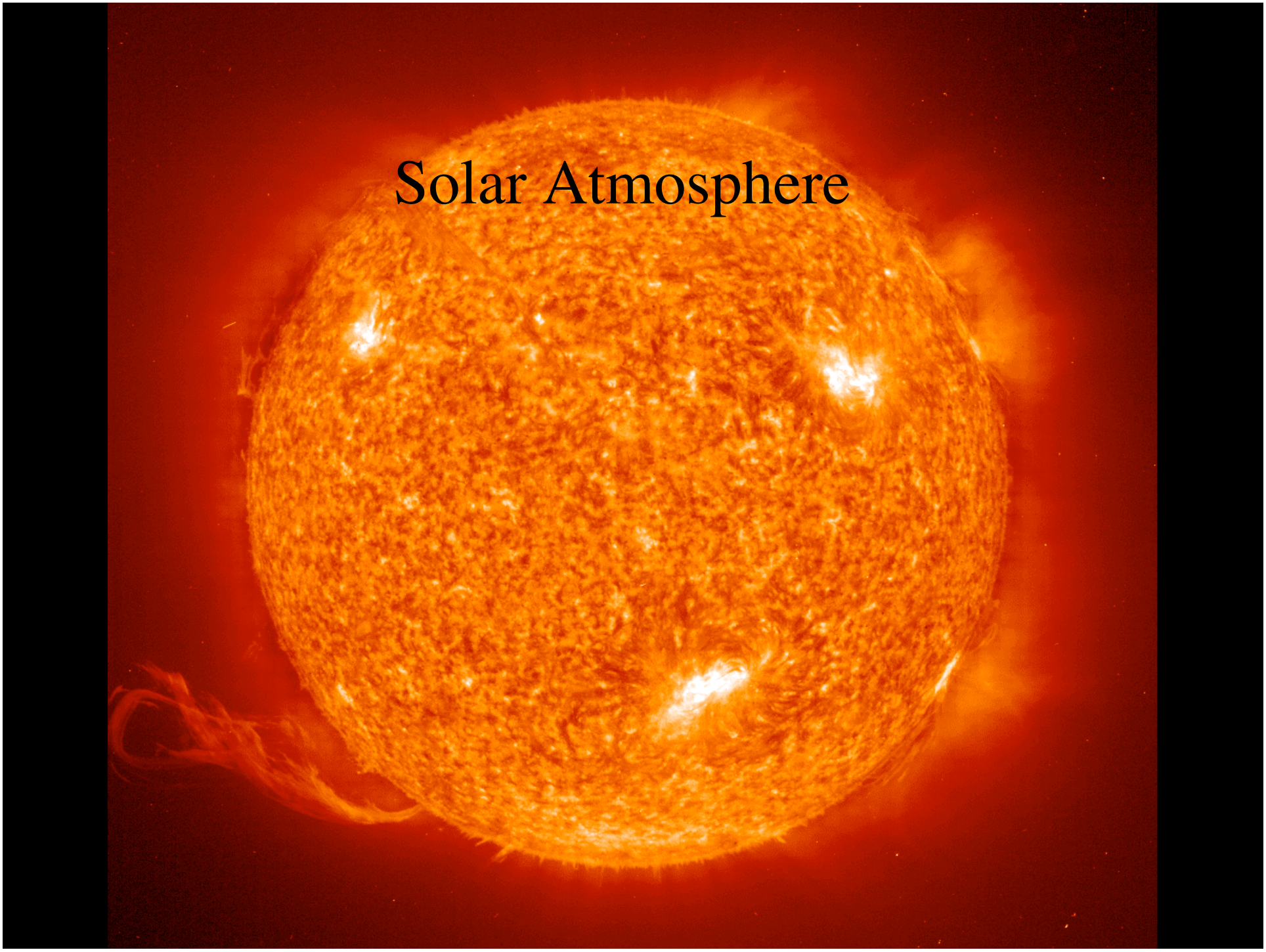
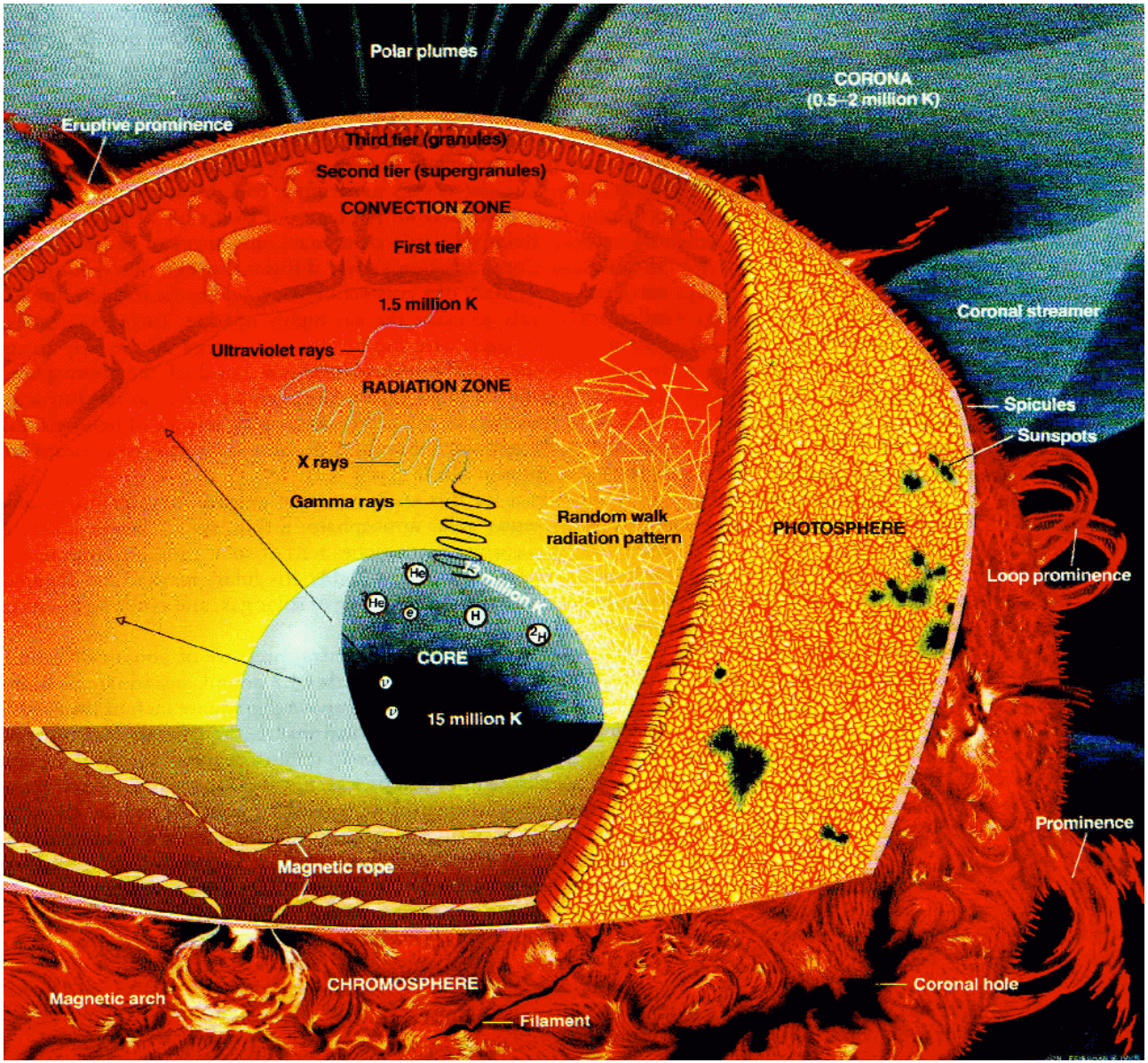
Solar Interior

- Sources of energy for Sun
- Nuclear fusion
- Solar neutrino problem
- Helioseismology

Solar Atmosphere



Solar interior



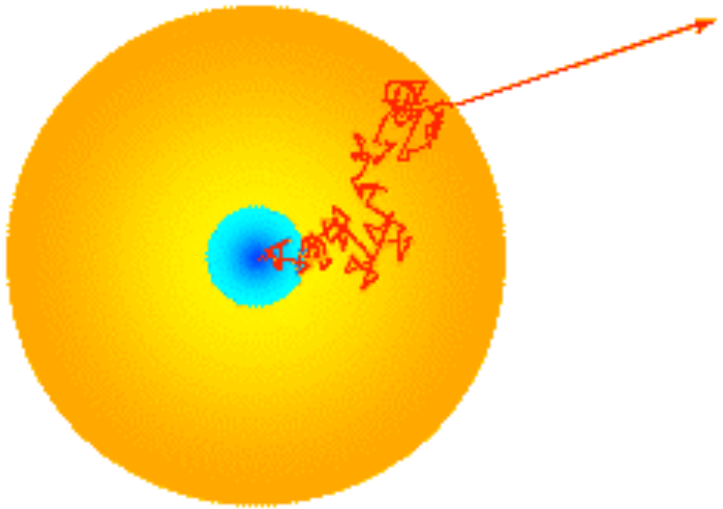
Solar facts

- **Luminosity**: 3.8×10^{26} J/s
- **Mass**: 2.0×10^{30} kg
- **Composition**: 73% Hydrogen, 25% Helium, 2% "heavy elements" (by mass)
- **Radius**: 7.0×10^{8}m
- **Avg Density**: 1400 kg/m^3
- $\mathbf{T_{eff}} = (L/(\sigma 4\pi R^2))^{1/4} = 5800^{o}K$ (How does this compare with the average and central temperatures?)

