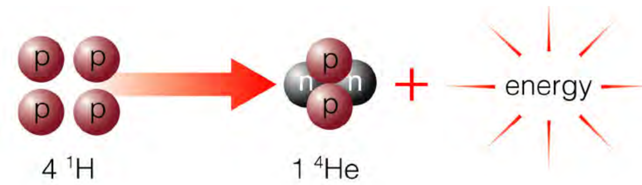
Agenda for Ast 309N, Sep. 6

- Feedback on card of 9/04
- Internal structure of the Sun
- Nuclear fusion in the Sun (details)
- The solar neutrino “problem” and its solution
- Index card: photons vs. neutrinos
- Next Tuesday: review basic properties of light

The Sun’s Core: Site of Nuclear Fusion



- The Sun generates energy via *fusion* reactions
- Hydrogen is converted into Helium in the Sun’s core (innermost regions, out to about 0.25 $R_{\odot}$)
- The helium has less mass than the initial 4 H nuclei
- The difference in mass (sometimes called the “mass defect”) is converted into energy, according to $E = m c^2$

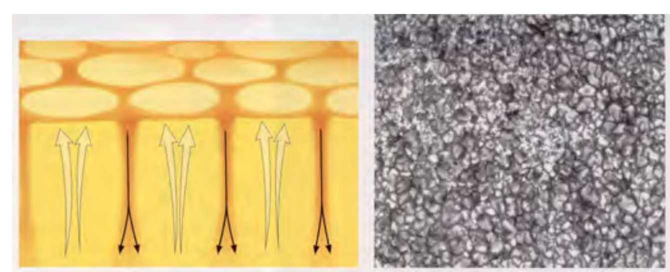
Transporting Energy by Radiation

- Deep in the Sun, energy is transported by photons which are absorbed, then re-emitted by the atoms
- With each such interaction, they can change direction (*random walk*), *and* energy (hence wavelength)

- This “random walk” is a slow process! It takes about a hundred thousand years for the energy to reach the surface.

Transporting Energy by Convection

- Photons from below are absorbed by an opaque layer that effectively “blocks” radiative transport
- This layer is strongly heated, causing hot gas to rise up and cooler gas to sink …a convection current
- The net effect is that energy is carried upward along with the moving material

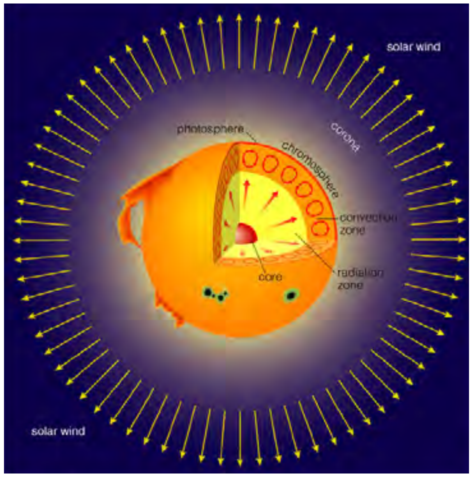


Summary: Inner Layers of the Sun

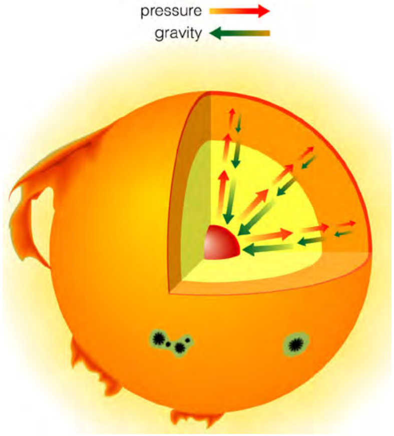
Convection Zone: where the energy is transported by rising cells of hot gas

