The Sudbury Neutrino Observatory

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XIVth International School
"PARTICLES and COSMOLOGY"
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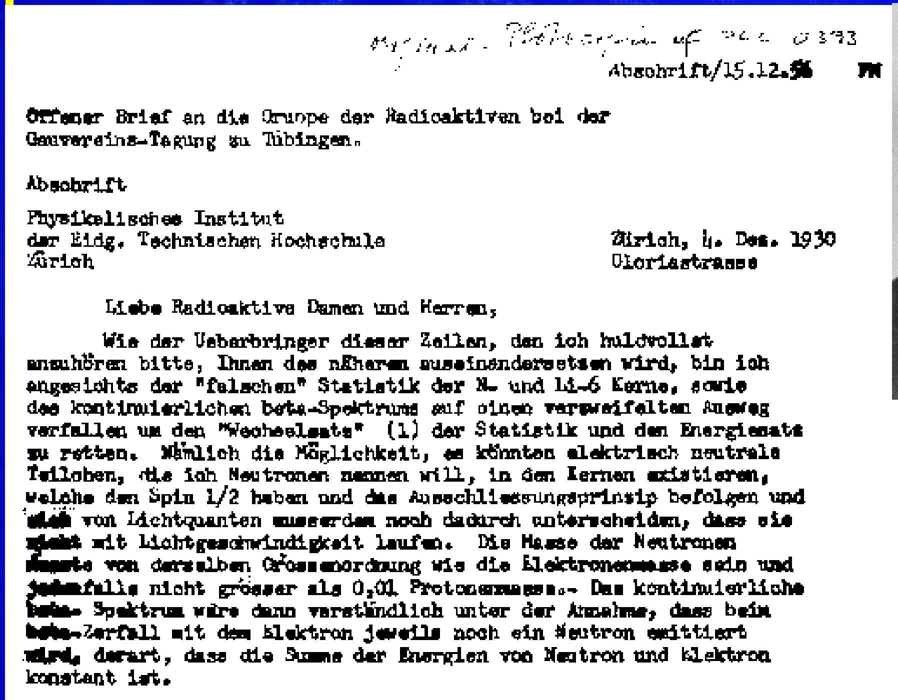
Contents

- Introduction
- The Sudbury Neutrino Observatory
- Signals and Backgrounds at SNO
- Results after the SNO salt phase
- The NCD phase

How it all began...

- 1914: Chadwick & Ellis
  Beta decay has a continues spectrum (+spin?)
- 1930: Pauli: another particle?



Abschrift/15.12.56 PM

Offener Brief an die Gruppe der Radioaktiven bei der Gauvereins-Tagung zu Tübingen.

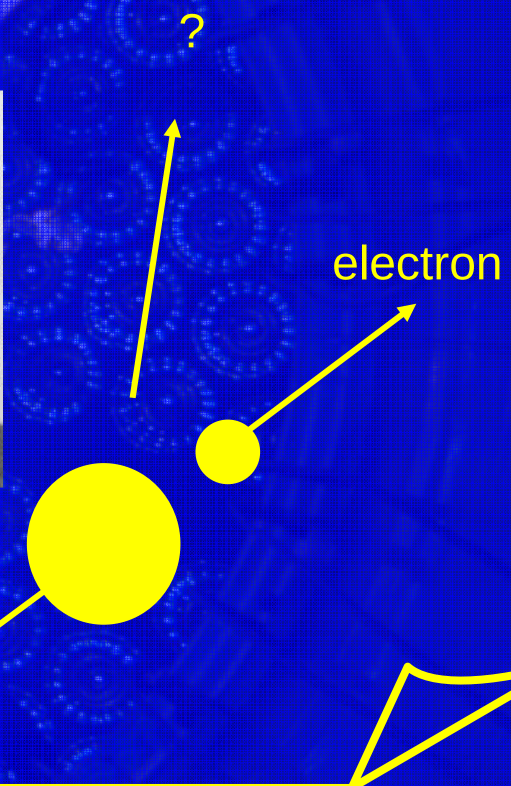
Abschrift

Physikalisches Institut
der Eidg. Technischen Hochschule
Zürich

Zürich, 4. Dez. 1930
Gloriastrasse

Liebe Radioaktive Damen und Herren,

Wie der Ueberbringer dieser Zeilen, den ich huldvollst anzuhören bitte, Ihnen des näheren auseinandersetzen wird, bin ich angesichts der "falschen" Statistik der N- und Li-6 Kerne, sowie des kontinuierlichen beta-Spektrums auf einen verzweifelten Ausweg verfallen um den "Wechselsatz" (1) der Statistik und den Energiesatz zu retten. Nämlich die Möglichkeit, es könnten elektrisch neutrale Teilchen, die ich Neutronen nennen will, in den Kernen existieren, welche den Spin 1/2 haben und das Ausschliessungsprinzip befolgen und sich von Lichtquanten ausserdem noch dadurch unterscheiden, dass sie nicht mit Lichtgeschwindigkeit laufen. Die Masse der Neutronen müsste von derselben Grössenordnung wie die Elektronenmasse sein und jedenfalls nicht grösser als 0,01 Protonenmasse.- Das kontinuierliche beta- Spektrum wäre dann verständlich unter der Annahme, dass beim beta-Zerfall mit dem Elektron jeweils noch ein Neutron emittiert wird, derart, dass die Summe der Energien von Neutron und Elektron konstant ist.



First observation of neutrinos

1956: Project Poltergeist
(26 years later!)

Nobelprice 1995

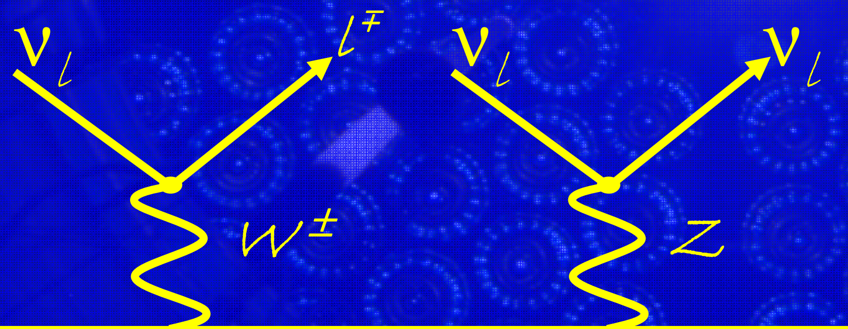
Frederick REINES and Clyde COWAN
Box 1663, LOS ALAMOS, New Mexic
Thanks for message. Everything comes to him who knows how to wait.
Pauli

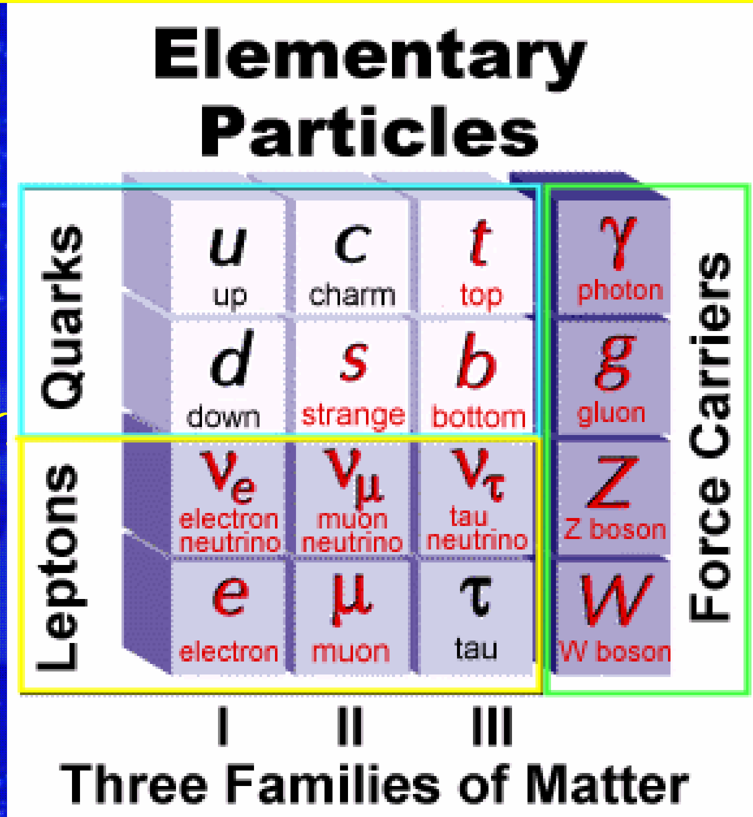
"Pre-1998" Standard Model of Particle Physics

Neutrinos are massless, weakly interacting particles and come in three families or flavours

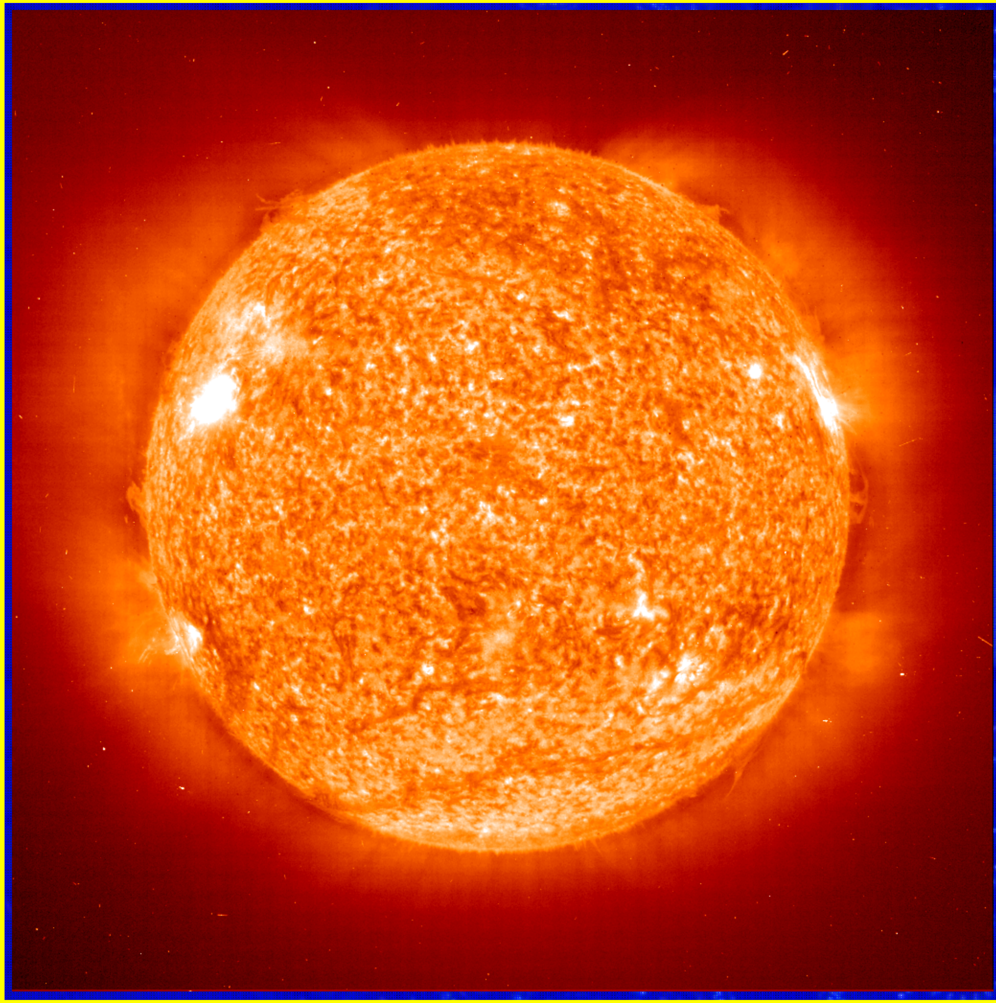
Weak Interaction:

Charged Current Neutral Current





Neutrinos from solar fusion



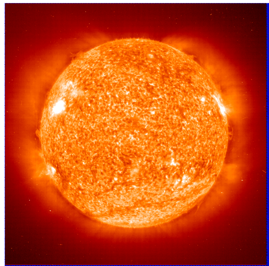
$$4p \rightarrow {}^4He + 2e^+ + 2\nu_e$$

$$2e^- + 4p \rightarrow$$

$${}^4He + 2e^+ + 2\nu_e + 26.73\ \text{MeV}$$

(energy relevant equation)

Using the
Solar irradiance:
S=8.5 x 10^{11} MeV cm^{-2} s^{-1}
an estimate of the solar neutrino flux on earth is:
~65,000,000,000 cm^{-2} s^{-1}



Solar neutrinos

solar physics *and* fundamental particle physics

Light Element Fusion Reactions

$p + p \rightarrow {}^2H + e^+ + \nu_e$ (99.75%)

$p + e^- + p \rightarrow {}^2H + \nu_e$ (0.25%)

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

85%: $^3He + {}^3He \rightarrow {}^4He + 2p$

~15%: $^3He + {}^4He \rightarrow {}^7Be + \gamma$

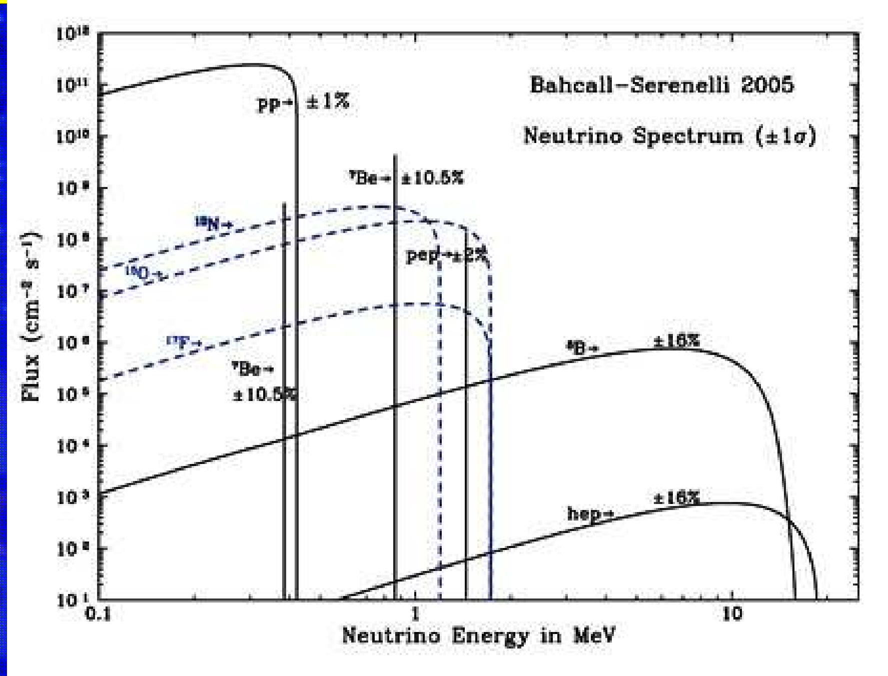
~10^{-5}%: $^3He + p \rightarrow {}^4He + e^+ + \nu_e$

