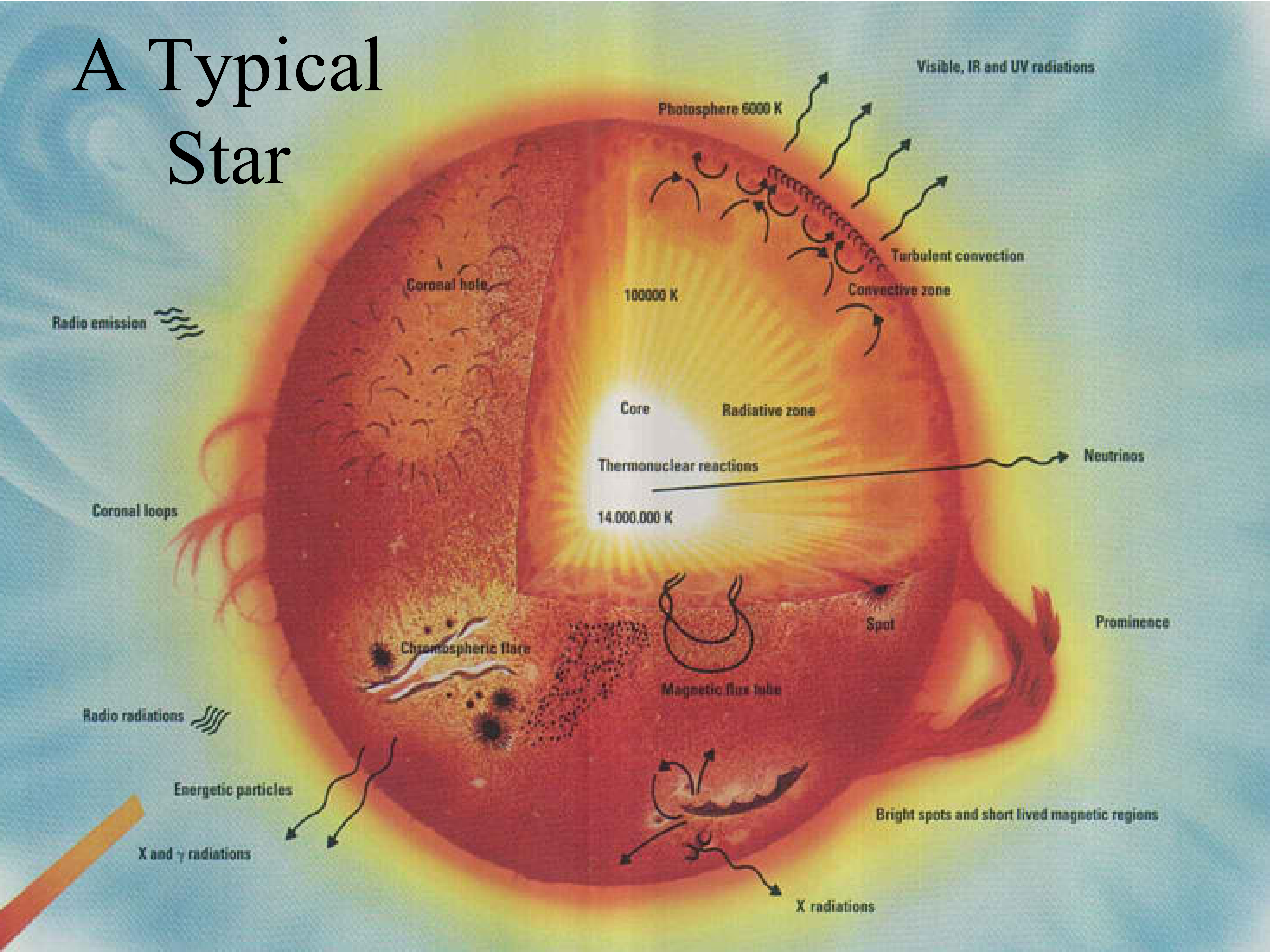
Contents of the Universe

- Stars
- Milky Way
- Galaxies
- Clusters

A Typical Star

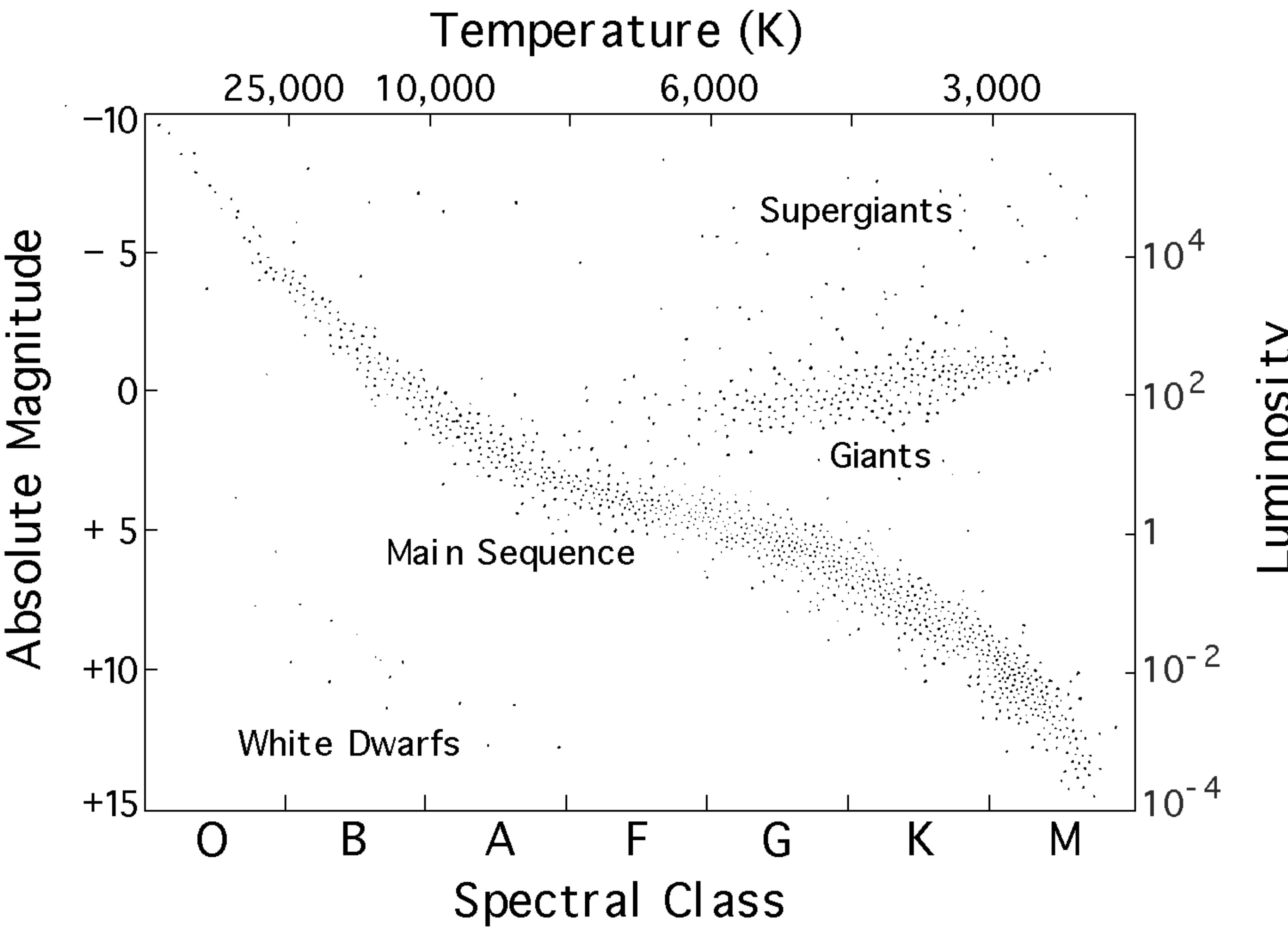


Properties of Stars

- Mass, radius, density, surface temperature, core temperature
- "Vogt-Russell" theorem: the mass and chemical composition of a star determine all of its other properties and its evolution over its entire life. For example, the Stefan-Boltzmann law relates luminosity, temperature, and size:

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

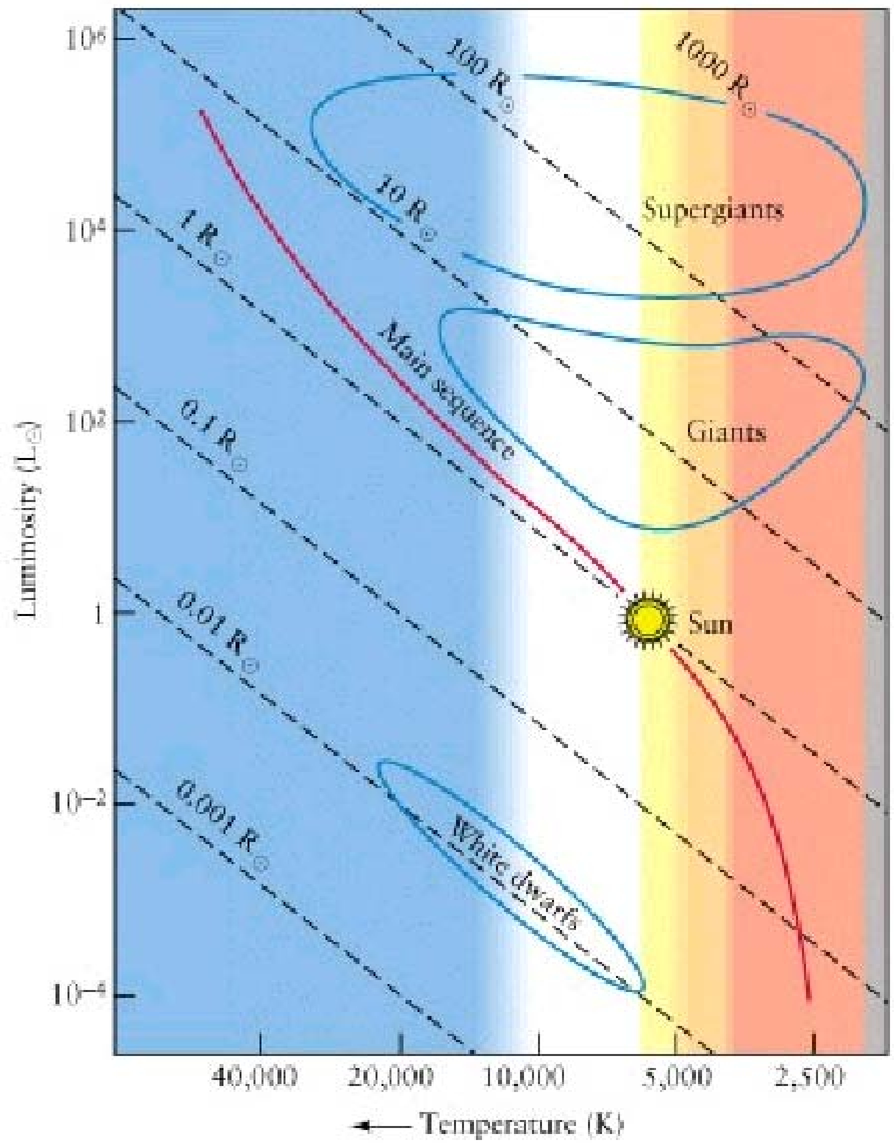
HR diagram



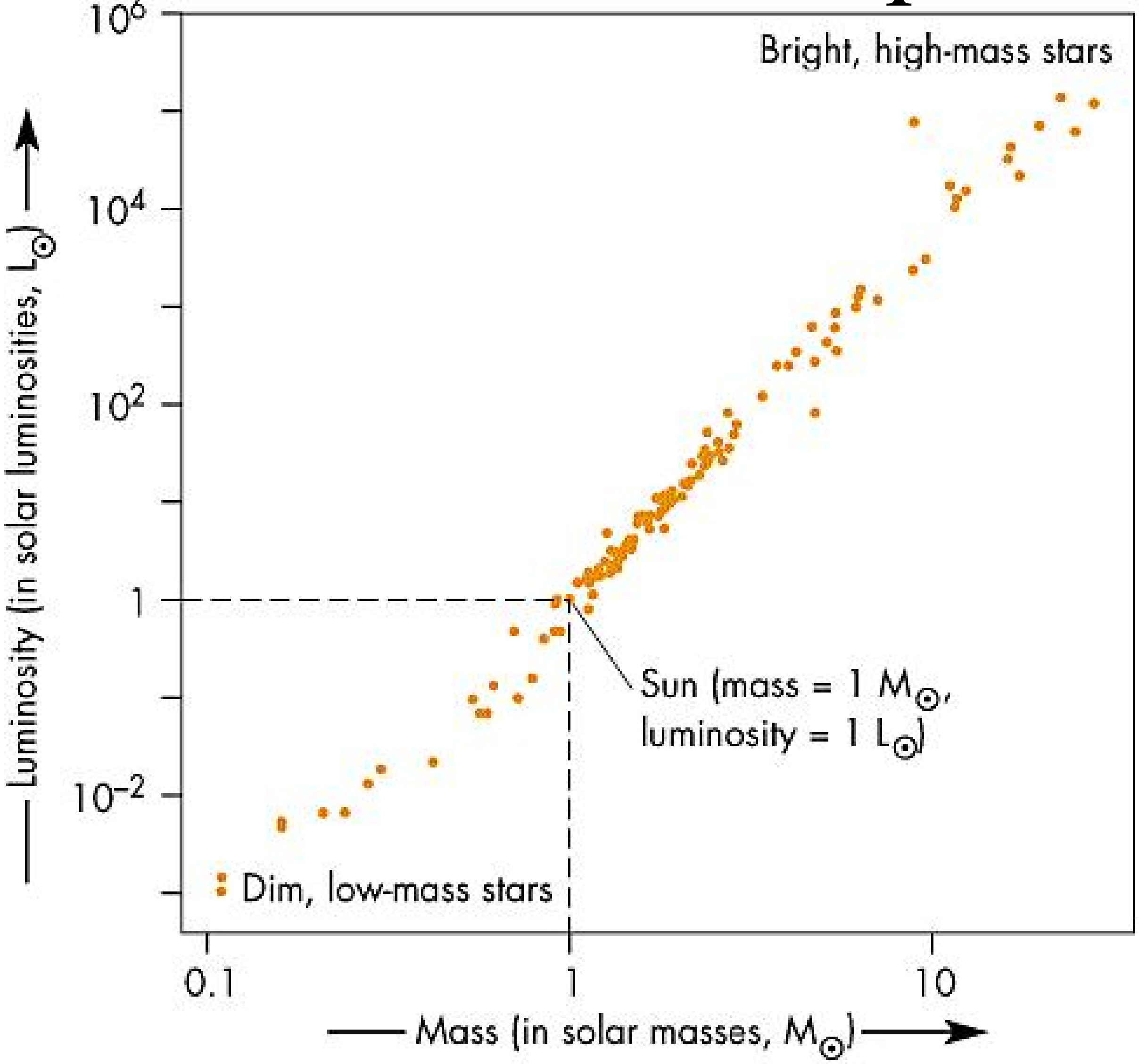
Temperature (K)
25,000
10,000
6,000
3,000
−10
− 5
0
+ 5
+10
+15
Absolute Magnitude
Supergiants
Giants
Main Sequence
White Dwarfs
10^4
10^2
1
10^-2
10^-4
Luminosity
O
B
A
F
G
K
M
Spectral Class

Sizes of Stars on an HR Diagram

- We can calculate R from L and T.
- Main sequence stars are found in a band from the upper left to the lower right.
- Giant and supergiant stars are found in the upper right corner.
- Tiny white dwarf stars are found in the lower left corner of the HR diagram.

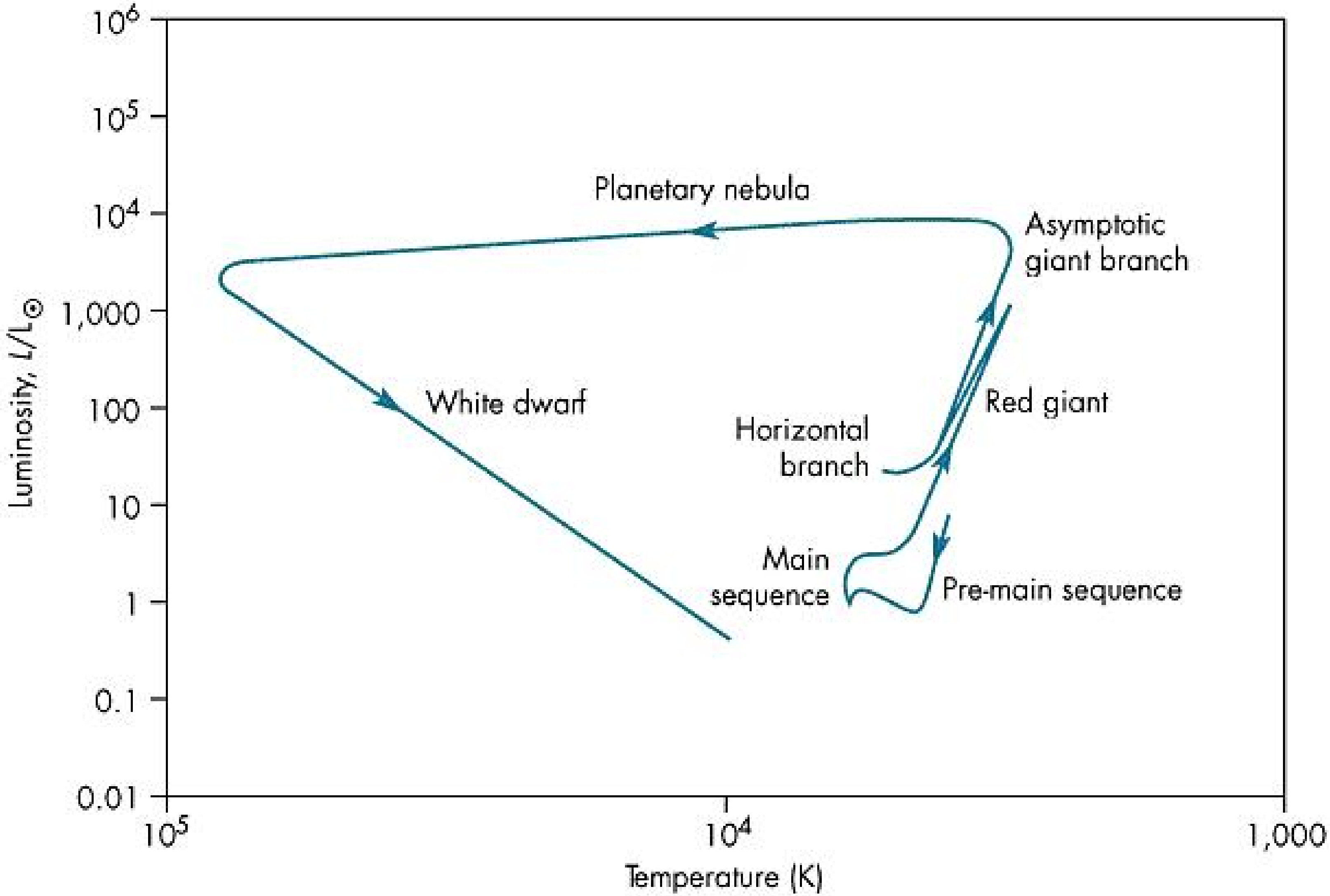


Mass-Luminosity relation on the main sequence



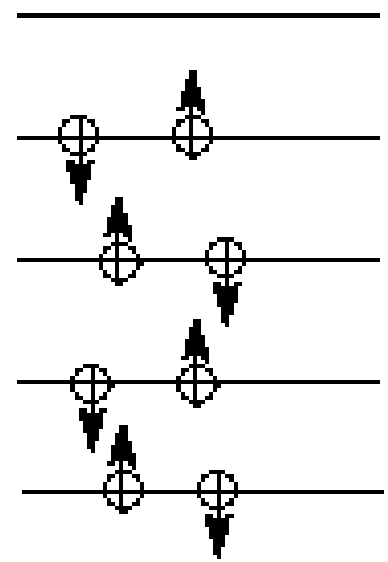
$$\frac{L}{L_{\Theta}} \approx \left(\frac{M}{M_{\Theta}} \right)^{3.5}$$

Movement on HR diagram



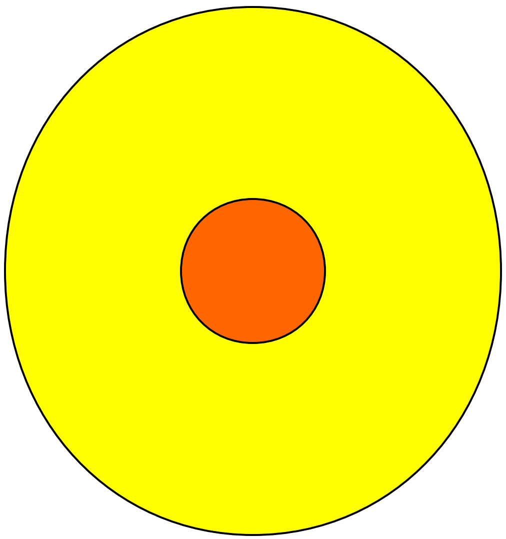
Normal versus degenerate gases

- Normal gas
  - Pressure is the force exerted by atoms in a gas
  - Temperature is how fast atoms in gas move
- Degenerate gas
  - Motion of atoms is not due to kinetic energy, but instead due to quantum mechanical motions – all the lower energy levels are filled due to Fermi exclusion
  - Pressure no longer depends on temperature



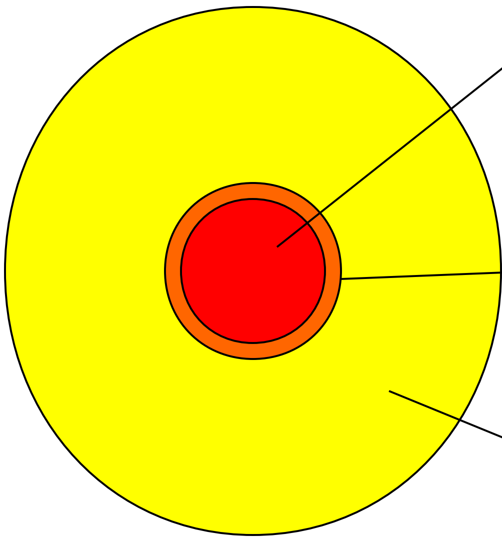
Degenerate gas: all lower energy levels filled with two particles each (opposite spins). Particles **locked** in place.

