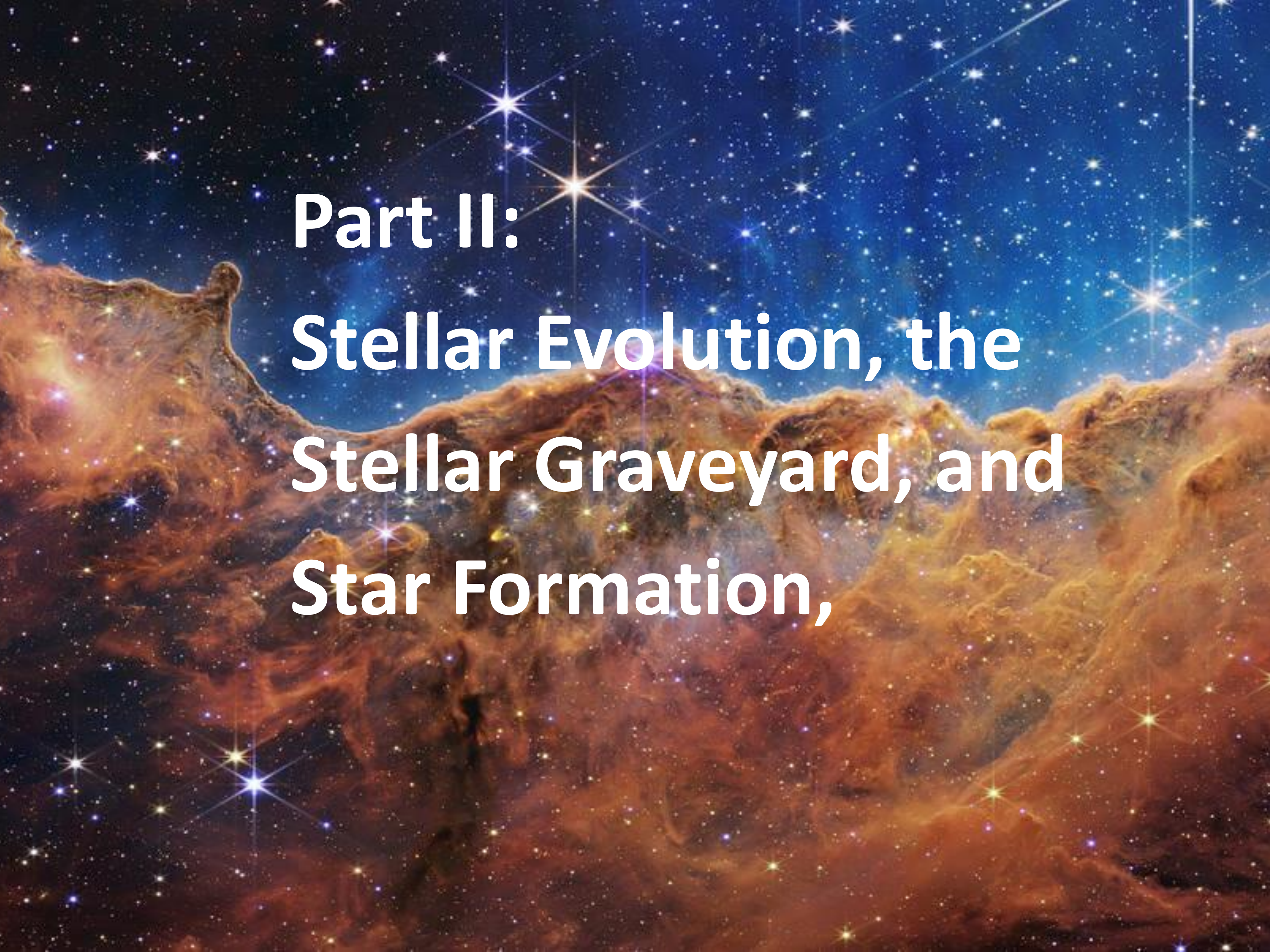
Stars:
Part I: The Building Blocks of the Universe

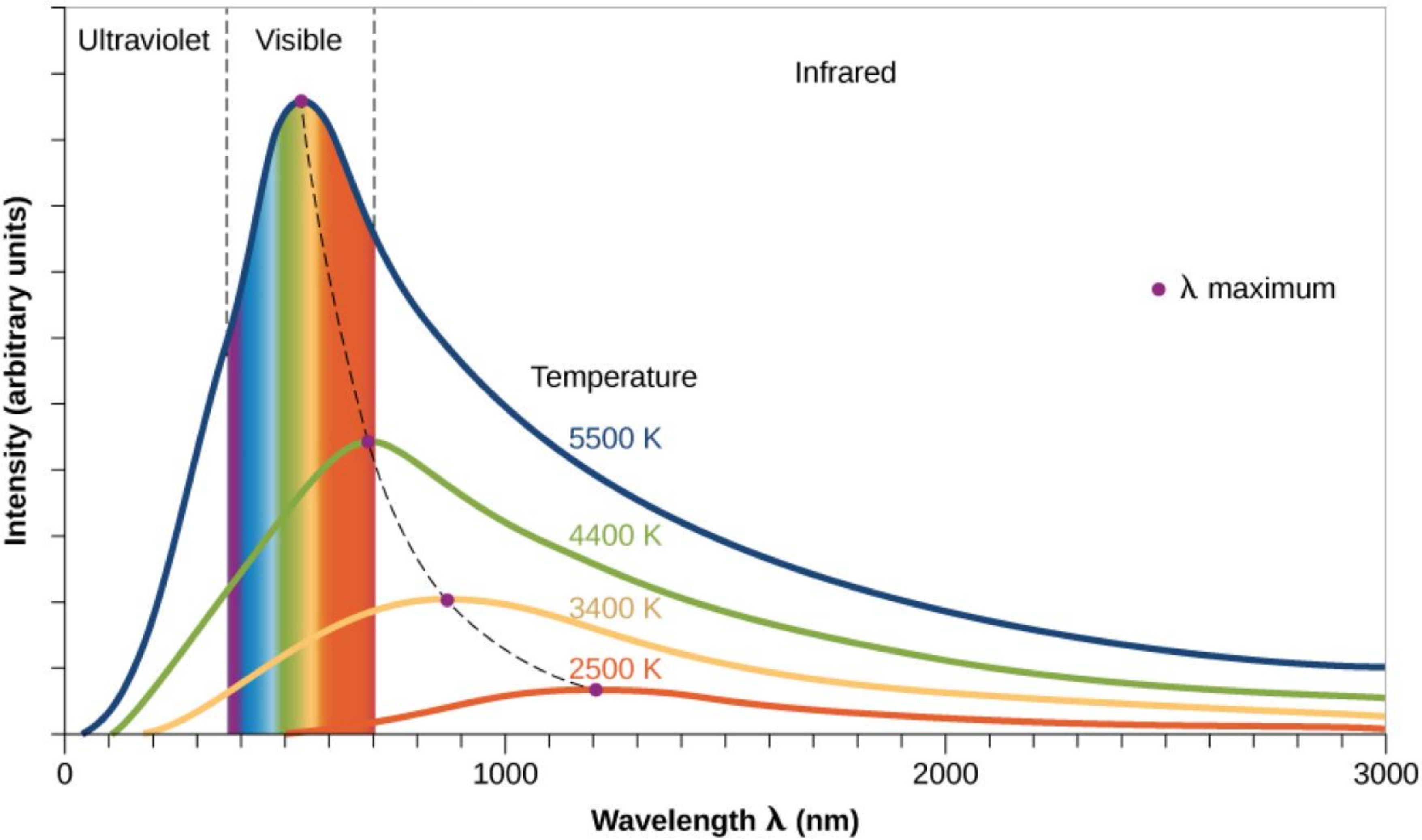


Part II:
Stellar Evolution, the Stellar Graveyard, and Star Formation,

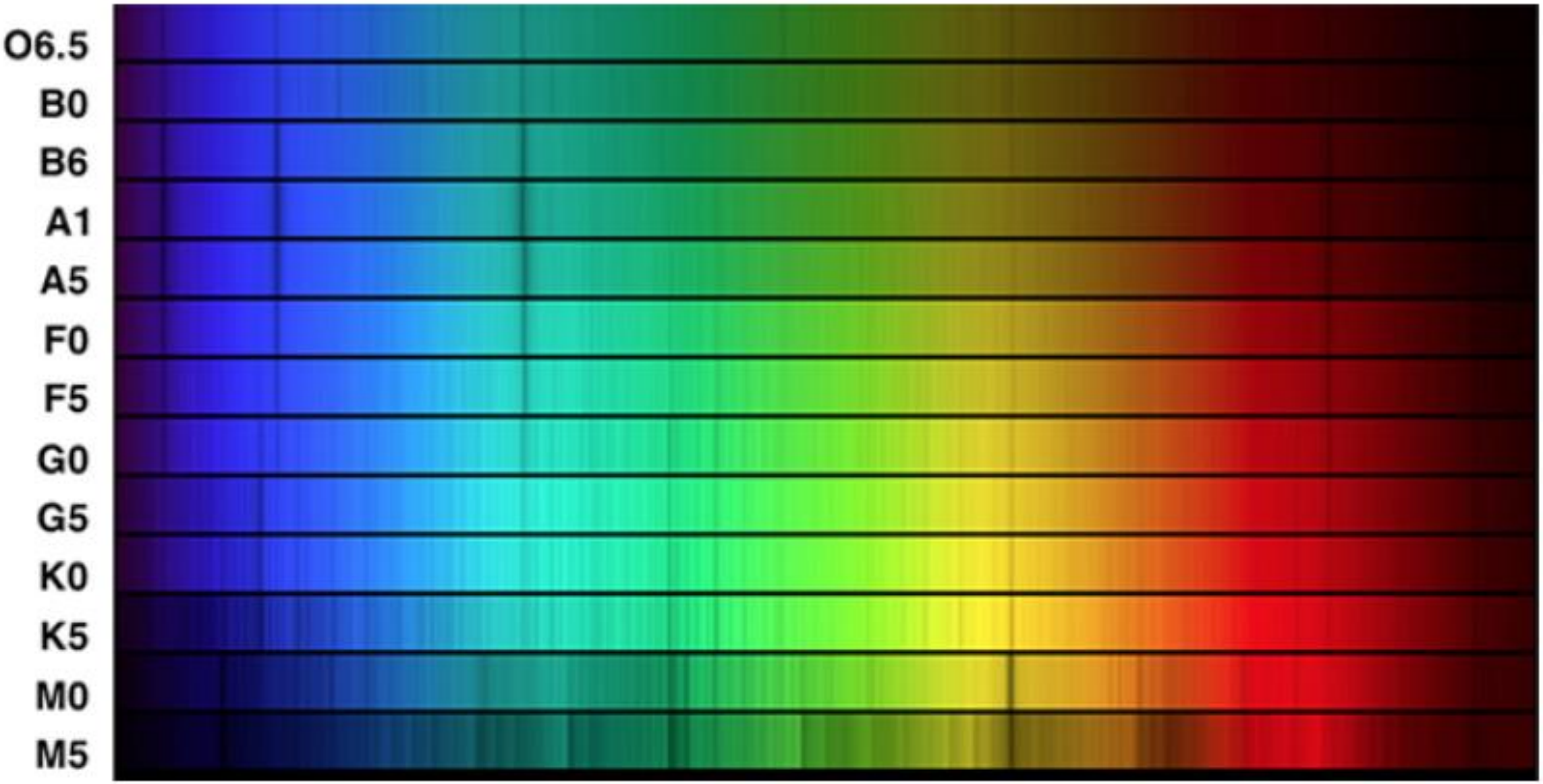
Questions on homework?

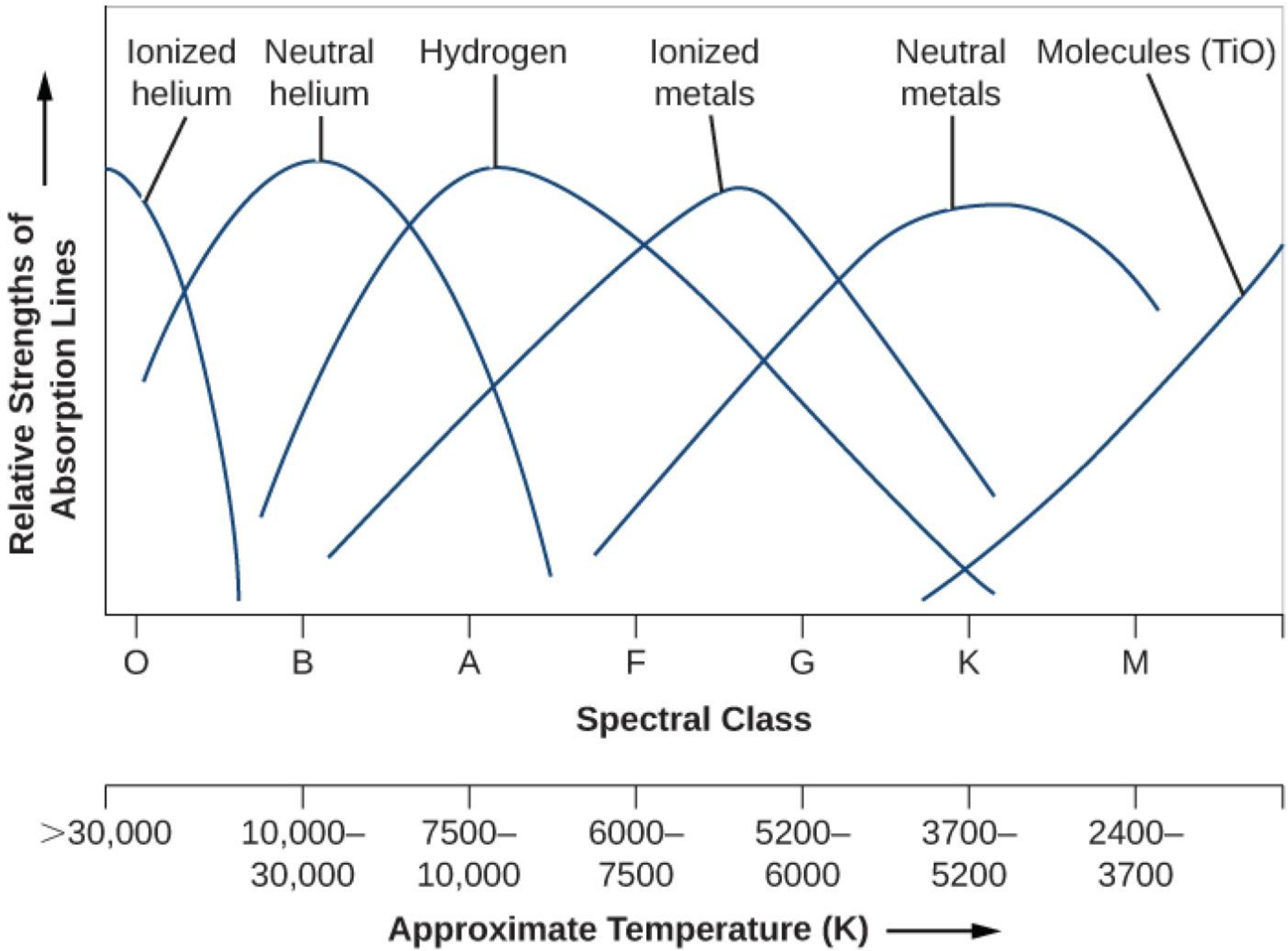
Blackbody emission: hotter things emit at higher energies (=shorter wavelengths)

Peak of blackobody: $$\lambda_{\mathrm{max}} \cdot T = 0.288 \text{ cm} \cdot \text{K}$$



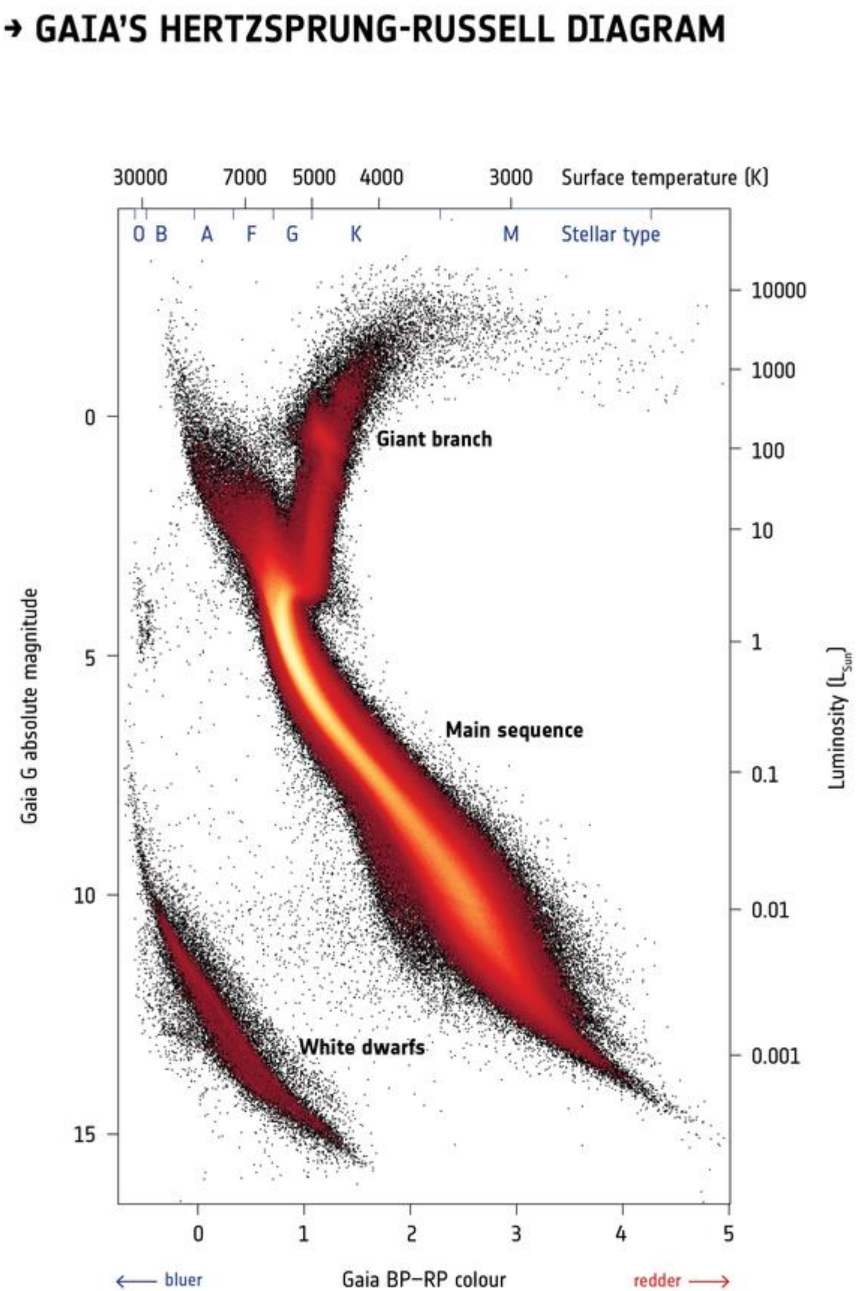
Spectral type = temperature squence





Ionized helium
Neutral helium
Hydrogen
Ionized metals
Neutral metals
Molecules (TiO)
Relative Strengths of Absorption Lines
O
B
A
F
G
K
M
Spectral Class
>30,000
10,000–30,000
7500–10,000
6000–7500
5200–6000
3700–5200
2400–3700
Approximate Temperature (K)

HR diagram (Hertsprung-Russell)



Main sequence:

- most stars on main sequence
- Defined by hydrogen burning

Stars in other locations:

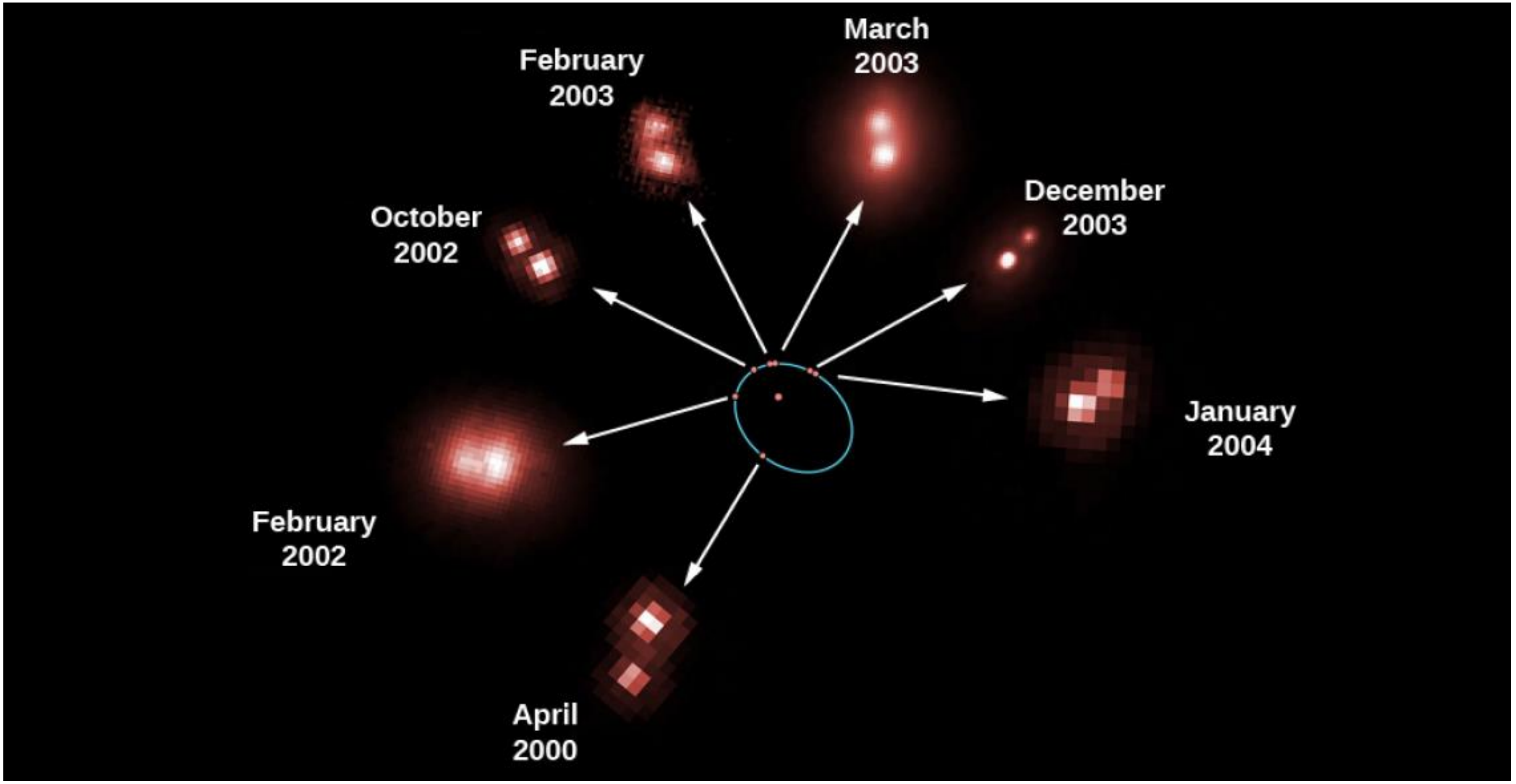
- Stellar evolution! (age)

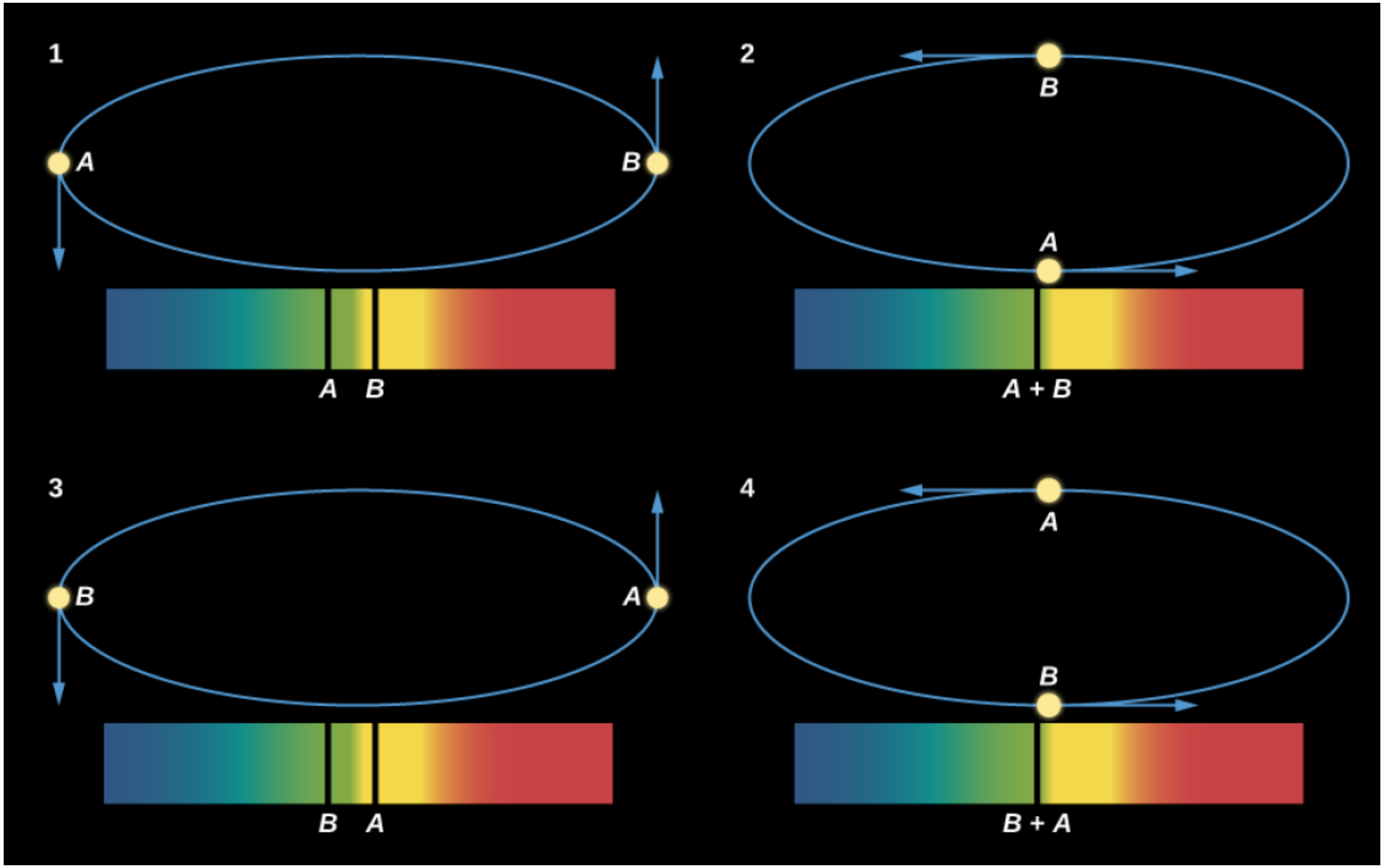
The Abundance of Elements in the Sun

Element	Percentage by Number of Atoms	Percentage By Mass
Hydrogen	92.0	73.4
Helium	7.8	25.0
Carbon	0.02	0.20
Nitrogen	0.008	0.09
Oxygen	0.06	0.80
Neon	0.01	0.16
Magnesium	0.003	0.06
Silicon	0.004	0.09
Sulfur	0.002	0.05
Iron	0.003	0.14

Measuring the Characteristics of Stars

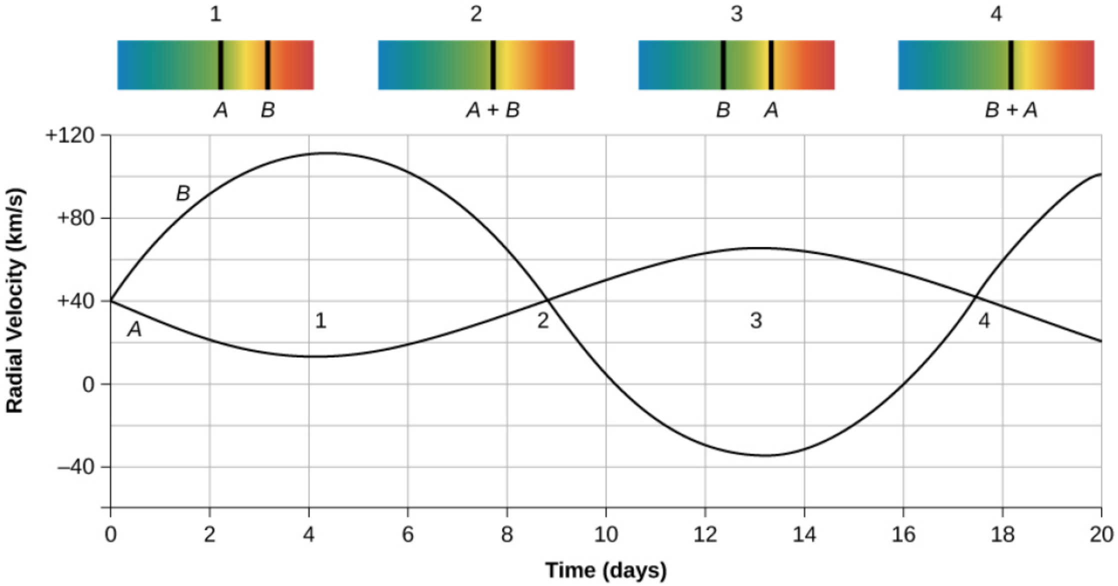
Characteristic	Technique
Surface temperature	1. Determine the color (very rough). 2. Measure the spectrum and get the spectral type.
Chemical composition	Determine which lines are present in the spectrum.
Luminosity	Measure the apparent brightness and compensate for distance.
Radial velocity	Measure the Doppler shift in the spectrum.
Rotation	Measure the width of spectral lines.
Mass	Measure the period and radial velocity curves of spectroscopic binary stars.
Diameter	1. Measure the way a star’s light is blocked by the Moon. 2. Measure the light curves and Doppler shifts for eclipsing binary stars.

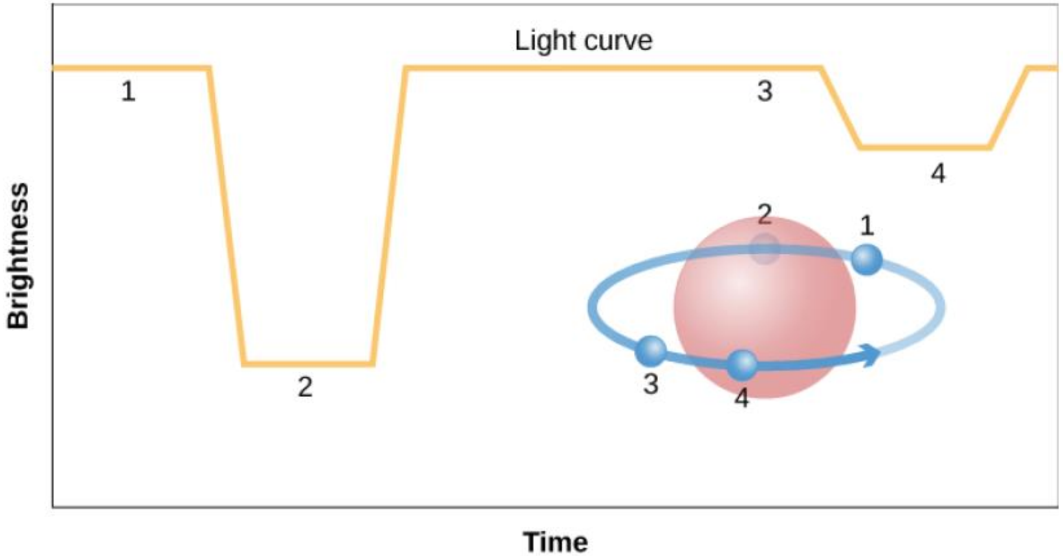

March
2003
February
2003
December
2003
October
2002
January
2004
February
2002
April
2000



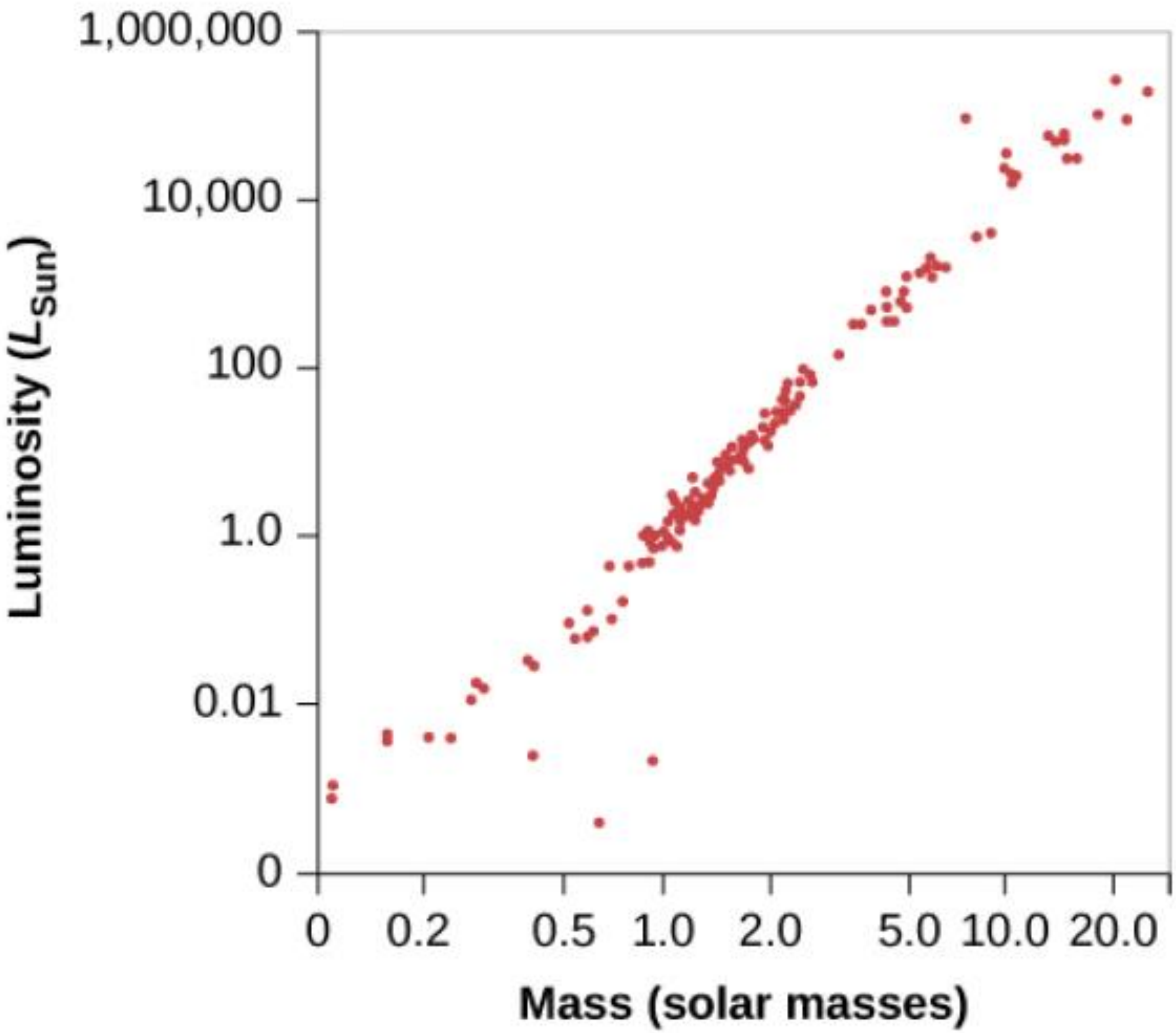
1
A
B
A
B
2
B
A
A + B
3
B
A
B
A
4
A
B
B + A