15.07%: $^7Be + e^- \rightarrow {}^7Li + \gamma + \nu_e$

$^7Li + p \rightarrow \alpha + \alpha$

0.02%: $^7Be + p \rightarrow {}^8B + \gamma$

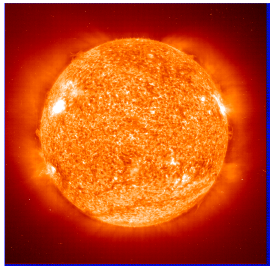
$\mathbf{^8B} \rightarrow {}^8Be^* + e^+ + \nu_e$



SNO detects ^8B (and hep)

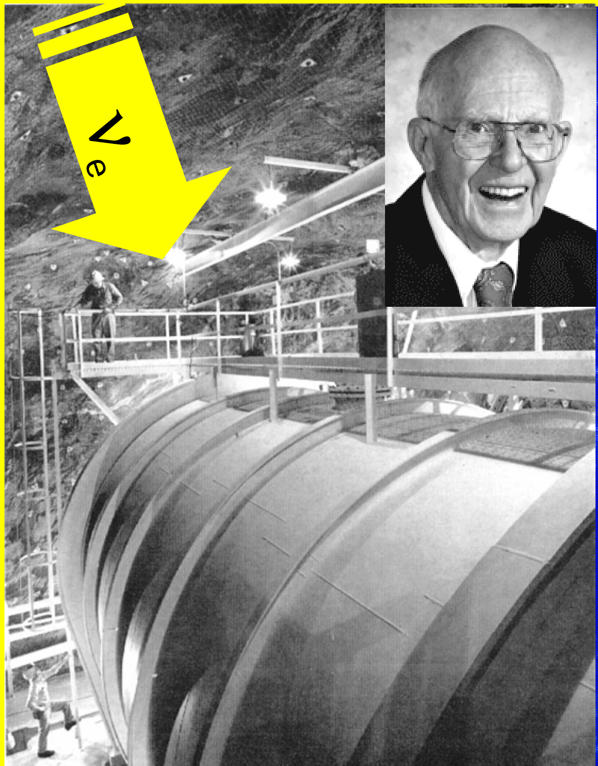
~ 1/10,000 of solar neutrino flux

New Solar Opacities, Abundances, Helioseismology, and Neutrino Fluxes
John N. Bahcall, Aldo Serenelli, and Sarbani Basu, ApJ, **621, L85 (2005)**



The Solar Neutrino Problem

Ray Davis



Homestake Gold Mine
(South Dakota, US)

$$\nu_e + {}^{37}Cl = {}^{37}Ar + e^-$$

The experiment ran from 1970-1995 (!)

Expected reaction rate from expected solar neutrino flux: ~0.5 day^{-1}

However, only:

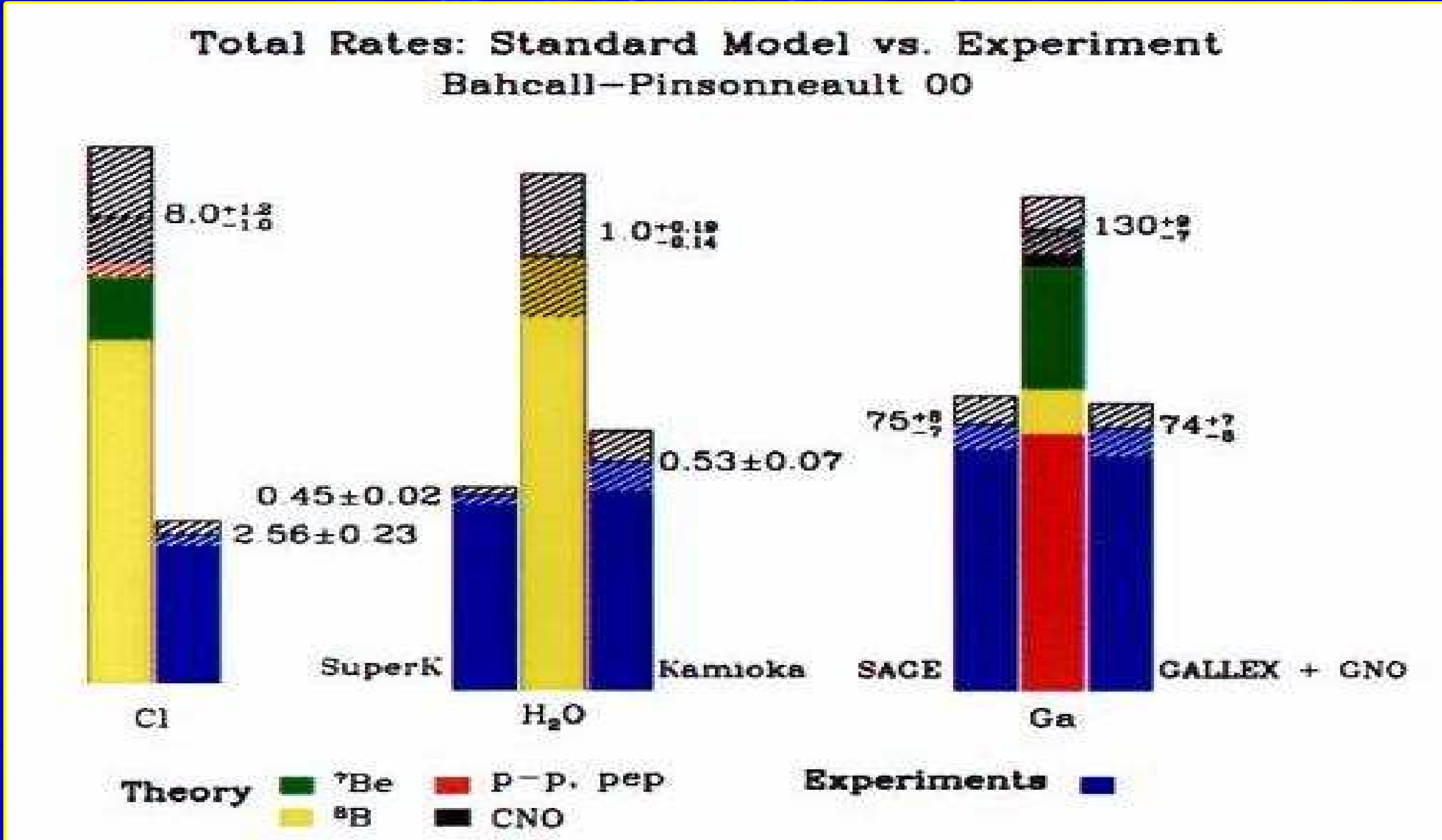
$0.33 \pm 0.03 \pm 0.05$

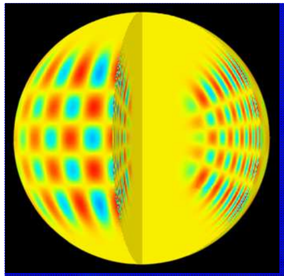
of the expected number of neutrinos has been observed.

SOLAR NEUTRINO PROBLEM

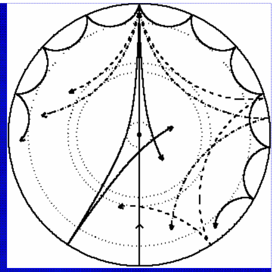
Ray Davis shared the
Nobel Price for Physics of 2003
(just after SNO's publication on neutrino flavour transformation)

Experimental confirmation

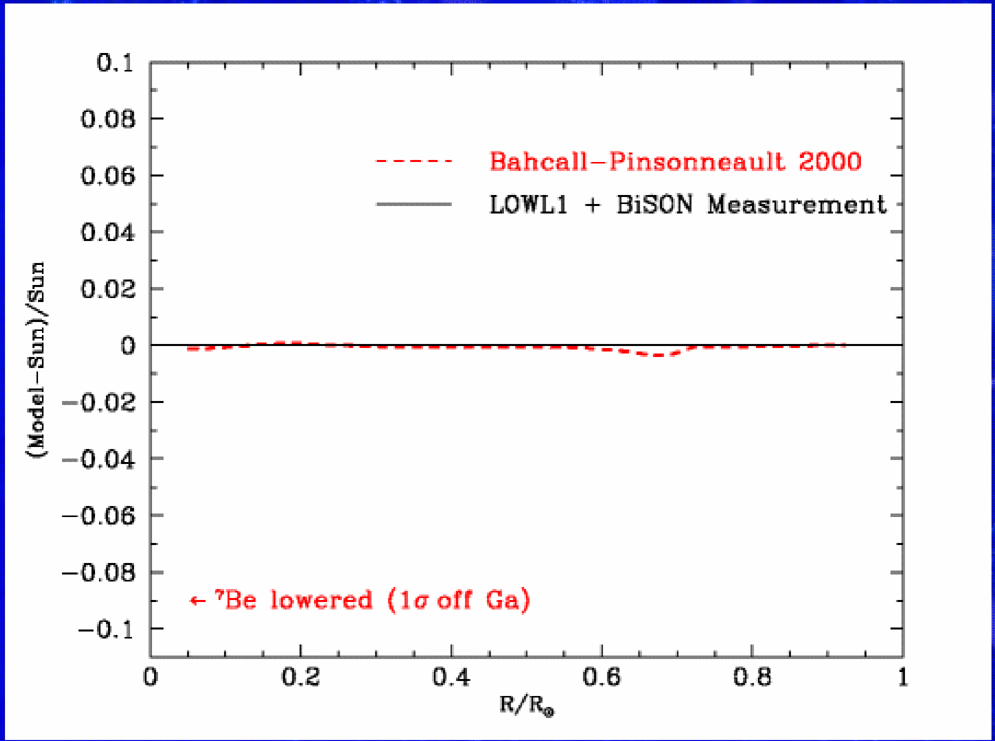




Standard Solar Model



Helioseismology ruled out that the Solar Neutrino Problem was due to the incorrect modelling of the interior of the sun.



(Dis)agreement model and observed oscillations:

$\lesssim$ 3% error in ^8B neutrino flux

Solar Models: current epoch and time dependences, neutrinos, and helioseismological properties
Author(s):John N. Bahcall, M. H. Pinsonneault, and Sarbani Basu
Journal:The Astrophysical Journal, 555, 990-1012 (2001)

Neutrino have mass and "oscillate"

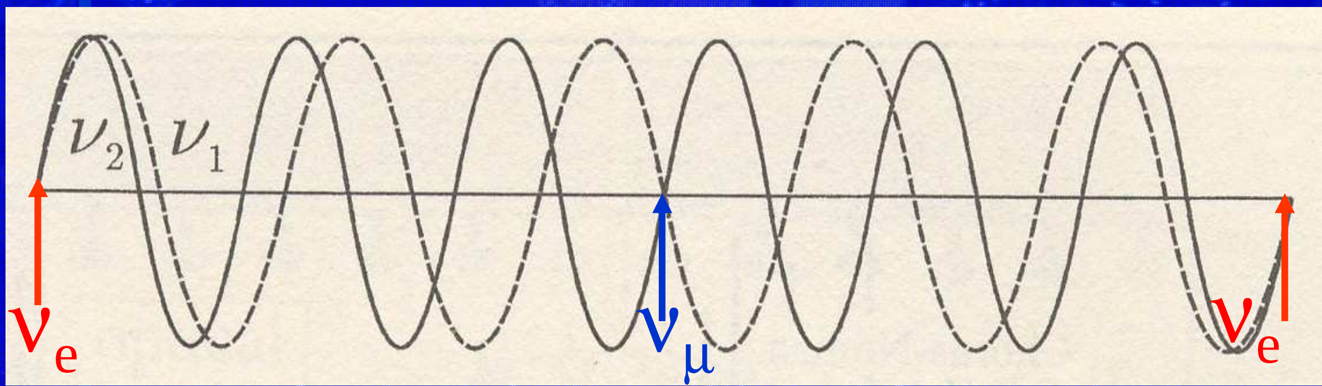
$$\begin{pmatrix} \nu_\mu \\ \nu_e \end{pmatrix} = \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \end{pmatrix}$$

Consider $\theta = 45^\circ$ then

$$\nu_e = {}^1/_{\sqrt{2}}\nu_1 + {}^1/_{\sqrt{2}}\nu_2$$

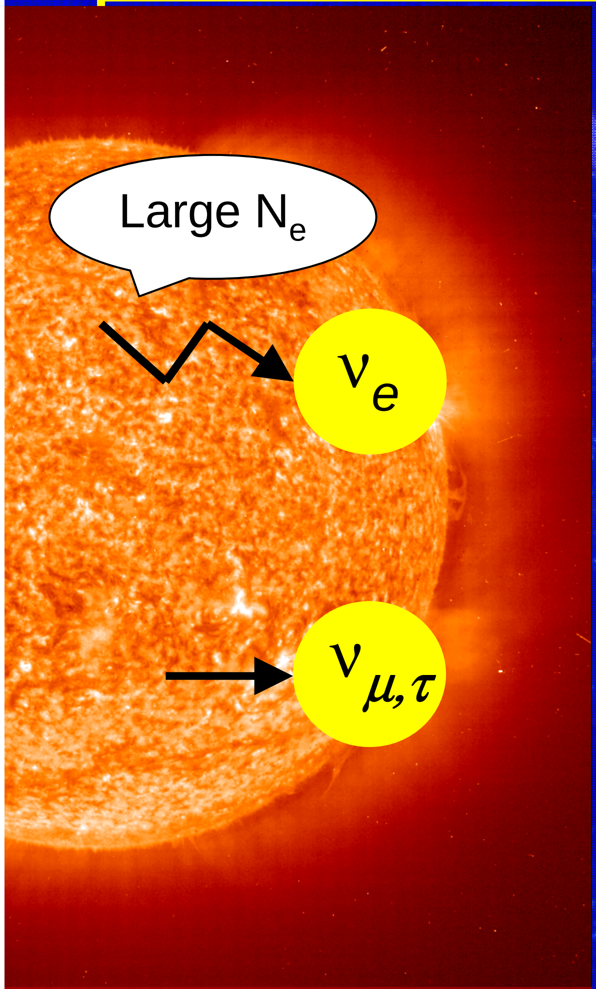
$$\nu_e(t) = {}^1/_{\sqrt{2}}(\nu_1 \exp i\omega_1 t + \nu_2 \exp i\omega_2 t)$$

