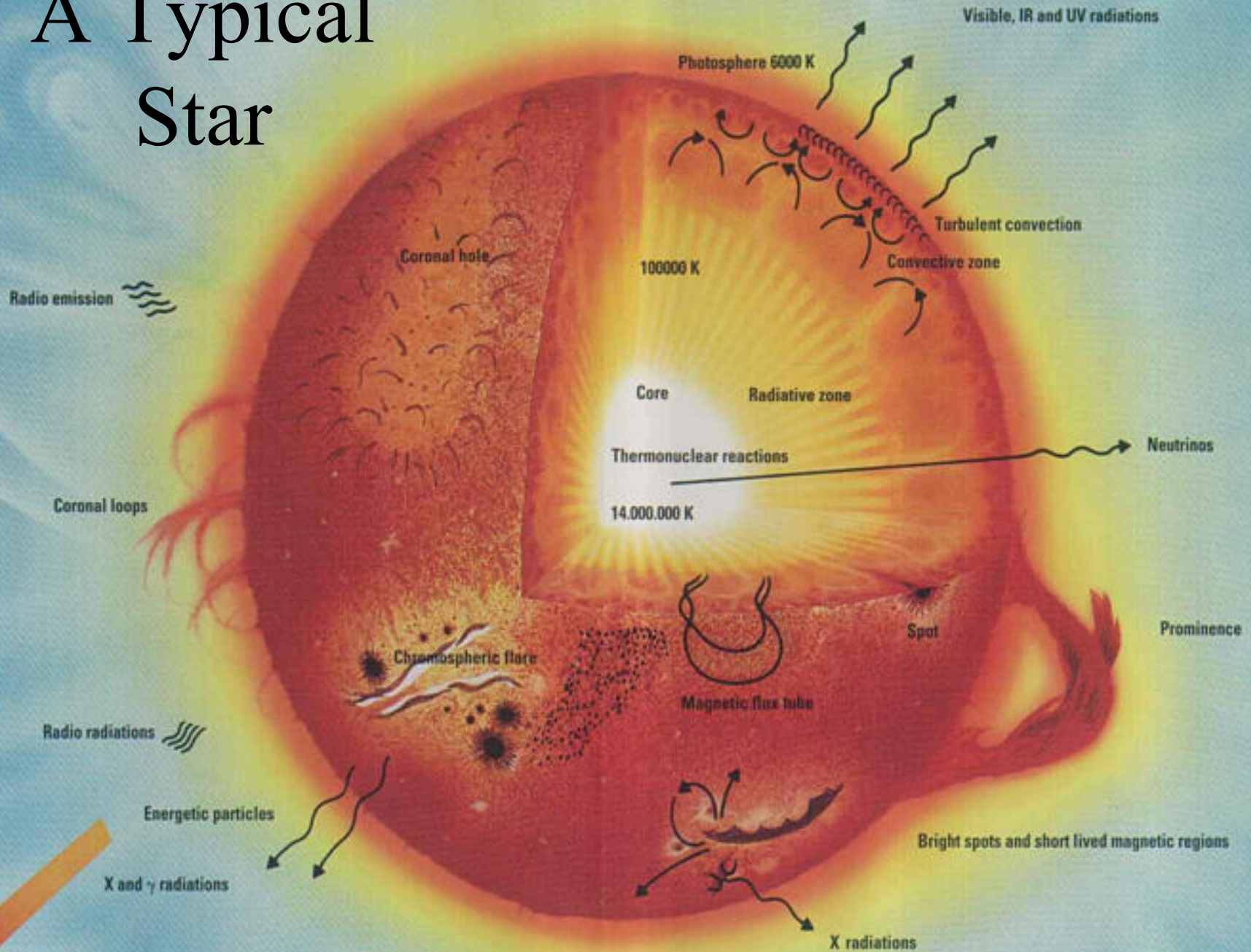


# Contents of the Universe

- Stars
- Milky Way
- Galaxies
- Clusters

# A Typical Star

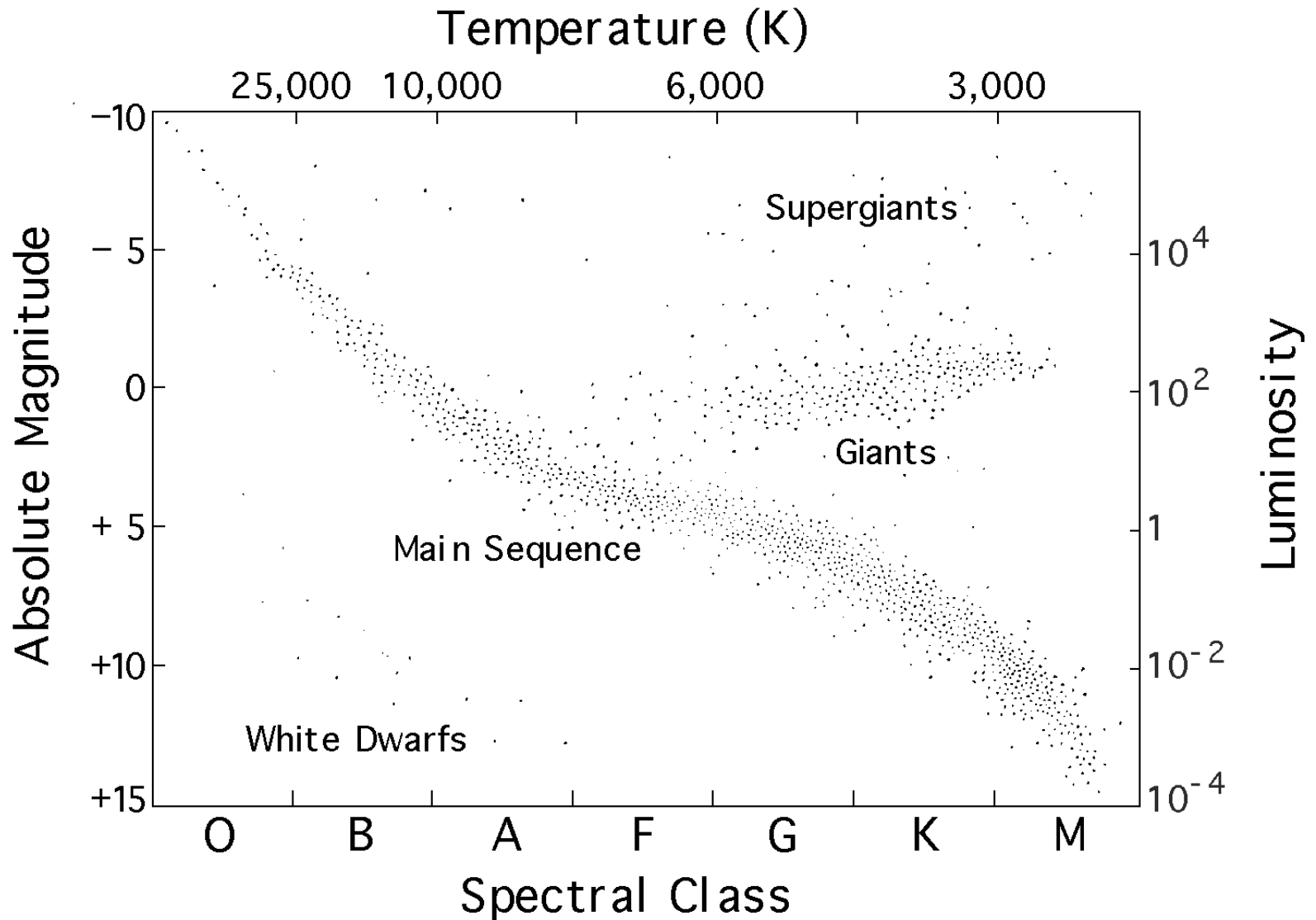


# Properties of Stars

- 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:

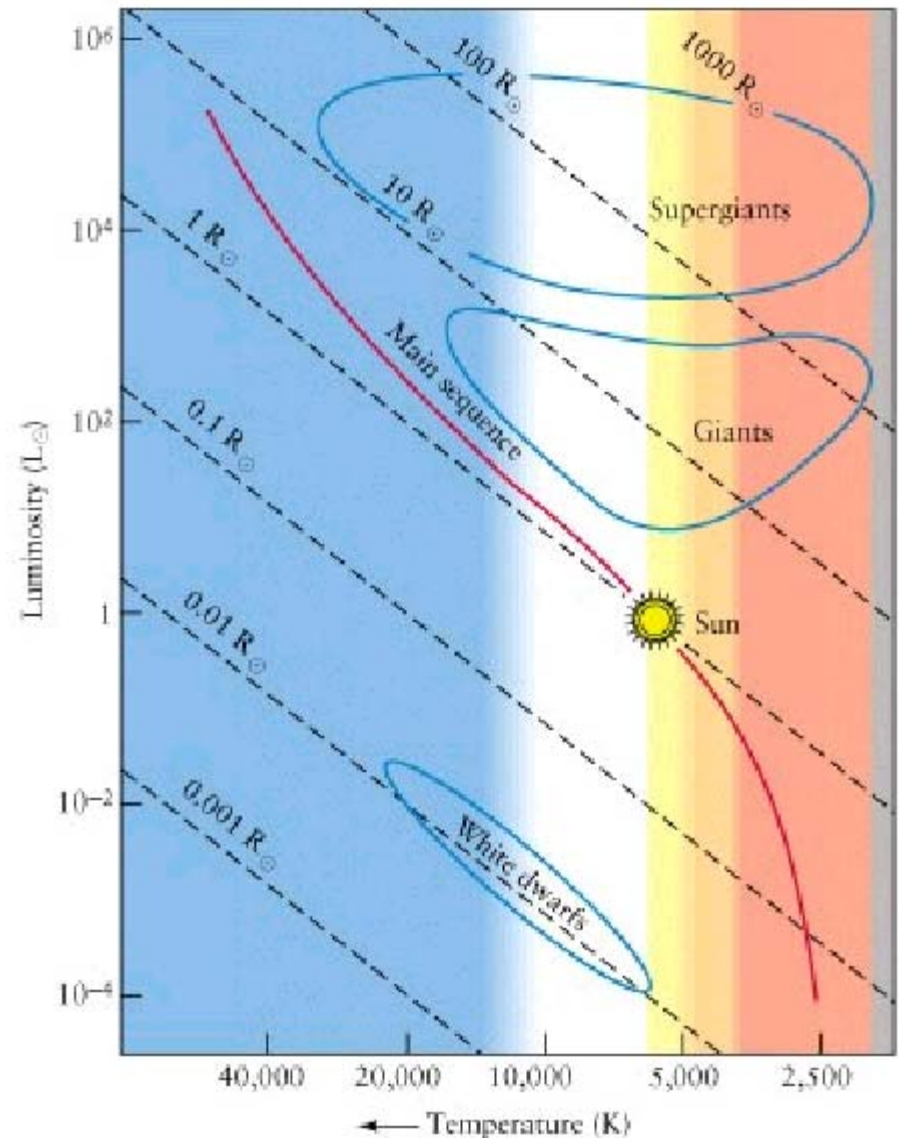
$$L = 4\pi R^2 \sigma T^4$$

# HR diagram

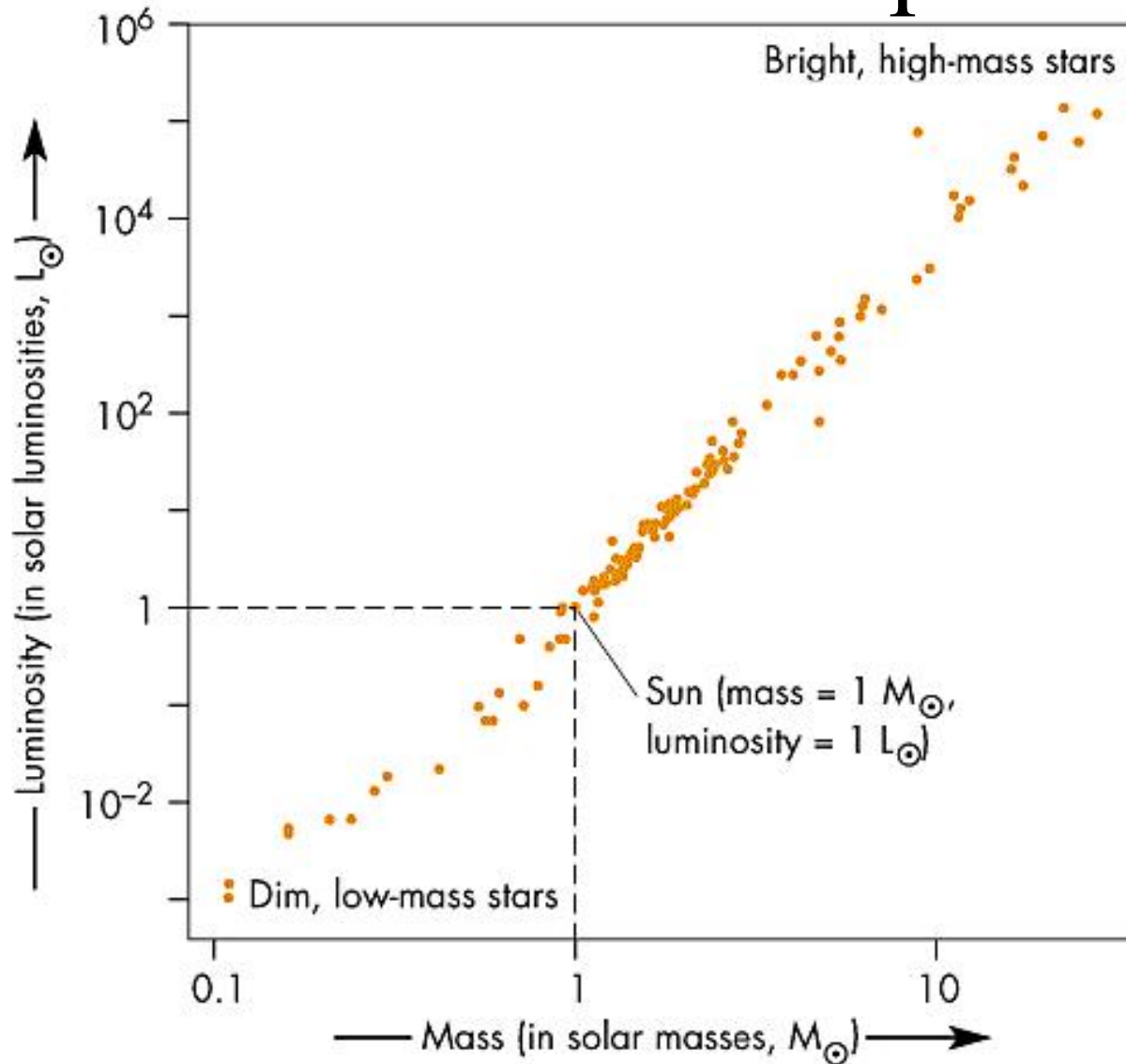


# Sizes of Stars on an HR Diagram

- 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.

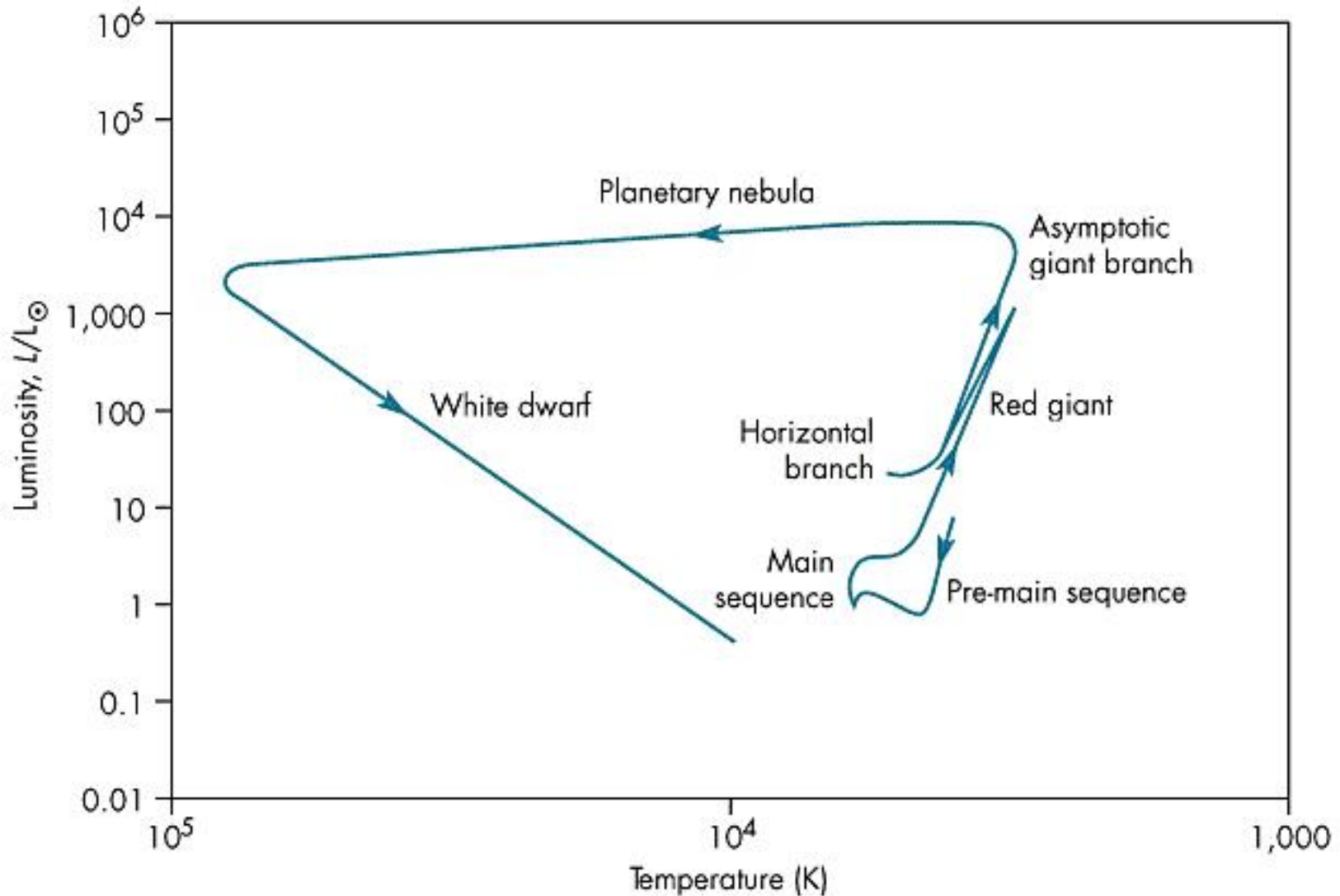


# Mass-Luminosity relation on the main sequence



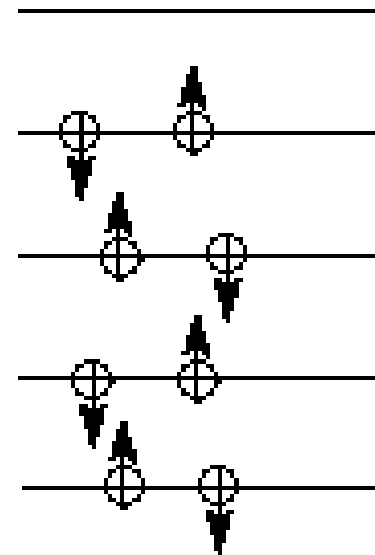
$$\frac{L}{L_{\odot}} \approx \left( \frac{M}{M_{\odot}} \right)^{3.5}$$

# Movement on HR diagram



# Normal versus degenerate gases

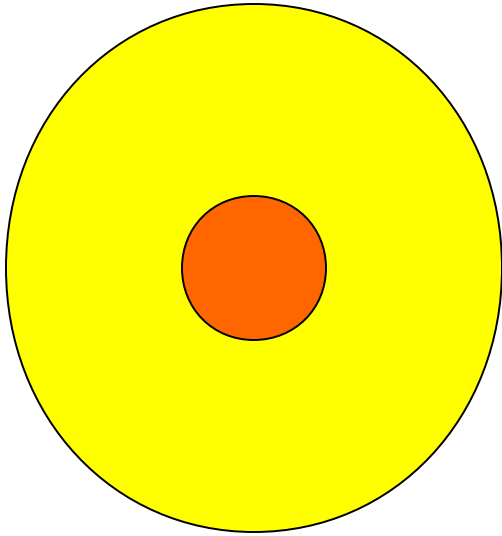
- Normal gas
  - Pressure is the force exerted by atoms in a gas
  - Temperature is how fast atoms in gas move
- Degenerate gas
  - Motion of atoms is not due to kinetic energy, but instead due to quantum mechanical motions – all the lower energy levels are filled due to Fermi exclusion
  - Pressure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