Main Sequence Evolution



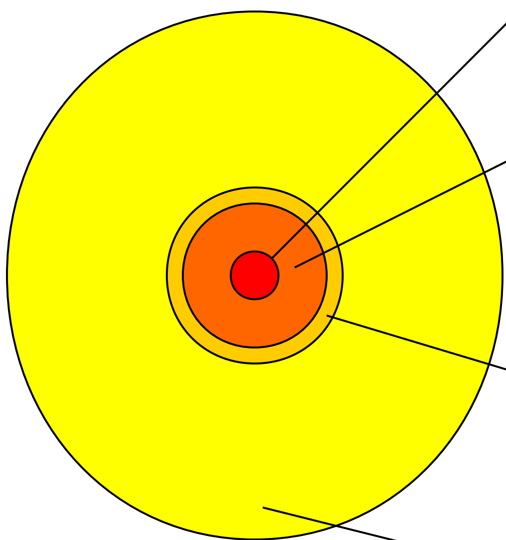
- Fusion changes H $\rightarrow$ He
- Core depletes of H
- Eventually there is not enough H to maintain energy generation in the core
- Core starts to collapse

Red Giant Phase



- He core
  - No nuclear fusion
  - Gravitational contraction produces energy
- H layer
  - Nuclear fusion
- Envelope
  - Expands because of increased energy production
  - Cools because of increased surface area

Red Giant after Helium Ignition



- He burning core
  - Fusion burns He into C, O
- He rich core
  - No fusion
- H burning shell
  - Fusion burns H into He
- Envelope
  - Expands because of increased energy production

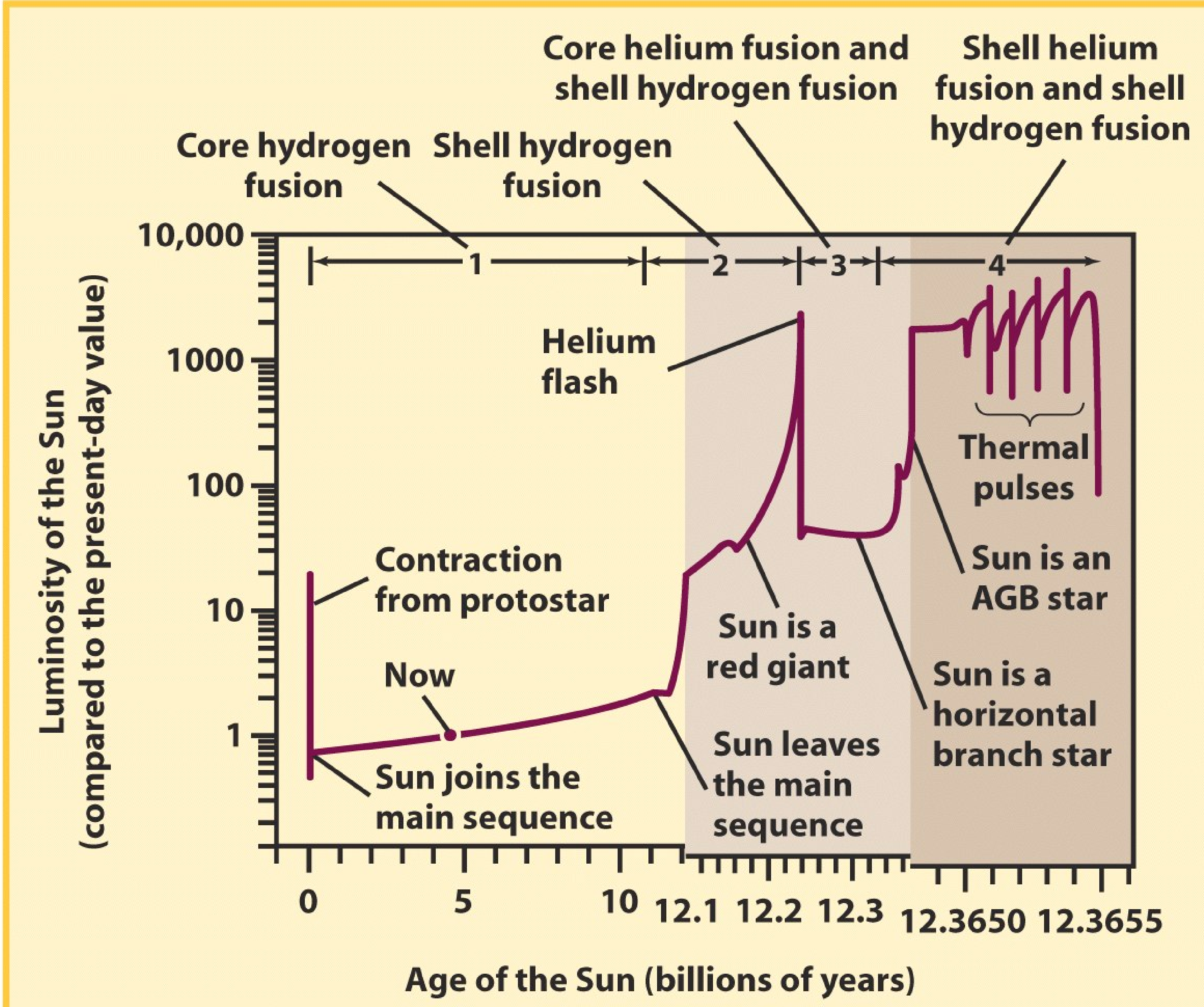
Asymptotic Giant Branch

- Fusion in core stops, H and He fusion continues in shells
- Star moves onto Asymptotic Giant Branch (AGB) looses mass via winds
- Creates a "planetary nebula"
- Leaves behind core of carbon and oxygen surrounded by thin shell of hydrogen

Hourglass nebula

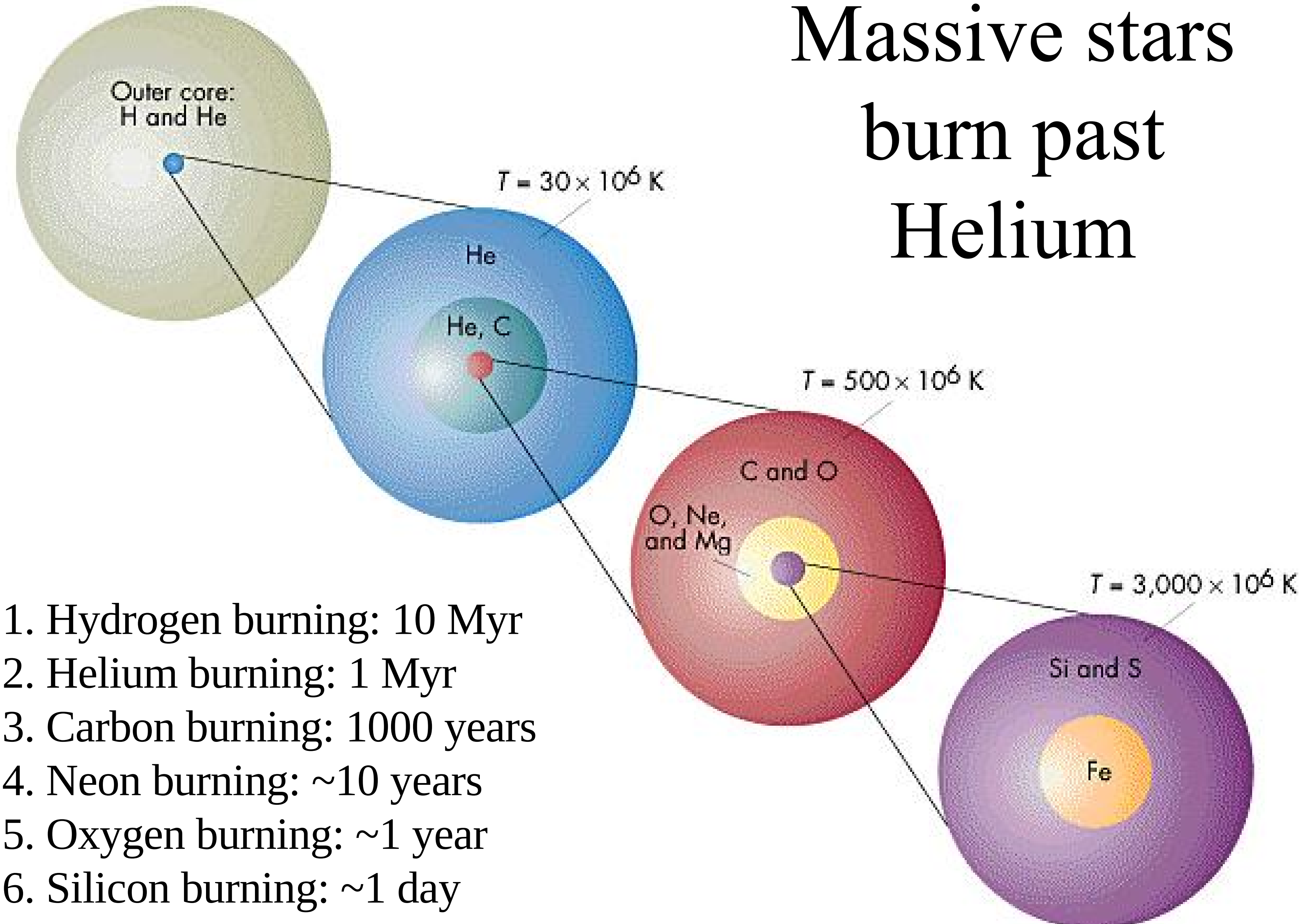
White dwarf

- Star burns up rest of hydrogen
- Nothing remains but degenerate core of Oxygen and Carbon
- “White dwarf” cools but does not contract because core is degenerate
- No energy from fusion, no energy from gravitational contraction
- White dwarf slowly fades away…



Core helium fusion and shell hydrogen fusion
Shell helium fusion and shell hydrogen fusion
Core hydrogen fusion
Shell hydrogen fusion
10,000
1000
100
10
1
1
2
3
4
Helium flash
Thermal pulses
Luminosity of the Sun (compared to the present-day value)
Contraction from protostar
Now
Sun joins the main sequence
Sun is a red giant
Sun leaves the main sequence
Sun is an AGB star
Sun is a horizontal branch star
0
5
10
12.1
12.2
12.3
12.3650
12.3655
Age of the Sun (billions of years)

