Today

- Stars
  - Properties (Recap)
    - Binaries
  - Stellar Lifetimes

Exam Review Session

- This Tuesday, 6-8 PM, PHYS 1410 (the large lecture hall next to ours)
- Completely driven by your questions! The TAs will not prepare summary slides, but can go to the lecture slides if needed.
- When your questions are done, the review is over
- Don't ask TAs what will be on the exam; they don't know :)

Stellar Properties Review

Luminosity: from brightness and distance

$10^{-4}\ L_{Sun}$–$10^{6}\ L_{Sun}$

Temperature: from color and spectral type

3,000 K–50,000 K

Mass: from period (P) and average separation (a) of binary-star orbits

$0.08\ M_{Sun}$–$100\ M_{Sun}$

Stellar Properties Review

Luminosity: from brightness and distance

(0.08 M_{Sun}) $10^{-4}\ L_{Sun}$–$10^{6}\ L_{Sun}$ (100 M_{Sun})

Temperature: from color and spectral type

(0.08 M_{Sun}) 3,000 K–50,000 K (100 M_{Sun})

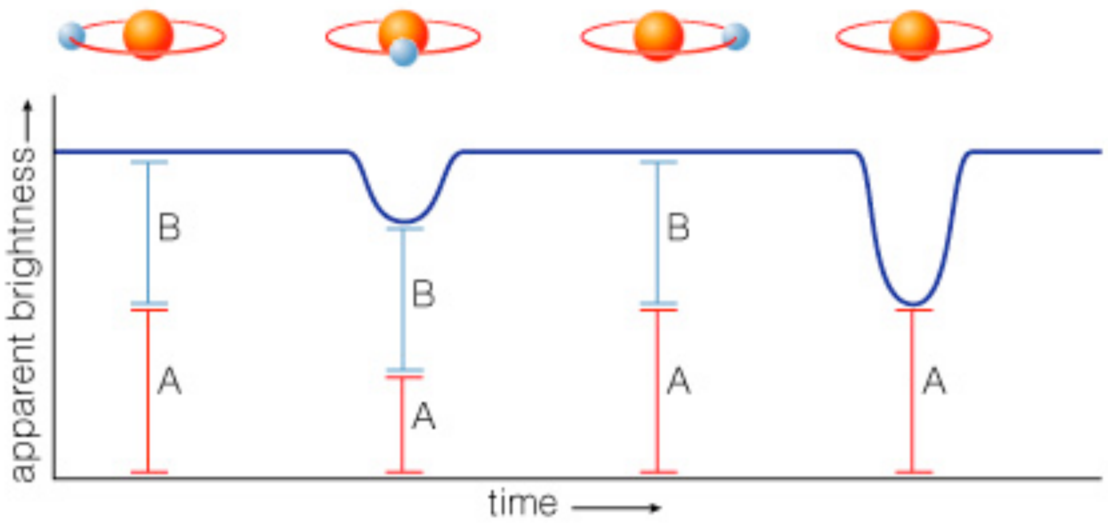
Mass: from period (P) and average separation (a) of binary-star orbits

0.08 M_{Sun}–100 M_{Sun}

The lowest mass star

- main sequence stars are "hydrogen burning"
- 0.08 solar masses
  - lowest mass star
  - not arbitrary:
  - This is the limit for hydrogen fusion
    - objects with less mass can not ignite fusion

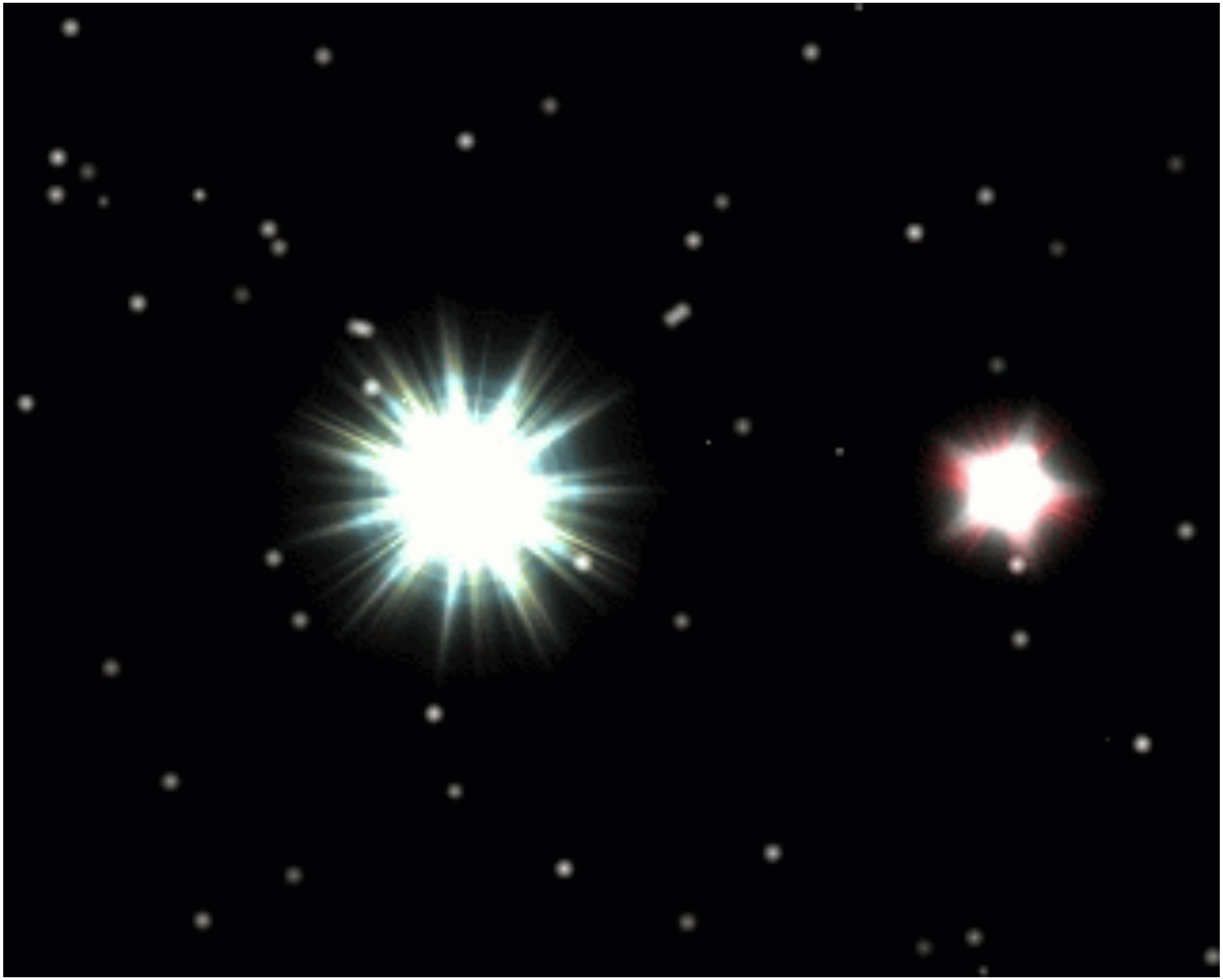
How do we measure stellar masses?



with binary stars!