Stellar masses from radial velocity and gravity

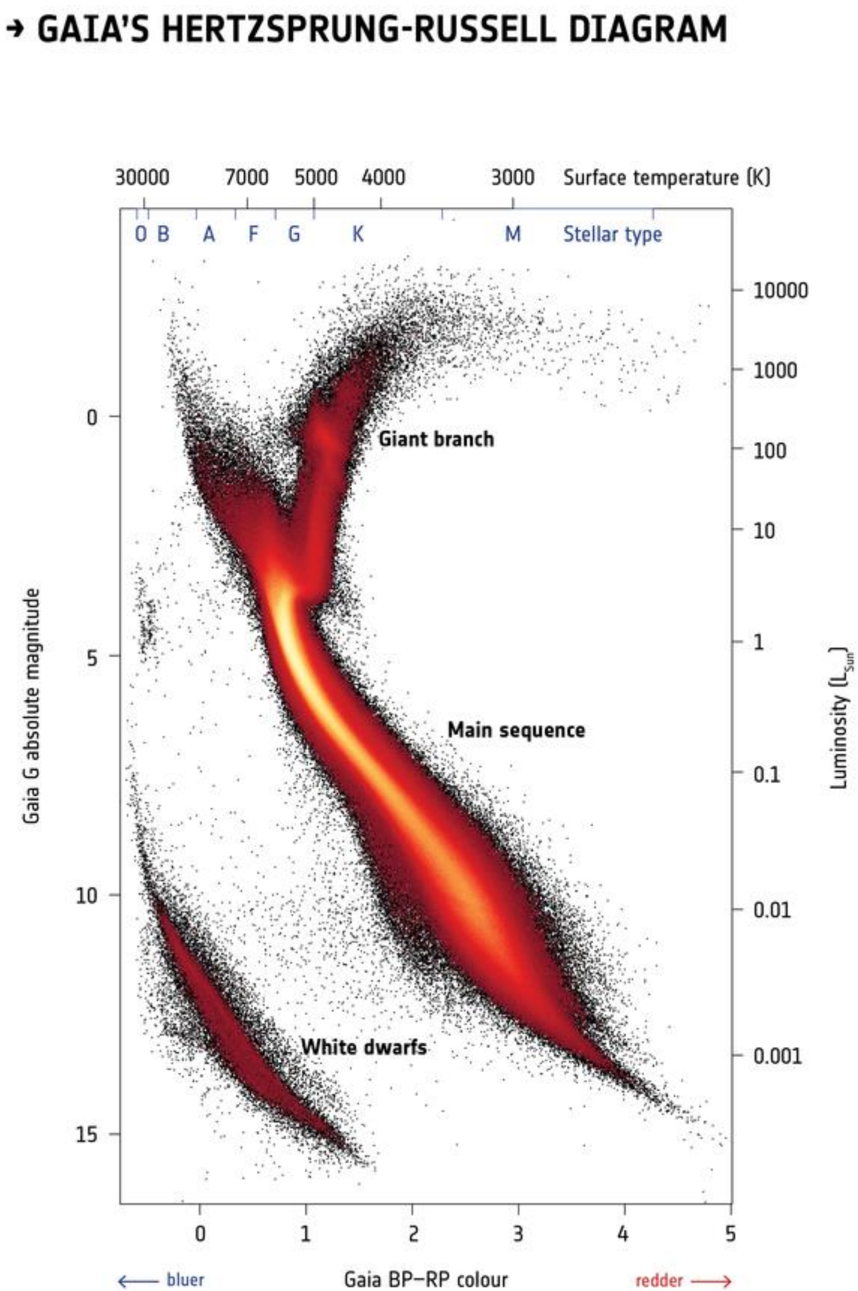




Eclipsing binary systems: Benchmarks for stellar masses



1,000,000
10,000
100
1.0
0.01
0
Luminosity (L_{Sun})
0
0.2
0.5
1.0
2.0
5.0
10.0
20.0
Mass (solar masses)



HR diagram (Hertsprung-Russell)

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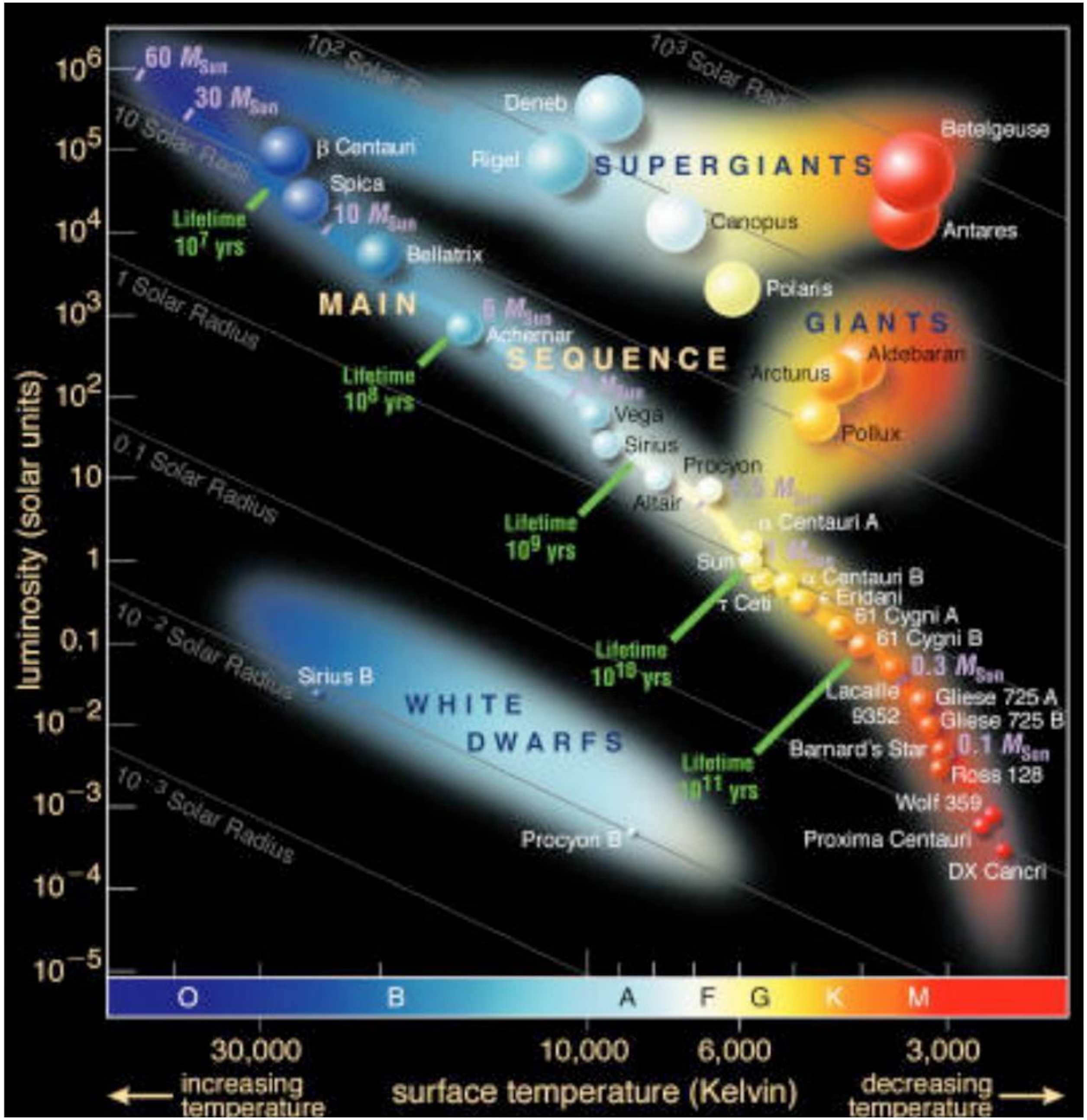
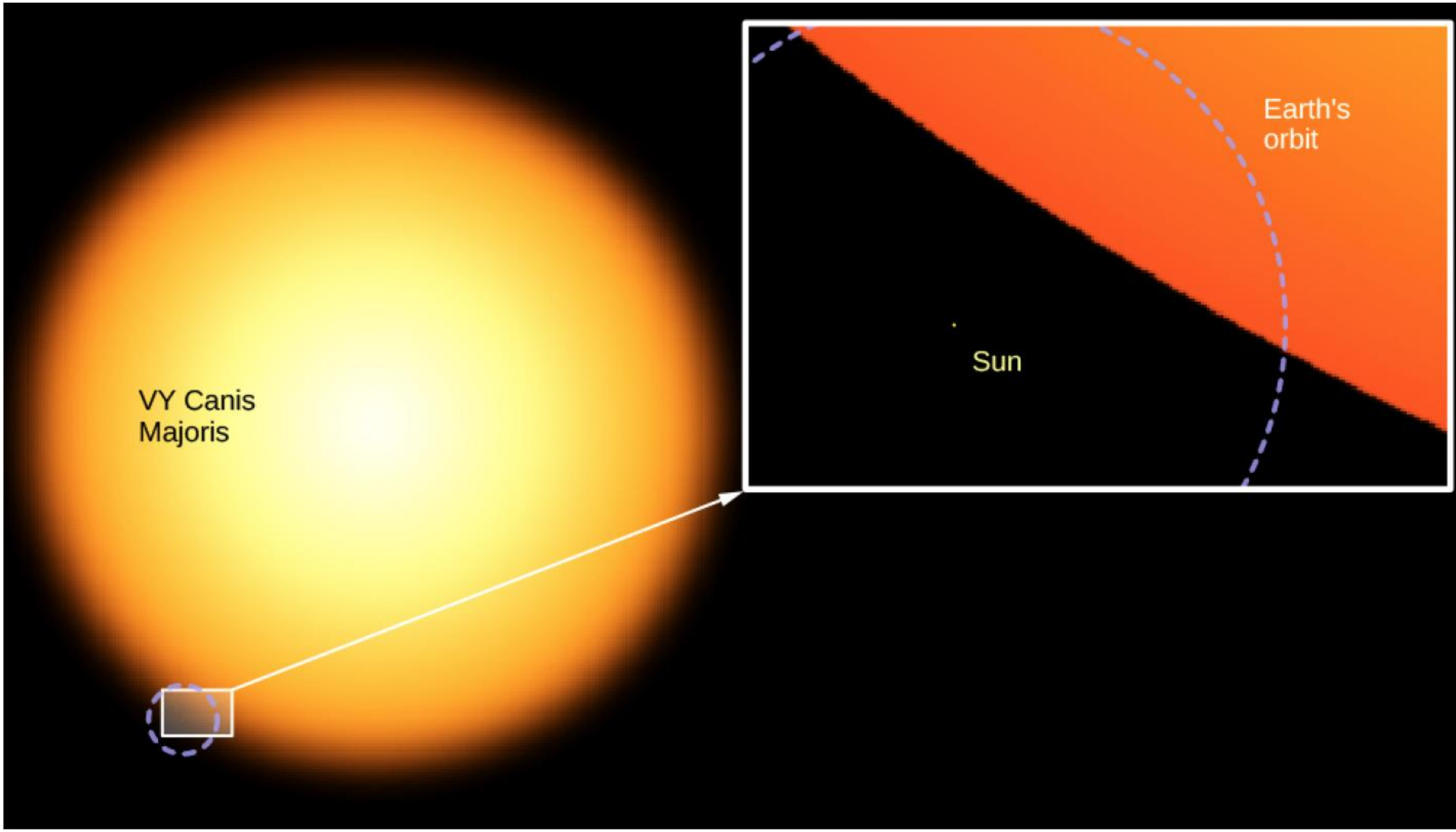
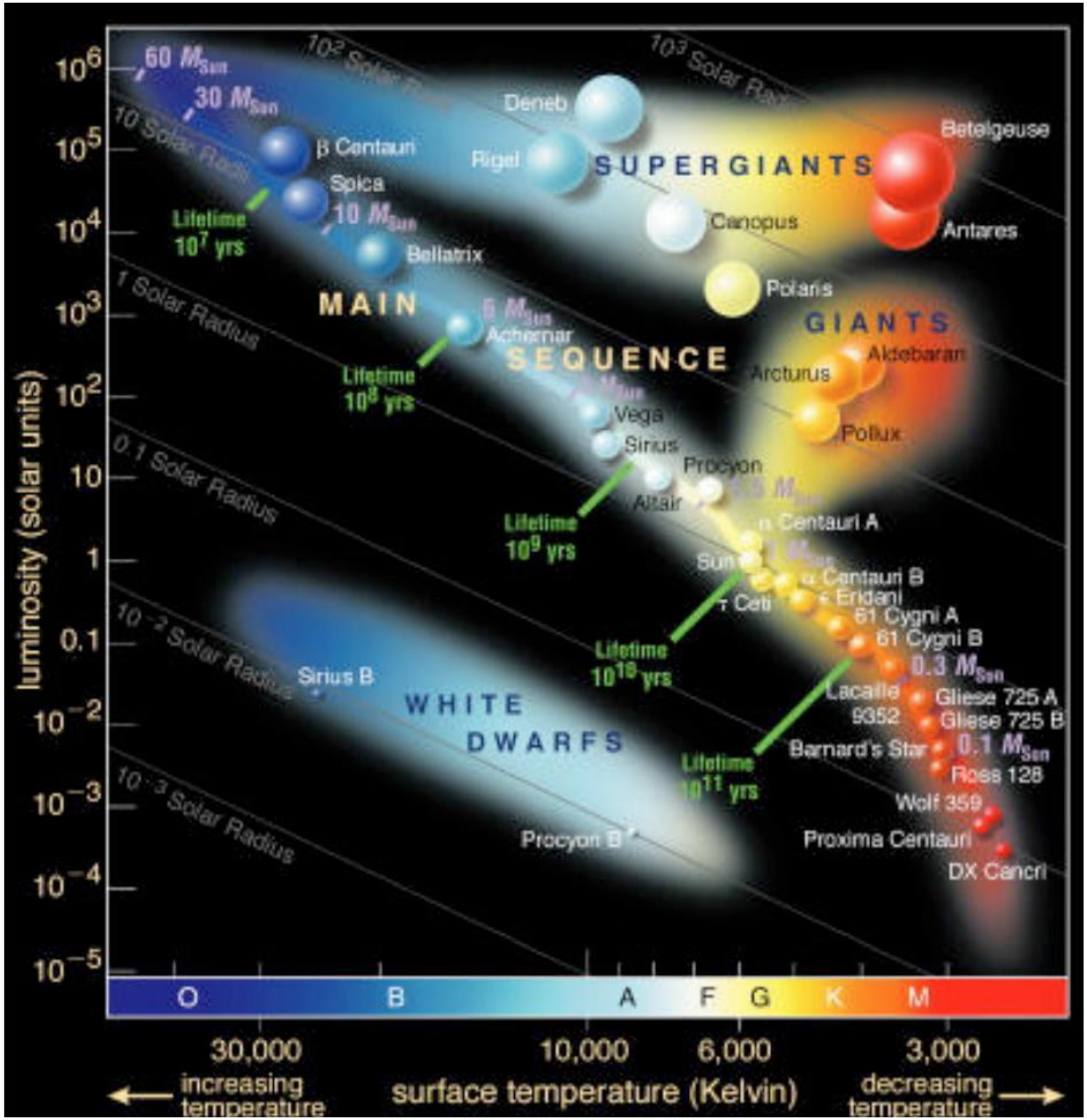

luminosity (solar units)
surface temperature (Kelvin)
increasing temperature
decreasing temperature
30,000
10,000
6,000
3,000
O
B
A
F
G
K
M
MAIN
SEQUENCE
SUPERGIANTS
GIANTS
WHITE
DWARFS
10 Solar Radii
1 Solar Radius
0.1 Solar Radius
10^-2 Solar Radius
10^-3 Solar Radius
60 M_Sun
30 M_Sun
10 M_Sun
1 M_Sun
0.3 M_Sun
0.1 M_Sun
Lifetime 10^7 yrs
Lifetime 10^8 yrs
Lifetime 10^9 yrs
Lifetime 10^10 yrs
Lifetime 10^11 yrs
Deneb
Rigel
β Centauri
Spica
Bellatrix
Achernar
Betelgeuse
Antares
Canopus
Polaris
Aldebaran
Arcturus
Pollux
Vega
Sirius
Procyon
Altair
α Centauri A
Sun
α Centauri B
τ Ceti
ε Eridani
61 Cygni A
61 Cygni B
Lacaille 9352
Gliese 725 A
Gliese 725 B
Barnard's Star
Ross 128
Wolf 359
Proxima Centauri
DX Cancri
Sirius B
Procyon B

Characteristics of Main-Sequence Stars

Spectral Type	Mass (Sun = 1)	Luminosity (Sun = 1)	Temperature	Radius (Sun = 1)
O5	40	7×10^5	40,000 K	18
B0	16	2.7×10^5	28,000 K	7
A0	3.3	55	10,000 K	2.5
F0	1.7	5	7500 K	1.4
G0	1.1	1.4	6000 K	1.1
K0	0.8	0.35	5000 K	0.8
M0	0.4	0.05	3500 K	0.6

Evolved stars: red giants, can be huge!





luminosity (solar units)
surface temperature (Kelvin)
increasing temperature
decreasing temperature
30,000
10,000
6,000
3,000
O
B
A
F
G
K
M
SUPERGIANTS
GIANTS
MAIN
SEQUENCE
WHITE
DWARFS
Deneb
Rigel
Betelgeuse
Antares
Canopus
Polaris
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Arcturus
Pollux
β Centauri
Spica
Bellatrix
Achernar
Vega
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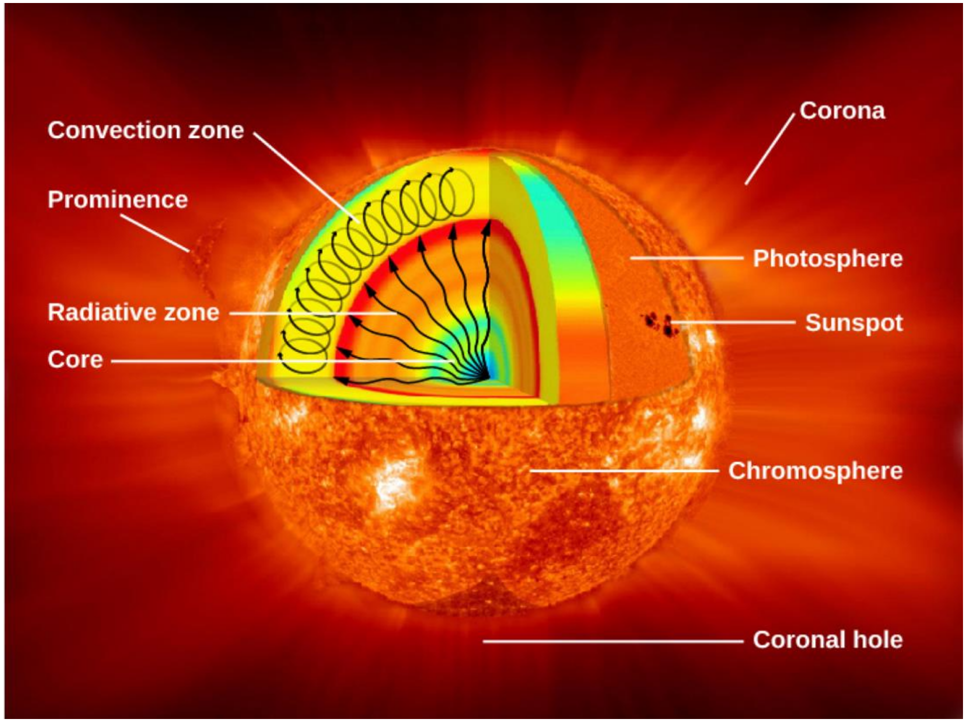
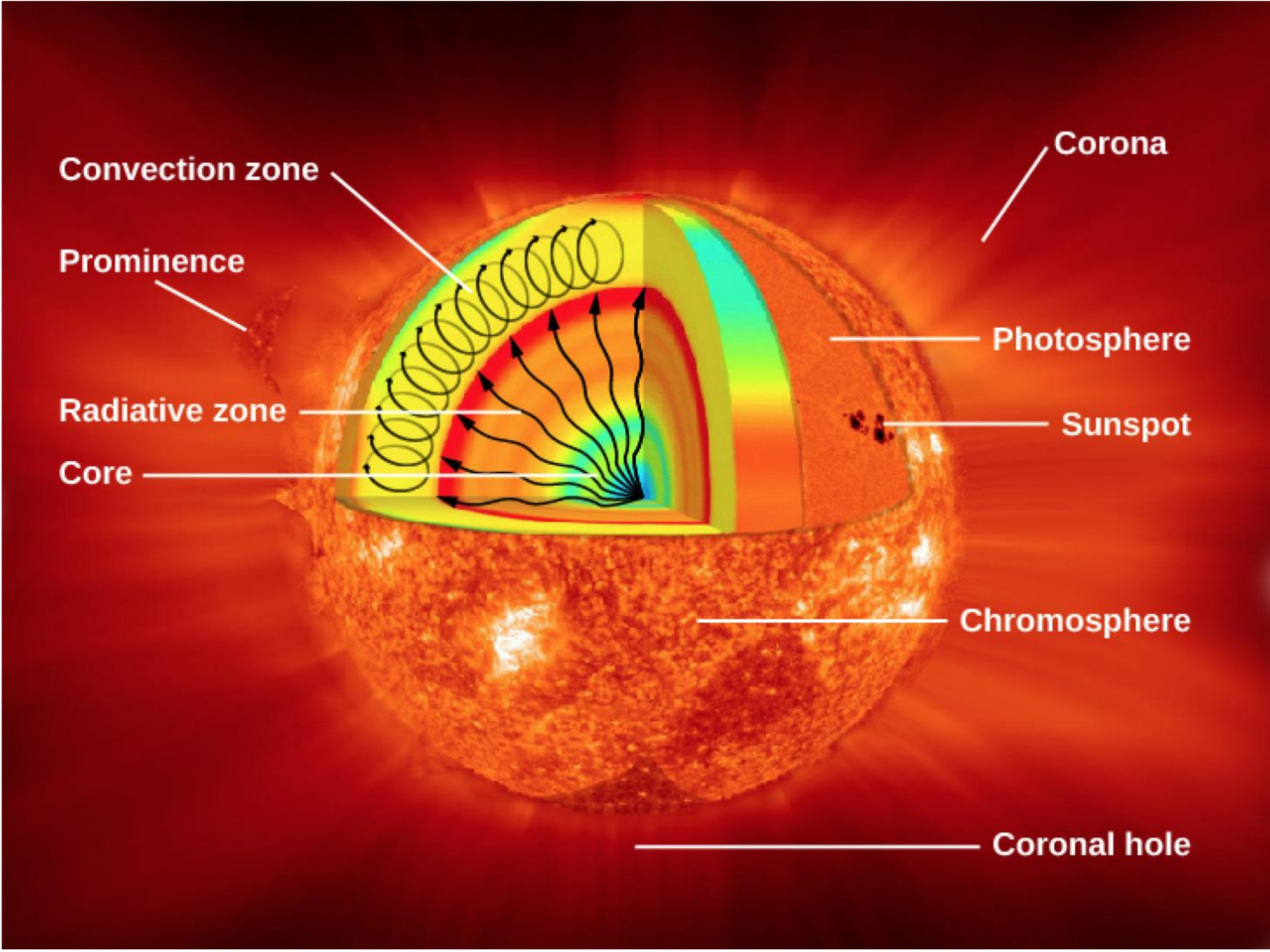
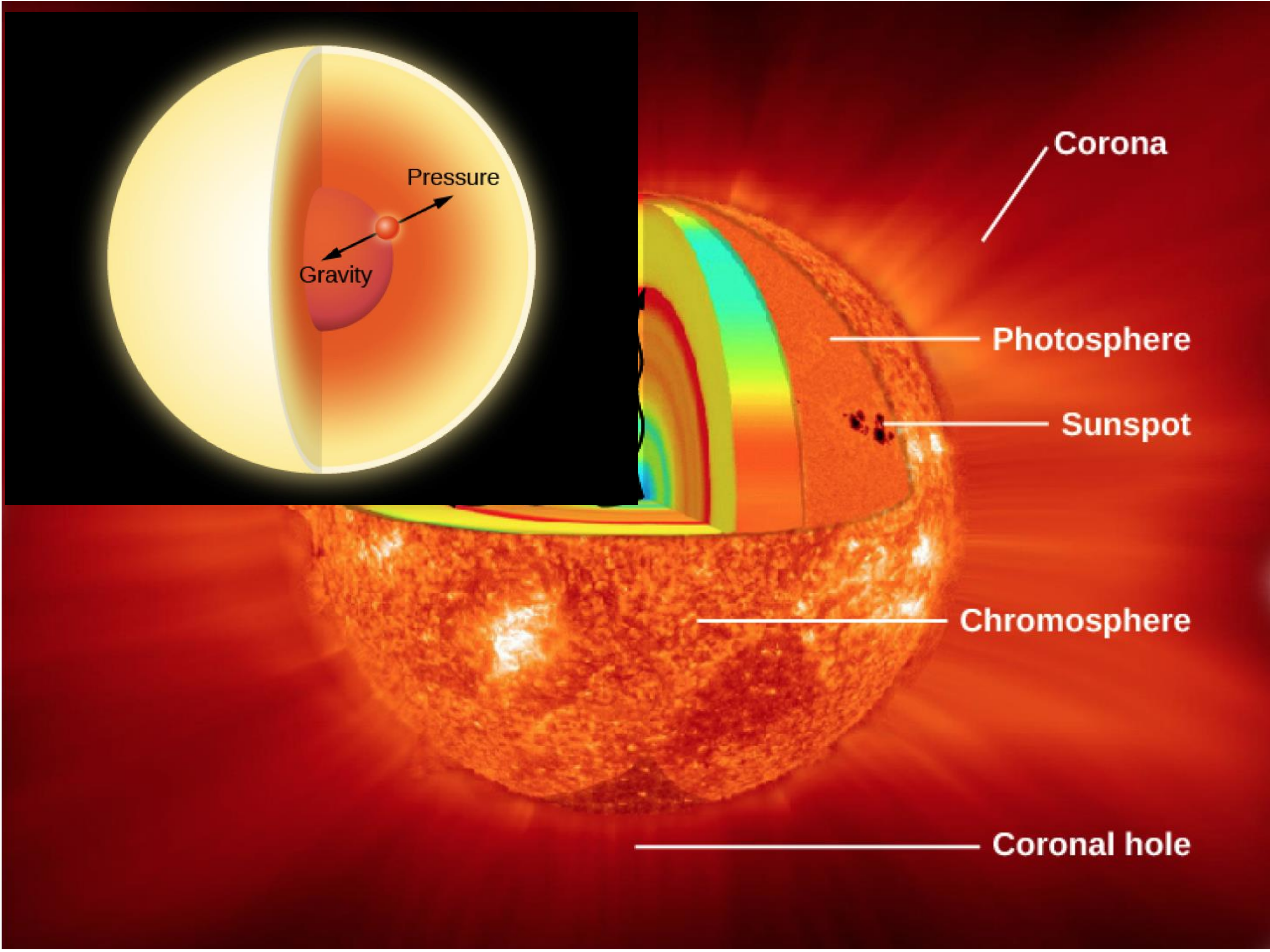
60 M_{Sun}
30 M_{Sun}
10 M_{Sun}
6 M_{Sun}
0.3 M_{Sun}
0.1 M_{Sun}
Lifetime 10^7 yrs
Lifetime 10^8 yrs
Lifetime 10^9 yrs
Lifetime 10^{10} yrs
Lifetime 10^{11} yrs
10^2 Solar Radii
10^3 Solar Radii
10 Solar Radii
1 Solar Radius
0.1 Solar Radius
10^{-2} Solar Radius
10^{-3} Solar Radius
10^6
10^5
10^4
10^3
10^2
10
1
0.1
10^{-2}
10^{-3}
10^{-4}
10^{-5}

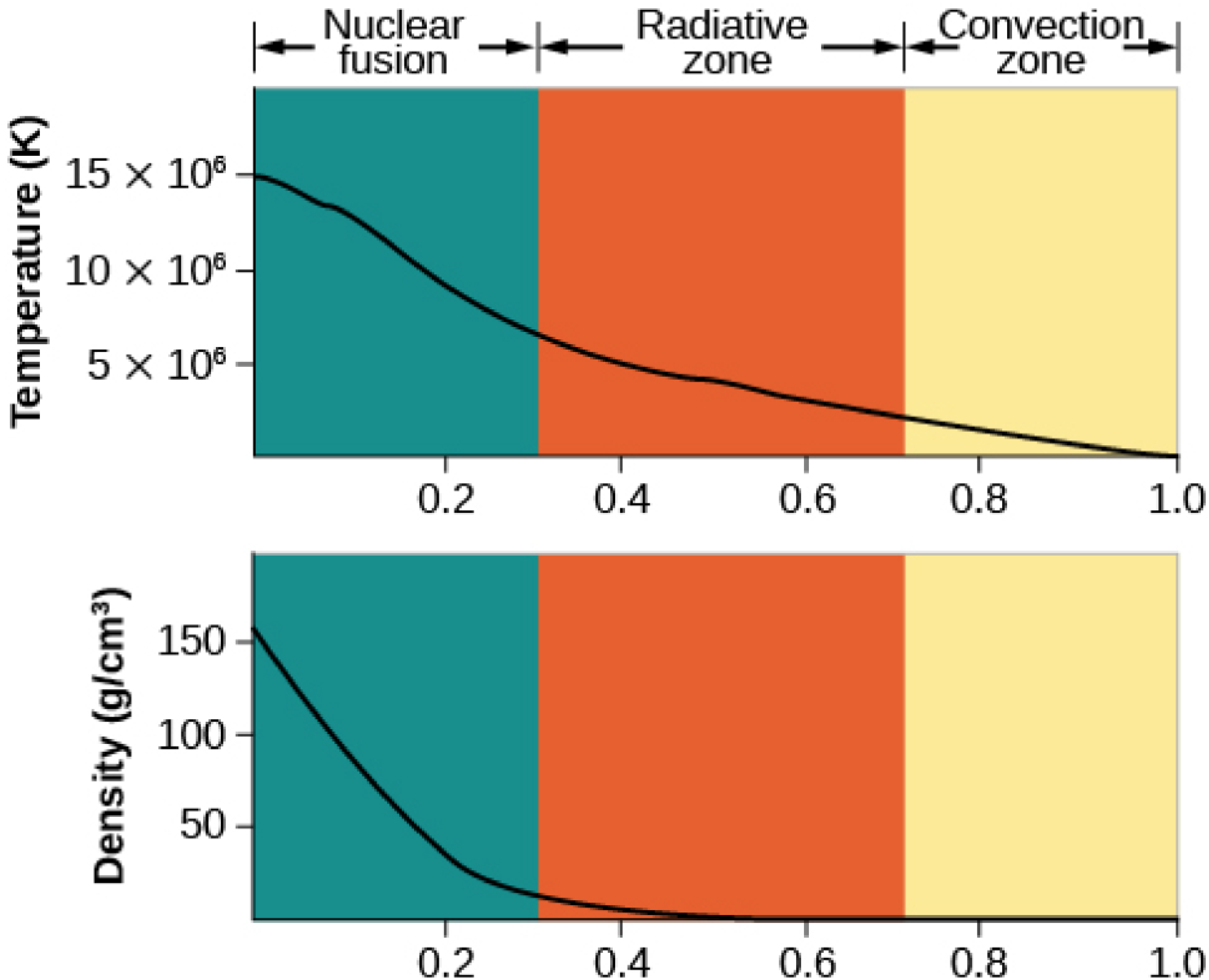
Where does the sun's energy come from? Hydrogen burning and the interior of the sun




Corona
Convection zone
Prominence
Photosphere
Radiative zone
Sunspot
Core
Chromosphere
Coronal hole