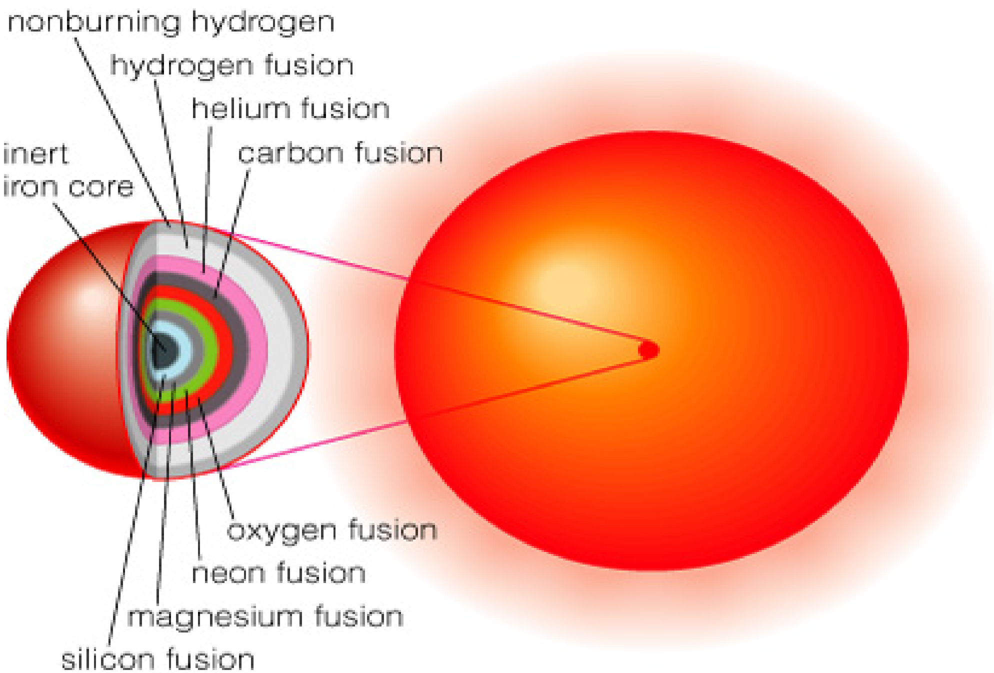
Massive stars burn past Helium



1. Hydrogen burning: 10 Myr
2. Helium burning: 1 Myr
3. Carbon burning: 1000 years
4. Neon burning: ~10 years
5. Oxygen burning: ~1 year
6. Silicon burning: ~1 day

Finally builds up an inert Iron core

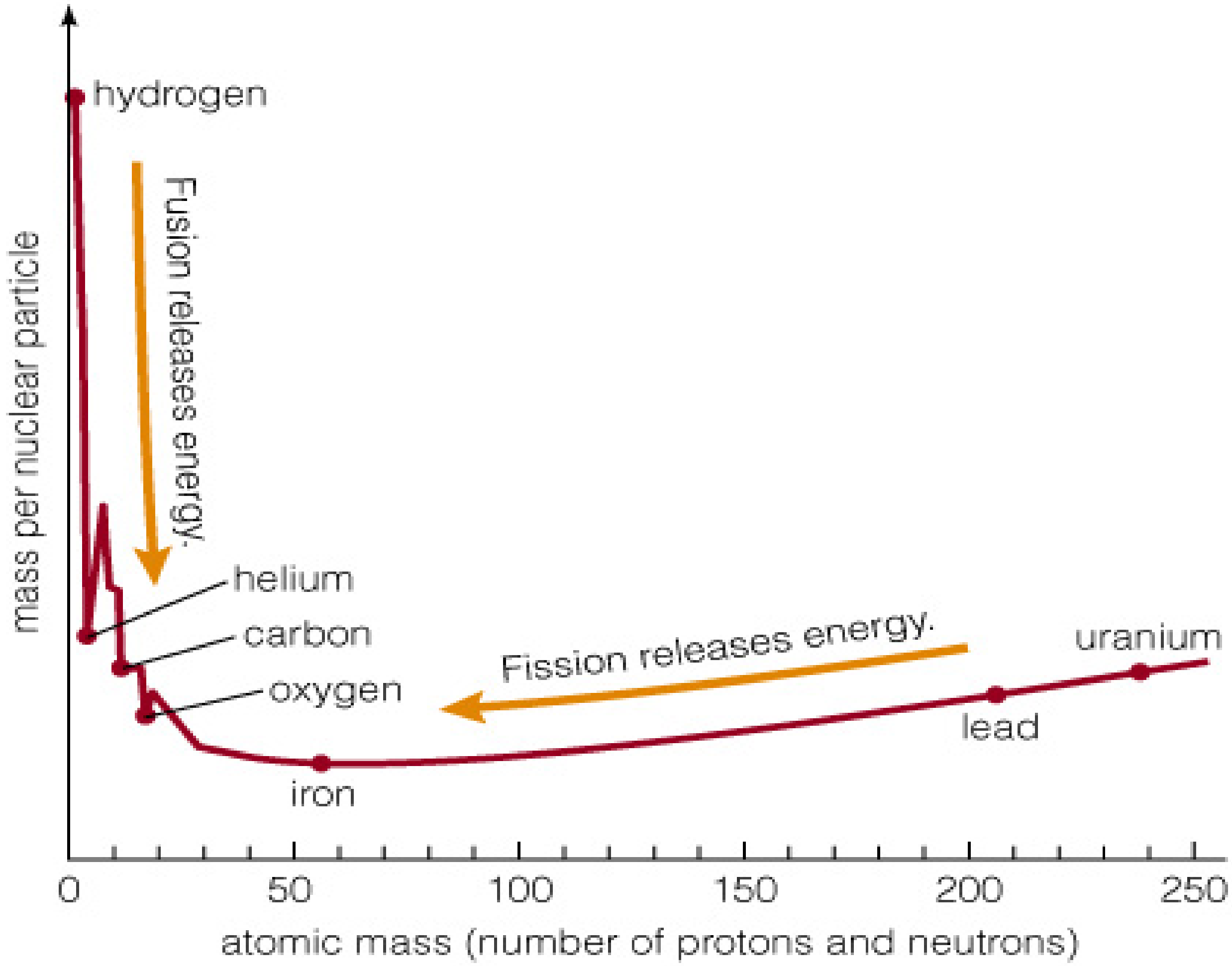
Multiple Shell Burning



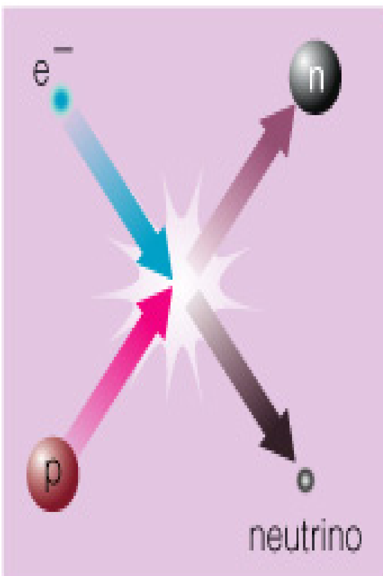
Interactive Figure

- Advanced nuclear burning proceeds in a series of nested shells

Why does fusion stop at Iron?



Supernova Explosion

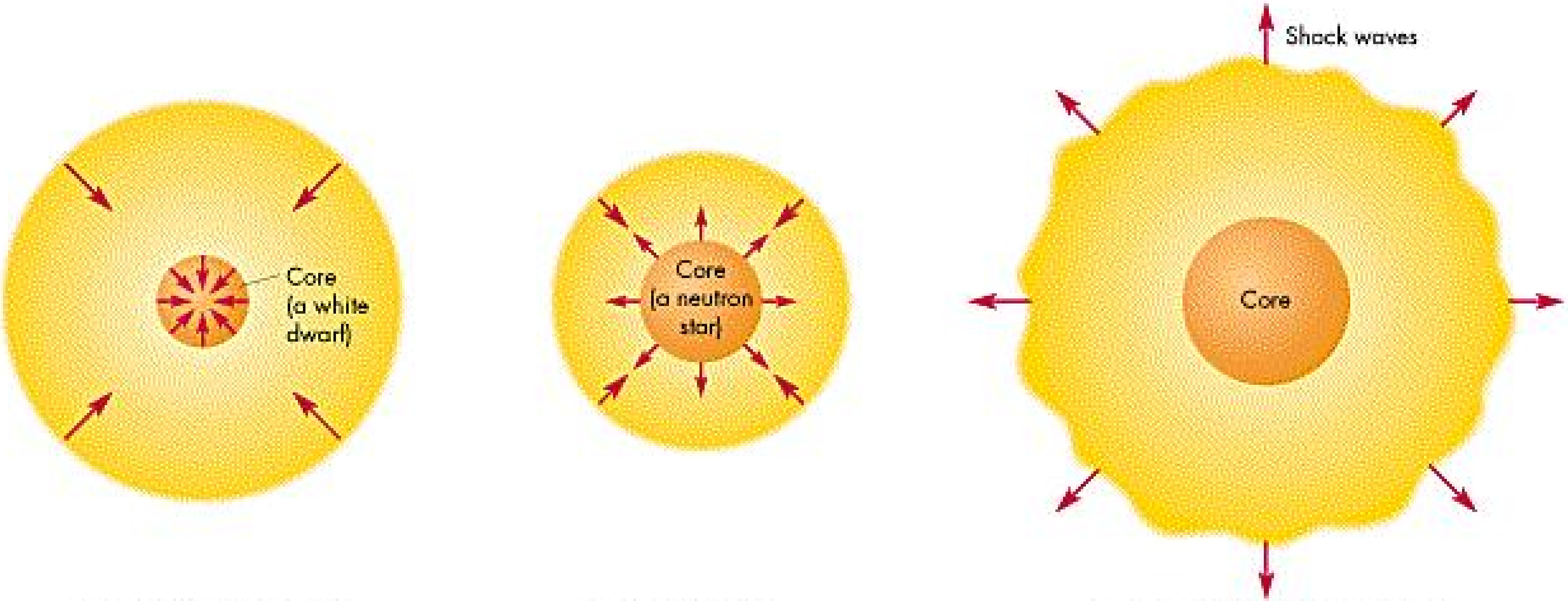


- Core degeneracy pressure goes away because electrons combine with protons, making neutrons and neutrinos
- Neutrons collapse to the center, forming a **neutron star**

Core collapse

- Iron core is degenerate
- Core grows until it is too heavy to support itself
- Core collapses, density increases, normal iron nuclei are converted into neutrons with the emission of neutrinos
- Core collapse stops, neutron star is formed
- Rest of the star collapses in on the core, but bounces off the new neutron star (also pushed outwards by the neutrinos)

