SNO

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ON BEHALF OF THE SNO COLLABORATION

XVII INTERNATIONAL WORKSHOP ON NEUTRINO TELESCOPES
VENEZIA, MARCH 13, 2017

THE SNO COLLABORATION

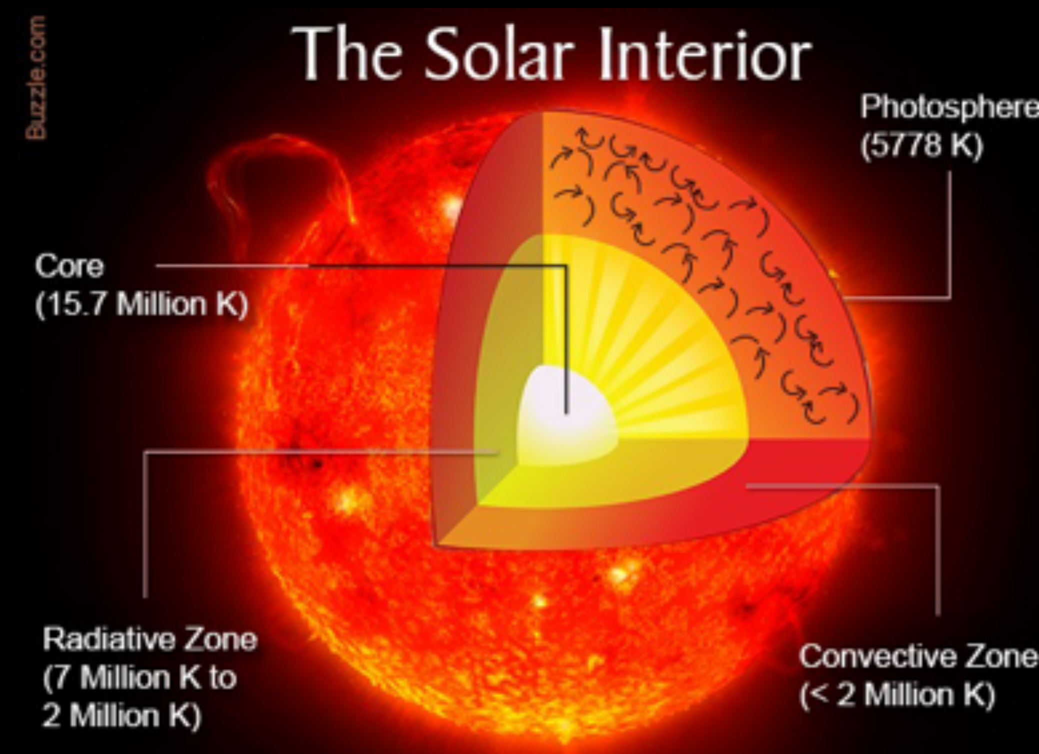
August 2008 meeting @ SNOLAB

dedicated to

Fraser Duncan, Davis Earle, Cliff Hargrove, John Simpson

SOLAR NEUTRINOS

THE SUN AS A NEUTRINO SOURCE

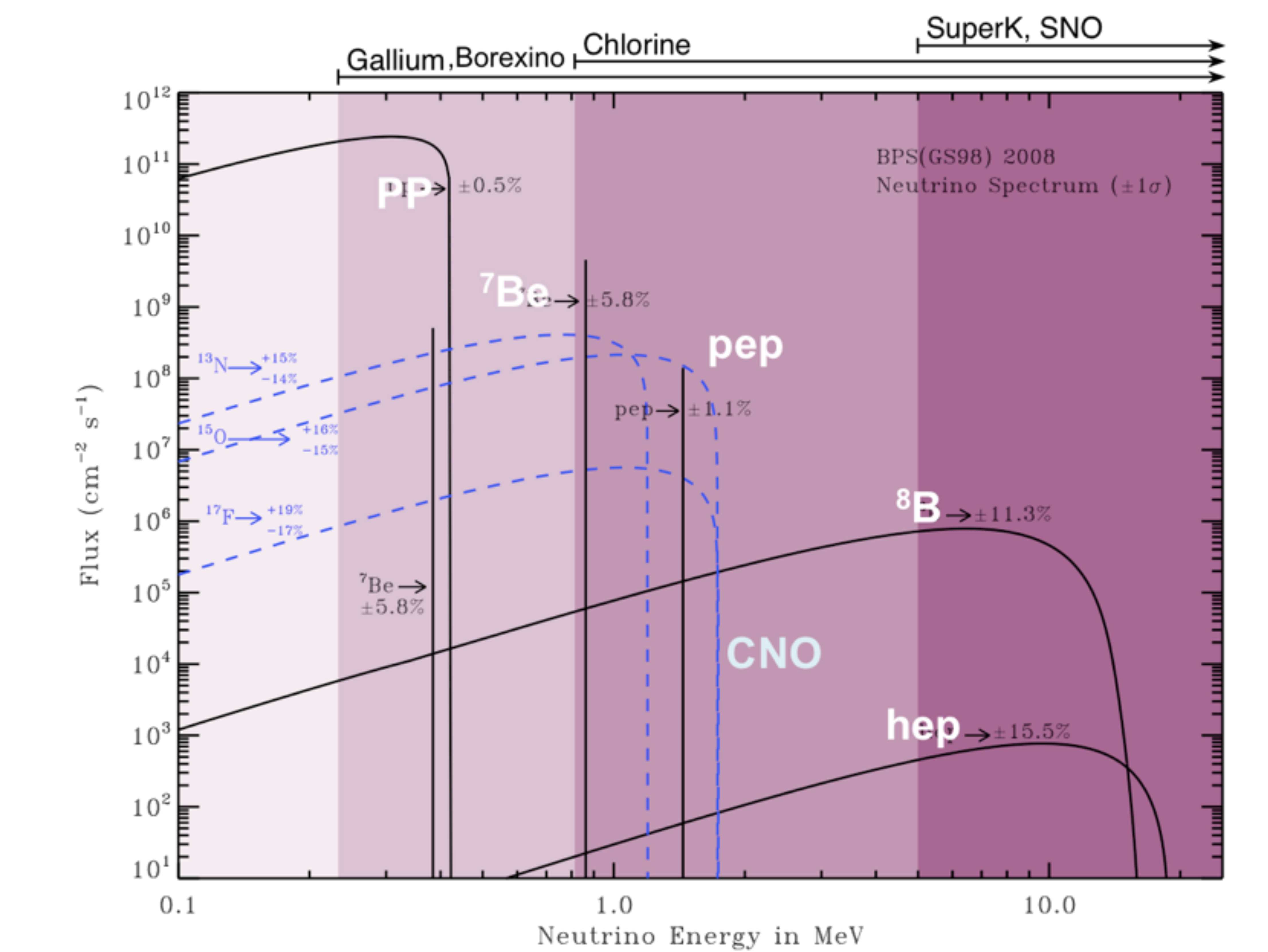


- Nuclear fusion reactions recognized early on as the only viable source of stellar energy production
- Hans Bethe (1930's): first solar model based on nuclear reactions

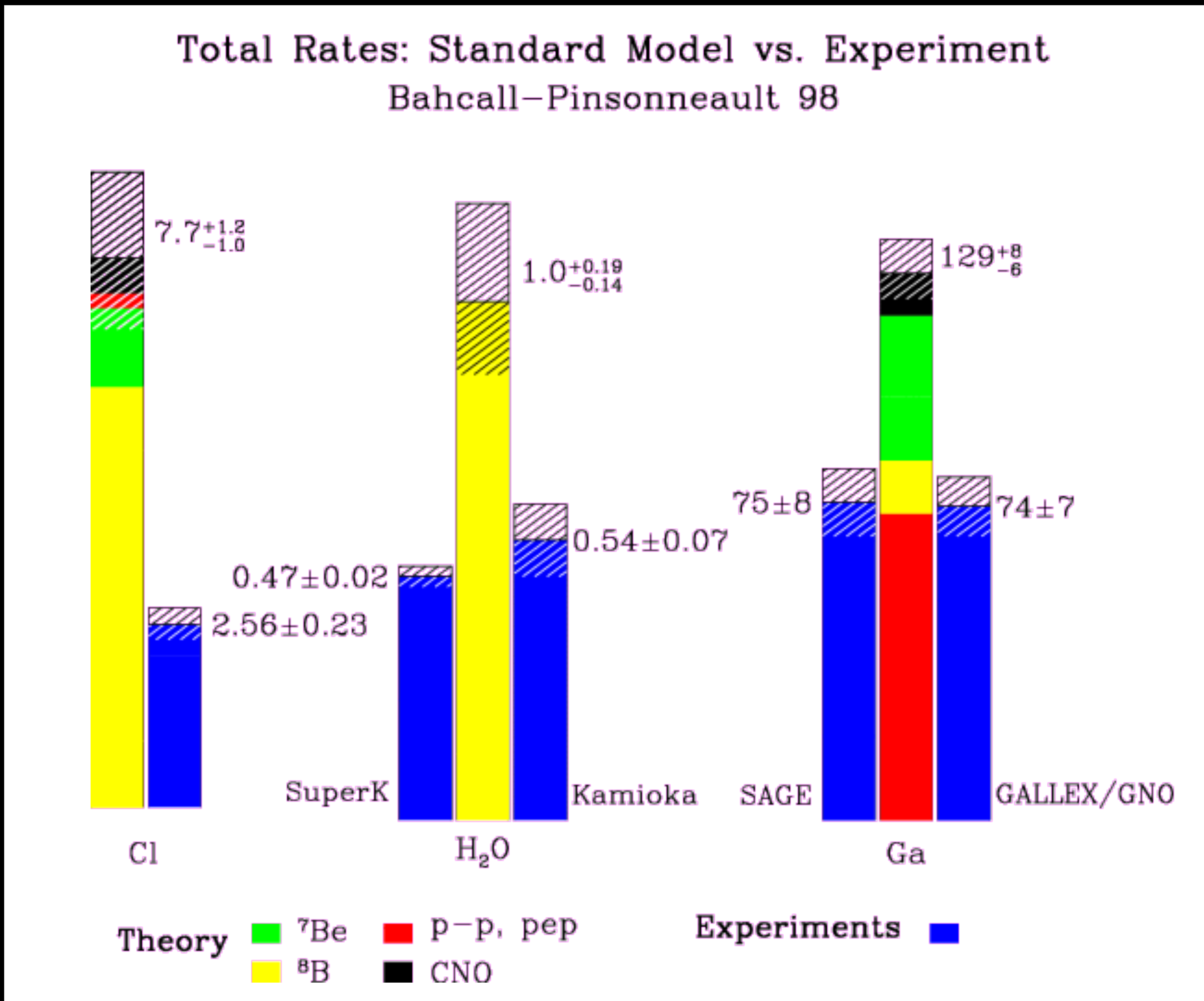
- John Bahcall: increasingly detailed solar model calculations of the solar neutrino fluxes, since the 60's

- 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

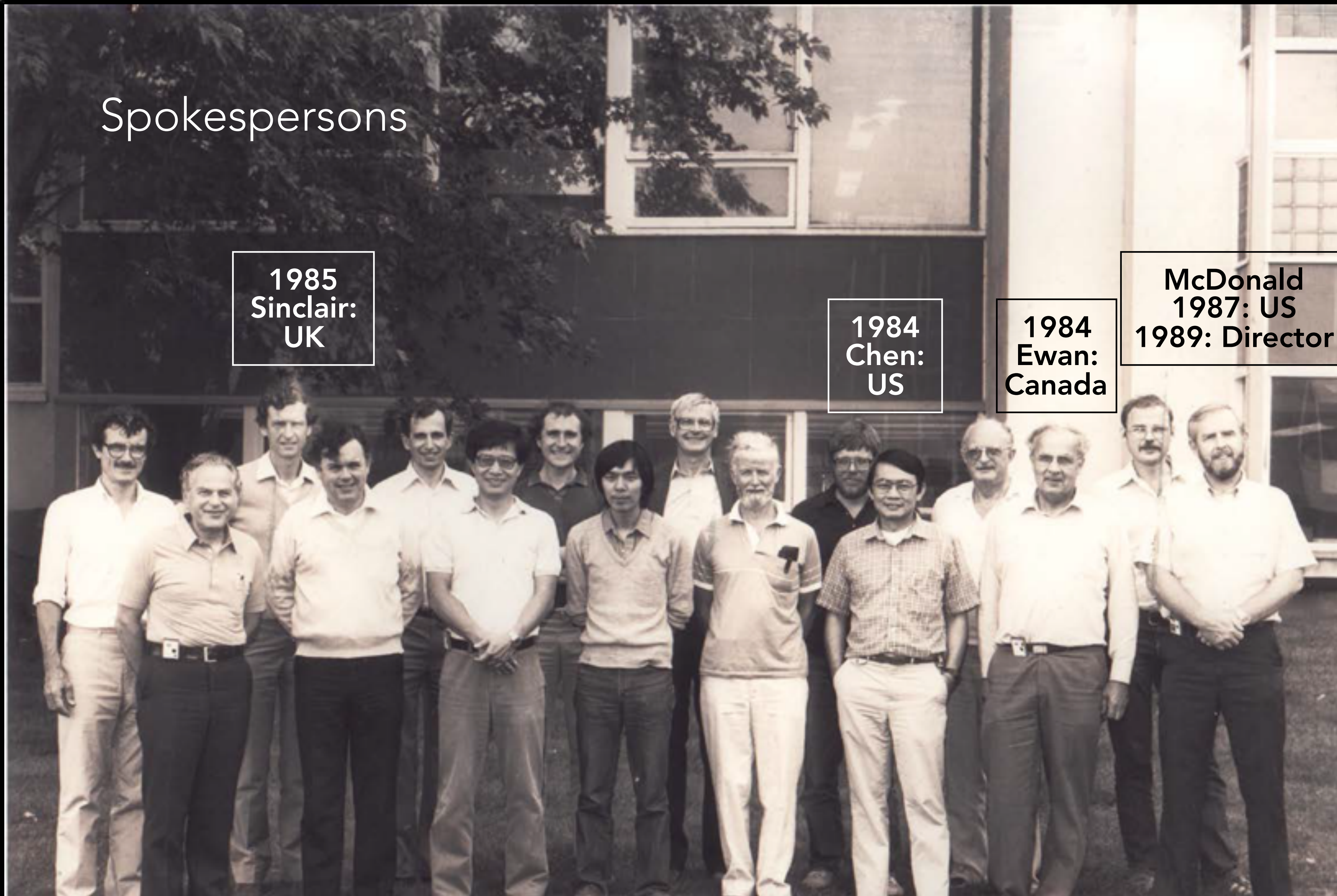
[ref. 1]

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



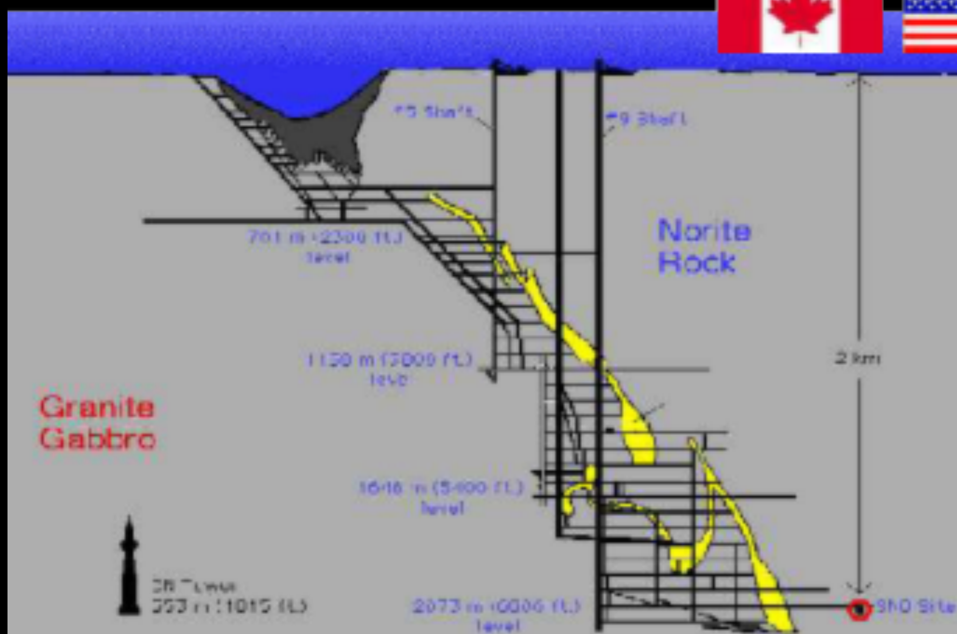
SNO Collaboration Meeting, Chalk River, 1986

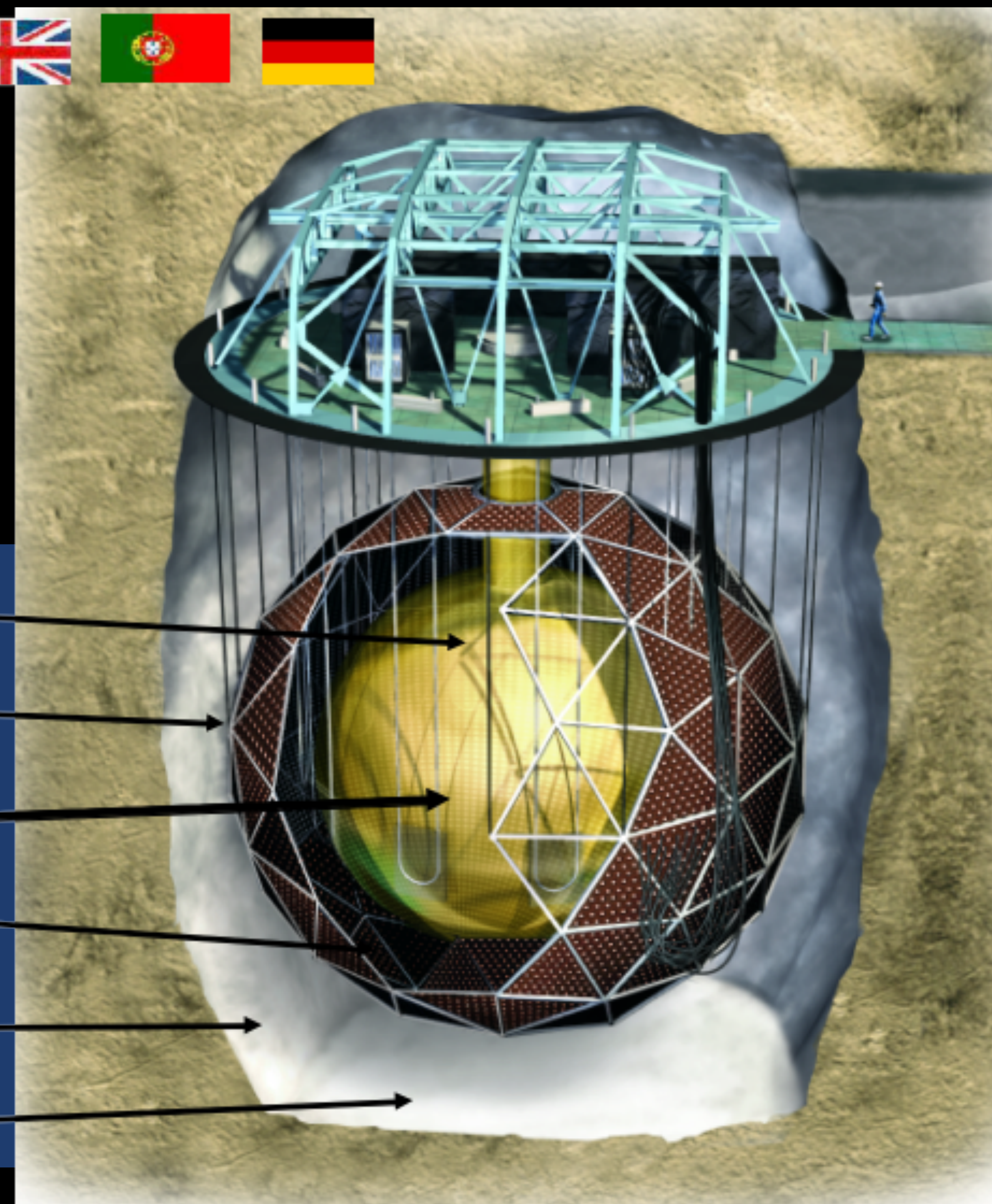
[ref. 2]

