From Anomaly to Problem to Physics: Lessons from Solar Neutrinos

- Overview
- Some Pre-History
- The Development of the `Problem'
- The Solution(s)
- What's Next

SLAC Summer Institute 2022
"Puzzles and Surprises, Past & Future"

Joshua R Klein
University of Pennsylvania

A Familiar Story

Scientists disbelieved….

A Familiar Story

…until it was too late.

~35 Years

Why so long?

Plenty of good reasons!

But also plenty of bad ones.

Not to mention:

Ambiguity Principle:

~35 Years

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But also plenty of bad ones.

Not to mention:

<u>Ambiguity Principle:</u> For any given experimental test of a hypothesis, Nature will always strive to return the most ambiguous answer possible.

~35 Years

What it wasn't:

A chaotic period in which many results did not make sense until some unifying theory or measurement provided clarity.

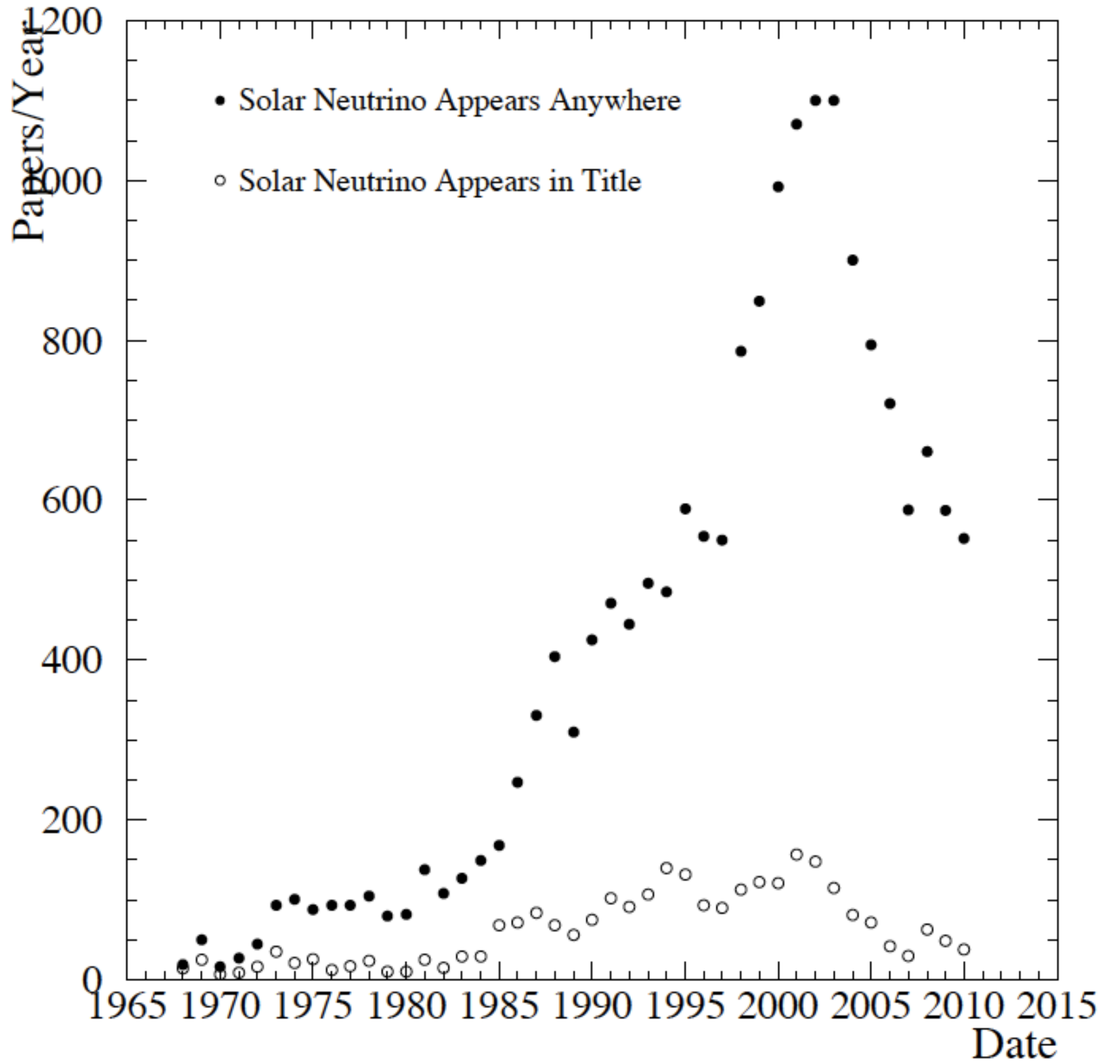
What it was:

A long, slow, slog in which each new piece—experimental and theoretical--fell into place, with an accompanying marginal increase in `degree-of-belief.'

Far more `evolution' than `revolution'

~35 Years

No really good metric….



~35 Years

The cartoon version:

- 1964: Bahcall convinces Davis to publish simultaneous papers suggesting a Chlorine-based experiment to test Bahcall's `Standard Solar Model' predictions.
- 1968: Davis publishes a flux of neutrinos 1/3 of Bahcall's predicted value. The Sun is broken! Neutrinos oscillate!
- ~20 years pass. Davis continues dutifully cooking his chlorine. Bahcall becomes the party guest who stays too late.
- 1989: Kamiokande II publish the first `realtime' solar neutrino detection, correlated with the Sun's position. But their results disagree with Davis's.
- 1990s: Gallium experiments publish initially confusing results, then show a deficit.
- 1998: Super-K sees clear evidence of oscillations in atmospheric neutrinos.
- 2001-2: SNO unambiguously sees neutral current `appearance' of oscillated neutrinos.
- 2002: KamLAND puts the final nail in the coffin by observing disappearance with a terrestrial source.

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Some Pre-History

1919: Eddington suggests solar fusion:

> A star is drawing on some vast reservoir of energy by means unknown to us. This reservoir can scarcely be other than the sub-atomic energy which, it is known, exists abundantly in all matter… The store is well-nigh inexhaustible, if only it could be tapped. There is sufficient [energy stored] in the Sun to maintain its output of heat for 15 billion years….

Some Pre-History

1938: Bethe and stellar energy generation

MARCH 1, 1939 PHYSICAL REVIEW VOLUME 55

Energy Production in Stars*

H. A. Bethe
Cornell University, Ithaca, New York

(Received September 7, 1938)

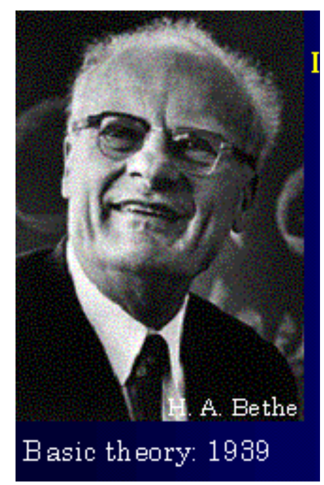
It is shown that the *most important source of energy in ordinary stars is the reactions of carbon and nitrogen with protons*. These reactions form a cycle in which the original nucleus is reproduced, *viz.* $C^{12}+H=N^{13}$, $N^{13}=C^{13}+\epsilon^+$, $C^{13}+H=N^{14}$, $N^{14}+H=O^{15}$, $O^{15}=N^{15}+\epsilon^+$, $N^{15}+H=C^{12}+He^4$. Thus carbon and nitrogen merely serve as catalysts for the combination of four protons (and two electrons) into an α-particle (§7). integration of the Eddington equations gives 19. For the brilliant star Y Cygni the corresponding figures are 30 and 32. This good agreement holds for all bright stars of the main sequence, but, of course, not for giants.

For fainter stars, with lower central temperatures, the reaction $H+H=D+\epsilon^+$ and the reactions following it, are believed to be mainly responsible for the energy production. (§10)

B^8

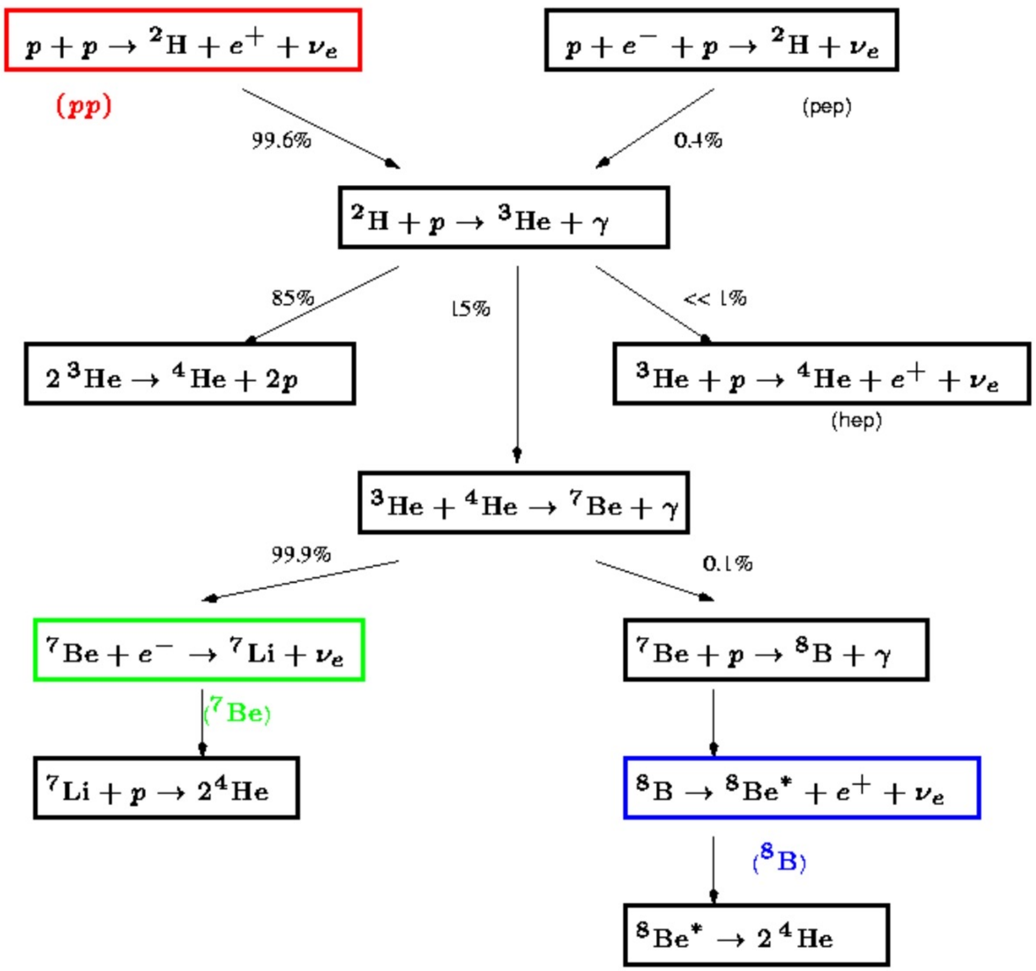
The existence is doubtful; calculation[21] by comparison with its isobar Li^8 gives a binding energy between -0.4 and $+0.4$ mMU. This nucleus is not very important for astrophysics.

Prof. Bethe will redeem himself nearly 50 years later…



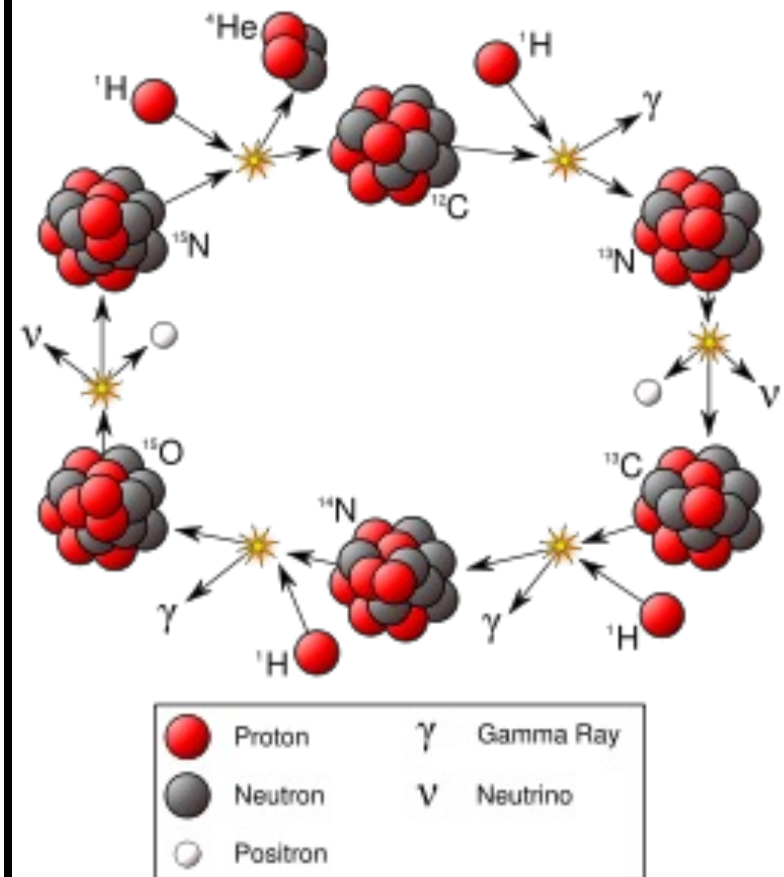
(The Modern View)

pp Chain

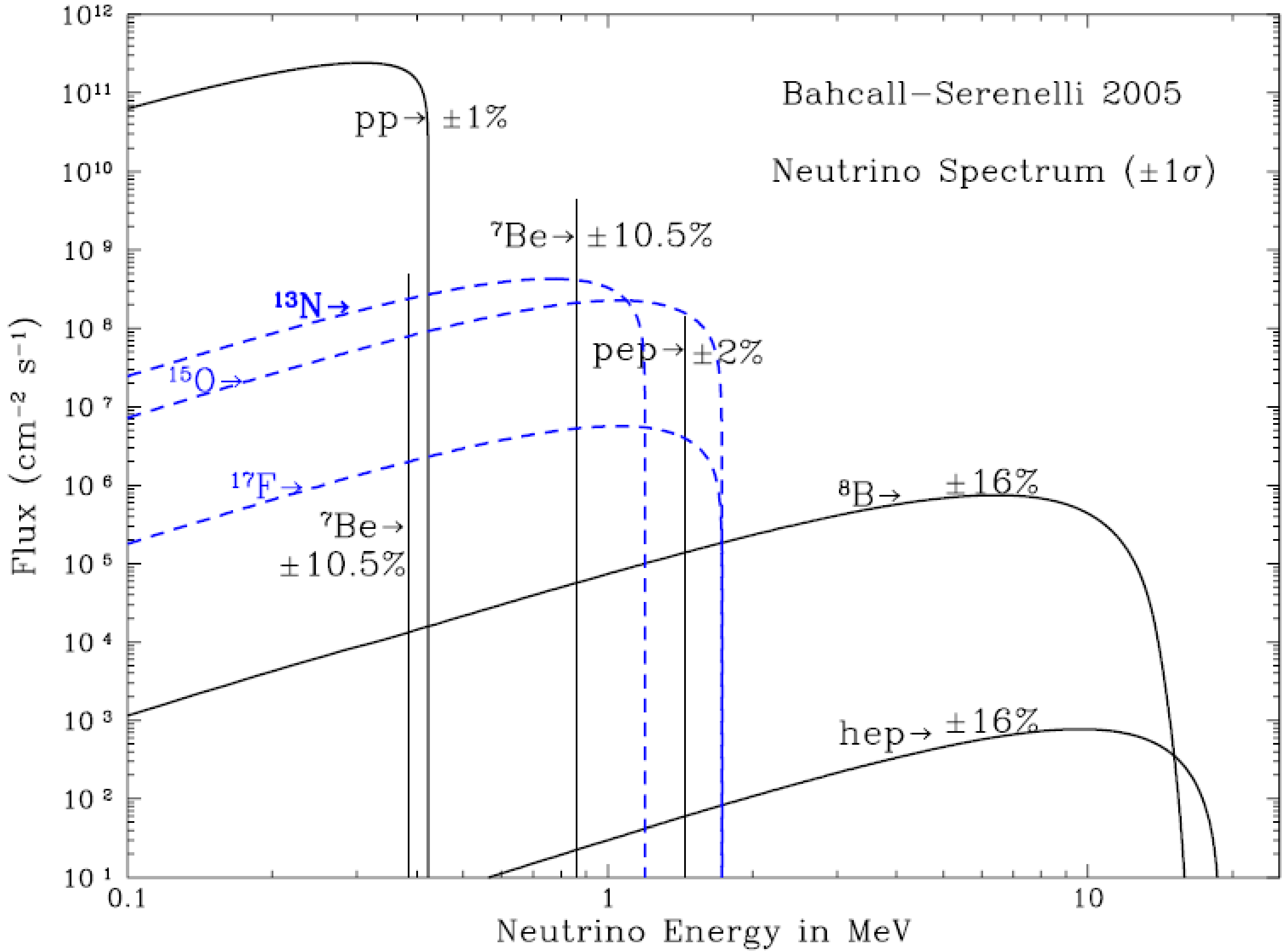


CNO Cycle

(contributes ~1% of solar energy)



(The Modern View)



Some Pre-History

1946: Pontecorvo suggests neutrino detection using Chlorine:

$$\nu_e + {}^{37}Cl \rightarrow e^- + {}^{37}Ar \qquad \text{(0.86 MeV threshold)}$$

Subsequent detection of the decay of ^{37}Ar with a ~35 day half-life

Suggests Sun as a neutrino source, but points out that the energy from pp and CNO neutrinos is too low. Suggests reactors instead.

(His paper is classified; fear is that it could be used to detect nuclear submarines…).

1949: Alvarez discusses the same idea, with details about background rejection.

Some Pre-History

1954-58: Davis tried Chlorine experiment with reactor and sets limits on solar flux…most sensitive neutrino experiment to date.

PHYSICAL REVIEW VOLUME 97, NUMBER 3 FEBRUARY 1, 1955

Attempt to Detect the Antineutrinos from a Nuclear Reactor by the $Cl^{37}(\bar{\nu},e^-)A^{37}$ Reaction*

RAYMOND DAVIS, JR.
Department of Chemistry, Brookhaven National Laboratory, Upton, Long Island, New York

(Received September 21, 1954)

Tanks containing 200 and 3900 liters of carbon tetrachloride were irradiated outside of the shield of the Brookhaven reactor in an attempt to induce the reaction $Cl^{37}(\bar{\nu},e^-)A^{37}$ with fission product antineutrinos. The experiments serve to place an upper limit on the antineutrino capture cross section for the reaction of 2×10^{-42} cm² per atom. Cosmic-ray-induced A^{37} was observed and the production rate measured at 14 100 feet altitude and sea level. Measurements with the 3900-liter container shielded from cosmic rays with 19 feet of earth permit placing an upper limit on the neutrino flux from the sun.

$\phi_\nu < 1\times10^{14}$ /cm²-s assuming CNO neutrinos

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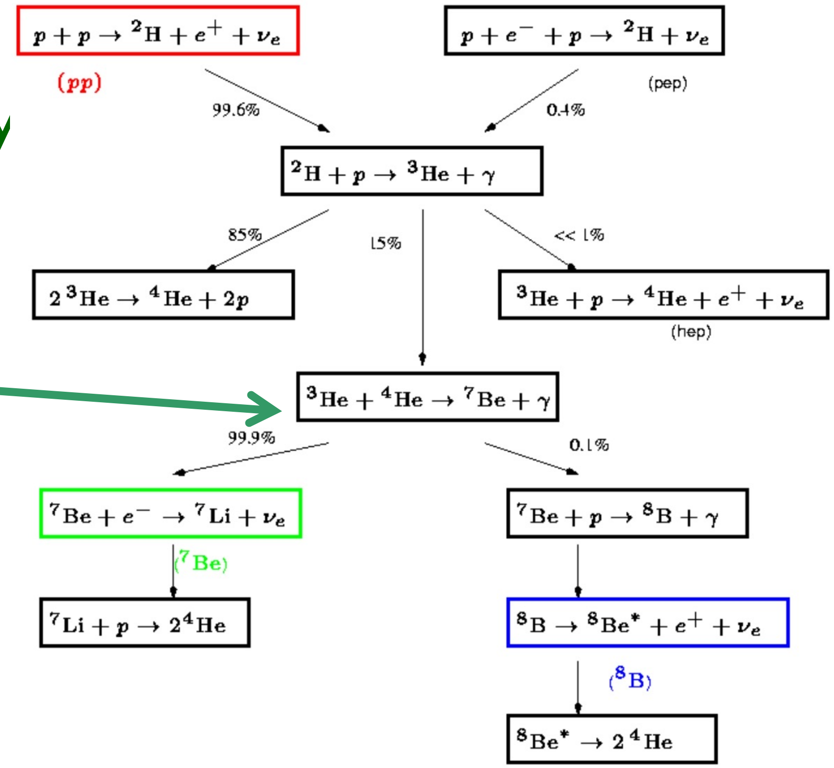
Referee comment:

Any experiment such as this, which does not have the requisite sensitivity, really has no bearing on the question of the existence of neutrinos. To illustrate my point, one would not write a scientific paper describing an experiment in which an experimenter stood on a mountain and reached for the moon, and concluded that the moon was more than eight feet from the top of the mountain.