$E_i^2 = p^2 + m_i^2$ so $2E.\Delta E = \Delta m^2$ $\omega_1 - \omega_2 = \Delta m^2/2E$



neutrino oscillation

$P(\nu_e \rightarrow \nu_e) = 1 - \sin^2(2\theta)\ \sin^2(\Delta m^2\ L\ /\ E)$

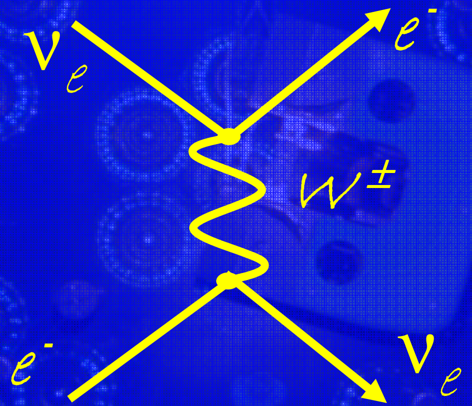


Sun: extended source, energy spectrum

$P(\nu_e \rightarrow \nu_e) = ½\ (1 + \cos^2 2\theta\ ) > 0.5$

MSW effect

Mikhaev, Smirnov, Wolfenstein



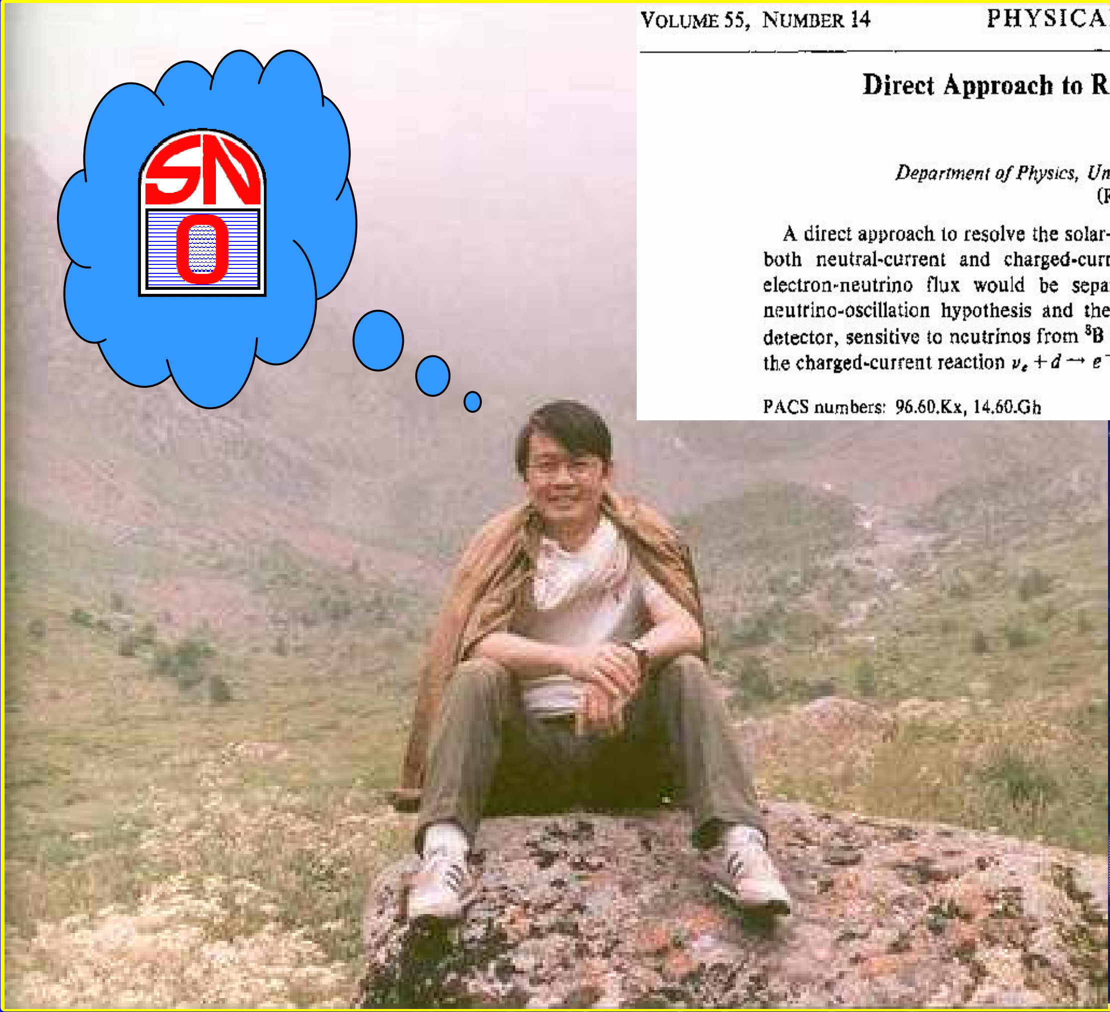
$V_e = G_F\ \sqrt{2}\ \ N_e$

(See for example:
The MSW effect and solar neutrinos
A.Yu. Smirnov
hep-ph/0305106)

$< 0 : P\ (\nu_e \rightarrow \nu_e\ ) < 0.5$

$P(\nu_e \rightarrow \nu_e) = ½\ (1 + \cos 2\theta_m \cos 2\theta\ )$

Get a more complete picture!



VOLUME 55, NUMBER 14 PHYSICAL REVIEW LETTERS 30 SEPTEMBER 1985

Direct Approach to Resolve the Solar-Neutrino Problem

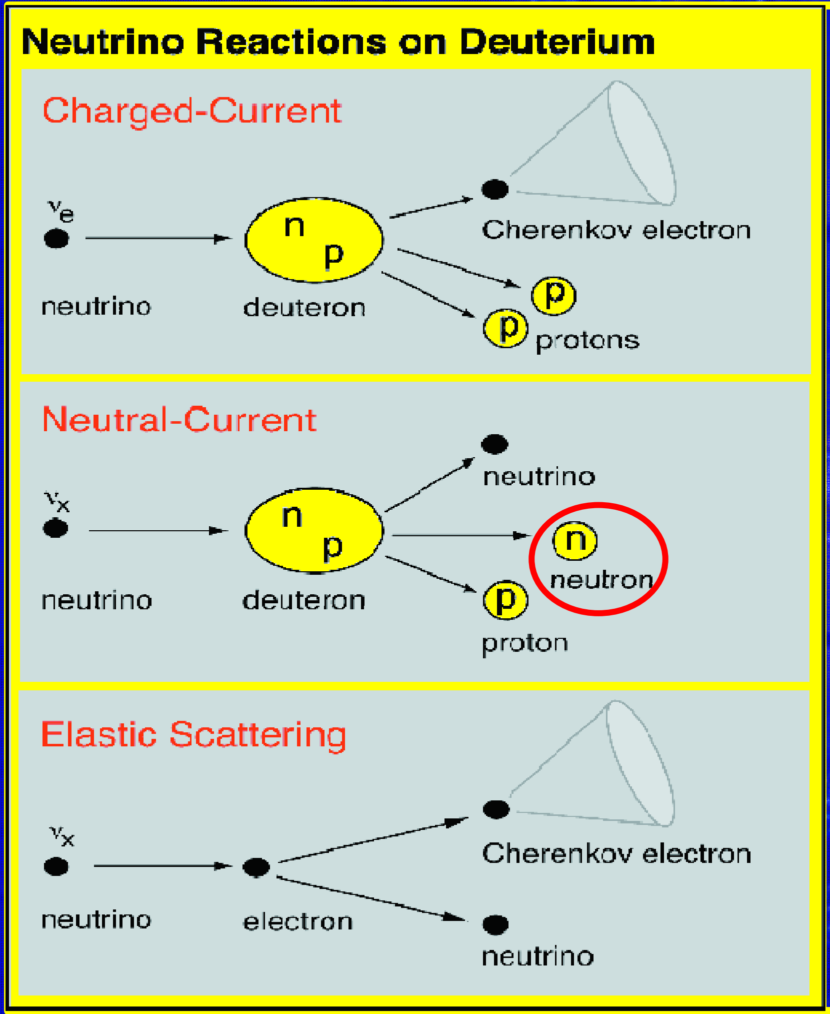
Herbert H. Chen
Department of Physics, University of California, Irvine, California 92717
(Received 27 June 1985)

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 ^8B 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

Herb Chen in 1985: Use deuterium

Neutrino reactions on D_2O



- CC: sensitive to electron neutrino flavour only. Energy electron directly correlated with ν energy.
- NC: sensitive to all neutrino flavours.
- ES: mostly electron flavour, direction (solar ν_e), ~ 10 times smaller interaction cross section