Binary and Multiple Stars

- Most stars have companions!
- Binaries (i.e., pair of stars) have stable orbits
- But multiples require special configurations to be stable
- Observations of binaries allow us to measure the masses of stars



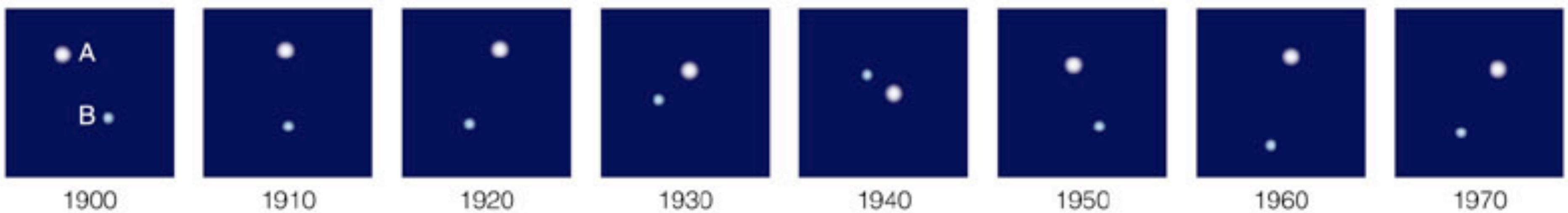
Orbit of a binary star system depends on strength of gravity

Types of Binary Star Systems

- Visual binary
- Eclipsing binary
- Spectroscopic binary

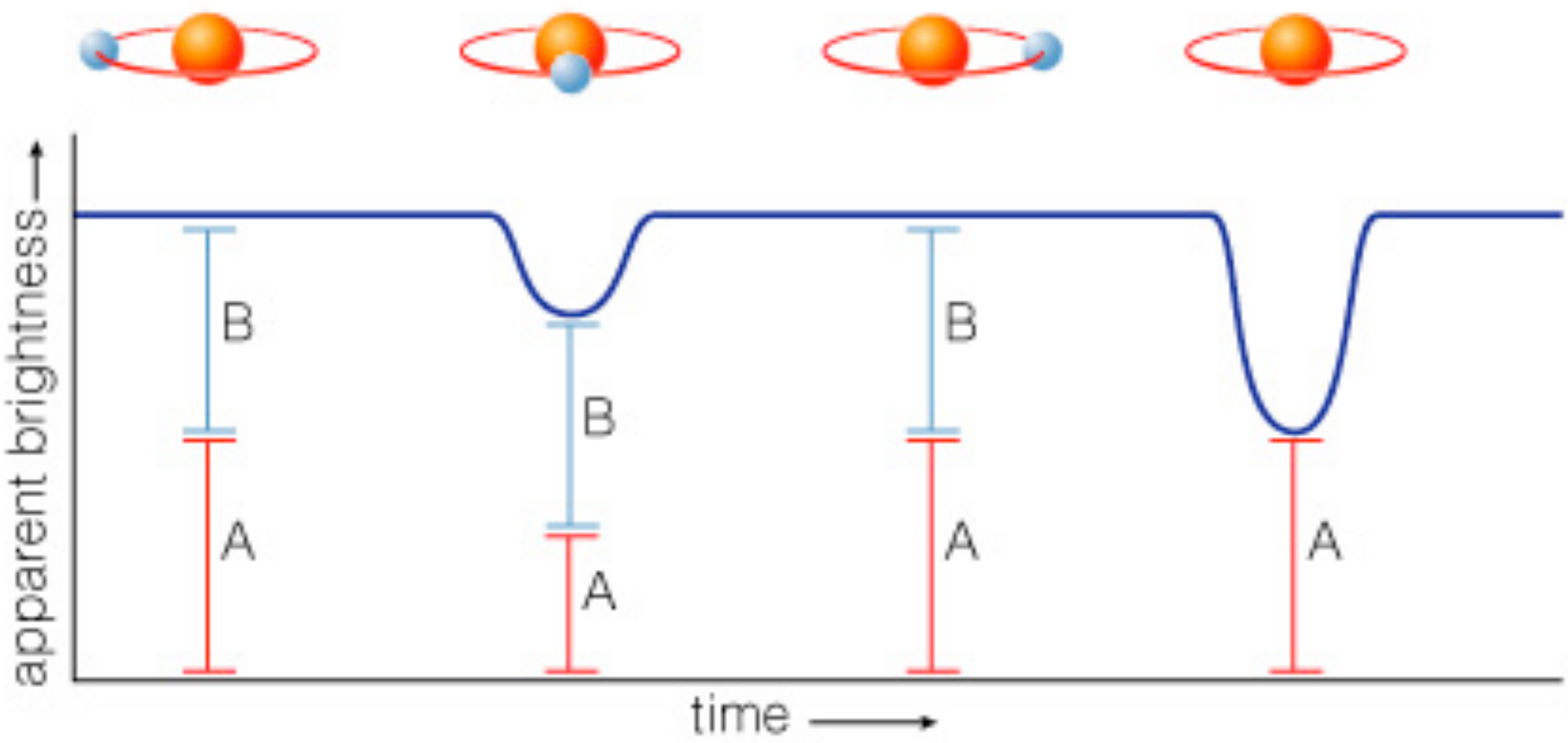
About half of all stars are in binary systems. Most big stars are in binaries when they are born.

Visual Binary



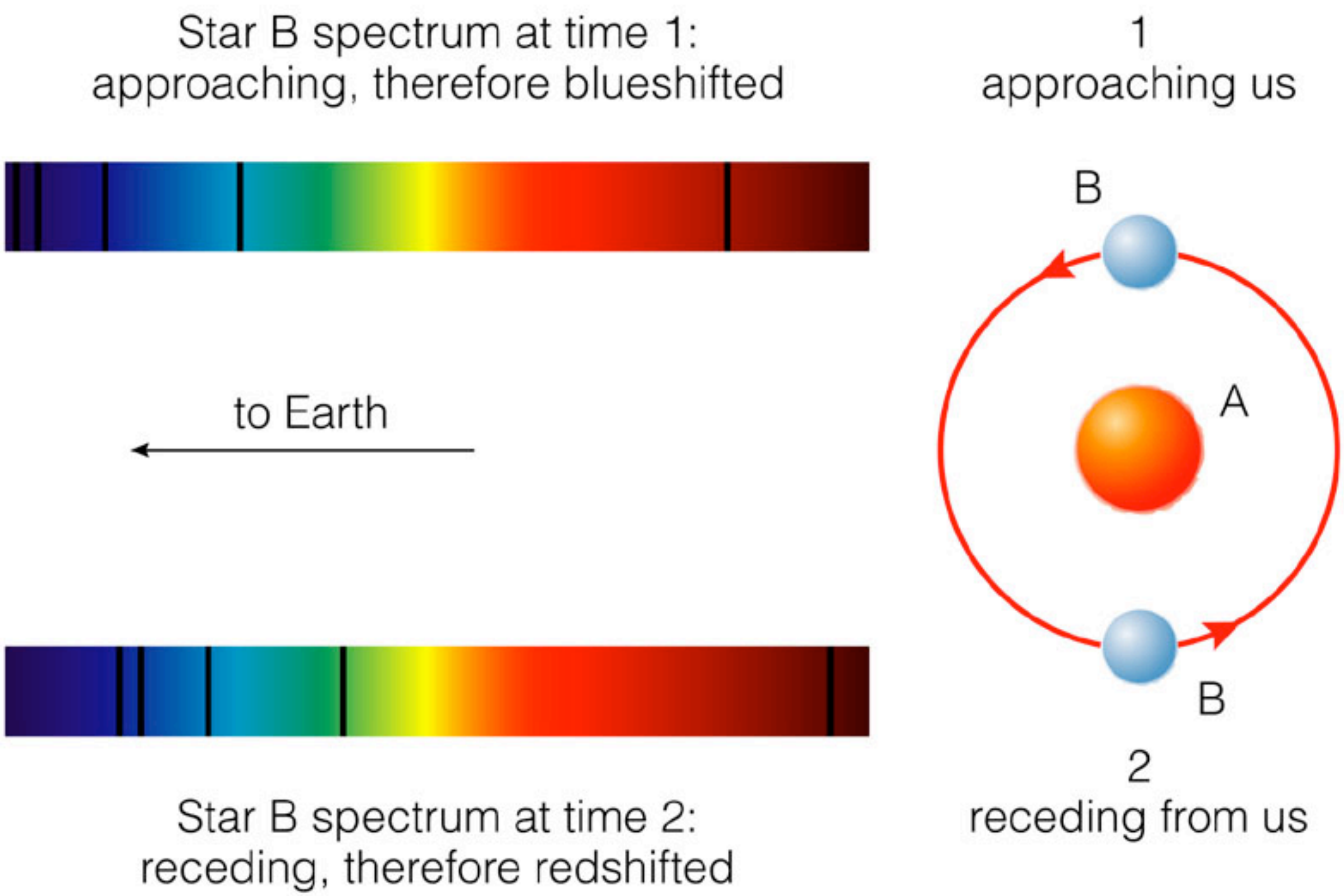
We can directly observe the orbital motions of these stars.

