THE SUN

Our own star

HOW DOES THE SUN SHINE?

- The sun is a mass of incandescent gas
- A gigantic nuclear furnace
- Where hydrogen is built into helium
- At a temperature of millions of degrees

- The Sun is hot the sun is not
- A place where we could live
- But here on Earth there'd be no life
- Without the light it gives

Sung by John Flansburgh
& John Linnell
They Might Be Giants
Severe Tire Damage

HOW DOES THE SUN SHINE?

- We need its light
- We need its heat
- The sunlight that we see
- The sunlight comes from our own sun's
- Atomic energy

- The sun is a mass of incandescent gas
- A gigantic nuclear furnace
- Where hydrogen is built into helium
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HOW DOES THE SUN SHINE?

- The sun is hot
  - It is so hot that everything on it is a gas: aluminum, copper, iron, and many others.
- The sun is large
  - If the sun were hollow, a million Earths would fit inside. And yet, it is only a middle-sized star.
- The sun is far away
  - About 93 million miles away, and that's why it looks so small.

HOW DOES THE SUN SHINE?

- For even when it's out of sight
- The sun shines night and day

- We need its heat
- We need its light
- The sunlight that we see
- The sunlight comes from our own sun's
- Atomic energy

HOW DOES THE SUN SHINE?

- Scientists have found that the sun is a huge atom-smashing machine. The heat and light of the sun are caused by nuclear reactions between hydrogen, nitrogen, carbon, and helium.

- The sun is a mass of incandescent gas
- A gigantic nuclear furnace
- Where hydrogen is built into helium
- At a temperature of millions of degrees

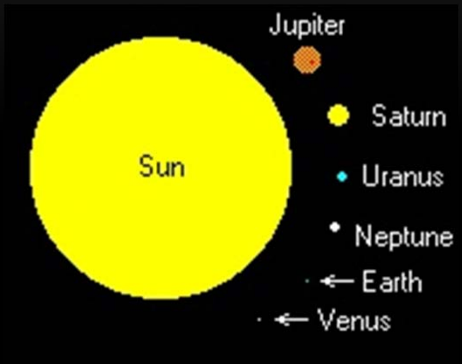
THE SHORT FORM

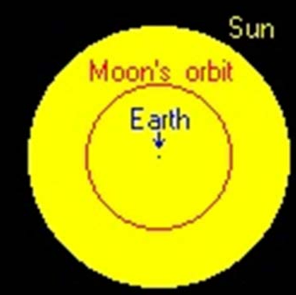
- TMBG are pretty much right on the money
  - Caveat – it's really "plasma" (fully ionized gas) not gas, but ok
  - They did correct this by releasing "The Sun is a miasma of incandescent plasma", but that's kind of awkward
- We will go into more detail

THE SUN

- 99.85% of the mass in the solar system
- Ultimate source of all Earth’s energy (except nuclear and geothermal)
- Center of Solar System
- So why wait till now to talk about it?
  - It’s very un-planetlike
  - But it’s a very typical example of a star
  - The nearest star!

THE SUN IS LARGE





Earth is
1 pixel

Figures by Harry Foundalis, Indiana Univ.

- Subtends 0.5º and is 1 AU away
  - So diameter is 1.4 million km
  - 109 Earths
  - One “Solar Radius”, $R_\odot$
- Mass is 2×10^{30} kg
  - 333,000 Earths
  - One “Solar Mass”, $M_\odot$

COMPOSITION

- Do the geometry, divide volume by mass, find density
  - 1.41 g/cm^3
  - Similar to Jupiter
- Measure chemical composition using absorption spectra
  - 73% H, 25% He by weight
  - Similar to Jupiter, universe in general