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

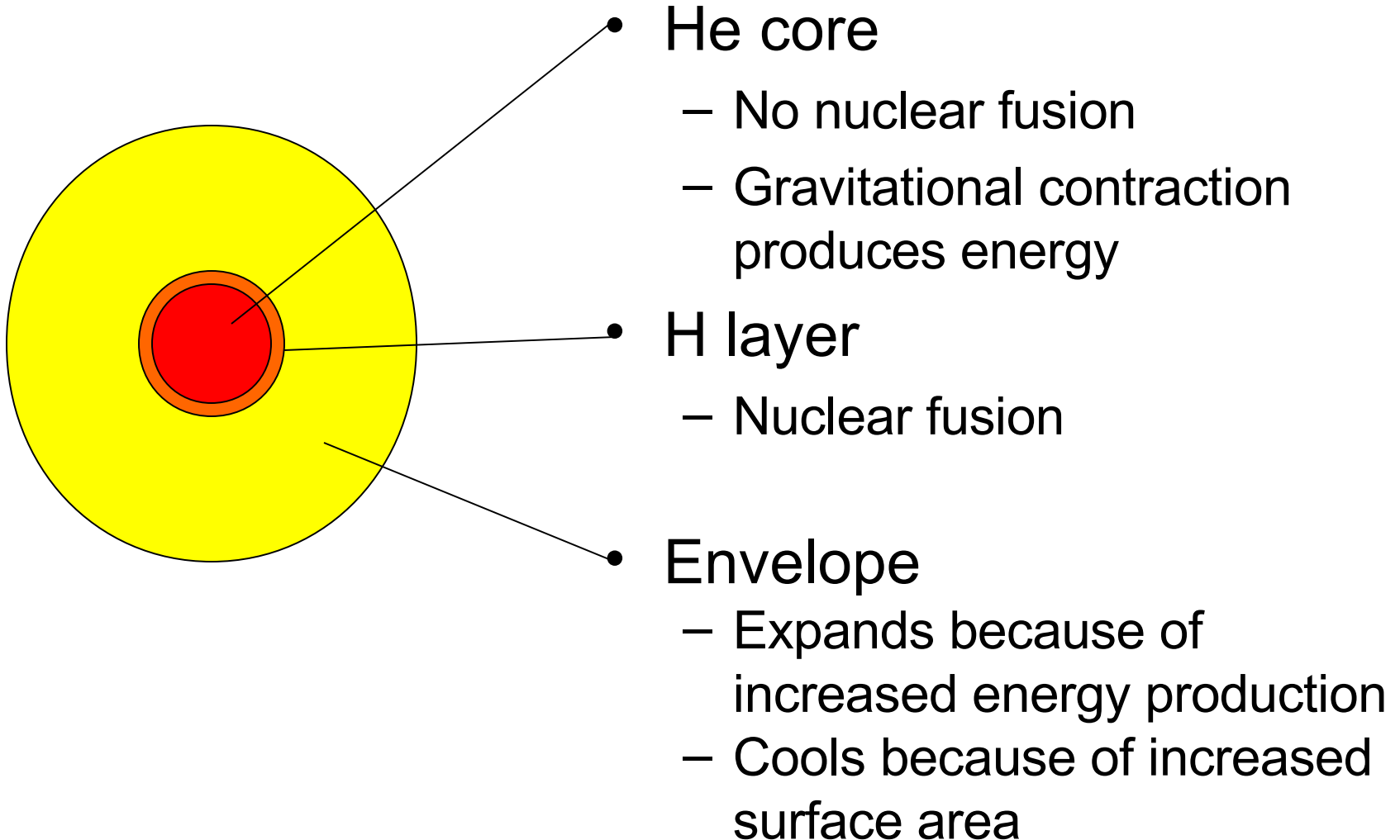


# Main Sequence Evolution

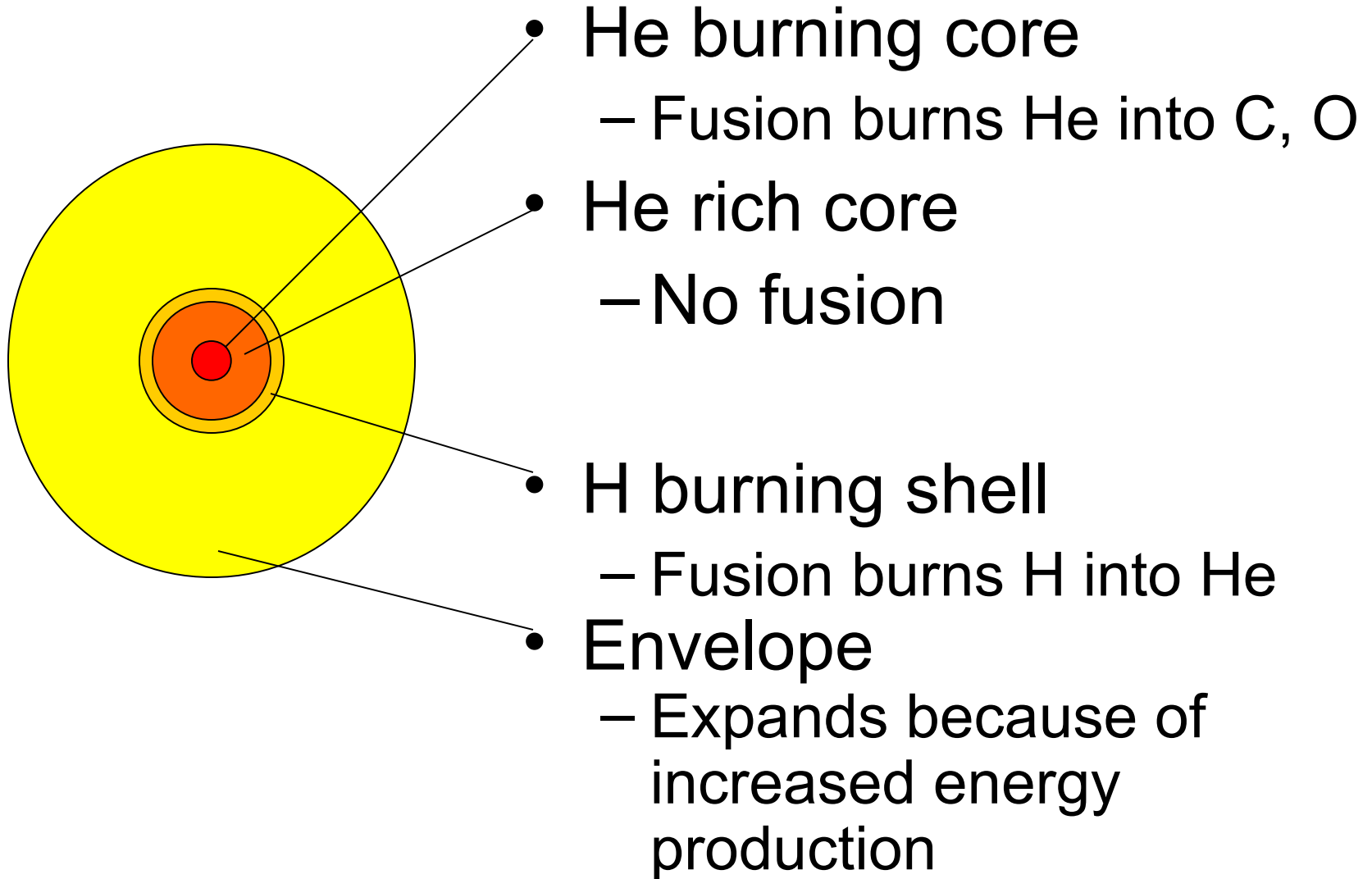


- Fusion changes  $H \rightarrow He$
- Core depletes of H
- Eventually there is not enough H to maintain energy generation in the core
- Core starts to collapse

# Red Giant Phase



# Red Giant after Helium Ignition



# Asymptotic Giant Branch

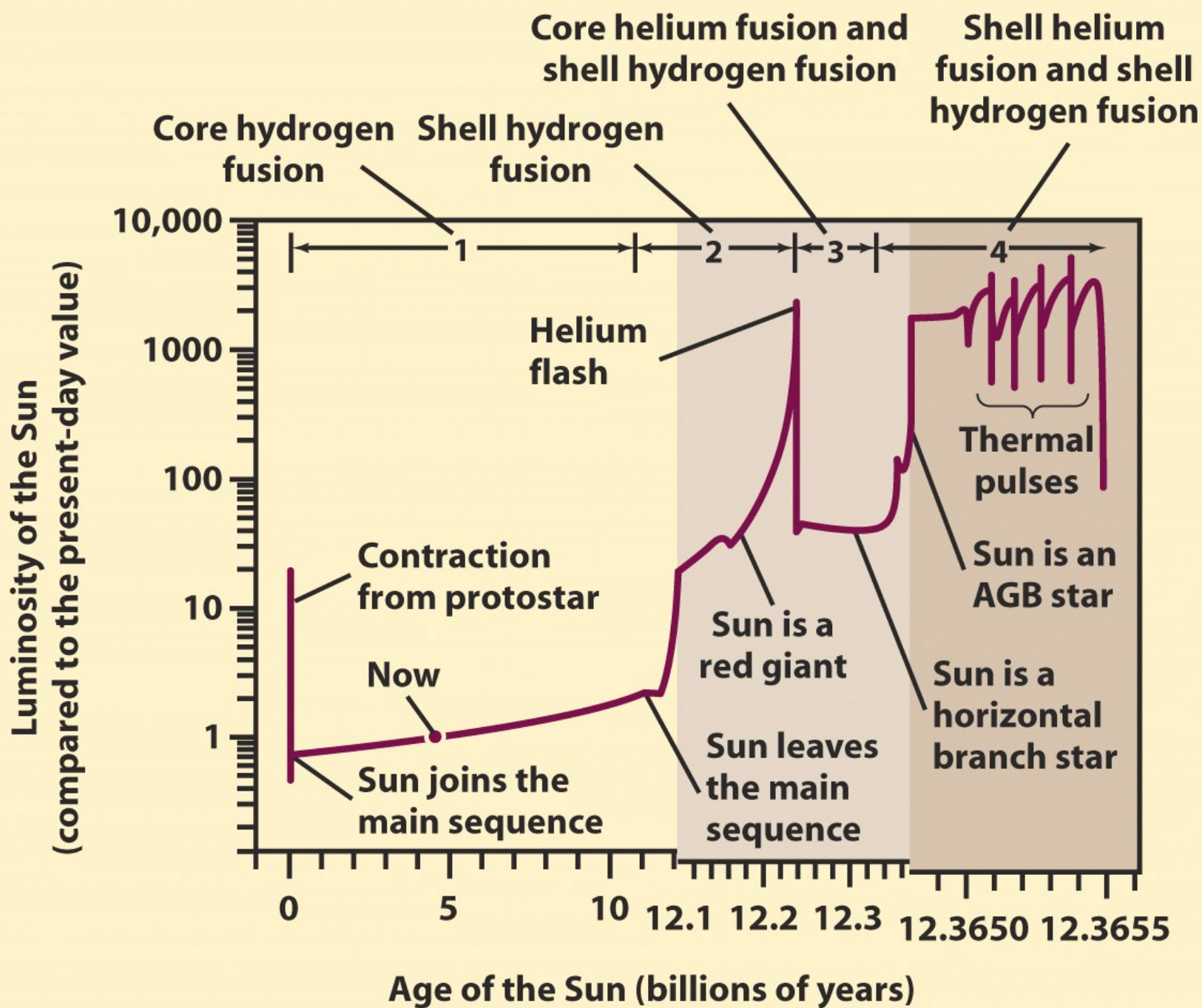
- Fusion in core stops, H and He fusion continues in shells
- Star moves onto Asymptotic Giant Branch (AGB) loses mass via winds
- Creates a “planetary nebula”
- Leaves behind core of carbon and oxygen surrounded by thin shell of hydrogen



