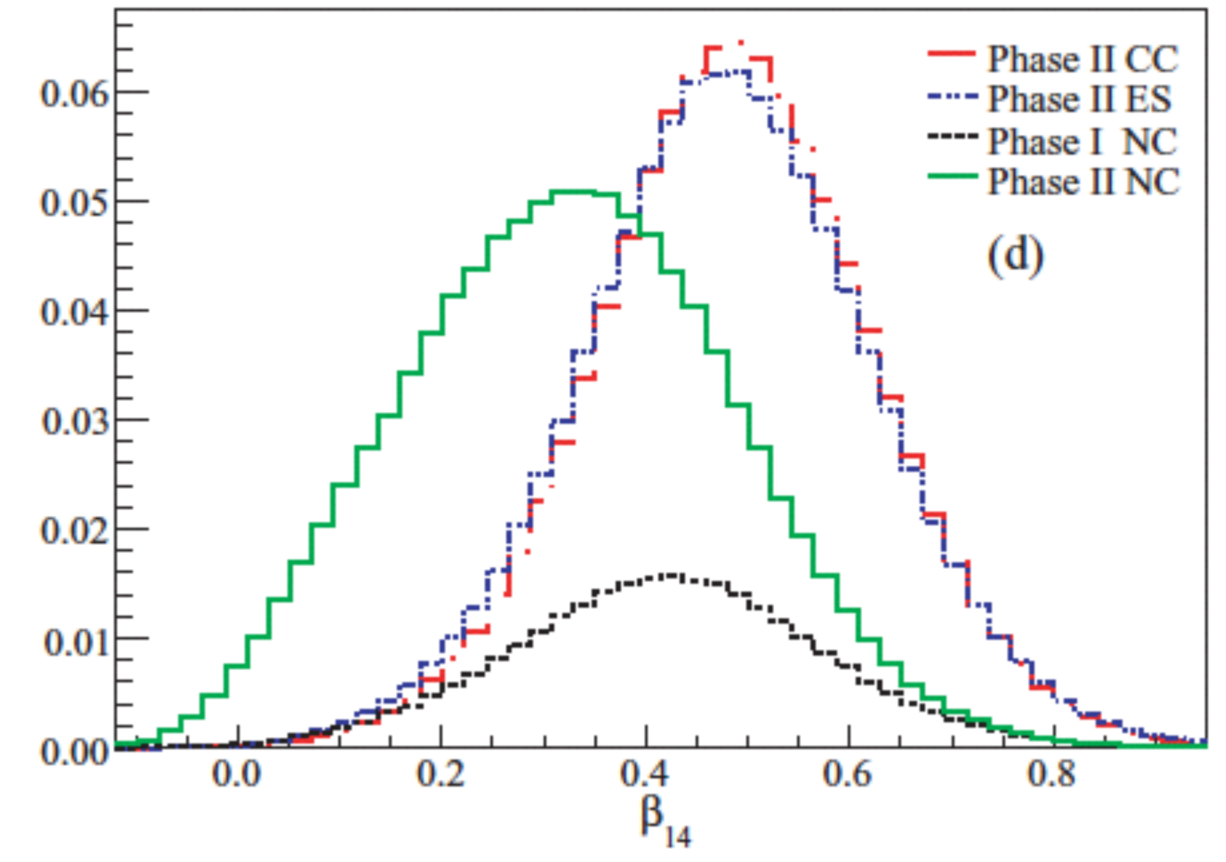
1) ν_e is 1/3 of all ν: neutrinos change flavour!
2) measurement in all flavours confirms solar model