Eclipsing Binary



We can measure periodic eclipses.

Spectroscopic Binary



We determine the orbit by measuring Doppler shifts.

Isaac Newton

Direct mass measurements are possible for stars in binary star systems using Newton's generalization of Kepler's third law:

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

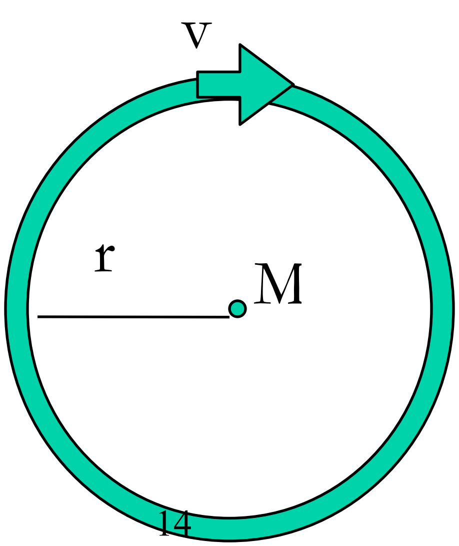
P = period

a = separation

Need two out of three observables to measure mass:

1. Orbital period (P)
2. Orbital separation (a or r = radius)
3. Orbital velocity (v)

For circular orbits, $v = 2\pi r / p$



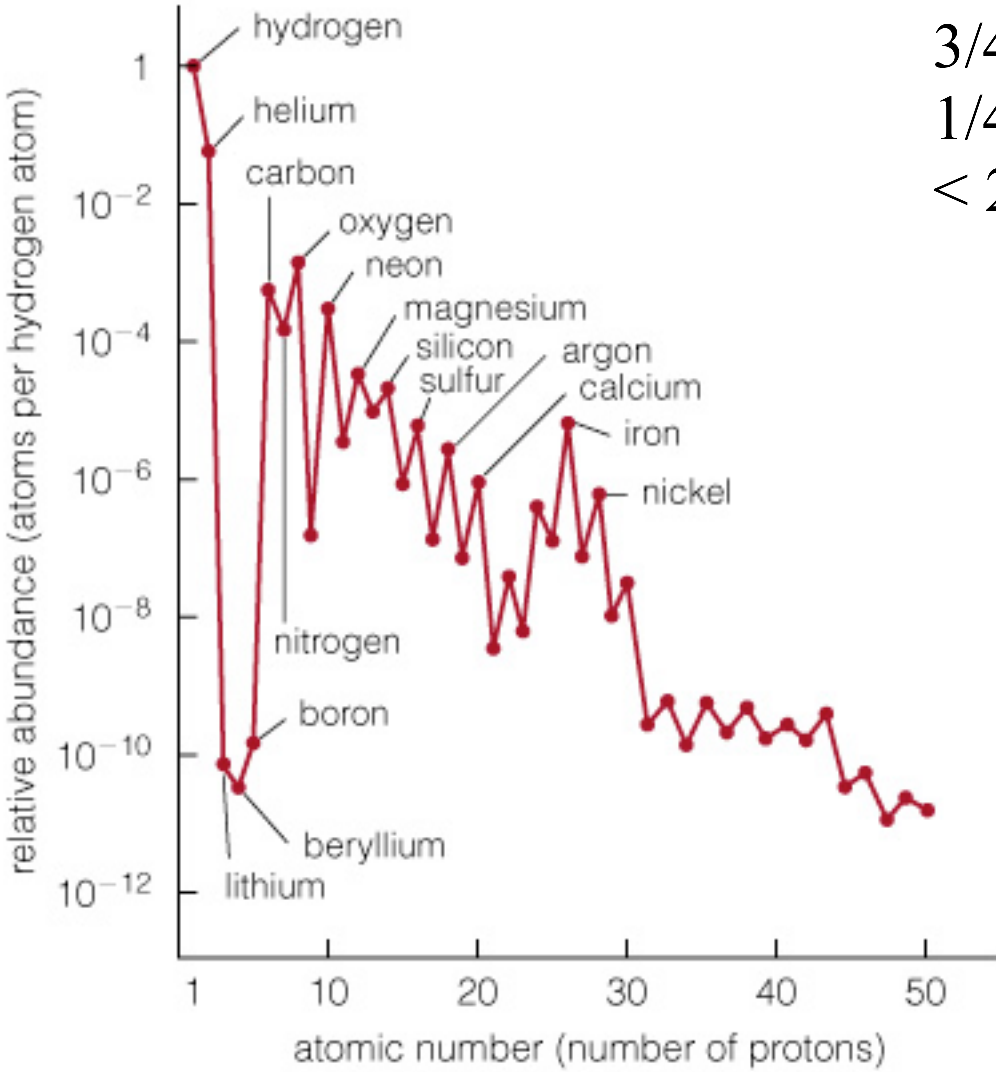
The most massive stars:

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

The least massive stars:

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

(M_{Sun} is the mass of the Sun.)