Solar interior

Solar interior

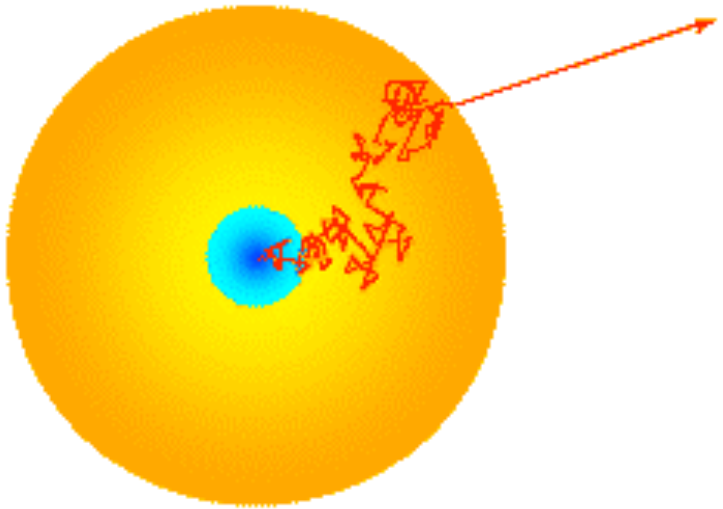
- At avg density of 1400 kg/m^3 and avg temp of $4.5 \times 10^6 K$ "mean free path" of photon before interacting with matter is < 1 cm. Optical depth is very high, effective path length is much longer than $R_\odot$; time to escape is much longer than $R_\odot/c \sim 2$ sec



Solar interior

- Timescale for radiation to diffuse out is > few 10^4 years

- Slow leakage of photons regulates $L_\odot$



Solar Energy

- Sun is radiating copious amounts of energy
- What is the source of this radiation?
- What if we just consider the fact that the sun is a ball of hot gas, no additional heat source?
- According the ideal gas law, the thermal energy of a gas at temperature T is:

$$E=3/2(NkT)$$

(N=# of particles, k=Boltzmann's constant)

Solar Energy

- (see derivation on board about K-H timescale)
- Heating from gravitational contraction can only sustain sun for ~10^7 years (K-H timescale)
- Yet we know that the age of the solar system is ~4.5 billion years

Radioactive dating

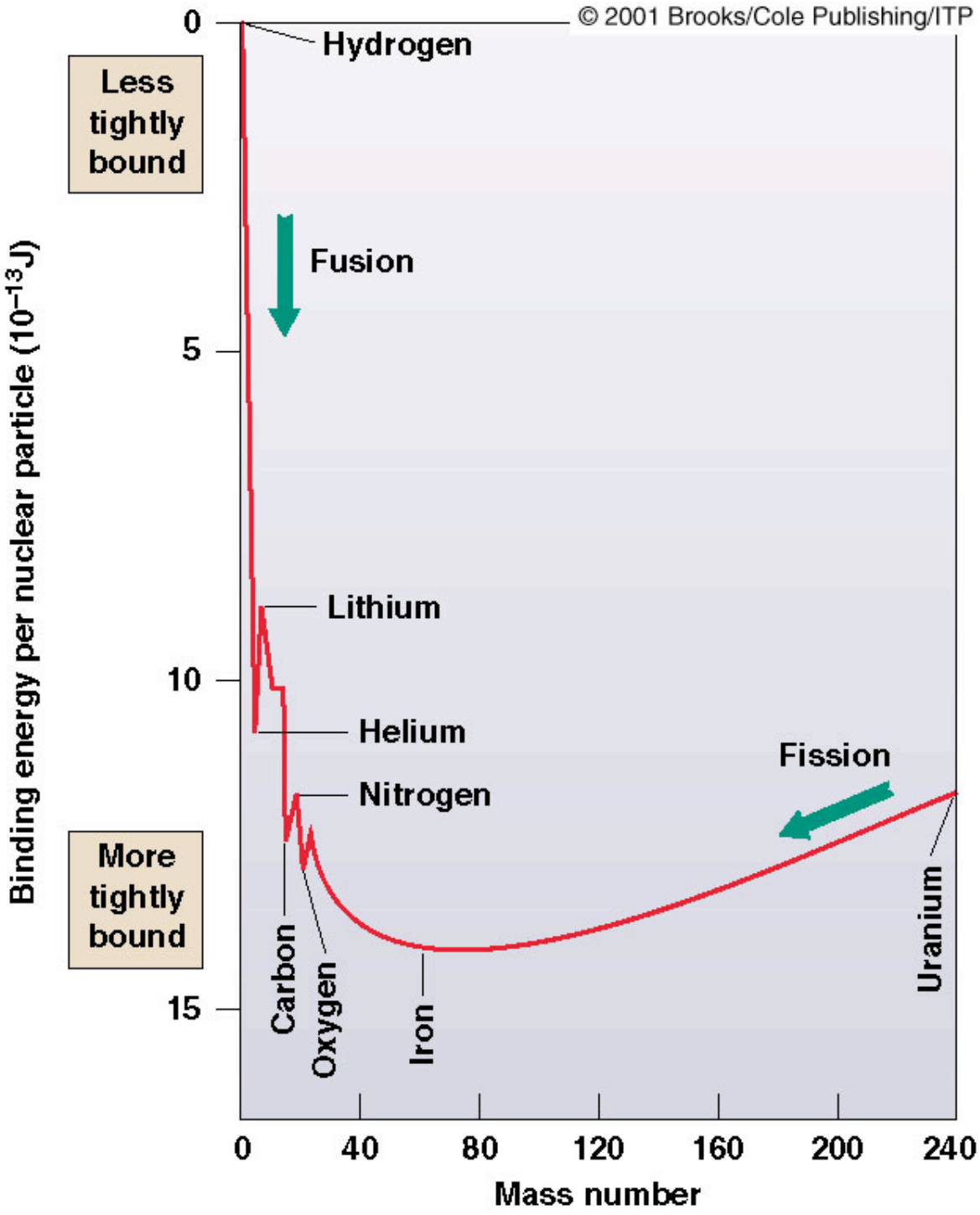
- Oldest rocks found so far:
  - ✶Earth: 3.9 billion years
  - ✶Moon: 4.5 billion years
  - ✶Mars: 4.5 billion years
  - ✶Meteorites: 4.6 billion years
- The *smaller* an object, the *faster* it cools and therefore solidifies, the *older* it is
  - ➢Planets, moon, meteorites (entire solar system) formed 4.6 billion years ago (Sun too)

Solar Energy

- (see derivation on board about K-H timescale)
- Heating from gravitational contraction can only sustain sun for ~10^7 years (K-H timescale)
- Yet we know that the age of the solar system is ~4.5 billion years
- We need another source of energy: nuclear fusion!