Radiative Zone: region where energy is transported mainly by photons

Core: where the energy is created by nuclear fusion



Inside the Sun: Striking a Balance

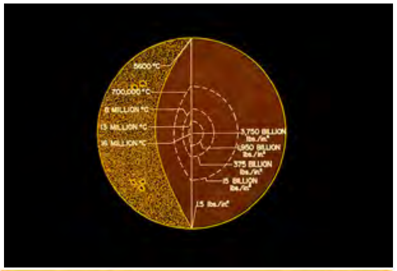


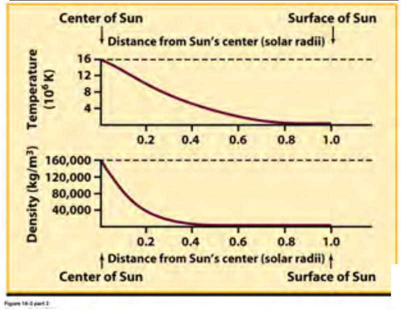
There must be a stable balance between inward (gravity) and outward forces (resistance to compression due to thermal pressure), for the Sun to stay in equilibrium, neither collapsing nor blowing itself apart!

How did the Sun reach its present state?

- The Sun began as a cloud of gas, contracting under gravity. It had the same composition throughout, a mixture of approximately 75% H, 25% He by mass.
- The contraction released energy that was ultimately converted to thermal energy, heating the central regions.
- When the center became hot and dense enough, H began fusing into He, supplying a new energy source. This fuel will last until all the H is converted into He, *in the core, the region that's hot enough for fusion*.
- This energy kept up the outward pressure to balance gravity's inward force, so the Sun achieved a long-term balance, with its present radius and luminosity.

Models of the Solar Interior





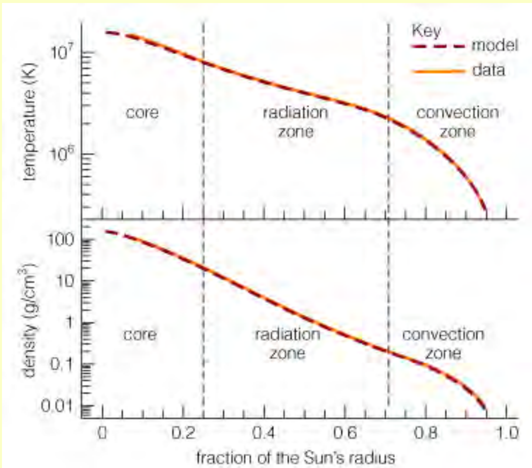
Changing conditions with greater depth:

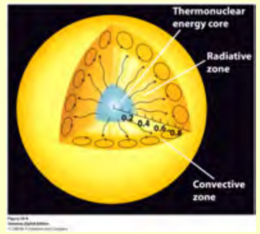
The deeper levels must be hotter and denser, to support the layers above.

– pressure is strongest where gravity is strongest (in the central regions)

– the pressure is weakest where gravity is weakest (near the surface)

Current Solar Model

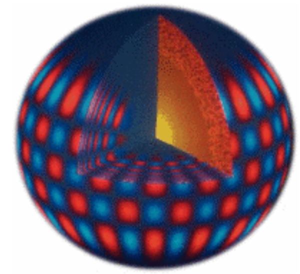




Current models of the Sun explain observed solar vibrations

They also predict the nuclear fusion reaction rate, hence the number of neutrinos emitted

Helioseismology: A Tool for Studying the Solar Interior

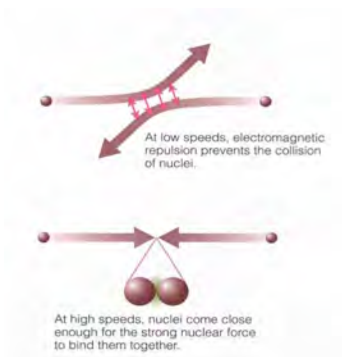


http://solarscience.msfc.nasa.gov/helioseismology.shtml

http://solarscience.msfc.nasa.gov/interior.shtml

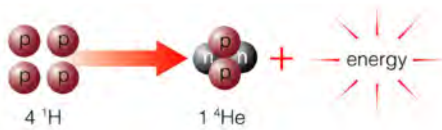
Why Fusion Happens Only in the Core

- Both nuclei have positive charge, so they repel each other.
- For fusion to occur, the nuclei must have enough kinetic energy to overcome this repulsion
- High kinetic energy means high temperature (and pressure)
- When the nuclei get close enough, the strong nuclear force overcomes the repulsion and fuses the nuclei together