$$\Phi_{NC} \equiv \Phi_{SSM}$$

$$\Phi_{CC} / \Phi_{NC} \equiv P(\nu_e \rightarrow \nu_e)$$

The Sudbury Neutrino Observatory

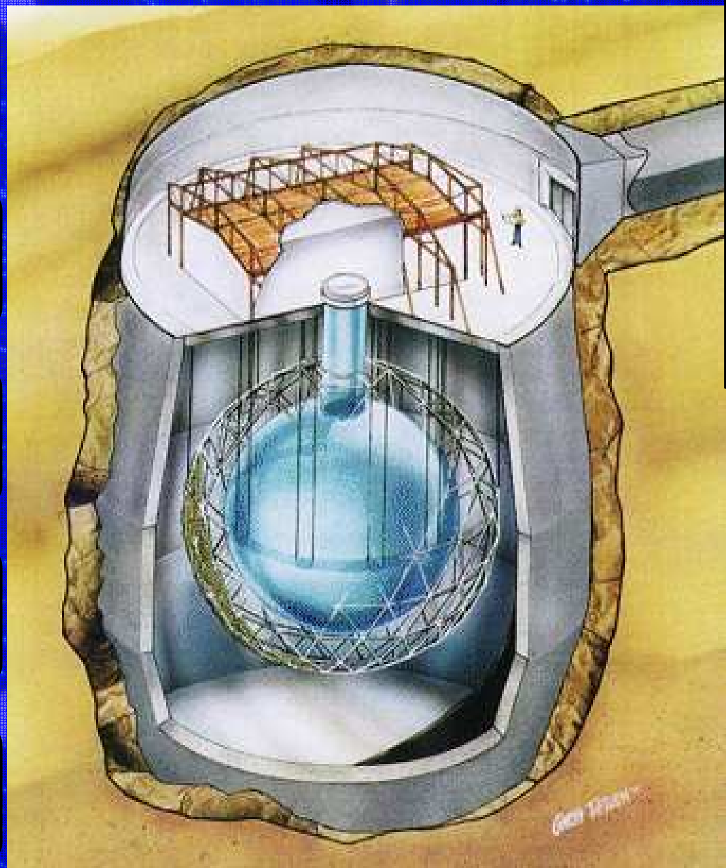
Acrylic vessel (AV)
12 m diameter

1000 tonnes D_2O

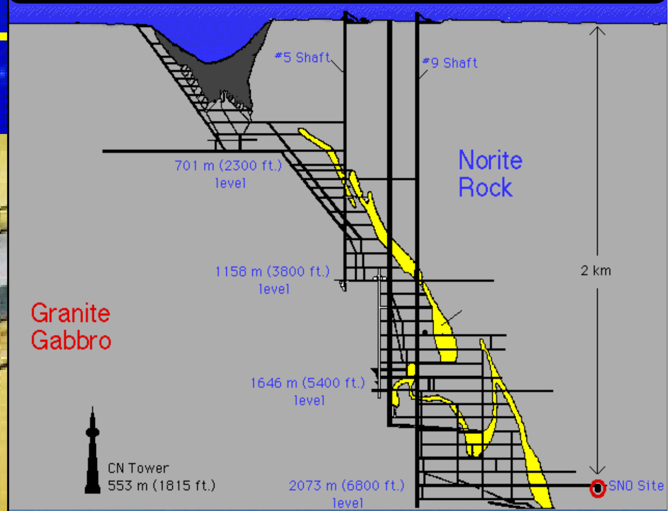
1700 tonnes H_2O
inner shielding

5300 tonnes H_2O
outer shielding

~9500 PMTs,
54% coverage

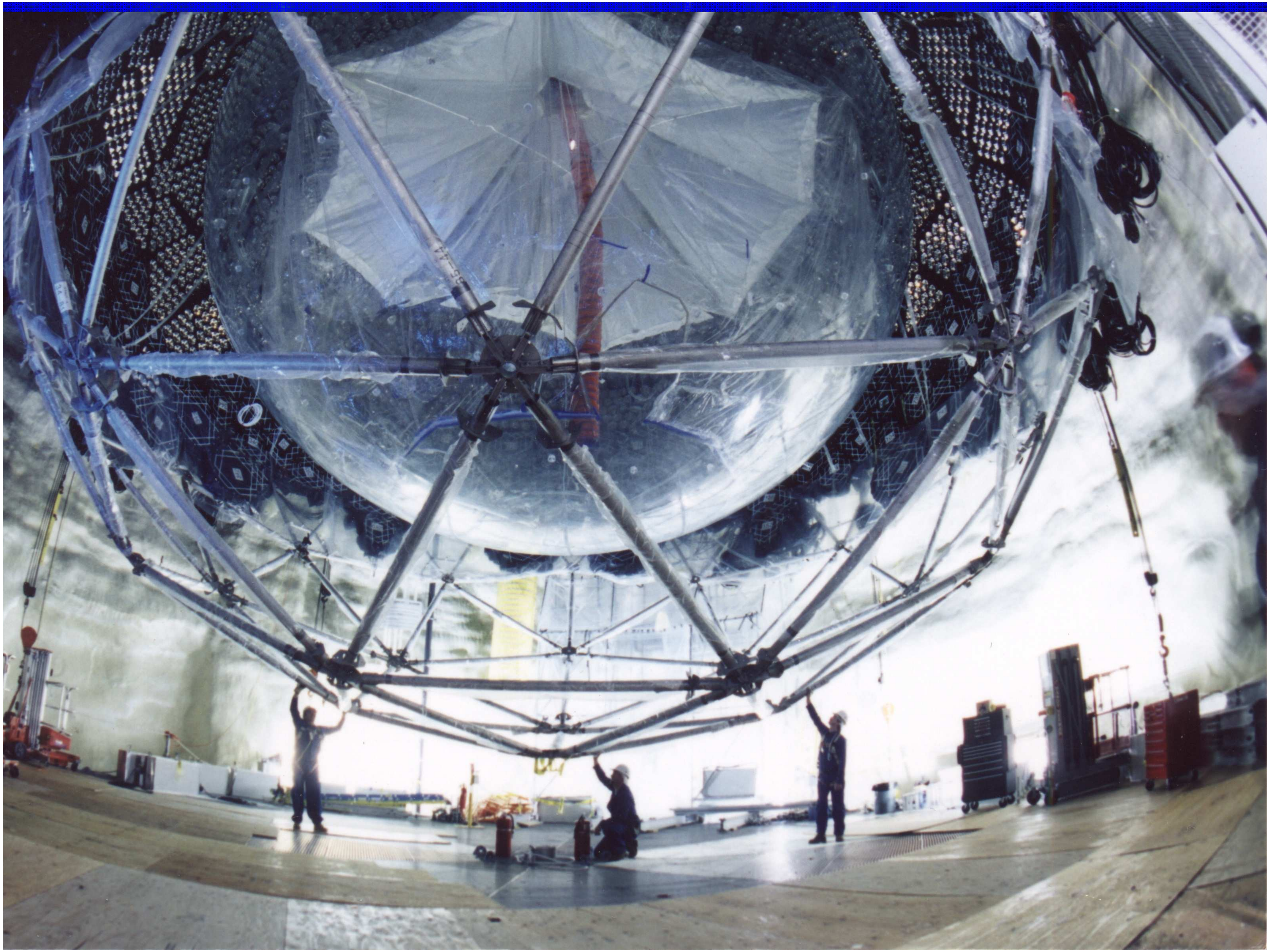


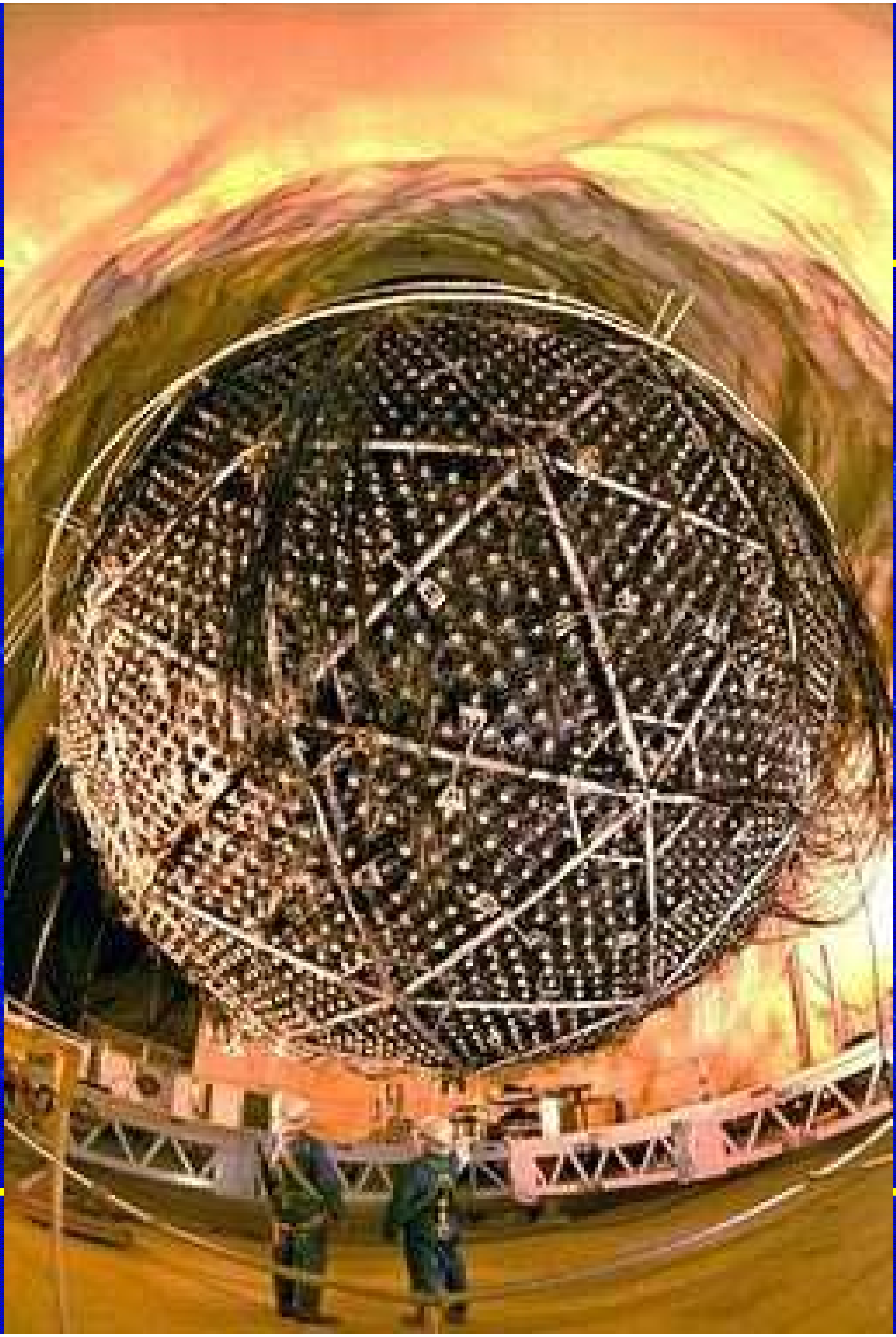
6800 feet (~2km) underground



Creighton mine
Sudbury, CA

"The Sudbury Neutrino Observatory" , The SNO Collaboration
Nuclear Instruments and Methods in Physics Research A449 (2000) pp. 172-207





The SNO program

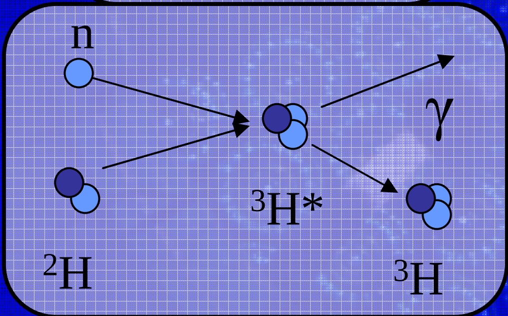
1998 | 1999 | 2000 | 2001 | 2002 | 2003 | 2004 | 2005 | 2006

Comm.	**Phase I**	**Phase II**		**Phase III**
	D_2O	Salt (NaCl)	D_2O	^{3}He Counters

n captures on deuterium

$\sigma = 0.0005$b

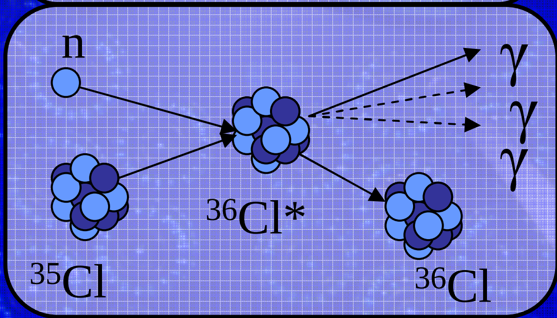
6.25 MeV γ



n captures on chlorine

$\sigma = 44$b

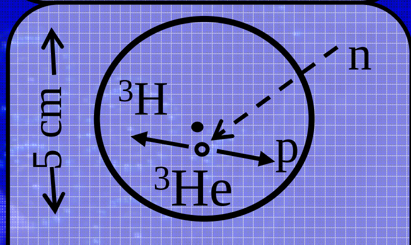
8.6 MeV multiple γs



n captures on ^{3}He prop. counter array

$\sigma = 5330$b

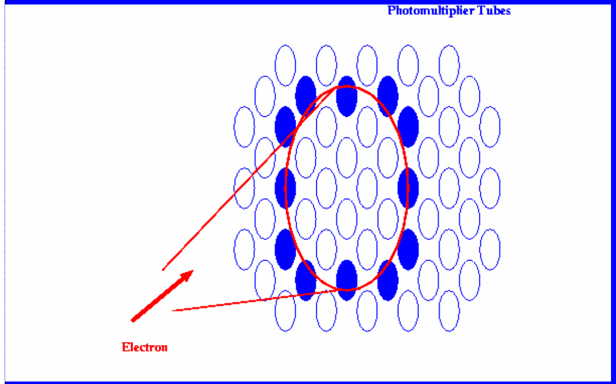
0.764 MeV

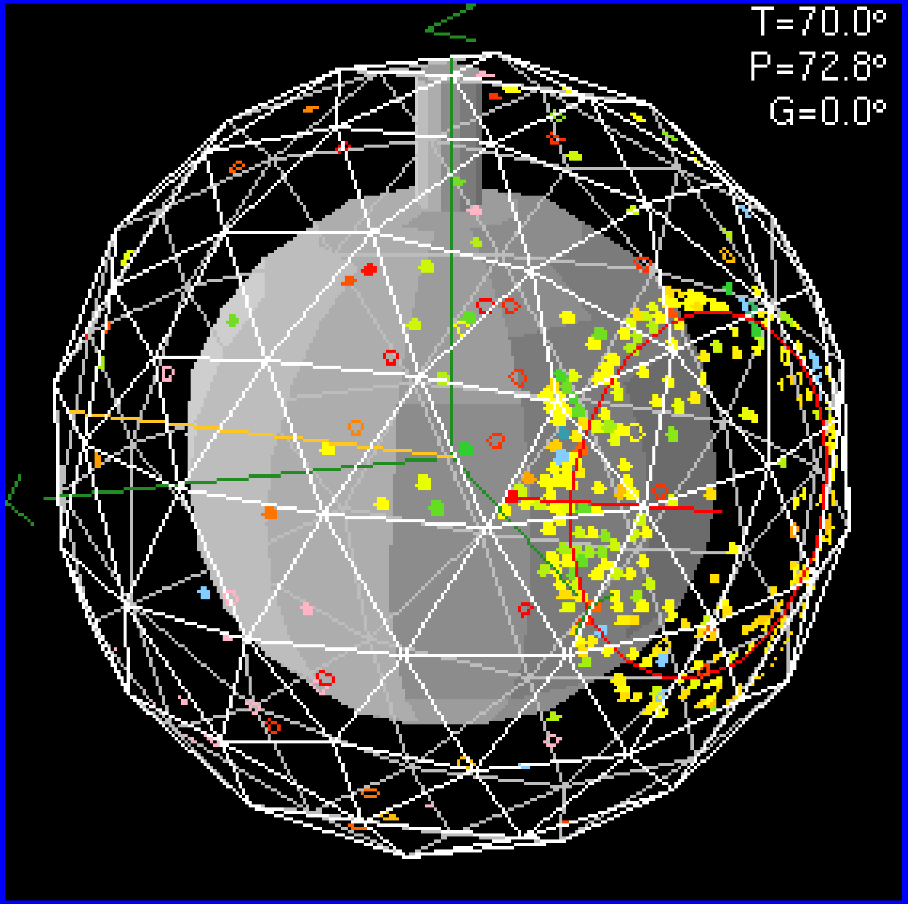


$n + {}^3He \rightarrow p + {}^3H$

ν Interactions as seen by SNO

(neutron captured produces gammas)
(gammas Compton scatter)
relativistic electrons
produce Cherenkov light



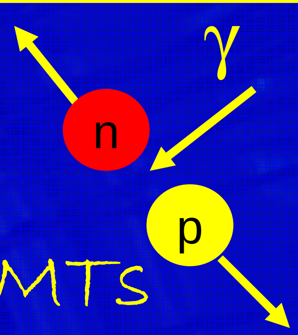


PMT positions
Times
Charges

Reconstructed event position (radius), direction, kinetic energy, isotropy

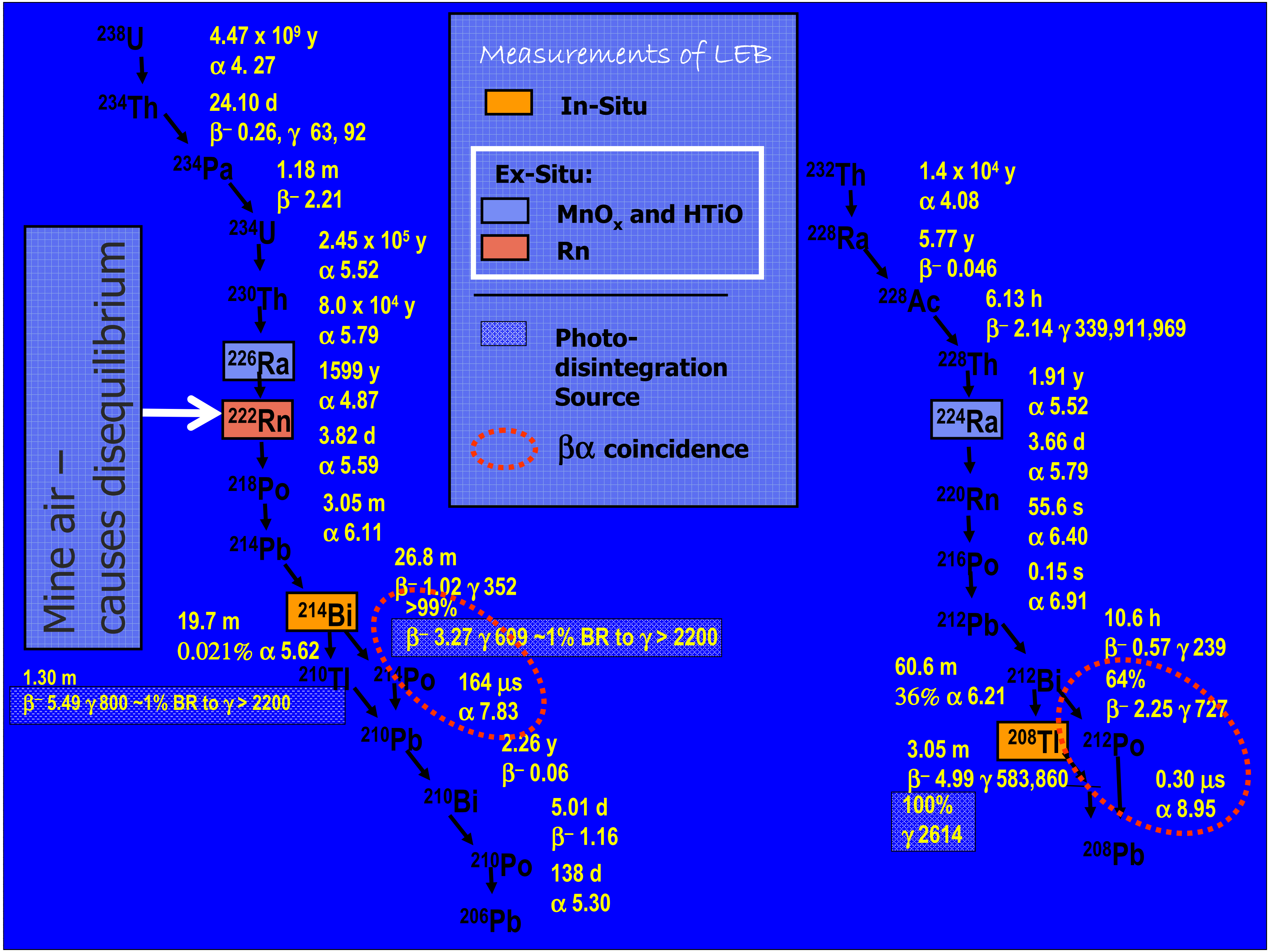
Main background

Gamma > 2.2 MeV pd's the deuteron:



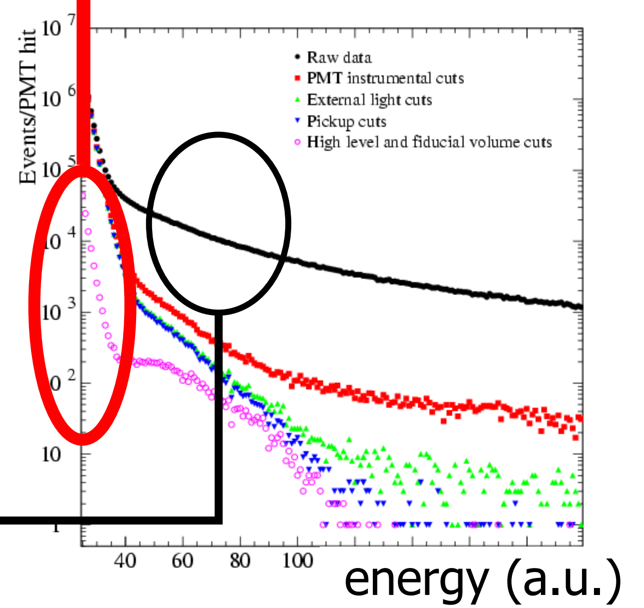
- Hence the water shielding from radioactivity in the rock, mine air, PMTs
- Hence the depth: shielding for cosmic rays (only 3 μ's per hour)
- Cleanliness of detector materials: ^{238}U, ^{232}Th
- D_2O: less than one teaspoon of minedust ~ 1.5 n/day (~10% of NC flux)