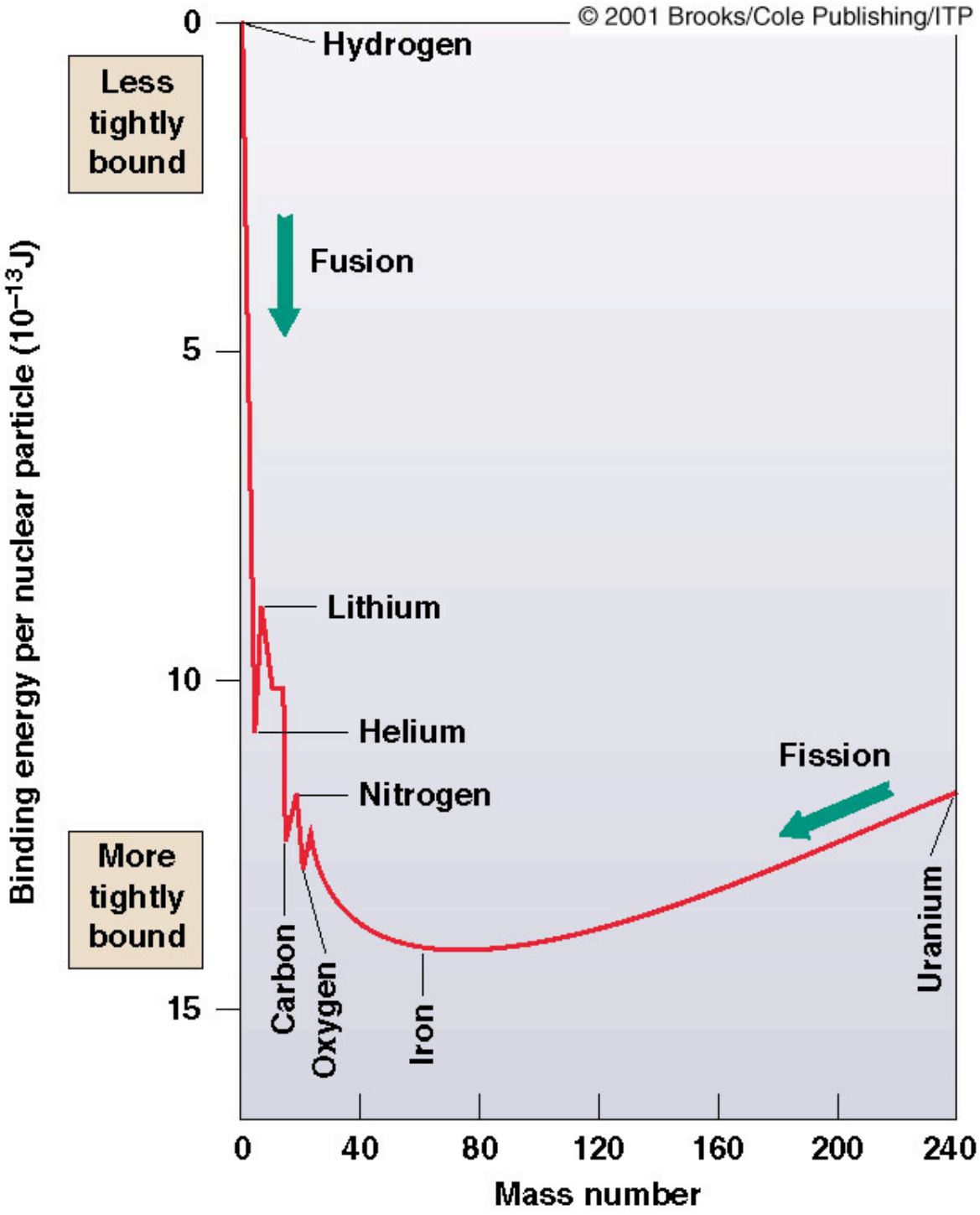
Fusion & Fission

- ***Fusion*** (joining) of ***light*** elements results in more tightly bound elements
  - ★Releases energy up to Fe



Fusion & Fission

- ***Fission*** (splitting) of ***heavy*** elements results in more tightly bound element
  - ★Releases energy above Fe

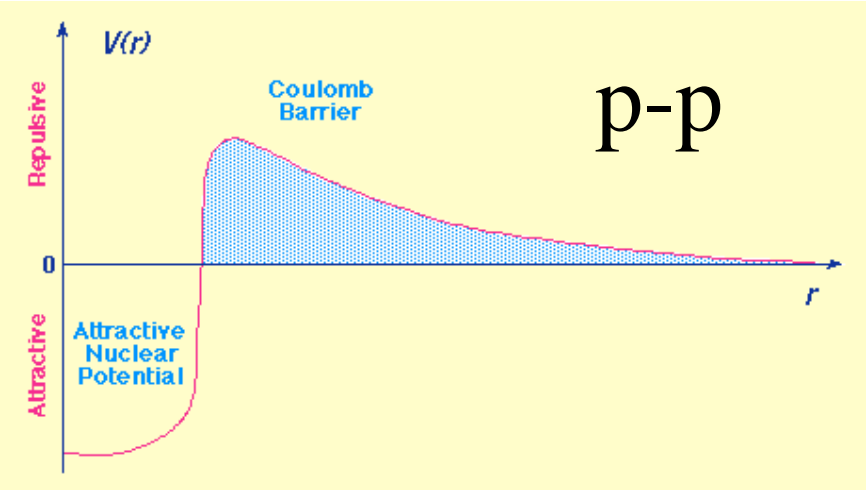


How does fusion release energy?

- So 0.7% of mass of H in Sun is converted into energy.
- Total energy available $E_{nuc} = 0.007 M_{Sun} c^2$ (compare with $E_{therm} = (3/2) NkT$ or $E_{grav} = (3/10) GM_{sun}^2 / R_{sun}$)
- Nuclear lifetime $t = E_{nuc}/L_{sun} = 10^{11}$ yrs
- Actually, we'll see drastic things happen to Sun once H in core exhausted, which is only 10% of total
- So Sun "lives" for about 10^{10} yrs.

How does fusion happen?

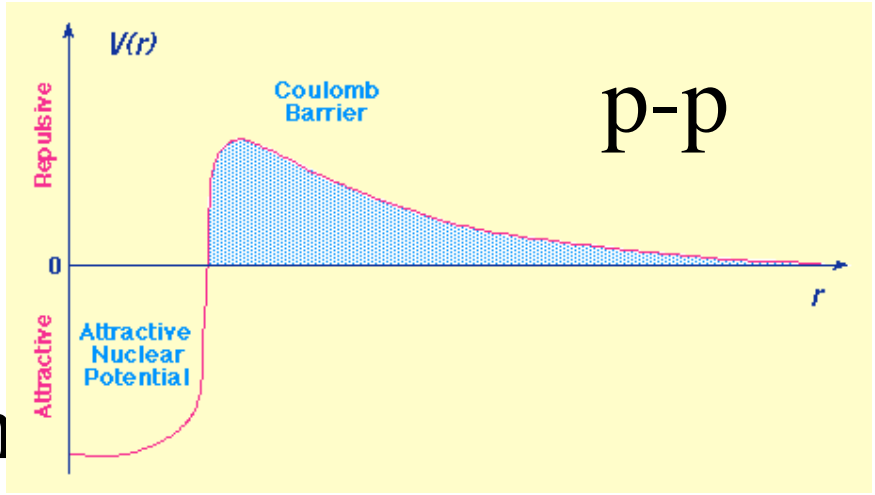
- In order for reaction to occur, colliding nuclei must have enough KE to overcome Coulomb repulsion of like charges



- First, think classically: energy required to overcome barrier is provided by gas thermal energy…

How does fusion happen?

- Including effects of QM tunneling indicates that fusion can happen in the center of the sun, with $T \sim 10^7$ K



- Next, calculate reaction and energy generation rates, which are strong functions of temperature.