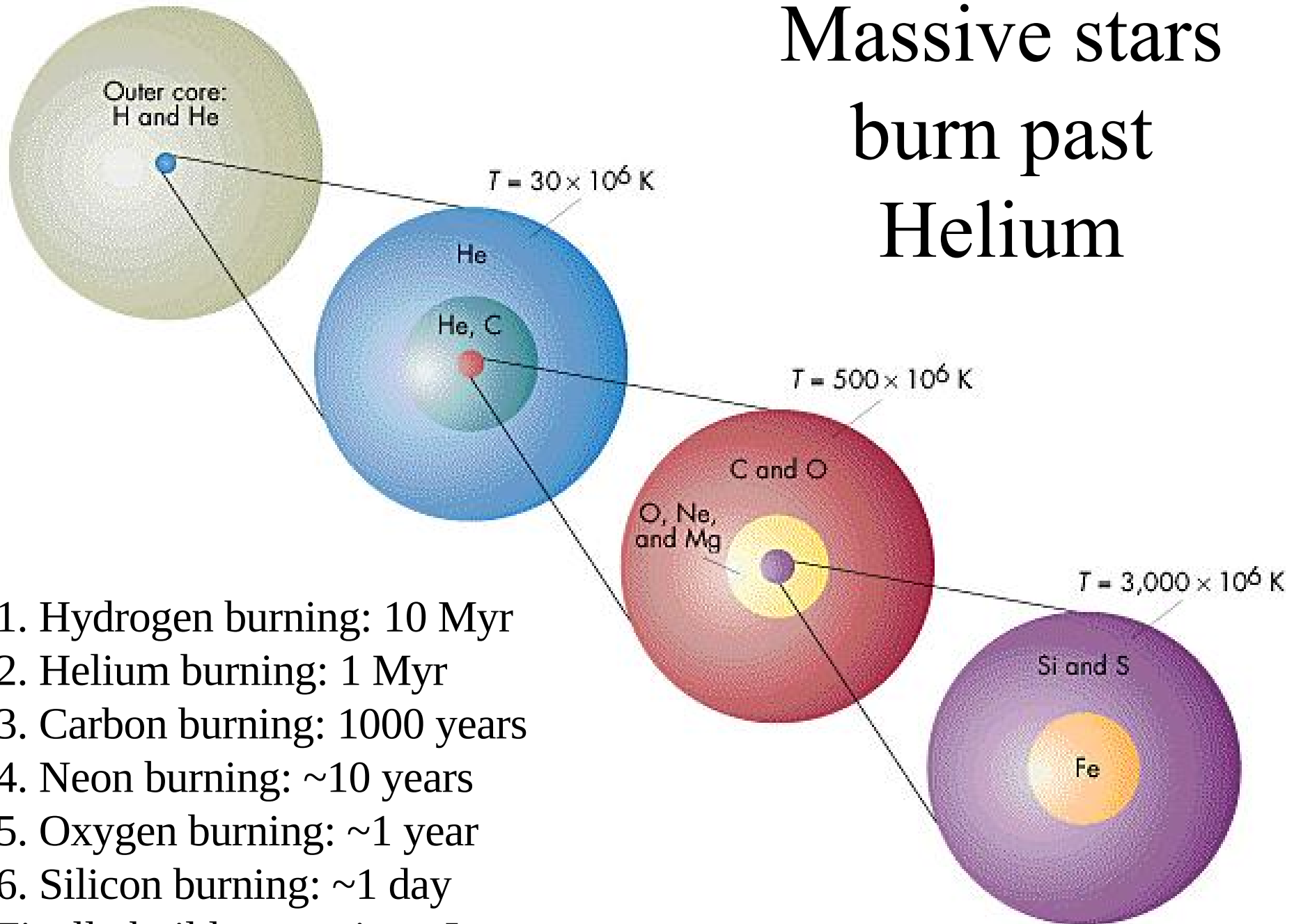
Hourglass  
nebula

# 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...



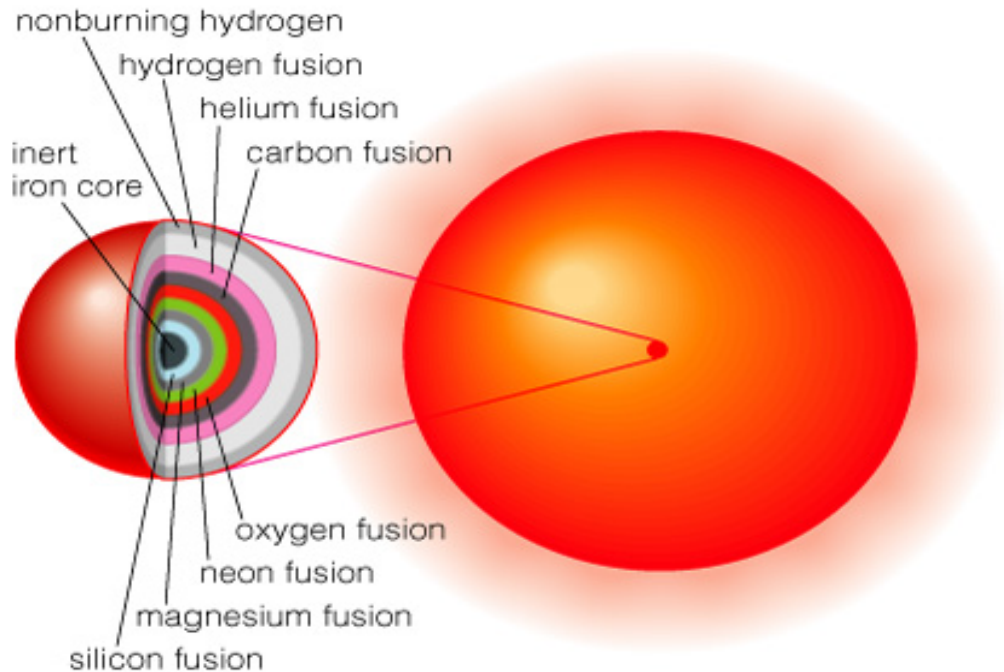
# Massive stars burn past Helium



1. Hydrogen burning: 10 Myr
  2. Helium burning: 1 Myr
  3. Carbon burning: 1000 years
  4. Neon burning:  $\sim 10$  years
  5. Oxygen burning:  $\sim 1$  year
  6. Silicon burning:  $\sim 1$  day
- Finally builds up an inert Iron core



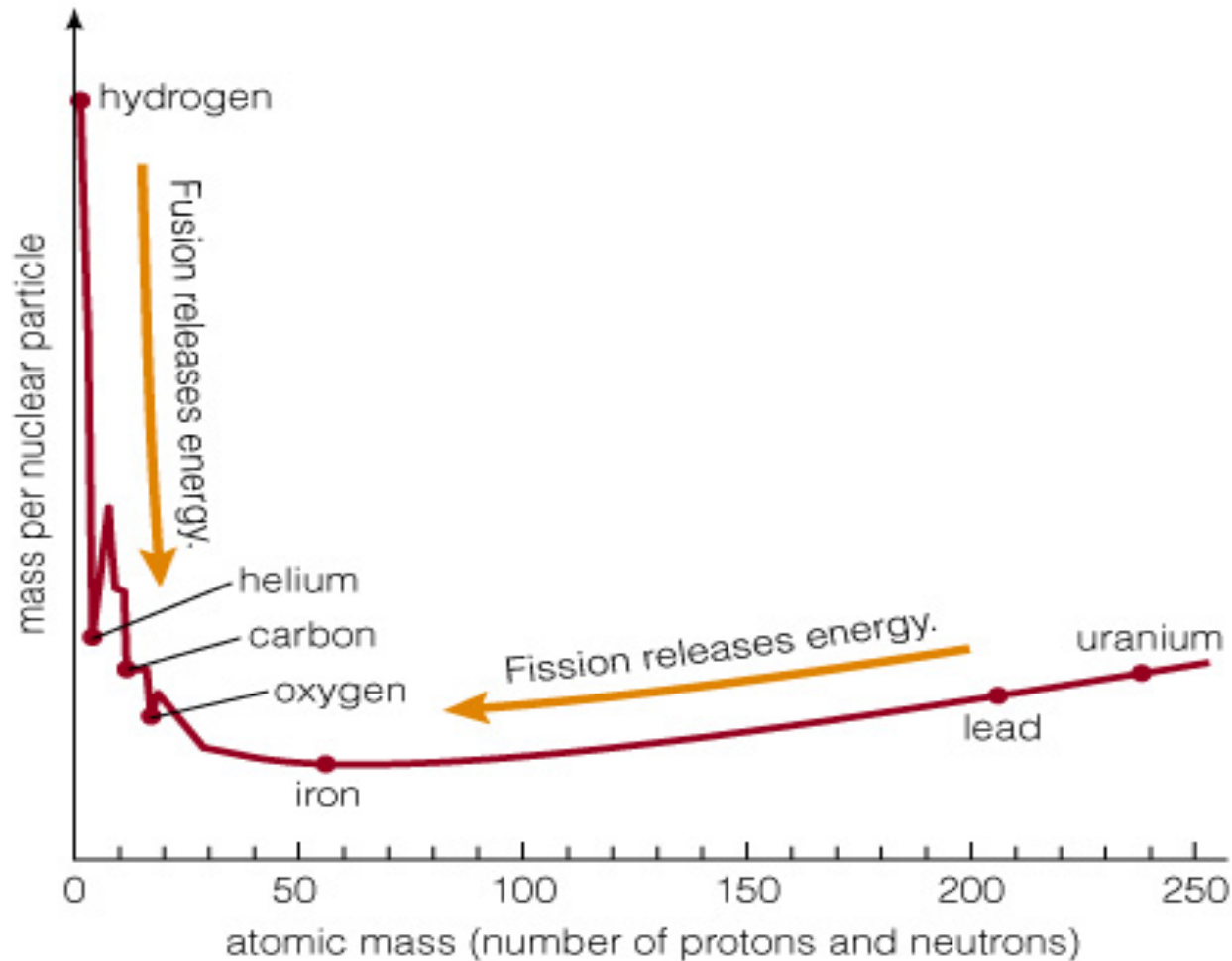
# Multiple Shell Burning



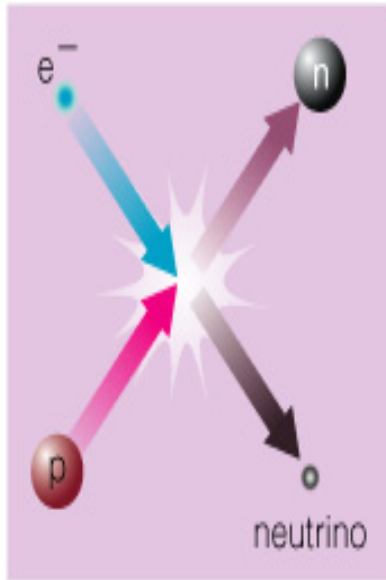
- Advanced nuclear burning proceeds in a series of nested shells



# Why does fusion stop at Iron?



# Supernova Explosion



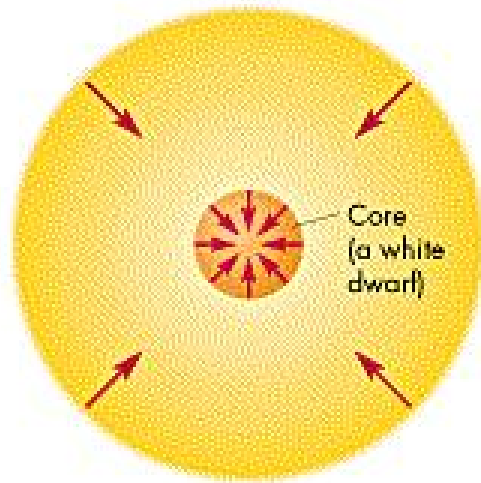
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- Core degeneracy pressure goes away because electrons combine with protons, making neutrons and neutrinos
- Neutrons collapse to the center, forming a **neutron star**

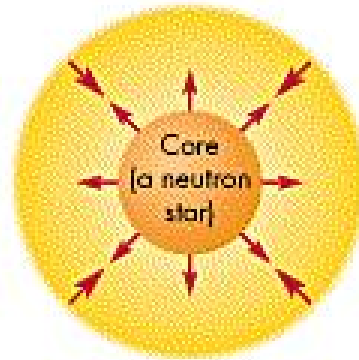
# Core collapse

- 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)