MASS OF INCANDESCENT GAS

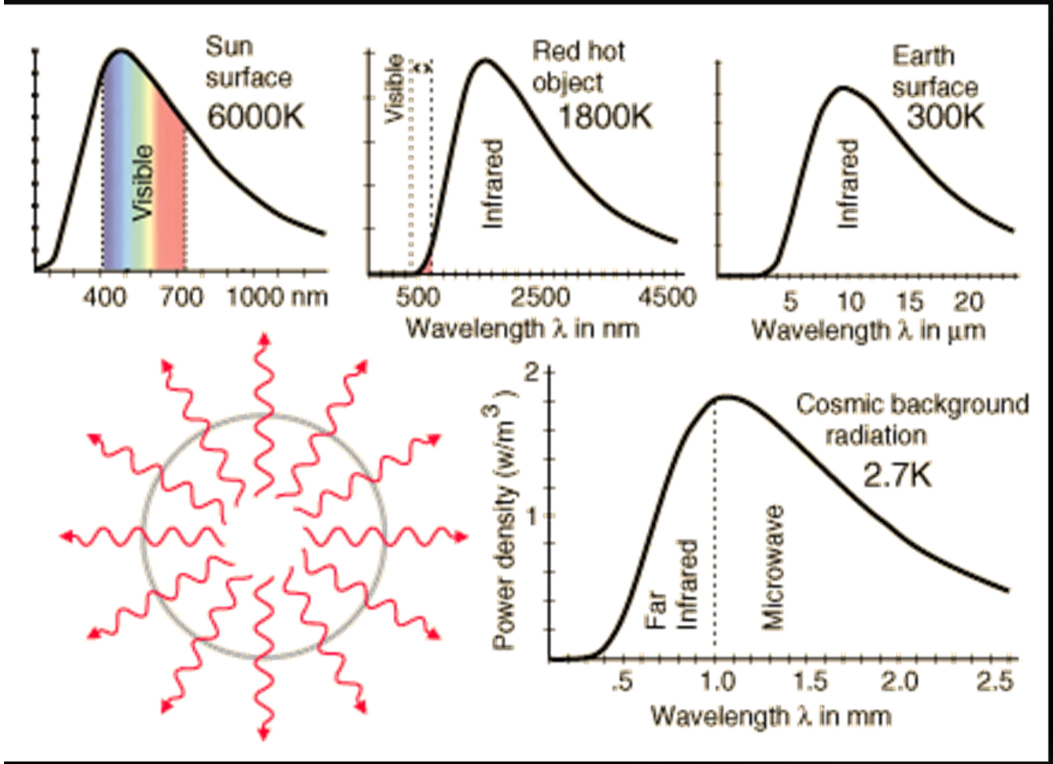


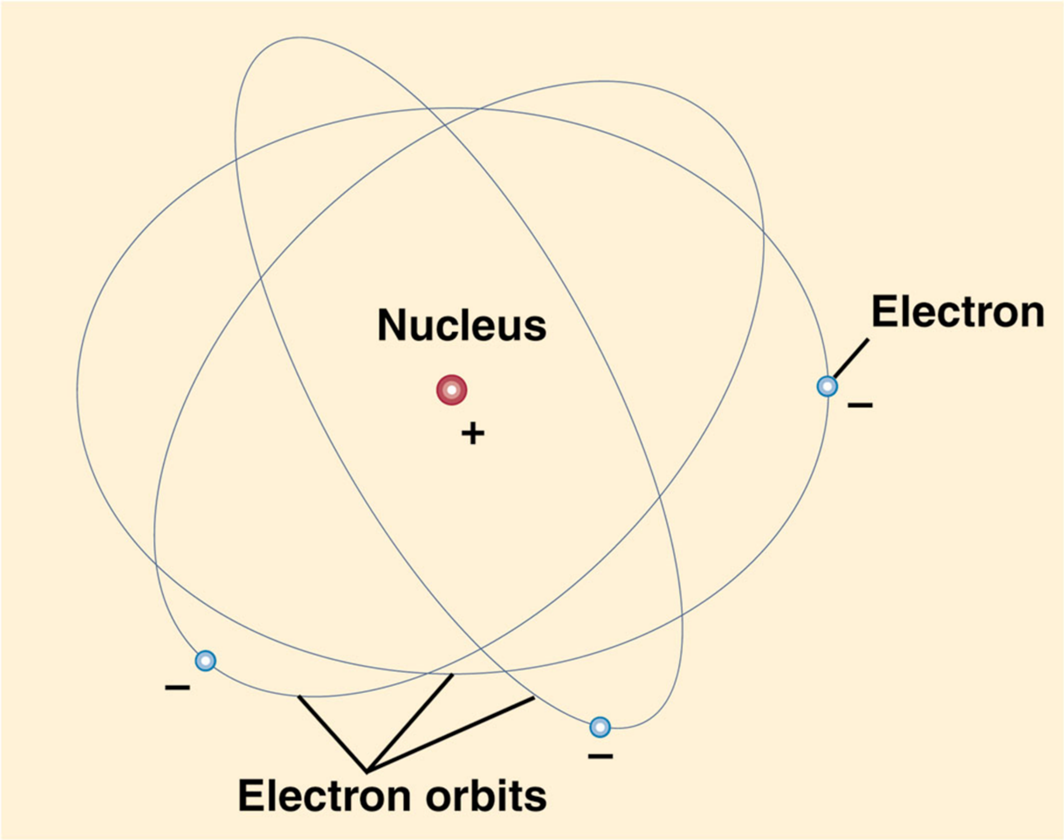
Diagram from GSU

- Continuum part of the spectra shows sun is a 5780 K blackbody
- Use σT^4 plus surface area of sun, find "Solar Luminosity"
  - 3.9×10^{26} W
  - Crosscheck by measuring power in sunlight seen at Earth, work back with $1/r^2$

SOURCE OF ALL THAT ENERGY?

- That's 100 million 1-megaton A-bombs worth of energy per second
- How about ordinary burning?
  - Is a chemical reaction
  - Coal, Oil would last only a few thousand years (say, if half solar mass is fuel, half is oxygen)

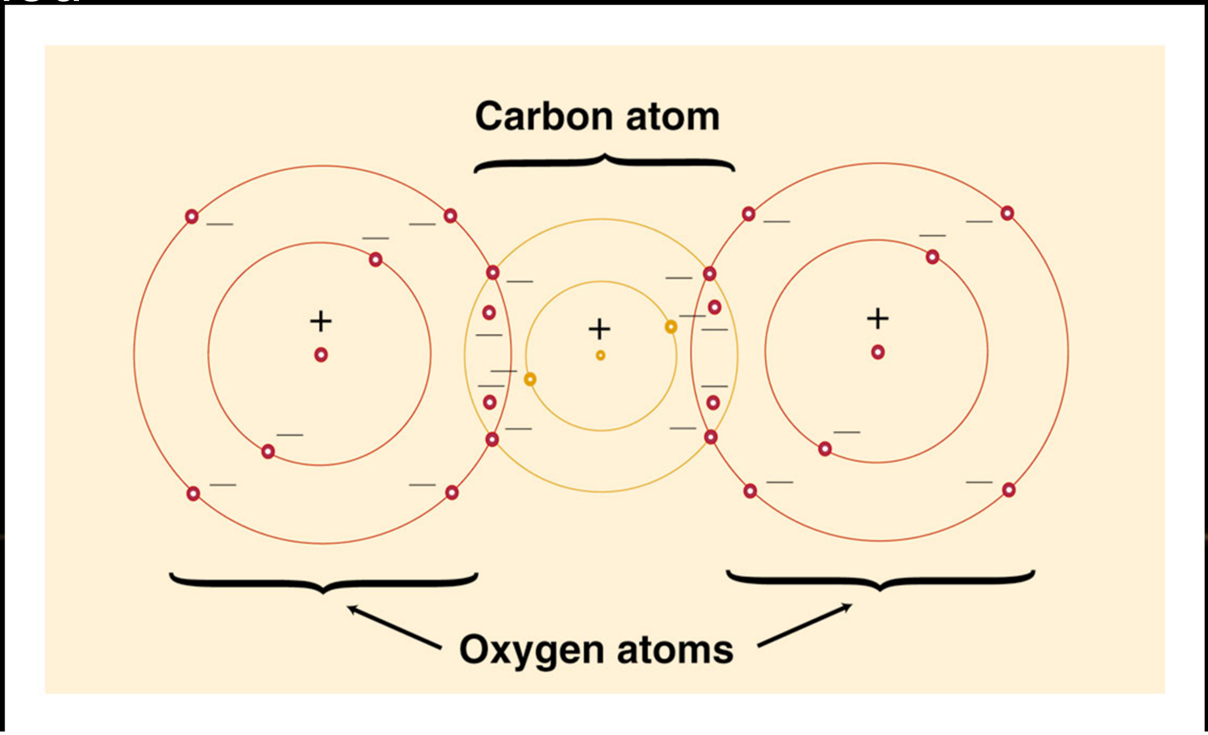
ATOMS



- Atom: smallest chunk of an element
- Made up of light, negatively charged electrons
- Orbiting a heavy, positively charged nucleus
  - Nucleus has positive protons and neutral neutrons

CHEMICAL ENERGY

- Chemistry happens when different elements bind together via electrical attraction
- Leftover energy released as heat after the bond is formed

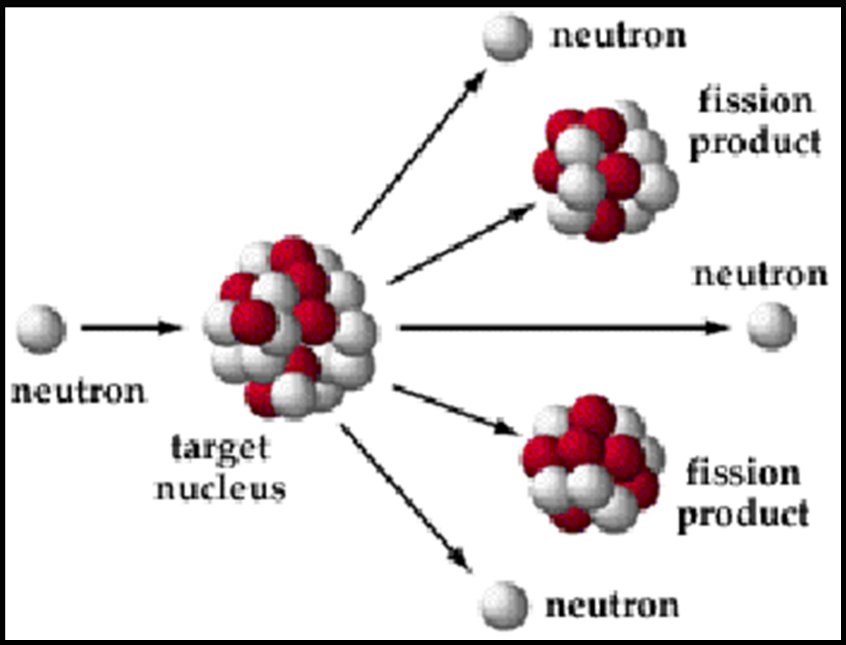


Produces a fraction of an "eV" worth of energy per reaction

ANOTHER SOURCE

- Lots of gas and dust compressing into the Sun will make heat
  - Quite a lot!
  - Sun big, so takes a looong time to cool
- Calculations show this could make the sun shine for ~500 million years
  - But many rocks are billions of years old, so why is Sun still hot?

NUCLEAR ENERGY?



- Nuclei are held together with the “strong force”
  - Millions of times more powerful than electromagnetism
- If a heavy, unstable nucleus splits, it releases energy
  - Millions of times more than breaking a chemical (electromagnetic) bond

SO HOW ABOUT RADIOACTIVITY?