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

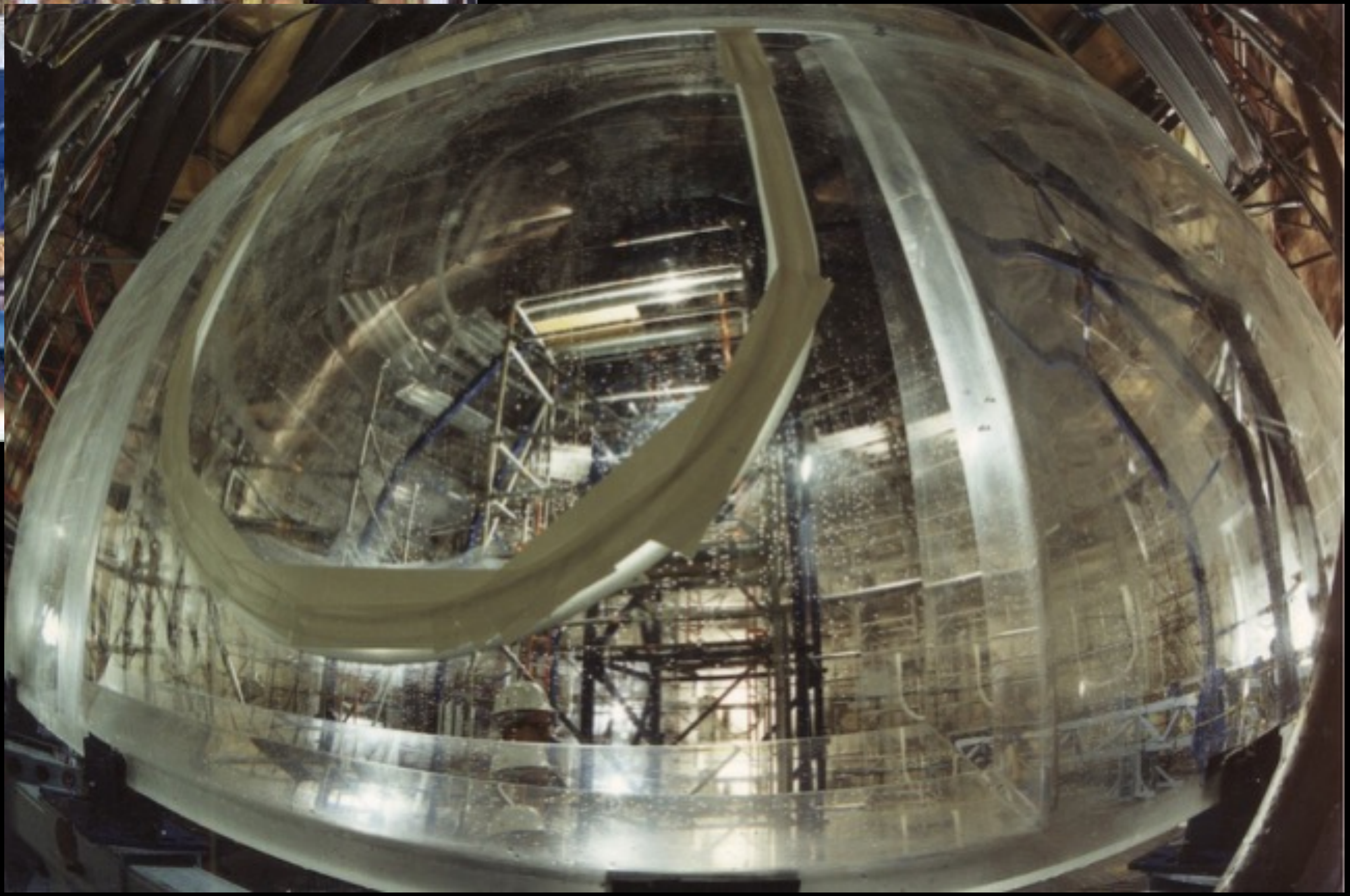
[ref. 3]

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

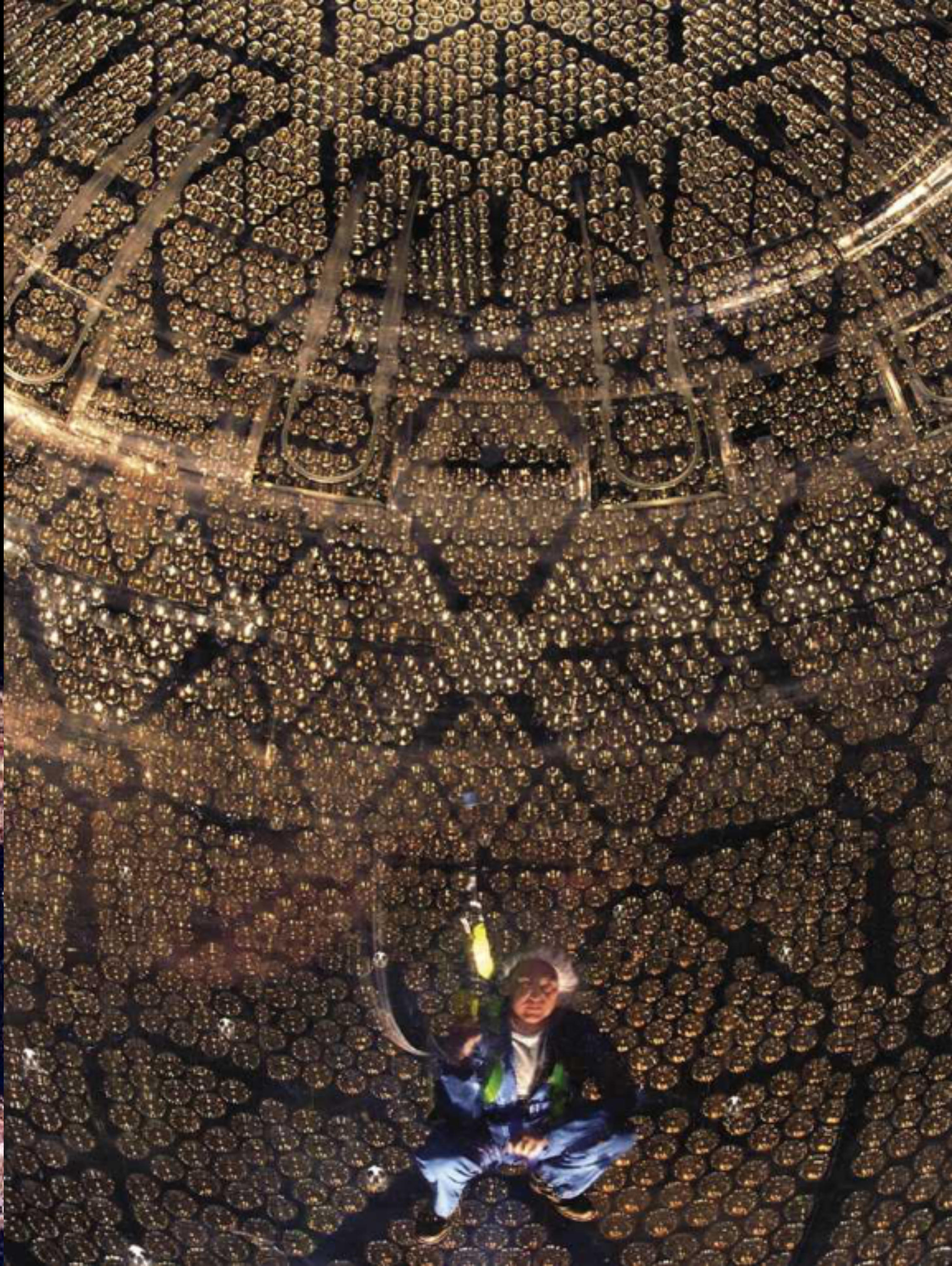
ACRYLIC VESSEL (AV)



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

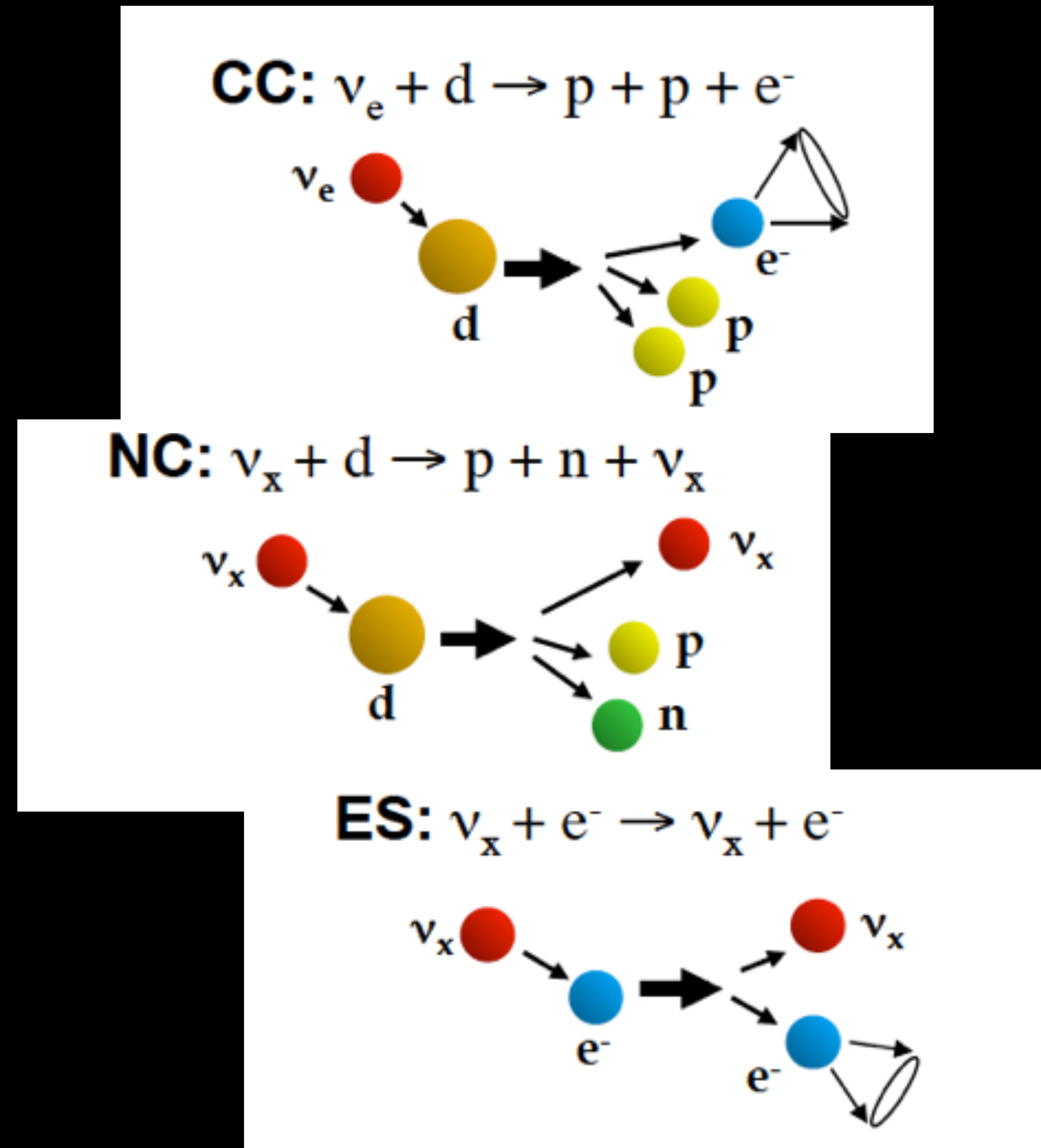
$$\nu_x + d \Rightarrow p + n + \nu_x$$

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)

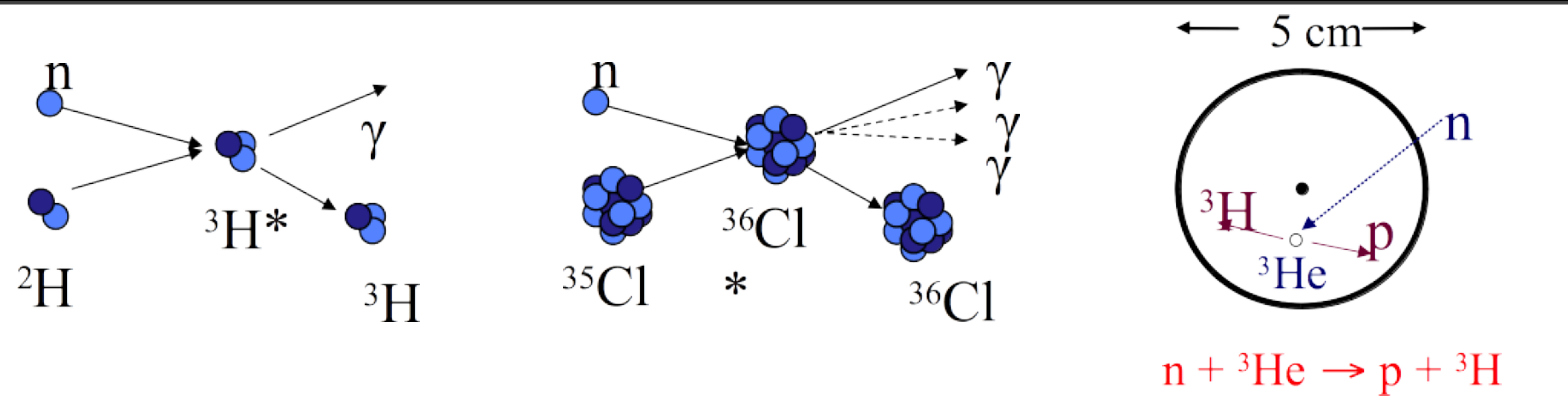
Nov. 99 - May 2001

Phase II (salt)

July 2001 - Sept. 2003

Phase III (NCD)

Nov. 2004 - Dec. 2006



neutrons captured by deuterons

$E(\gamma) = 6.25$ MeV

neutrons captured by chlorine

$\Sigma(E(\gamma)) = 8.6$ MeV

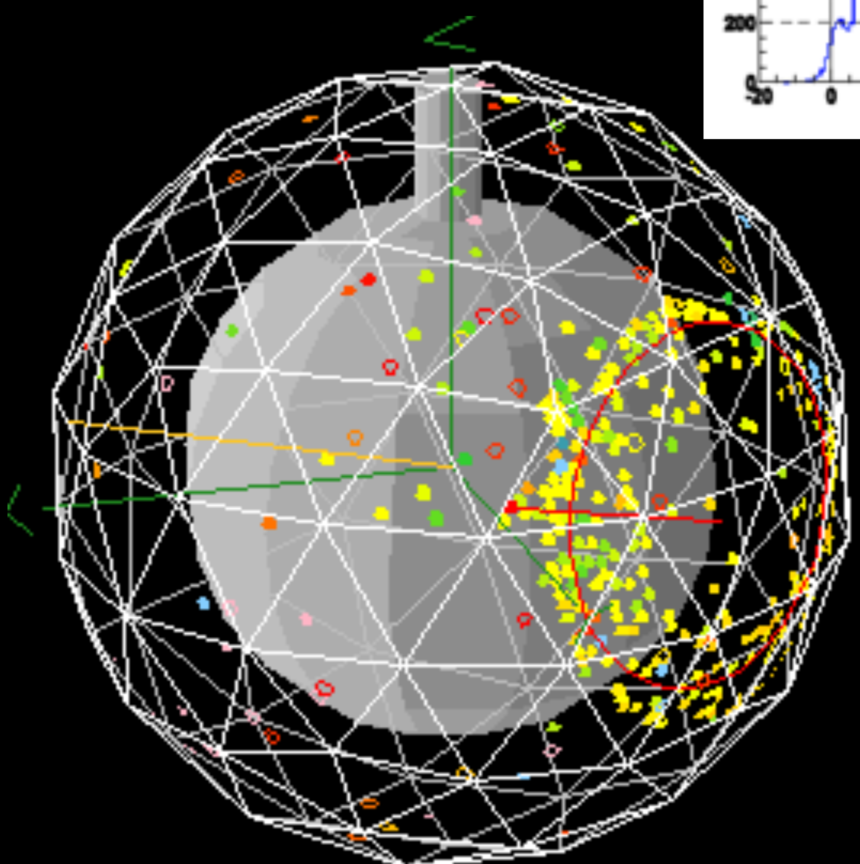
neutrons captured by ^3He

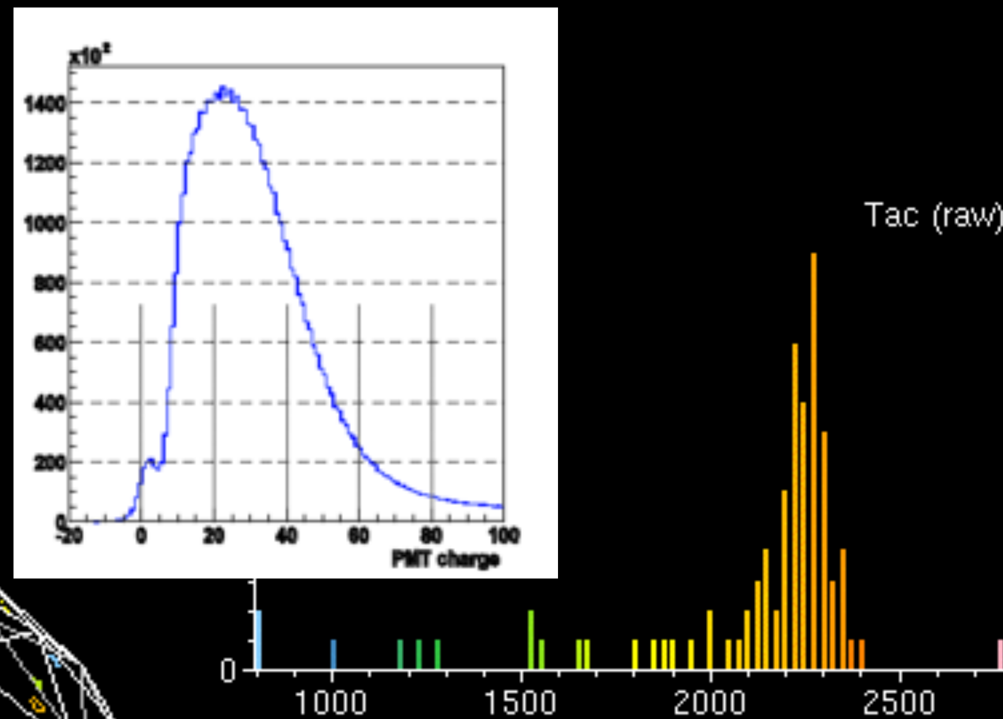
array of 40 proportional counters

EXPERIMENTAL OBSERVABLES

hit PMTs:

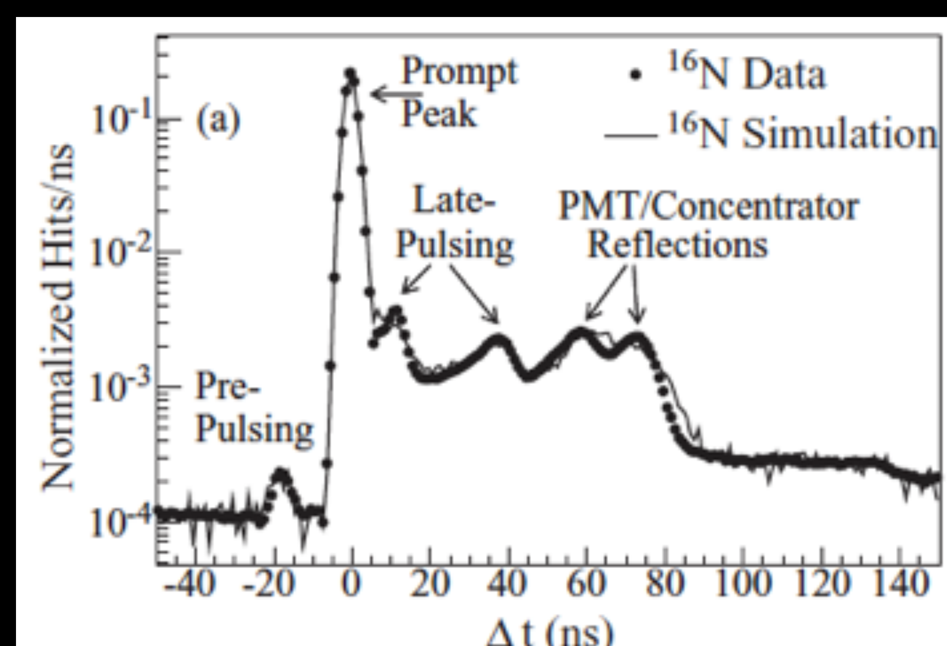
- position
- time
- charge





From these we calculate:

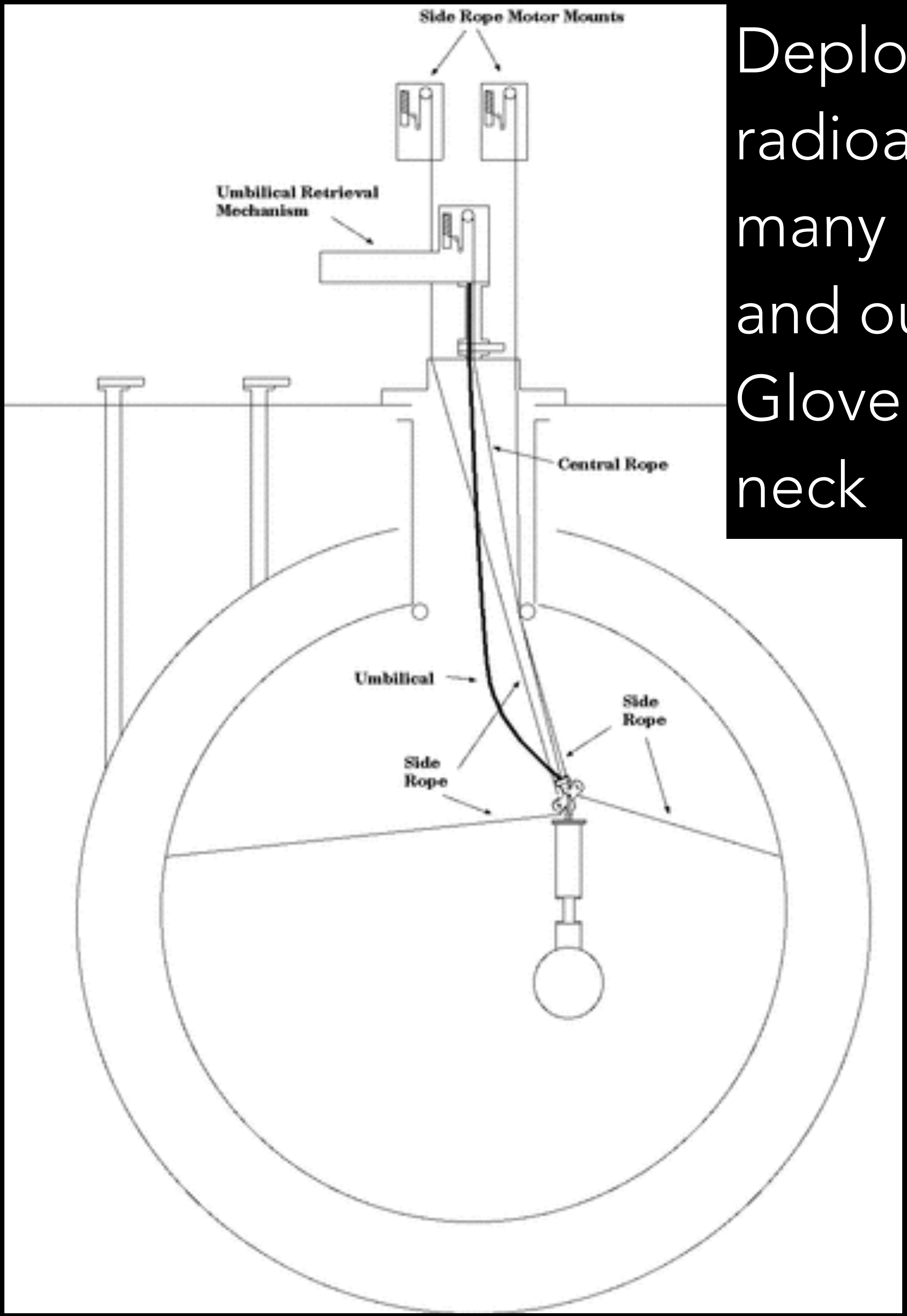
- event position
- direction
- energy
- isotropy



SNO used extensive calibrations to tune response models and determine systematics

CALIBRATIONS

[refs. 4-8]

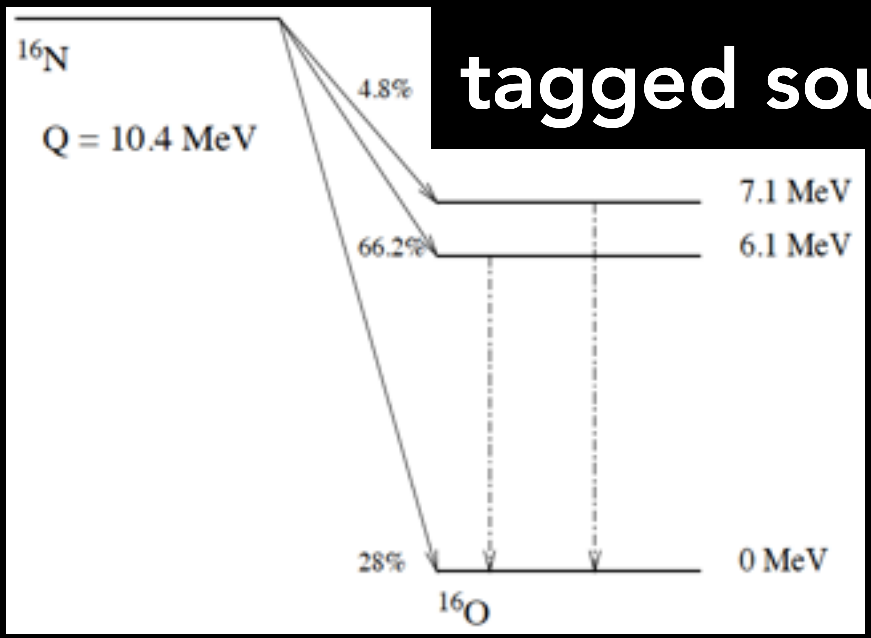


Deploy optical and radioactive sources in many positions inside and outside the AV

Glove box on top of AV neck

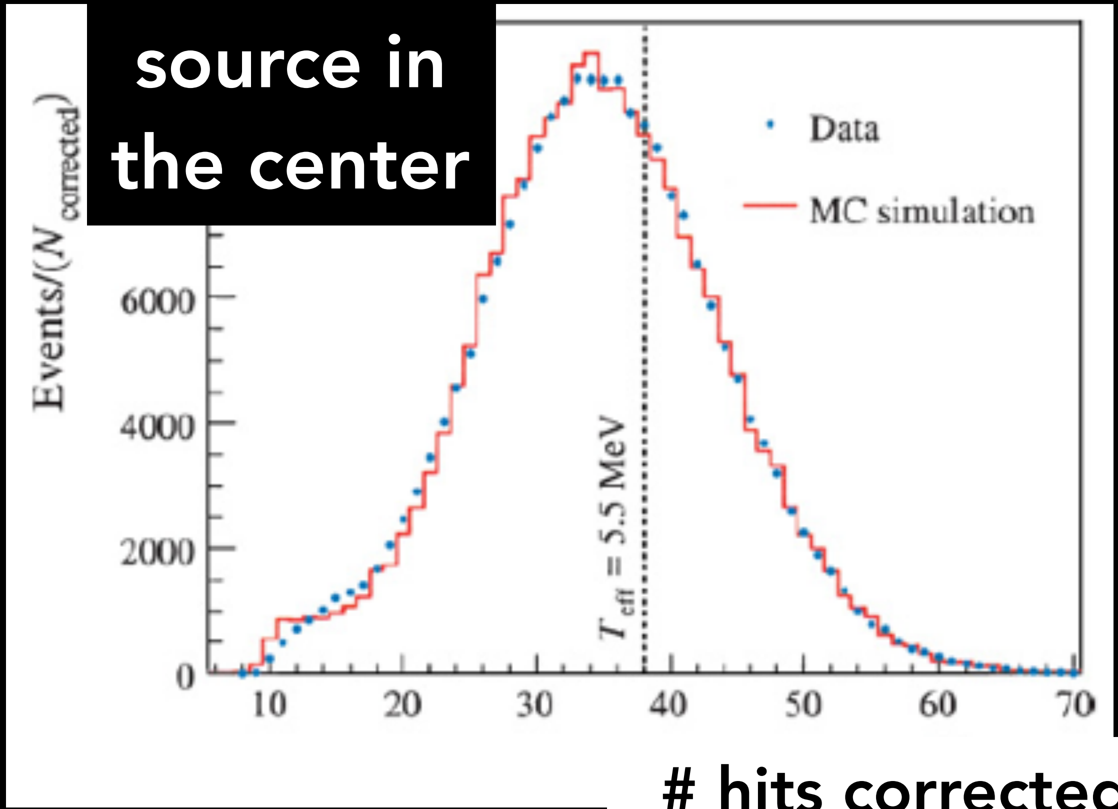
Also: radioactivity spikes uniformly distributed in the heavy water: ^{222}Rn, ^{24}Na

N16 ENERGY CALIBRATION



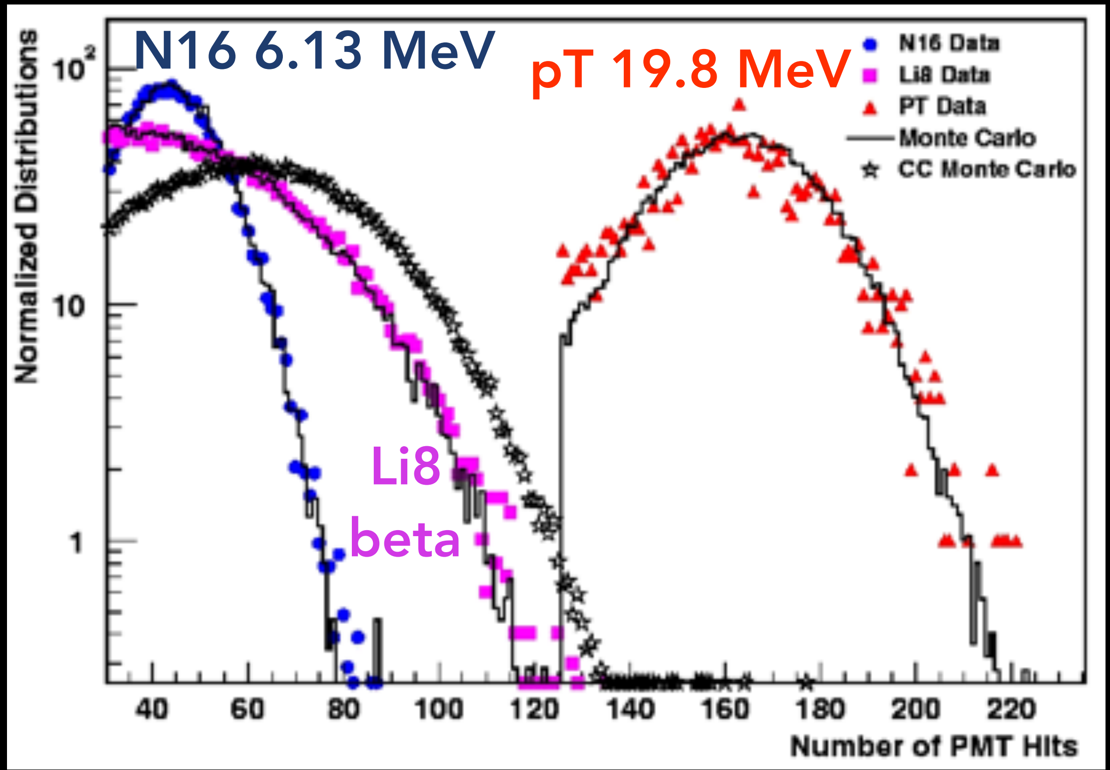
6.13 MeV γ tagged source

source in the center



 # hits corrected for optical response

Other sources used to validate higher energies

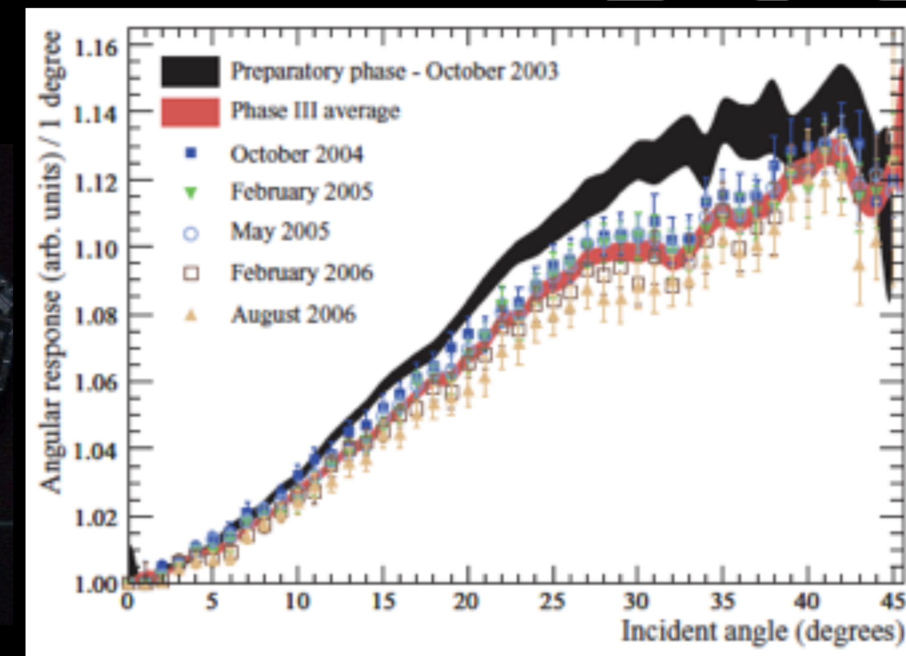


- Energy estimator using number of prompt hits
  - later using all PMT hits, including late times
- # of detected PMT hits varies with event position by up to 8% due to PMT angular response, attenuation in heavy and light water, and acrylic
  - Need to measure the optical properties *in-situ* -> optical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

OPTICAL CALIBRATION

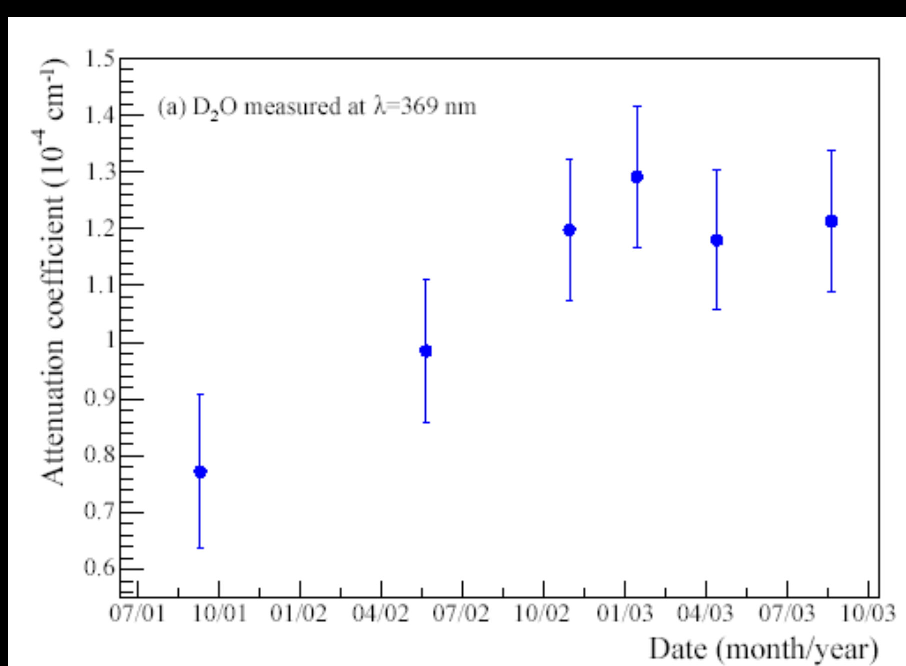
- PMT + reflector response versus incidence angle
- reflectivity degraded over time

[refs. 7, 14, 17]

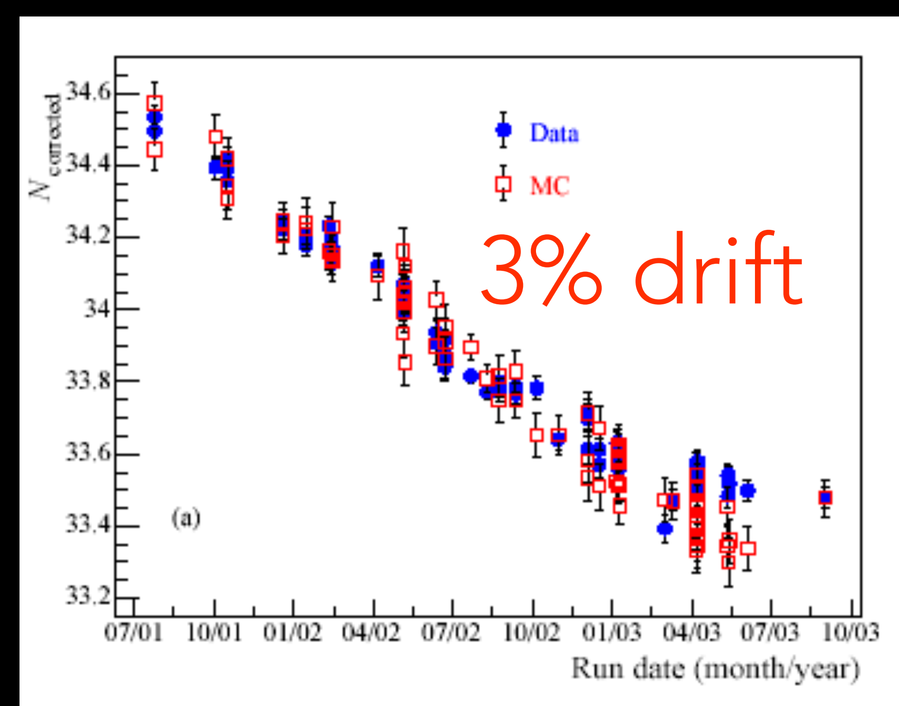


- In salt phase, a drift in energy response was identified as caused by increasing attenuation of heavy water