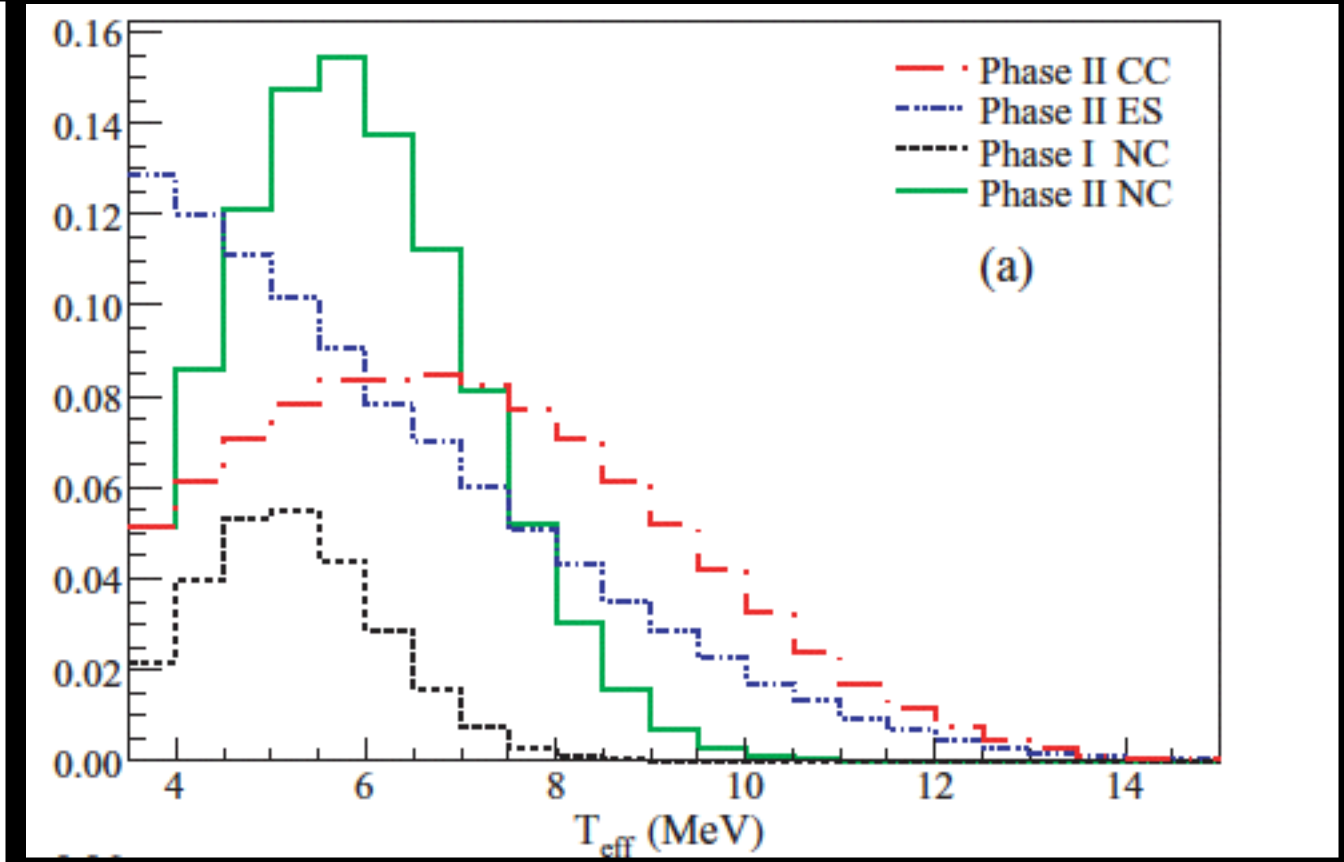
[ref. 14]

SNO SOLAR NEUTRINO RESULTS
AIMING FOR PRECISION

COMBINING PHASES

- Instead of measuring CC, NC, ES ν_e-equivalent fluxes independently for each phase, fit data of all 3 phases with less free parameters: flux of ^{8}B solar neutrinos, and parametrization of oscillation survival probability





- Need to consider different responses to signals across different phases, and correlated systematics
- Example: NC isotropy and energy in phase I and II

[ref. 16]

LOWERING THE THRESHOLD

- Improved energy resolution and background description, pushed threshold down to 3.5 MeV
- Search for LMA survival probability upturn; allows much better NC detection efficiency

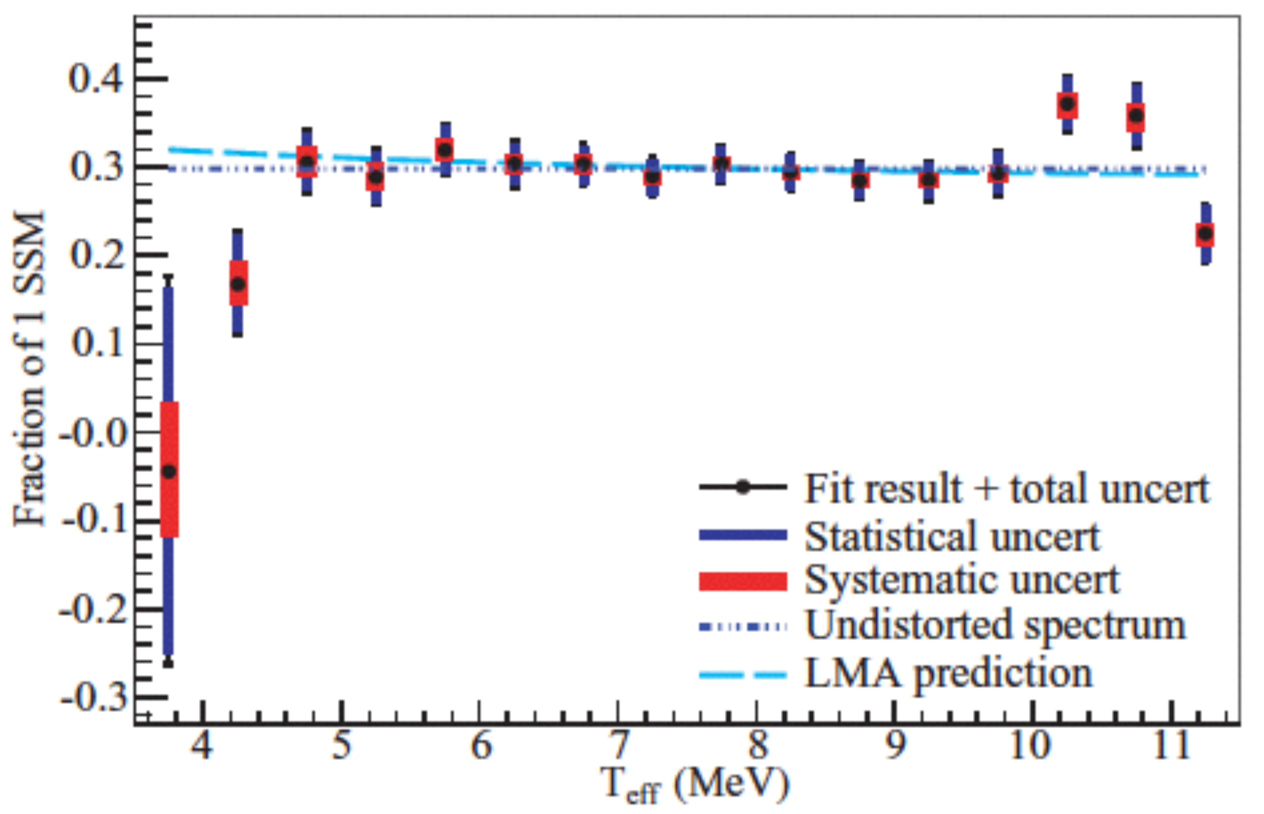
[ref. 16]

