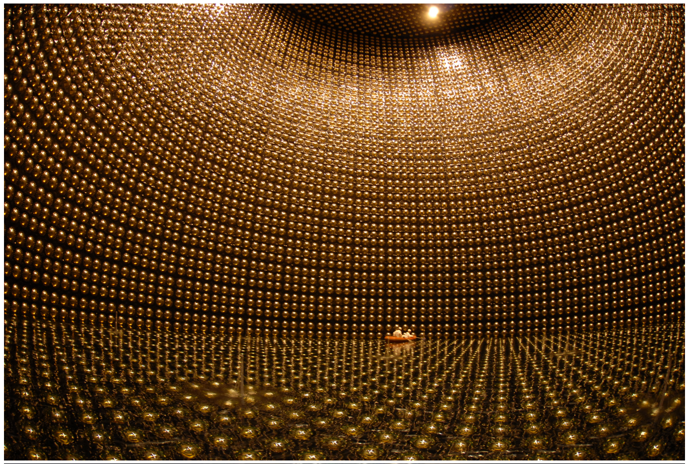
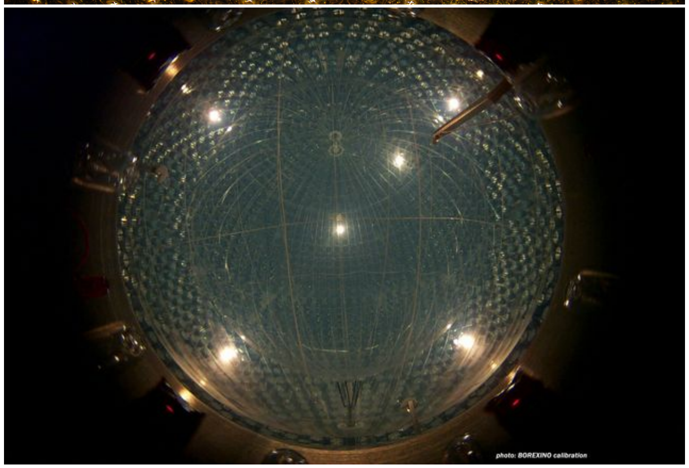
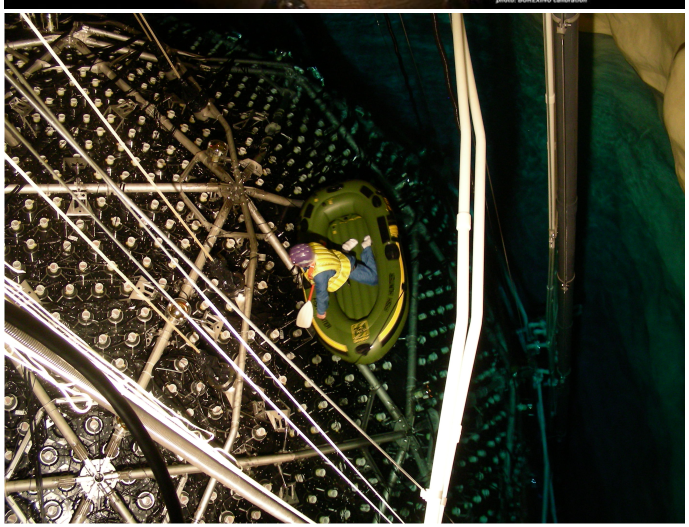






Solar Neutrinos: Status and Prospects

Mark Chen

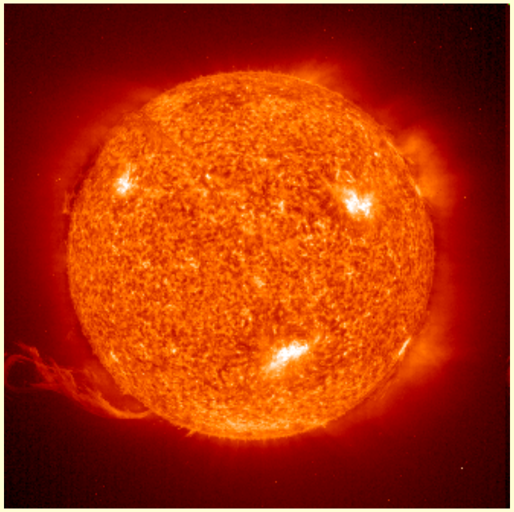
Queen's University

IV Pontecorvo Neutrino Physics School

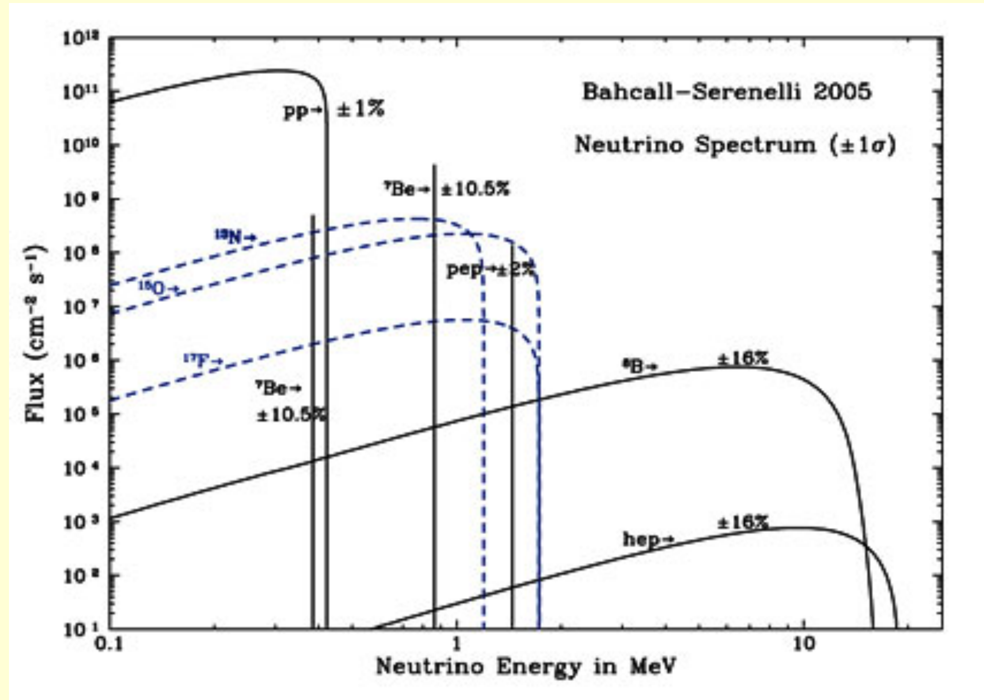
These Lectures

- a quasi-historical journey, with flash forward to the present day, looking back at solar neutrino experiments to establish the present day status
  - radiochemical, water Čerenkov, liquid scintillator
- a look at future prospects
  - new experiments being built and what new physics they will explore
  - brief look at some experiments being proposed

- Note: I have borrowed figures and material from many experiments and many people. Thanks to all of them!



Solar Neutrinos



pp Solar Fusion Chain

$p + p \rightarrow {}^2H + e^+ + \nu_e$ $\quad$ $p + e^- + p \rightarrow {}^2H + \nu_e$

$${}^2H + p \rightarrow {}^3He + \gamma$$

${}^3He + {}^3He \rightarrow {}^4He + 2\,p$ $\quad$ ${}^3He + p \rightarrow {}^4He + e^+ + \nu_e$

$${}^3He + {}^4He \rightarrow {}^7Be + \gamma$$

${}^7Be + e^- \rightarrow {}^7Li + \gamma + \nu_e$ $\quad$ ${}^7Be + p \rightarrow {}^8B + \gamma$

${}^7Li + p \rightarrow \alpha + \alpha$ $\quad$ ${}^8B \rightarrow 2\,\alpha + e^+ + \nu_e$

CNO Cycle

${}^{12}C + p \rightarrow {}^{13}N + \gamma$ $\quad$ ${}^{13}N \rightarrow {}^{13}C + e^+ + \nu_e$

${}^{13}C + p \rightarrow {}^{14}N + \gamma$

${}^{14}N + p \rightarrow {}^{15}O + \gamma$ $\quad$ ${}^{15}O \rightarrow {}^{15}N + e^+ + \nu_e$

${}^{15}N + p \rightarrow {}^{12}C + \alpha$

Solar Neutrino Pioneers

Ray Davis built the Chlorine Experiment in the 1965-67

John Bahcall produces the “Standard Solar Model” neutrino calculations

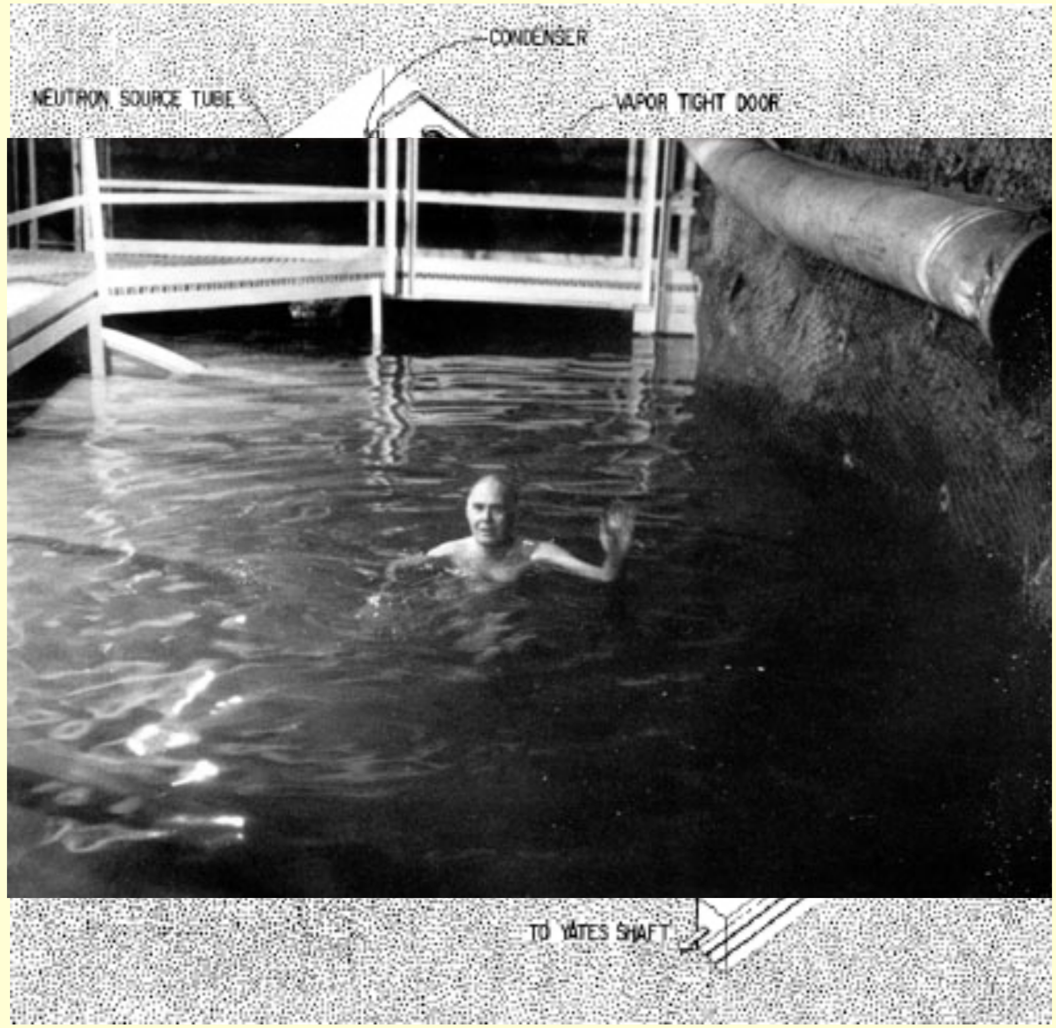
“…to see into the interior of a star and thus verify directly the hypothesis of nuclear energy generation in stars…”

Ray Davis' Chlorine Experiment

- neutrino capture reaction:

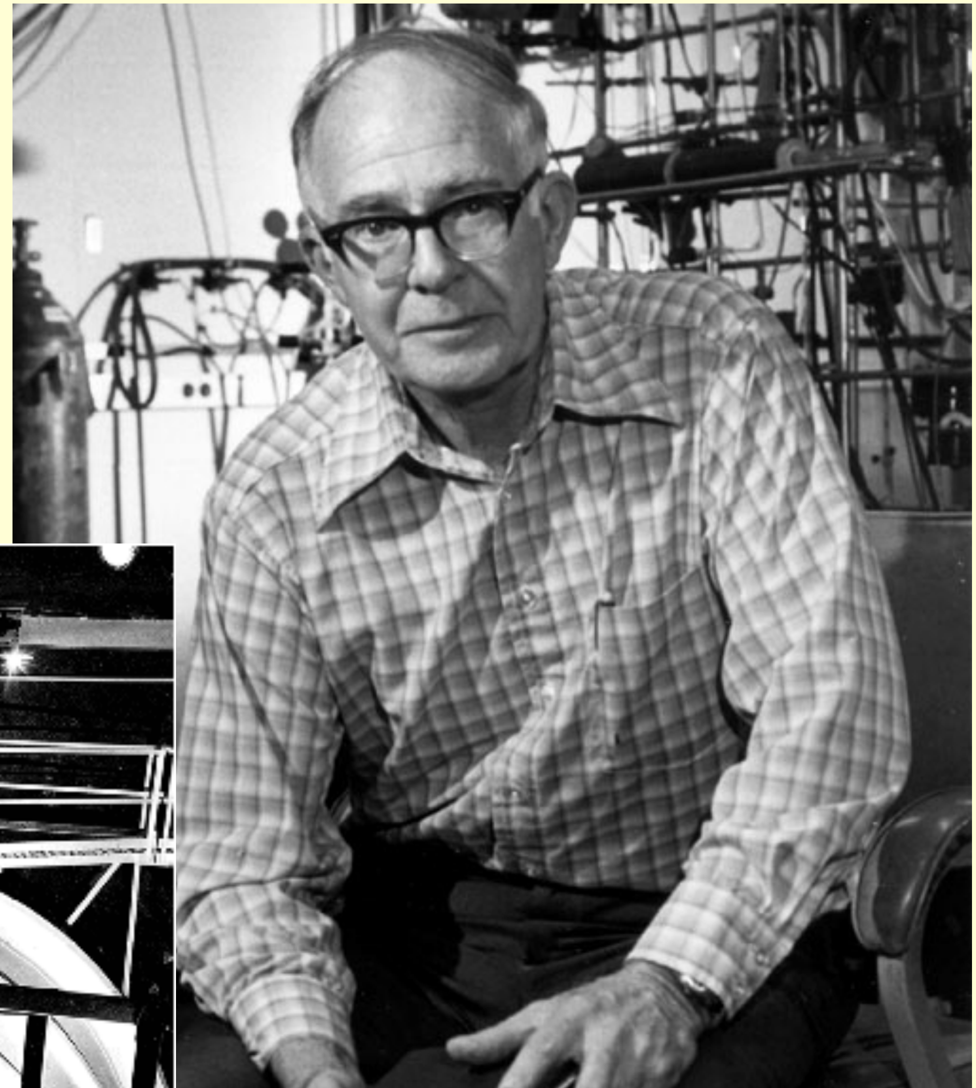
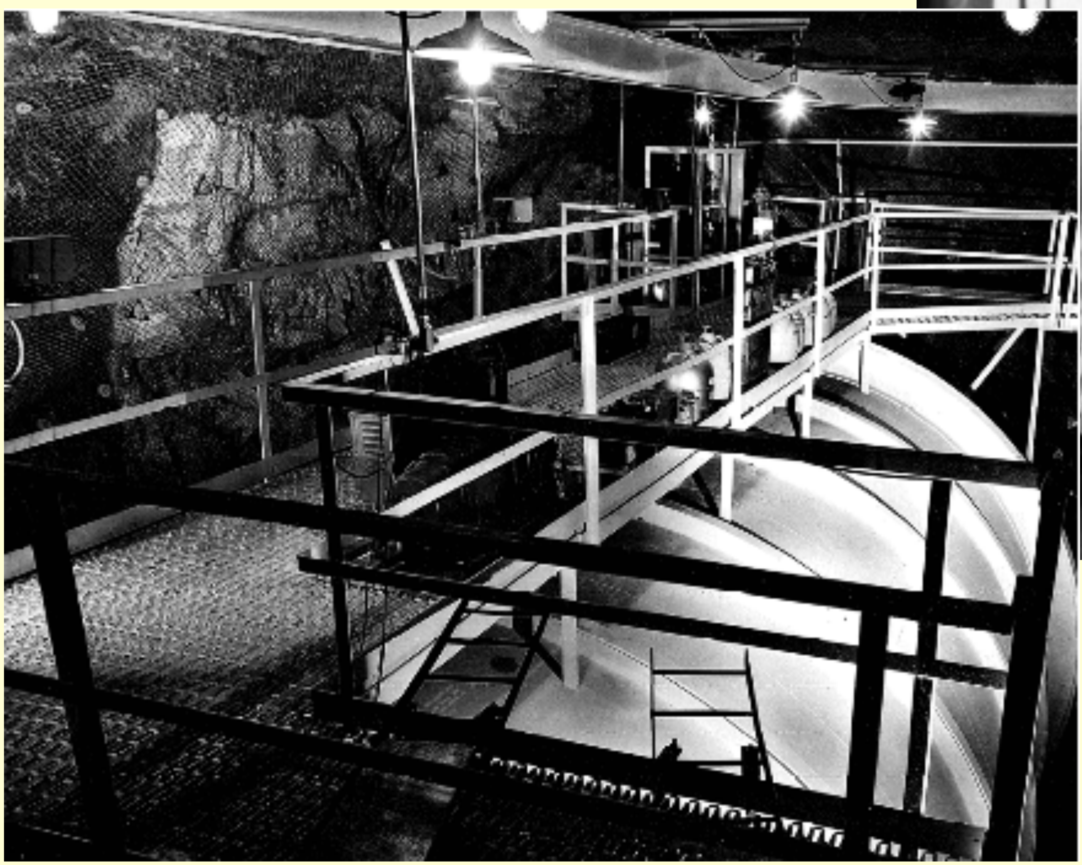
$$\frac{\nu_e + {}^{37}\mathrm{Cl} \rightarrow {}^{37}\mathrm{Ar} + e^-}{{}^{37}\mathrm{Ar} + e^- \rightarrow {}^{37}\mathrm{Cl} + \nu_e}$$

- $E_{threshold}$ = 0.814 MeV
- ^{37}Ar half-life is 35 days
- "expose" chlorine to solar neutrino flux for ~2 $t_{1/2}$
- chemistry to collect/purify ~10 atoms of argon produced in the tank
- count ^{37}Ar EC decays in a low-background proportional counter



615 tons of C_2Cl_4

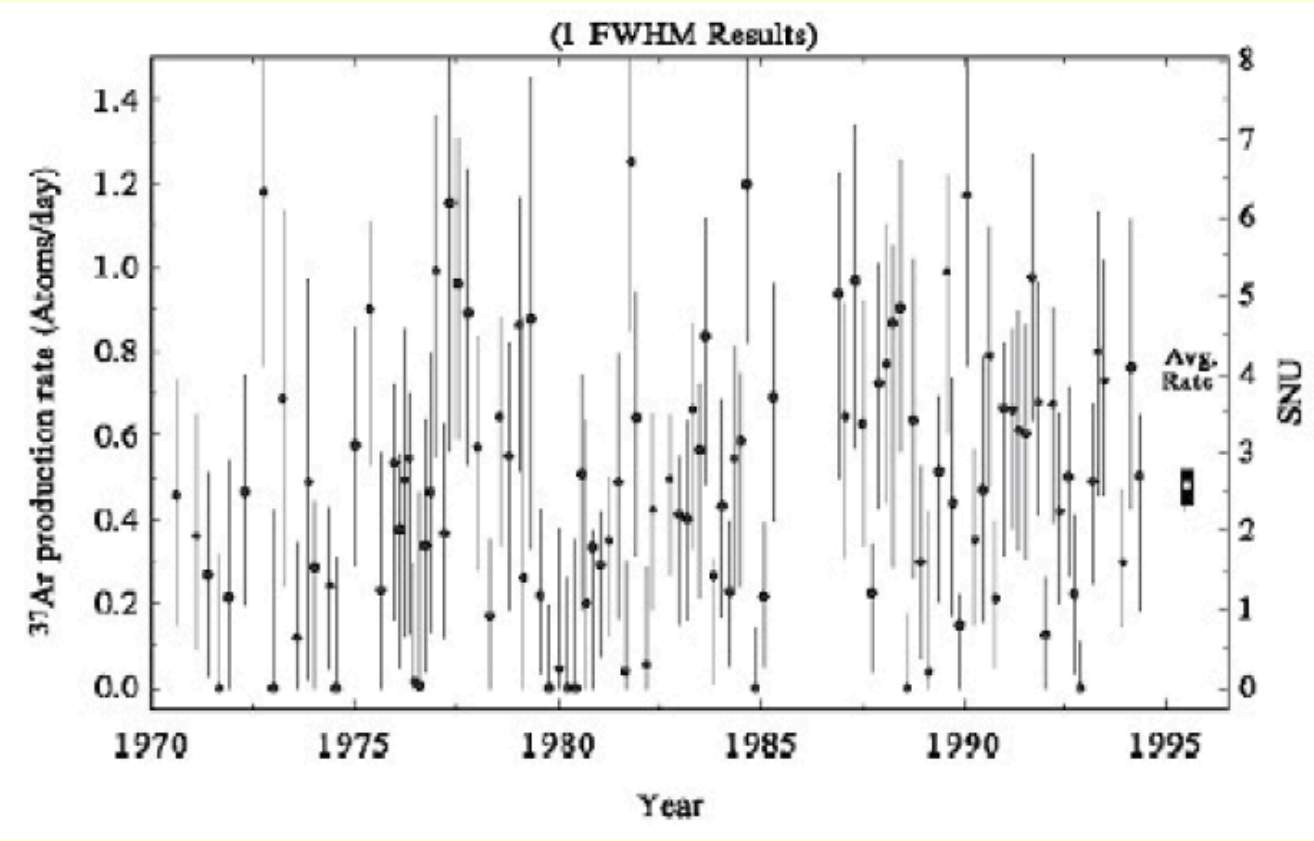
location: Homestake Mine in South Dakota, USA

