Stars:
Part I: The Building Blocks of the Universe

Homeworks and lectures

- github: slides and homework
- Videos on zoom/circulated
- Introduction homework 1: grades mailed back
  - Too many of you play video games.
  - 11/47 said that you were shy or introverts
    - Probably a lot more!
  - Grades all returned
  - If you did not receive a grade, email me: gjh1@pku.edu.cn
- Homework 2: due Mon, Mar. 23, 3:00pm
  - Submit to PKUdisk (see assignment, will circulate on wechat)
  - Some files circulated at github
  - https://gherczeg.github.io/modernastronomy/
- Questions? (don't wait until the end of class, I leave at 5pm)

47 responses, all 47 use LLMs

Deepseek	41	Most used; strong for reasoning/math/coding
Doubao	38	Multimodal (images/files); strong for Chinese content/translation
Gemini (Google)	15	Preferred for complex reasoning; free Pro subscription for some
ChatGPT	14	Strong for English/academic writing; requires VPN in China
Qwen	3	Fast for mundane tasks; open-source
Grok	3	Good for programming; low error rate
Claude	2	Excellent for coding/bug fixing
Kimi	1	Used for information collection/polishing
AI4S (PKU)	2	PKU platform tool; for paper searching/research
Copilot	1	For coding assistance

表格

Usage Category	Specific Actions	Number of Students (Primary Use)
Academic Problem-Solving	Math/physic formula derivation, coding/debugging, homework answer checking	39
Information Retrieval	Topic research, paper/article summarization, niche knowledge explanation	45
Language Support	Translation (CN/EN/other), grammar polishing, academic writing/outlines	37
Daily Task Automation	Citation formatting, email drafting, travel planning, data organization	18
Creative/Emotional Use	Essay writing, emotional consolation, brainstorming	8
PKU-Specific Research	Paper searching/field analysis via AI4S (PKU platform)	2

Table 3: Top LLM Models – Strengths and Drawbacks (Reported by Students)

表格

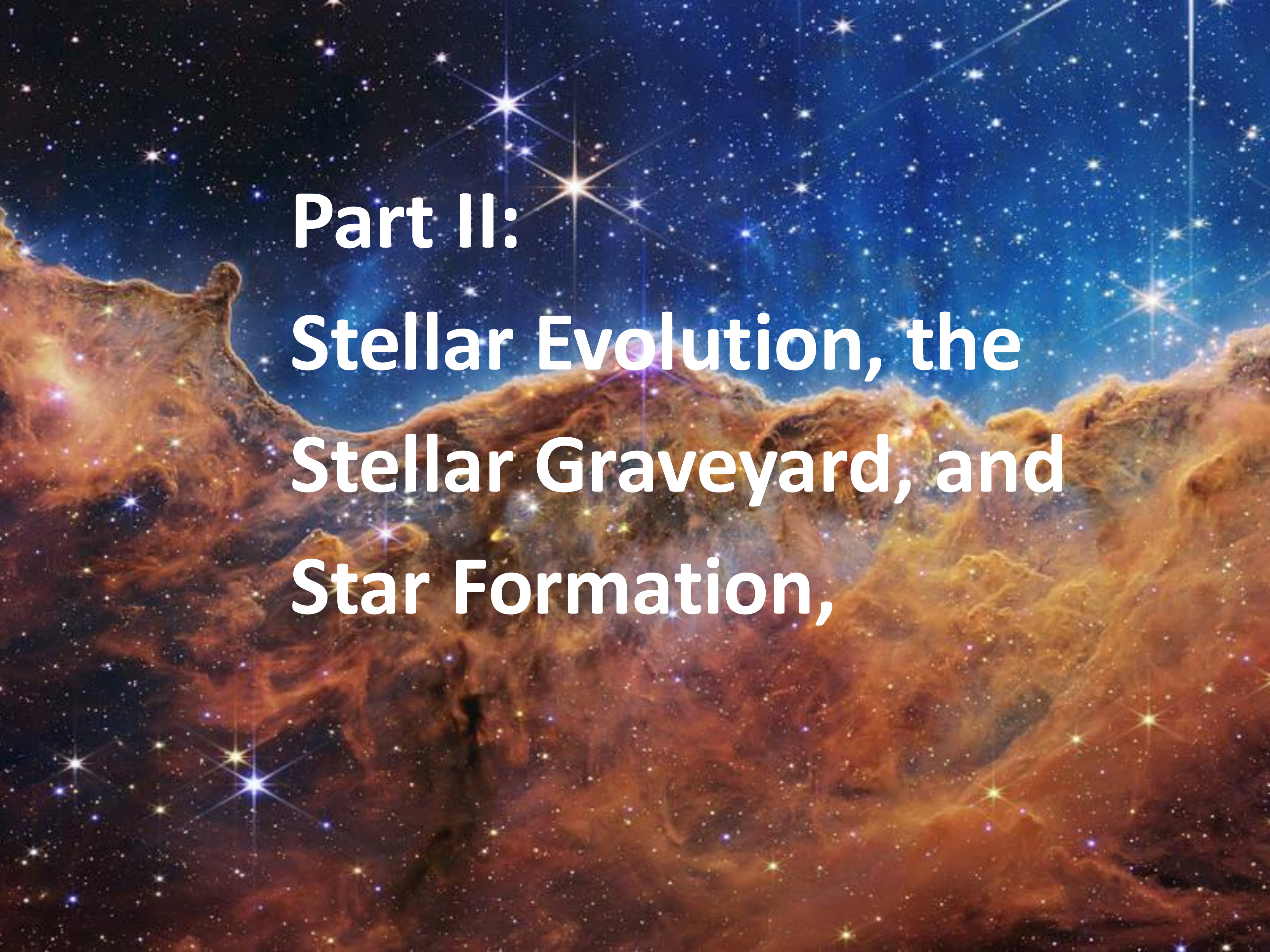
LLM Model	Key Strengths (Student Feedback)	Key Drawbacks (Student Feedback)
Deepseek	Strong reasoning/coding/math; clear thought process; fast for Chinese content; good for long context summarization	Text-only (no images); rigid language; occasional fake theorems/ citations; slow reasoning for complex tasks
Doubao	Multimodal (images/files/videos); fast response; strong for Chinese humanities/social sciences; good for translation	Less rigorous than Deepseek/Gemini; inaccurate answers for unknown topics; weaker reasoning than international models
Gemini	Complex reasoning/math; free Pro subscription; good for data analysis; image generation	Hallucinations with fake data; limited for niche professional questions; average for subjective tasks (planning)
ChatGPT	Fluent English/academic writing; personalized responses; good for cross-language work (CN/EN/RU/FR)	Requires VPN in China; slow processing; poor at image analysis; verbose explanations

Undergraduate Major	Number of Students	Most Used LLMs	Primary LLM Use Case
Engineering (All)	9	Deepseek, Doubao, Gemini	Formula derivation, coding, technical term translation
Computer Science	7	Deepseek, Gemini, Claude	Coding/debugging, simulation analysis, paper summarization
Pharmacy/Pharmaceutics	6	Deepseek, Doubao	Homework answer checking, drug science concept explanation
Clinical Medicine/Basic Medical Sciences	5	Deepseek, Doubao	Medical knowledge sorting, professional paper translation
Mathematics	4	Deepseek, Gemini	Math problem-solving, theorem explanation, data analysis

LLM Concern/Limitation	Number of Students Reporting	Key Context/Student Sentiment
Hallucination (fabricated references, false data/calculations, fake information)	6	Generates non-existent references, incorrect math/phys results, and untrue details that require manual verification; e.g., "fabricated references during literature searches" and "cheats with false results".
Over-reliance risk (erosion of personal coding/writing skills)	4	Worry that heavy LLM use for coding/writing will make students unable to complete these tasks independently; e.g., "am worrying that if I could code by myself without LLM".
Redundant/overly complex output (unnecessary detail, fancy academic writing, over-predicting next steps)	5	LLMs provide too many answers/choices for simple questions, use overly complex phrasing for academic writing, and add redundant info; e.g., "give you too many answers or choices if you ask them a simple question" and "give me many redundant information, and predict what should do next too much".
Free version limitations (text length, file uploads, usage caps)	3	Free LLM versions have restrictions on long text, file uploads, and overall usage; e.g., "the free version has limitations on file uploads and text length (ChatGPT)".
Slow response speeds (primarily DeepSeek)	3	DeepSeek (especially self-deployed instances) has slow server/response times; e.g., "DeepSeek V3.2... relatively slow in official website and slower in self-deployed server".
Random code errors (GitHub Copilot/Cursor)	2	Integrated coding tools make unprompted, incorrect changes to finished code and generate buggy auto-complete; e.g., "sometimes it makes random changes and errors to my finished code (Copilot)".
Misunderstanding user requests (unrelated answers, off-topic responses)	2	LLMs fail to interpret specific questions and provide answers that do not address the user's intent; e.g., "sometimes they don't answer correctly and not exactly to my question".
Unnatural translations (CN/EN)	2	LLMs produce overly dramatic or logically mismatched translations when converting Chinese draft writing to English; e.g., "the translation may come across as overly dramatic or the logic might differ slightly from my original intent".
Instability (inconsistent output quality)	1	Gemini (free version) has variable reasoning and output quality; e.g., "Gemini has better reasoning and output quality (among all free versions), but it appears to be less stable".
Diminished logic in newer versions	1	ChatGPT 5.0 has worse logical reasoning than 4.0; e.g., "ChatGPT got 'stupid' somewhere between version 4.0 and 5.0, as the logic in its response got unclear".

Part II:

Stellar Evolution, the Stellar Graveyard, and Star Formation,



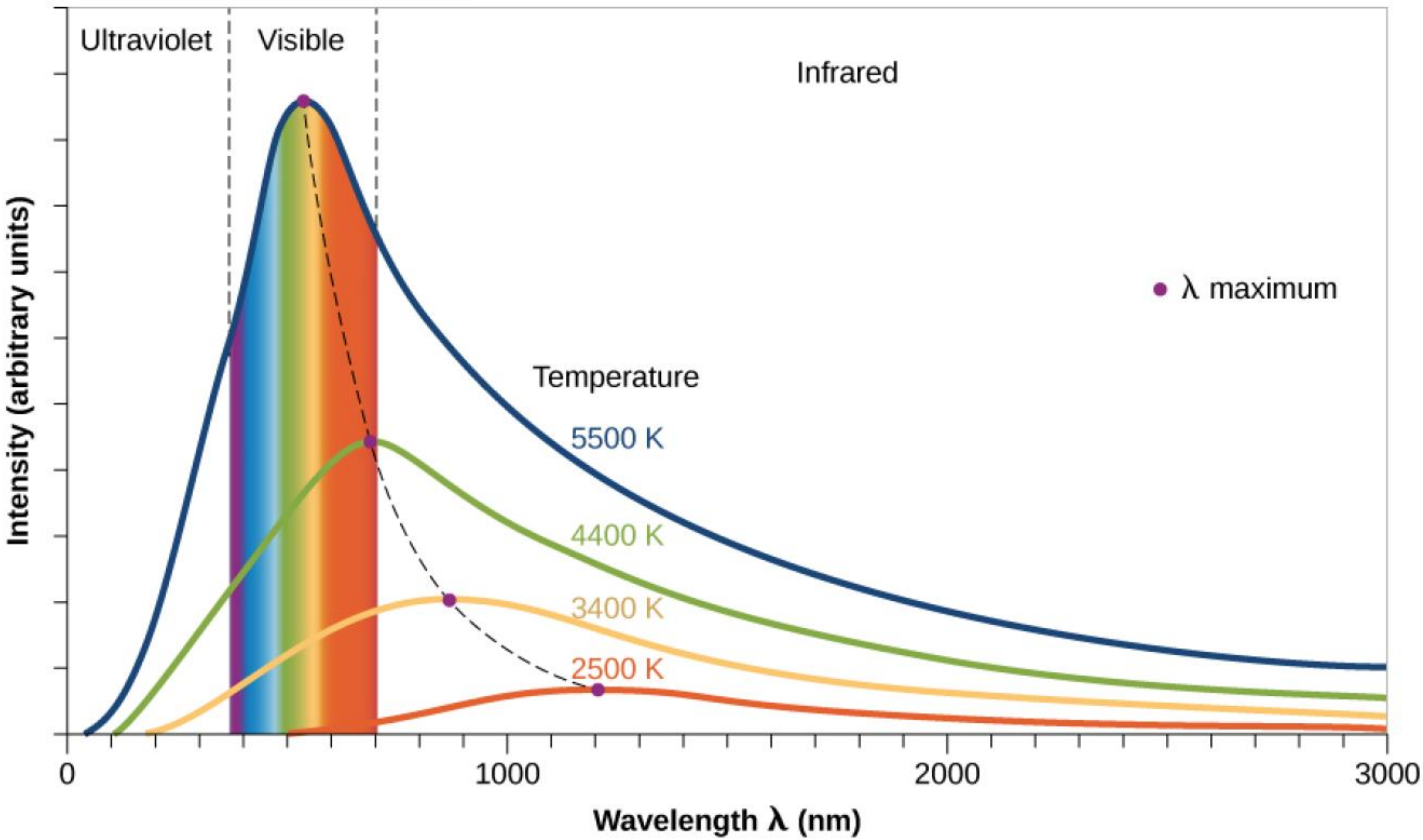
Stars: similar to the sun

- Speculation by many
  - Anaxagoras (5th century BC) and Aristarchus (but Aristotle was opposed)
  - Modernized by Giordano Bruno in 1580s
- Galileo, 1610s: many distant stars (Huygens with calculations)
- Spectroscopy in 1860s

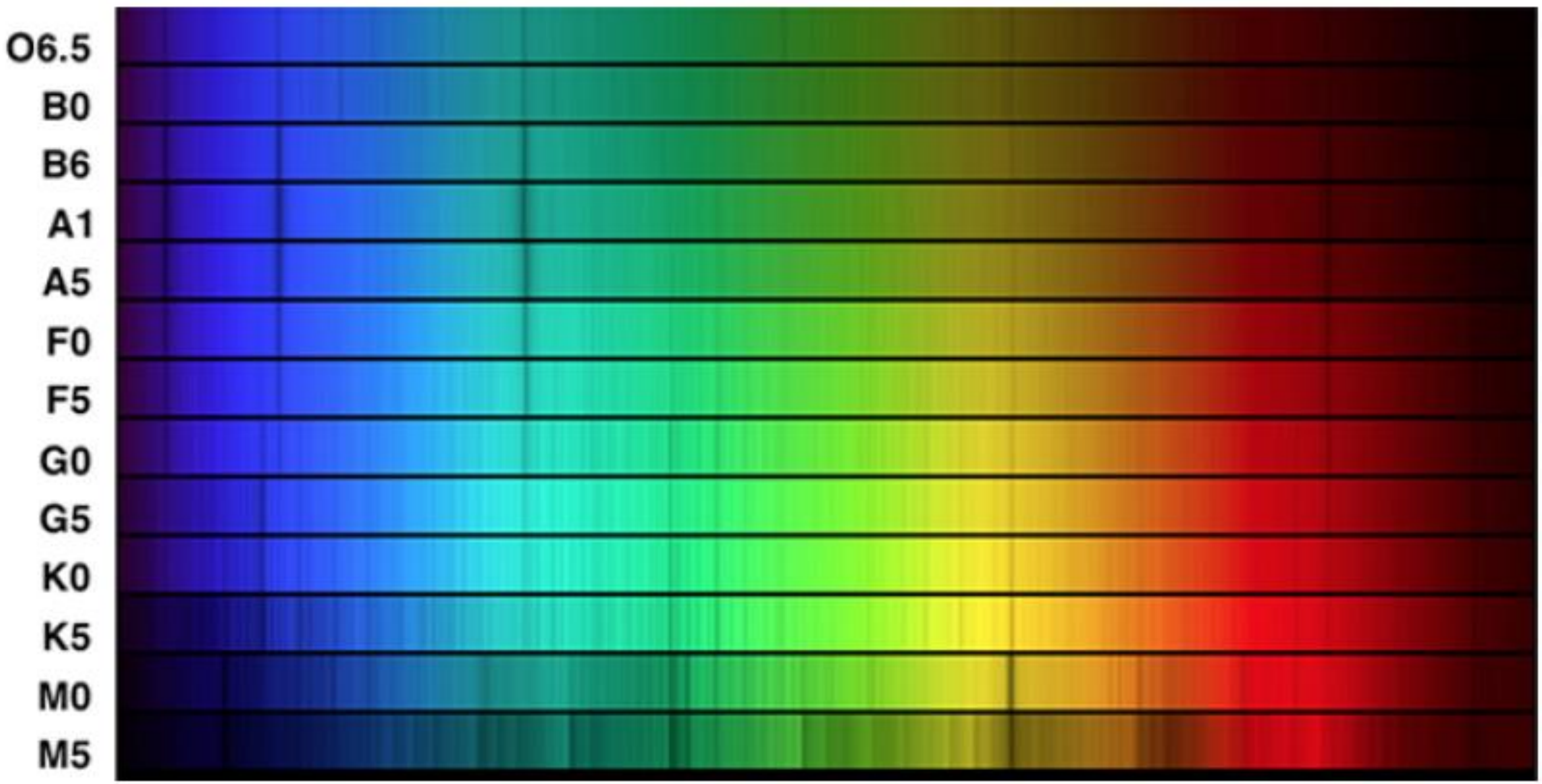
Twinkle Twinkle Little Star
(written in 1806 by Jane Taylor)

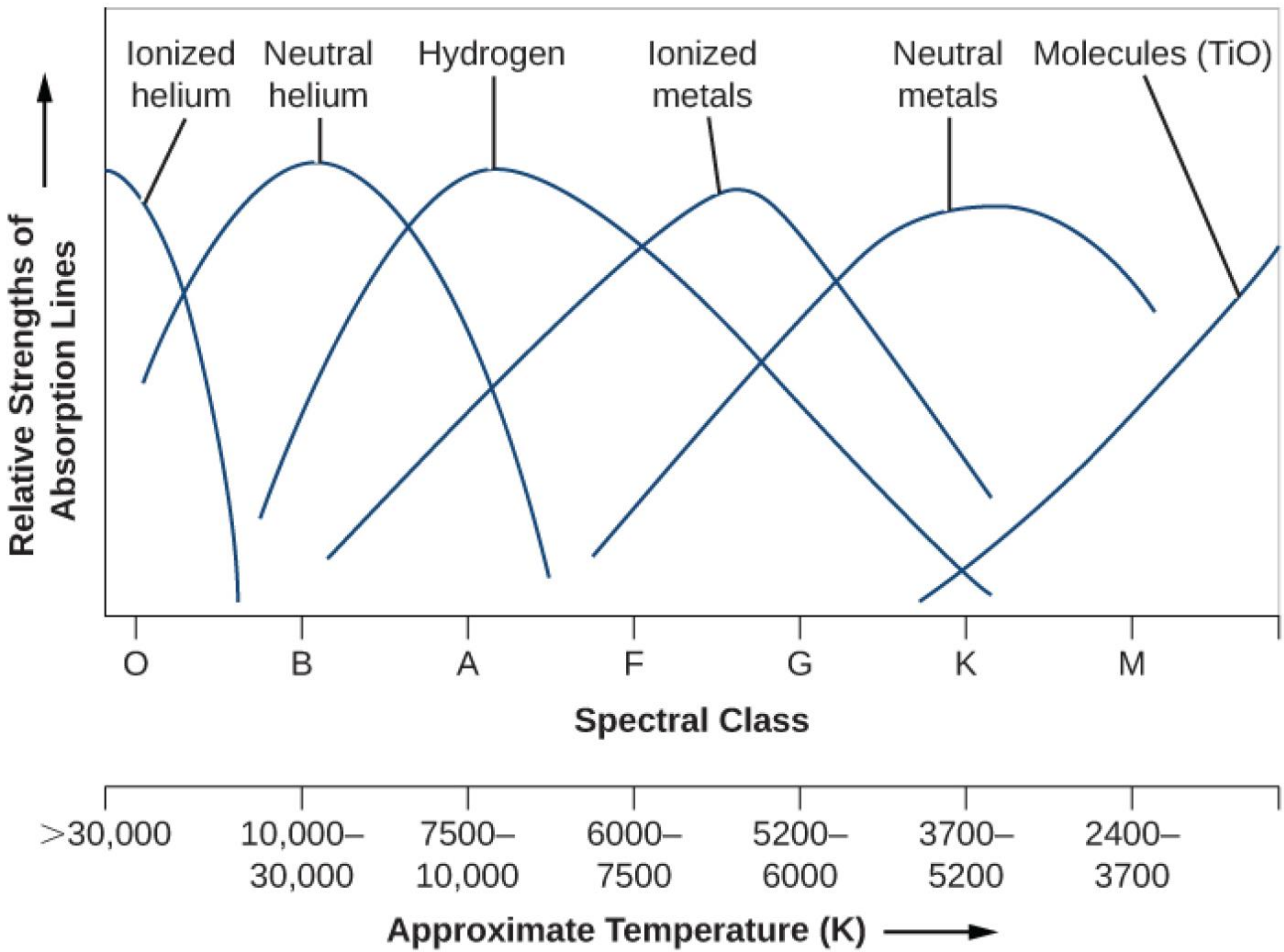
Blackbody emission: hotter things emit at higher energies (=shorter wavelengths)

