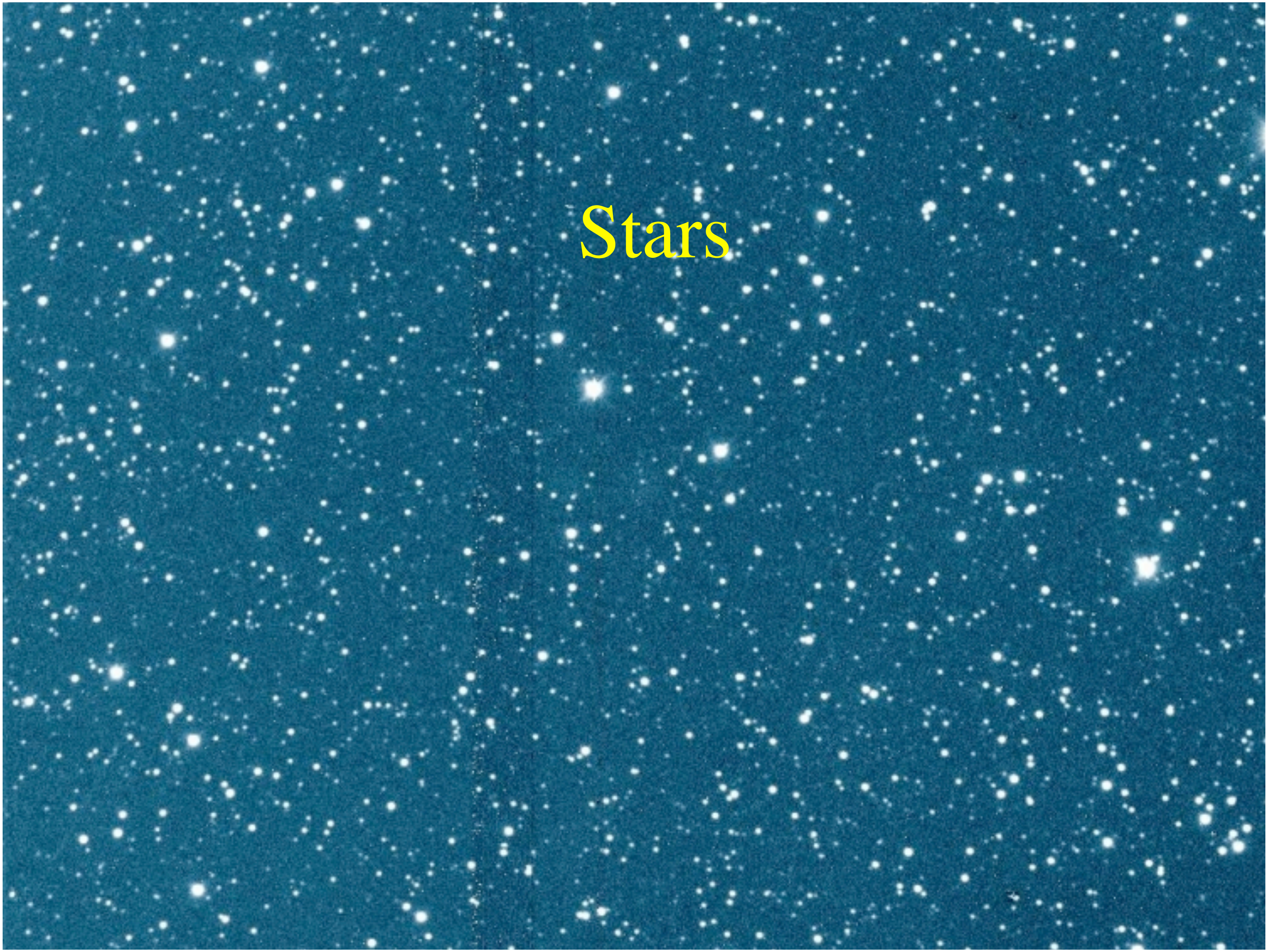
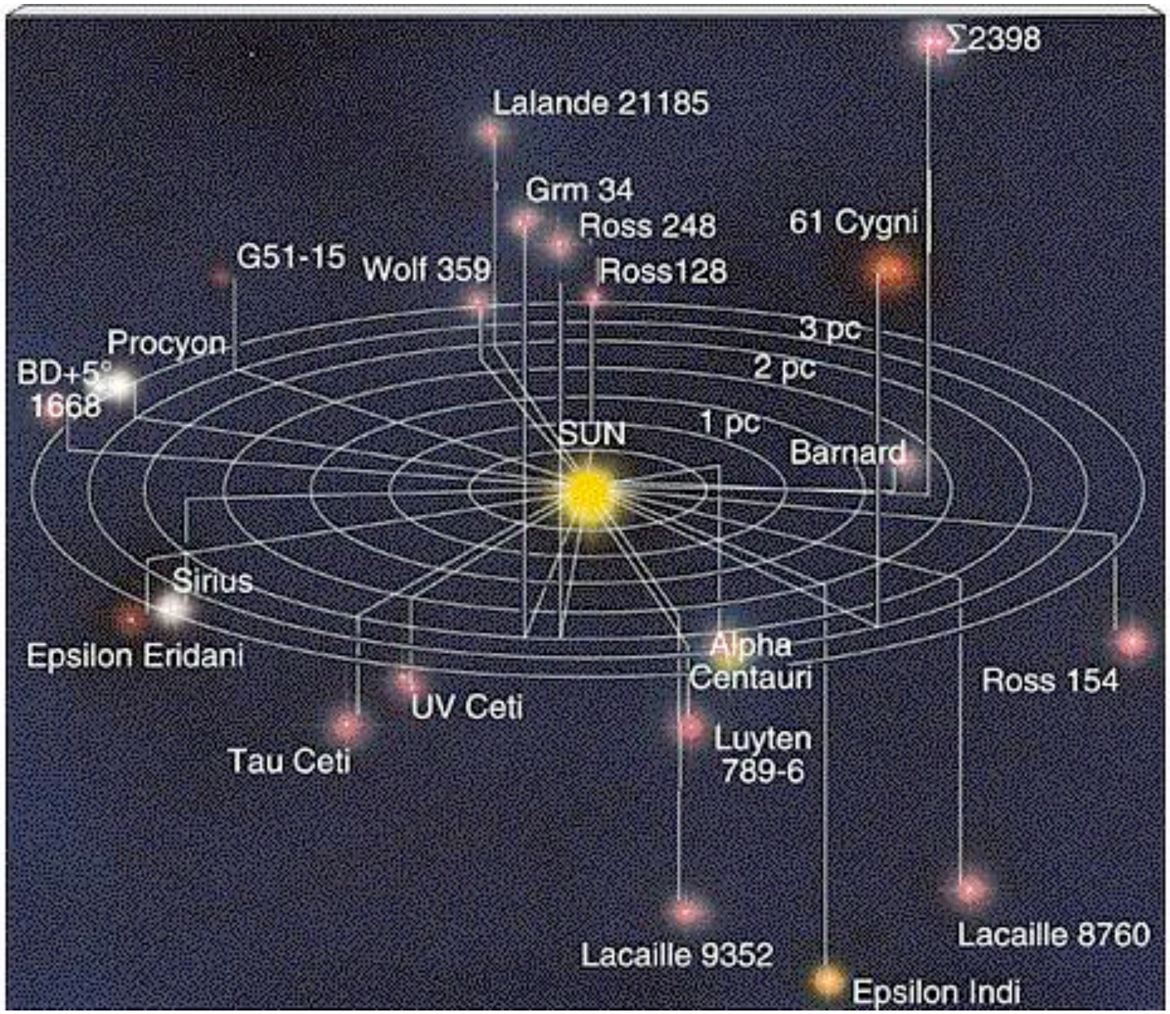