Heavy water attenuation



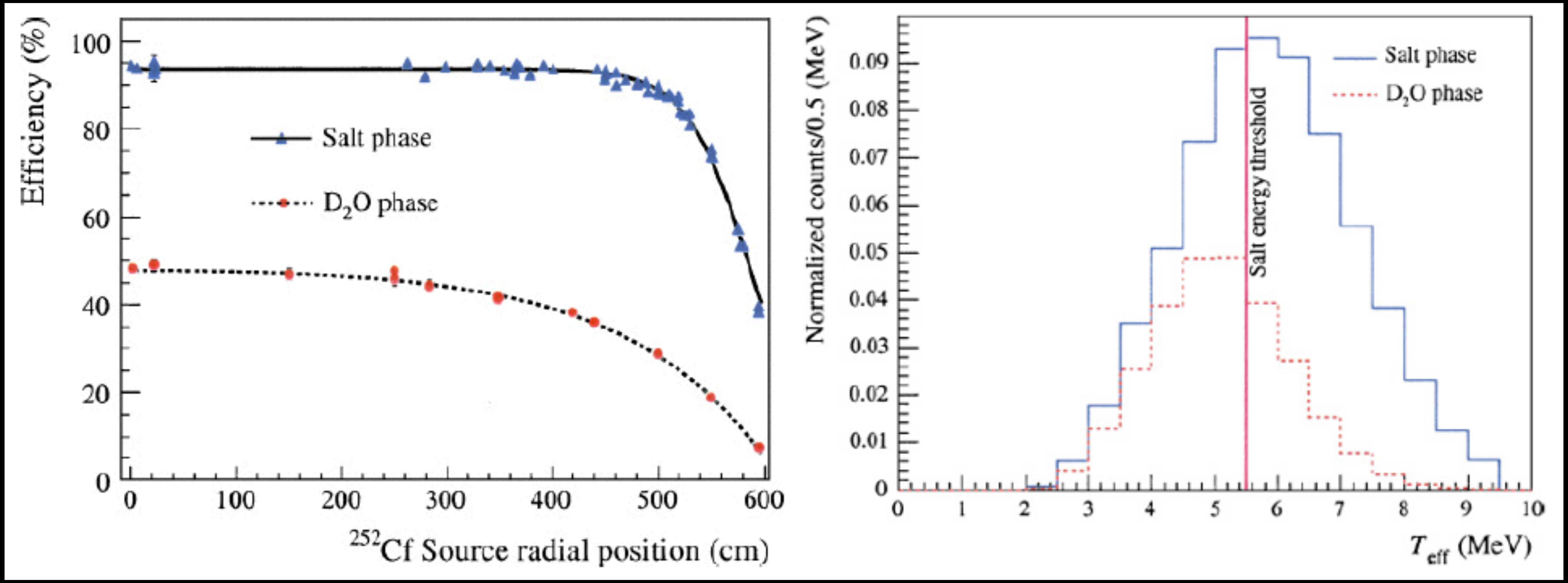
Number of PMT hits



After all corrections, energy scale systematics were < 0.6%

NEUTRON CALIBRATION

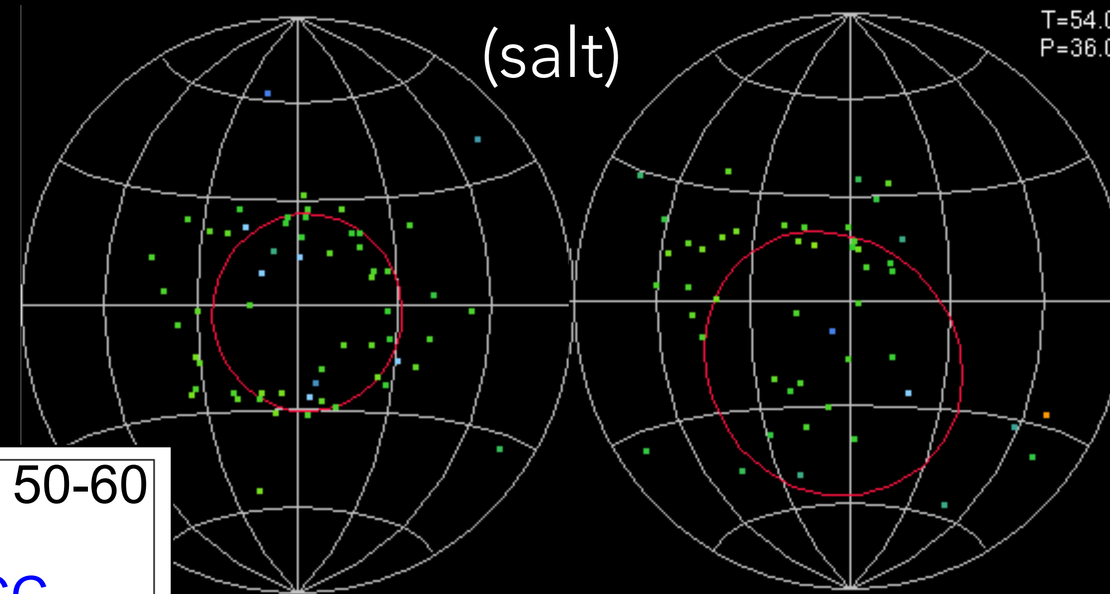
- AmBe and ^{252}Cf point sources
- Adding salt improved capture and detection efficiencies

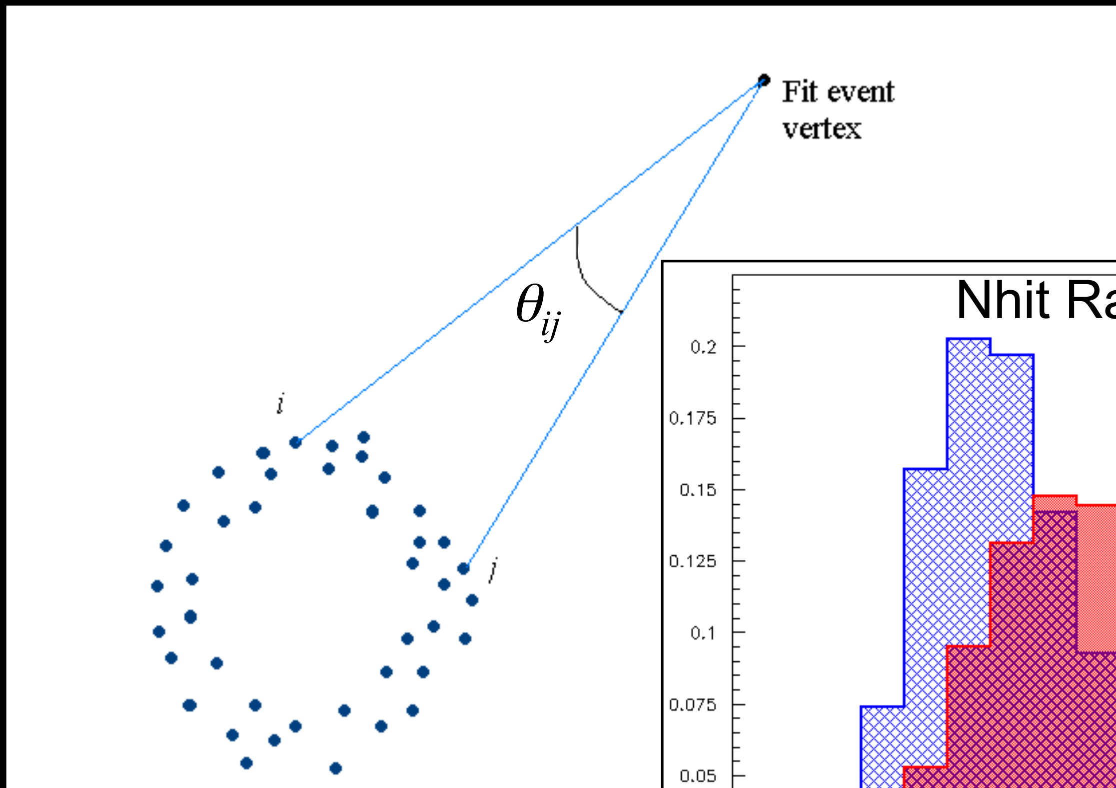


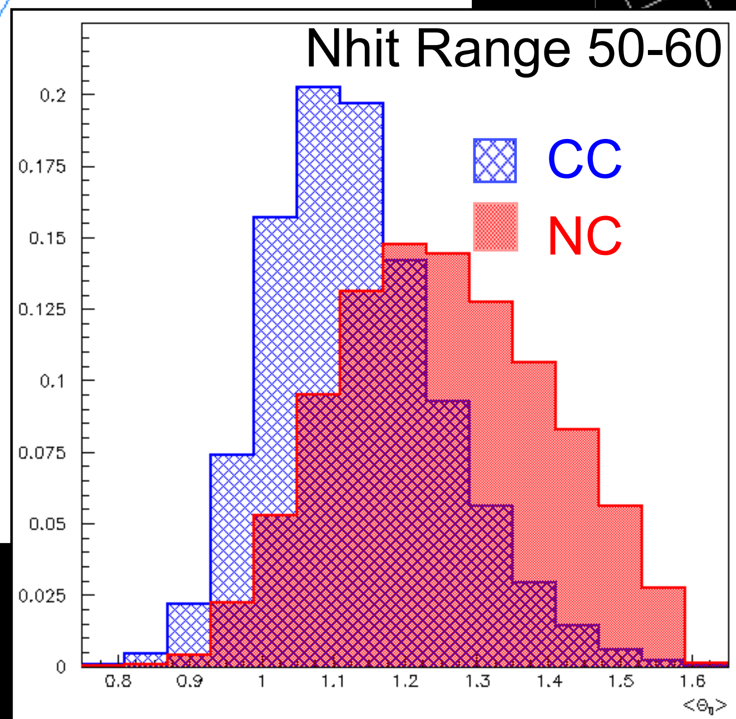
[ref. 14]

ISOTROPY

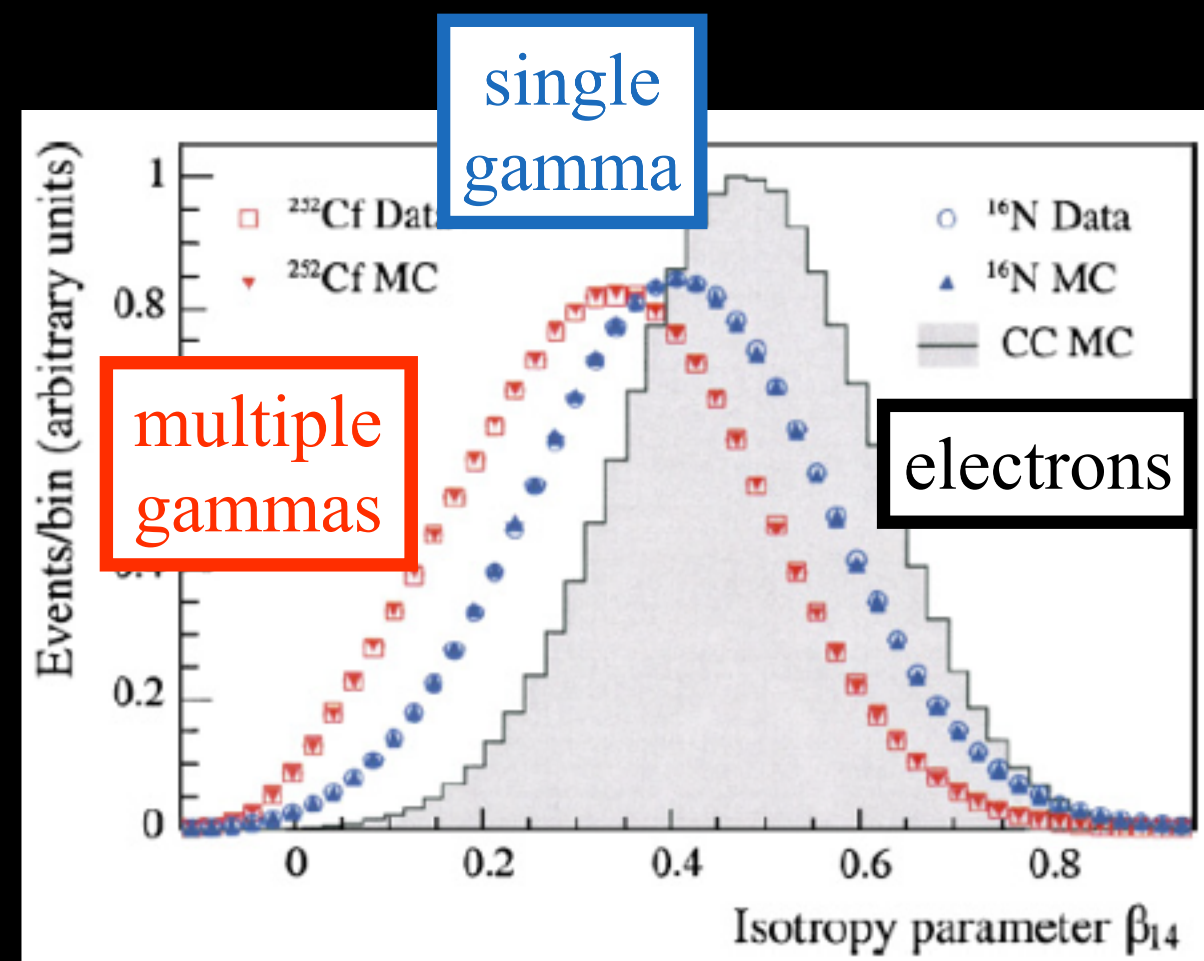
Electron Neutron (salt)







<θ_{ij}> average over all PMT pairs



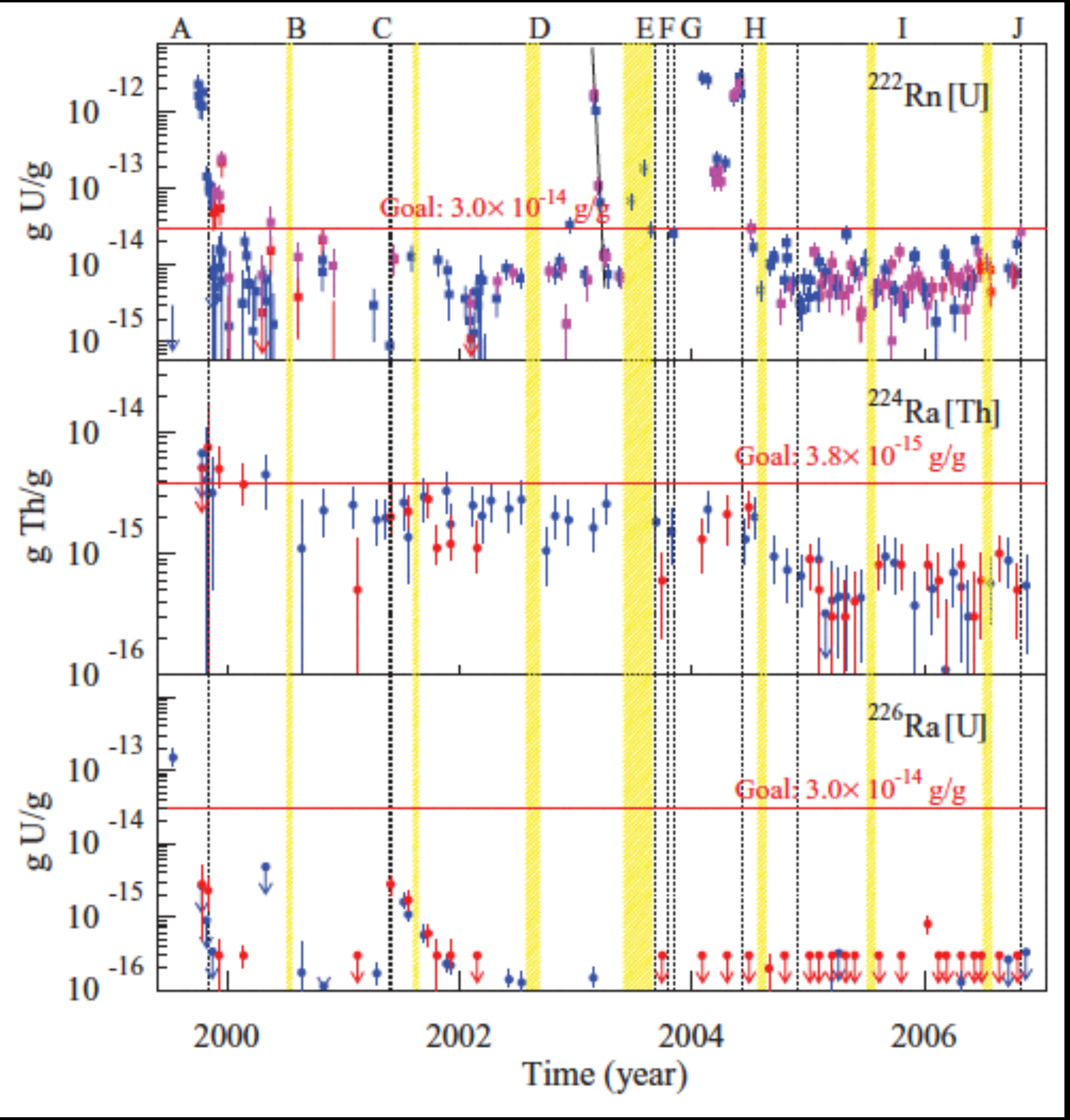
[ref. 14]

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

P_l = l_{th} order Legendre polynomial

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

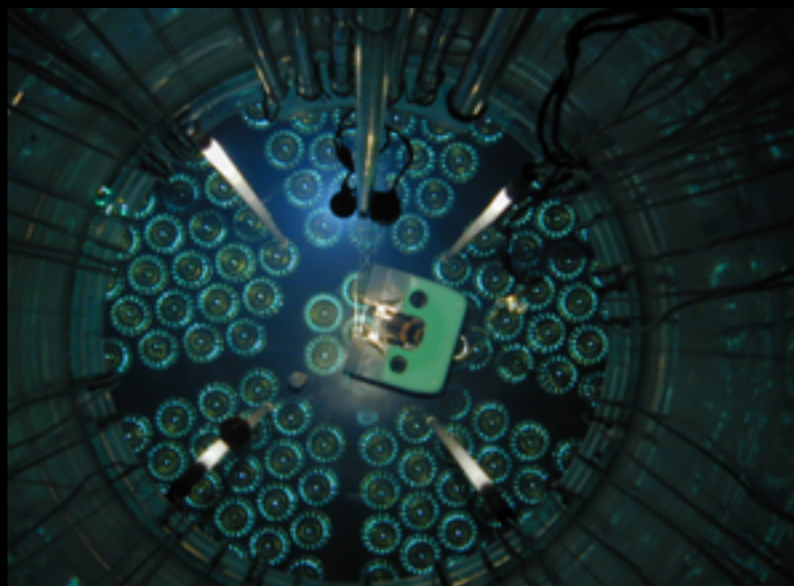
CHALLENGE: RADIOACTIVITY



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

[refs. 9-10, 17]