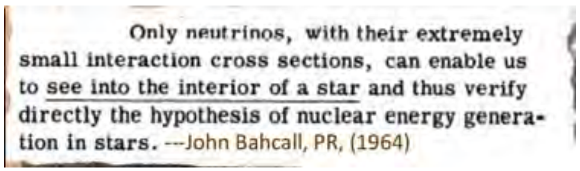


Solar neutrinos star in a Hollywood disaster movie: junk science !

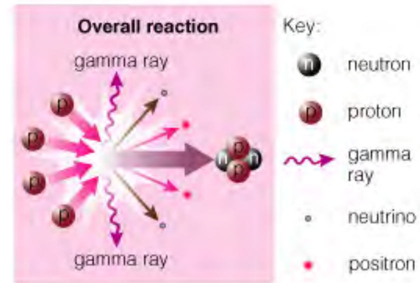
The **Real** Story of Solar Neutrinos



- Starting in the 1950's, astronomers proposed that the Sun and stars produce energy by nuclear fusion
- But we do not directly see this happening – why not?
- Is there a way we can be sure about it?


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. ---John Bahcall, PR, (1964)

Hydrogen Fusion into Helium



IN	***OUT***	
4 protons	^{4}He nucleus 2 gamma rays 2 positrons 2 neutrinos	*Converted mass (called the "mass defect") is 0.7% of the initial mass*

Neutrons and Protons

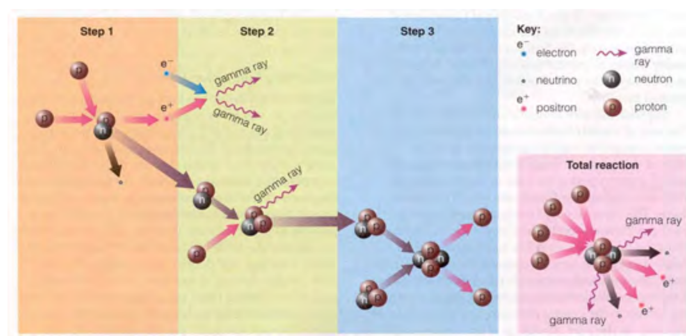
Neutrons can change into protons, and vice versa.

$$n \longrightarrow p^+ + e^- + \bar{\nu}_e \qquad (\beta\text{-decay})$$

$$p^+ \longrightarrow n + e^+ + \nu_e \qquad (\text{inverse } \beta\text{-decay})$$

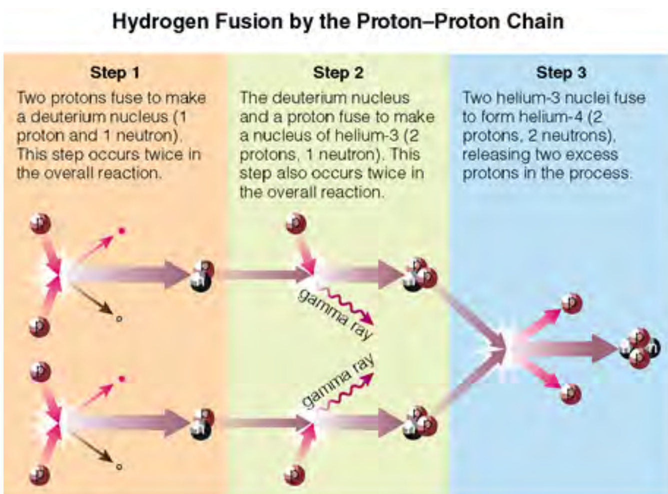
ν_e is a **neutrino** ---- a weakly interacting particle which has low mass and travels at nearly the speed of light.