Stars

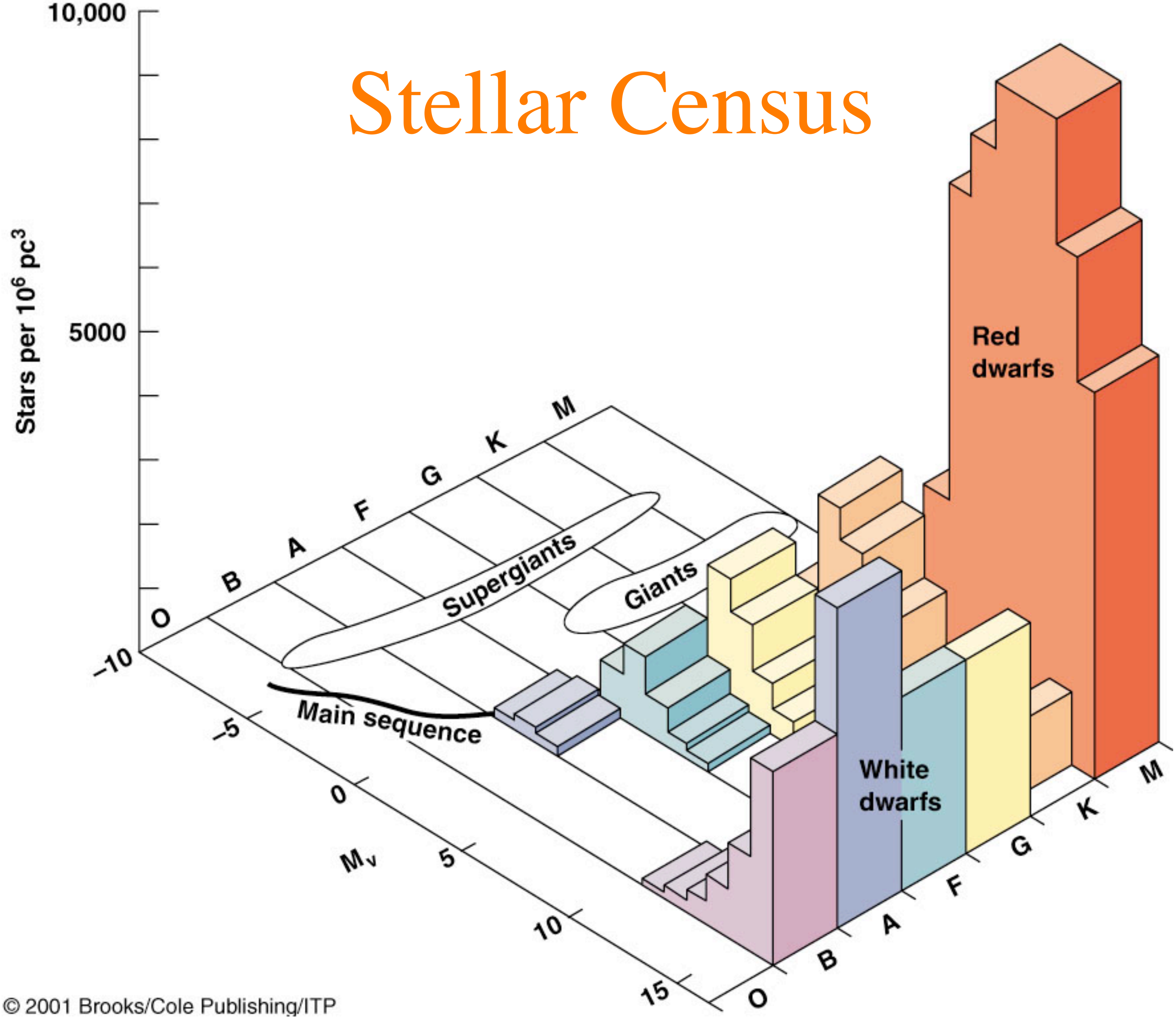
Nearest stars are almost all low mass stars



Stellar Census

- Luminous stars are very rare:
  - ✶High-mass main-sequence stars (O stars) are fewer than 1 in a million
  - ✶Supergiants are similarly rare
- Since they are rare, most are very far away.
- Most stars seen with naked eye are intrinsically luminous = *Malmquist bias*