Abundance (by number relative to Hydrogen)

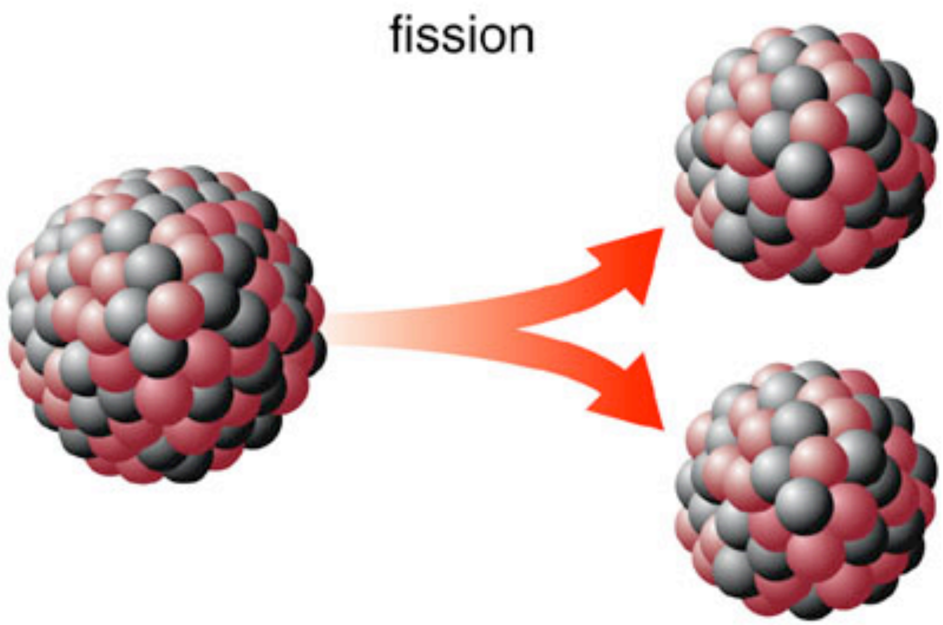
Atomic number (number of protons)

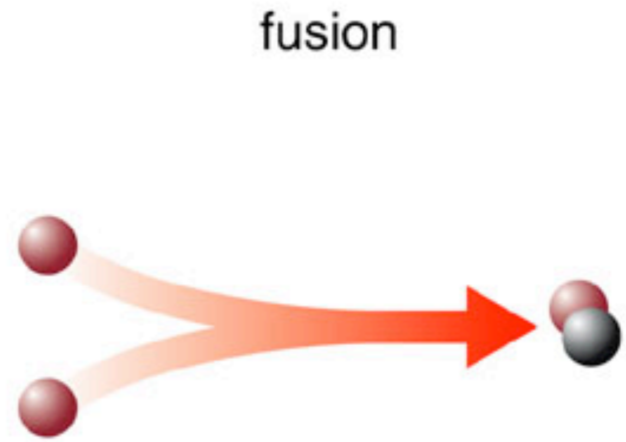
By mass, stars are roughly

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

Nuclear fusion in the stars

Burning hydrogen to make
Helium and energy





Fission

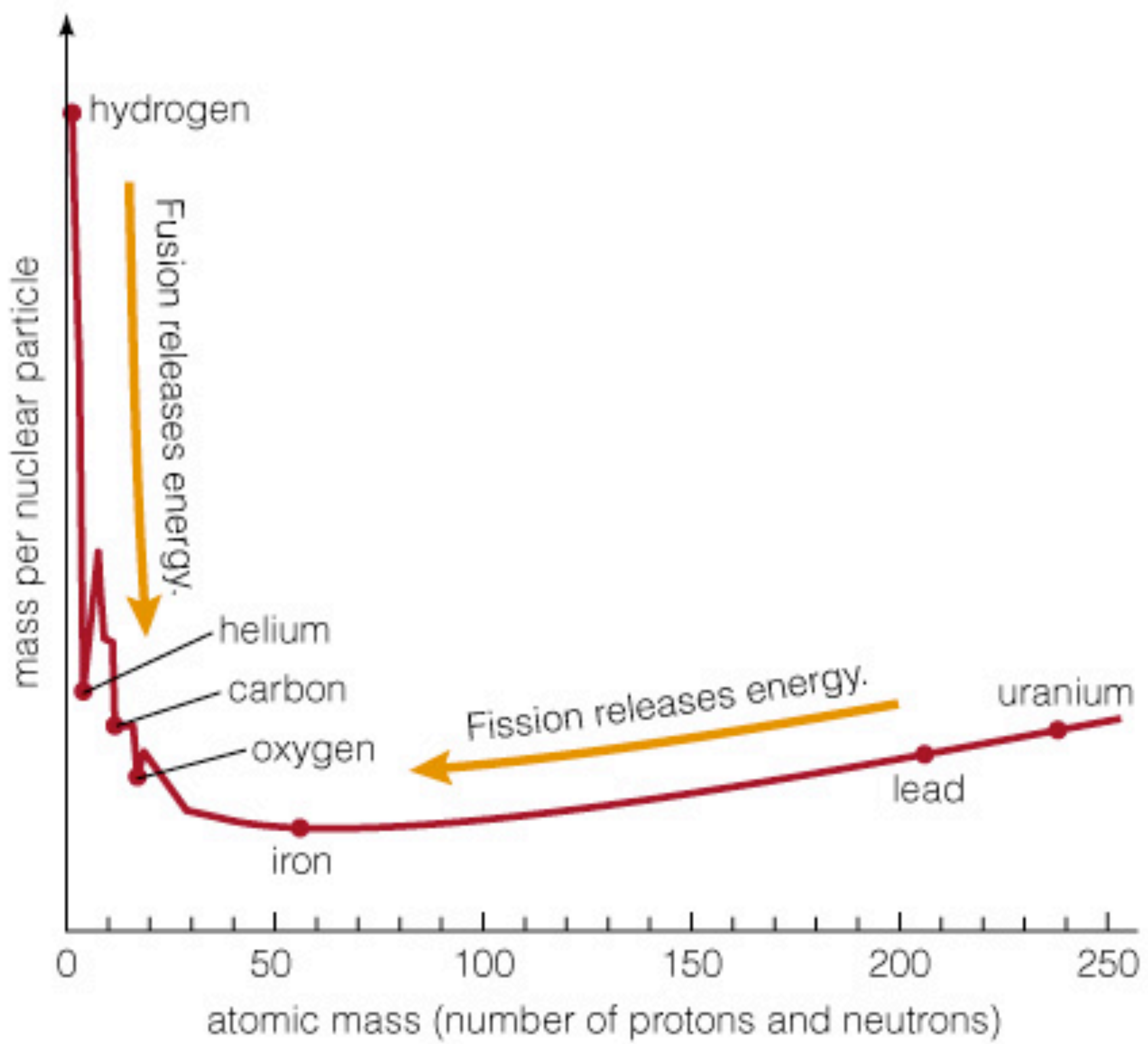
Big nucleus splits into smaller pieces

(Nuclear power plants)