Hydrogen Fusion in the Sun

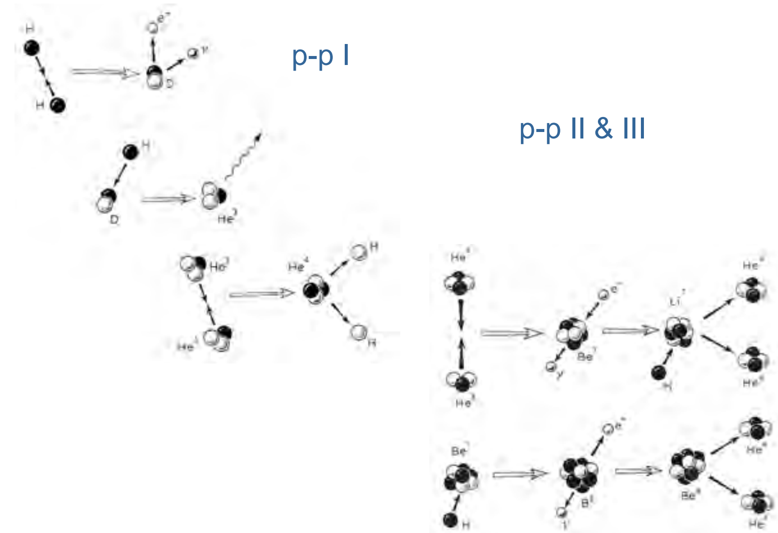


In the first step of the p-p chain, a proton turns into a neutron, yielding deuterium, a positron (anti-electron), and neutrino. The positron is anti-matter; when it meets an electron, they "annhilate," and all their mass turns into energy (photons).

The "Main Highway" of H fusion (p-p I)

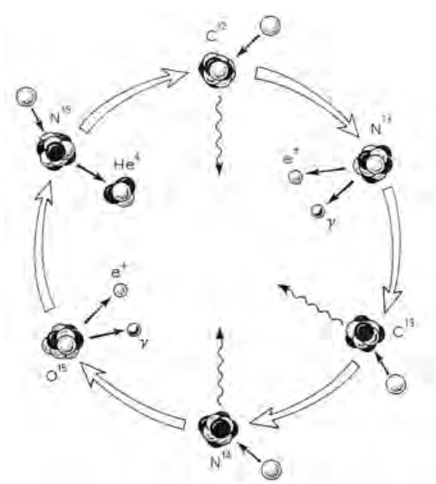


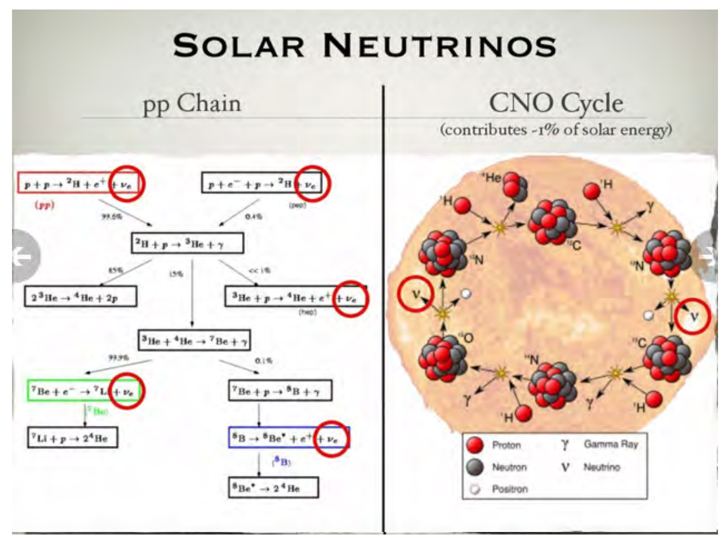
"Side Roads" of the p-p reaction



H Fusion via the CNO Cycle

Only a small fraction (1%) of the fusion in the Sun occurs via the CNO cycle, but it is the main fusion reaction in high mass stars





