TODAY

- STARS
  - PROPERTIES (RECAP)
  - NUCLEAR REACTIONS
    - PROTON-PROTON CHAIN
    - CNO CYCLE
  - STELLAR LIFETIMES

HOMEWORK DUE

Stellar Properties

- Luminosity
- Surface Temperature
- Size
- Mass
- Composition

Stellar Properties

- **Luminosity**
  - measure from **distance** and
  - **apparent brightness**

$$L = 4\pi d^2 b$$

- Surface Temperature
- Size
- Mass
- Composition

Example question: How does a star's apparent brightness change if it is moved twice as far away?

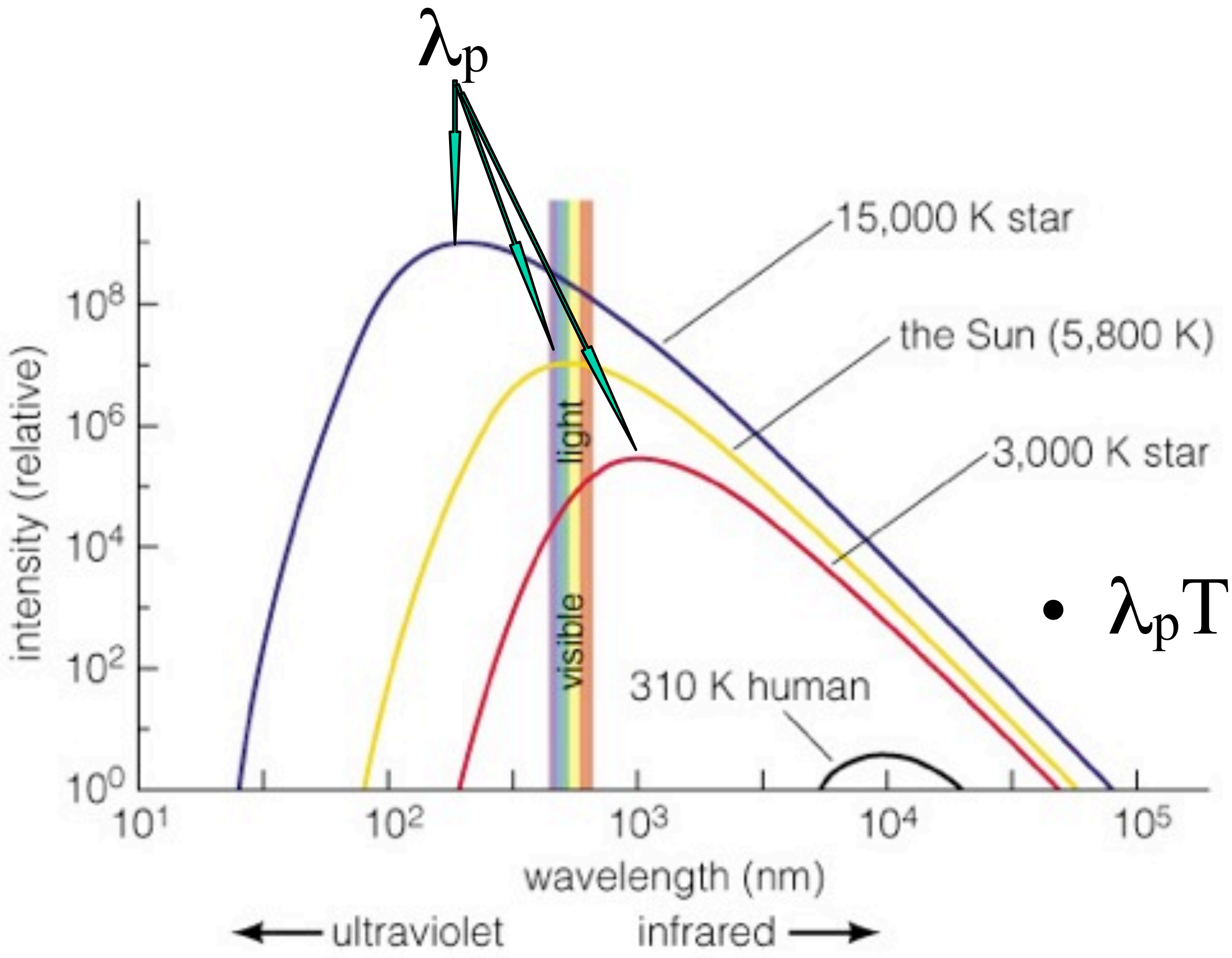
Stellar Properties

- Luminosity
- **Surface Temperature**
  - measured from **color** (Wien’s Law) or
  - **spectral type** (OBAFGKM)