Pressure
Gravity
Corona
Photosphere
Sunspot
Chromosphere
Coronal hole

Core of the sun: very dense, 15 million K

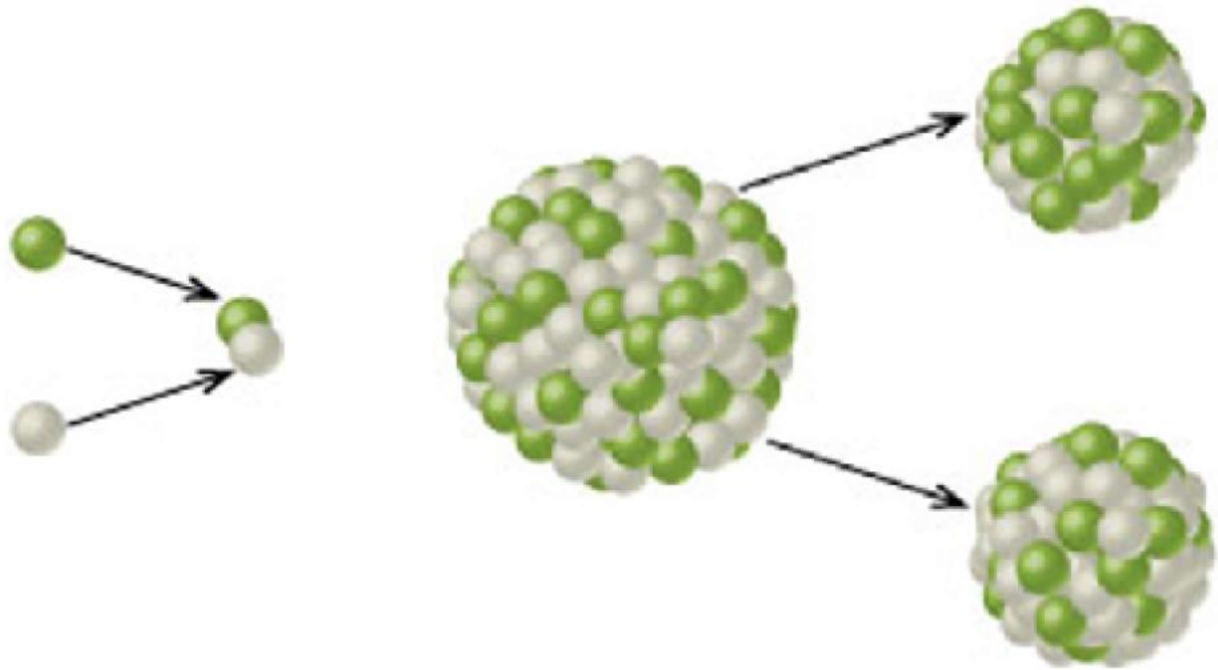


Fusion

2 light => 1 heavy

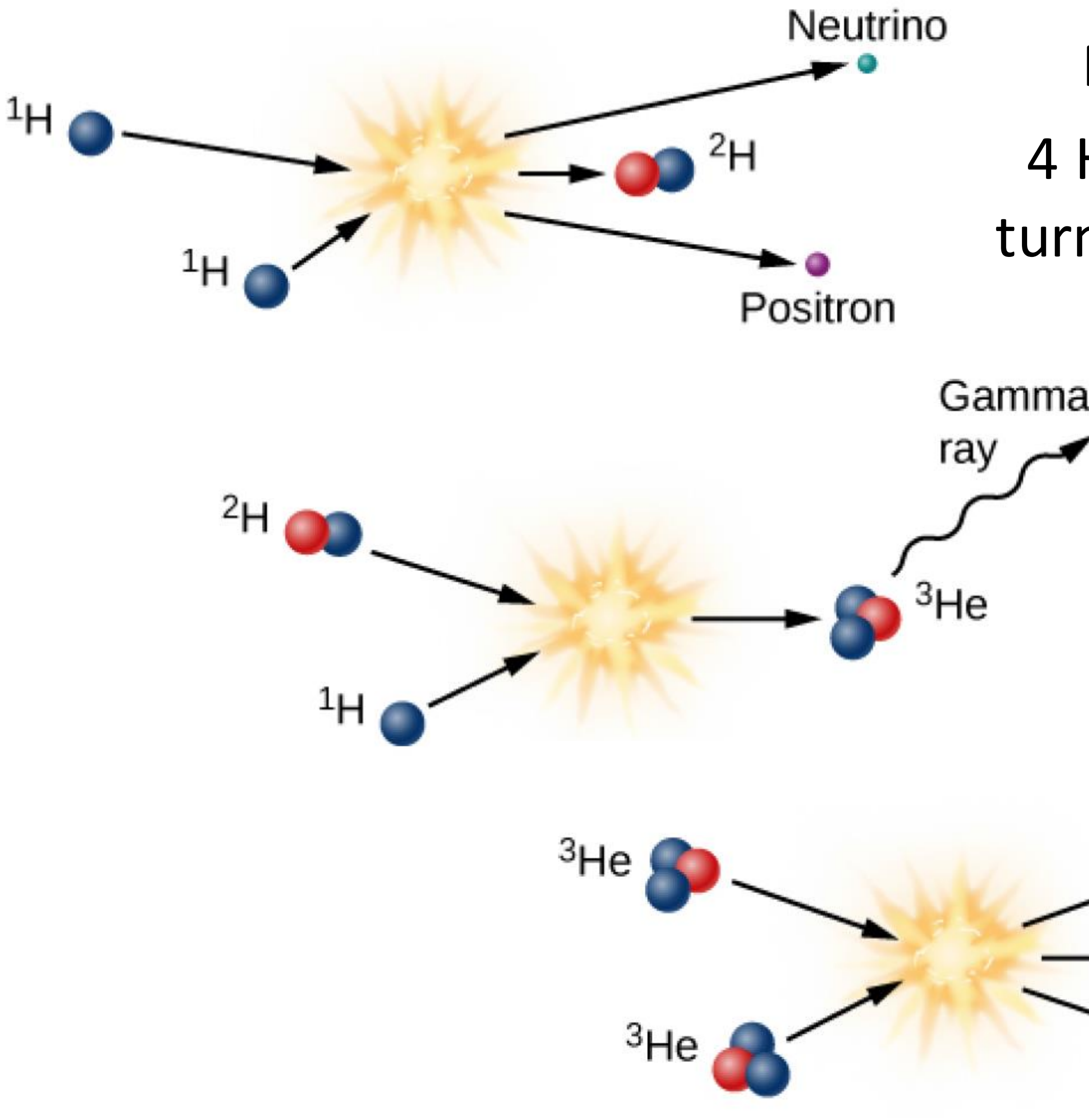
Fission

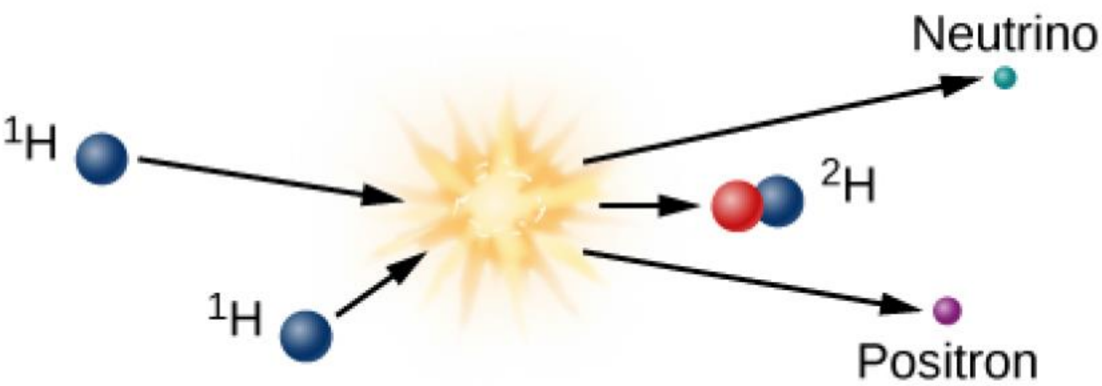
1 heavy => 2 light



Fusion at core

4 Hydrogen atoms turns into 1 He atom





Fusion at core

4 Hydrogen atoms turns into 1 He atom

Atomic weights

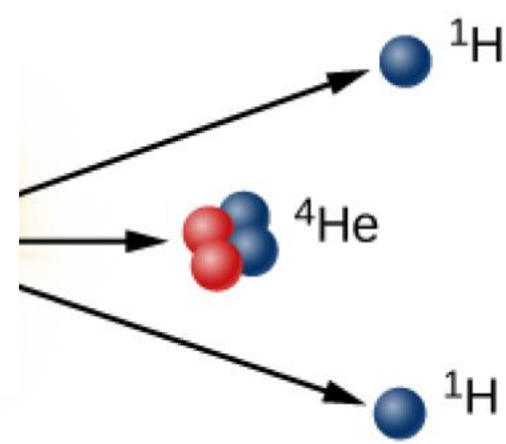
4 H: 4.032

1 He: 4.003

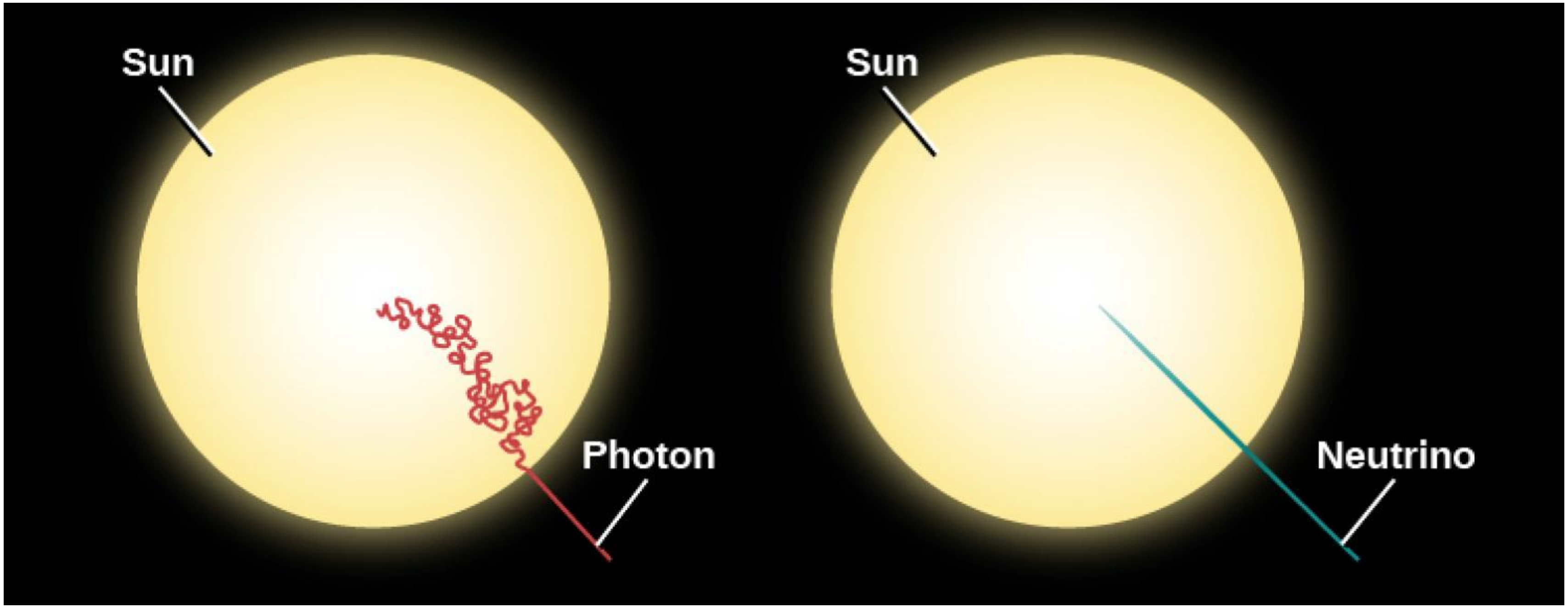
Lose 0.7% of the mass:
it turns into energy!

$$E=mc^2$$

(c=speed of light, E=energy, m=mass)



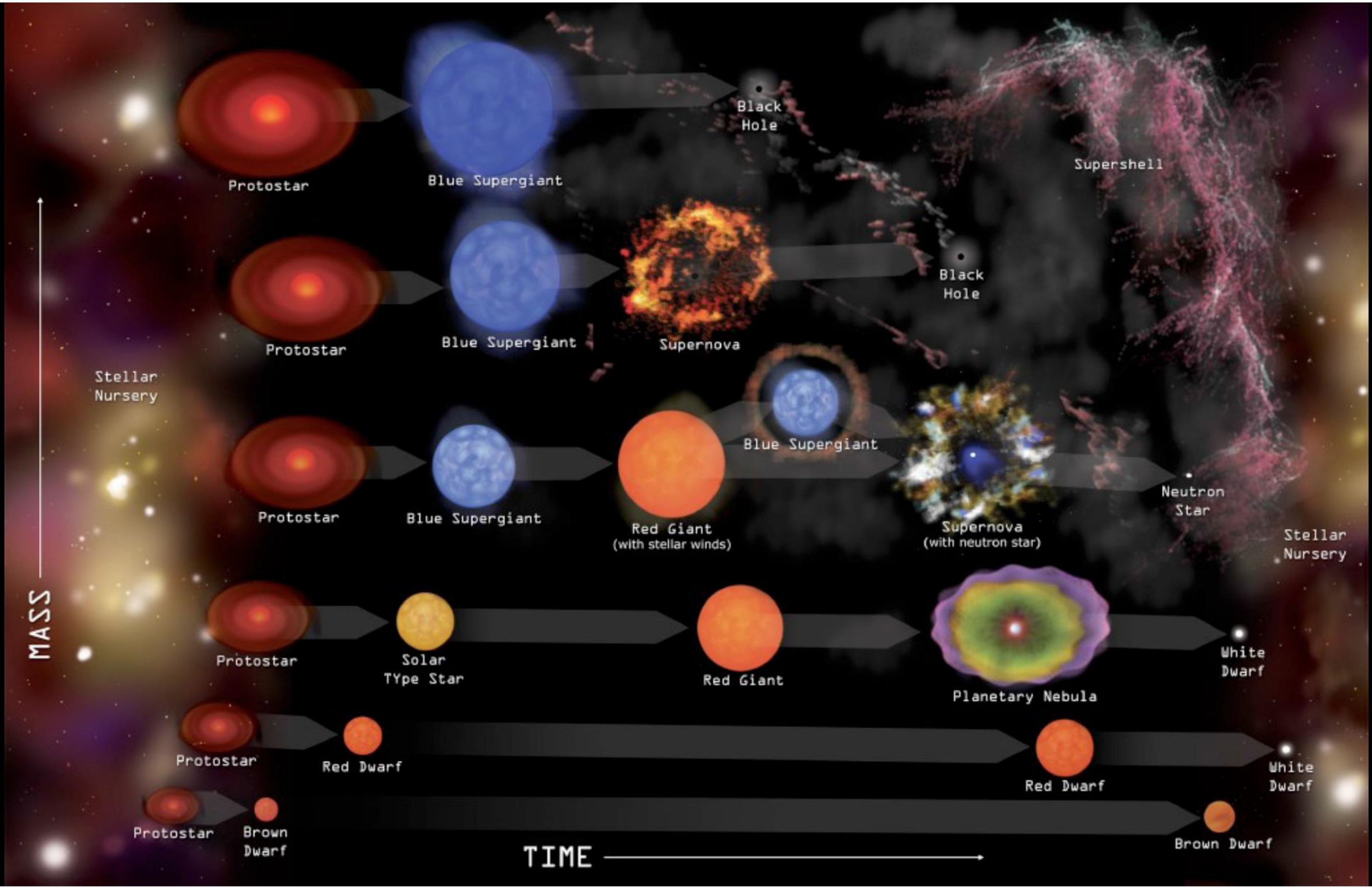
How long does it take energy to escape from the sun's core?



Most energy: 1 million years!

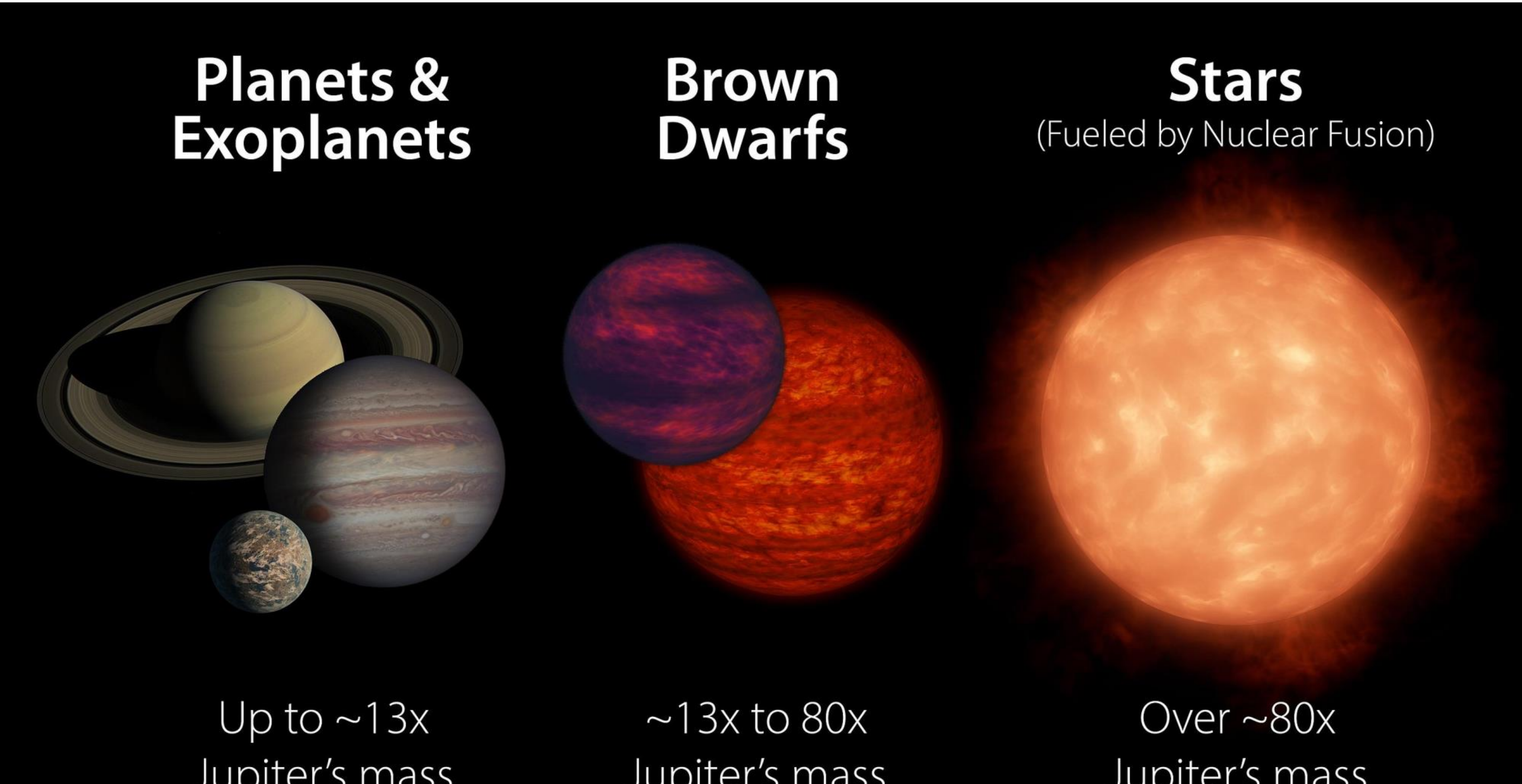
Neutrinos: do not interact with matter, so escapes immediately

Solar neutrino problem: recent Nobel Prize

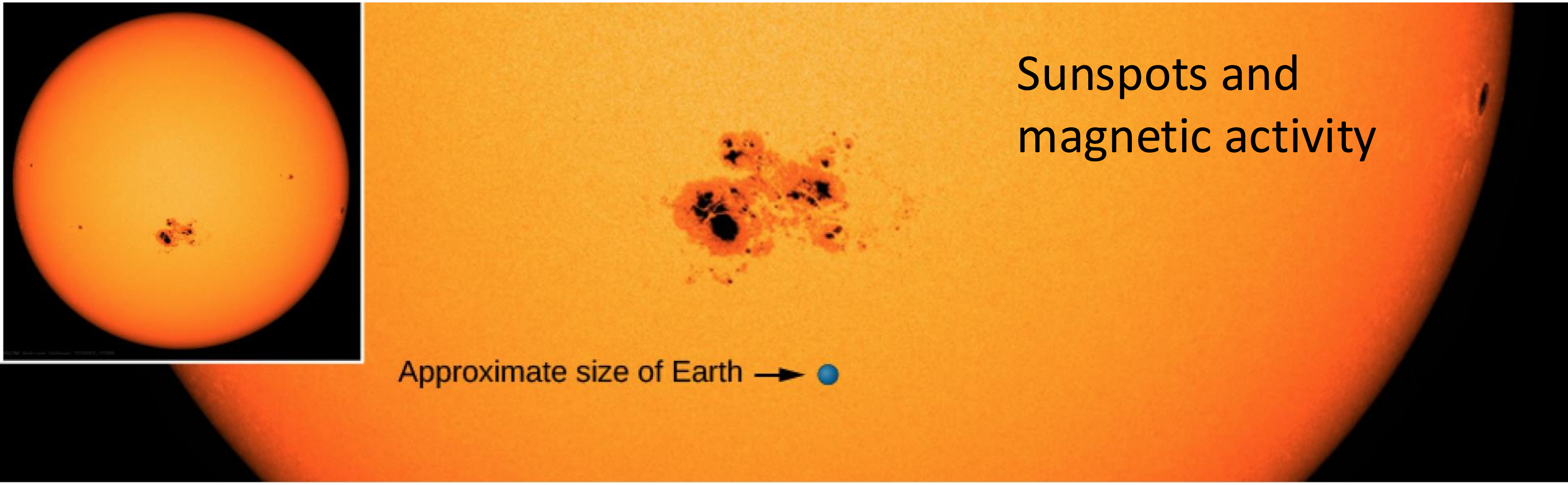

Protostar
Blue Supergiant
Black Hole
Supershell
Protostar
Blue Supergiant
Supernova
Black Hole
Stellar Nursery
Protostar
Blue Supergiant
Red Giant
(with stellar winds)
Blue Supergiant
Supernova
(with neutron star)
Neutron Star
Stellar Nursery
MASS
Protostar
Solar TYpe Star
Red Giant
Planetary Nebula
White Dwarf
Protostar
Red Dwarf
Red Dwarf
White Dwarf
Protostar
Brown Dwarf
Brown Dwarf
TIME

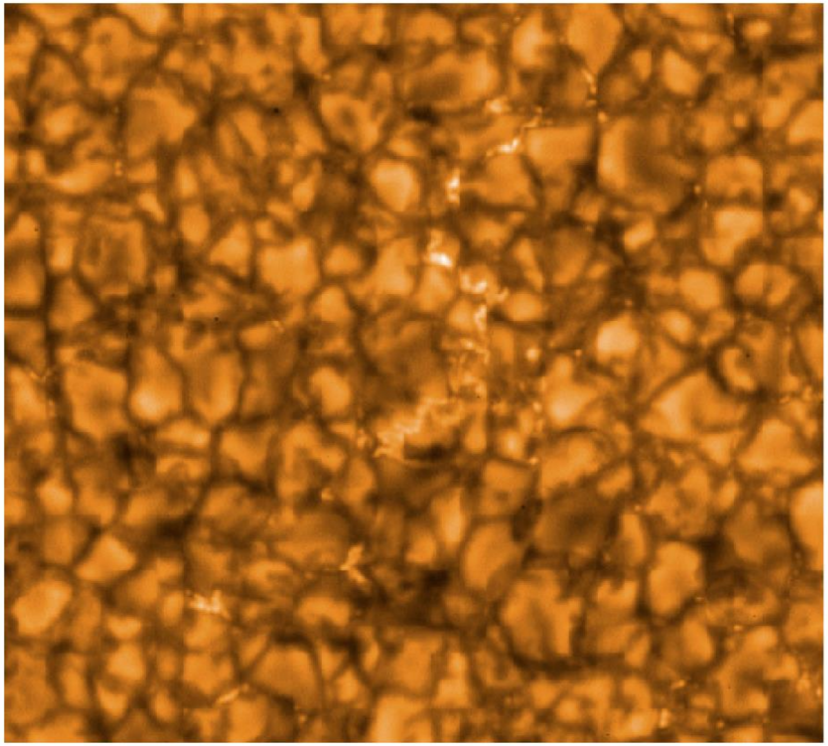
Brown dwarfs

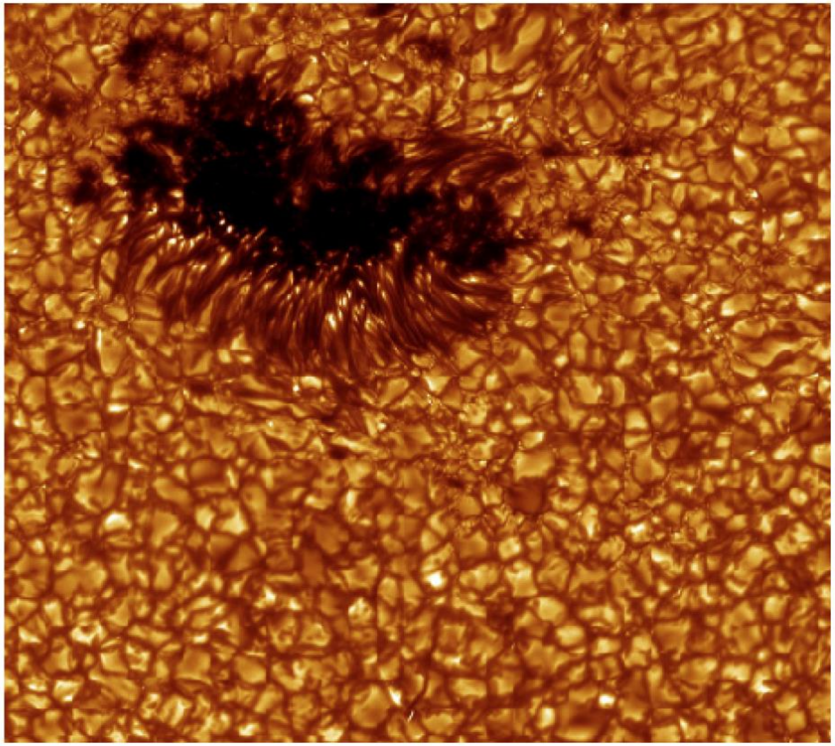
- Central temperature in core: depends on mass
- Very faint, cool, and red: hard to find!



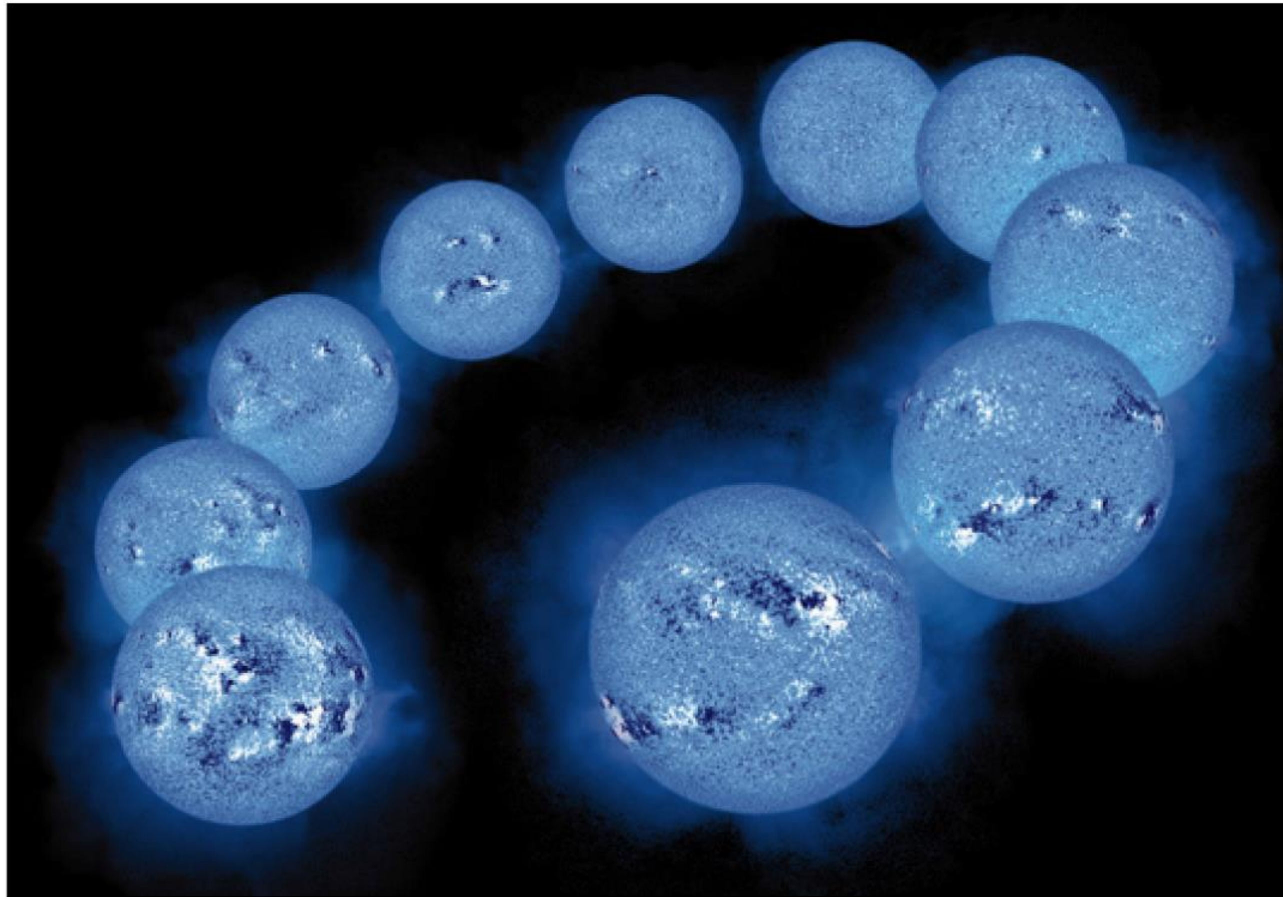
Sunspots and magnetic activity



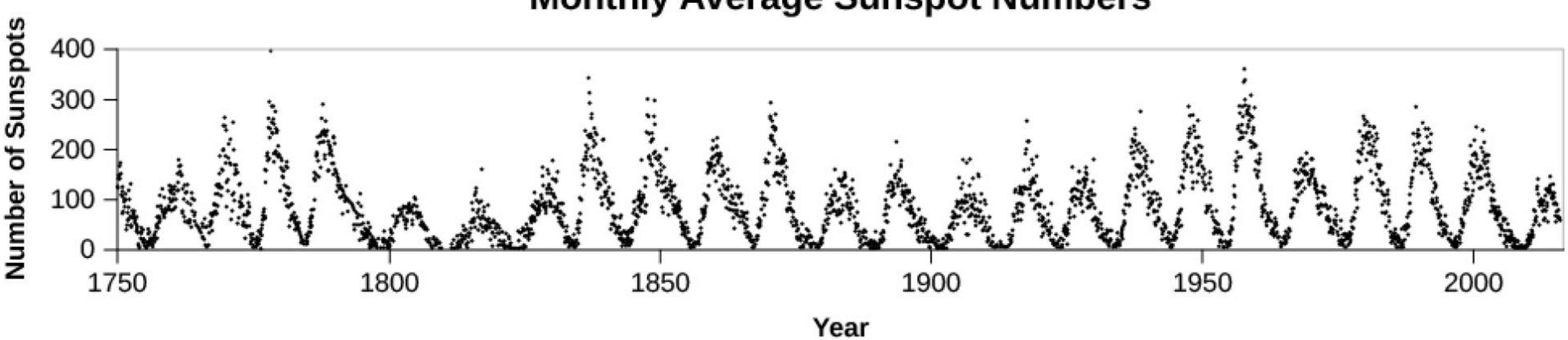


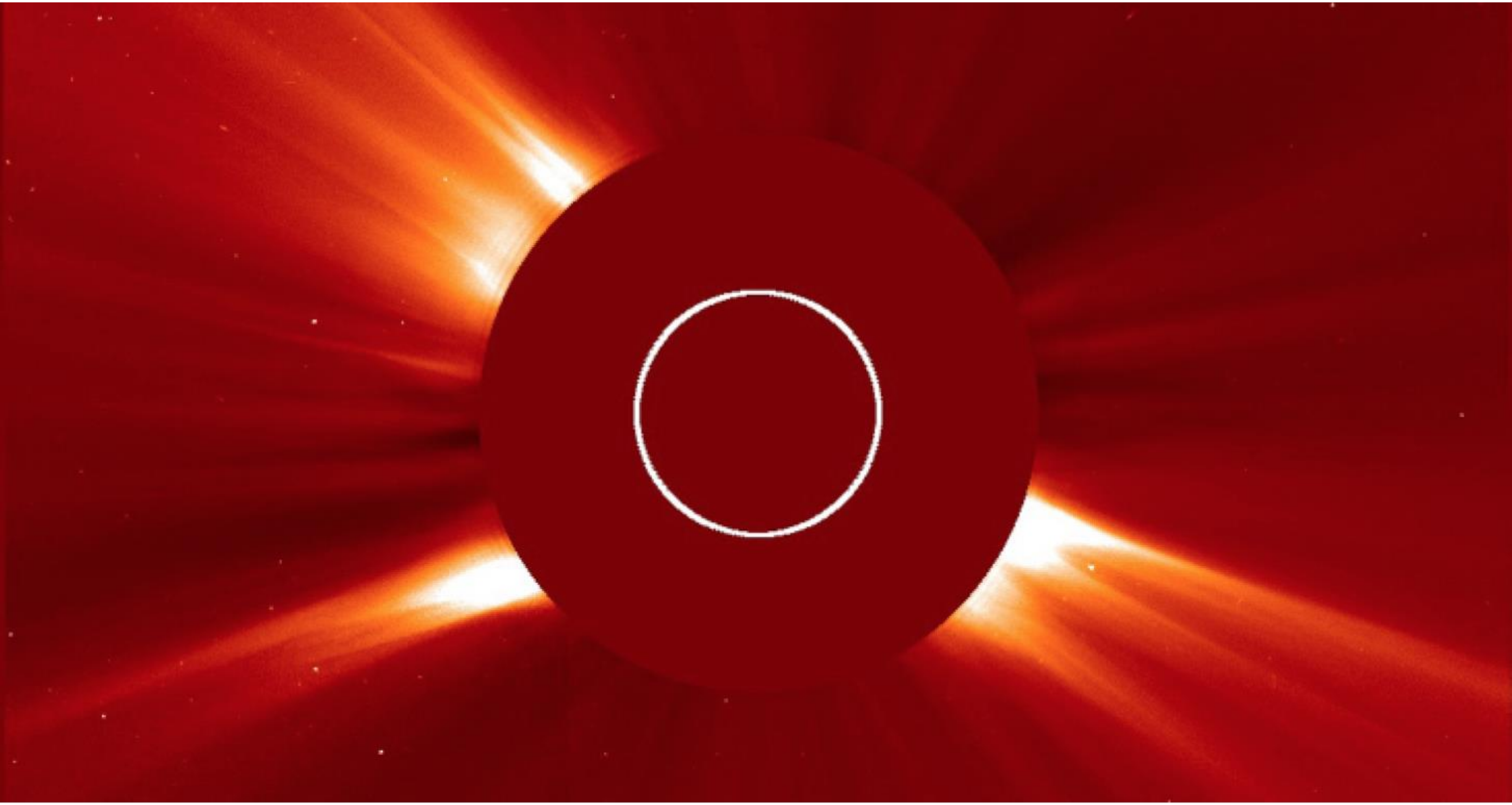


11 year
magnetic cycles

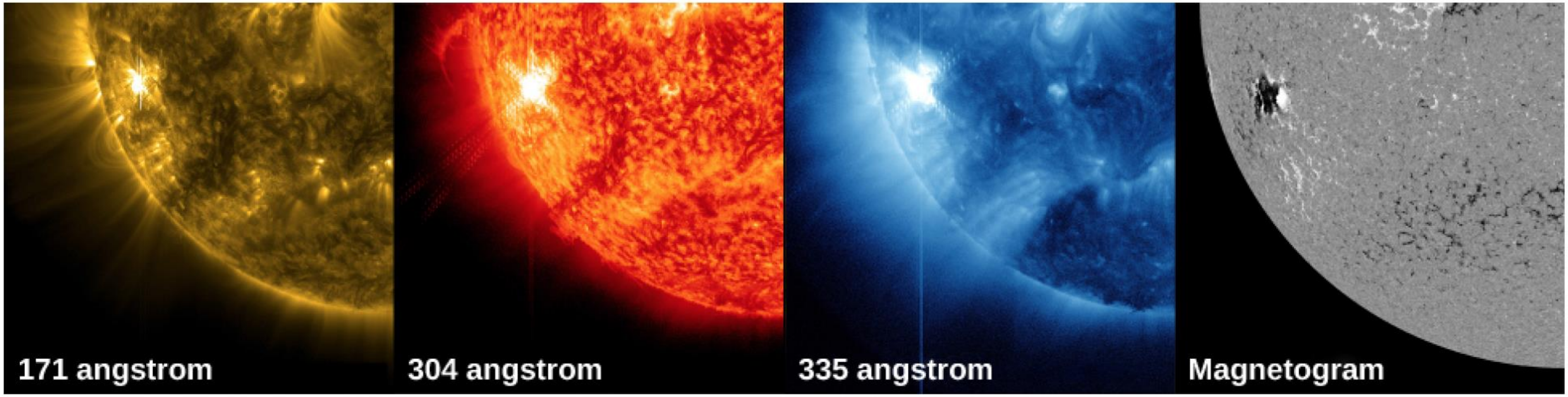


Monthly Average Sunspot Numbers



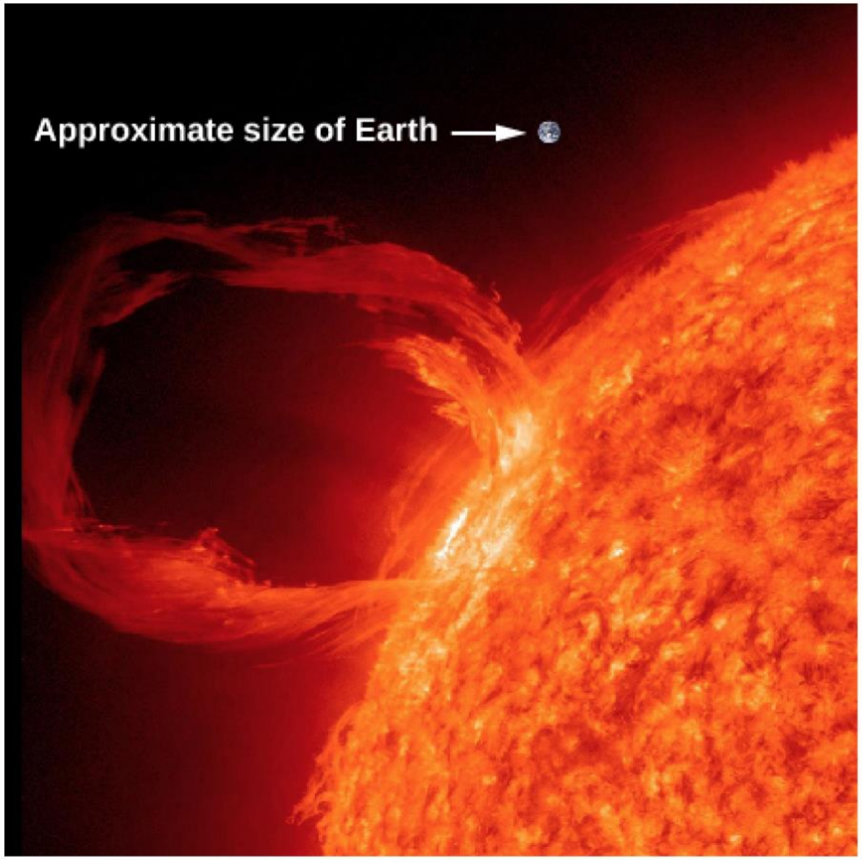


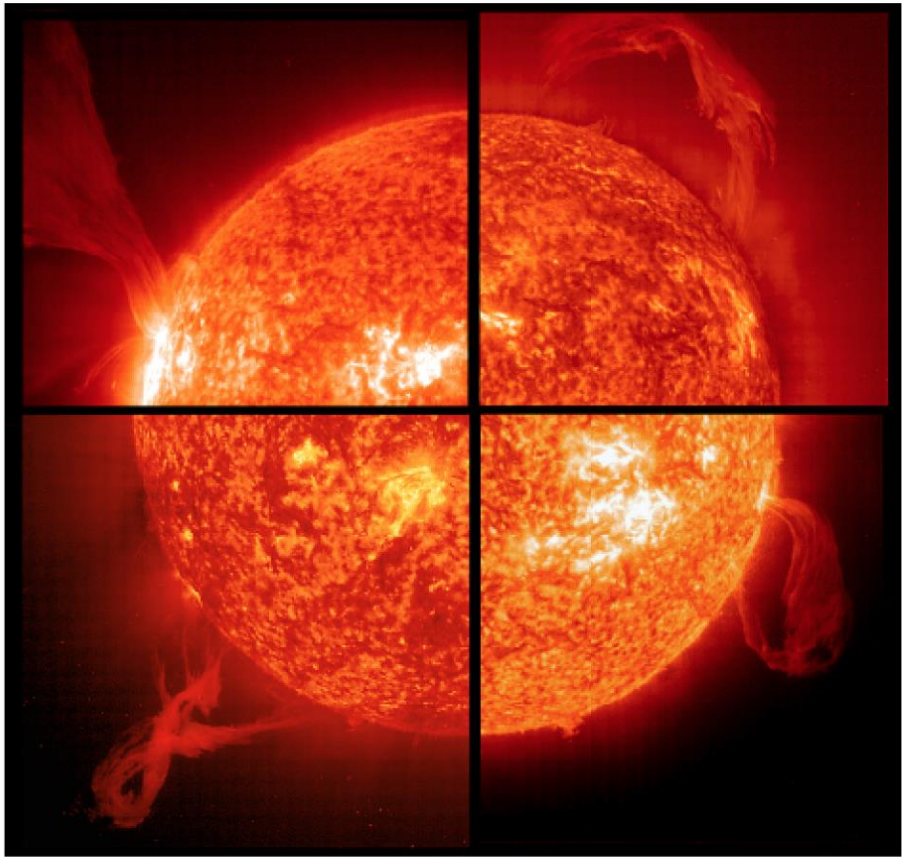
“White Satin”
© Todd Salat
AuroraHunter.com



Sun: looks different at different wavelengths: magnetic activity!

