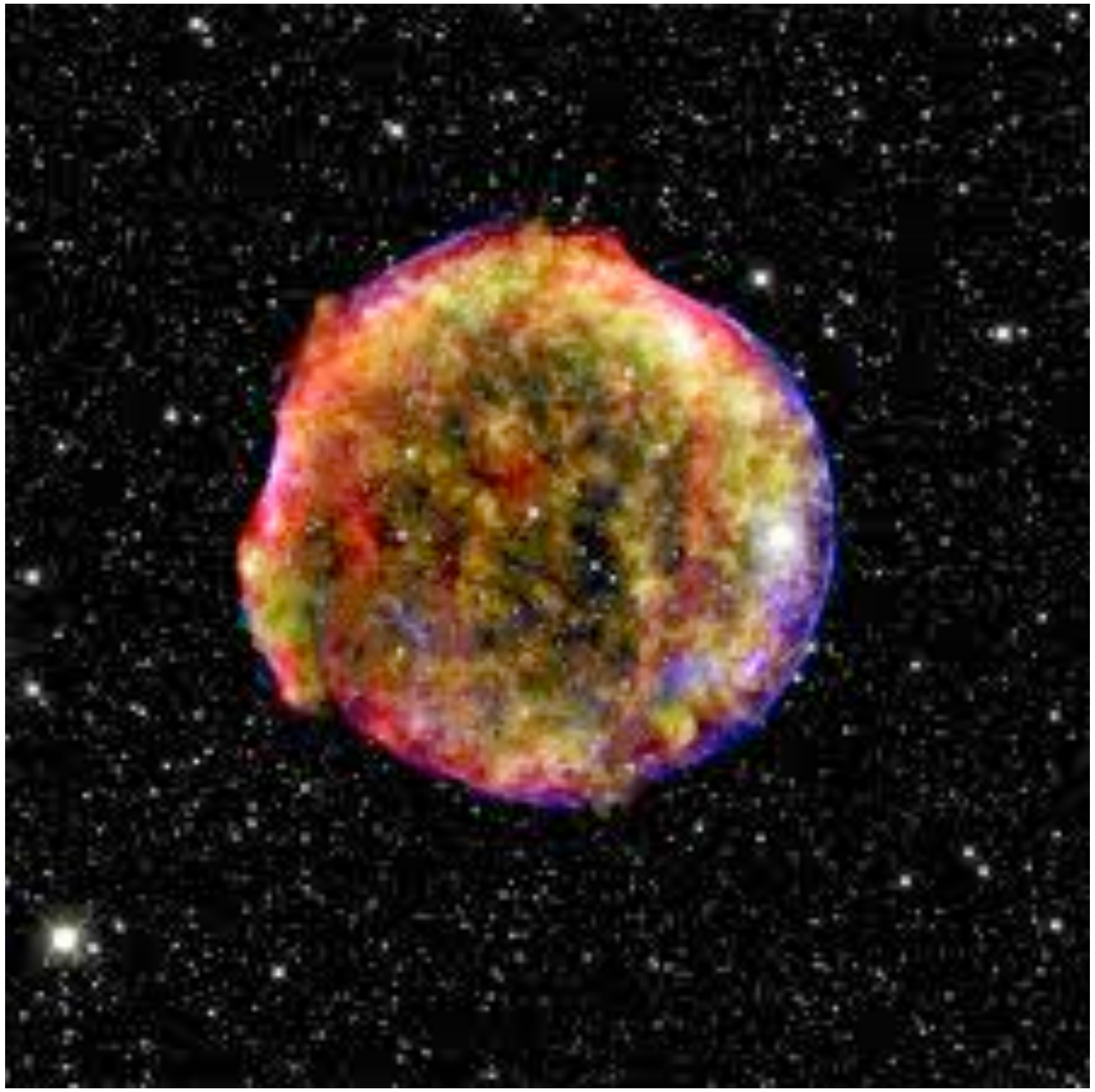
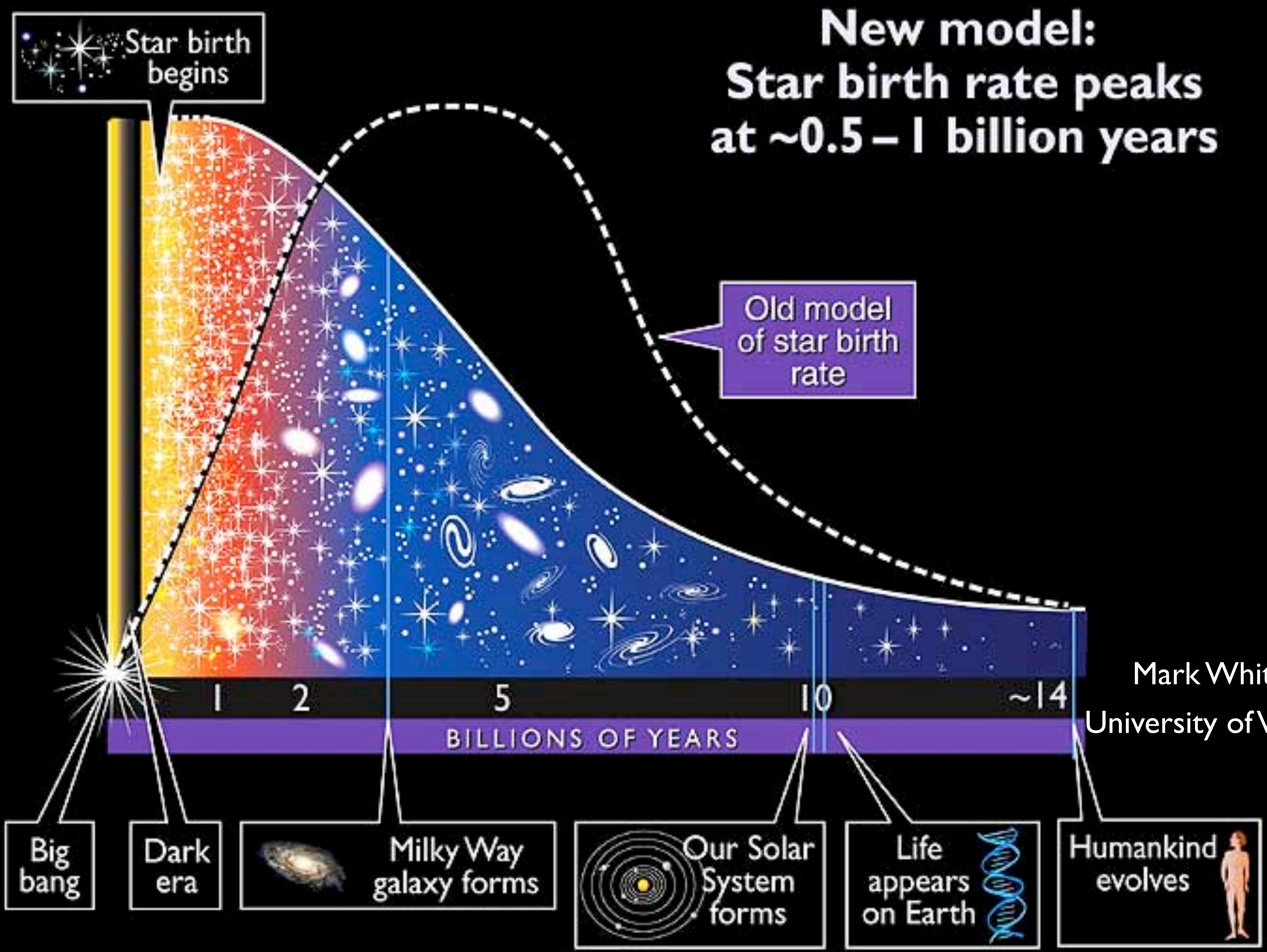
Lecture 7: "Basics of Star Formation and Stellar Nucleosynthesis"

"We've discovered a massive dust and gas cloud which is either the beginning of a new star, or just an awful lot of dust and gas."



Outline

1. Formation of elements in stars
2. Injection of new elements into ISM
3. Phases of star-formation
4. Evolution of stars



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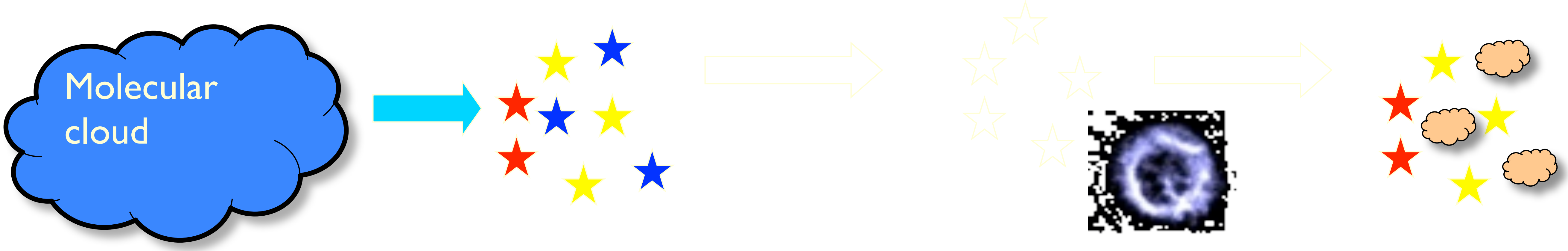
University of Virginia

Life Cycle of Matter in Milky Way

Molecular clouds
gravitationally collapse
to form stellar clusters of stars

New clouds with
heavier composition
are formed



Stars synthesize
He, C, Si, Fe via
nucleosynthesis

Most massive stars evolve
quickly and die as supernovae –
heavier elements are
injected in space

Solar abundances

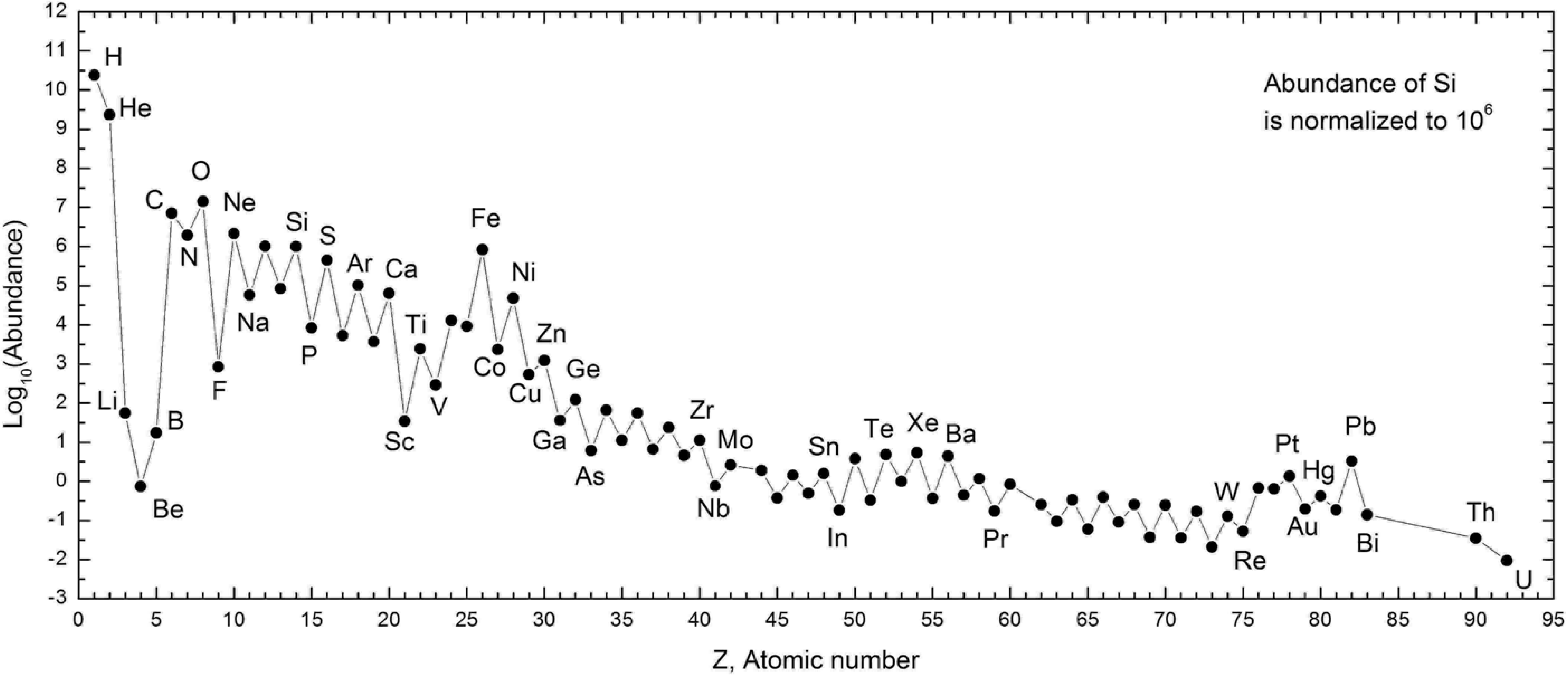
- Observation of atomic absorption lines in the solar spectrum

- For some (heavy) elements meteoritic data are used

Solar abundance pattern:

- Regularities reflect nuclear properties
- Several different processes
- Mixture of material from many, many stars

Solar abundances: key facts



- Decrease in abundance with atomic number:
  - Large negative anomaly at Be, B, Li
  - Moderate positive anomaly around Fe
  - Sawtooth pattern from odd-even effect

Origin of elements

- The Big Bang: H, D, ^{3,4}He, Li
- All other nuclei were synthesized in stars
- Stellar nucleosynthesis ⇔ 3 key processes:
  - Nuclear fusion: PP cycles, CNO bi-cycle, He burning, C burning, O burning, Si burning ⇒ till ^{40}Ca
  - Photodisintegration rearrangement: Intense gamma-ray radiation drives nuclear rearrangement ⇒ ^{56}Fe
  - Most nuclei heavier than ^{56}Fe are due to neutron capture:
    - s-process, in which neutron addition is slow compared to β-decay
    - r-process, in which neutron addition is rapid compared to β-decay

Nuclear Reactions

$$ {}^{A1}_{Z1}X + {}^{A2}_{Z2}Y \Rightarrow {}^{A3}_{Z3}A + {}^{A4}_{Z4}B $$

$$\text{Conservation laws: } \begin{cases} A1 + A2 = A3 + A4 & \text{(mass numbers)} \\ Z1 + Z2 = Z3 + Z4 & \text{(atomic numbers)} \end{cases}$$

Amount of energy liberated in a nuclear reaction (Q-value):

$$Q = [\underbrace{(m_1 + m_2)}_{\text{initial}} - \underbrace{(m_3 + m_4)}_{\text{final}}]c^2$$

Q > 0: exothermic process (release of energy)
Q < 0: endothermic process (absorption of energy)

Hydrogen Burning

- Coulomb repulsion vs proton wavefunction tunneling

- No efficent two-particle reactions in H & He matter:

  $^{1}H + {}^{1}H = {}^{2}He$ (unstable) $= {}^{1}H + {}^{1}H$

  $^{1}H + {}^{4}He = {}^{5}Li$ (unstable) $= {}^{1}H + {}^{4}He$

  $^{4}He + {}^{4}He = {}^{8}Be$ (unstable) $= {}^{4}He + {}^{4}He$

- Hans Bethe (1939): hydrogen burning via formation of D:

  $^{1}H + {}^{1}H = {}^{2}D + \beta^{+} + \nu + 1.442$ MeV

Hydrogen Burning

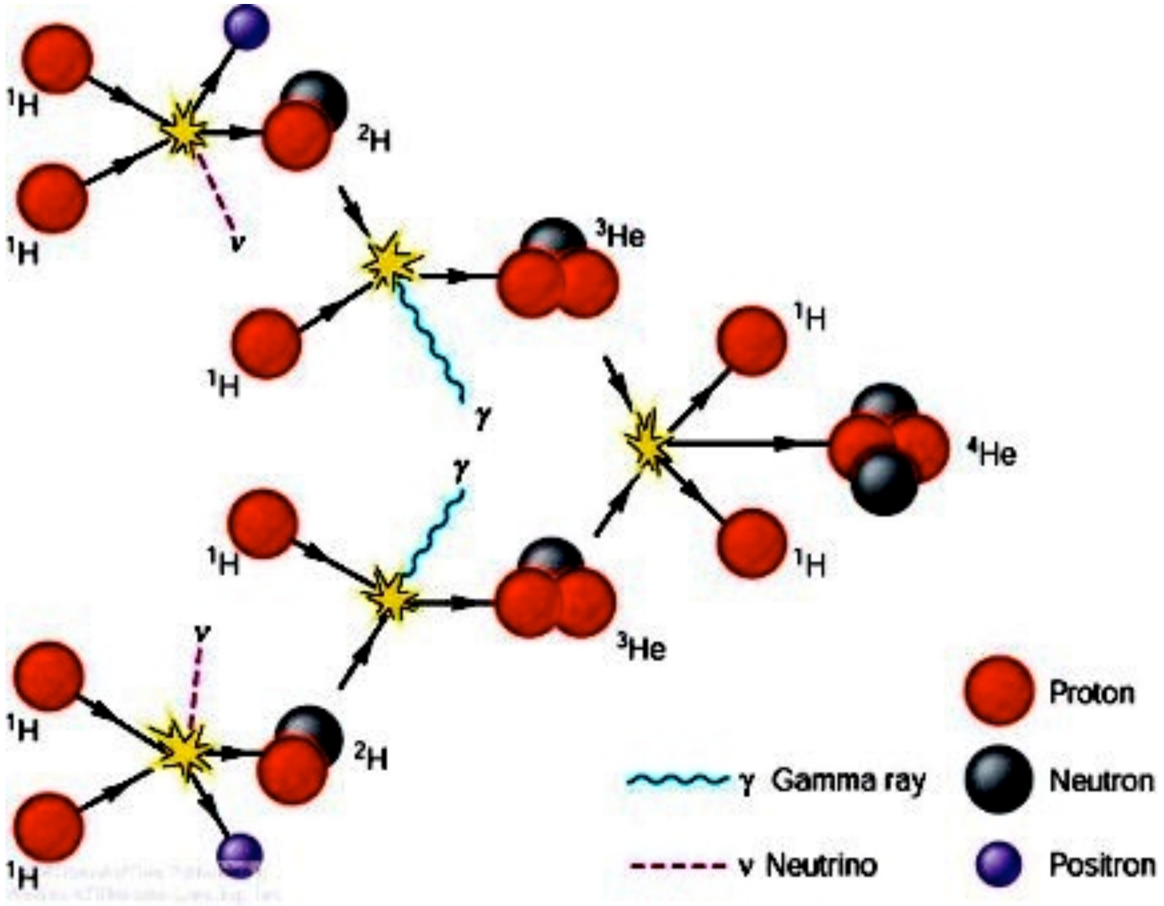
- PP-I cycle, $T > 4 \times 10^6$ K: $4\ {}^1H \Rightarrow {}^4He$:

  $2\ ({}^1H + {}^1H = {}^2D + \beta^+ + \nu_e + 0.42\ \mathrm{MeV})$

  $(\beta^+ + \beta^- = \gamma + 1.02\ \mathrm{MeV})$

  $2\ ({}^1H + {}^2D = {}^3He + \gamma + 5.49\ \mathrm{MeV})$

  ${}^3He + {}^3He = {}^4He + 2\ {}^1H + 12.86\ \mathrm{MeV}$



- PP-II cycle, $T > 14 \times 10^6$ K:

  ${}^3He + {}^4He = {}^7Be + \gamma$

  ${}^7Be + \beta^- = {}^7Li + \nu_e$

  ${}^7Li + {}^1H = 2\ {}^4He$

- In the Sun, PP-I = 86 %, PP-II = 14 %

The Solar Neutrino Problem

- Neutrinos can penetrate huge amounts of material without being absorbed ⇒ study solar interior!

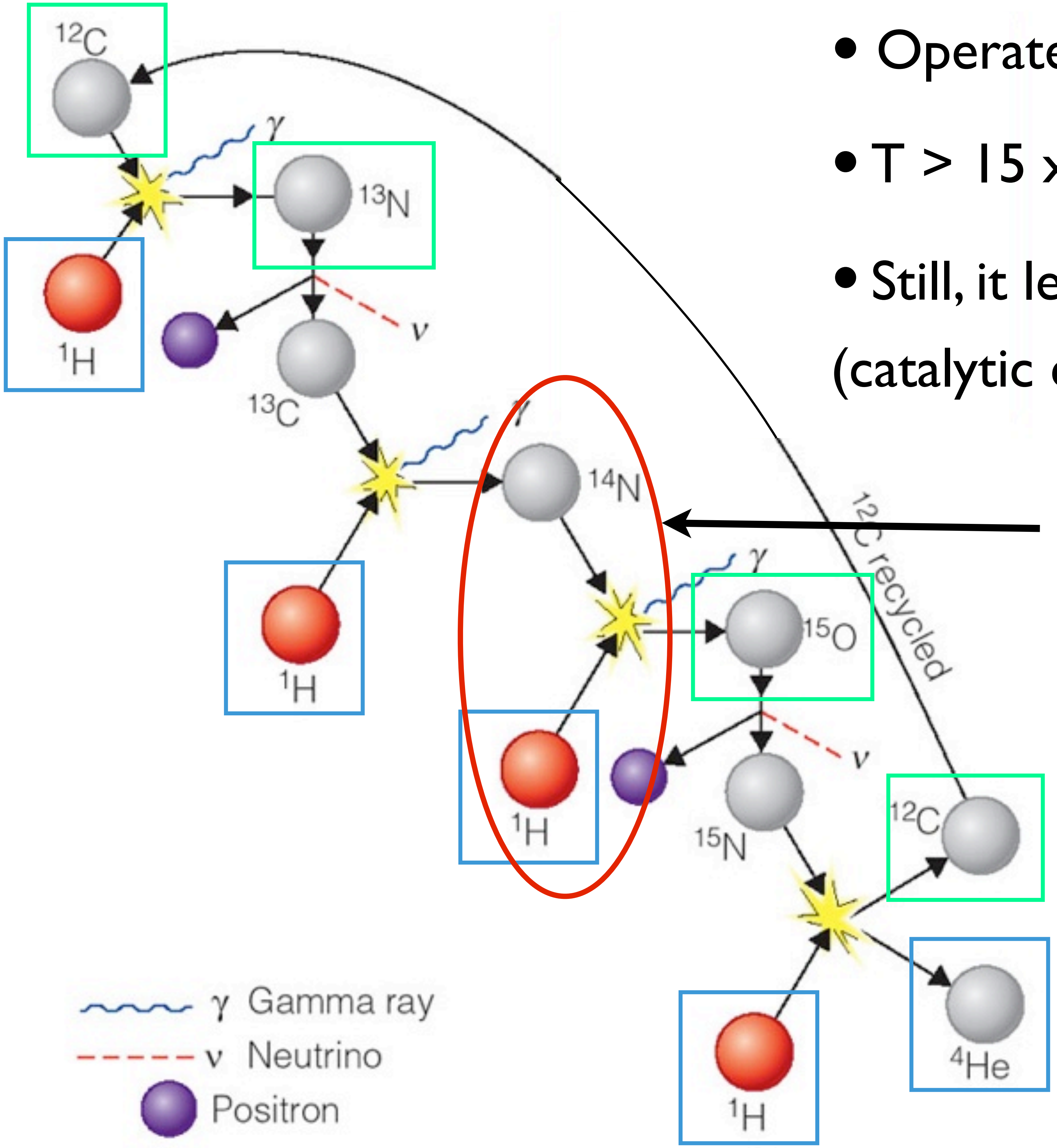
- Early experiments detected a much lower flux of neutrinos than expected (“solar neutrino problem”).

- Recent results have proven that neutrinos change (“oscillate”) between different types (“flavors”) on the way to Earth

Davis solar neutrino experiment

The CNO Cycle

- Bethe–Weizsäcker cycle
- Operates in stars with M > 1.3 M_{sun}
- $T > 15 \times 10^6$ K
- Still, it leads to: $4\,^1H \rightarrow\, ^4He$ + energy (catalytic cycle)



limiting (slowest) step

Helium Burning and More

- When H depletes, $^{1}H+^{1}H$ collisions become too rare to drive PPI chain fast enough to maintain pressure
- Then core collapses and T rises

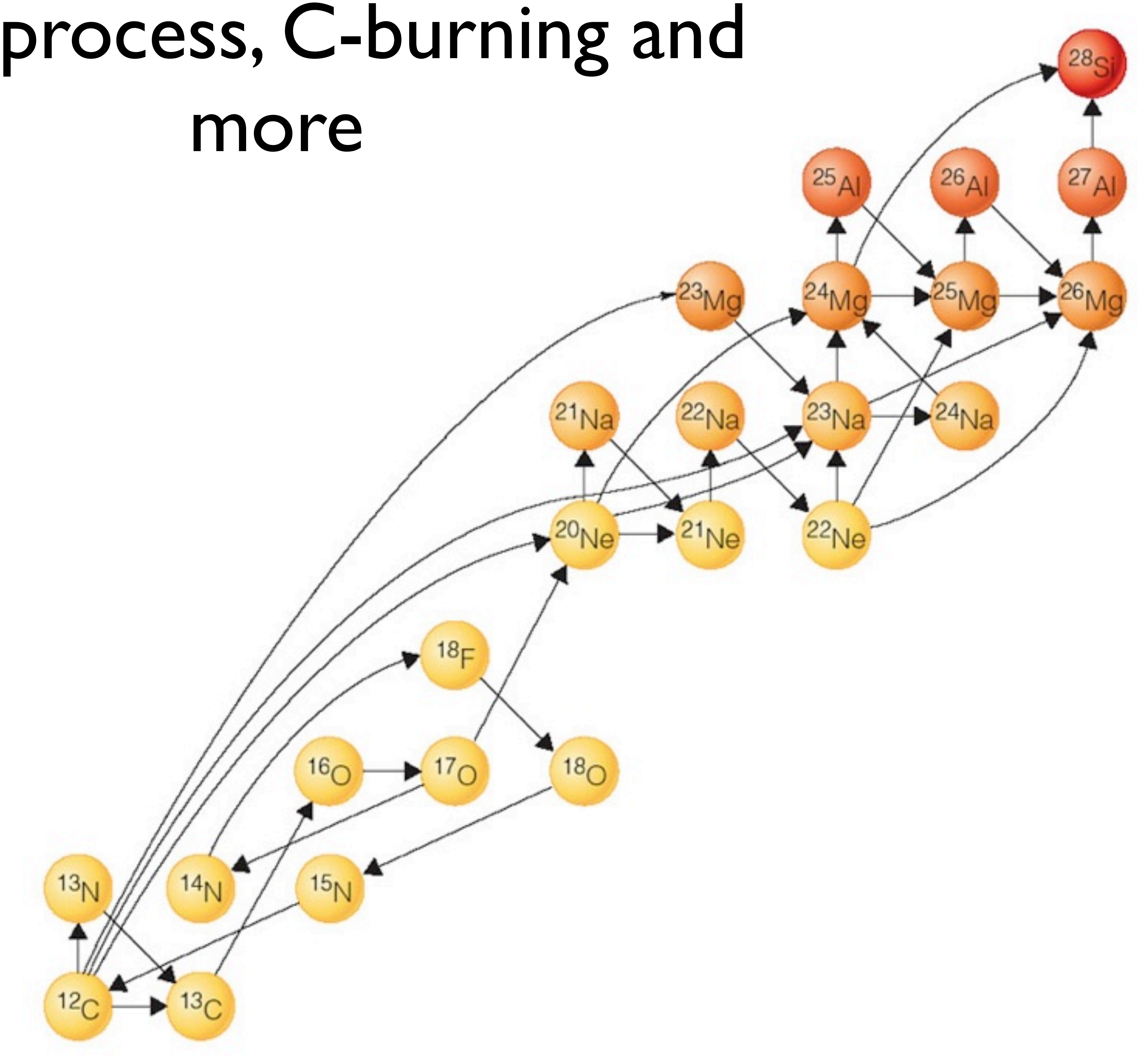
- At T ~ 2 x 10^{8} K, He burning becomes possible:

$^{4}He + ^{4}He + ^{4}He = ^{12}C + \gamma$ (via formation of ^{8}Be)

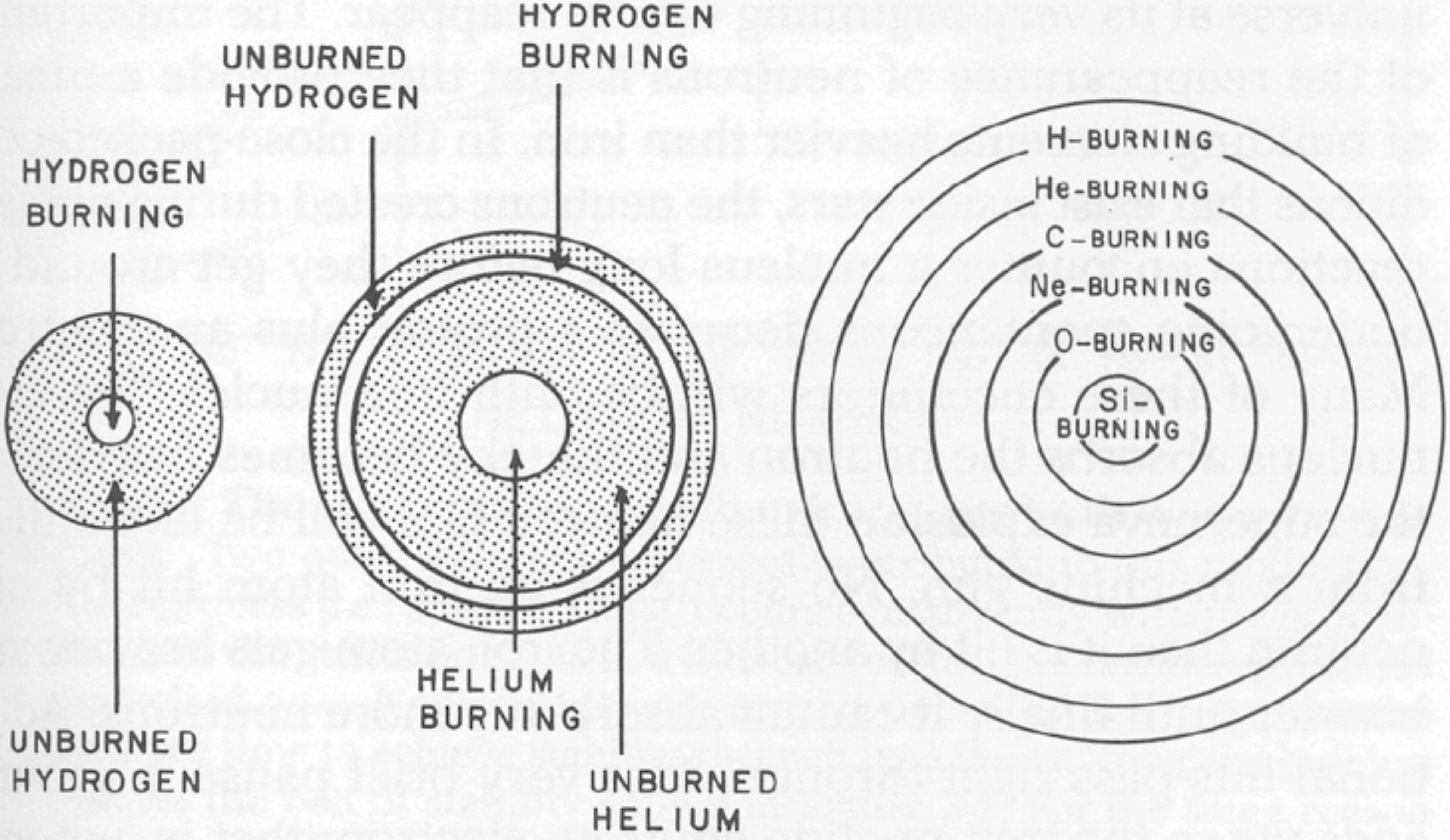
- When ^{4}He runs out, another core collapse occurs: C-burning
- This continues up through Si-burning