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



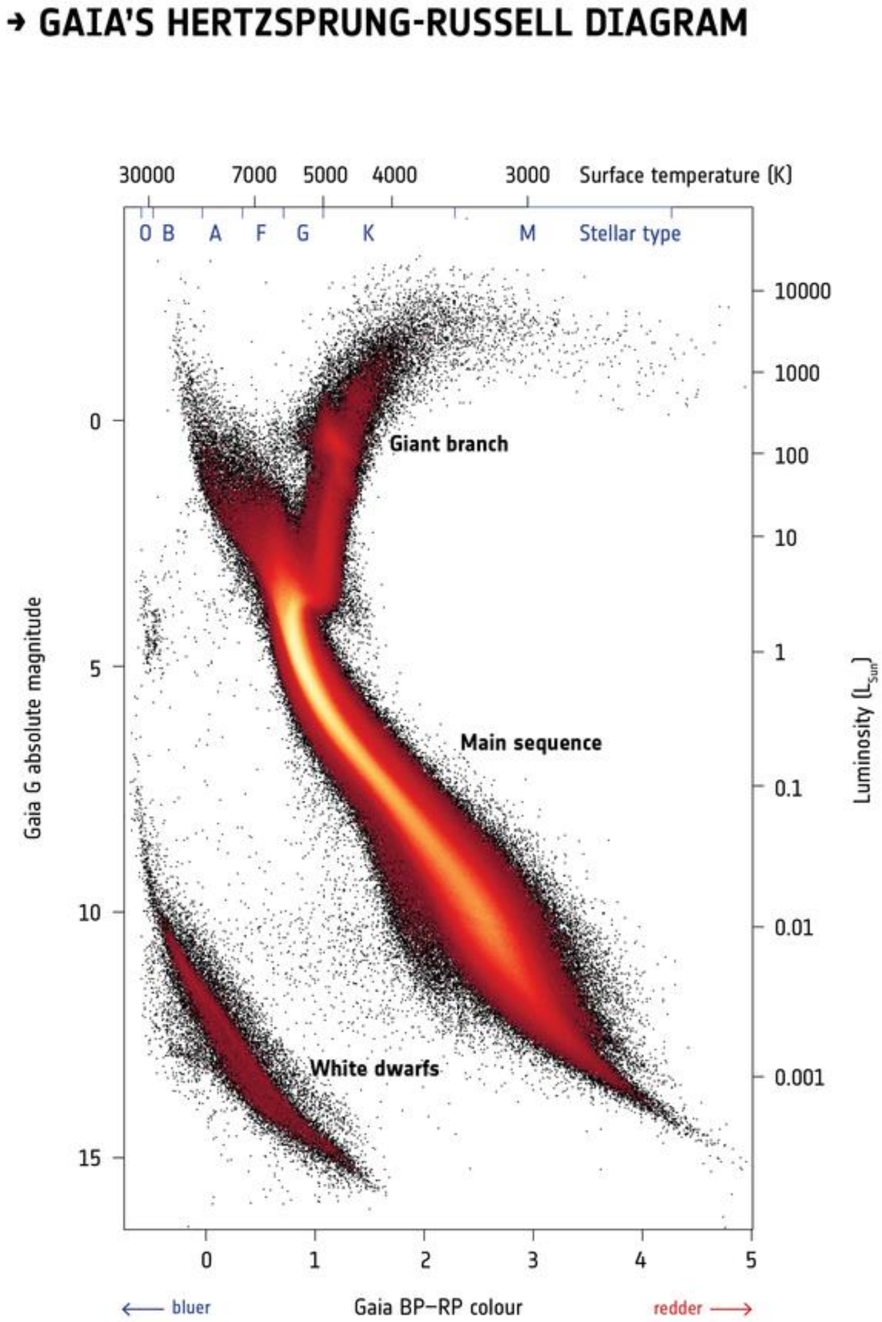
Spectral type = temperature sequence





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:

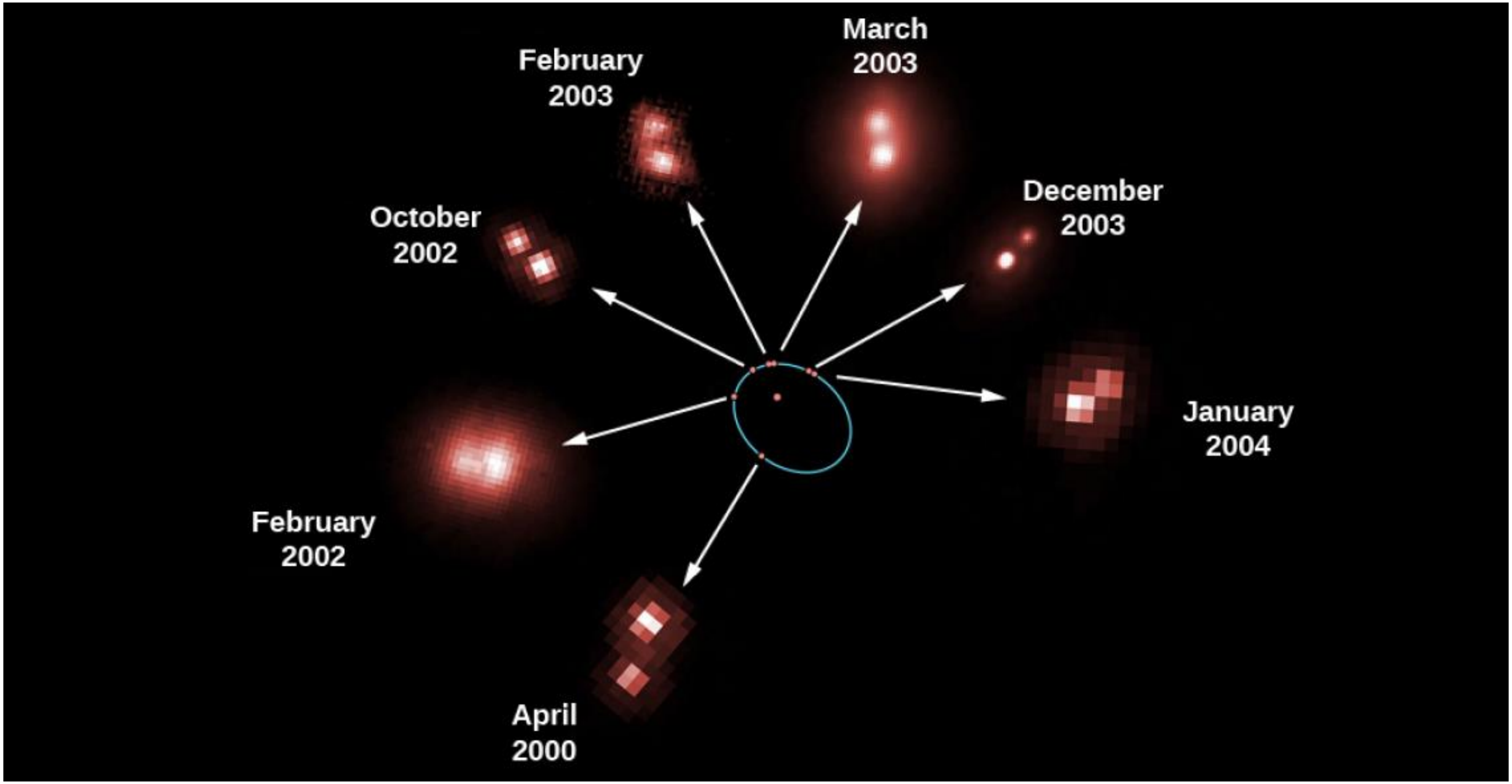
- Stellar evolution! (age)

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

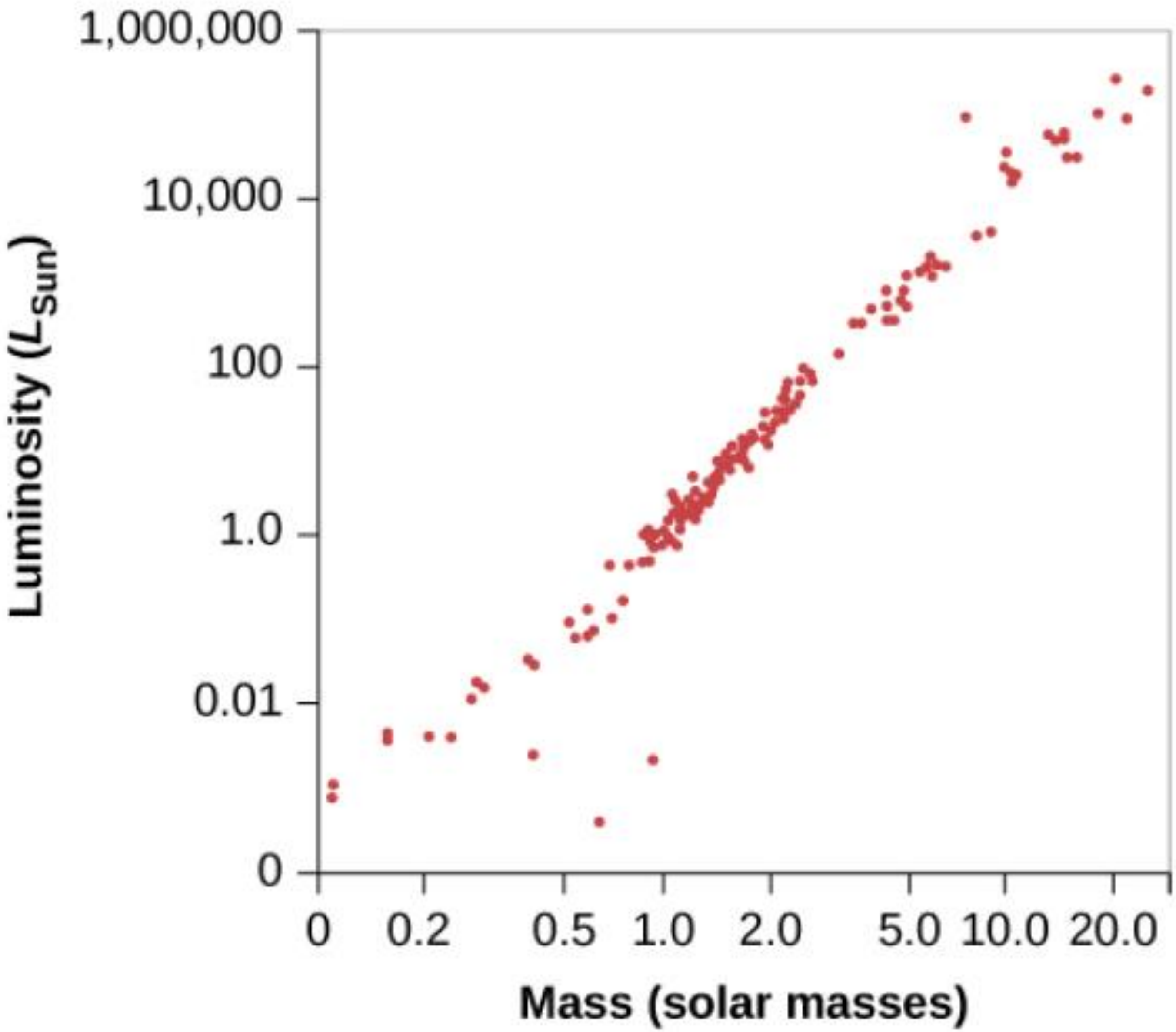
Measuring the Characteristics of Stars

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.

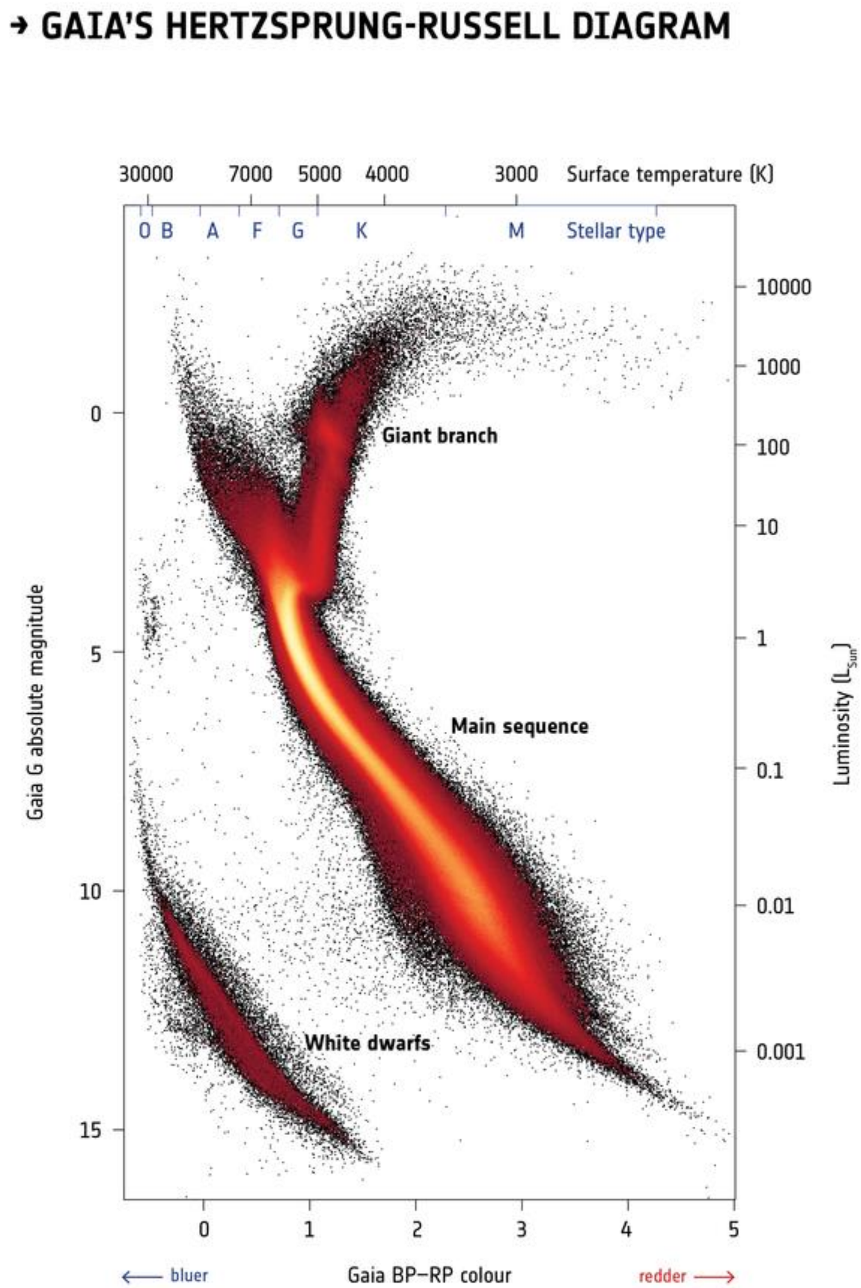

March
2003
February
2003
December
2003
October
2002
January
2004
February
2002
April
2000

Mass of the sun (1 Msun!)

- Kepler: orbital periods and distances
- Newton: gravity
- Earth-Sun distance from transit of Venus
  - A topic for next week!
- Gravitational constant (1798)
  - Measured by Canvendish, attraction of lead spheres



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)

Main sequence:

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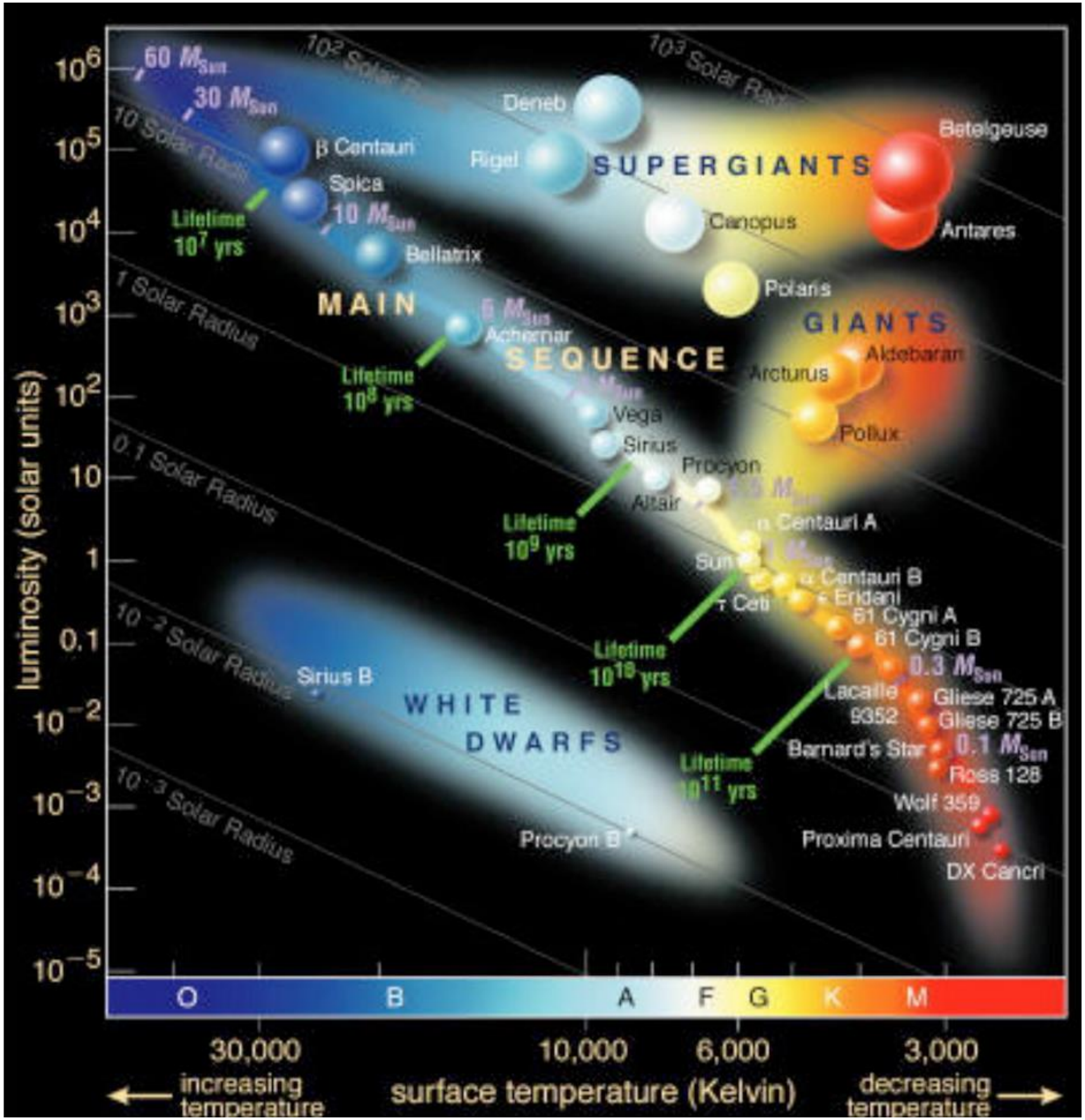
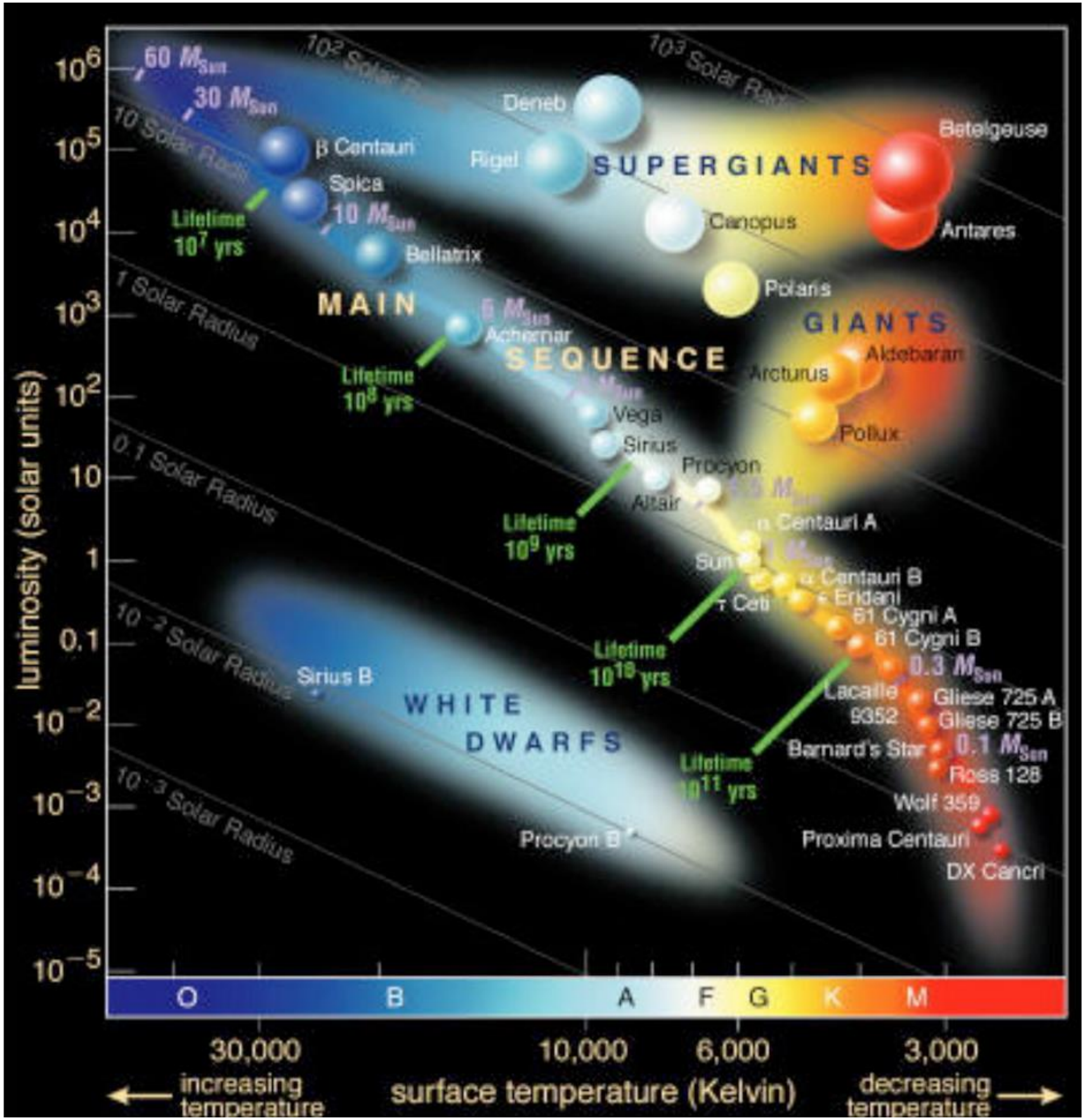