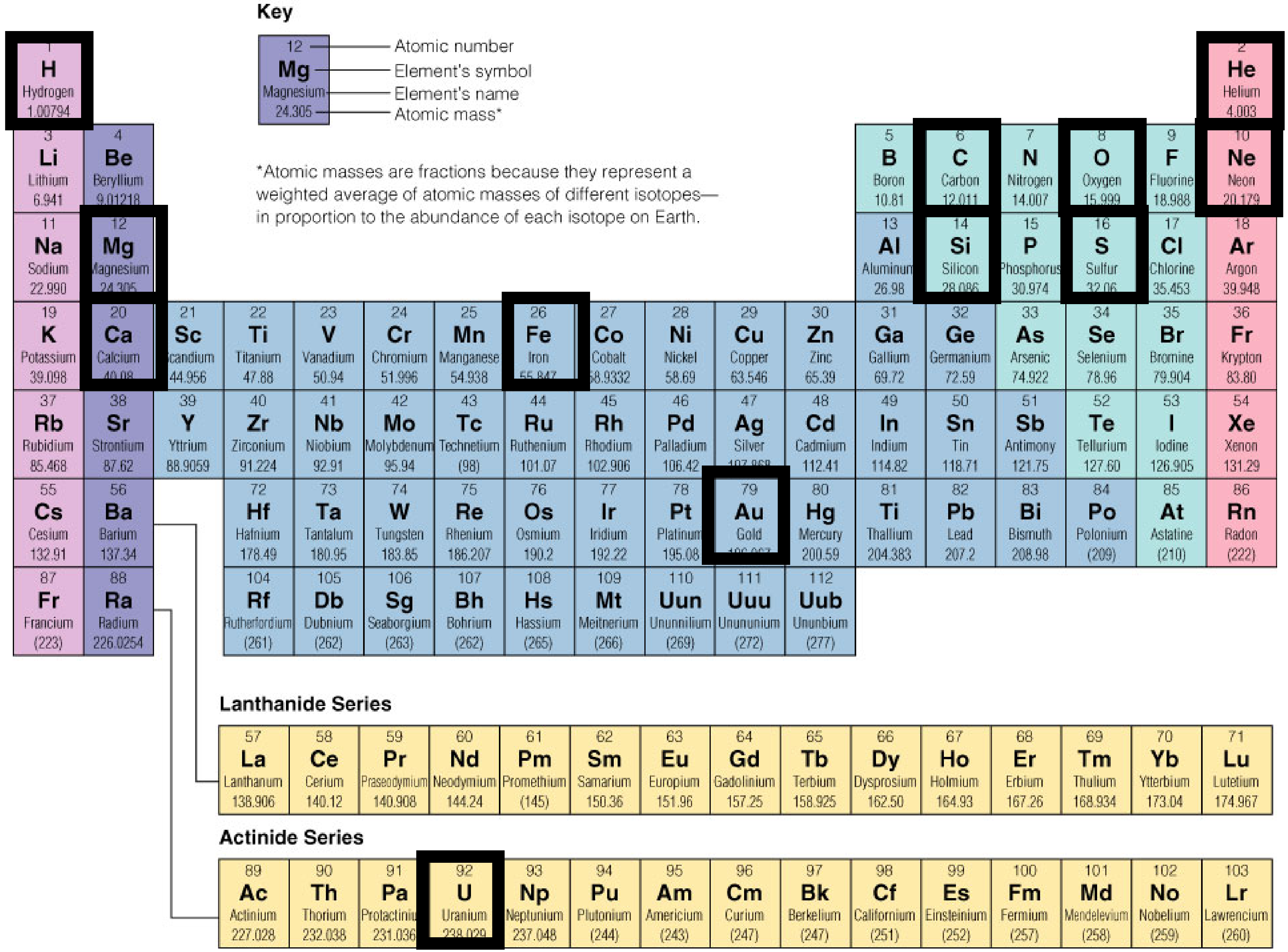
Supernova explosion



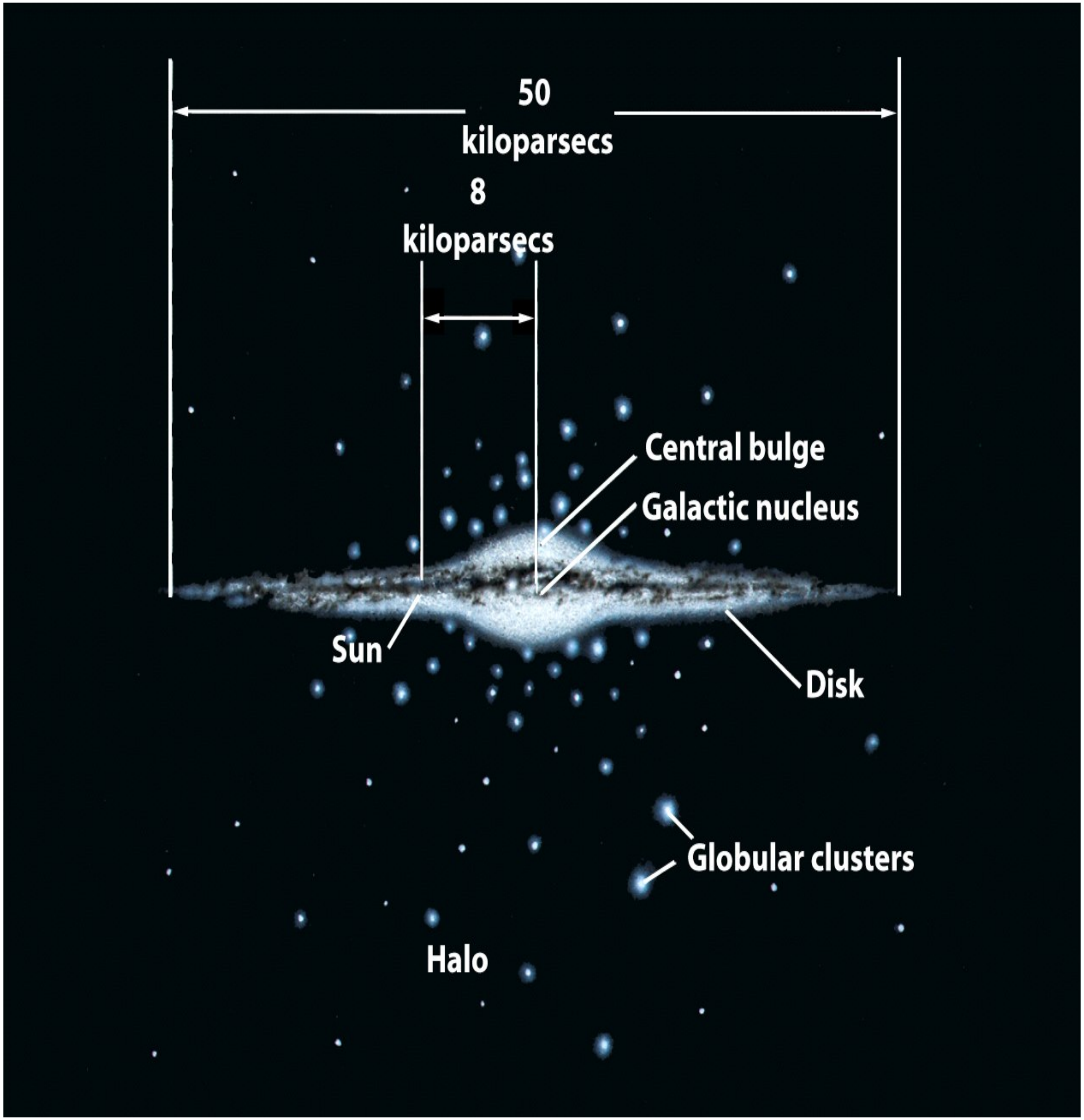
A Step 1: The iron core of the red giant collapses