Chlorine Results: 1970-1994 (Final)

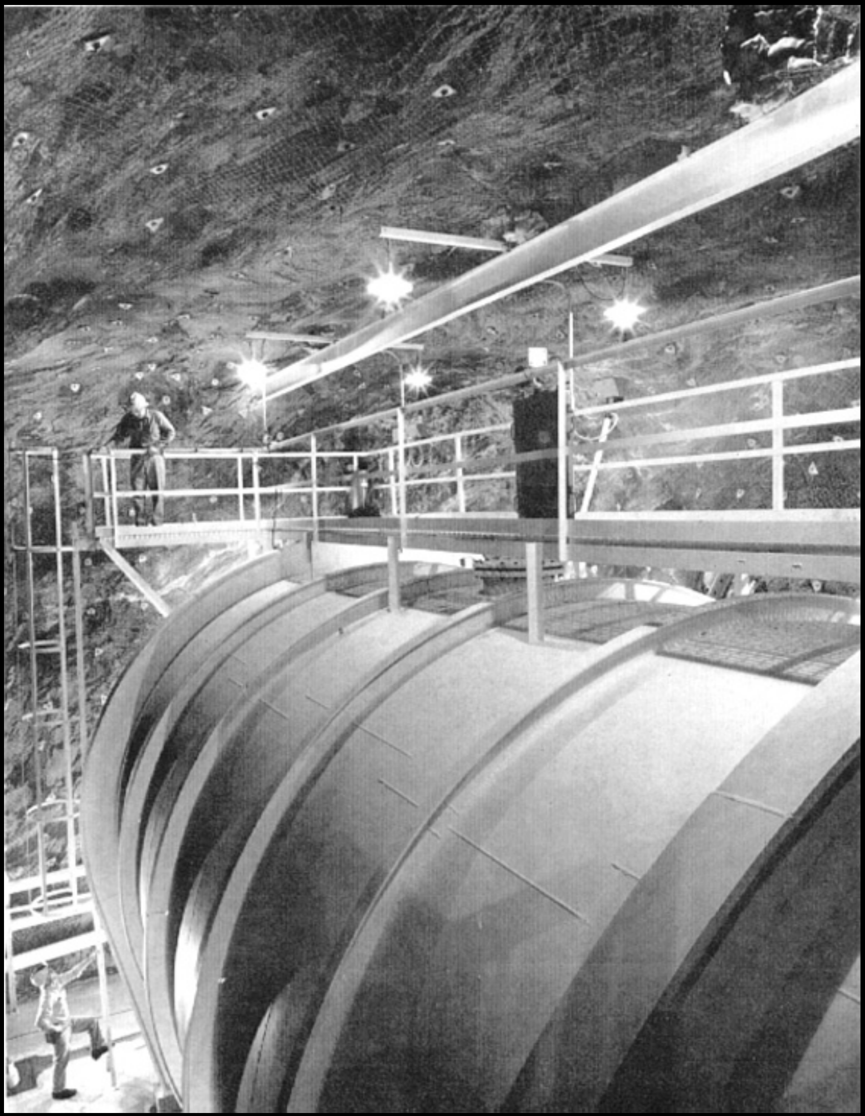
- average: 2.56 ± 0.23 SNU (Solar Neutrino Unit)
- solar model predicted rate: 7-8 SNU

1 SNU = 1 neutrino capture per second per 10^{36} target atoms



Solar Neutrino Problem

- deficit of solar neutrinos detected by experiments compared to solar models is due to:
  - experiment(s) are wrong
    - is Ray Davis wrong?
  - incorrect model/physics of the solar interior
    - is John Bahcall wrong?
  - incorrect understanding of nuclear reactions?
  - new properties of massive neutrinos produce an *apparent* deficit?



What Experiments Followed?

- radiochemical experiments with gallium
- water Čerenkov detector
- heavy water Čerenkov detector
- liquid scintillator detector
- other ideas that were proposed or attempted:
  - boron-loaded scintillator CC and NC reactions
  - iodine-to-xenon radiochemical experiment
  - lithium-to-beryllium radiochemical
  - bromine-to-krypton radiochemical
  - indium experiment (very low threshold) – more on this later
  - fluorine neutrino capture (with coincidence tag)

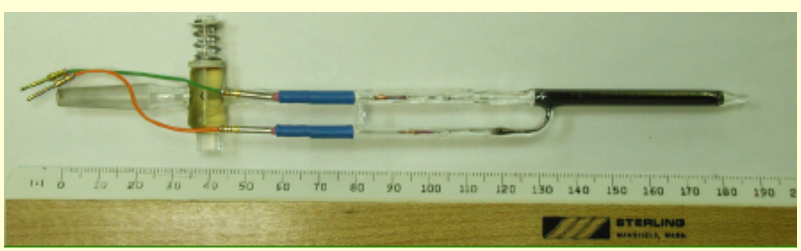
I will describe the final status of these efforts rather than the chronological contributions to our understanding of solar neutrinos, as the results came to be.

SAGE Experiment

- neutrino capture reaction:

$$\nu_e + {}^{71}\mathrm{Ga} \rightarrow {}^{71}\mathrm{Ge} + e^-$$

- $E_{threshold}$ = 0.233 MeV
- sensitive to *pp* solar ν
- $t_{1/2}$ is 11.4 days
- germanium atoms are extracted with sensitivity: 1 germanium atom extracted from 5×10^{29} atoms of gallium, with 90% efficiency

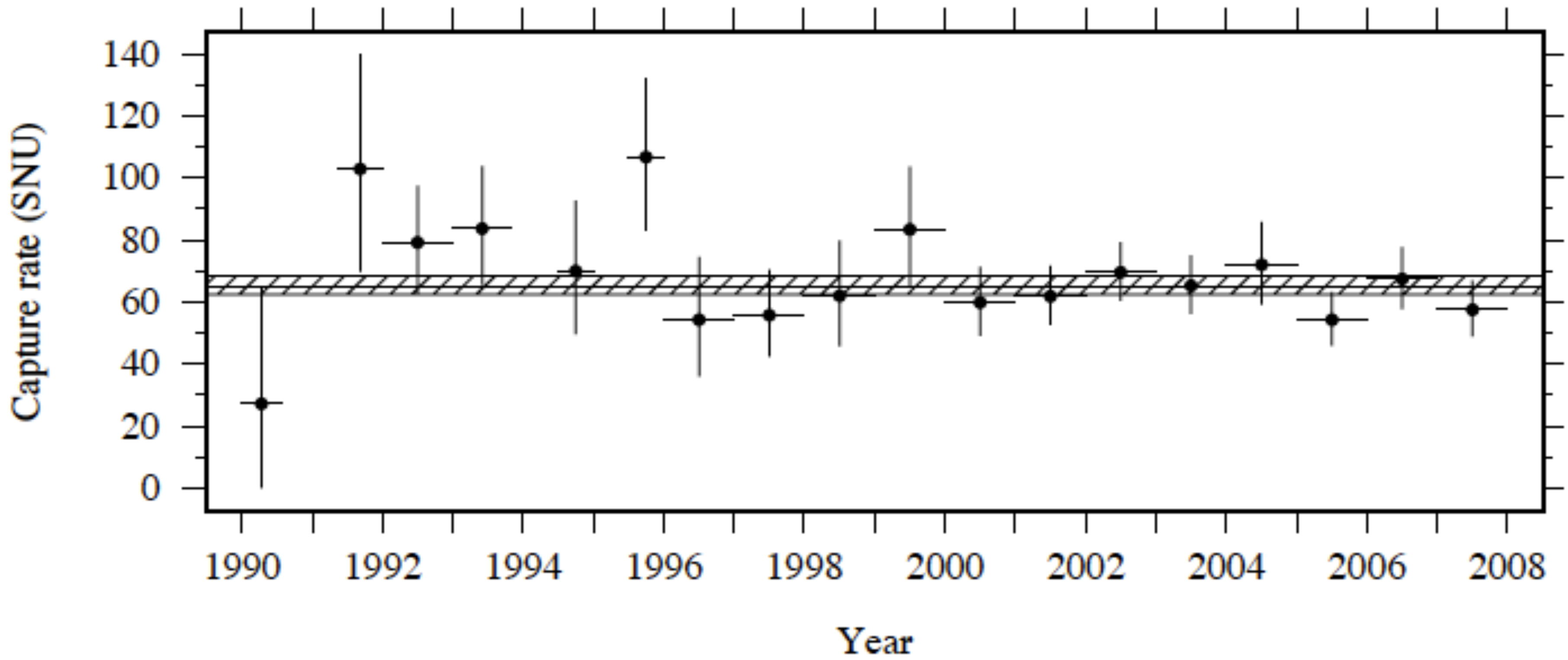


50 tons of metallic gallium
location: Baksan Underground Lab, northern Caucasus

SAGE Results: 1990-2008

$$65.4^{+3.1}_{-3.0}\,(stat.)^{+2.6}_{-2.8}\,(syst.)\ \mathrm{SNU}$$

solar model
predicted rate:
120-130 SNU



SAGE continues to perform regular extractions every ~4 weeks.

SAGE – Soviet American Gallium Experiment

- radiochemical Ga experiment at Baksan Neutrino Observatory with 50 tons of metallic gallium
- running since 1990-present

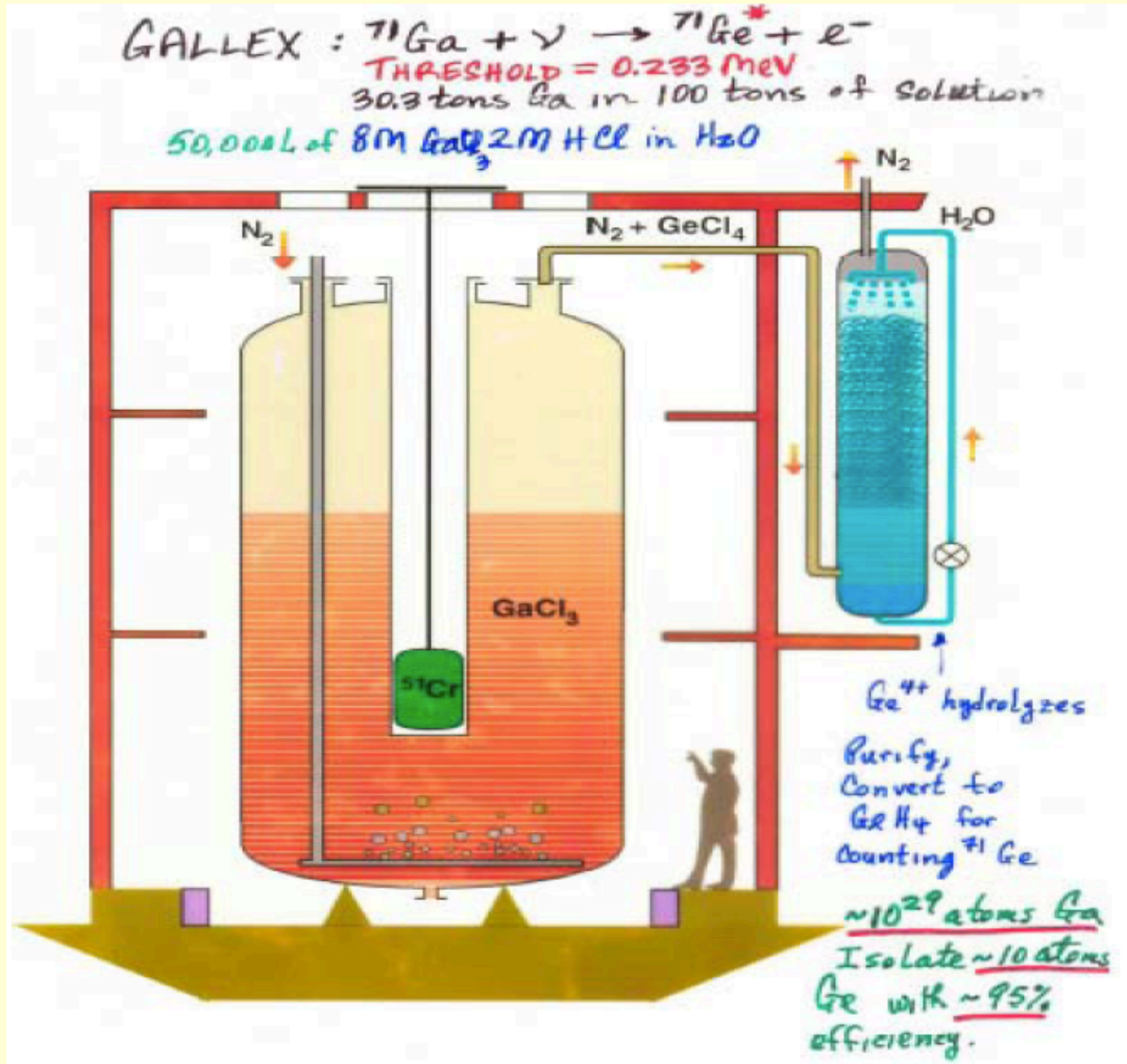
M. Chen
TAUP 2007

measures *pp* solar flux in agreement with SSM when oscillations are included – the predicted signal is

$$67.3^{+3.9}_{-3.5}\ \mathrm{SNU}$$

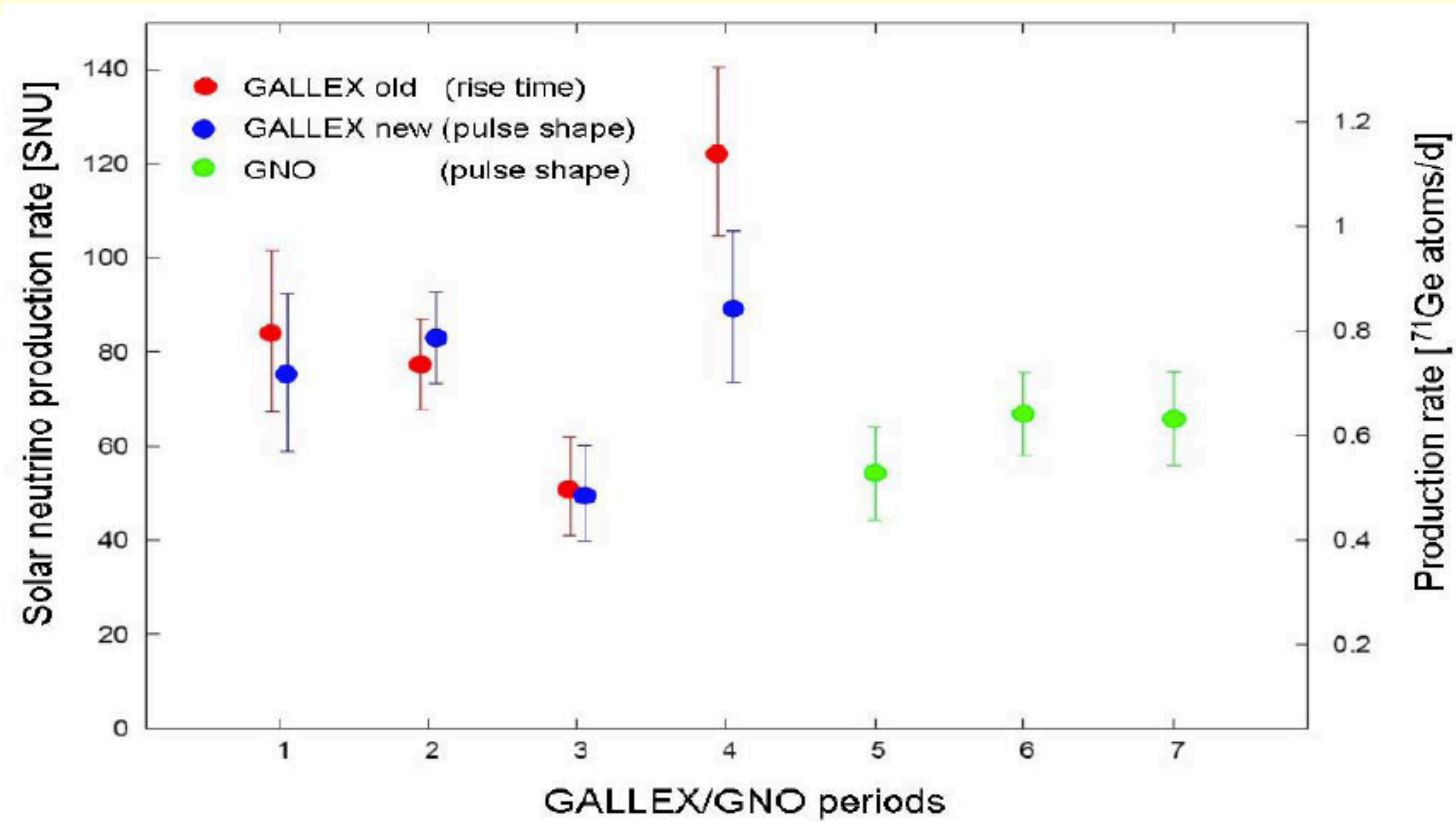
Gallex/GNO Experiment

- similar to SAGE except with gallium chloride
- ran as Gallex (1991-97)
- then as GNO (1998-2003)
- Gallex recently reanalyzed all their data
- re-calibrated all low-background counters with large Ge spike
- used pulse-shape analysis like for GNO analysis
- improved Rn cut efficiency and background determination



100 tons of gallium chloride solution (30 tons ^{71}Ga)
location: Gran Sasso National Lab in Abruzzo, Italy

Gallex/GNO Results



Summary of Radiochemical Gallium Solar Neutrino Results

- updated Gallex combined: $73.4^{+6.1}_{-6.0}\,^{+3.7}_{-4.1}$ SNU
- GNO combined: $62.9^{+5.5}_{-5.3}\,^{+2.5}_{-2.5}$ SNU
- Gallex+GNO combined: 67.6 ± 4.0_{stat} ± 3.2_{syst} SNU
- SAGE average: $66.2^{+3.3}_{-3.2}\,^{+3.5}_{-3.2}$ SNU
- both experiments calibrated with neutrino sources; and measured hot chemical extraction efficiency
- they see a clear deficit of the fundamental *pp* fusion solar neutrinos; results in agreement with each other and with solar model predictions when oscillations are included