Flares, coronal mass ejections, corona


Approximate size of Earth

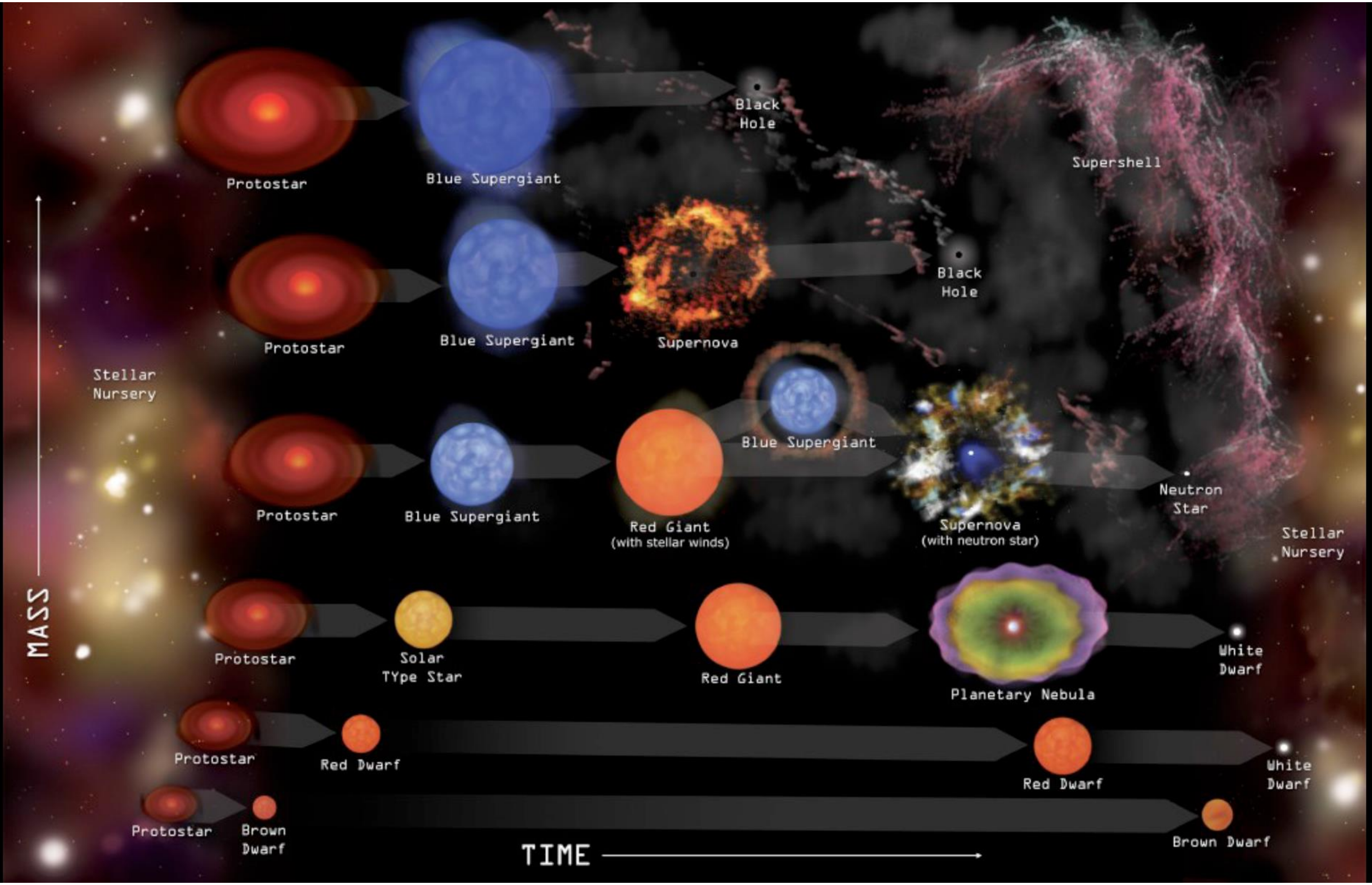


Important concepts for lecture 2

- HR Diagram: how we understand stars and stellar evolution
  - Apparent magnitude: the magnitude we see
  - Absolute magnitude (luminosity): corrected for distance
  - x-axis: temperature (measured from spectra or colors)
- Main sequence: where stars spend most of their life
  - H burning
- After H burning: stars become giants
  - Core shrinks until He burning
- Fusion: lighter elements => heavier elements
  - Difference in mass converted to energy
  - Occurs in very hot core
- Sun: we see the cool photosphere in optical light
  - Hot corona in X-rays
- Stars often born in clusters:
  - same time, same location+proper motion

Part II:

Star Formation, Stellar Evolution, and the Stellar Graveyard



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Black Hole
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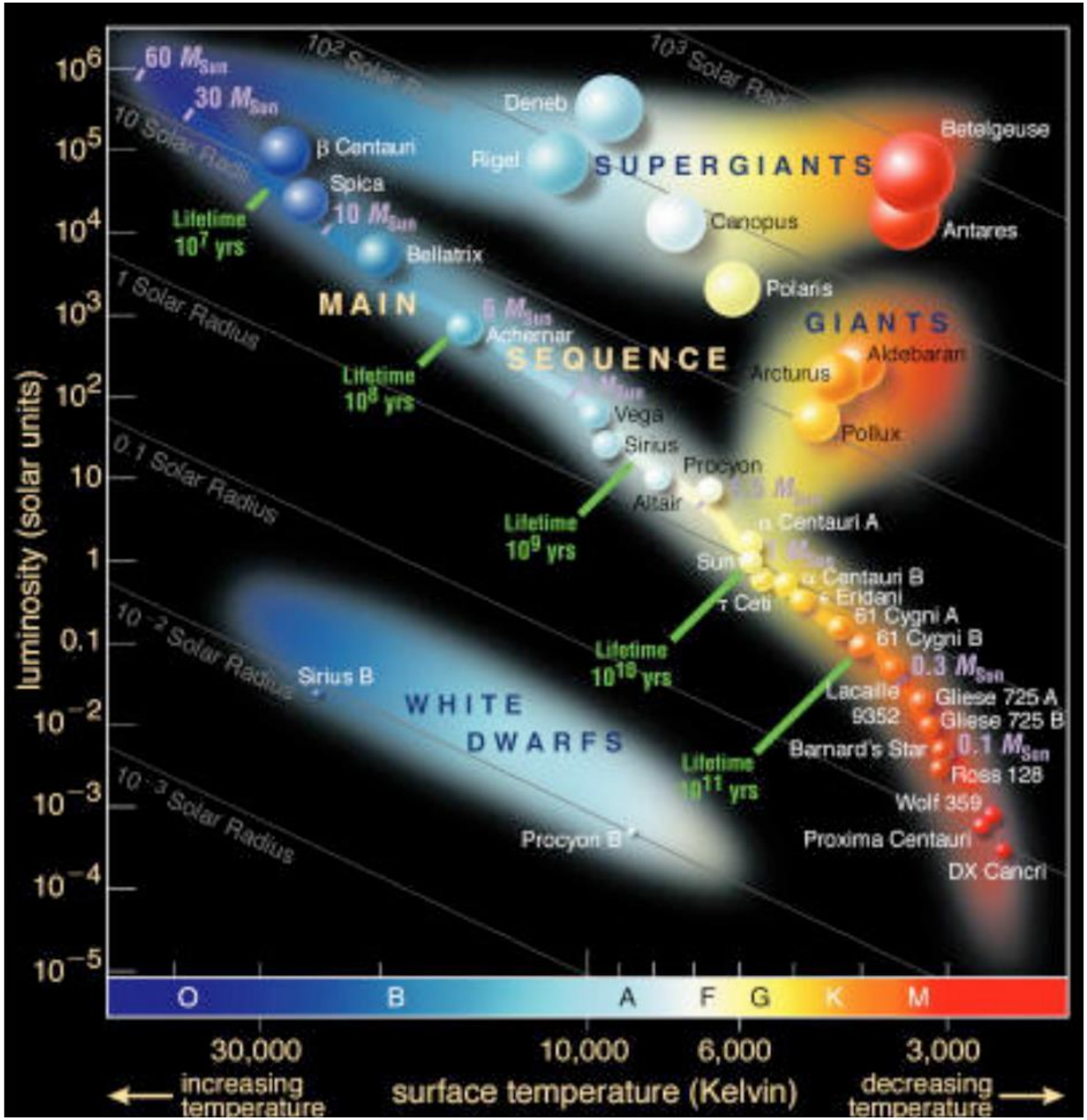
Planetary Nebula
White Dwarf
Protostar
Red Dwarf
Red Dwarf
White Dwarf
Protostar
Brown Dwarf
Brown Dwarf
MASS
TIME



luminosity (solar units)
10^6
10^5
10^4
10^3
10^2
10
1
0.1
10^{-2}
10^{-3}
10^{-4}
10^{-5}
60 M_{Sun}
30 M_{Sun}
10 M_{Sun}
6 M_{Sun}
0.3 M_{Sun}
0.1 M_{Sun}
10^2 Solar Radii
10^3 Solar Radii
10 Solar Radii
1 Solar Radius
0.1 Solar Radius
10^{-2} Solar Radius
10^{-3} Solar Radius
SUPERGIANTS
GIANTS
MAIN SEQUENCE
WHITE DWARFS
Lifetime 10^7 yrs
Lifetime 10^8 yrs
Lifetime 10^9 yrs
Lifetime 10^{10} yrs
Lifetime 10^{11} yrs
Deneb
Rigel
Betelgeuse
Antares
Canopus
Polaris
Aldebaran
Arcturus
Pollux
β Centauri
Spica
Bellatrix
Achernar
Vega
Sirius
Procyon
Altair
α Centauri A
Sun
α Centauri B
τ Ceti
ε Eridani
61 Cygni A
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Ross 128
Wolf 359
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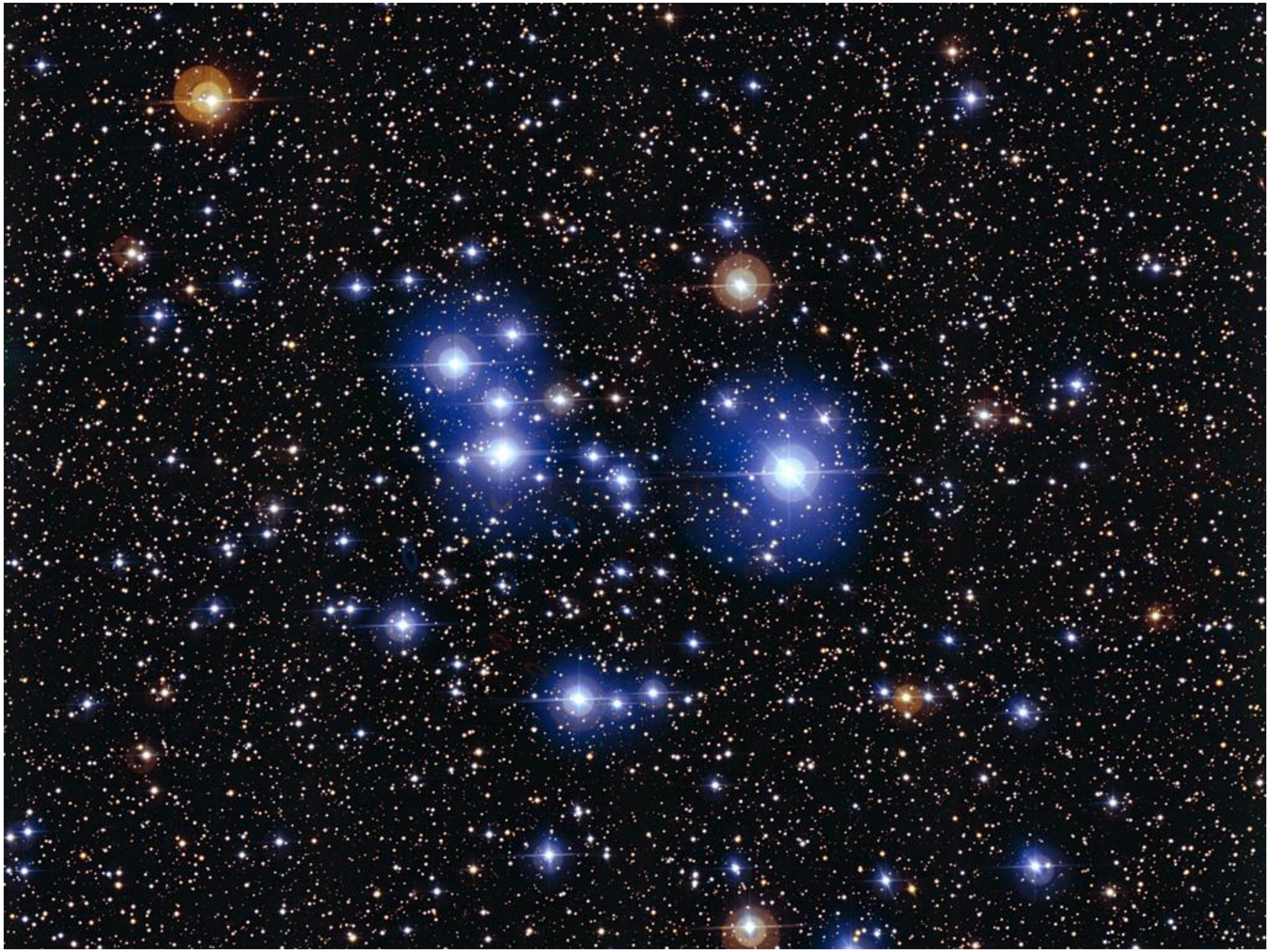
DX Cancri
Sirius B
Procyon B
O
B
A
F
G
K
M
30,000
10,000
6,000
3,000
increasing temperature
surface temperature (Kelvin)
decreasing temperature

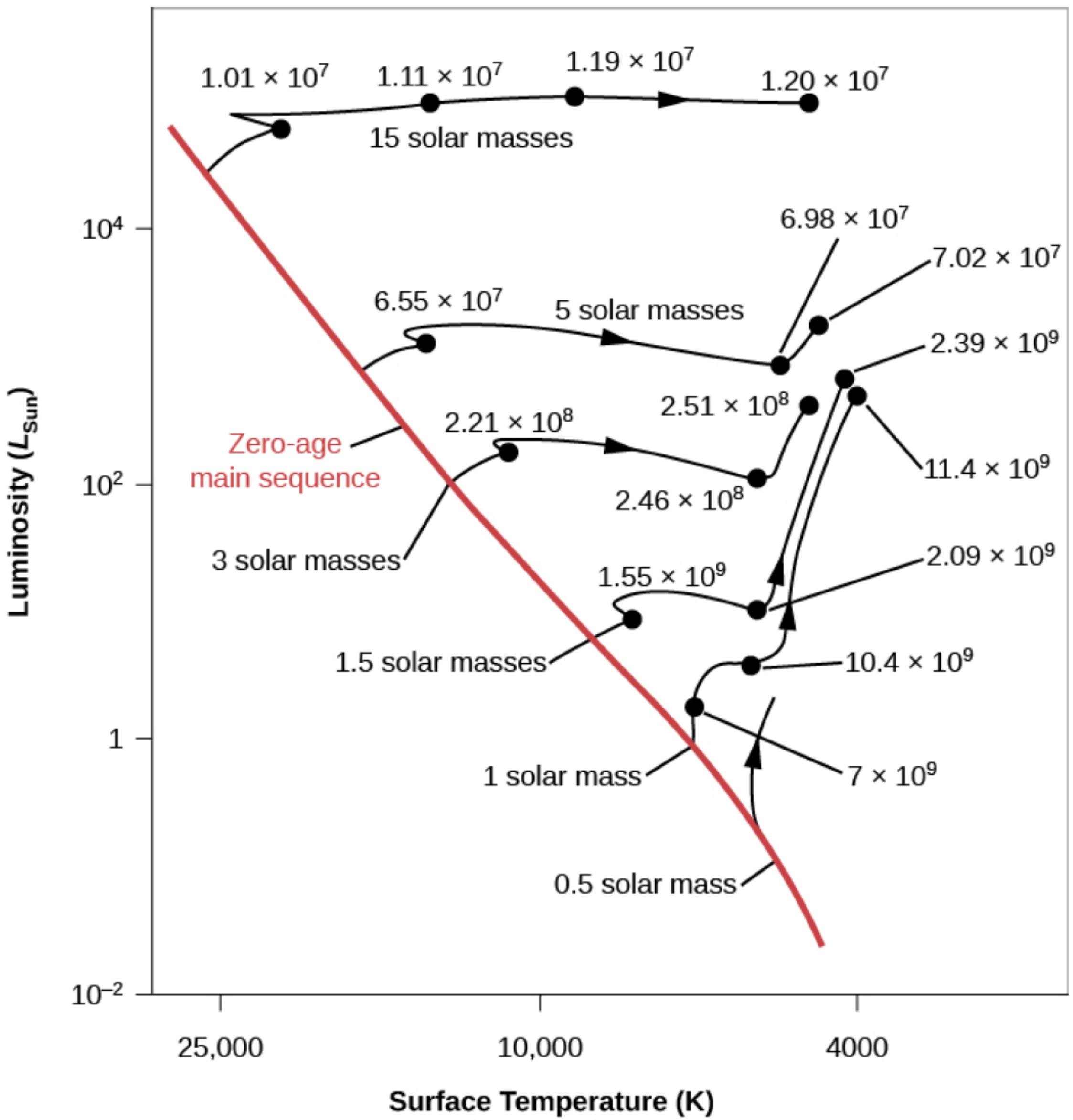
Clusters: stars born at same time and travel together in space

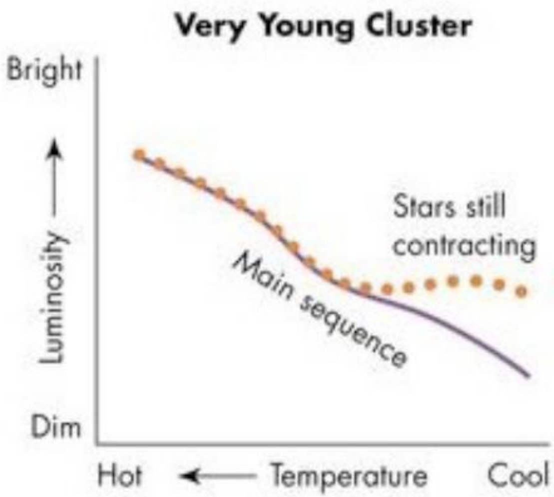
Pleiades (seven sisters, Subaru)

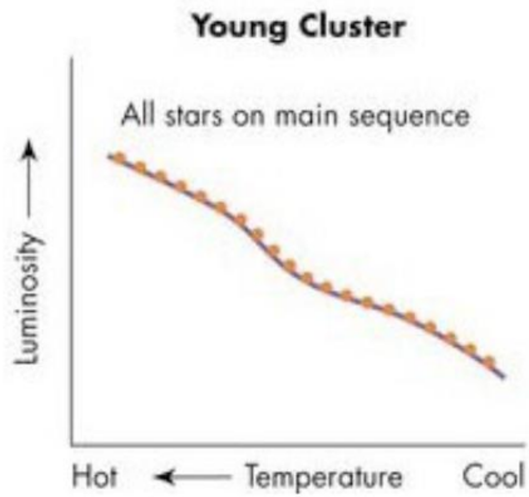
Pleiades: famous and benchmark cluster for young stars

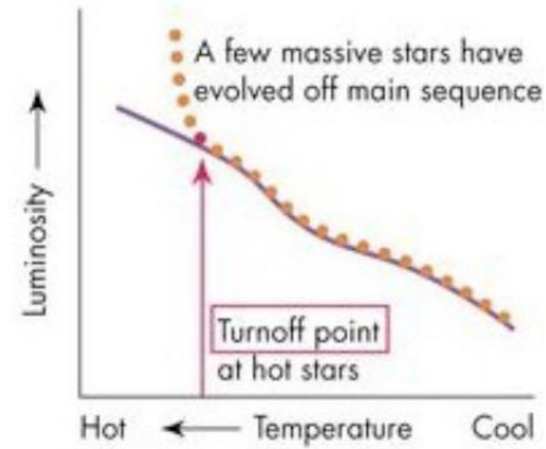


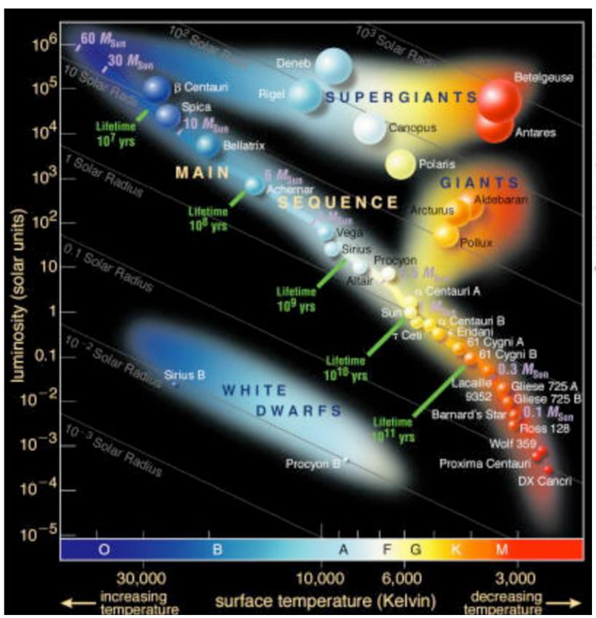
Location of stars tells us age of cluster




Very Young Cluster
Bright
Dim
Luminosity
Stars still contracting
Main sequence
Hot
Temperature
Cool


Young Cluster
All stars on main sequence
Luminosity
Hot
Temperature
Cool


A few massive stars have evolved off main sequence
Luminosity
Turnoff point at hot stars
Hot
Temperature
Cool


luminosity (solar units)
SUPERGIANTS
GIANTS
MAIN SEQUENCE
WHITE DWARFS
Deneb
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Canopus
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Arcturus
Pollux
Vega
Sirius
Procyon
Altair
Sun
Sirius B
Procyon B
Proxima Centauri
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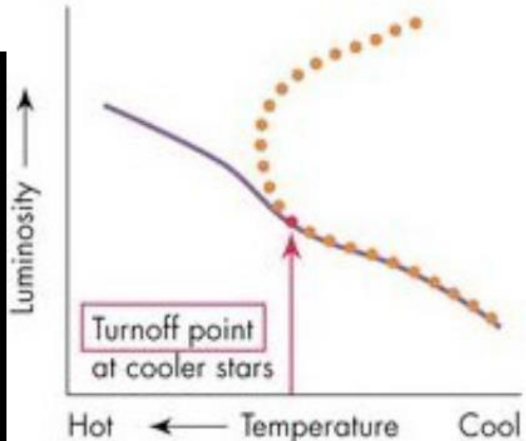
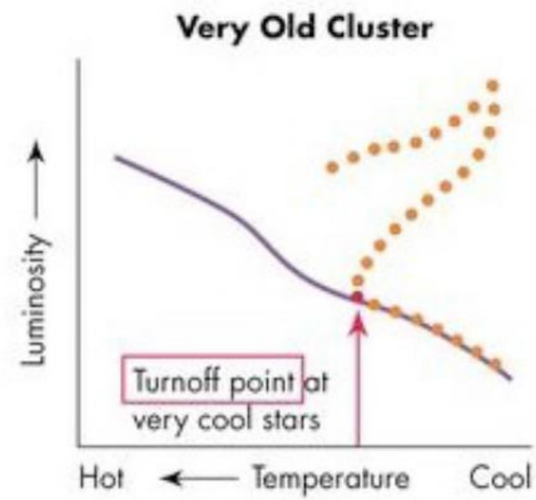
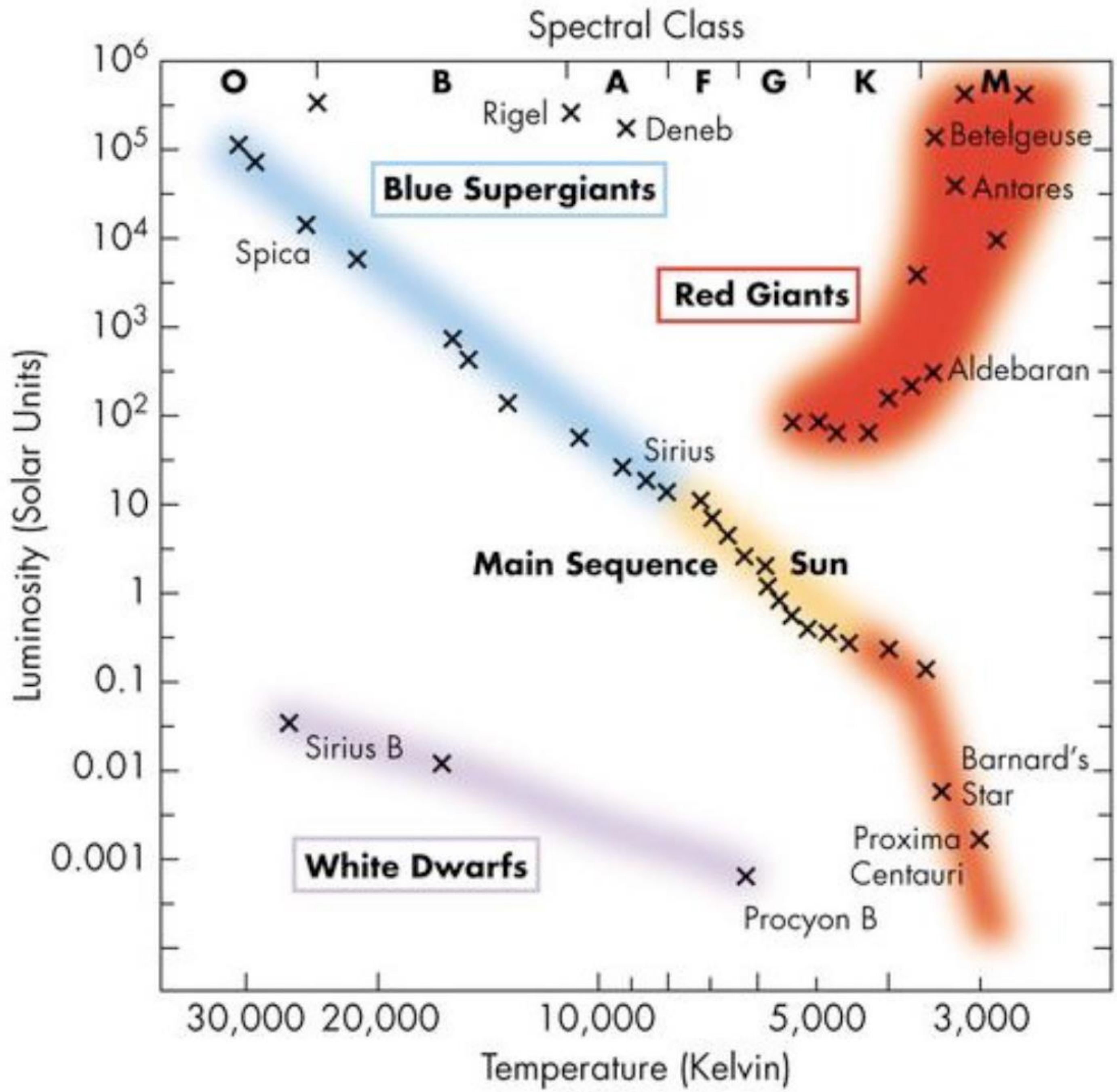
Wolf 359
DX Cancri
surface temperature (Kelvin)
increasing temperature
decreasing temperature


Luminosity
Turnoff point at cooler stars
Hot
Temperature
Cool


Very Old Cluster
Luminosity
Turnoff point at very cool stars
Hot
Temperature
Cool

Key concepts

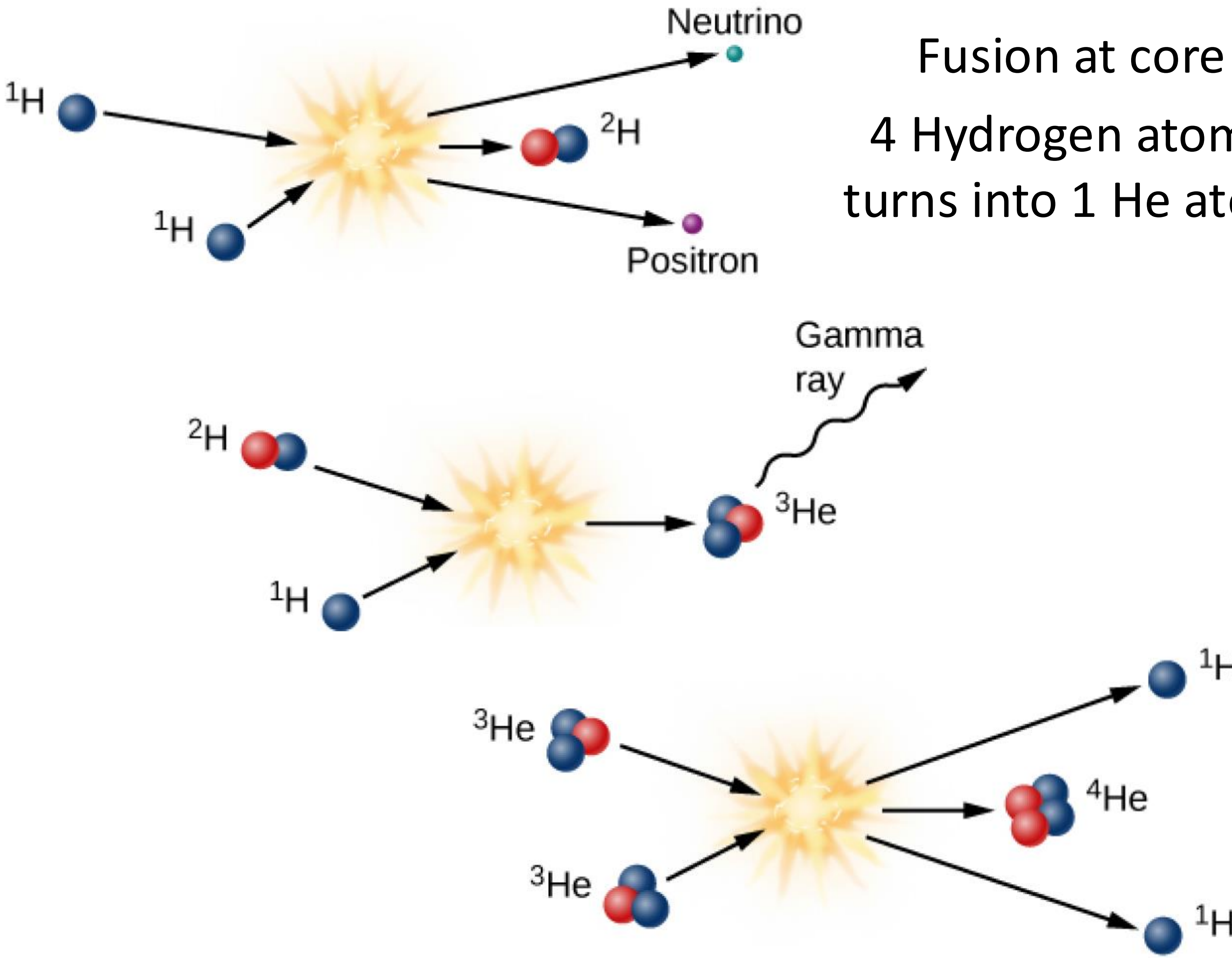
- **Blackbody radiation:** temperature/color of star
- **Main sequence:** where a star spends most of its life
  - Hydrogen burning in core
- **Hydrogen burning:** how most stars get energy
- **Core:** hot core where H burns
- **Stellar evolution:** how star changes, from birth to death
- **HR Diagram:** Luminosity and temperature of stars
  - How we understand stars and stellar evolution
- **Molecular cloud:** dense material where stars form
- **White dwarfs:** end state of the sun and low-mass stars
- **Neutron stars/black holes:** end state of high-mass stars
- **Supernova!**
- **Origin of the Elements:** mostly in stars+explosions

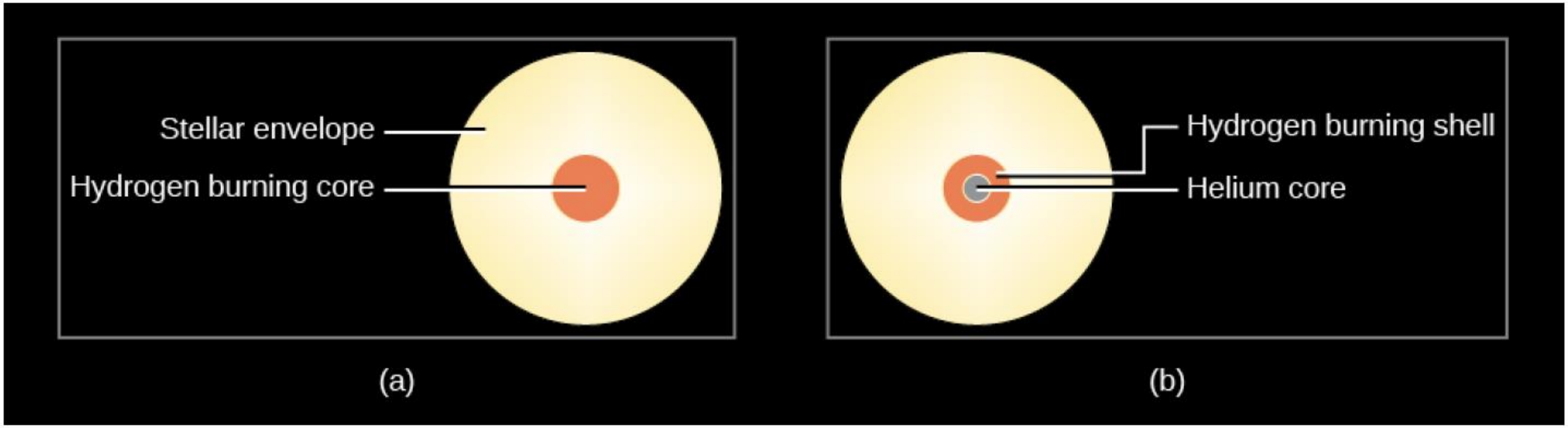


Spectral Class
O
B
A
F
G
K
M
Rigel
Deneb
Betelgeuse
Antares
Blue Supergiants
Spica
Red Giants
Aldebaran
Sirius
Main Sequence
Sun
Sirius B
Barnard's Star
Proxima Centauri
White Dwarfs
Procyon B
Luminosity (Solar Units)
10^6
10^5
10^4
10^3
10^2
10
1
0.1
0.01
0.001
30,000
20,000
10,000
5,000
3,000
Temperature (Kelvin)