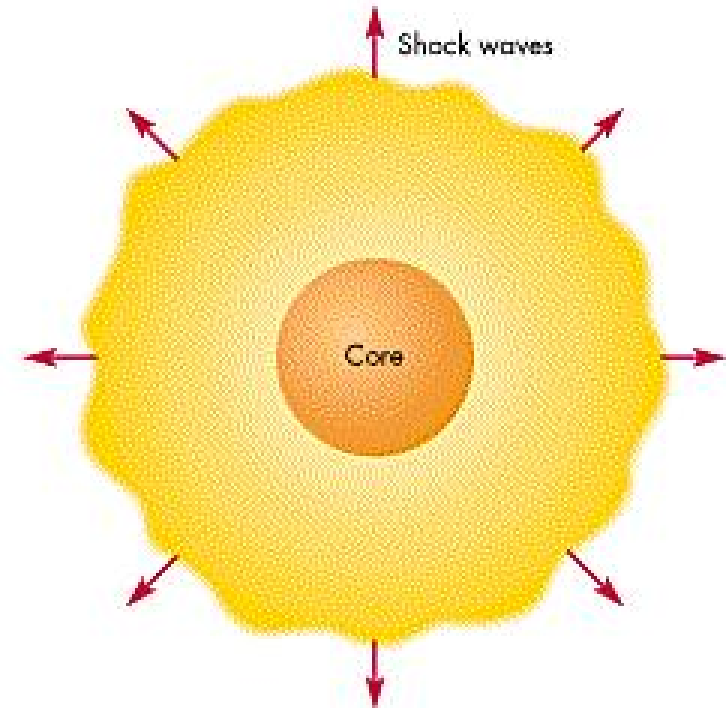
# Supernova explosion



**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

1 <b>H</b> Hydrogen 1.00794	2 <b>He</b> Helium 4.003																
3 <b>Li</b> Lithium 6.941	4 <b>Be</b> Beryllium 9.01218	5 <b>B</b> Boron 10.81	6 <b>C</b> Carbon 12.011	7 <b>N</b> Nitrogen 14.007	8 <b>O</b> Oxygen 15.999	9 <b>F</b> Fluorine 18.988	10 <b>Ne</b> Neon 20.179										
11 <b>Na</b> Sodium 22.990	12 <b>Mg</b> Magnesium 24.305	13 <b>Al</b> Aluminum 26.98	14 <b>Si</b> Silicon 28.086	15 <b>P</b> Phosphorus 30.974	16 <b>S</b> Sulfur 32.06	17 <b>Cl</b> Chlorine 35.453	18 <b>Ar</b> Argon 39.948										
19 <b>K</b> Potassium 39.098	20 <b>Ca</b> Calcium 40.08	21 <b>Sc</b> Scandium 44.956	22 <b>Ti</b> Titanium 47.88	23 <b>V</b> Vanadium 50.94	24 <b>Cr</b> Chromium 51.996	25 <b>Mn</b> Manganese 54.938	26 <b>Fe</b> Iron 55.847	27 <b>Co</b> Cobalt 58.9332	28 <b>Ni</b> Nickel 58.69	29 <b>Cu</b> Copper 63.546	30 <b>Zn</b> Zinc 65.39	31 <b>Ga</b> Gallium 69.72	32 <b>Ge</b> Germanium 72.59	33 <b>As</b> Arsenic 74.922	34 <b>Se</b> Selenium 78.96	35 <b>Br</b> Bromine 79.904	36 <b>Fr</b> Francium 83.80
37 <b>Rb</b> Rubidium 85.468	38 <b>Sr</b> Strontium 87.62	39 <b>Y</b> Yttrium 88.9059	40 <b>Zr</b> Zirconium 91.224	41 <b>Nb</b> Niobium 92.91	42 <b>Mo</b> Molybdenum 95.94	43 <b>Tc</b> Technetium (98)	44 <b>Ru</b> Ruthenium 101.07	45 <b>Rh</b> Rhodium 102.906	46 <b>Pd</b> Palladium 106.42	47 <b>Ag</b> Silver 107.8682	48 <b>Cd</b> Cadmium 112.41	49 <b>In</b> Indium 114.82	50 <b>Sn</b> Tin 118.71	51 <b>Sb</b> Antimony 121.75	52 <b>Te</b> Tellurium 127.60	53 <b>I</b> Iodine 126.905	54 <b>Xe</b> Xenon 131.29
55 <b>Cs</b> Cesium 132.91	56 <b>Ba</b> Barium 137.34	72 <b>Hf</b> Hafnium 178.49	73 <b>Ta</b> Tantalum 180.95	74 <b>W</b> Tungsten 183.85	75 <b>Re</b> Rhenium 186.207	76 <b>Os</b> Osmium 190.2	77 <b>Ir</b> Iridium 192.22	78 <b>Pt</b> Platinum 195.084	79 <b>Au</b> Gold 196.96657	80 <b>Hg</b> Mercury 200.59	81 <b>Tl</b> Thallium 204.383	82 <b>Pb</b> Lead 207.2	83 <b>Bi</b> Bismuth 208.98	84 <b>Po</b> Polonium (209)	85 <b>At</b> Astatine (210)	86 <b>Rn</b> Radon (222)	
87 <b>Fr</b> Francium (223)	88 <b>Ra</b> Radium 226.0254	104 <b>Rf</b> Rutherfordium (261)	105 <b>Db</b> Dubnium (262)	106 <b>Sg</b> Seaborgium (263)	107 <b>Bh</b> Bohrium (262)	108 <b>Hs</b> Hassium (265)	109 <b>Mt</b> Meitnerium (266)	110 <b>Uun</b> Ununnilium (269)	111 <b>Uuu</b> Unununium (272)	112 <b>Uub</b> Ununbium (277)							

**Key**

- 12 — Atomic number
- Mg** — Element's symbol
- Magnesium — Element's name
- 24.305 — Atomic mass\*

\*Atomic masses are fractions because they represent a weighted average of atomic masses of different isotopes—in proportion to the abundance of each isotope on Earth.

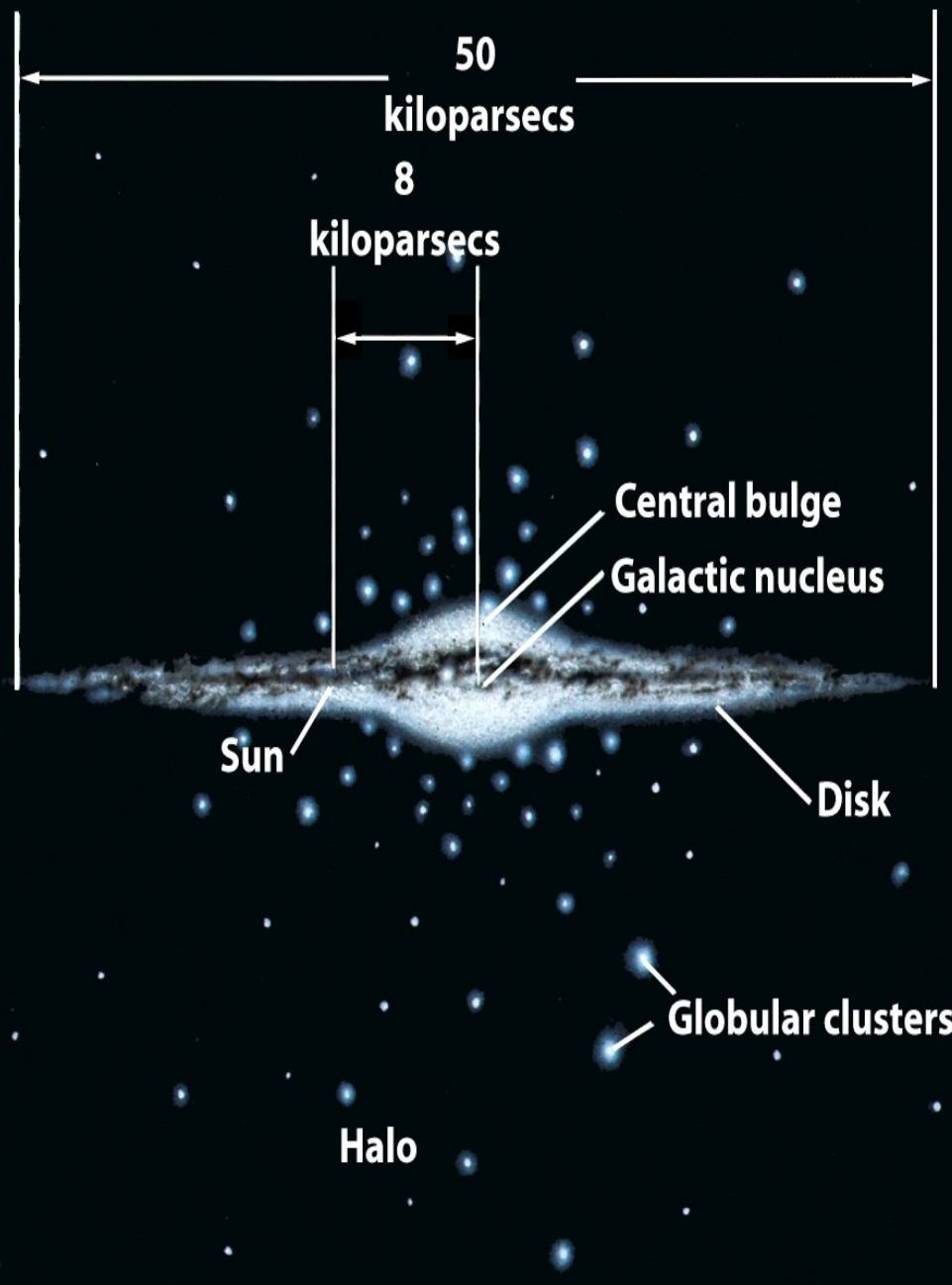
**Lanthanide Series**

57 <b>La</b> Lanthanum 138.906	58 <b>Ce</b> Cerium 140.12	59 <b>Pr</b> Praseodymium 140.908	60 <b>Nd</b> Neodymium 144.24	61 <b>Pm</b> Promethium (145)	62 <b>Sm</b> Samarium 150.36	63 <b>Eu</b> Europium 151.96	64 <b>Gd</b> Gadolinium 157.25	65 <b>Tb</b> Terbium 158.925	66 <b>Dy</b> Dysprosium 162.50	67 <b>Ho</b> Holmium 164.93	68 <b>Er</b> Erbium 167.26	69 <b>Tm</b> Thulium 168.934	70 <b>Yb</b> Ytterbium 173.04	71 <b>Lu</b> Lutetium 174.967
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**Actinide Series**

89 <b>Ac</b> Actinium 227.028	90 <b>Th</b> Thorium 232.038	91 <b>Pa</b> Protactinium 231.036	92 <b>U</b> Uranium 238.02891	93 <b>Np</b> Neptunium 237.048	94 <b>Pu</b> Plutonium (244)	95 <b>Am</b> Americium (243)	96 <b>Cm</b> Curium (247)	97 <b>Bk</b> Berkelium (247)	98 <b>Cf</b> Californium (251)	99 <b>Es</b> Einsteinium (252)	100 <b>Fm</b> Fermium (257)	101 <b>Md</b> Mendelevium (258)	102 <b>No</b> Nobelium (259)	103 <b>Lr</b> Lawrencium (260)
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Energy and neutrons released in supernova explosion enable elements heavier than iron to form, including Au and U