Gallex and SAGE Calibrations

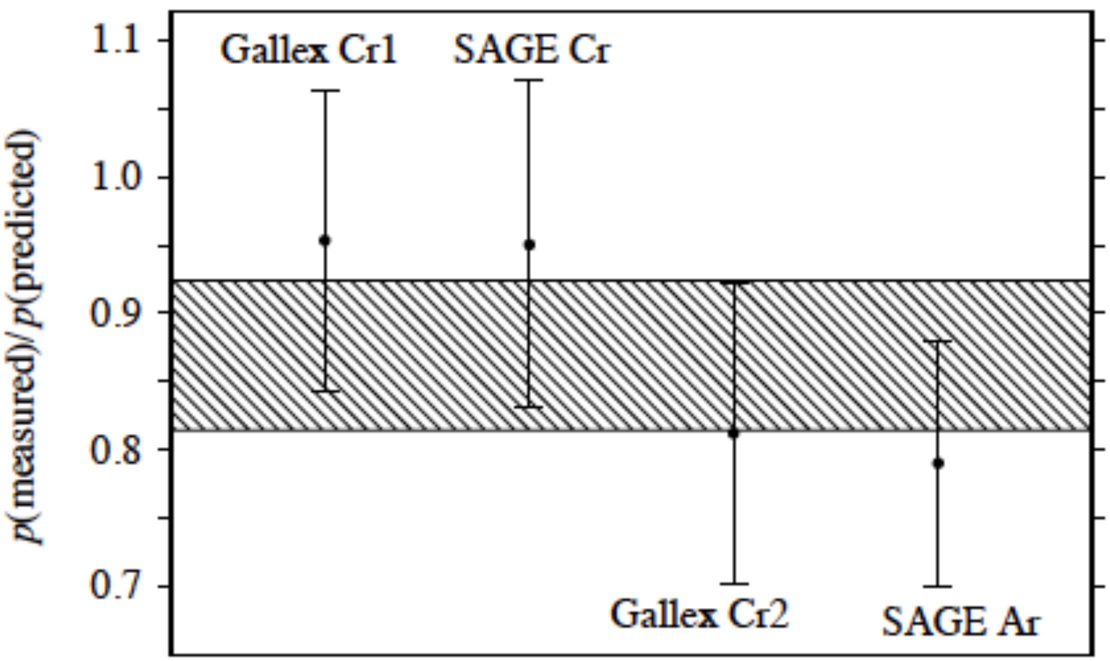


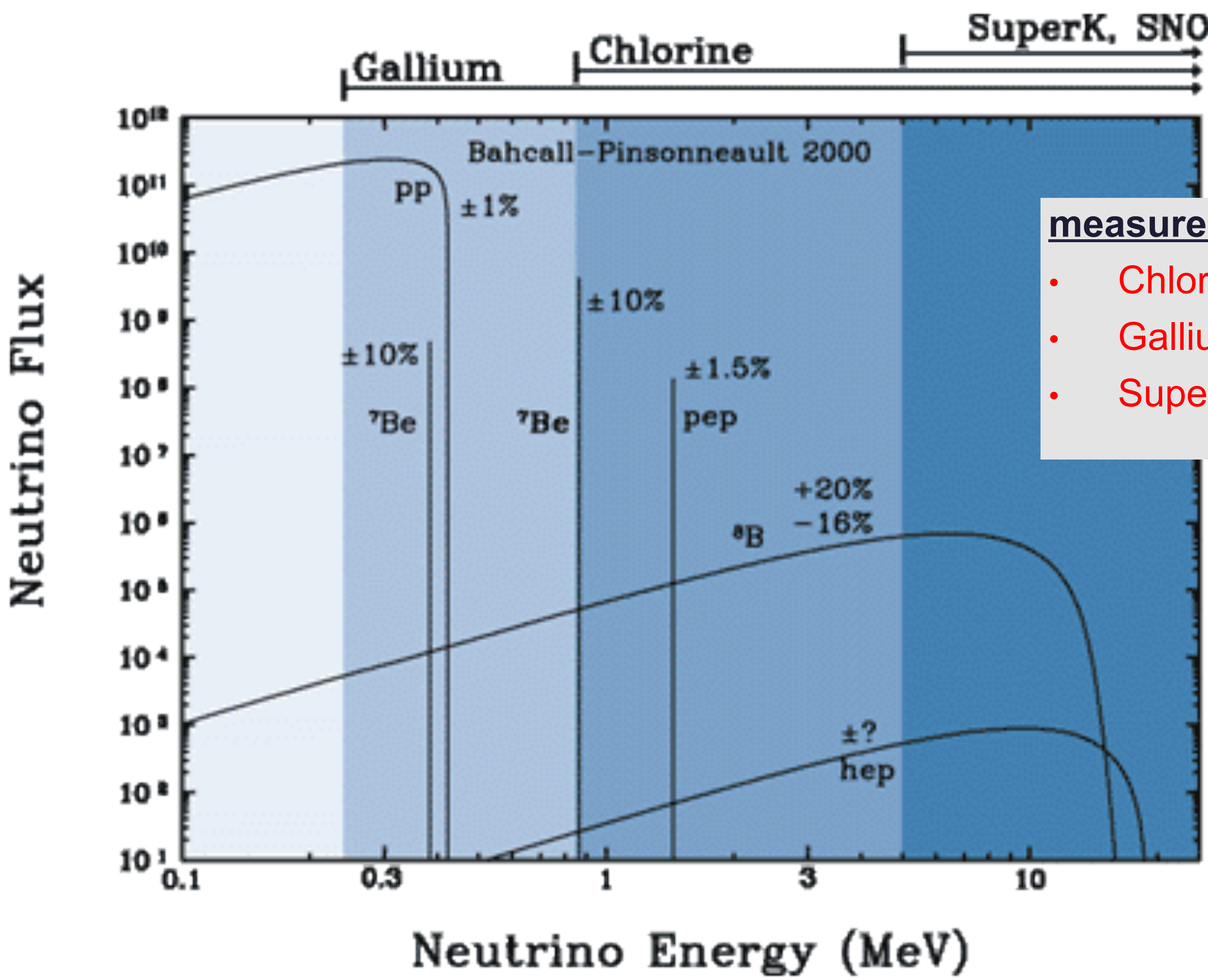
FIG. 3: Results of all neutrino source experiments with Ga. Gallex results are from the recent pulse shape analysis of Kaether [9]; SAGE results are from Refs. [11] and [4]. Hashed region is the weighted average of the four experiments.

- all are low?
  - just statistics?
  - efficiency of extraction is incorrect?
  - oscillations cause disappearance?
  - production rate from source (i.e. cross section for absorption) not as large as assumed in calculation?

Outstanding Issues with Gallium?

- calibrations are low?
- time dependence?
  - Gallex (1991-97) runs higher than GNO (1998-2003)
  - same is observed by SAGE
- …or, is all of this just fine and within experimental errors? Probably.

Energy Dependence of Solar ν Deficit



measured / no oscillation expectation

- Chlorine 0.34 ± 0.03
- Gallium 0.52 ± 0.03
- Super-K 0.46 ± 0.02

The "Solar Neutrino Problem"

Imaging Water Čerenkov Detectors

- Kamiokande and IMB built in the 80's
  - large water Čerenkov detectors that searched for proton decay
- Kamiokande was then upgraded, beginning in 1985, to detect ^{8}B solar neutrinos (1st solar ν results in 1988)
- Super-Kamiokande (larger and improved) was built and became operational on April 1, 1996
- SNO – a heavy water Čerenkov detector was built and started taking production data on November 1, 1999

Masatoshi Koshiba shared 2002 Nobel Prize with Ray Davis (and Giacconi)

Čerenkov Light

- emitted by charged particles whose velocity exceed c/n
- for electrons in water, threshold:
  E > 0.768 MeV
- cone of light, half angle given by:
  $\cos\theta = 1 / (\beta n)$; 41° in water for $\beta \approx 1$
- spectrum of photons emitted:

$$\frac{dN}{d\lambda} = \frac{2\pi c\alpha}{c}\left(1 - \frac{1}{n^2\beta^2}\right)\frac{1}{\lambda^2}$$

- in water: 390 photons per cm, between 300 nm and 700 nm

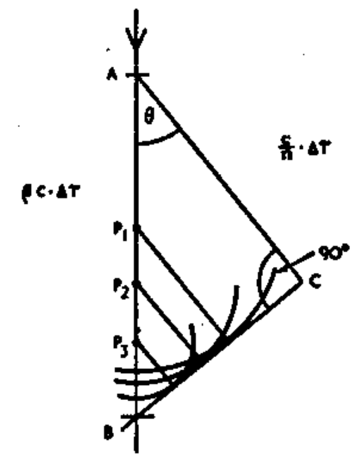
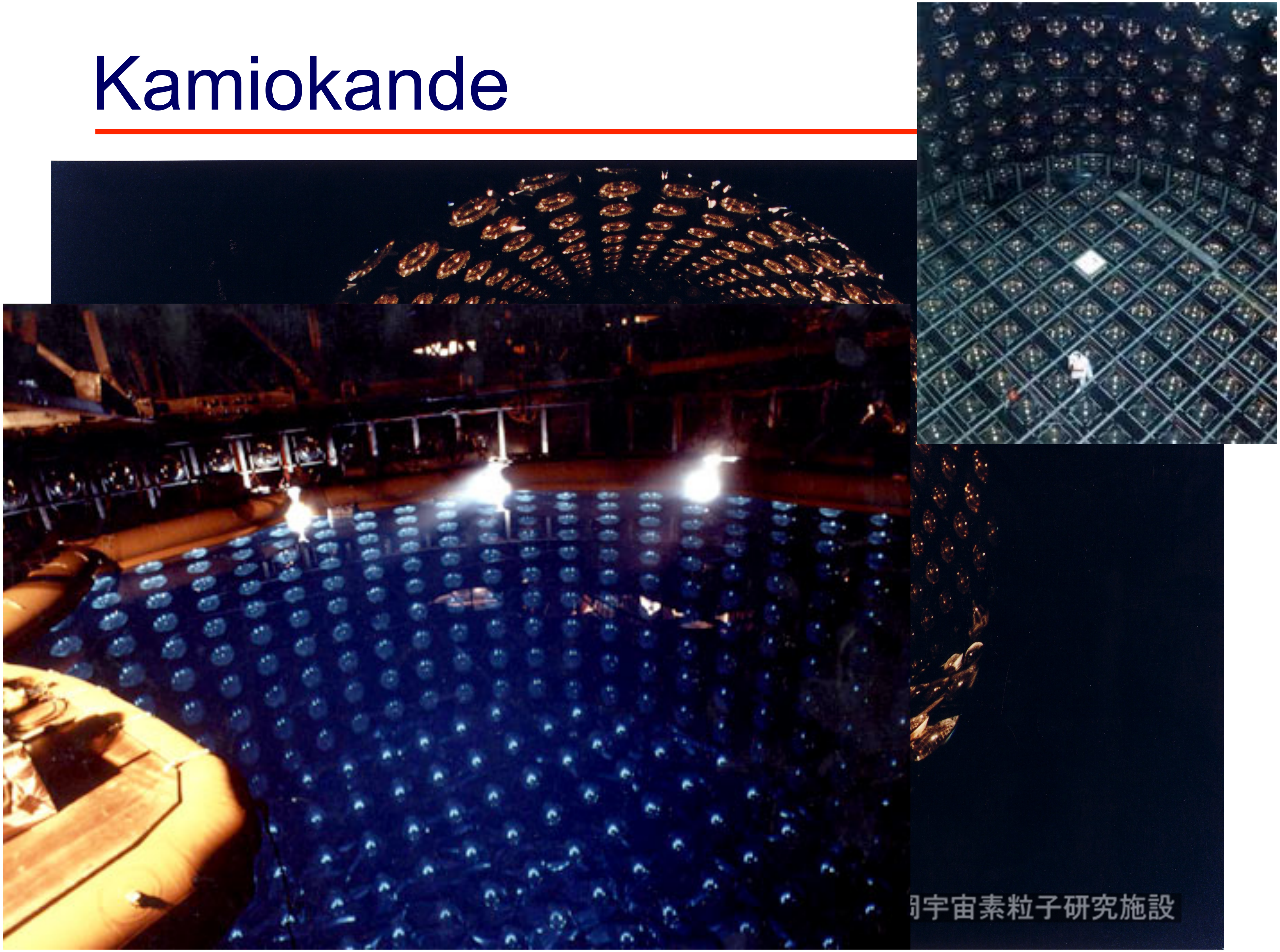


FIG. 1.2. Huygens construction to illustrate coherence.

5 MeV e⁻ travels ~2 cm in water; ~800 photons produced; 20% average PMT efficiency; 33% photocathode coverage → ~50 photoelectrons or 10 p.e./MeV

Kamiokande



Kamiokande ^{8}B Solar Neutrinos

- confirmed deficit of ^{8}B solar neutrinos
- flux measured by Kamiokande of 2.67×10^{6} cm^{-2} s^{-1} compared to solar model calculated flux of ~$5\text{-}6\times10^{6}$ cm^{-2} s^{-1}

- Bahcall and Bethe made the following inference: from the Kamiokande measured flux (of ν_e), this would result in at least 3 SNU in the Chlorine experiment
- at that time, the Cl result was 2.2 ± 0.2 SNU (in 1993)
-

PHYSICAL REVIEW D VOLUME 47, NUMBER 4 15 FEBRUARY 1993

Do solar-neutrino experiments imply new physics?

John N. Bahcall
Institute for Advanced Study, Princeton, New Jersey 08540

H. A. Bethe
Newman Laboratory of Nuclear Studies, Cornell University, Ithaca, New York 14853

(Received 24 August 1992)

Interesting to Note…

- it turns out that today we know that neither of these two possibilities are correct!
- Bahcall-Bethe was a test case hypothesis that refuted a conventional astrophysical solution to the solar neutrino problem
  - they scaled the whole Kamiokande signal as ν_e
  - but, today we know how to calculate the actual ^8B ν_e contribution to the Chlorine experiment…by using the SNO charged-current result (more on this later)

Super-K Solar Neutrino Detection

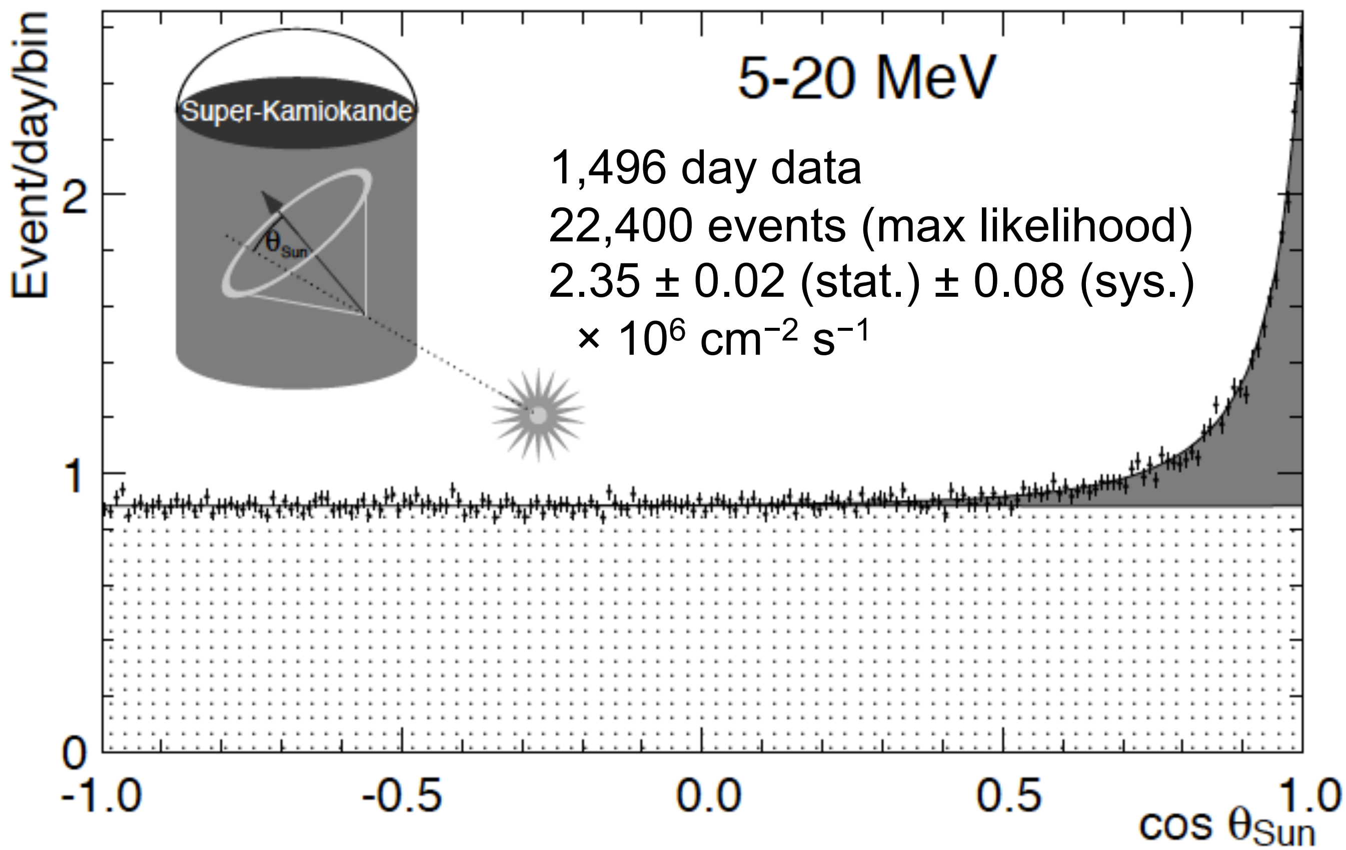
neutrino-electron scattering

$\nu_x + e^- \rightarrow \nu_x + e^-$ (ES)