Fusion at core

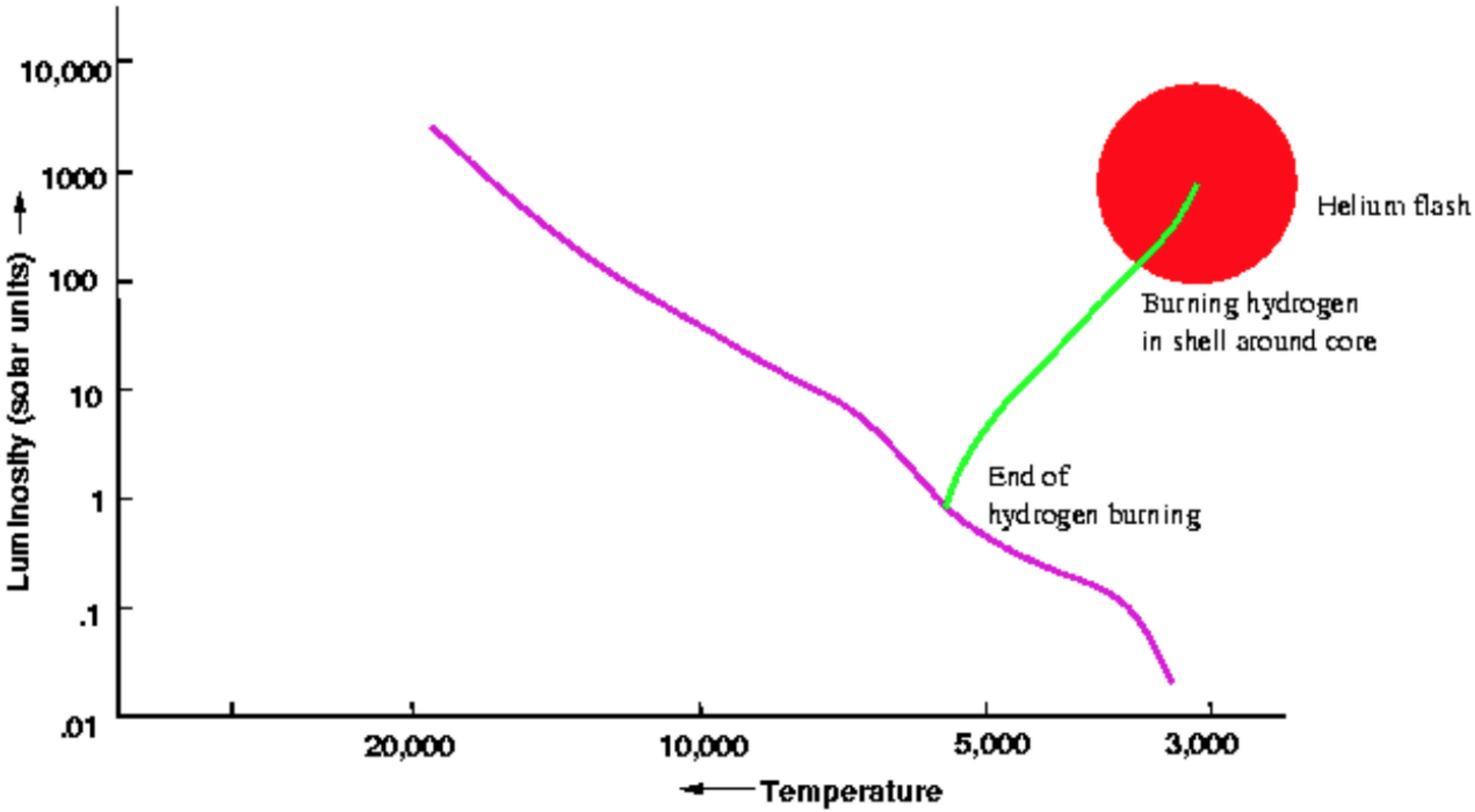
4 Hydrogen atoms turns into 1 He atom

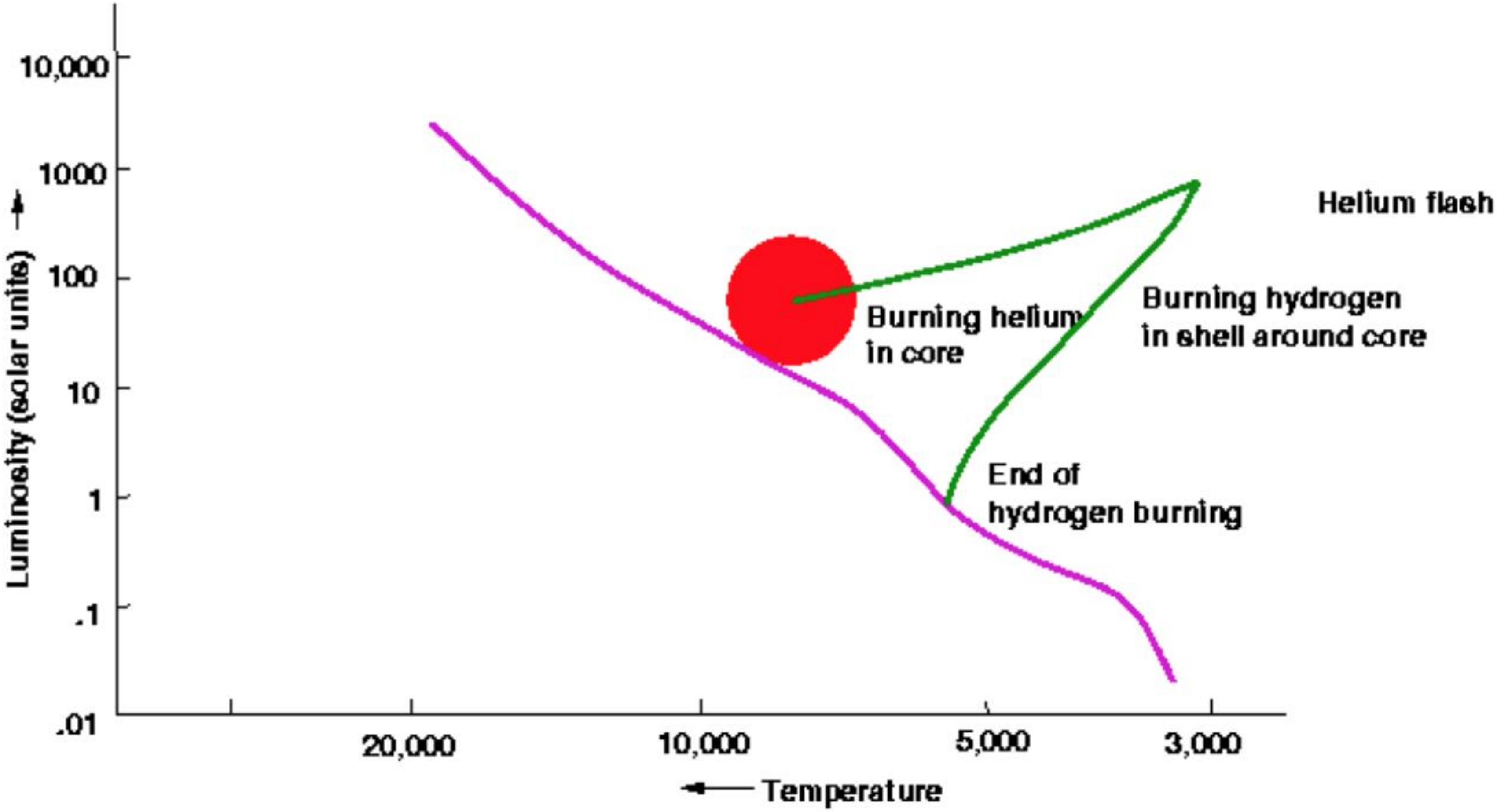




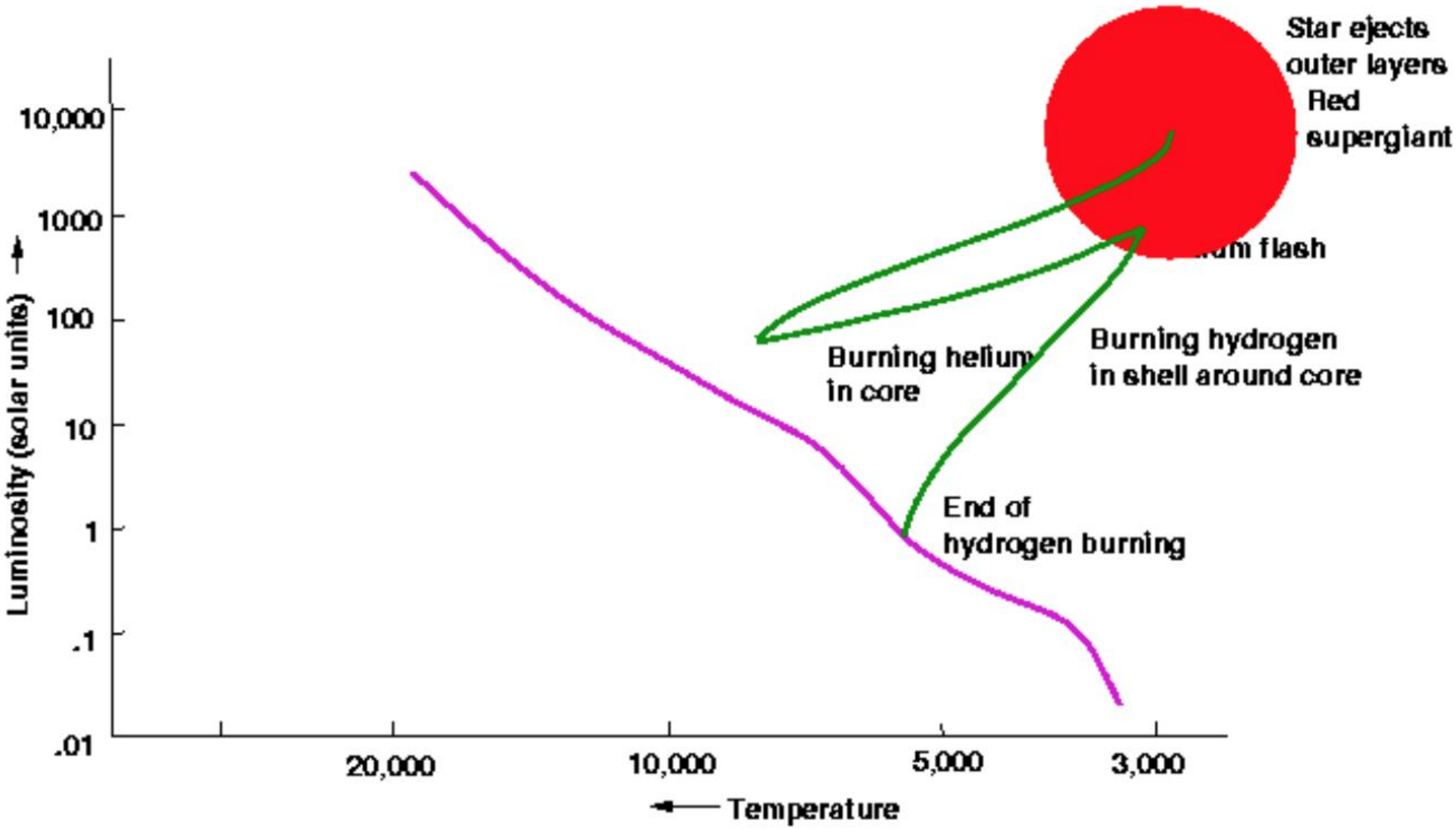
Main sequence: Hydrogen burning in core

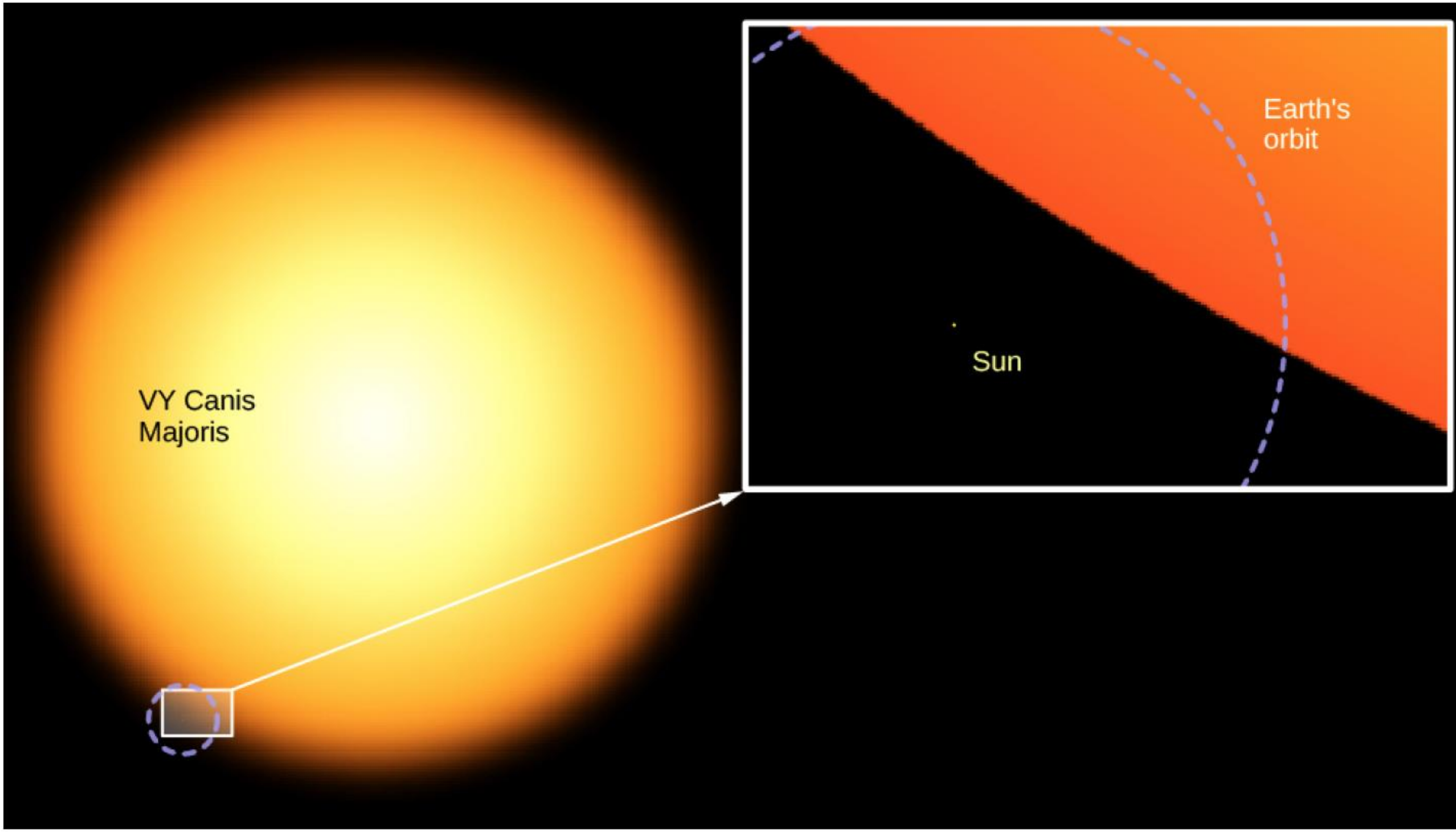
What happens when the core runs out of Hydrogen?


10,000
1000
100
10
1
.1
.01
Luminosity (solar units)
20,000
10,000
5,000
3,000
Temperature
Helium flash
Burning hydrogen
in shell around core
End of
hydrogen burning

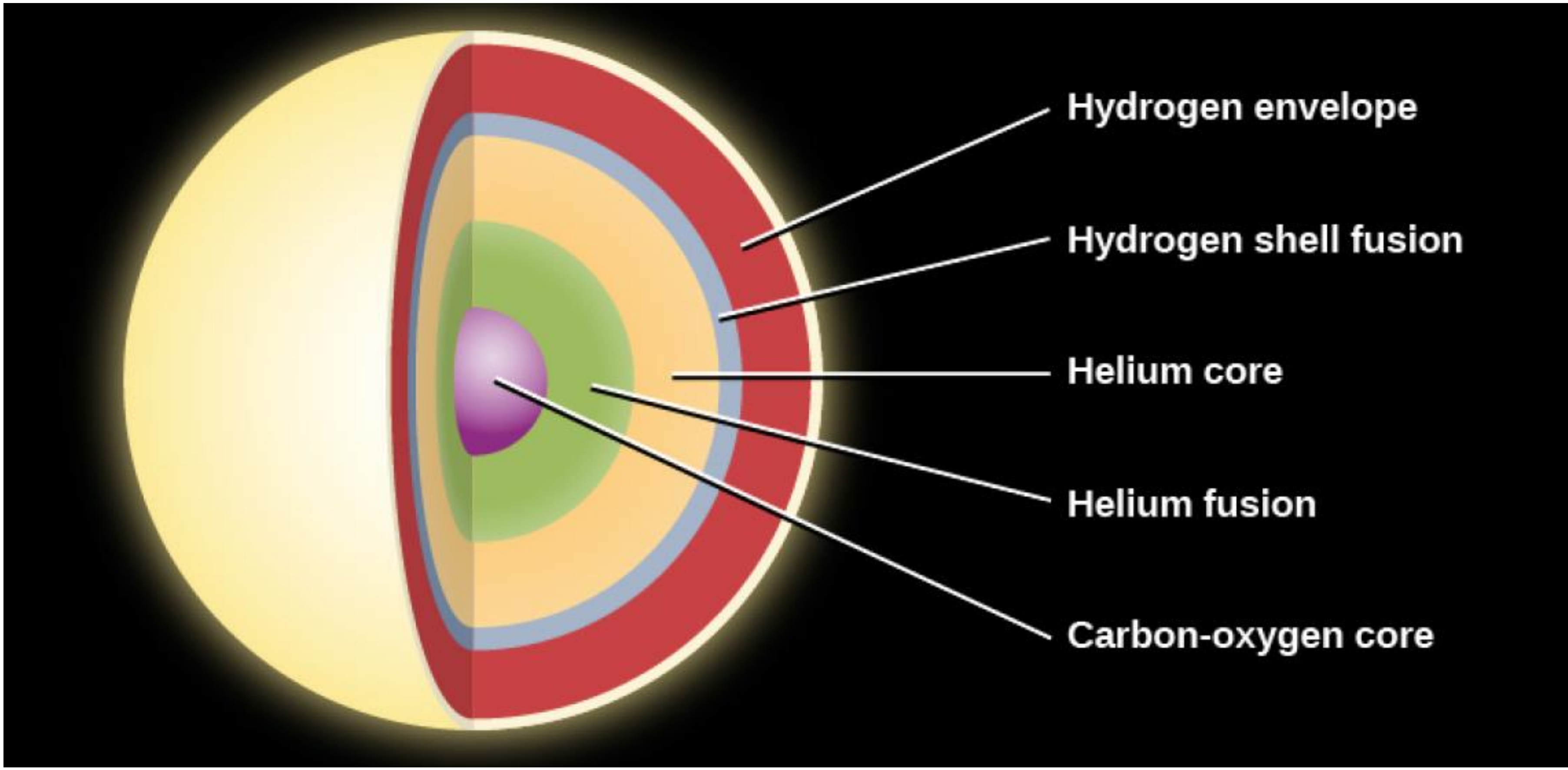

10,000
1000
100
10
1
.1
.01
Luminosity (solar units)
Helium flash
Burning hydrogen
in shell around core
Burning helium
in core
End of
hydrogen burning
20,000
10,000
5,000
3,000
Temperature

Evolution of a solar-mass star

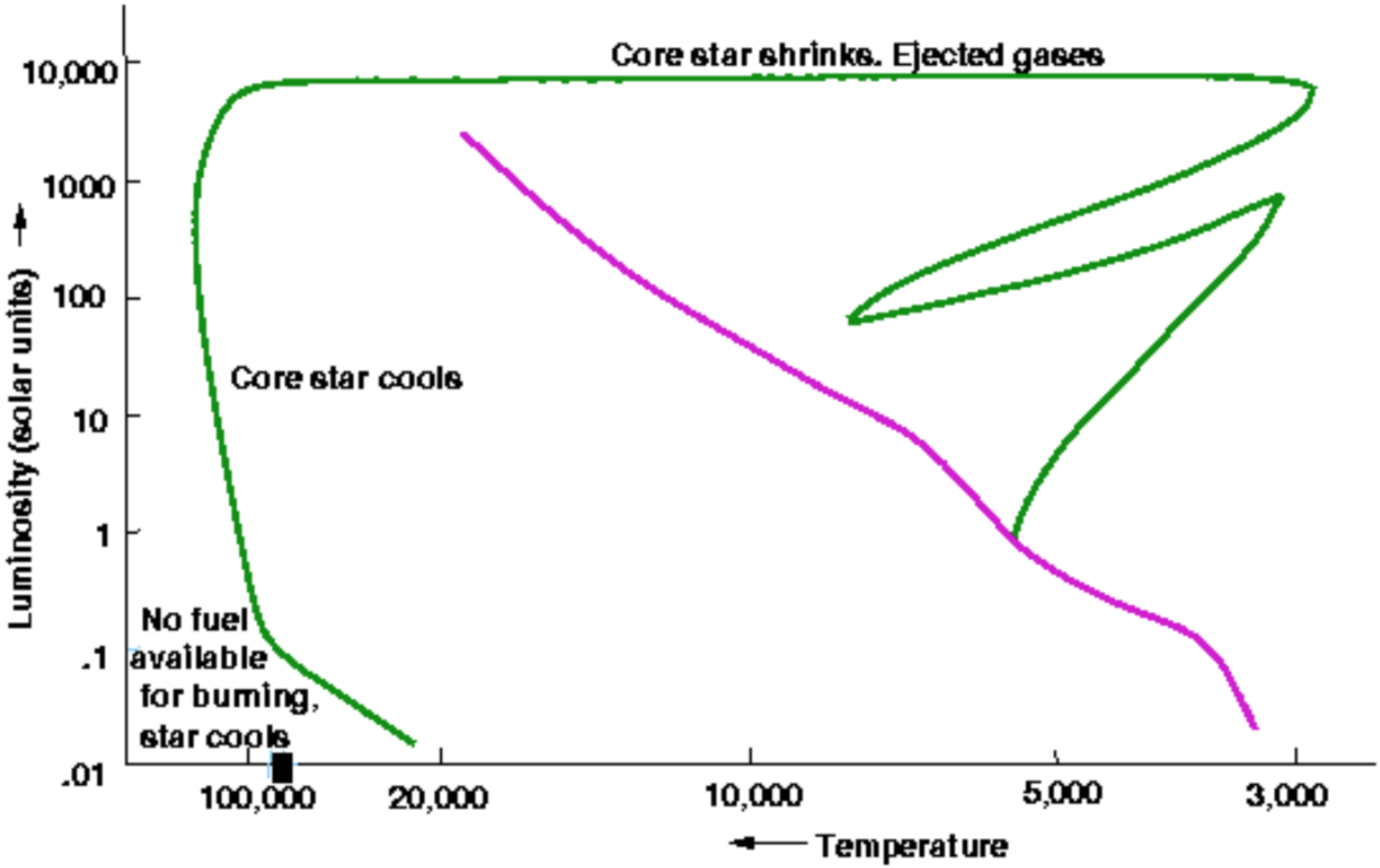



Earth's
orbit
Sun
VY Canis
Majoris

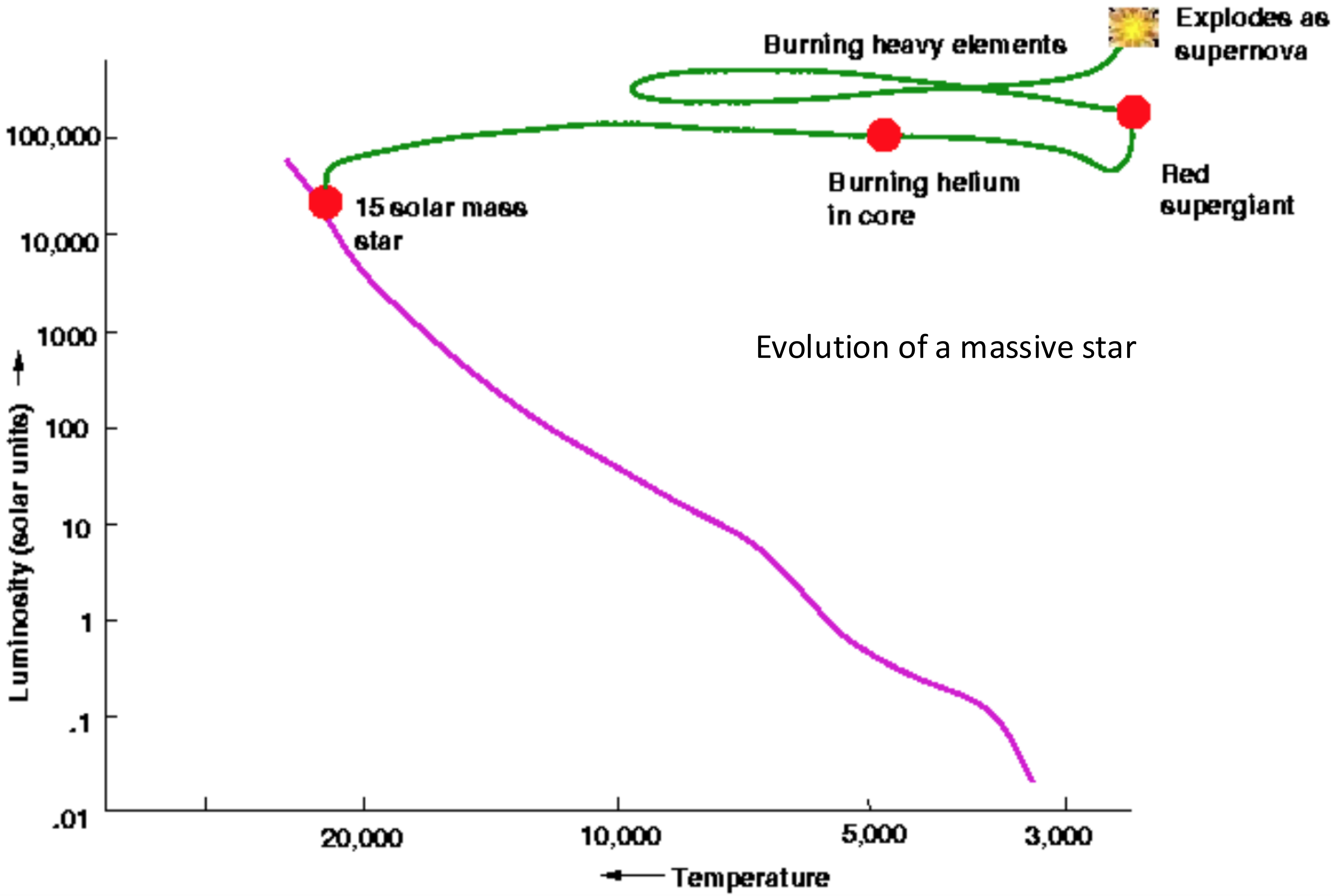
Interior structure of evolved star; Will lose the envelope (outer region)



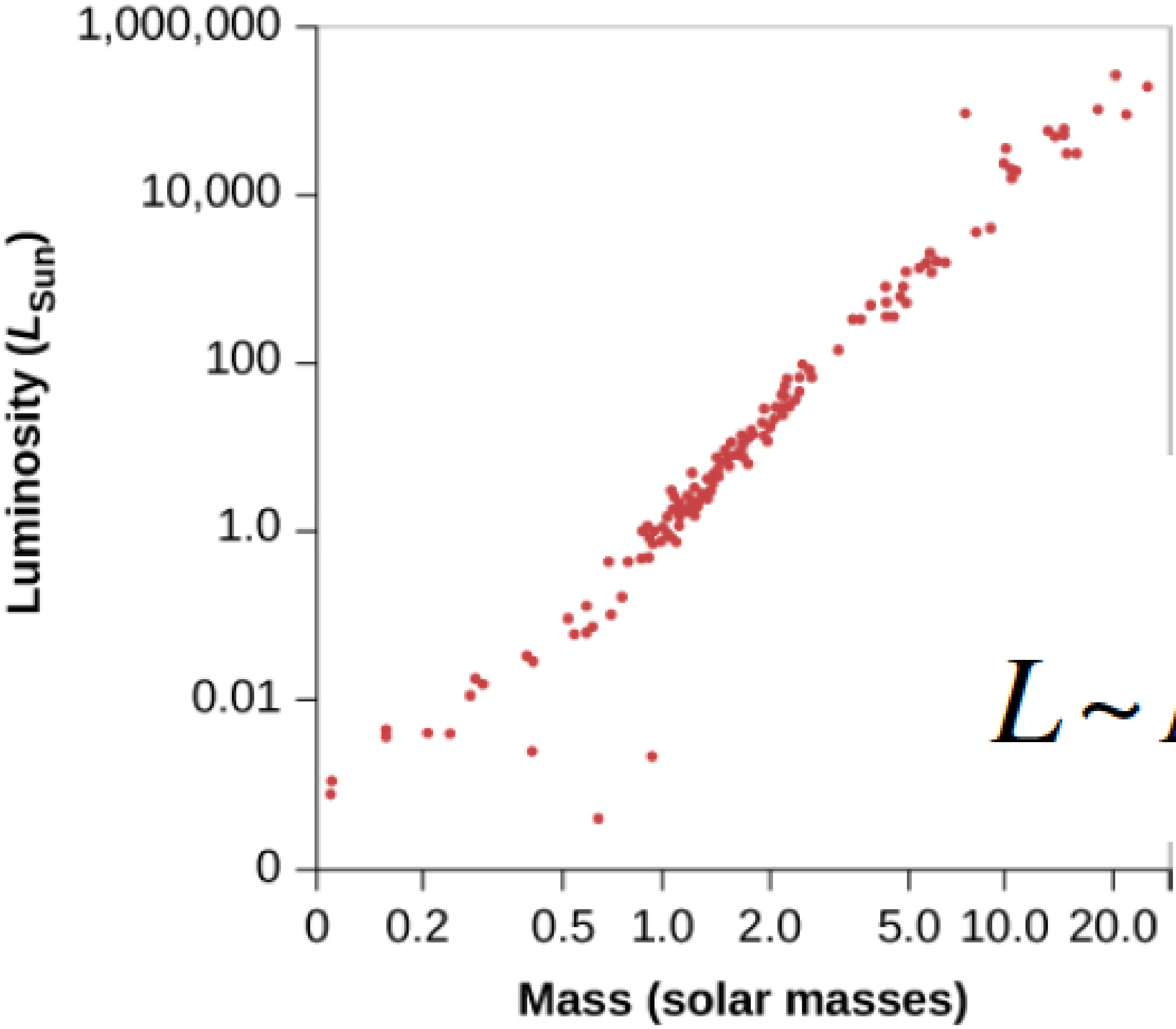
Evolution of a solar-mass star



Stage	Time in This Stage (years)	Surface Temperature (K)	Luminosity (L_{Sun})	Diameter (Sun = 1)
Main sequence	11 billion	6000	1	1
Becomes red giant	1.3 billion	3100 at minimum	2300 at maximum	165
Helium fusion	100 million	4800	50	10
Giant again	20 million	3100	5200	180

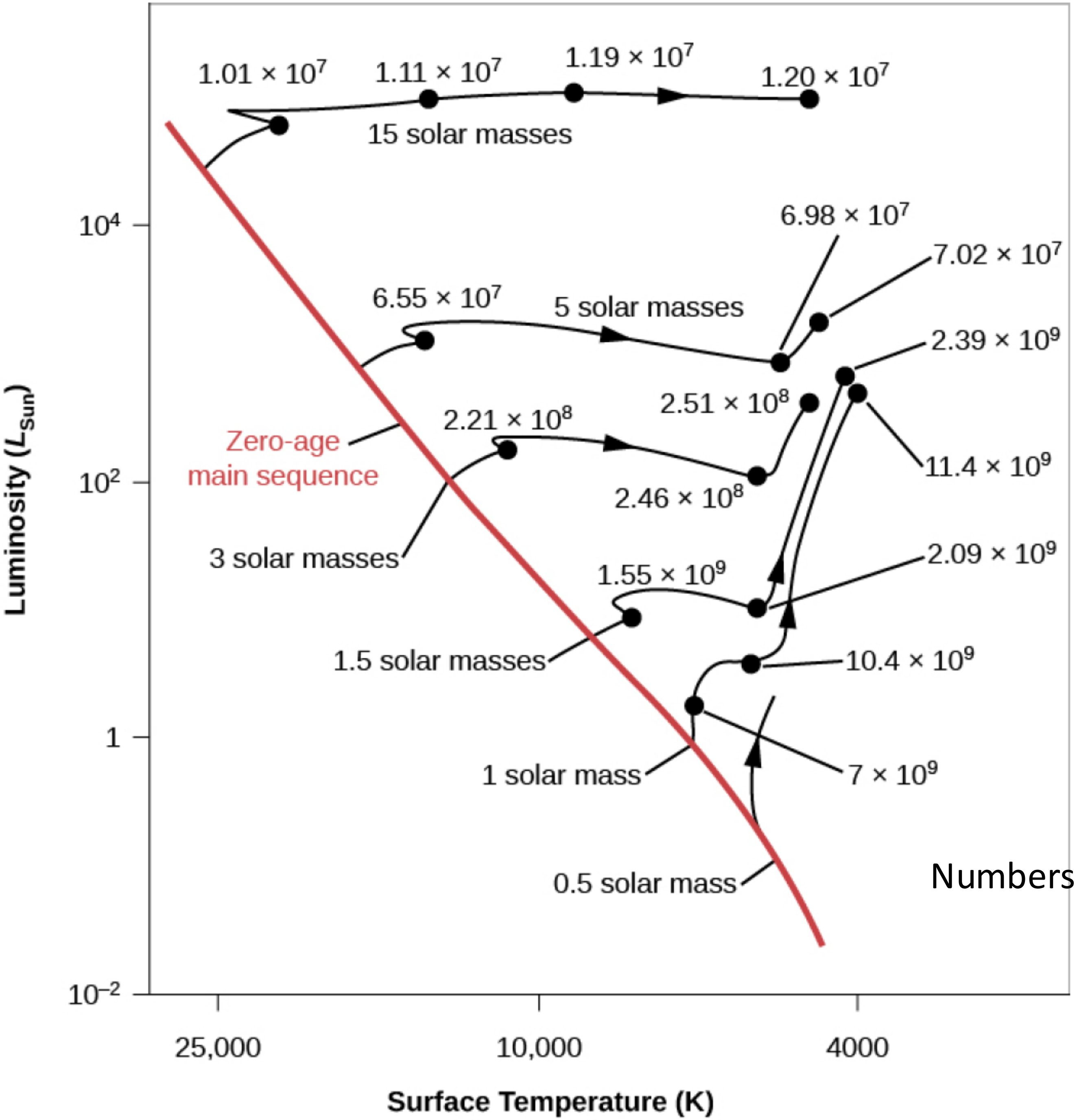


Explodes as supernova
Burning heavy elements
Red supergiant
Burning helium in core
15 solar mass star
Evolution of a massive star
100,000
10,000
1000
100
10
1
.1
.01
Luminosity (solar units)
20,000
10,000
5,000
3,000
Temperature



Massive stars burn out quickly!