- Size
- Mass
- Composition

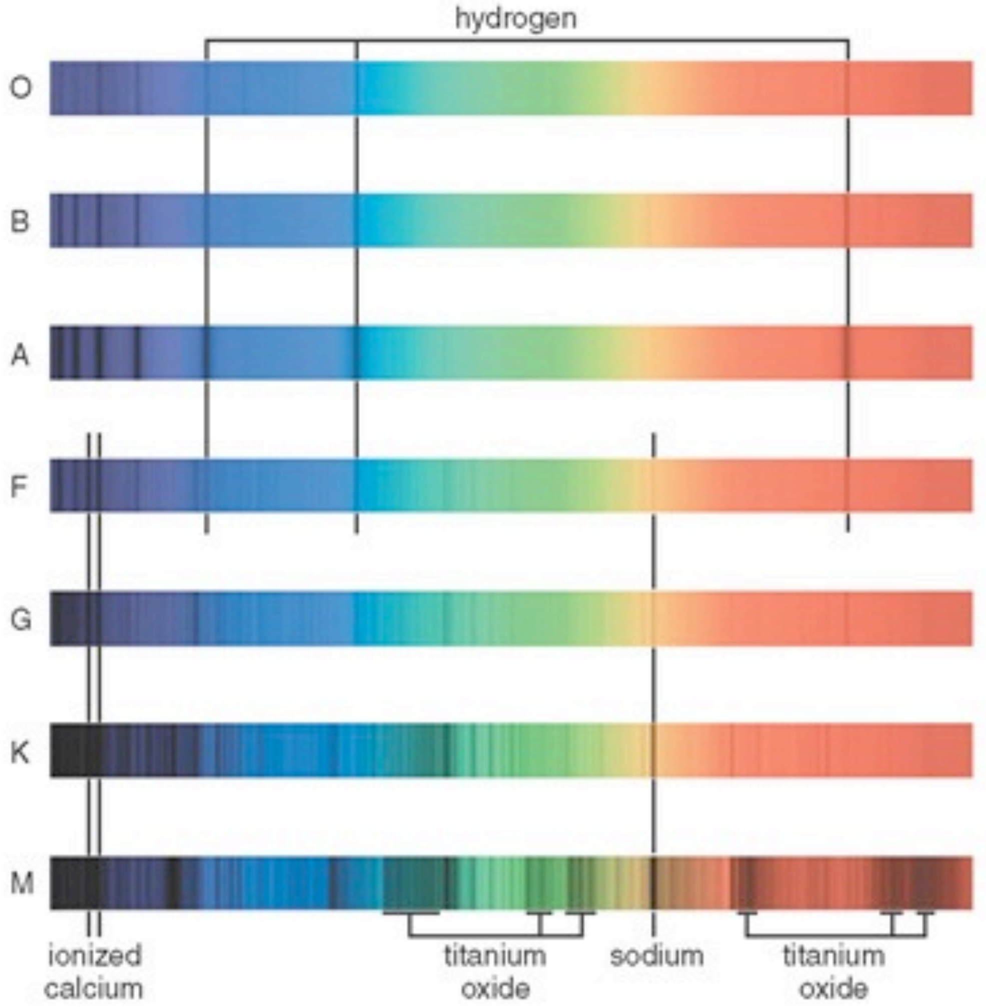
Wien's Law

Hotter objects emit photons with a higher energy.



Example question: How does a star's color, as measured by the peak wavelength, change if it's surface temperature doubles?

- $\lambda_p T = 2.9 \times 10^6$ nm K



Example questions:
What is the order of the spectral type sequence, from hot to cold?
or
Which is hotter: a B star or a K star?

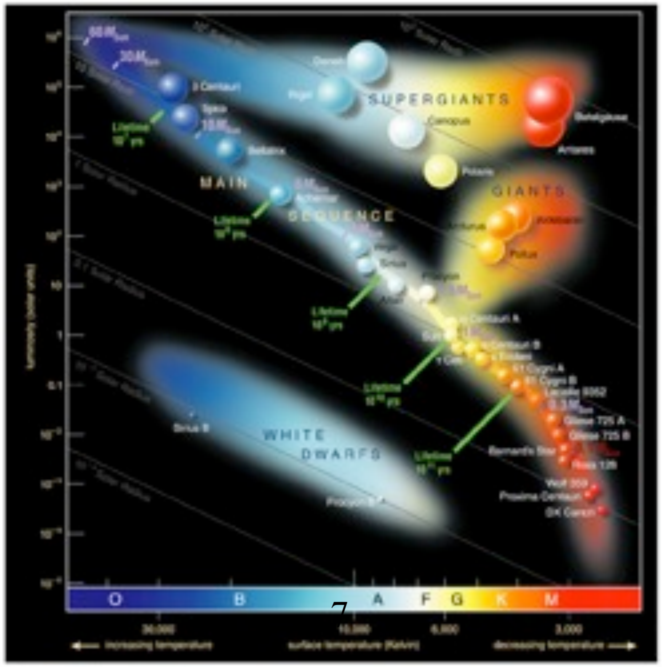
Lines in a star's spectrum correspond to a ***spectral type*** that reveals its temperature:

(Hottest) O B A F G K M (Coolest)

Stellar Properties

- **Luminosity**
- **Surface Temperature**

Ingredients for HR diagram:



- Size
- Mass
- Composition

Stellar Properties

- Luminosity
- Surface Temperature
- **Size**
  - – inferred from **HR diagram** (Stefan-Boltzmann)
  - – **eclipsing binary stars**

