Solar Neutrinos: Puzzle, Neutrino Oscillations, and the Sun

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Physics 290E
April 24, 2024

Outline

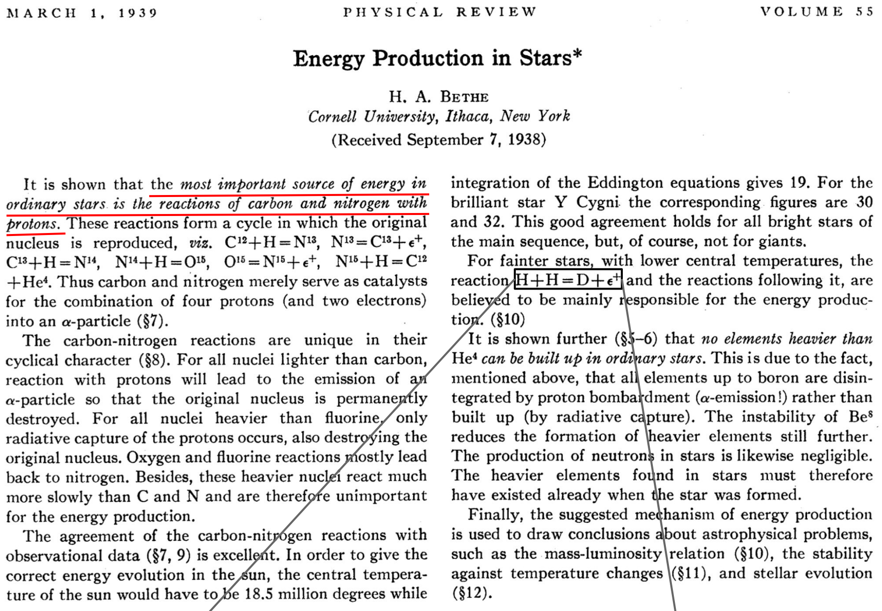
- History
  - Davis (Homestake) experiment
- Development of the anomaly
  - Kamiokande-II
  - Radiochemical experiments
  - Sudbury Neutrino Observatory
- The solution
  - Neutrino oscillations
  - MSW effect
- Are there still things to learn from solar neutrinos?
  - Borexino

History

- 1930: Pauli first proposed the existence of neutrinos while investigating radioactive beta decay

$$n \rightarrow p + e^{-} + ?$$

- 1938: Bethe proposes a model of the energy production in stars
    - First model of how the Sun works
    - Sun, and other stars alike, are mainly fueled by pp chain and CNO cycle
    - Side note: the paper mentions that the existence of B8 neutrinos is doubtful:
        - “...This nucleus is not very important for astrophysics”



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).

The carbon-nitrogen reactions are unique in their cyclical character (§8). For all nuclei lighter than carbon, reaction with protons will lead to the emission of an α-particle so that the original nucleus is permanently destroyed. For all nuclei heavier than fluorine, only radiative capture of the protons occurs, also destroying the original nucleus. Oxygen and fluorine reactions mostly lead back to nitrogen. Besides, these heavier nuclei react much more slowly than C and N and are therefore unimportant for the energy production.

The agreement of the carbon-nitrogen reactions with observational data (§7, 9) is excellent. In order to give the correct energy evolution in the sun, the central temperature of the sun would have to be 18.5 million degrees while 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 $\boxed{H+H=D+\epsilon^{+}}$ and the reactions following it, are believed to be mainly responsible for the energy production. (§10)

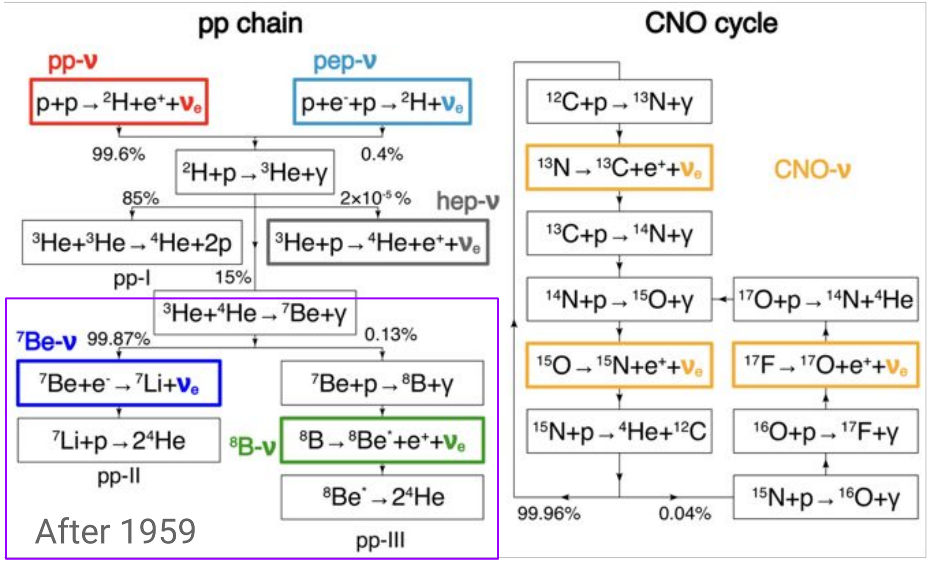
It is shown further (§5–6) that *no elements heavier than* He^{4} *can be built up in ordinary stars*. This is due to the fact, mentioned above, that all elements up to boron are disintegrated by proton bombardment (α-emission!) rather than built up (by radiative capture). The instability of Be^{8} reduces the formation of heavier elements still further. The production of neutrons in stars is likewise negligible. The heavier elements found in stars must therefore have existed already when the star was formed.

Finally, the suggested mechanism of energy production is used to draw conclusions about astrophysical problems, such as the mass-luminosity relation (§10), the stability against temperature changes (§11), and stellar evolution (§12).