50  
kiloparsecs

8  
kiloparsecs

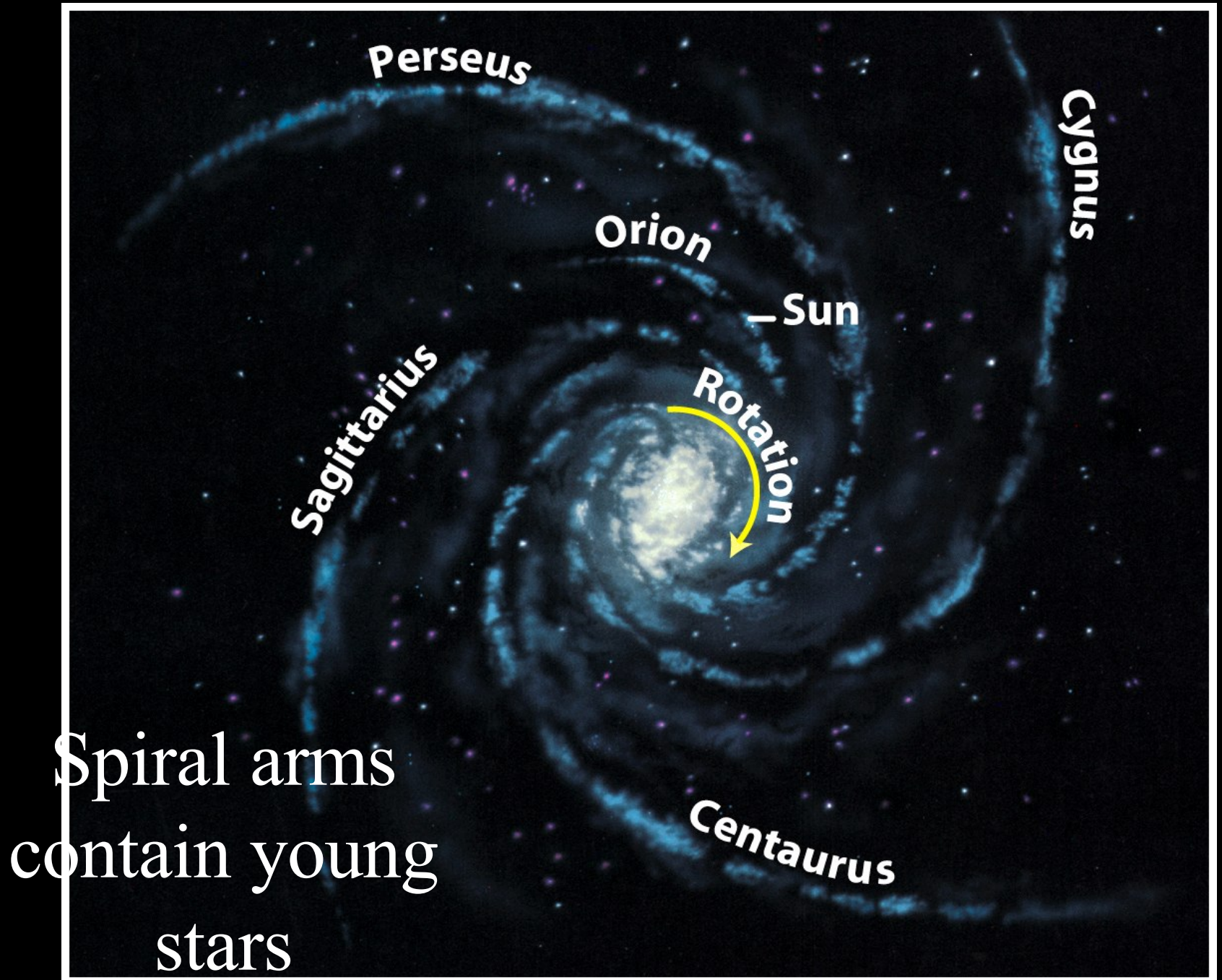
Central bulge  
Galactic nucleus

Sun

Disk

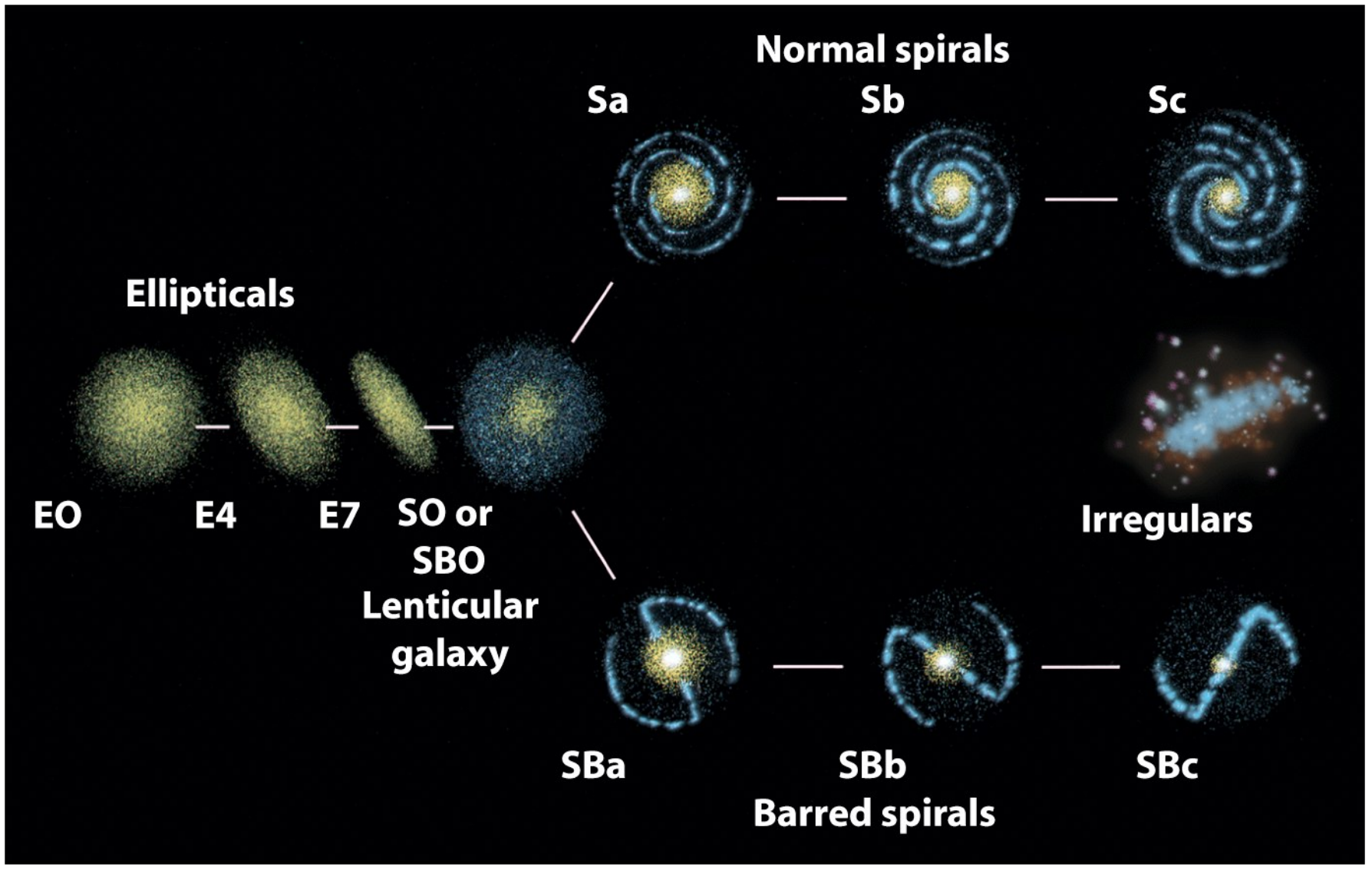
Globular clusters

Halo