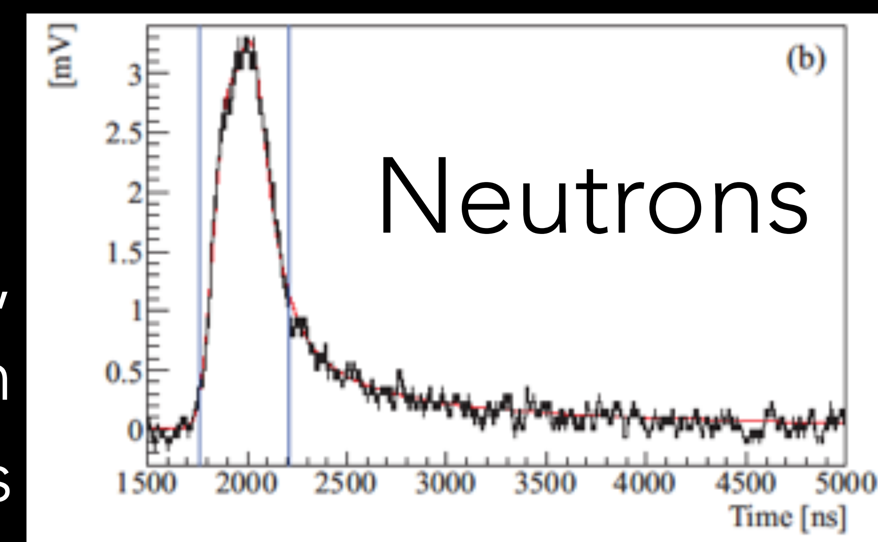
NEUTRAL CURRENT DETECTORS



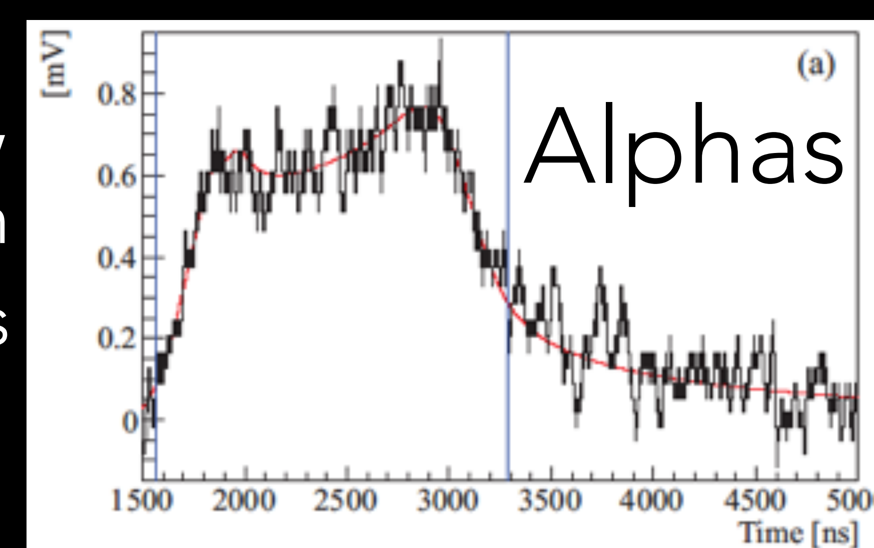
- Array of ^{3}He-filled proportional counters deployed in the AV

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

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



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

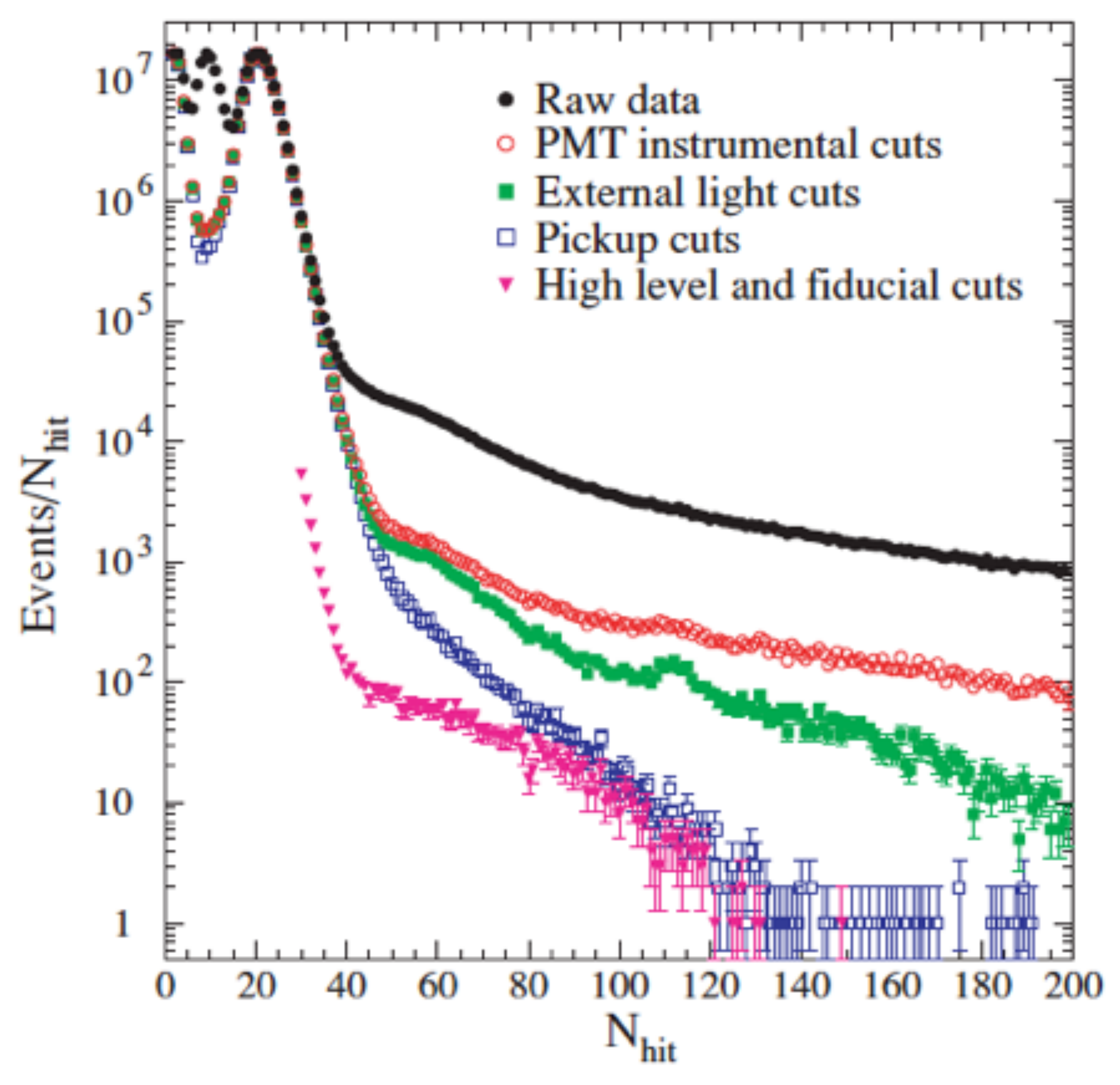


[refs. 11, 17,18]

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

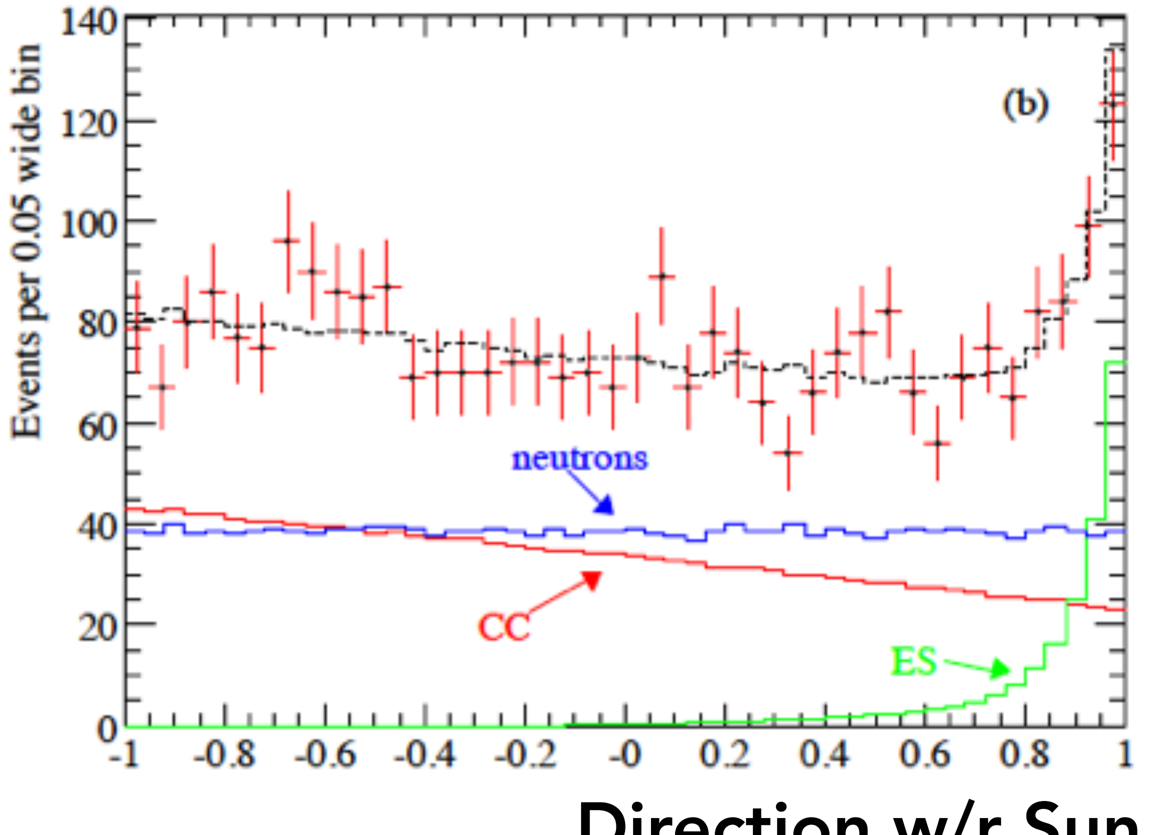
$$\text{CC: } \left(1.43^{+0.39}_{-0.21}\right)\%,$$
$$\text{ES: } \left(1.46^{+0.40}_{-0.21}\right)\%,$$
$$\text{neutrons: } \left(2.28^{+0.41}_{-0.23}\right)\%.$$

Signal-loss from cuts, phase I

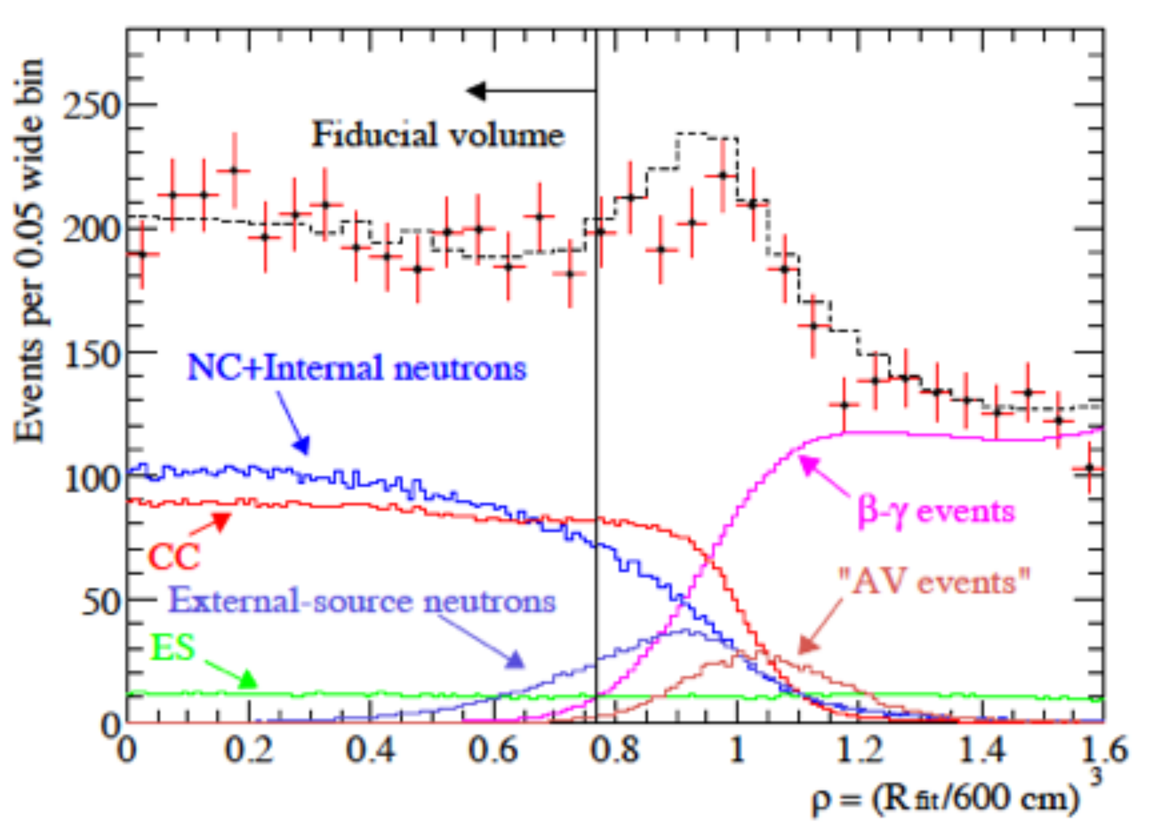
[ref. 15]

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)

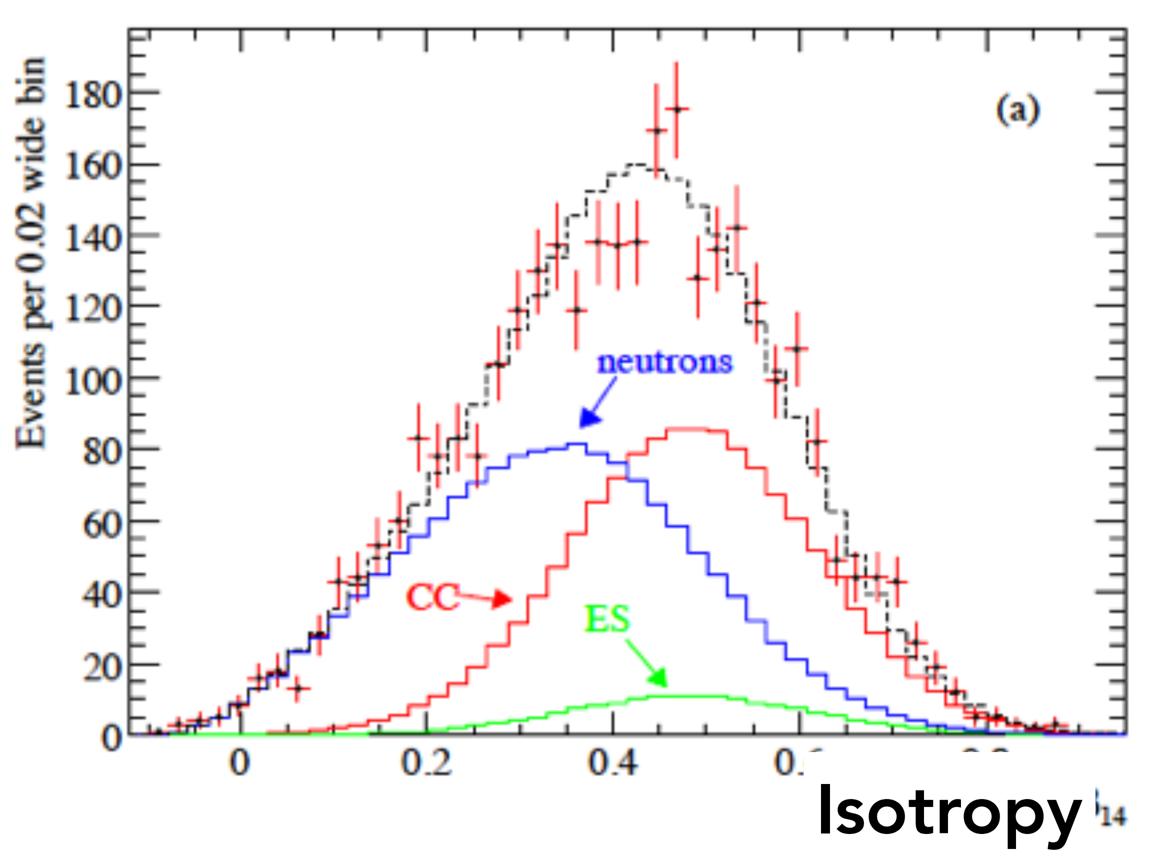


Direction w/r Sun



Radial position

[ref. 13]