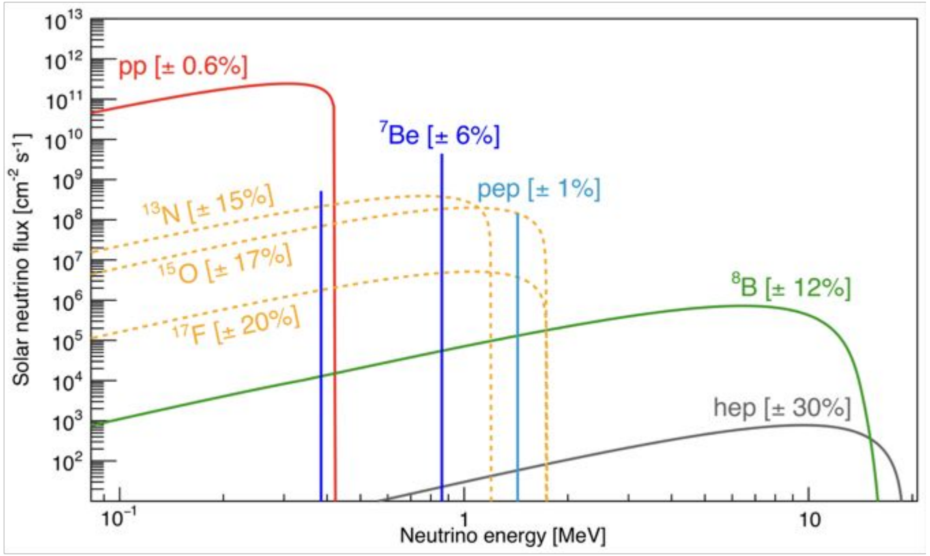
$$\boxed{H + H \rightarrow D + e^{+}}$$

Phys. Rev. 55, 434 (1949)

History cont.



After 1959



Contributes ~1% of solar energy

Figures from 2105.13858

History cont.

- 1946: Pontecorvo suggested neutrino detection using Chlorine:

$$\nu_e + \mathrm{Cl}^{37} \rightarrow e^- + \mathrm{Ar}^{37} \text{ (0.814 MeV threshold)}$$

  - Count the Ar37 radioactive decay (~35 day half-life)
- 1954-1958: Davis tried the Chlorine experiment with reactor (at the Brookhaven Graphite Research Reactor) and sets limit on solar flux
  - Assuming CNO neutrinos

$$\phi_\nu < 1 \times 10^{14}/\mathrm{cm}^2\,\mathrm{s}$$

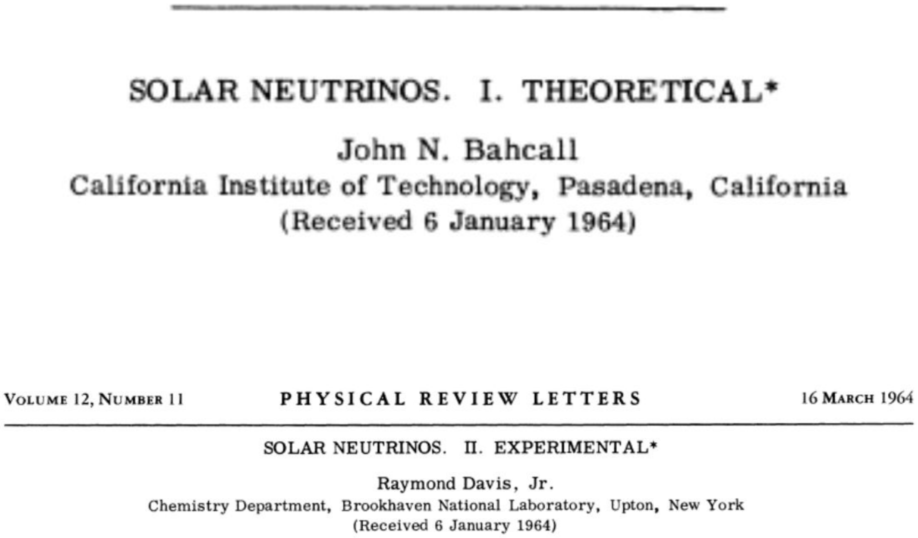
- 1959: Holmgren and Johnston reported a higher rate of reaction of (originally off by a factor ~1000):

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

Hist cont.

- 1964: Bahcall and Davis publish their twin papers to test the Standard Solar Model predictions (neutrino flux and spectra expected from the Sun)
    - Re-calculates cross section on chlorine
        - 18 times larger for B8 neutrinos than previously believed
    - Test the solar fusion hypothesis
        - “Only neutrinos, with their extremely small interaction cross section, can enable us to see into the interior of a star.”
    - Davis’ earlier limits are used to limit central core temperature of the Sun
- From the work of Holmgren and Johnston

-> Go bigger!



SOLAR NEUTRINOS. I. THEORETICAL*
John N. Bahcall
California Institute of Technology, Pasadena, California
(Received 6 January 1964)

VOLUME 12, NUMBER 11 PHYSICAL REVIEW LETTERS 16 MARCH 1964

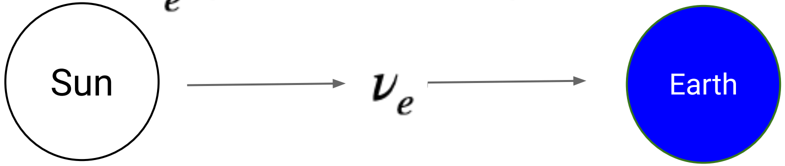
SOLAR NEUTRINOS. II. EXPERIMENTAL*
Raymond Davis, Jr.
Chemistry Department, Brookhaven National Laboratory, Upton, New York
(Received 6 January 1964)