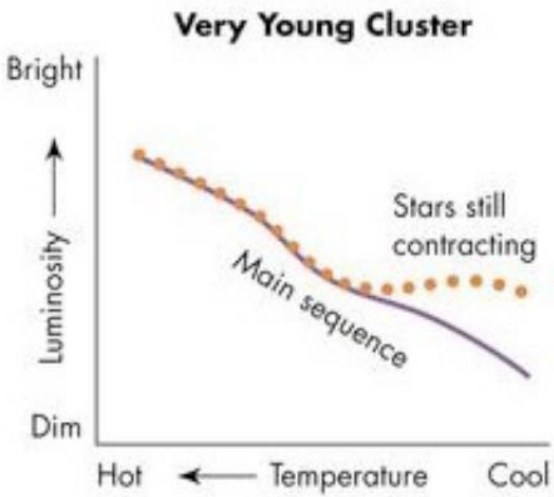
$$L \sim M^{3.9}$$

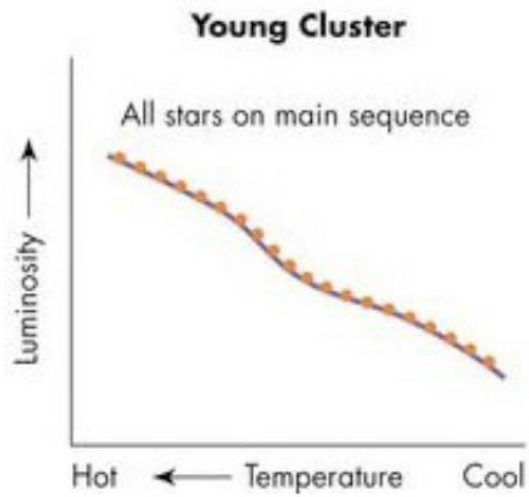


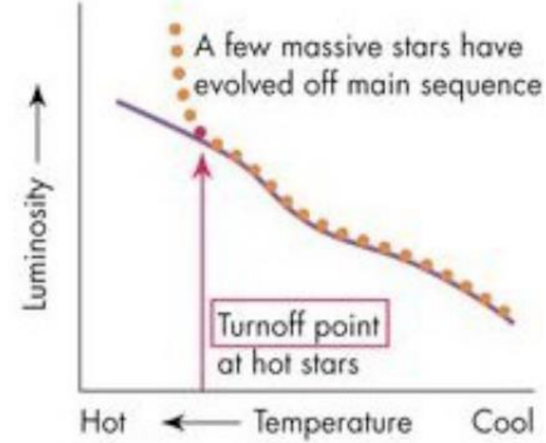
$L = R^2 T^4$

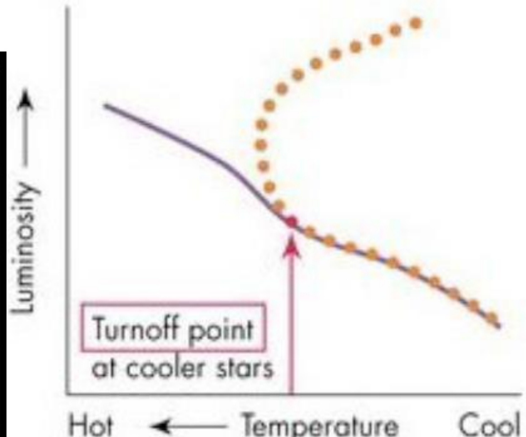
Stars get cool at surface, but luminous: radius must get very large

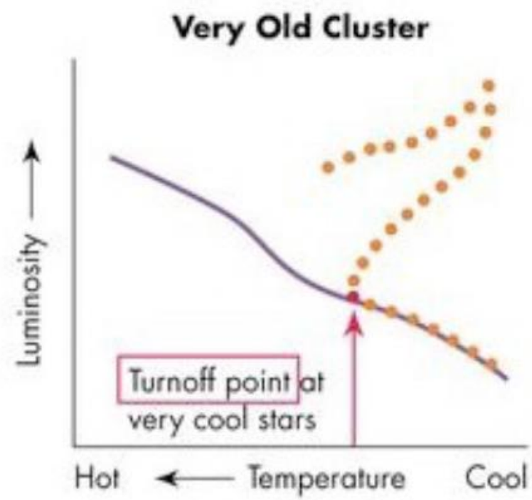
Numbers are ages

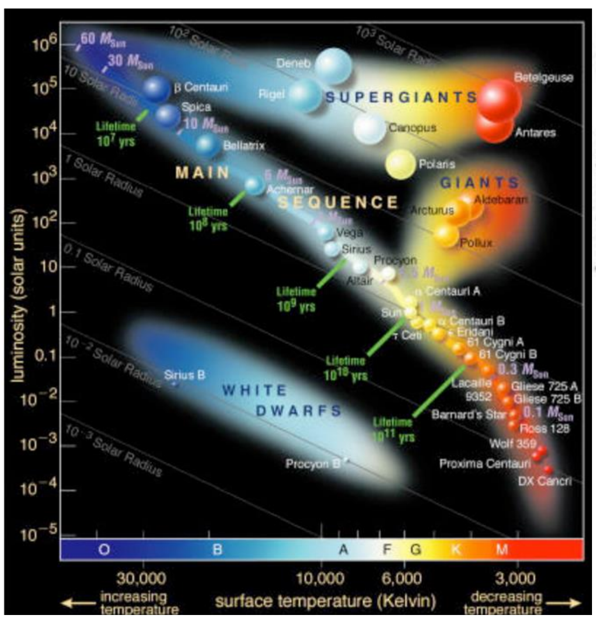

Very Young Cluster
Bright
Dim
Luminosity
Stars still
contracting
Main sequence
Hot
Temperature
Cool

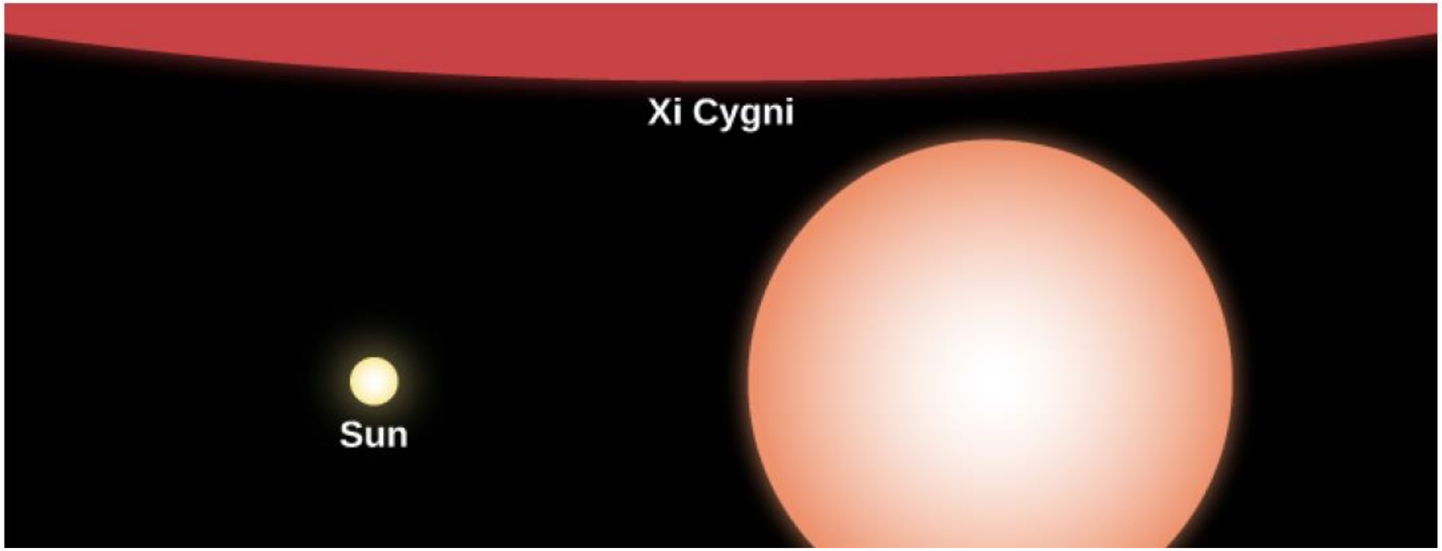

Young Cluster
All stars on main sequence
Luminosity
Hot
Temperature
Cool


A few massive stars have
evolved off main sequence
Luminosity
Turnoff point
at hot stars
Hot
Temperature
Cool


Luminosity
Turnoff point
at cooler stars
Hot
Temperature
Cool


Very Old Cluster
Luminosity
Turnoff point at
very cool stars
Hot
Temperature
Cool

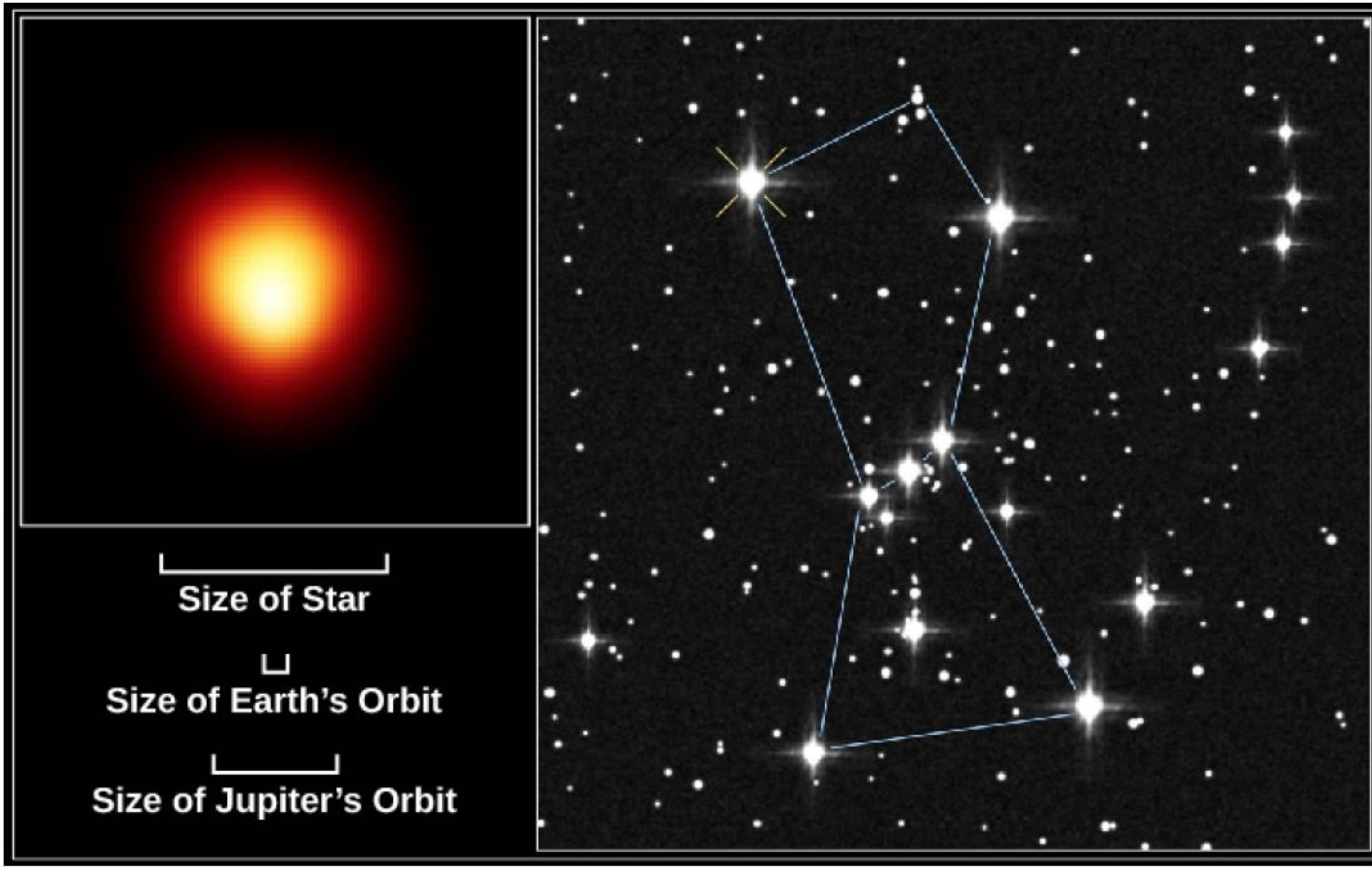

SUPERGIANTS
GIANTS
MAIN
SEQUENCE
WHITE
DWARFS
Deneb
Rigel
Betelgeuse
Antares
Canopus
Polaris
β Centauri
Spica
Bellatrix
Achernar
Arcturus
Aldebaran
Pollux
Vega
Sirius
Procyon
Altair
Sun
Sirius B
Procyon B
Proxima Centauri
Barnard's Star
Wolf 359
DX Cancri
Ross 128
luminosity (solar units)
surface temperature (Kelvin)
30,000
10,000
6,000
3,000
increasing
temperature
decreasing
temperature
O
B
A
F
G
K
M



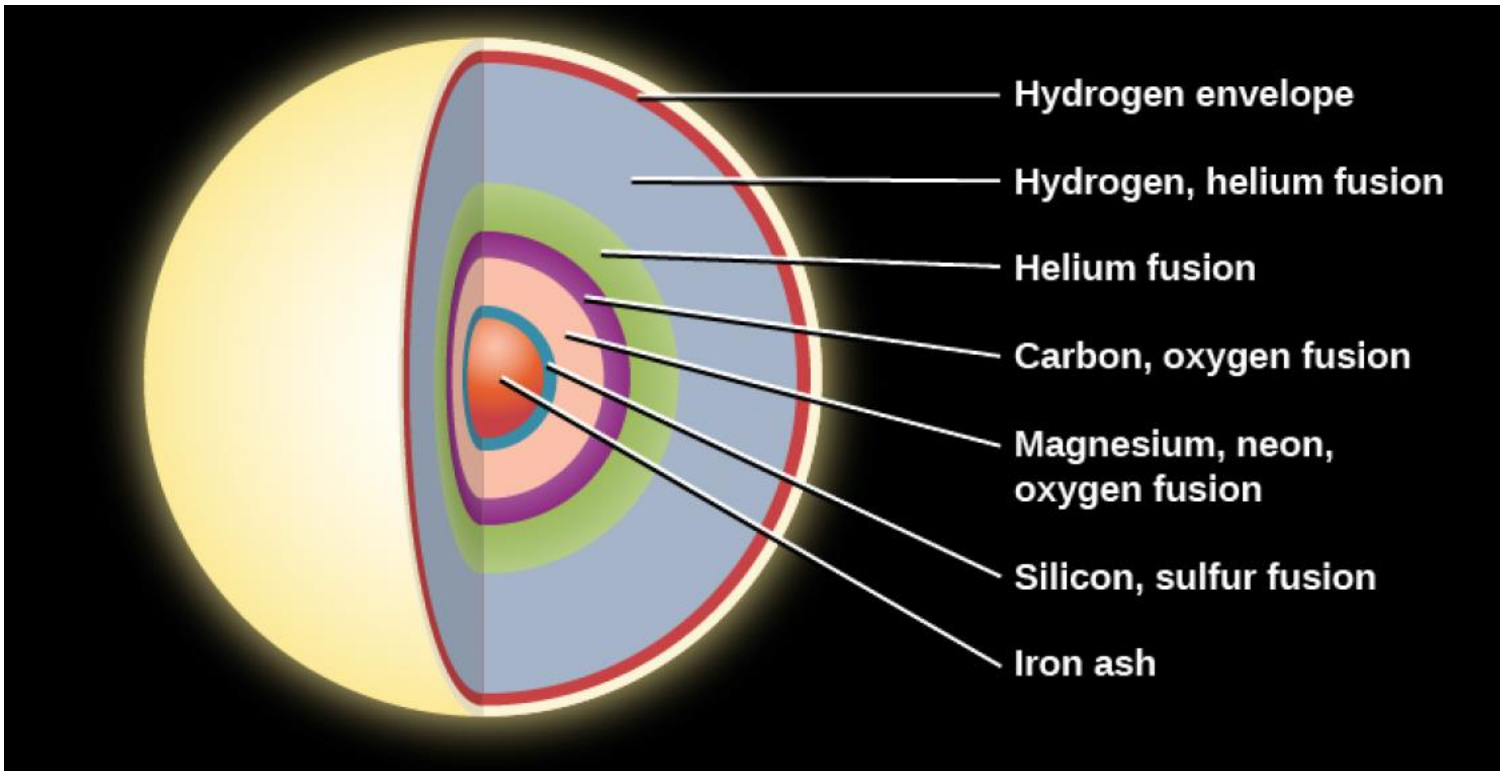
Comparing a Supergiant with the Sun

Property	Sun	Betelgeuse
Mass (2×10^{33} g)	1	16
Radius (km)	700,000	500,000,000
Surface temperature (K)	5,800	3,600
Core temperature (K)	15,000,000	160,000,000
Luminosity (4×10^{26} W)	1	46,000
Average density (g/cm^3)	1.4	1.3×10^{-7}
Age (millions of years)	4,500	10

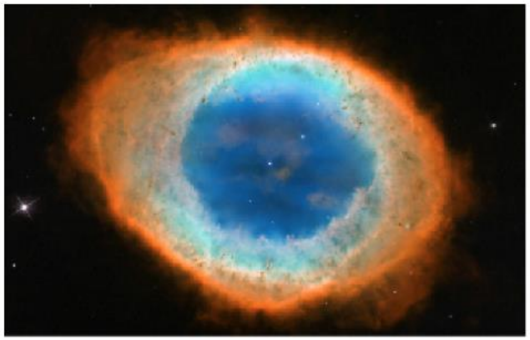
The supergiant star Betelgeuse



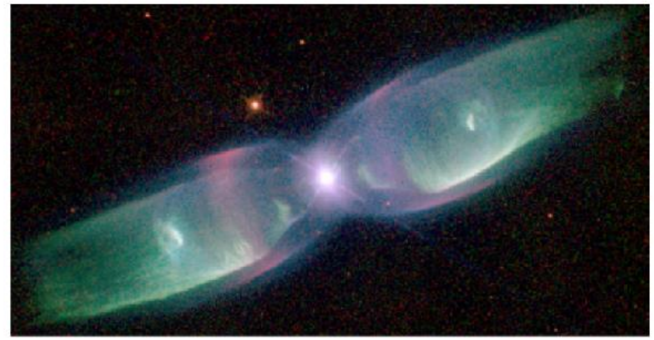
Planetary nebula: lost envelopes, only core is left; we see lost material



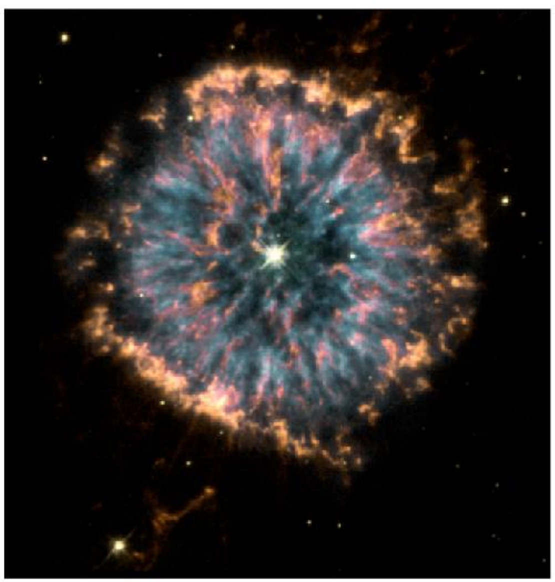
Planetary nebula: lost envelopes, only core is left; we see lost material



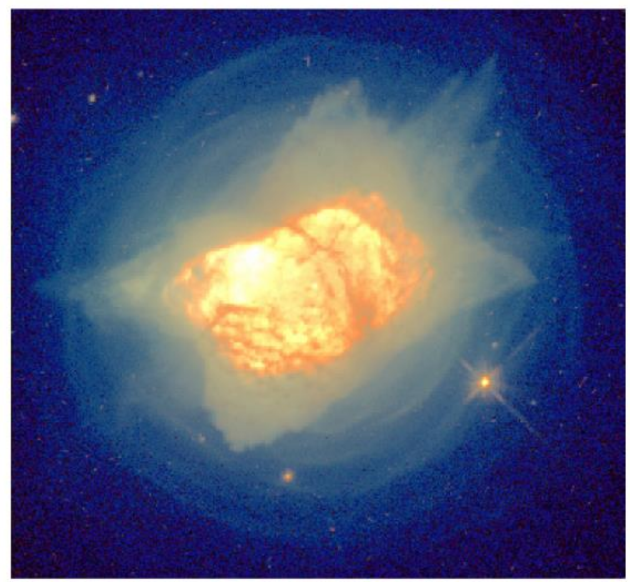
(a)



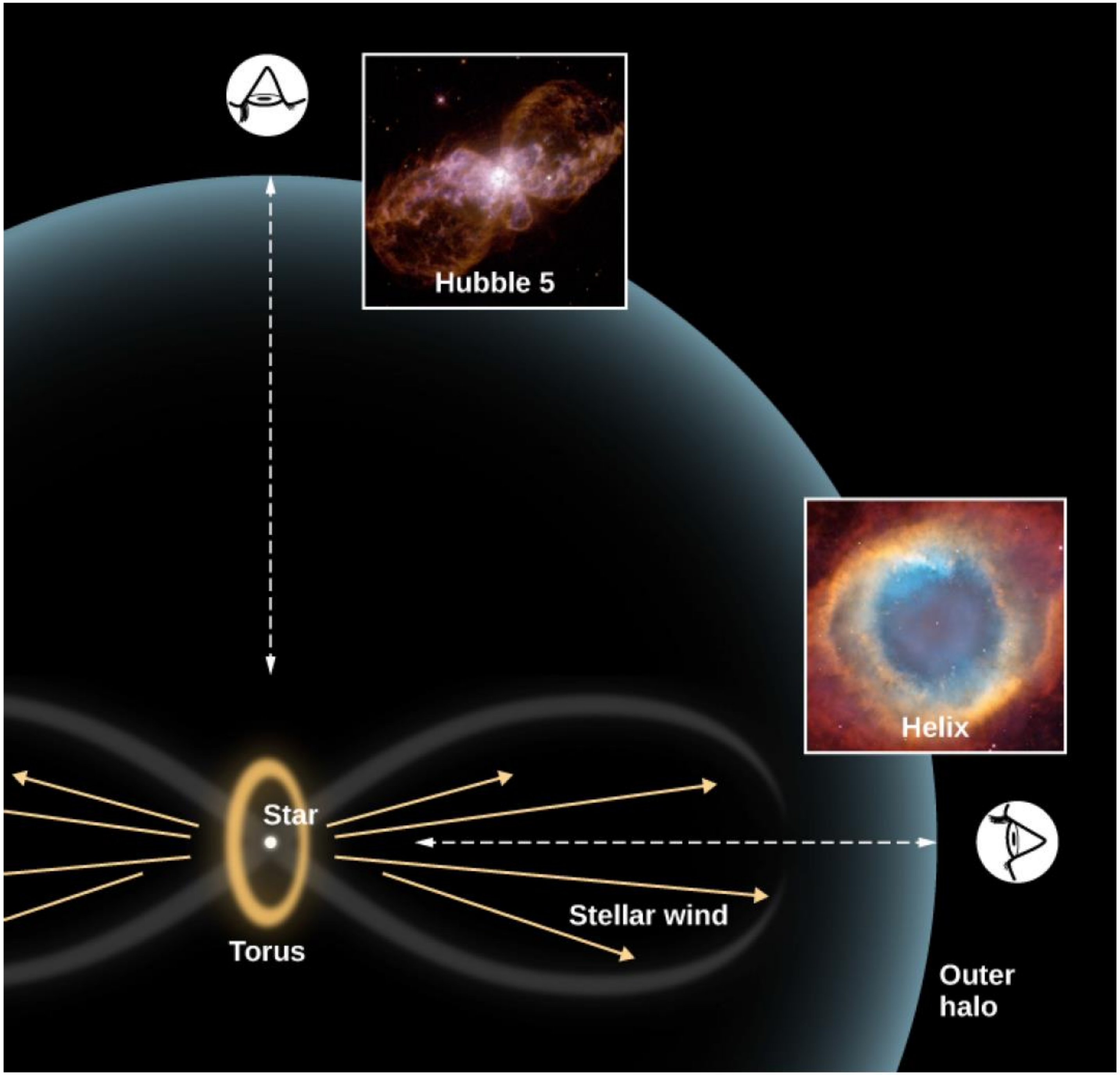
(b)



(c)

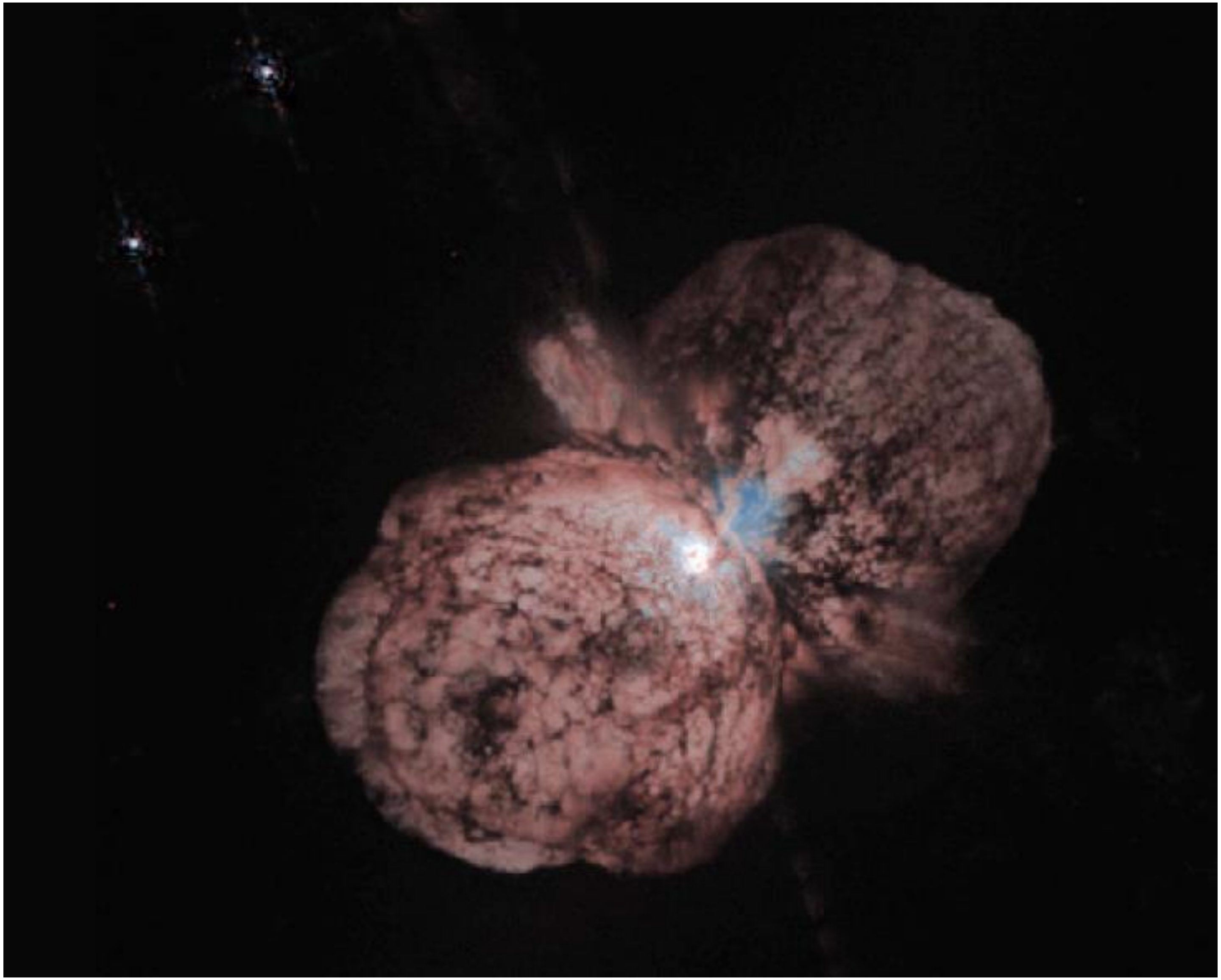


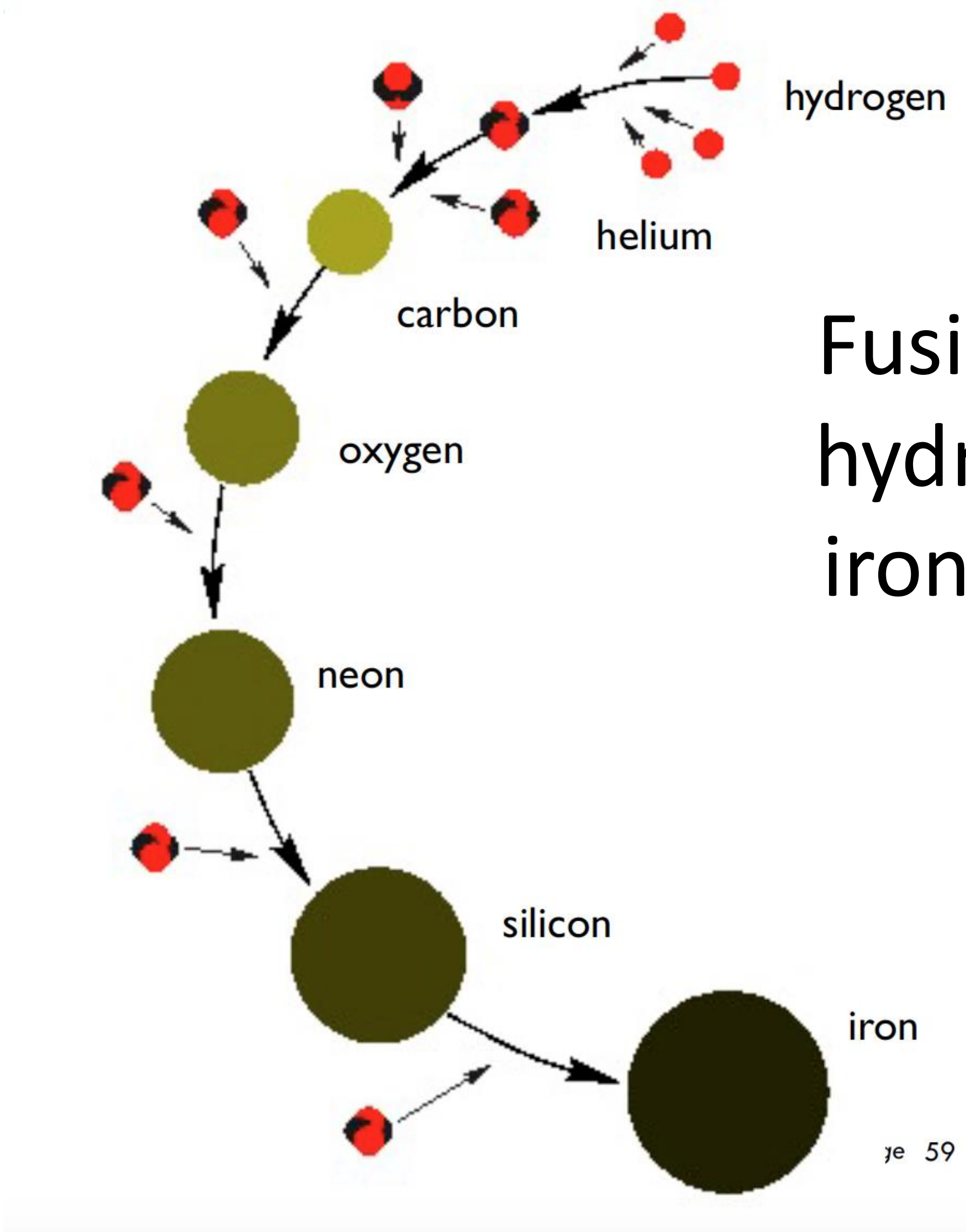
(d)



Hubble 5
Helix
Star
Torus
Stellar wind
Outer
halo

Eta Carina: what a 100 Msun star looks like

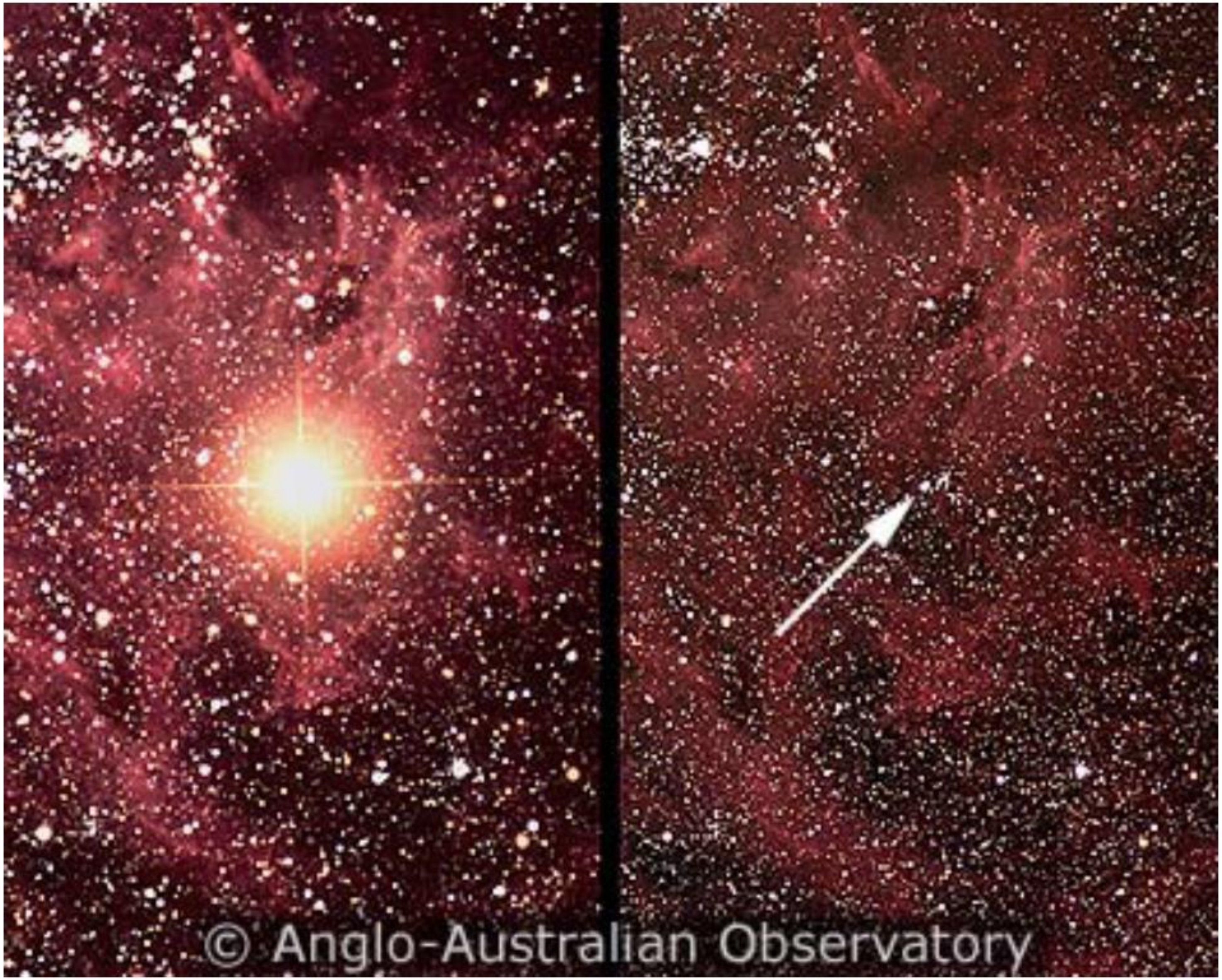


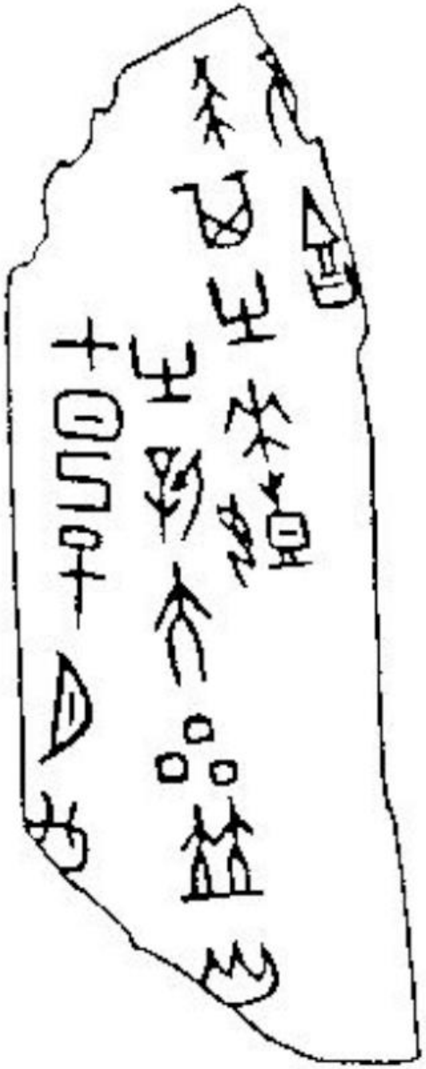


Fusion from hydrogen to iron in stars

Phase	Central Temperature (K)	Central Density (g/cm^3)	Time Spent in This Phase
Hydrogen fusion	40×10^6	5	8×10^6 years
Helium fusion	190×10^6	970	10^6 years
Carbon fusion	870×10^6	170,000	2000 years
Neon fusion	1.6×10^9	3.0×10^6	6 months
Oxygen fusion	2.0×10^9	5.6×10^6	1 year
Silicon fusion	3.3×10^9	4.3×10^7	Days
Core collapse	200×10^9	2×10^{14}	Tenths of a second

Supernova 1987A (brightest in modern times)



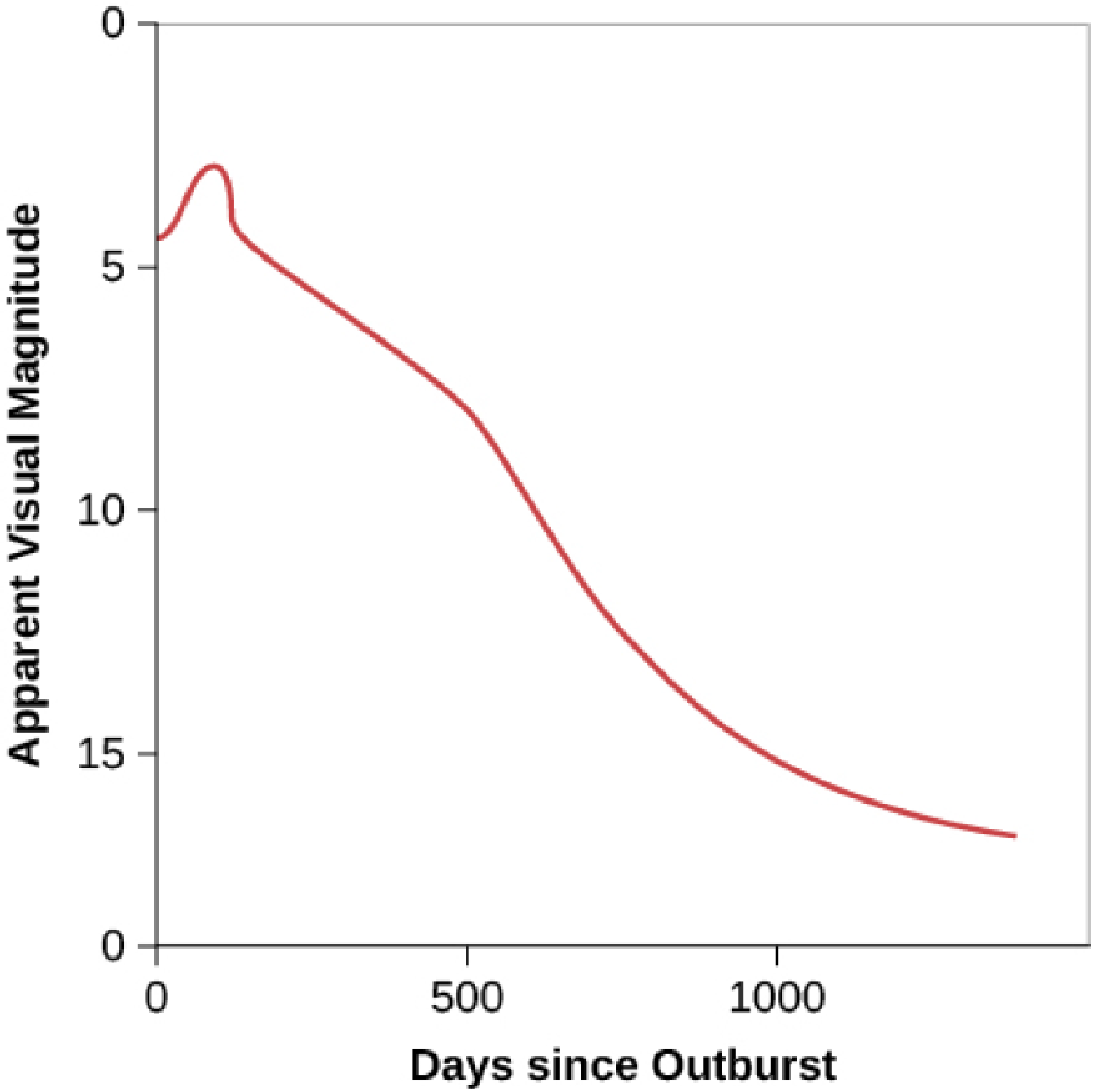


"On the Jisi day, the 7th day of the month, a big new star appeared in the company of the Ho star."