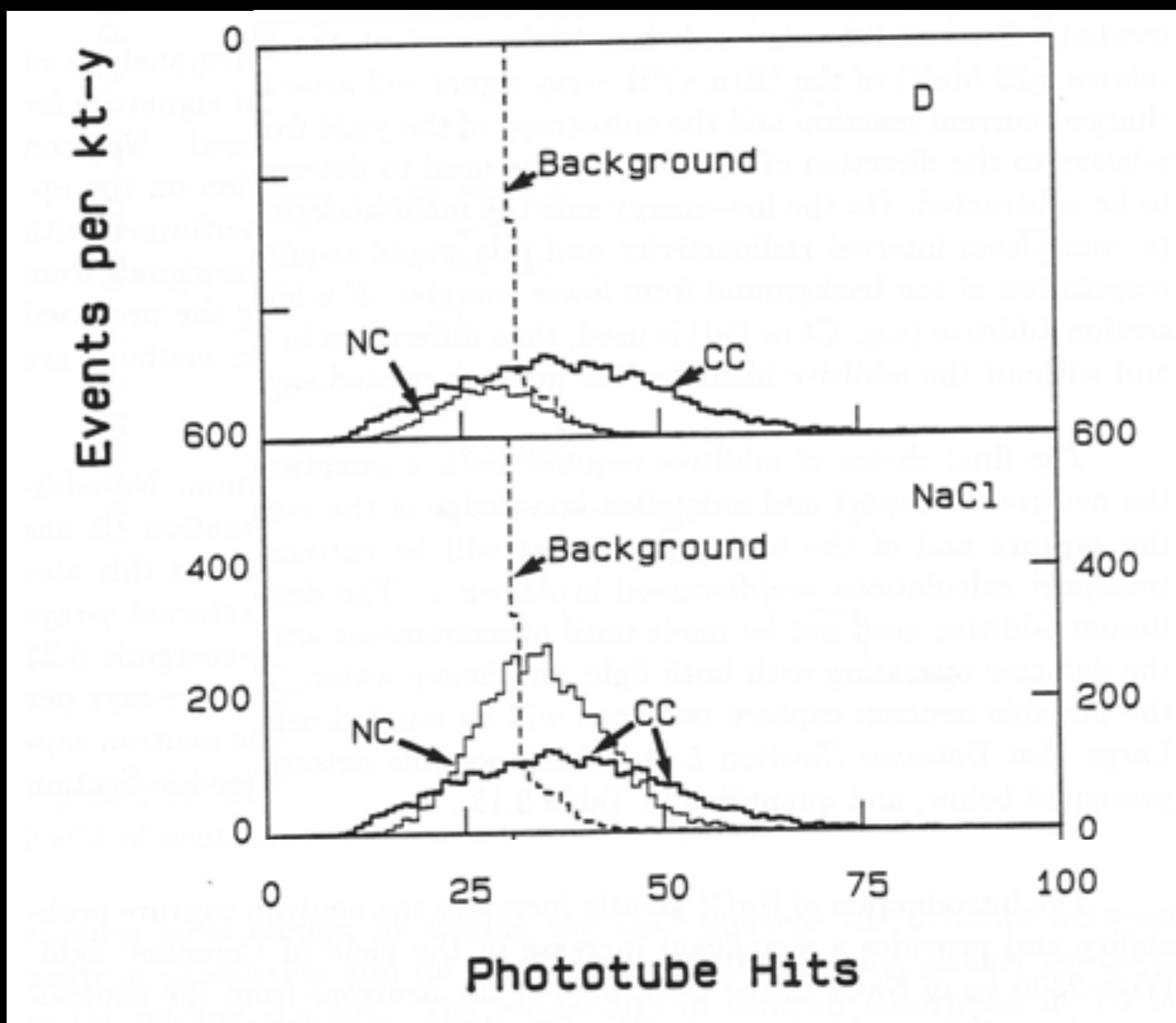


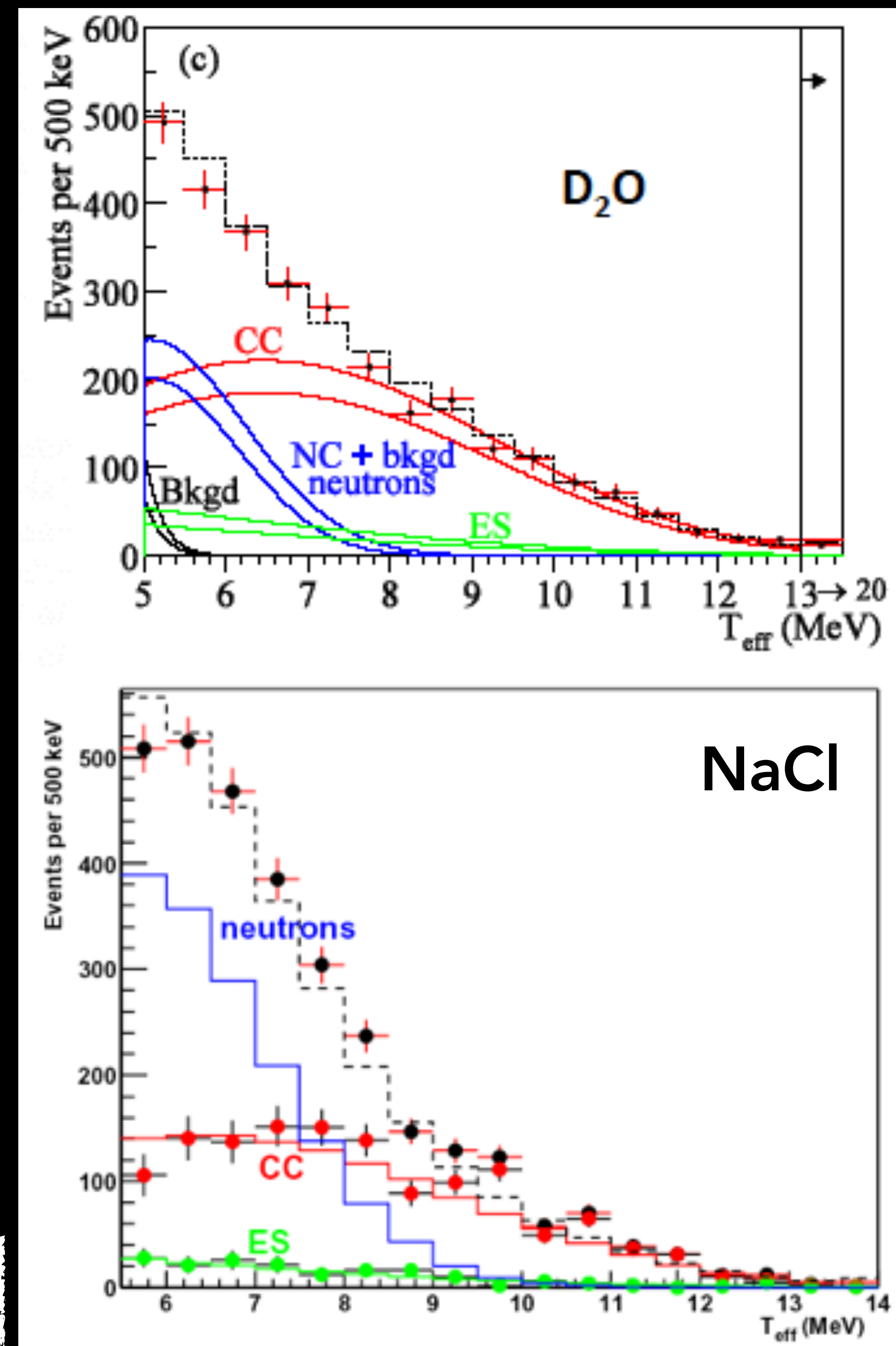
Isotropy

RESULTS, D2O AND SALT

measured 1999-2003

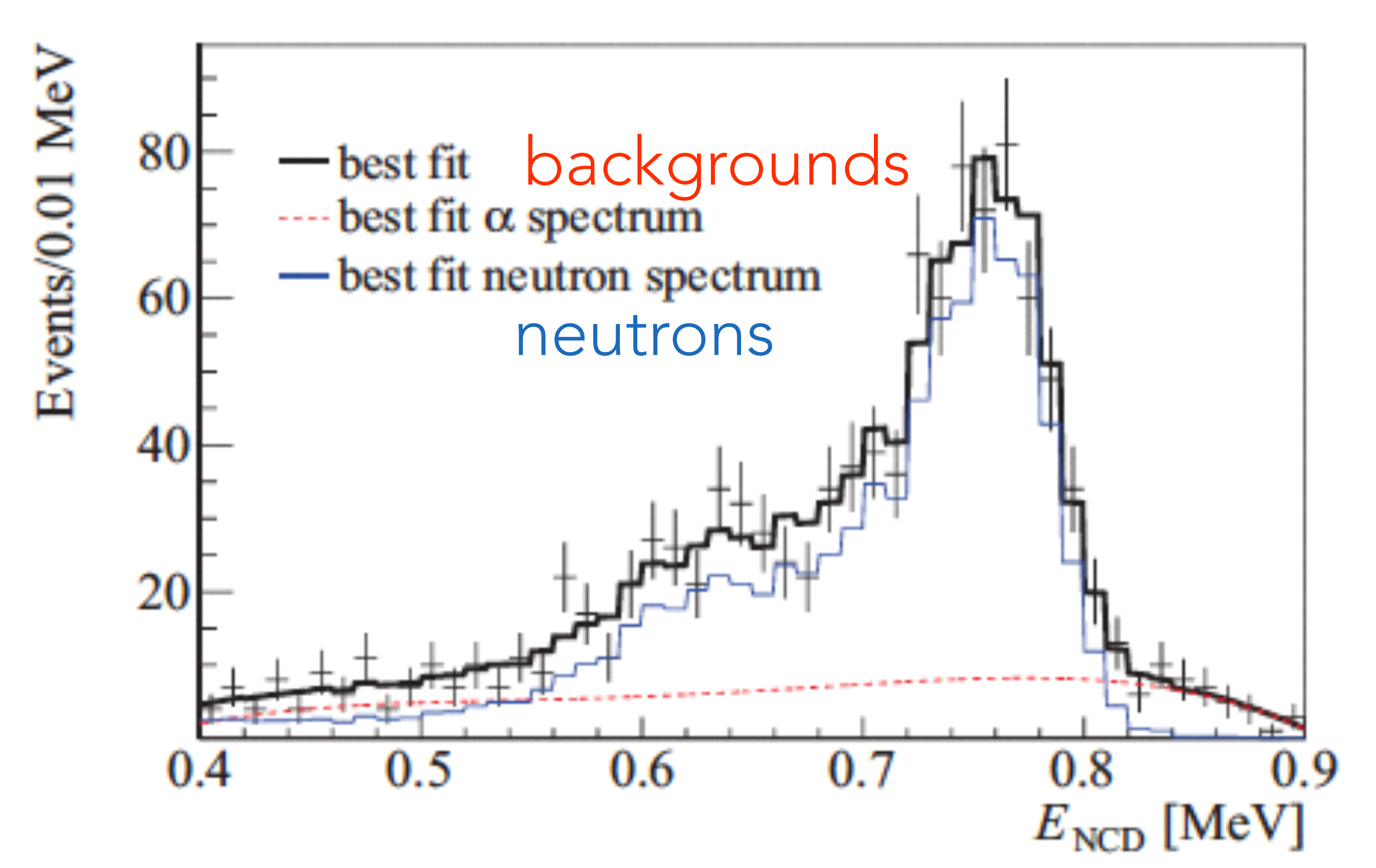
simulated in 1987

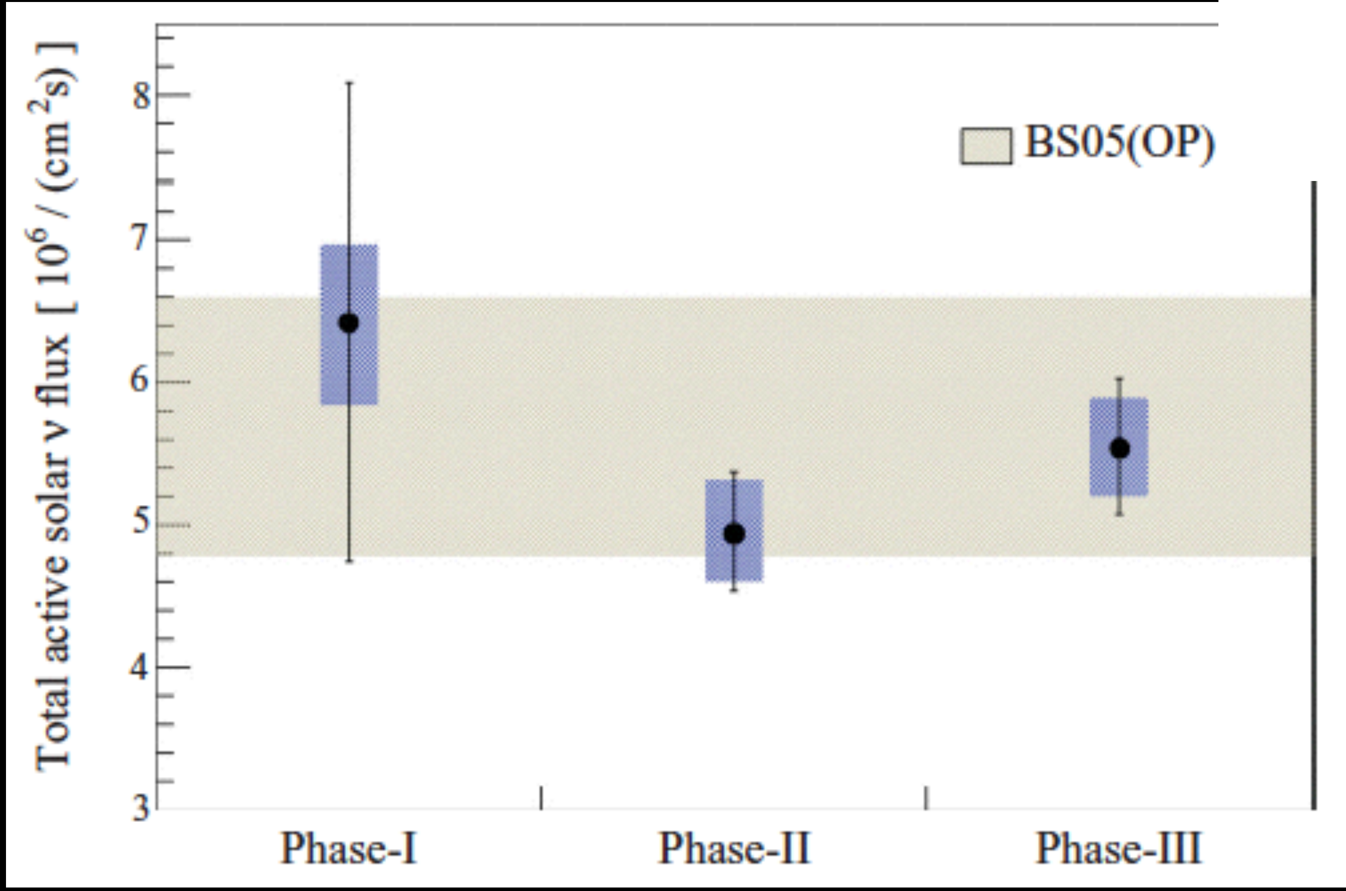




[refs. 12,13]

RESULTS, PHASE III

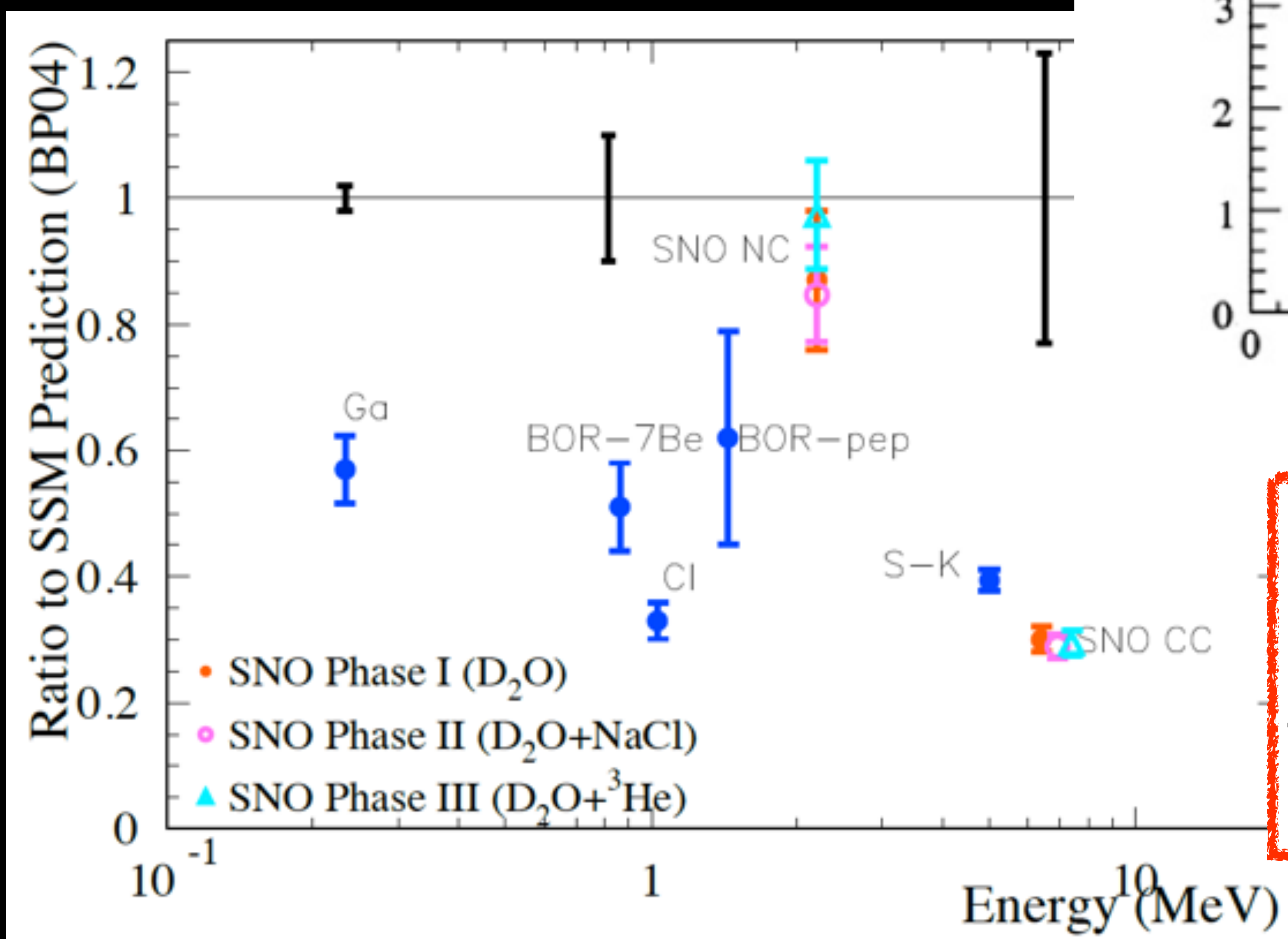


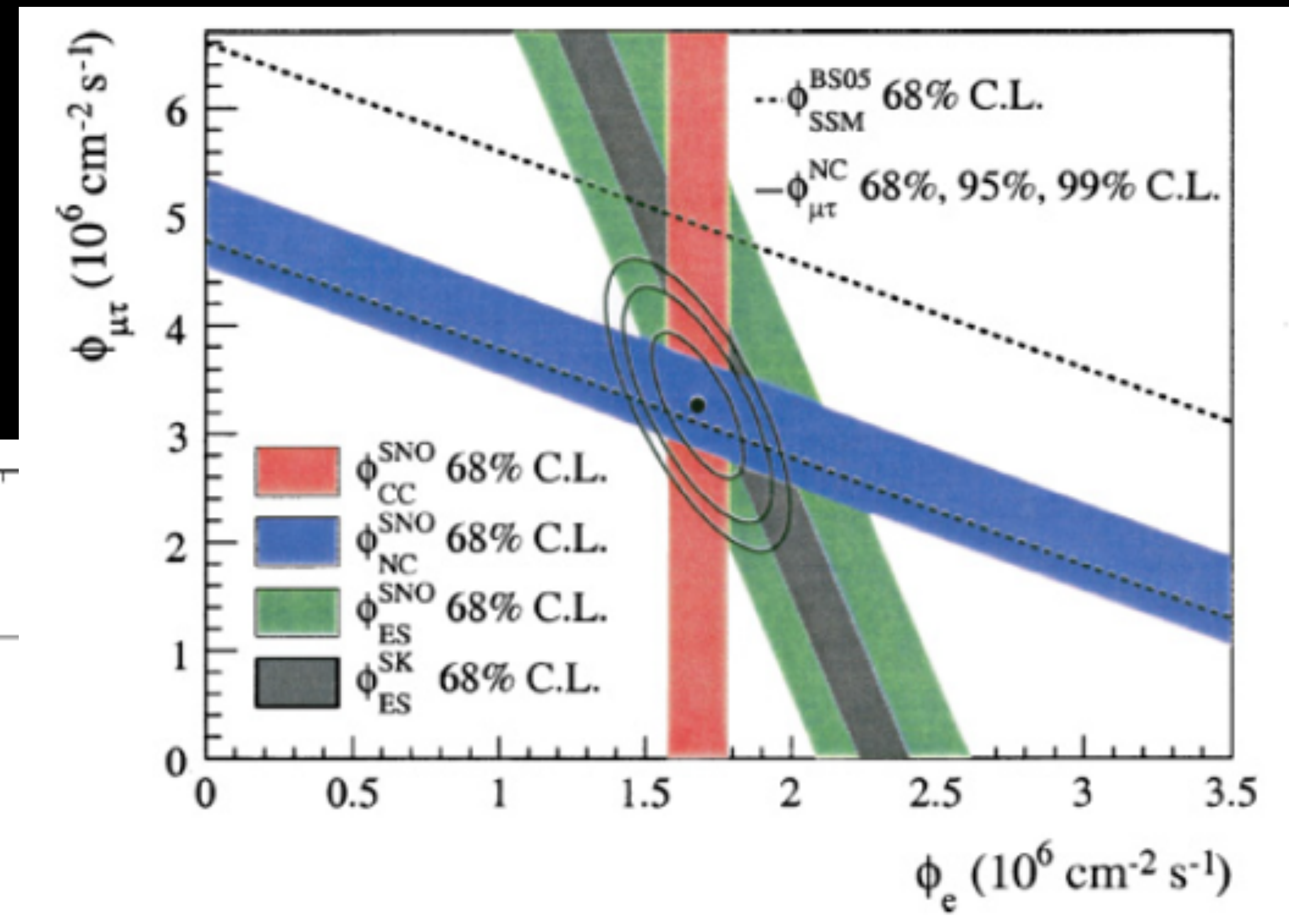


Results of all 3 phases compatible

[ref. 17, 18]

SOLAR NEUTRINO PROBLEM, SOLVED!