"I will show you fear in a handful of dust." -- T.S. Eliot



238U
4.47 x 10^9 y
α 4. 27
234Th
24.10 d
β− 0.26, γ 63, 92
234Pa
1.18 m
β− 2.21
234U
2.45 x 10^5 y
α 5.52
230Th
8.0 x 10^4 y
α 5.79
226Ra
1599 y
α 4.87
222Rn
3.82 d
α 5.59
218Po
3.05 m
α 6.11
214Pb
26.8 m
β− 1.02 γ 352
214Bi
>99%
β− 3.27 γ 609 ~1% BR to γ > 2200
19.7 m
0.021% α 5.62
210Tl
1.30 m
β− 5.49 γ 800 ~1% BR to γ > 2200
214Po
164 µs
α 7.83
210Pb
2.26 y
β− 0.06
210Bi
5.01 d
β− 1.16
210Po
138 d
α 5.30
206Pb
Mine air – causes disequilibrium
Measurements of LEB
In-Situ
Ex-Situ:
MnOx and HTiO
Rn
Photo-disintegration Source
βα coincidence
232Th
1.4 x 10^4 y
α 4.08
228Ra
5.77 y
β− 0.046
228Ac
6.13 h
β− 2.14 γ 339,911,969
228Th
1.91 y
α 5.52
224Ra
3.66 d
α 5.79
220Rn
55.6 s
α 6.40
216Po
0.15 s
α 6.91
212Pb
10.6 h
β− 0.57 γ 239
212Bi
60.6 m
36% α 6.21
64%
β− 2.25 γ 727
208Tl
3.05 m
β− 4.99 γ 583,860
100%
γ 2614
212Po
0.30 µs
α 8.95
208Pb

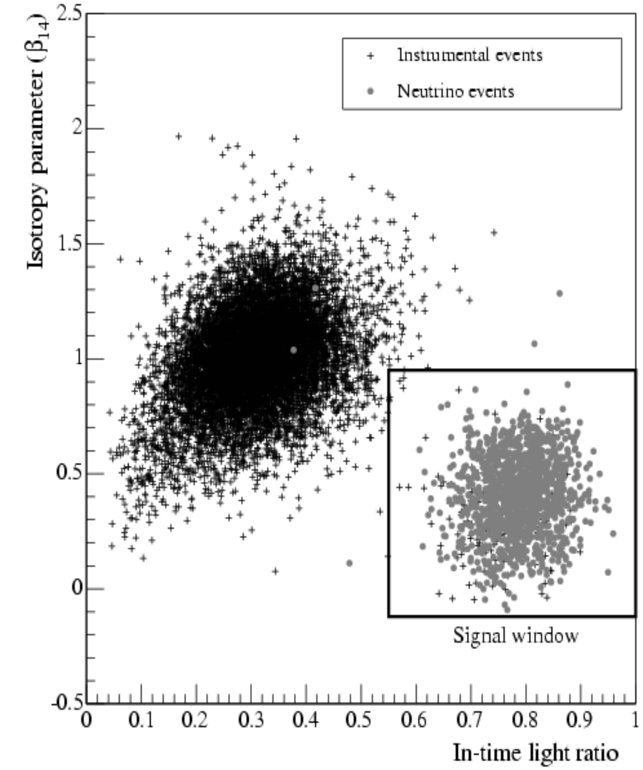
In-situ measurements



^{238}U, ^{232}Th:

* Different branching fractions to γ > 2.2 MeV
* Observation is different: single γ vs $\gamma + \beta$:

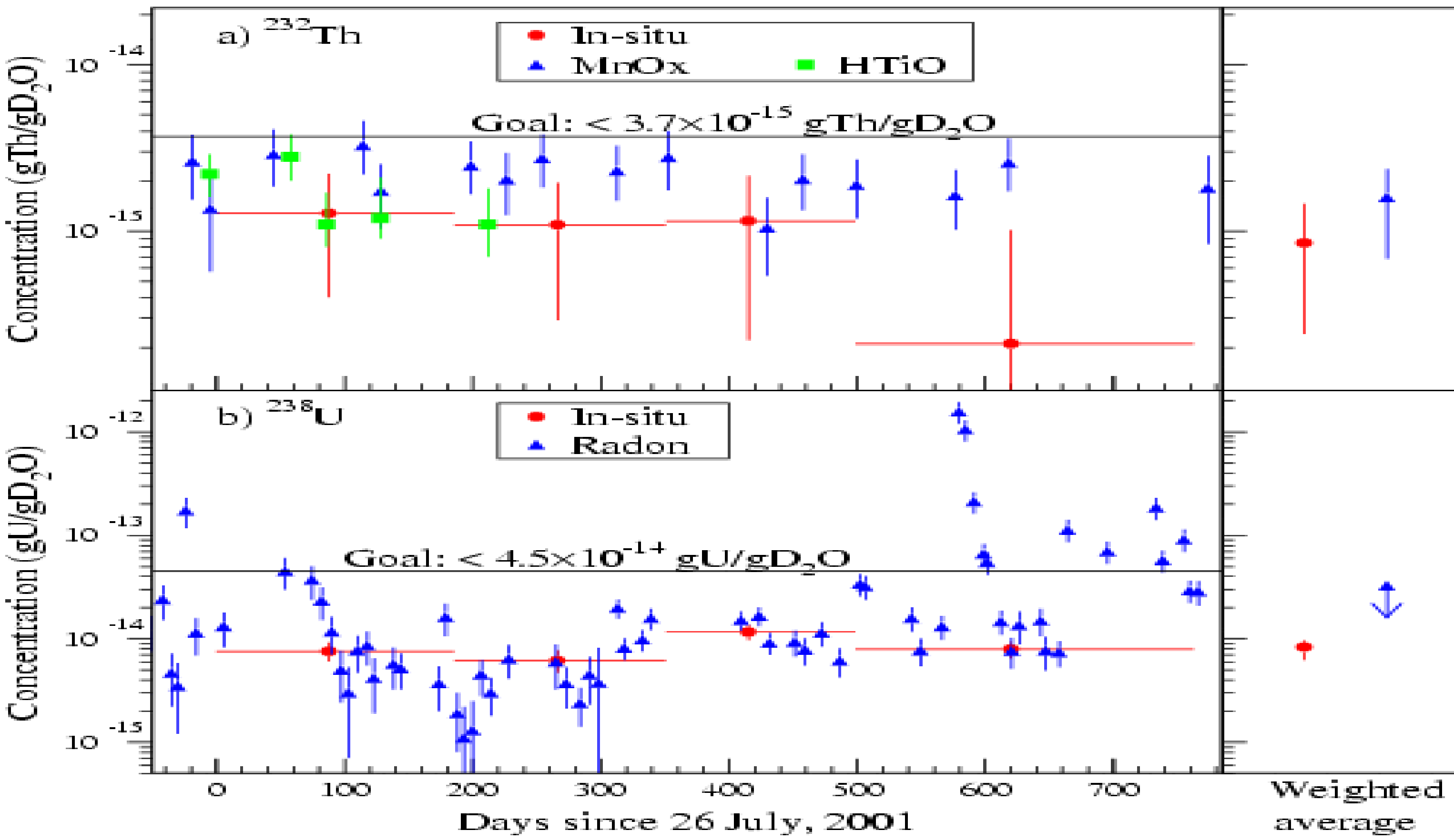
!different isotropy!



Instrumental events: data taking rate ~ 20 Hz
Uncharacteristic spatial distributions
make them easy to separate from the data.

Comparison in-situ/ex-situ

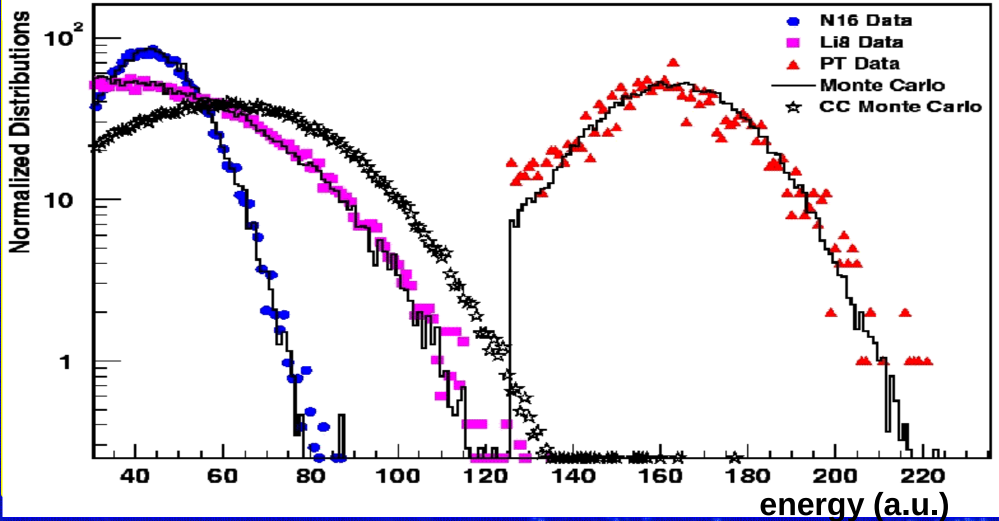
(salt phase)

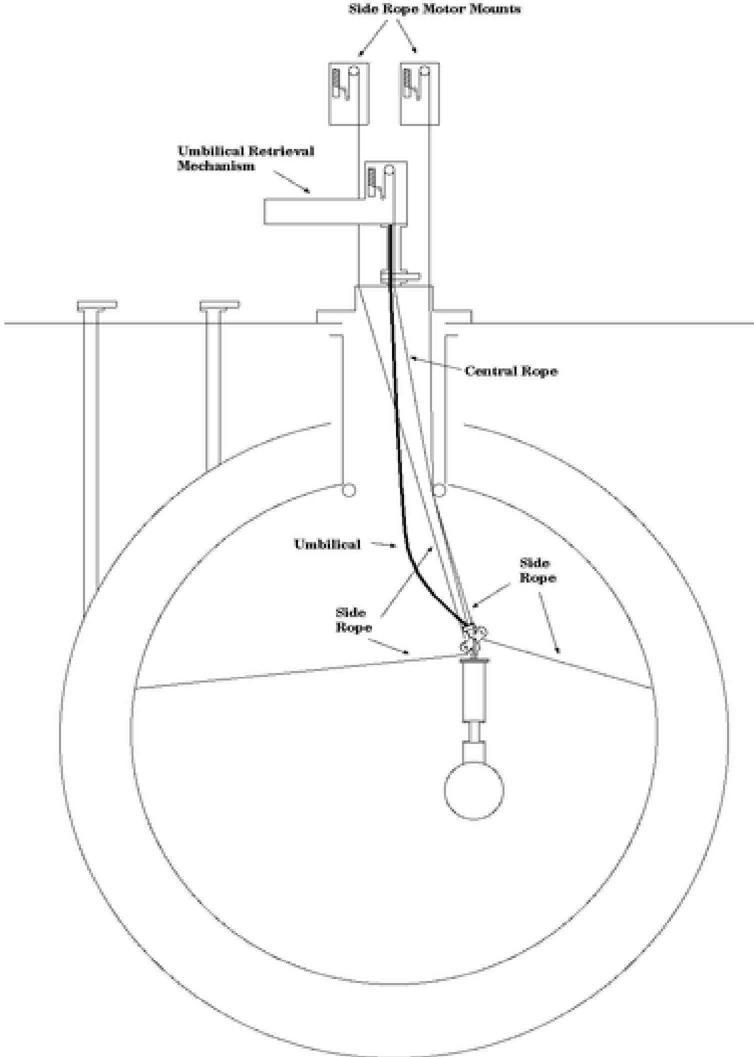


Calibrations

TABLE III: Primary calibration sources.

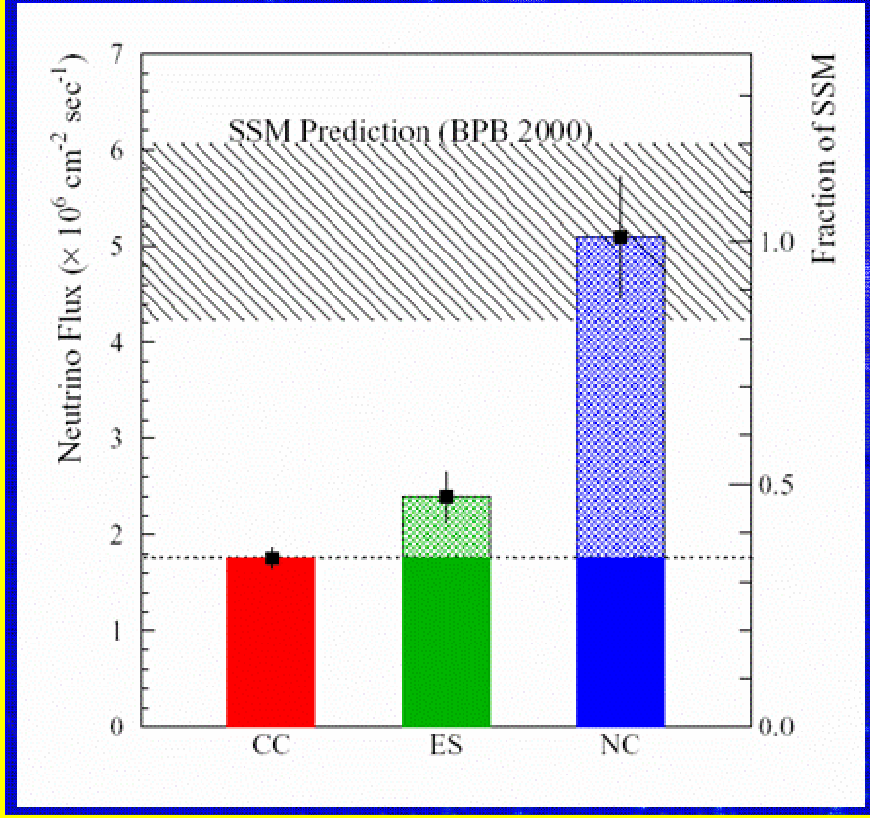
Calibration source	Details	Calibration	Ref.
Pulsed nitrogen laser	337, 369, 385, 420, 505, 619 nm	Optical & timing calibration	[1]
^{16}N	6.13-MeV γ-rays	Energy & reconstruction	[23]
^{8}Li	β spectrum	Energy & reconstruction	[22]
^{252}Cf	neutrons	Neutron response	[1]
Am-Be	neutrons	Neutron response	
^{3}H$(p,\gamma)^{4}$He ("pT")	19.8-MeV γ-rays	Energy linearity	[24]
U, Th	$\beta-\gamma$	Backgrounds	[1]
^{88}Y	$\beta-\gamma$	Backgrounds	
Dissolved Rn spike	$\beta-\gamma$	Backgrounds	
In-situ ^{24}Na activation	$\beta-\gamma$	Backgrounds	





Results D_2O phase

"Direct Evidence for Neutrino Flavor Tranformation from Neutral-Current Interactions in the Sudbury Neutrino Observatory", *The SNO Collaboration* Phys. Rev. Lett. volume 89, No. 1, 011301 (2002).