Fusion

Small nuclei stick together to make a bigger one

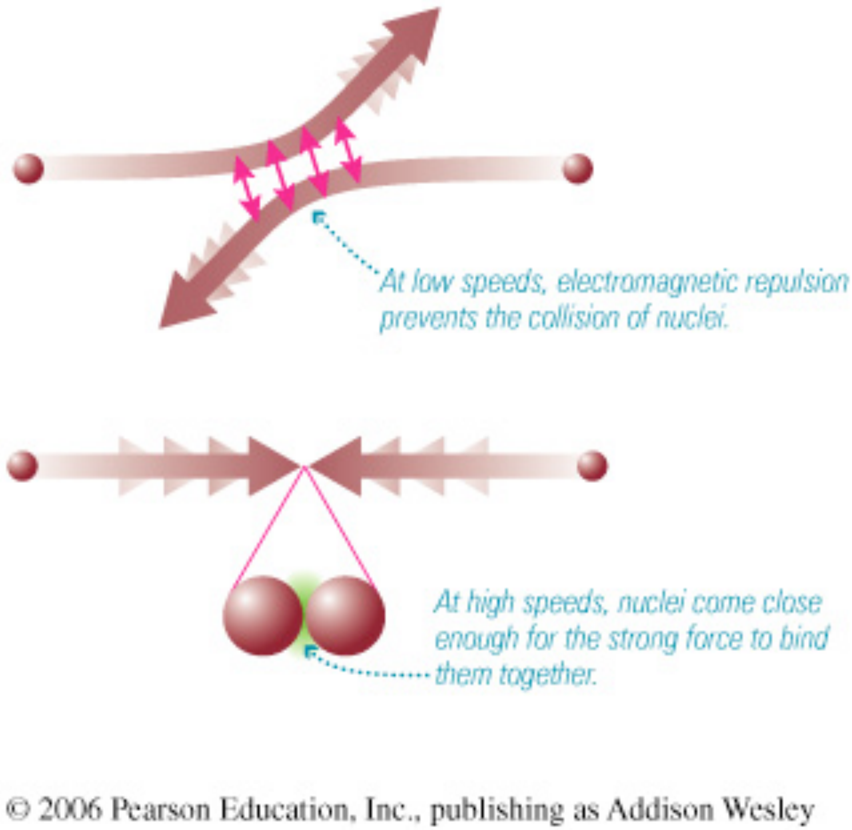
(Sun, stars)



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.

K2-62 electromagnetic can crusher

Temperature of Fusion

Helium has two protons, versus one for hydrogen. Does bringing helium together for fusion require higher or lower temperatures than for hydrogen?

A. There is not enough information to say

B. Helium fusion needs lower temps

C. The same temperature is required

D. Helium fusion needs higher temps

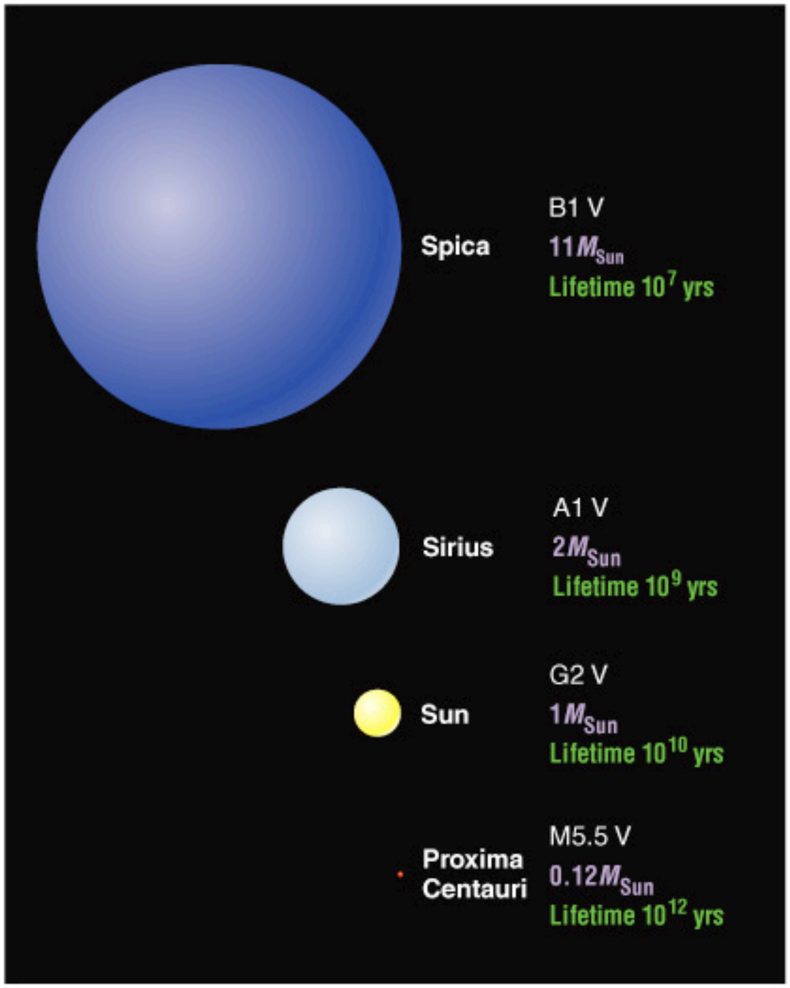
E. I don't know

Four fundamental forces

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

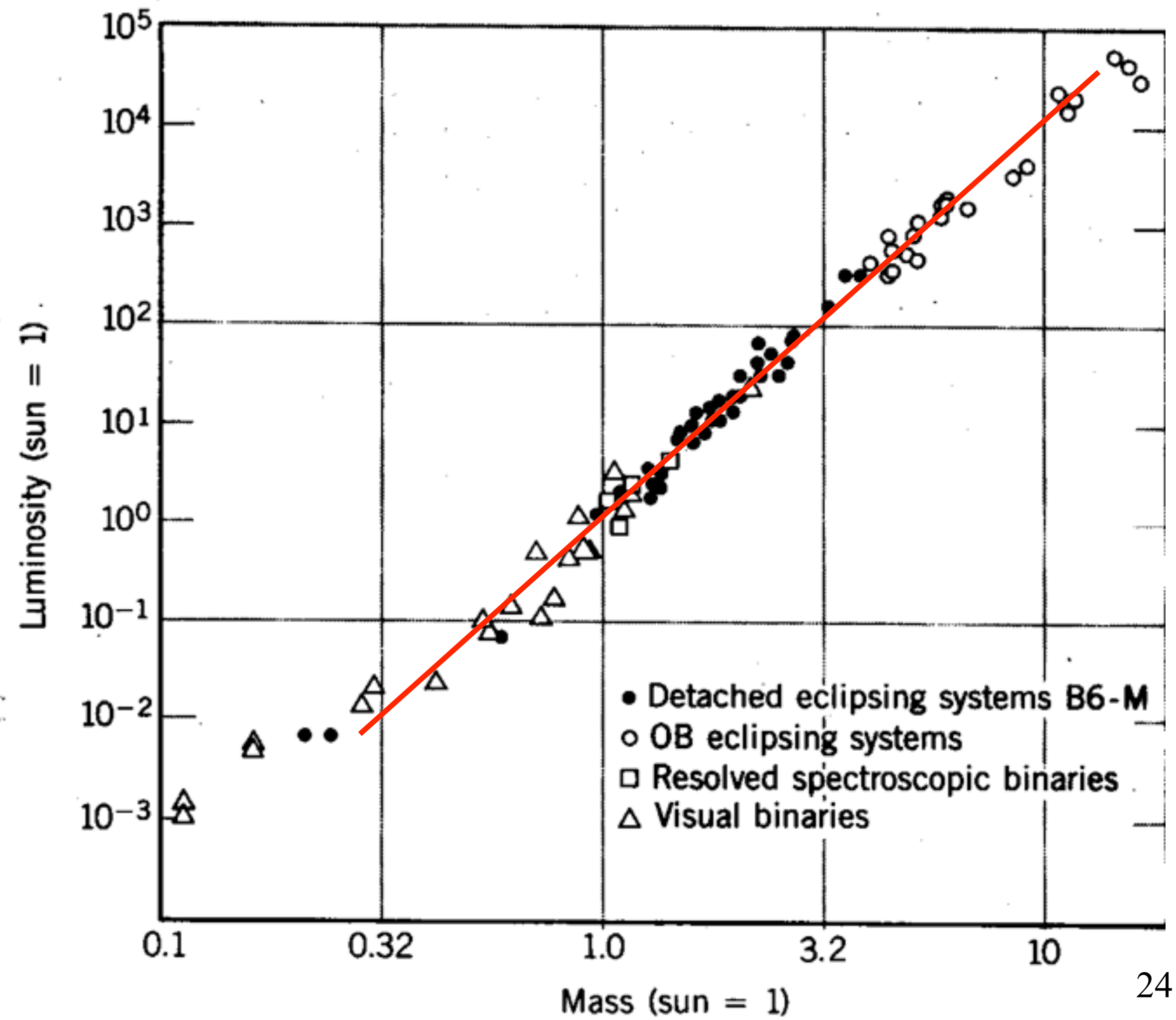
Main Sequence Stars

- Obey scaling relations
- Mass-Radius relation
  - more massive stars are bigger
- Mass-Luminosity relation
  - more massive stars are brighter



Main-sequence stars (to scale)

Mass-Luminosity Relation



The mass–luminosity relation for stars, as determined from binary systems, in which the individual masses can be found.