Some Pre-History

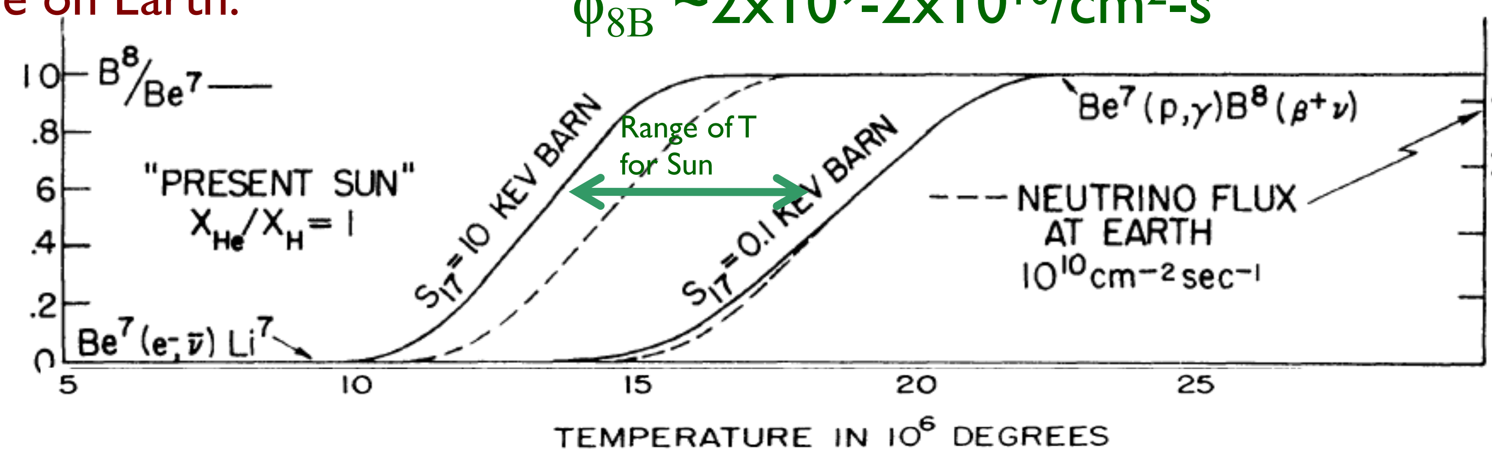
1958

Breakthrough: Holmgren and Johnston measure a surprisingly large value for the ^{3}He+^{4}He reaction creating ^{7}Be:



Fowler, Cameron independently point out that this means `high-energy' (14 MeV endpoint) ^{8}B νs are produced in the Sun and possibly detectable on Earth:

ϕ_{8B} ~2x10^9-2x10^{10}/cm^2-s



The Twin Papers

VOLUME 12, NUMBER 11 PHYSICAL REVIEW LETTERS 16 MARCH 1964

SOLAR NEUTRINOS. I. THEORETICAL*

John N. Bahcall
California Institute of Technology, Pasadena, California
(Received 6 January 1964)

SOLAR NEUTRINOS. II. EXPERIMENTAL*

Raymond Davis, Jr.
Chemistry Department, Brookhaven National Laboratory, Upton, New York
(Received 6 January 1964)

What was new here?

1. Bahcall re-calculates cross section on chlorine---18 times larger for ^{8}B νs than previously believed. ϕ_{8B}~$2.5\text{x}10^{7}$/cm^{2}-s, based primarily on models of other authors.
2. The goal is an explicit, unambiguous test of the solar fusion hypothesis:

   the tar. Only neutrinos, with their extremely small interaction cross sections, can enable us to see into the interior of a star and thus verify directly the hypothesis of nuclear energy generation in stars.

3. Davis's earlier limits used to limit central core temp.

The Experiment

Goldhaber convinced at Brookhaven to move forward, perhaps because result would help prove "astrophysicists do not know what they're doing."

Particle physicist's view of astronomers, ca. 1964

Dodson, in negotiations with the AEC for funding, writes Fowler to ask,

"Why spend a substantial sum trying to measure something which is calculated with great confidence by nuclear astrophysicists - and who cares about confirming the central temperature of the sun anyway?"

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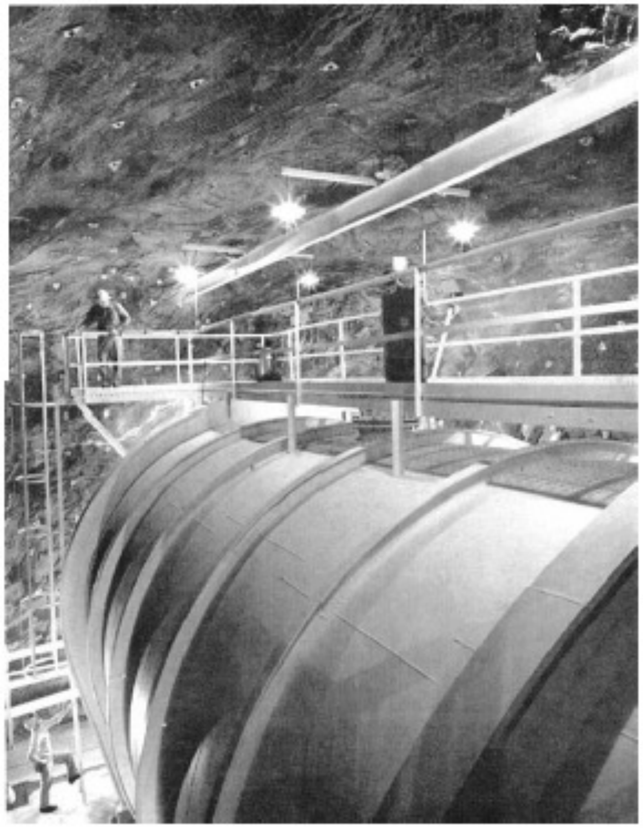
nuclear astrophysicists - and who cares about confirming the central temperature of the sun anyway?"

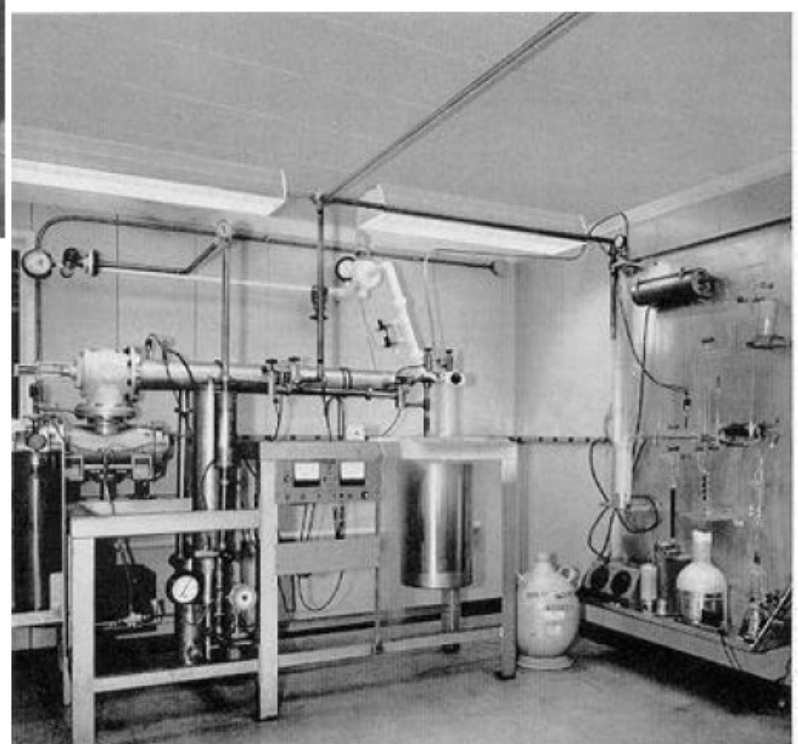
The Experiment

Nevertheless…



~600 tons of C_2Cl_4 at newly excavated cavity at 4850 ft level of Homestake.

$600k = $5.7M in 2022, before accounting for modern safety, project management, outreach center….



Davis:
"Just plumbing"

The Results

All counts consistent with cosmogenic and other backgrounds.

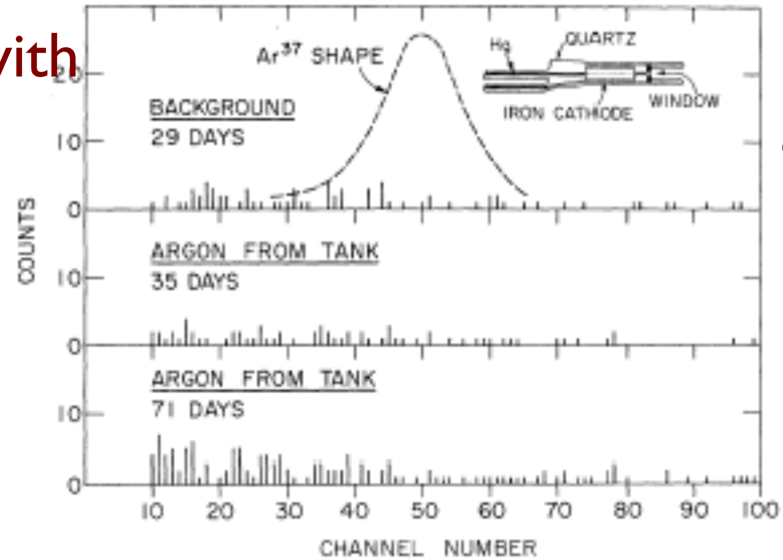


FIG. 2. Pulse-height spectra.

*PRL, **20**, 1205, (1968)*

The discovery of ν oscillations?

Gives limit on ^{8}B flux $\phi_{8B}<2\text{x}10^{6}/\text{cm}^{2}\text{-s}$

Bahcall, Bahcall, and Shaviv:
When accounting for uncertainties, "…not in obvious conflict with theory of stellar structure." Give best estimate of $\phi_{8B} = 4.7\text{x}10^{6}/\text{cm}^{2}\text{-s}$, with large uncertainties.

Is there a Problem Here?

"Nice try"?

A match between prediction and experiment required:

- That solar model neutrino predictions were correct.

Relied on many keV-energy nuclear physics cross sections, assumptions about the solar core, and made no other testable prediction than the neutrino flux.

Over 30 years, ϕ_{8B} went from 0 (Bethe) to 10^{10} (Fowler, Cameron) to 3×10^{7} (Sears) to 2×10^{7} (Bahcall) to 4.7×10^{6} (B,B,S) and scaled as $\sim T^{25}$.

- That Bahcall's cross section calculation was correct.

Did make prediction of ^{37}Ca state that was later discovered, but no other way of measuring this.

- That Davis and collaborators could possibly do what they claimed.

Is there a Problem Here?

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A match between prediction and experiment required: □

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✓ Believability tip: Don't base anything on anything that depends on *anything* to the 25^{th} power.

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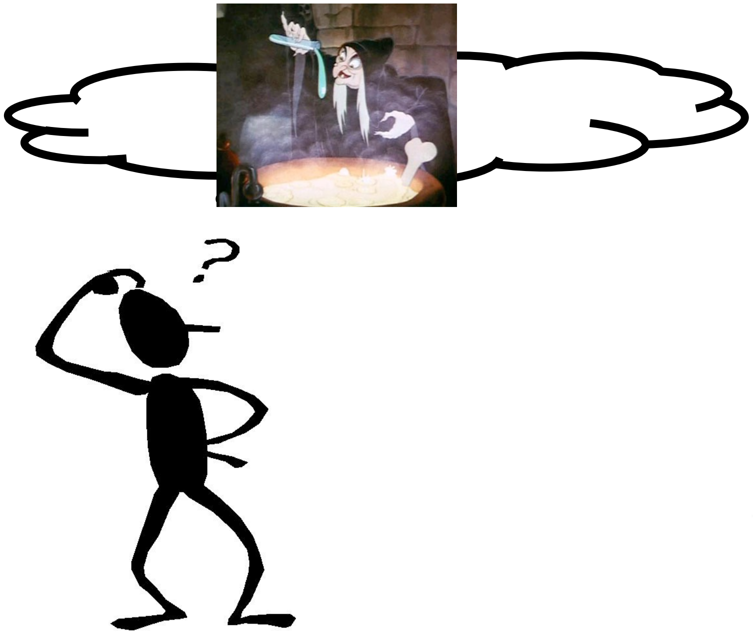
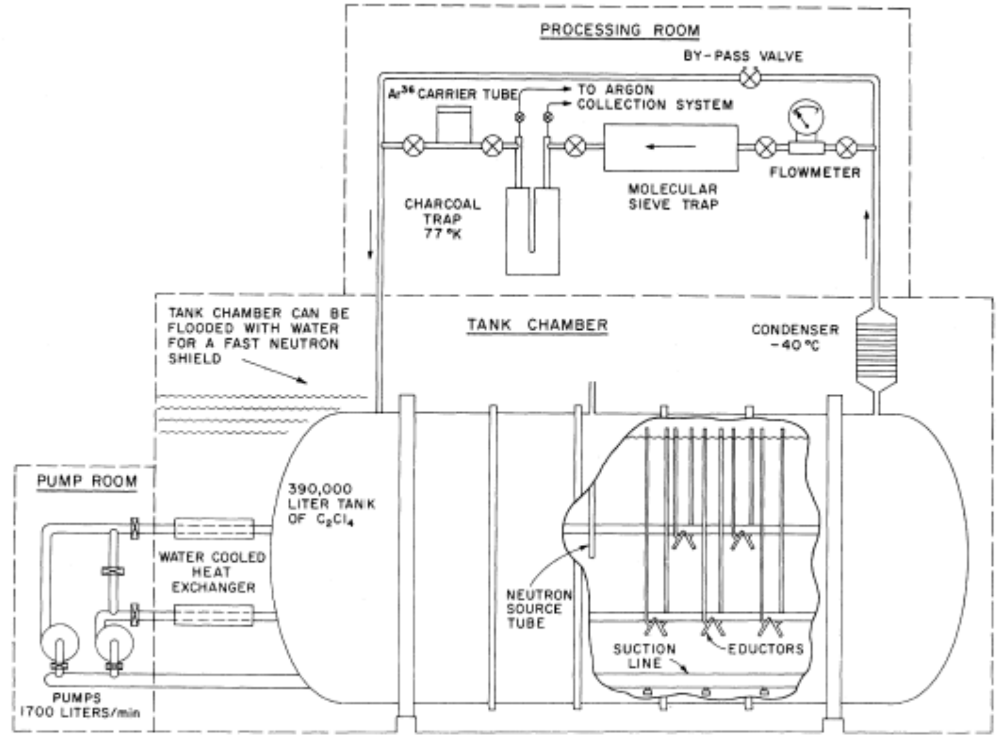
Is there a Problem Here?





To a physicist, Davis's method is incredibly complex, as he pulls the 12 atoms or so of ^{37}Ar from the 600 tons of fluid in each purge, and effectively shepherds them to his counters.

No events, no cuts, no simulation, no fit to anything.

But: a serious effort to determine efficiencies is described.

Is there a Problem Here?

Yet Davis never publishes a Cl result again in PRL or PR.
30 years pass before any results from the experiment again published in a refereed journal (ApJ). First non-zero value was in a proceedings, first significant observation in an APS Bulletin→basis for the Nobel Prize.

MU – 52 *Proc. 11th Int. Conf. on Cosmic Rays, Budapest 1969*

A PROGRESS REPORT
ON THE BROOKHAVEN SOLAR NEUTRINO EXPERIMENT

R. Davis, Jr.

Brookhaven National Laboratory, Upton, New York 11973, U.S.A.

The present report gives the results of an experimental search for neutrino radiation from the sun, using the neutrino capture reaction: $Cl^{37}(\nu, e^-)Ar^{37}$. The number of Ar^{37} decays gives a neutrino capture rate $(2.5 \pm 1.4) \times 10^{-36}$ sec^{-1} per terrestrial Cl^{37} atom confirming the upper limit 3×10^{-36} sec^{-1} previously reported.

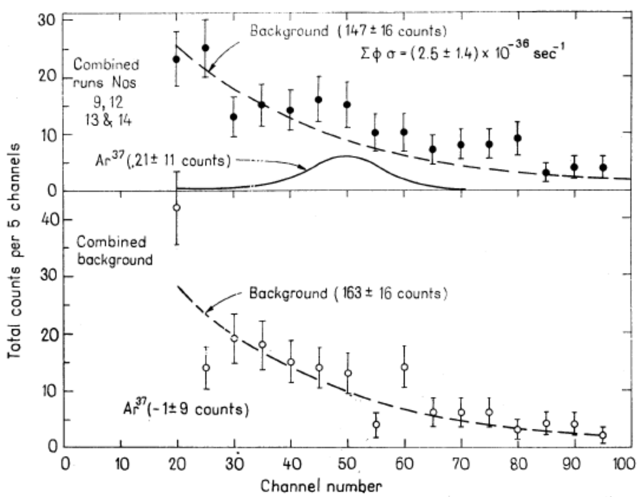


Fig. 2. The sum of counts in each five channels

Monitor

New Scientist, 1971

The first observation of neutrinos from the Sun

After four years of effort, Raymond Davis, Jr., and his colleagues from Brookhaven National Laboratory have finally detected neutrinos which originate from the centre of the Sun. All previous measurements on the Sun give us information about its surface only. The Sun's interior is only accessible through neutrino measurements. Latest results from the Brookhaven experiment are the first direct evidence that nuclear transmutations are the internal source of energy for the Sun (Bulletin of the American Physical Society, vol 16, p 631). measured all of the accessible reaction rates and can find no easy explanation there for the small discrepancy in the neutrino results. Yet Fowler is confident that nothing is grossly out of order.

One definite conclusion from Davis' results is the dominance of the proton-proton chain over the carbon-nitrogen cycle for solar energy. If the carbon-nitrogen cycle predominated in the Sun, the neutrino flux would have been 30 times the observed value. The neutrino experiment serves to confirm all of the terrestrial nuclear physics experiments and

✓ Believability tip: Present your biggest results in refereed journals, not proceedings, popular articles, or elevators.

Is there a Problem Here?

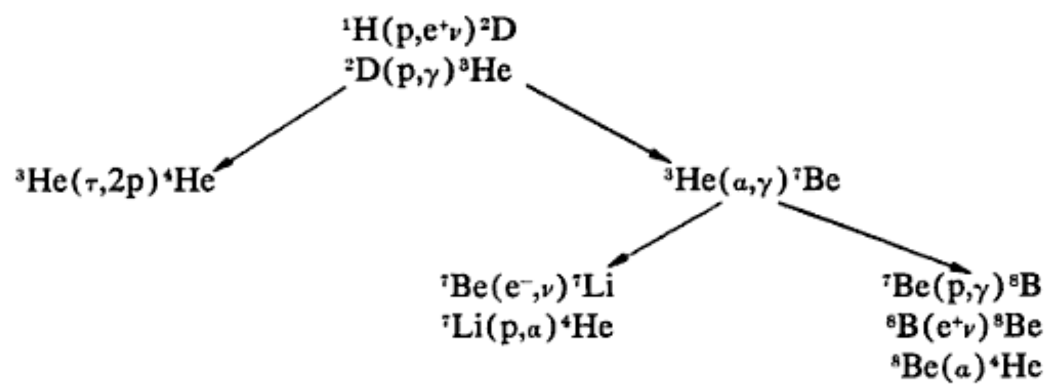
Some people were worried, even in the beginning.

New Uses for Low-Energy Accelerators

PREPARED BY
THE AD HOC PANEL ON
NEW USES FOR LOW-ENERGY ACCELERATORS
OF THE COMMITTEE ON NUCLEAR SCIENCE
NATIONAL RESEARCH COUNCIL

National Academy of Sciences
Washington, D.C.
1968

The chains of reactions which convert hydrogen into helium[11] are the most thoroughly studied set in nuclear astrophysics.[21,22] However, the field is still not closed, and a number of problems remain open. Of these, undoubtedly the most serious one involves the lack of high-energy solar neutrinos[20] with observed flux $\lesssim 2\times10^6/\mathrm{cm}^2/\mathrm{sec}$ at the earth and the predicted flux[23] $\approx 5\times10^6/\mathrm{cm}^2/\mathrm{sec}$. The predicted neutrinos come predominantly from the beta decay of ^{8}B to ^{8}Be after the ^{8}B has been formed as part of the proton–proton chain.



The rates of essentially all the important nuclear reactions involved directly in this problem have been measured "reliably" and independently checked with fair to good agreement, e.g.,

^{3}He(τ,2p)^{4}He	Winkler and Dwarakanath[8] and Bacher and Tombrello[7]
^{3}He(α,γ)^{7}Be	Parker and Kavanagh[24] and Nagatani *et al.*[25]
^{7}Be(p,γ)^{8}B	Parker[26] and Vaughn *et al.*[27]

However, particularly in this case involving the solar neutrino problem,

Perhaps first use of the term `solar neutrino problem' in print.