Proton-proton chain

Most important reaction in Sun is PPI chain

$^{1}H + {}^{1}H \rightarrow {}^{2}H + e^{+} + \nu$

e^{+} = positron

ν = neutrino

γ = photon

$^{2}H + {}^{1}H \rightarrow {}^{3}He + \gamma$

$^{3}He + {}^{3}He \rightarrow {}^{4}He + {}^{1}H + {}^{1}H$

Net result is 4H fused into ^{4}He

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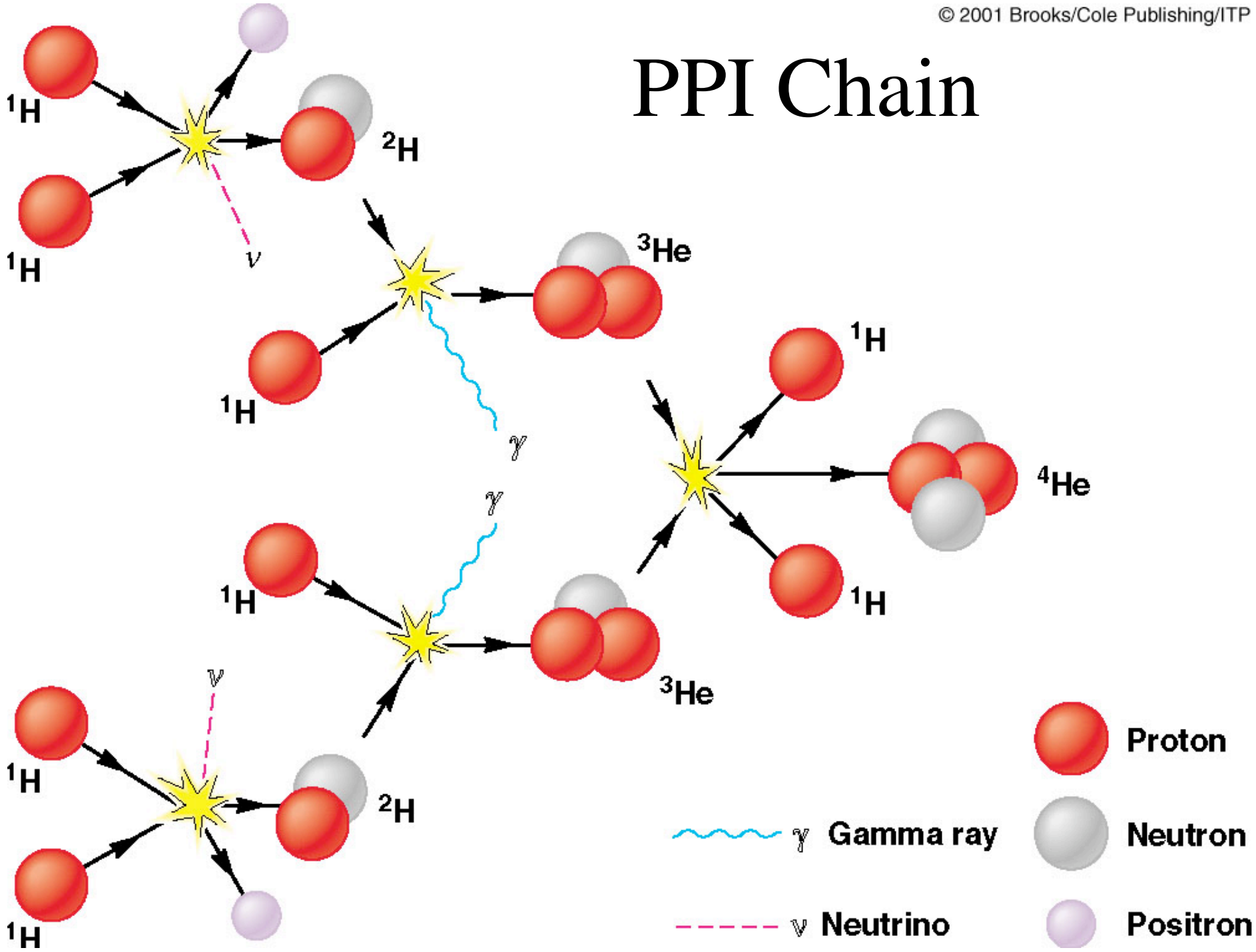
PPI Chain



PPII & PPIII

- After first 2 steps, 31% of reactions proceed with $^{3}He + ^{4}He \rightarrow ^{7}Be + \gamma$, and further branch between:

ppII:

(3) $^{3}He + ^{4}He \quad ^{7}Be + \gamma$

(4) $^{7}Be + e \quad ^{7}Li + \nu_e$

(5) $^{7}Li + ^{1}H \quad ^{4}He + ^{4}He$

ppIII:

(3) $^{3}He + ^{4}He \quad ^{7}Be +$

(4) $^{7}Be + ^{1}H \quad ^{8}B + \gamma$

(5) $^{8}B \quad ^{8}Be + e^{+} + \nu_e$

(6) $^{8}Be \quad ^{4}He + ^{4}He$

•69% of the time, H fusion occurs via PPI chain in Sun

•31% of the time, PPII chain occurs

$$^{1}H + {}^{1}H \rightarrow {}^{2}H + e^{+} + \nu$$

$$^{2}H + {}^{1}H \rightarrow {}^{3}He + \gamma$$

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

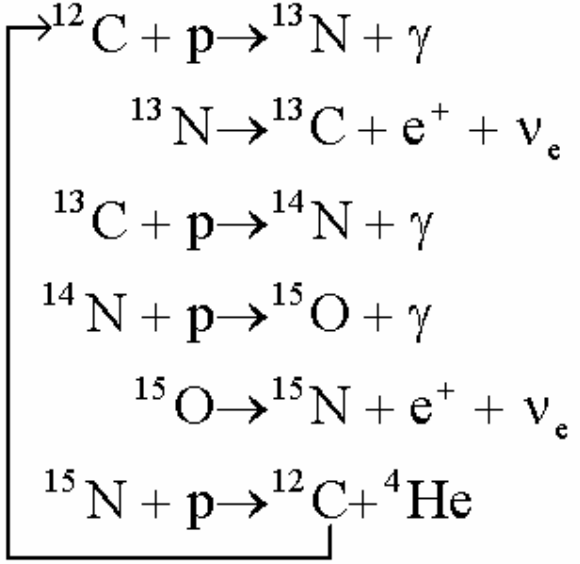
$$^{7}Be + e^{-} \rightarrow {}^{7}Li + \nu$$

$$^{7}Li + {}^{1}H \rightarrow 2\ {}^{4}He$$

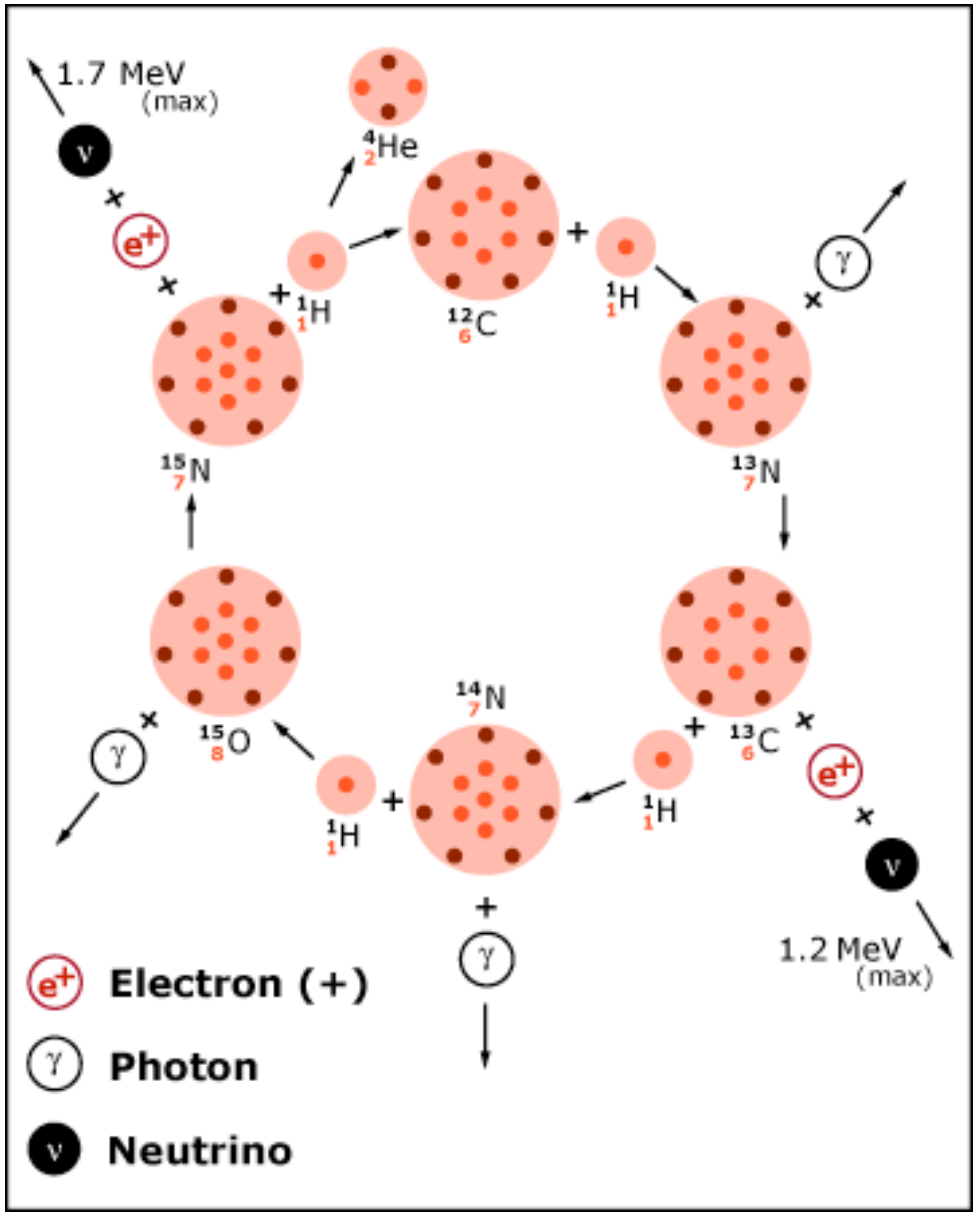
•Other chains (CNO cycle) are negligible, but important in other stars