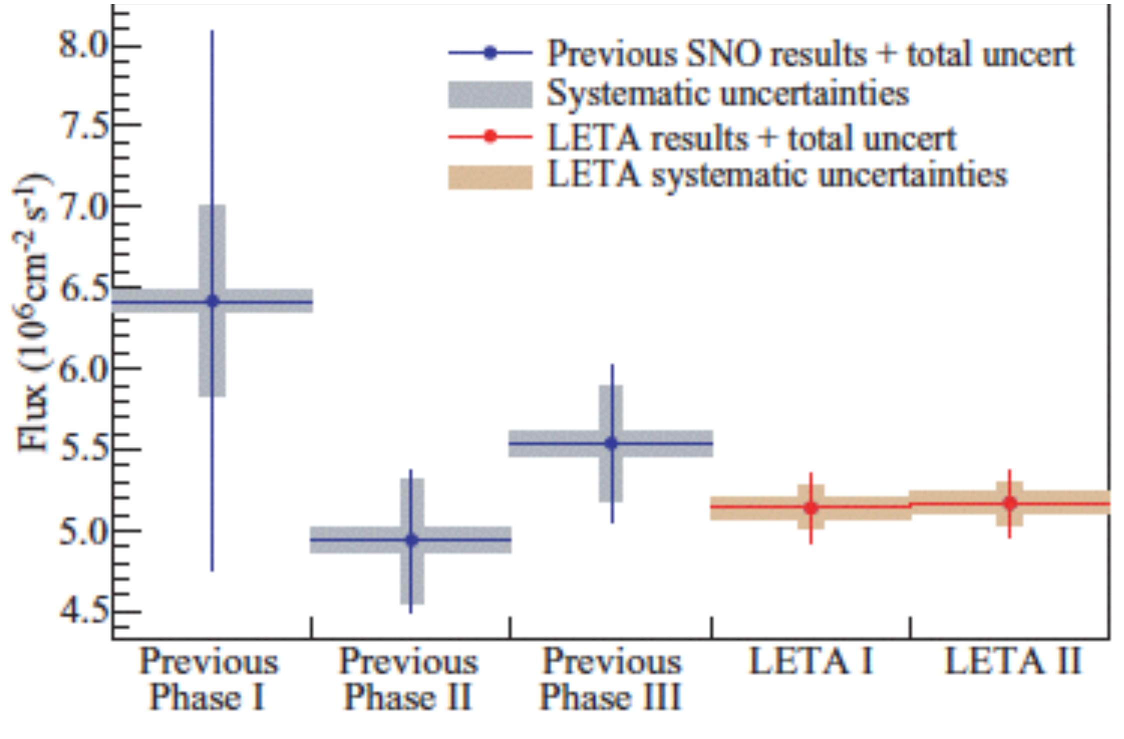
(i) binned-histogram method

$$\Phi_{NC}^{binned} = 5.140^{+0.160}_{-0.158}(\text{stat})^{+0.132}_{-0.117}(\text{syst}) \times 10^6\ \text{cm}^{-2}\ \text{s}^{-1}$$