luminosity (solar units)
10^6
10^5
10^4
10^3
10^2
10
1
0.1
10^-2
10^-3
10^-4
10^-5
60 M_Sun
30 M_Sun
10 M_Sun
6 M_Sun
0.3 M_Sun
0.1 M_Sun
10^2 Solar Radii
10^3 Solar Radii
10 Solar Radii
1 Solar Radius
0.1 Solar Radius
10^-2 Solar Radius
10^-3 Solar Radius
Deneb
Rigel
Betelgeuse
SUPERGIANTS
Antares
Canopus
Polaris
β Centauri
Spica
Bellatrix
Lifetime 10^7 yrs
MAIN
SEQUENCE
Achernar
Lifetime 10^8 yrs
GIANTS
Aldebaran
Arcturus
Pollux
Vega
Sirius
Procyon
Altair
Lifetime 10^9 yrs
α Centauri A
Sun
α Centauri B
τ Ceti
ε Eridani
61 Cygni A
61 Cygni B
Lifetime 10^10 yrs
Sirius B
WHITE
DWARFS
Lacaille 9352
Gliese 725 A
Gliese 725 B
Barnard's Star
Ross 128
Lifetime 10^11 yrs
Wolf 359
Procyon B
Proxima Centauri
DX Cancri
O
B
A
F
G
K
M
30,000
10,000
6,000
3,000
increasing temperature
surface temperature (Kelvin)
decreasing temperature

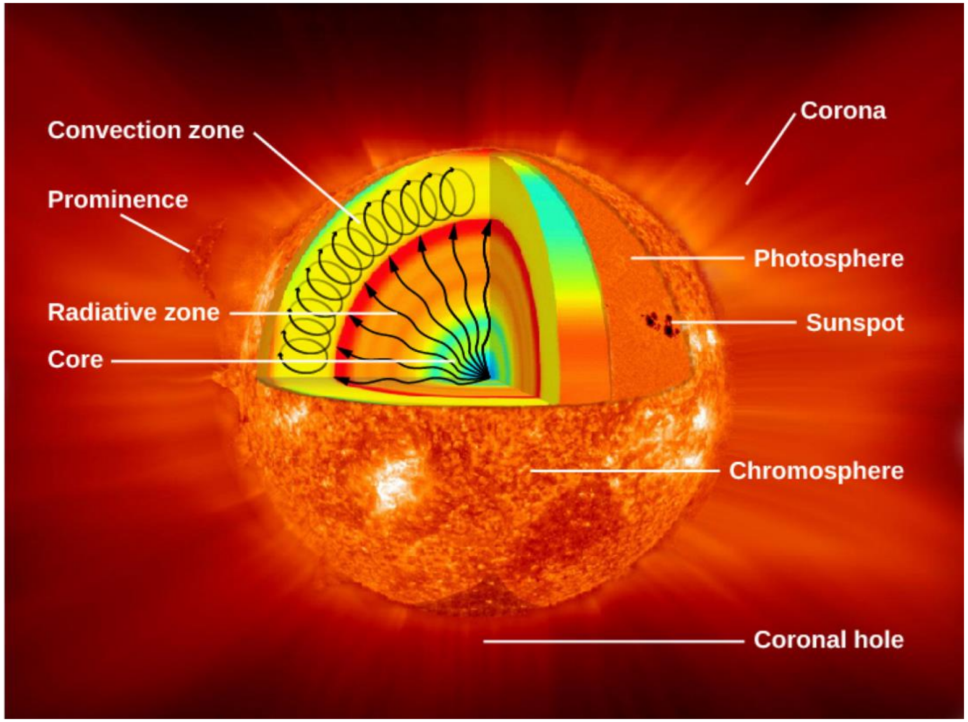
Characteristics of Main-Sequence Stars

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

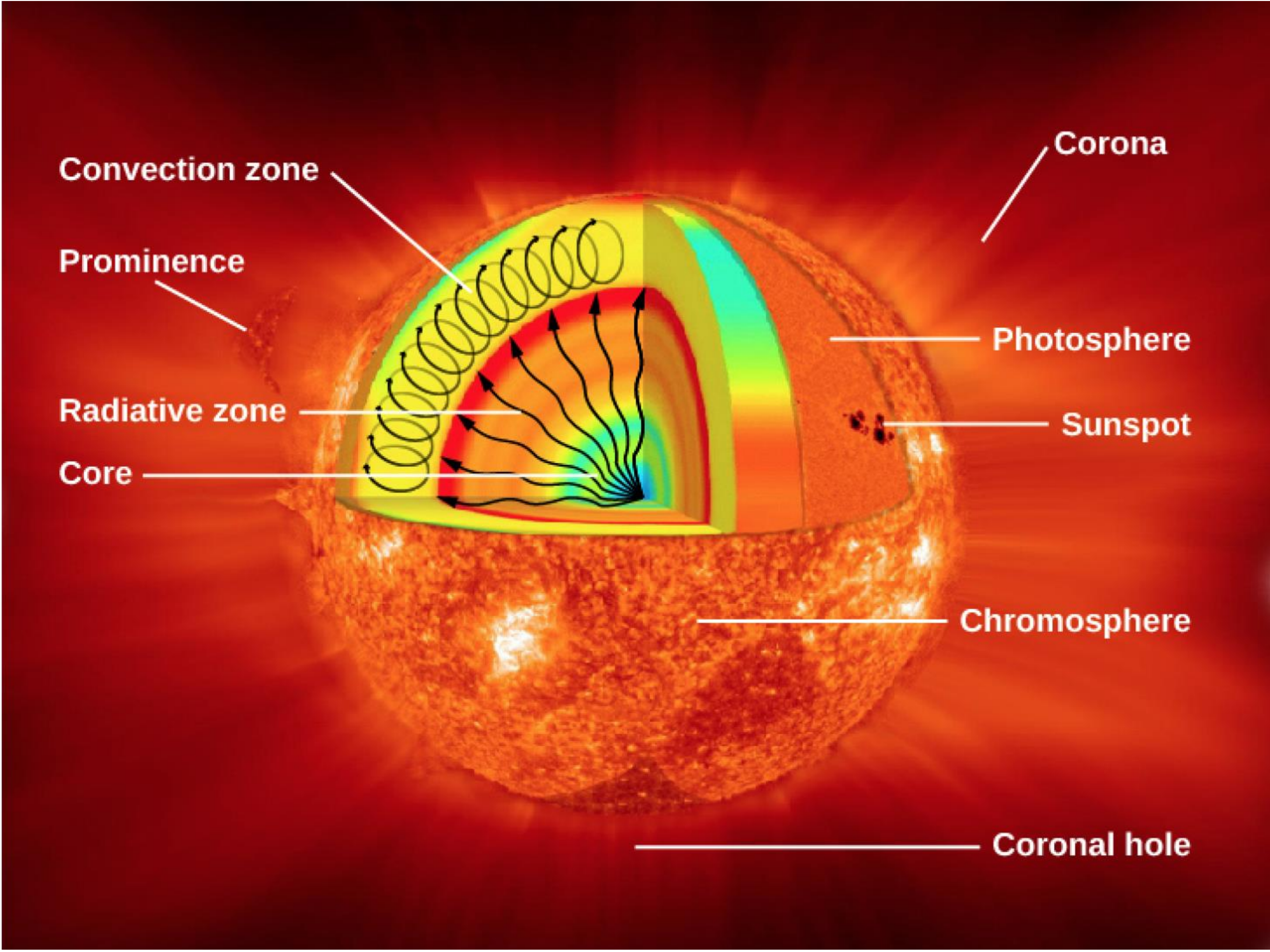


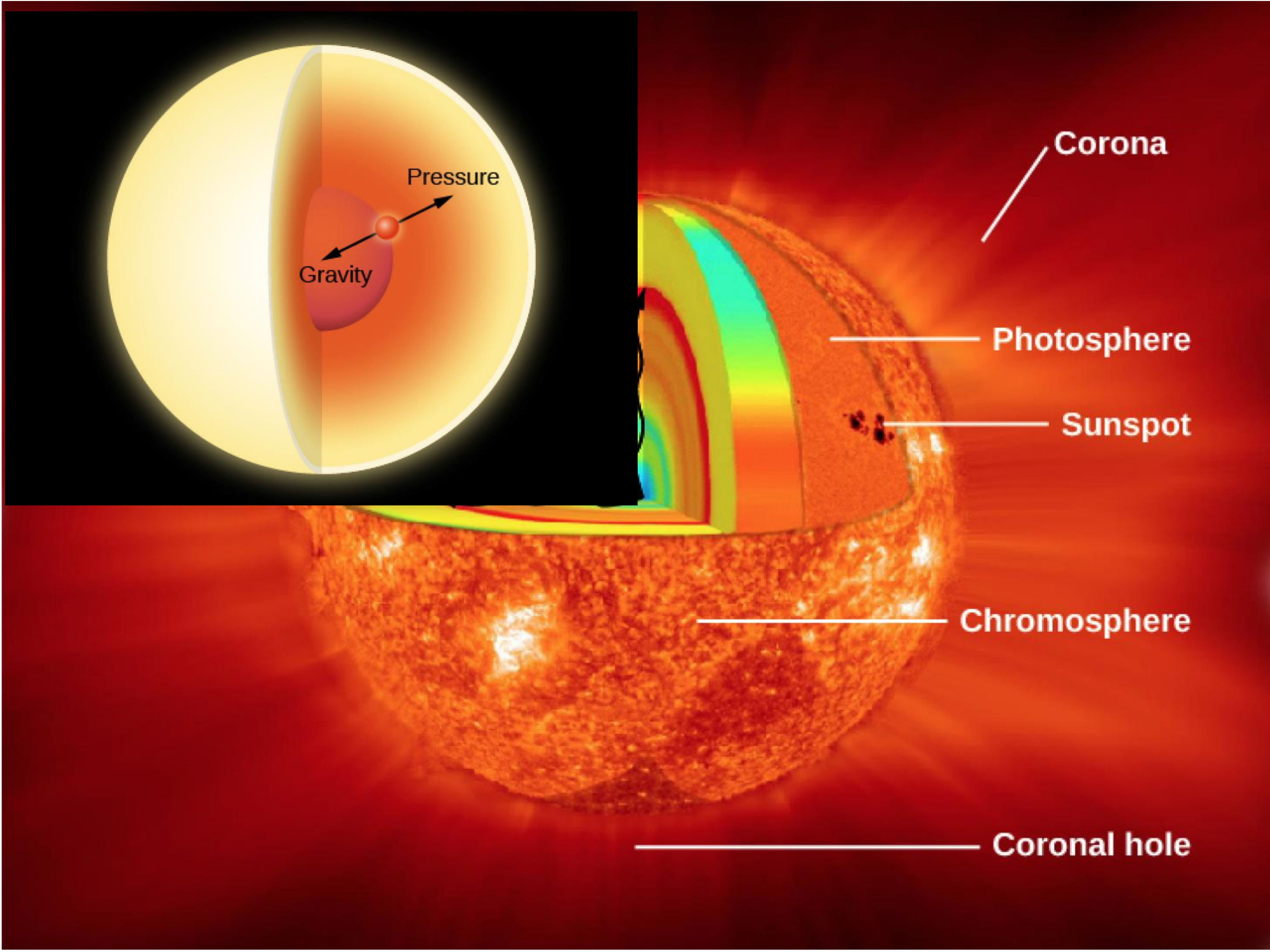
luminosity (solar units)
10^6
10^5
10^4
10^3
10^2
10
1
0.1
10^-2
10^-3
10^-4
10^-5
60 M_Sun
30 M_Sun
10 M_Sun
6 M_Sun
0.3 M_Sun
0.1 M_Sun
10^2 Solar Radii
10^3 Solar Radii
10 Solar Radii
1 Solar Radius
0.1 Solar Radius
10^-2 Solar Radius
10^-3 Solar Radius
SUPERGIANTS
GIANTS
MAIN
SEQUENCE
WHITE
DWARFS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

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



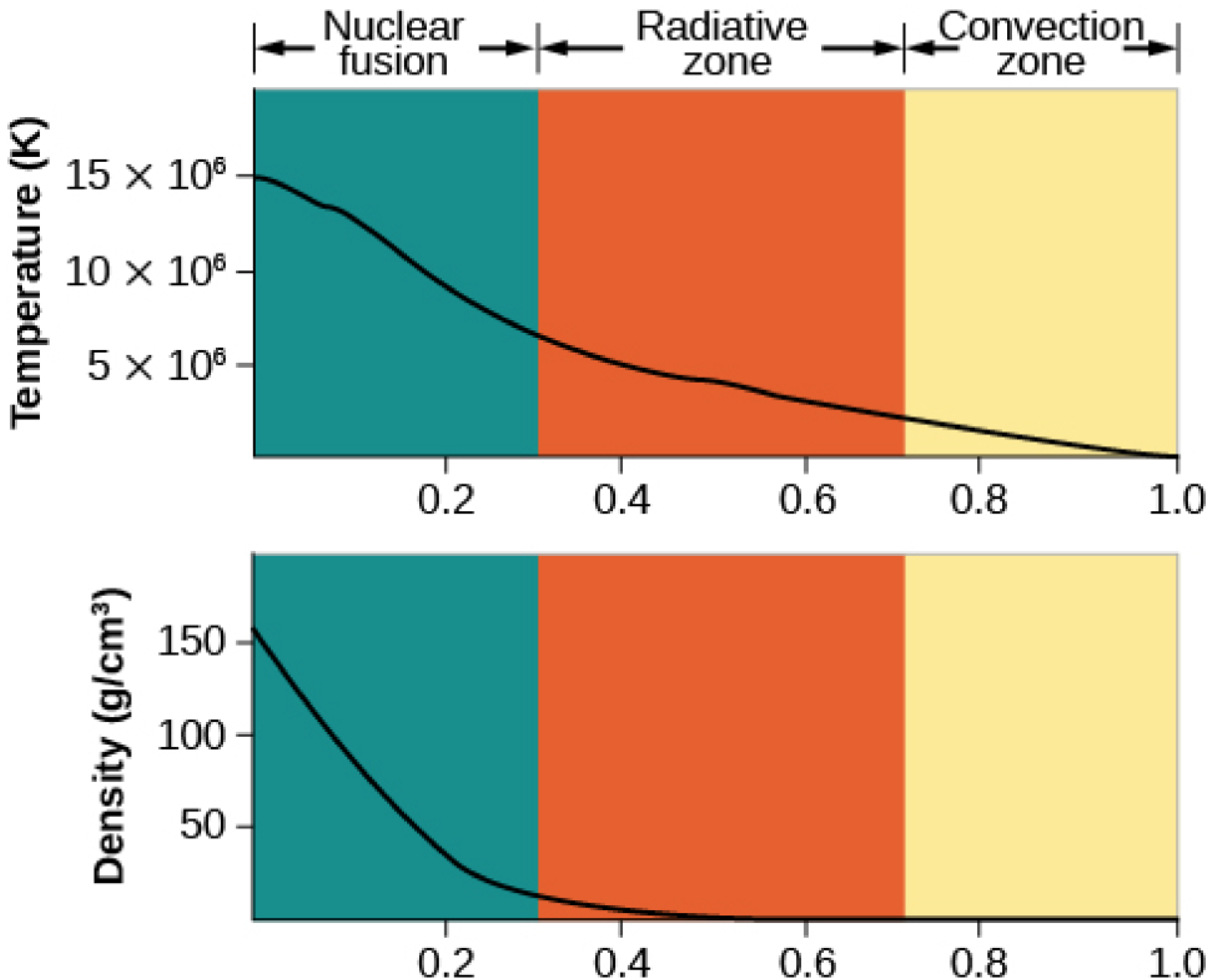
- 15 The Sun: A Garden-Variety Star
  - Thinking Ahead
  - 15.1 The Structure and Composition of the Sun
  - 15.2 The Solar Cycle
  - 15.3 Solar Activity above the Photosphere
  - 15.4 Space Weather
  - Key Terms
  - Summary
  - For Further Exploration
  - Collaborative Group Activities
  - Exercises
- 16 The Sun: A Nuclear Powerhouse
  - Thinking Ahead
  - 16.1 Sources of Sunshine: Thermal and Gravitational Energy
  - 16.2 Mass, Energy, and the Theory of Relativity
  - 16.3 The Solar Interior: Theory
  - 16.4 The Solar Interior: Observations
  - Key Terms
  - Summary
  - For Further Exploration
  - Collaborative Group Activities
  - Exercises


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



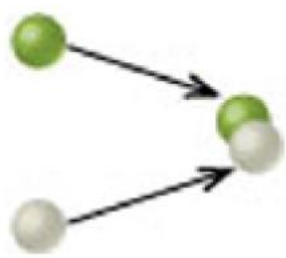
Pressure
Gravity
Corona
Photosphere
Sunspot
Chromosphere
Coronal hole