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

~6 times higher cross section than

$\nu_\mu + e^- \rightarrow \nu_\mu + e^-$

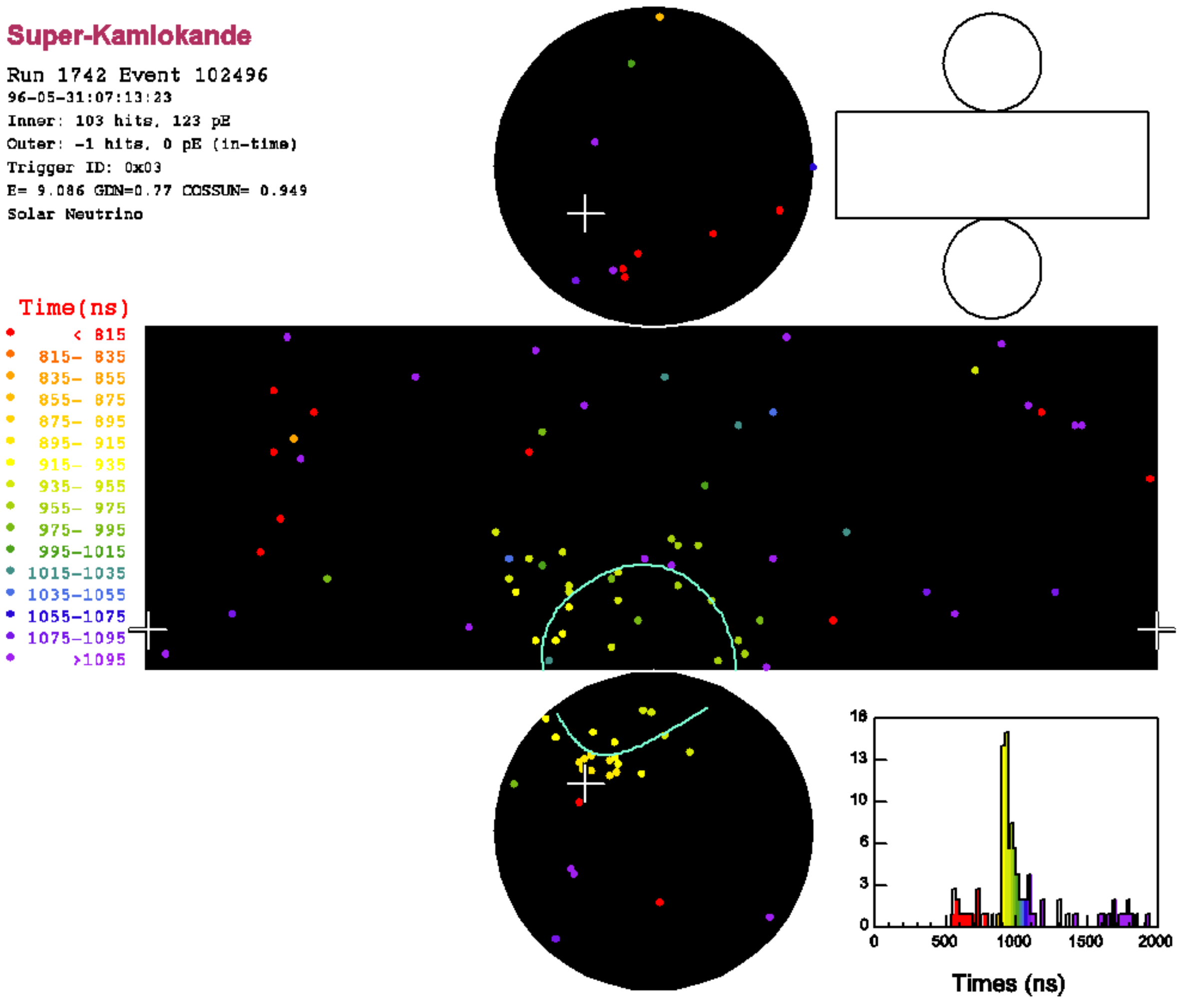


find ring in pattern of hit PMTs

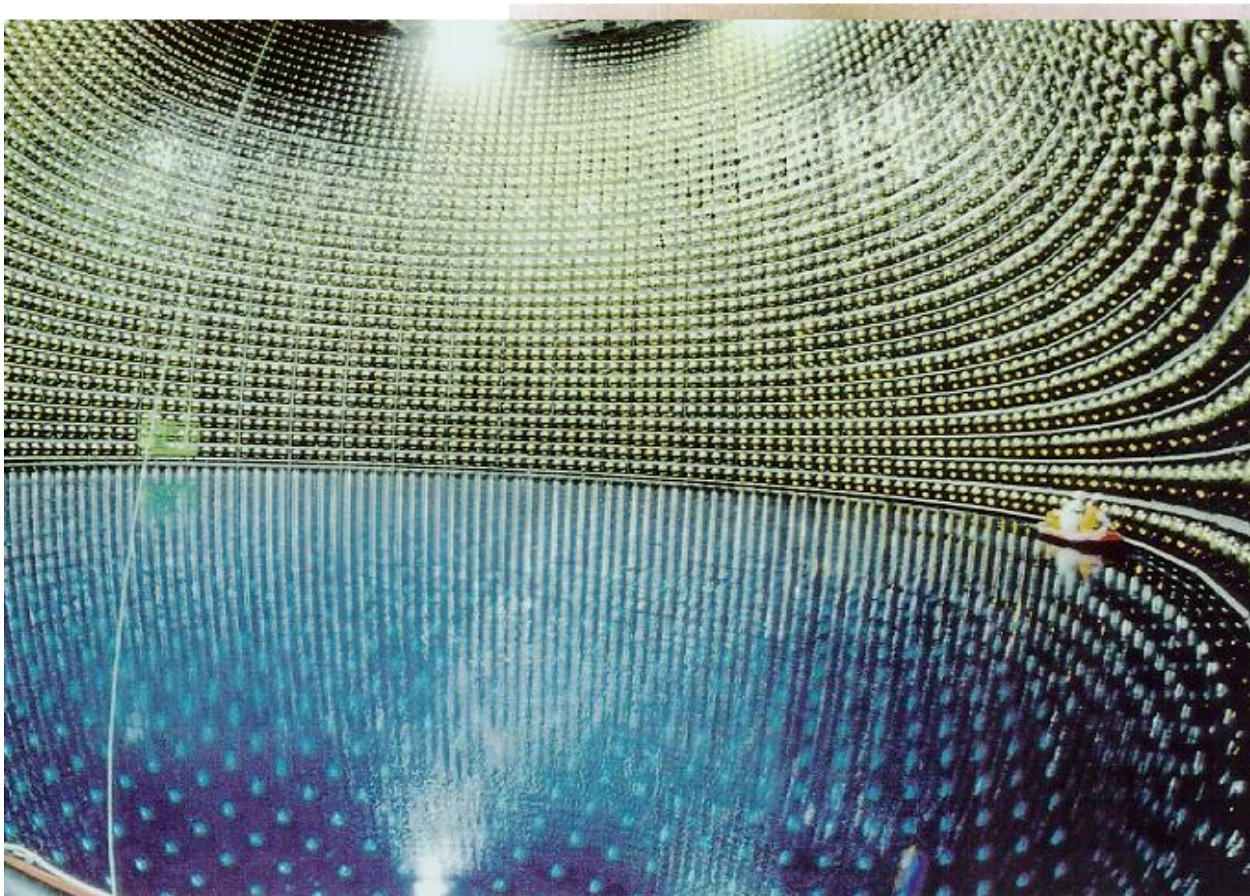
reconstruct direction of incoming neutrino and correlate to the Sun direction

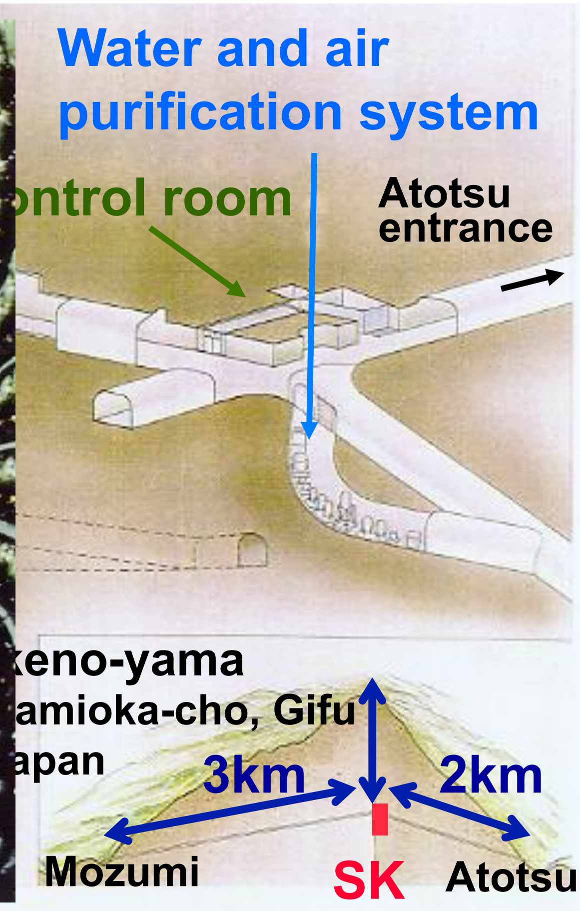
kinematics of ES gives forward-peaked distribution

Typical Low Energy Event in SK



Super-Kamiokande





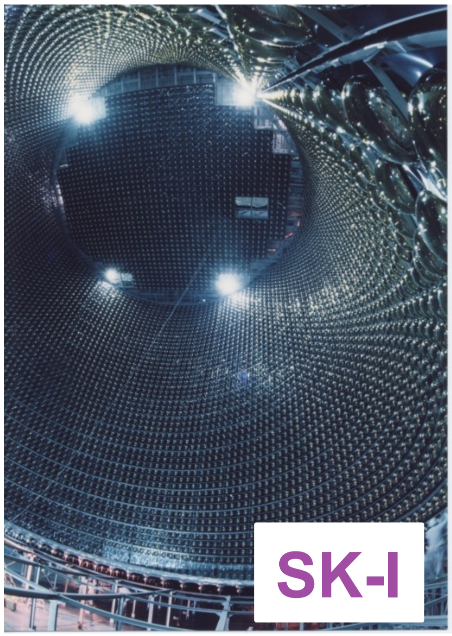
50 kilotons water; cylinder 39.3 m diameter and 41.4 m high;
11,146 PMT’s (20-inch) for 40% photocathode coverage

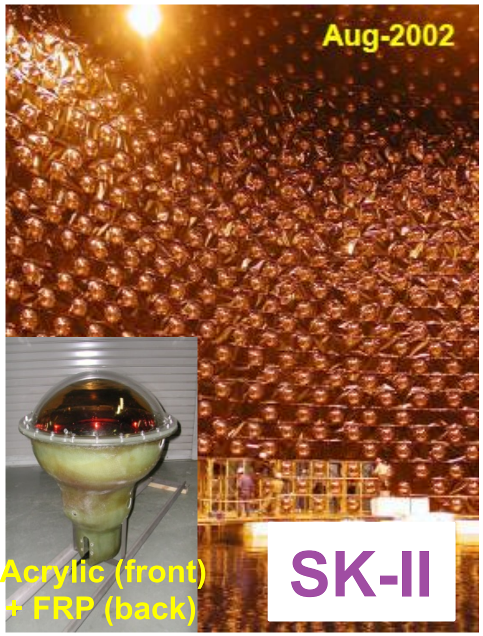
location: Kamioka mine, near Mozumi, Japan

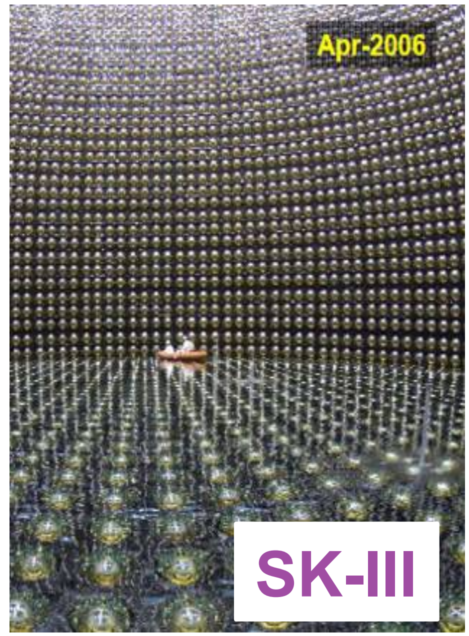
History of Super-Kamiokande

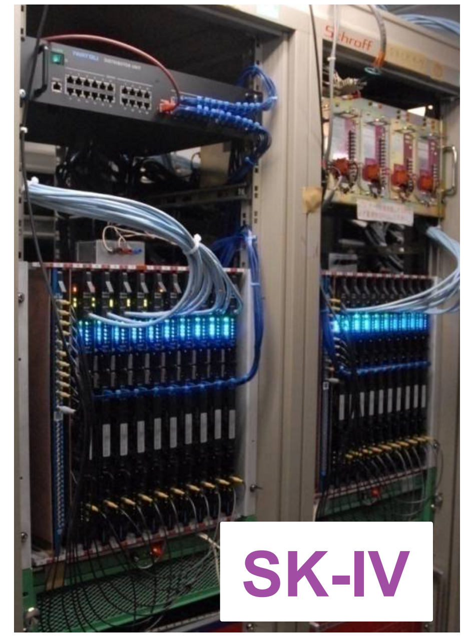
1996	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010

SK-I SK-II SK-III SK-IV



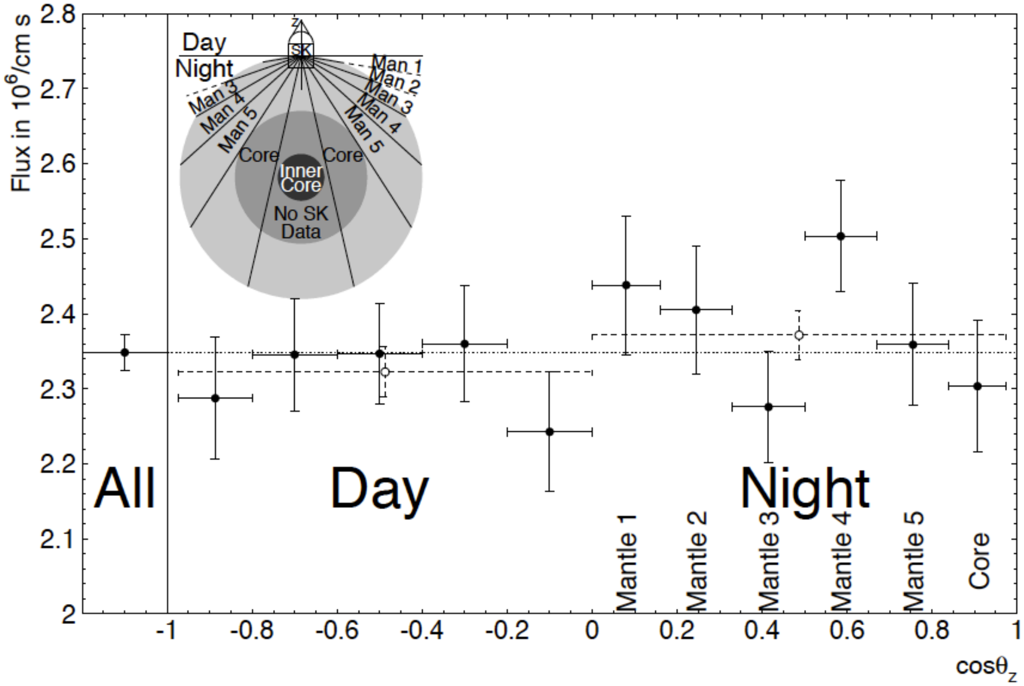






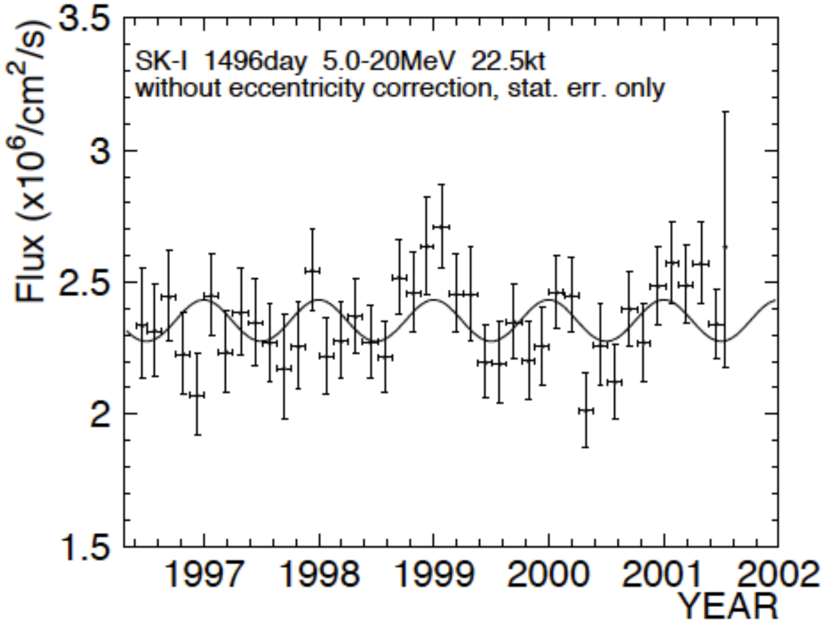
	SK-I	SK-II	SK-III	SK-IV	
	11146 ID PMTs (40% coverage)	5182 ID PMTs (19% coverage)	11129 ID PMTs (40% coverage)	Electronics Upgrade	
Energy Threshold (Total energy)	5.0 MeV	7.0 MeV	5.0 MeV	~4.5 MeV	< 4.0 MeV
(Kinetic energy)	~4.5 MeV	~6.5 MeV	~4.5 MeV	~4.0 MeV	<~3.5 MeV
				Current	Target

SK-I Solar Neutrino Results



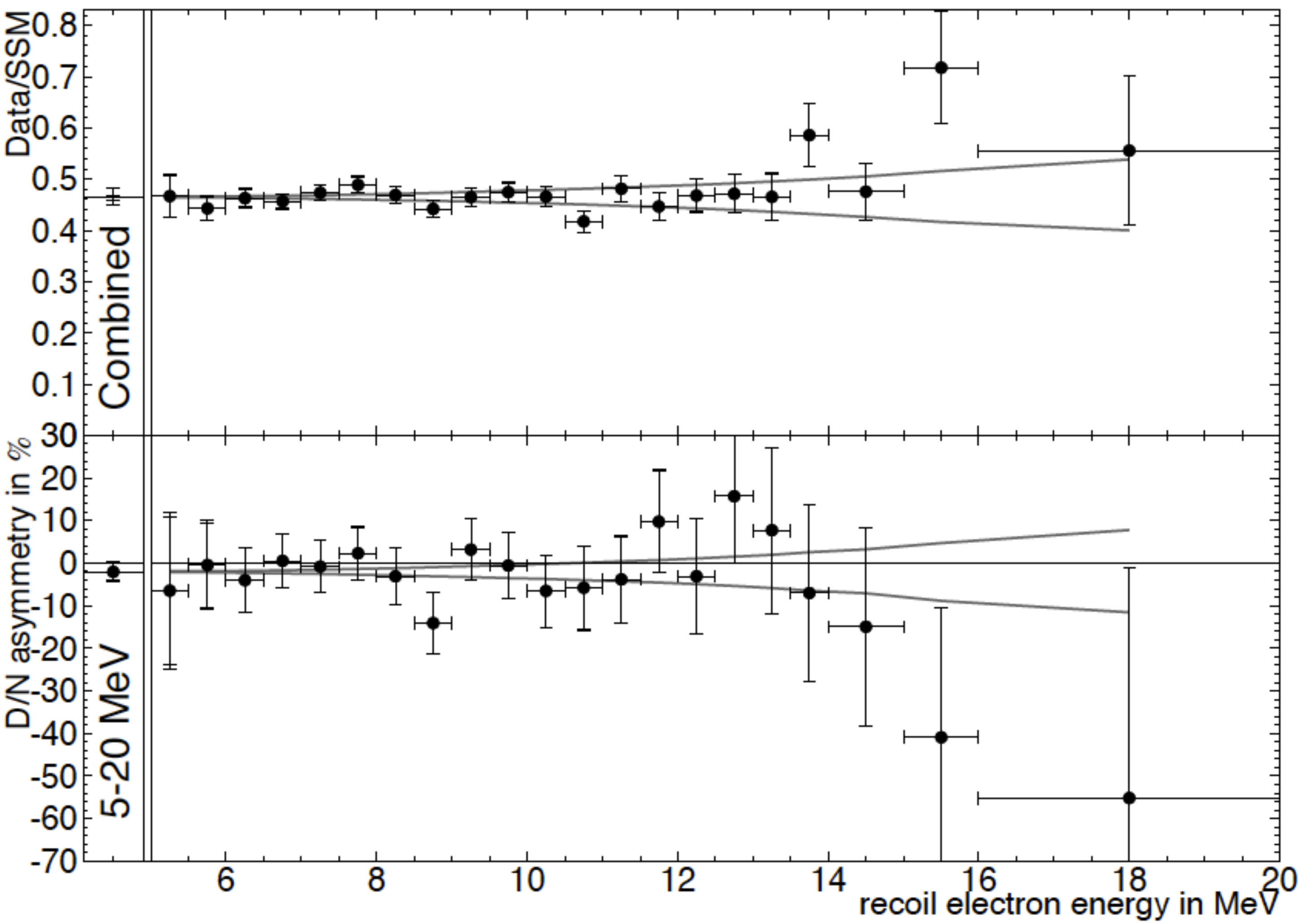
$$A_{DN} = \frac{(\Phi_{day} - \Phi_{night})}{(\Phi_{day} + \Phi_{night})/2}$$

$$= -0.021 \pm 0.020(stat.)^{+0.013}_{-0.012}(syst.)$$



SK-I Energy Spectrum

- and D/N asymmetry versus energy



SK-III solar neutrino results

May 2010

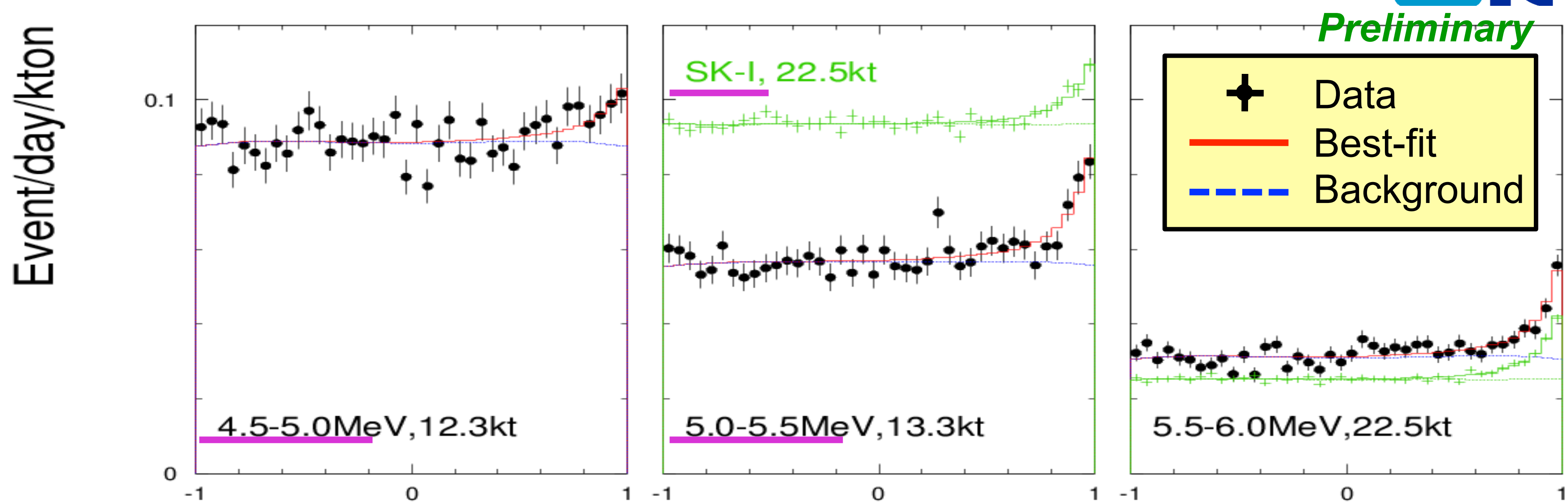
Preliminary

- Total live time : 548 days, $E_{total} \geq 6.5$ MeV
  289 days, $E_{total} < 6.5$ MeV
- Energy region: E_{total}=5.0-20.0MeV
- ^{8}B Flux: 2.32+/-0.04(stat.)+/-0.05(syst.) ($\times 10^6$/cm^2/s)
  - SK-I: 2.38+/-0.02(stat.)+/-0.08(syst.)
  - SK-II: 2.41+/-0.05(stat.)+0.16/-0.15(syst.)