Stellar Census

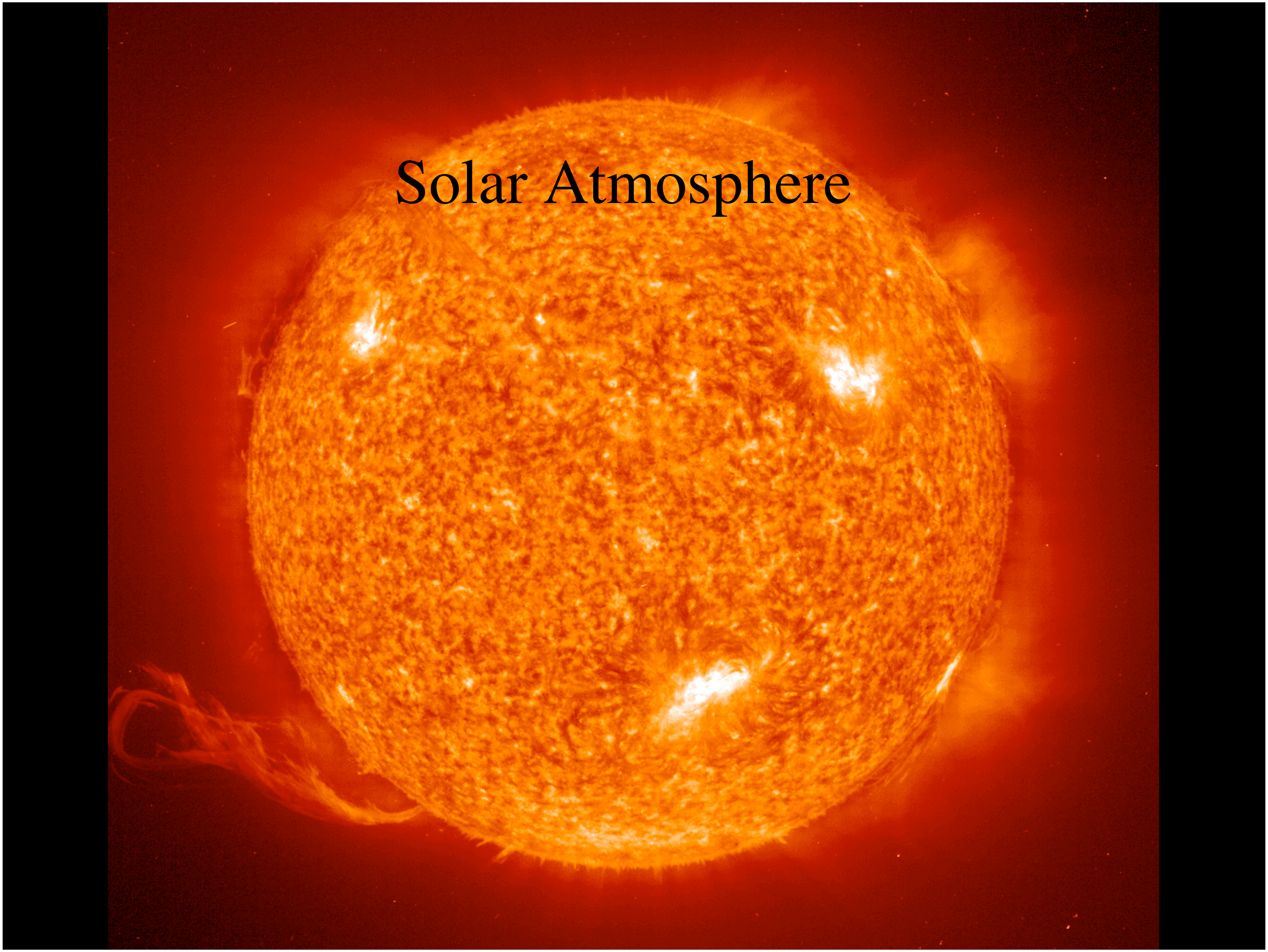


Stellar Physics and Interiors

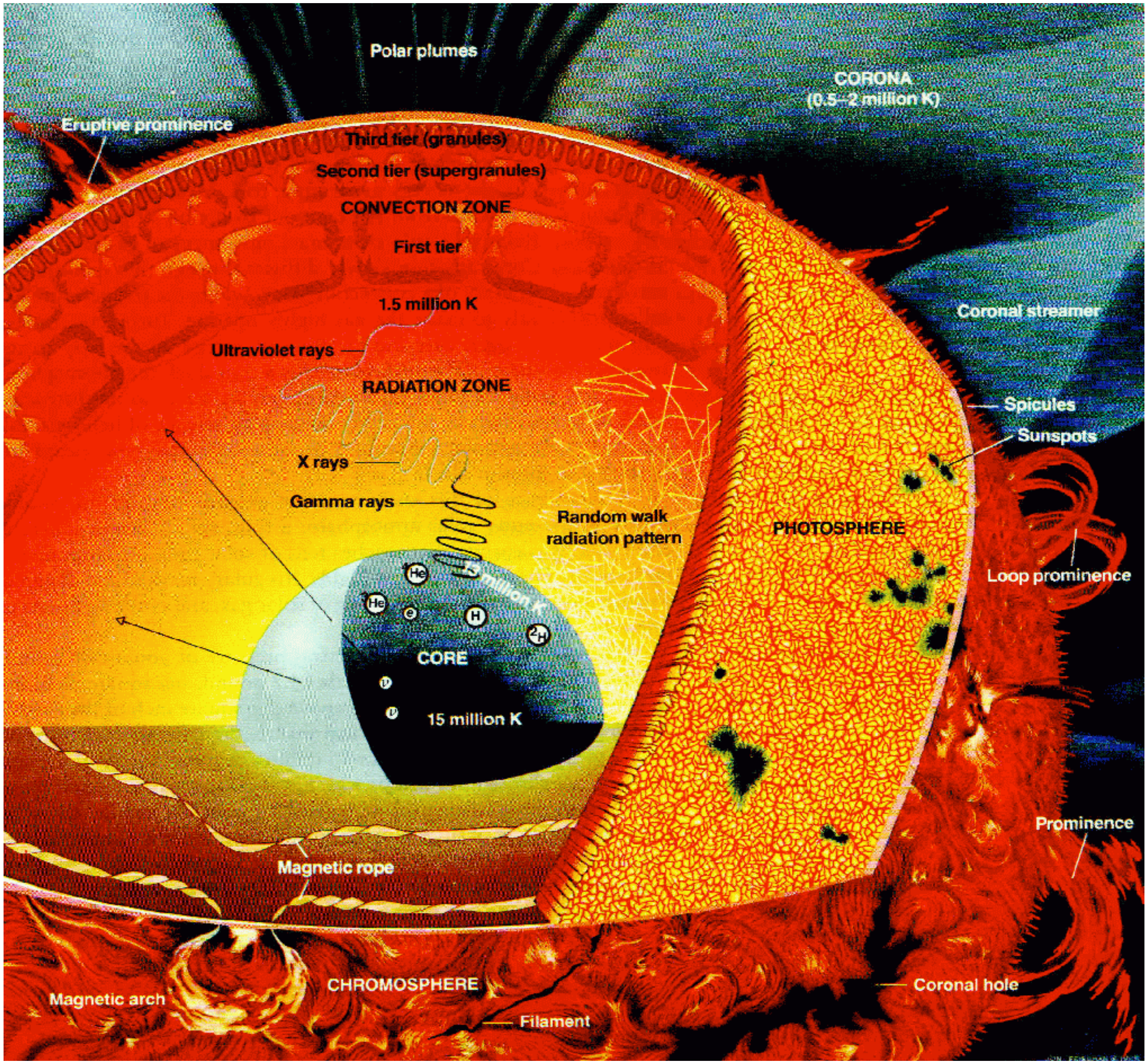
Solar Interior

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

Solar Atmosphere



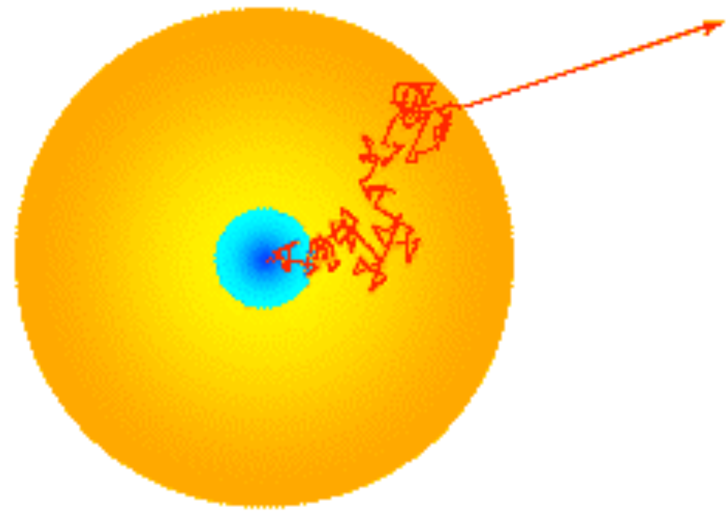
Solar interior



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

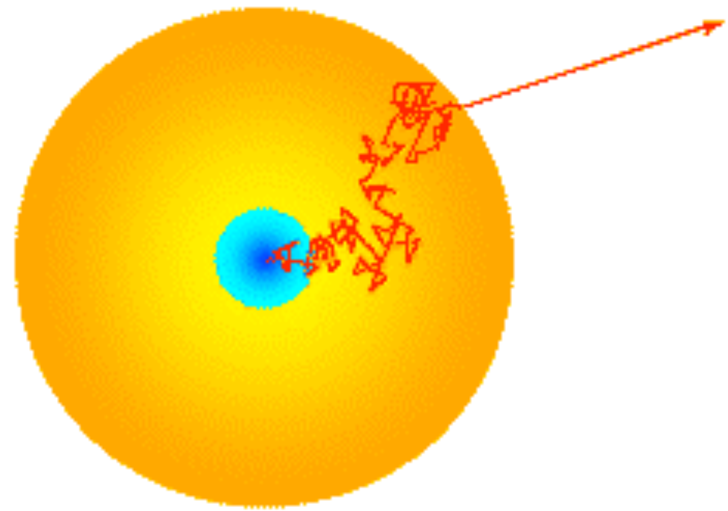


- At avg density of 1400 kg/m^3 and avg temp of 4.5x10^{6}K "mean free path" of photon before interacting with matter is < 1 cm. Optical depth is very high, effective path length is much longer than $R_\odot$; time to escape is much longer than $R_\odot$/c~2 sec

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

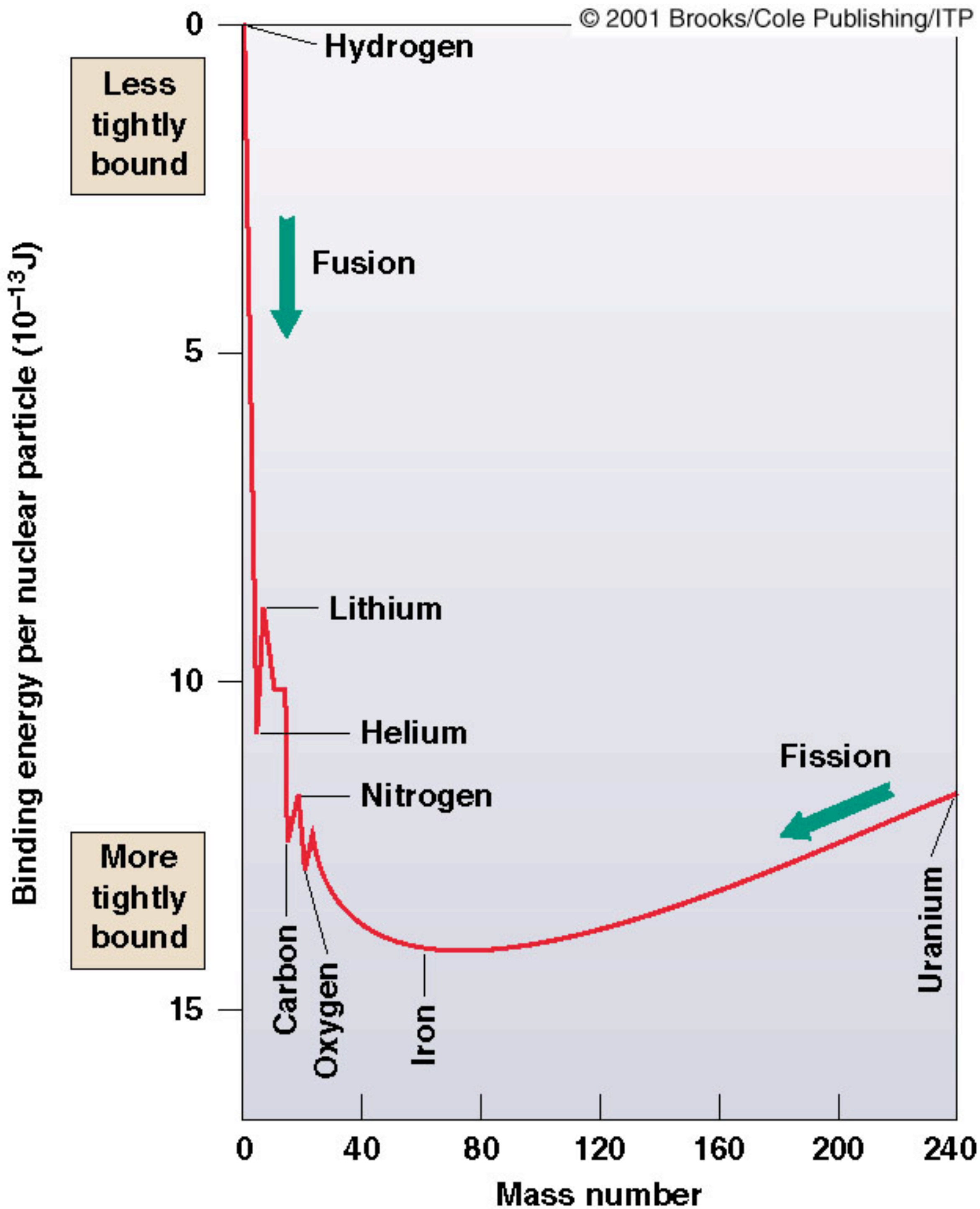
- Oldest rocks found so far:
  - ✶Earth: 3.9 billion years
  - ✶Moon: 4.5 billion years
  - ✶Mars: 4.5 billion years
  - ✶Meteorites: 4.6 billion years
- The *smaller* an object, the *faster* it cools and therefore solidifies, the *older* it is
  - ➢Planets, moon, meteorites (entire solar system) formed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