Core of the sun: very dense, 15 million K



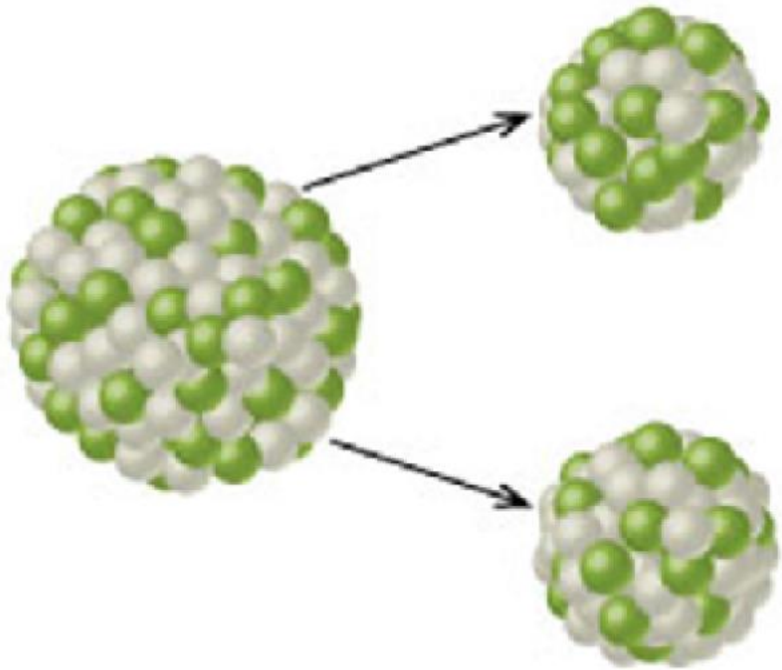
Fusion

2 light => 1 heavy



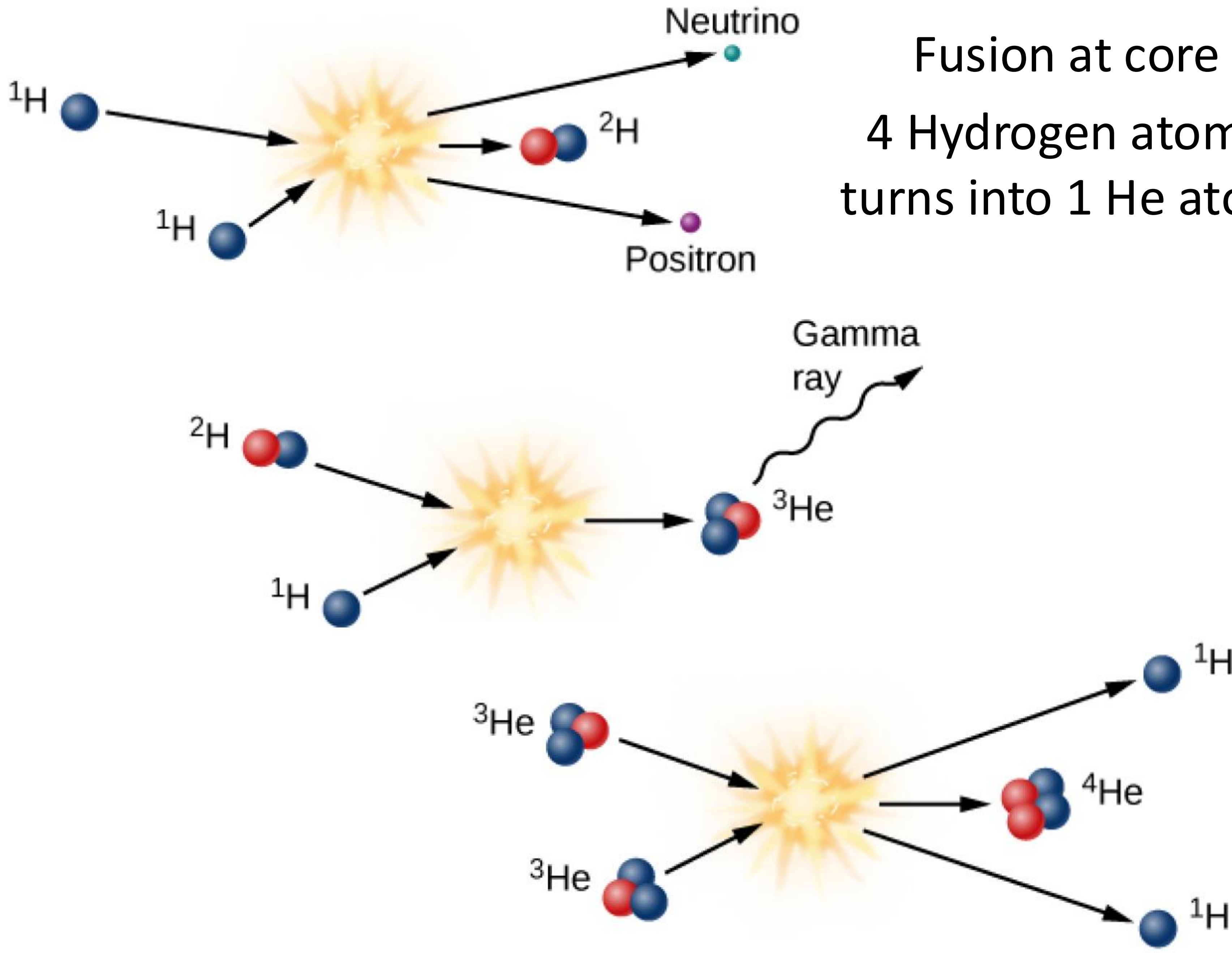
Fission

1 heavy => 2 light



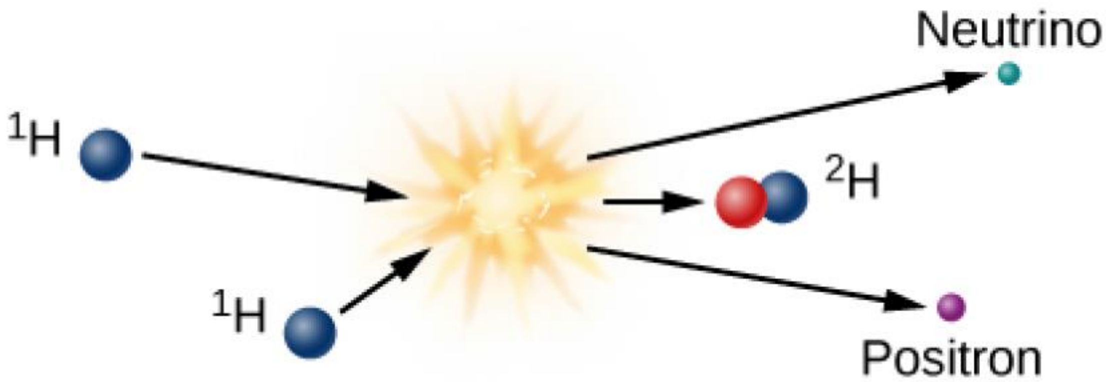
Fusion at core

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

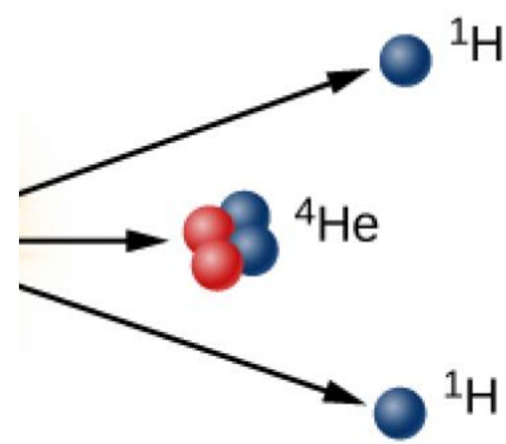
1 He: 4.003

Lose 0.7% of the mass:

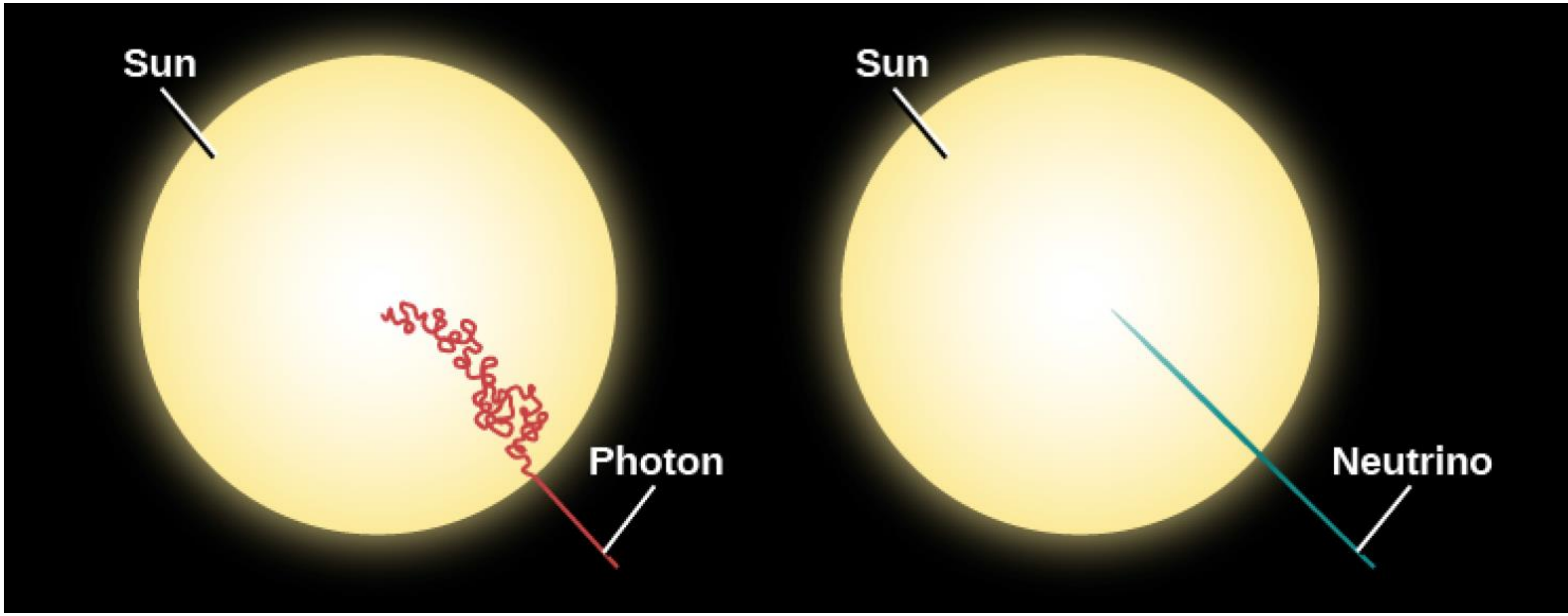
it turns into energy!

E=mc^2

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



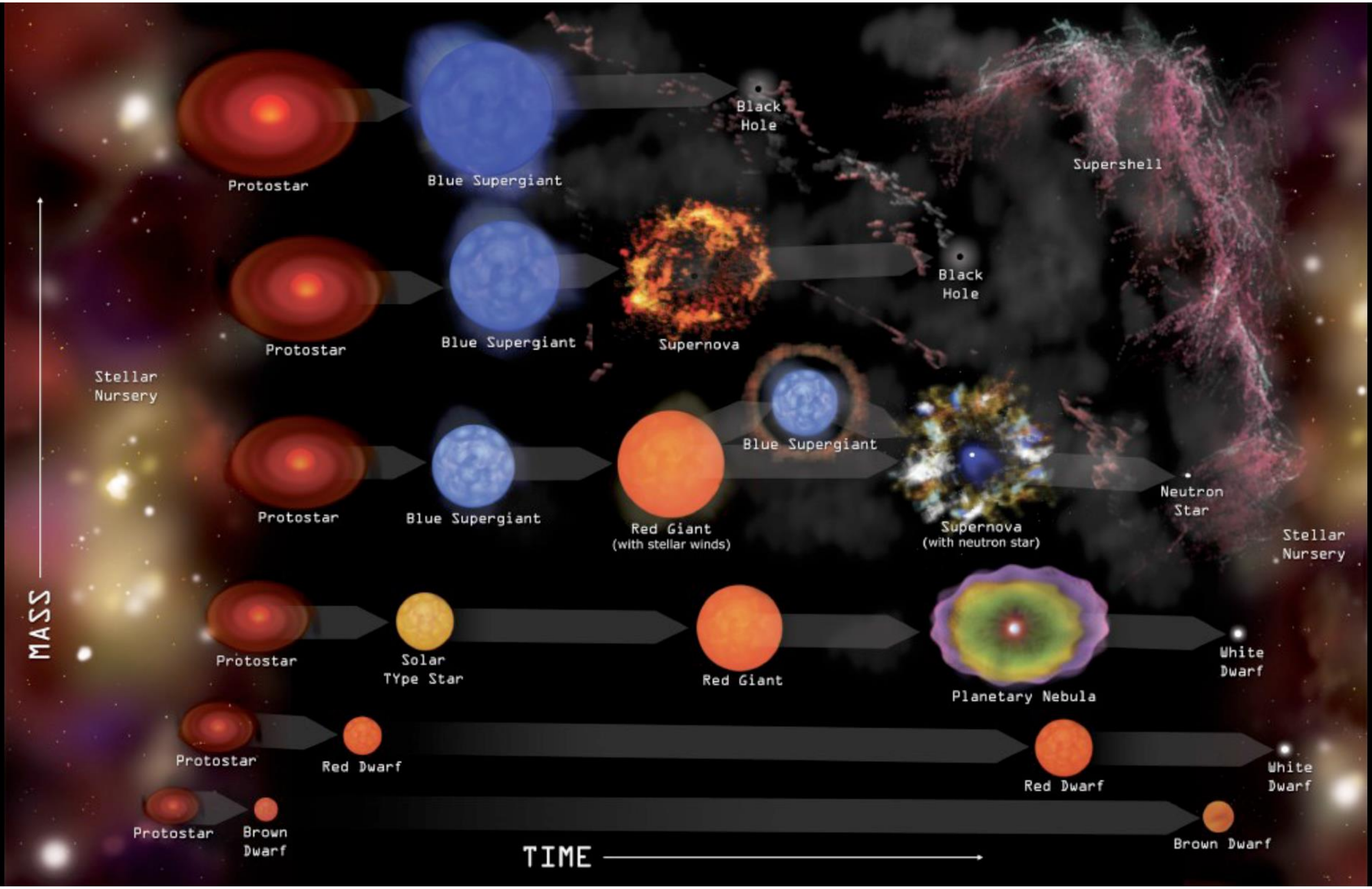
How long does it take energy to escape from the sun's core?



Most energy: 1 million years!

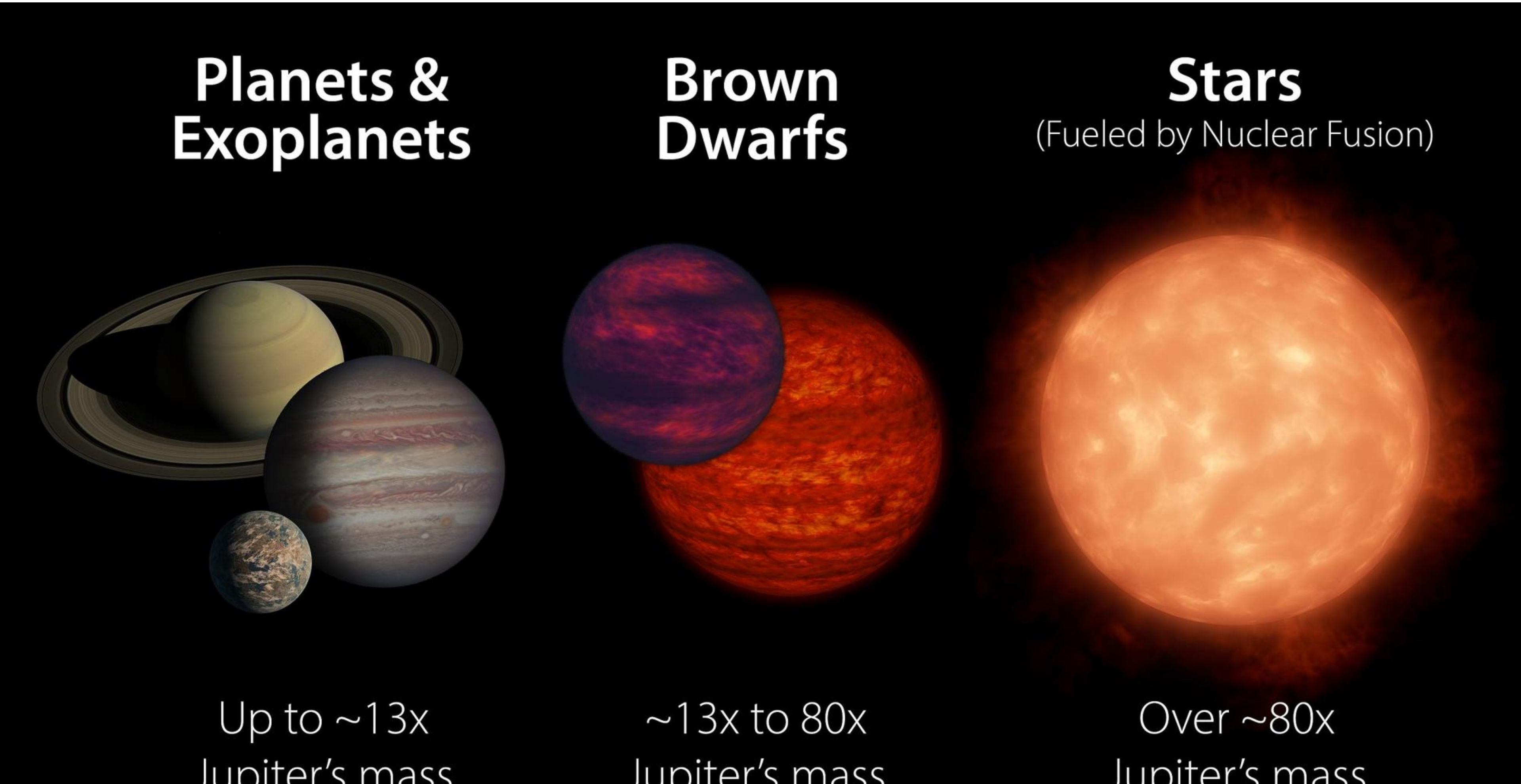
Neutrinos: do not interact with matter, so escapes immediately

Solar neutrino problem: recent Nobel Prize

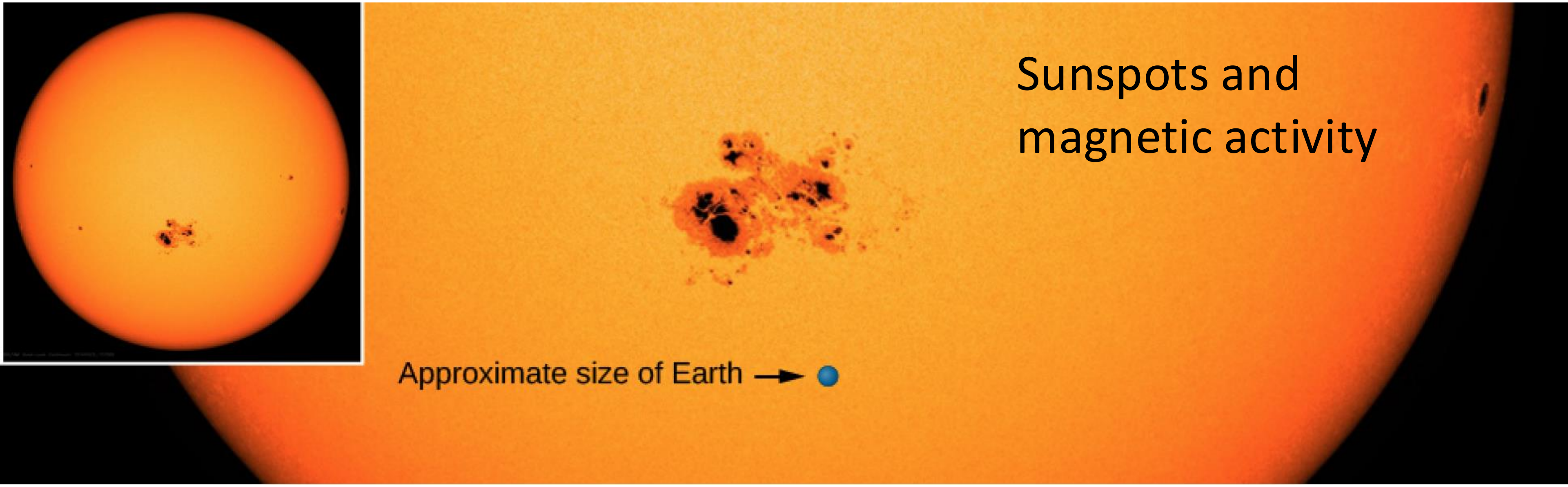

Protostar
Blue Supergiant
Black Hole
Supershell
Protostar
Blue Supergiant
Supernova
Black Hole
Stellar Nursery
Protostar
Blue Supergiant
Red Giant
(with stellar winds)
Blue Supergiant
Supernova
(with neutron star)
Neutron Star
Stellar Nursery
Protostar
Solar TYpe Star
Red Giant
Planetary Nebula
White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