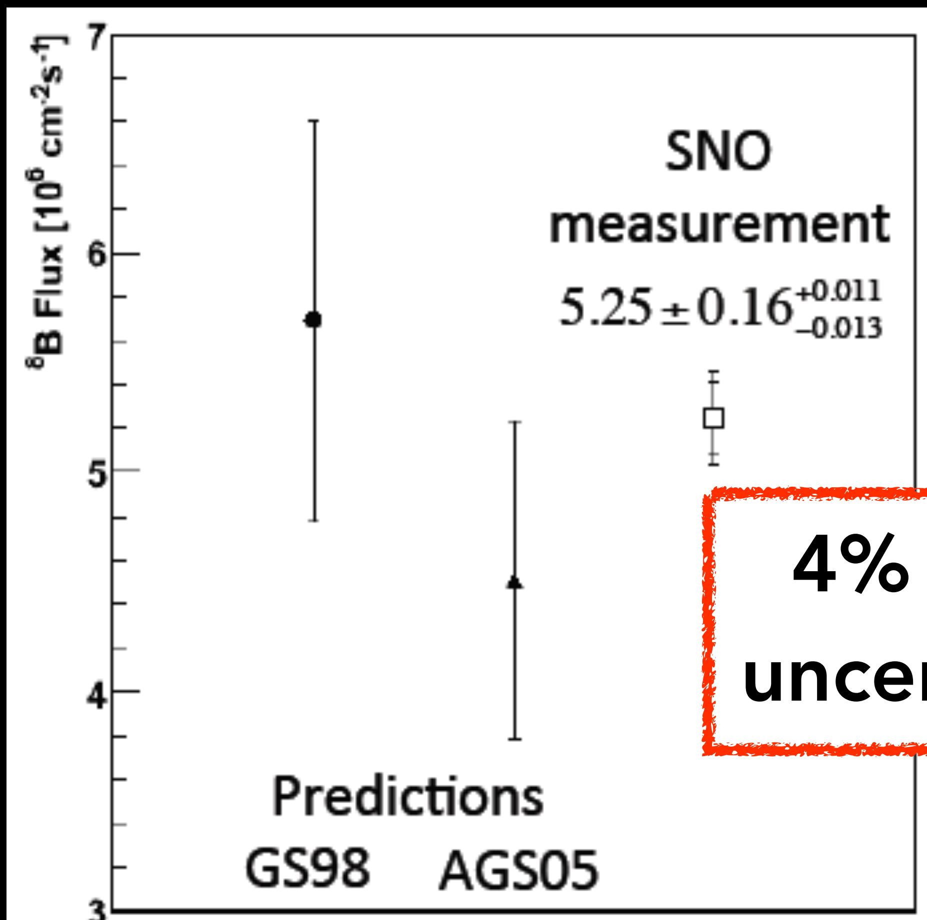
(ii) kernel estimation method

$$\Phi_{NC}^{kernel} = 5.171^{+0.159}_{-0.158}(\text{stat})^{+0.132}_{-0.114}(\text{syst}) \times 10^6\ \text{cm}^{-2}\ \text{s}^{-1}$$