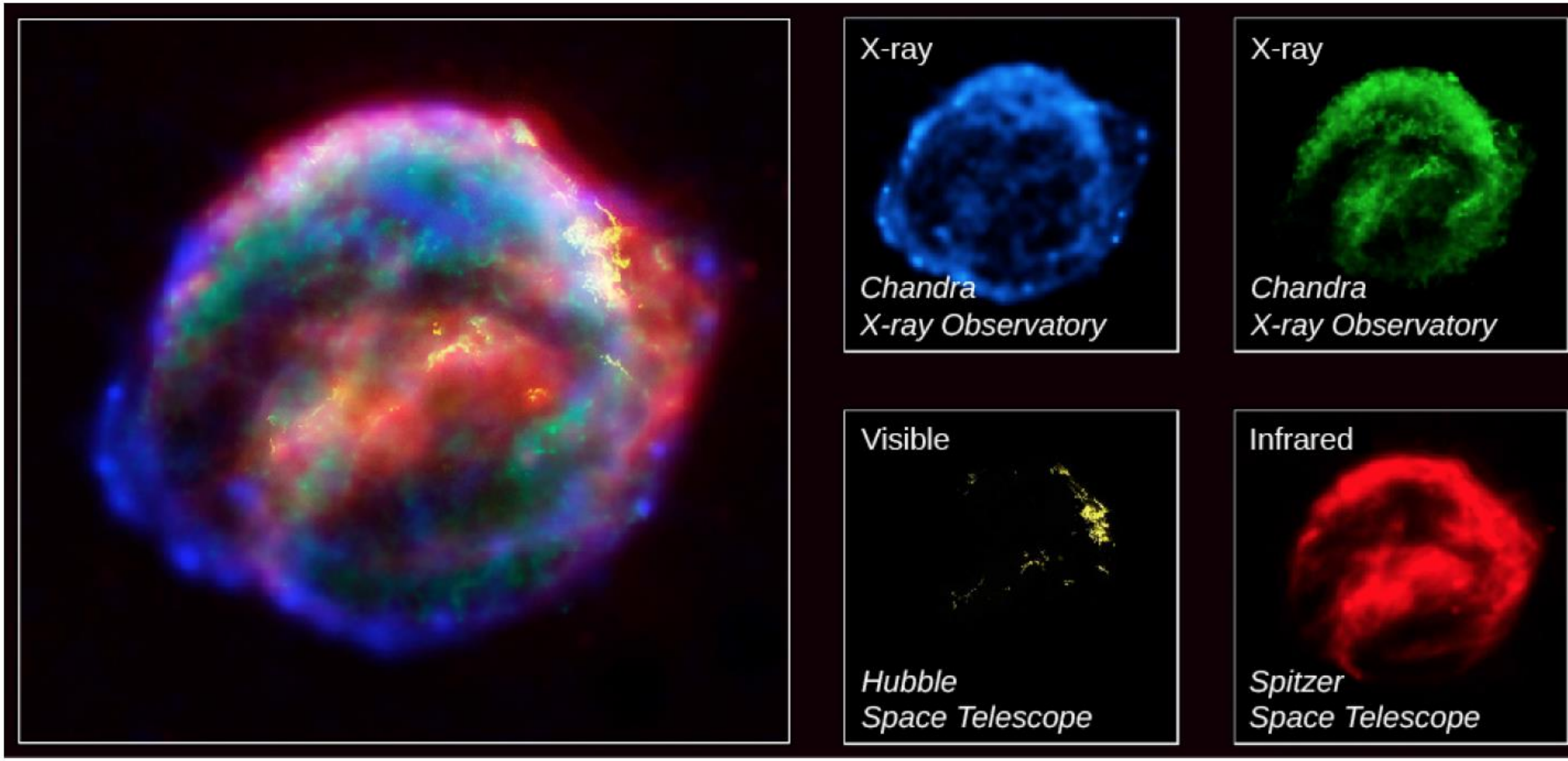
"On the Xinwei day the new star dwindled."

Year	Where observed	Brightness
185	China	Brighter than Venus
369	China	Brighter than Mars or Jupiter
1006	China, Japan, Korea, Europe, Arabia	Brighter than Venus
1054	China, SW India, Arabia ➔ Crab Nebula	Brighter than Venus
1572	Tycho	Nearly as bright as Venus
1604	Kepler	Brighter than Jupiter
1987	Ian Shelton (Chile)	-

Brightness of supernova with time

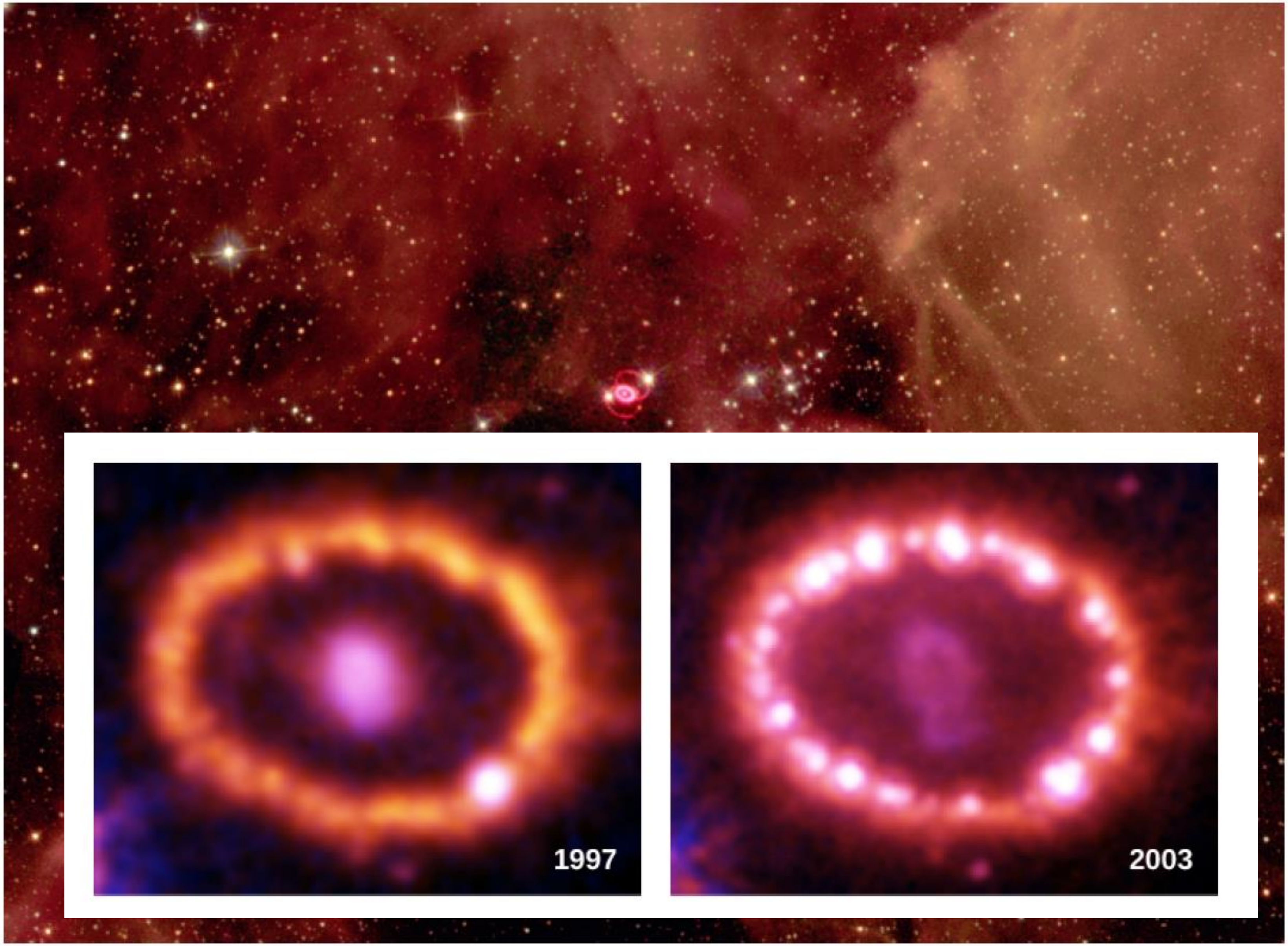


Supernova remnant

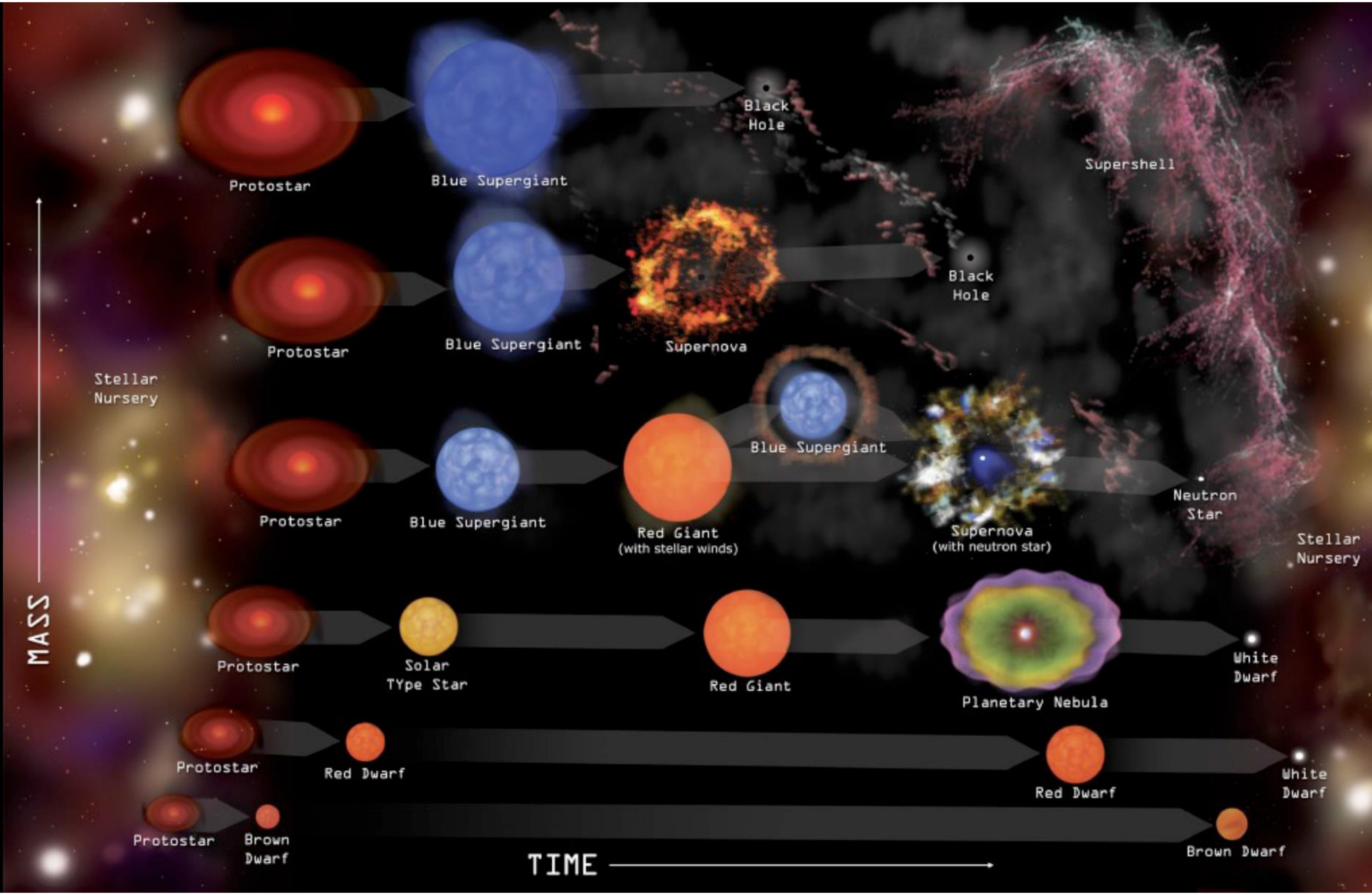


Supernova remnant

Supernova remnant



Initial Mass (Mass of Sun = 1)[1]	Final State at the End of Its Life
< 0.01	Planet
0.01 to 0.08	Brown dwarf
0.08 to 0.25	White dwarf made mostly of helium
0.25 to 8	White dwarf made mostly of carbon and oxygen
8 to 10	White dwarf made of oxygen, neon, and magnesium
10 to 40	Supernova explosion that leaves a neutron star
> 40	Supernova explosion that leaves a black hole



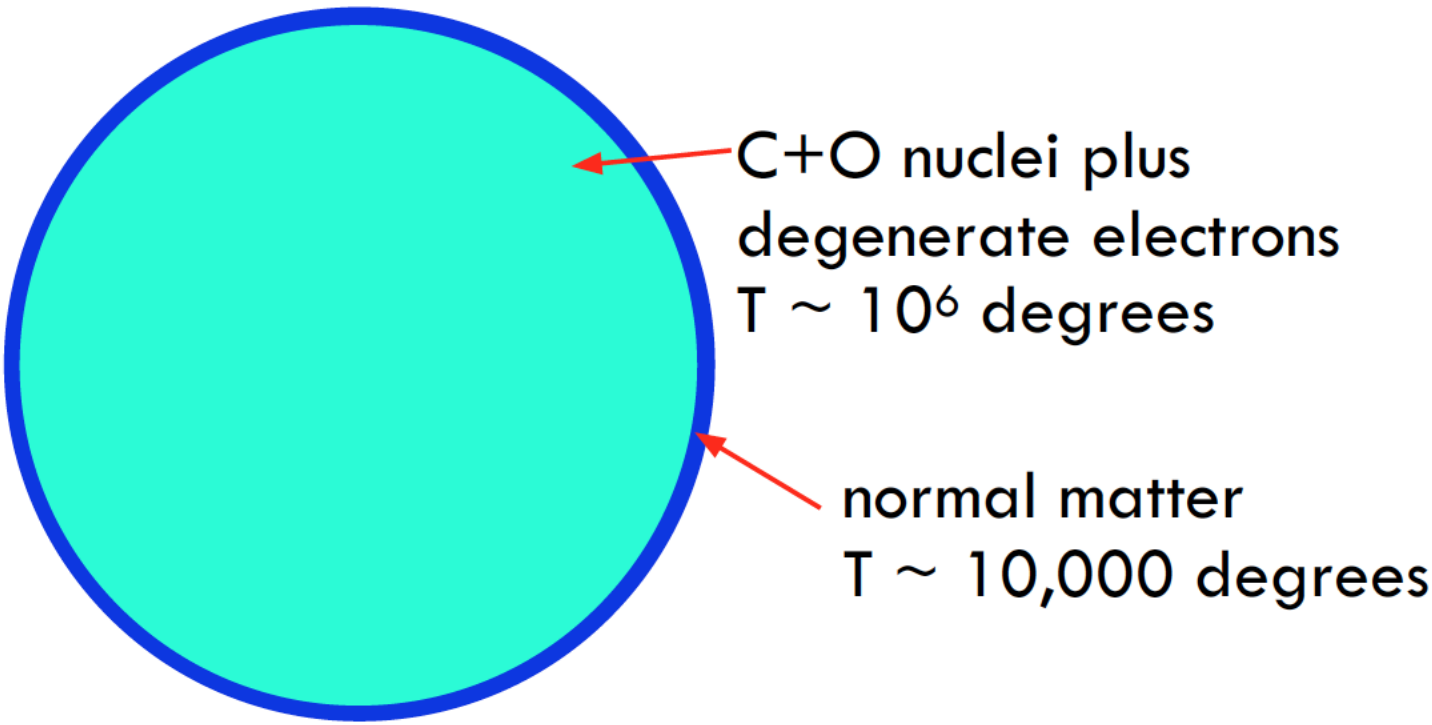
Protostar
Blue Supergiant
Black Hole
Supershell
Protostar
Blue Supergiant
Supernova
Black Hole
Stellar Nursery
Protostar
Blue Supergiant
Red Giant
(with stellar winds)
Blue Supergiant
Supernova
(with neutron star)
Neutron Star
Stellar Nursery
Protostar
Solar TYpe Star
Red Giant
Planetary Nebula
White Dwarf
Protostar
Red Dwarf
Red Dwarf
White Dwarf
Protostar
Brown Dwarf
Brown Dwarf
MASS
TIME

Properties of a Typical White Dwarf and a Neutron Star

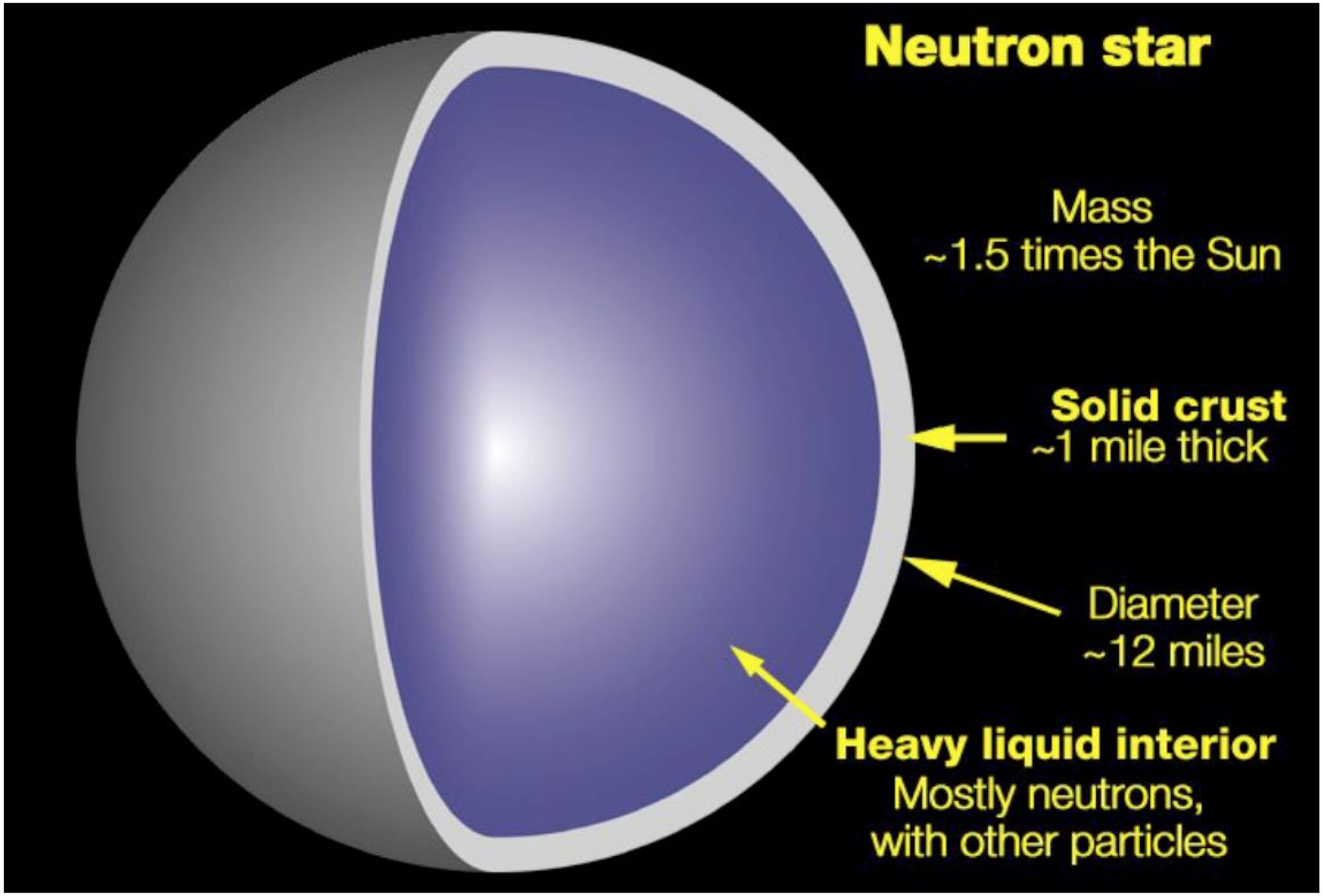
Property	White Dwarf	Neutron Star
Mass (Sun = 1)	0.6 (always <1.4)	Always >1.4 and <3
Radius	7000 km	10 km
Density	8×10^5 g/cm^3	10^{14} g/cm^3

X-ray image of accreting neutron star

White dwarf


C+O nuclei plus
degenerate electrons
T ~ 10^6 degrees
normal matter
T ~ 10,000 degrees

Neutron star: density of nucleus!



- **white dwarf:** electrons run out of room and halt the collapse of the star

maximum mass
1.4 solar masses

- **neutron star:** neutrons run out of room and halt the collapse of the star

maximum mass
~3 solar masses

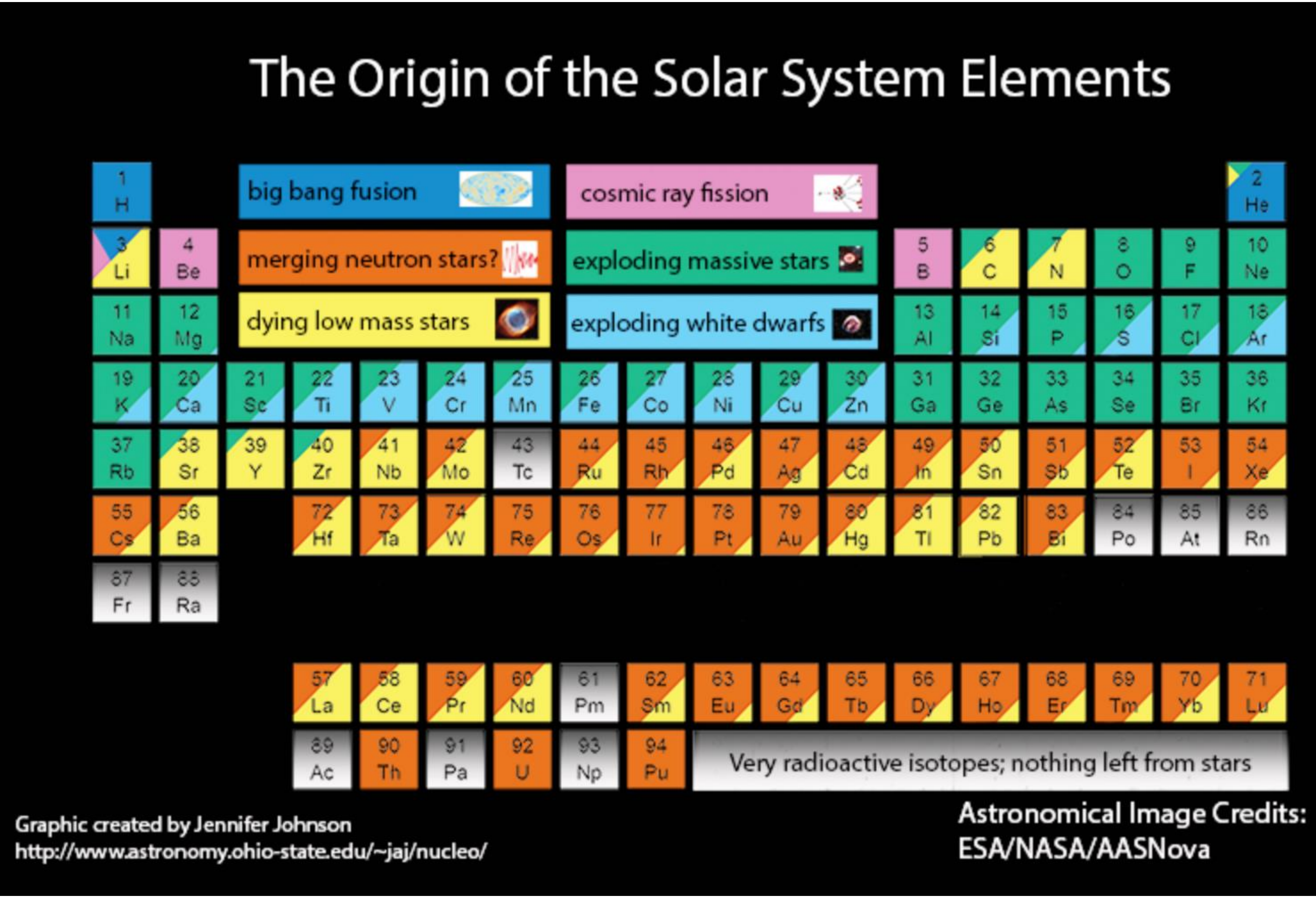
- **black hole:** gravity wins: collapse continues

Sun: size 1.4×10^6 km

rotation period 27 days = 2.3×10^6 s

Neutron star: size 14 km = 1 million times smaller

☞ rotation period 1 million times shorter = 2.3 s


The Origin of the Solar System Elements
big bang fusion
cosmic ray fission
merging neutron stars?
exploding massive stars
dying low mass stars
exploding white dwarfs
1 H
2 He
3 Li
4 Be
5 B
6 C
7 N
8 O
9 F
10 Ne
11 Na
12 Mg
13 Al
14 Si
15 P
16 S
17 Cl
18 Ar
19 K
20 Ca
21 Sc
22 Ti
23 V
24 Cr
25 Mn
26 Fe
27 Co
28 Ni
29 Cu
30 Zn
31 Ga
32 Ge
33 As
34 Se
35 Br
36 Kr
37 Rb
38 Sr
39 Y
40 Zr
41 Nb
42 Mo
43 Tc
44 Ru
45 Rh
46 Pd
47 Ag
48 Cd
49 In
50 Sn
51 Sb
52 Te
53 I
54 Xe
55 Cs
56 Ba
72 Hf
73 Ta
74 W
75 Re
76 Os
77 Ir
78 Pt
79 Au
80 Hg
81 Tl
82 Pb
83 Bi
84 Po
85 At
86 Rn
87 Fr
88 Ra
57 La
58 Ce
59 Pr
60 Nd
61 Pm
62 Sm
63 Eu
64 Gd
65 Tb
66 Dy
67 Ho
68 Er
69 Tm
70 Yb
71 Lu
89 Ac
90 Th
91 Pa
92 U
93 Np
94 Pu
Very radioactive isotopes; nothing left from stars
Graphic created by Jennifer Johnson
http://www.astronomy.ohio-state.edu/~jaj/nucleo/
Astronomical Image Credits:
ESA/NASA/AASNova

Interstellar medium

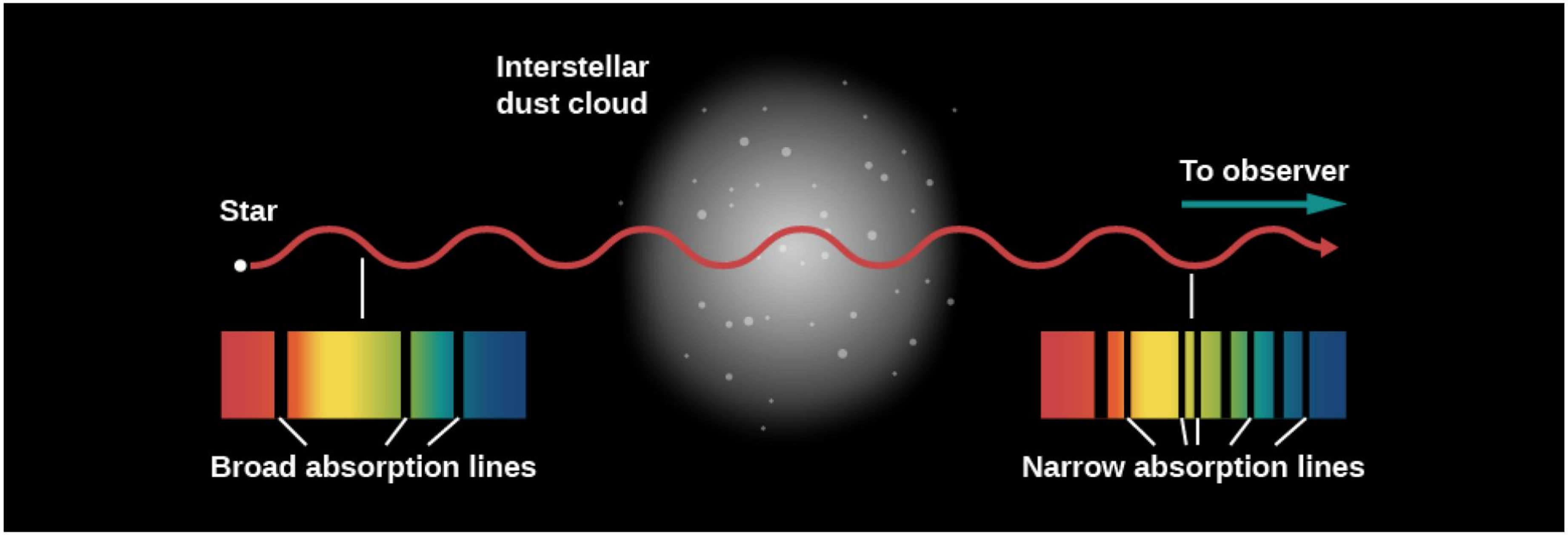
- Space is not quite empty
  - Hot interstellar medium: 10^{-4} ions per cm^3
  - In this room: 10^{19} molecules/cm^3
  - Best vacuum in lab: 10^{10} molecules/cm^3
- Some places are denser and colder
  - **Molecular clouds**, where stars form
  - Densities of 10^2-10^6 molecules/cm^3

Interstellar medium, supernova remnants

Intestellar medium: how to detect?