- Decay of radioactive elements helps keep Earth’s core hot
  - Decay of radioactive isotopes of potassium, uranium, etc
  - Same method as a nuclear power plant – “Fission”
- But – these are all heavy elements
  - Sun is mostly non-radioactive H, He
  - So not enough energy

NUCLEAR ENERGY AND LIGHT ELEMENTS

- While heavy nuclei release energy when broken, light nuclei release energy when put together
  - Iron is best-balanced nucleus
- Sun has gobs of light elements
- Can fusion of light elements provide enough energy?

ENERGY FROM FUSION

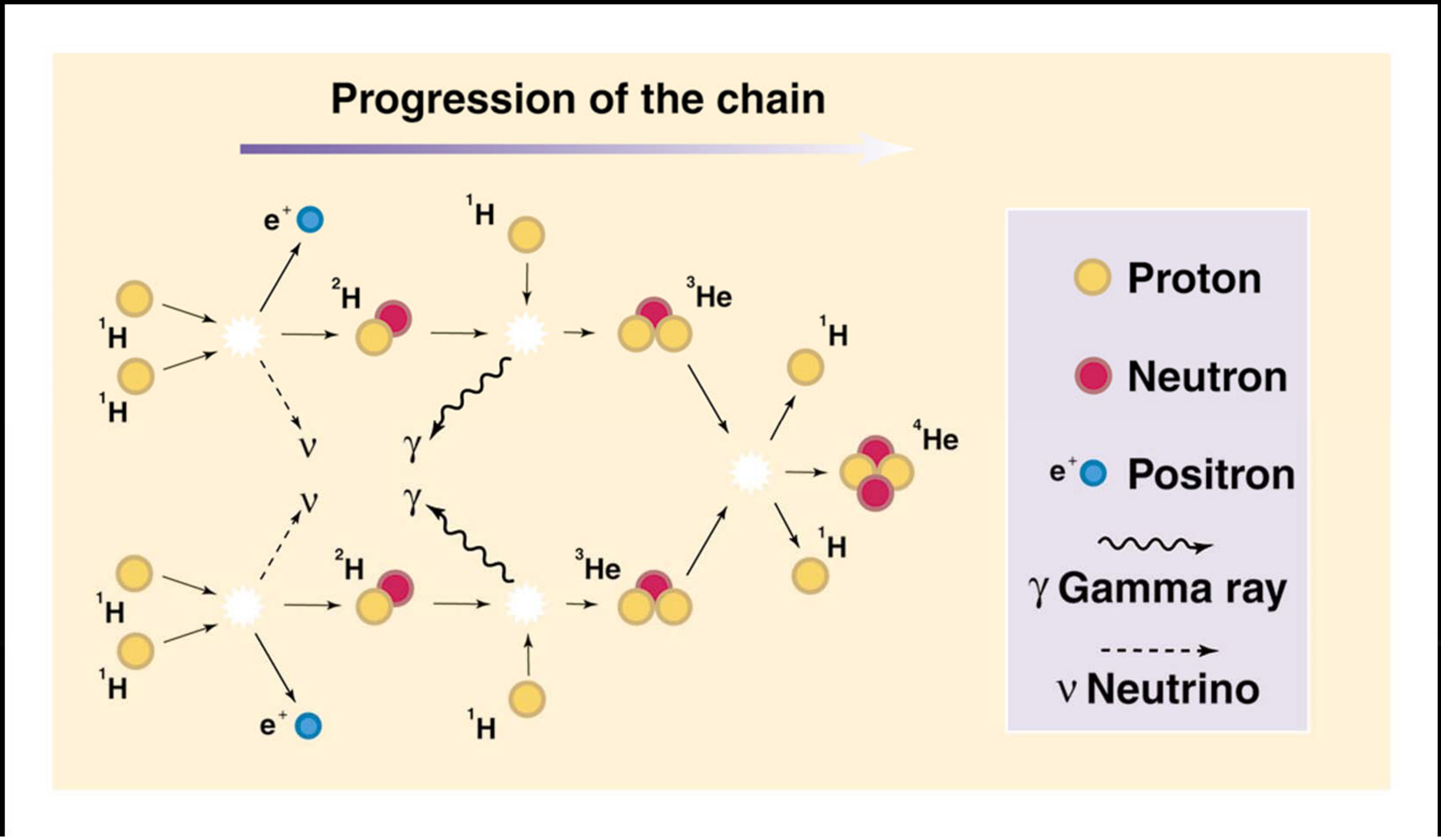
- An easy calculation to check without knowing the gory details of the strong force:
  - Mass of 4 Hydrogen nuclei = 6.6905×10^{-27} kg
  - Mass of 1 Helium nucleus = 6.6447×10^{-27} kg
  - Difference: 0.0458×10^{-27} kg
- $E=mc^2$, so if that missing mass was changed to energy, you'd get
  - 0.0458×10^{-27} kg * $(3\times10^{8}\text{m/s})2 = 4.122\times10^{-12}$ J or 25.8 *million* eV
  - Much more energy per reaction than chemical burning

IS THAT ENOUGH?

- To produce 3.9×10^{26} W (the Solar *Luminosity* – energy radiated by the Sun per second, $L_{\odot}$):
  - You would need 10^{38} fusions per second!
  - That's 630×10^{9} kg of H…
  - turned into 626×10^{9} kg of He *each second!*
- But – Sun has 1.5×10^{30} kg of H to work with
  - So this could last 100 billion years
- So it could work in principle – how about the details?

THE PROTON-PROTON CHAIN

- Detailed study of nuclear reactions shows how you turn 4 H into 1 He:



PLAY

NEED EXTREME CONDITIONS!

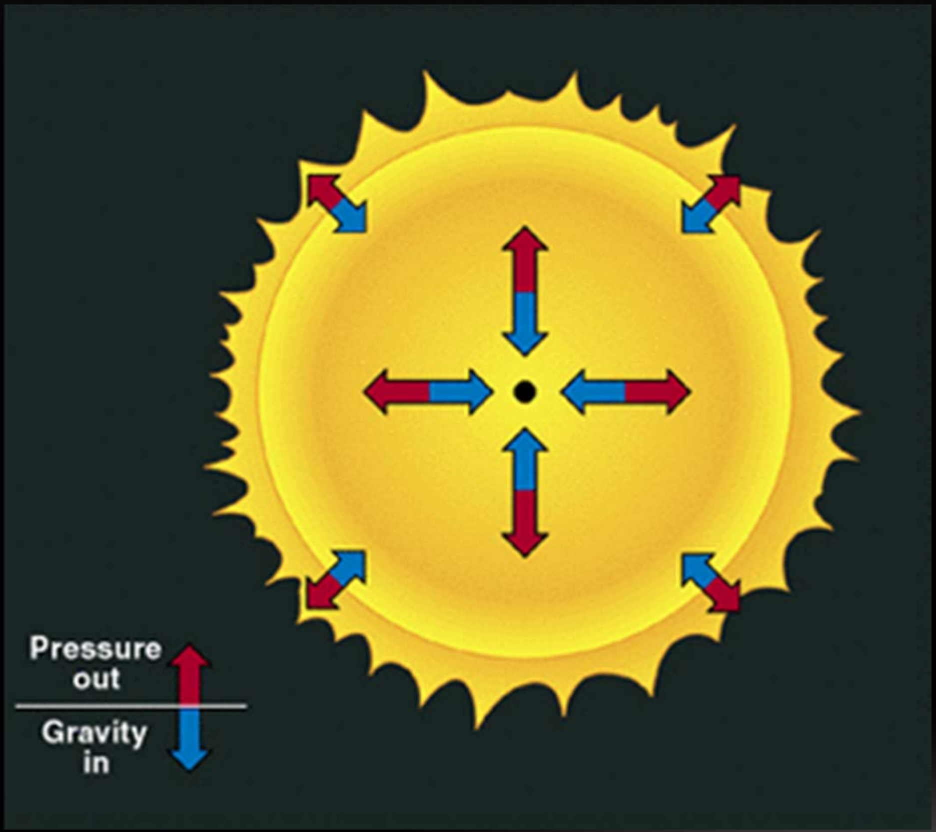
- Crushing H nuclei together is hard
  - Two “+” charges repel each other
- Need tremendous pressure and density
  - to provide enough stuff close to each other
- And heat
  - to rattle the atoms hard enough so they overcome the electrostatic repulsion
- Is this available in the Sun?
  - Avg. density only 1.41 g/cm^3!
  - Surface temperature only 5780 K!