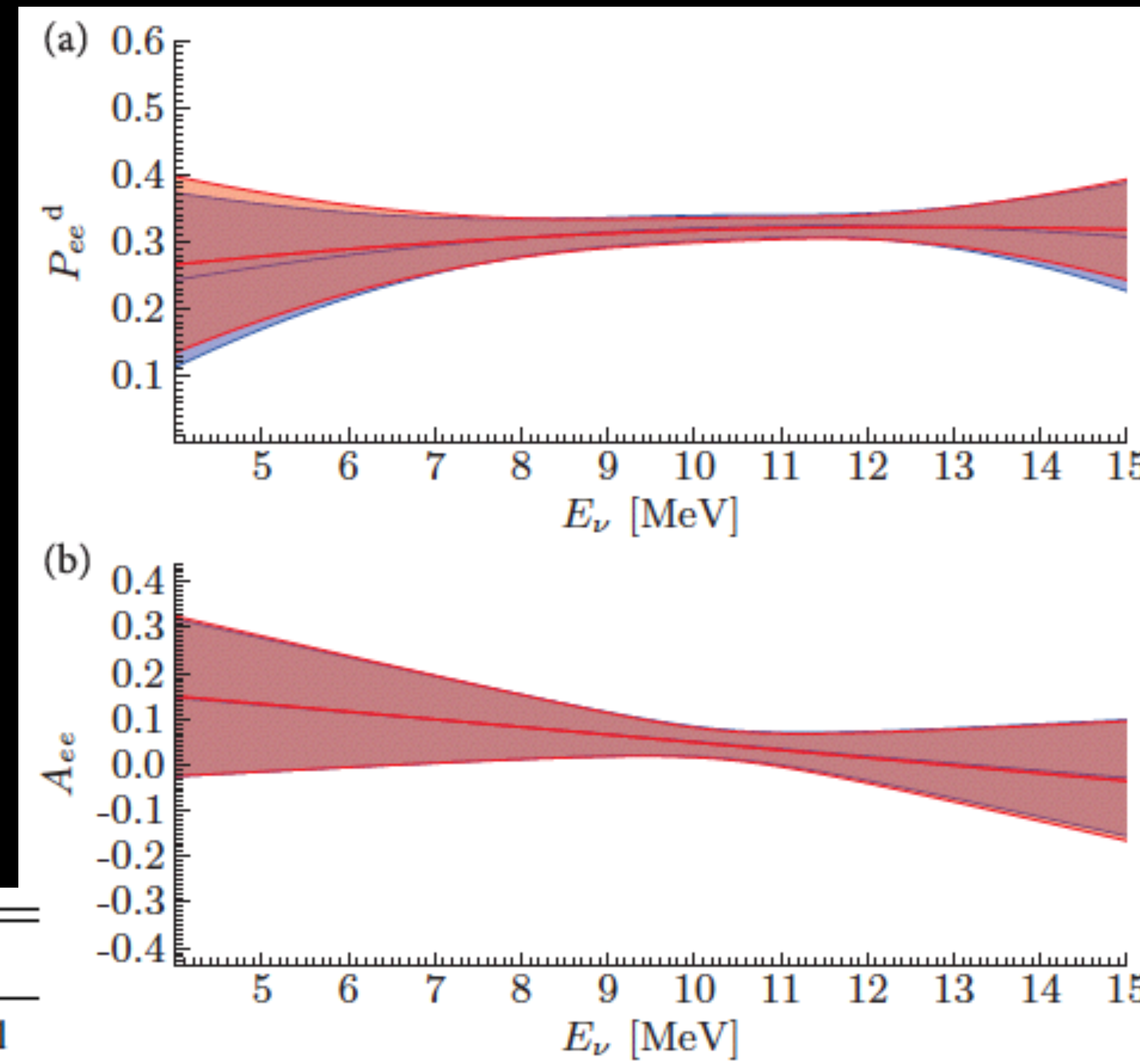


COMBINATION ALL PHASES



4% total uncertainty

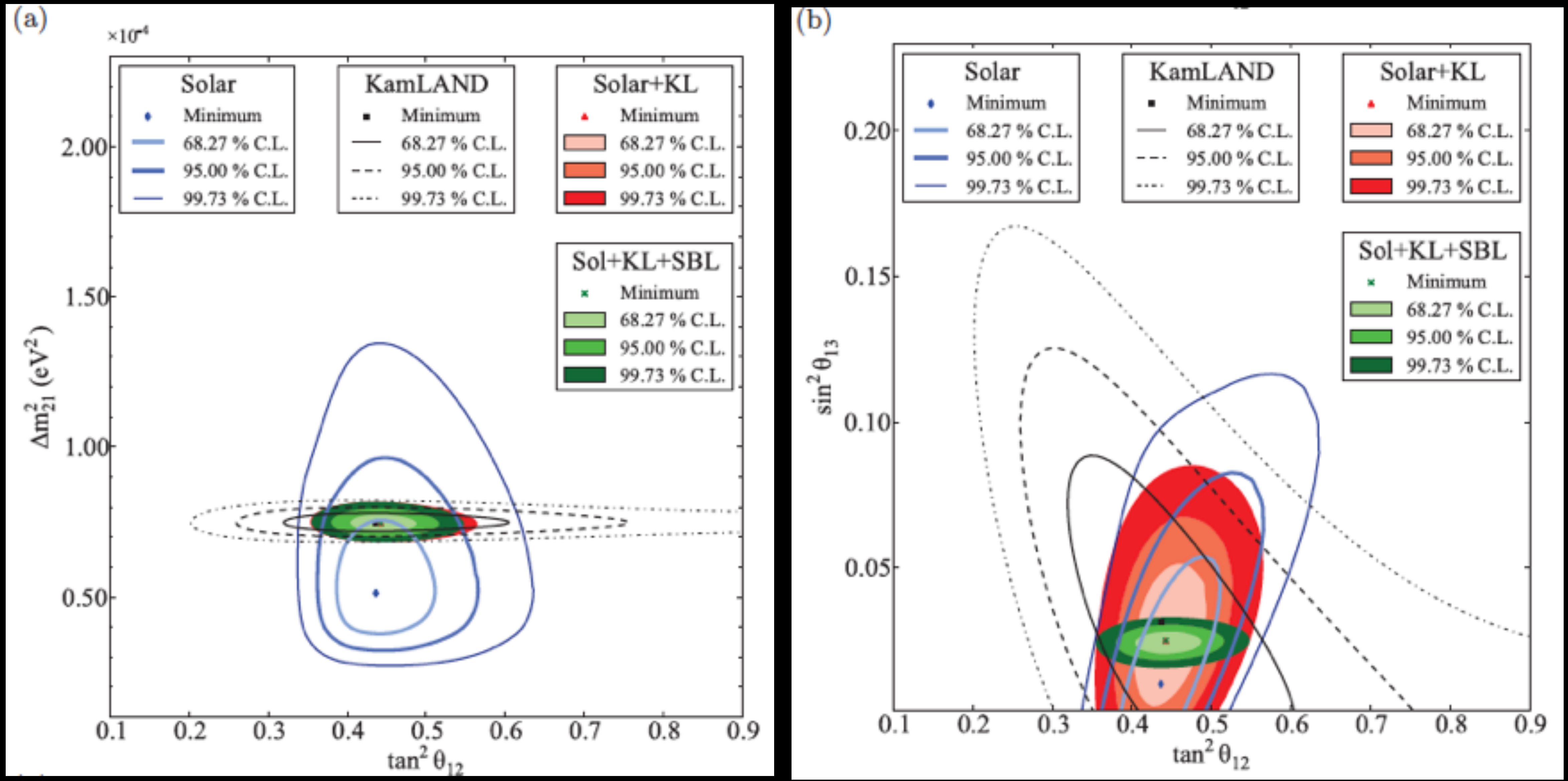
	Best fit	Stat.	Systematic uncertainty			
			Basic	D/N	MC	Total
Φ_B	5.25	± 0.16	$^{+0.11}_{-0.12}$	± 0.01	$^{+0.01}_{-0.03}$	$^{+0.11}_{-0.13}$
c_0	0.317	± 0.016	$^{+0.008}_{-0.010}$	± 0.002	$^{+0.002}_{-0.001}$	± 0.009
c_1	0.0039	$^{+0.0065}_{-0.0067}$	$^{+0.0047}_{-0.0038}$	$^{+0.0012}_{-0.0018}$	$^{+0.0004}_{-0.0008}$	± 0.0045
c_2	-0.0010	± 0.0029	$^{+0.0013}_{-0.0016}$	$^{+0.0002}_{-0.0003}$	$^{+0.0004}_{-0.0002}$	$^{+0.0014}_{-0.0016}$
a_0	0.046	± 0.031	$^{+0.007}_{-0.005}$	± 0.012	$^{+0.002}_{-0.003}$	$^{+0.014}_{-0.013}$
a_1	-0.016	± 0.025	$^{+0.003}_{-0.006}$	± 0.009	± 0.002	$^{+0.010}_{-0.011}$