- Mass
- Composition

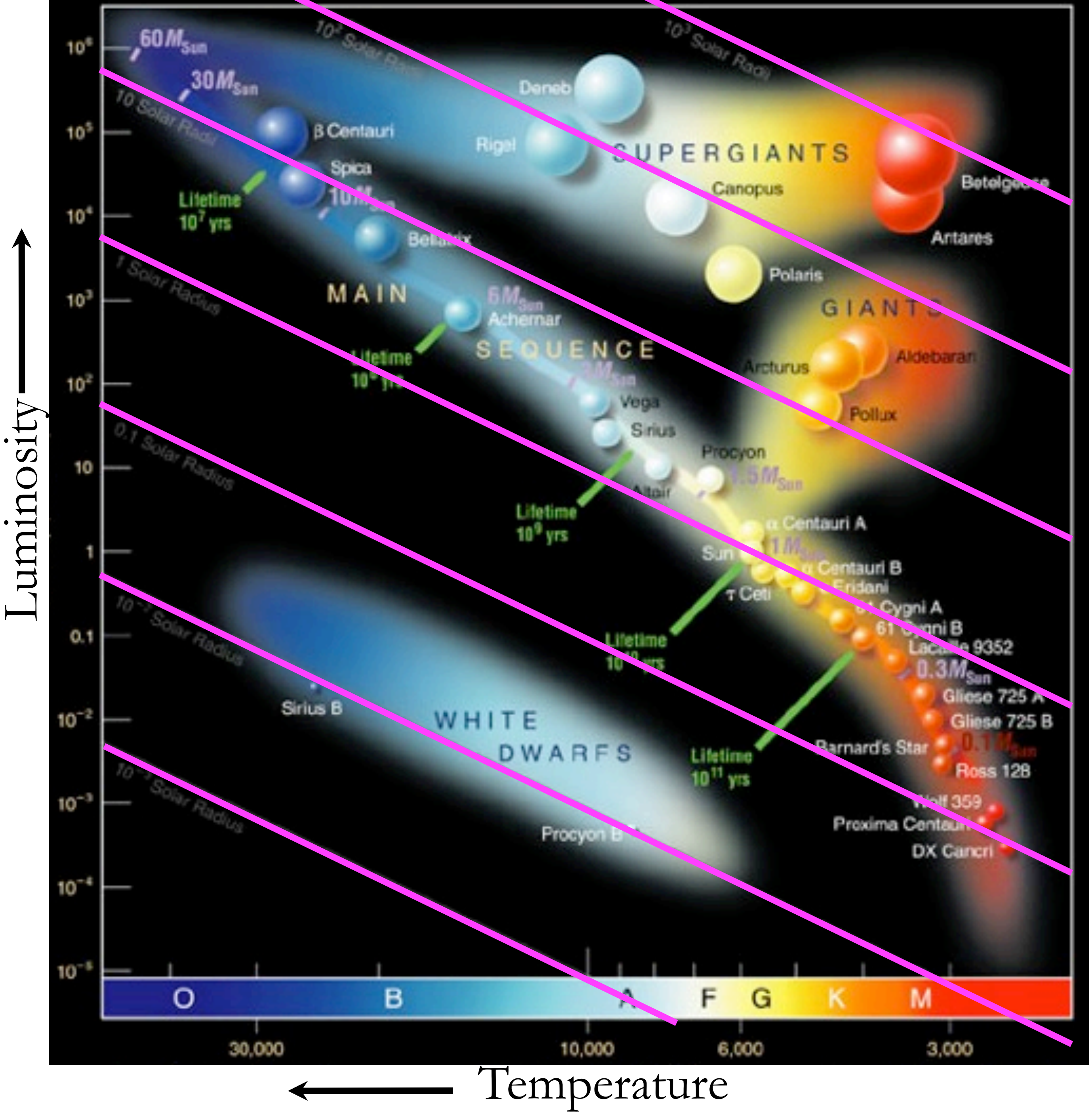
Stefan-Boltzmann Law

$$L = 4\pi R^2 \sigma T^4$$

- **L** = Luminosity (power radiated)
- **R** = Radius (of star)
- **T** = Temperature (of surface, in K)
- **σ** = Stefan-Boltzmann constant
  - just a number to make units work right

If the Luminosity (**L**) and temperature (**T**) are known, can solve for size (**R**).

Example question: What is the size of a star that is the same temperature as the sun but is 100 times more luminous?



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Lines of constant radius (differing by factors of 10)

$$L = 4\pi R^2 \sigma T^4$$

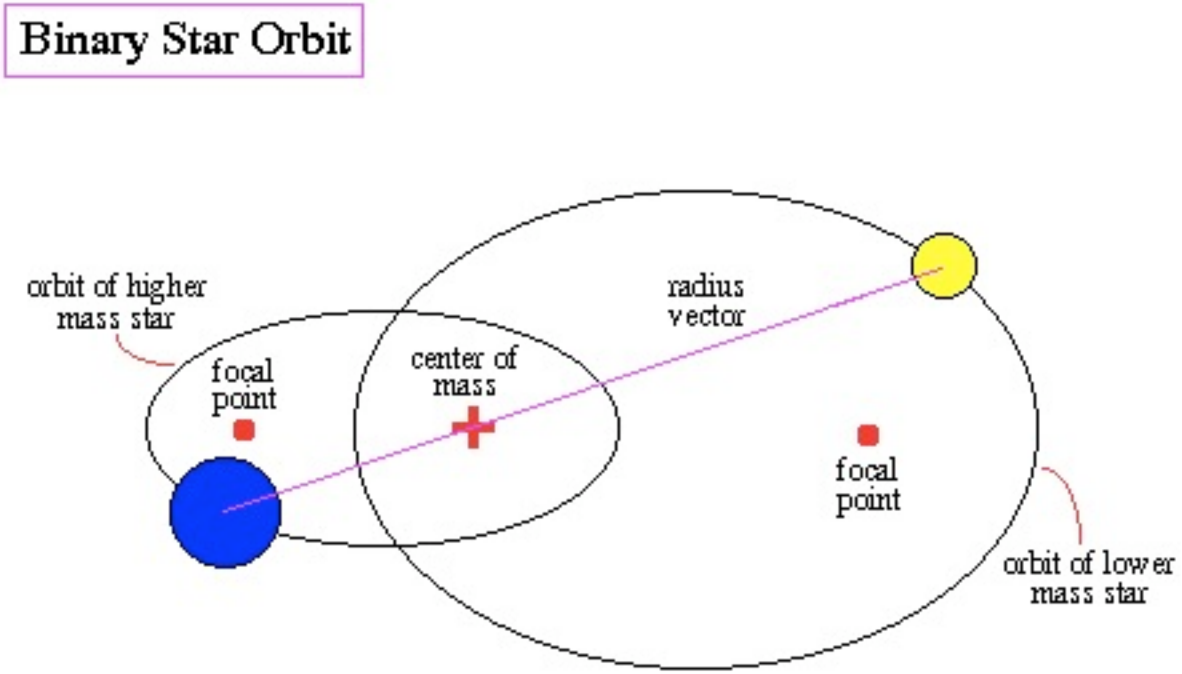
Stellar Properties

- Luminosity
- Surface Temperature
- Size
- **Mass**
  - – measured from orbits:
  - – Newton's generalization of Kepler's 3rd Law
- Composition