Is there a Problem Here?

A `flurry' of papers---about seven in 4 years, three from Bahcall---suggest possible `solutions', among them is Gribov and Pontecorvo's suggestion of neutrino oscillations.

NEUTRINO ASTRONOMY AND LEPTON CHARGE

V. GRIBOV * and B. PONTECORVO
Joint Institute for Nuclear Research, Dubna, USSR

Received 20 December 1968

It is shown that lepton nonconservation might lead to a decrease in the number of detectable solar neutrinos at the earth surface, because of $\nu_e \rightleftarrows \nu_\mu$ oscillations, similar to $K^0 \rightleftarrows \bar{K}^0$ oscillations. Equations are presented describing such oscillations for the case when there exist only four neutrino states.

"From the point of view of detection possibilities, an ideal object is the sun...Unfortunately, the weight of the various thermonuclear reactions in the sun, and the central temperature of the sun, are insufficiently well known in order to allow a useful comparison of expected and observed solar neutrinos, from the point of view of this article."

They effectively assume maximal mixing. In modern terms:

$$|\nu_e> = \cos\theta|\nu_1> + \sin\theta|\nu_2>$$
$$|\nu_\mu> = -\sin\theta|\nu_1> + \cos\theta|\nu_2>$$

$$\rightarrow P_{\upsilon_e\rightarrow\upsilon_e} = 1 - \sin^2 2\theta_{12} \sin^2\left(\frac{1.27\Delta m^2 L}{E}\right)$$

$$\text{For } \Delta m^2 >> E/L,\ P_{\upsilon_e\rightarrow\upsilon_e} \rightarrow \frac{1}{2}\sin^2 2\theta \text{ (`washed out')}$$

$$\text{For } \Delta m^2 << E/L,\ P_{\upsilon_e\rightarrow\upsilon_e} \rightarrow 1 \text{ (no sensitivity)}$$

Is there a Problem Here?

Also: ν magnetic moments (Cisneros), ν decay (Bahcall et al.), mixing of solar material (Ezer and Cameron), solar helium abudance (Iben), the solar cycle (Sheldon) and uncertainties on the now-named `Standard Solar Model' (Bahcall et al.).

Bahcall invents the SNU($=10^{-36}$ captures/target-s).

✓ Believability tip: Don't invent your own unit.

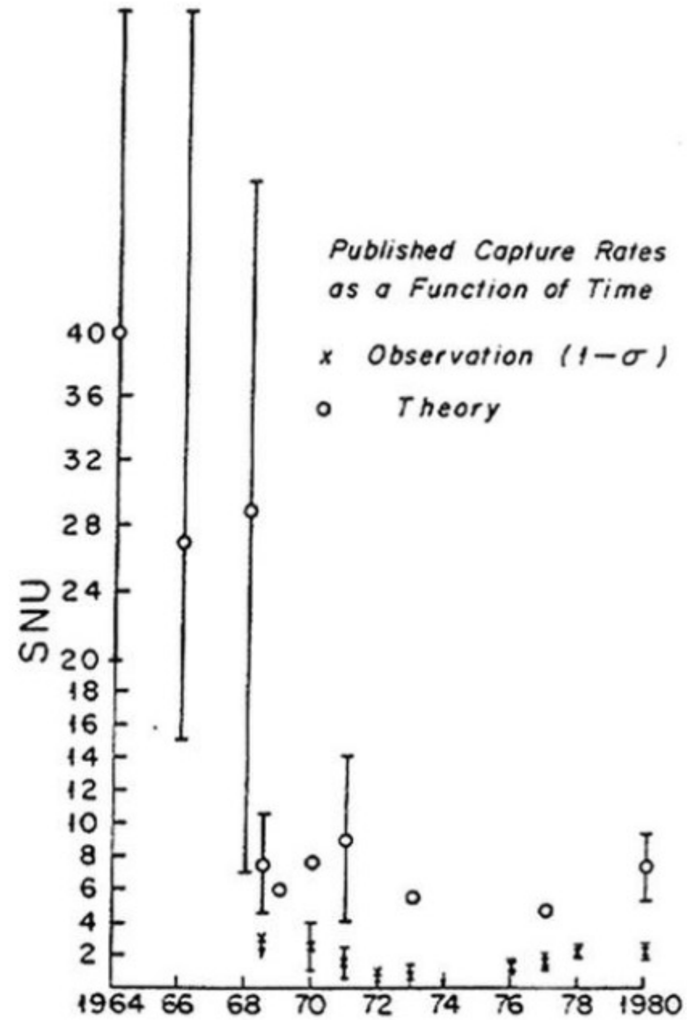
The Wilderness

New Scientist, 1971

The number of argon-37 decays recorded by the Brookhaven team averaged about 0.5 counts per day with a statistical uncertainty of 0.2 counts. They calculate a corrected solar neutrino capture rate per chlorine-37 atom of $(1.5 \pm 1.0) \times 10^{-36}$ per second. This is the first positive signal to emerge above the background. It can be compared with the current theoretical calculations of 10^{-35} per second. Although slightly low, the experimental result probably will not cause any serious problems.

measured all of the accessible reaction rates and can find no easy explanation there for the small discrepancy in the neutrino results. Yet Fowler is confident that nothing is grossly out of order.

More data from Cl, but no one plans to redo the experiment.



New experiments are suggested;
Davis's is the last solar ν experiment to ever run in the US.

The Wilderness

Occasionally, the honest feelings slip out:

NEUTRINO MOMENTS, MASSES AND CUSTODIAL SU(2) SYMMETRY *

Howard GEORGI and Michael LUKE

Lyman Laboratory of Physics, Harvard University, Cambridge, MA 02138, USA

1. The problem

Most likely, the solar neutrino problem [1] has nothing whatever to do with particle physics. It is a great triumph that astrophysicists are able to predict the number of B^8 neutrinos coming from the sun as well as they do, to within a factor of 2 or 3 [2]. However, one aspect of the so r neutrino data, the apparent

The Wilderness

Overheard in the Ludwig A. Wittgenstein Memorial Library:

The Wilderness

Overheard in the Ludwig A. Wittgenstein Memorial Library:

"Yeah, as if they know what is going on inside the Sun"
"Sounds like an `observational' problem to me"
"Like we're exactly the right distance from the Sun?"
"How do they even know they're from the Sun?
"Even so, the mixing angles have to be small, not large"
"Never believe a disappearance experiment"
"It's—it's—it's chemistry!"
"What do you expect? There's no calibration."

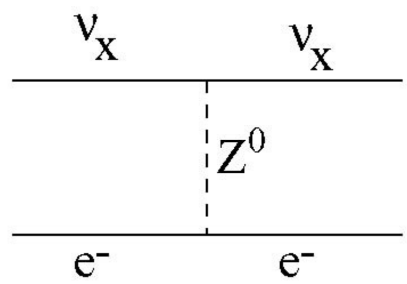
The less informed one was, the more likely to assume the entire thing was nonsense.

Theorists Help Out

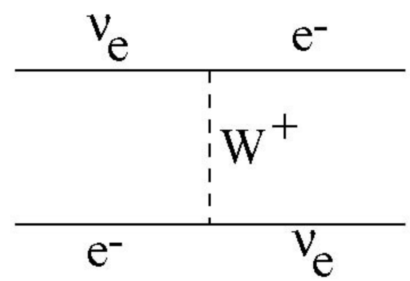
Oscillations in Matter (MSW Effect)

Wolfenstein (1978) points out birefringence of neutrinos within the Sun, from coherent forward scattering in ν_e CC reactions:

$\sigma(\nu_{\mu,\tau}) = 0.15\sigma(\nu_e)$



All neutrino flavors



Only electron neutrinos

$$< \nu_e | H_W | \nu_e > = \sqrt{2} G_F N_e$$

$$\tilde{H} = \tilde{H}_f + \tilde{H}_W$$

Bulk matter just treated as a potential term!

Theorists Help Out

Oscillations in Matter (MSW Effect)

If we calculate mixing matrix elements in flavor basis:

$$
\begin{aligned}
|\nu_1> &= \sin\theta|\nu_e> + \cos\theta|\nu_\mu> \\
|\nu_2> &= \cos\theta|\nu_e> - \sin\theta|\nu_\mu>
\end{aligned}
$$

$$
\begin{aligned}
<\nu_1|H|\nu_1> &= <\nu_1|H_f|\nu_1> + <\nu_1|H_W|\nu_e\cos\theta - \nu_\mu\sin\theta> \\
&= E_1 + \sqrt{2}G_f N_e\cos\theta
\end{aligned}
$$

$$
\imath\frac{\partial}{\partial t}\begin{pmatrix}\nu_e \\ \nu_\mu\end{pmatrix} = \begin{pmatrix}\sqrt{2}G_f N_e - \frac{\Delta m^2}{2p}\cos^2\theta & \frac{\Delta m^2}{4p}\sin 2\theta \\ \frac{\Delta m^2}{4p}\sin 2\theta & -\frac{\Delta m^2}{2p}\sin^2\theta\end{pmatrix}\begin{pmatrix}\nu_1 \\ \nu_2\end{pmatrix}
$$

Theorists Help Out

The Standard Scenario in Matter (MSW)

Hamiltonian matrix now has new `matter' eigenvalues and –vectors:

$$\imath \frac{\partial}{\partial t}\begin{pmatrix}\nu_e \\ \nu_\mu\end{pmatrix} = \begin{pmatrix}\sqrt{2}G_f N_e - \frac{\Delta m^2}{2p}\cos^2\theta & \frac{\Delta m^2}{4p}\sin 2\theta \\ \frac{\Delta m^2}{4p}\sin 2\theta & -\frac{\Delta m^2}{2p}\sin^2\theta\end{pmatrix}\begin{pmatrix}\nu_1 \\ \nu_2\end{pmatrix}$$

$$\begin{aligned}\nu_{1m} > &= \cos\theta_m|\nu_e > - \sin\theta_m|\nu_\mu > \\ \nu_{2m} > &= \sin\theta_m|\nu_e > + \cos\theta_m|\nu_\mu >\end{aligned}$$

Which evolve again as $P(E_{\nu_e}, x, \theta, \Delta m^2) = 1 - \sin^2\theta_m \sin^2\frac{\pi x}{L_m}$

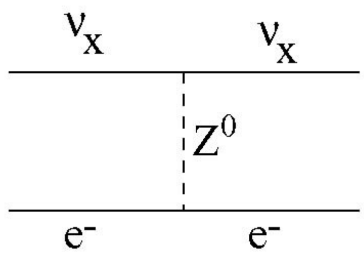
But with

$$\tan 2\theta_m = \frac{\frac{\Delta m^2}{2E}\sin 2\theta}{\frac{\Delta m^2}{2E}\cos 2\theta - \sqrt{2}\,G_F\,N_e}$$

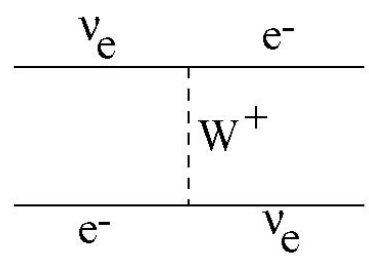
Depends on sign of Δm^2

Theorists Help Out

Conceptual Model

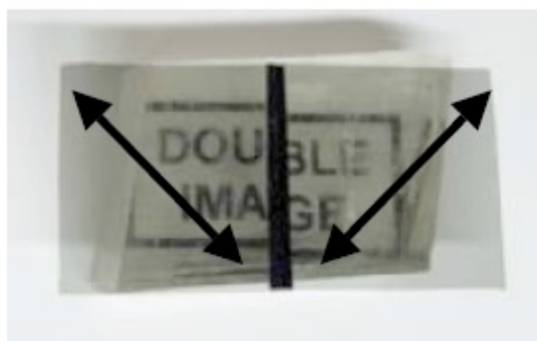


All neutrino flavors



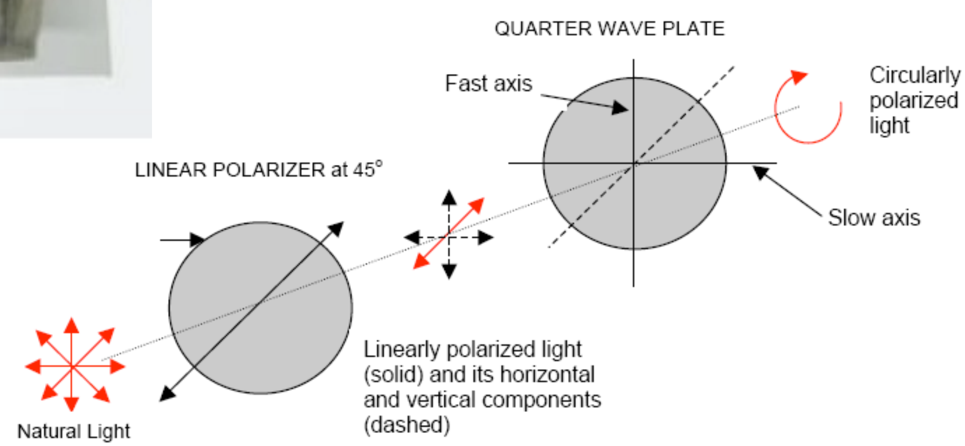
Only electron neutrinos

This makes the Sun birefringent to neutrinos!



Transformation probability can be much higher than vacuum oscillations alone

A ν_e turns into ν_2 like the way linearly polarized light becomes circular.



Theorists Help Out

Mixing angle and oscillation length in matter are different from vacuum:

$$\tan 2\theta_m = \frac{\frac{\Delta m^2}{2E}\sin 2\theta}{\frac{\Delta m^2}{2E}\cos 2\theta - \sqrt{2}\,G_F\,N_e} \qquad l_m = \frac{2\pi}{\sqrt{\left(\frac{\Delta m^2}{2E}\cos 2\theta - \sqrt{2}\,G_F\,N_e\right)^2 + \left(\frac{\Delta m^2}{2E}\right)^2 \sin^2 2\theta}}$$

But Wolfenstein concludes:

In general, if one is considering the possibility of large vacuum oscillation lengths, as in the discussion of solar neutrinos, the oscillations should be calculated for the actual vacuum path[16] ignoring the passage through matter. Thus, in the detailed solar neutrino calculations[10] the effective distance over which neutrino oscillations take place is from the solar surface to the earth's surface; there are no significant oscillations inside the sun or in traversals through the earth.

If you read just the abstract (about flavor-changing neutral currents) and the conclusion, you wouldn't have thought much more about the paper.

Theorists Help Out

Eight years later…Mikheyev and Smirnov point out that

$$\tan 2\theta_m = \frac{\frac{\Delta m^2}{2E}\sin 2\theta}{\frac{\Delta m^2}{2E}\cos 2\theta - \sqrt{2}\,G_F\,N_e}$$

Resonance when

$$\sqrt{2}G_f N_e - \frac{\Delta m^2}{2E}\cos 2\theta = 0$$

(Eight years? Really??)

MS point out that the resonance condition can be satisfied either by the broad energy spectrum, or by the varying matter density in the Sun.

Bethe publishes MS ideas in a PRL:

VOLUME 56, NUMBER 12 PHYSICAL REVIEW LETTERS 24 MARCH 1986

Possible Explanation of the Solar-Neutrino Puzzle

H. A. Bethe

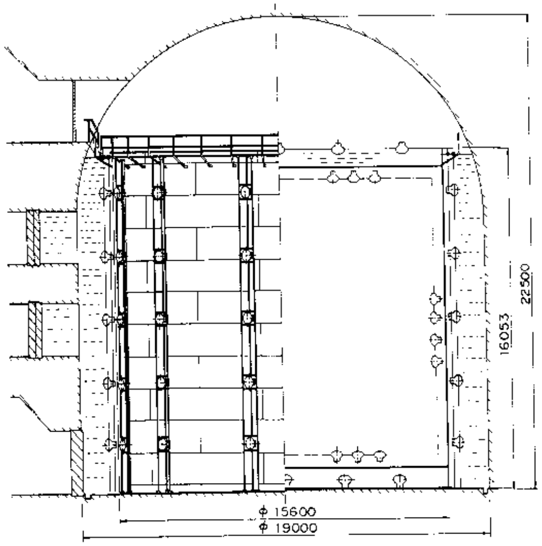
Biggest point perhaps that Langacker found a sign error carried over from one of W's papers that would have required $m_2 < m_1$. But maybe this was really just good P-R?

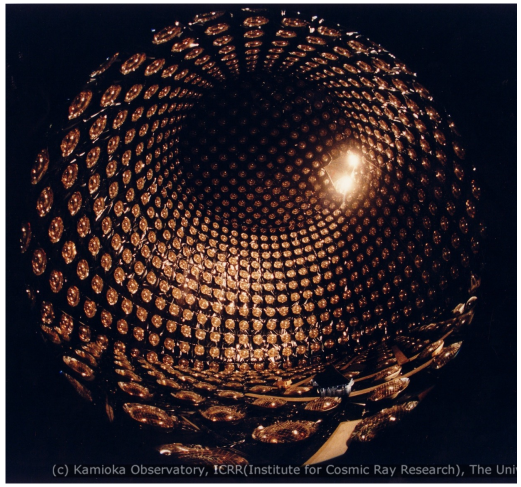
Theorists Help Out

Irony 1: The excitement over MSW was in large part because it provided a way to get large ν_e suppression out of small mixing angles.

Irony 2: The sign error pointed pointed out by Langacker reassured people that the MSW effect was a real possibility, because of course the hierarchy had to `look like' the charged leptons (i.e., `normal', not `inverted').

From Out of the East



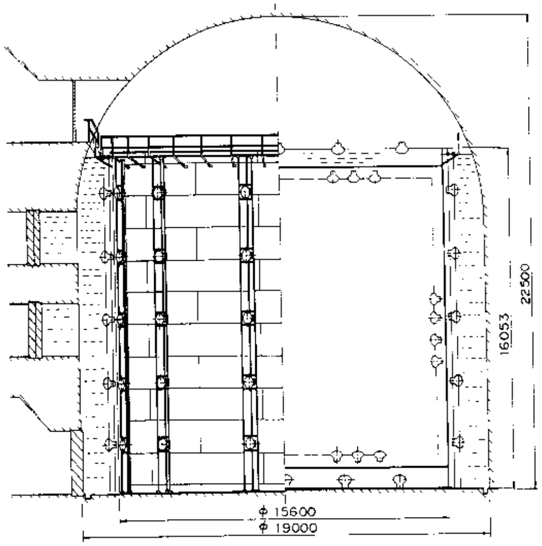


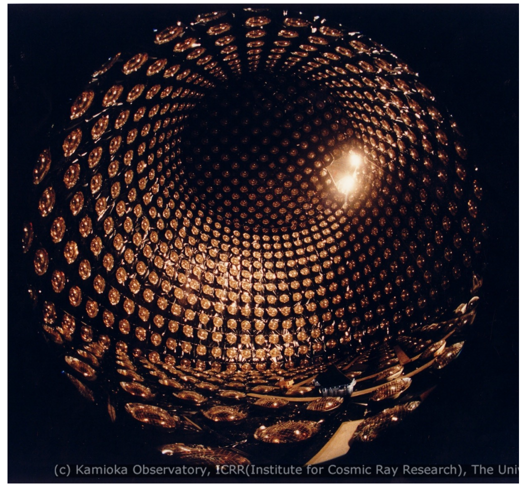
Kamiokande I designed with threshold of ~30 MeV, for a search for proton decay.

Penn group joined, upgraded electronics, for threshold <10 MeV, making detection of ^{8}B νs via $\upsilon + e \rightarrow \upsilon + e$ with Cherenkov light possible (Kamiokande II).

Beier:

From Out of the East





Kamiokande I designed with threshold of ~30 MeV, for a search for proton decay.

Penn group joined, upgraded electronics, for threshold <10 MeV, making detection of ^{8}B νs via $\upsilon + e \rightarrow \upsilon + e$ with Cherenkov light possible (Kamiokande II).

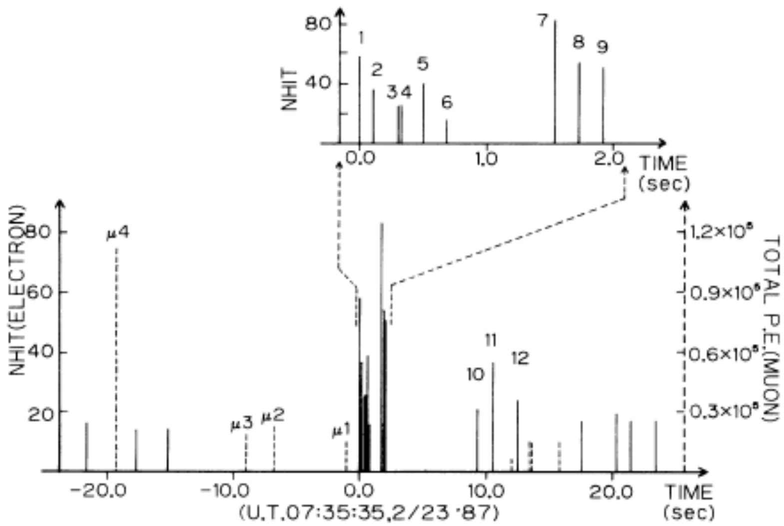
Beier: "Seemed interesting."