Consistent with LMA (including MSW effect)

[ref. 18]

NEUTRINO OSCILLATIONS



- SNO results crucial to good precision on θ_{12}
- Complementary with KamLAND's Δm^2_{12} sensitivity
- Tension led to early hints of non-zero θ_{13} , SBL experiments (Daya Bay, Reno, Double-Chooz, and also T2K, Minos) then measured it

[ref. 18]

SUMMARY

- SNO designed to solve the Solar Neutrino Problem
- Challenges on detector construction, keeping cleanliness, nailing systematics down with calibrations
- Groundbreaking results showing Solar Models were correct and that neutrinos do change flavor
- Precision contributing to global oscillations analysis
- Recently reactivated analysis group into new searches
- Field wide open for new experiments
  - CP violation
  - Dirac or Majorana neutrinos?
  - Absolute neutrino mass and ordering

REFERENCES

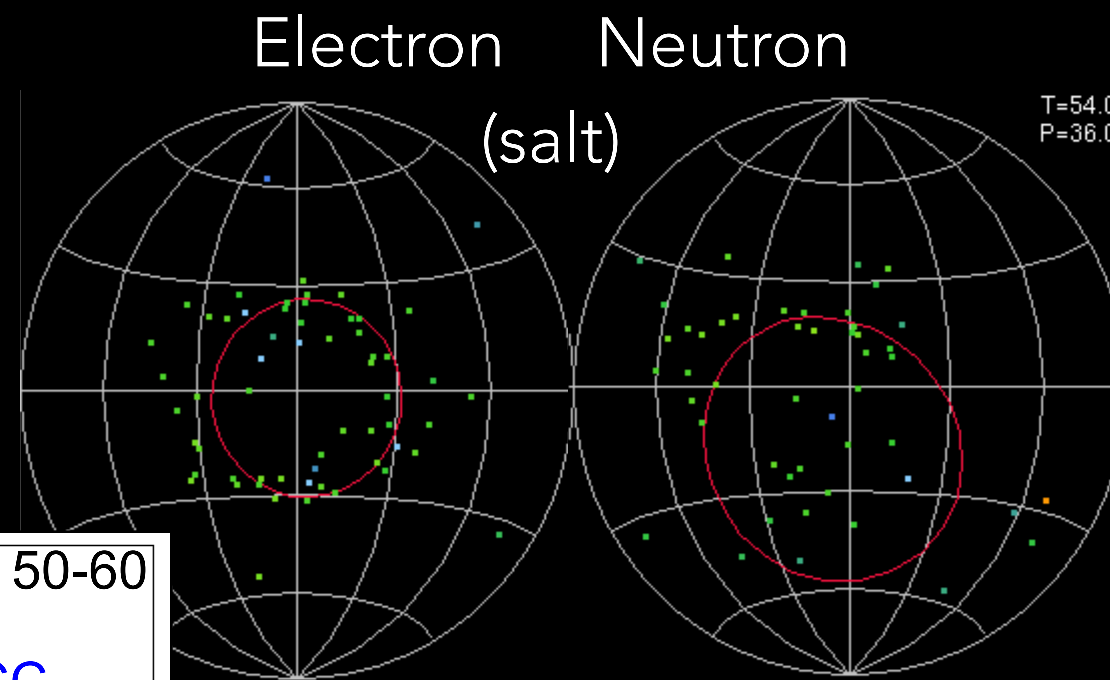
- [1] H.H. Chen, PRL 55, vol. 14 (1985), p. 1534
- [2] D. Sinclair et al., Il Nuovo Cimento C (1986) 9: 308