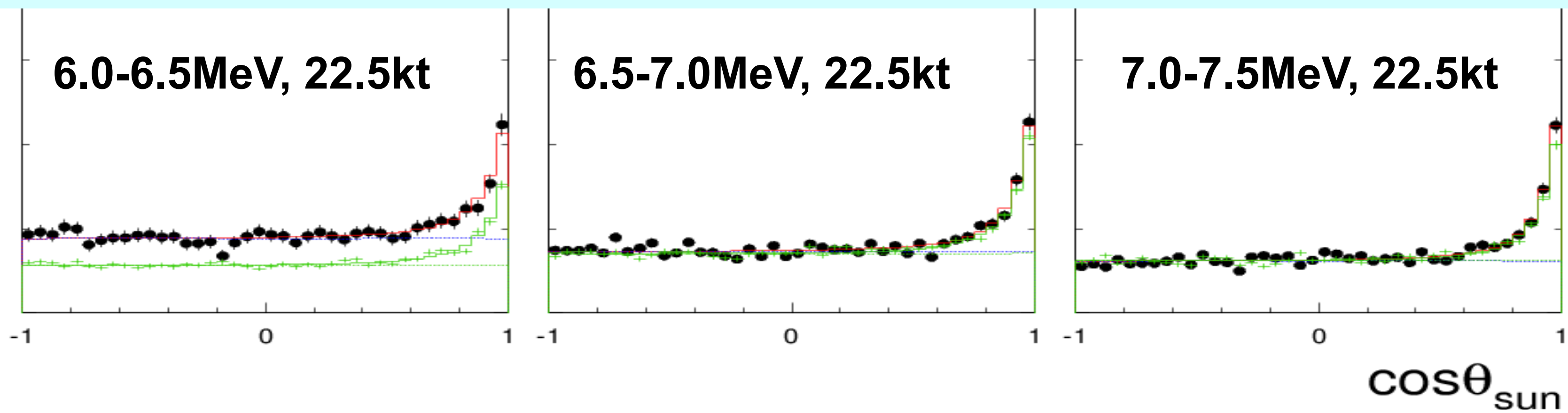
    (SK-I,II are recalculated with the Winter06 ^{8}B spectrum)
- Day / Night ratio:

$$A_{DN} = \frac{(\Phi_{Day} - \Phi_{Night})}{(\Phi_{Day} + \Phi_{Night})/2} = -0.056 \pm 0.031(\text{stat.}) \pm 0.013(\text{syst.})$$

Angular distributions in SK-III

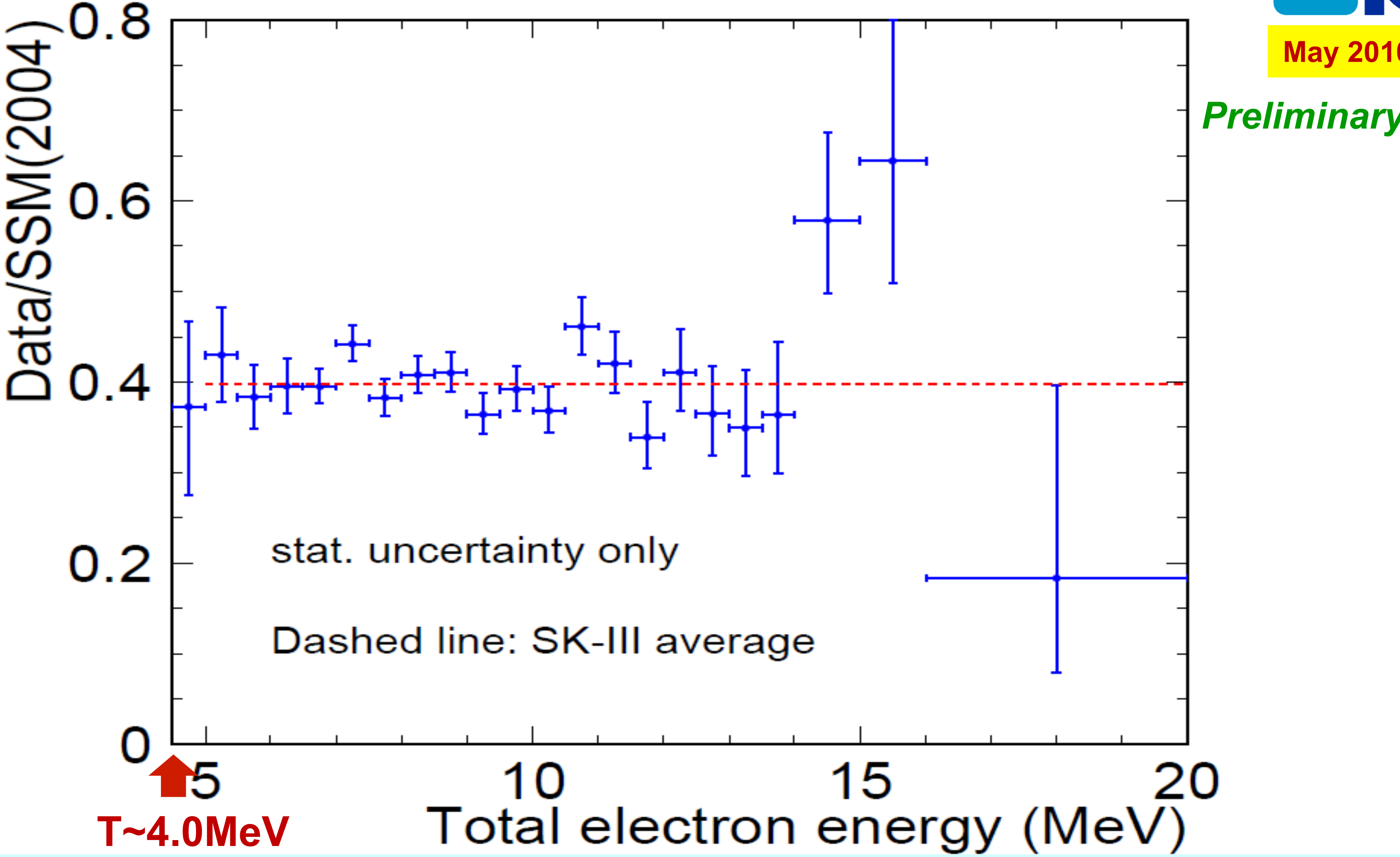


- Angular resolution in SK-III is better
- In E_{total}=5.0-5.5MeV, SK-III has better Signal to Noise ratio.
- BG level in 4.5-5.0MeV region is similar as that in 5.0-5.5MeV of SK-I

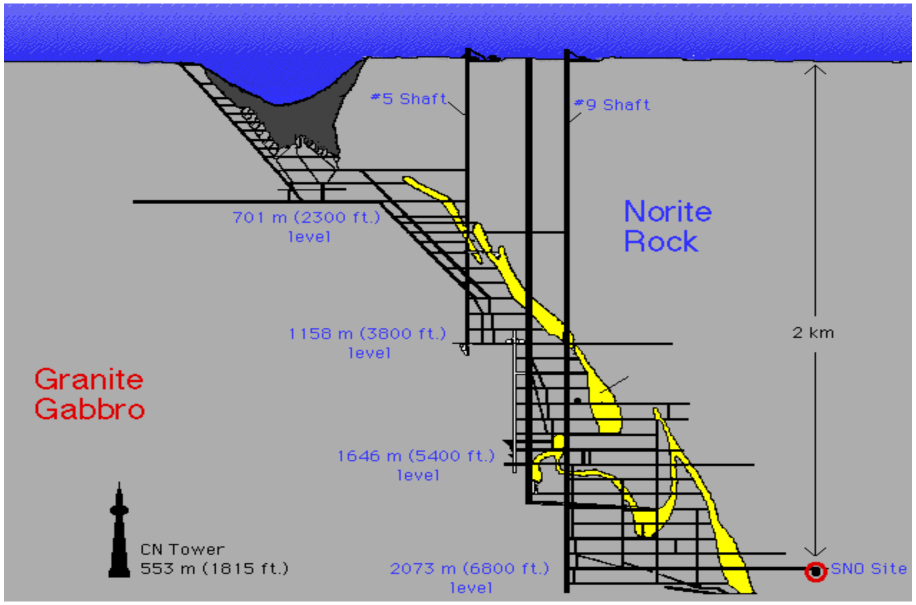


SK-III ^{8}B energy spectrum

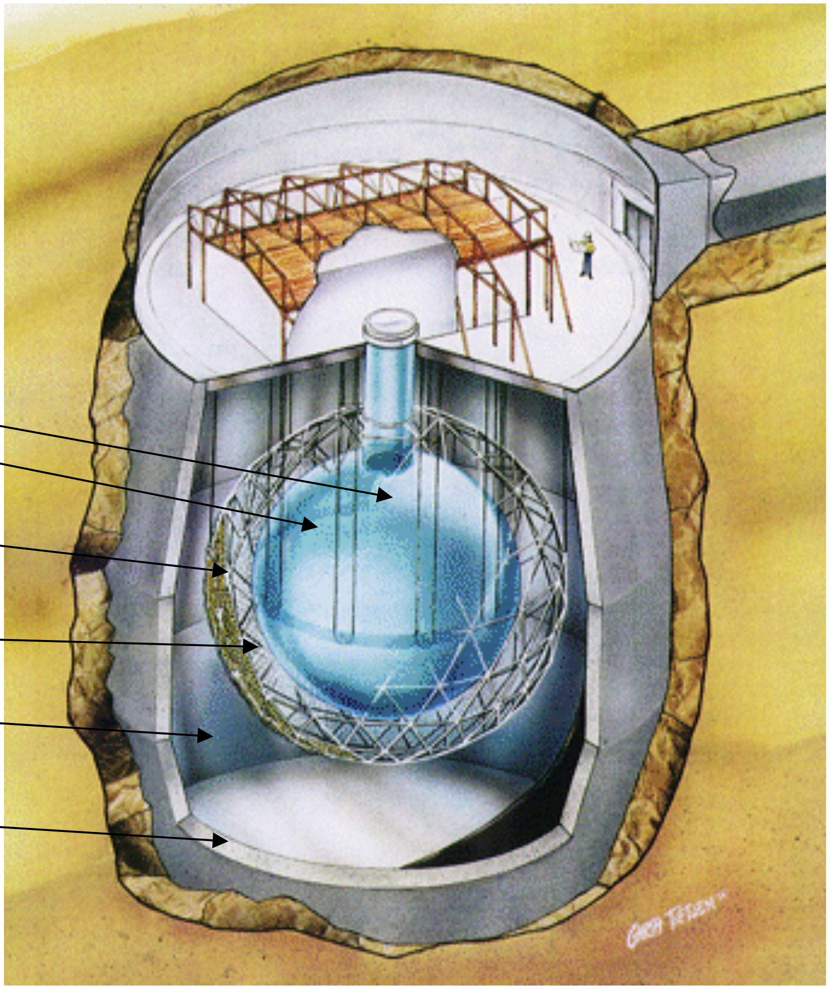
May 2010



- Consistent with no distortion
- E_{total}=4.5-5.0MeV data isn't used in the oscillation analysis.



Sudbury Neutrino Observatory



1000 tonnes D_2O

12 m diameter Acrylic Vessel

18 m diameter support structure; 9500 PMTs
(~55% photocathode coverage)

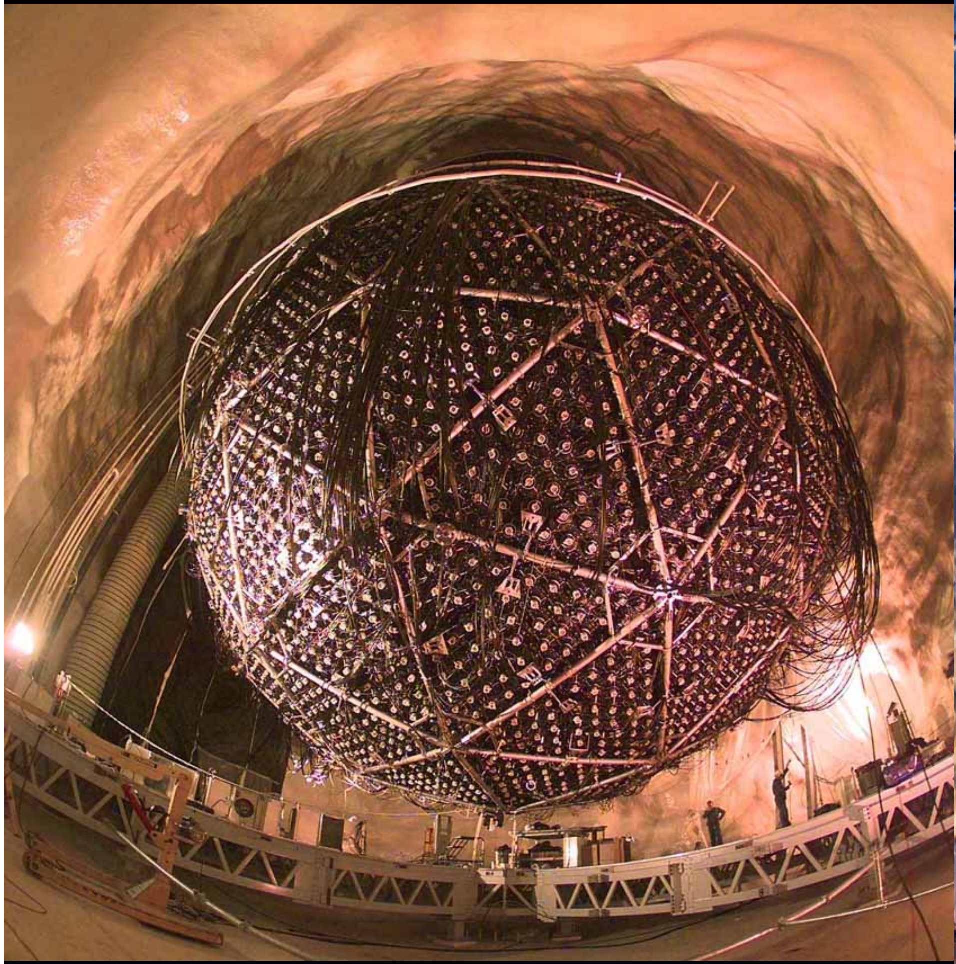
1700 tonnes inner shielding H_2O

5300 tonnes outer shielding H_2O

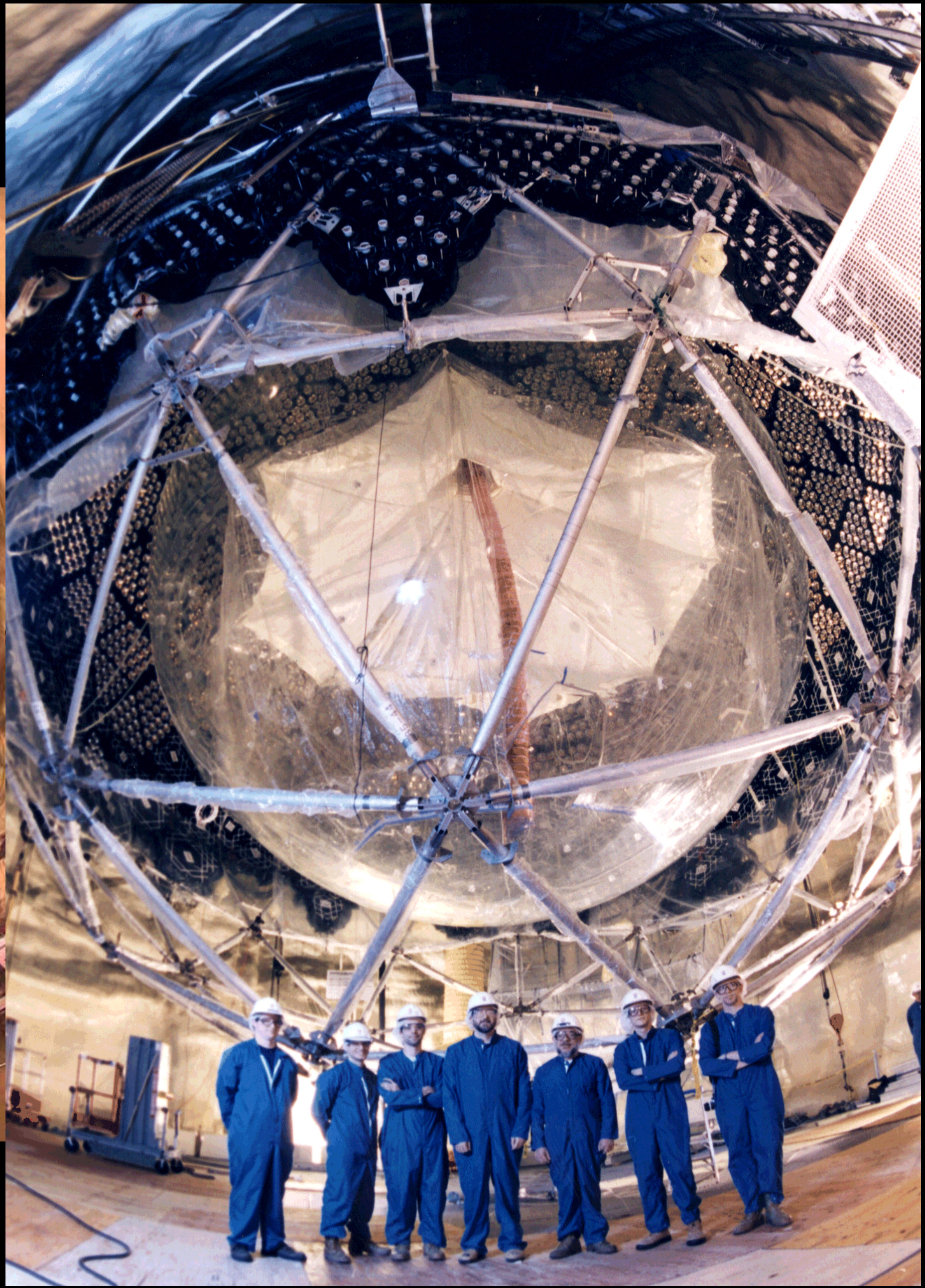
Urylon liner radon seal

depth: 2092 m (~6010 m.w.e.) ~70 muons/day

Photos



SNO detector



Neutrino Reactions in SNO

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

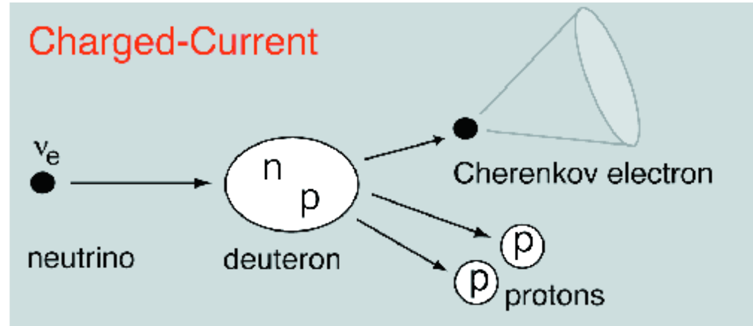
- only detects ν_e flavor
- good measure of neutrino energy spectrum
- Q-value 1.44 MeV
- directionality $\propto (1 - \frac{1}{3}\cos\theta)$

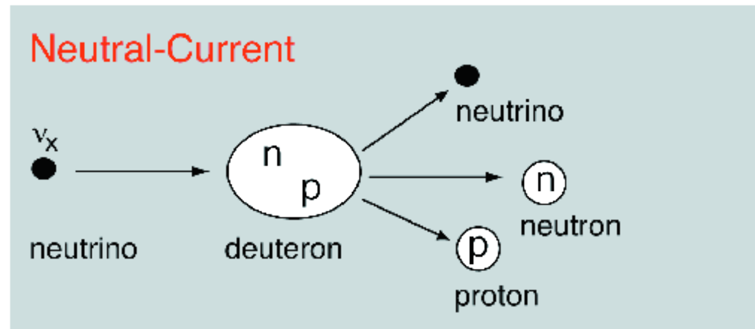
NC $$\nu_x + d \rightarrow p + n + \nu_x$$

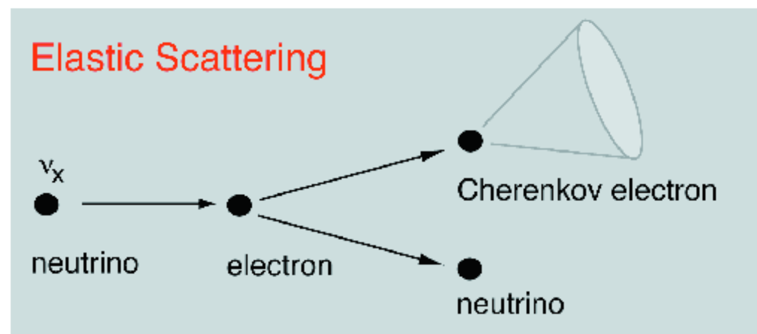
- measures total ^{8}B ν flux from the Sun
- equal cross section for all active ν flavors
- Q-value 2.22 MeV

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

- lower statistics
- points to the Sun

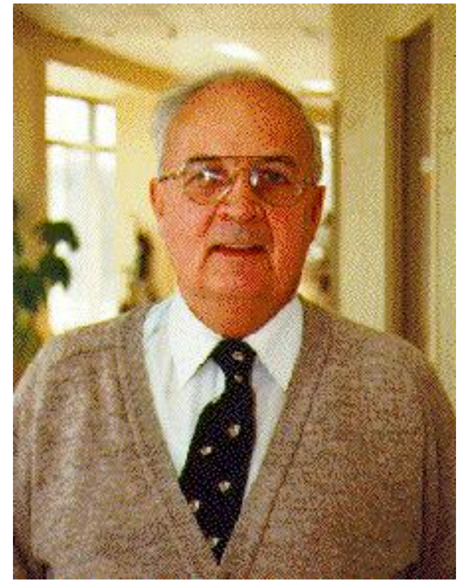






SNO Pioneers

Herb Chen



George Ewan

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Direct Approach to Resolve the Solar-Neutrino Problem

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

A direct approach to resolve the solar-neutrino problem would be to observe neutrinos by use of both neutral-current and charged-current reactions. Then, the total neutrino flux and the electron-neutrino flux would be separately determined to provide independent tests of the neutrino-oscillation hypothesis and the standard solar model. A large heavy-water Cherenkov detector, sensitive to neutrinos from ^{8}B decay via the neutral-curent reaction $\nu + d \rightarrow \nu + p + n$ and the charged-current reaction $\nu_e + d \rightarrow e^- + p + p$, is suggested for this purpose.