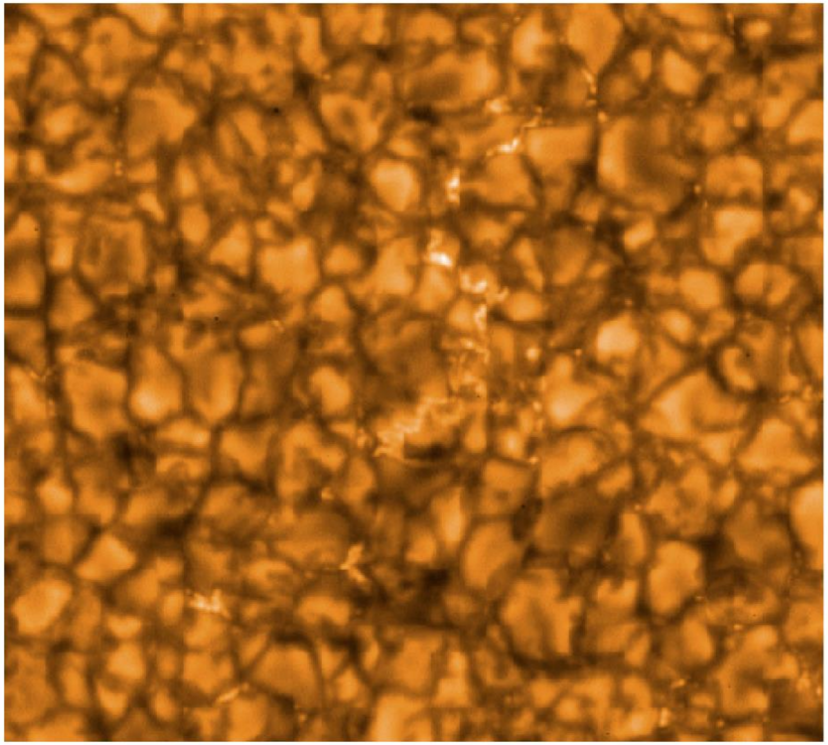
Brown dwarfs

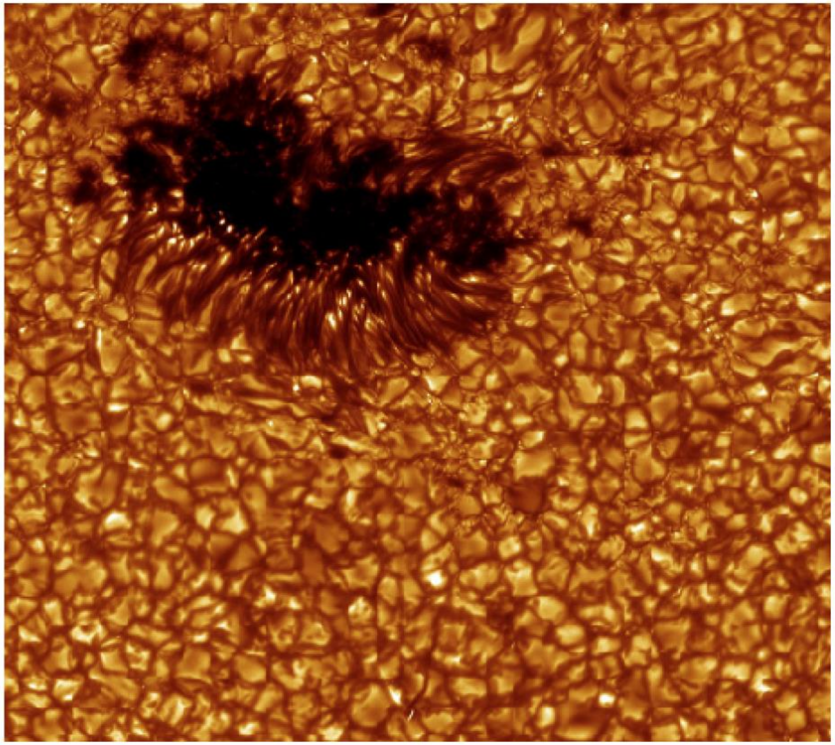
- Central temperature in core: depends on mass
- Very faint, cool, and red: hard to find!



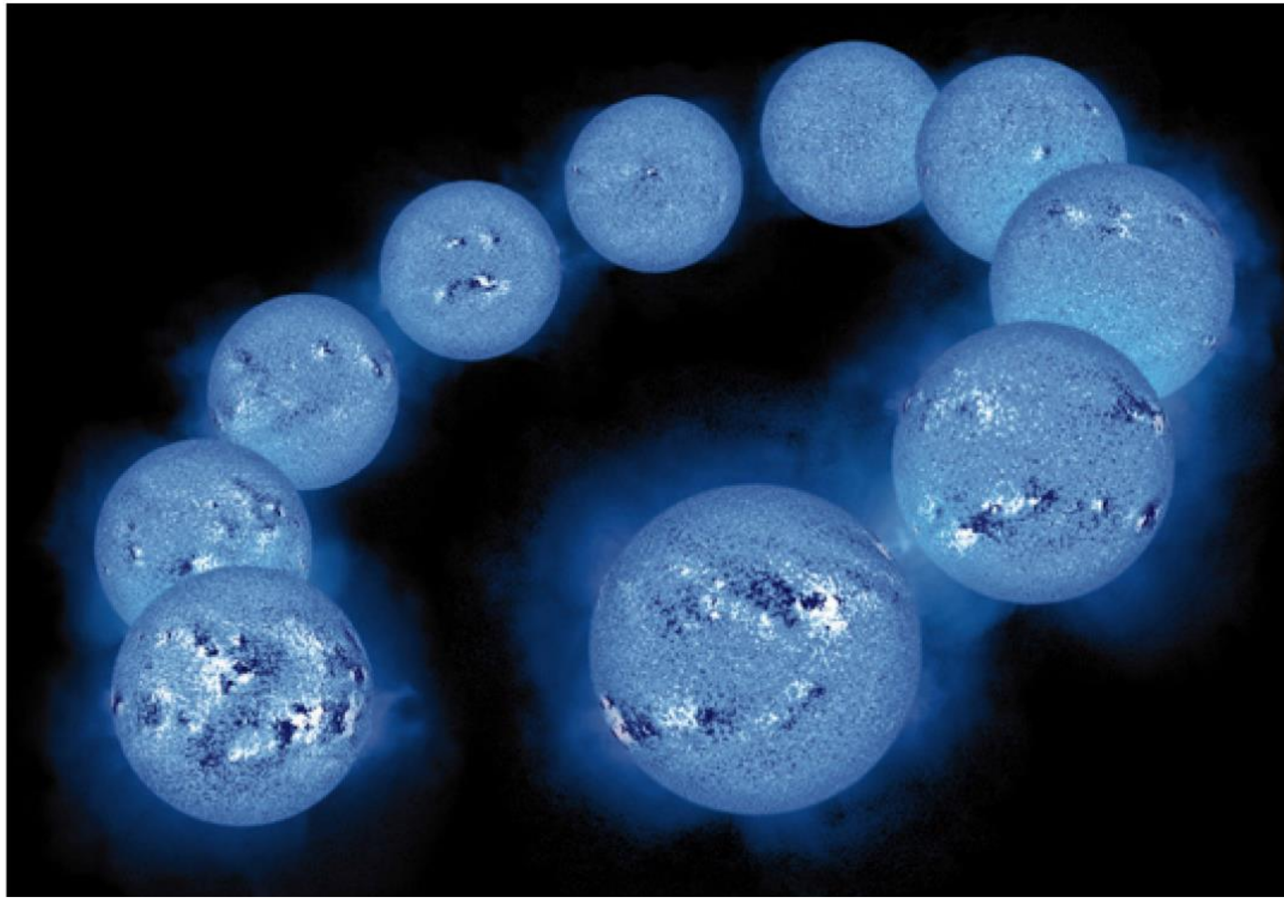
Sunspots and magnetic activity

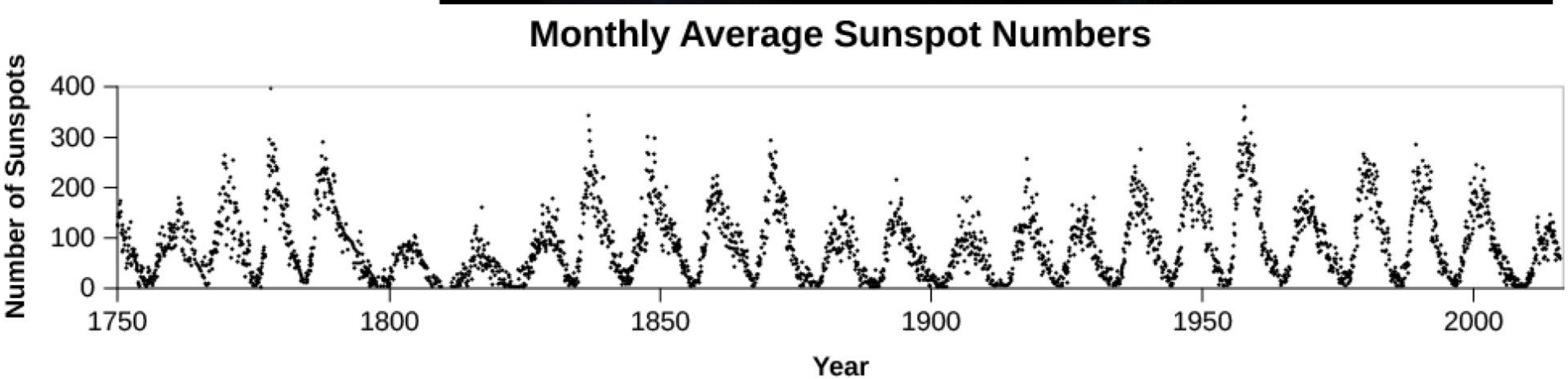






11 year
magnetic cycles

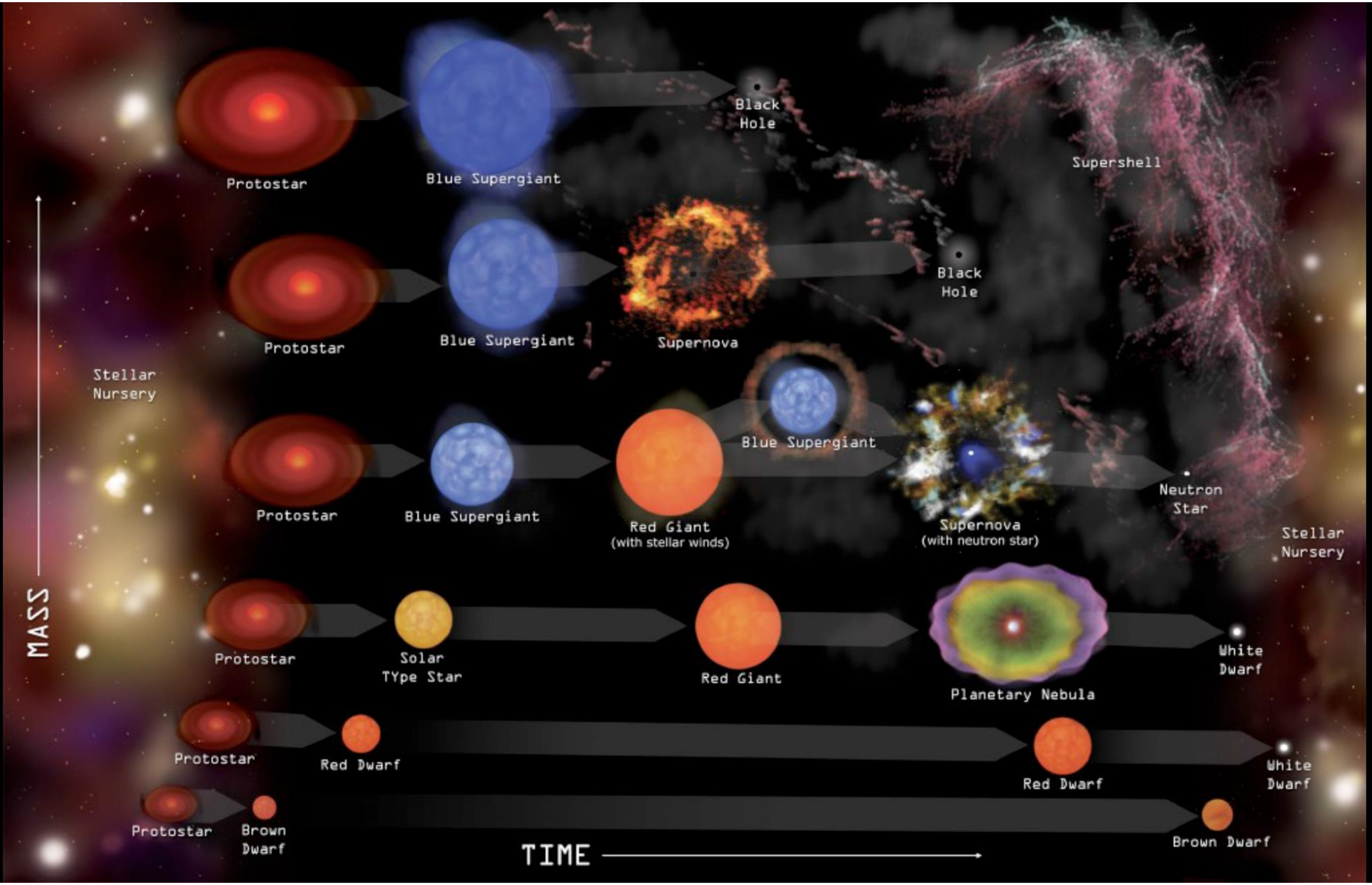




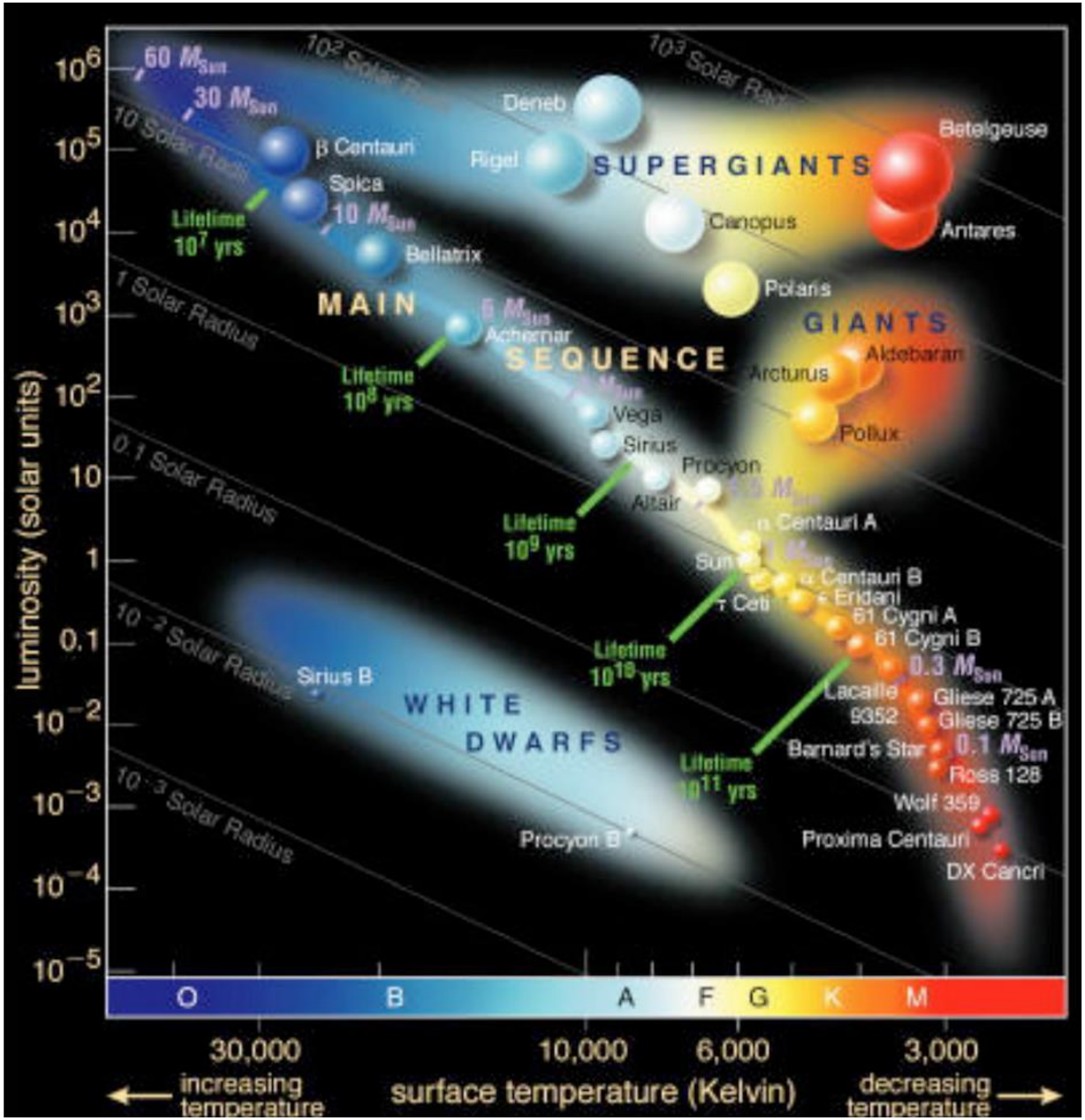
Important concepts for lecture 2

- 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



Black
Hole
Protostar
Blue Supergiant
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