CNO Cycle

- H can also be converted to ^{4}He through the CNO cycle
- Carbon, Nitrogen, Oxygen used as catalysts
- Much more T-dependent than P-P chain, CNO cycle occurs in stars slightly more massive than the Sun



CNO cycle: stars with $M > 1.2M_{Sun}$



Uses C, N, and O nuclei to catalyze fusion of H into He

Solar neutrino problem

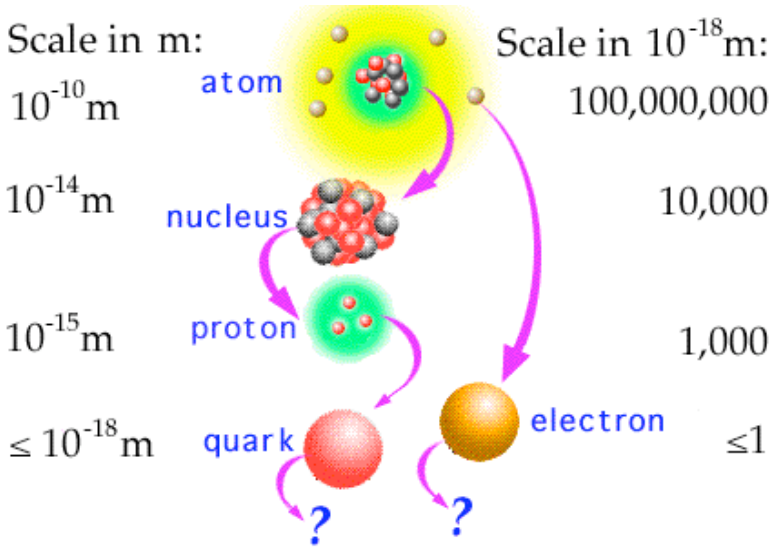
- 4 fundamental forces: gravitational, electromagnetic, strong, weak

- Elementary particles

Leptons (electrons, muons, taus, 3 neutrinos) participate in weak and EM interactions

Quarks, 3 at a time make up protons and neutrons (baryons), participate in strong, weak, EM interactions

Both leptons and quarks are acted on by gravity



Solar neutrino problem

- Neutrinos: zero charge, non-zero mass, each type ν_e, ν_μ, ν_τ, is associated with a charged particle (electron, muon, tau)

- Rarely interact with matter: 10^{11} neutrinos pass through your thumb every second. For every 10^{11} neutrinos from the sun that pass through the earth, only one interacts with terrestrial material

Solar neutrino problem

- Spectacular confrontation of solar and theoretical particle physics

- Background: the P-P chain predicts the production of *neutrinos* along the way to forming ^{4}He, e.g.:

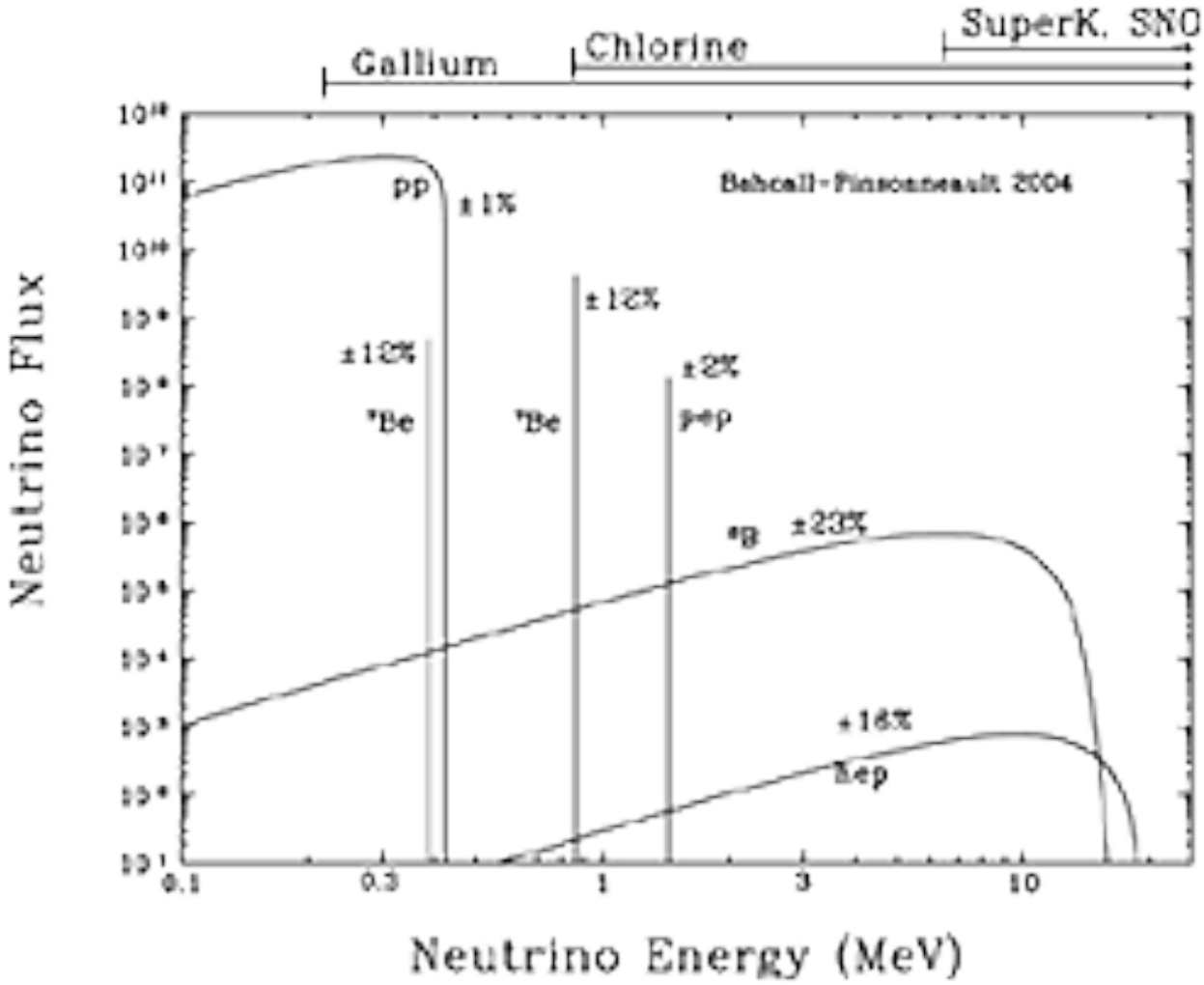
$$^8\mathrm{B} \rightarrow {}^8\mathrm{Be} + e^+ + \nu_e$$

Ultimately results in:

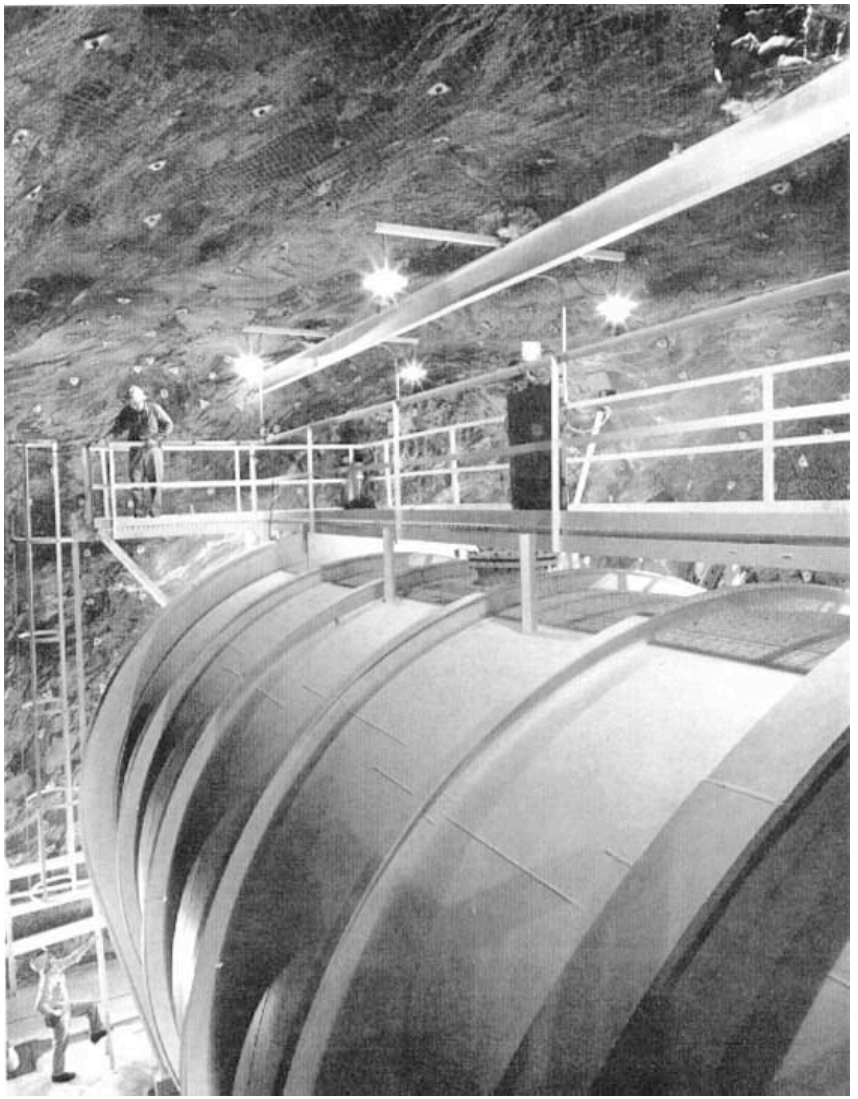
$$4\ {}^1\mathrm{H} \rightarrow {}^4\mathrm{He} + 2e^+ + 2\,\nu_e + 2\gamma$$

(e^+ positrons, γ photons, ν_e neutrinos)

Energy spectrum of neutrinos produced in different reactions



In 1970, in the underground Homestake Gold Mine in SD, physicists started measuring solar neutrino flux produced by p-p chain



- Underground tank of 615,000 kg of C_2Cl_4
- Detects ^{37}Ar produced by reaction between ^{37}Cl and ν
- Sensitive to production of few Ar atoms per month

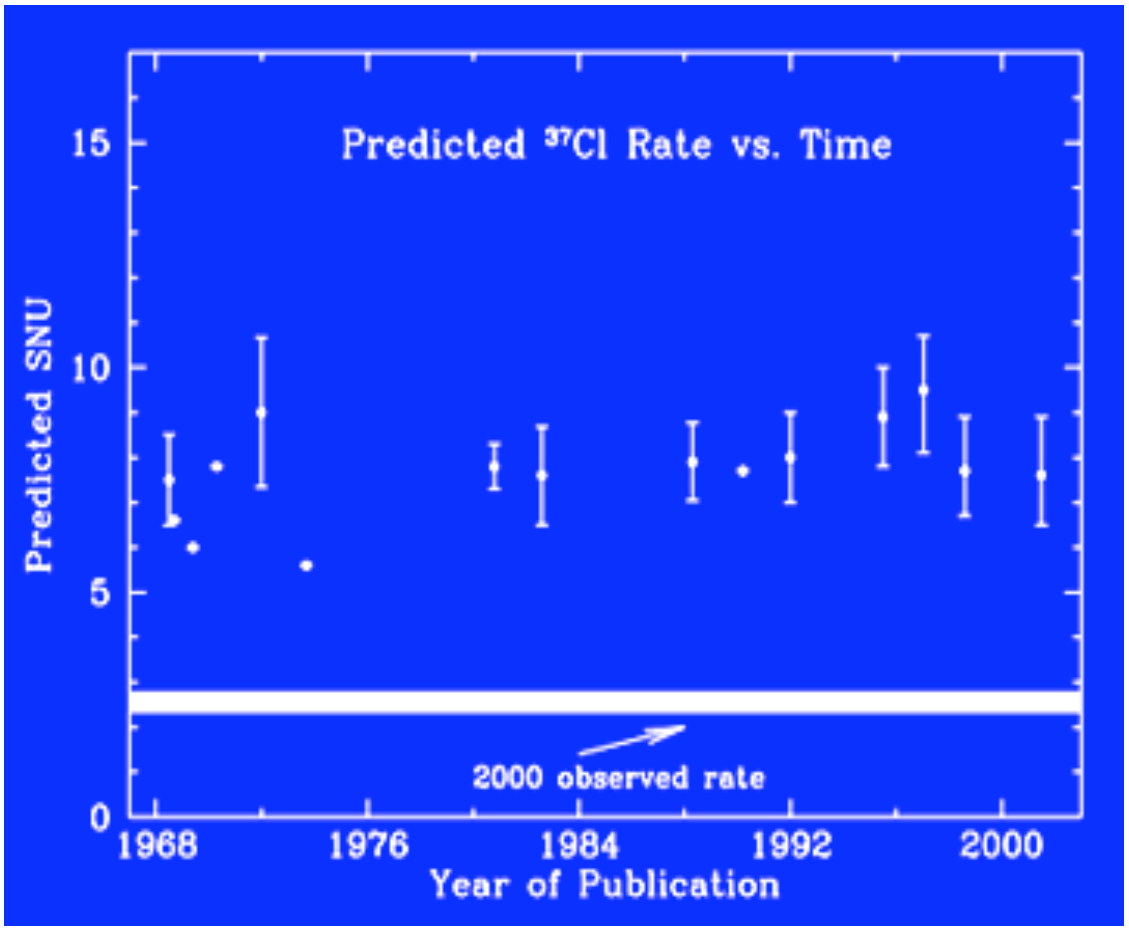
Solar neutrino results

- Measured rate was ~1/3 predicted rate from standard solar model = "**solar neutrino problem**"

- Physicists blamed this on Solar models

- But experiments measured only electron neutrinos

...



Solar neutrino solutions?

3 possibilities:

1. Predicted # of ν from the solar interaction, or predicted # of argon incorrect
2. Experimental data wrong
3. Theory of neutrinos incorrect: in terms of behavior while traversing large distances

Solar neutrino results

- For 30 years, measured rate was ~1/3 predicted rate from standard solar model = "**solar neutrino problem**"
- 3 possibilities:

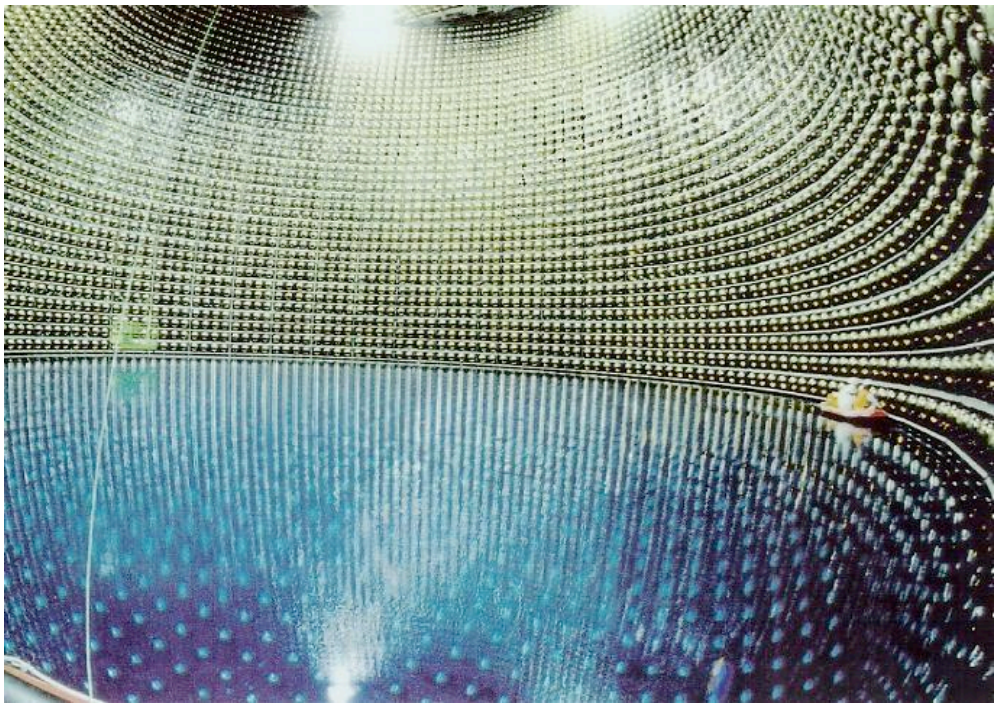
1. Predicted # of ν from the solar interaction, or predicted # of argon incorrect
2. Experimental data wrong
3. Theory of neutrinos incorrect: in terms of behavior while traversing large distances