PACS numbers: 96.60.Kx, 14.60.Gh

Three Phases of SNO

Pure D_2O

Nov 99 – May 01

$n + d \rightarrow t + \gamma$

(E_γ = 6.25 MeV)

PRL **87**, 071301 (2001)

PRL **89**, 011301 (2002)

PRL **89**, 011302 (2002)

PRC **75**, 045502 (2007)

Salt

Jul 01 – Sep 03

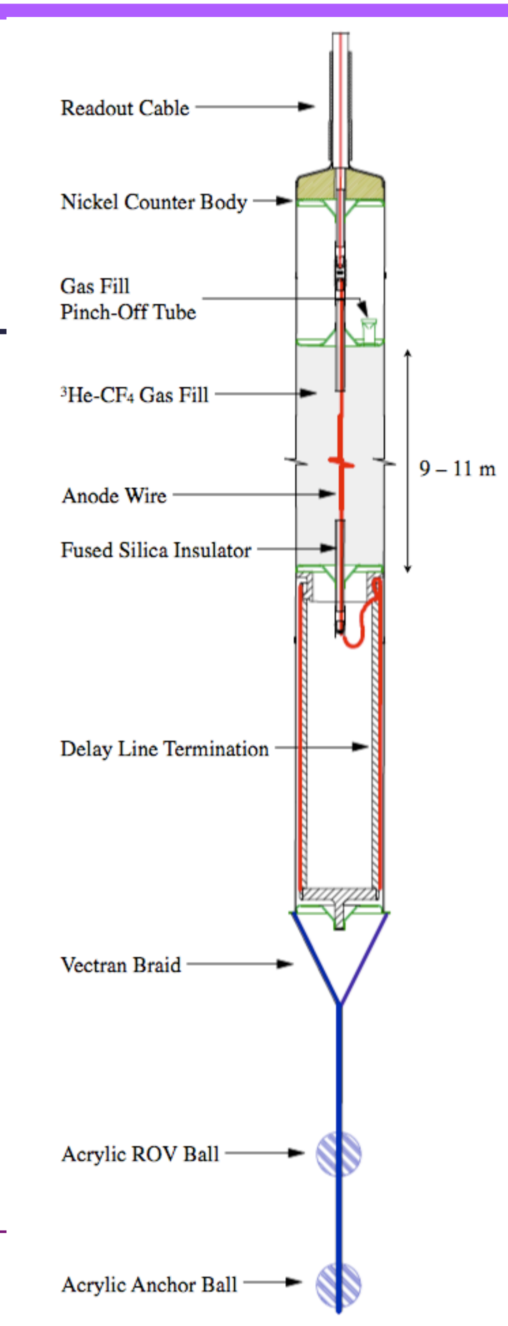
$n + {}^{35}Cl \rightarrow {}^{36}Cl + \gamma$

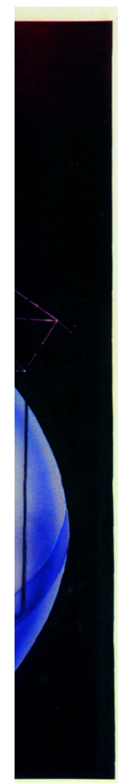
($E_{\Sigma\gamma}$ = 8.6 MeV)

enhanced NC rate and separation

PRL **92**, 181301 (2004)

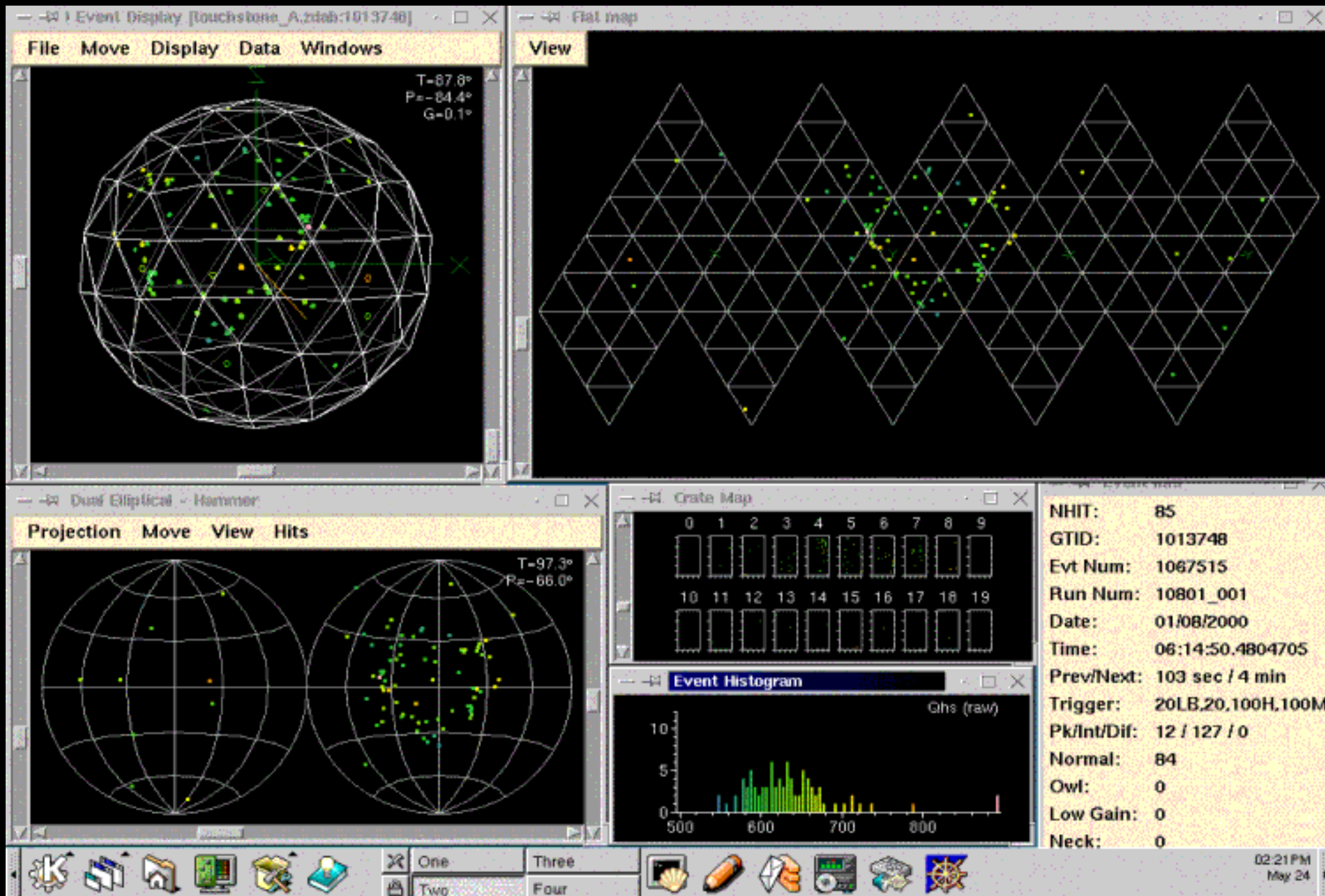
PRC **72**, 055502 (2005)





A Neutrino Event

Event Information: PMT hits – position, time, charge



Event Reconstruction: vertex, direction, energy, isotropy

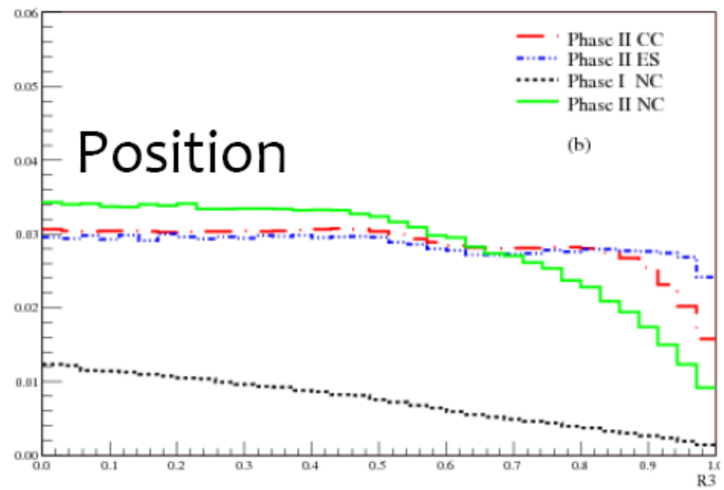
Fitting CC, NC, ES in SNO

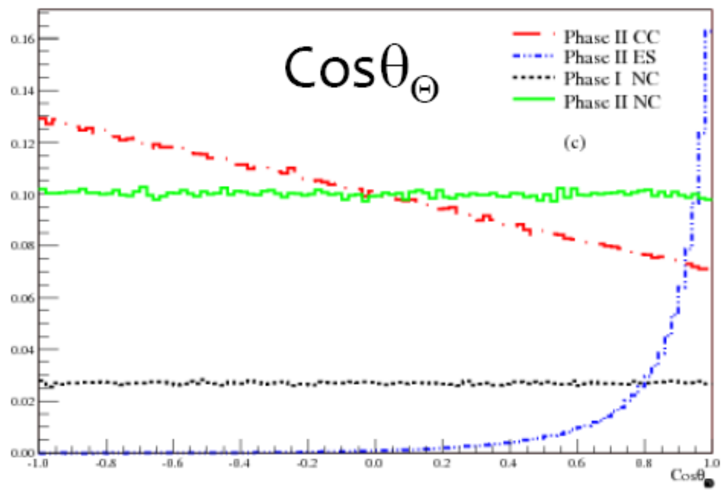
7) Signal Extraction Technique

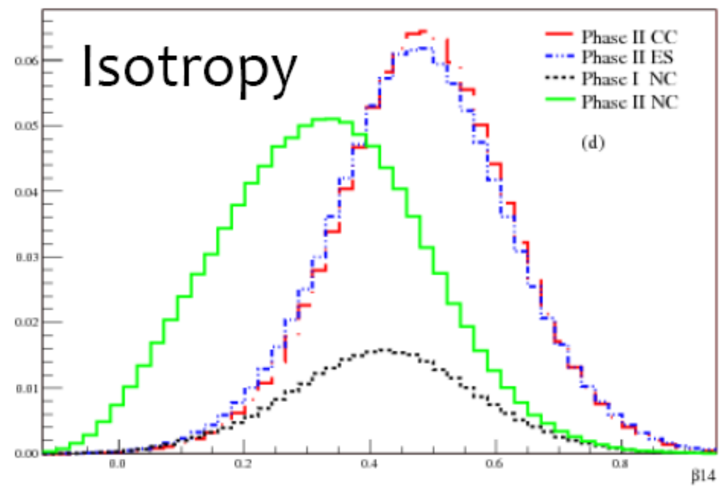
a) Fit for all signal

Charged Current (CC)
Elastic Scattering (ES)
Neutral Current (NC)

Fully 4D PDFs for CC & ES



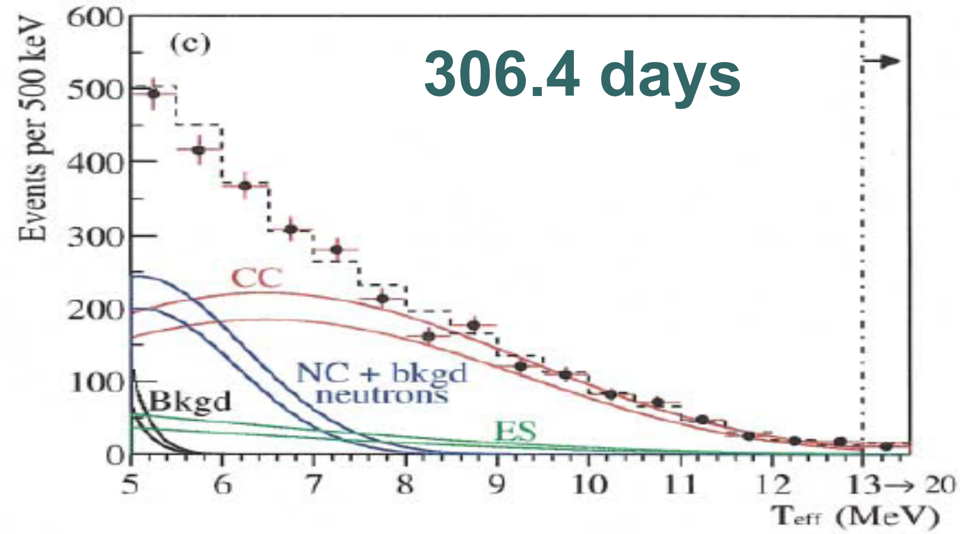


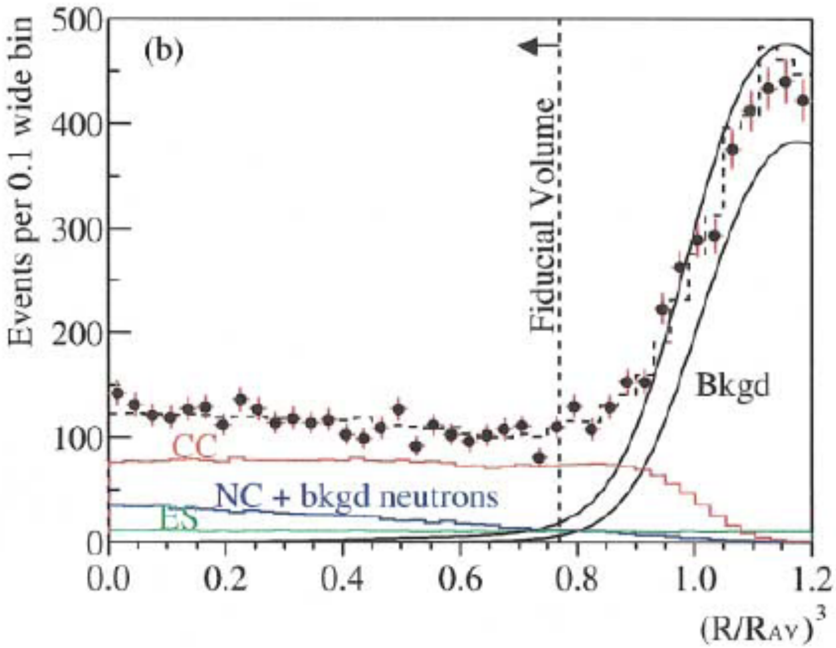


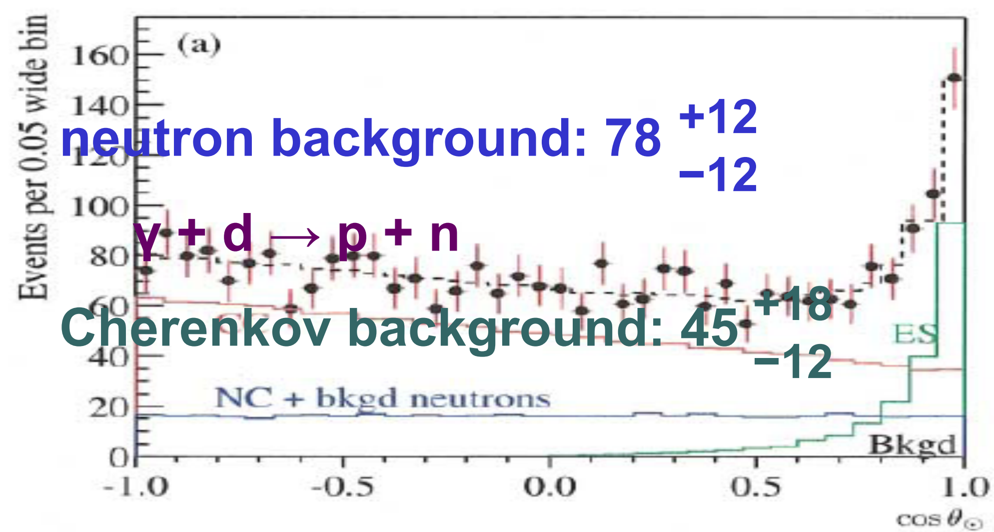
SNO Pure D_2O Results (2002)

#EVENTS

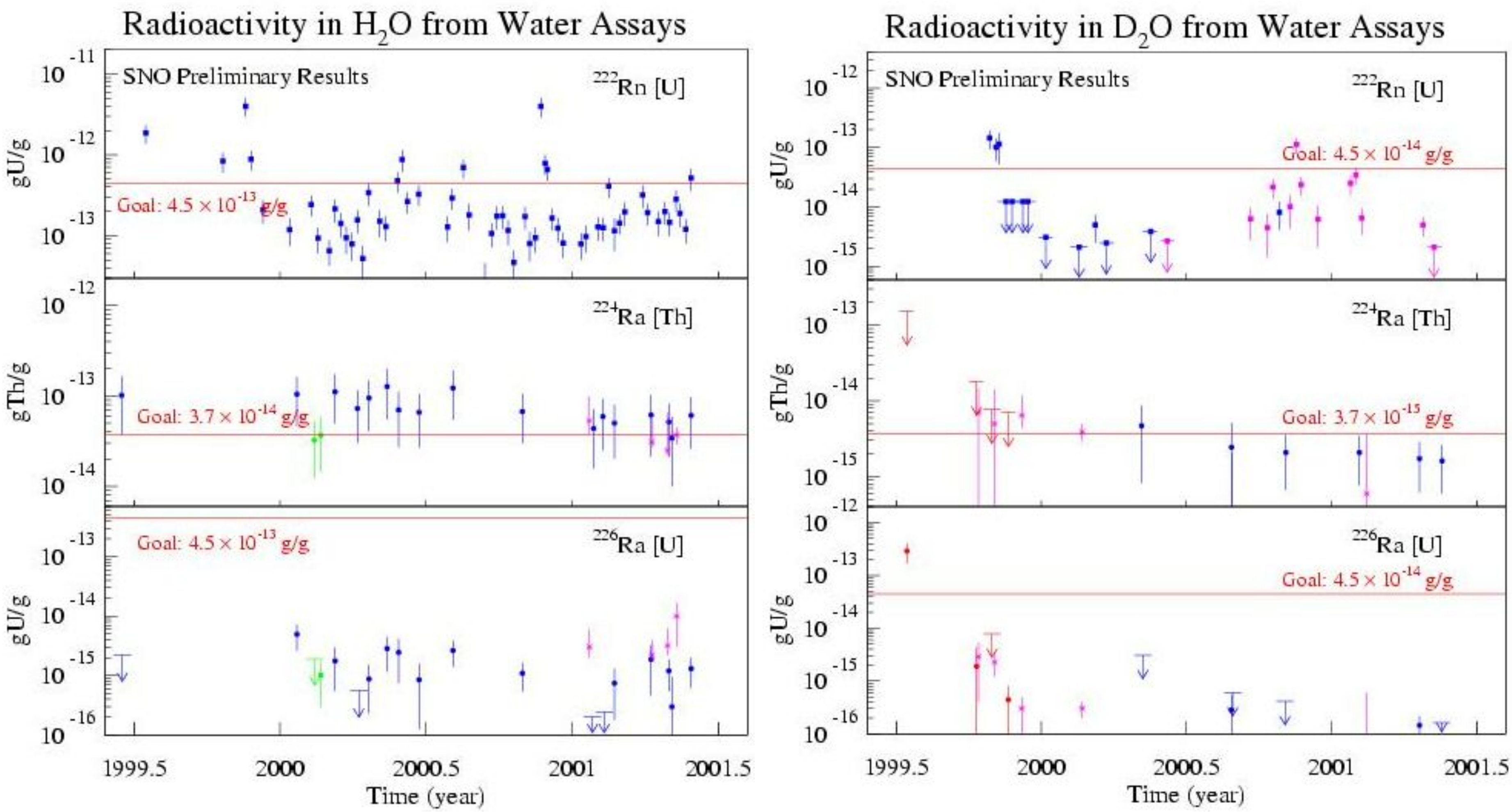
CC	1967.7	$^{+61.9}_{+60.9}$
ES	263.6	$^{+26.4}_{+25.6}$
NC	576.5	$^{+49.5}_{+48.9}$