Credit: G. Orebi Gann, APS presentation (see slide 34)

The Hunt for Solar Neutrinos I. - The Davis Experiment

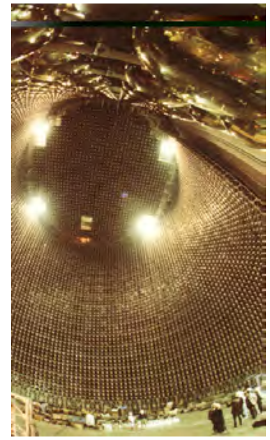
An experiment started in the late 1960's in the Homestake, S.D. gold mine, detected neutrinos via:

$Cl + \nu \rightarrow Ar$

They found only about 1/3rd of the expected number of neutrinos.

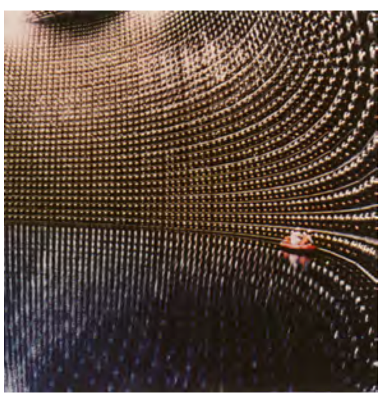
This discrepancy came to be known as **the solar neutrino problem.**

The Hunt for Solar Neutrinos II. – (the original) Kamiokande



Using a large tank of H_2O to detect ν-e^- collisions via light flashes,(Cerenkov radiation), Kamiokande proved that the ν's came from the Sun, but also saw "too few" of them.

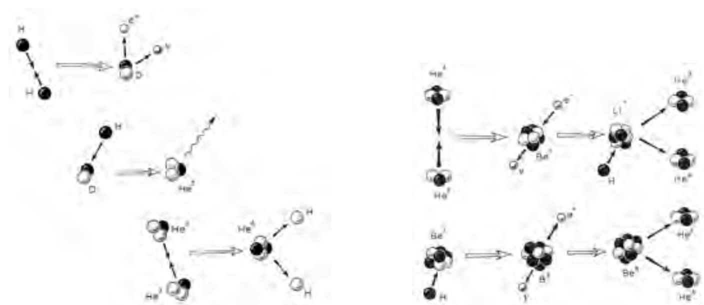
Solar ν's: Super Kamiokande



An accident in 2001 blew out most of the sensors; but they were repaired, and operations resumed

Which Neutrinos Could they See?

Both the Davis and Kamiokande experiments could detect only *high-energy* neutrinos; they could not detect the neutrinos produced in the first step of the p-p chain (which makes deuterium), but only some of the rare ones made by the alternate paths, p-p II and p-p III.



Neutrinos of Different Energies

Solar Neutrino Fluxes

The spectrum of solar neutrinos that is predicted by the standard solar model is shown in the graph below. The basic low-energy neutrino fluxes, from *pp* and *pep* neutrinos, are most closely related to the total solar luminosity and are calculated to an estimated accuracy of about 1 percent. These reactions initiate the nuclear fusion chain in the Sun and produce neutrinos with a maximum energy of 0.4 MeV (*pp* neutrinos) or an energy of 1.4 MeV (*pep* neutrinos). Electron-capture by ^{7}Be ions produces the next most abundant source of neutrinos, a 0.86 MeV neutrino line, whose flux has an estimated theoretical error of 6 percent. Neutrinos from the beta decay of ^{8}B can have energies as high as 14 MeV; they are rare and their flux is calculated to an estimated accuracy of only 15 percent.