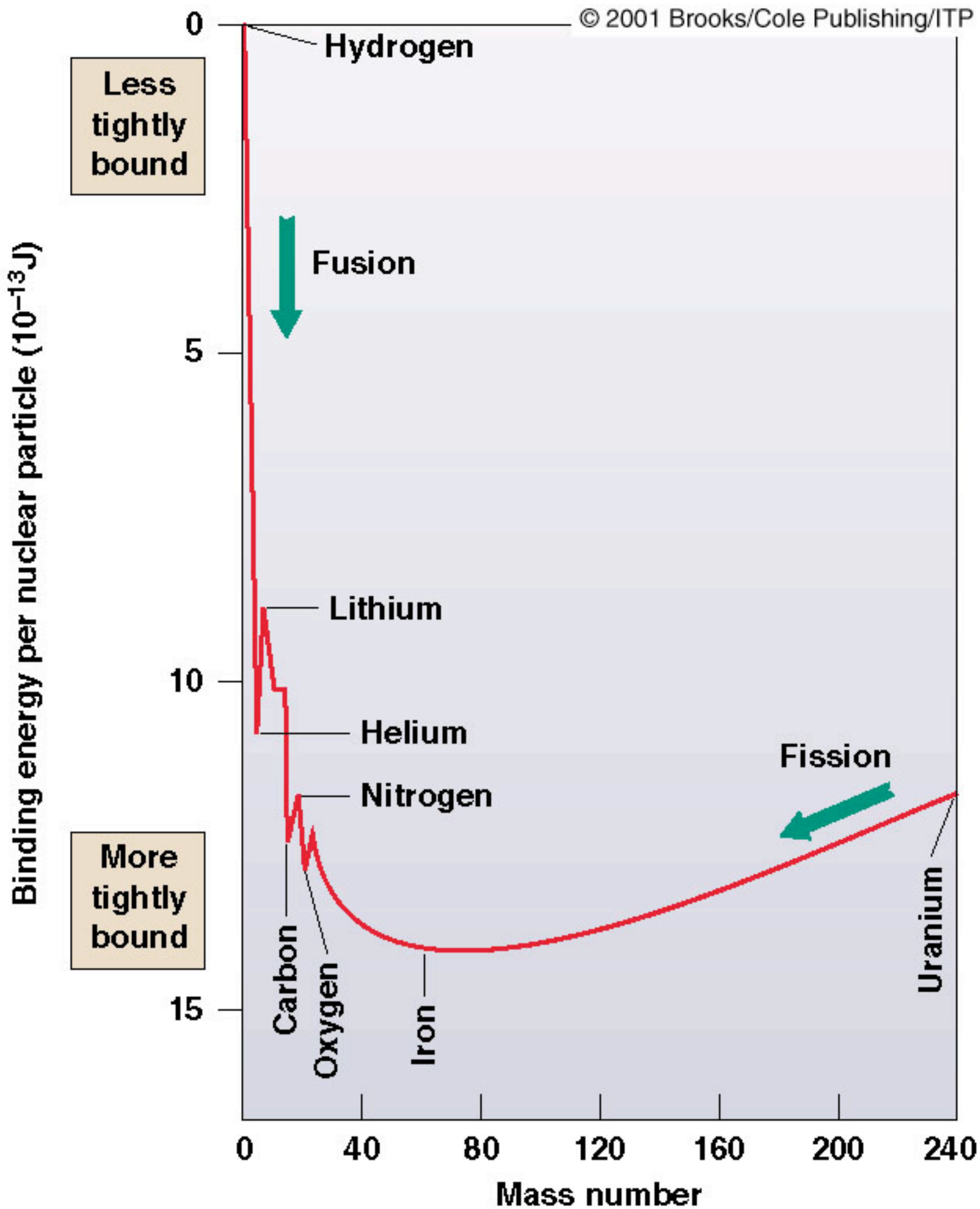
Fusion & Fission

- ***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.

Proton-proton chain

Most important reaction in Sun is PPI chain

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

e^{+} = positron

ν = neutrino

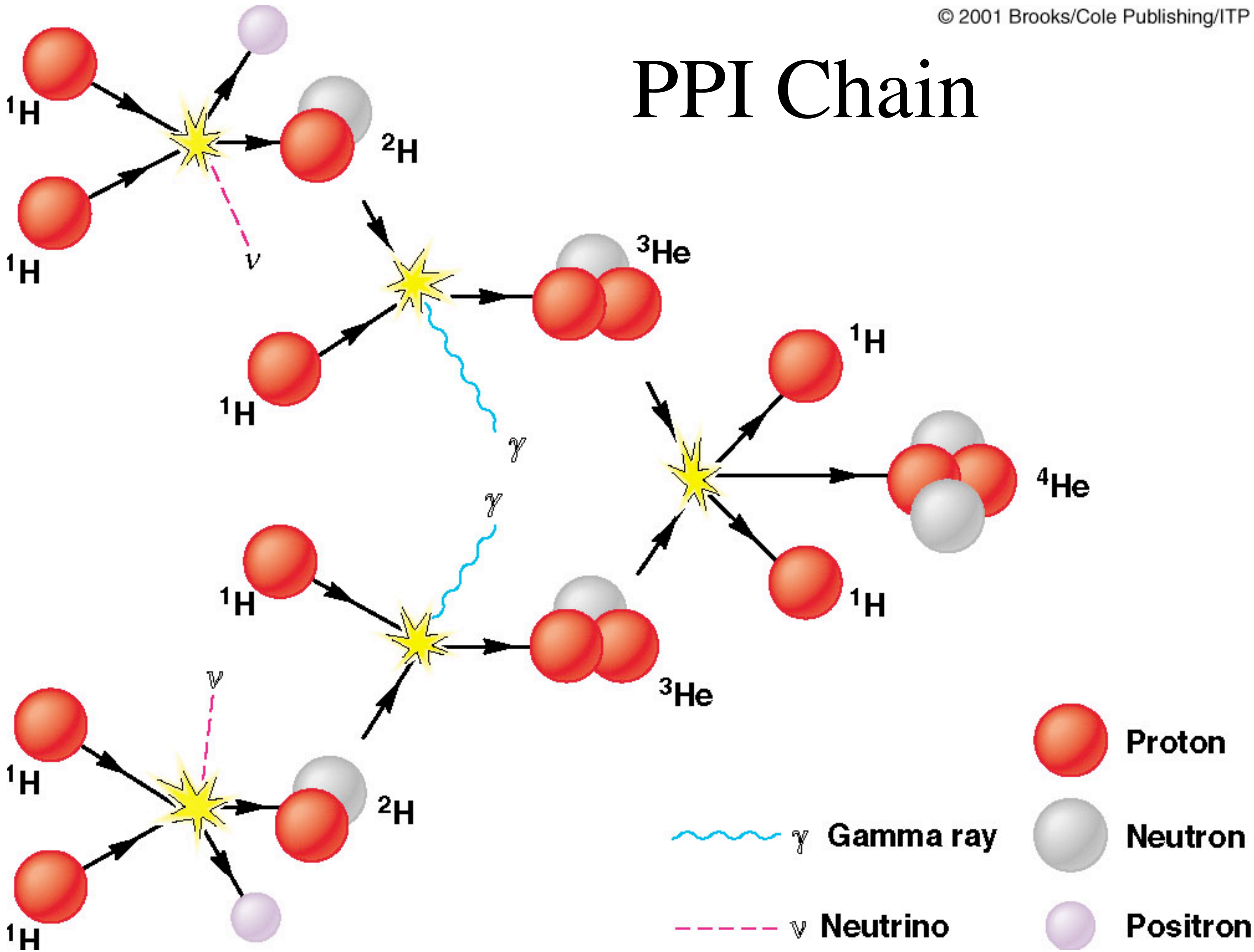
γ = photon

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

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

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

PPI Chain



^{1}H
^{1}H
ν
^{2}H
^{3}He
^{1}H
γ
γ
^{1}H
^{4}He
^{1}H
^{1}H
ν
^{3}He
^{1}H
^{2}H
^{1}H
γ Gamma ray
ν Neutrino
Proton
Neutron
Positron

PPII & PPIII

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

ppII:

(3)	$^3He + ^4He$	$^7Be + \gamma$
(4)	$^7Be + e$	$^7Li + \nu_e$
(5)	$^7Li + ^1H$	$^4He + ^4He$

ppIII:

(3)	$^3He + ^4He$	$^7Be +$
(4)	$^7Be + ^1H$	$^8B + \gamma$
(5)	^8B	$^8Be + e^+ + \nu_e$
(6)	^8Be	$^4He + ^4He$