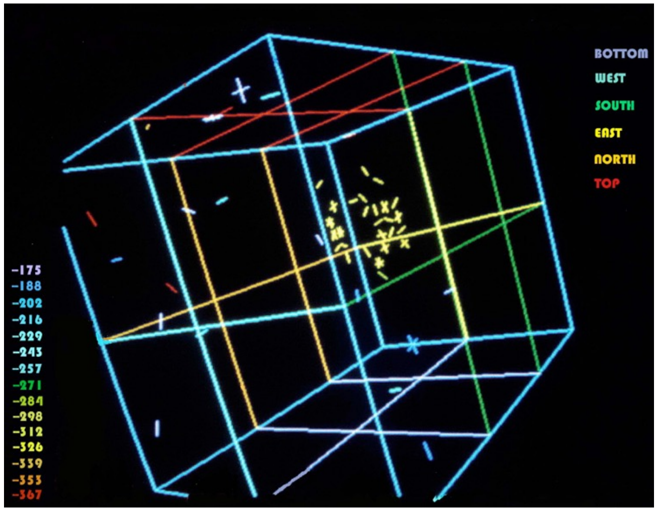
But would anyone believe another crazy cosmic ray experiment, particularly one with a (mostly) unknown Japanese collaboration?

From Out of the East

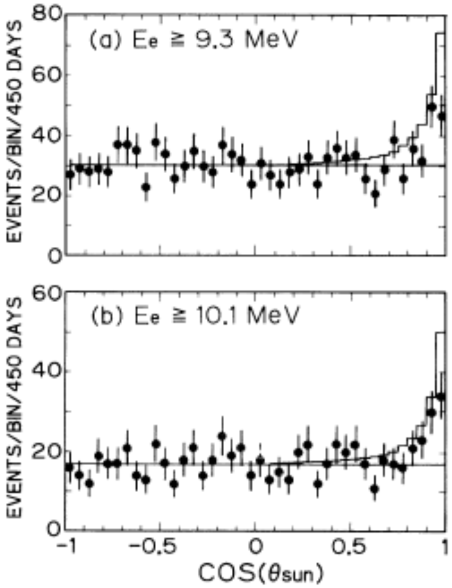
Fortunately…

SN1987A establishes KII `creds'





Two years later first solar neutrino observation:



First demonstration νs are from the Sun;

$$\frac{\text{Kam-II data}}{\text{SSM}} = 0.46 \pm 0.13(\text{stat.}) \pm 0.08(\text{syst.}) \,,$$

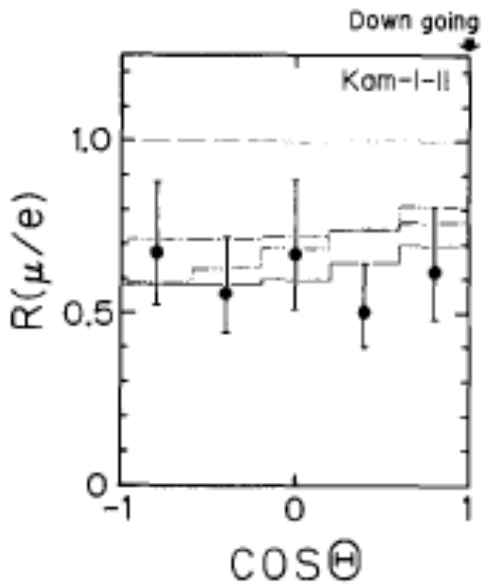
This is larger than Davis's value, but consistent if looking at just ^{8}B

Meanwhile…

Atmospheric neutrino `anomaly'

`Ratio of ratios' supposedly robust to flux uncertainties:

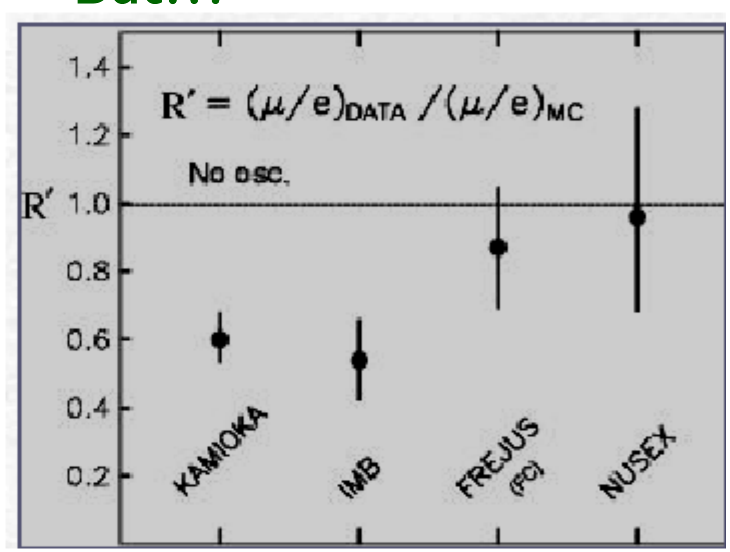
$R(\mu/e) = (\mu/e)_{data}/(\mu/e)_{MC}$



We are unable to explain the data as the result of systematic detector effects or uncertainties in the atmospheric neutrino fluxes. Some as-yet-unaccounted-for physics such as neutrino oscillations might explain the data.

*Hirata et al, PLB, **205**, 416, (1988) and Hirata et al, PLB, **280**, 146, (1992)*

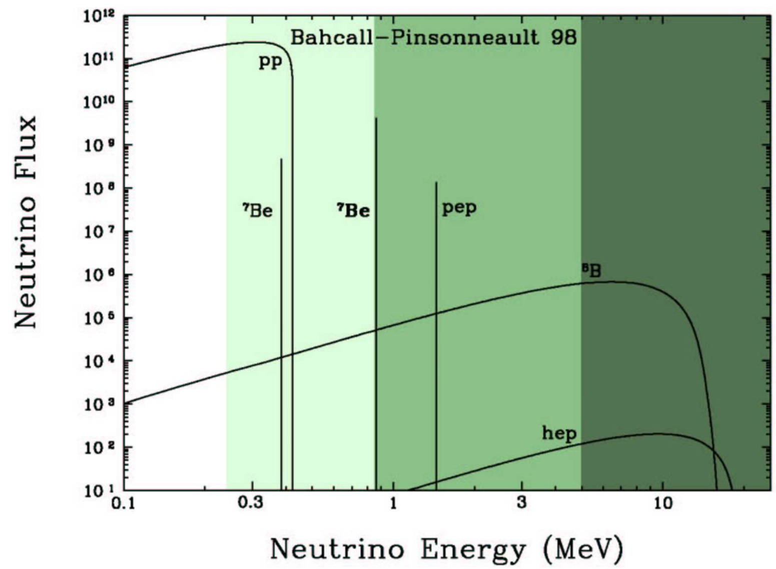
But…



"No one ever lost money betting a neutrino experiment was wrong."
(Don Perkins)

Finally Gallium

1965 Kuzmin points out reaction $\nu_e + {}^{71}Ga \rightarrow e^- + {}^{71}Ge$ has threshold of 233 keV, low enough to detect pp neutrinos (and everything else):



pp neutrinos are primary fusion products---

- fixed lower limit based on solar power output, ~79 SNU.
- Standard Solar Model prediction is ~130 SNU.

So: suppressed rate like Cl or K-II (40-60 SNU), unambiguous discovery of non-astrophysical solution.
But if rate ~130 SNU, then everyone else is wrong.

Finally Gallium

Two independent experiments

SAGE

First results (1991):

$^{71}\mathrm{Ga}$ capture rate $= 20^{+15}_{-20}(\mathrm{stat}) \pm 32(\mathrm{syst})$ SNU

Big suppression?

Gallex

First results (1992):

83 ± 19 (stat.) ± 8 (syst.) SNU

Consistent with SSM

Finally Gallium

Two independent experiments

SAGE

First results (1991):

^{71}Ga capture rate $= 20^{+15}_{-20}$(stat) $\pm$ 32(syst) SNU

Eventually (1999):

$$67.2^{+7.2+3.5}_{-7.0-3.0}\ \text{SNU}$$

Gallex

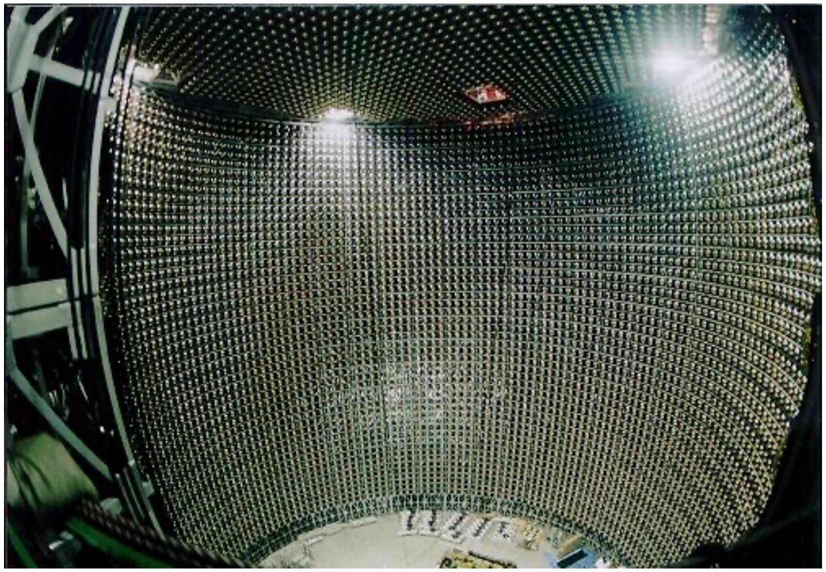
First results (1992):

83 $\pm$ 19 (stat.) $\pm$ 8 (syst.) SNU

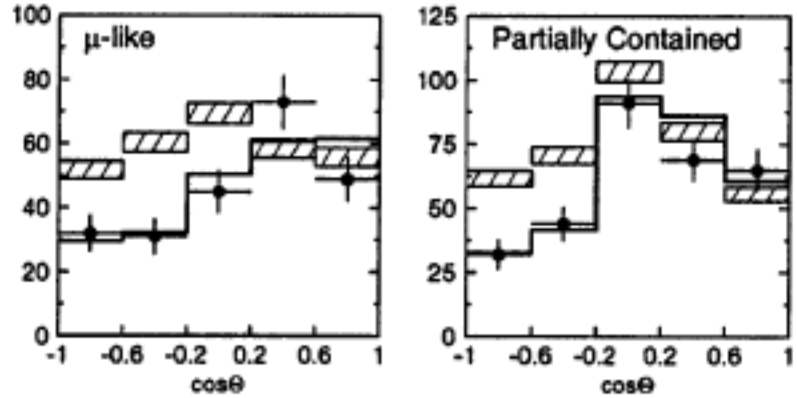
$$76.4 \pm 6.3\ ^{+4.5}_{-4.9}\ \text{SNU}$$

$\longrightarrow$ Including calibrations with ^{51}Cr

Super-Kamiokande

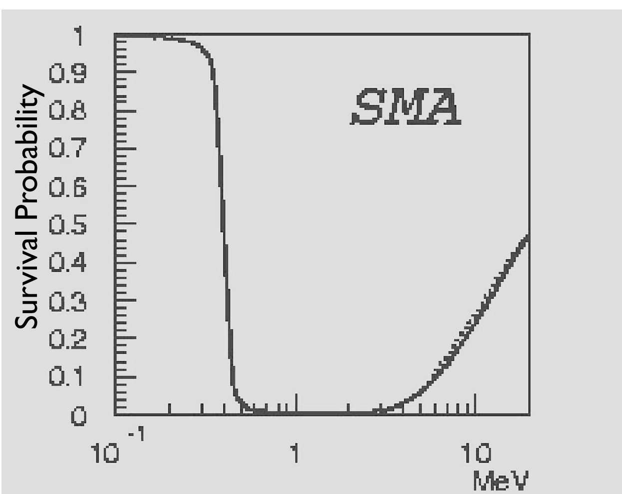


The big news (1998):



Atmospheric ν disappearance fit extremely well by oscillations

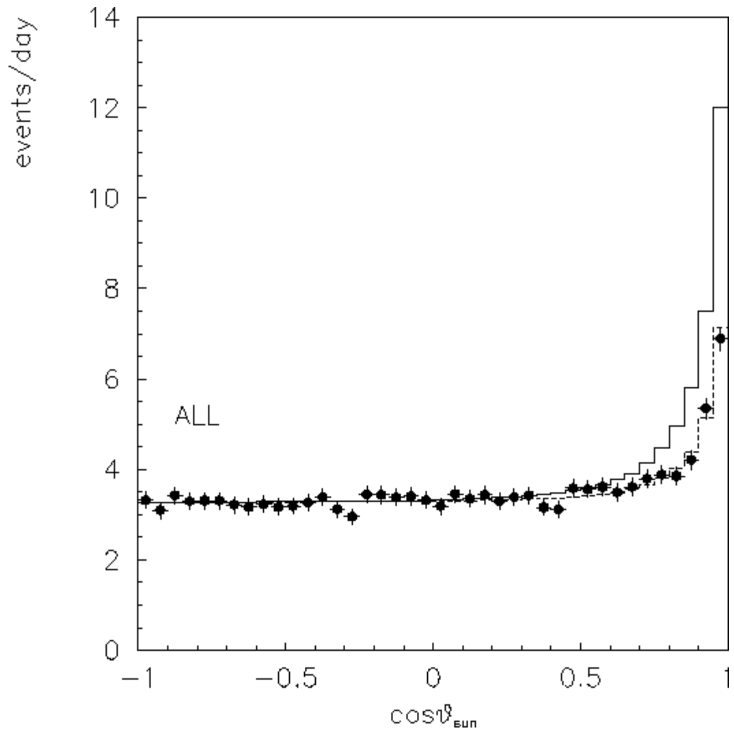
For solar ν's, MSW+small angle mixing predicts:

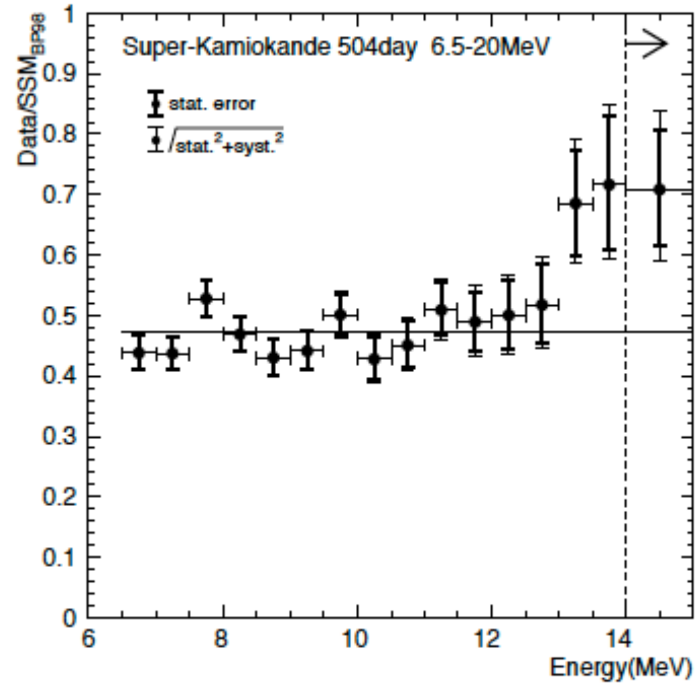


Big distortion in ν energy spectrum!
Or could see Day/Night asymmetry via MSW in Earth!

Either would be unambiguous solution to solar ν problem…

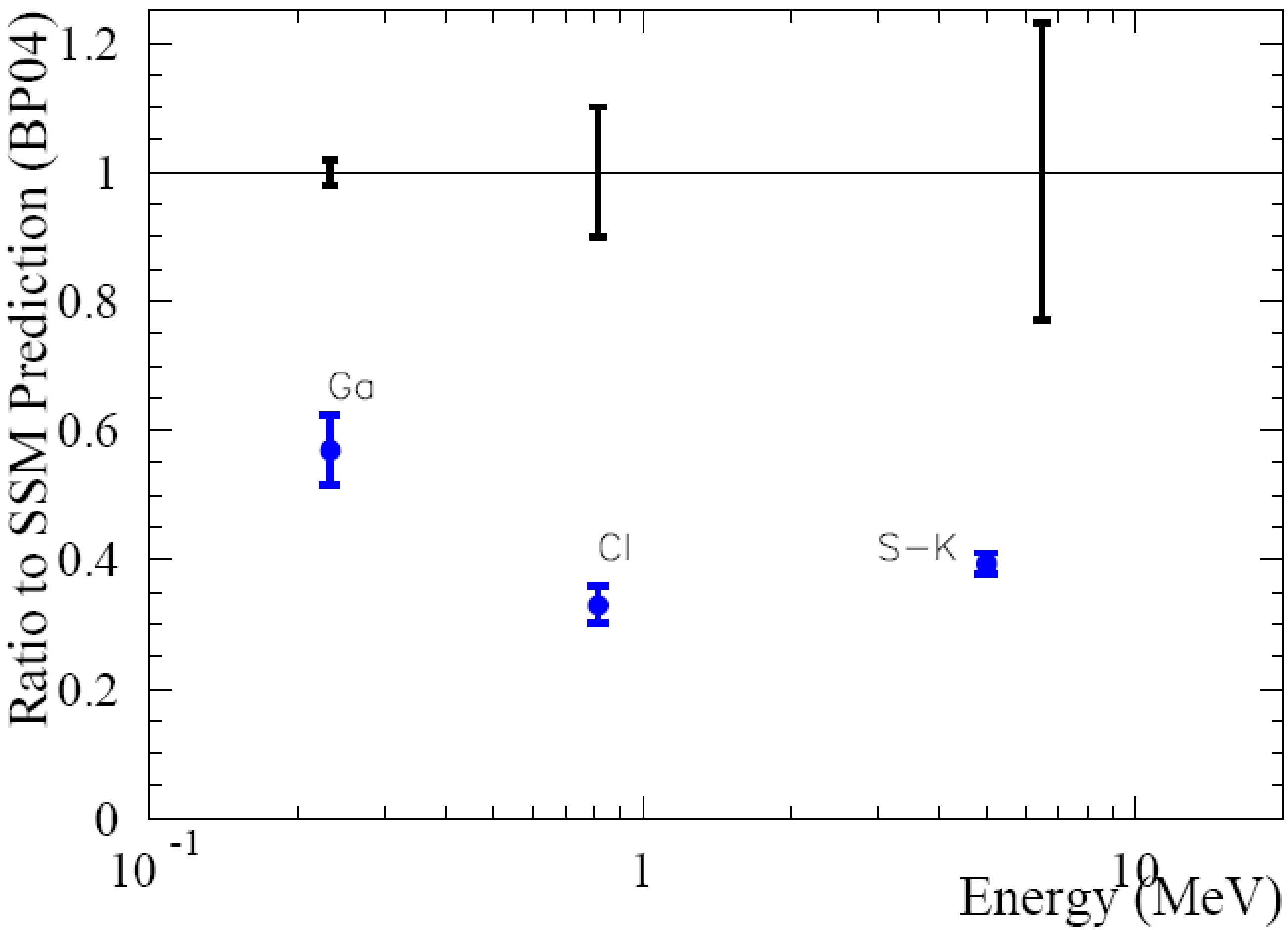
Super-Kamiokande





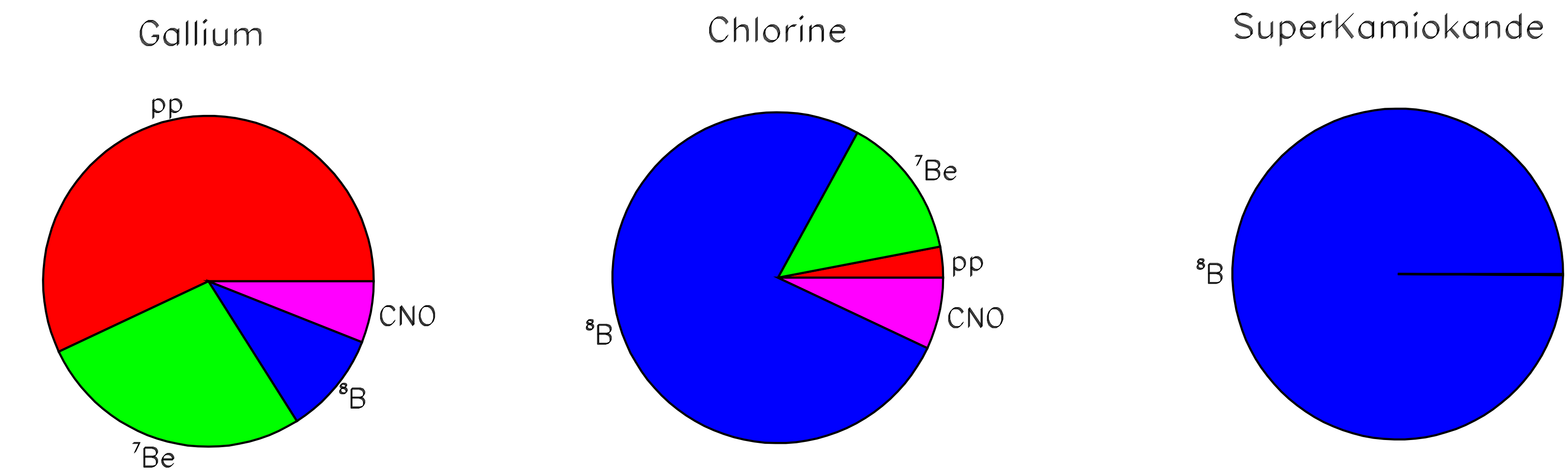
Nope. Clear confirmation of K II results with high precision, but no smoking gun.