pp: $p + p \rightarrow {}^2\mathrm{H} + e^+ + \nu_e$

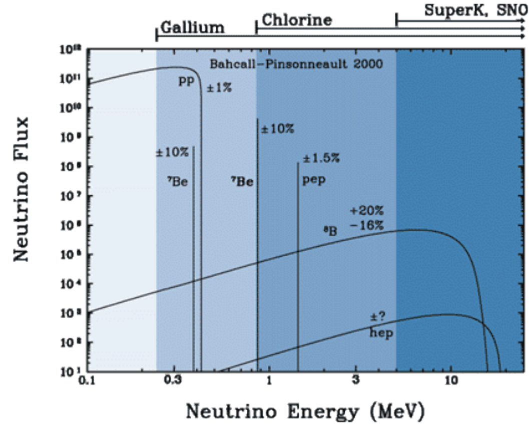
pep: $p + e^- + p \rightarrow {}^2\mathrm{H} + \nu_e$

^{7}Be: $^7\mathrm{Be} + e^- \rightarrow {}^7\mathrm{Li} + \nu_e$

^{8}B: $^8\mathrm{B} \rightarrow {}^8\mathrm{Be} + e^+ + \nu_e$

The Solar Neutrino "Spectrum"

The shaded areas show which neutrinos can be detected by different methods or experiments: Davis (chlorine), SuperK (water), and gallium.

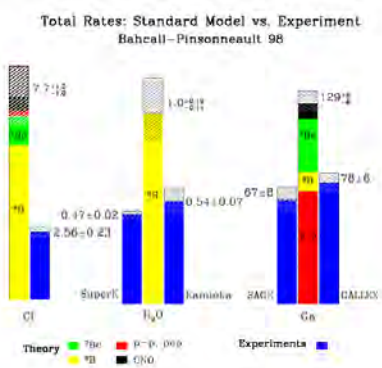


Chasing the Low-Energy Neutrinos: The Gallium Experiments

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

The Solar Neutrino Problem

TOO FEW SOLAR NEUTRINOS DETECTED COMPARED TO PREDICTIONS FROM MODELS



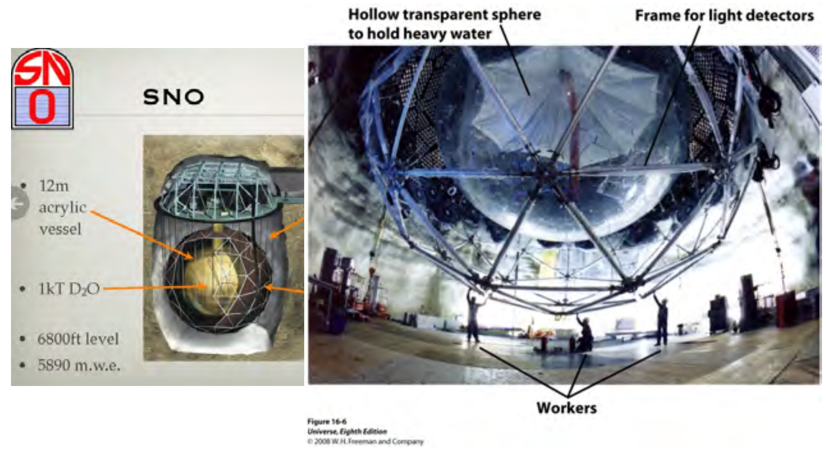
The Solution: Neutrino Oscillations

- Solar fusion reactions create only one type of neutrinos, “electron neutrinos” but two other kinds (muon, tau) exist
- Some people theorized that some of the neutrinos were changing into other kinds *en route* from the Sun’s core
- The Davis experiment could see only electron neutrinos
- Kamiokande was used to detect a beam of neutrinos coming from 250 km away (“Kam-LAND”), proving that the neutrinos were indeed changing their types.