Mass-Luminosity Relation

$$L \propto M^4$$

- more massive stars **much** brighter
- use their fuel **much** faster
  - Mass: fuel supply ($E = mc^2$)
  - Luminosity: rate of fuel usage

Mass is finite - the stars don't shine forever!

Mass and Lifetime

Sun's life expectancy: 10 billion years

Has lived about half of its "main sequence lifetime"

For stars, mass is destiny

Mass and Lifetime

Until core hydrogen (10% of total) is used up

Sun's life expectancy: 10 billion years

Has used about half of the hydrogen fuel available in the core

For stars, mass is destiny

Mass and Lifetime

$$lifetime \propto \frac{energy(mc^2)}{power(L)}$$

$$t \propto \frac{M}{L}$$

M ← fuel

L ← rate of fuel use

Mass and Lifetime: $t \propto \frac{M}{L}$

Mass-Luminosity Relation: $L \propto M^4$

$$t \propto \frac{M}{L} \propto \frac{M}{M^4} \propto M^{-3}$$

So as mass increases, the main sequence lifetime decreases.

Mass and Lifetime

Until core hydrogen (10% of total) is used up

Sun's life expectancy: 10 billion years

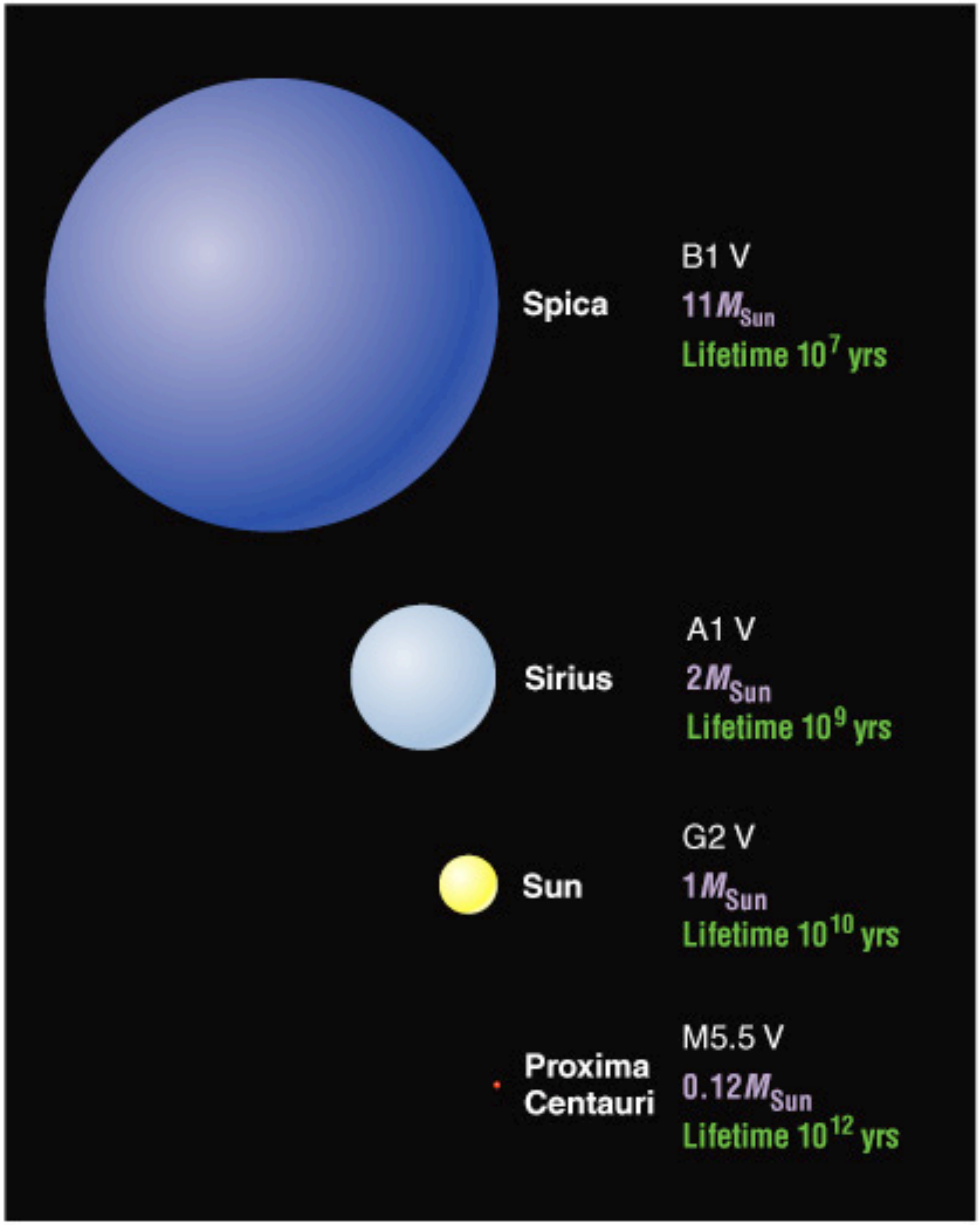
Life expectancy of a 10 M_{Sun} star:

10 times as much fuel, uses it 10^4 times as fast

10 million years ~ 10 billion years × $10/10^4$

$$lifetime \propto \frac{energy(mc^2)}{power(L)}$$

$$t \propto \frac{M}{L}$$



For Main-Sequence Stars:

High-mass:

- High luminosity
- Short-lived
- Large radius

Blue

Low-mass:

- Low luminosity
- Long-lived
- Small radius

Red

Off the Main Sequence

- Stellar properties depend on both mass and age: those that have finished fusing H to He in their cores are no longer on the main sequence.