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

$$^{12}C + p \rightarrow {}^{13}N + \gamma$$

$$^{13}N \rightarrow {}^{13}C + e^{+} + \nu_{e}$$

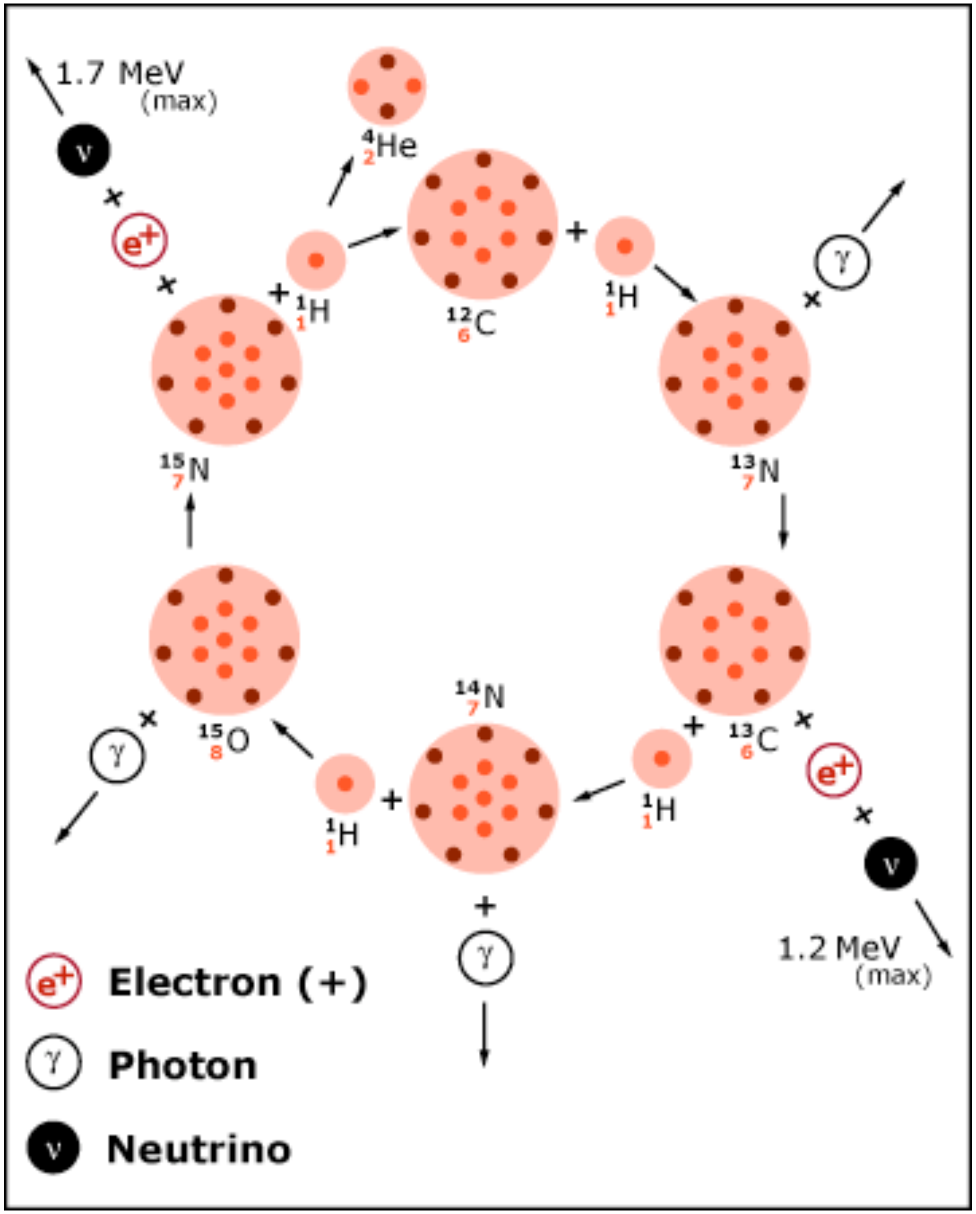
$$^{13}C + p \rightarrow {}^{14}N + \gamma$$

$$^{14}N + p \rightarrow {}^{15}O + \gamma$$

$$^{15}O \rightarrow {}^{15}N + e^{+} + \nu_{e}$$

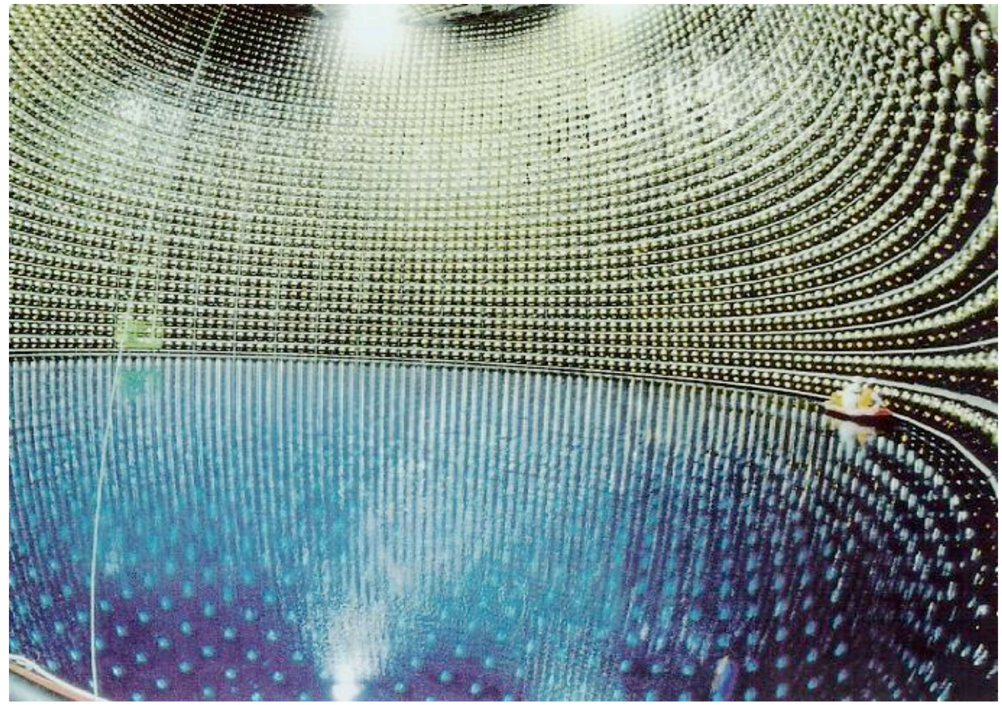
$$^{15}N + p \rightarrow {}^{12}C + {}^{4}He$$