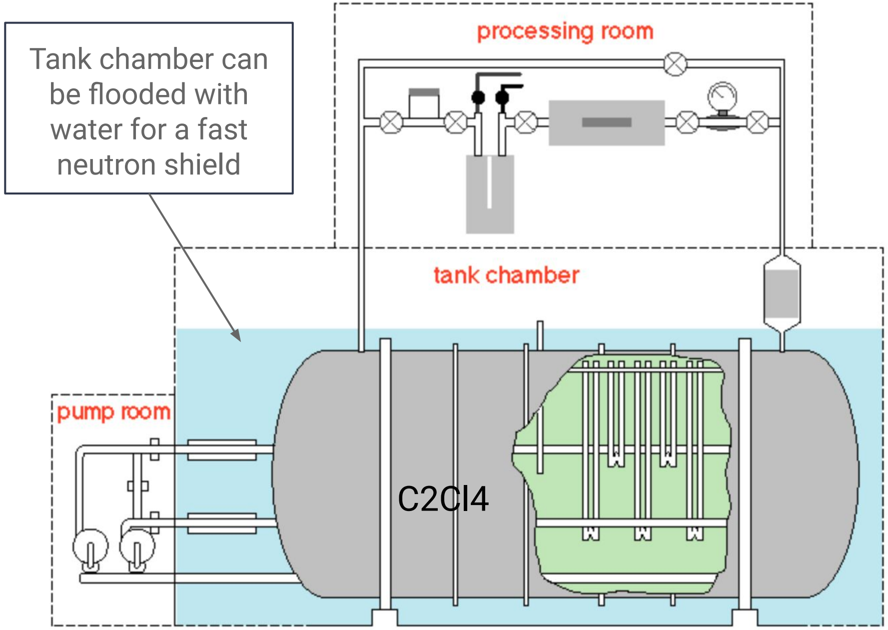
Phys. Rev. Lett. 12, 300 (1964) and
Phys. Rev. Lett. 12, 303 (1964)

Davis (Homestake) experiment

- 615 tons of cleaning fluid (C2Cl4) are stored in a tank chamber at 4850 ft underground in Homestake mine, South Dakota
    - Shield from cosmic rays
- Davis bubbled helium through the tank to collect the argon than formed
- A small gas counter was filled by the collected few tens of atoms to detect its decays

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





Tank chamber can be flooded with water for a fast neutron shield

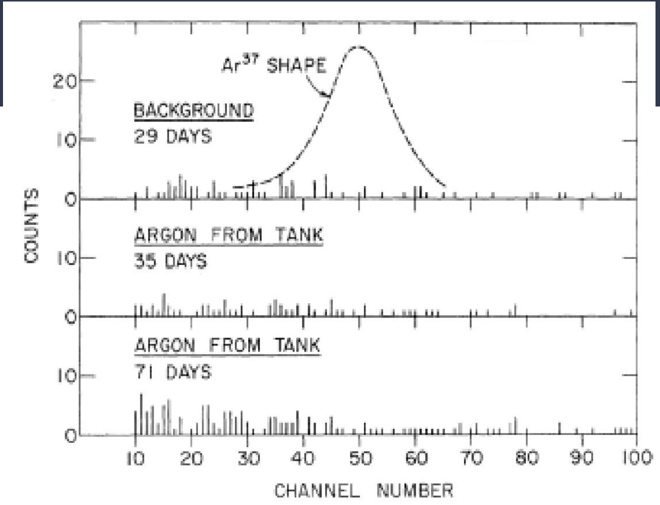
Davis (Homestake) experiment cont.

- Results: all counts consistent with cosmogenic and other backgrounds

$$\phi_{B8} < 2 \times 10^6/\text{cm}^2\text{s}$$

    - Prediction relies on many assumptions (i.e. nuclear physics ranging many keV-energies, solar composition, …)
- 1971+: Find non-zero counts (in a proceeding) show a deficit of ⅓ of the expected number of solar neutrinos detected!
    - Measured: 2.56 ± 0.23 SNU
    - Expected: 7.3 ± 2.3 SNU

SNU = 1 capture/s/10^36 target atoms



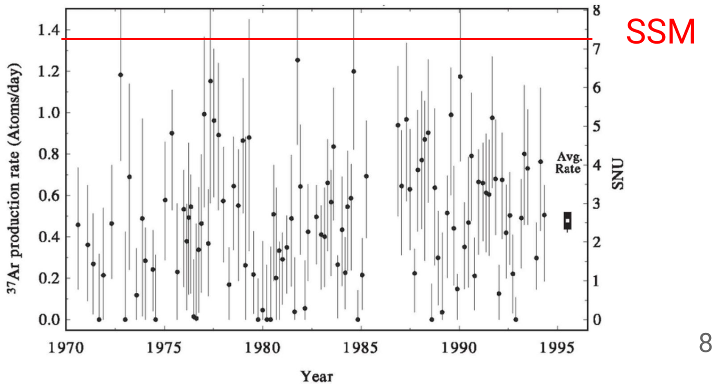
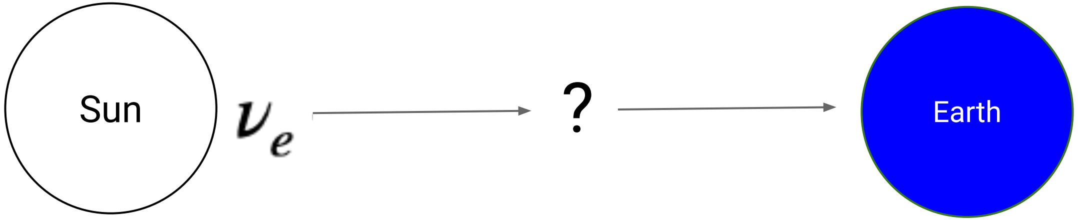


Figure from Phys. Rev. Lett. 20, 1205 (1968) and ApJ **496** 505

Development of the anomaly

- Only ⅓ of the expected number of solar neutrinos detected!
- Start of the Solar Neutrino Puzzle
    - Does the Homestake experiment suffer from some large systematic error (measurement of Davis)?
    - Is the Standard Solar Model wrong (Bachall’s calculation)?
        - What is going on in the Sun?
    - *Do neutrinos oscillate among different neutrino flavors along their flight?*
    - Something else is happening to the solar neutrinos?