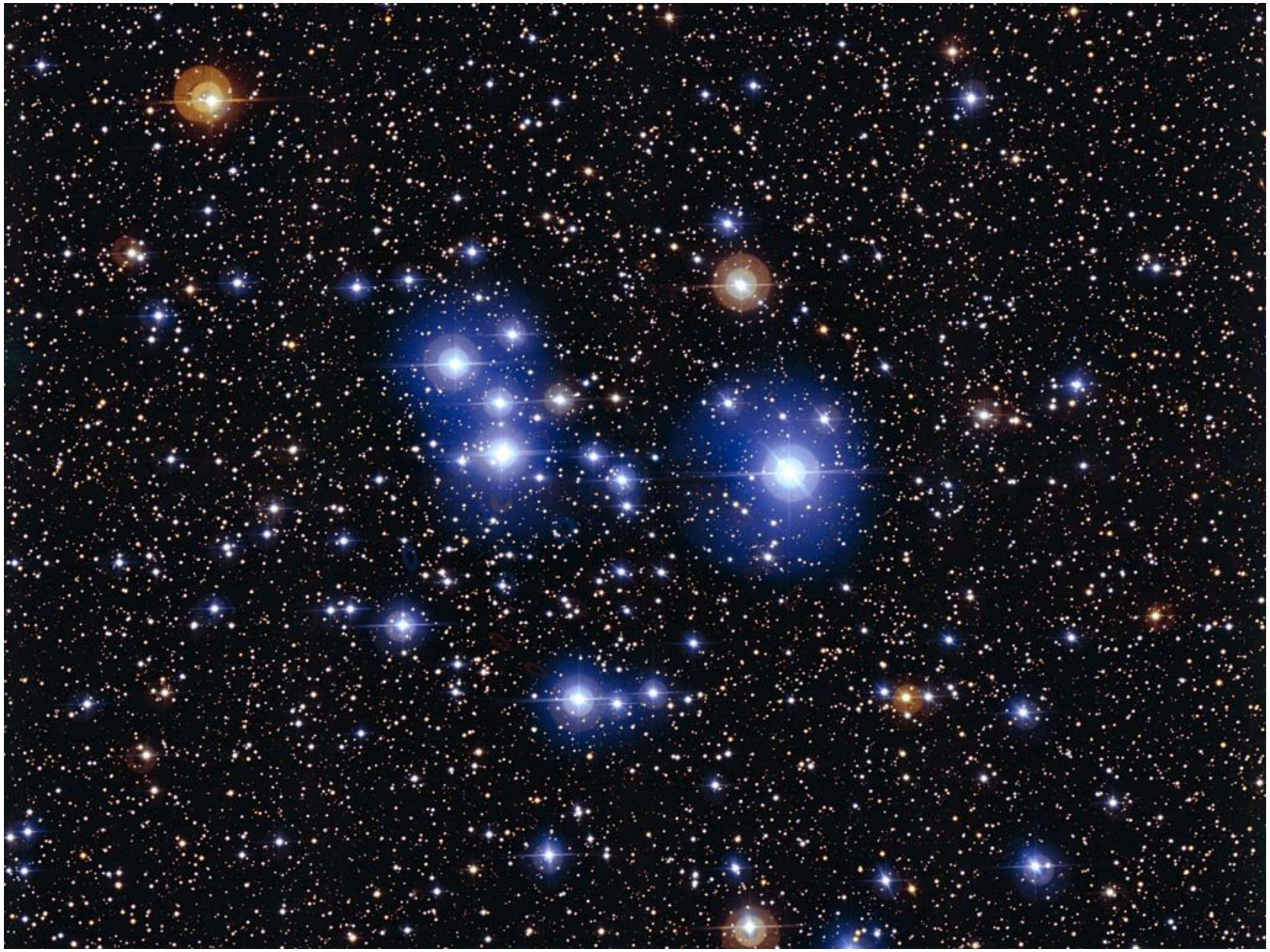
luminosity (solar units)
10^6
10^5
10^4
10^3
10^2
10
1
0.1
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^2 Solar Radii
10^3 Solar Radii
10 Solar Radii
1 Solar Radius
0.1 Solar Radius
10^{-2} Solar Radius
10^{-3} Solar Radius
60 M_{Sun}
30 M_{Sun}
10 M_{Sun}
6 M_{Sun}
1.5 M_{Sun}
1 M_{Sun}
0.3 M_{Sun}
0.1 M_{Sun}
Lifetime 10^7 yrs
Lifetime 10^8 yrs
Lifetime 10^9 yrs
Lifetime 10^{10} yrs
Lifetime 10^{11} yrs
SUPERGIANTS
GIANTS
MAIN SEQUENCE
WHITE DWARFS
Deneb
Rigel
Betelgeuse
Antares
Canopus
Polaris
β Centauri
Spica
Bellatrix
Achernar
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
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

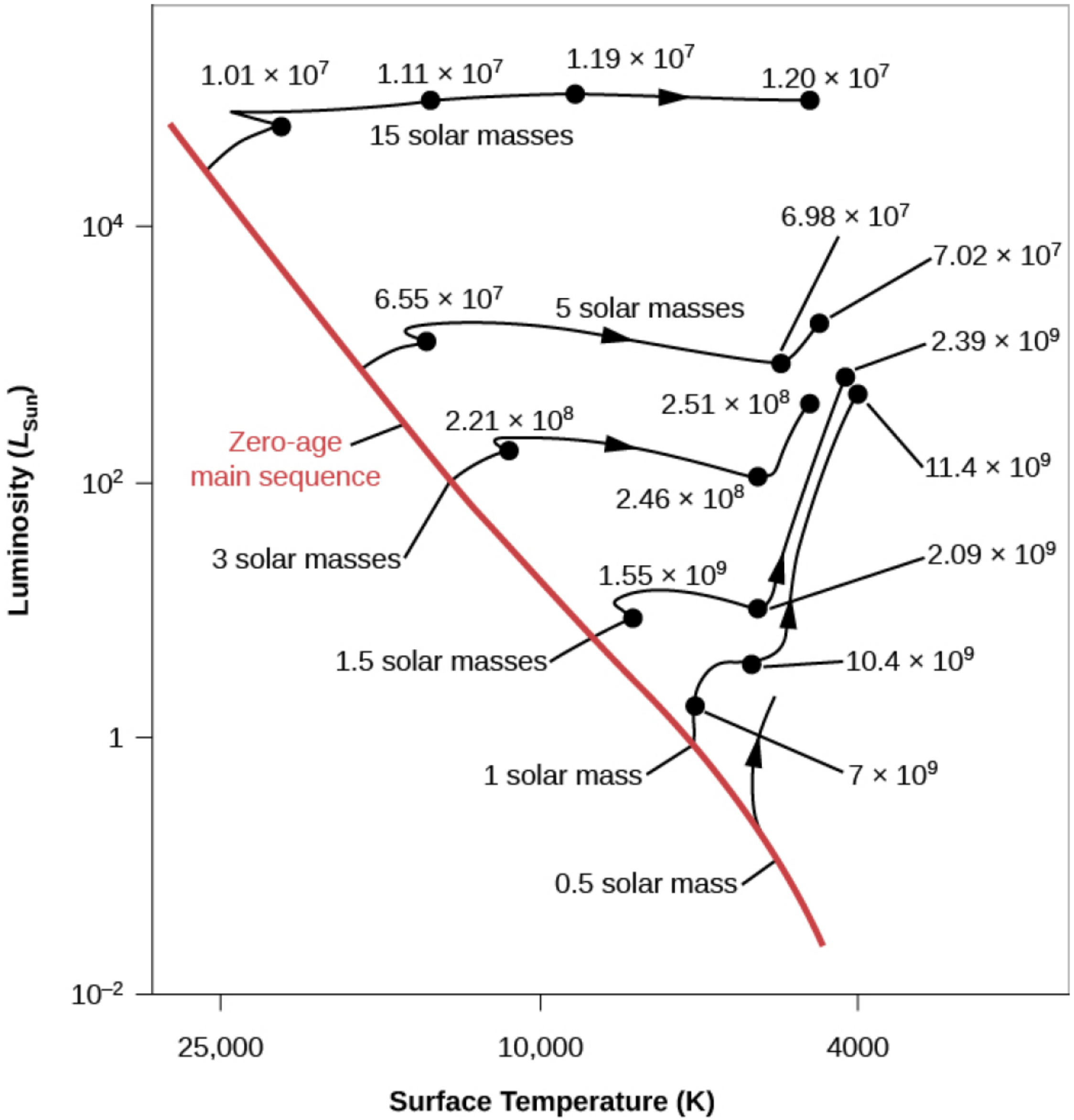
(distance to all stars in a cluster is similar)

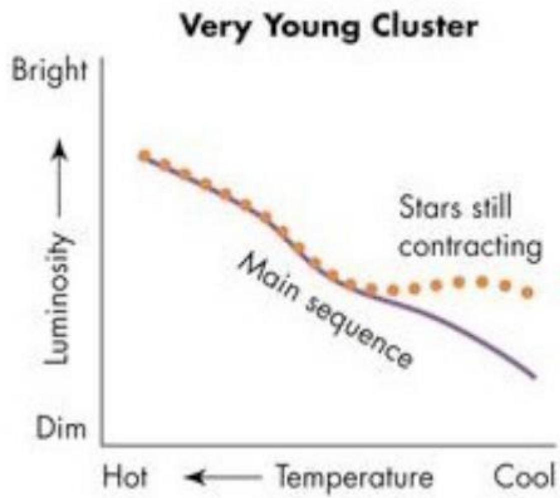
Pleiades (seven sisters, Subaru, 昴)

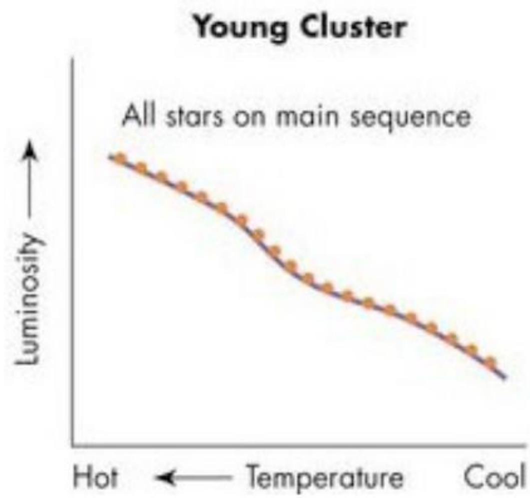
Pleiades (昴): famous and benchmark cluster for young stars

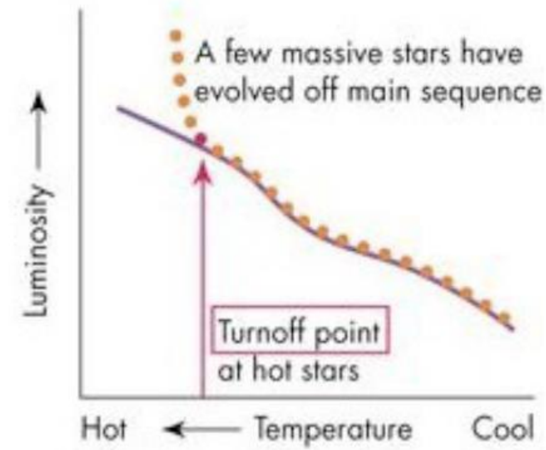


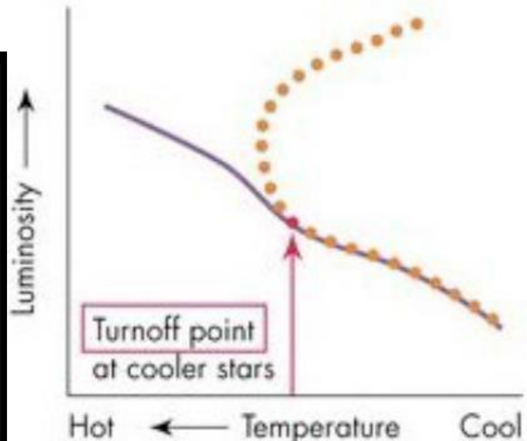
Location of stars tells us age of cluster

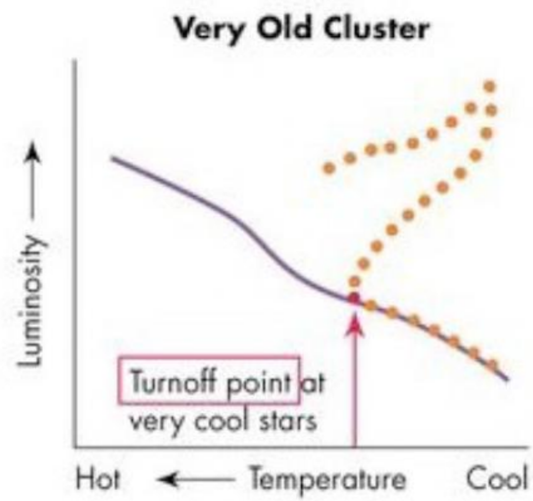


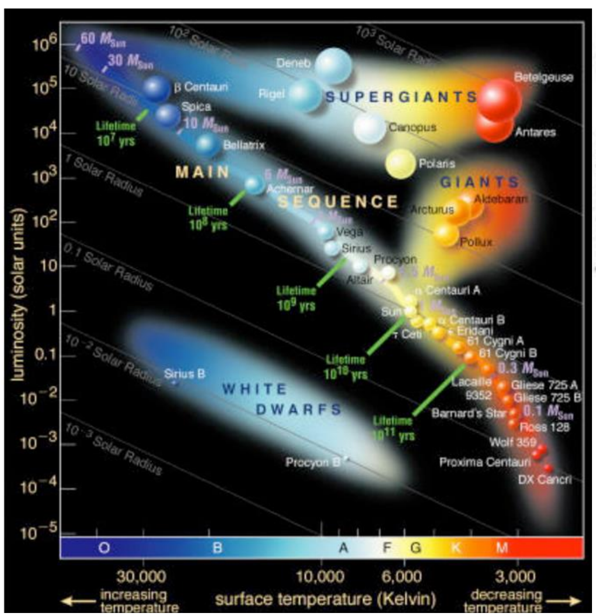

Very Young Cluster
Bright
Luminosity
Dim
Stars still contracting
Main sequence
Hot
Temperature
Cool


Young Cluster
Luminosity
All stars on main sequence
Hot
Temperature
Cool


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

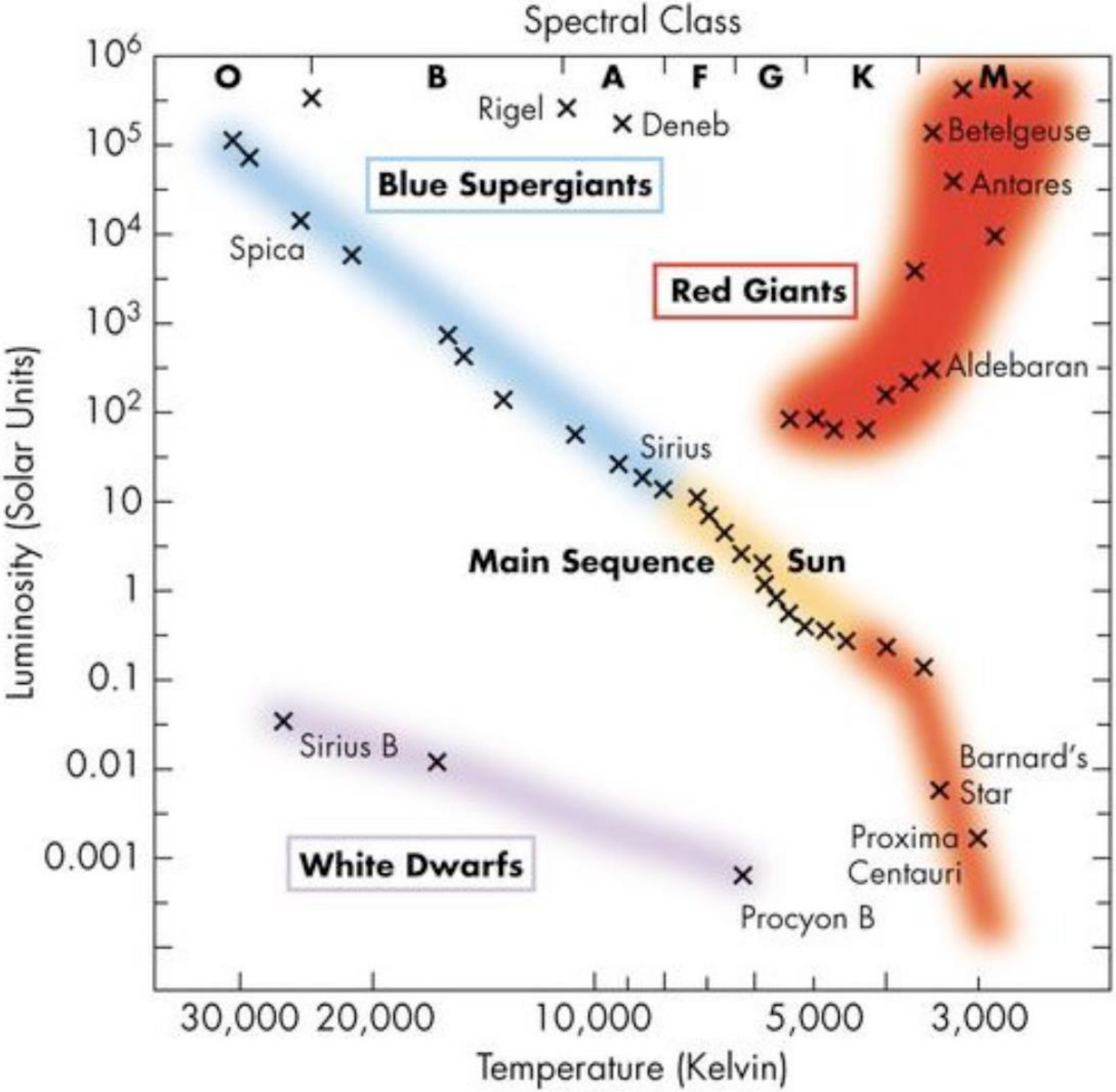

Luminosity
Turnoff point at cooler stars
Hot
Temperature
Cool


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


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

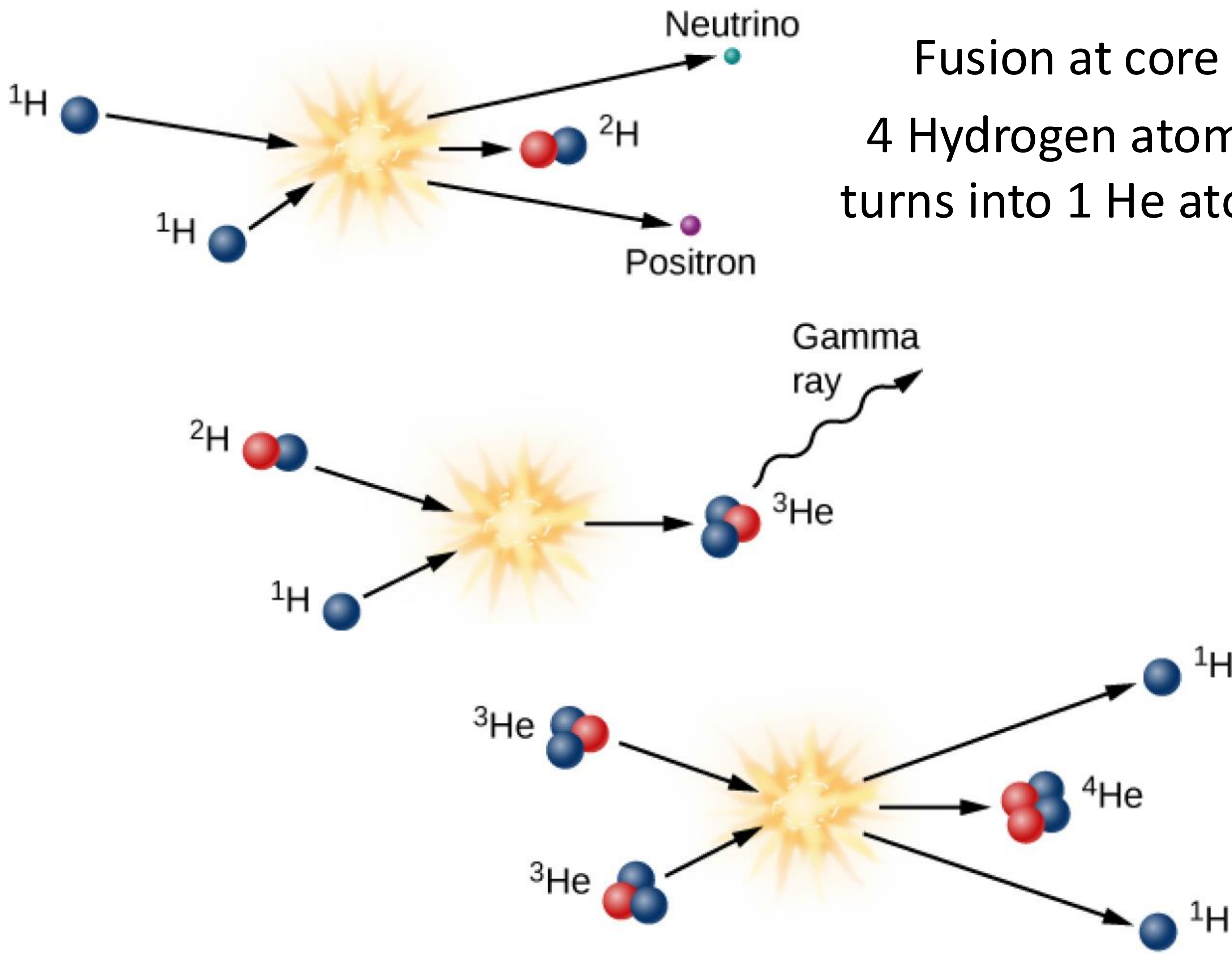
Key concepts

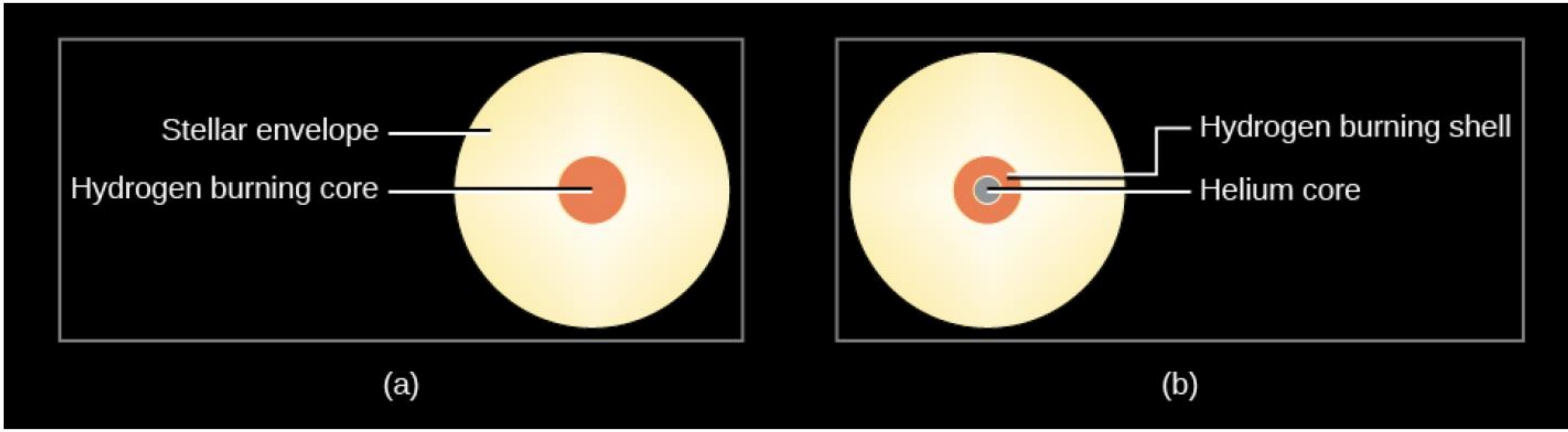
- **Blackbody radiation:** temperature/color of star
- **Main sequence:** where a star spends most of its life
  - Hydrogen burning in core
- **Hydrogen burning:** how most stars get energy
- **Core:** hot core where H burns
- **Stellar evolution:** how star changes, from birth to death
- **HR Diagram:** 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
10^6
10^5
10^4
10^3
10^2
10
1
0.1
0.01
0.001
Luminosity (Solar Units)
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
30,000
20,000
10,000
5,000
3,000
Temperature (Kelvin)