ν_e ν_μ ν_μ ν_τ

Sudbury Neutrino Observatory (SNO)

The definitive experiment; in Sudbury, Ontario (Canada)



Sudbury Neutrino Observatory (SNO)

Used heavy water (D_2O) as the detector

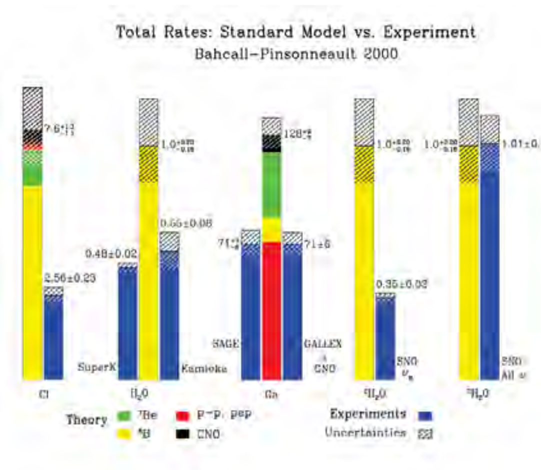
Counted ν_x, ν_e separately: (ν_x means any ν)

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

$D + \nu_x \rightarrow p + n + \nu_x$

Two experiments in one: could clearly see how many of the solar ν ‘s “oscillate”

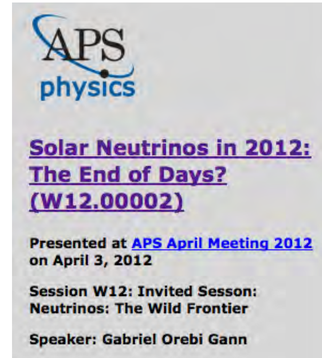
SNO proves the predictions were right!

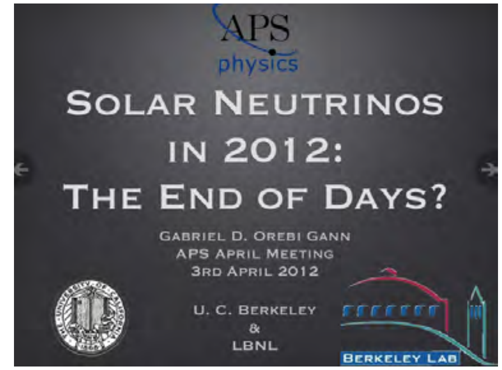


The blue bar (measurement by SNO) is the same height as the yellow bar (theory), within the uncertainty (shaded region)

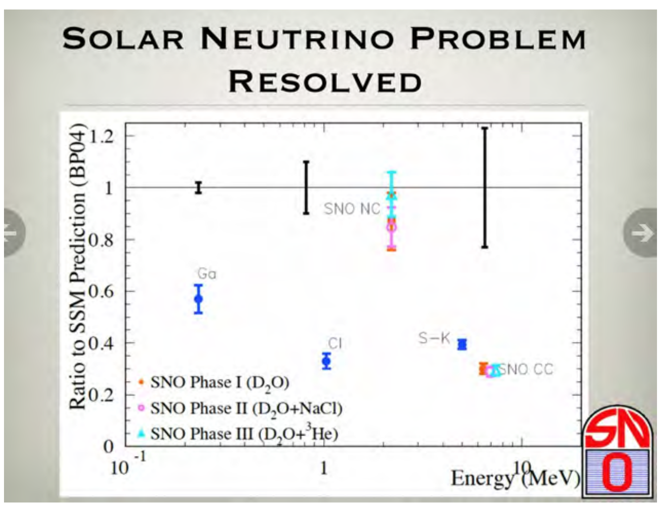
Nobel Prize in Physics, 2002

Was shared by Ray Davis (left) and M. Koshiba (leader of the Kamiokande and KamLAND team) for their major discoveries about the Sun and the nature of neutrinos





The full, highly technical presentation is posted at http://absuploads.aps.org/presentation.cfm?pid=10380