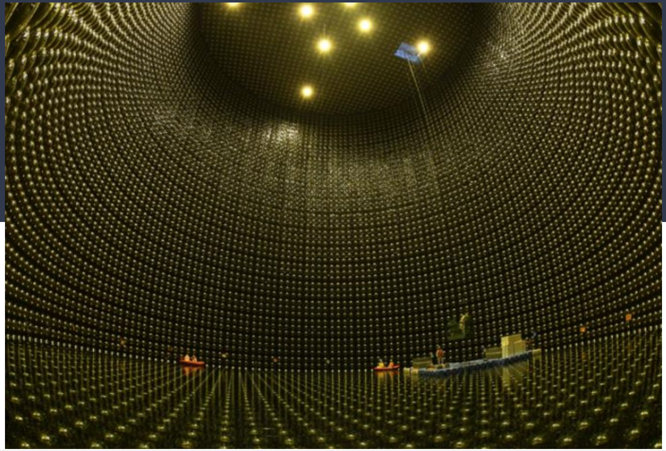


Kamiokande-II

- 1983: Originally a proton decay experiment in Kamioka Mine in Japan
    - 2340 tons of pure water
- Altered the electronics to allow for measurements of much lower energy events (<10 MeV)

$$\nu + e^- \rightarrow \nu + e^-$$

- 1988: They measured neutrinos as well, and they wound up with the same results as Davis
    - Also noticed a deficit in the solar neutrino flux



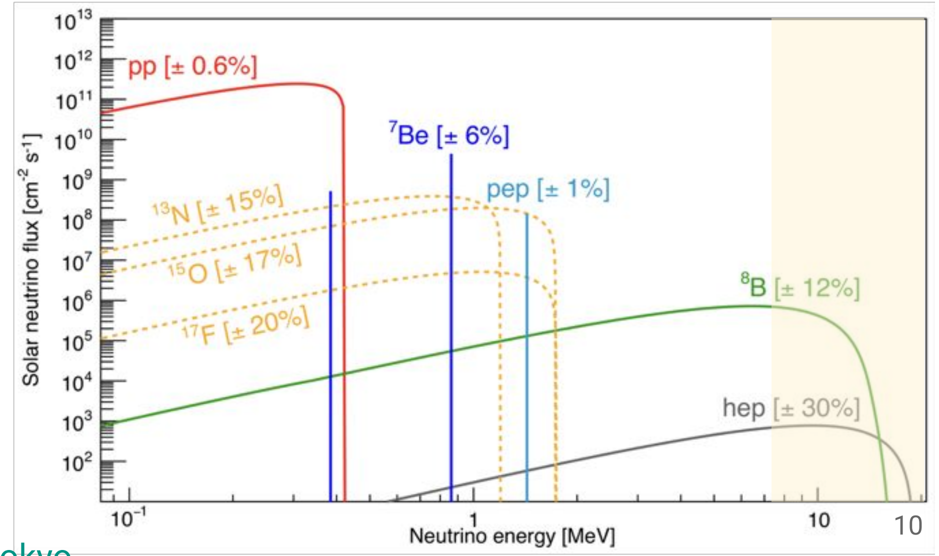


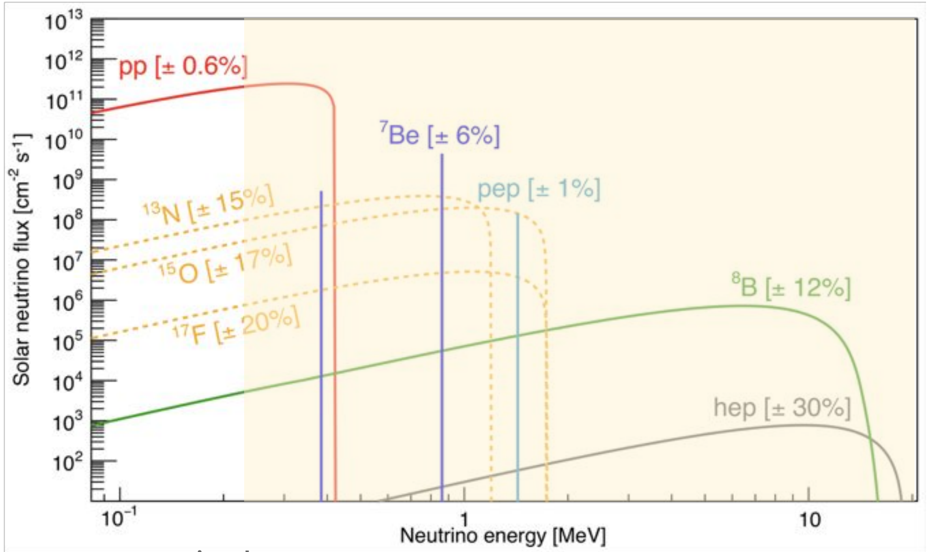
Photo credit Kamioka Observatory, ICRR, The University of Tokyo