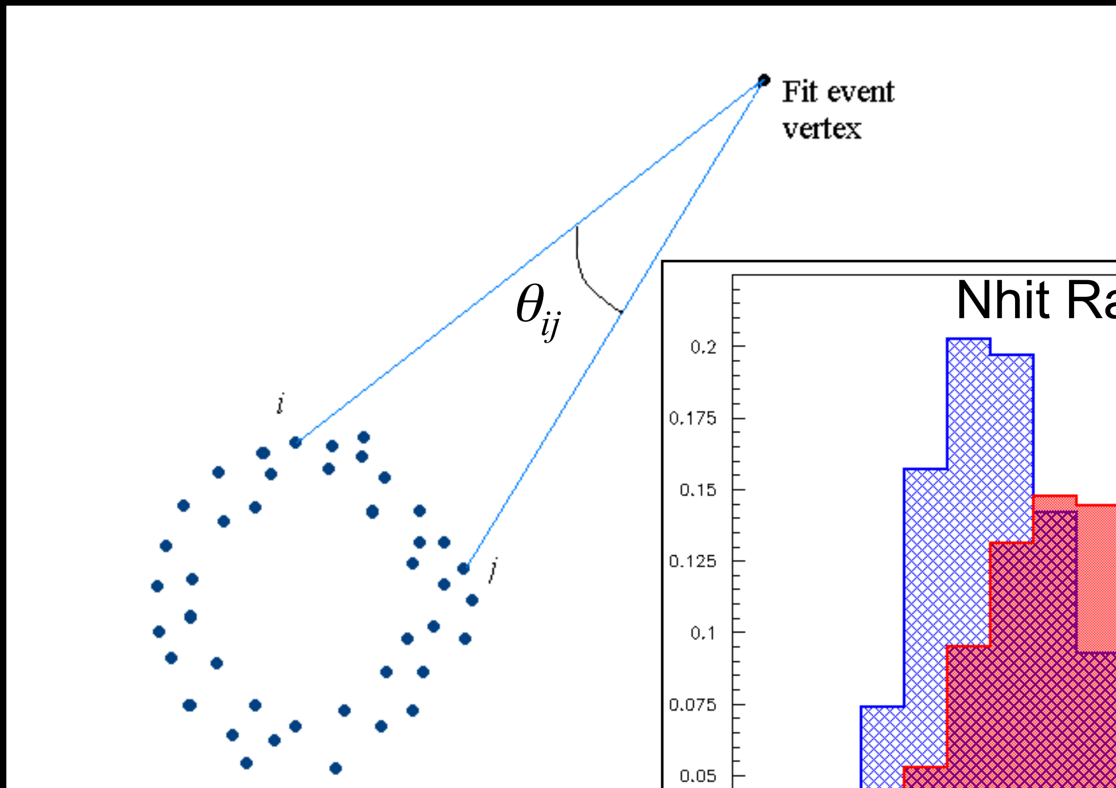
- [3] SNO Collab., NIM A449 (2000) pp. 172-207
- [4] M.R. Dragowsky et al, NIMA481 (2002) 284-296
- [5] A.W.P. Poon et al, NIM A452 (2000)15-129
- [6] N. Tagg et. al., NIM A489 (2002) 92-102
- [7] B.A. Moffat et al, NIMA554 (2005) 255-265
- [8] K. Boudjemline et al, NIMA 620 (2010) 171-181
- [9] T.C. Andersen et al, NIM A501 (2003) 386-398 and 399-417
- [10] B. Aharmim et al, NIM A604 (2009) 531-535
- [11] J.F. Amsbaugh et al, NIM A579 (2007) 1054-1080

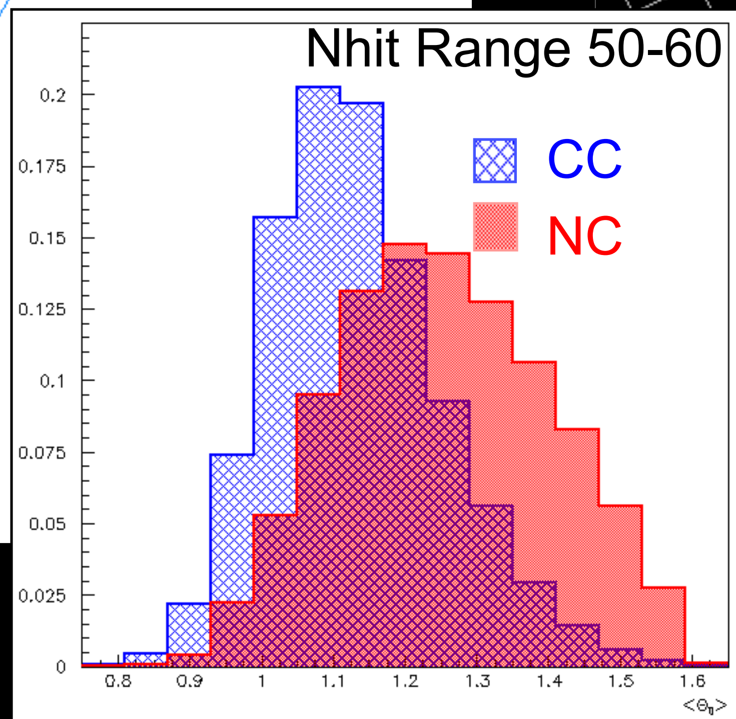
- [12] SNO Collab., PRL 89, 011301 (2002)
- [13] SNO Collab., PRL92, 181301 (2004)
- [14] SNO Collab., PRC 72, 055502 (2005)
- [15] SNO Collab., PRC 75 045502 (2007)
- [16] SNO Collab., PRC 81, 055504 (2010)
- [17] SNO Collab., PRC 87, 015502 (2013)
- [18] SNO Collab., PRC 88, 025501 (2013)