- Total flux agrees with the Standard Solar Model (Solar SM OK)
- Neutrino change flavour in between their production point and SNO (Particle SM has to be adjusted)

BBC NEWS

You are in: **Sci/Tech**

Monday, 18 June, 2001, 16:24 GMT 17:24 UK

Ghostly particle mystery 'solved'

The underground neutrino detector viewed from above

By BBC News Online science editor Dr David Whitehouse

An international team of physicists claims to have solved a 30-year-old mystery: the puzzle of the missing solar neutrinos.

In the past scientists detected only about a third of the

'High confidence'

The research was carried out at the Sudbury Neutrino Observatory (SNO), Ontario, in collaboration with Oxford University, UK.

"We now have high confidence that the discrepancy is not caused by problems with the models of the Sun but by changes in the neutrinos themselves as they travel from the core of the Sun to the Earth," says Dr Art McDonald, SNO project director and professor of physics at Queen's University in Kingston, Ontario, Canada.

Light detectors around the water tank detect the neutrinos

"It's taken longer than we thought, but it's all been well worthwhile," says Dr Steve Biller, of Oxford University. "We've pushed the limits of engineering, chemistry... and patience, in order to push the limits of physics."

Fundamental particles

Neutrinos are fundamental part... are often called 'ghostly' becau... weakly with other forms of mat...

They come in three types: the e...

Installing the giant underground tank

But despite its large size the SNO only detects about 10 neutrinos a day.

'Mind-boggling'

"The engineering requirements alone are mind-boggling. We were breaking new ground in every sense and there were times that we weren't sure we were going to make it," says Professor Nick Jelley of Oxford University.

"It is incredibly exciting, after all the years spent by s... many people building SNO, to see such intriguing results coming out of our first data analysis - with so

The New York Times

June 19, 2001

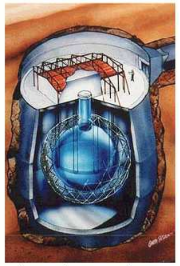
Sun's Missing Neutrinos: Hidden in Plain Sight

By KENNETH CHANG

After three decades of searching, physicists have tracked down subatomic particles that have eluded them for 30 years. The particles, it turns out, were right there all the while but had hidden themselves as if by magic.

"We've solved a 30-year-old puzzle of the missing neutrinos of the Sun," said Dr. Arthur B. McDonald, director of the Sudbury Neutrino Observatory, near Sudbury, Ontario. In doing so, though, the researchers have answered questions about neutrino behavior and the fate of the universe.

Neutrinos are ghostly particles, one of the fundamental building blocks of the universe, like quarks, electrons and photons. Billions of them, produced by fusion reactions within the Sun, fly ...ry second. ...electric ...unnoticed. In



A drawing of the neutrino detector, built 1-mile underground and immersed in water within a cavity 110 feet deep.

Lawrence Berkeley National Laboratory

The bottom of the neutrino detector.

...her different result." The data ran contrary to his hopes of finding a ...w kind of neutrino.

...ill, he said, the Sudbury results look "quite solid."

Neutrinos come in three types (physicists call them flavors): electron neutrinos, muon neutrinos and tau neutrinos, named according to the subatomic particles they usually associate with. Muon and tau particles are heavier particles that otherwise act like electrons. The neutrinos produced by the Sun are all electron neutrinos.

Spotting the rare occasions when a neutrino collides with another particle requires large quantities of material for the neutrinos collide with.

The detector in the Sudbury Neutrino Observatory consists of a 40-foot-wide acrylic sphere containing 1,000 tons of heavy water, in which the two hydrogen atoms of the water molecules have been replaced with deuterium atoms, a heavier version of hydrogen. The sphere is submerged within a 10-story cavity that was carved out of a nickel mine 1 1/4 miles underground and filled with 40,000 tons of ordinary water.

Occasionally, an electron neutrino will slam into one of the deuterium atoms in the heavy water, splitting it into a proton and a neutron. Detectors around the sphere of heavy water are able to spot the debris. The other two types of neutrinos cannot break up deuterium. The scientists have seen 1,169 such collisions since the experiment began in 1999.

The researchers compared their results with earlier neutrino counts from the Super-Kamiokande neutrino experiment in Japan, which primarily detects collisions between electron neutrinos and electrons. But muon and tau neutrinos can also occasionally bounce off electrons.

If all the neutrinos reaching Earth from the Sun were of the electron variety, then the neutrino rates measured by Super-Kamiokande and Sudbury should match up. But Super- Kamiokande detected more. Since the Sun produces only electron neutrinos - the production of muon and tau neutrinos require higher-energy events, like matter falling into black holes or an exploding star - that means some of them must change into muon or tau neutrinos.

"It's the first direct evidence for the changing of solar neutrinos from electron type to another type," Dr. Klein said. Most physicists had considered neutrino morphing to be the most likely explanation for the missing neutrinos.

Dr. Caldwell's theory was that the electron neutrinos were changing into "sterile" neutrinos that did not interact with ordinary matter. "It looks like they've done a very thorough job," he said. "It then is a real question if there is any room for a sterile neutrino. I don't see much hope for it right now."

According to the equations of particle physics, for this transformation of flavors to occur, at least one of the neutrino types must possess a smidgeon of mass. Coupled with earlier experimental results, the researchers conclude that each of the three neutrino flavors weigh, at most, one- 60,000th as much as an electron.

LA NACION

Buenos Aires, miércoles 20 de junio de 2001

En un observatorio canadiense

Detectan una partícula fantasmal

Permite explicar la transformación de los neutrinos, ladrillos elementales del universo

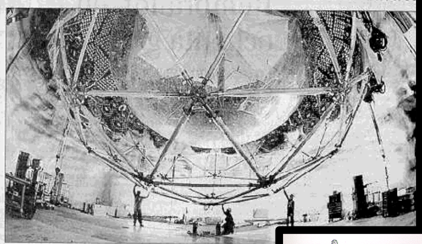
• El hallazgo se produjo luego de tres décadas de investigaciones • Los expertos midieron el comportamiento de estos componentes en su viaje desde el Sol hacia la Tierra

NUEVA YORK (The New York Times).- Después de tres décadas de búsqueda, los físicos han rastreado partículas subatómicas que los habían eludido durante tres décadas. Las partículas, resulta ser, estaban todo el tiempo allí, pero se habían escondido como por arte de magia.

"Hemos resuelto un rompecabezas sobre los neutrinos faltantes del Sol", dijo Arthur B. McDonald, director del Sudbury Neutrino Observatory, cerca de Sudbury, Ontario. Al hacerlo, sin embargo, los investigadores han contestado preguntas sobre el comportamiento de los neutrinos y el destino del universo.

Los neutrinos son partículas fantasmales, uno de los ladrillos fundamentales del universo, como los quarks, los electrones y los fotones. Billones de ellos, producidos por reacciones de fusión que ocurren en el interior del Sol, nos atraviesan cada segundo. Minúsculos y desprovistos de carga eléctrica, sin embargo, ellos pasan sin ser advertidos. De hecho, son prácticamente indetectables.

Un misterio resuelto



La esfera del detector de neutrinos con el que se realizaron las medicio...

El número de neutrinos del Sol, concluyen, es de alrededor de 35 millones por pulgada cuadrada por segundo. "Hay bastante coincidencia entre las predicciones y la medición", afirmó Joshua Klein, profesor de Física de la Universidad de Pensilvania que coordinó el análisis de los datos.

Un dibujo del detector de neutrinos

CNN

Physicists solve weighty neutrino mystery

June 19, 2001 Posted: 11:33 AM EDT (1533 GMT)

(AP) -- Solving a 30-year-old scientific mystery, physicists have found the most convincing evidence yet that neutrinos -- elusive subatomic particles that were thought to have no mass whatsoever -- have a tiny wisp of heft after all.

Express & Star

WOLVERHAMPTON The Millennium City

Telephone 01902 31 31 31 — Tuesday, June 19, 2001 — www.westmidlands.com

Solved: riddle of missing neutrino

A 30-year-old mystery surrounding a tiny elementary particle has been solved using a £34 million monster machine buried two kilometres underground.

British physicists were among those celebrating after unravelling the riddle of the missing neutrinos. Neutrinos are ghostly elementary particles of matter with no electric charge and very little mass. Scientists have calculated that huge numbers of solar electron-neutrinos should be showering the Earth - but only a fraction of the expected amount are ever detected. So how are the missing neutrinos explained?

It took a gigantic engineering project, massive investment, and an international team of 100 scientists to find the answer.

The scientists said they had discovered that the "missing" electron-neutrinos were there all along, but in disguise. On their way to Earth, they changed into other kinds of neutrino called muon and tau neutrinos.

This was revealed by the Sudbury Neutrino Observatory 2,000 metres below ground near Sudbury, Ontario, Canada.

YOMIURI ON-LINE

YomyClub ヨミークラブ YOMIURI ON-LINE — オレにピッタリ来るサイトないかなぁ…

14:37 / 2001.6.19(火) 更新 | ENGLISH | 購読はこちら | イベント | インパクアメリカ横断ウオーク

| ヨミークラブ | 新着情報 | @マネー | 教育メール | 大手小町 | @CARS | 芸能 | SPORTS | W杯2002 |

社会

「太陽ニュートリノに問題」解決へ進展

太陽から地球に到達する素粒子「ニュートリノ」が、理論予測の半分以下しか検出されない「太陽ニュートリノ問題」の解決を目指していたサドベリー・ニュートリノ観測所（カナダ・オンタリオ州）は、１８日（日本時間１９日）、「ニュートリノに質量があることが原因」と発表した。東大宇宙線研究所グループが測定器「スーパーカミオカンデ」で得た、昨年夏の発表内容を支持する結果。太陽ニュートリノは、太陽の中心部で核融合反応が起きるときに発生しており、太陽構造の理論の不備が「太陽ニュートリノ問題」の原因である可能性も残されていたが、今回の発表で否定された。

同観測所は、地下約２キロにある球形水槽に、約１０００トンの「重水」と呼ばれる特殊な水をため、そこで起きる反応を使って太陽からのニュートリノを１９９９年春から観測してきた。ニュートリノが持つエネルギーなどを測定し、「スーパーカミオカンデ」の結果とも比較した結果、やはりニュートリノ質量が太陽ニュートリノ問題の原因であることを突き止めた。

(6月19日14:37)

▶社会面一覧

The Salt Phase

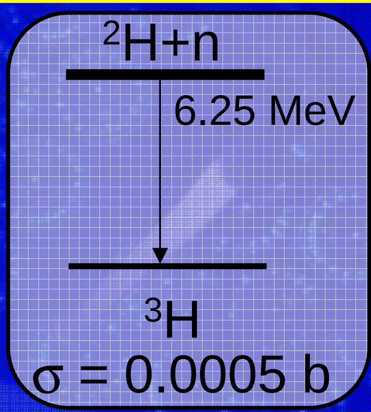
I. Higher capture cross section

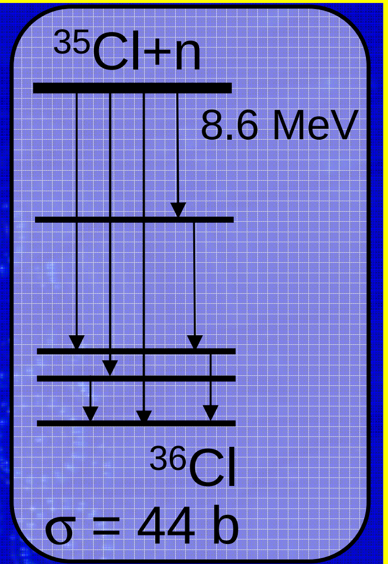
II. Higher energy release

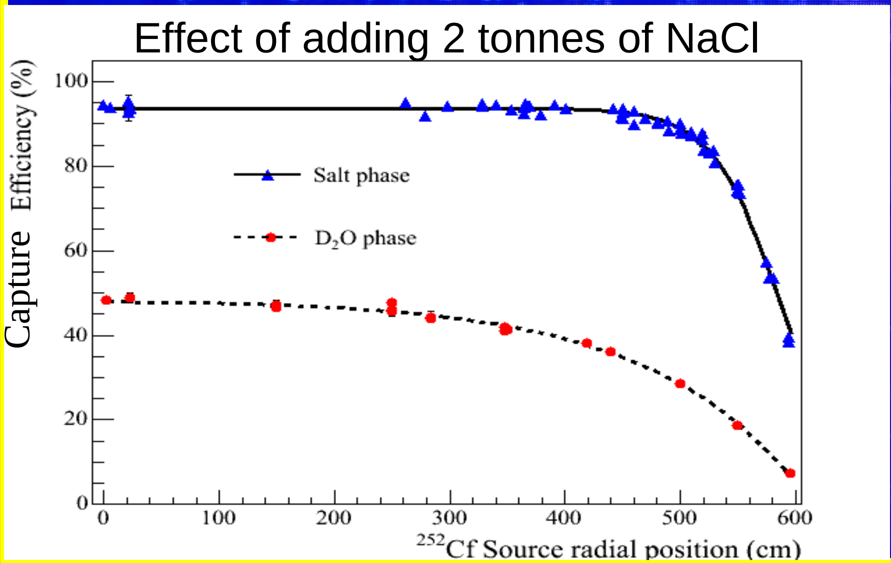
III. Multiple γs means greater isotropy

D_2O phase: CC 1e , NC 1e (γ)

Salt phase: CC 1e , NC ~2,3es (γs)