Solar neutrino radiochemical experiments

- Similar to the Davis experiment, only now with Gallium

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

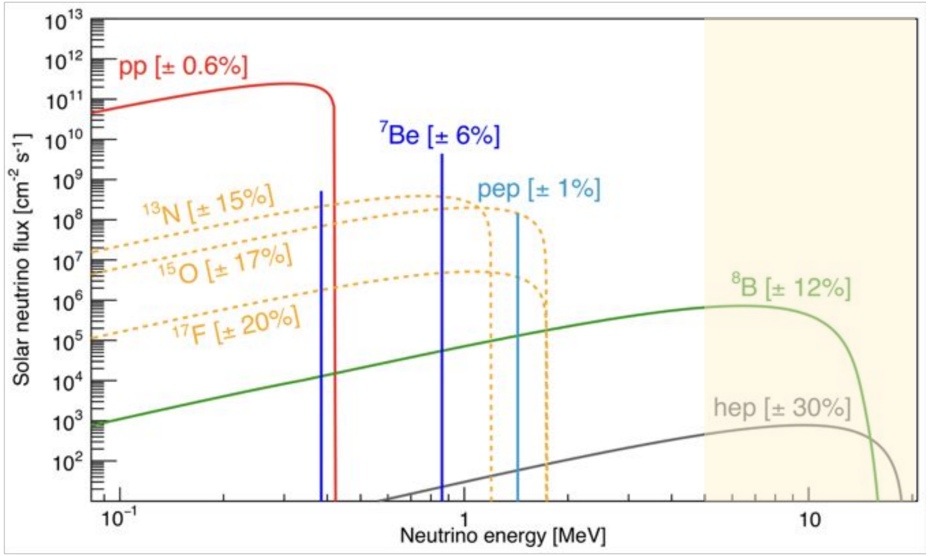
  - Has a threshold of 233 keV
- 1991: Relevant experiments are GALLEX and SAGE
- First time you can begin to measure pp neutrinos
- Gallium experiments confirm the deficit observed by Davis experiment
  - Measured: 65 ± 7 SNU (SAGE), 69 ± 7.7 SNU (GALLEX)
  - Expected: ~ 130 SNU



See a suppression!

Sudbury Neutrino Observatory (SNO)

- 1999: SNO is a 1000 ton heavy water Cherenkov detector located 2 km underground in the Creighton Mine near Sudbury, Ontario, Canada
- Three detection channels available. Can separate the electron neutrino and heavy-flavor components of the 8B solar neutrino flux

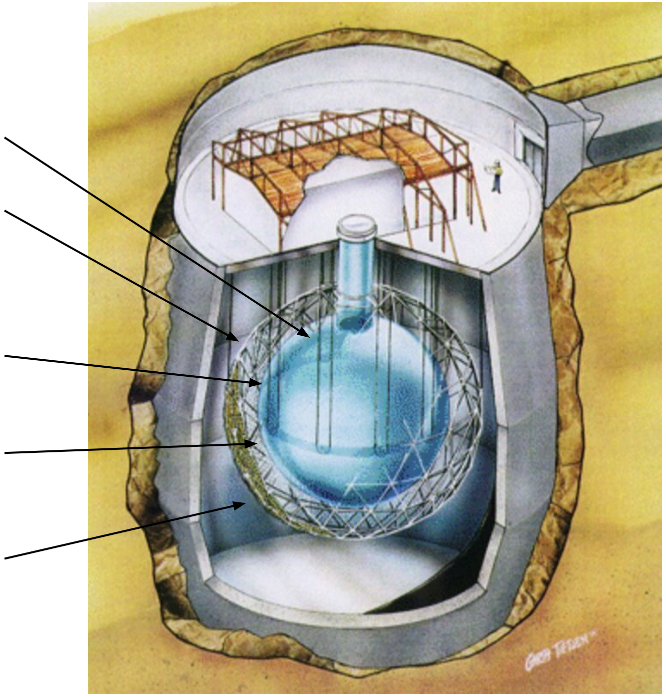


$$\nu_e + d \rightarrow e^- + p + p$$ (CC)

$$\nu_x + d \rightarrow \nu_x + n + p$$ (NC, threshold 2.2 MeV)

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

SNO cont.



1000 tons of D2O

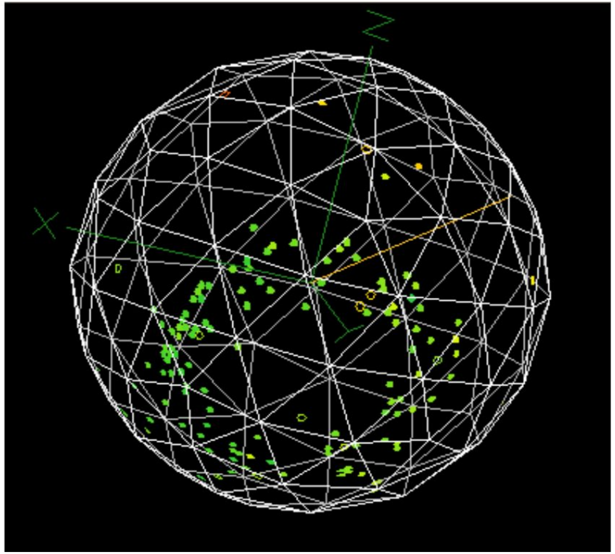
Support structure for 9500 PMTs

12 m diameter acrylic vessel

1700 tons inner water shield

5300 tones outer water shield

Figure from 1602.02469



$$\nu_e + d \rightarrow e^- + p + p$$
$$\nu_x + e^- \rightarrow \nu_x + e^-$$
$$\nu_x + d \rightarrow \nu_x + n + p$$

SNO results

- There were 3 main data-taking campaigns spanning from 1999 to 2006
- Take the three fluxes that SNO measures and plot what fraction of the flux coming from electron and muon plus tau neutrinos
- Tells you that ⅓ of the neutrinos that are arriving on Earth are electron neutrinos and ⅔ are muon and/or tau neutrinos
- So Davis actually got the right answer, but the other neutrinos that were predicted by a model had transmuted into different neutrinos, evading detection!