- All alpha-particle nuclides are synthesized: ^{4}He, ^{12}C, ^{16}O, ^{20}Ne, ^{24}Mg, ^{28}Si, ^{32}S, ^{36}Ar, ^{40}Ca
- Smaller quantities of ^{14}N, ^{15}N, ^{13}C, Na, P

alpha-process, C-burning and more

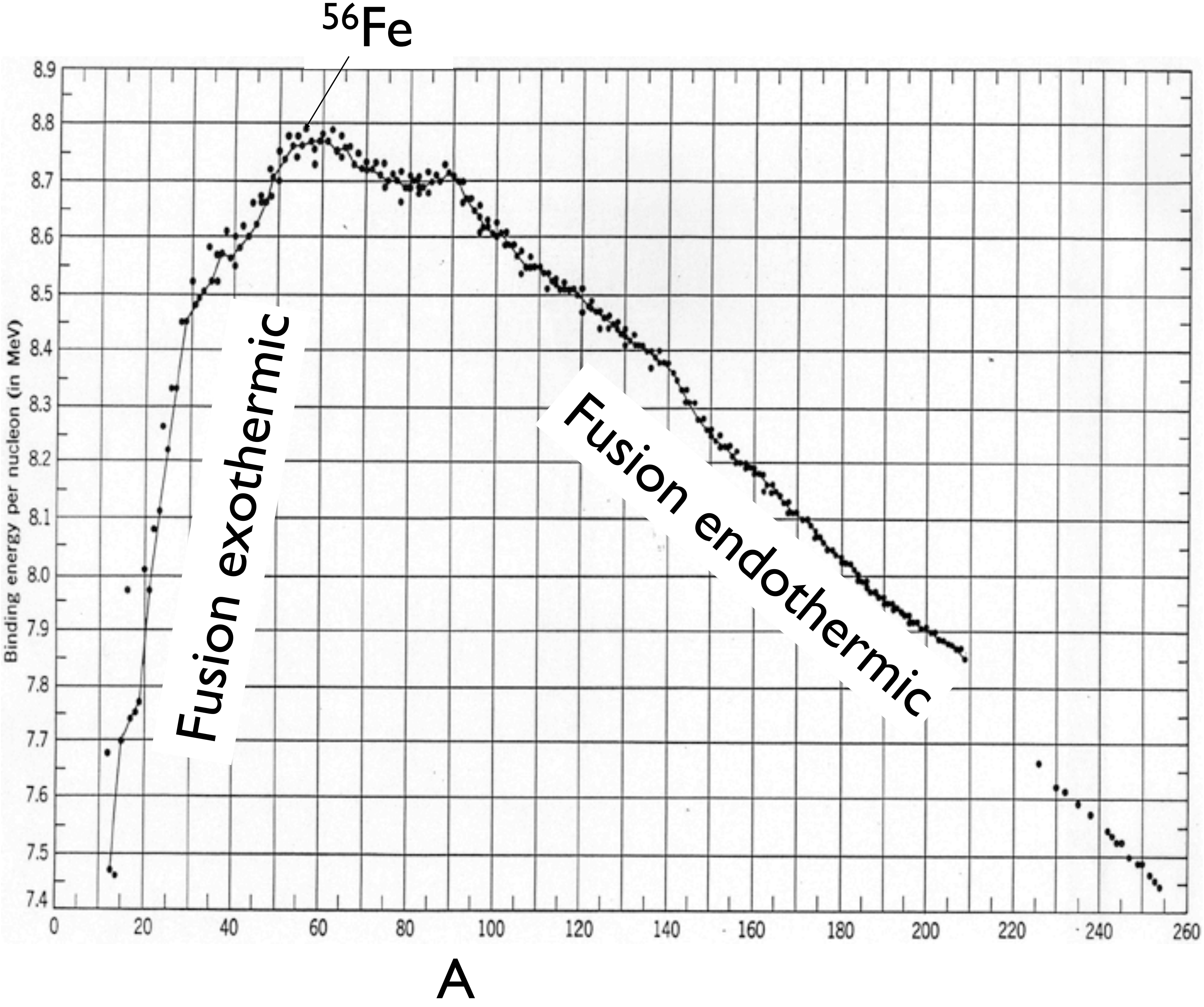


Helium Burning and More



Name of Process	Fuel	Products	Temperature
Hydrogen-Burning	H	He	60 × 10^6 °K
Helium-Burning	He	C, O	200 × 10^6 °K
Carbon-Burning	C	O, Ne, Na, Mg	800 × 10^6 °K
Neon-Burning	Ne	O, Mg	1500 × 10^6 °K
Oxygen-Burning	O	Mg to S	2000 × 10^6 °K
Silicon-Burning	Mg to S	Elements near FE	3000 × 10^6 °K

Nuclear binding energy

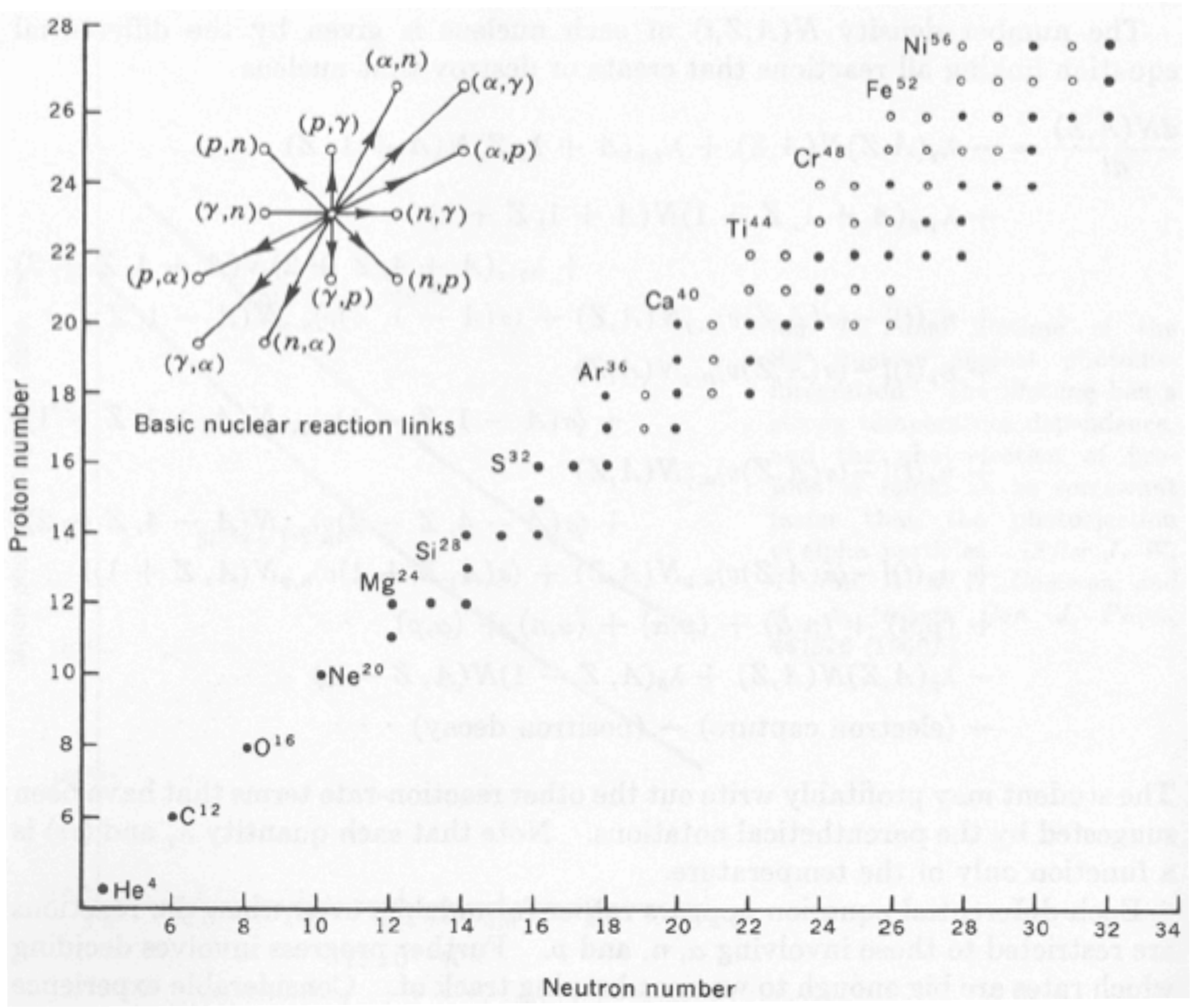


Problem: nuclear burning by fusion can continue only up to ^{56}Fe

Nuclear statistical equilibrium

- At Si-burning stage T ~ 3 x 10^9 K ⇒ gamma-ray energy

$E \sim 5kT \sim 4 \times 10^{-9}\,T$ MeV



- 1 MeV photons ⇒ energy production via transmutation reactions

- When equilibrium ratios of all nuclear products up to ^{56}Fe is reached, energy production ceases

- Total collapse of the stellar core: white dwarf, neutron star, or black hole (depending on mass)

Stellar Nucleosynthesis

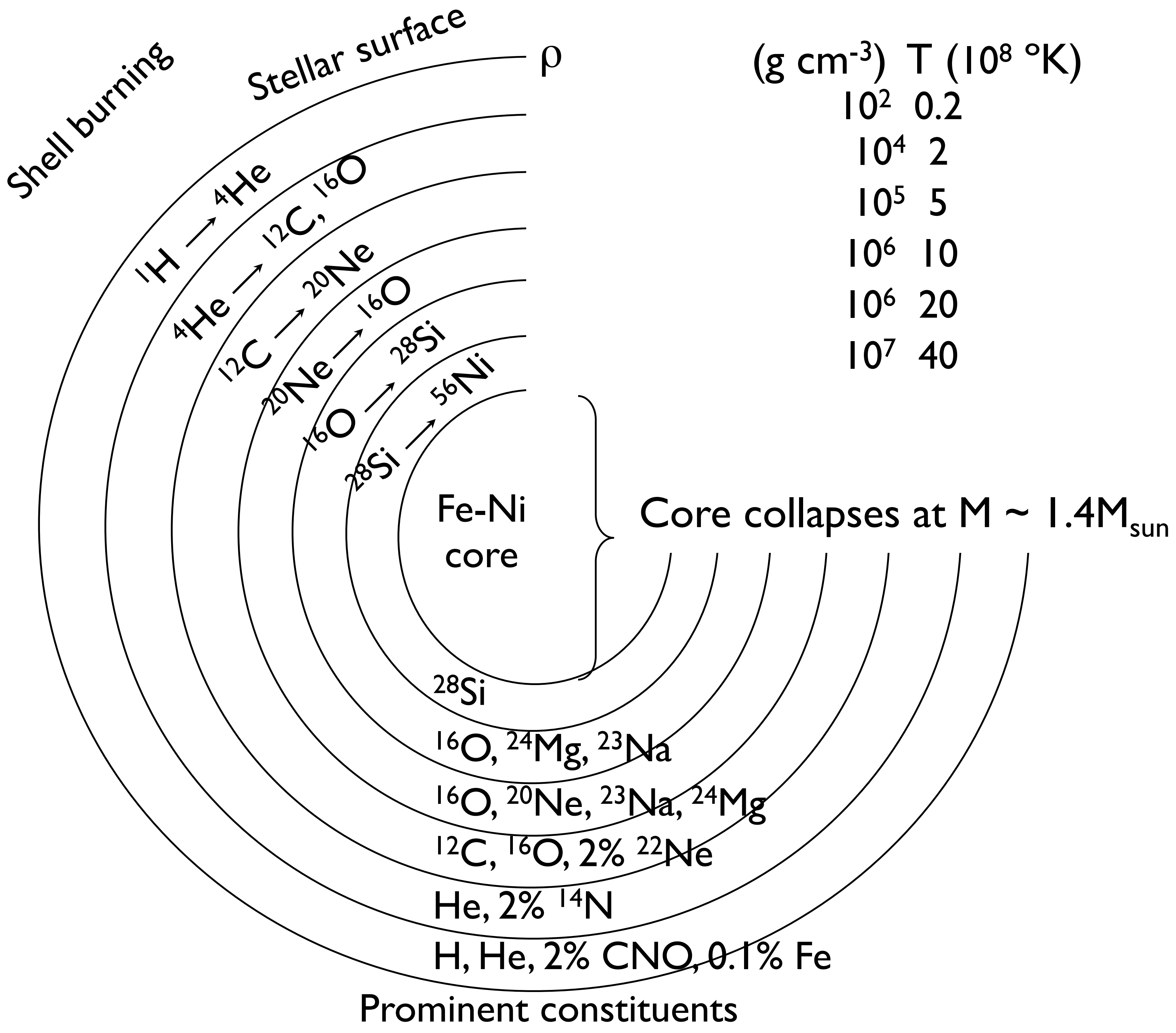
Evolutionary Time Scales for a 15 M_{sun} Star

Fused	Products	Time	Temperature
H	^{4}He	10^{7} yrs.	4×10^{6} K
^{4}He	^{12}C	Few X 10^{6} yrs	1×10^{8} K
^{12}C	^{16}O, ^{20}Ne, ^{24}Mg, ^{4}He	1000 yrs.	6×10^{8} K
^{20}Ne +	^{16}O, ^{24}Mg	Few yrs.	1×10^{9} K
^{16}O	^{28}Si, ^{32}S	One year	2×10^{9} K
^{28}Si +	^{56}Fe	Days	3×10^{9} K
^{56}Fe	Neutrons	< 1 second	3×10^{9} K

Pre-Supernova “Onion Skin” Structure

- Heavy elements settle into layers
- Shell burning at interfaces.

Composition of layers dominated by more stable nuclei (A multiple of 4)



Shell burning

Stellar surface

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

$^{4}He \rightarrow {}^{12}C, {}^{16}O$

$^{12}C \rightarrow {}^{20}Ne$

$^{20}Ne \rightarrow {}^{16}O$

$^{16}O \rightarrow {}^{28}Si$

$^{28}Si \rightarrow {}^{56}Ni$

ρ (g cm^{-3})	T (10^8 °K)
10^2	0.2
10^4	2
10^5	5
10^6	10
10^6	20
10^7	40

Fe-Ni core

Core collapses at M ~ 1.4M_{sun}

^{28}Si

^{16}O, ^{24}Mg, ^{23}Na

^{16}O, ^{20}Ne, ^{23}Na, ^{24}Mg

^{12}C, ^{16}O, 2% ^{22}Ne

He, 2% ^{14}N

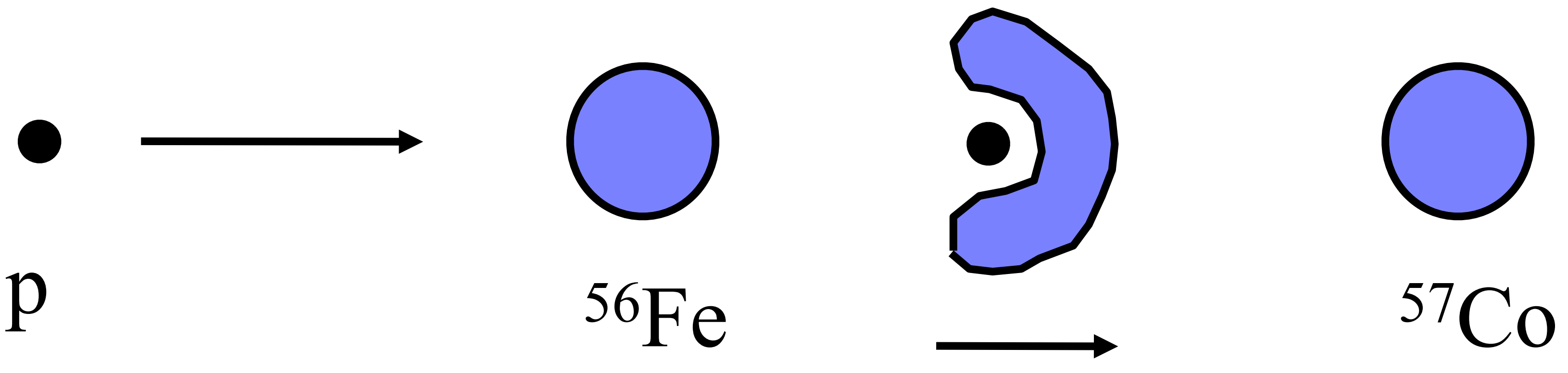
H, He, 2% CNO, 0.1% Fe

Prominent constituents

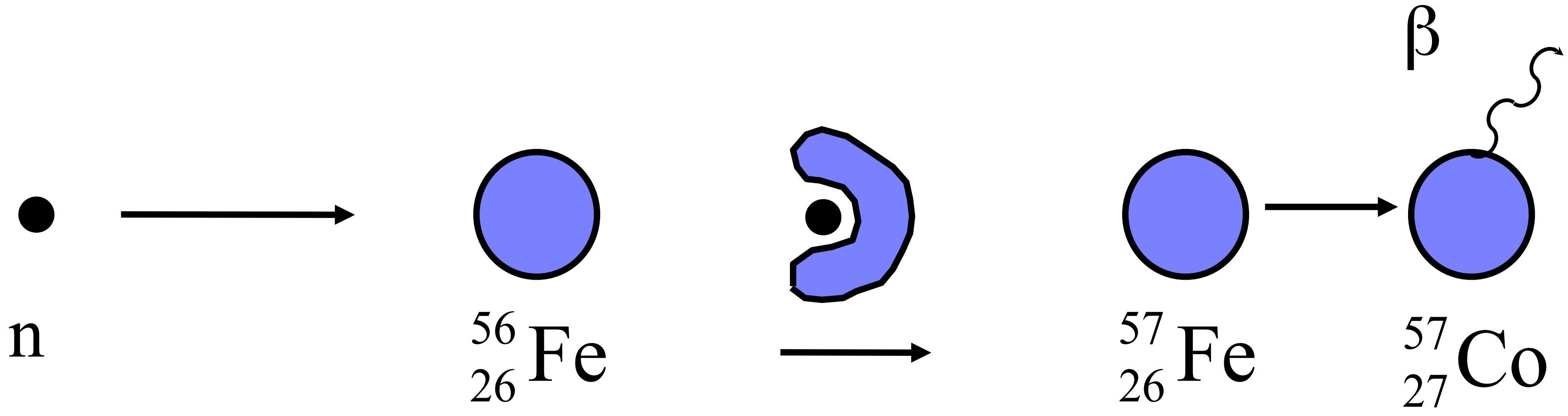
Going beyond ^{56}Fe: neutron capture

- Coulomb repulsion prevents reactions between charged nuclei at solar temperatures
- Yet neutrons have no charge and neutron capture reactions can proceed even at room temperature
- Individual nuclei captures neutrons in proportion to their neutron capture cross-section

p-process: Proton capture:



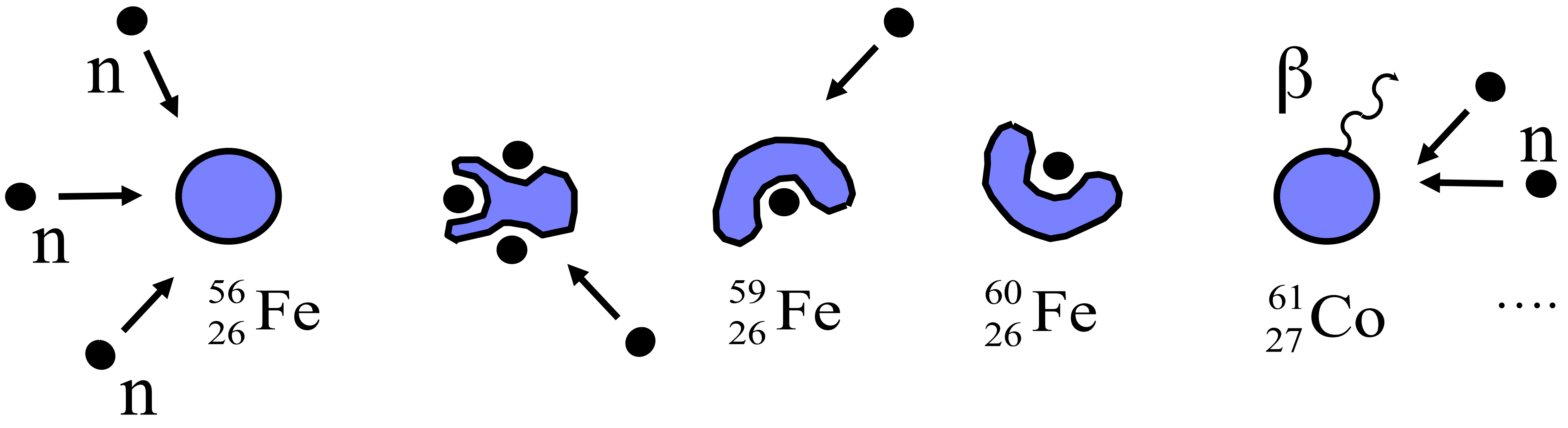
s-process: Slow neutron capture:



Absorb n^0, then … later … emit e$^-$ (β-particle)

Progress up the valley of stability.

r-process: Rapid neutron capture:



High n^0 flux: absorb many n^0s before β emission

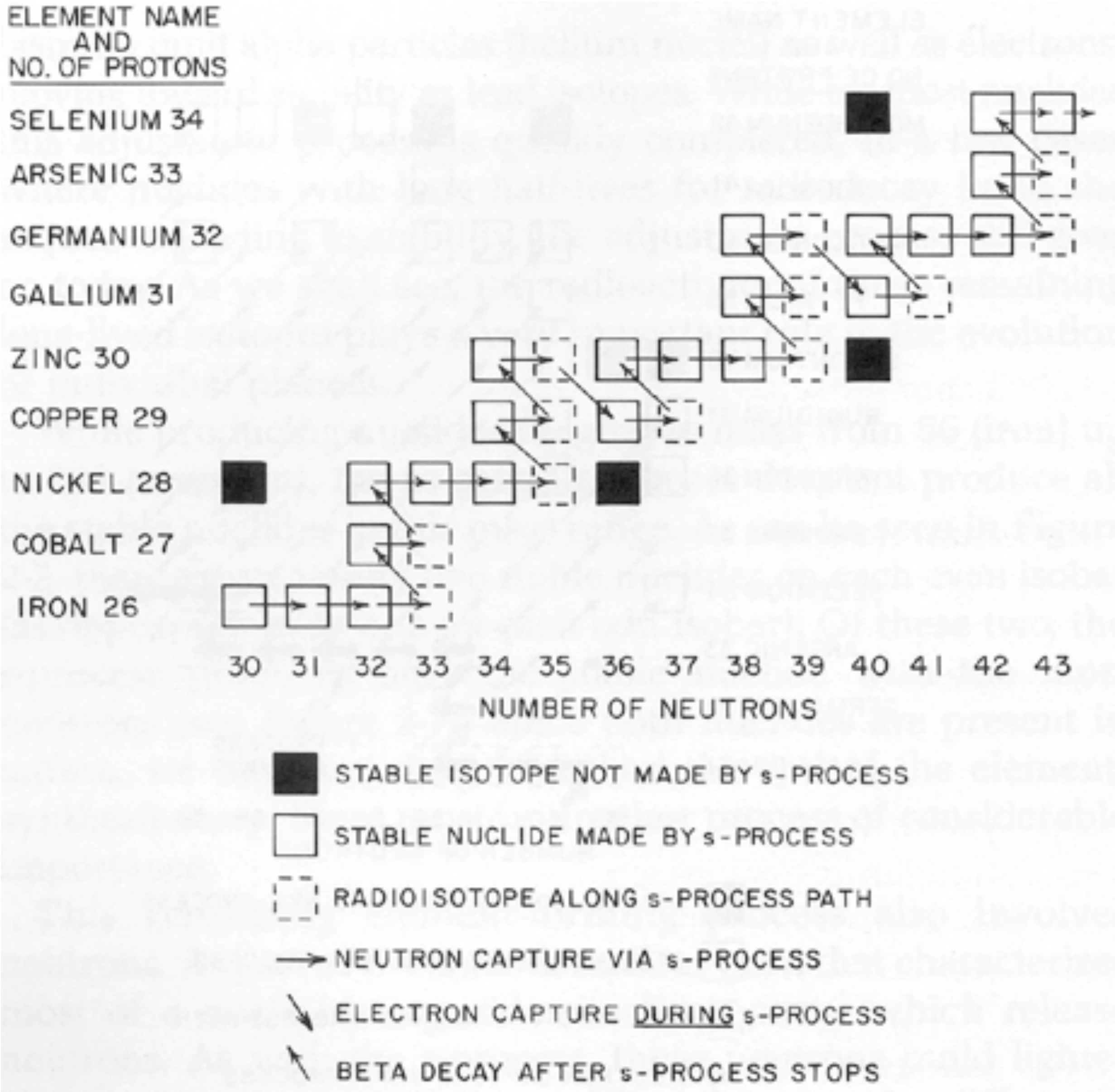
These processes require energy and occur only at high ρ & T :

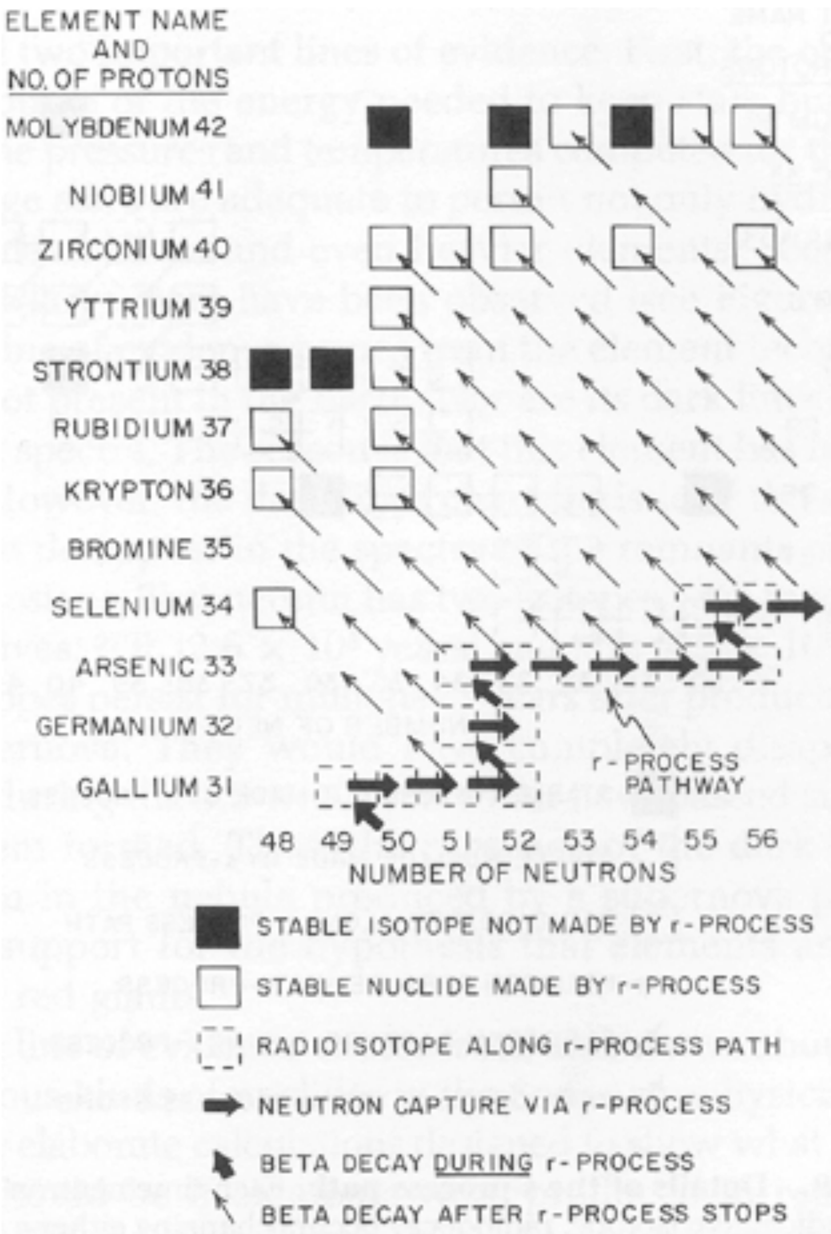
Core & shell burning: p- & s- process

Supernovae: p- & r- process

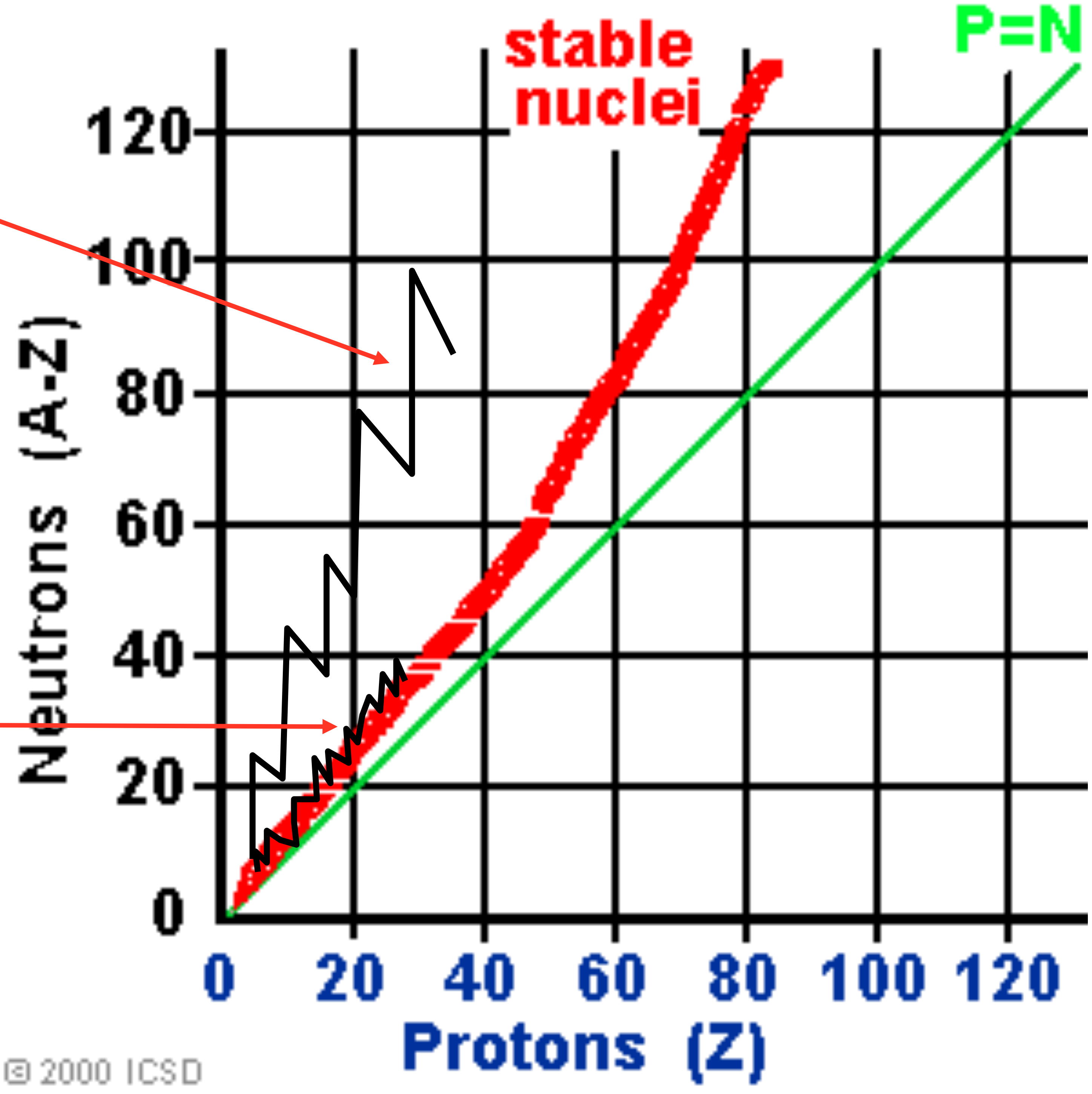
Neutron capture processes

- s-process: "valley of stability" nuclei
- r-process: nuclei on the neutron dripline (capture rate goes to zero) ⇒ these decay back to first stable nuclide on each isobar





Neutron Capture: Speed Matters



r-process

departs from

valley of stability

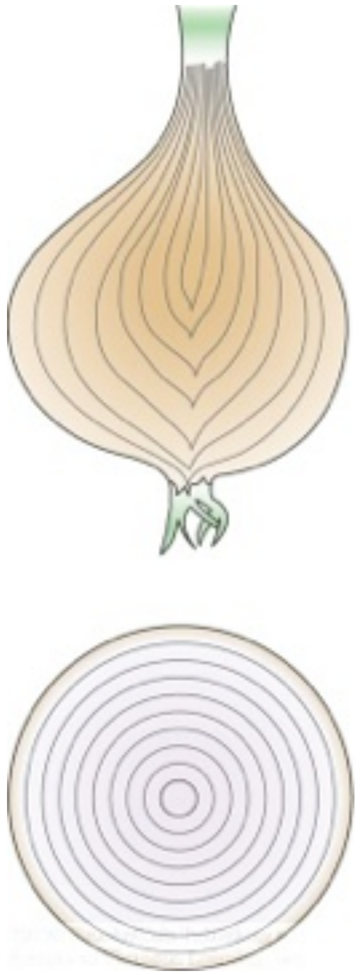
s-process

Pause

Stellar Evolution

- Depends on the initial mass of the star
- Depends on stellar initial abundances of elements
- Nuclear fusion
- Radiative/thermal pressure vs gravitation
- Low-mass (Sun-like) stars vs and high-mass (and intermediate-mass stars
- Low-mass stars: PP-cycle, white dwarf
- High-mass stars: He-burning, CNO-cycle, (super)nova, neutron star/black hole