HEY, PHYSICS IS SNEAKING IN AGAIN!

(specifically, “Thermodynamics”)

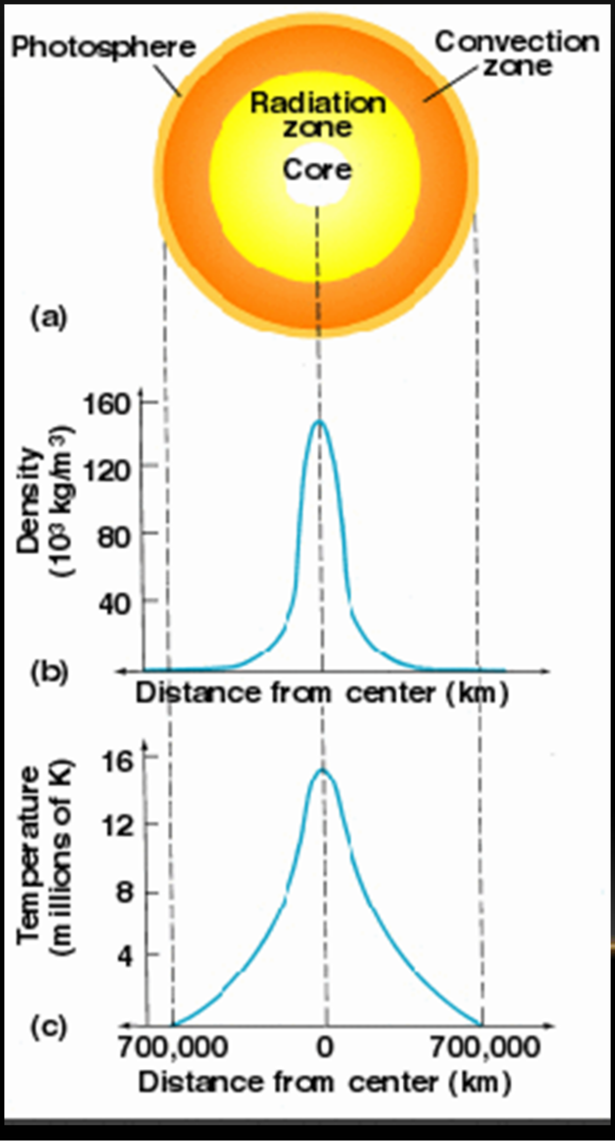
- Density
  - How many things there are per unit volume
- Temperature
  - How fast those things rattle around
- Pressure
  - The force caused by those rattling things smacking into other stuff
  - Increase Temperature or Density, you increase the pressure – and vice-versa
- Here, these “things” are all H, He nuclei

HYDROSTATIC EQUILIBRIUM



- The Sun is a big ball of gas
- At any given point inside the sun
  - Gravity presses down, as does the weight of all the gas above that point
  - Pressure pushes up, holding up all that weight
- Things aren’t collapsing or exploding – so these two forces are in equilibrium

WORKING OUT THE DETAILS



- Solve the equations of thermodynamics for hydrostatic equilibrium with gravity
- The density and temperature graphs to the left are produced

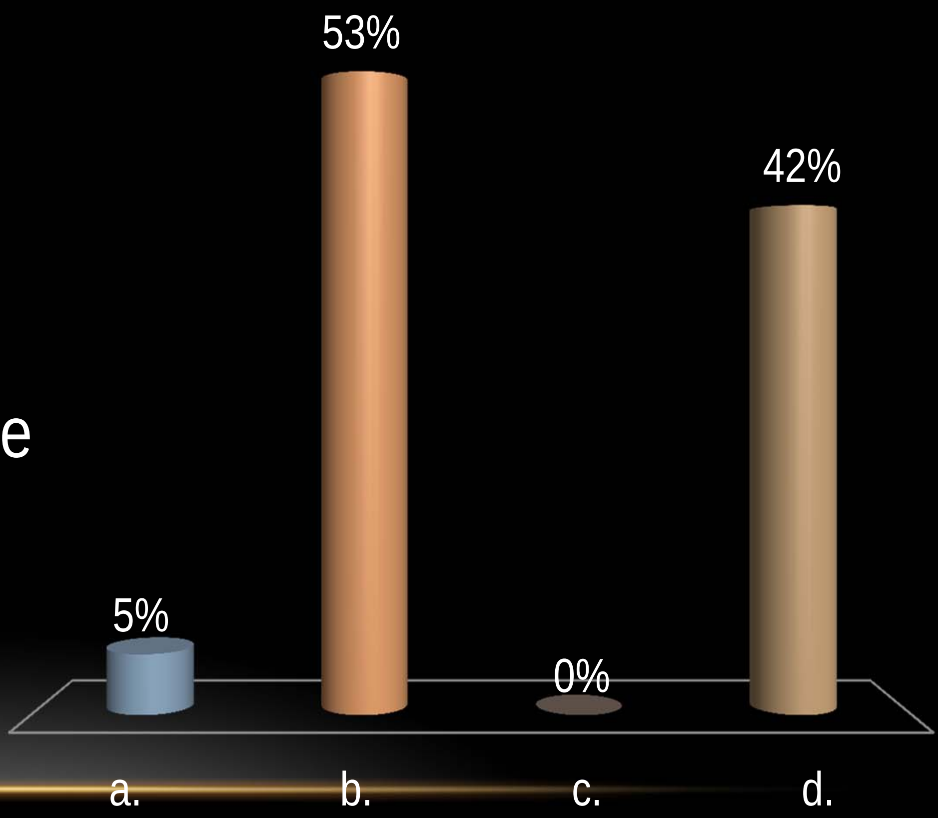
WHY IS THE SUN VERY DENSE ON THE INSIDE?

a. Denser materials sank to the center.

✓ b. Pressure of the overlying gas keeps the density high.

c. It formed from dense material.

d. Nuclear fusion increases the density in the core by changing hydrogen into helium.