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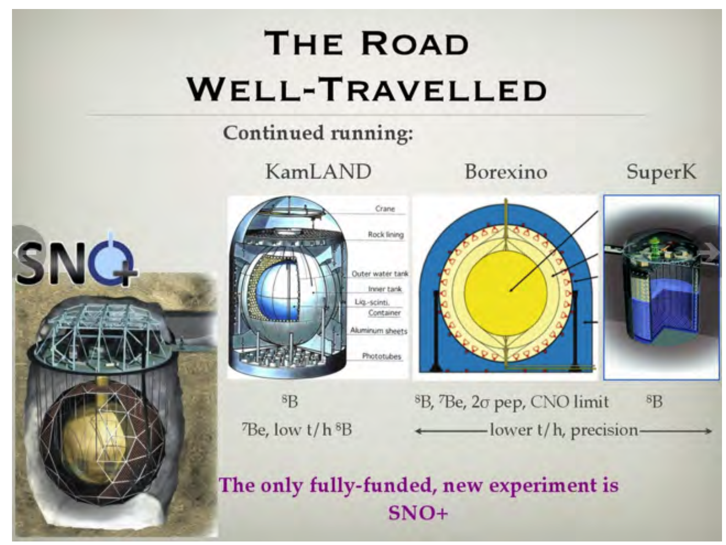

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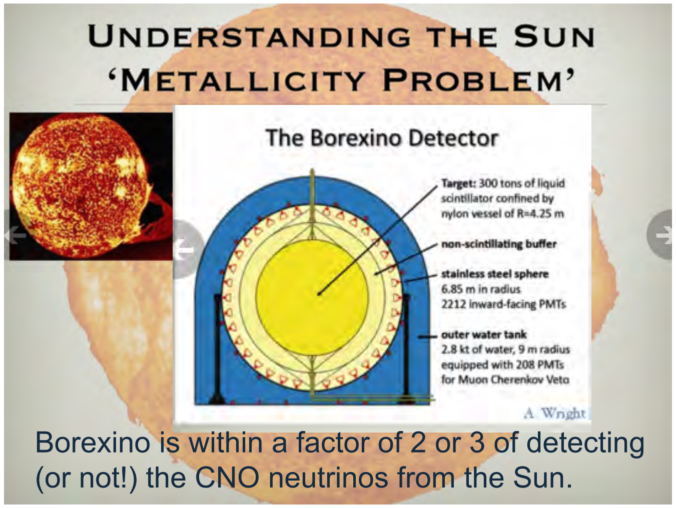

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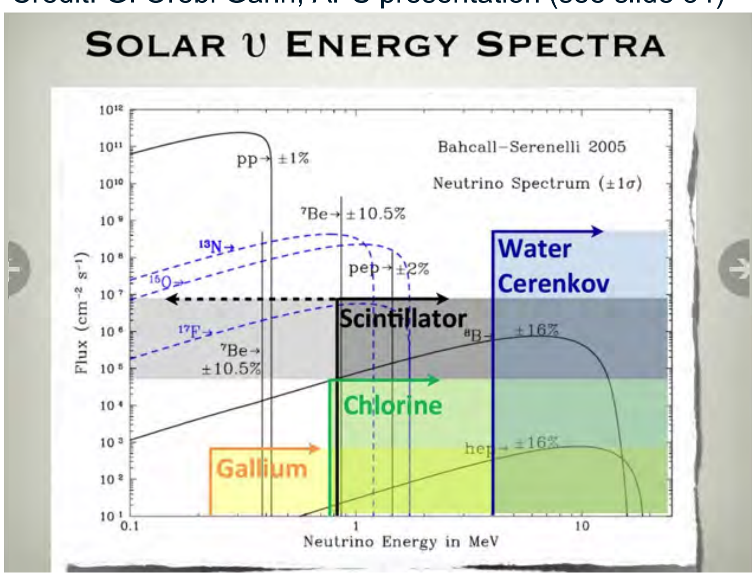

Neutrinos, by John Updike

Neutrinos: they are very small
They have no charge; they have no mass;
They do not interact at all.
The Earth is just a silly ball
To them, through which they simply pass
Like dustmaids down a drafty hall
Or photons through a sheet of glass.
They snub the most exquisite gas,
Ignore the most substantial wall,
Cold shoulder steel and sounding brass,
Insult the stallion in his stall,
And, scorning barriers of class,
Infiltrate you and me. Like tall
And painless guillotines they fall
Down through our heads into the grass.