BACKUP SLIDES

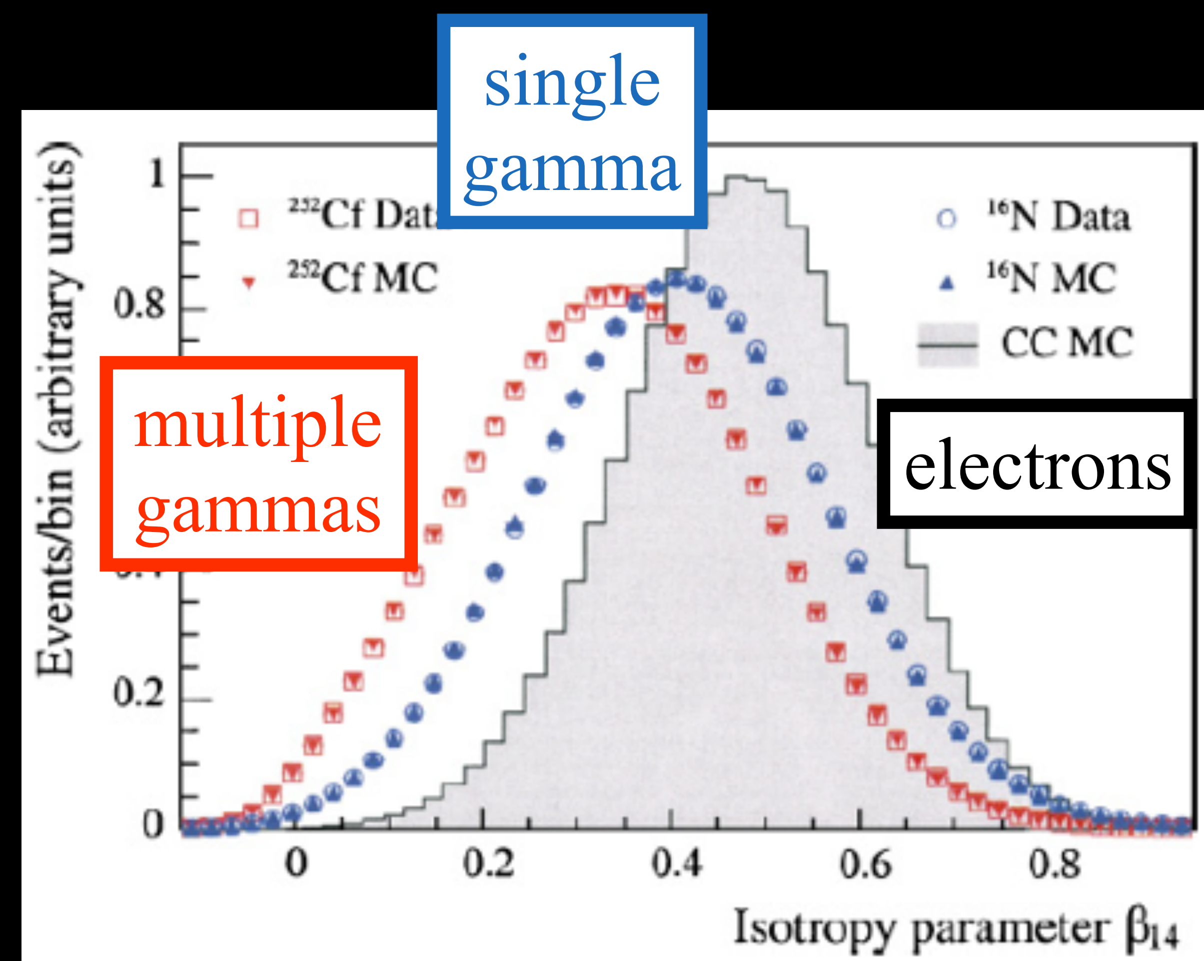
ISOTROPY







$<\theta_{ij}>$ average over all PMT pairs



$$\beta_l \approx \left\langle P_l\left(\cos\theta_{ij}\right)\right\rangle_{i\neq j}$$

P_l = l_{th} order Legendre polynomial

best separation found with $\beta_{14} = \beta_1 + 4\beta_4$

[ref. 14]

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