Fusion at core

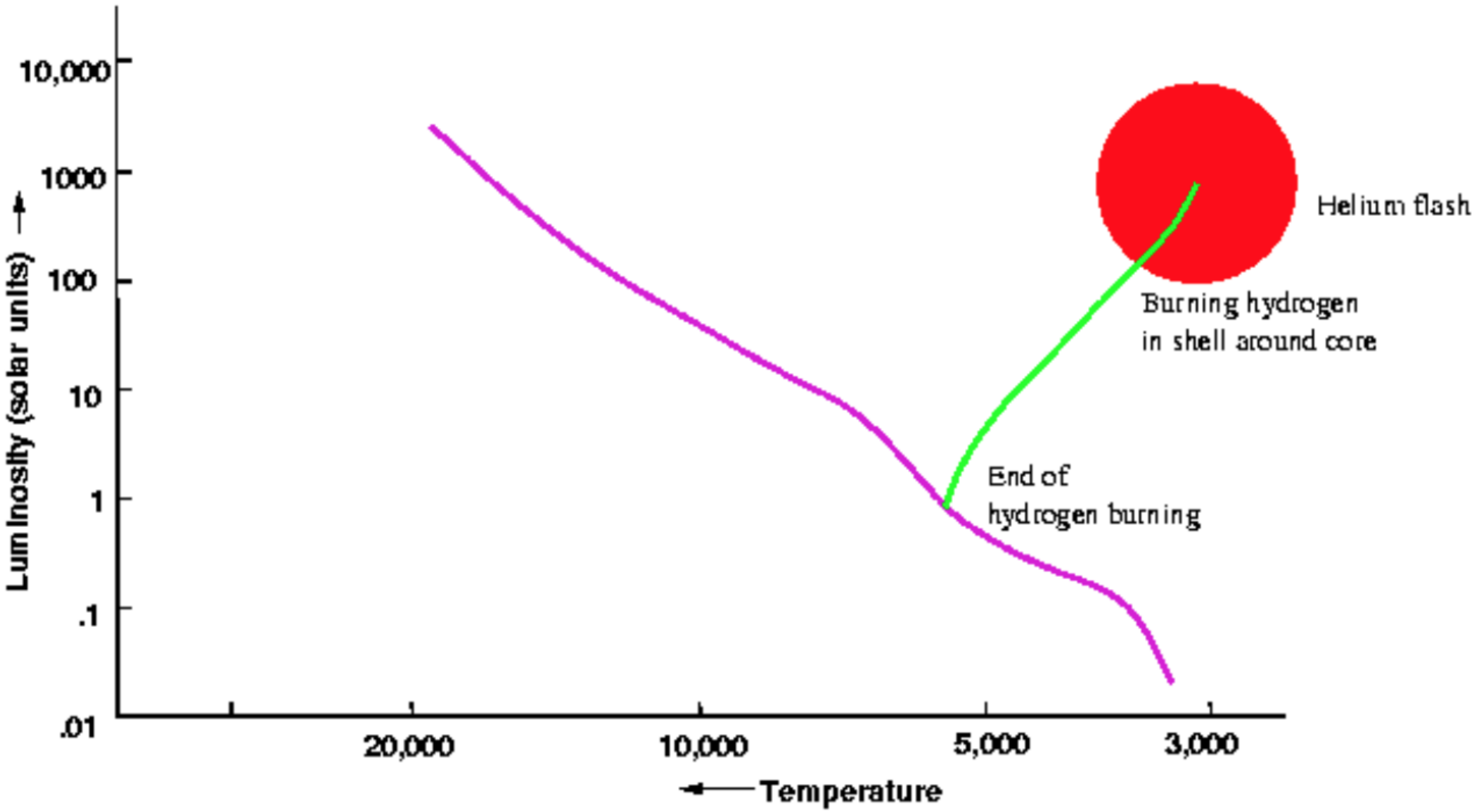
4 Hydrogen atoms turns into 1 He atom



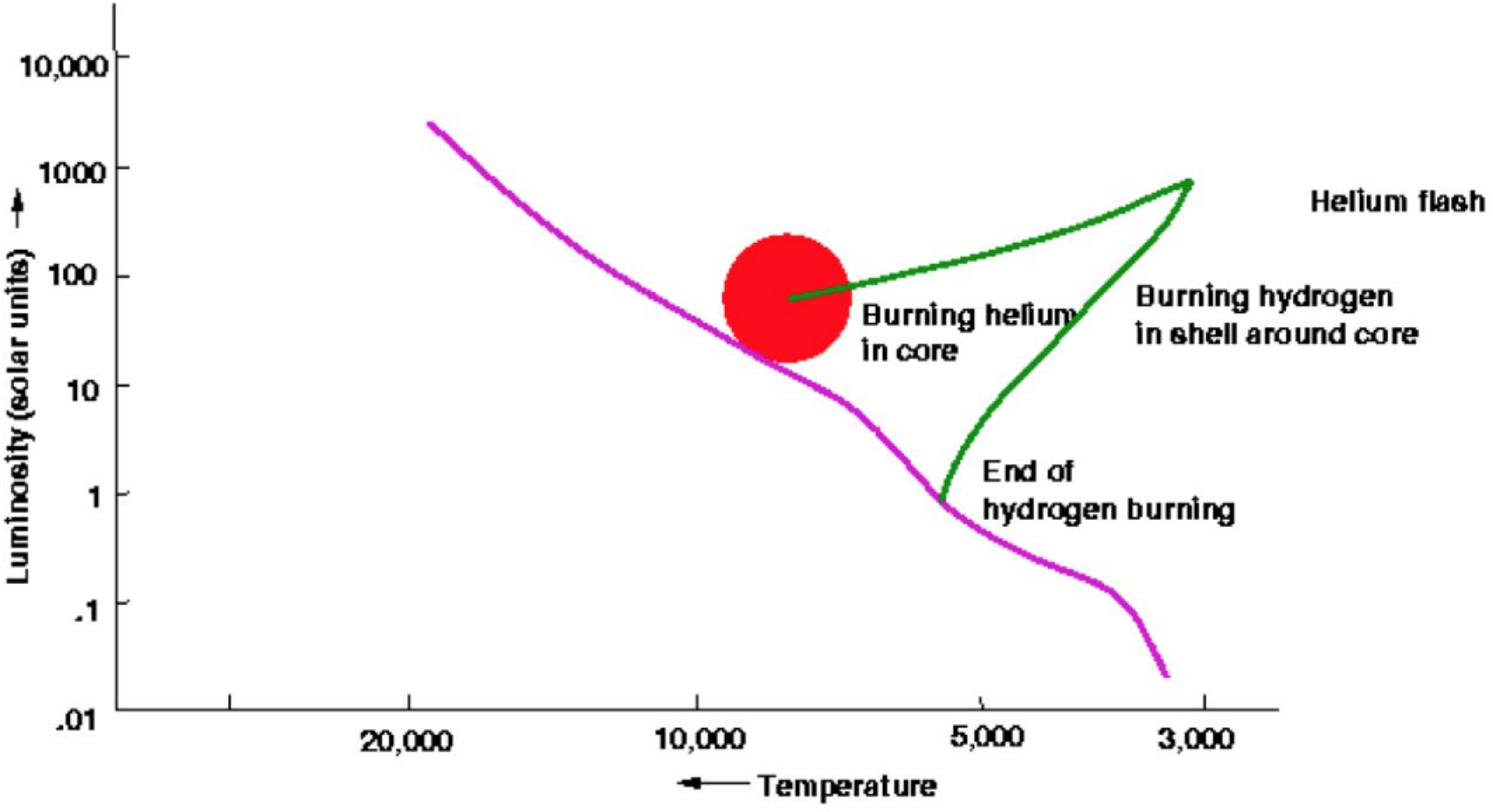


Main sequence: Hydrogen burning in core

What happens when the core runs out of Hydrogen?
(actually burns ~10% of the hydrogen in the star)

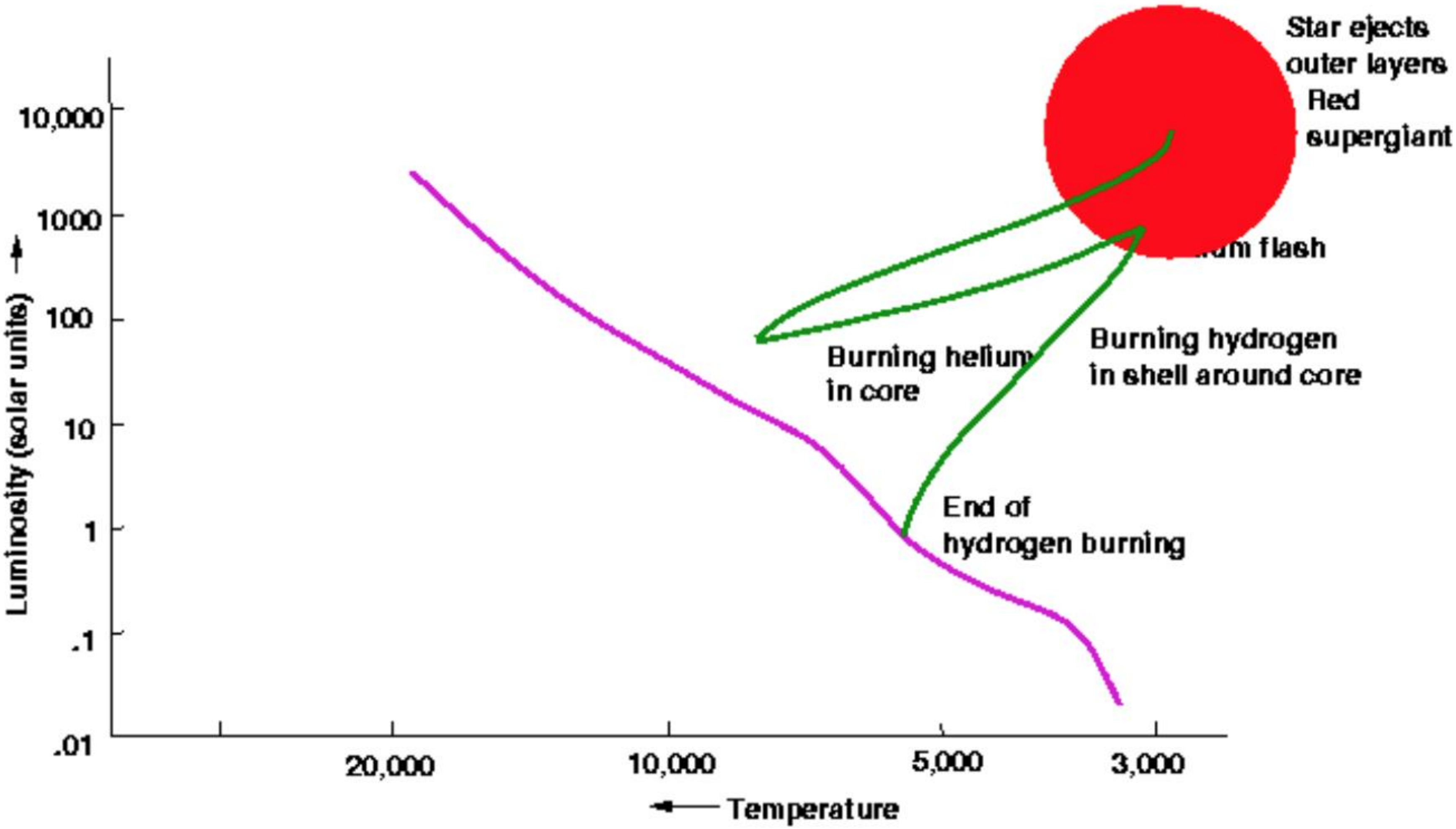


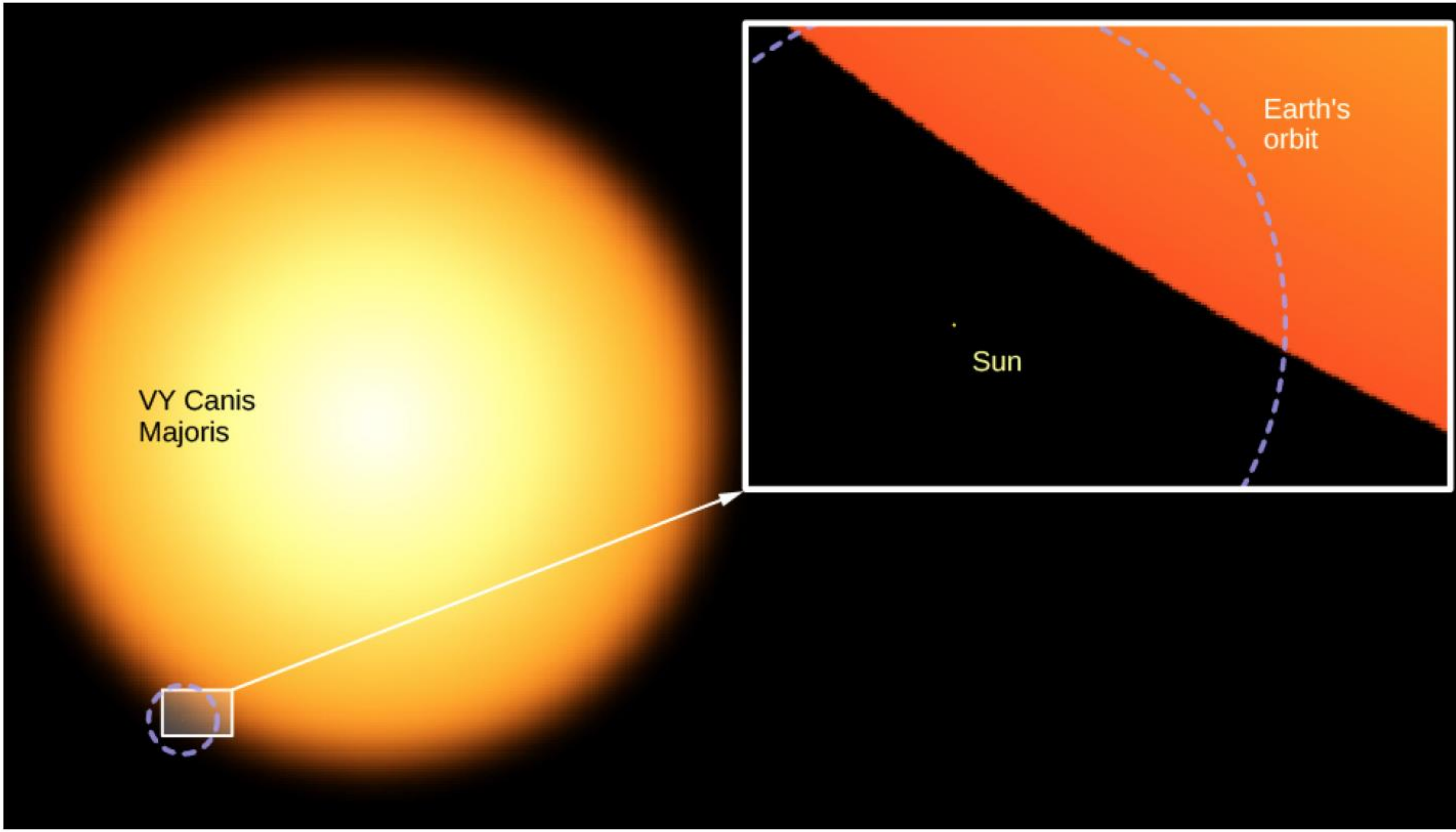
10,000
1000
100
10
1
.1
.01
Luminosity (solar units)
20,000
10,000
5,000
3,000
Temperature
Helium flash
Burning hydrogen
in shell around core
End of
hydrogen burning



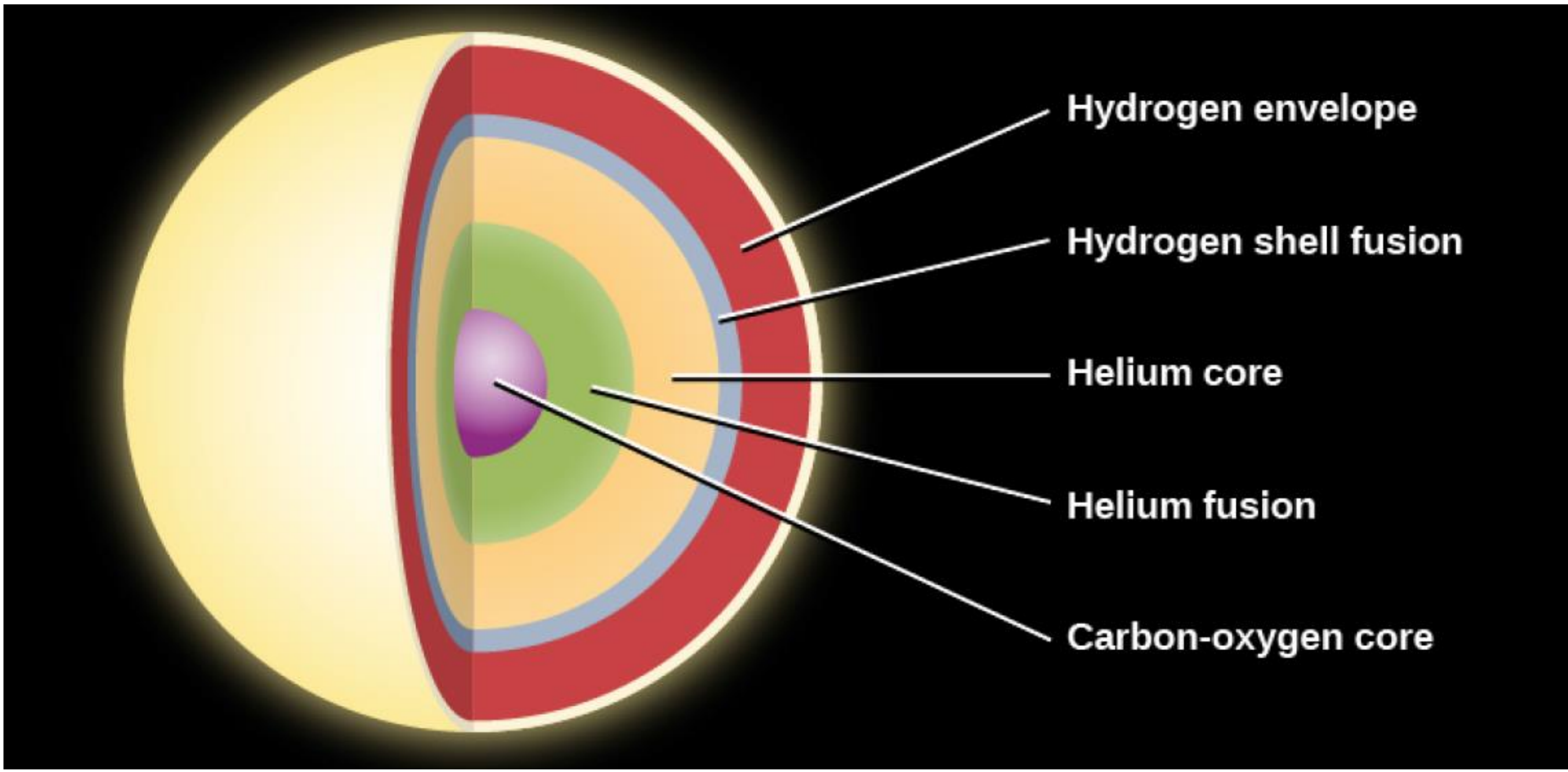
10,000
1000
100
10
1
.1
.01
Luminosity (solar units)
20,000
10,000
5,000
3,000
Temperature
Helium flash
Burning hydrogen
in shell around core
Burning helium
in core
End of
hydrogen burning