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

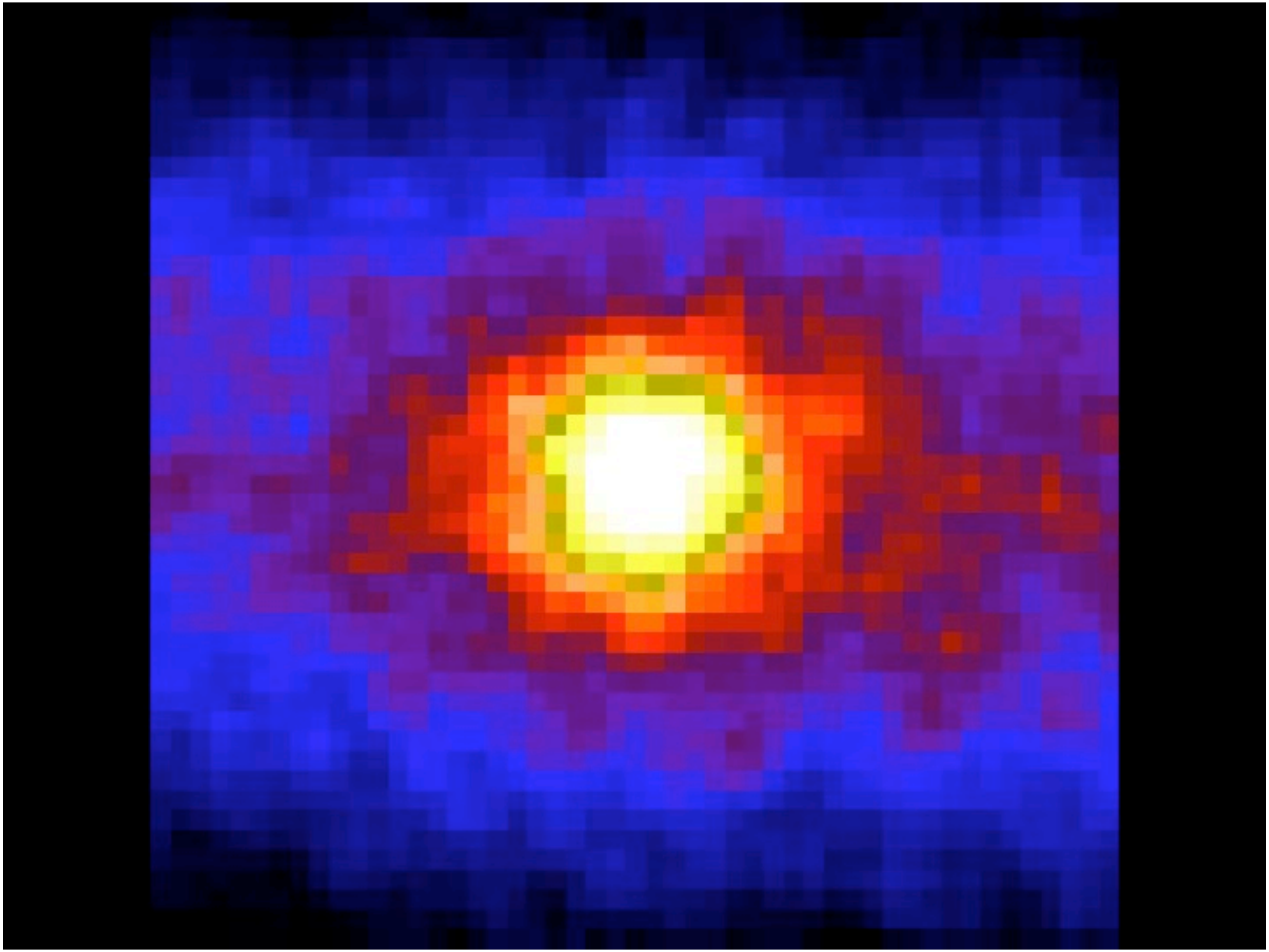


Uses C, N, and O nuclei to catalyze fusion of H into He

Solar neutrino observatories

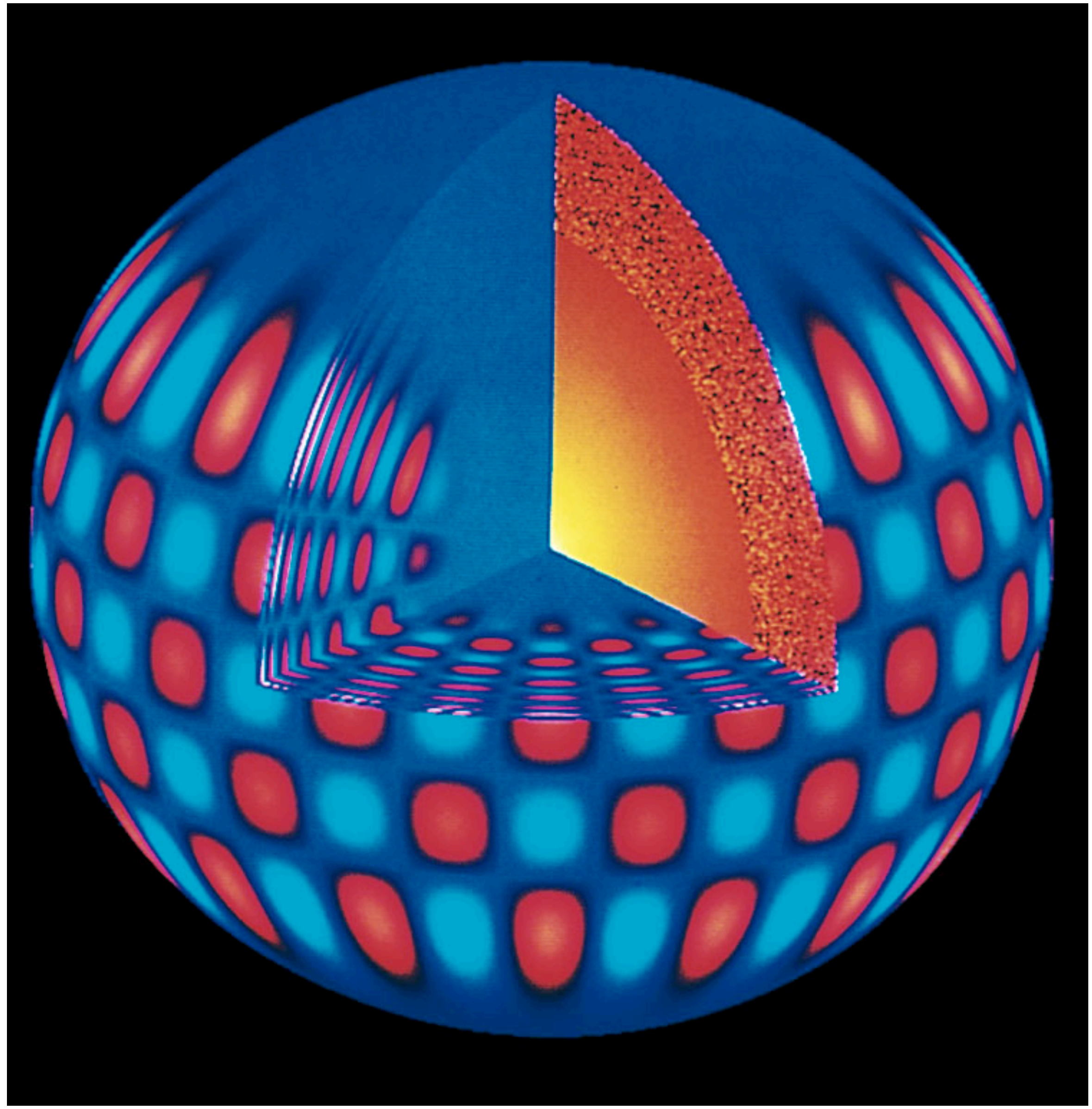


- Sudbury Neutrino Obs.
- Super-Kamiokande

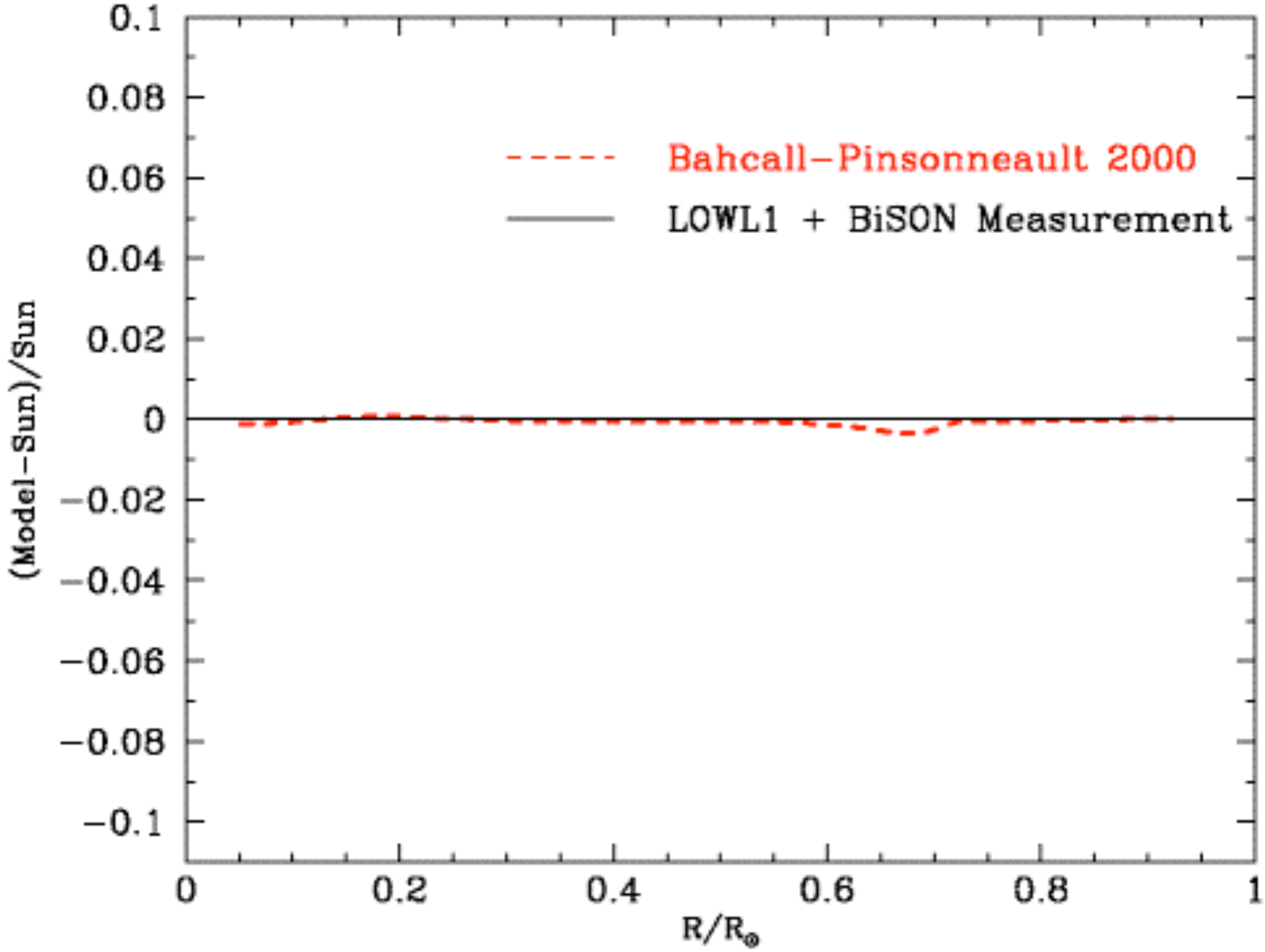


Helioseismology

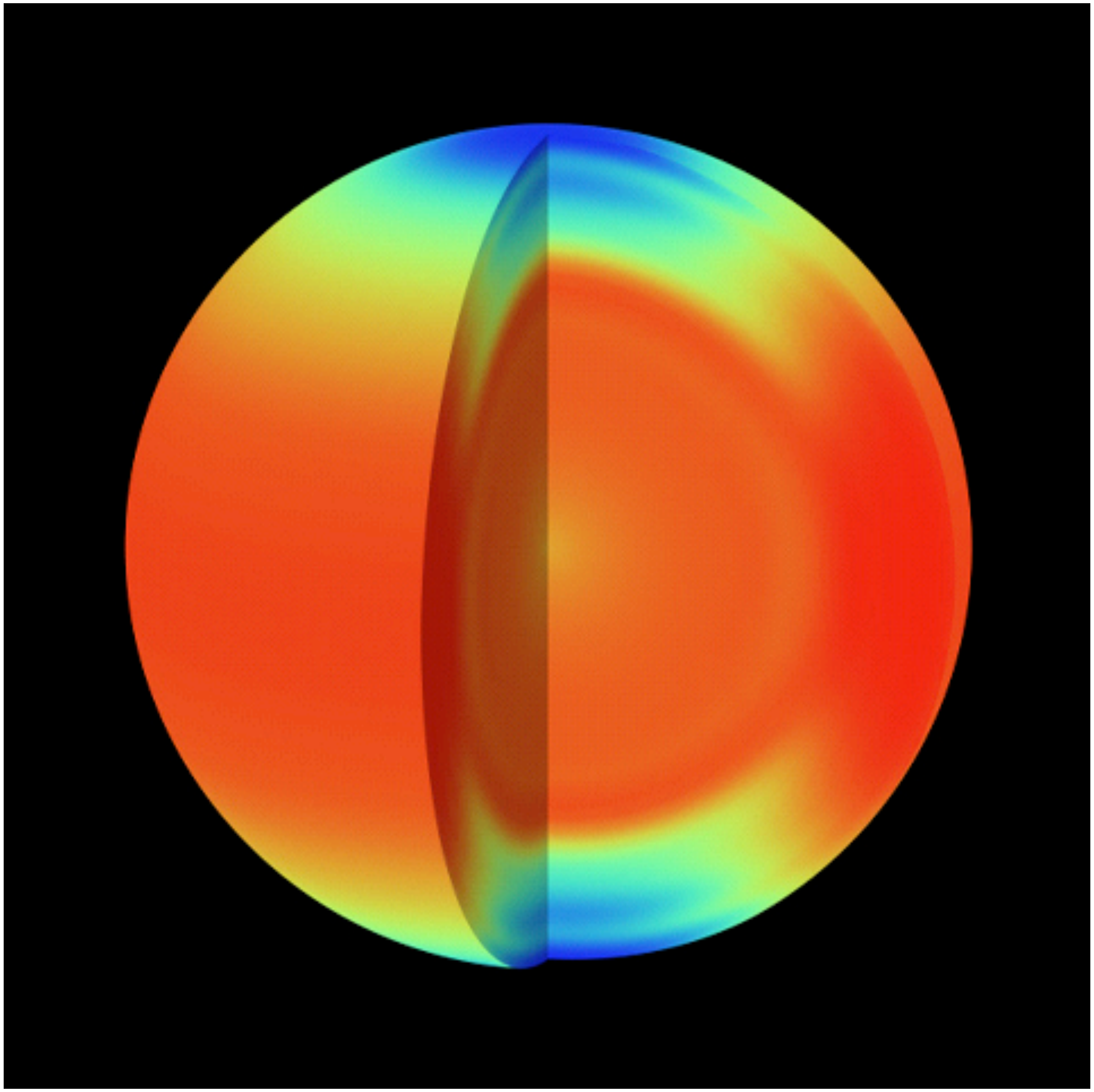
- Vibrations of solar atmosphere measured by Doppler shifts
- Pattern of observed frequencies tells us about sun’s interior (e.g. sound speed)



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.

Stars come in all different masses and sizes…