The Story So far:

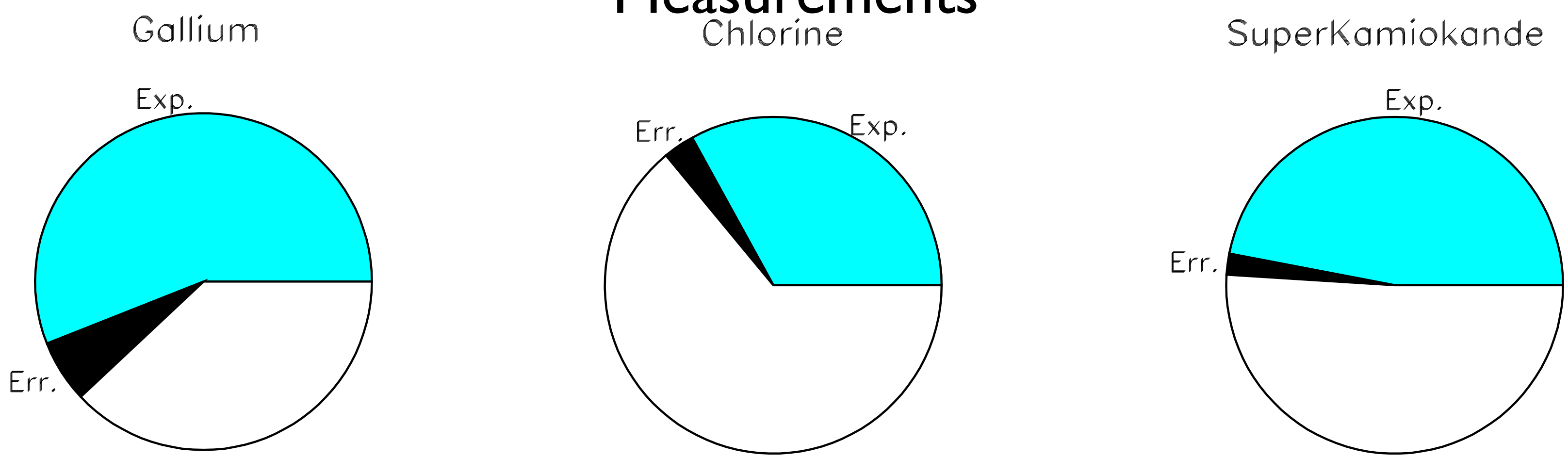


After Six Solar ν Experiments

Expectations



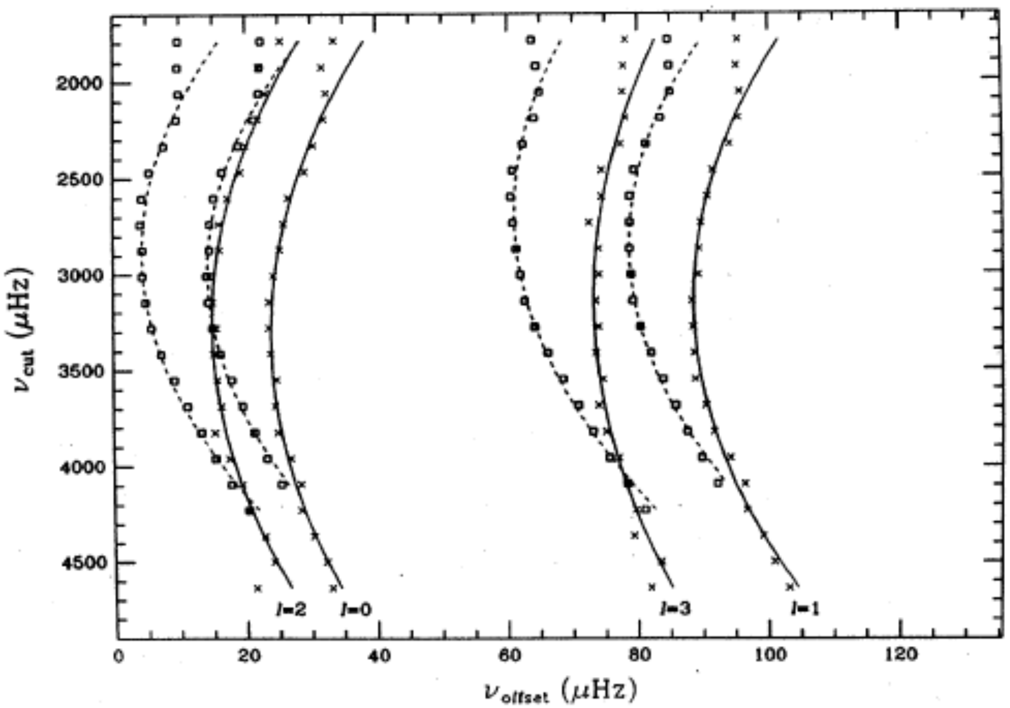
Measurements



- Looks like complete absence of ^{7}Be neutrinos.

A Second Prediction of the SSM

Acoustical modes of Sun can be measured very precisely



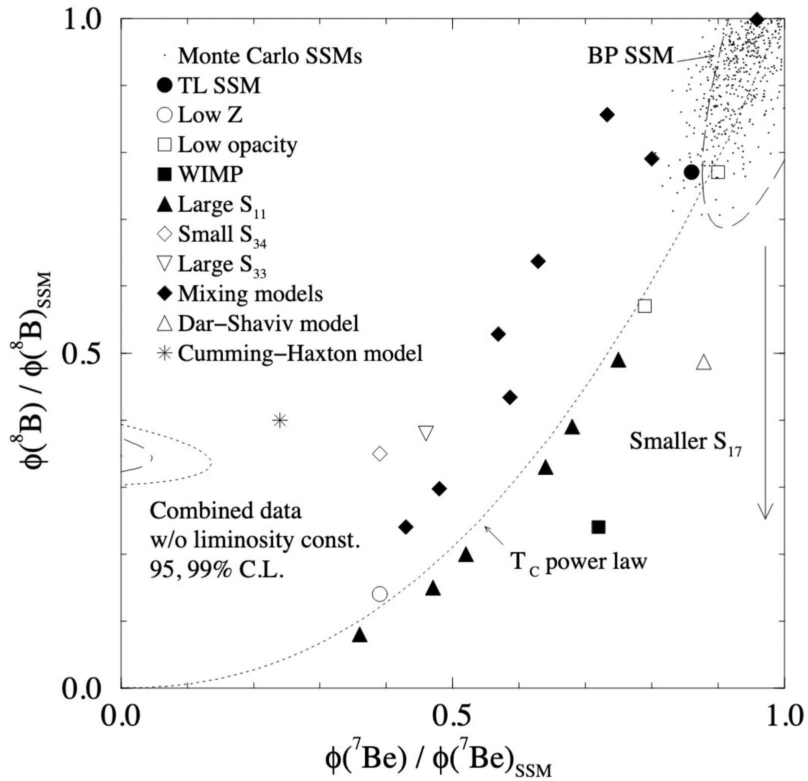
And agreement with SSM predictions good to 0.5%!

(Note: depends critically on CNO content!)

Desperation?

Or Anticipation?

People begin running Monte Carlo simulations of 1000s of solar models, to prove astrophysics is not to blame….



Hata and Langacker, Phys. Rev. D56, 6107 (1997)

Bahcall begins quoting 3σ errors on everything.

Papers often contain phrases like,
"Even without the Cl results.."
and
"Allowing the Cl rate to float…"

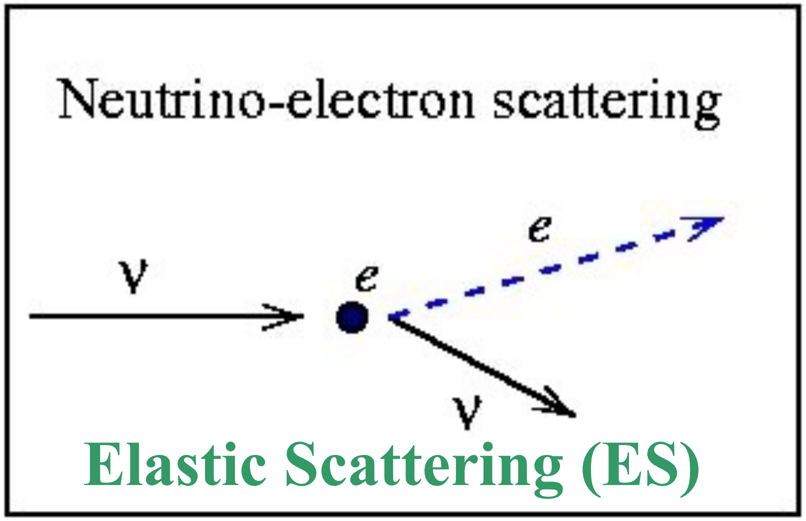
With the Super-K atmospheric results, these arguments are compelling…but not quite the smoking gun people need.

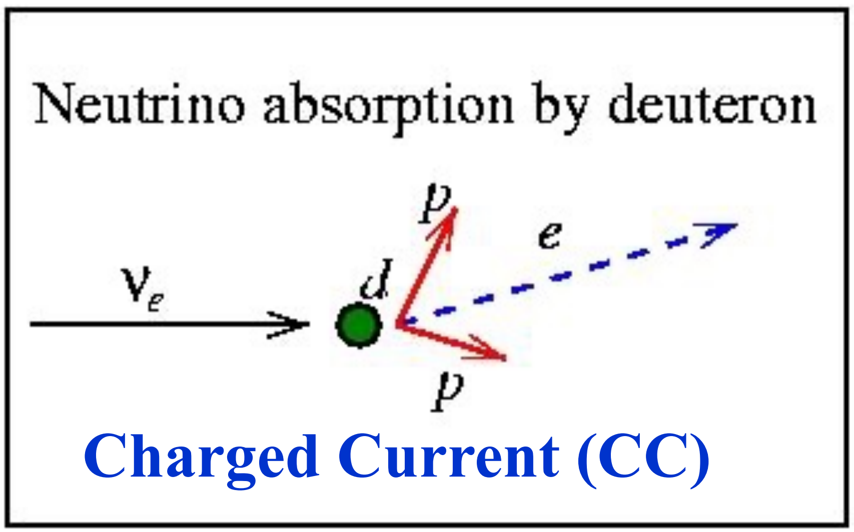
Heavy Water and Neutrinos

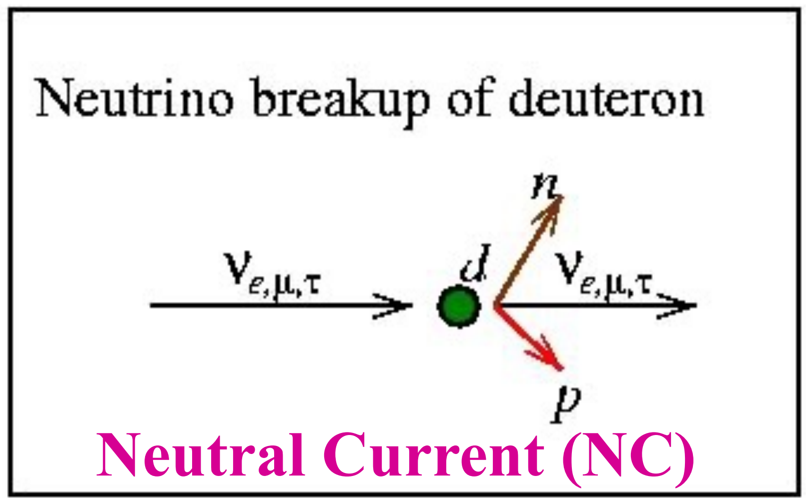
VOLUME 55, NUMBER 14 PHYSICAL REVIEW LETTERS 30 SEPTEMBER 1985

Direct Approach to Resolve the Solar-Neutrino Problem

Chen suggests an (inclusive) appearance measurement using D_2O







Sudbury Neutrino Observatory

All that's needed is:

- About 1 kton of heavy water (~$250M)
- 2 km underground in a mine
- With enough PMTs to see γ-rays from neutron capture

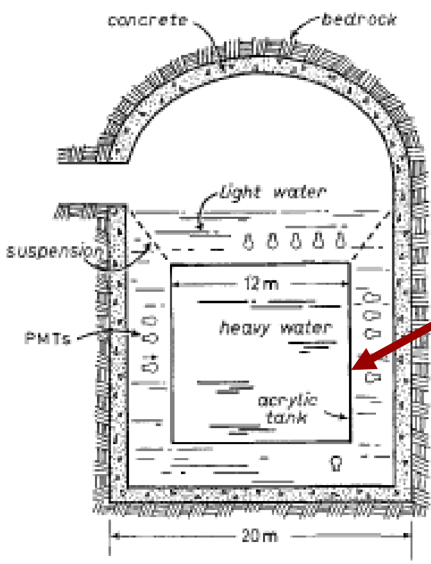
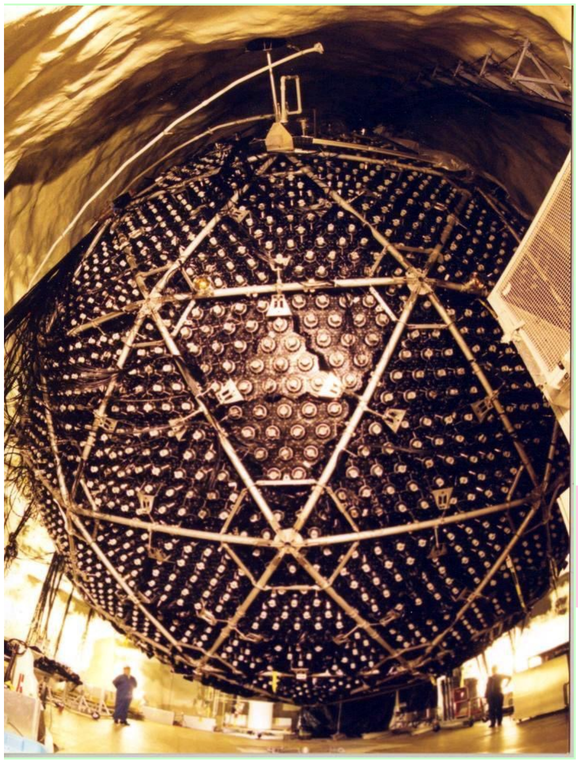


Fig. 5. – Conceptual design of the light/heavy-water detector. The heavy water is contained in an acrylic tank and is shielded from activity in the rock by low activity concrete and light water. The Čerenkov light produced in the water is detected by an array of 2400 50 cm diameter phototubes.

`Sea World tank' to use H_2O as shielding

Sure. Review committee says "Physics goals…are of outstanding value." Funding agency award (1985): $0.

Sudbury Neutrino Observatory



1000 tonnes D_2O

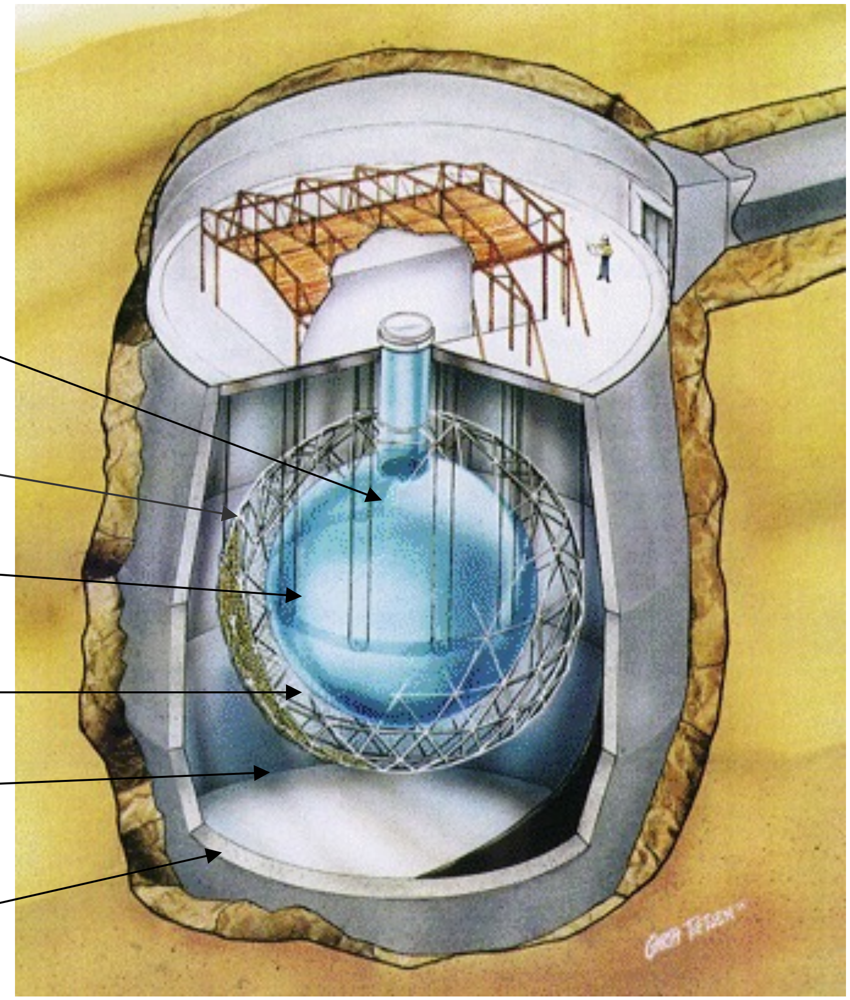
Support Structure for 9500 PMTs, 60% coverage