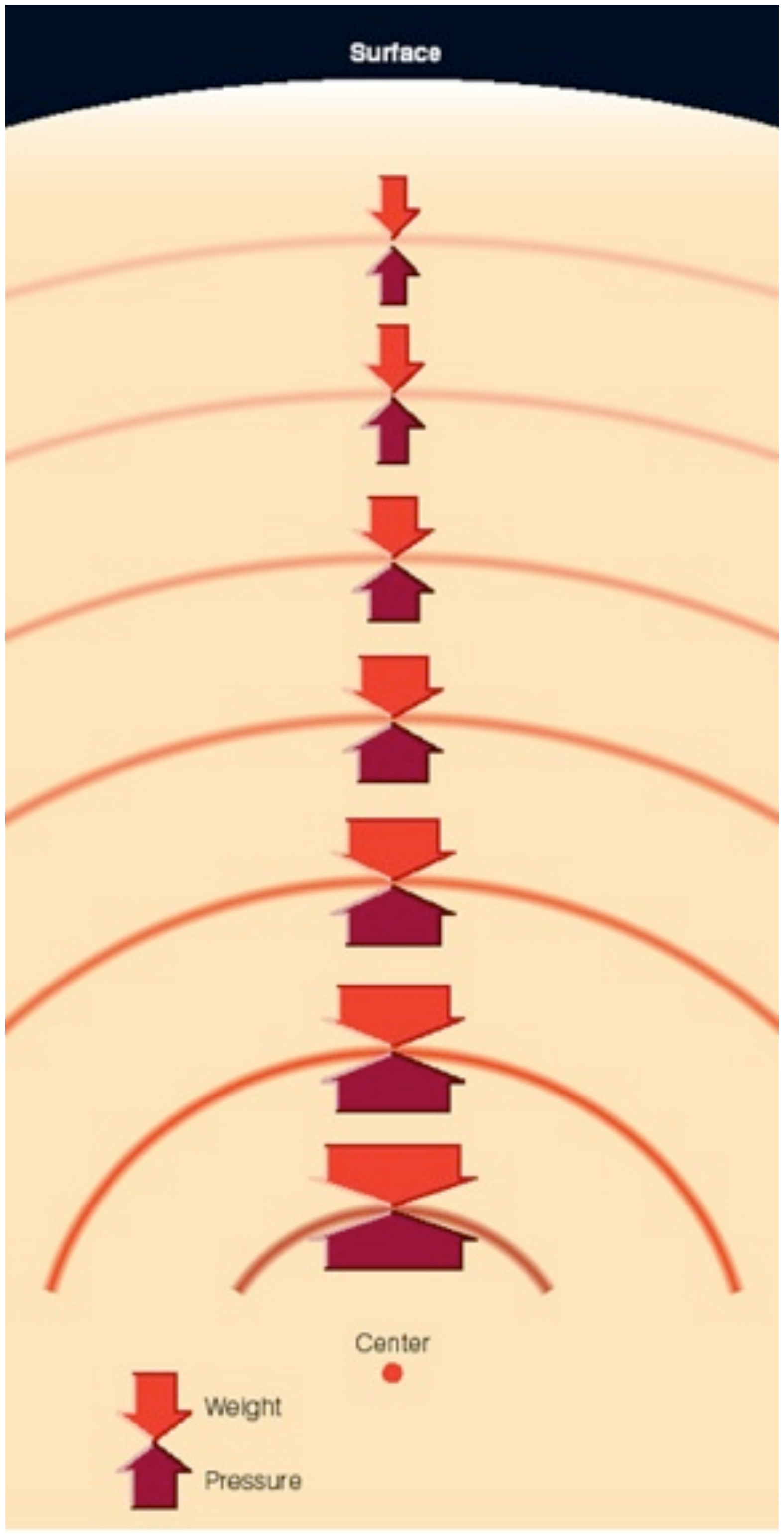
Stellar Models



"Onion skin layer model"

Four laws of stellar structure:

- Conservation of Mass
- Conservation of Energy
- Hydrostatic Equilibrium
- Energy Transport



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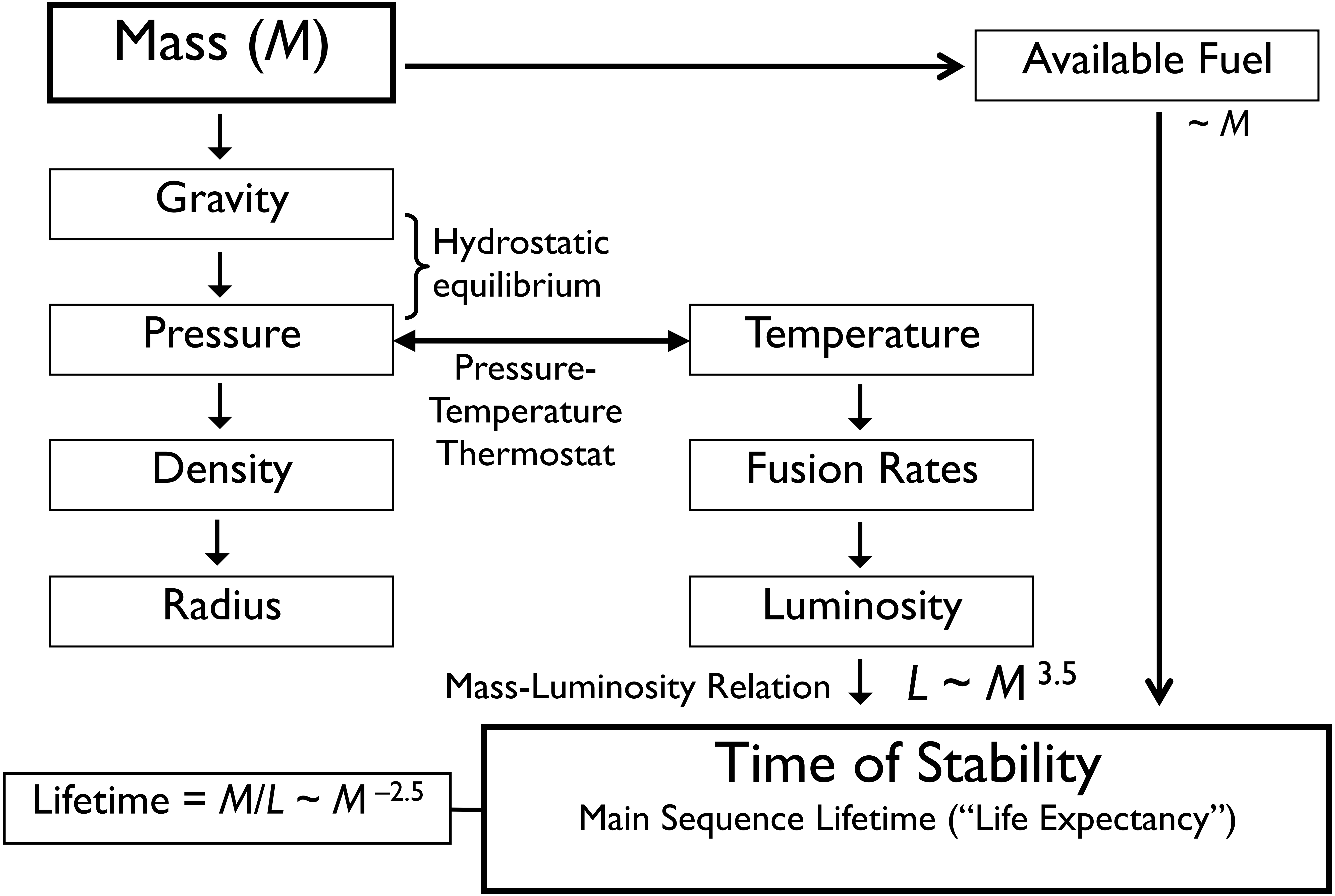
Modeling stellar structure



Mass (M)

Available Fuel

$\sim M$

Gravity

Hydrostatic equilibrium

Pressure

Pressure-Temperature Thermostat

Temperature

Density

Fusion Rates

Radius

Luminosity

Mass-Luminosity Relation $L \sim M^{3.5}$

Time of Stability

Main Sequence Lifetime (“Life Expectancy”)

Lifetime = $M/L \sim M^{-2.5}$

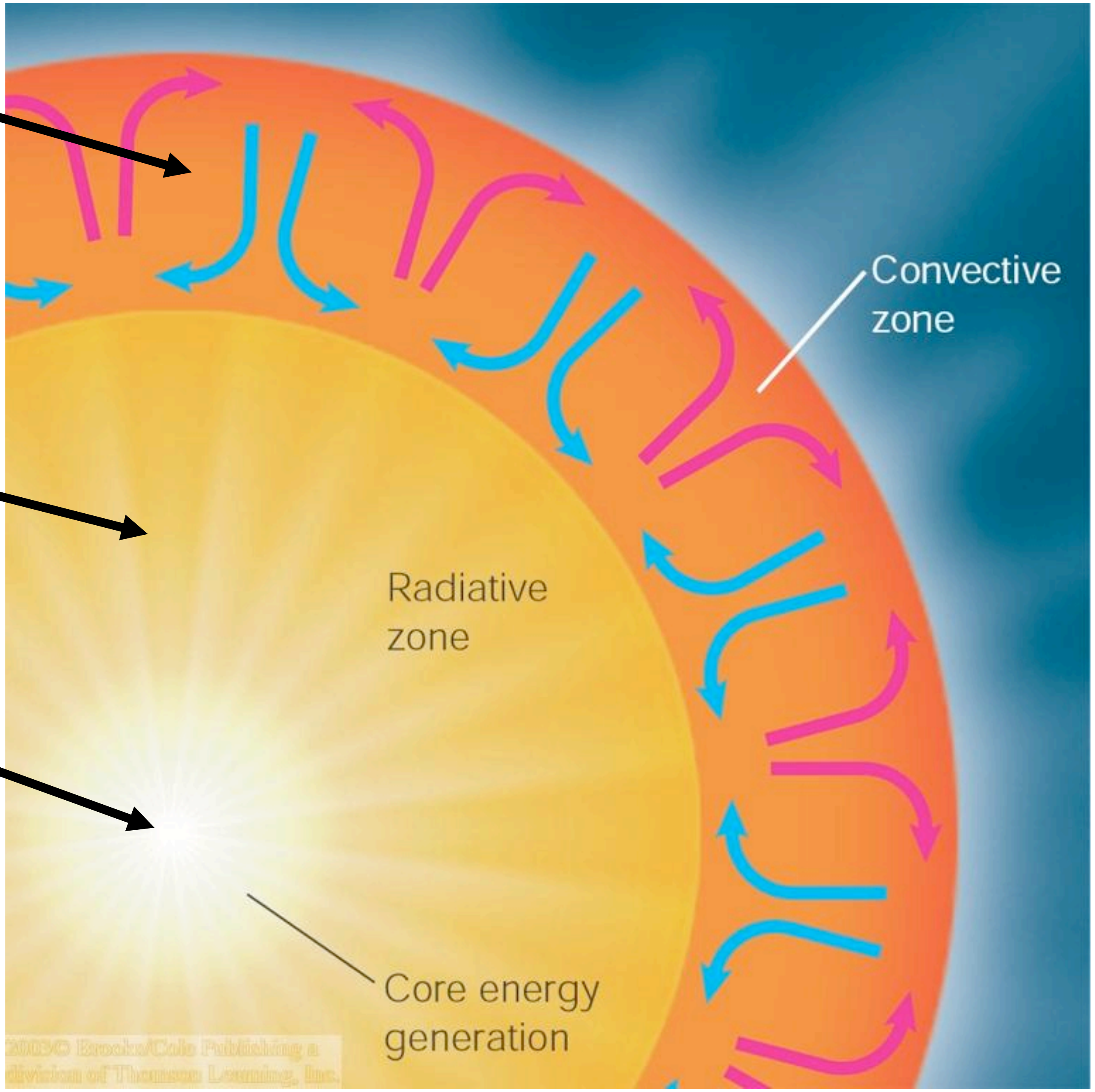
Structure of the Sun

Flow of energy

Energy transport
via convection

Energy transport
via radiation

Energy generation
via nuclear fusion



Star's total mass determines
which part of the star has
convection or radiation

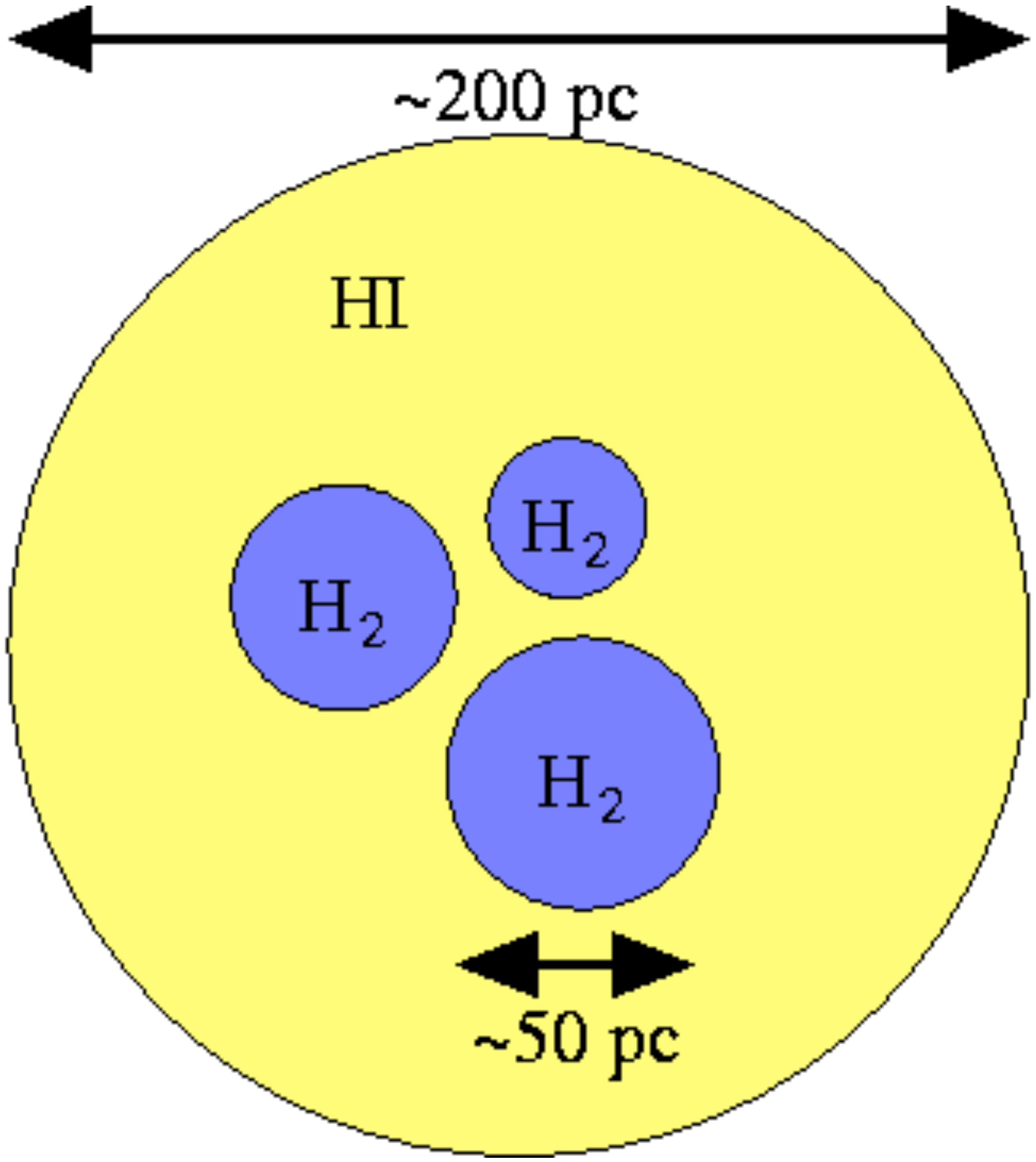
Temperature, density and
pressure decreasing