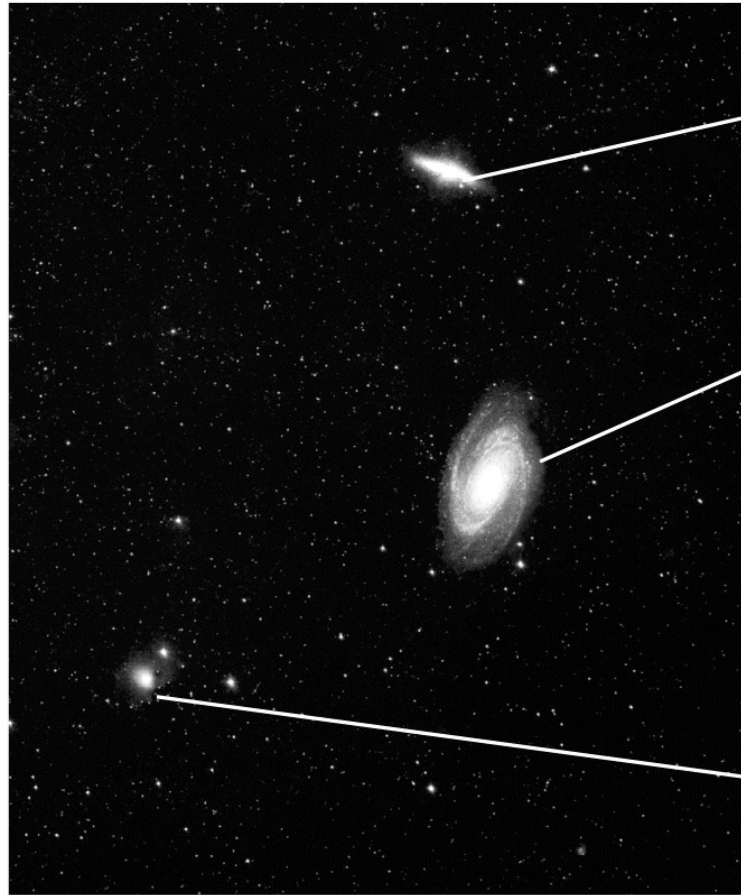




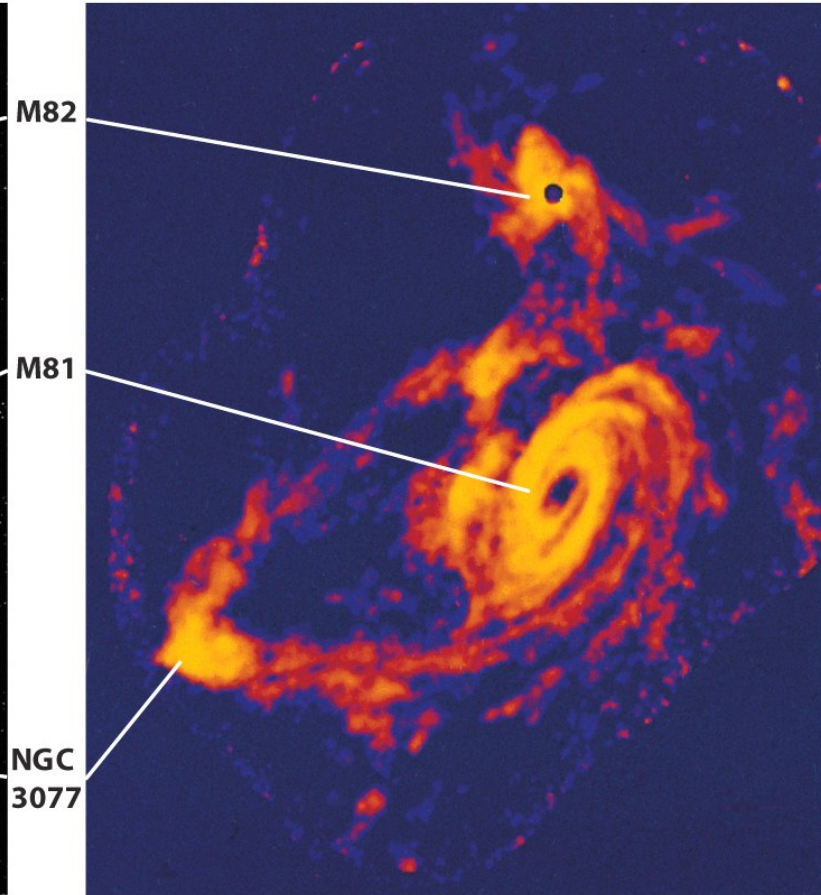
# Classifying Galaxies



# Interacting galaxies

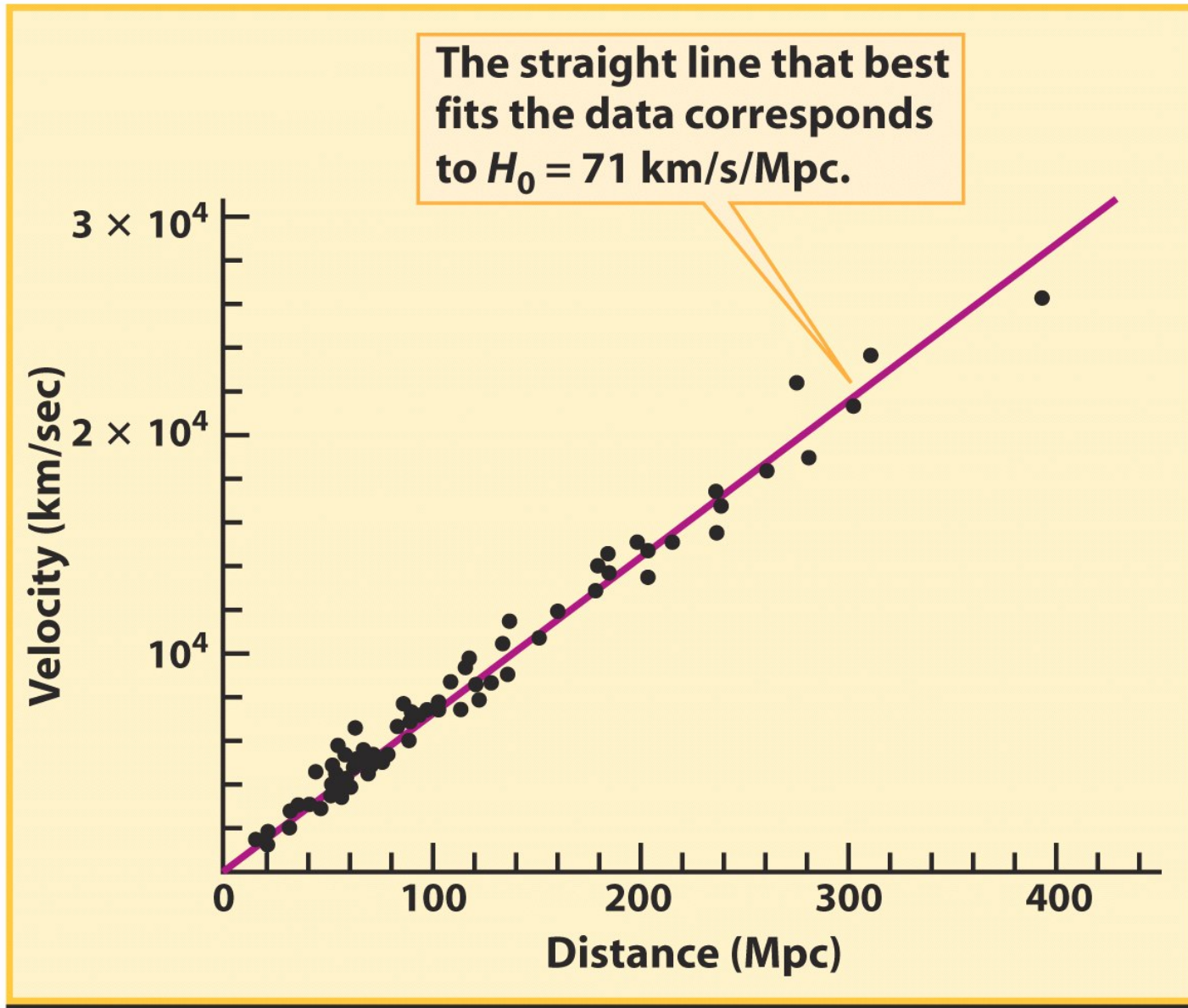


(a)

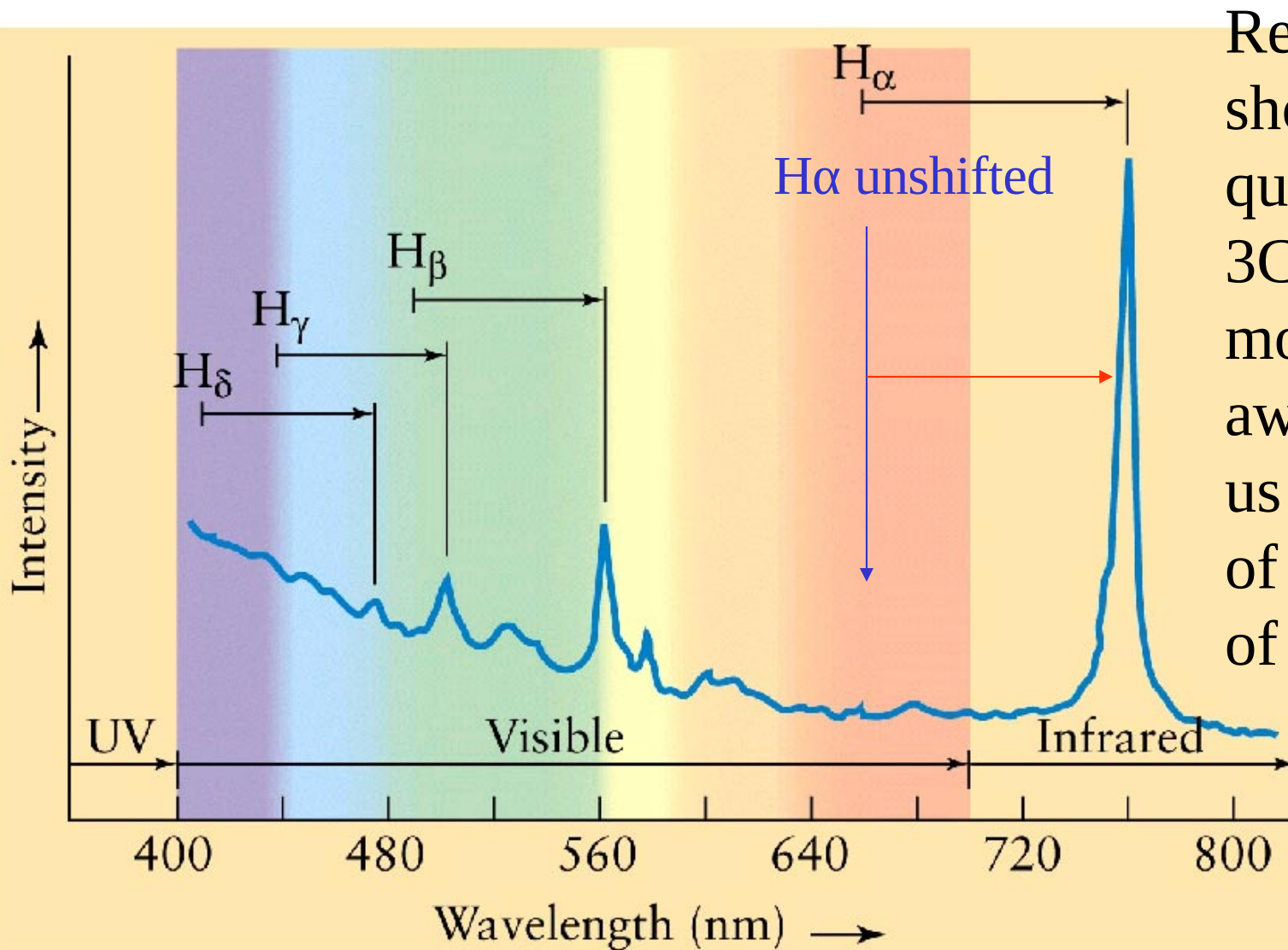


(b)