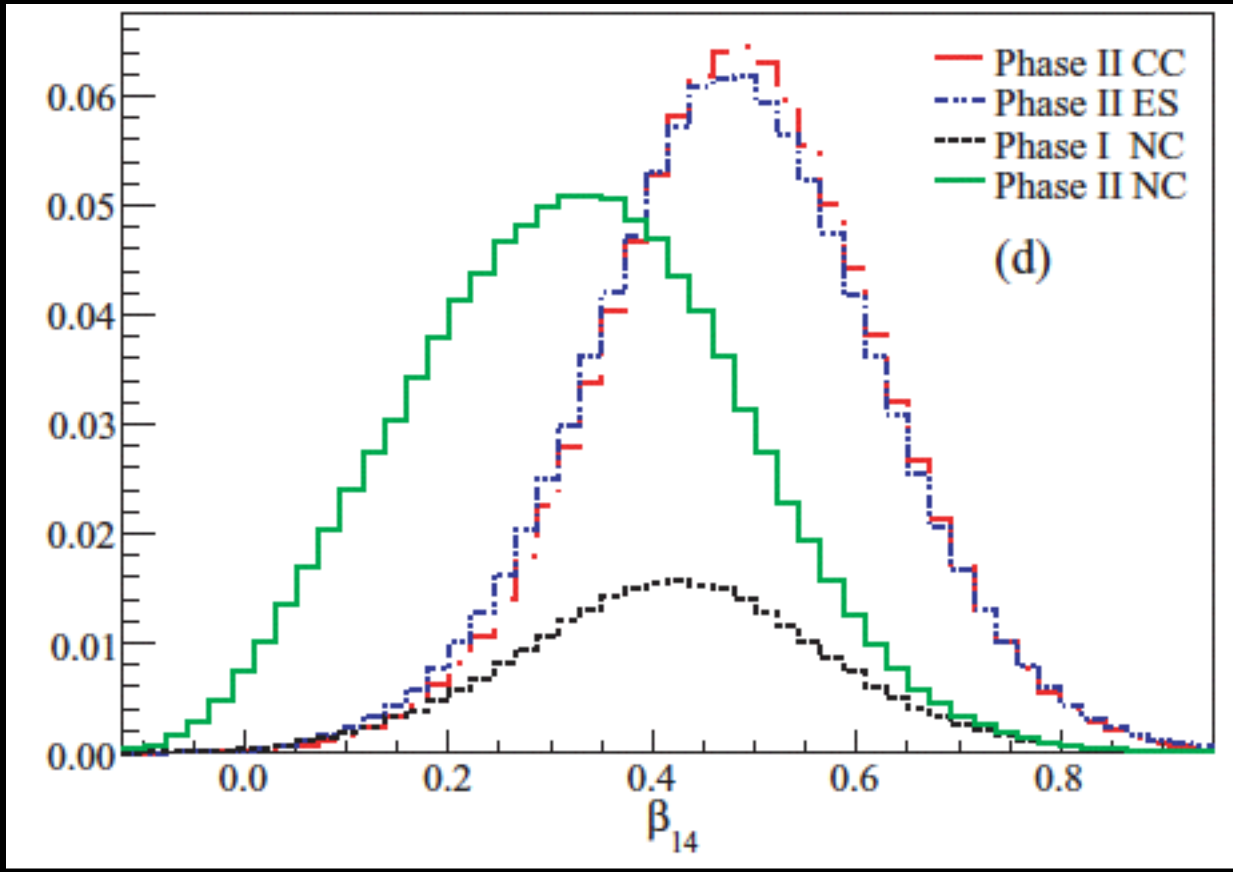
1) ν_e is 1/3 of all ν: neutrinos change flavour!
2) measurement in all flavours confirms solar model

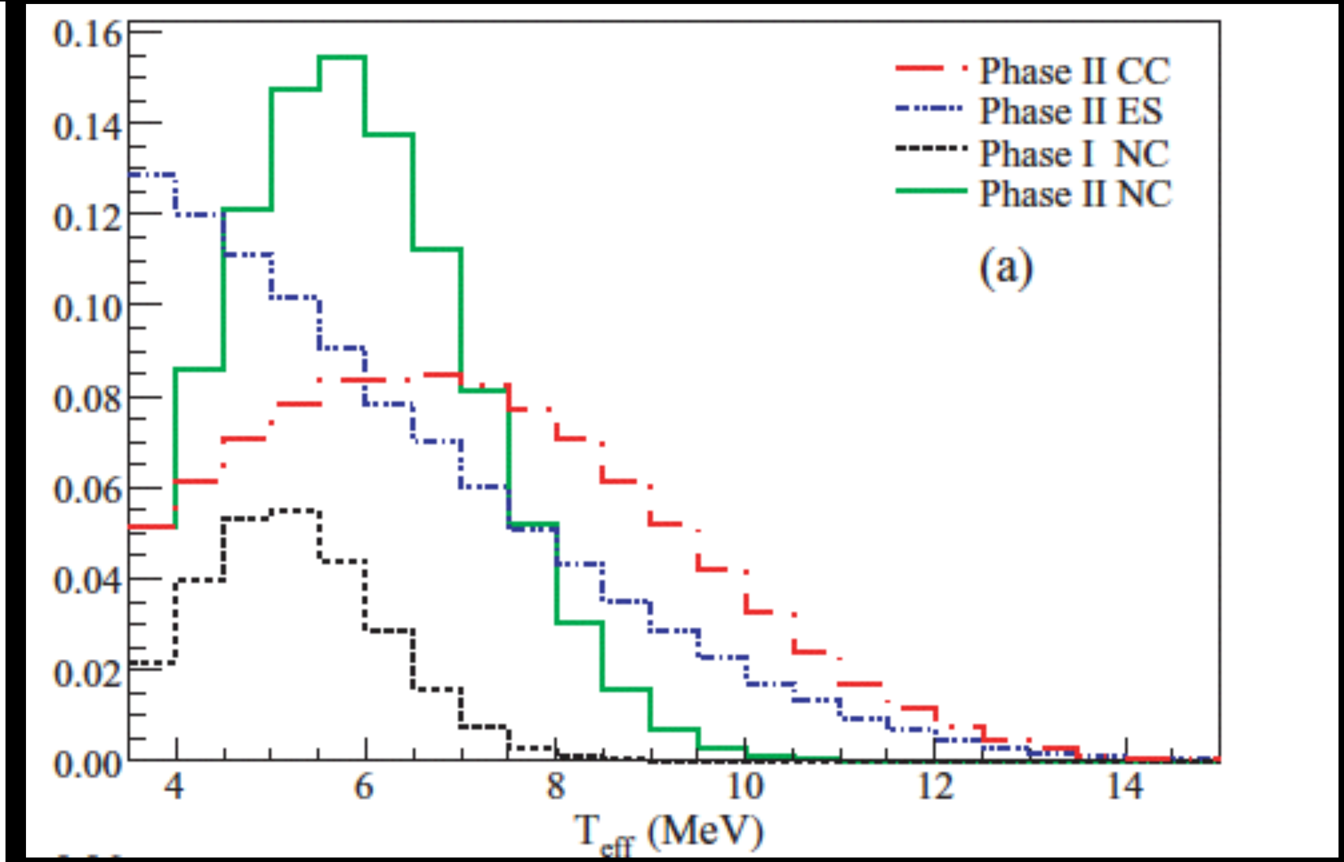
[ref. 14]

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

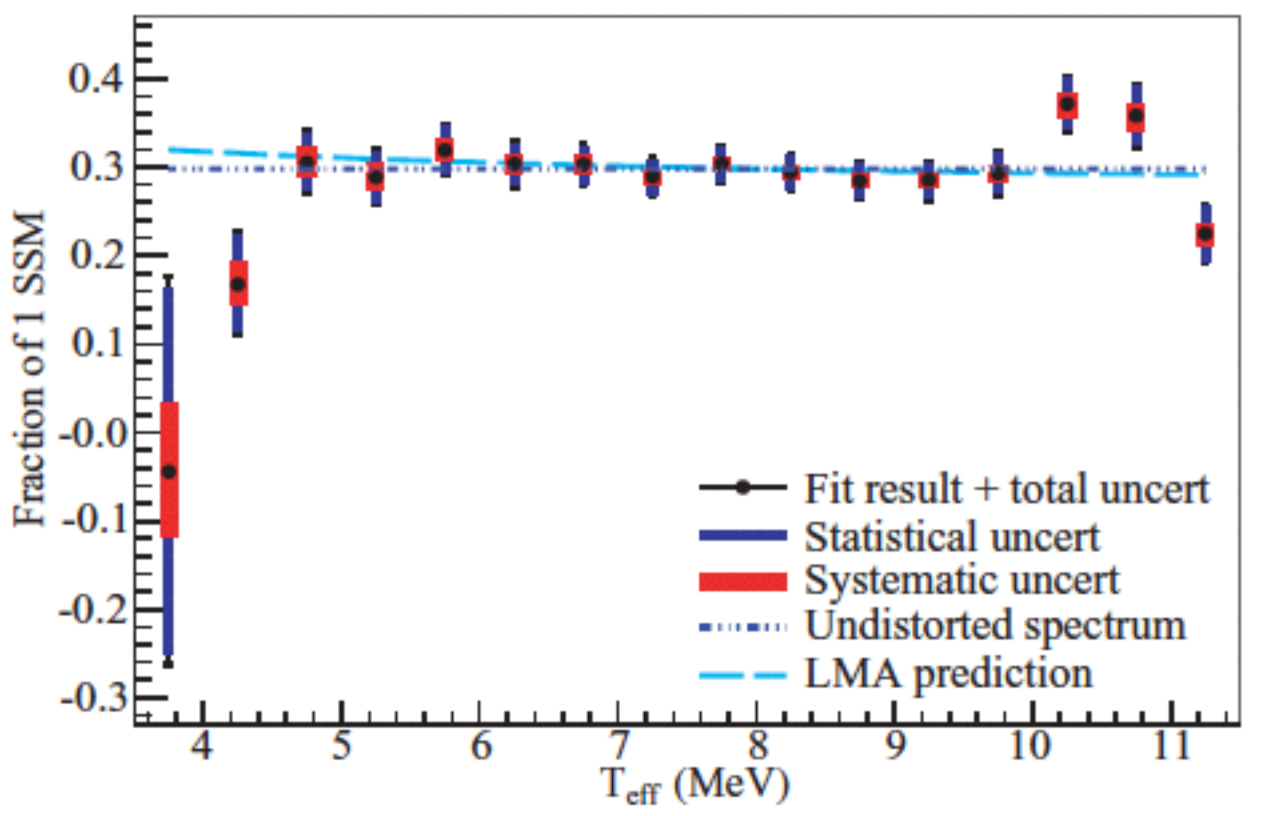
[ref. 16]