But fundamentally, they all have the same structure – they are just giant balls of gas, mostly H and He.

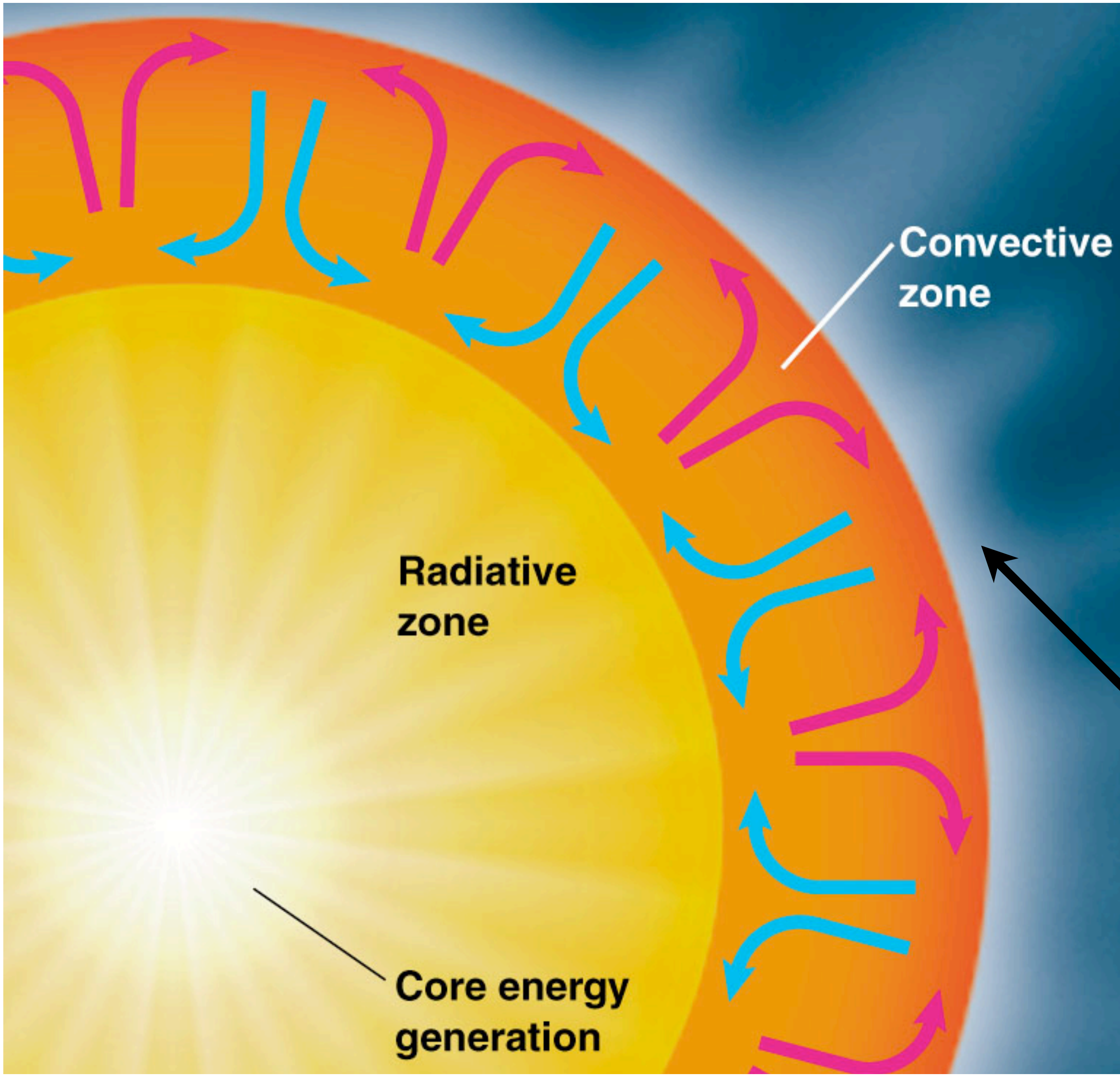
Stars of different masses differ primarily in

- Internal energy transport mechanism
- Primary H fusion network
  - PP chain in low mass stars
  - CNO cycle in high mass stars

Energy Transport in stars

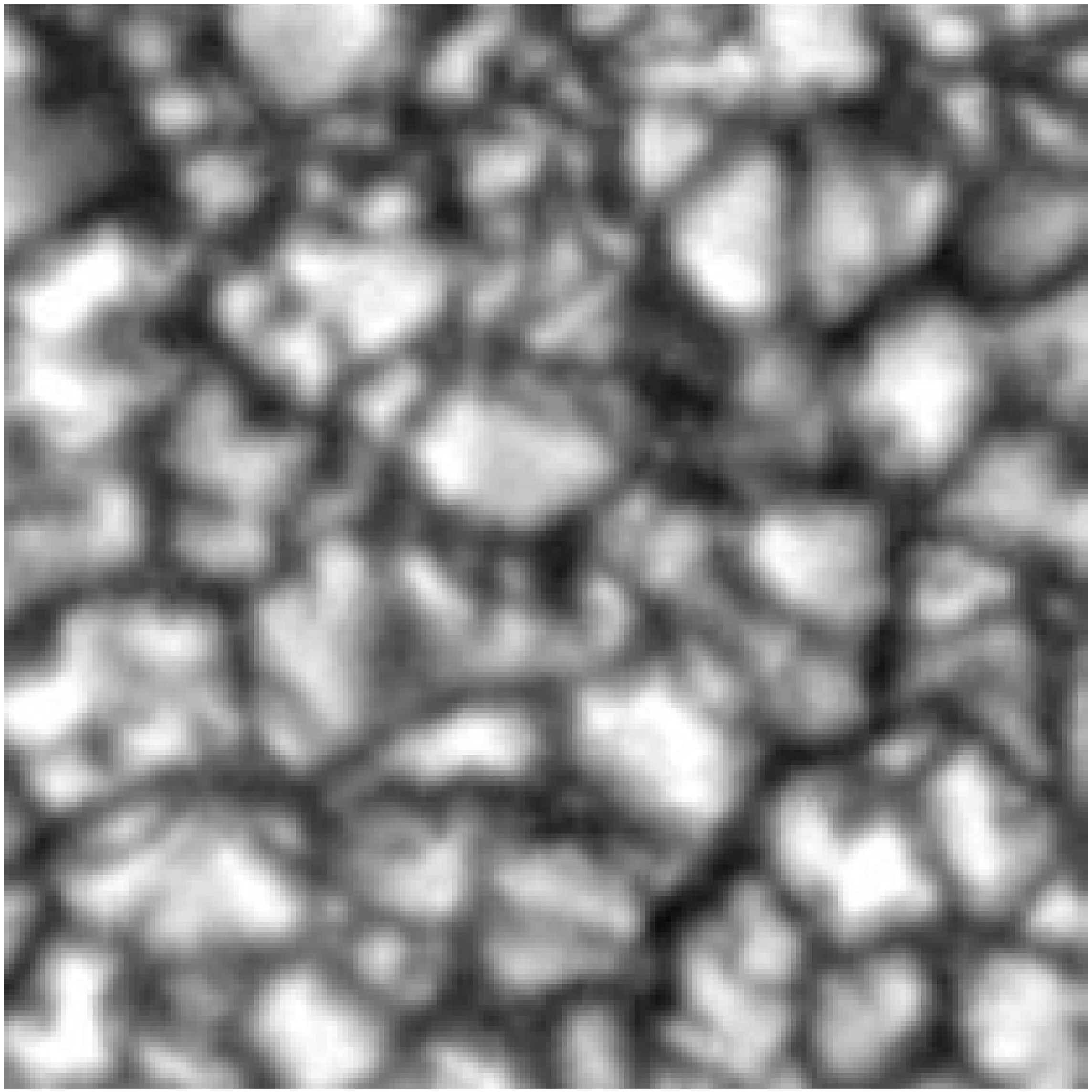
- **Radiation**: energy is carried towards surface via photons
- **Convection**: energy transported via hot buoyant mass elements rising outwards while cool elements fall inwards
- **Conduction**: energy transported via collisions through particles