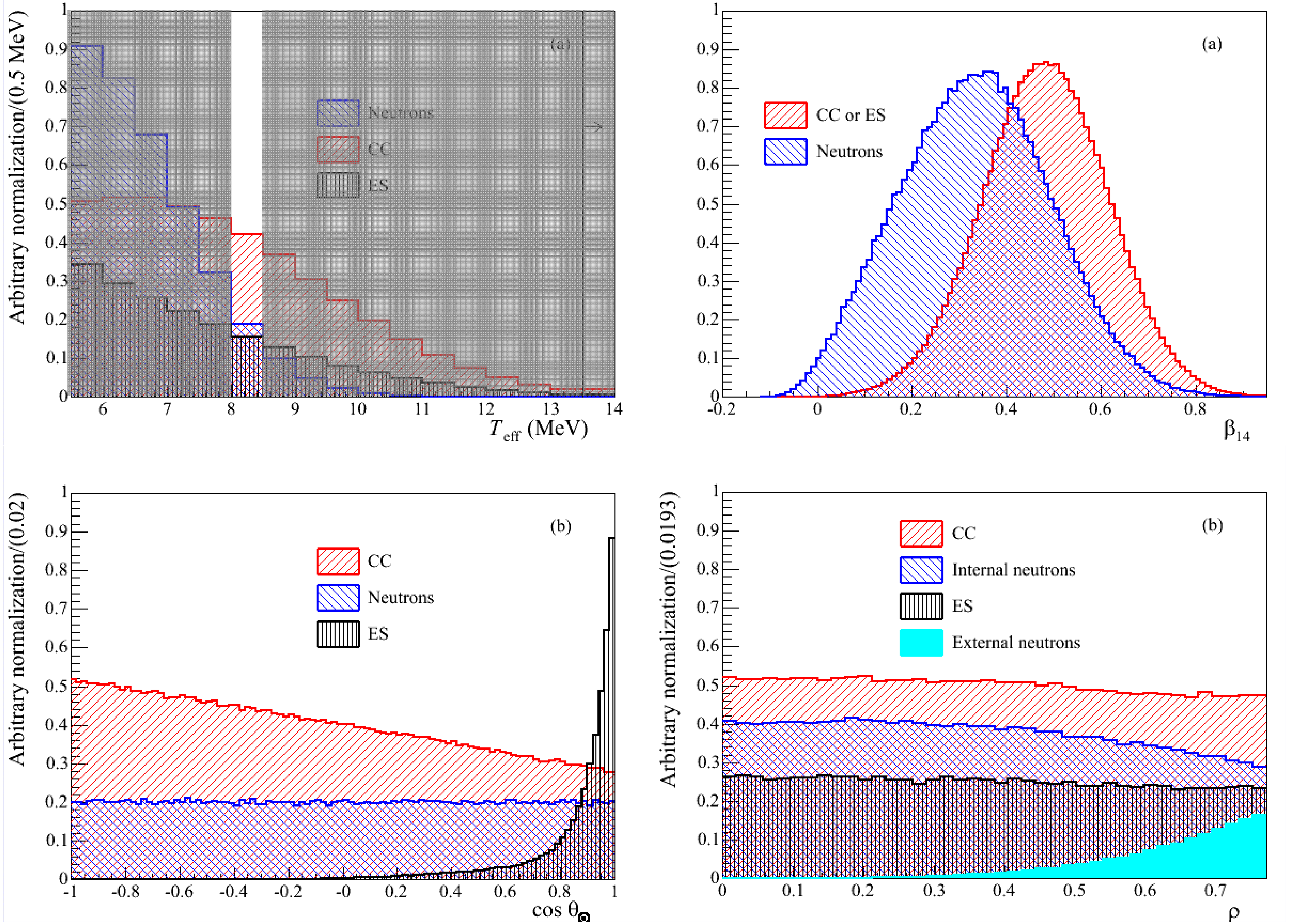


Difference

Event Isotropy

NC vs CC:

Extra handle on statistical separation of NC and CC events.



Arbitrary normalization/(0.5 MeV)
(a)
Neutrons
CC
ES
T_{eff} (MeV)
(a)
CC or ES
Neutrons
β_{14}
Arbitrary normalization/(0.02)
(b)
CC
Neutrons
ES
cos $\theta_{\odot}$
Arbitrary normalization/(0.0193)
(b)
CC
Internal neutrons
ES
External neutrons
ρ

Results

391 days of salt data 4722 events

r<550cm T_{eff}>5.5MeV

(1D projections from multidim. fit)

Extracted Events:

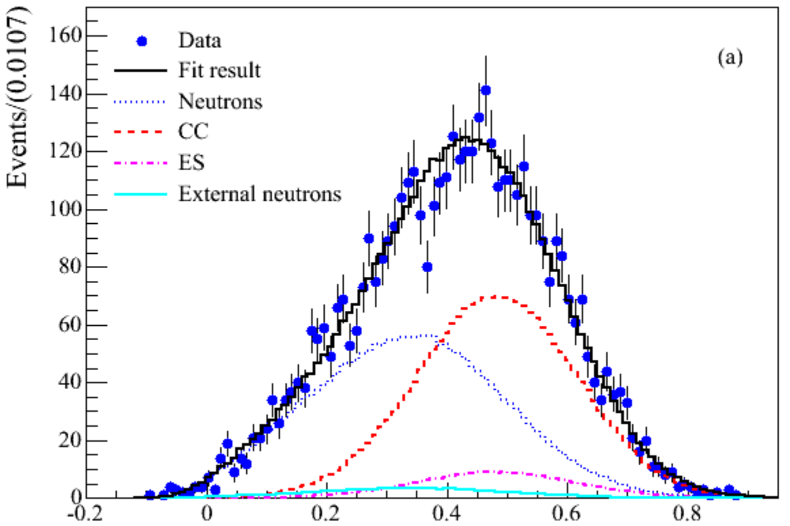
CC: 2176 ± 78

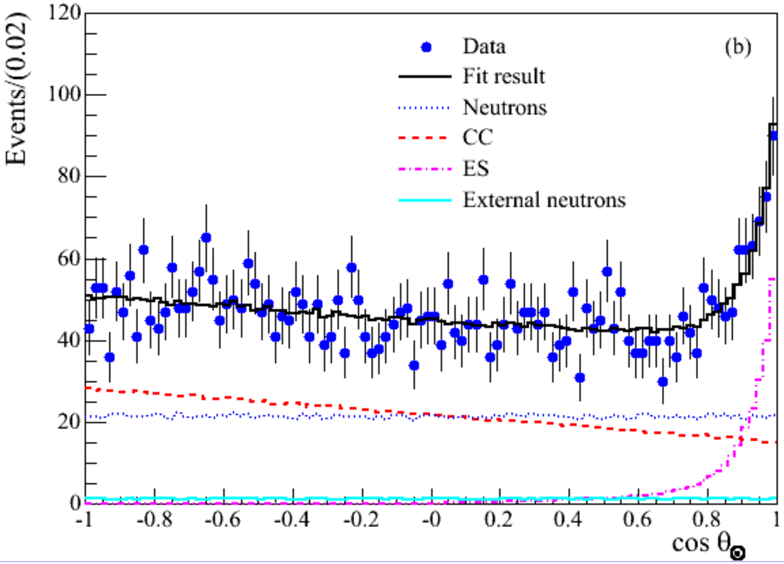
NC: 2010 ± 85

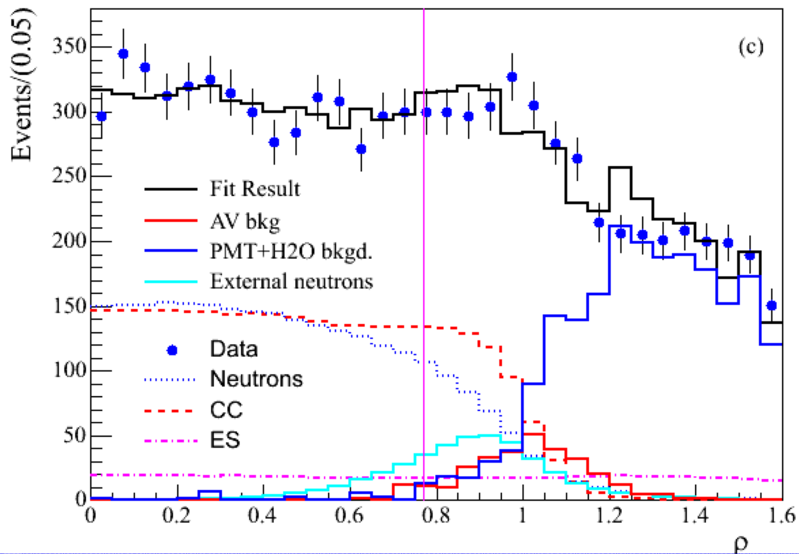
ES: 279 ± 26

External neutrons: 129 ± 42

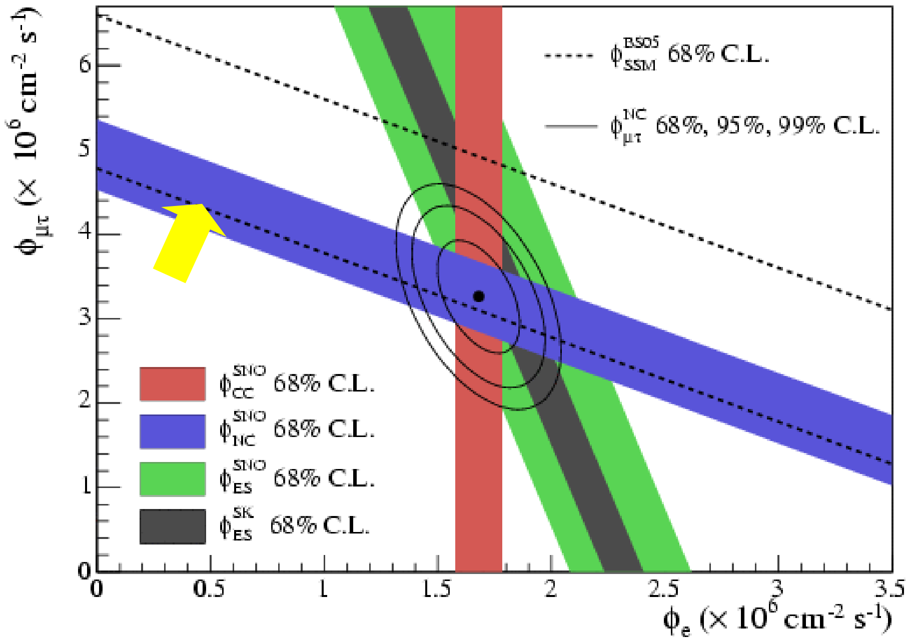
Internal neutrons: 125 (fixed)







Flux Interpretation



$$\phi_{NC} = \left(4.94 \pm 0.21(\text{stat.})^{+0.38}_{-0.34}\right)\times 10^5 \text{ cm}^{-2}\text{s}^{-1}$$

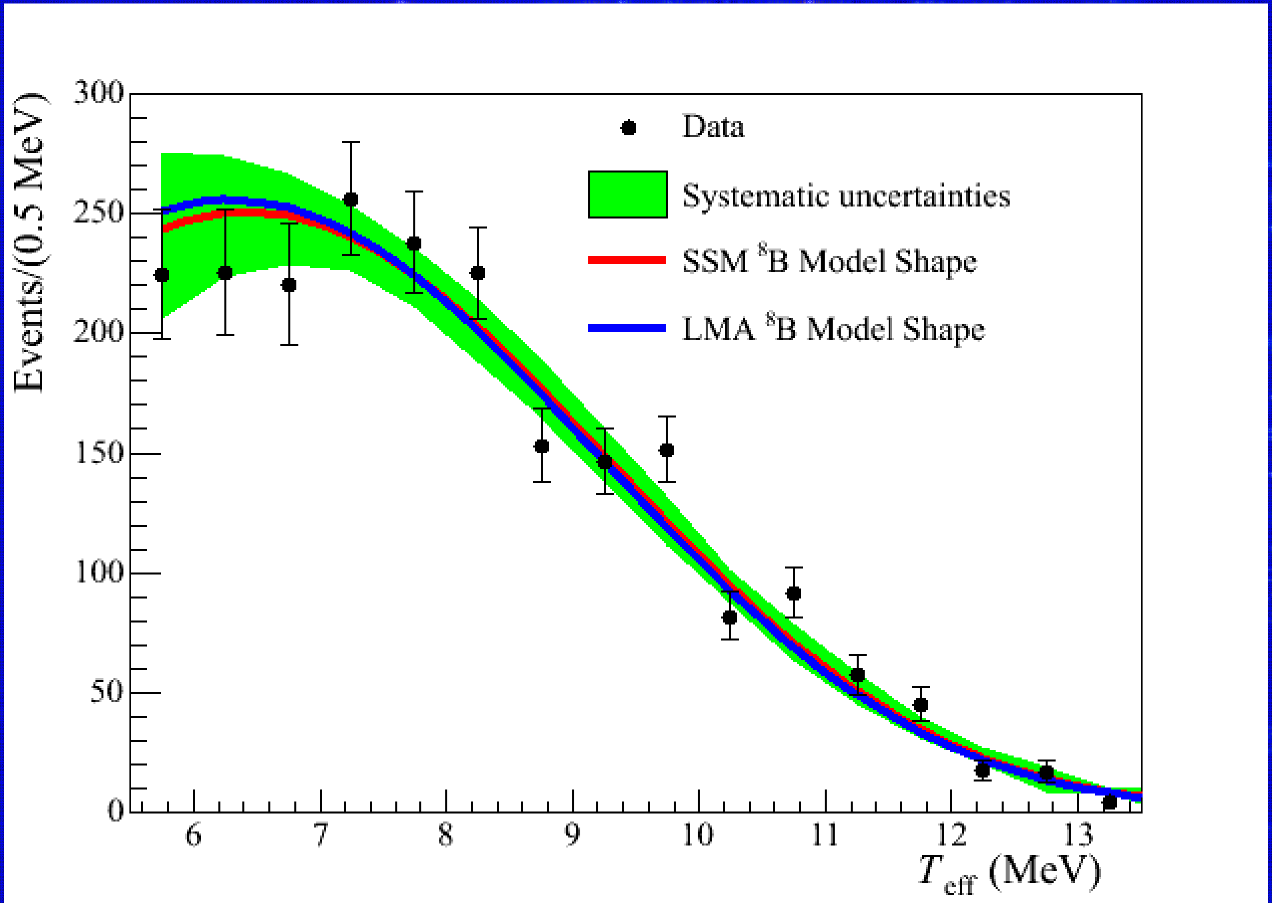
Agrees with SSM

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

Agrees with Davis' measurement

nucl-ex/0502021 (25 Feb 2005), submitted to Phys. Rev. C
Electron Energy Spectra, Fluxes, and Day-Night Asymmetries of ^{8}B Solar Neutrinos from the 391-Day Salt Phase SNO Data Set 45 pages, 49 figures in 36 eps files