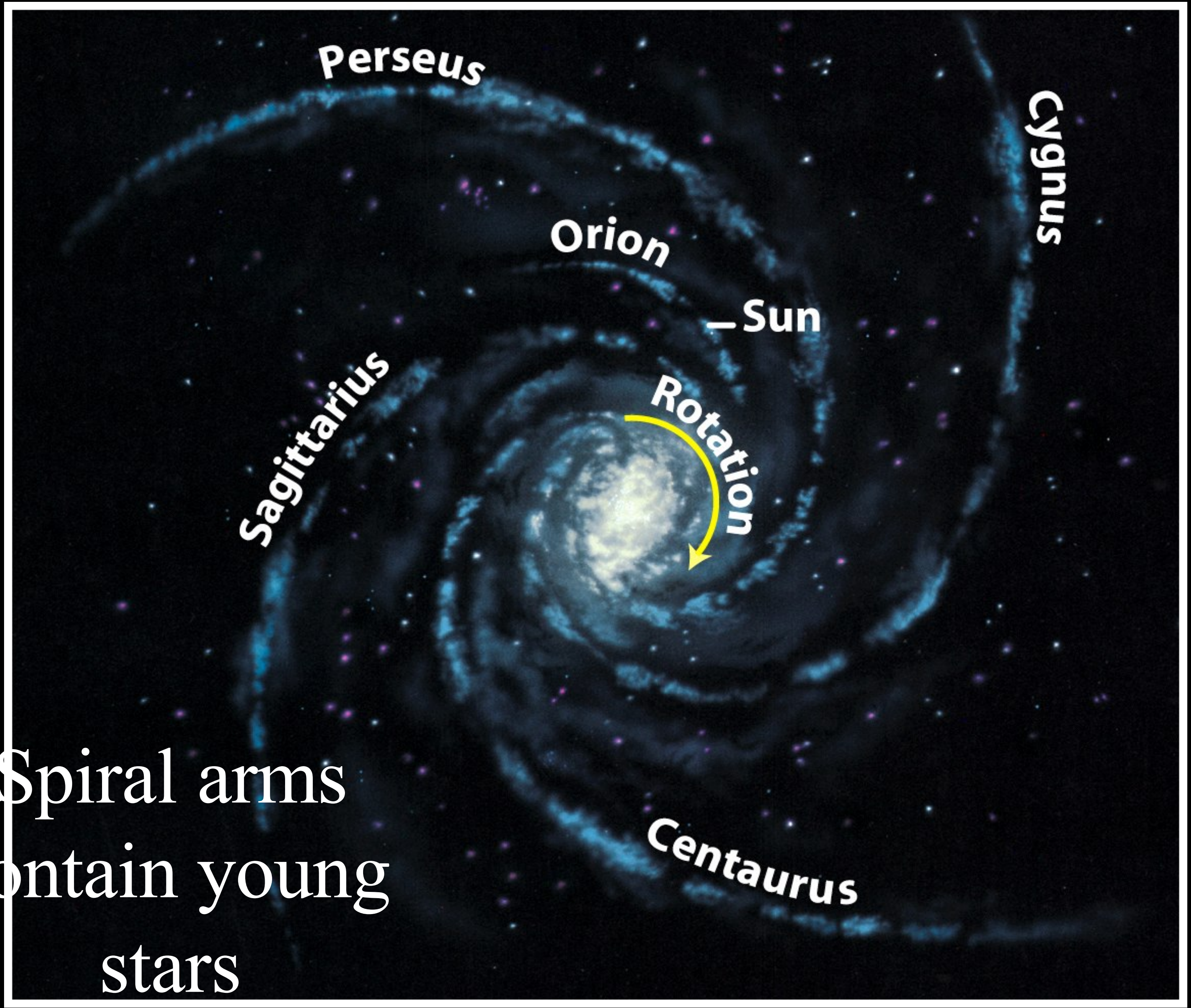
B Step 2: Neutron-rich core rebounds

C Step 3: The shock wave moves outward through the star



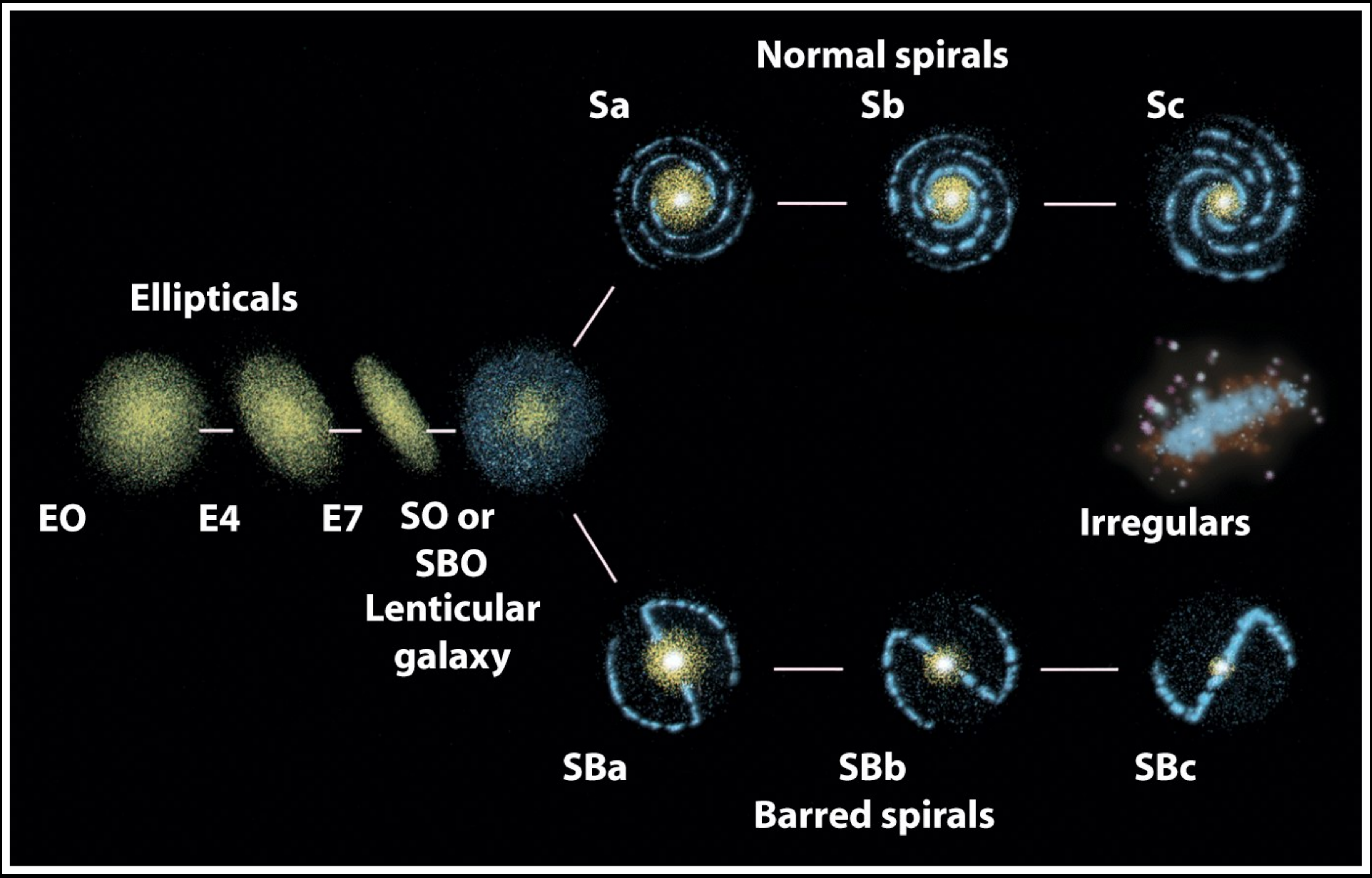
Energy and neutrons released in supernova explosion enable elements heavier than iron to form, including Au and U


50
kiloparsecs
8
kiloparsecs
Central bulge
Galactic nucleus
Sun
Disk
Globular clusters
Halo