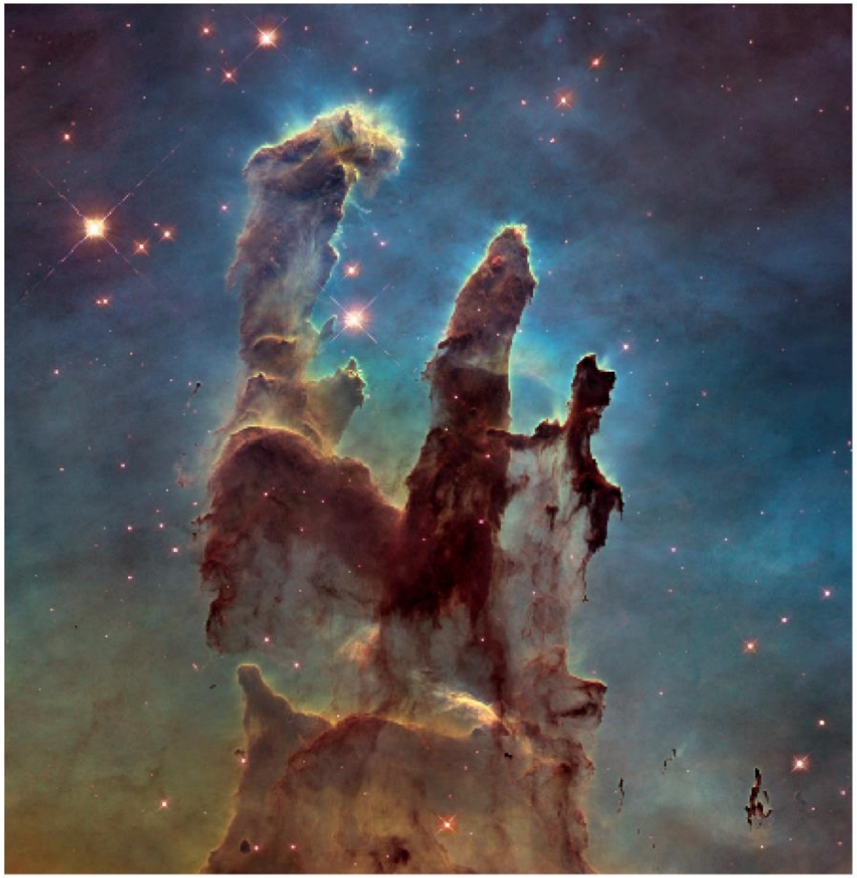
Absorption of photons by gas

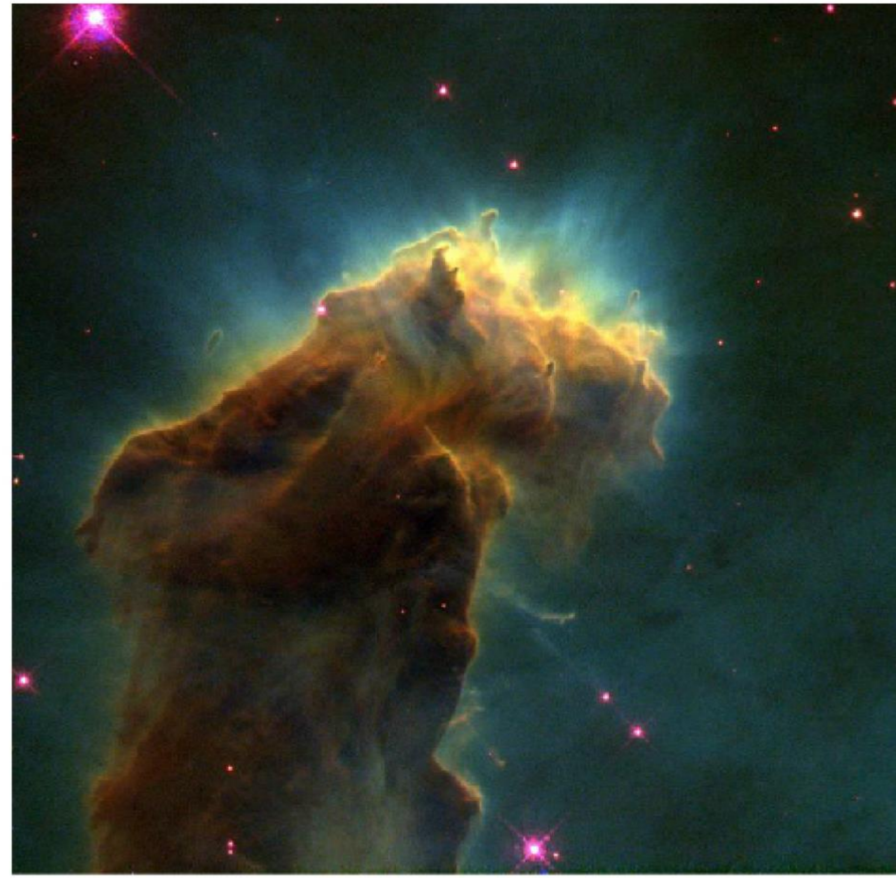
Emission from gas/dust



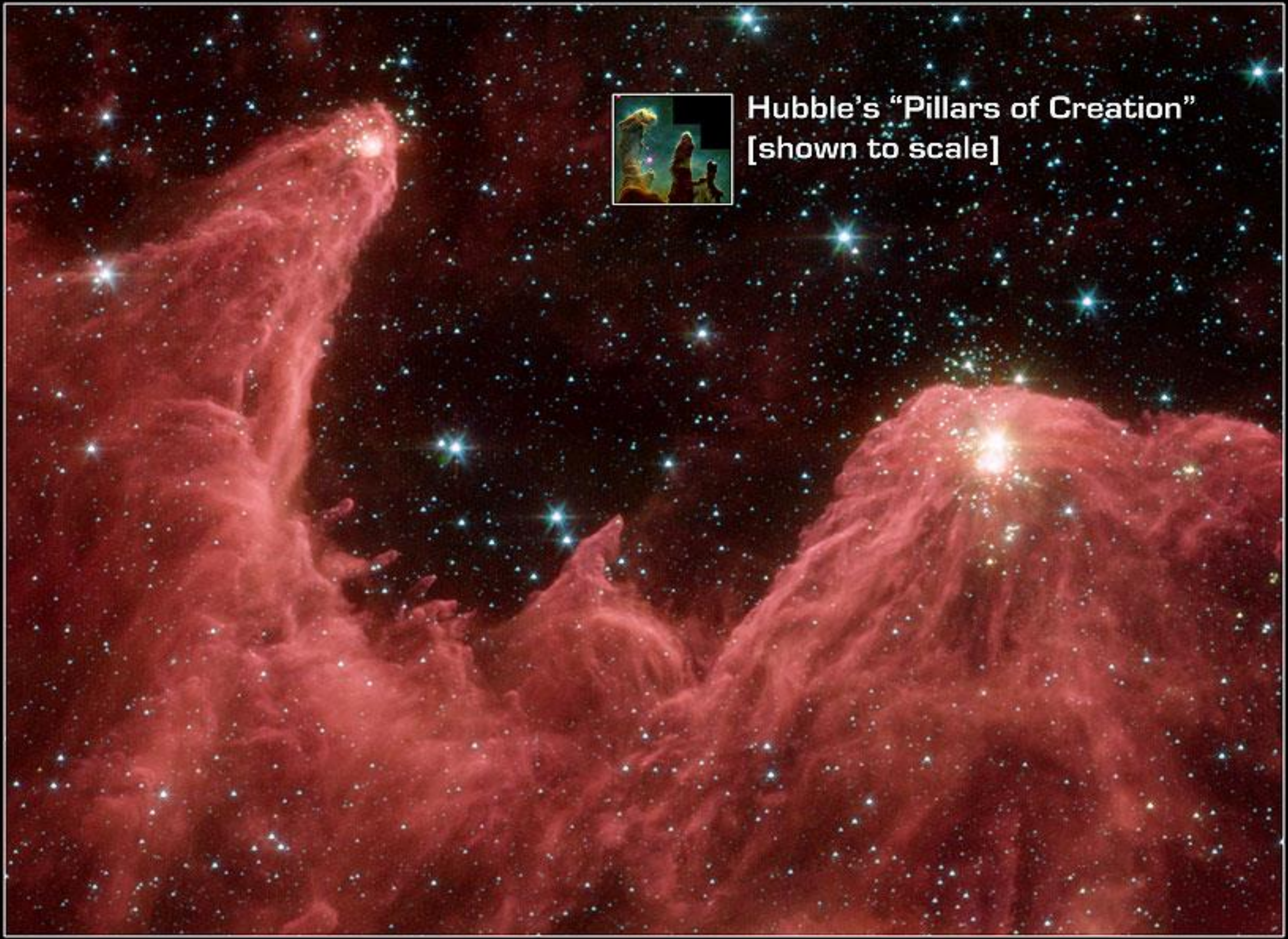

Orion Nebula
Largest nearby star-forming region

Eta Carina Cluster,
Hubble Space Telescope
Much larger than Orion Nebula





Hubble Space Telescope: dust in a star-forming region blocking background light

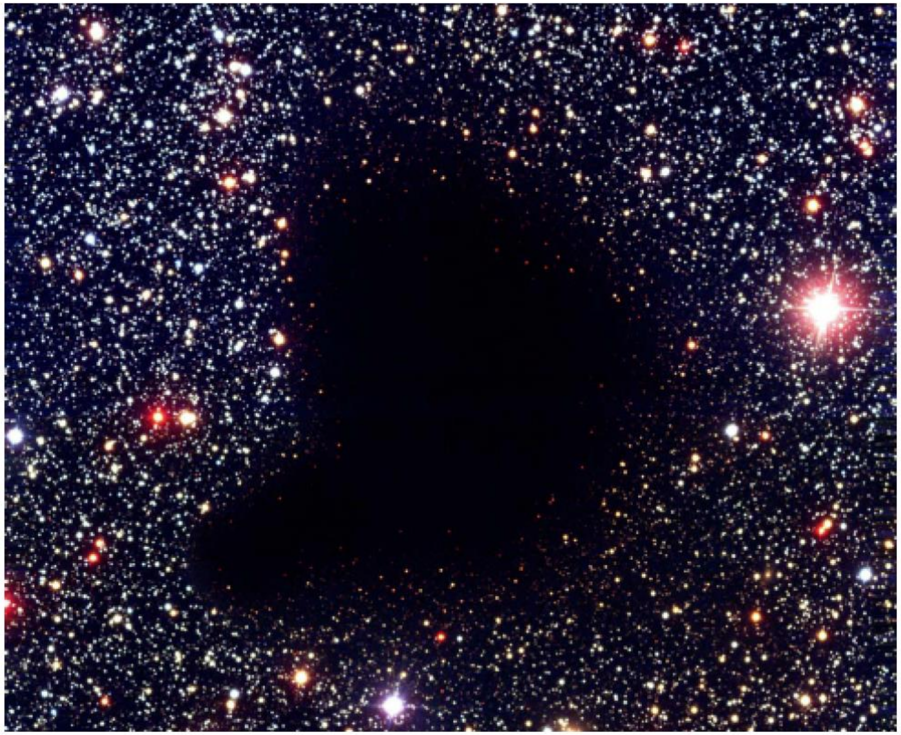


"Pillars" and "Mountains" of Star Formation

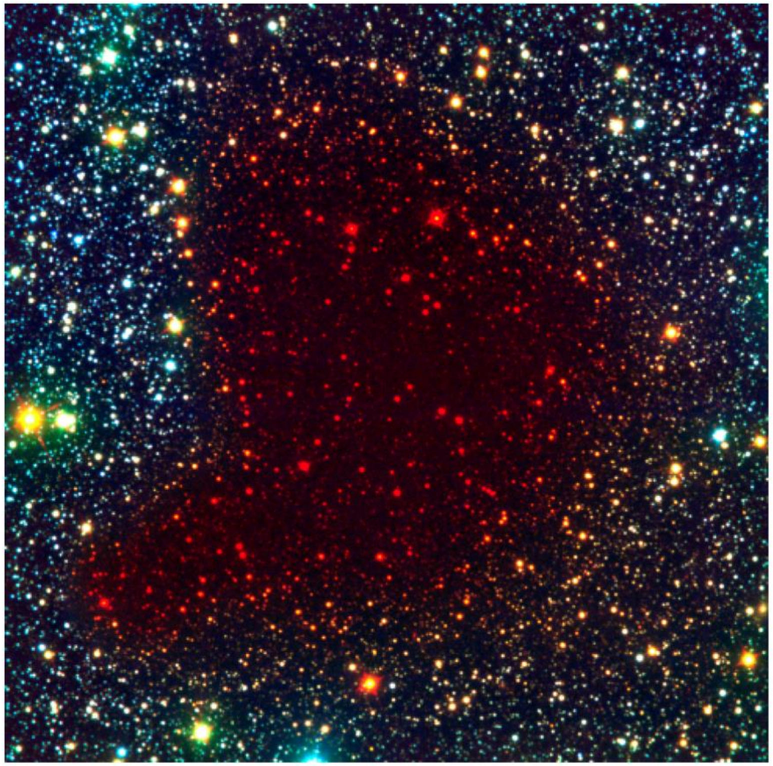
Spitzer Space Telescope • IRAC

Inset: Hubble Space Telescope

ssc2005-23b



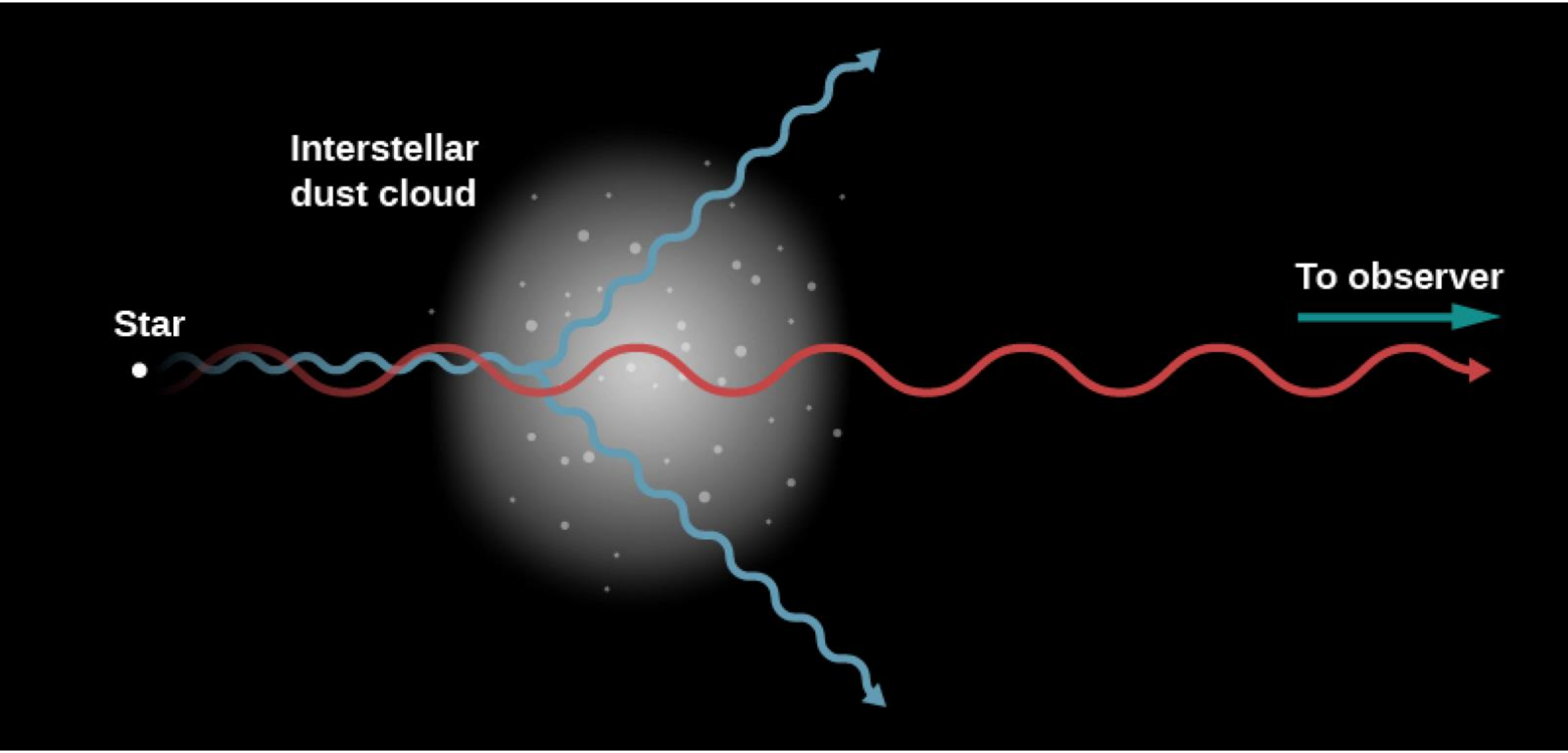
Optical



Near-infrared

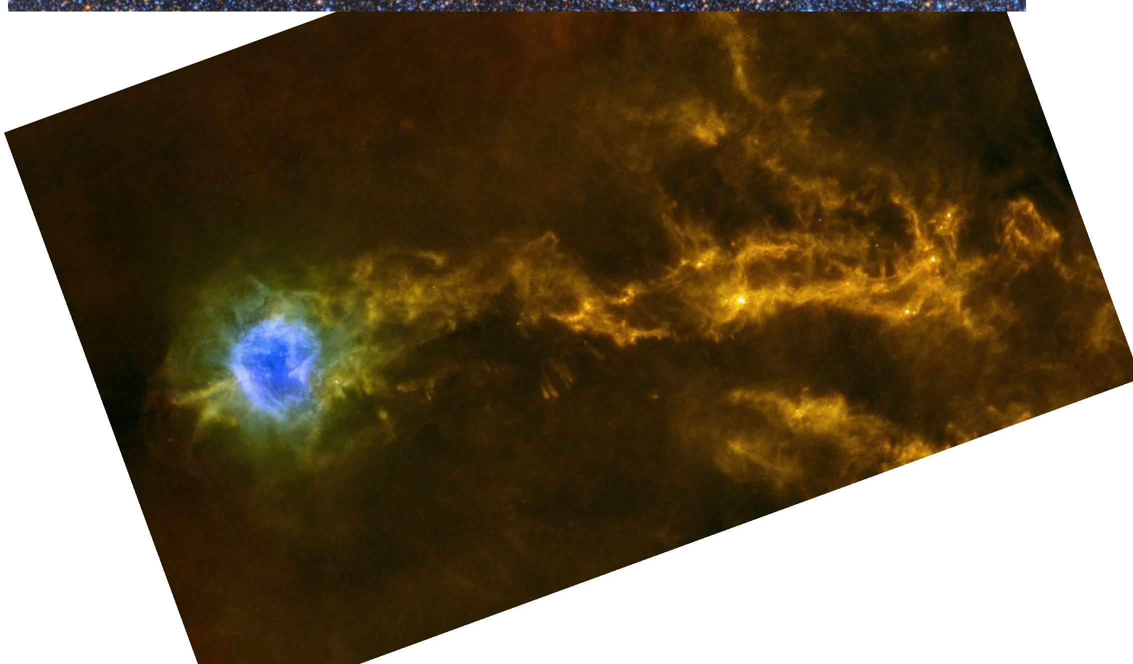
Barnard 68: very dusty!

Longer wavelengths look through dust (red objects on right)



Blue wavelengths: absorbed/scattered by dust
Red wavelengths: pass through dust


Rosette Nebula
Far-infrared: dust in emission

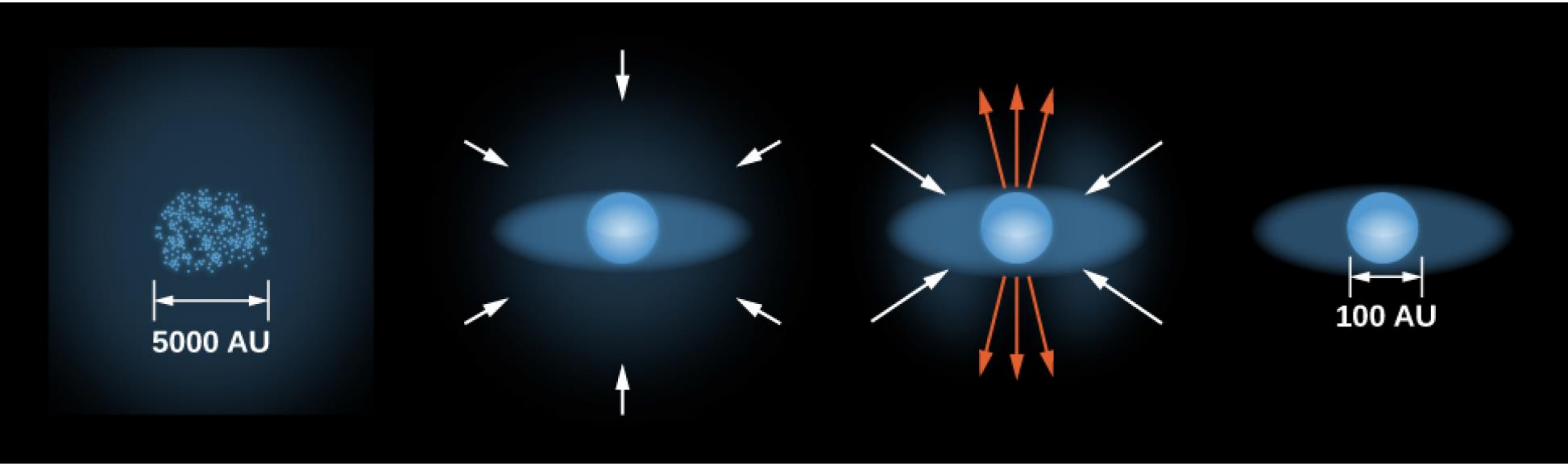


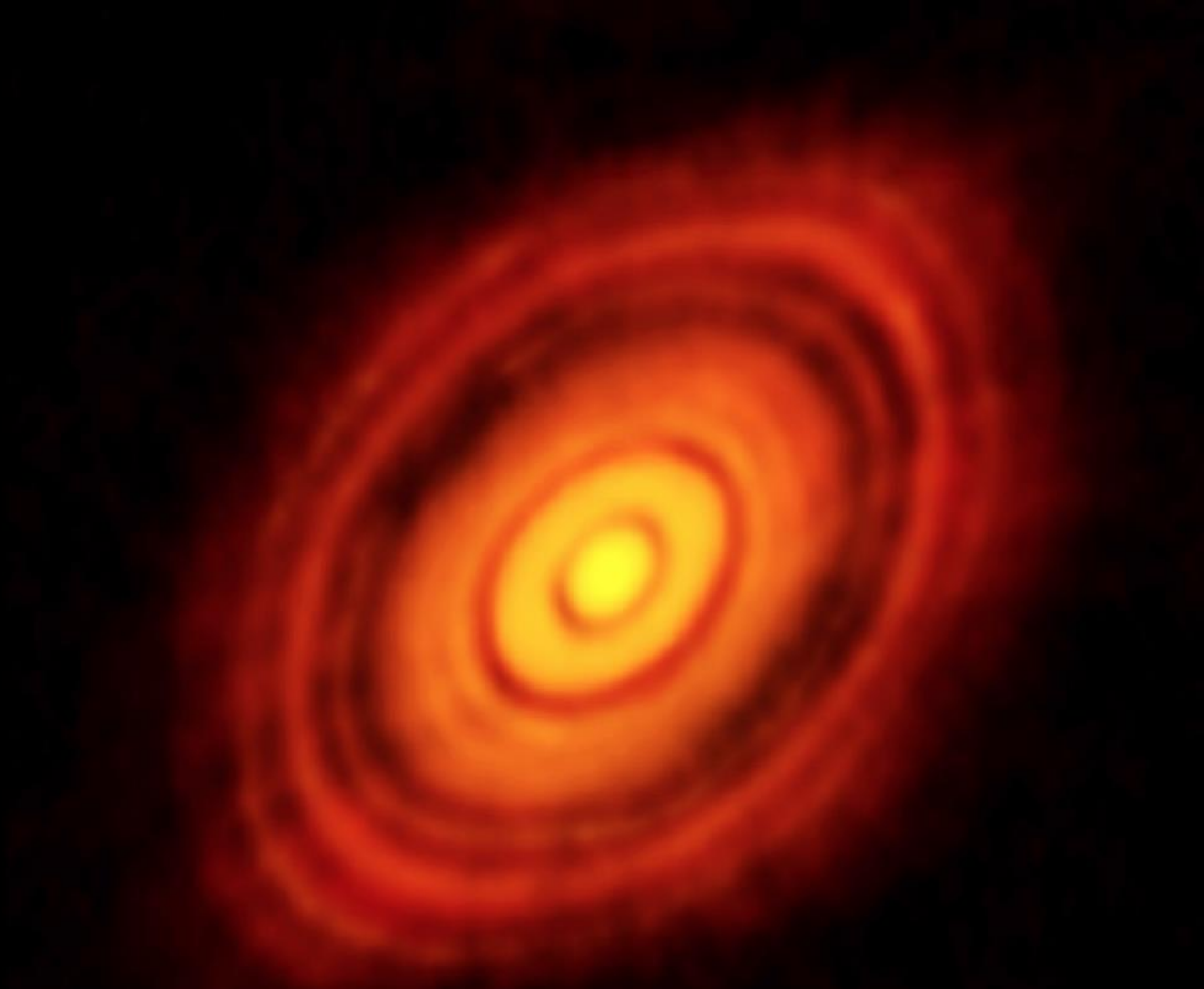
The same nebula can appear in both emission at short wavelengths and absorption at long wavelength

JWST image of Carina Nebula: hot stars ionize gas

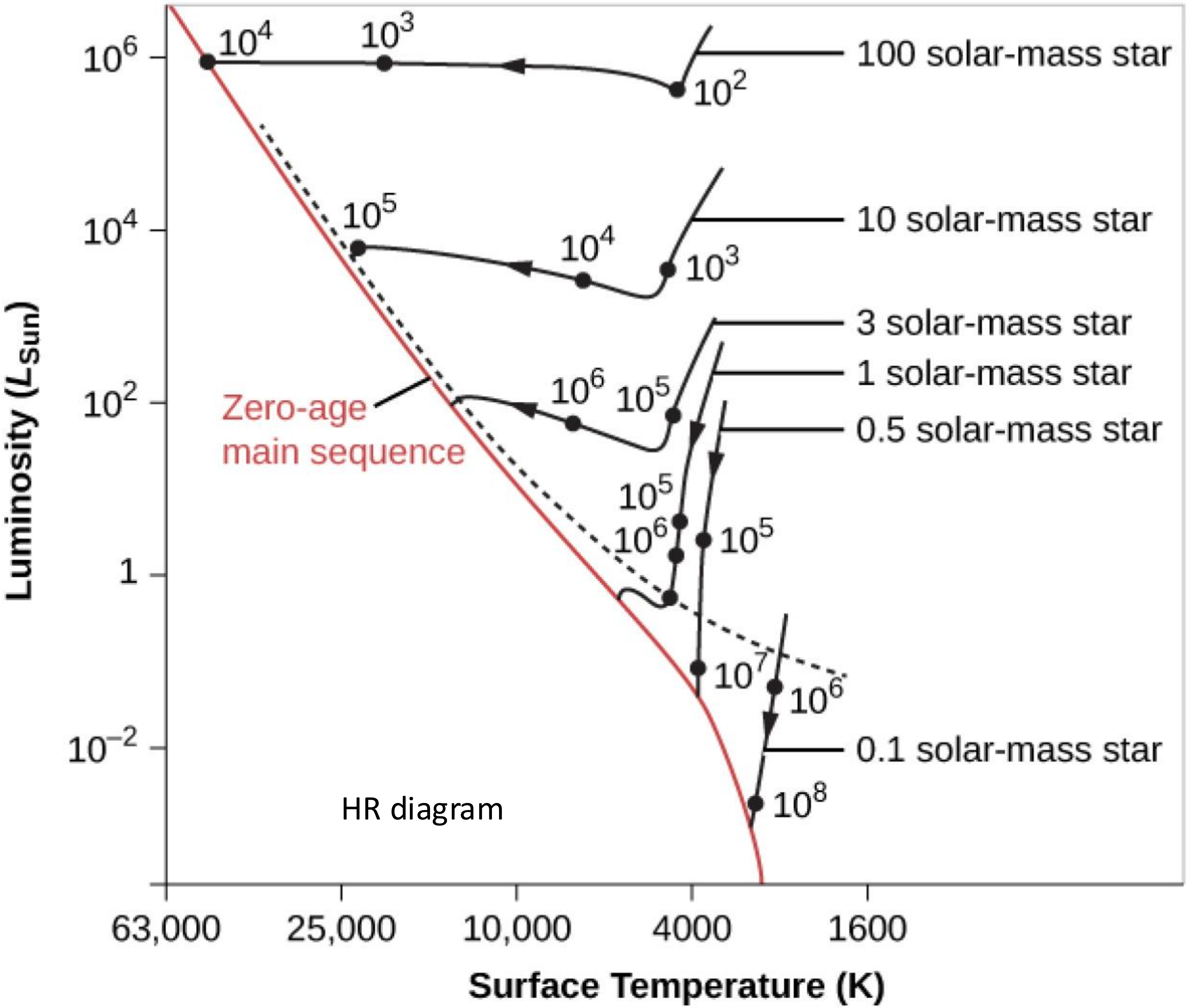
Steps of star formation:

1) Region is dense enough to be gravitationally unstable and collapse
2) Protostar forms, with envelope and disk
3) Star grows, leads to jets and outflows
4) Envelope and disk disappear, leaving behind planets+star





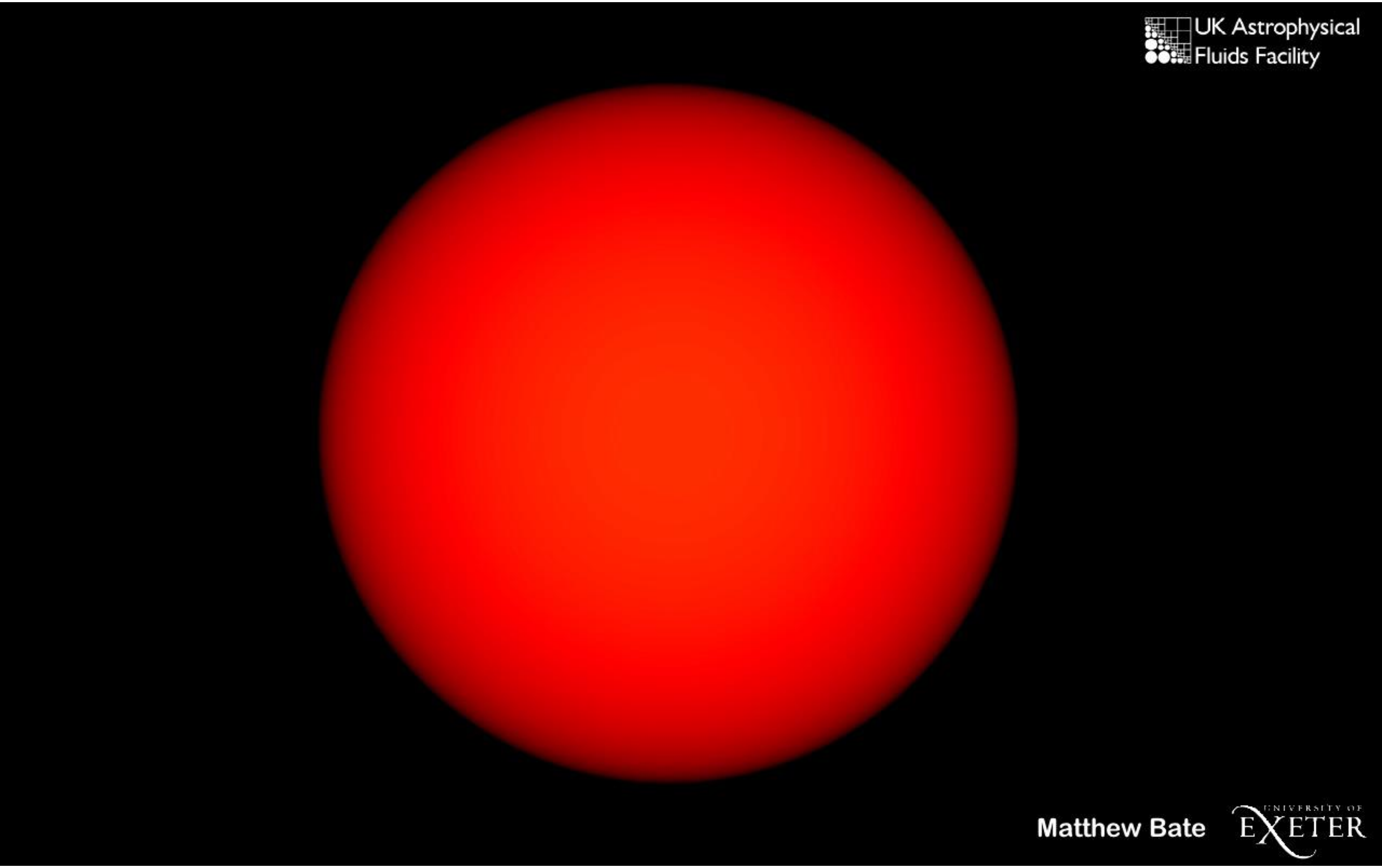
Protoplanetary disk: where planets form (next lecture)



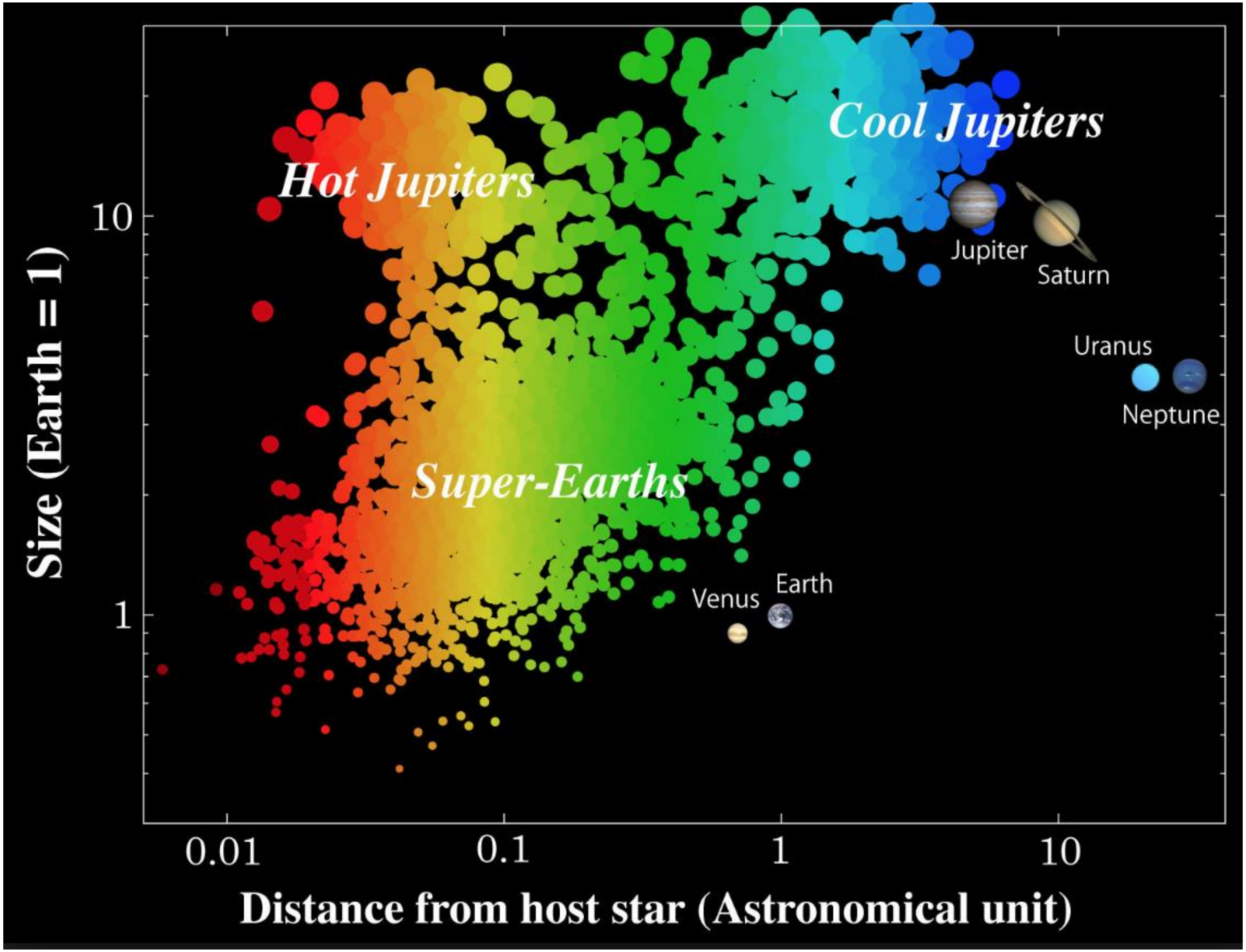
100 solar-mass star
10 solar-mass star
3 solar-mass star
1 solar-mass star
0.5 solar-mass star
0.1 solar-mass star
Zero-age main sequence
Luminosity (L_{Sun})
10^6
10^4
10^2
1
10^{-2}
63,000
25,000
10,000
4000
1600
Surface Temperature (K)

HR diagram

Simulation of a star-forming region



EXOPLANETS!


Cool Jupiters
Hot Jupiters
Super-Earths
Jupiter
Saturn
Uranus
Neptune
Venus
Earth
10
1
0.01
0.1
1
10
Size (Earth = 1)
Distance from host star (Astronomical unit)