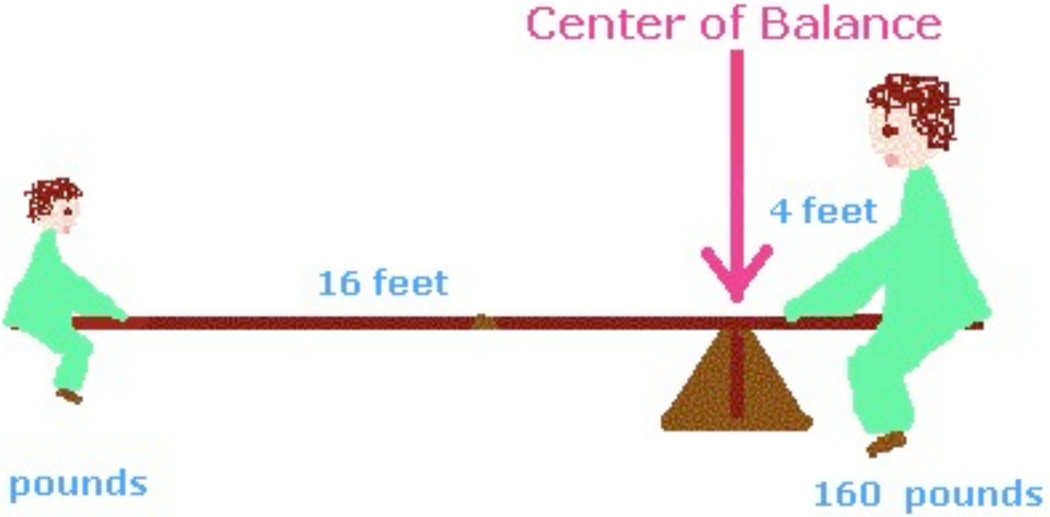
Isaac Newton

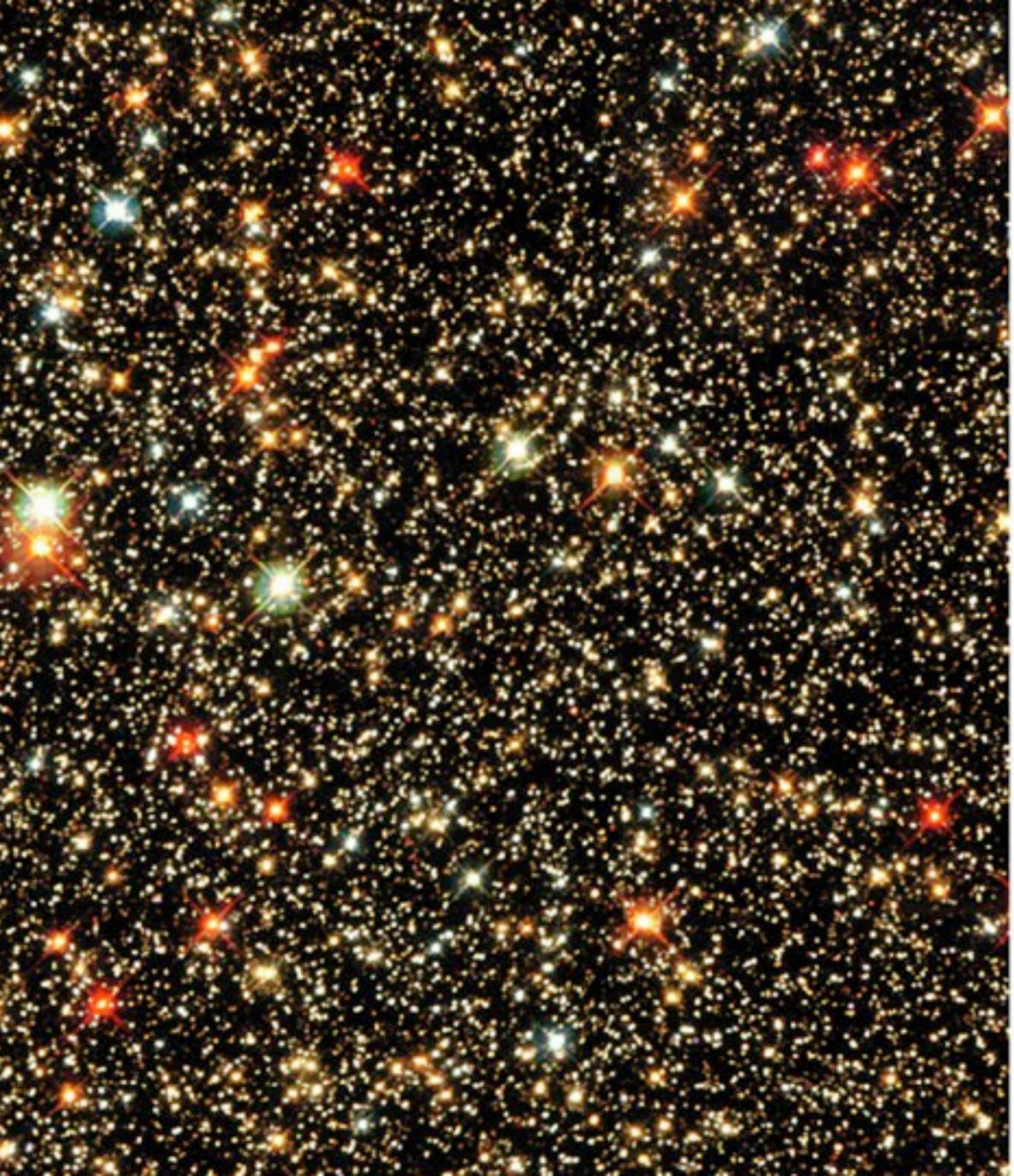
$$P^2 = \frac{4\pi^2}{G\,(M_1 + M_2)}\,a^3$$

Example question:
A binary system composed of two equal mass stars is observed to have an orbital period of one year and a separation of one AU. What is the mass of each star?