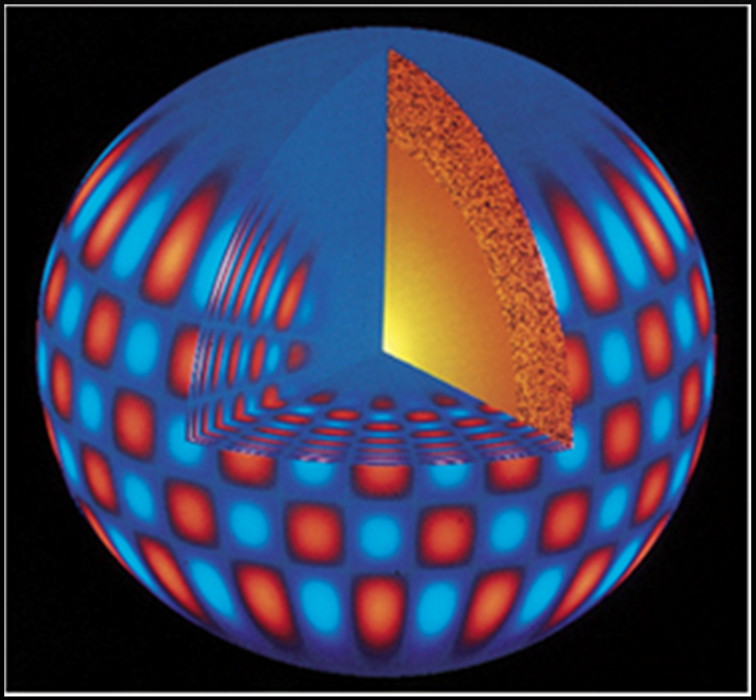


CONDITIONS IN THE SUN'S CORE

- Deeper in the Sun, there's more stuff pushed down by gravity
- So, the pressure must be larger to hold it all up
- Larger pressure means:
  - Larger density
  - Larger temperature
- In the core:
  - Density ~ 180 g/cm^3
  - Temperature ~ 15 million K
  - Pressure – 2.5×10^{11} atmospheres

Enough for Fusion!

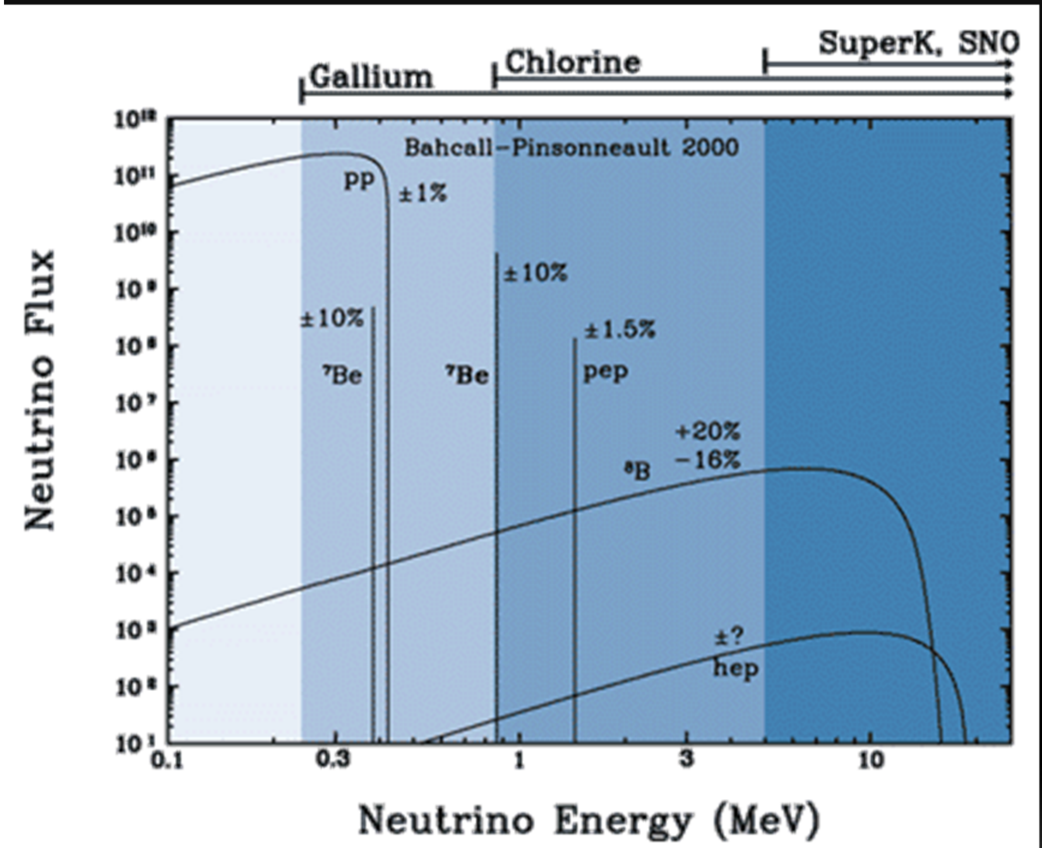
TESTING THE THEORY



Solar vibrations from GONG network

- Does the Thermodynamics work?
- Look at vibrations of sun, same as we look at earthquakes to determine the Earth's interior
- "Helioseismology"
  - Uses Doppler shifts on surface of sun to detect the waves
  - Model verified almost all the way to the middle of the Sun!

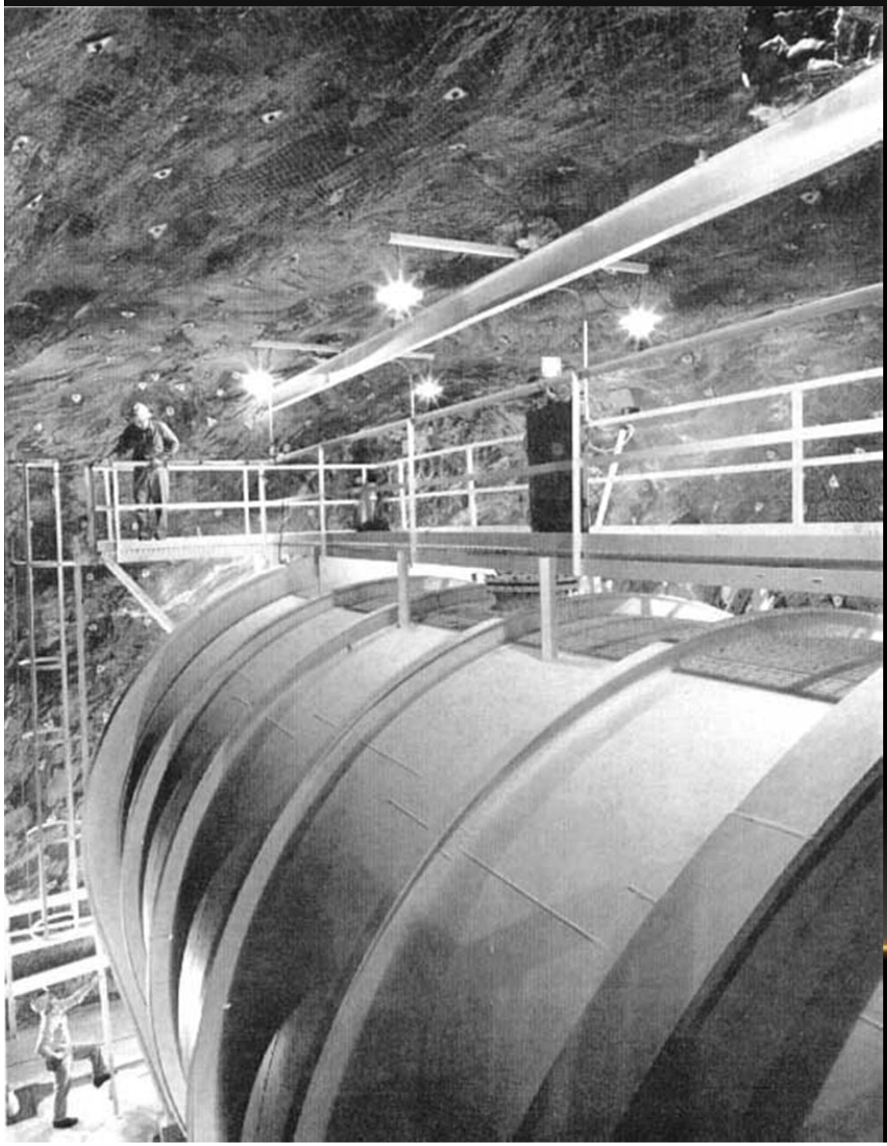
ANOTHER TEST



Solar ν spectrum
Courtesy of John Bahcall

- Neutrinos ("ν") are a byproduct of the fusion reactions
- ν are particles that very rarely interact with matter
  - So they zip right out of the Sun
  - But are really hard to detect!
  - Trillions are zipping through you right now
- Look for solar ν, see if they match predictions