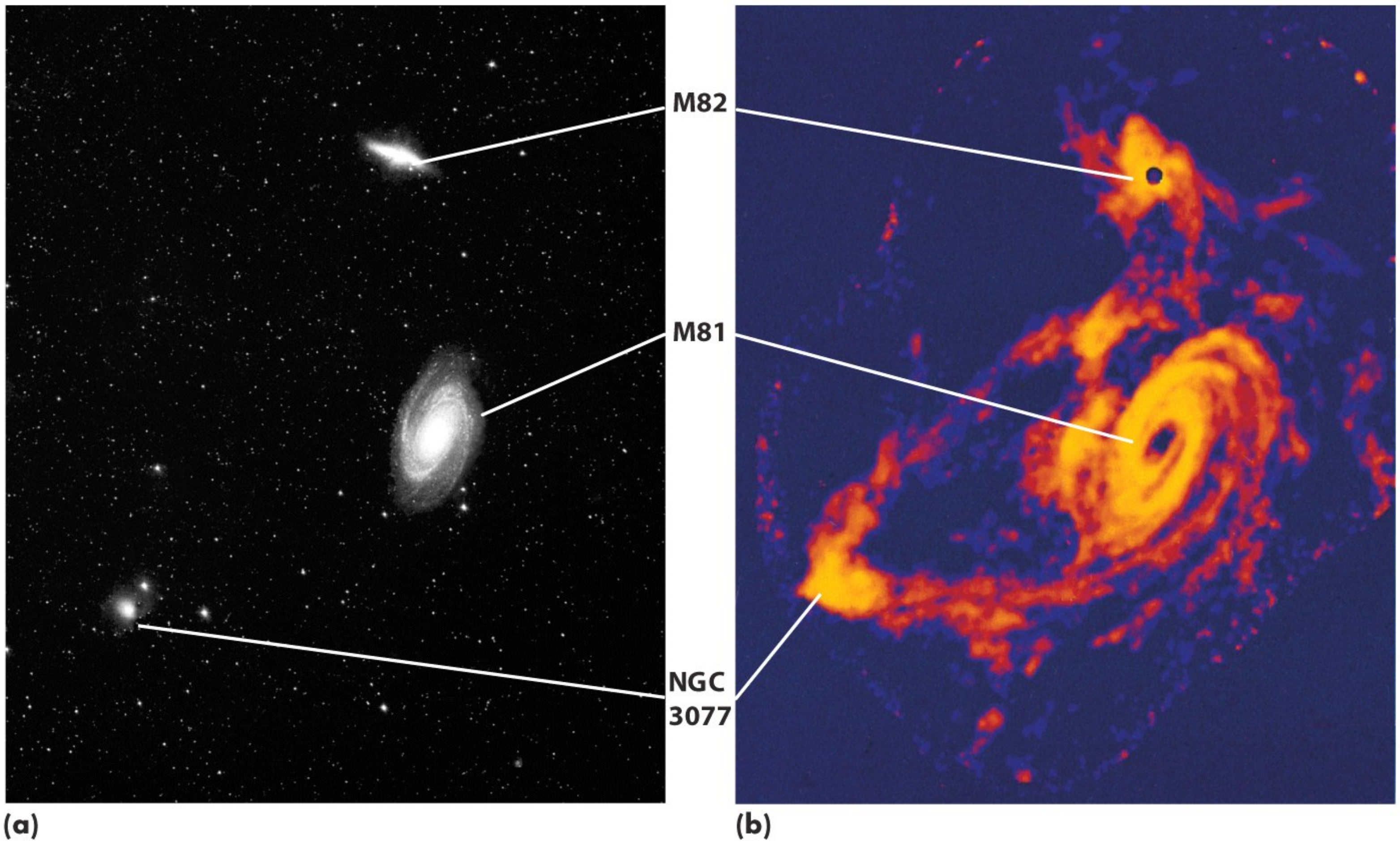


Spiral arms contain young stars

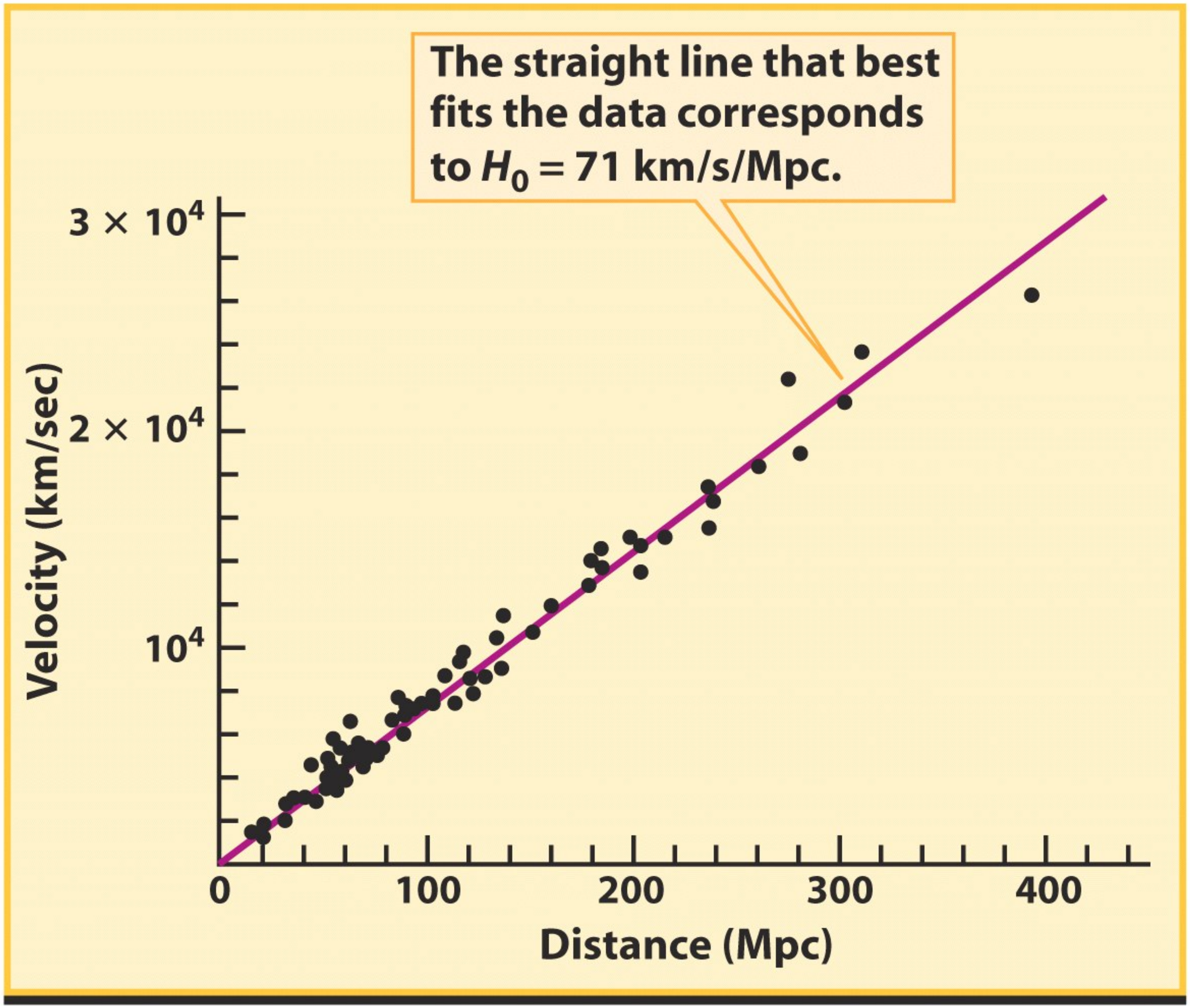
Classifying Galaxies



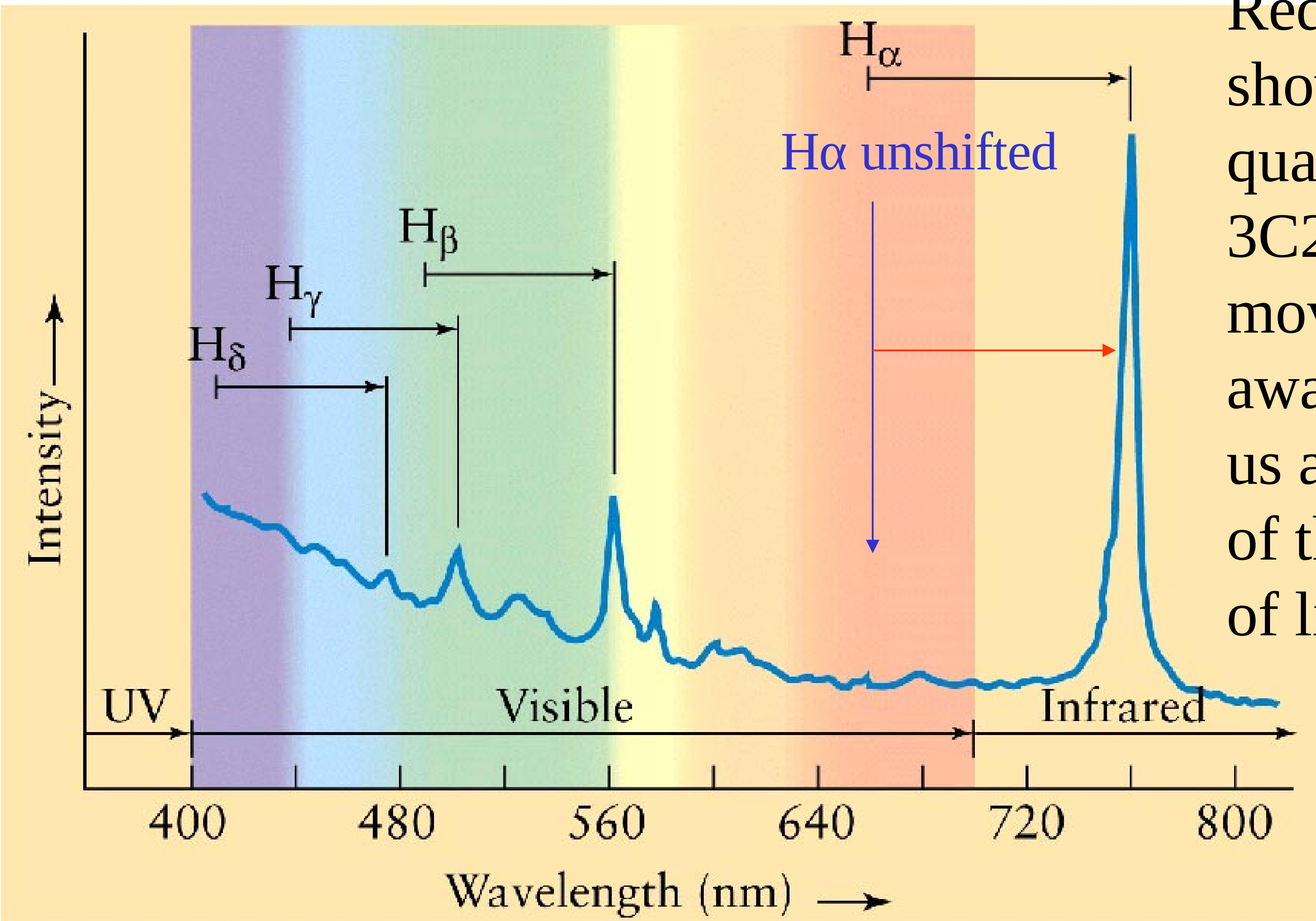
Interacting galaxies



Hubble expansion $v = H_0 d$

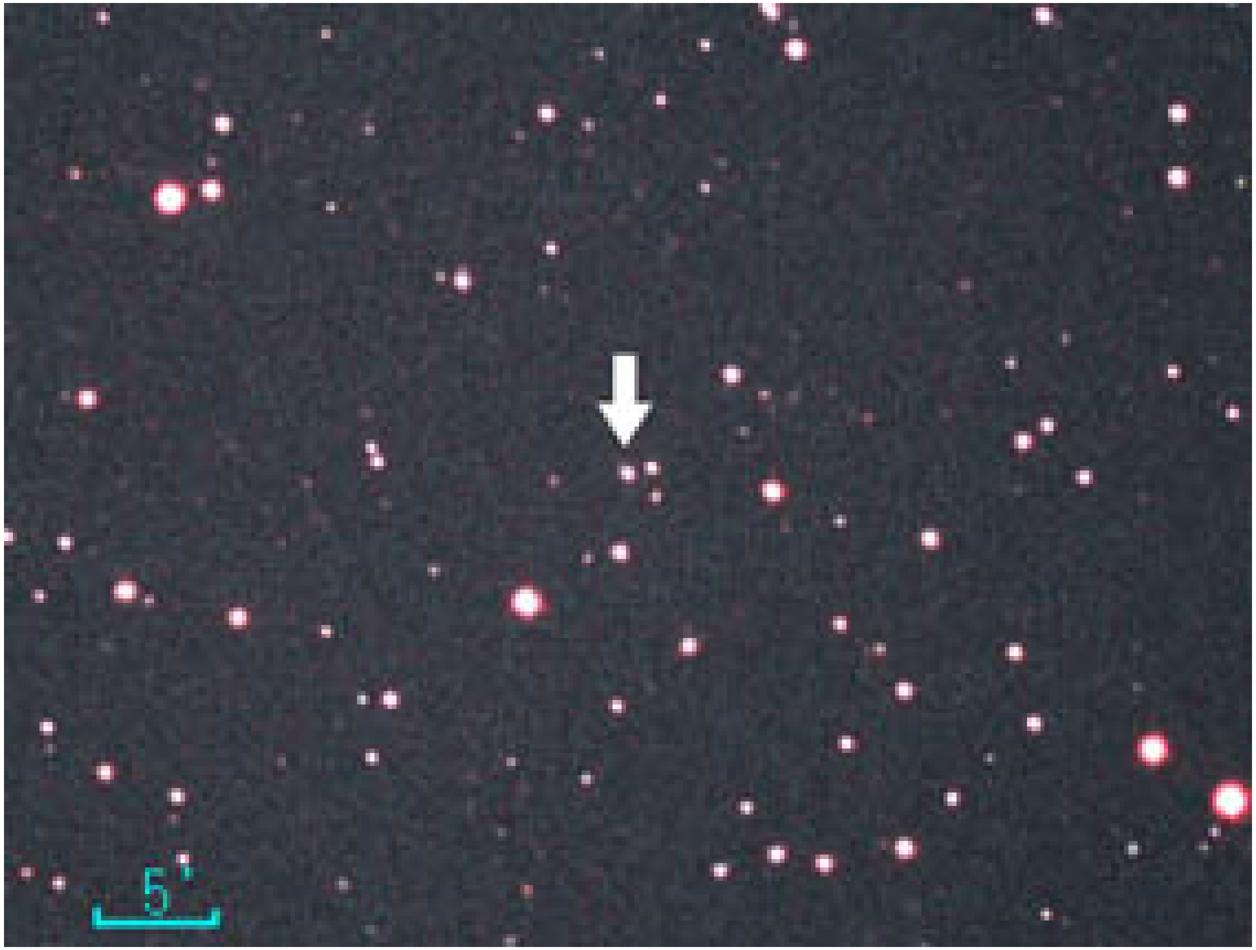


Quasar optical spectrum



Redshift shows this quasar, 3C273, is moving away from us at 16% of the speed of light

3C273

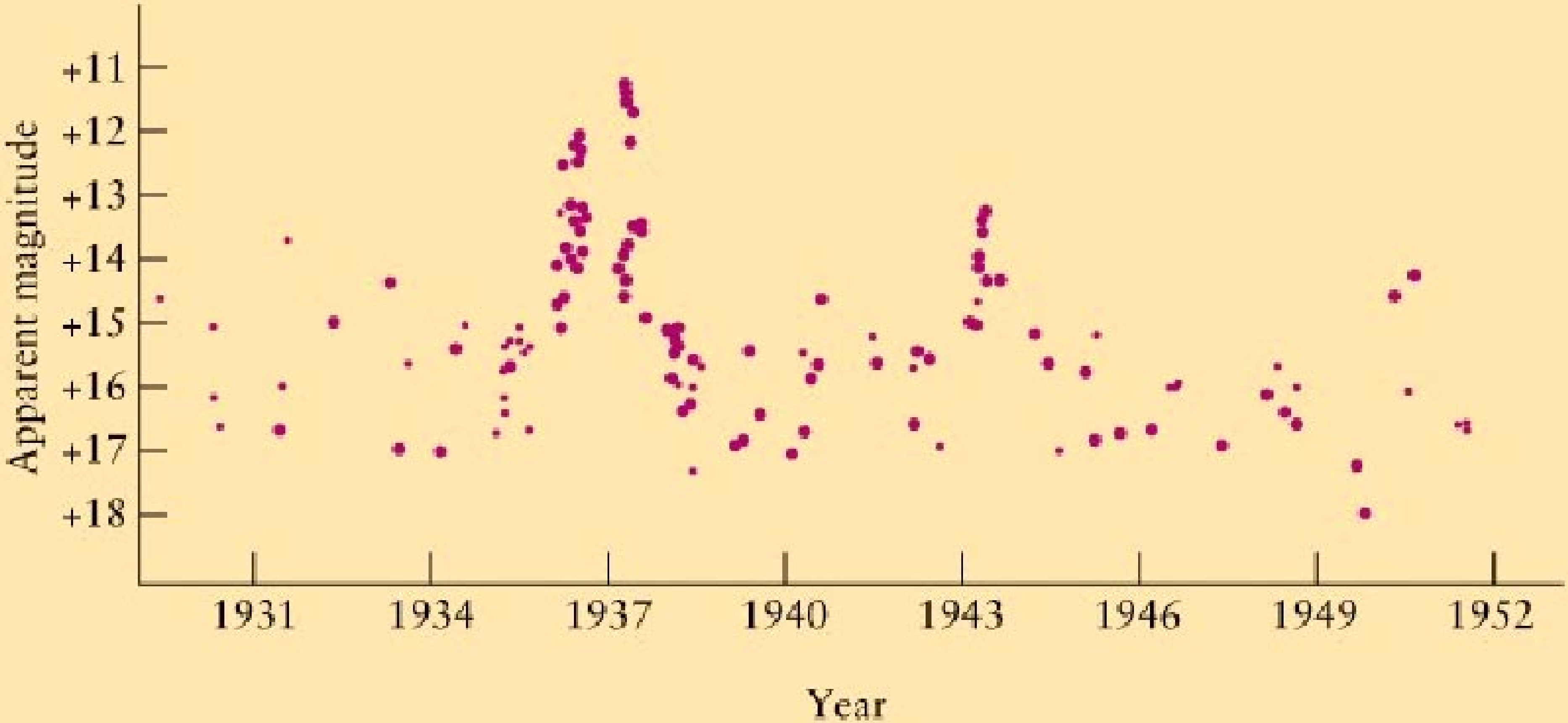


The quasar 3C273 is 2.6 billion light years away.