SNO Water Assays



targets are set to reduce βγ events reconstructing inside 6 m

targets for D_2O represent a 5% background from $\gamma + d \rightarrow n + p$

Water Purification and Assay

MnOx	^{224}Ra, ^{226}Ra extraction ➥ decay products counted in electrostatic counters	Purification Assay of ^{224}Ra, ^{226}Ra
HTiO	Th, Ra, & Pb extraction ➥ chemically stripped and counted with β-α counter	Purification Assay of ^{224}Ra, ^{226}Ra, ^{228}Th
Vacuum & Membrane De-Gassing	radon removal Lucas cells	Purification Assay of ^{222}Rn
Reverse Osmosis	conc. collection liquid scintillator	Purification Assay
Ion Exchange & Ultra-Filtration		Purification

Measuring U/Th Content

Ex-situ

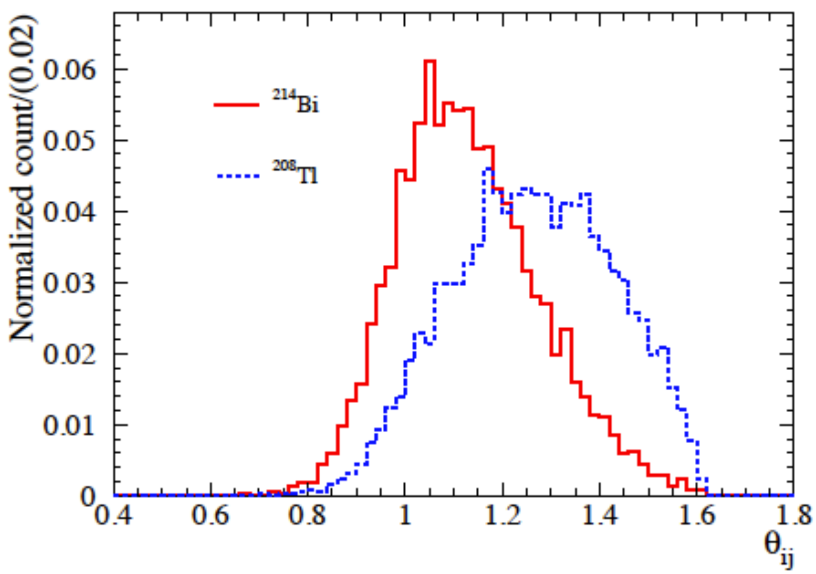
- Ion exchange (^{224}Ra, ^{226}Ra)
- Membrane degassing (^{222}Rn)

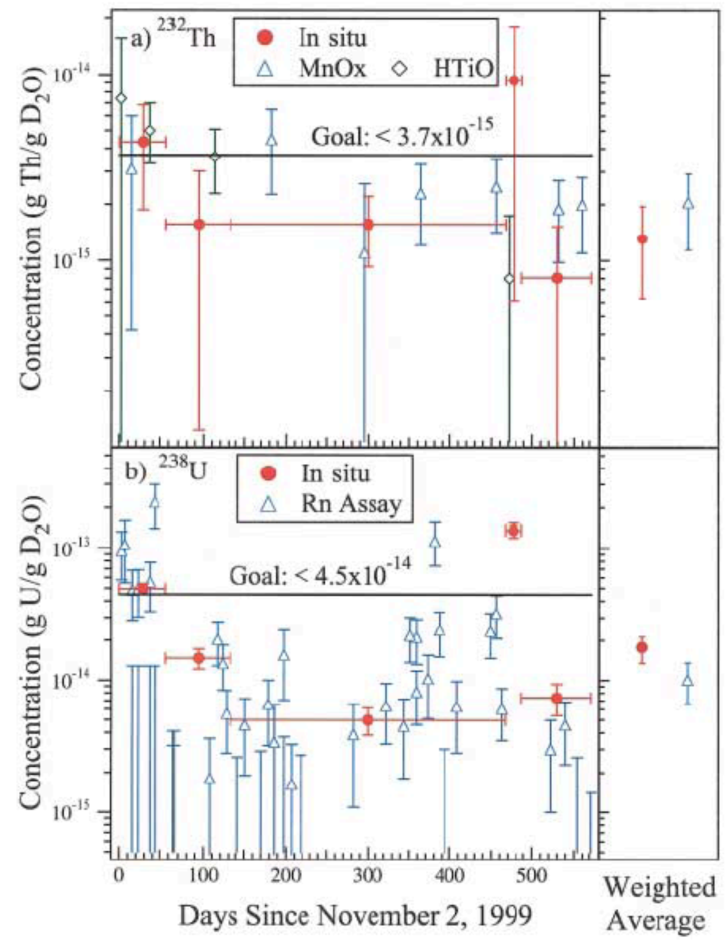
count daughter product decays

In-situ

- Low energy data analysis
- Separate ^{208}Tl & ^{214}Bi

using event isotropy





	D_2O	H_2O/AV
Neutron Background	44^{+8}_{-9}	27^{+8}_{-8}

$E_{threshold} > 5$ MeV

$^*E_{nc} > 2.2$ MeV

Constrained Shape Fluxes

$$\Phi_{cc}(\nu_e) = 1.76\,^{+0.06}_{-0.05}(\text{stat.})\,^{+0.09}_{-0.09}(\text{syst.}) \times 10^6\ \text{cm}^{-2}\text{s}^{-1}$$

$$\Phi_{es}(\nu_x) = 2.39\,^{+0.24}_{-0.23}(\text{stat.})\,^{+0.12}_{-0.12}(\text{syst.}) \times 10^6\ \text{cm}^{-2}\text{s}^{-1}$$

$$\Phi_{nc}(\nu_x) = 5.09\,^{+0.44}_{-0.43}(\text{stat.})\,^{+0.46}_{-0.43}(\text{syst.}) \times 10^6\ \text{cm}^{-2}\text{s}^{-1}\ ^*$$

$$\Phi_{e} = 1.76\,^{+0.05}_{-0.05}\ (\text{stat.})\,^{+0.09}_{-0.09}\ (\text{syst.}) \times 10^6\ \text{cm}^{-2}\text{s}^{-1}$$

$$\Phi_{\mu\tau} = 3.41\,^{+0.45}_{-0.45}\ (\text{stat.})\,^{+0.48}_{-0.45}\ (\text{syst.}) \times 10^6\ \text{cm}^{-2}\text{s}^{-1}$$

more than just ν_e coming from the Sun!

391-Day Salt Phase Flux Results (2005)

$$\frac{\phi_{CC}}{\phi_{NC}} = 0.340 \pm 0.023\ {}^{+0.029}_{-0.031}$$

$$\Phi_{CC}(\nu_e) = 1.68\ {}^{+0.06}_{-0.06}\,(\text{stat.})\ {}^{+0.08}_{-0.09}\,(\text{syst.}) \times 10^6\ \text{cm}^{-2}\,\text{s}^{-1}$$

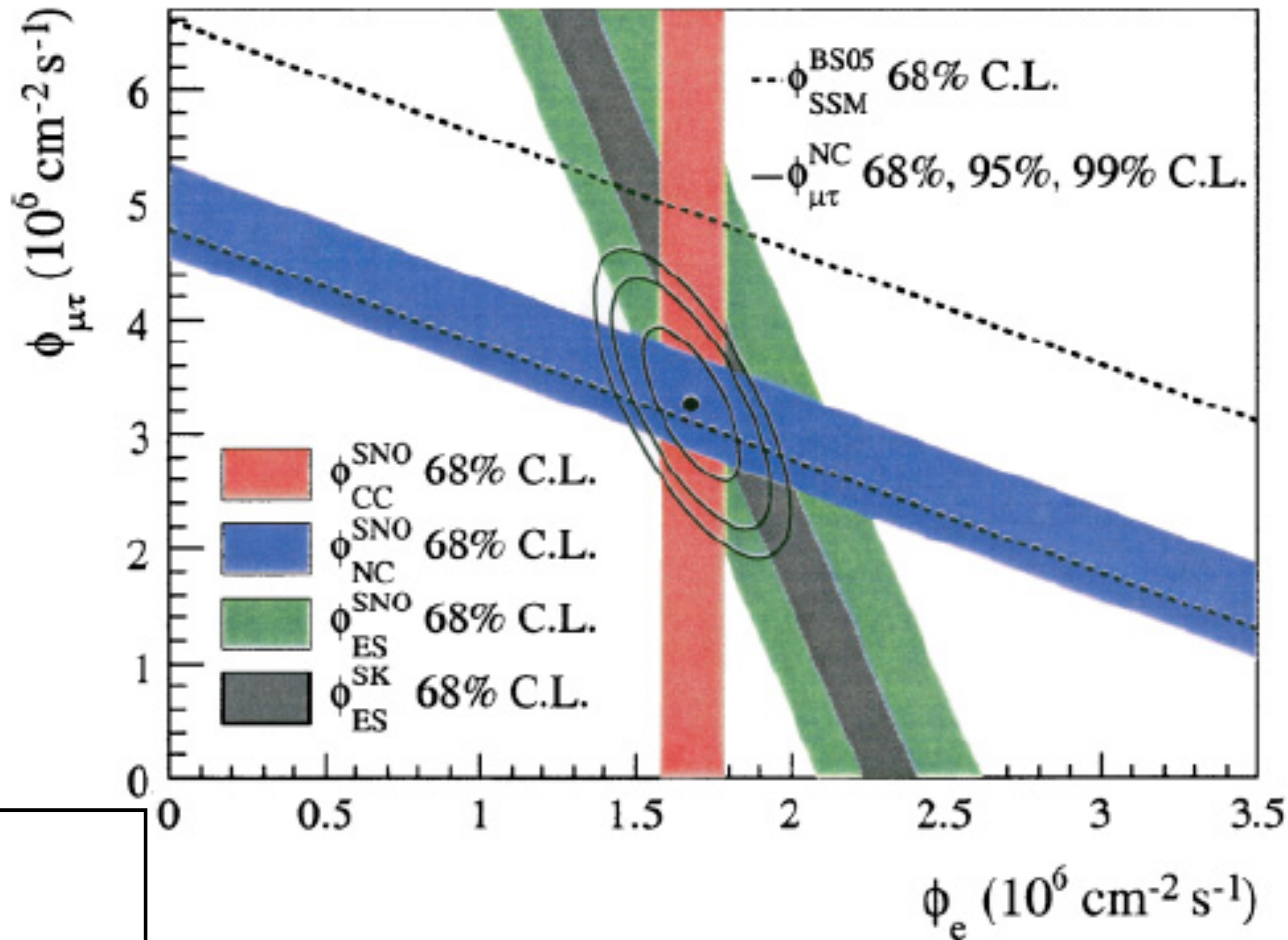
$$\Phi_{NC}(\nu_x) = 4.94\ {}^{+0.21}_{-0.21}\,(\text{stat.})\ {}^{+0.38}_{-0.34}\,(\text{syst.}) \times 10^6\ \text{cm}^{-2}\,\text{s}^{-1}$$

BS05(OP) Standard Solar Model Flux Calculation:
$(5.69 \pm 0.91) \times 10^6\ \text{cm}^{-2}\,\text{s}^{-1}$

2002: Solar Neutrino Problem Solved by Direct Observation of Solar Neutrinos Changing Flavor ➔ produced as electron neutrinos but only 0.34 surviving as ν_e

...the NC measurement is also confirmation that solar models are correct and that energy generation in stars is understood!

Solar Neutrino Flavour Content



$\Phi_{CC} = \Phi_e$

$\Phi_{NC} = \Phi_e + \Phi_{\mu\tau}$

$\Phi_{ES} = \Phi_e + 0.155\ \Phi_{\mu\tau}$

Summary of Main SNO Solar ν Results

- direct measure of the averaged survival probability of ^{8}B solar ν

$$\frac{\phi_{CC}}{\phi_{NC}} = 0.340 \pm 0.023(\text{stat.})^{+0.029}_{-0.031}$$ Phase II

$$\frac{\phi_{CC}}{\phi_{NC}} = 0.301 \pm 0.033$$ Phase III

- total active flux of ^{8}B solar ν agrees with solar model calculations

Phase II $$\phi_{NC} = \left(4.94 \pm 0.21(\text{stat.})^{+0.38}_{-0.34}\right) \times 10^6\ \text{cm}^{-2}\text{s}^{-1}$$

Phase III $$\phi_{NC} = \left(5.54^{+0.33}_{-0.31}(\text{stat.})^{+0.36}_{-0.34}\right) \times 10^6\ \text{cm}^{-2}\text{s}^{-1}$$

BS05(OP) (5.69 ± 0.91) × 10^6 cm^{-2} s^{-1}

- global fit of oscillation parameters including KamLAND and all solar neutrino data

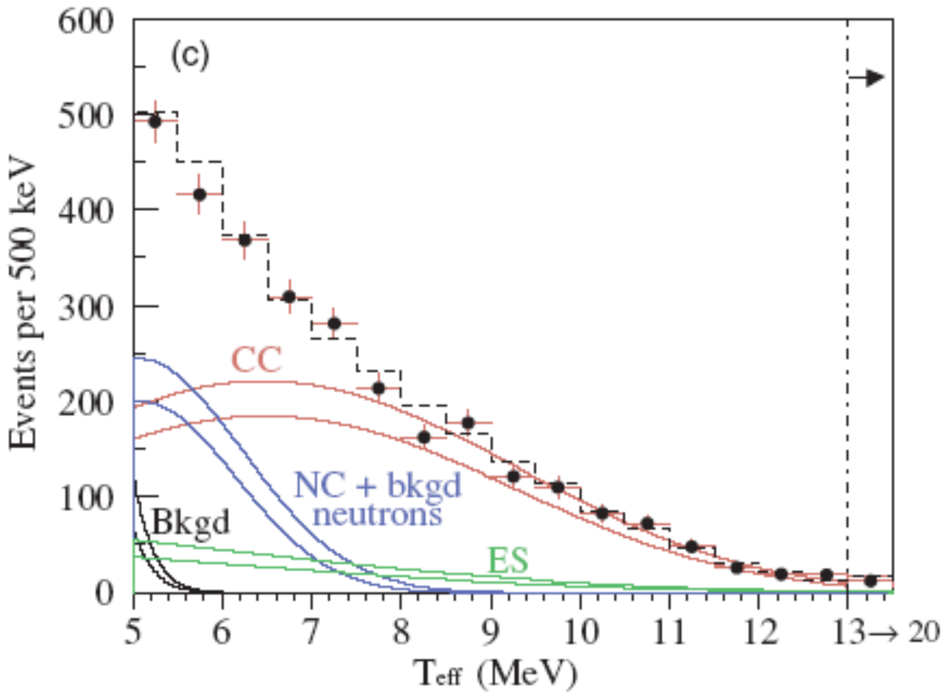
$$\boxed{\begin{aligned} \Delta m^2 &= 7.59^{+0.19}_{-0.21} \times 10^{-5}\,\text{eV}^2 \\ \sin^2\theta &= 0.32 \pm 0.02 \end{aligned}}$$

- ν_e day-night asymmetry

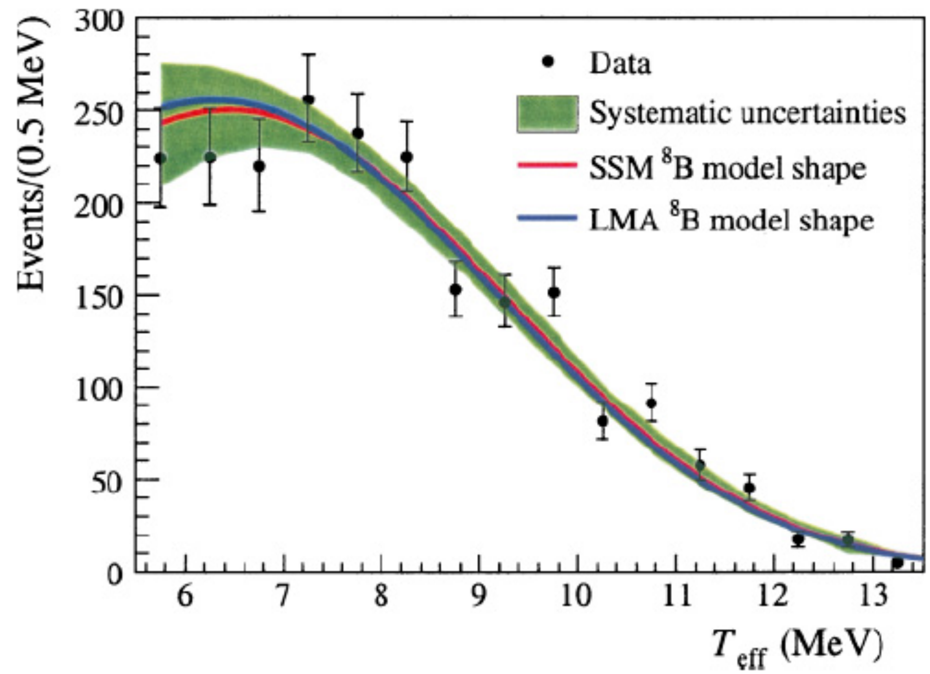
$$\frac{N - D}{(N + D)/2} = 0.037 \pm 0.040$$ combined Phase I+II

expected value is ~0.03

SNO Spectrum



Phase I – summed



Phase II – CC extracted

SNO and Chlorine Revisited

<u>Chlorine rate [SNU]:</u>

^{8}B	5.76
^{7}Be	1.15
pep	0.22
CNO	0.42
hep	0.04
total	7.82

SNO measures ν_e flux:
$\Phi(^{8}B) = 0.33$ SSM

better predictor of ^{8}B in Cl
1.92 ± 0.17 SNU

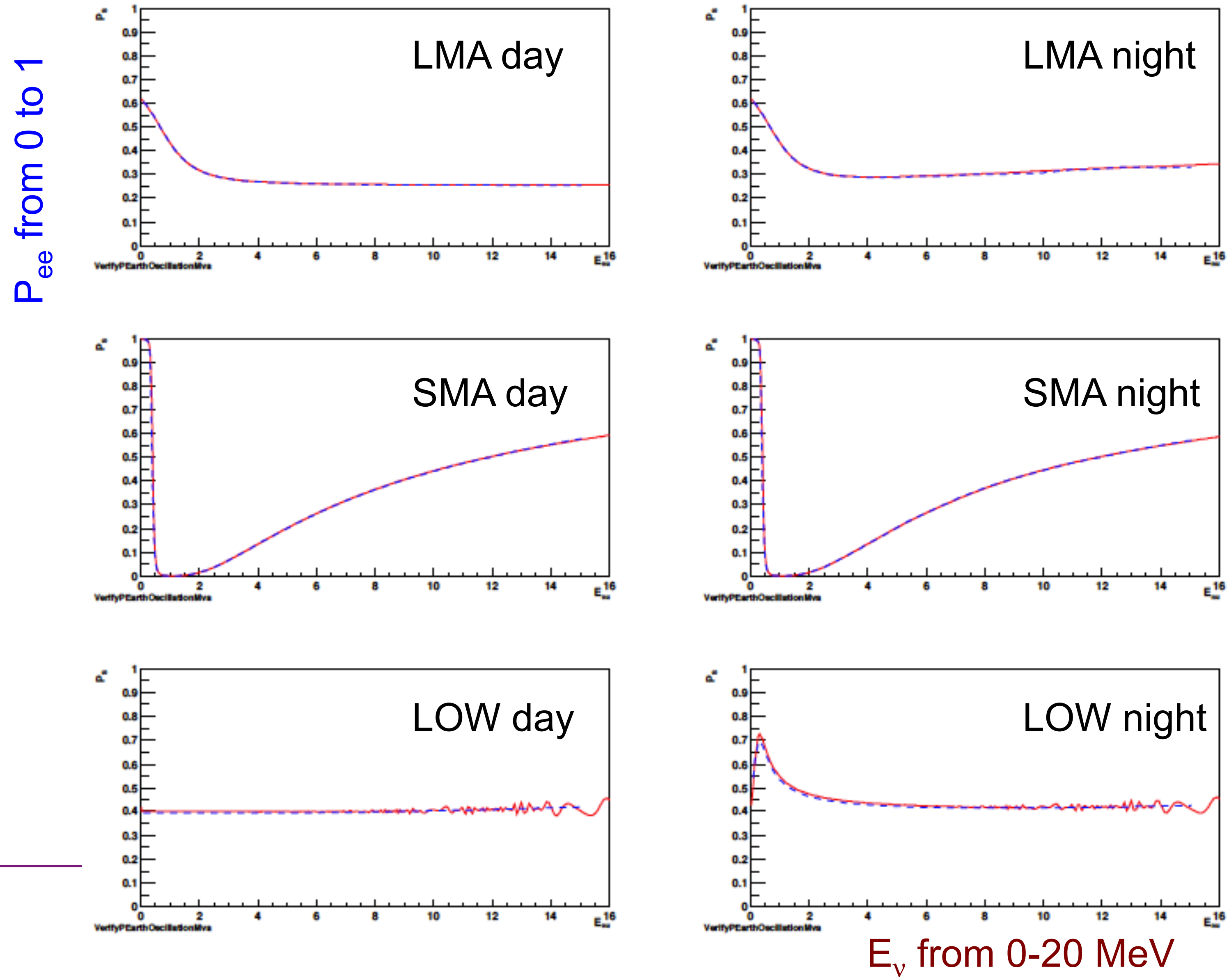
Cl experimental rate:
2.56 ± 0.23 SNU

there is room for ^{7}Be!