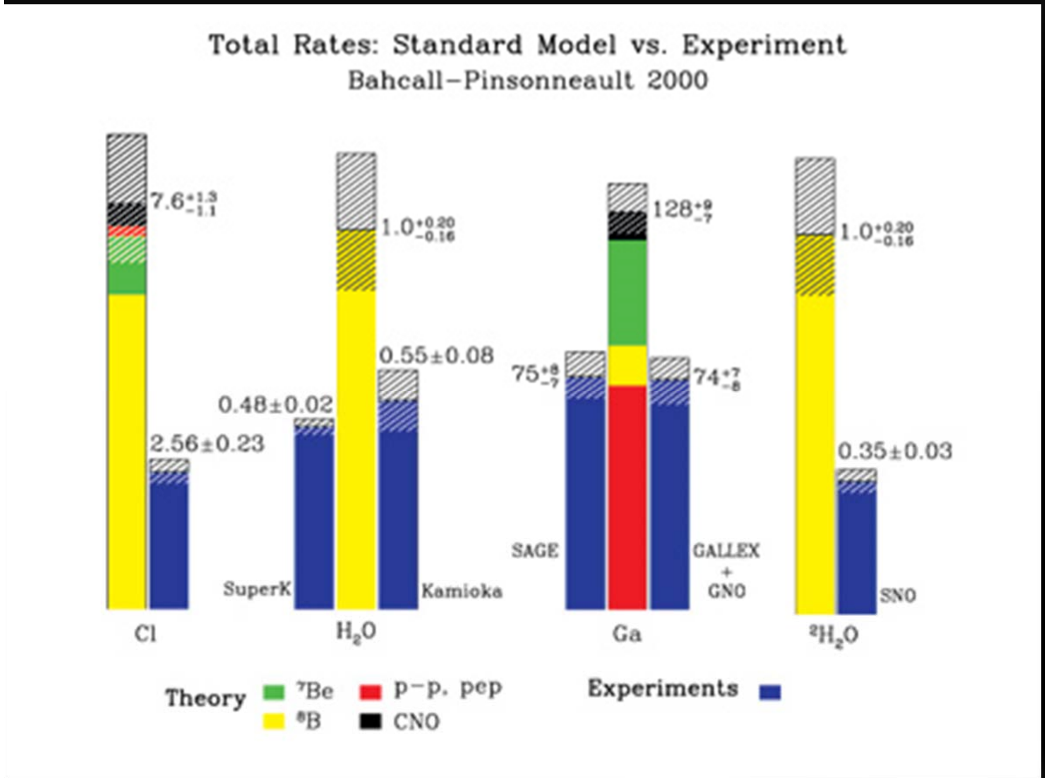
LOOKING FOR SOLAR NEUTRINOS



- Need something big to stop a few of these elusive particles
- First experiment – giant vat of dry cleaning fluid in the Homestake gold mine (Lead, SD)
  - ν's can turn a few Chlorine atoms into radioactive Argon atoms
  - Count the Argon!

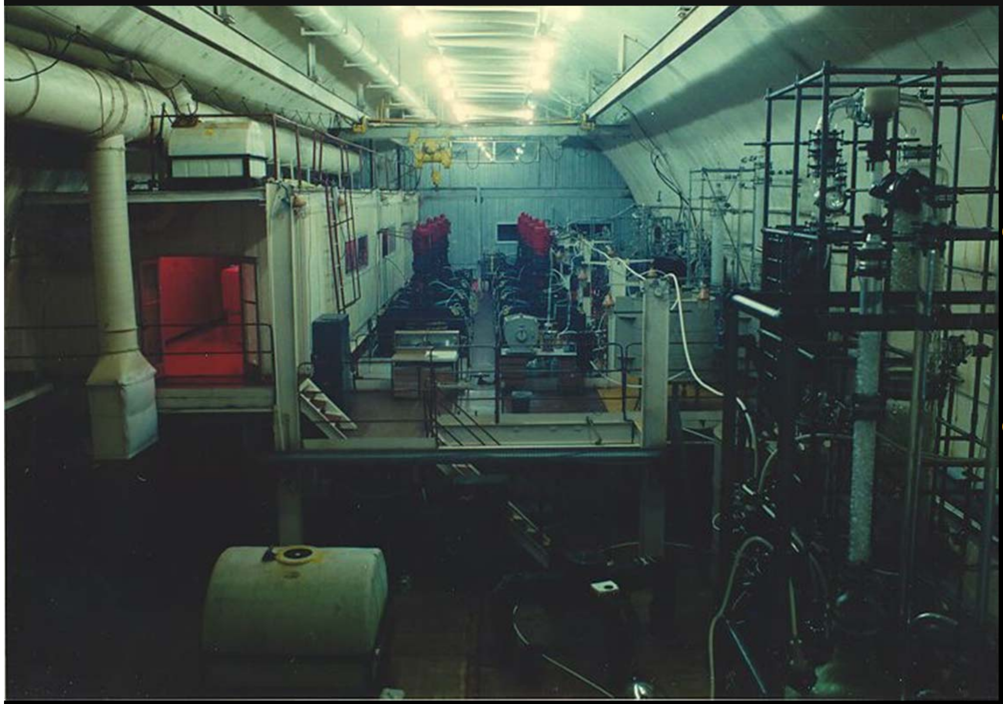
Ray Davis, 1967
2002's Nobel Prize Winner!

THE SOLAR NEUTRINO PROBLEM



- But, only about 1/3 the expected number of ν's were seen! (looked for 20 years)
- Other experiments using different techniques see other fractions

GALLIUM EXPERIMENTS



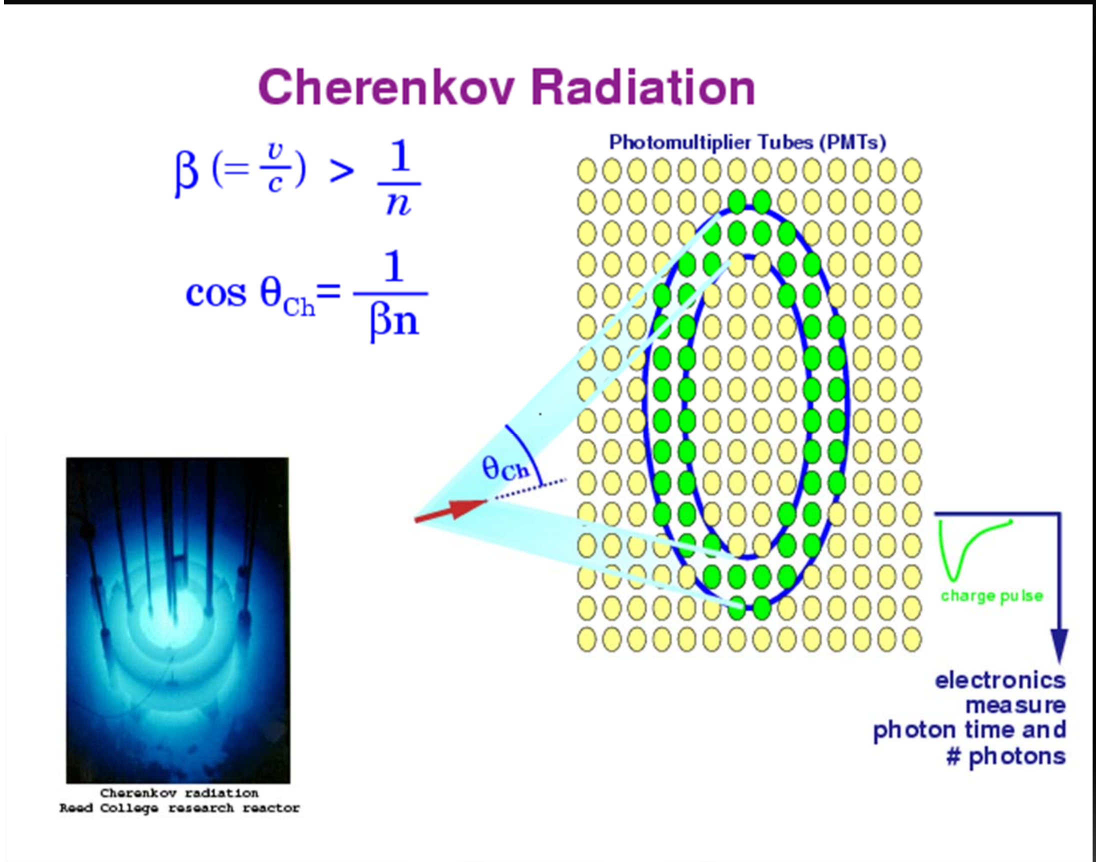
The SAGE experiment
(Soviet American Gallium Experiment
in the Caucases