Binary Star Orbit
orbit of higher mass star
focal point
center of mass
radius vector
focal point
orbit of lower mass star

$$M_1 r_1 = M_2 r_2$$


Center of Balance
4 feet
16 feet
40 pounds
160 pounds



Most massive stars:

$\sim 100\ M_{\text{Sun}}$

Least massive stars:

$0.08\ M_{\text{Sun}}$

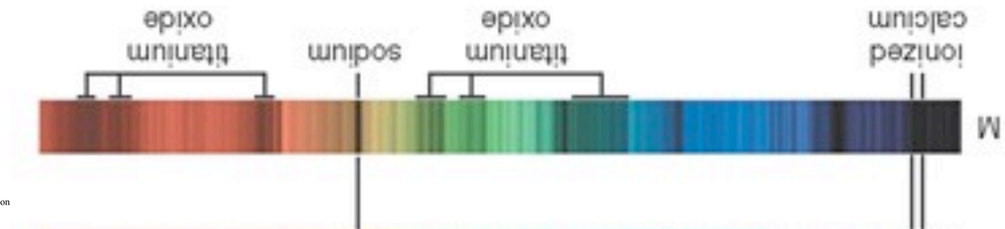
sub-stellar objects ($M < 0.08\ M_{\text{Sun}}$) are called brown dwarfs

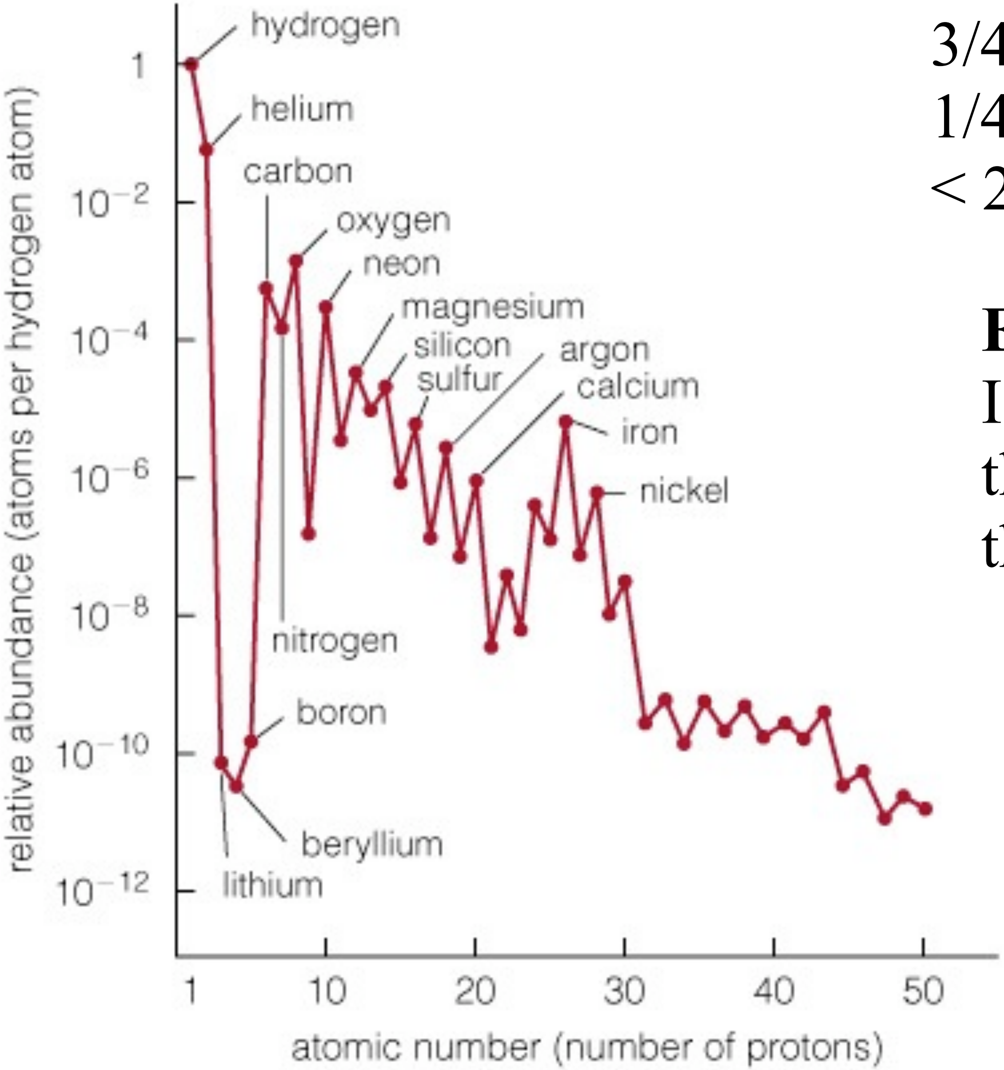
Stellar Properties

- Luminosity
- Surface Temperature
- Size
- Mass
- **Composition**
  - measured in spectra

By mass, stars are roughly

3/4 Hydrogen
1/4 Helium
< 2% everything else





Abundance (by number relative to Hydrogen)

Atomic number (number of protons)

©

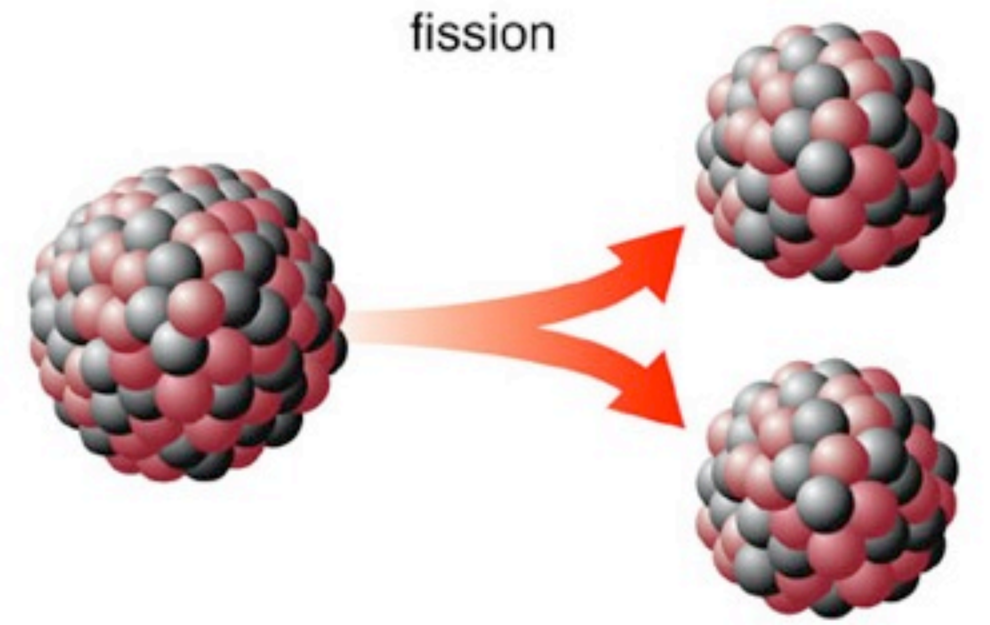
By mass, stars are roughly

3/4 Hydrogen
1/4 Helium
< 2% everything else

Example question:
Is the composition of the Earth typical of that of the stars?