Giant Molecular Clouds

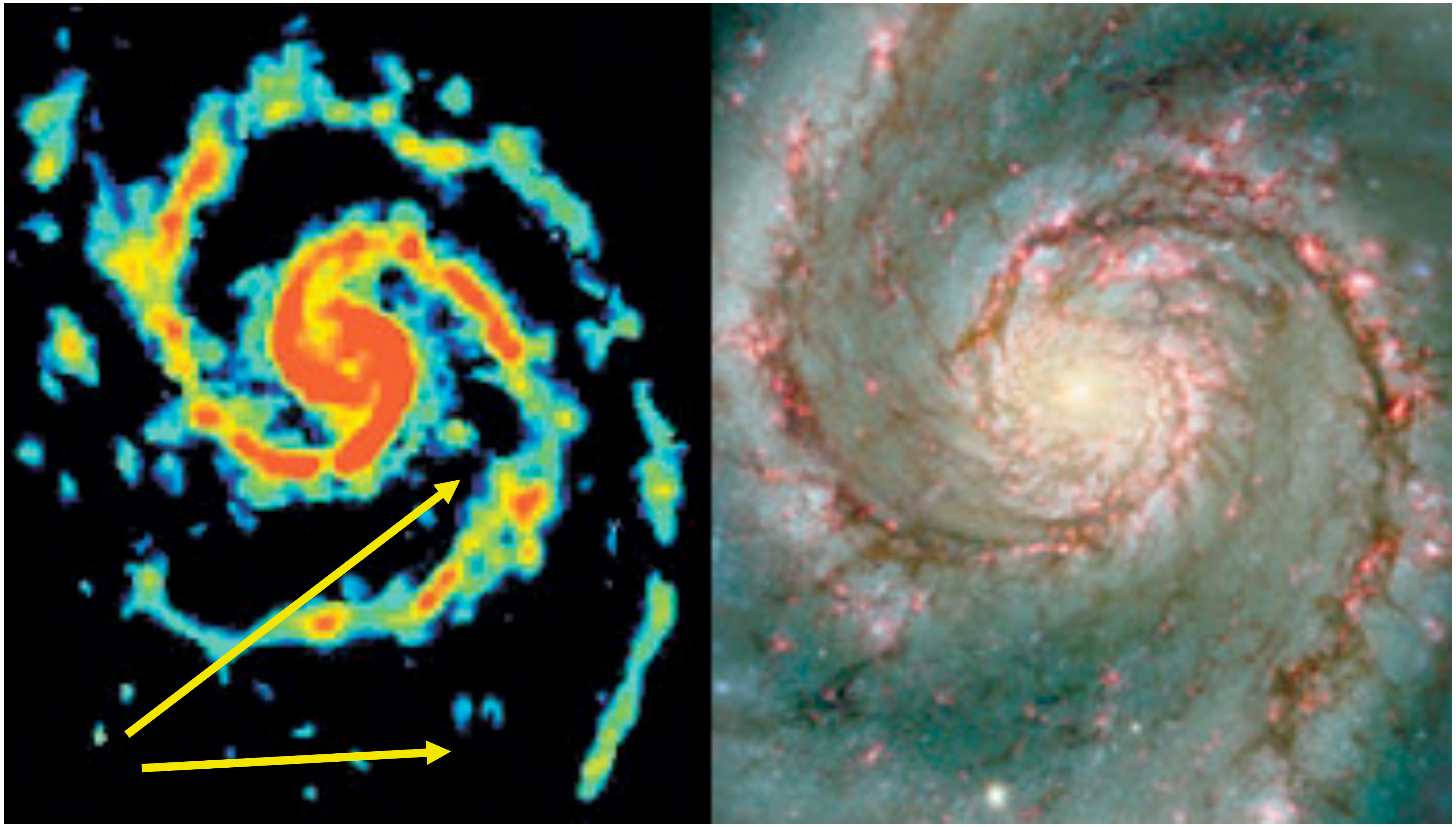
- Basic units of star formation
- Typical mass ~10^4 - 10^7 M_{sun}, size ~100 pc, density ~100–300 cm^{-3}, temperature ~10–20 K
- ~1/4 of ISM mass in our Galaxy
- Usually far away ⇒ distance uncertainty
- Hard to study in high-z galaxies

Anatomy of a GMC

- Atomic-molecular complexes
- H/H_2 due to FUV-dissociation
- Lifetime ~ 20 – 50 Myr



GMC locations

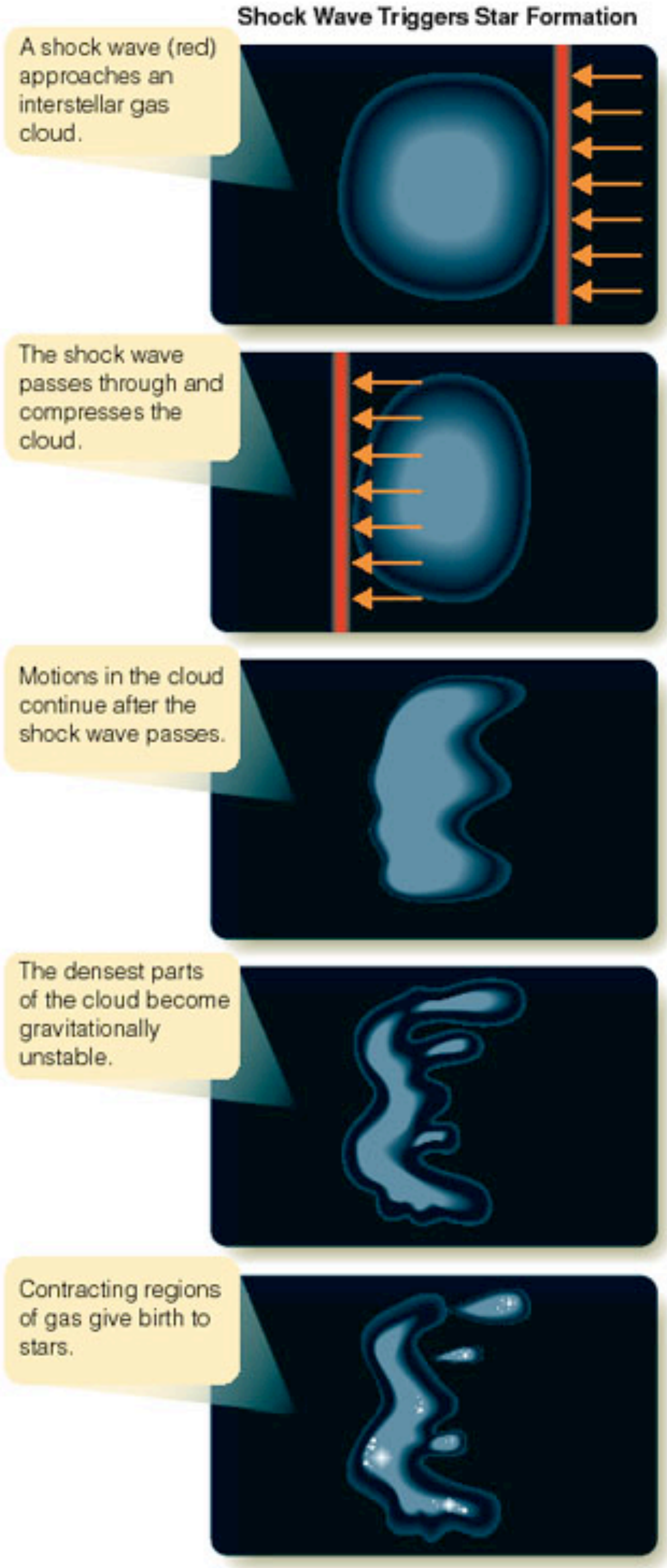


M51 seen in ^{12}CO (Koda et al.) and visible

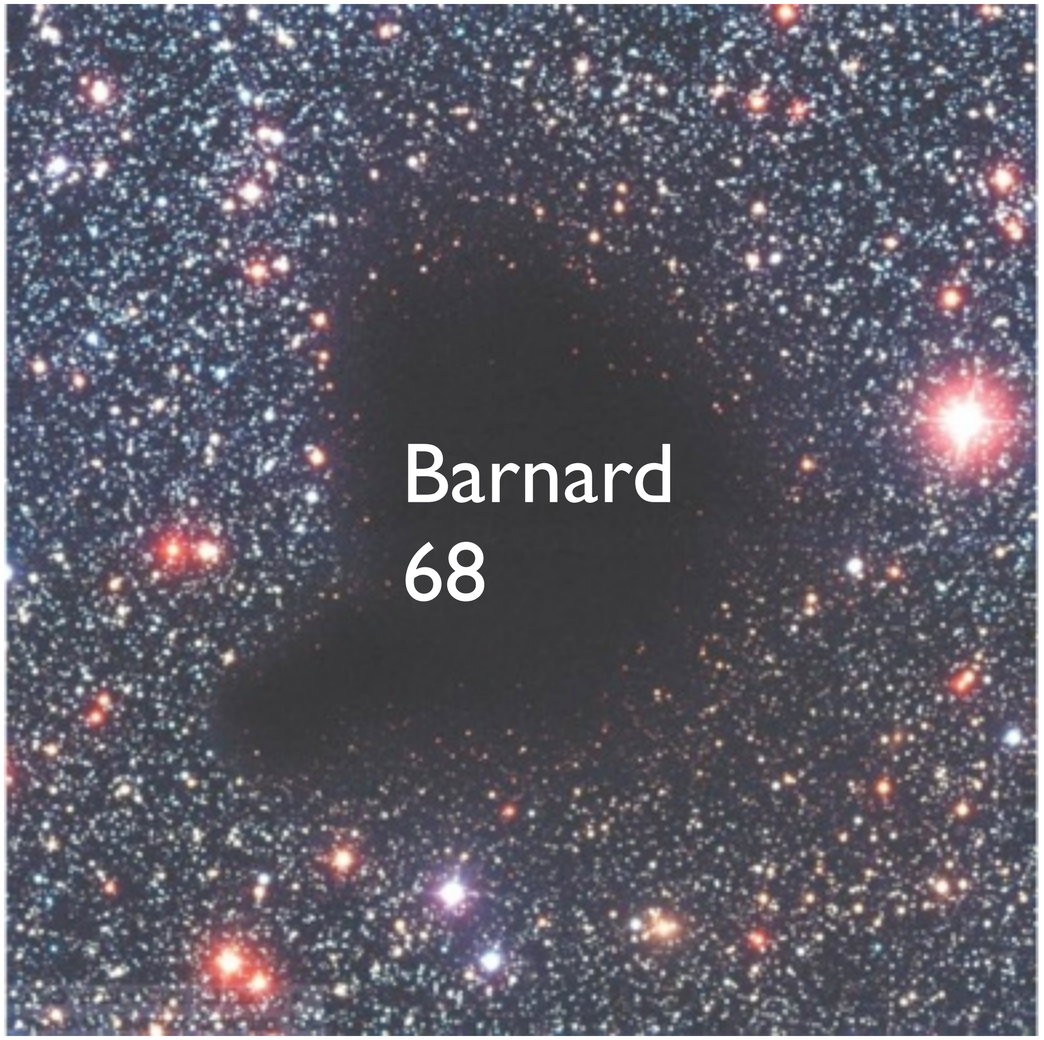
- Some are along spiral arms (lifetime <50 Myr)
- Some are far away (lifetimes ≳ 50 Myr)
- Star-formation efficiency: ~ 5–10 %

Supernova shocks trigger SF

Henize 206 (infrared)



Prestellar cores: cores of GMCs

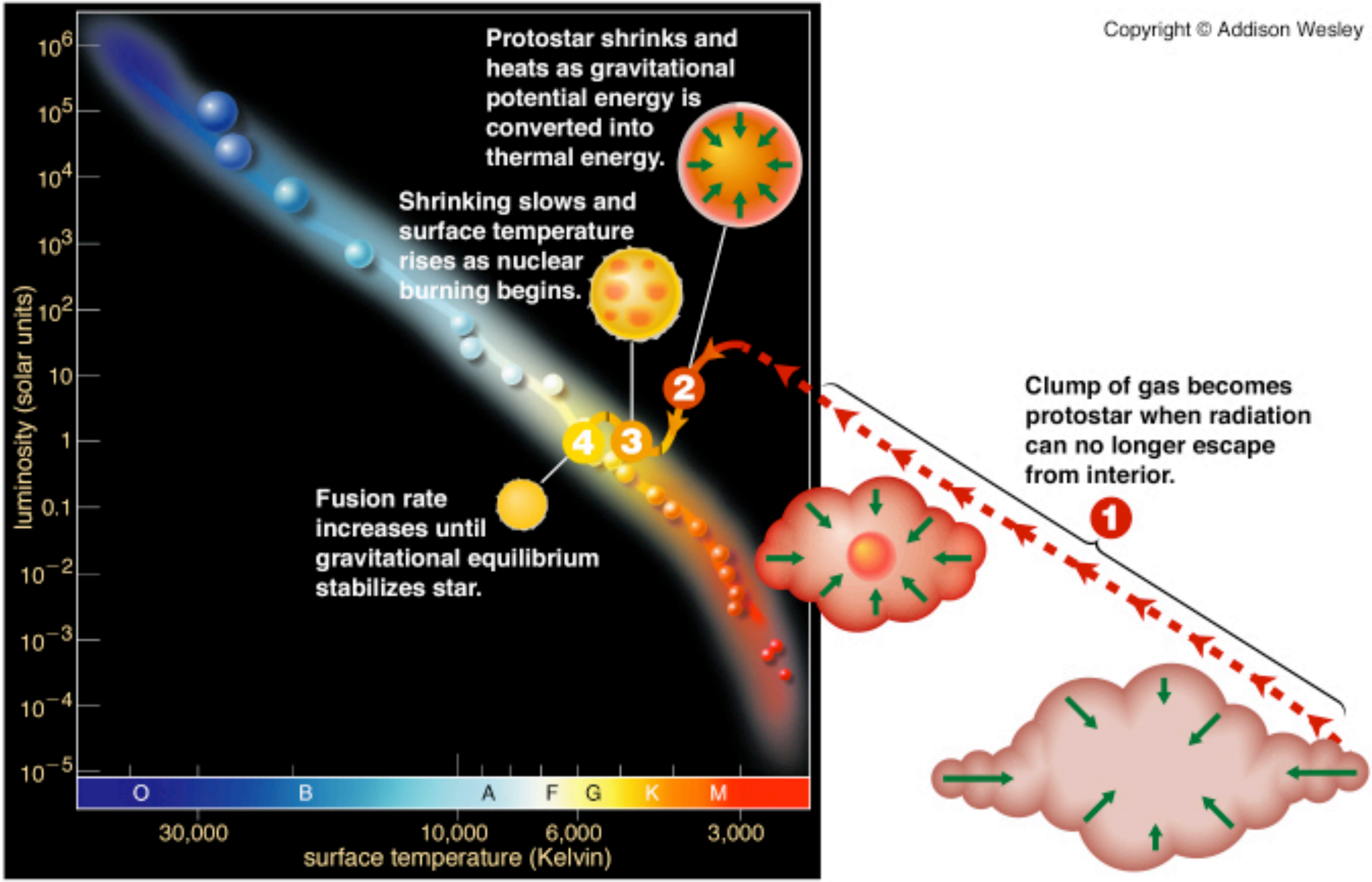


Visible

Infrared

- Typical mass ~10 - 10^3 M_{sun}, size < 1 pc, n >10^4 cm^{-3}, T ~10 K

Then a Protostar is born



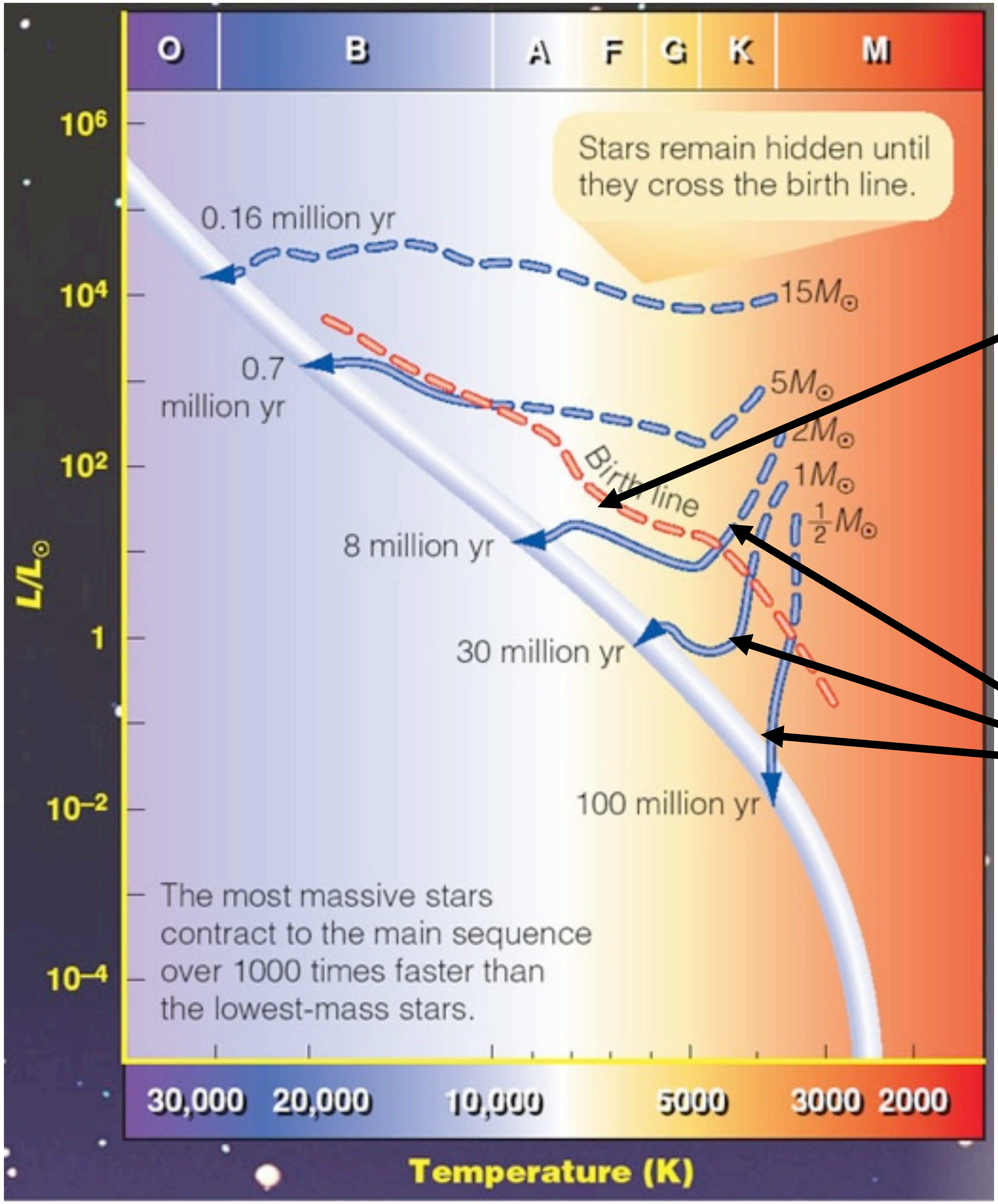
Protostar shrinks and heats as gravitational potential energy is converted into thermal energy.