12 m Diameter Acrylic Vessel

1700 tons Inner Shielding H_2O

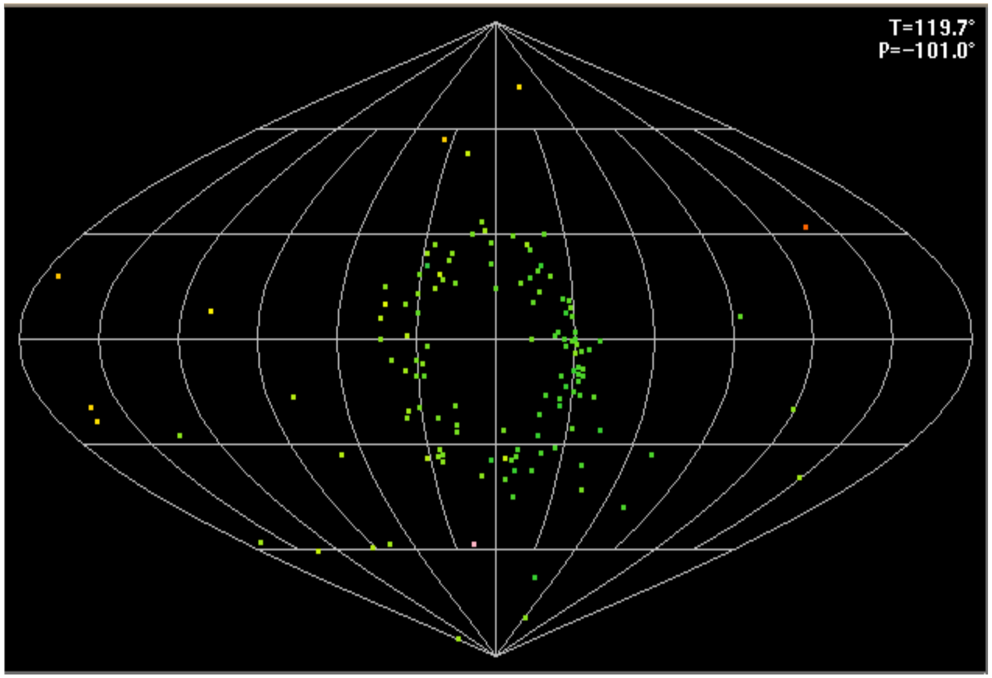
5300 tons Outer Shield H_2O

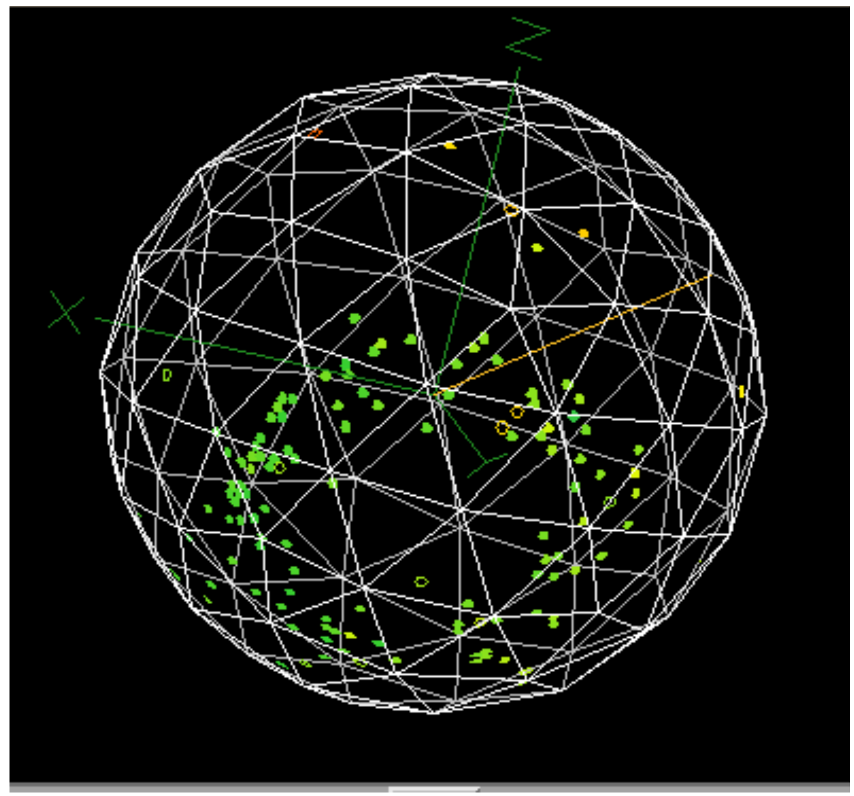
Urylon Liner and Radon Seal



Sudbury Neutrino Observatory

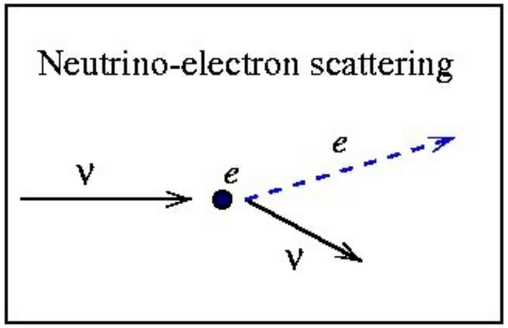
^8B Solar ν Event

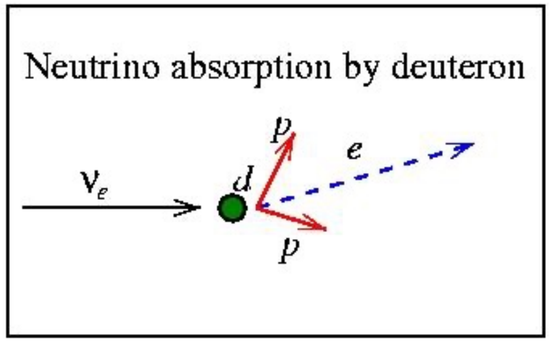


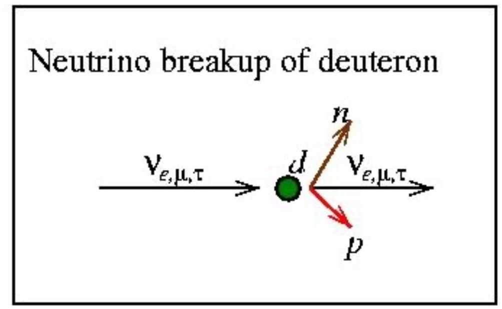


Sudbury Neutrino Observatory

Two ways of doing `inclusive appearance' measurement:







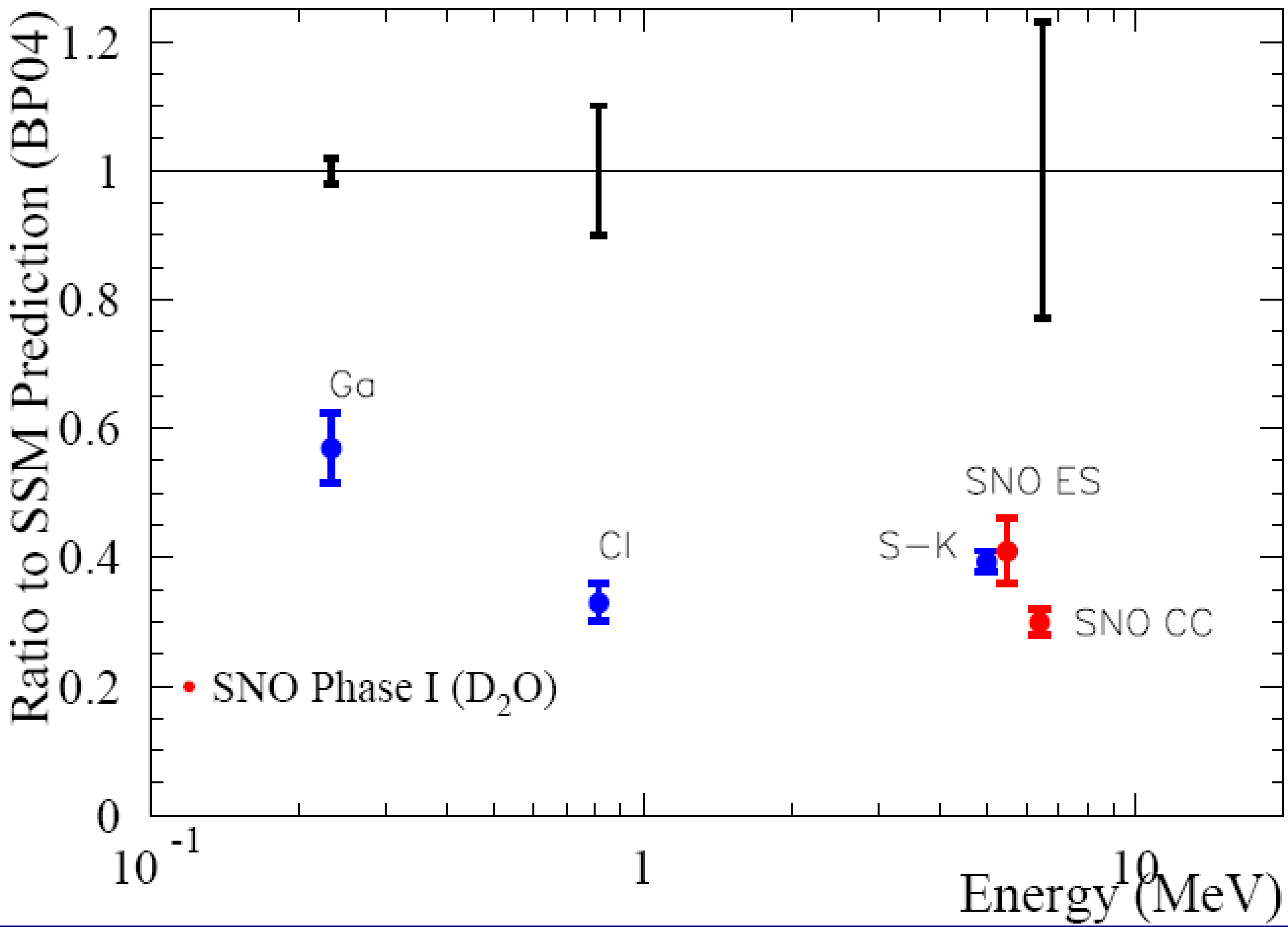
ES **CC** **NC**

$$\frac{\mathrm{CC}}{\mathrm{ES}} = \frac{\nu_{\mathrm{e}}}{\nu_{\mathrm{e}} + 0.15(\nu_{\mu} + \nu_{\tau})}$$

$$\frac{\mathrm{CC}}{\mathrm{NC}} = \frac{\nu_{\mathrm{e}}}{\nu_{\mathrm{e}} + \nu_{\mu} + \nu_{\tau}}$$

Sudbury Neutrino Observatory

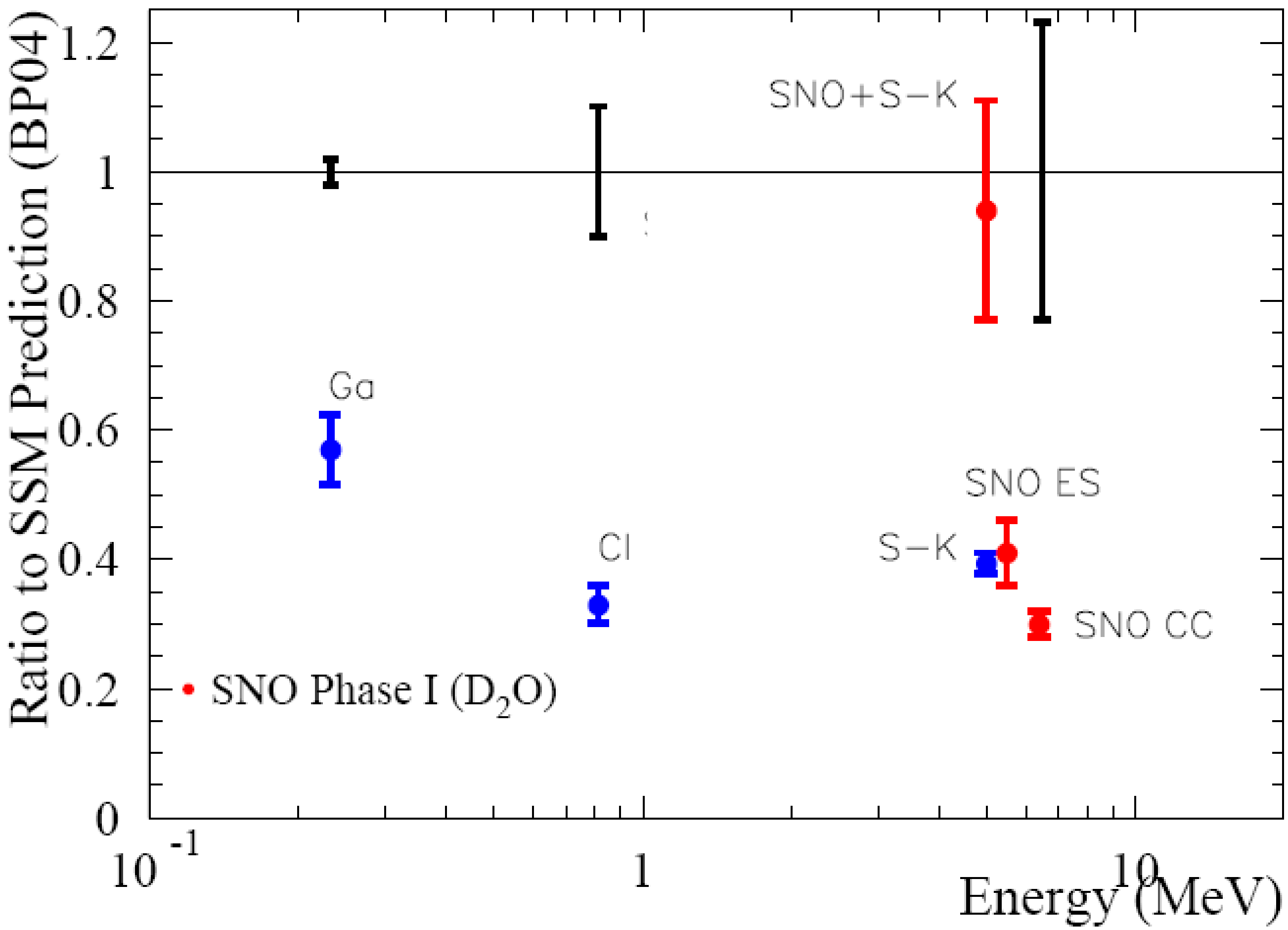
First Results (2001)



$$\Phi^{SK}_{ES} - \Phi^{SNO}_{CC} = 0.57 \pm 0.17 \quad \Rightarrow 3.3\sigma > 0$$

Sudbury Neutrino Observatory

First Results (2001)



Total flux agrees with Standard Solar Model!

A Bayesian World

VOLUME 87, NUMBER 7 PHYSICAL REVIEW LETTERS 13 AUGUST 2001

Measurement of the Rate of $\nu_e + d \rightarrow p + p + e^-$ Interactions Produced by ^{8}B Solar Neutrinos at the Sudbury Neutrino Observatory

Reaction to SNO results more positive than perhaps collaboration expected for just 3.3σ, e.g.,:

"…the standard model of the Sun appears to be in better shape than the standard model of electroweak interactions."

Fogli, Lisi, Montanino, Palazzo, Phys. Rev. D64, 2001

"I feel very much like the way I expect that these prisoners that are sentenced for life do when a D.N.A. test proves they're not guilty," Dr. Bahcall said. "For 33 years, people have called into question my calculations on the Sun."

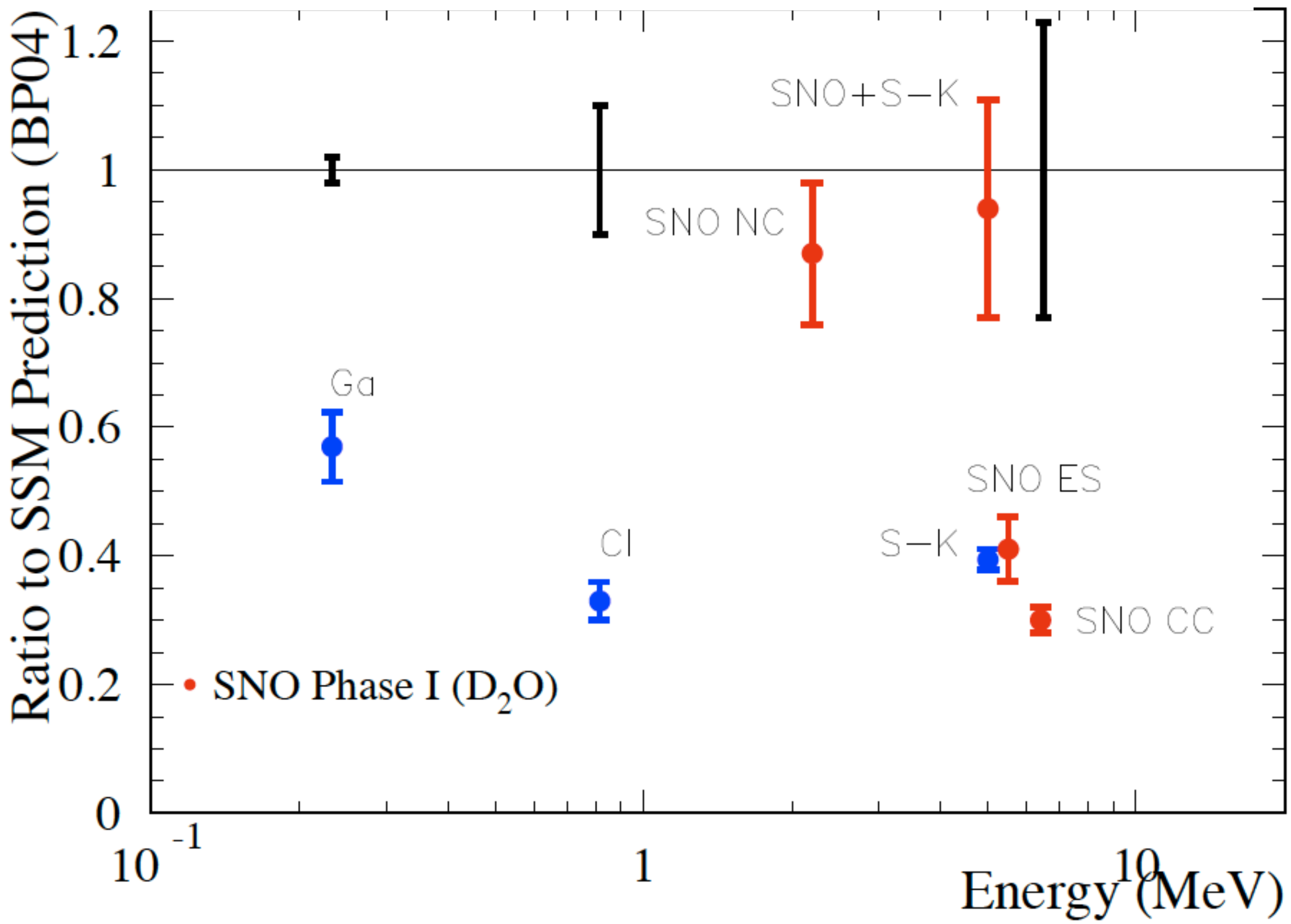
New York Times, June 19, 2001

Nevertheless, some skepticism for the next 10 months…

Sudbury Neutrino Observatory

VOLUME 89, NUMBER 1 PHYSICAL REVIEW LETTERS 1 JULY 2002

Direct Evidence for Neutrino Flavor Transformation from Neutral-Current Interactions in the Sudbury Neutrino Observatory

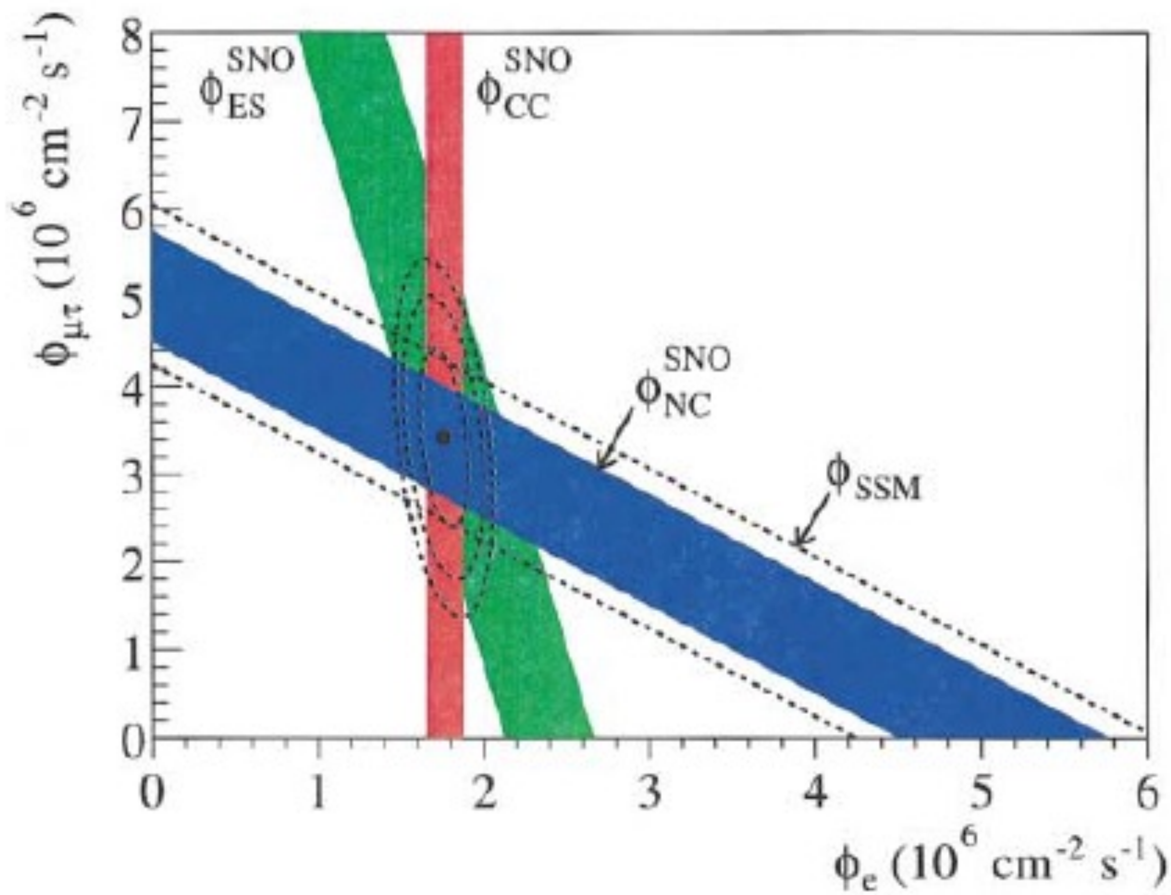


5.3σ difference between NC and CC

Sudbury Neutrino Observatory

VOLUME 89, NUMBER 1 PHYSICAL REVIEW LETTERS 1 JULY 2002

Direct Evidence for Neutrino Flavor Transformation from Neutral-Current Interactions in the Sudbury Neutrino Observatory



5.3σ difference between NC and CC

Back to 1964

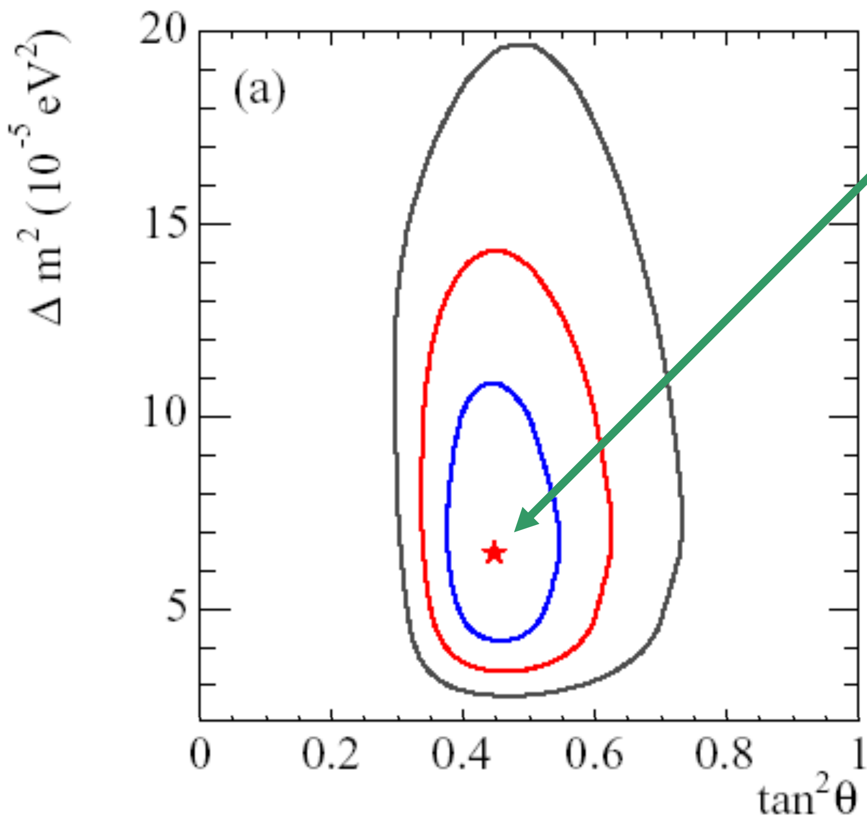
Standard Solar Model Predicts

$$\phi_{\upsilon}^{{}^8B} \propto T^{25}$$

$$\blacktriangleright \quad T_{\text{Sun}}^{\text{core}} \cong \boxed{1}5.6 \times 10^6\,\text{K}$$

Closing the Loop

Solar data:



This is the best fit value of the vacuum mass difference and mixing angle under the hypothesis that observations are due to MSW (matter) oscillations.