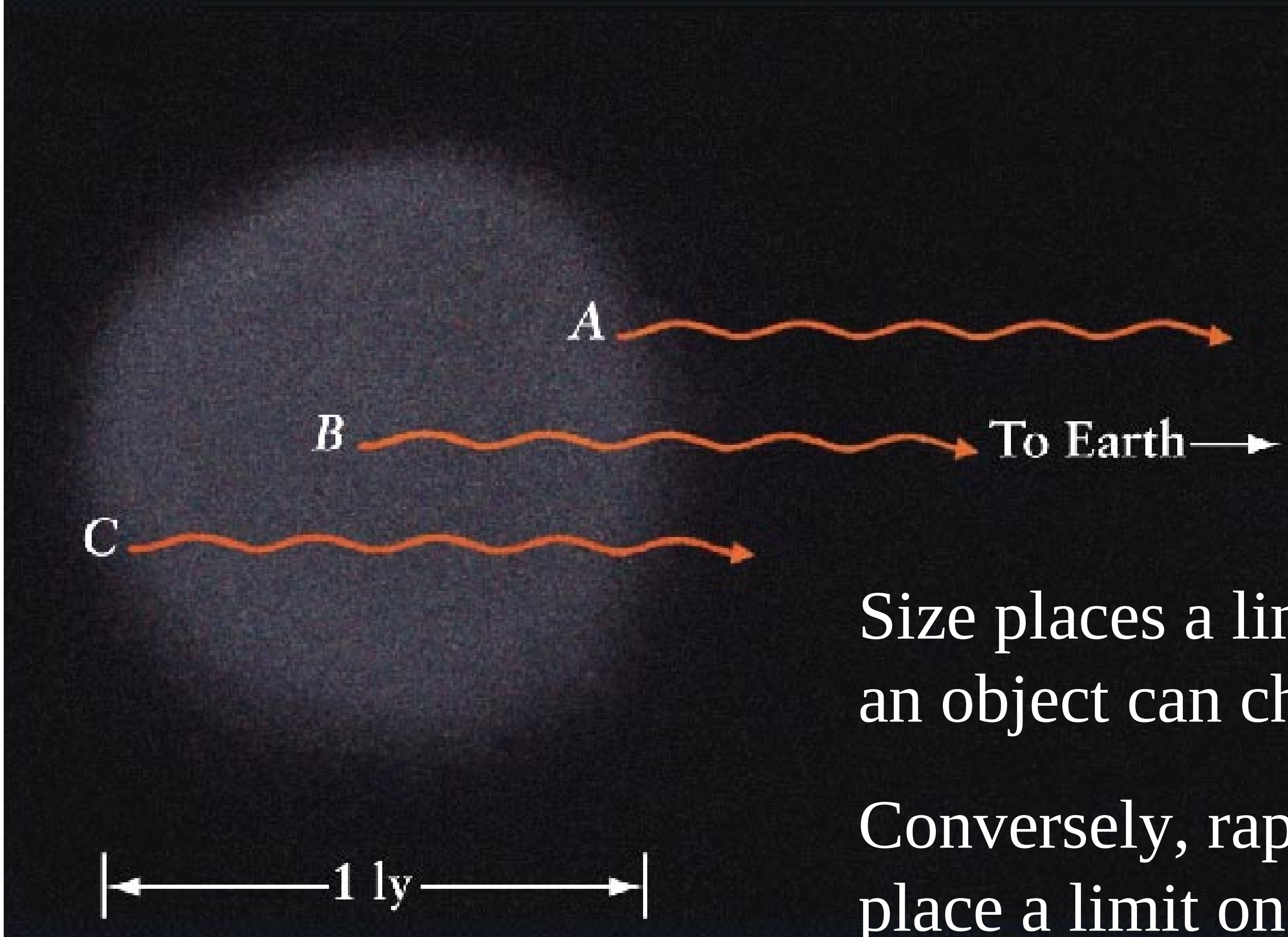
It looks dim, but must be extremely luminous to be visible as such distance.

The luminosity of 3C273 is more than one trillion times the entire energy output of our Sun, or 100 times the luminosity of our entire galaxy.

Quasars vary



Quasar size



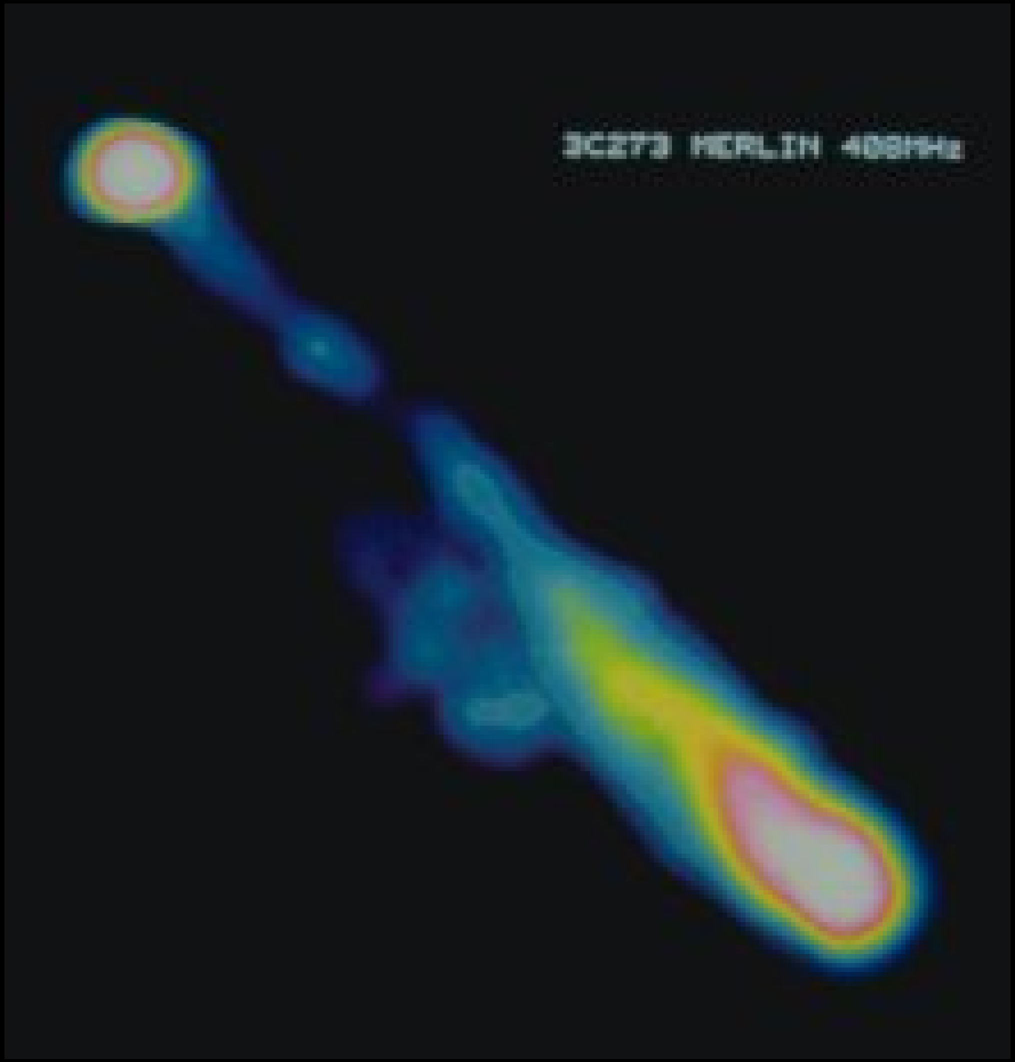
Size places a limit on how fast an object can change brightness.

Conversely, rapid variations place a limit on the size of the emitting object.

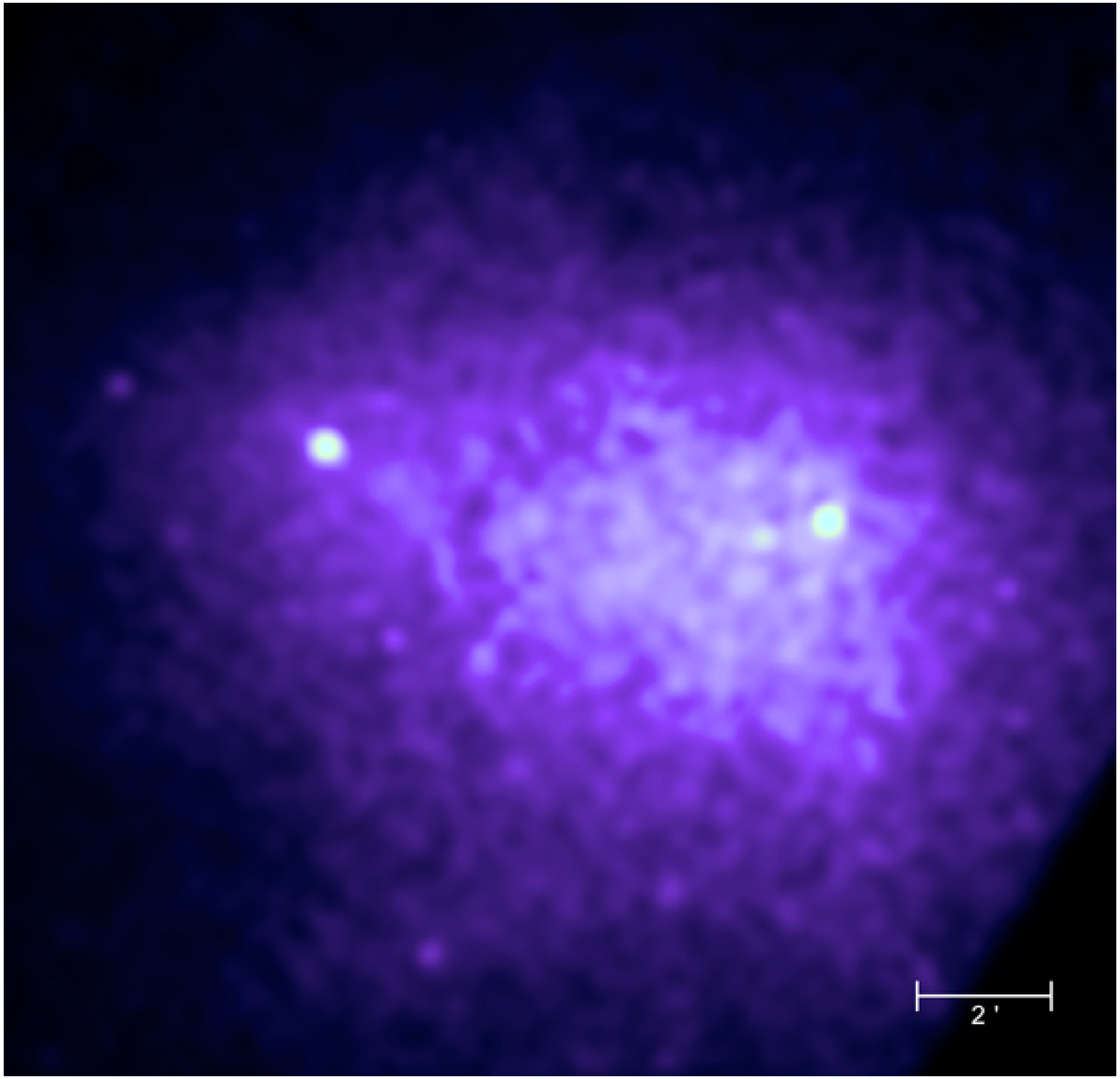
Quasar jets

Optical core →

Radio jet →



Coma cluster of galaxies



Coma cluster in X-rays

Coma cluster

- X-ray emitting gas is at a temperature of 100,000,000 K.
- The total X-ray luminosity is more than the luminosity of 100 billion Suns.

- From this, the amount of X-ray emitting gas can be calculated. The mass of X-ray emitting gas is greater than the mass in all the stars in all the galaxies in the cluster.