Solar neutrino results

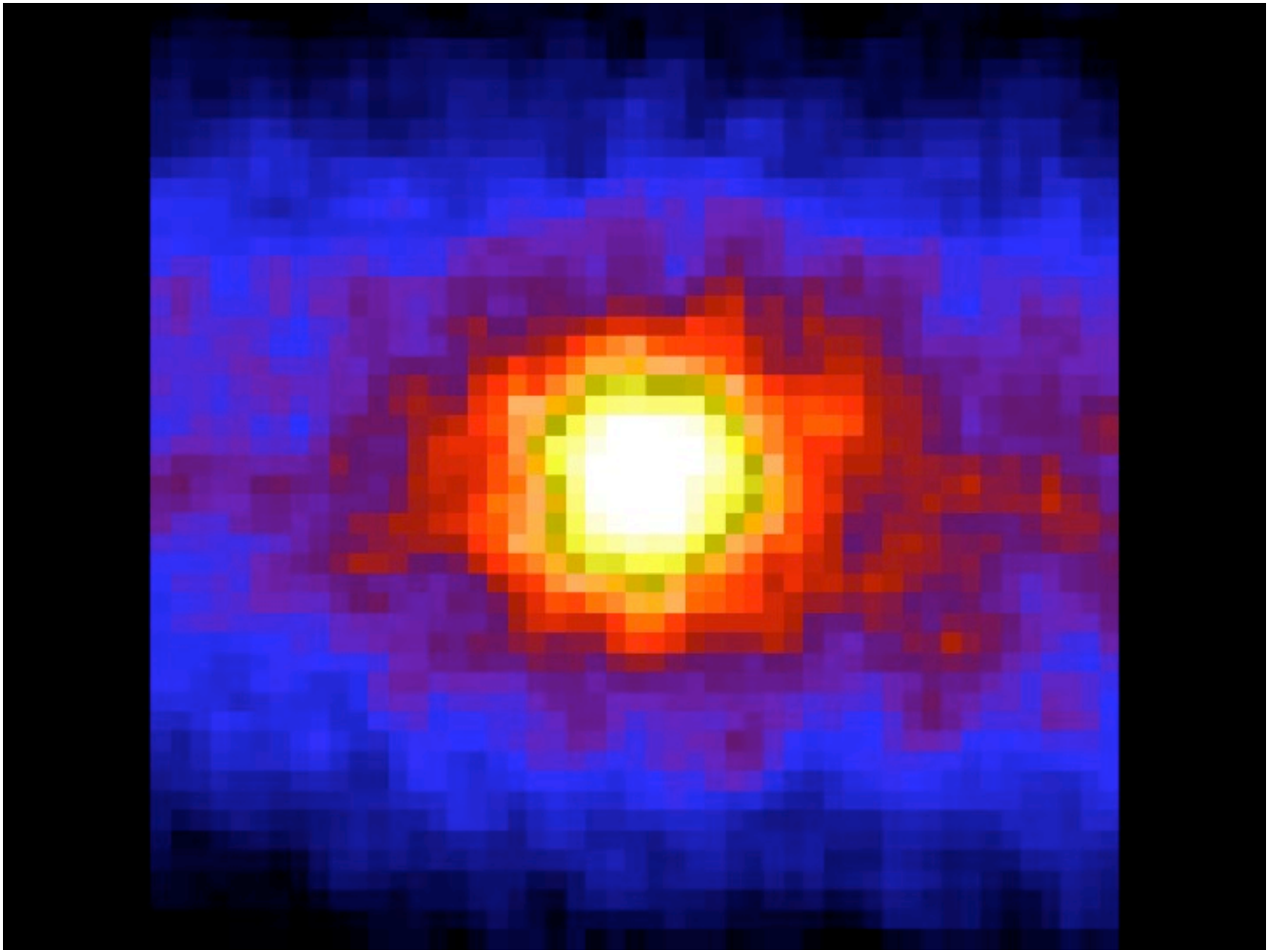
- The problem was not with the solar model, but our understanding of particle physics!
- Solution: while traveling from the sun at close to the speed of light, electron neutrinos change "flavor" to muon or tau neutrinos. Detector is only sensitive to electron neutrinos, hence the lower detection rate than expected
- Verified this model with recent observations of (Superkamiokande, Sudbury Neutrino observatory)

Solar neutrino observatories

•Sudbury Neutrino Obs.