- Big vats of Gallium
- ν's change Ga into Germanium atoms
- Very low threshold – can see the p-p ν's discussed earlier
  - Chlorine experiment sees higher energy ν's from a different reaction

ANOTHER GALLIUM EXPERIMENT

- SAGE uses metallic Gallium
- Gallex uses a gallium solution
- At the Laboratori Nazionali del Gran Sasso in Italy

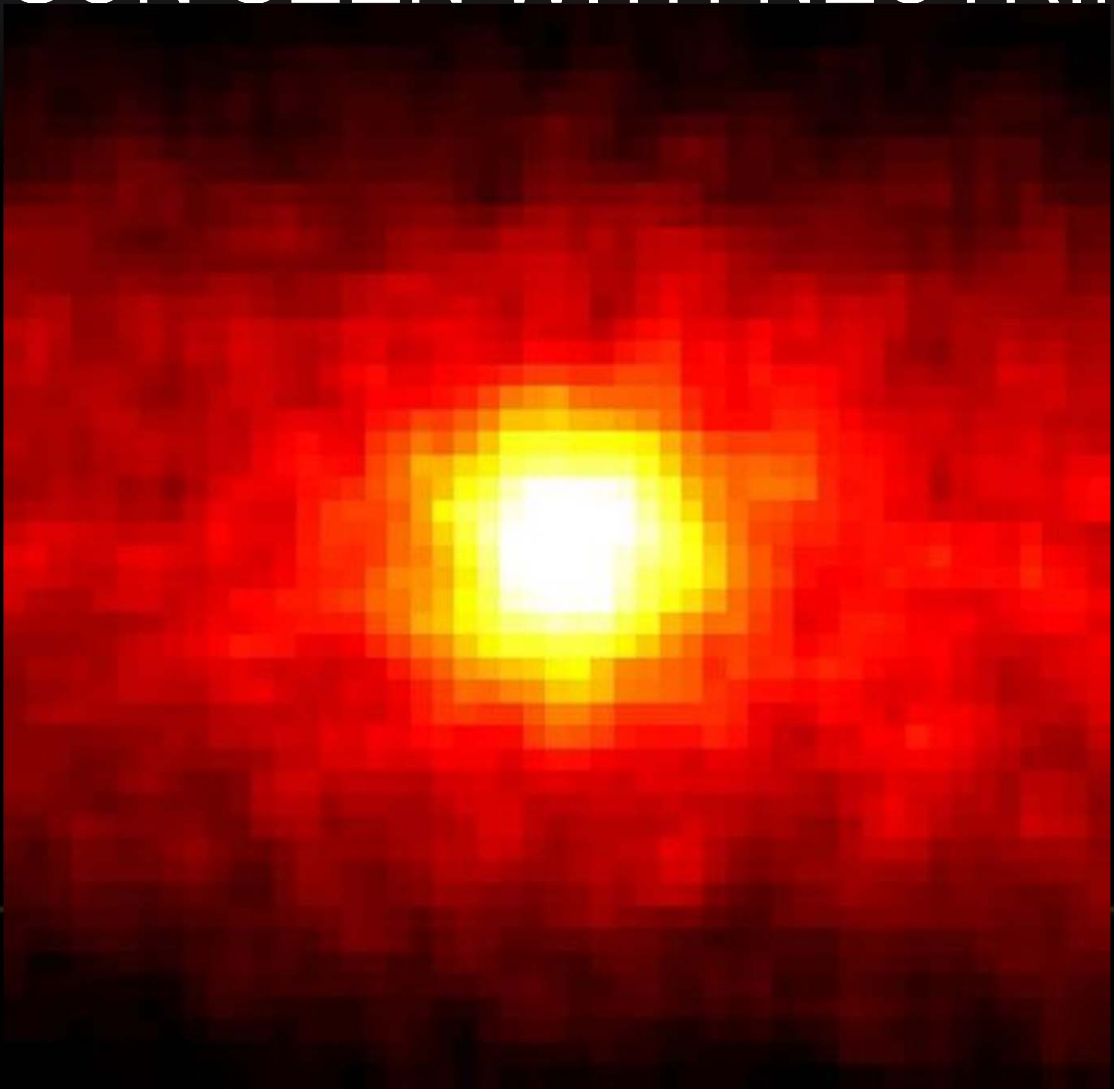
WATER EXPERIMENTS



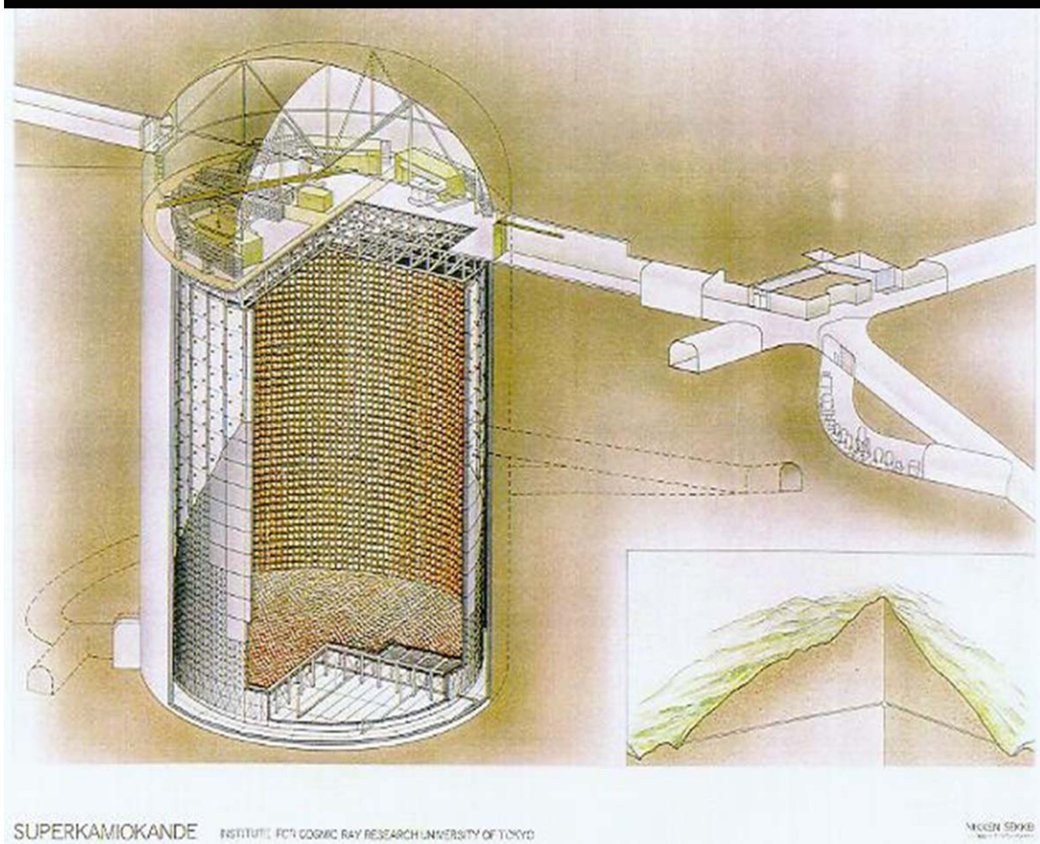
- ν's will sometimes knock loose electrons from their atoms
- These electrons give off light in water
  - Point back to Sun!