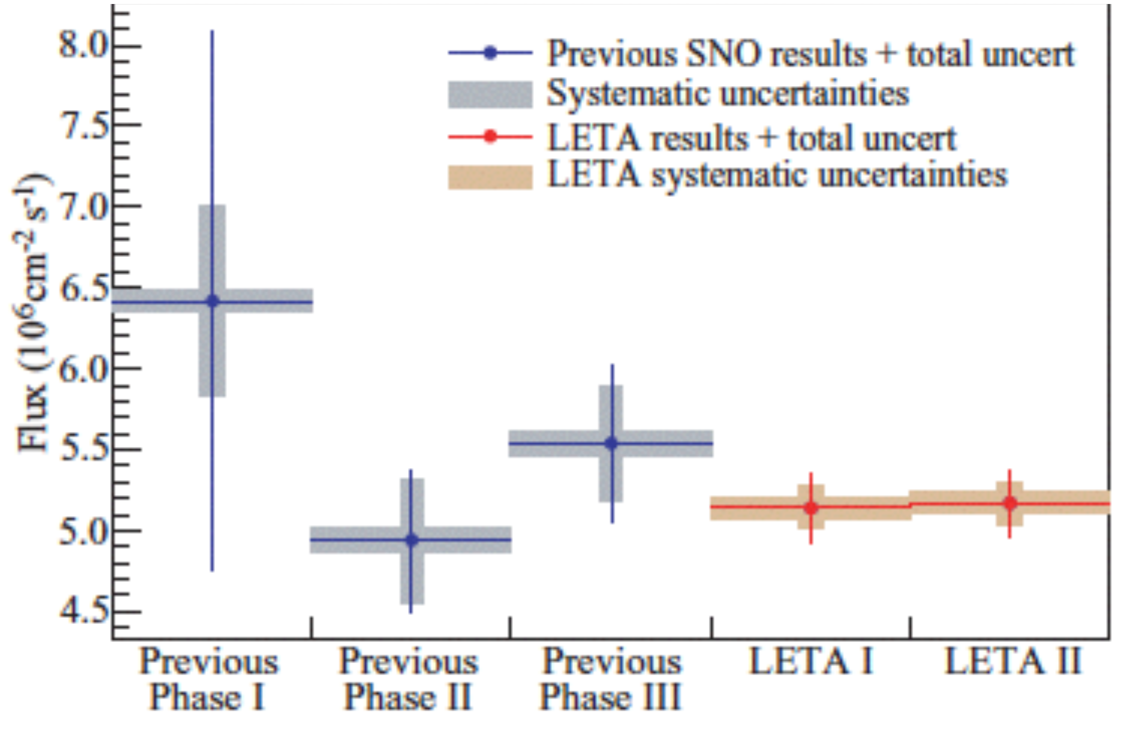
(i) binned-histogram method

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

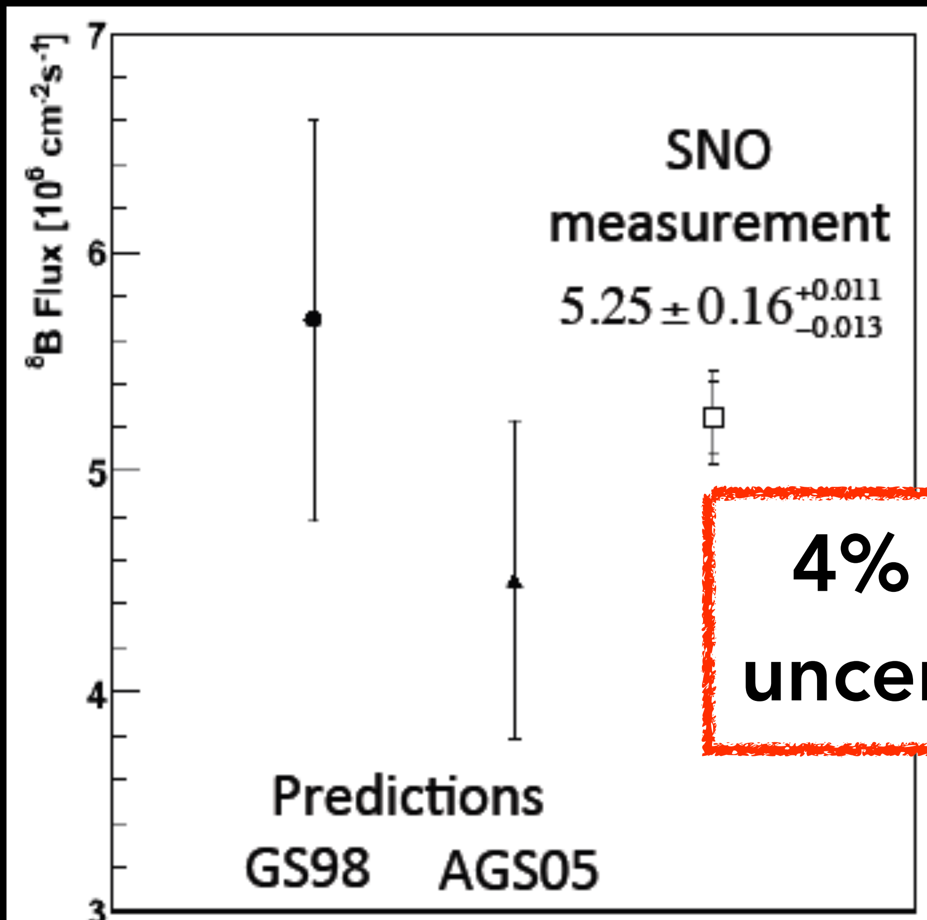
(ii) kernel estimation method

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

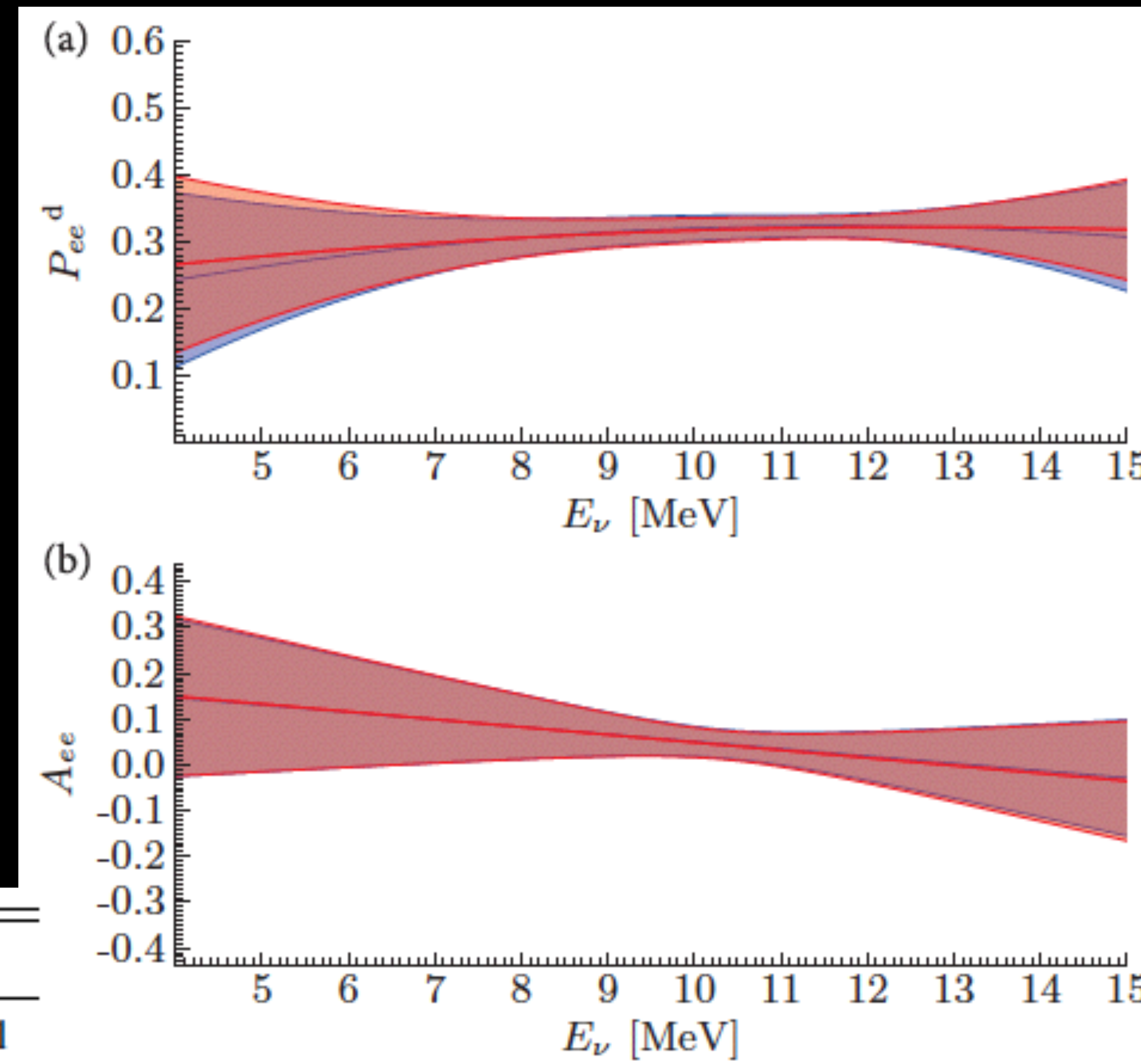




COMBINATION ALL PHASES



4% total uncertainty

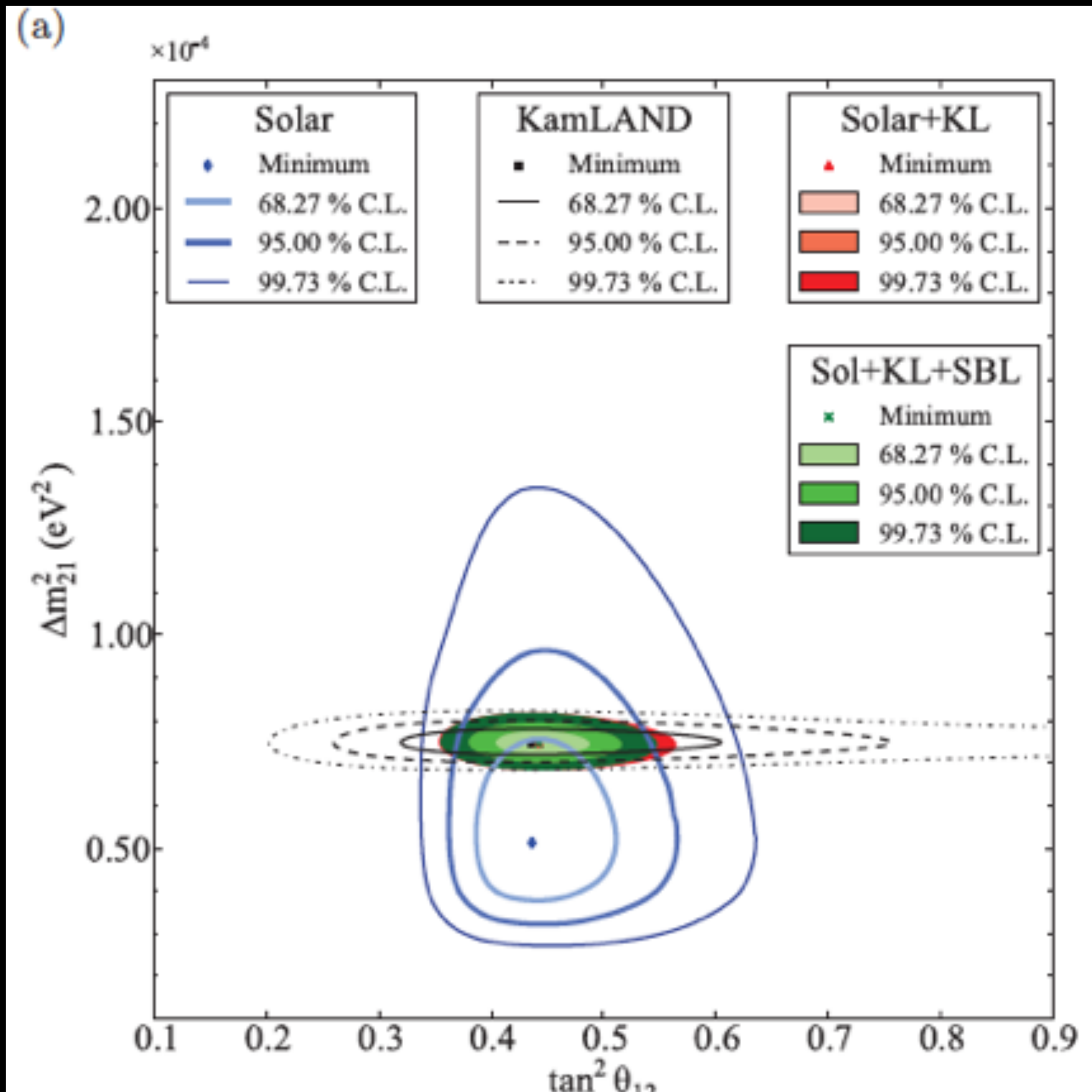


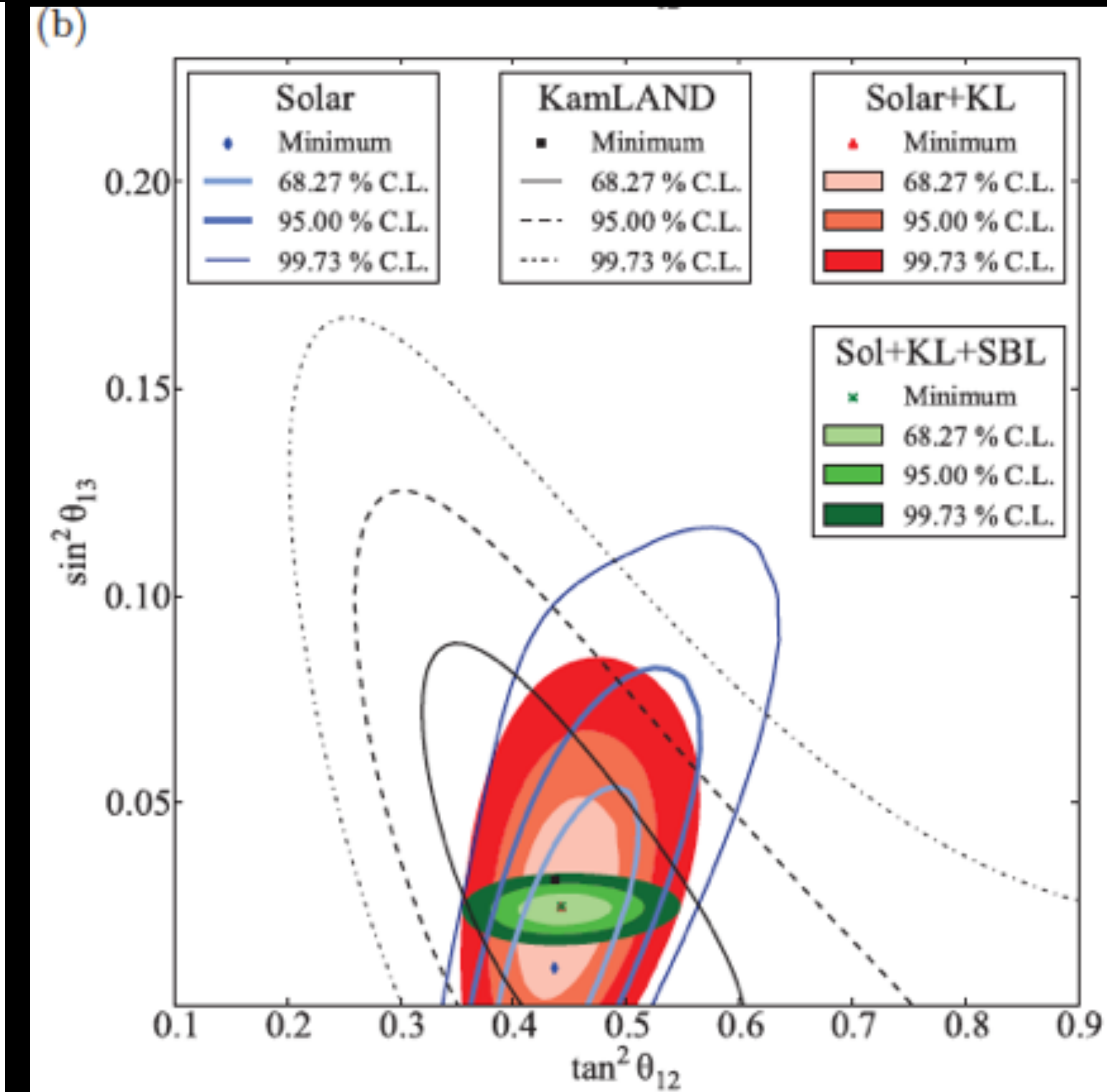
	Best fit	Stat.	Systematic uncertainty			
			Basic	D/N	MC	Total
Φ_B	5.25	± 0.16	$^{+0.11}_{-0.12}$	± 0.01	$^{+0.01}_{-0.03}$	$^{+0.11}_{-0.13}$
c_0	0.317	± 0.016	$^{+0.008}_{-0.010}$	± 0.002	$^{+0.002}_{-0.001}$	± 0.009
c_1	0.0039	$^{+0.0065}_{-0.0067}$	$^{+0.0047}_{-0.0038}$	$^{+0.0012}_{-0.0018}$	$^{+0.0004}_{-0.0008}$	± 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]

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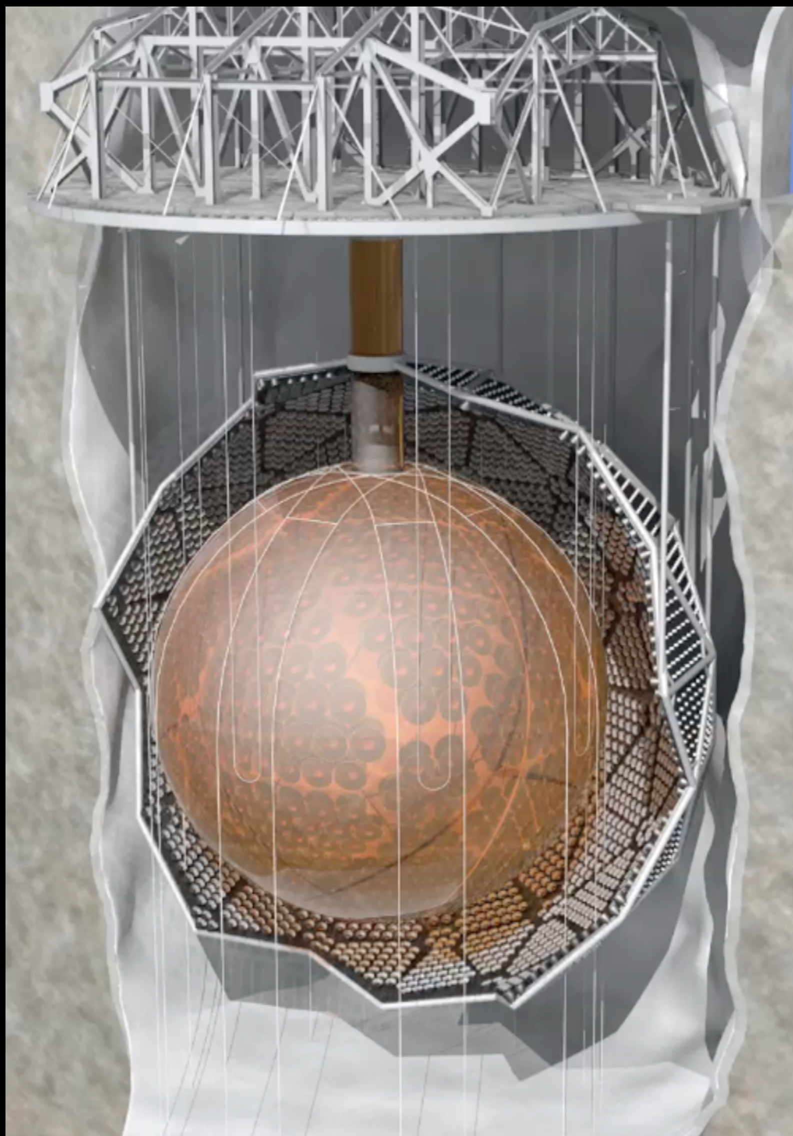
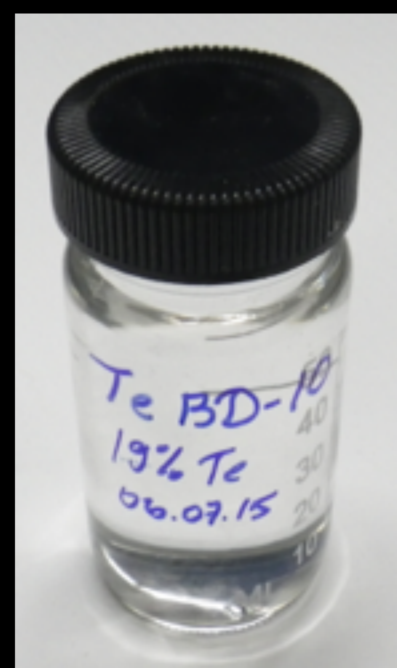
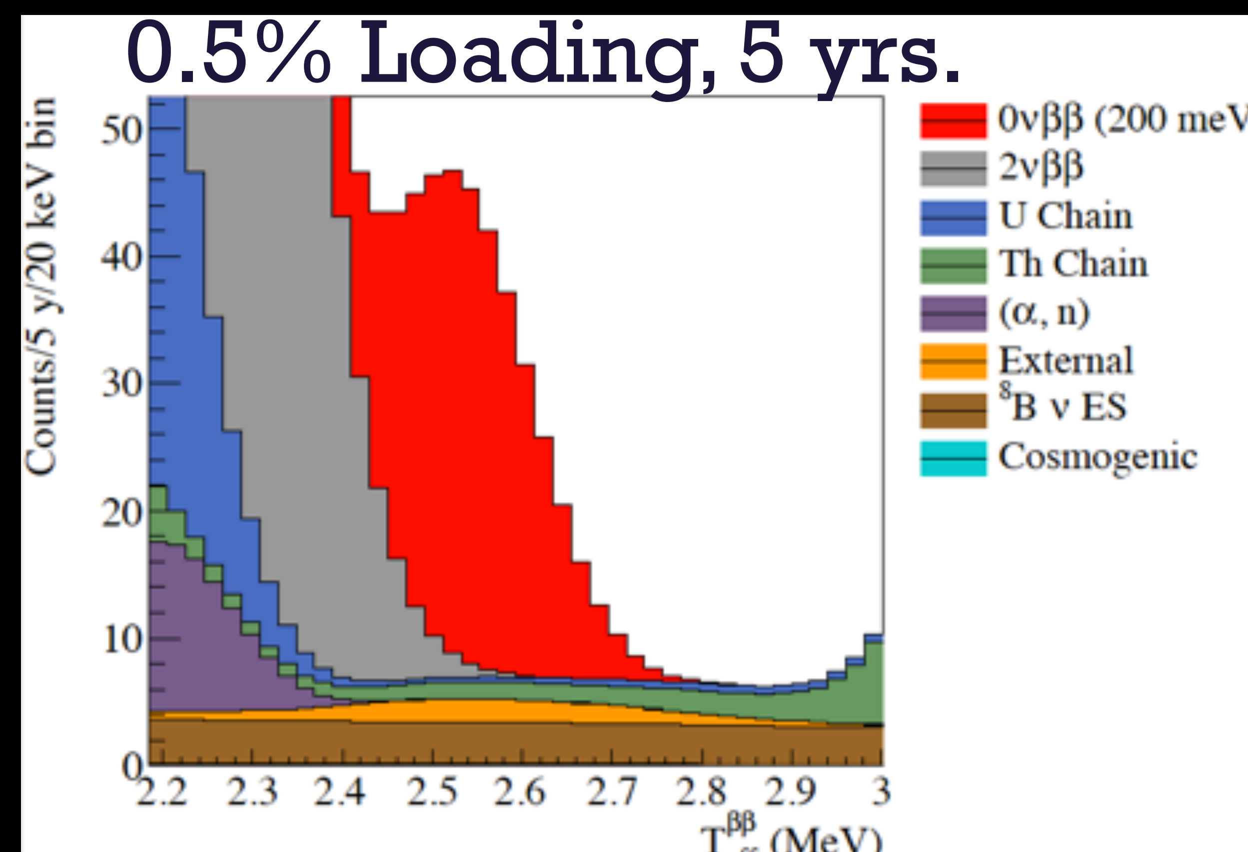
ONWARD TO SNO+



- replace heavy water with 780 tons of liquid scintillator (LAB+PPO)
- load it with 3900 kg of nat. Tellurium, but there is the potential to 6x higher loadings
- search for ^{130}Te neutrinoless double beta decay



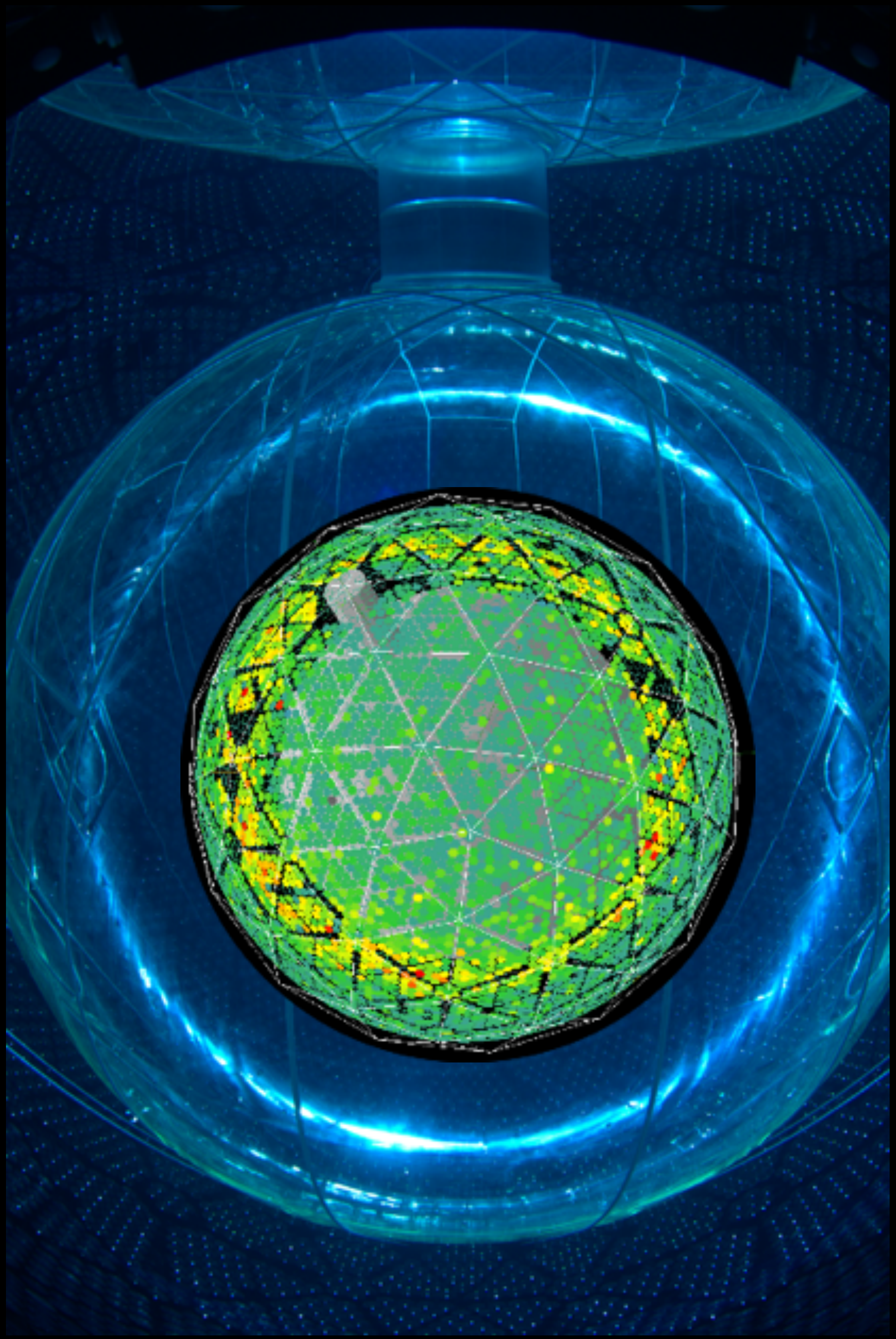
$T_{1/2} \geq 1.96 \times 10^{26}$ yr (90% CL, 5 yr)



- good self-shielding of externals
- purification on-site of LAB and Te
- variable loadings
- Tellurium: high isotopic abundance and 2ν mode half-life

STATUS OF SNO+

- Filled with water
- Water phase about to start, to measure backgrounds and calibrate
  - a few interesting events already
- Scintillator fill late 2017
- Tellurium loading 2018



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
- Field wide open for new experiments
  - CP violation
  - Dirac or Majorana neutrinos?
  - Absolute neutrino mass and ordering

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