Shrinking slows and surface temperature rises as nuclear burning begins.

Fusion rate increases until gravitational equilibrium stabilizes star.

Clump of gas becomes protostar when radiation can no longer escape from interior.

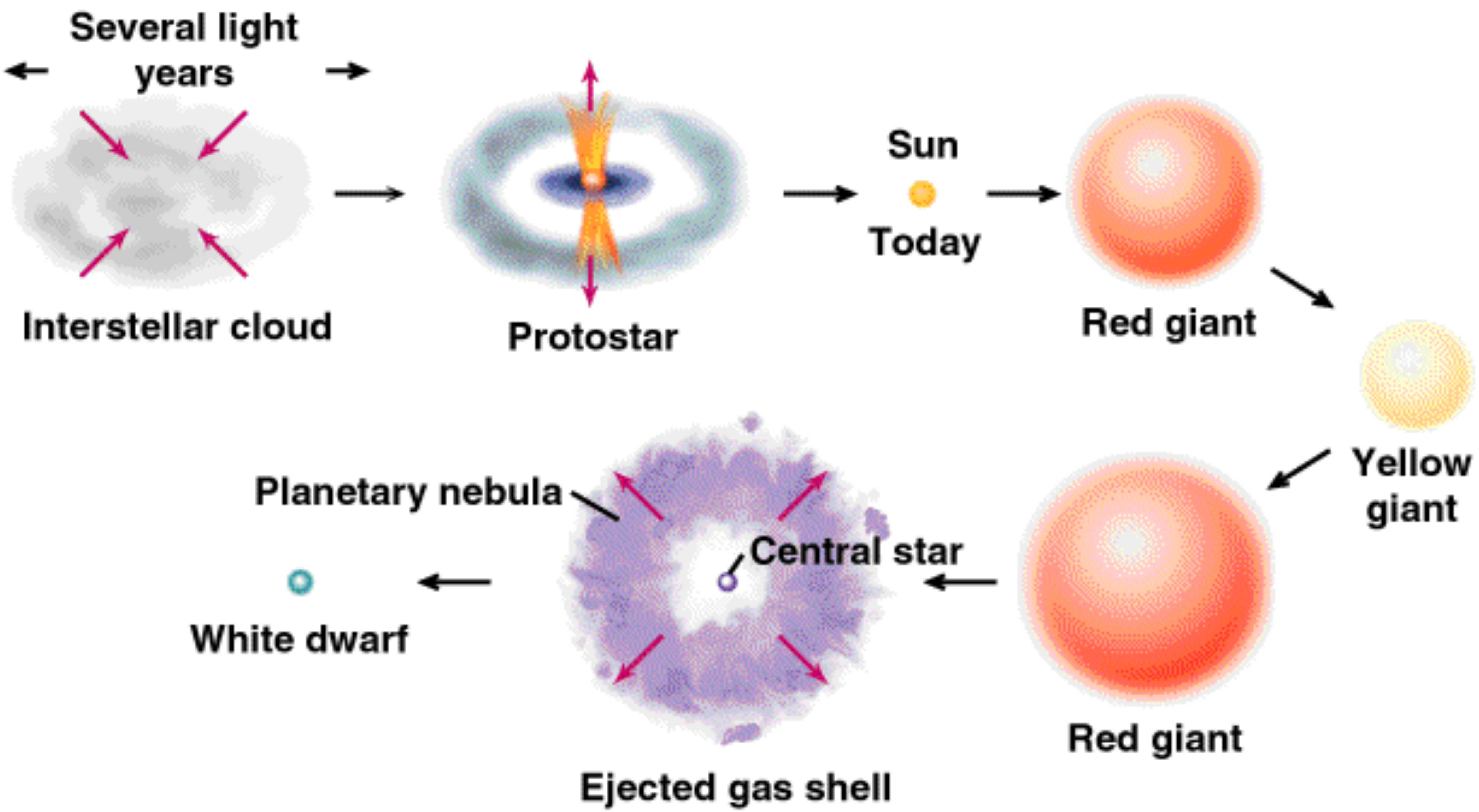
From Protostars to Stars



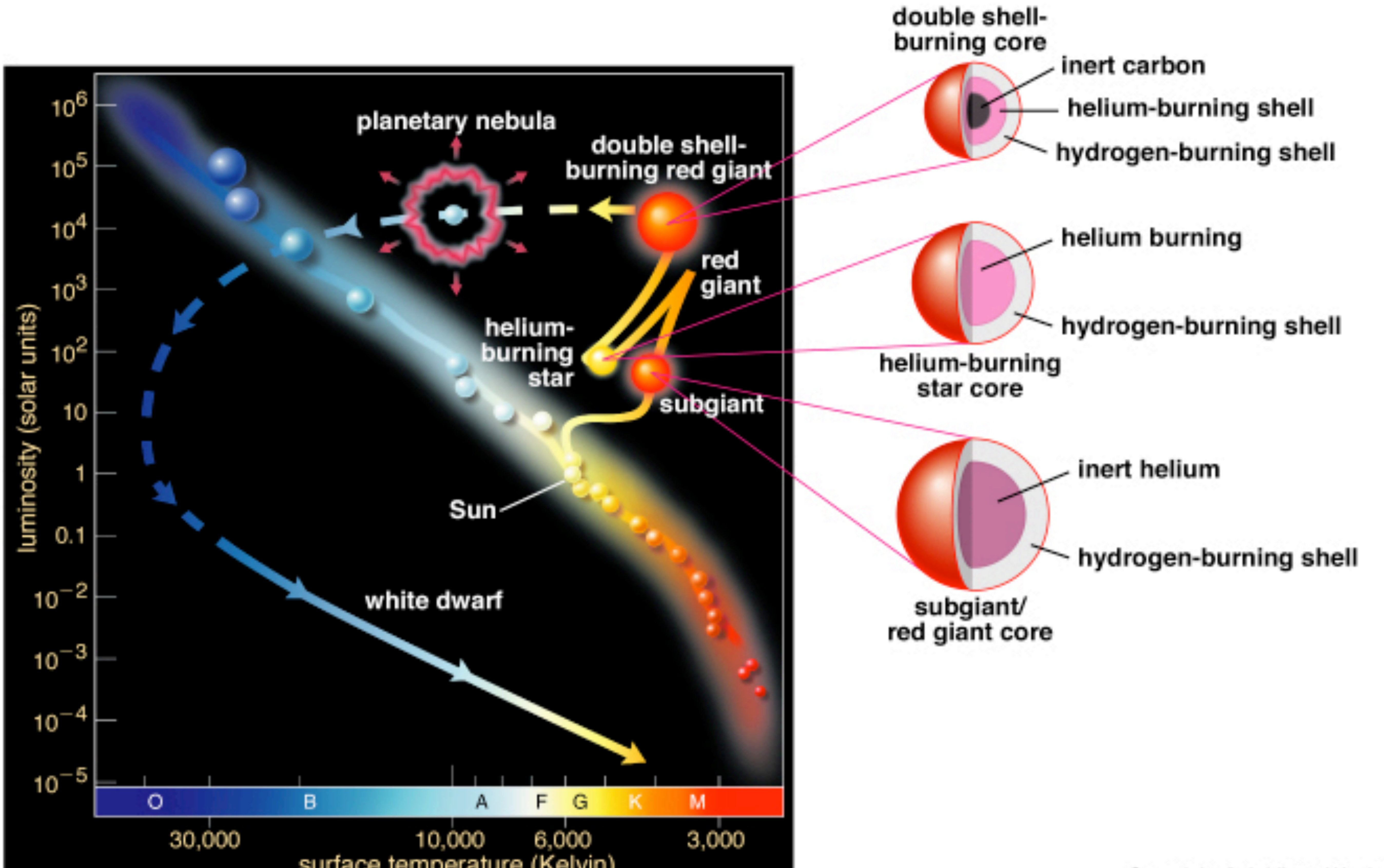
Star emerges from the enshrouding dust cocoon (T Tauri stage)

Ignition of $4\,{}^1H \rightarrow {}^4He$

Life of the Sun



The life track of a Sun-like star



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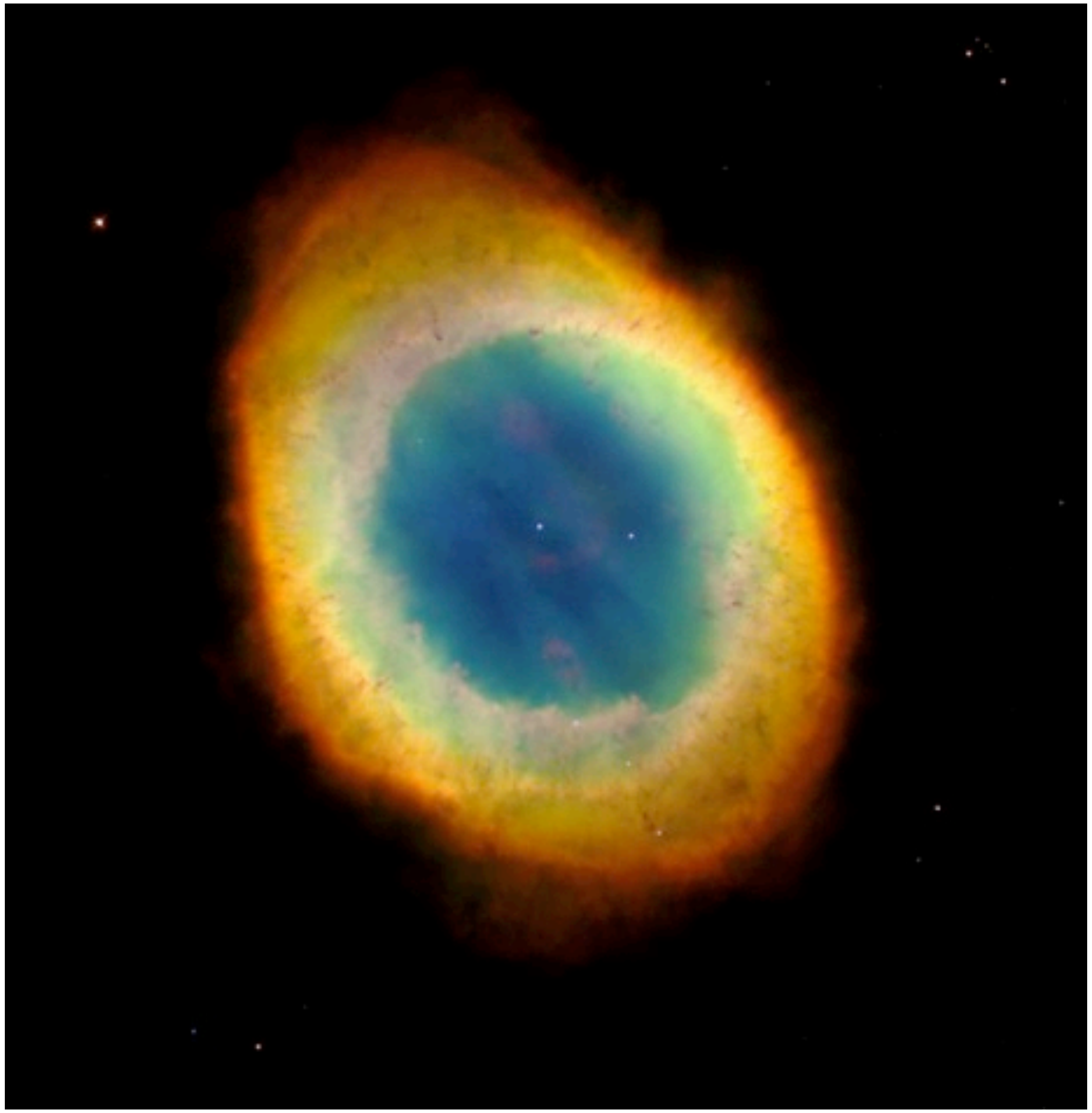
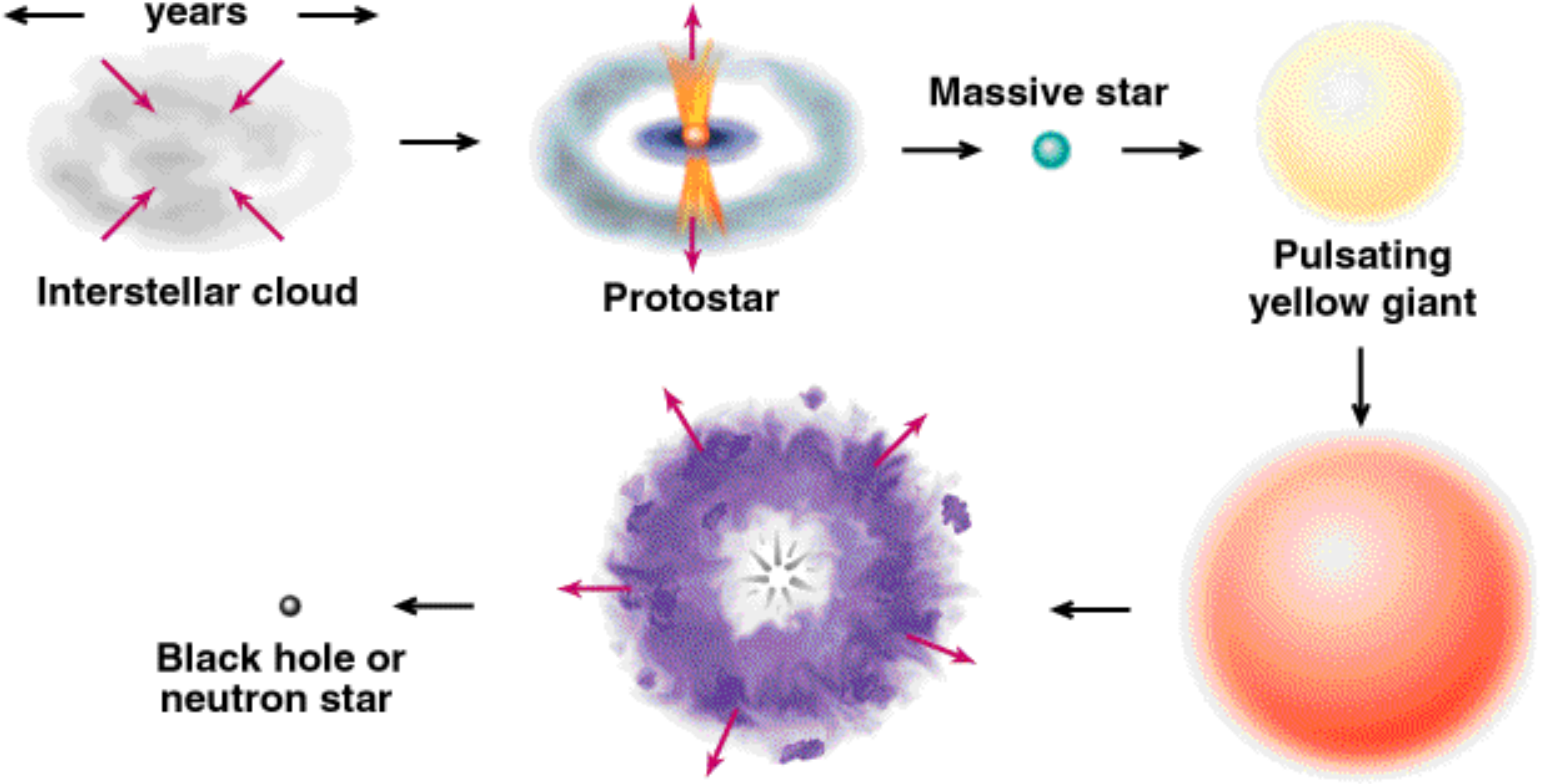
The beautiful end of the Sun