- All stars become larger and redder after exhausting their core hydrogen: **giants** and **supergiants.**

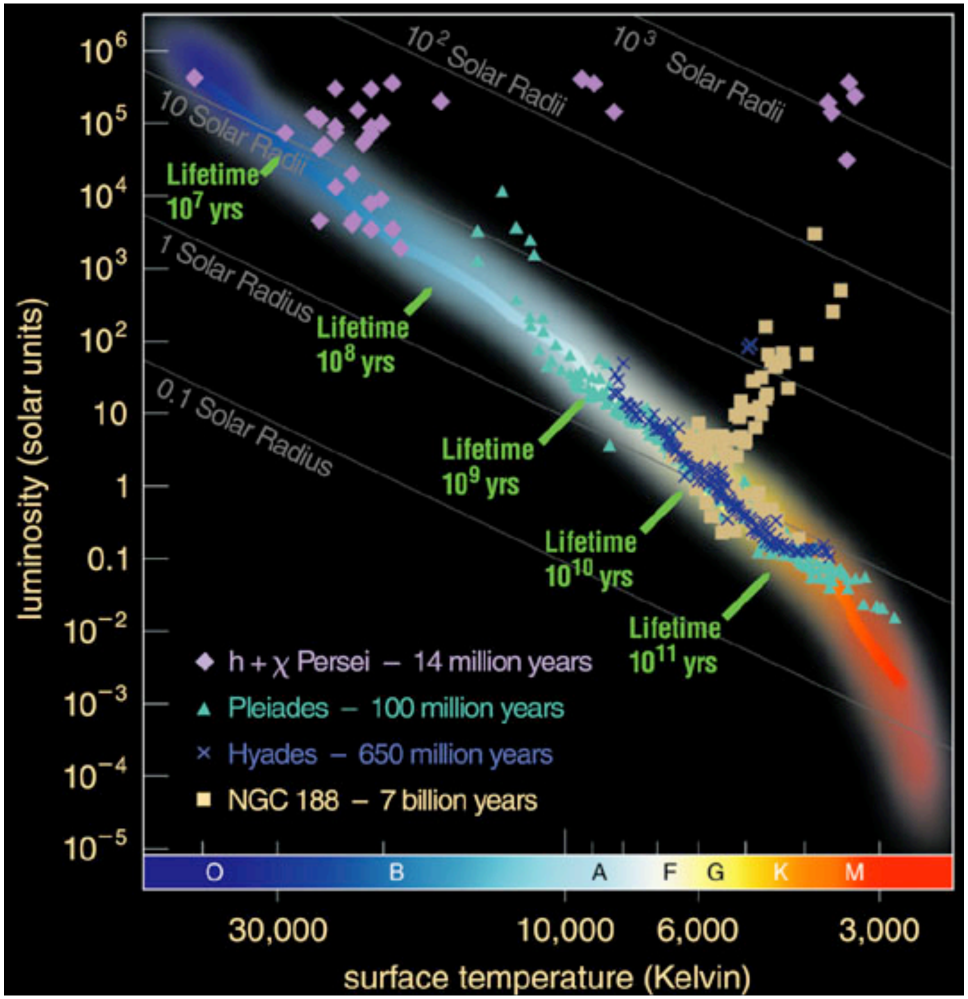
- Most stars end up small and dim after fusion has ceased: **white dwarfs.**