Liquid Scintillator Solar ν Detection

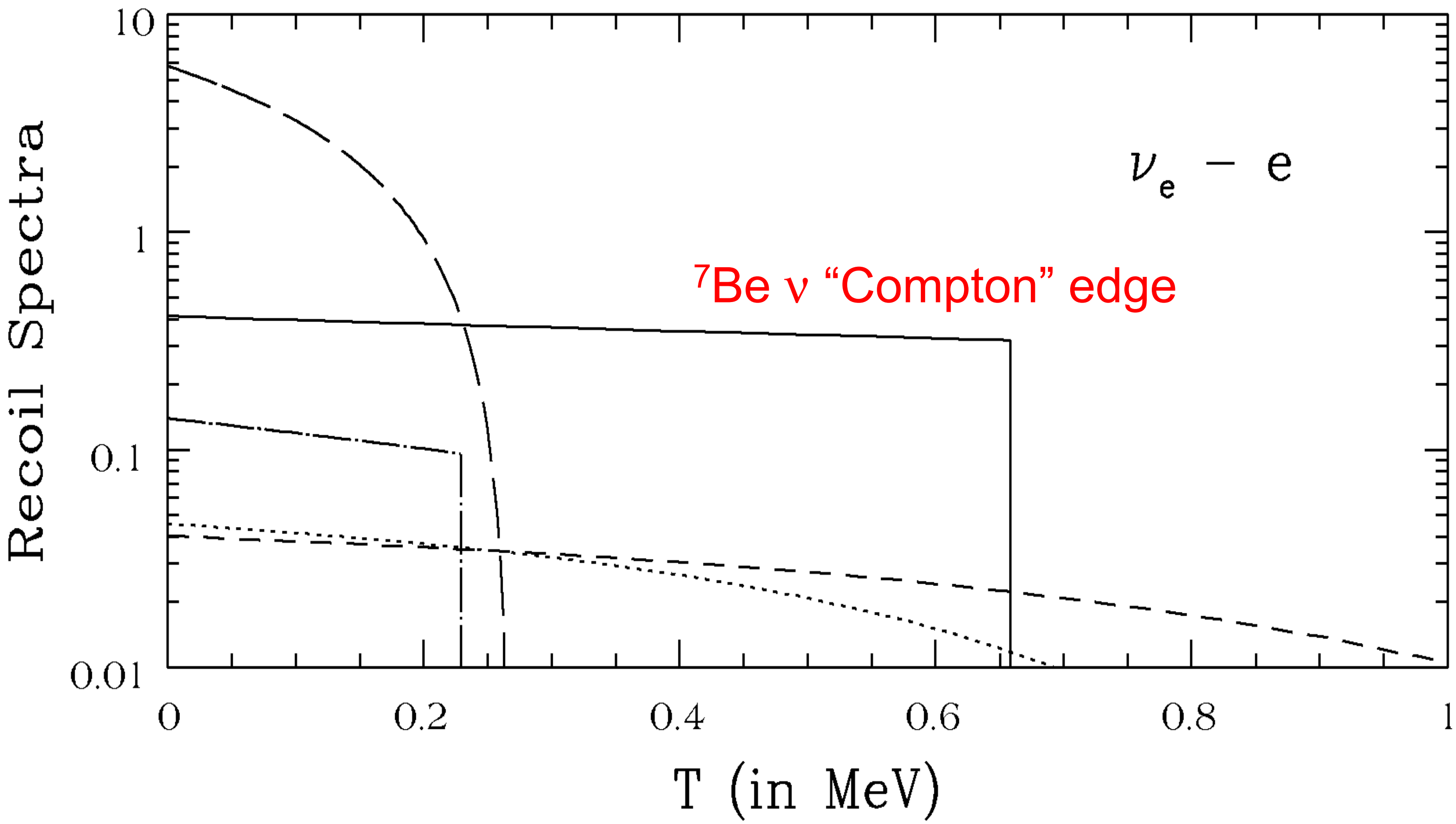
- Borexino was originally a boron-loaded liquid scintillator
  - was to look for CC and NC neutrino reactions on ^{11}B
- then, the interest turned to the "missing" ^{7}Be solar neutrinos
  - SMA (small mixing angle) MSW solution had this energy as maximum suppression (lowest survival probability)
- radiopurity requirements of a boron-loaded scintillator were also as stringent as requirements to see ^{7}Be solar neutrinos using neutrino-electron elastic scattering…
  - thus a switch to ^{7}Be focus eliminated the need for dealing with boron
- scintillation light is isotropic – no correlation with Sun direction (also kinematics at lower energy makes this less feasible)
- recoil-edge feature is thus very important for ^{7}Be ν detection

Solar Neutrino Survival Probability



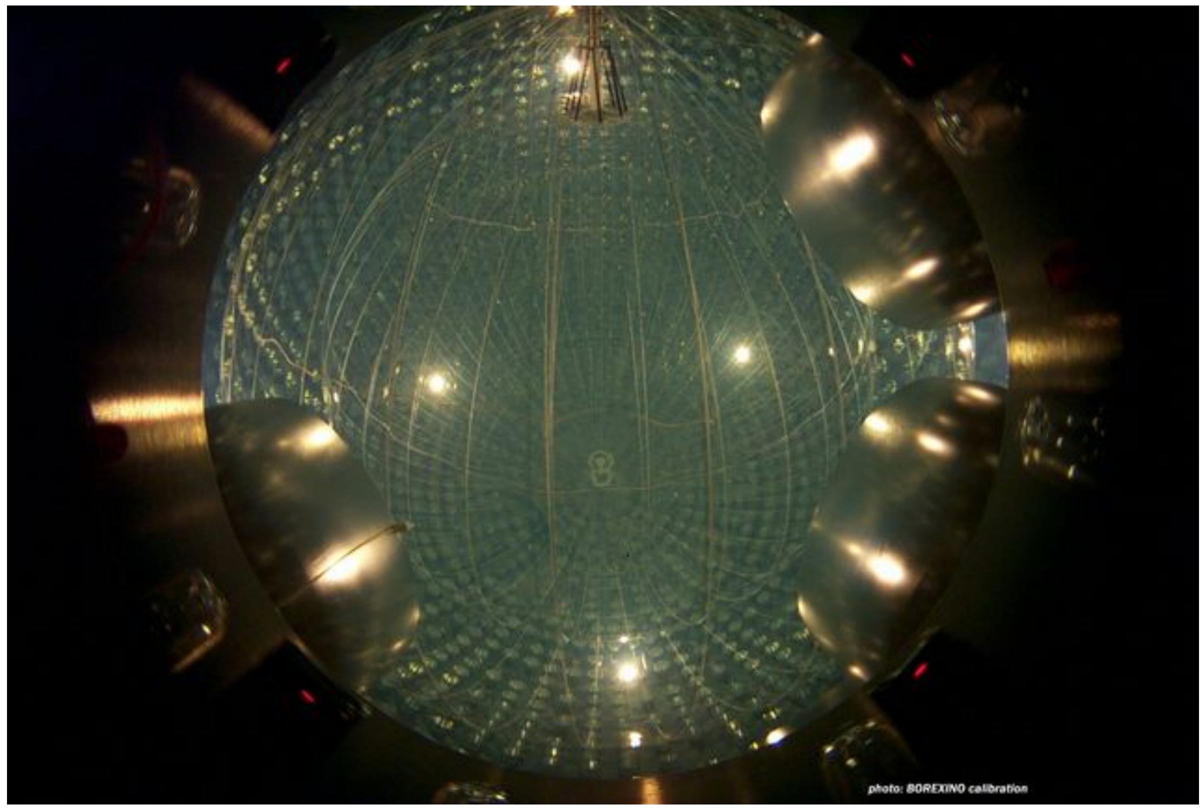
^{7}Be Solar Neutrino Detection

neutrino-electron scattering

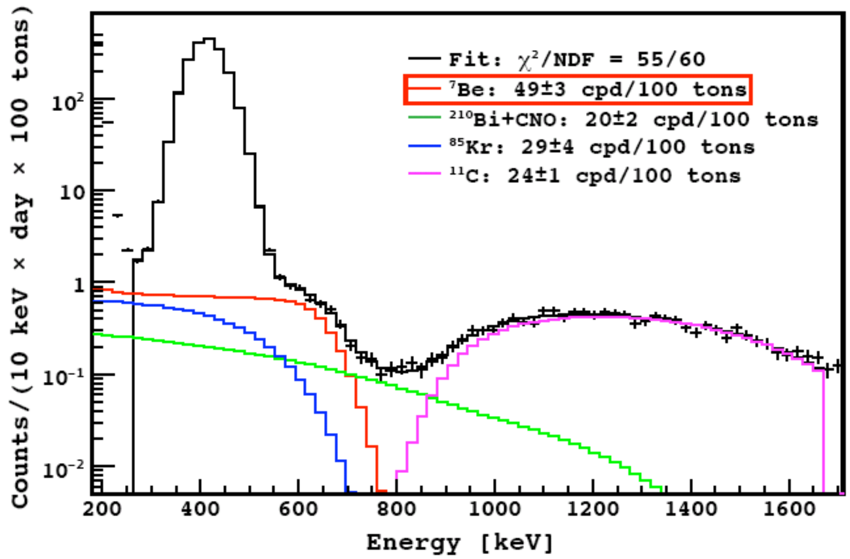


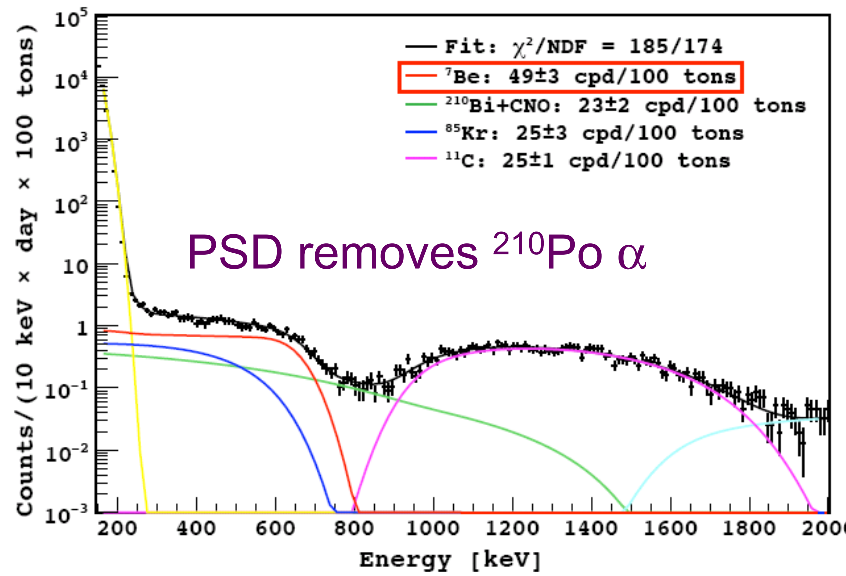
Borexino at Gran Sasso

- 300 tons of pseudocumene-based scintillator
- 100 ton fiducial volume
- ^{7}Be solar ν
  - ν-e scattering
- 2212 8” PMTs
- light yield
  - ~500 p.e./MeV
- detector filled
  - May 15, 2007



Borexino ^{7}Be Solar ν Measurement





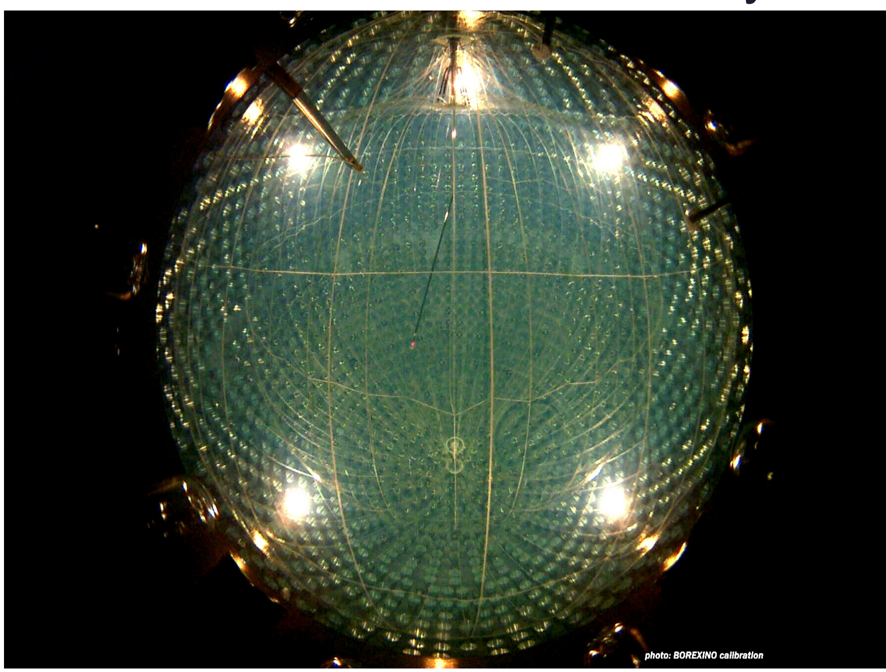
PRL **101**, 091302 (2008)

rate of ^{7}Be solar neutrinos: 49 ± 3 ± 4 counts/(day·100 tons)
SSM predicted no-osc rate: 74 counts/(day·100 tons)

SSM (high metallicity) predicted rate including
MSW-LMA oscillations: 48 ± 4 counts/(day·100 tons)

Additional Borexino Analysis Details

- light yield is free parameter in the fits: 500 ± 12 pe/MeV
- position resolution: 16 cm @ 500 keV
- systematics estimated prior to calibration of detector response
  - deployment of some calibration sources has now taken place
  - calibration data currently being analyzed



E II. Estimated systematic uncertainties [%].

lator mass	0.2
ss ratio	6.0
	0.1
ponse function	6.0
f cuts	0.3
atic error	8.5

hep Solar Neutrinos

- flux is ~750 times smaller than the ^{8}B solar neutrinos
- no detection from Super-K or SNO yet

pp Solar Fusion Chain

$p + p \rightarrow {}^{2}H + e^{+} + \nu_e$ $\qquad$ $p + e^{-} + p \rightarrow {}^{2}H + \nu_e$

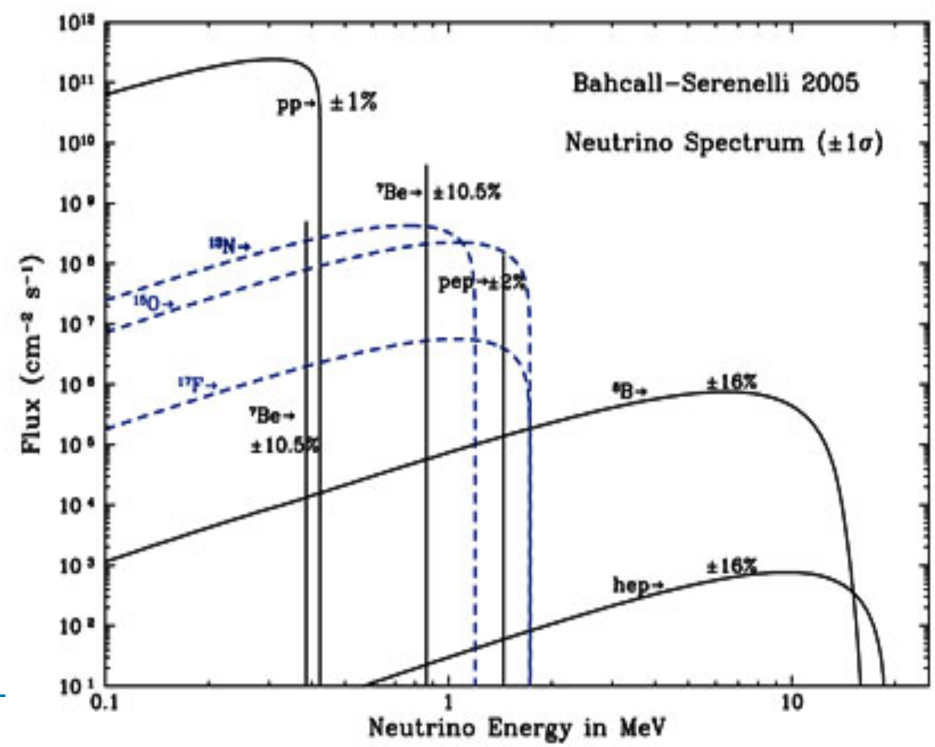
$^{2}H + p \rightarrow {}^{3}He + \gamma$

$^{3}He + {}^{3}He \rightarrow {}^{4}He + 2\,p$ $\qquad$ $^{3}He + p \rightarrow {}^{4}He + e^{+} + \nu_e$

$^{3}He + {}^{4}He \rightarrow {}^{7}Be + \gamma$

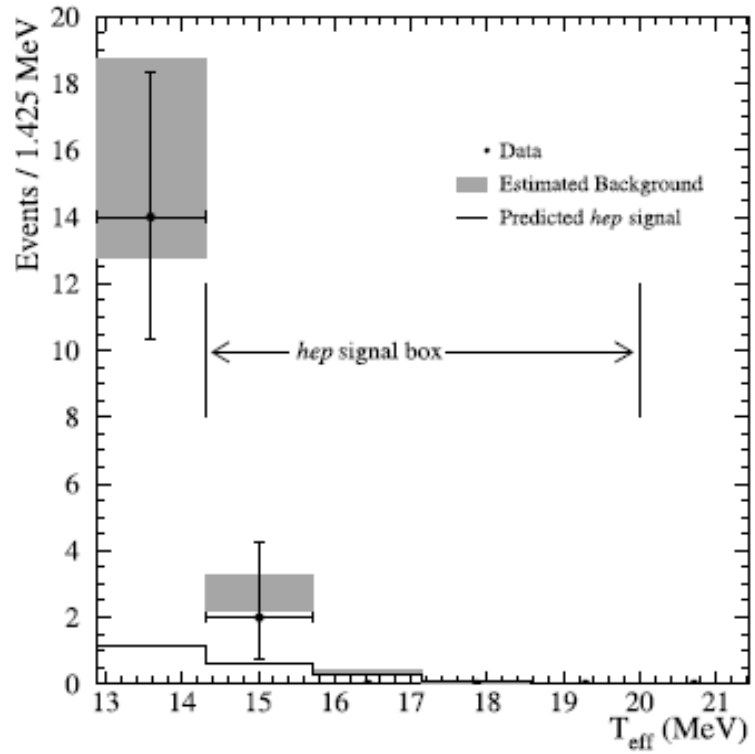
$^{7}Be + e^{-} \rightarrow {}^{7}Li + \gamma + \nu_e$ $\qquad$ $^{7}Be + p \rightarrow {}^{8}B + \gamma$

$^{7}Li + p \rightarrow \alpha + \alpha$ $\qquad$ $^{8}B \rightarrow 2\,\alpha + e^{+} + \nu_e$



SNO Solar *hep* Limit (from Phase I data)

- 2 events observed
- number events expected
  - background: 3.13 ± 0.60
  - SSM signal: 0.99 ± 0.09
- modified Feldman-Cousins 90% CL limit <2.9 times SSM or $< 2.3\times10^{4}\ \mathrm{cm}^{-2}\mathrm{s}^{-1}$
  - hep flux limit includes oscillations



SK-I *hep* Solar Neutrino Analysis

- between 18-21 MeV there are 4.9±2.7 events
- 90% CL upper limit: $< 7.3 \times 10^4 \,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$
- I don't know if this limit includes oscillations.