The Cat's Eye nebula

The Ring nebula



Life of a High Mass Star



Several light years

Interstellar cloud

Protostar

Massive star

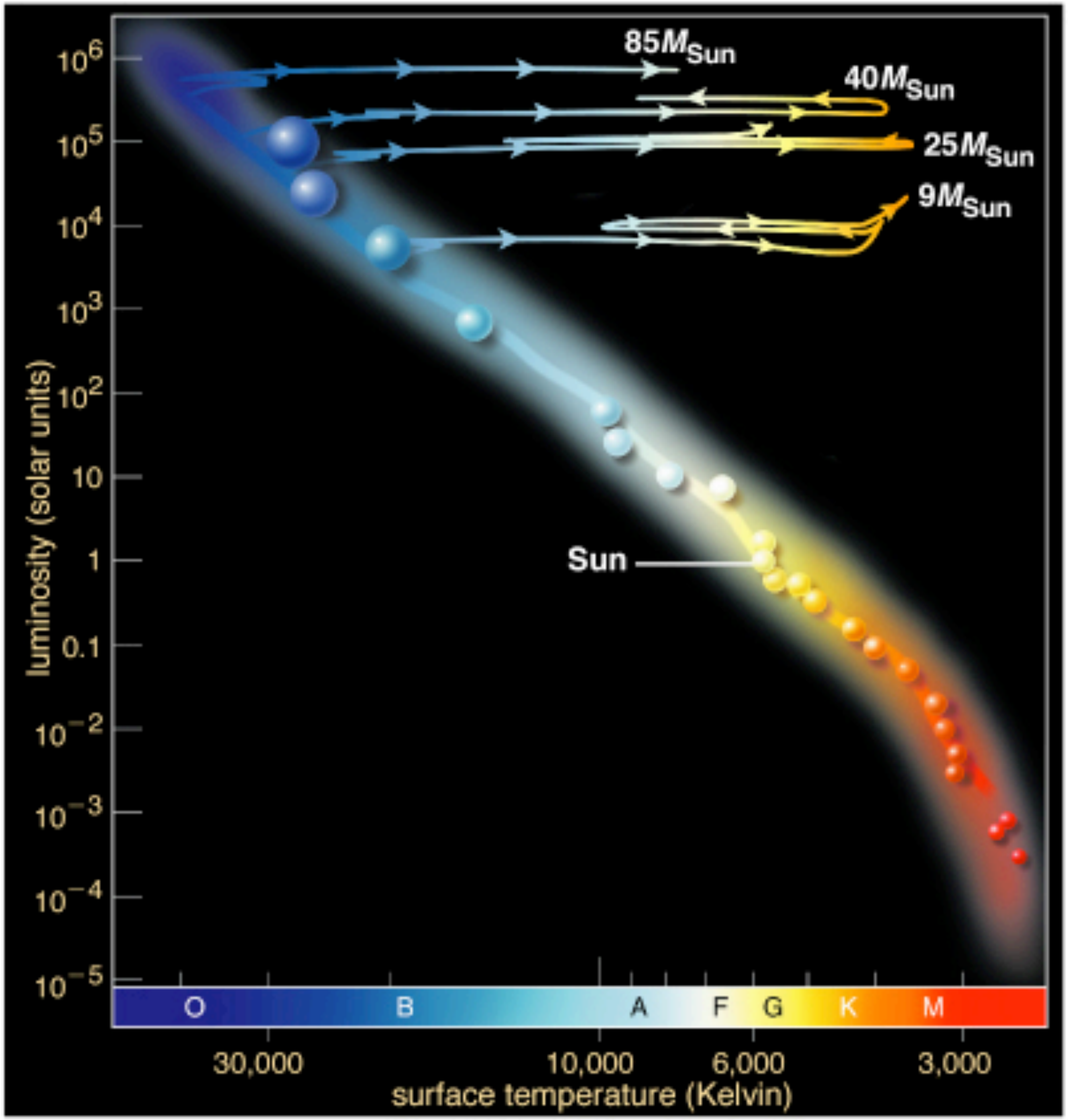
Pulsating yellow giant

Red giant

Supernova explosion

Black hole or neutron star

The life track of massive stars



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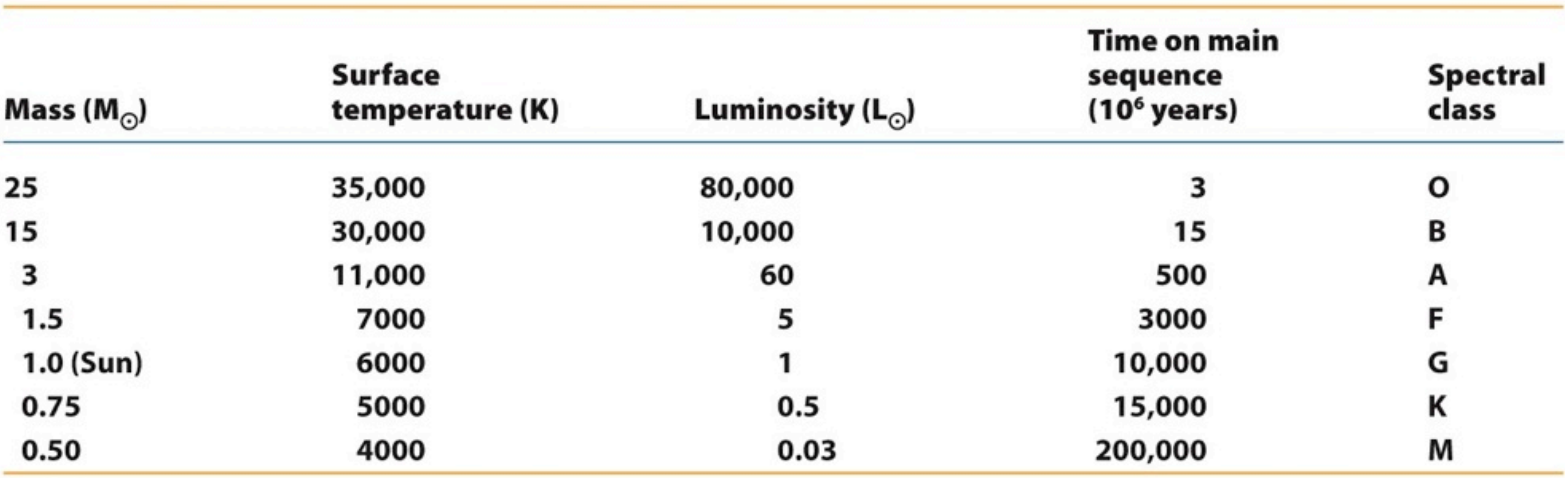
- Massive stars reach main sequence fast, ~0.1 Myr

- More massive stars evolve faster: O-stars explode only after ~ few Myr only!

The Lifetimes of Stars



Mass ($M_\odot$)	Surface temperature (K)	Luminosity ($L_\odot$)	Time on main sequence (10^6 years)	Spectral class
25	35,000	80,000	3	O
15	30,000	10,000	15	B
3	11,000	60	500	A
1.5	7000	5	3000	F
1.0 (Sun)	6000	1	10,000	G
0.75	5000	0.5	15,000	K
0.50	4000	0.03	200,000	M

Table 12-2
Discovering the Universe, Eighth Edition

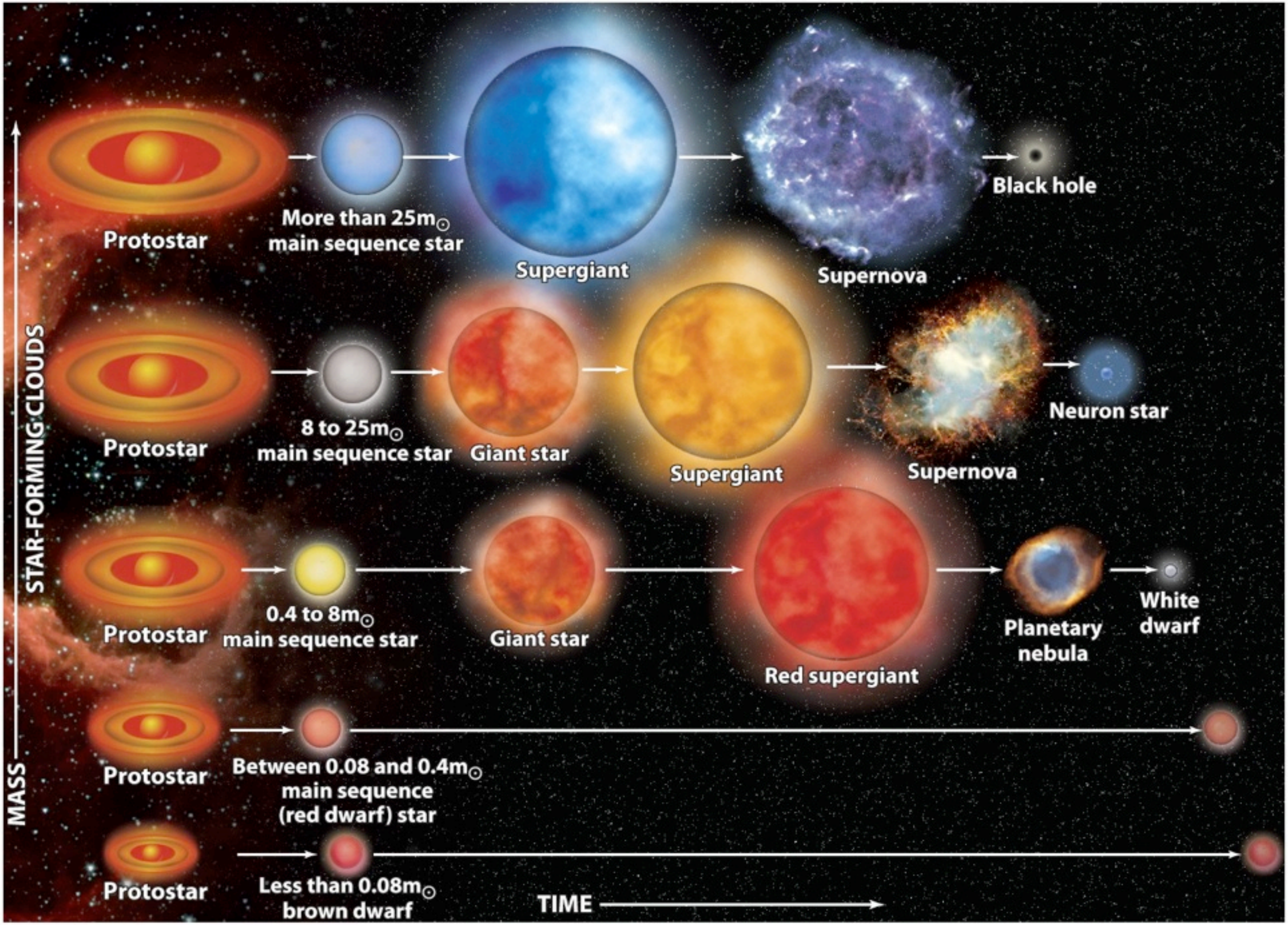


Figure 13-28a
Discovering the Universe, Eighth Edition

Orion nebula: Trapezium cluster

The 4 trapezium stars: Brightest, young stars (< 2 million years old) in the central region of the Orion nebula

Infrared image: ~ 50 very young, cool, low-mass stars

X-ray image: ~ 1000 very young, hot stars

Other star clusters: discerning ages via stellar evolution

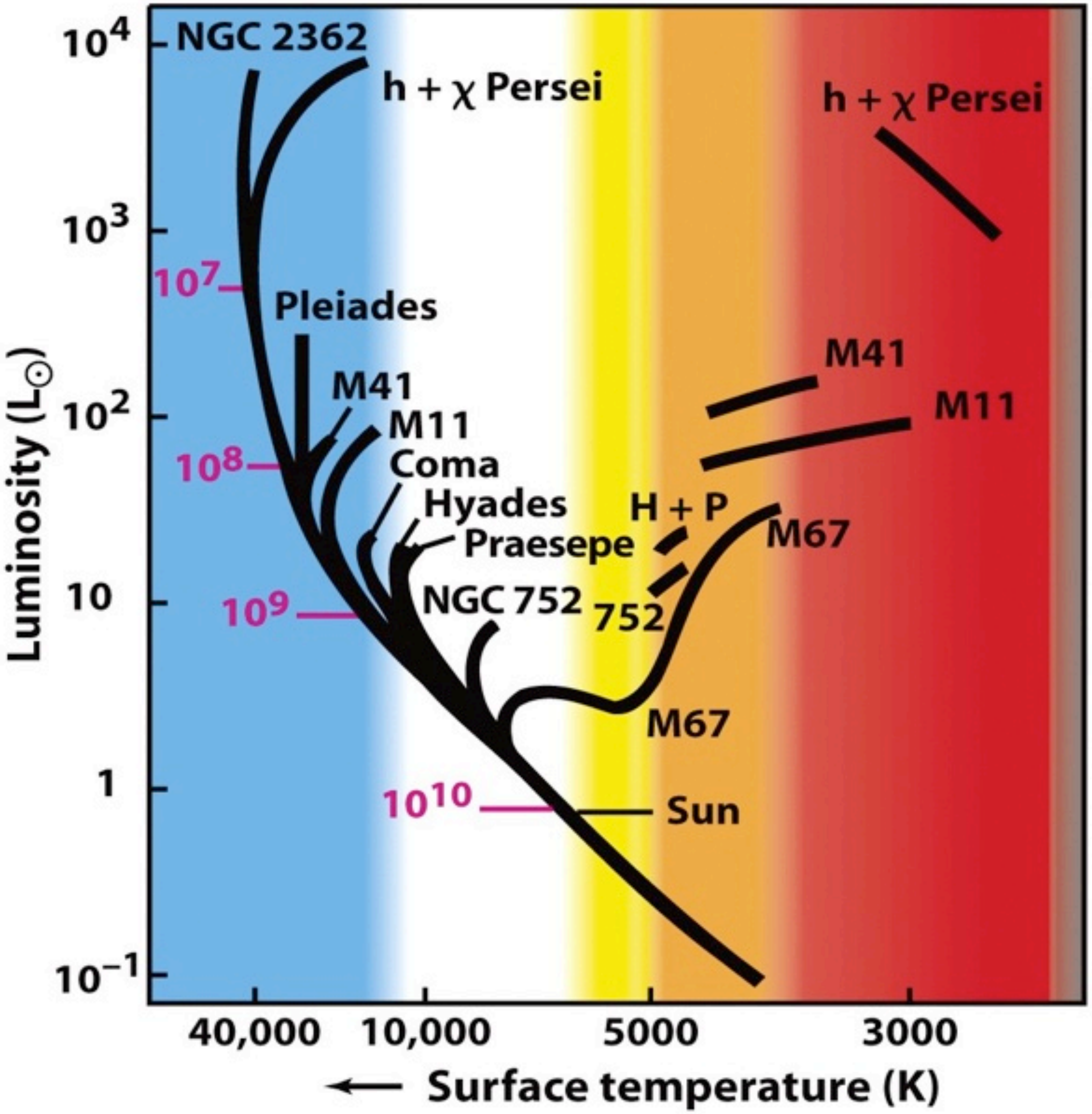


Figure 12-30b

Homework

1a) What is a lifetime of a 30 M_{Sun} star ($L_* = 50\ 000\ L_{Sun}$)?

1b) What is a lifetime of a 0.1 M_{Sun} star ($L_* = 10^{-5}\ L_{Sun}$)?

2) Why early stars were more massive then stars formed today?

3) Taking parameters of the Sun, $L_{sun} = 4 \times 10^{33}$ erg/s, $M_{sun} = 2 \times 10^{33}$ g, R_{sun}=699000 km, calculate its average density and average energy production rate per unit mass

4) How Universe would look like if there were no stars more massive than the Sun?

The End