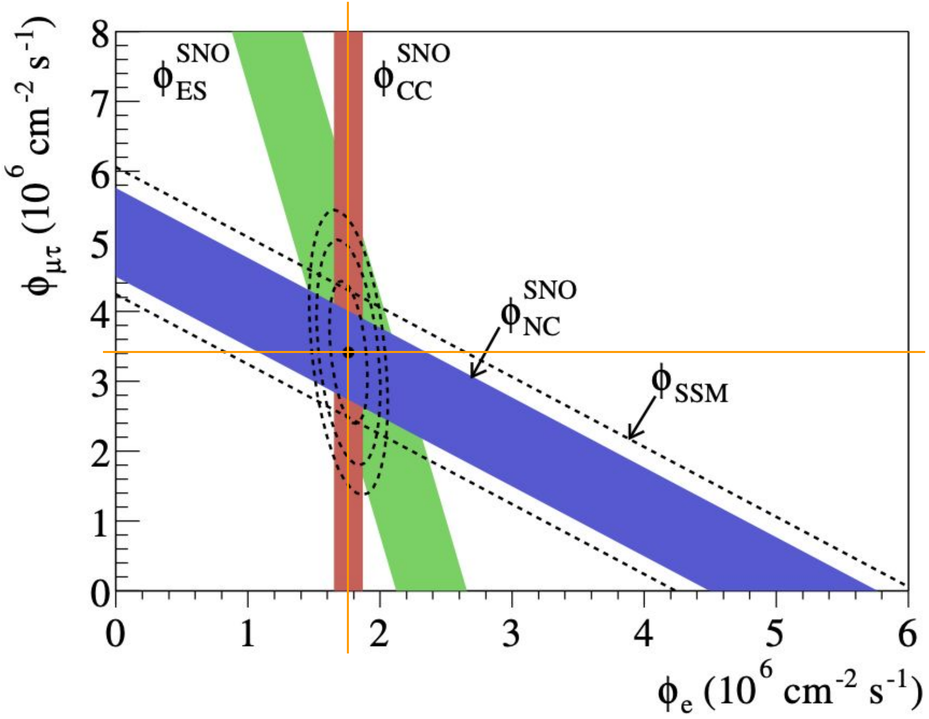


Figure from 1602.02469

Neutrino oscillations

- 1968: Numerous ideas suggesting possible “solutions”, among them is Gribov and Pontecorvo’s suggestion of neutrino oscillations. Would require there to be neutrino mass and flavor mixing

$$|\nu_{m_1}\rangle, |\nu_{m_2}\rangle \neq |\nu_e\rangle, |\nu_\mu\rangle$$

E.g. for the mixing of just two flavors

$$|\nu_e\rangle = \cos(\theta_{12})|\nu_1\rangle \; + \; \sin(\theta_{12})|\nu_2\rangle$$

$$|\nu_\mu\rangle = -\sin(\theta_{12})|\nu_1\rangle \; + \; \cos(\theta_{12})|\nu_2\rangle$$

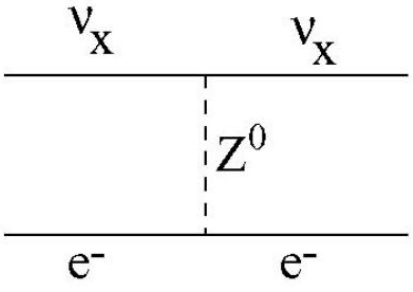
$$P(\nu_e \rightarrow \nu_e) = 1 - \sin^2(2\theta_{12}) \times \sin^2\left(1.27 \times \Delta m^2 \frac{L}{E}\right)$$

$\text{For } 1.27\Delta m^2\frac{L}{E} = \frac{\pi}{2}, P(\nu_e \rightarrow \nu_e) \rightarrow 1 - \sin^2(2\theta_{12})$ Assumed that the mixing angle is small

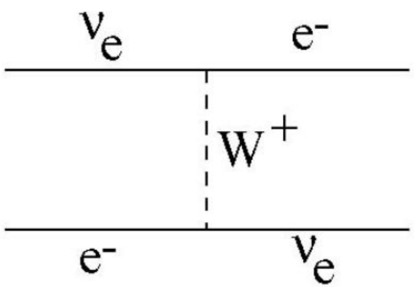
$\text{For } \Delta m^2 << \frac{E}{L}, P(\nu_e \rightarrow \nu_e) \rightarrow 1$ No change

MSW Effect

- 1978: Wolfenstein, Mikheyev, and Smirnov showed the oscillation probability can increase as they pass through matter. Neutrinos in matter are subject to a potential due to forward scattering with the medium (electrons and nucleons):



NC: All neutrino flavors



CC: Only electron neutrinos

$$\langle \nu_e | H_W | \nu_e \rangle = \sqrt{2} G_F N_e$$

Bulk matter treated as a potential term

MSW Effect cont.

- Hamiltonian matrix now has new ‘matter’ eigenvalues and eigenvectors depend on the matter density and on the neutrino energy. Notably the mixing angle in matter is given by

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

- A resonance condition can be seen (satisfied either by having the right energy or by the varying matter density in the Sun)

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

Provides a way to large electron neutrino suppression even with if you assume small mixing angles

Do we still study solar neutrinos?