Nuclear fusion in the stars

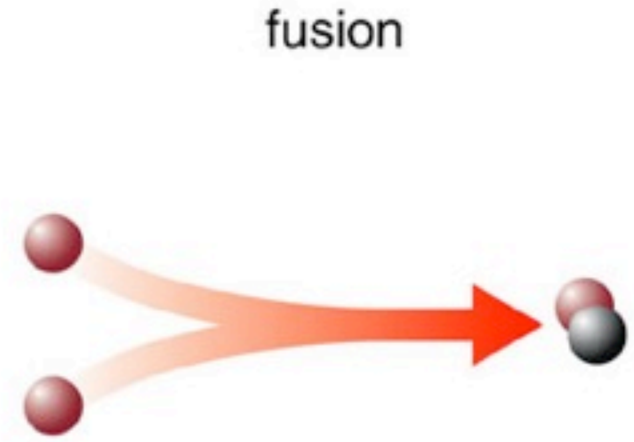
Burning hydrogen to make
Helium and energy



Fission

Big nucleus splits into smaller pieces

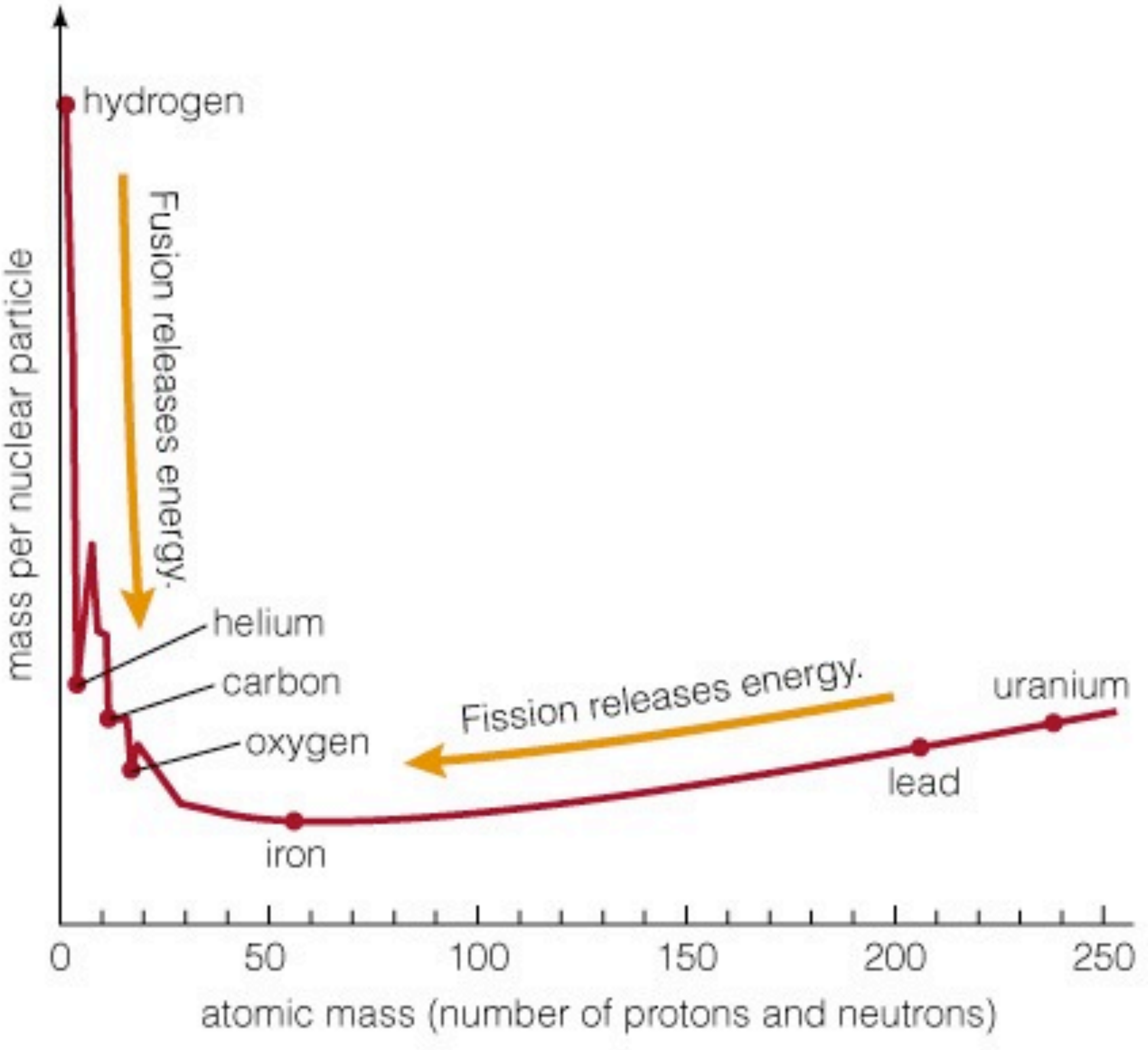
(Nuclear power plants)