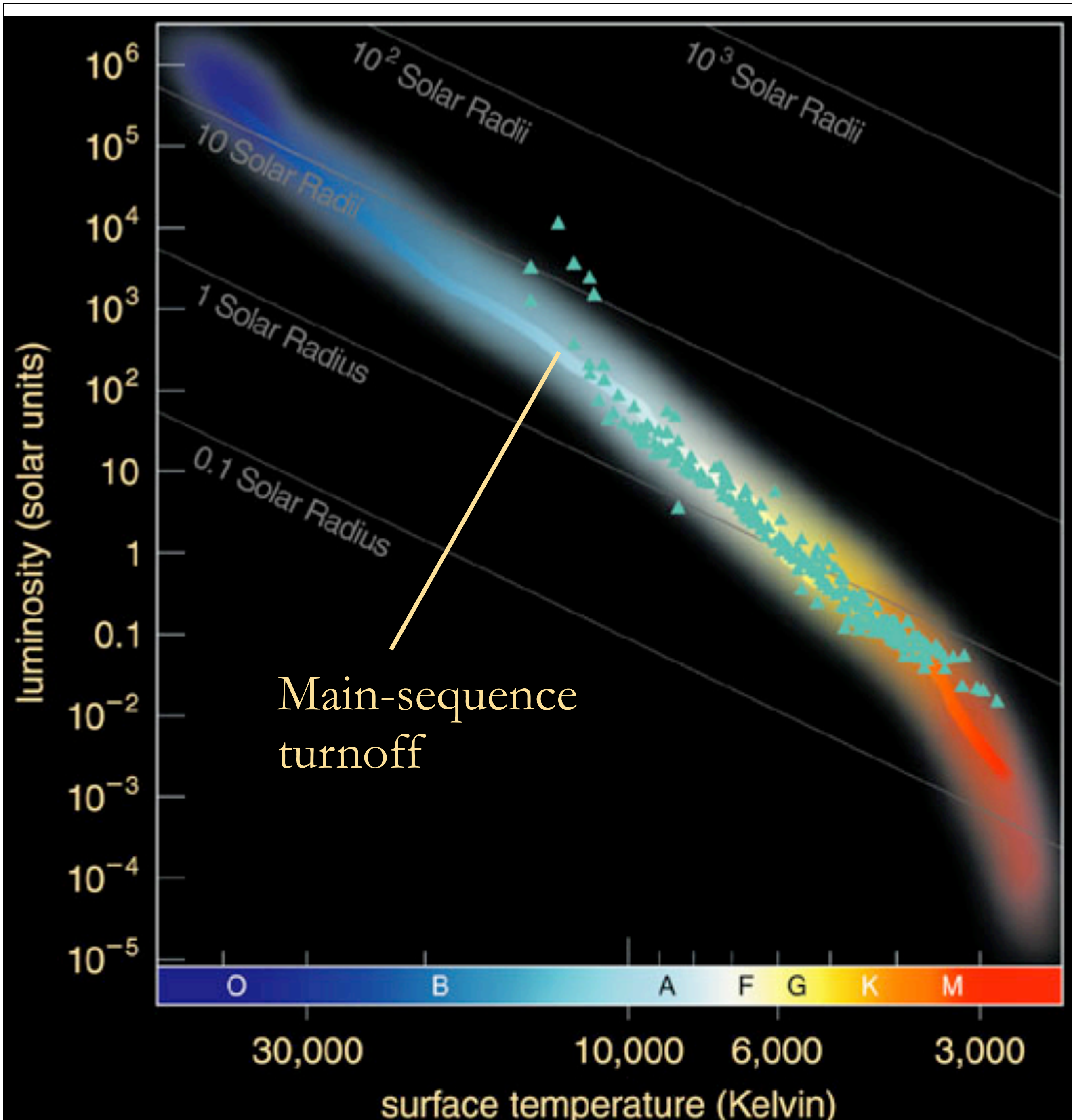
Star Clusters

Open cluster: A few thousand loosely packed stars

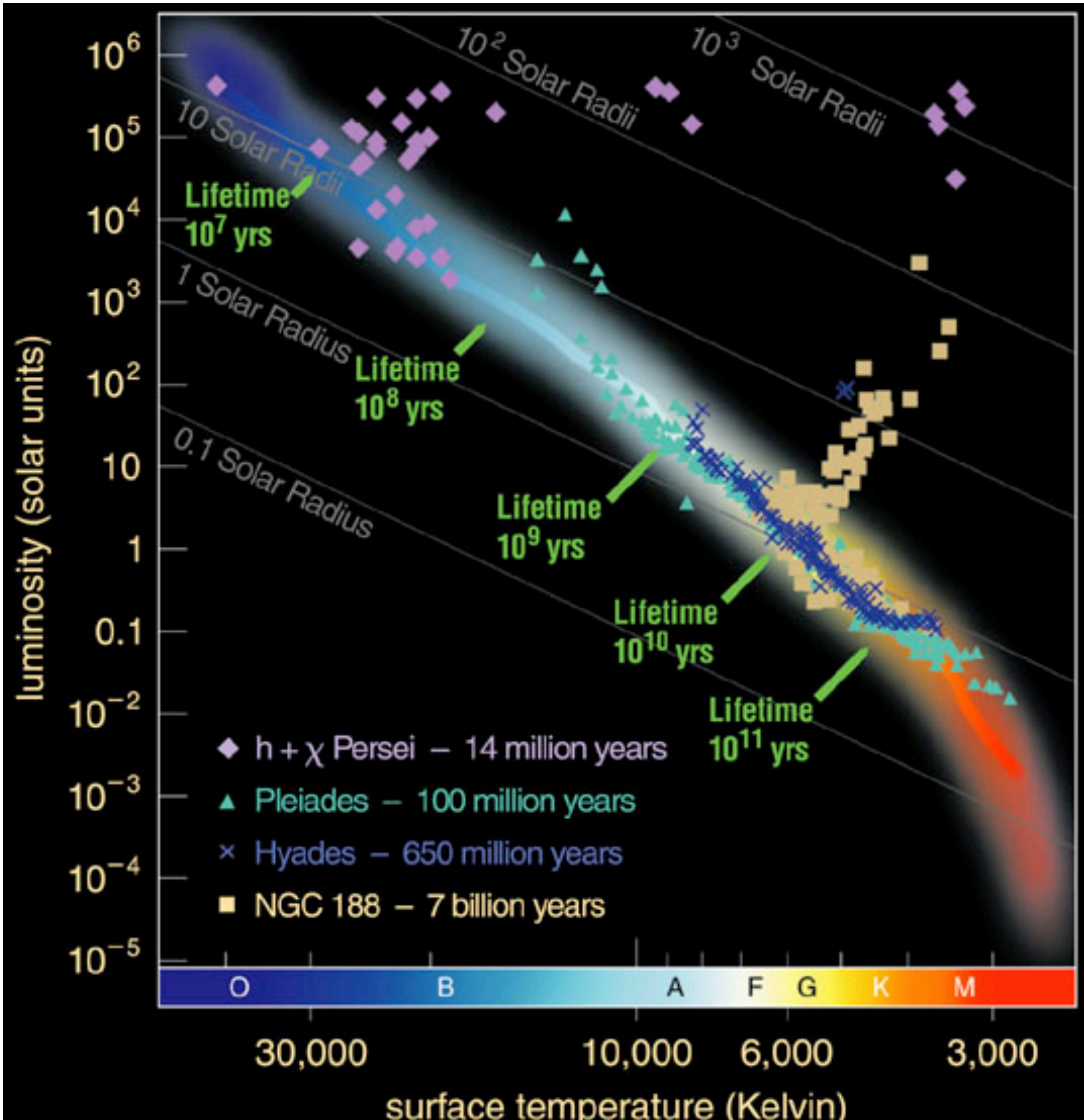
Globular cluster: Up to a million or more stars in a dense ball bound together by gravity

How do we measure the age of a star cluster?



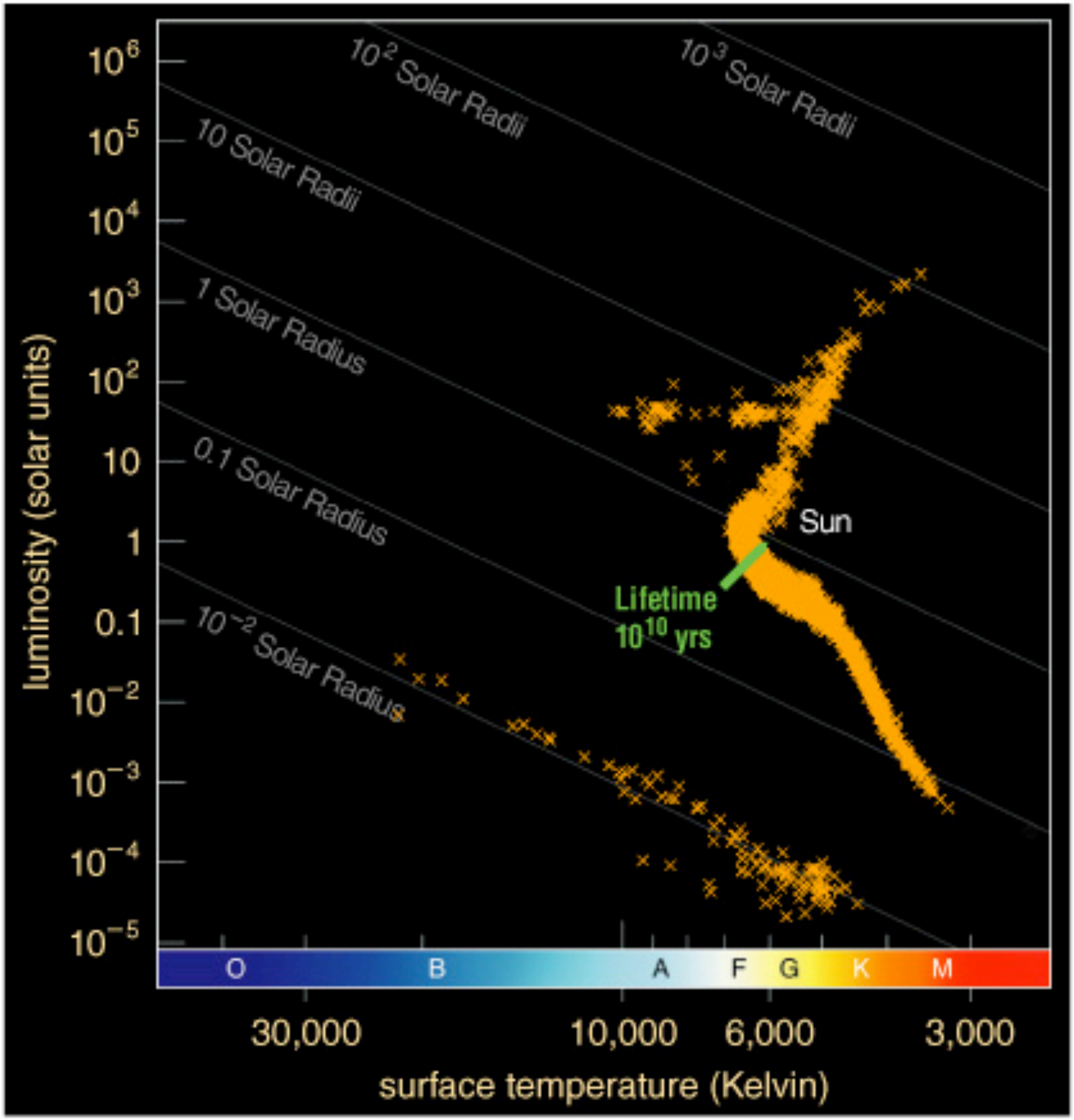


Pleiades now has no stars with life expectancy less than around 100 million years.



The main-sequence turnoff point of a cluster tells us its age.

11_HRDiagrAgeOfCluster



Detailed modeling of the oldest globular clusters reveals that they are about 13 billion years old.