Sun

Astrophysics

Particle physics

Solar neutrinos as messengers
Main purpose:

- Test and study stellar models
- Metallicity in the solar core
- Search for dark matter

Sun as neutrino source
Flavor oscillations physics:

- Precise measurement of neutrino oscillation parameters

Borexino

- A liquid scintillator with around 300 ton inner vessel located in the Gran Sasso Laboratory in Italy.
    - 1400 meters underground
- 2212 PMTs are attached to the stainless steel sphere
- ~ 1 kton external water tank
- With a high light yield of a liquid scintillator, the detector is sensitive to sub-MeV solar neutrinos

$$\nu + e^- \rightarrow \nu + e^-$$

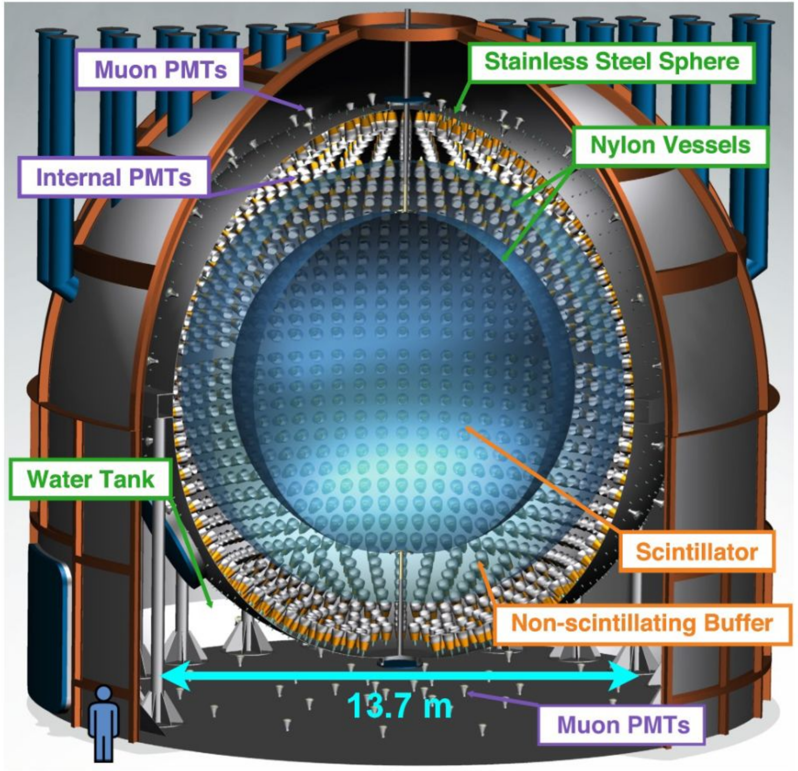


Figure from 2307.14636

Borexino results

- Spectrum of the Borexino data
- First direct measurements of CNO neutrinos
- The CNO cycle has a strong dependence on the assumed metallicity model (low-Z or high-Z) and hence it is a direct probe to the solar metallicity
  - The CNO neutrino flux can vary ~30% with different metallicity considerations

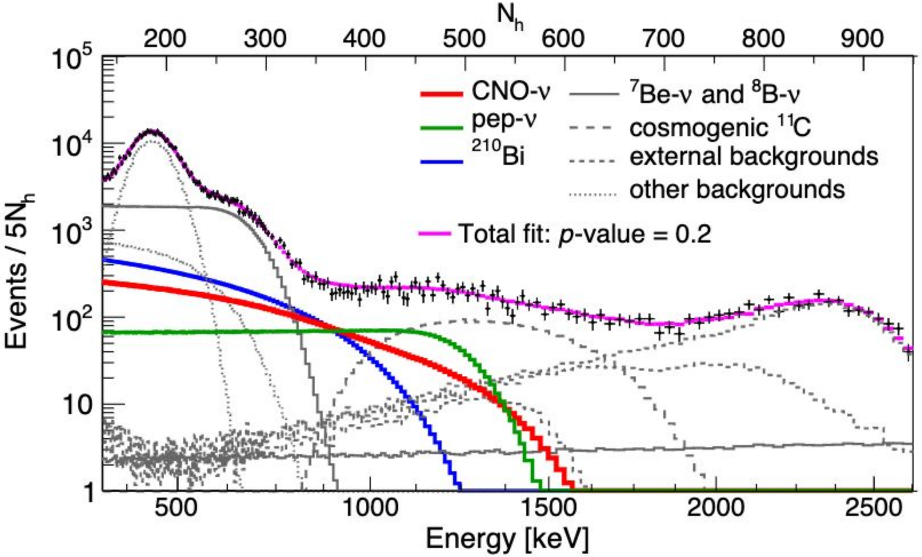


Figure from 2307.14636

Summary

- The Sun is a large source of neutrinos that have been measured a variety of ways
- A long road from anomalous results into interesting physics being found
  - Discovered that neutrinos have mass and oscillate
- There is still things to be known with regards to the details of how the Sun is being powered