Fusion

Small nuclei stick together to make a bigger one

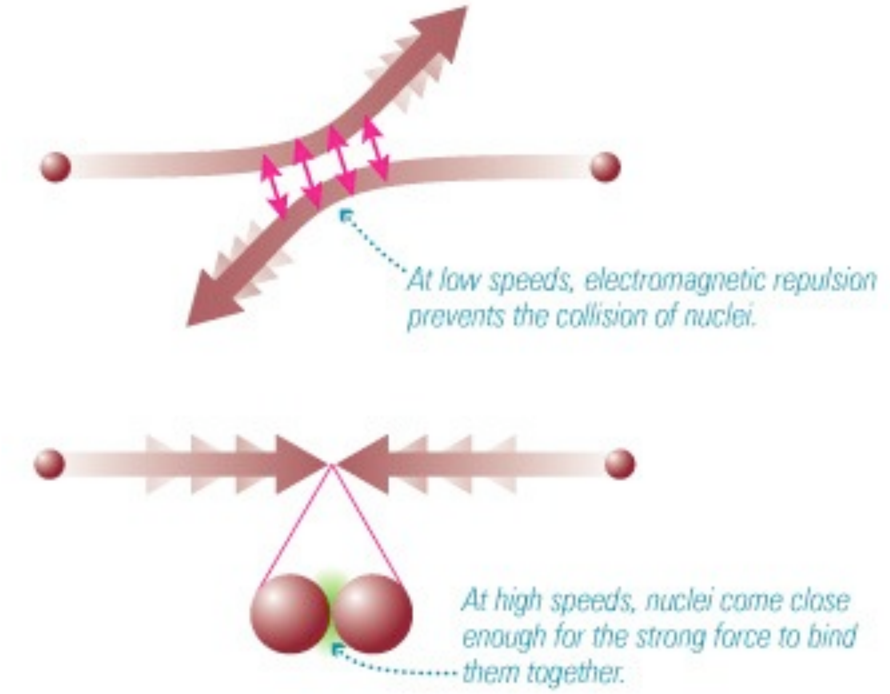
(Sun, stars)



Iron has the most stable nucleus.

Fusion up to iron releases energy.

For elements heavier than iron, Fission releases energy.



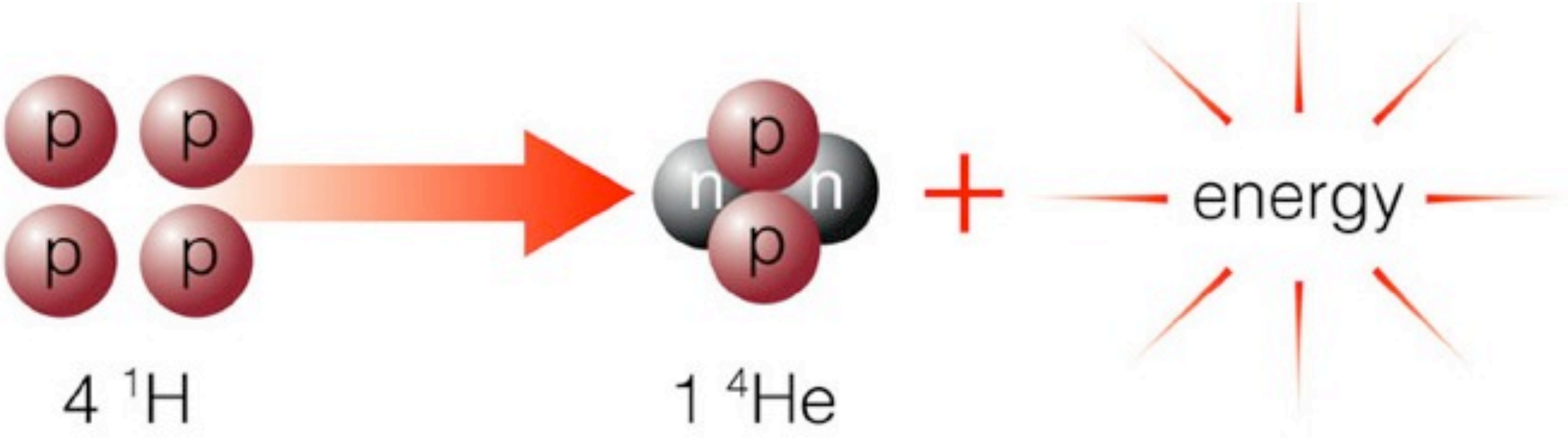
High temperatures enable nuclear fusion to happen in the core.

Positively charged protons repel each other.

Fusion only happens when the strong nuclear force is stronger than this repulsion, which only happens at very small separations. High temperatures are required to move fast enough to get that close.

Four fundamental forces

- Gravity
  - – e.g, planetary orbits
  - – falling objects
- Electromagnetism
  - – attraction and repulsion of electric charges
  - – magnets
- Strong nuclear force
  - – fusion: binds protons together in atomic nuclei
- Weak nuclear force
  - – fission; radioactive decay



Sun releases energy by fusing four hydrogen nuclei into one helium nucleus.

Starting point is 4 protons.
End point is 2 p + 2 n (a helium nucleus) + energy
There are several steps required to make this happen.