Energy Transport in Sun

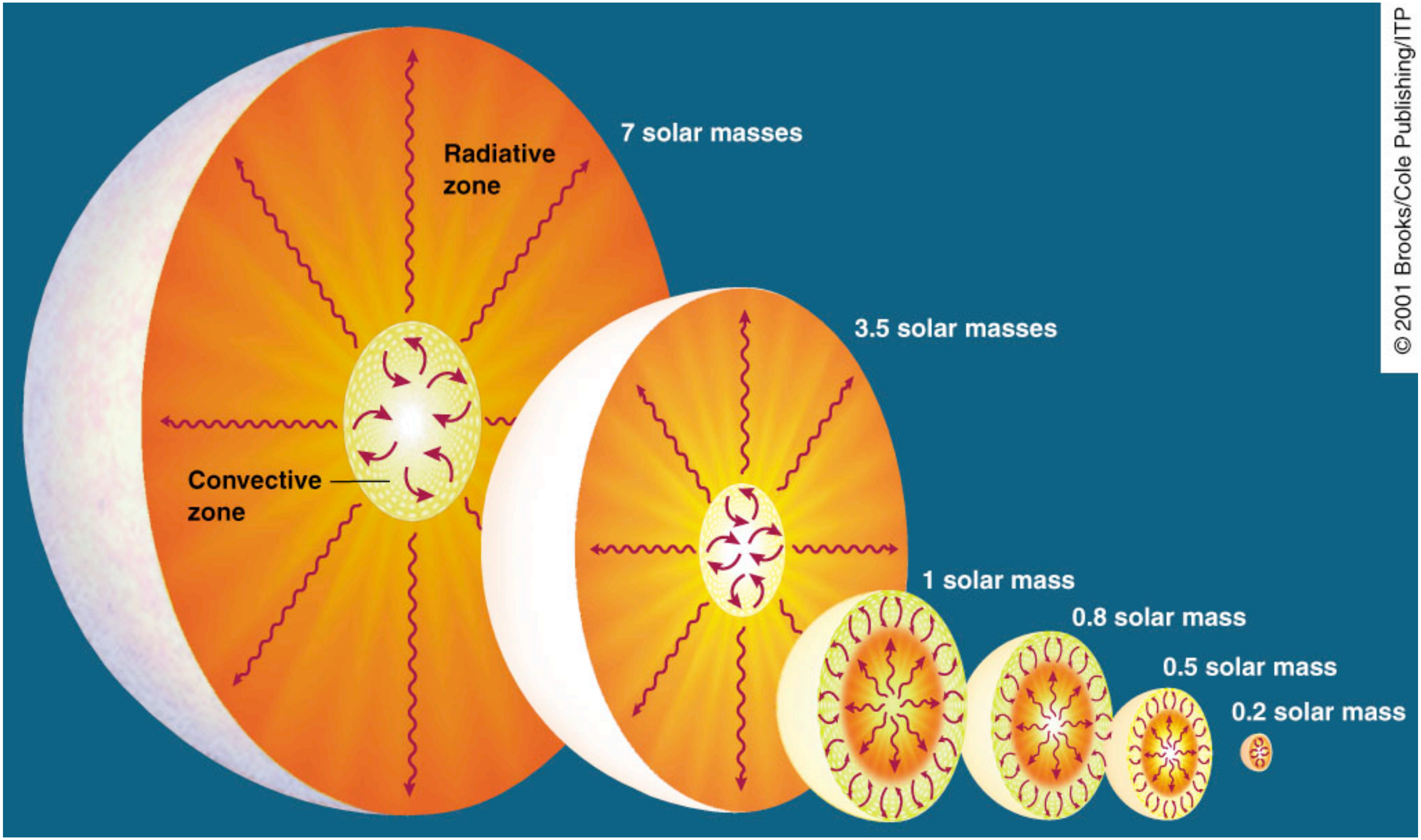


Photosphere:
Radiates to space

Solar Convection:



Energy Transport in other stars



Energy Transport in other stars

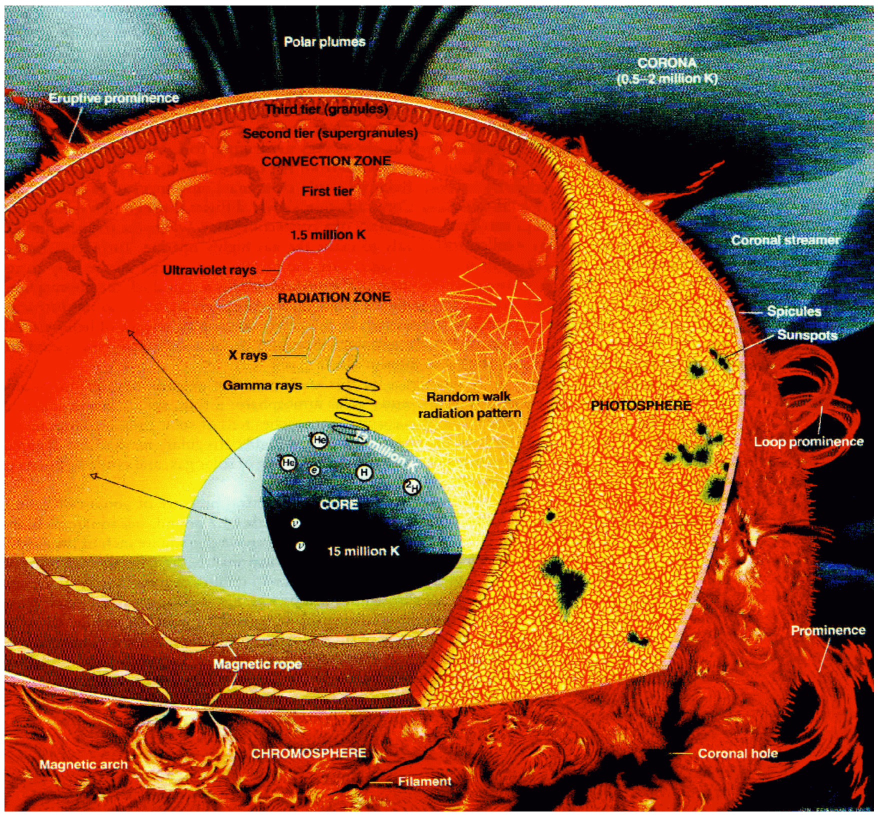
- High-mass stars ($M>1.2-1.3\ M_{sun}$): convective core, radiative envelope

- Low-mass stars ($M<1.2-1.3\ M_{sun}$): radiative core, convective envelope

- Really low-mass stars ($M<0.3\ M_{sun}$): entirely convective

- Relative importance of convection and radiation, depends on opacity and temperature gradient

How can we calculate conditions inside Sun and Stars?…(M, L, T, P, ρ)



…using equations of stellar structure.

Luminosity increases with *Mass*

- Bigger mass means higher gravity
- Higher gravity means higher pressure in core
- Higher pressure means higher T and density
- This means MUCH more nuclear fusion
- This means star is MUCH more luminous
- This means mass determines luminosity

Mass – Luminosity Relation

On the main sequence
high-mass stars are MUCH more luminous than *low-mass* stars:

0.1 M_{sun} → 0.0005 L_{sun}

40 M_{sun} → 400,000 L_{sun}

$$L \propto M^{3.5}$$