# Hubble expansion $v = H_0 d$

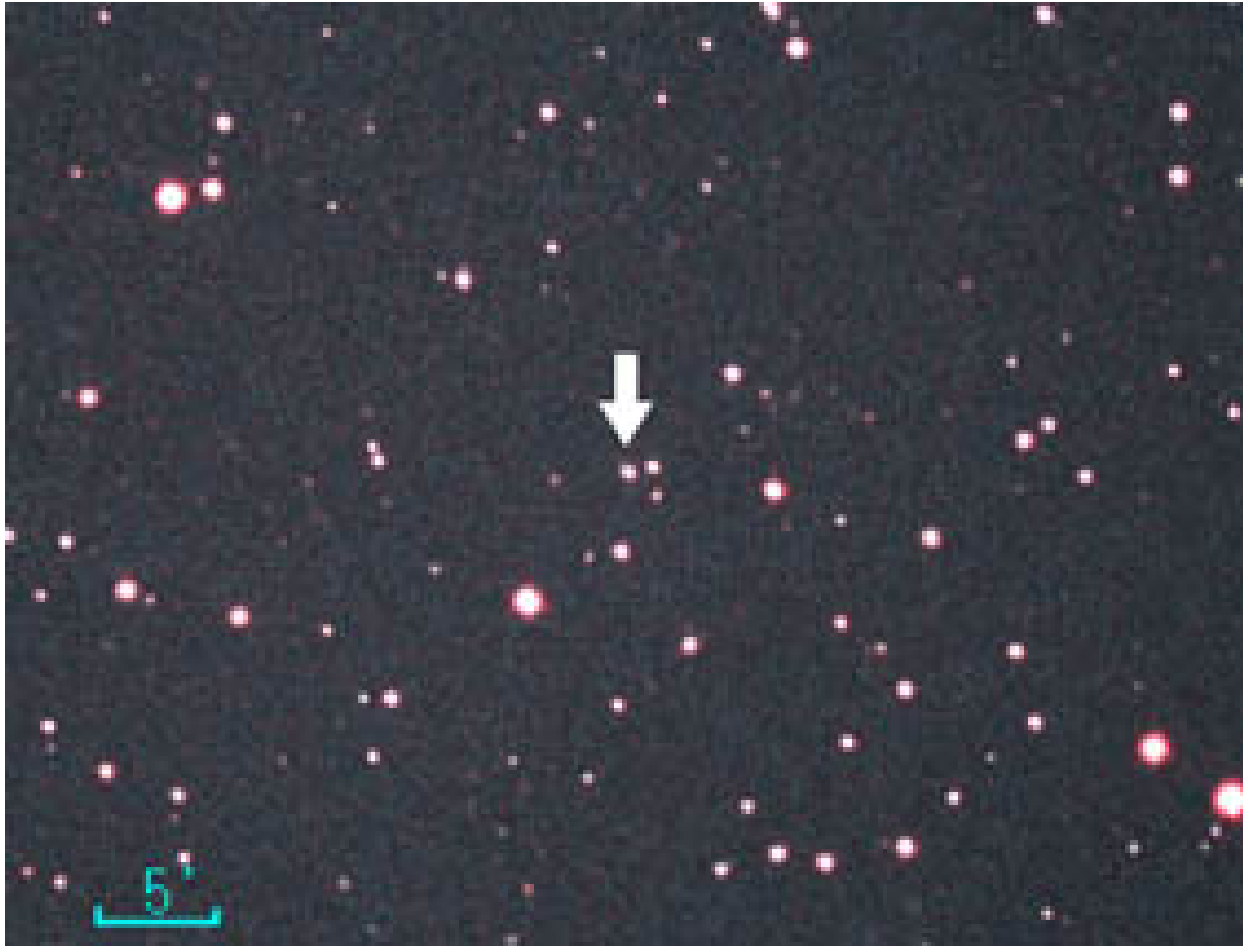


# Quasar optical spectrum



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

# 3C273

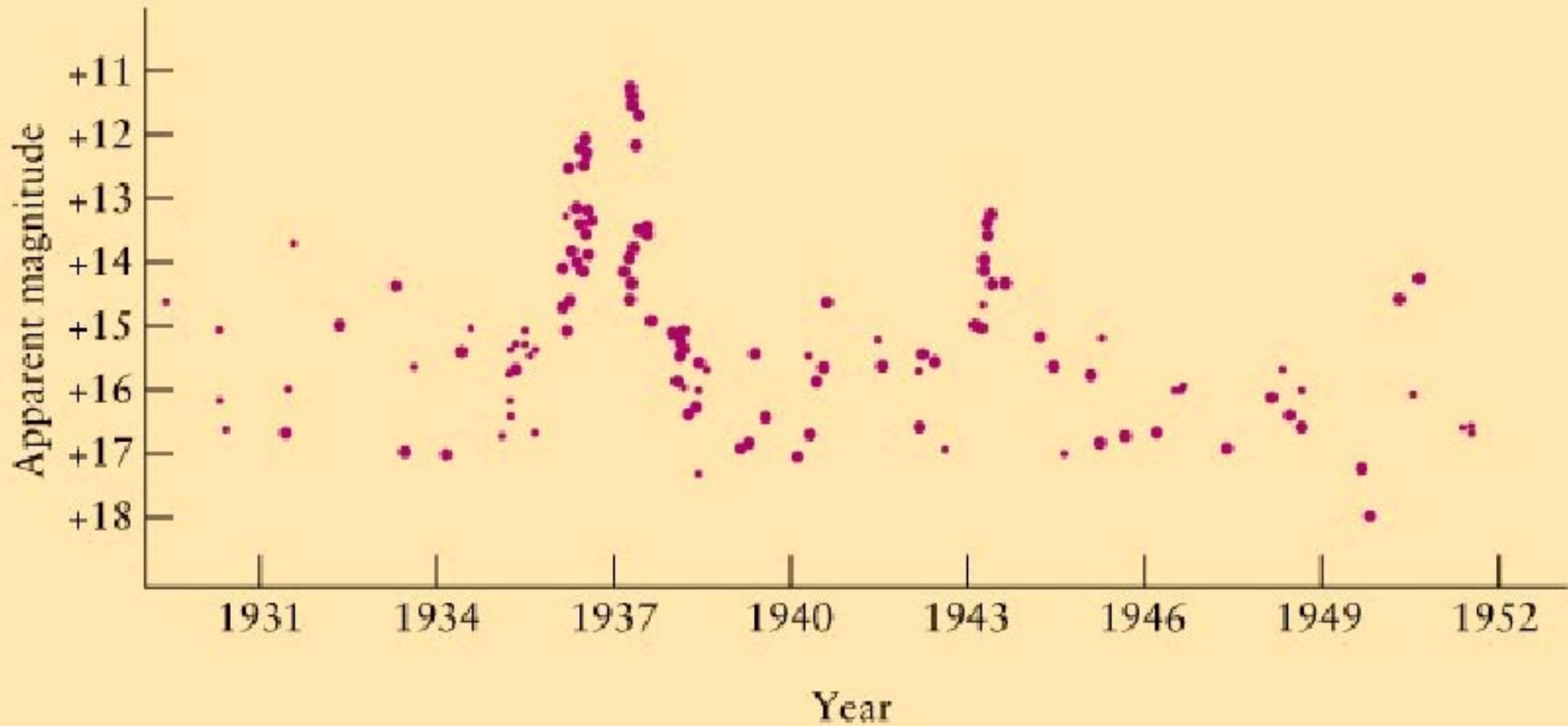


The quasar 3C273 is 2.6 billion light years away.

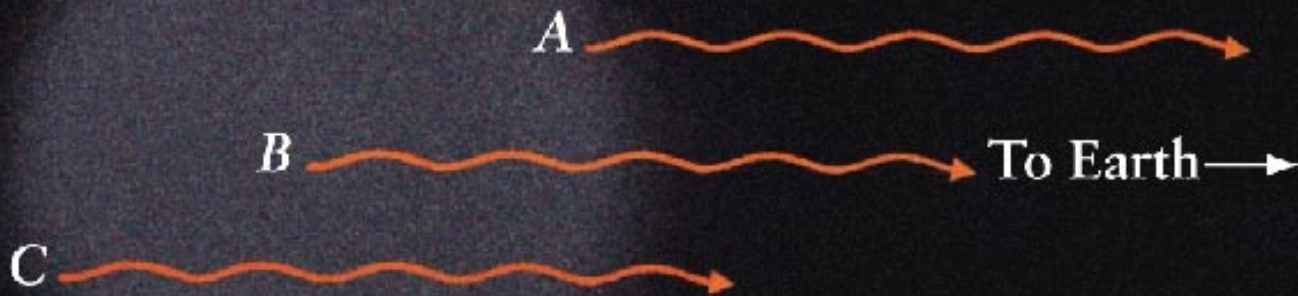
It looks dim, but must be extremely luminous to be visible as such distance.

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



← 1 ly →

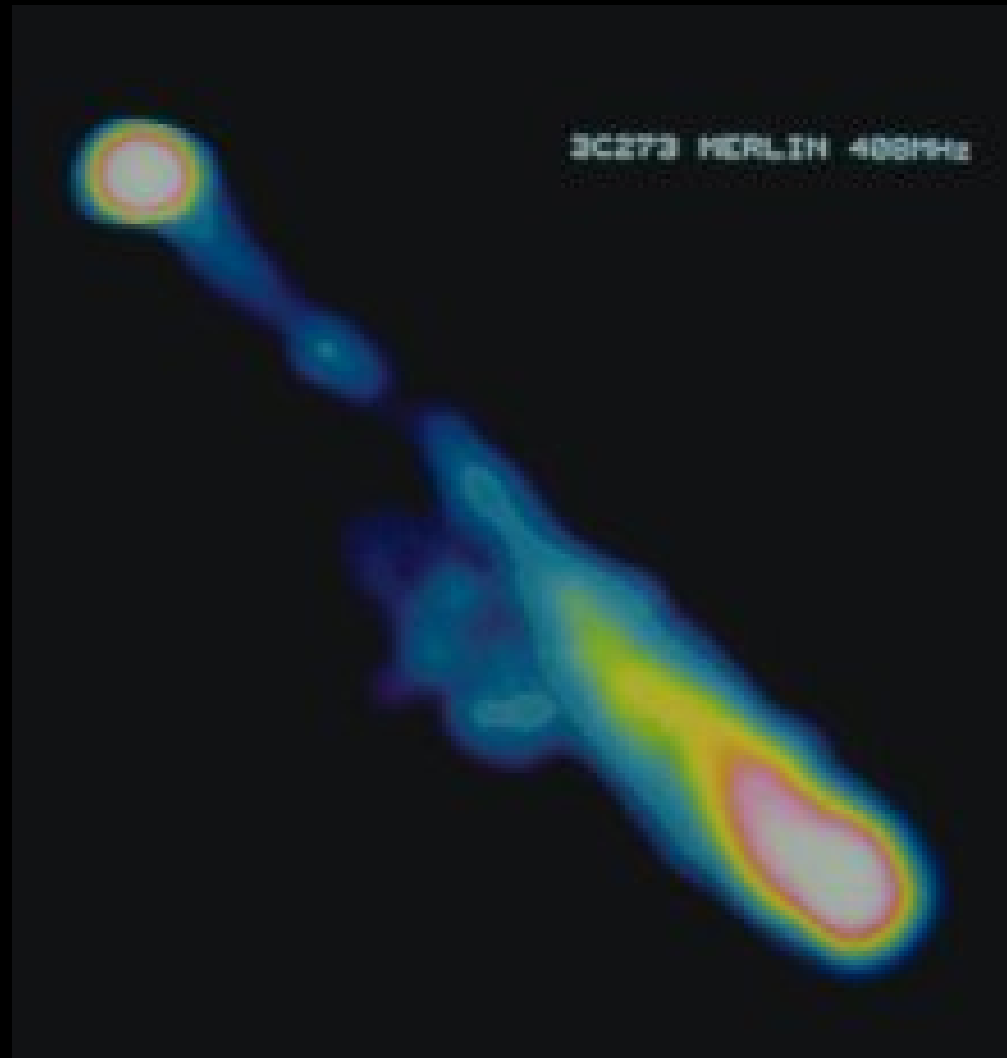
Size places a limit on how fast an object can change brightness.

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

# Quasar jets

Optical core →

Radio jet →

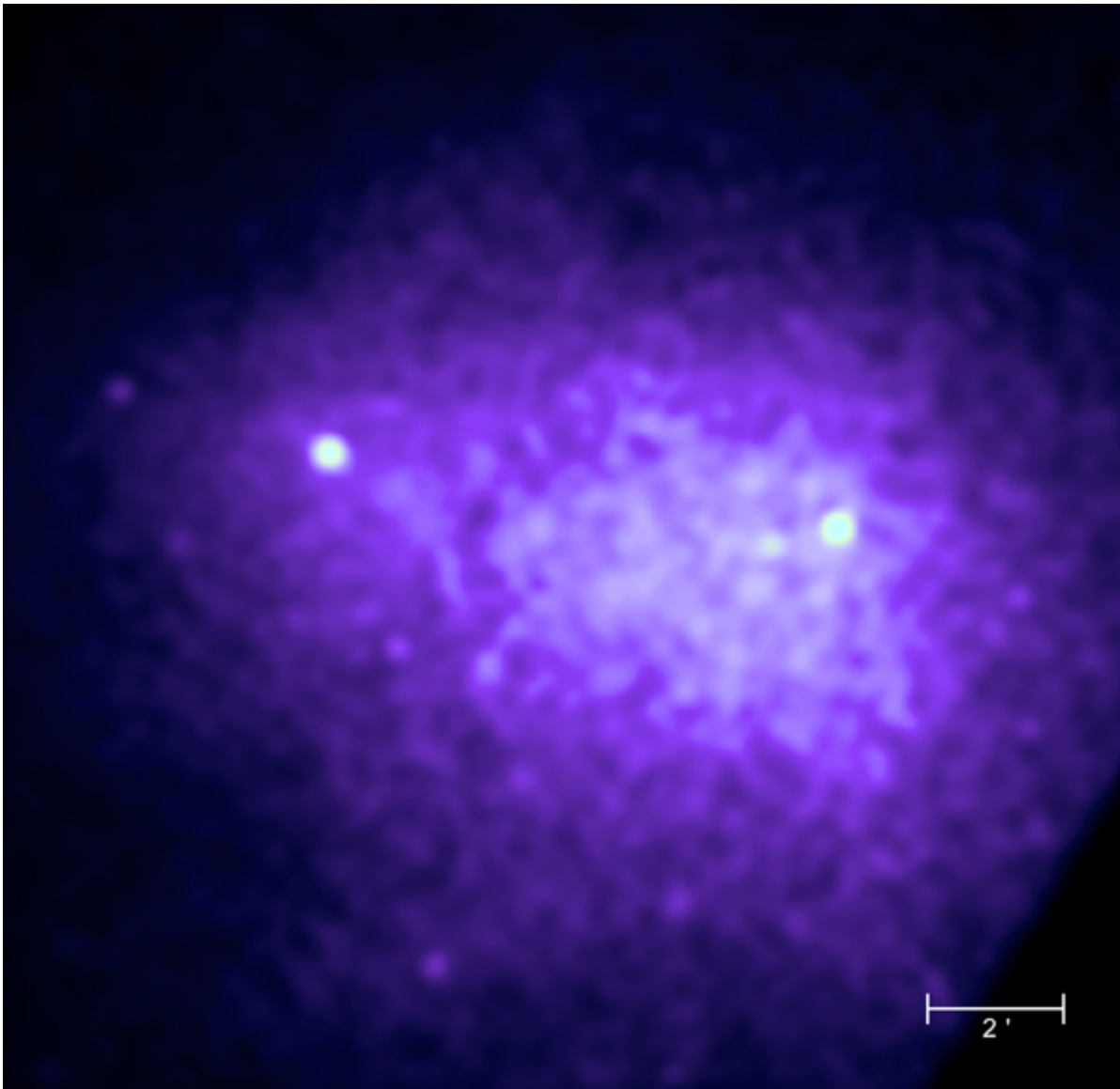






Coma  
cluster  
of  
galaxies

# 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.