Fusing ^{1}H into ^{4}He

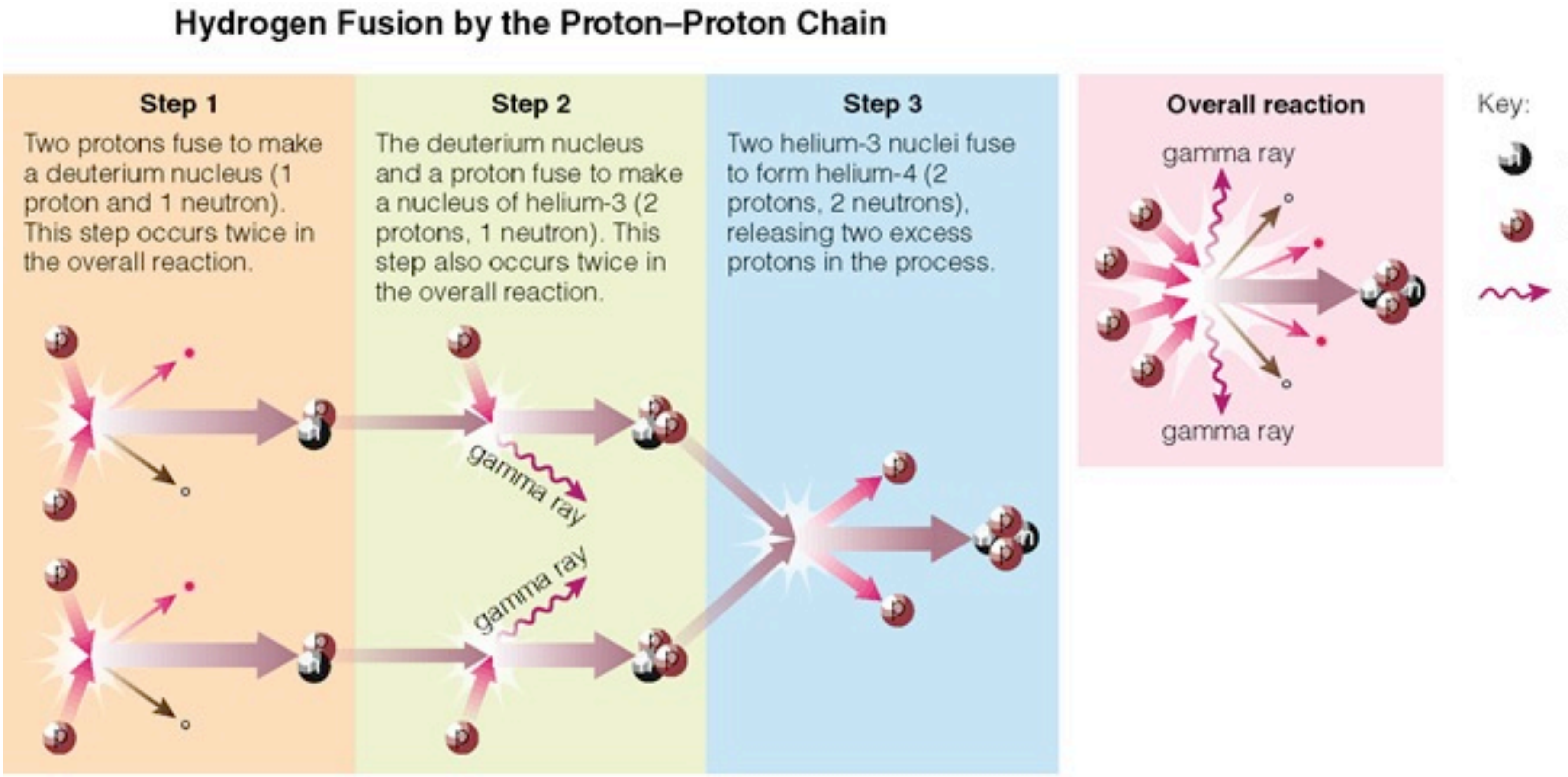
- Proton-proton chain
  - more effective in low mass stars

$$M < 1.5 M_{sun}$$

- CNO cycle
  - more effective in high mass stars

$$M > 1.5 M_{sun}$$

Both work; but are temperature sensitive.



Hydrogen Fusion by the Proton–Proton Chain

Step 1

Two protons fuse to make a deuterium nucleus (1 proton and 1 neutron). This step occurs twice in the overall reaction.

Step 2

The deuterium nucleus and a proton fuse to make a nucleus of helium-3 (2 protons, 1 neutron). This step also occurs twice in the overall reaction.

Step 3

Two helium-3 nuclei fuse to form helium-4 (2 protons, 2 neutrons), releasing two excess protons in the process.

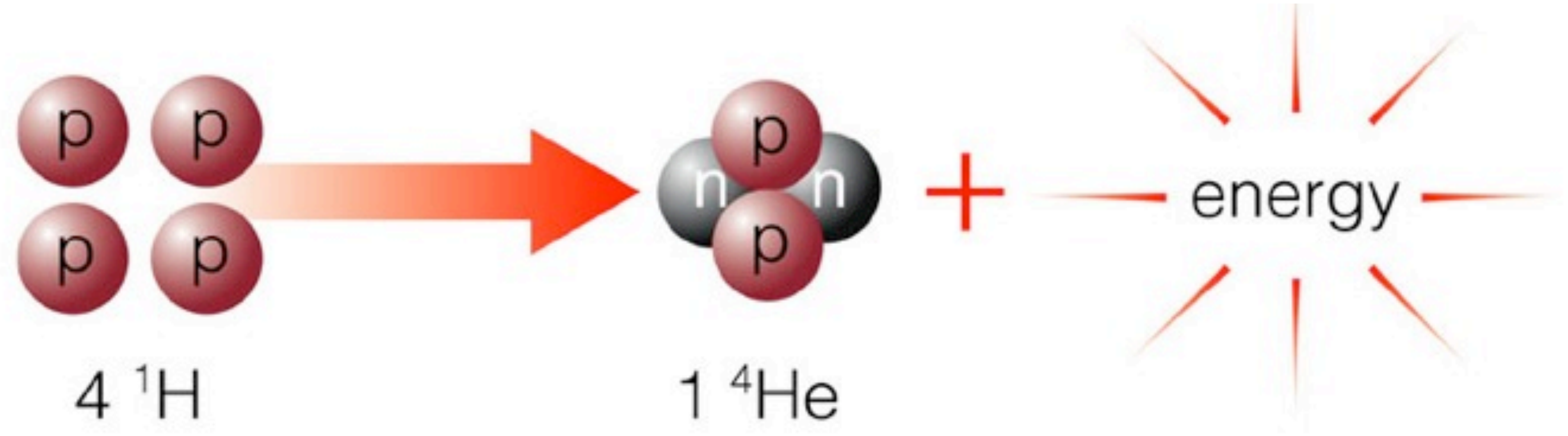
Overall reaction

Proton–proton chain is how hydrogen fuses into helium in Sun

Proton–proton chain is how hydrogen fuses into helium in Sun

- step 1: p + p makes D (deuterium)
- step 2: D + D makes ^{3}He (helium 3)
- step 3: ^{3}He + ^{3}He makes ^{4}He (helium 4)
  - plus energy plus 2 spare protons and neutrinos.

The first step is the hardest -
on average, takes 10,000,000 years to occur in the sun.



<u>IN</u>
4 protons

<u>OUT</u>
^{4}He nucleus
2 gamma rays
2 positrons
2 neutrinos

$E = mc^2$: ***Total mass is 0.7% lower.***