Prof. Koshiba shares Nobel with Davis for this experiment

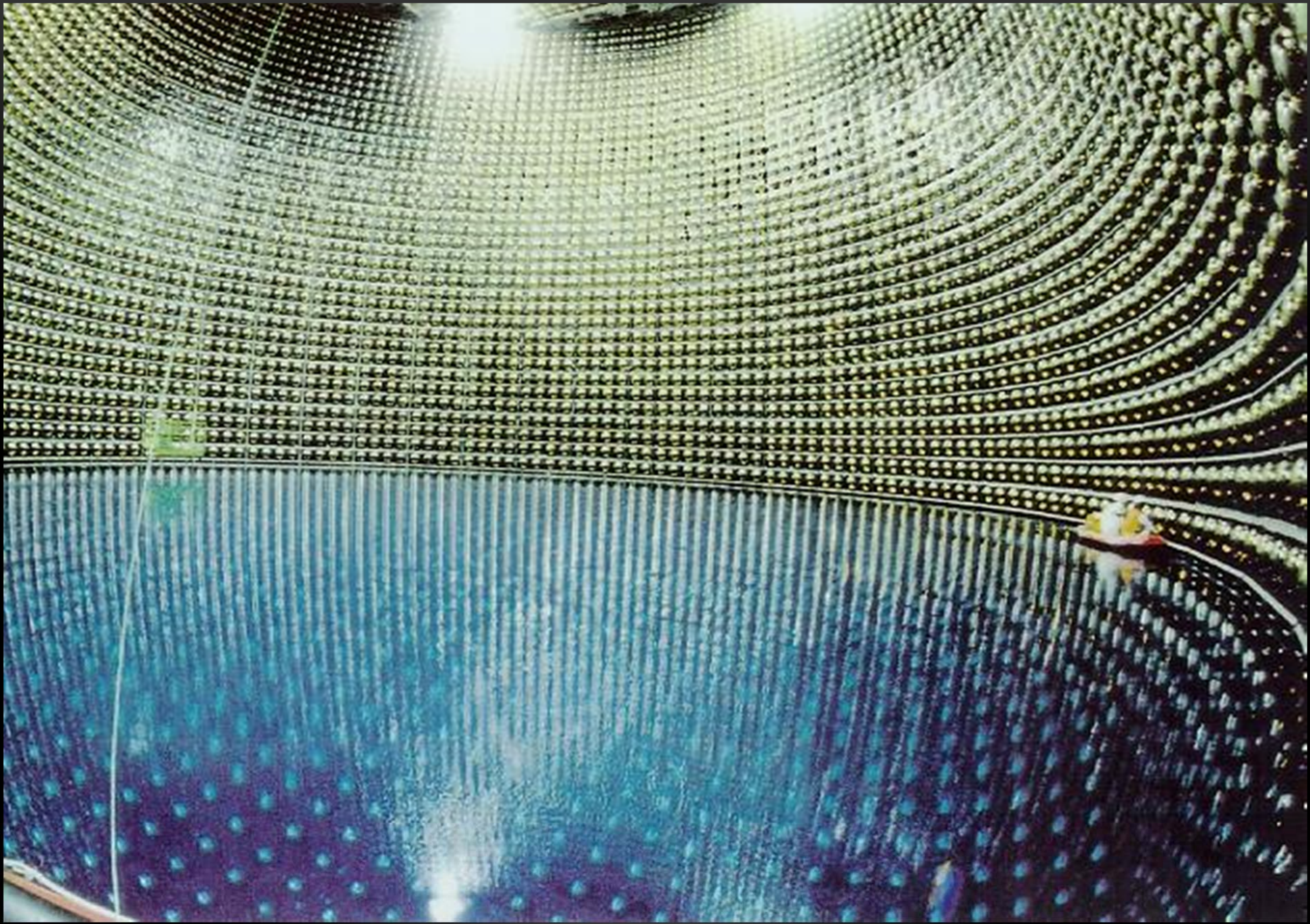
THE SUN SEEN WITH NEUTRINOS



(SUPER-) KAMIOKANDE



- Kamiokande was first water ν experiment
- New, improved, <u>much</u> larger Super-Kamiokande is an experiment I've worked on
- 40m tall & wide can
- 50,000 metric tonnes of ultrapure water
- 11,000 20" phototubes



SK images courtesy of Institute for Cosmic Ray Research, The University of Tokyo

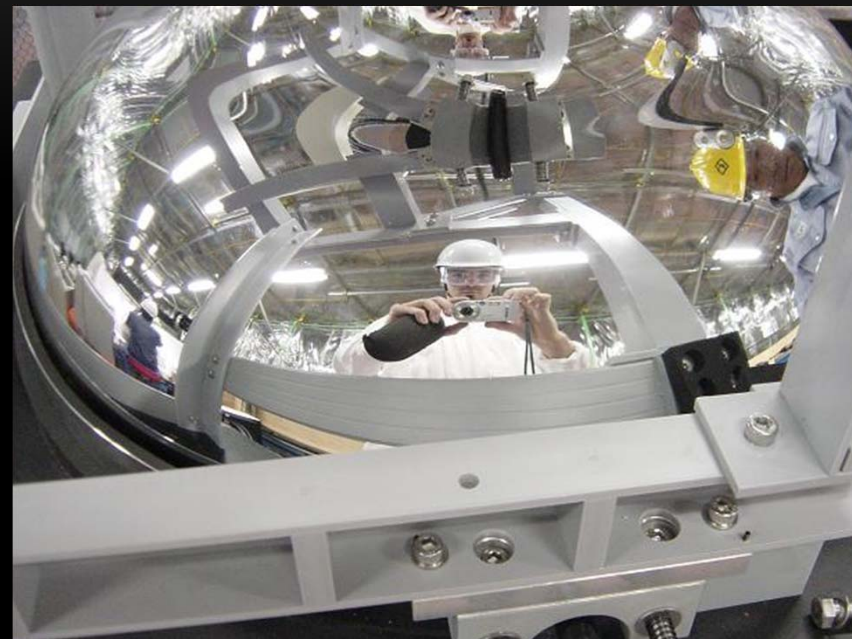
UMD@SUPER-K, SUMMER 2001

Dan Gastler (UMD),
floating in top of OD

Alec Habig (UMD) and Jim Stone (BU),
fixing Tyvek in barrel of OD

OUR WORK IN THE OD, 2002

UMD@SUPER-K, SUMMER 2005



Rose Smith (UMD),
with Tom Kreicbergs (Hawaii),
Aaron Herfurth (BU),
and Kirsti Hakala (UMD)

John Eastman (UMD) , Photographer

Prepared 6,000 replacement PMTs
(installed winter 2005/06, running again now!)

(lots more pictures at http://neutrino.d.umn.edu/~east0108)

BACK TO THE PROBLEM

- No one sees enough ν's
- Helioseismology checked that we know how the Sun is built
- Particle physics experiments show we know how ν are created and detected
- Maybe something happens along the way?