References

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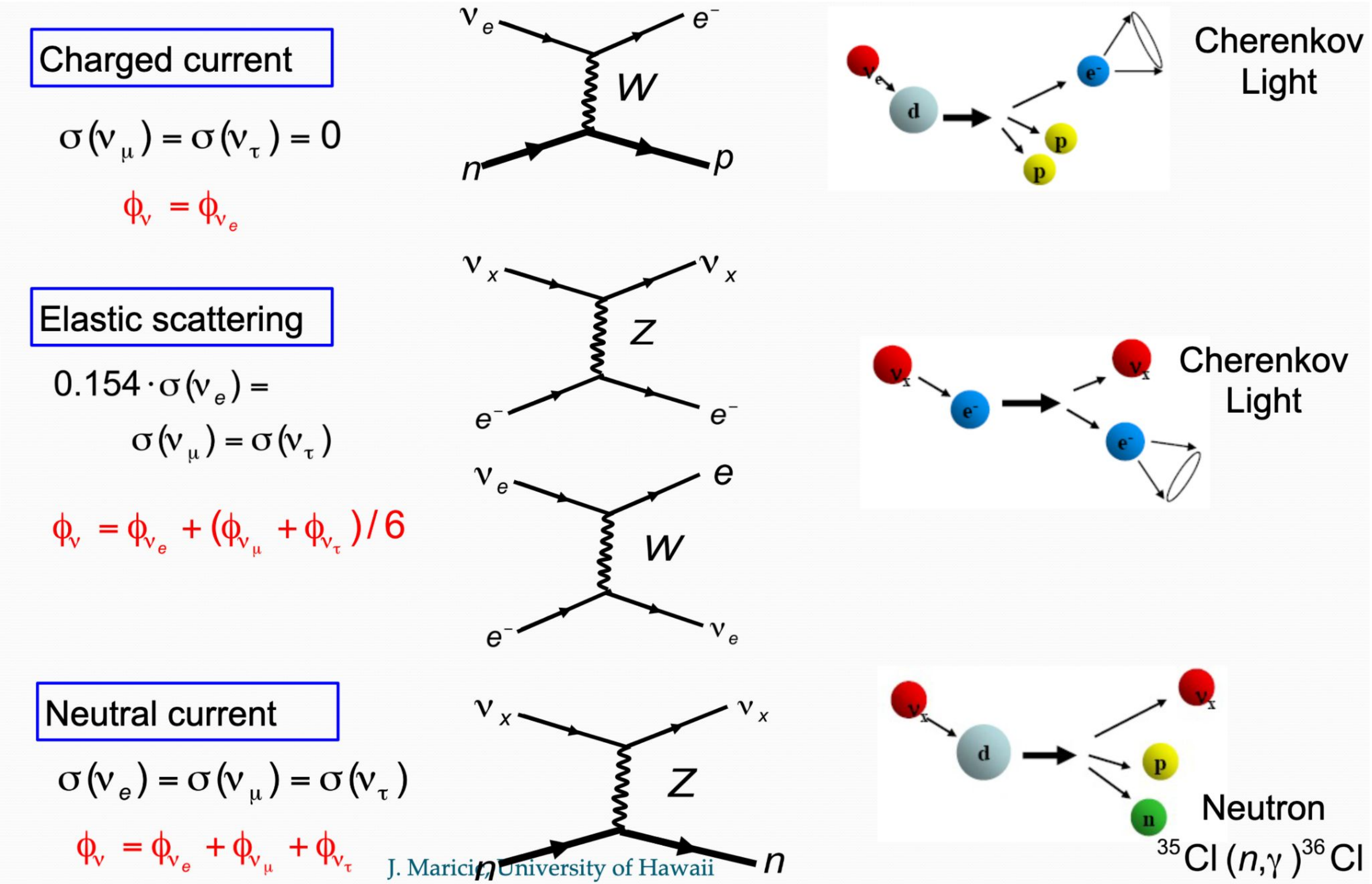
Backup

$$\phi_{\mathrm{CC}}^{\mathrm{SNO}} = 1.76^{+0.06}_{-0.05}(\mathrm{stat})^{+0.09}_{-0.09}(\mathrm{syst})\,,$$
$$\phi_{\mathrm{ES}}^{\mathrm{SNO}} = 2.39^{+0.24}_{-0.23}(\mathrm{stat})^{+0.12}_{-0.12}(\mathrm{syst})\,,$$
$$\phi_{\mathrm{NC}}^{\mathrm{SNO}} = 5.09^{+0.44}_{-0.43}(\mathrm{stat})^{+0.46}_{-0.43}(\mathrm{syst})\,.$$

Phys. Rev. Lett. 89
(2002) 011301



Charged current

$\sigma(\nu_\mu) = \sigma(\nu_\tau) = 0$

$\phi_\nu = \phi_{\nu_e}$

Elastic scattering

$0.154 \cdot \sigma(\nu_e) = \sigma(\nu_\mu) = \sigma(\nu_\tau)$

$\phi_\nu = \phi_{\nu_e} + (\phi_{\nu_\mu} + \phi_{\nu_\tau})/6$

Neutral current

$\sigma(\nu_e) = \sigma(\nu_\mu) = \sigma(\nu_\tau)$

$\phi_\nu = \phi_{\nu_e} + \phi_{\nu_\mu} + \phi_{\nu_\tau}$

Cherenkov Light

Cherenkov Light

Neutron

$^{35}\mathrm{Cl}(n,\gamma)^{36}\mathrm{Cl}$

J. Maricic, University of Hawaii

Slide from J. Maricic, University of Hawaii [International neutrino summer school]

Broad overview

1963

Publication of the first complete solar model by a team of Caltech researchers (Bahcall, Iben, and Sears)

1964

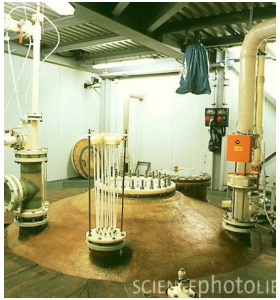
Bahcall convinces Davis to publish simultaneous papers suggesting a Chlorine-based experiment to test Bachall's Standard Solar Model predictions

1968

Davis finds an upper bound on the flux of neutrinos ⅓ Bahcall's predicted value.

1989

Kamiokande II publishes the first "real time" solar neutrino detection, correlated with the Sun's position.

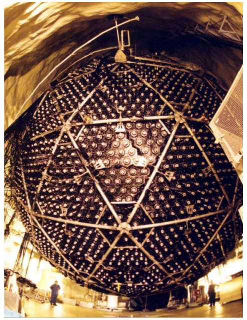


1990s

Gallium experiments (GALEX and SAGE) publish results showing a deficit

2001

SNO sees neutral current 'appearance' of oscillated neutrinos



2002

KamLAND puts the final nail in the coffin by observing disappearance with a terrestrial source