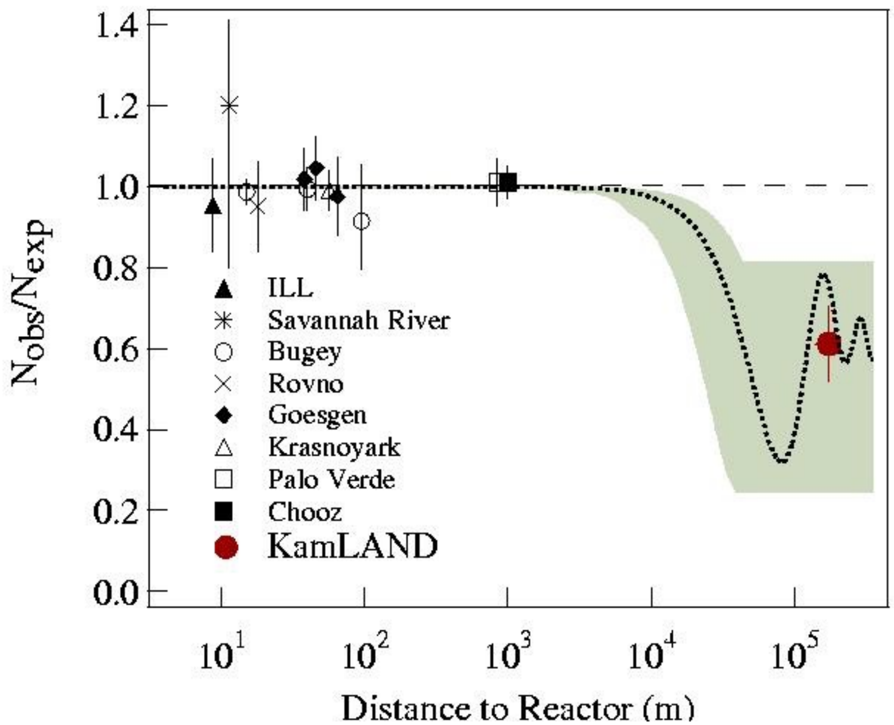
But if we plug these values into the vacuum survival probability:

$$P_{\upsilon_e \to \upsilon_e} = 1 - \sin^2 2\theta_{12} \sin^2\left(\frac{1.27\Delta m_{12}{}^2 L}{E}\right)$$

We find that oscillation length L~100 km for E=4 MeV.

Solar ν Oscillations with No Sun

➢ KamLAND—Reactor antinu's



(This could have been done in 1968!)

Event numbers for 766 ton-years of data:

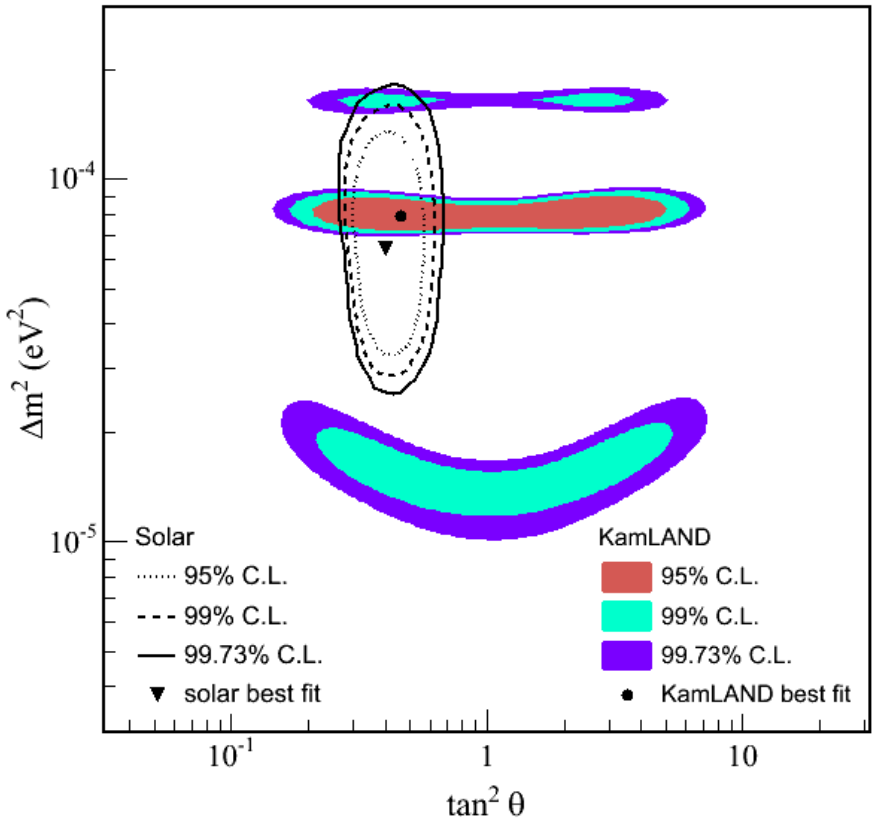
Expected (no oscillation)=365.2+17.8 background

Observed =258

Disappearance with significance of 99.998%

Solar ν Oscillations with No Sun

➢ `Precision' Comparison Across Regimes



	Reactor	Solar
E	2-10 MeV	0.1-15 MeV
L	150 km	1.5×10^8 km
MSW	No	Yes
ν	Anti-ν_e	ν_e

Large mixing means all transformation happens inside Sun

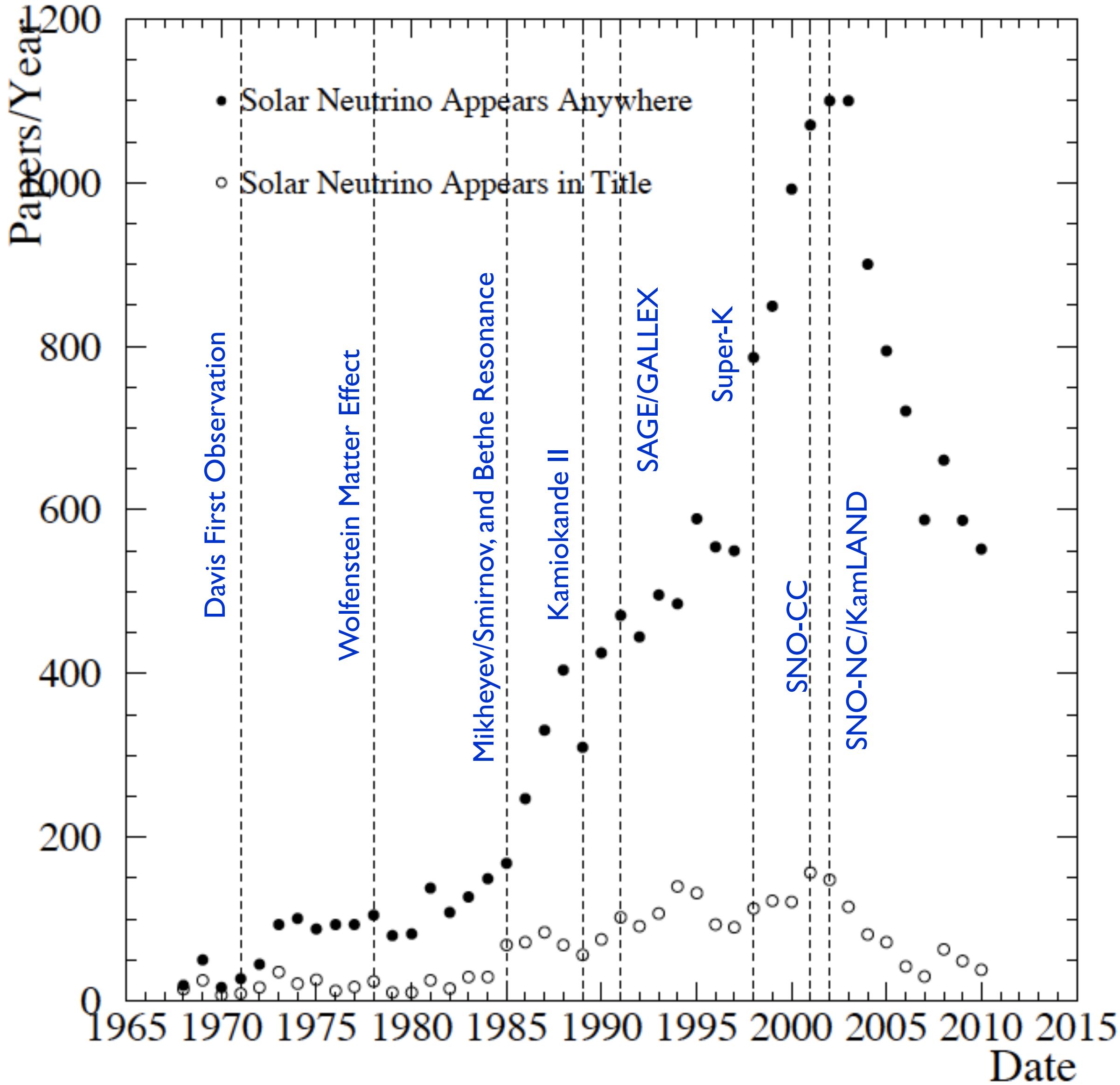
A Long Story

Punished by Success

"For 35 years people said to me: `John, we just don't understand the Sun well enough to be making claims about the fundamental nature of neutrinos, so we shouldn't waste time with all these solar neutrino experiments.' Then the SNO results came out. And the next day people said to me, `Well, John, we obviously understand the Sun perfectly well! No need for any more of these solar neutrino experiments.'"

---John Bahcall, 2003

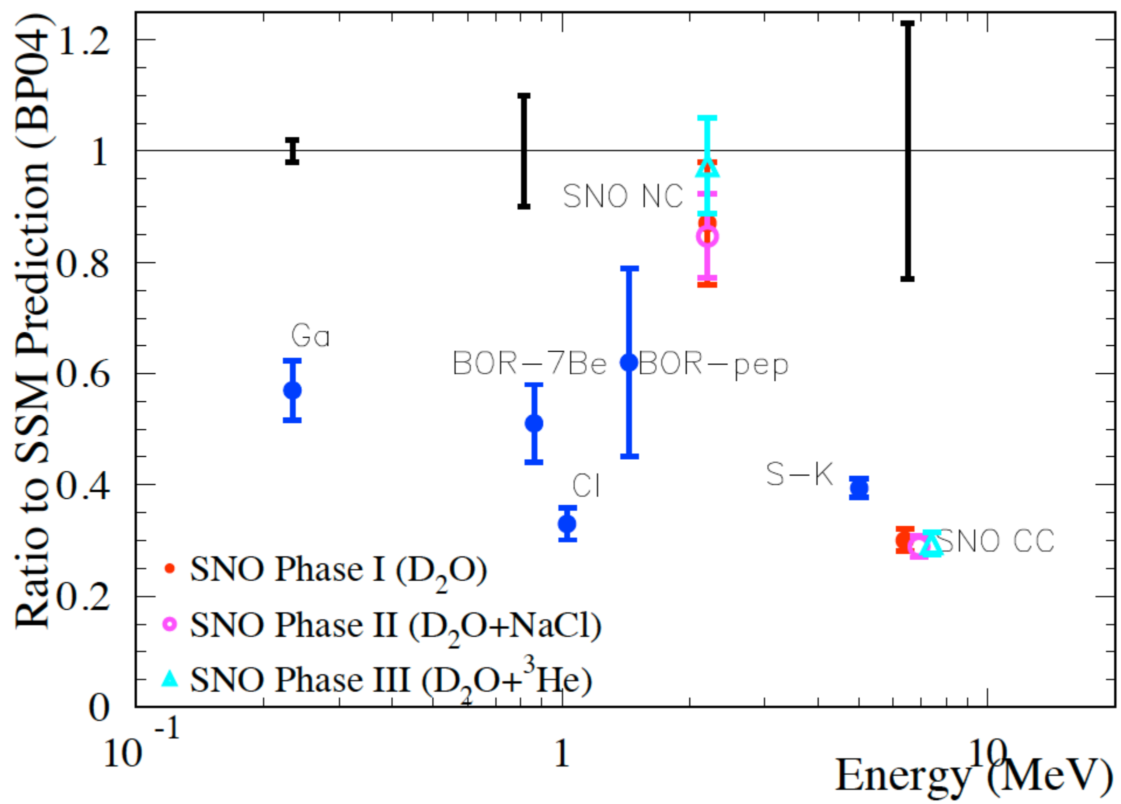
~35 Years



Papers/Year
Date
Solar Neutrino Appears Anywhere
Solar Neutrino Appears in Title
Davis First Observation
Wolfenstein Matter Effect
Mikheyev/Smirnov, and Bethe Resonance
Kamiokande II
SAGE/GALLEX
Super-K
SNO-CC
SNO-NC/KamLAND
0
200
400
600
800
1000
1200
1965
1970
1975
1980
1985
1990
1995
2000
2005
2010
2015

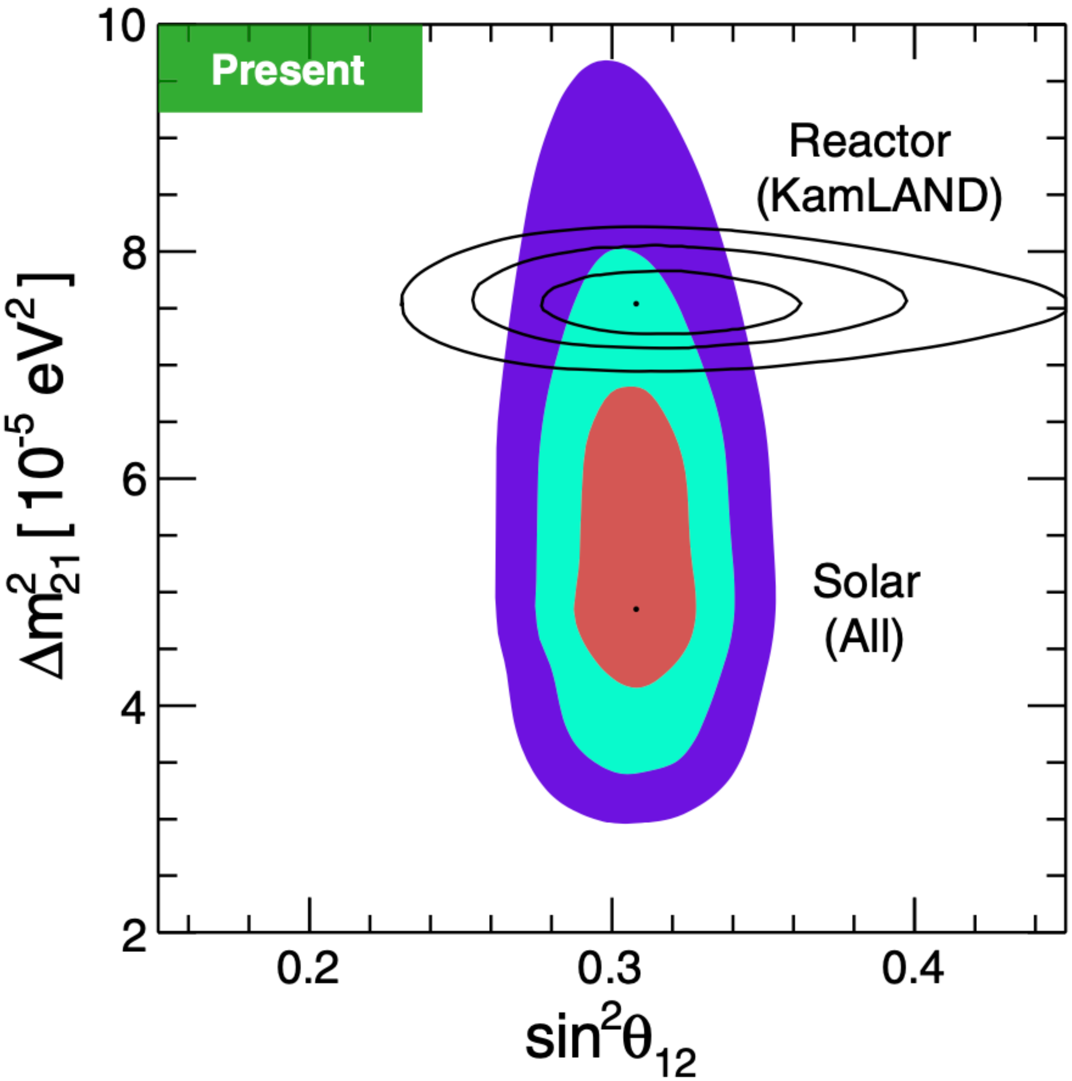
Current Status

Residual Paranoia



Three ways of detecting NC in SNO, to be `really sure.'

Current Status



Terrestrial vs. solar measurements of Δm^2
Agree at ~2σ level

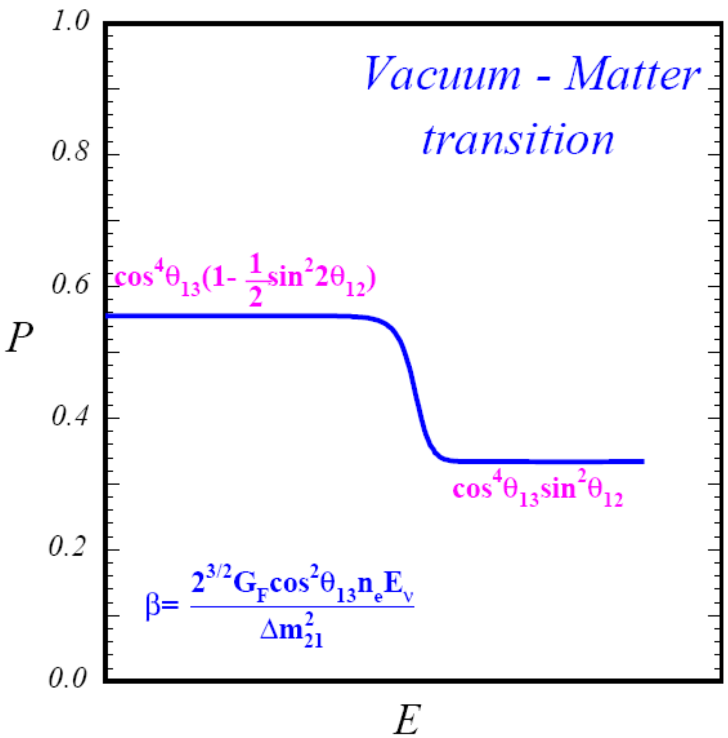
Should get new reactor measurements from SNO+ and JUNO soon.

Francesco Capozzi,[1,2,3,*] Shirley Weishi Li,[1,2,4,†] Guanying Zhu,[1,2,‡] and John F. Beacom[1,2,5,§]
PHYSICAL REVIEW LETTERS **123,** 131803 (2019)

Anything Left?