CC spectrum



CC spectrum consistent with LMA, undistorted ^{8}B

Day-night analysis

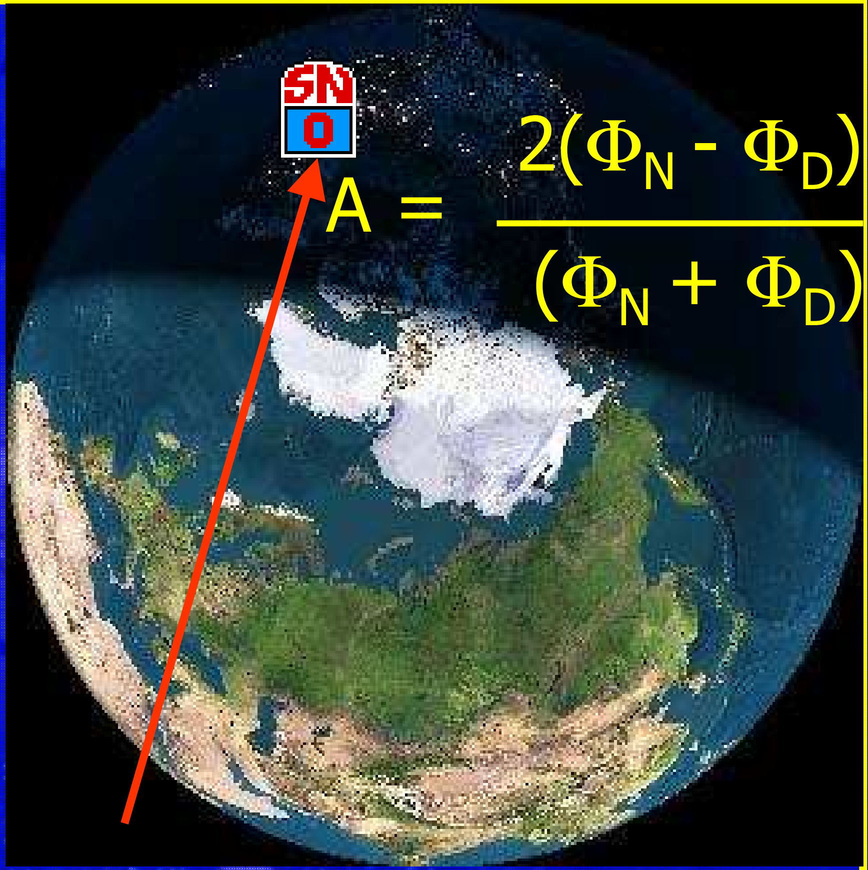
- CC,ES asymmetry:

ν_e regeneration inside the Earth

- NC asymmetry:

Admixture of sterile neutrinos
or unexpected matter
interactions inside the Earth

LMA:
small A_{CC}, A_{ES} & $A_{NC} = 0$



$$A = \frac{2(\Phi_N - \Phi_D)}{(\Phi_N + \Phi_D)}$$

Combined with D2O phase and SK:

$A_e = 0.035 \pm 0.027^*$

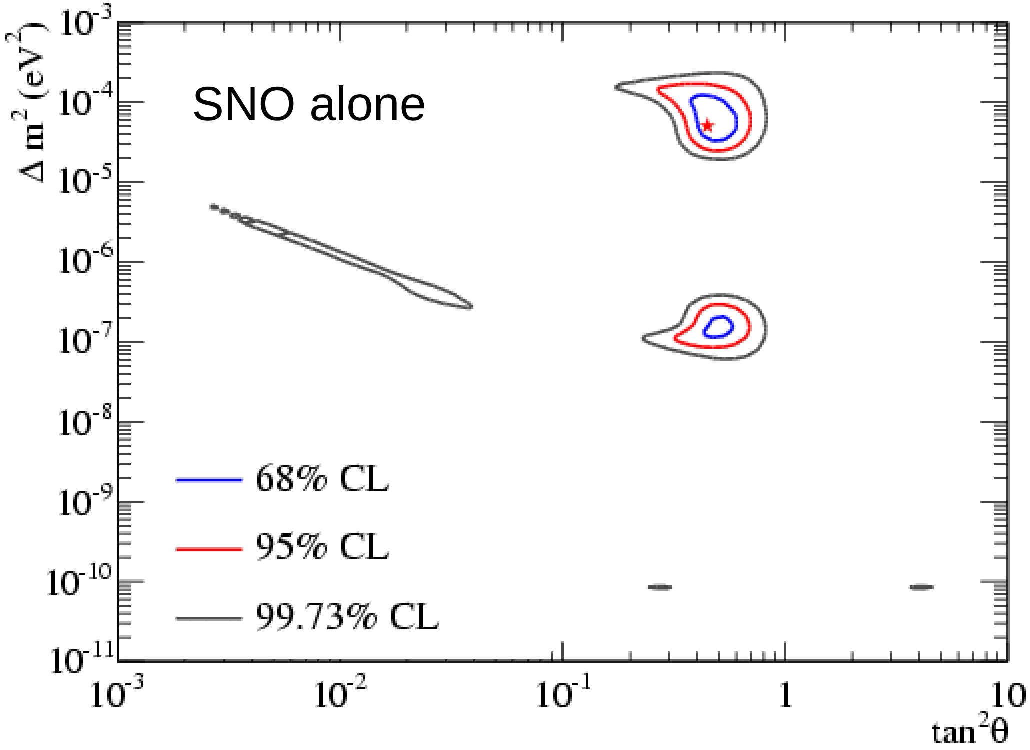
(*NC=0, shape constr.)

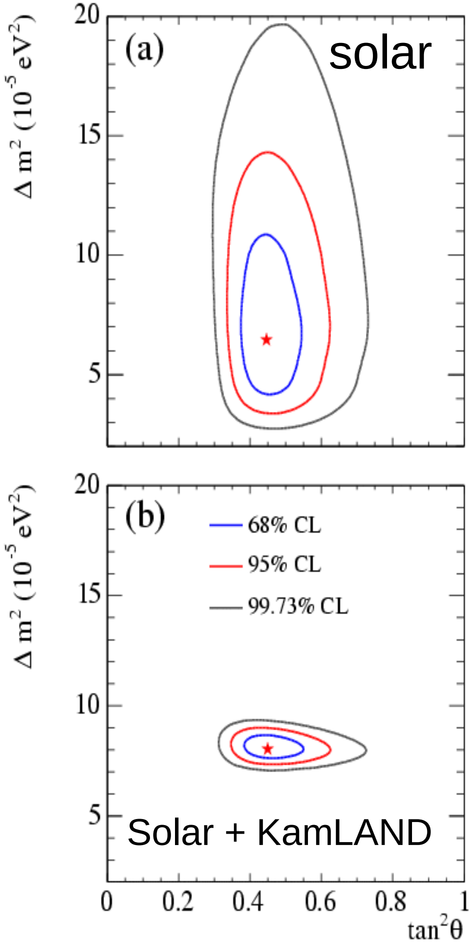
Oscillation interpretation

$P(\nu_e \rightarrow \nu_e) = 1 - \sin^2(2\theta)\,\sin^2(\Delta m^2 L / E)$

a) $\Delta m^2 = 6.5^{+4.4}_{-2.3} \times 10^{-5}\,\mathrm{eV}^2, \quad \tan^2\theta = 0.45^{+0.09}_{-0.08}$

b) $\Delta m^2 = 8.0^{+0.6}_{-0.4} \times 10^{-5}\,\mathrm{eV}^2, \quad \tan^2\theta = 0.45^{+0.09}_{-0.07}$





Other SNO results thus far

- **"Electron antineutrino search at the Sudbury Neutrino Observatory" Phys. Rev. D 70, 093014 (2004)**

  Upper limit consistent with KamLAND, extended energy region

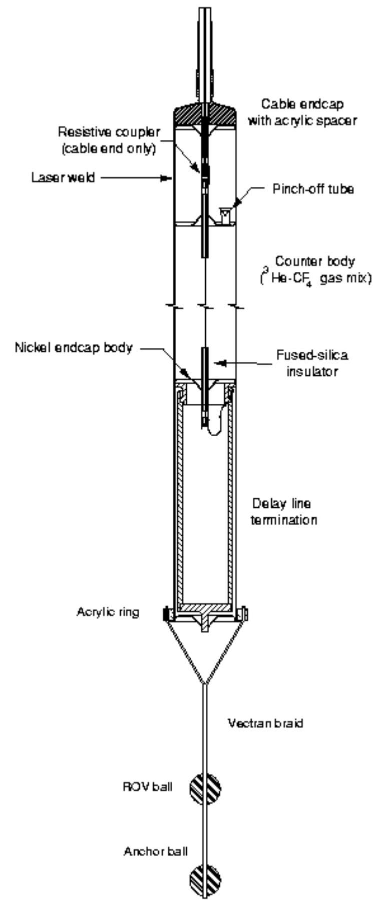
- **"Search for periodicities in the ^{8}B solar neutrino flux measured by the Sudbury Neutrino Observatory" Phys. Rev. D 72 052010 (2005)**

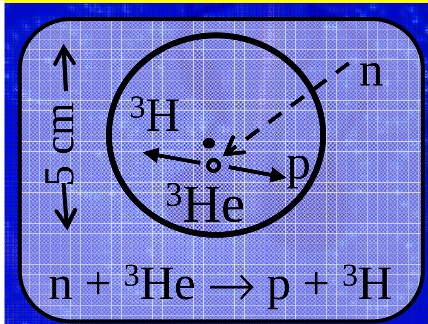
  No significant ($\geq$ 8% variation) sinusoidal periodicities found with periods between 1 day-10 years .

- **"A search for Neutrinos from the Solar hep Reaction and the diffuse Supernova background with the Sudbury Neutrino Observatory" ApJ 653 1545 (2006)**

  HEP: $14.3 < E\ (MeV) < 20$: upper limit of $2.3 \times 10^{4}\ cm^{-2}s^{-1}$ (90%CL)
  DSNB: $22.9 < E\ (MeV) < 36.9$: upper limit of $70\ cm^{-2}s^{-1}$ (90%CL)

The Neutral Current Detection array

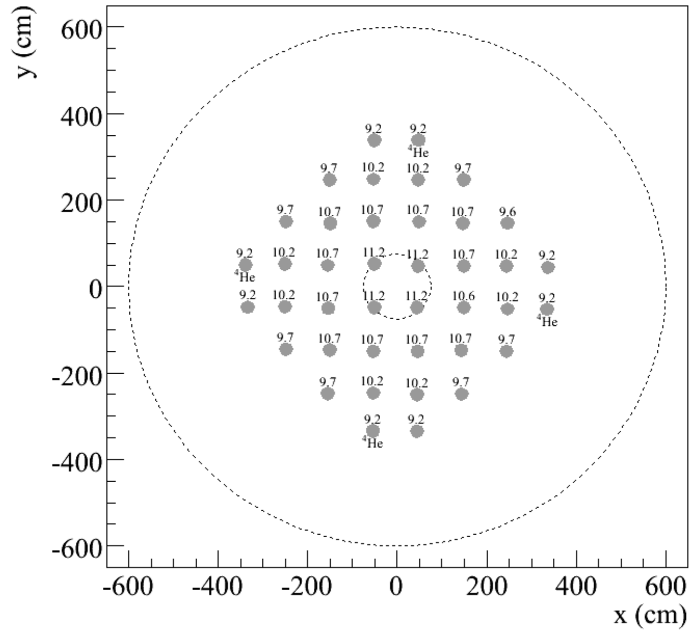




n captures on ^{3}He prop. counter array

$\sigma = 5330b$

0.764 MeV



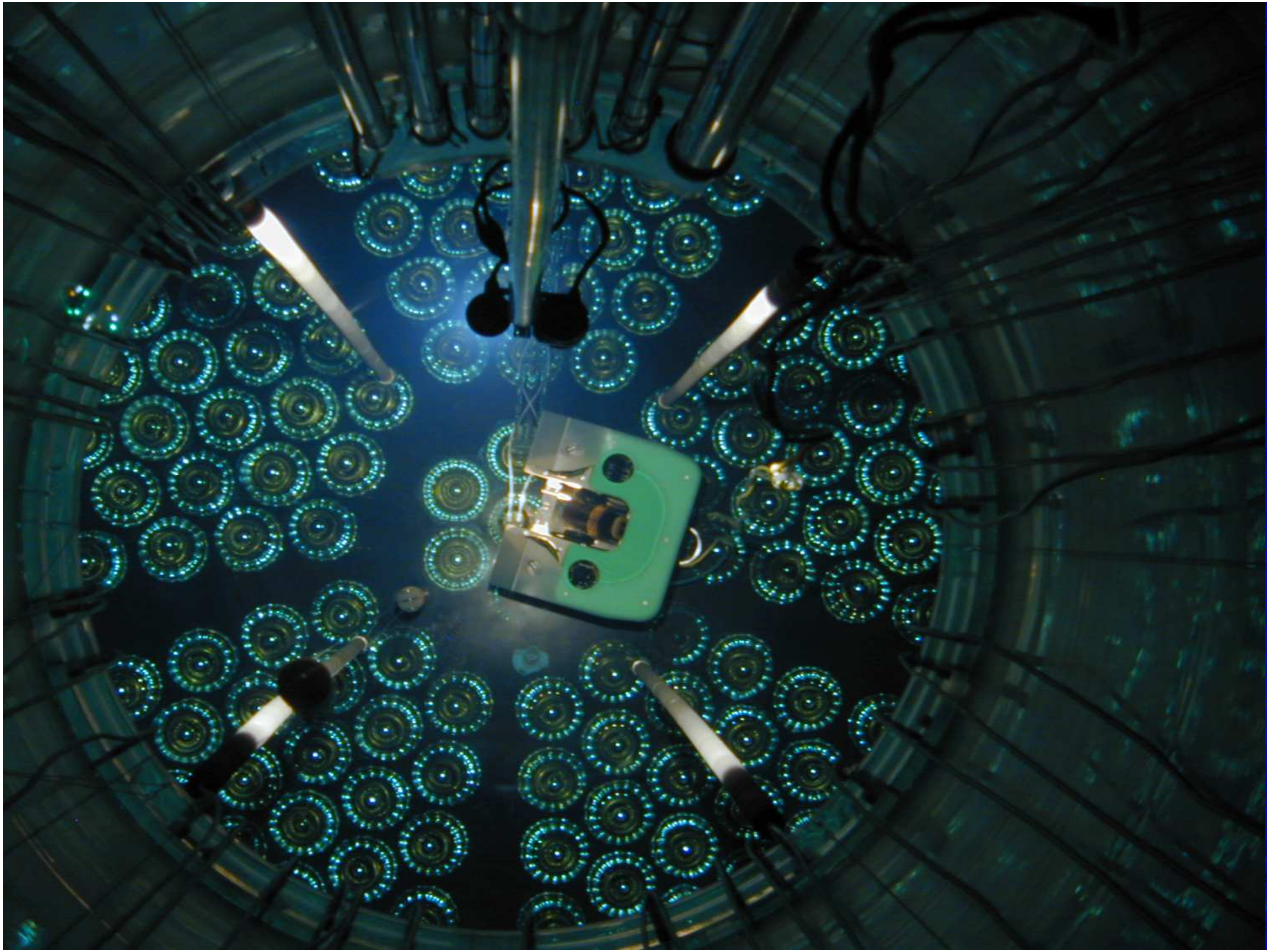
Geometry trade-off:

~8% light loss in centre vs ~ 26% capt. eff.

Extremely low background (nickel!):

~4 alphas m^{-2} day^{-1} (total ~22 day^{-1})

No more spherical geometry: calibration!



The End of SNO

November 2006: data taking stopped

D_2O is carefully being removed

(expected to take ~ 1 year)

Analysis of NCD phase data is ongoing.

Combined analysis of different phases.