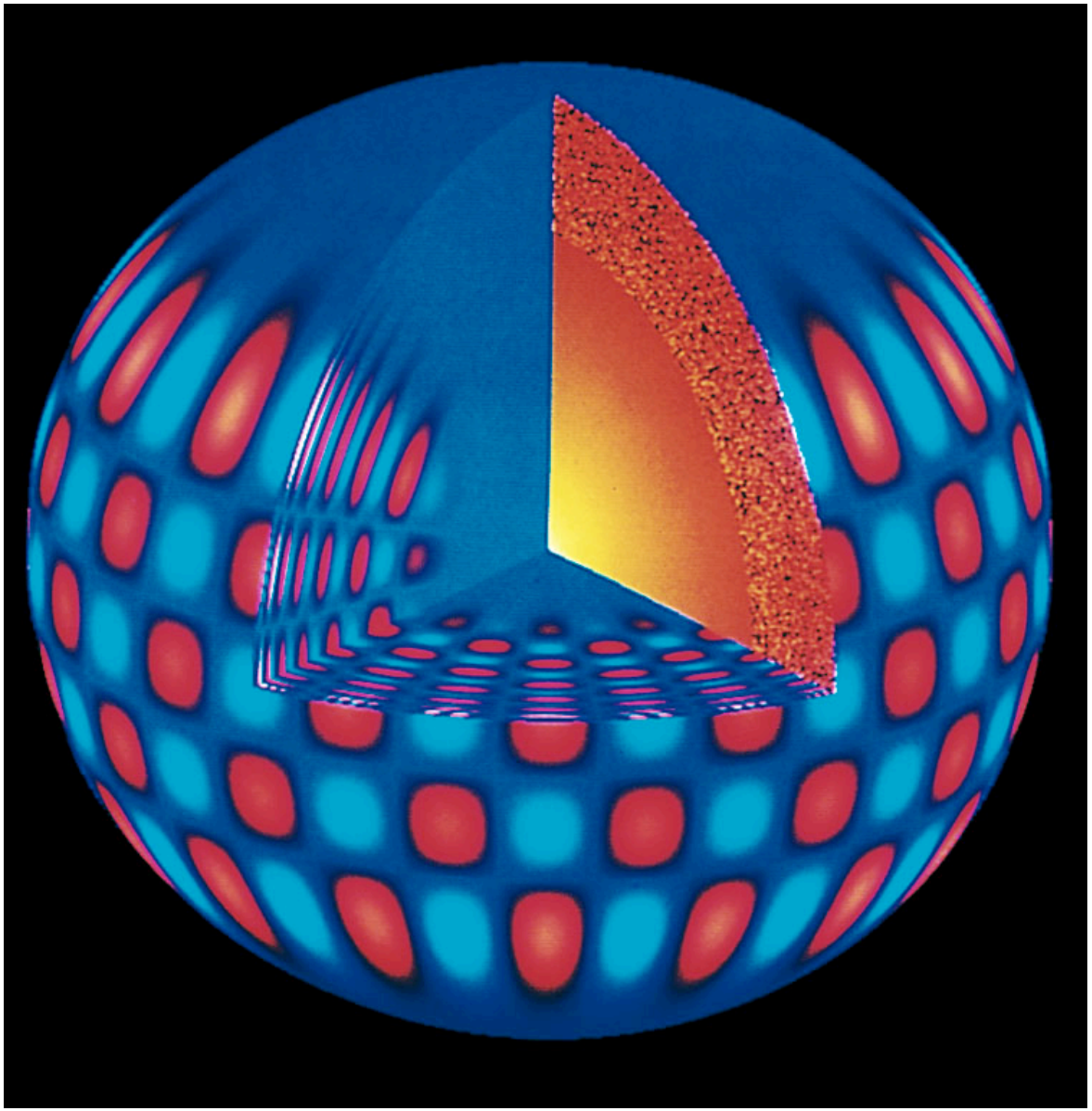


•Super-Kamiokande

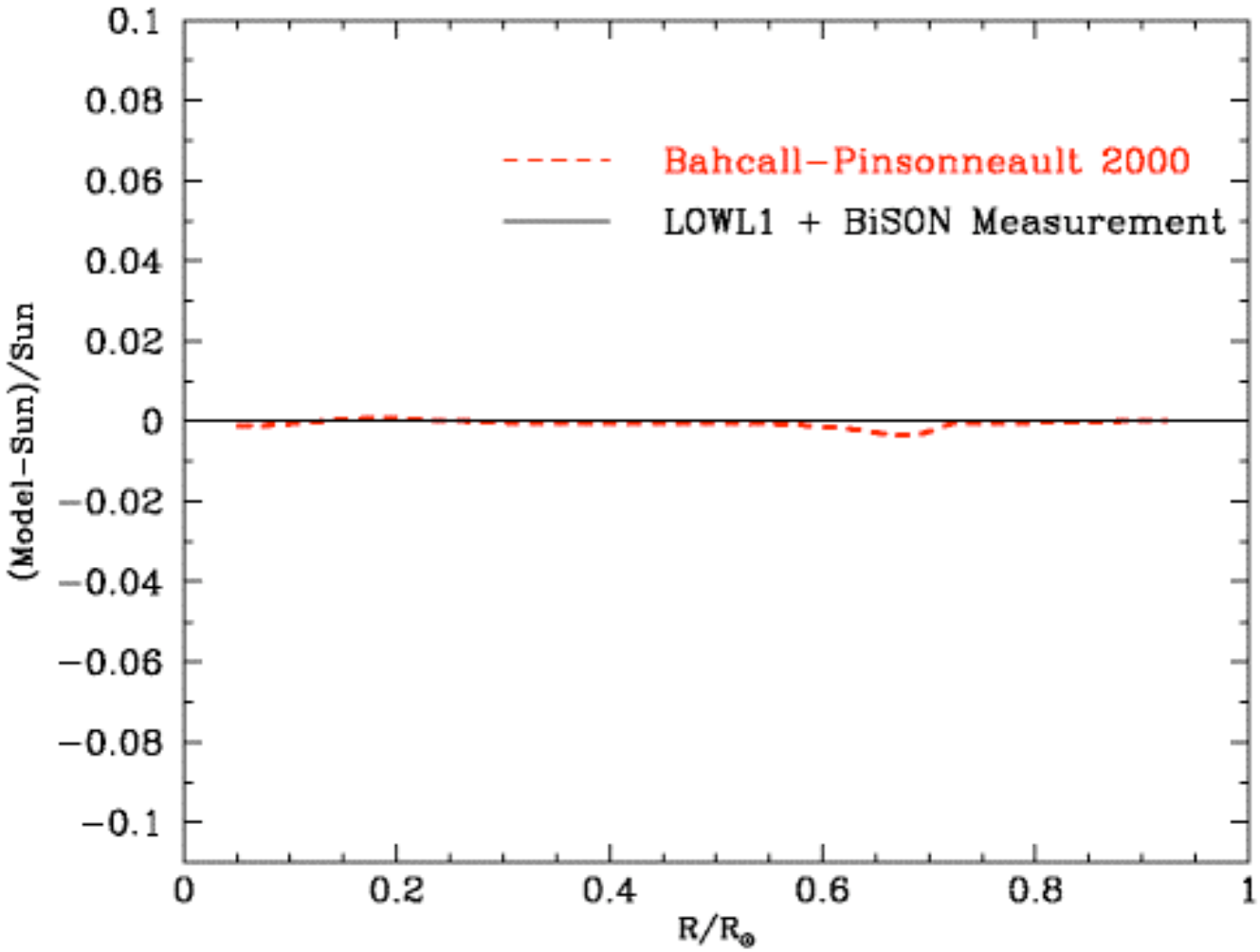


Helioseismology

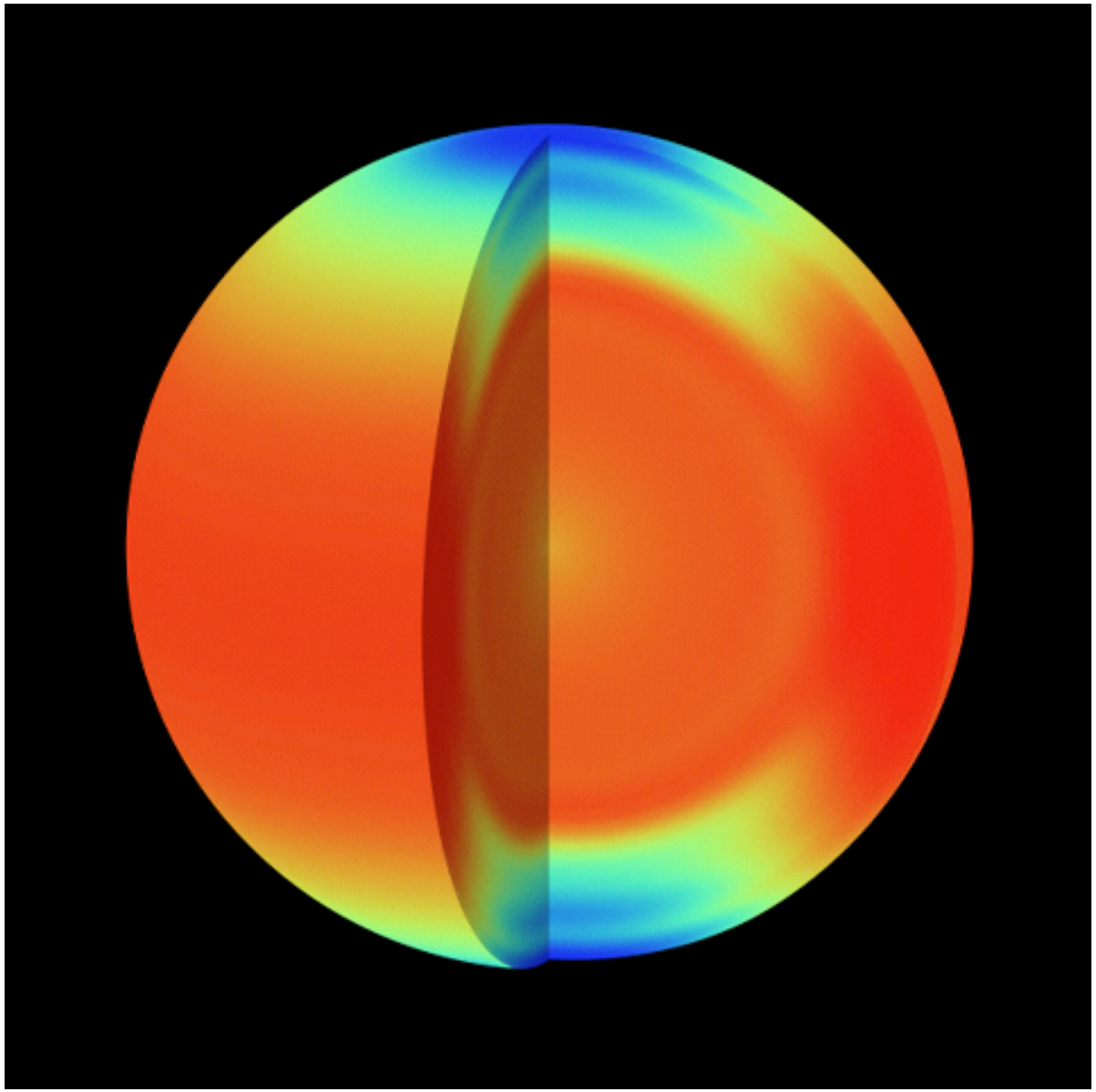
- Vibrations of solar atmosphere measured by Doppler shifts
- Pattern of observed frequencies tells us about sun's interior (e.g. sound speed)



Measured vs. predicted sound speed in Sun



Internal rotation rate of Sun measured through helioseismology



Convection and radiative zones rotate at different rates

Perhaps leads to generation of magnetic field

Red = fast rot.

Blue = slow rot.