- Test the model of massive neutrino mixing

Vacuum/Matter Transition



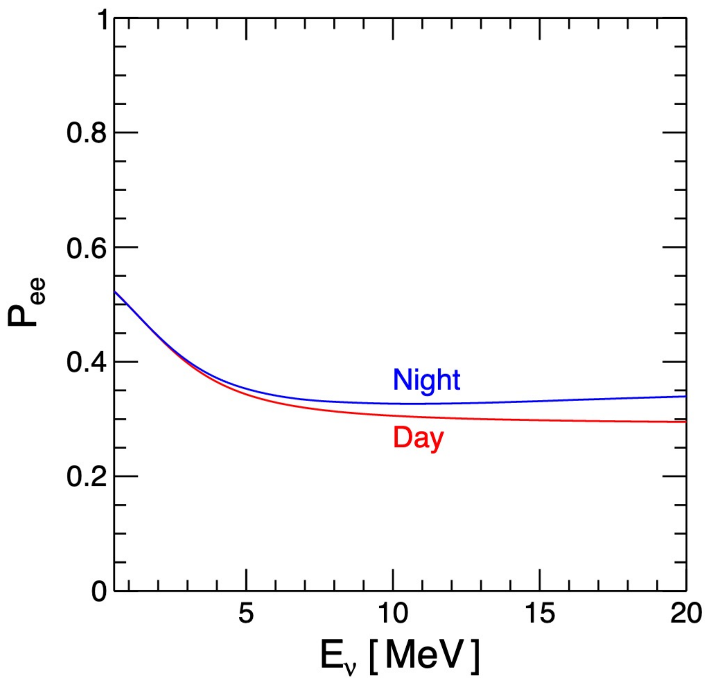
Day/Night ν_e Asymmetry

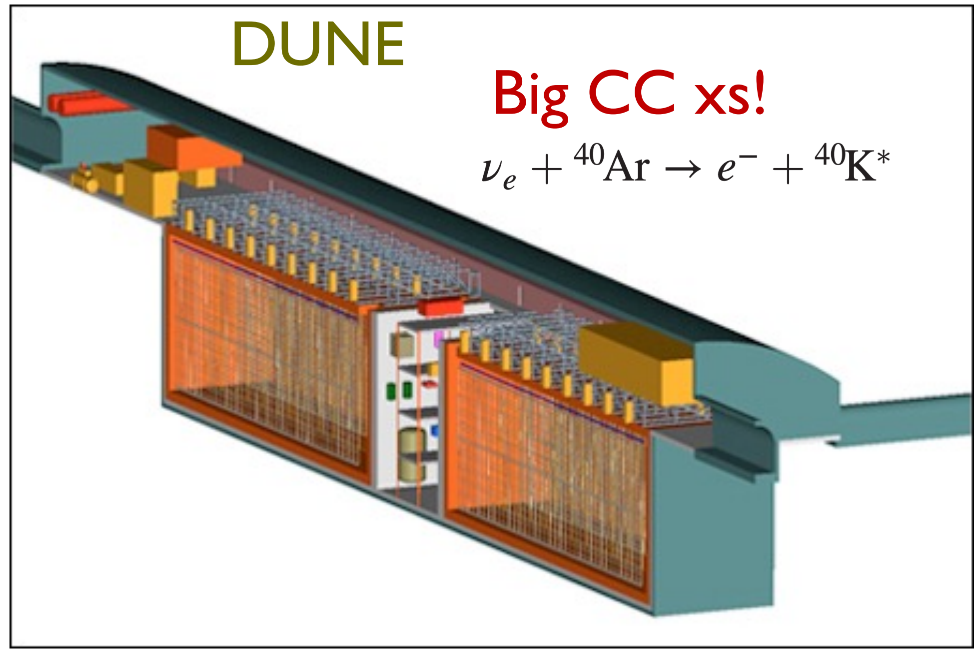
MSW effect predicts transition from matter to vacuum-dominated mixing, and Day/Night asymmetry

Anything Left?

- Test the model of massive neutrino mixing

Day/Night ν_e Asymmetry





Might be first solar neutrinos detected in US since Davis!

For DUNE, expect

$$A_{D/N} = -(7.67 \pm 0.74)\%.$$

With ~40,000 events/day, can measure this to ~1% statistically

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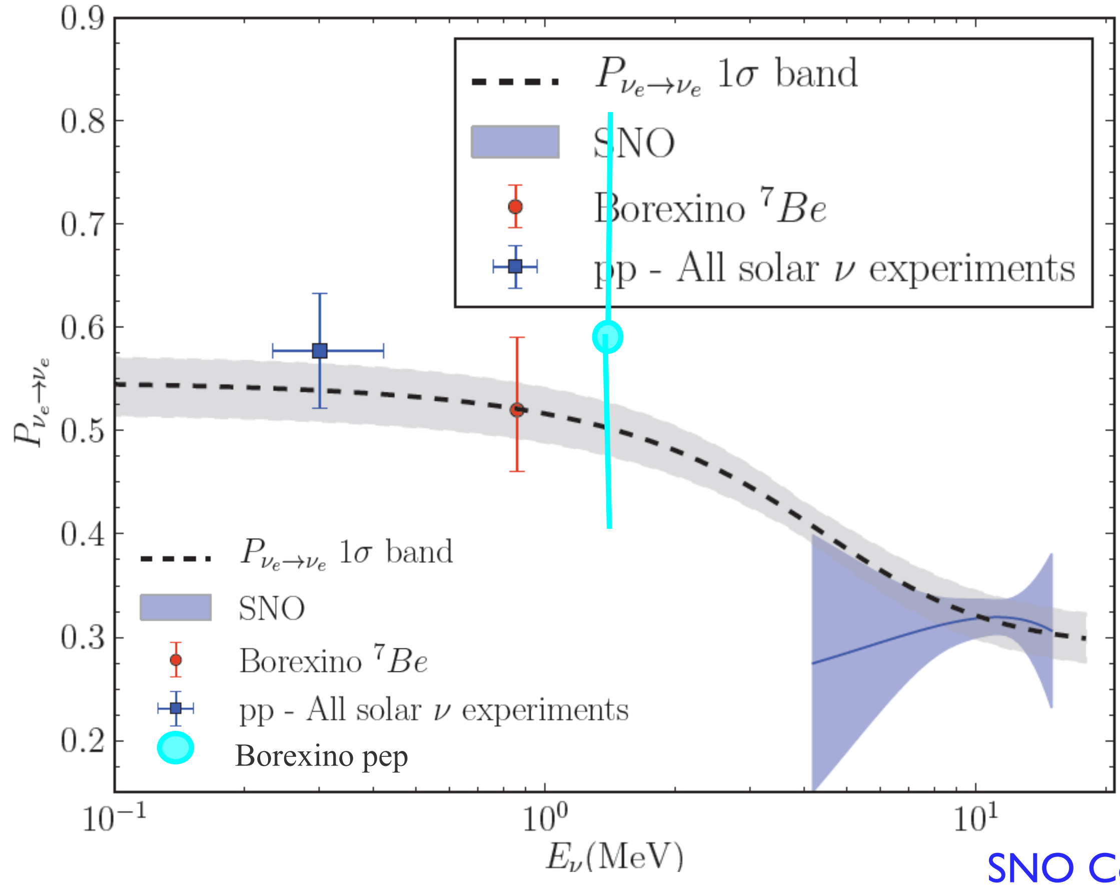
Observing MSW Phenomenology

Vacuum/matter transition region



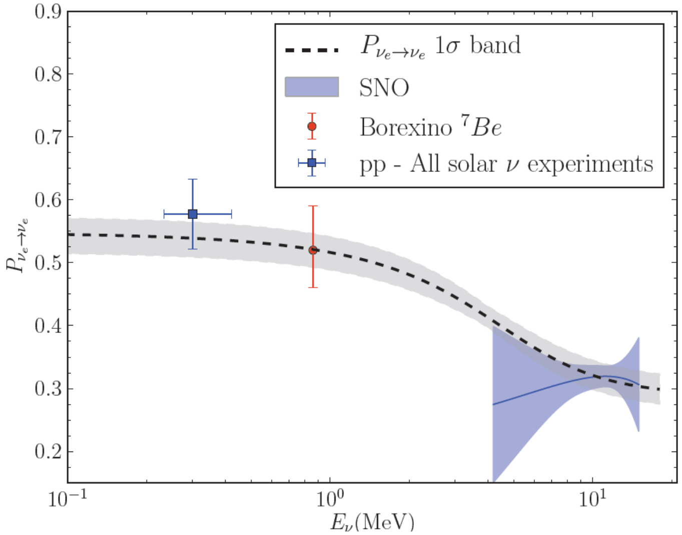
SNO Collaboration

This is a little frustrating.

Solar νs give us our only huge, observed matter effect.
The situation is ripe for a precision measurement program.

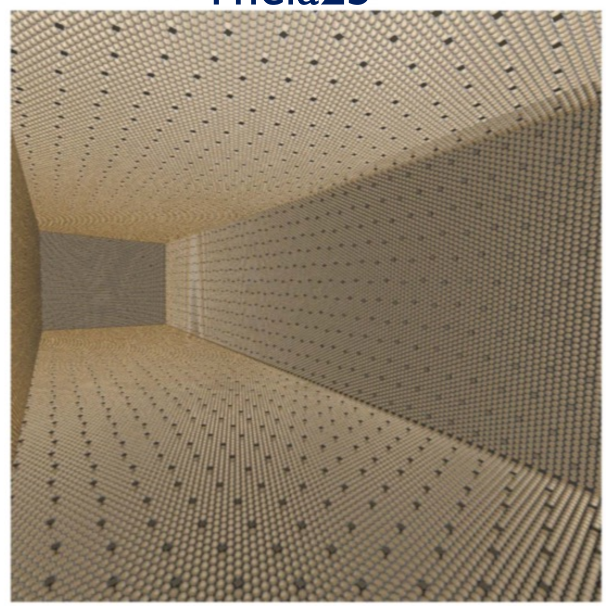
Observing MSW Phenomenology

Vacuum/matter transition region

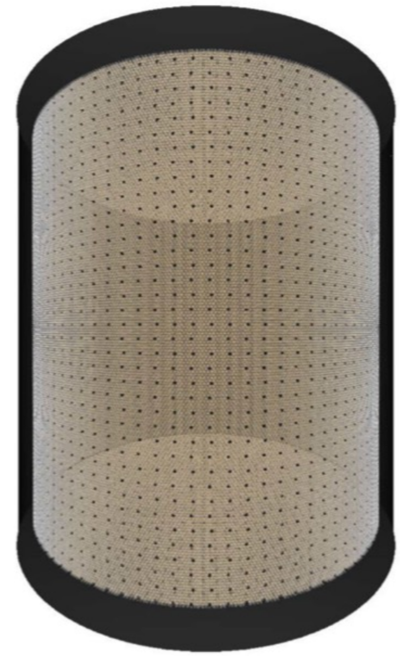


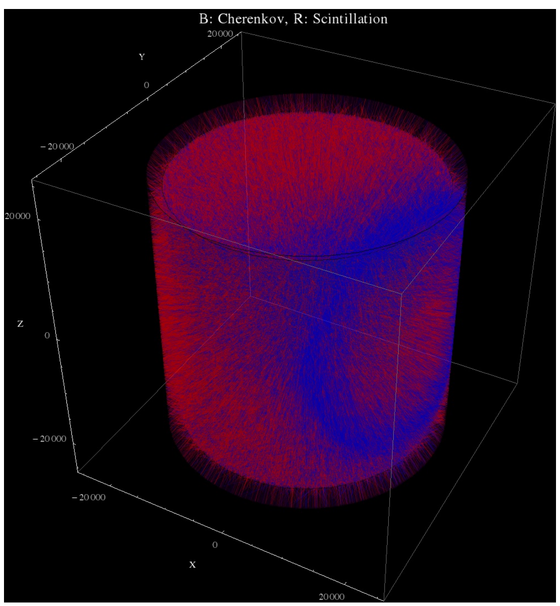
“Hybrid” Cherenkov/scintillation detector could allow threshold in 1 MeV region with statistics beyond Super-K

Theia25



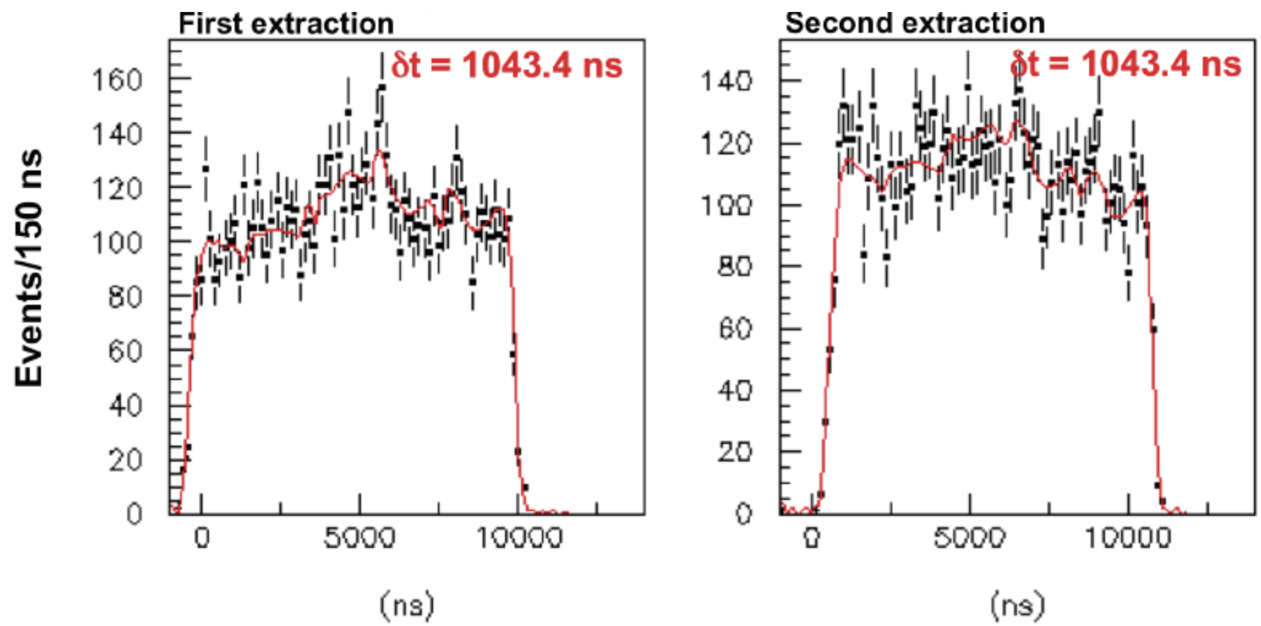
Theia100





Have We Learned the Lessons Too Well?

Measurement of the neutrino velocity with the OPERA detector in the CNGS beam*

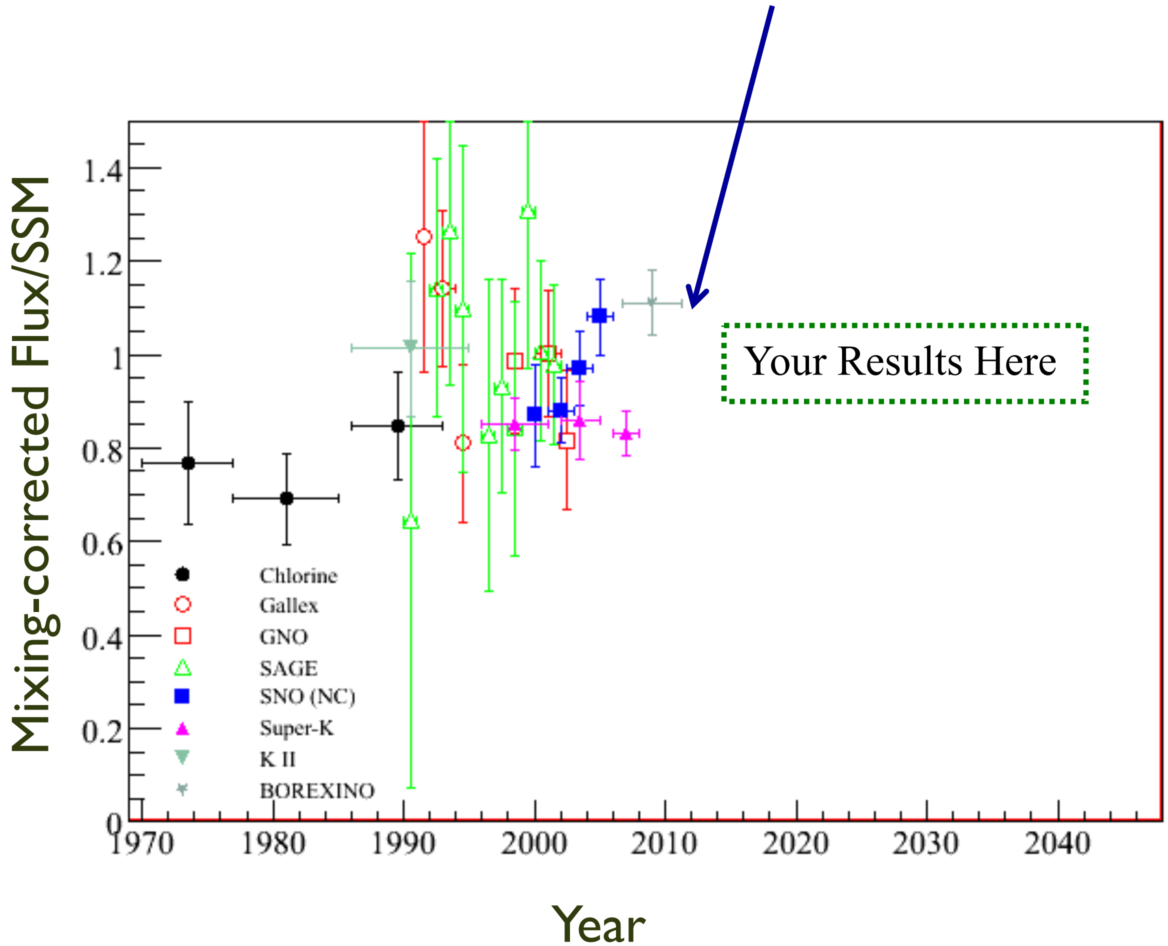


$$\delta t = TOF_c - TOF_\nu = 1043.4 \text{ ns} - 985.6 \text{ ns} = (57.8 \pm 7.8 \text{ (stat.)}) \text{ ns}.$$

~250 citations…

Summary

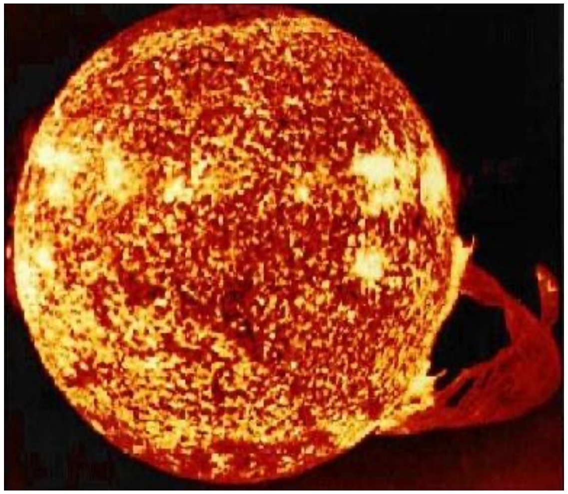
- A long road from `surprising' result to mystery to physics
- Most important element: tenacity
- Still things left to do…
- And we should at least keep watching…

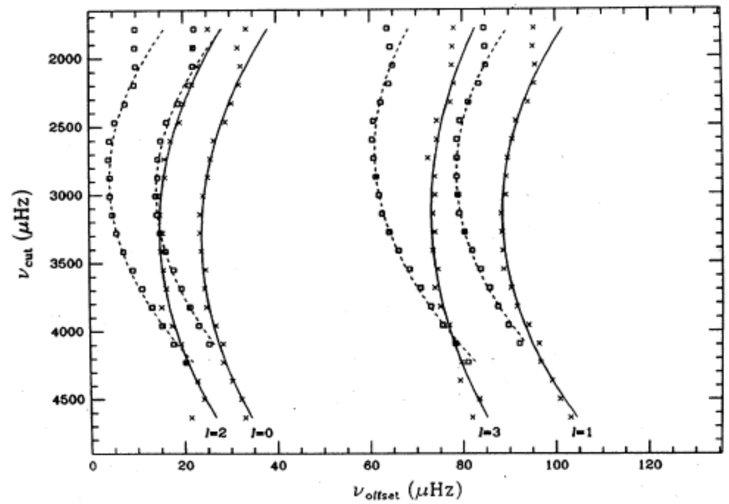


[redacted]

Anything Left?

The solar `metallicity problem'





- Helioseismology convinced `everyone' that SSM was correct
- Modern measurements of surface metallicity are lower than before
- Which makes SSM helioseismologic predictions wrong…

But! CNO neutrinos tell us metallicity of solar core

→ Flux may differ by factor of 2 between old/new metallicity

(Maybe Jupiter and Saturn `stole' metals from solar photosphere?

---Haxton and Serenelli, Astrophys.J. 687 (2008)

Gallium “Anomaly”