Evolution of a solar-mass star

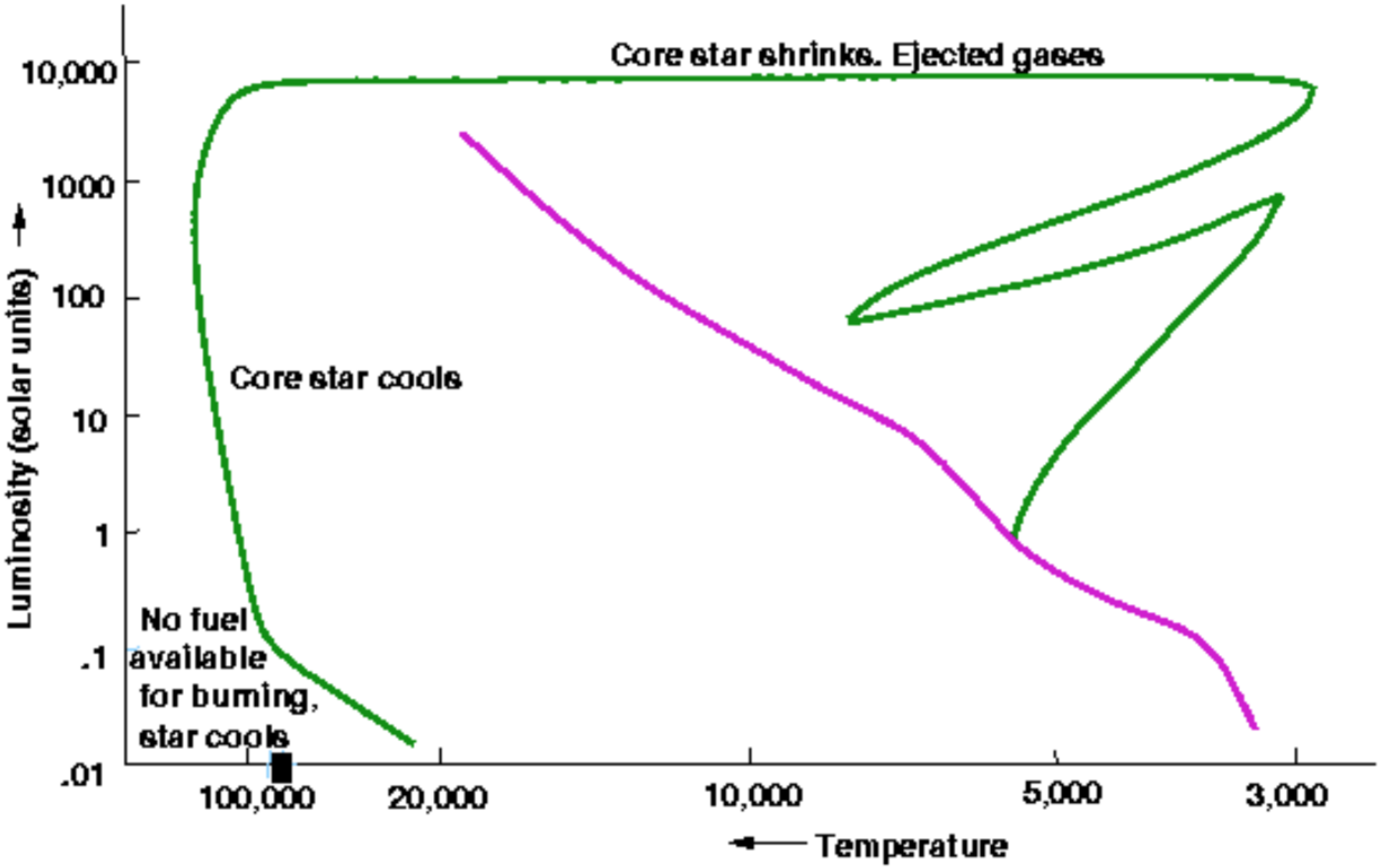



Earth's
orbit
Sun
VY Canis
Majoris

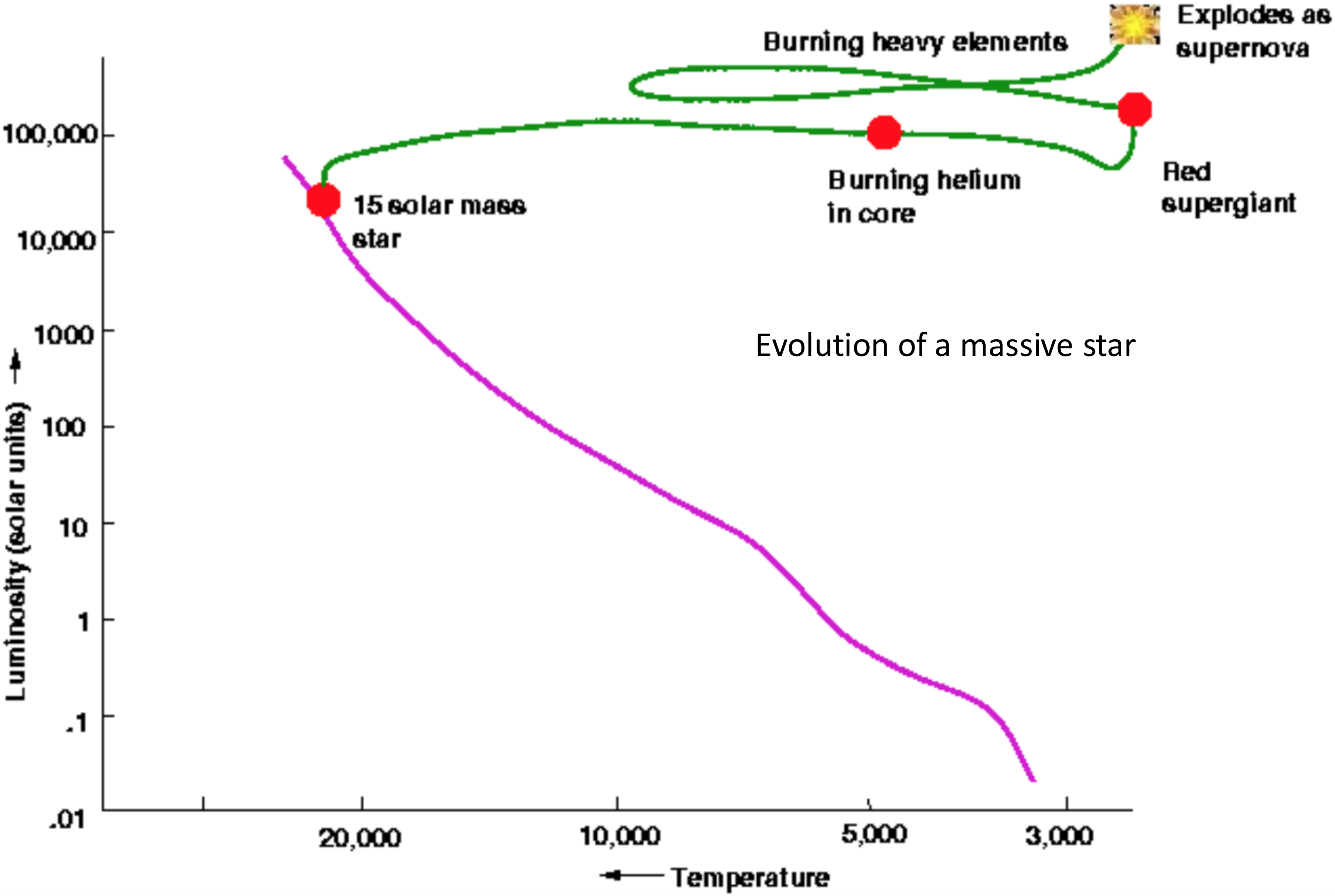
Interior structure of evolved star; Will lose the envelope (outer region)



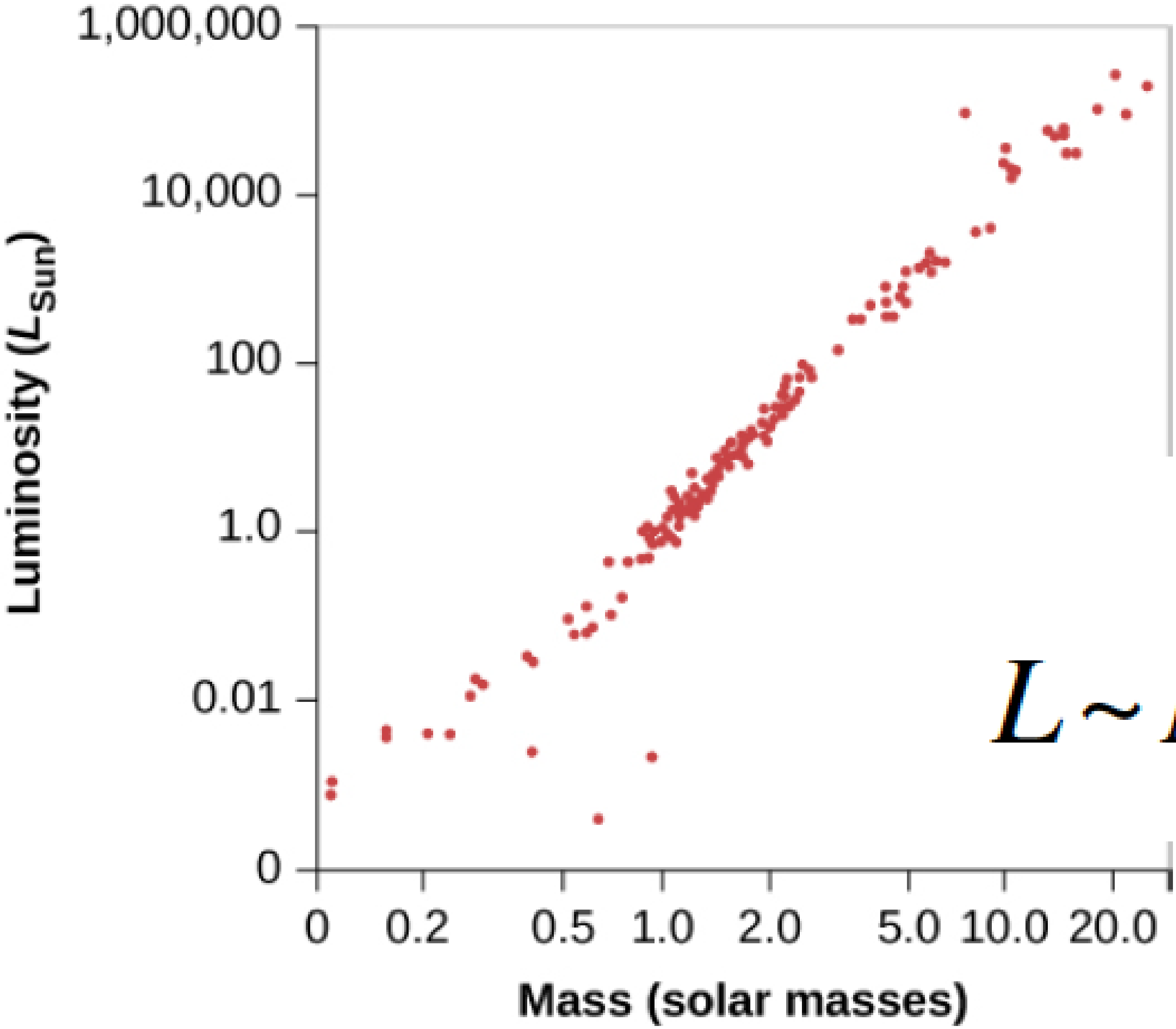
Evolution of a solar-mass star



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

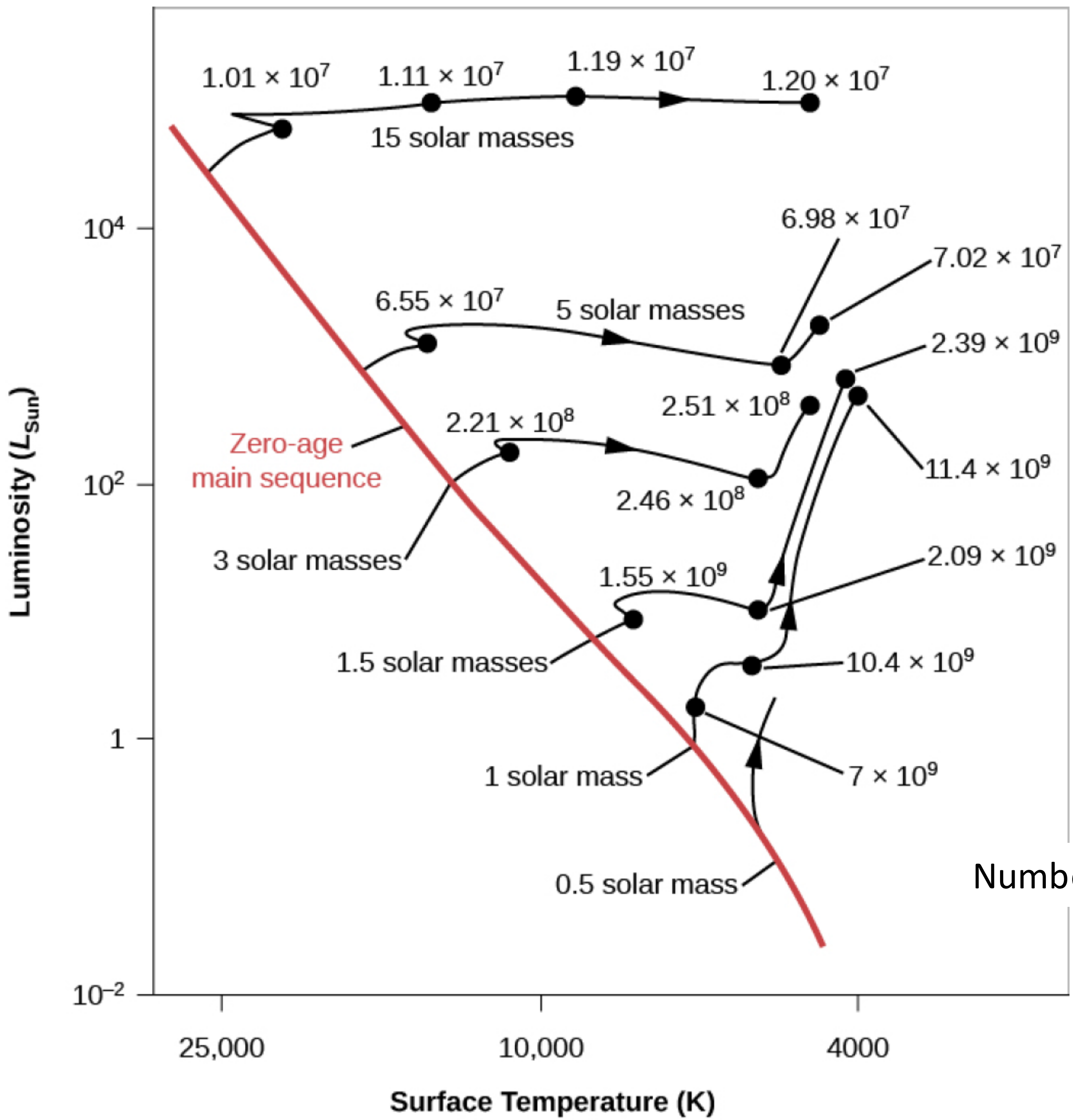


Evolution of a massive star



Massive stars burn out quickly!

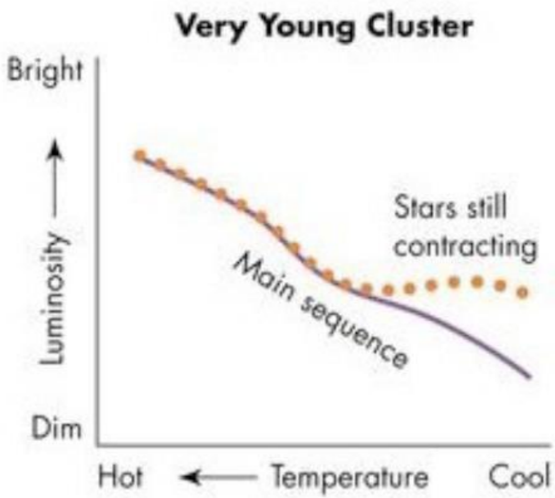
$$L \sim M^{3.9}$$

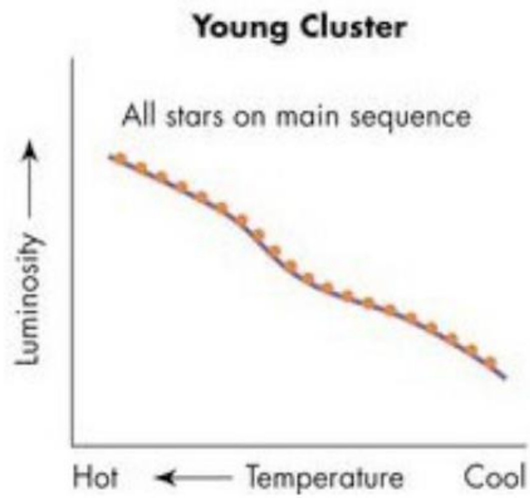


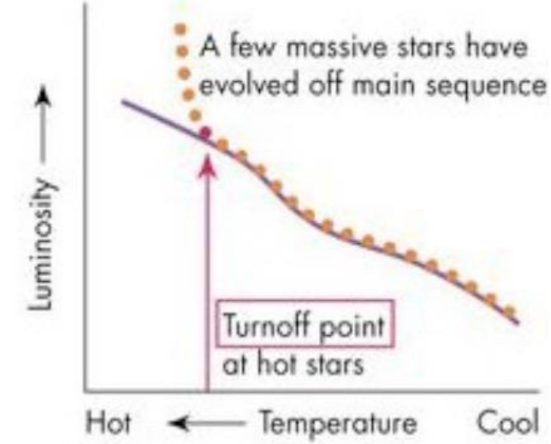
$L=R^2 T^4$

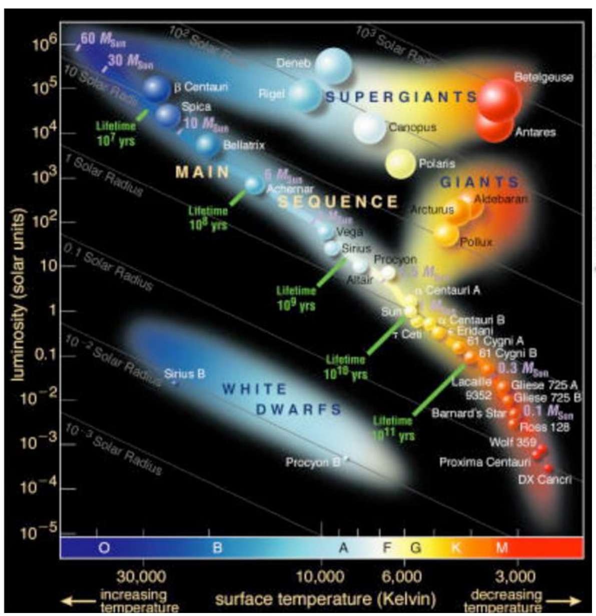
Stars get cool at surface, but luminous: radius must get very large

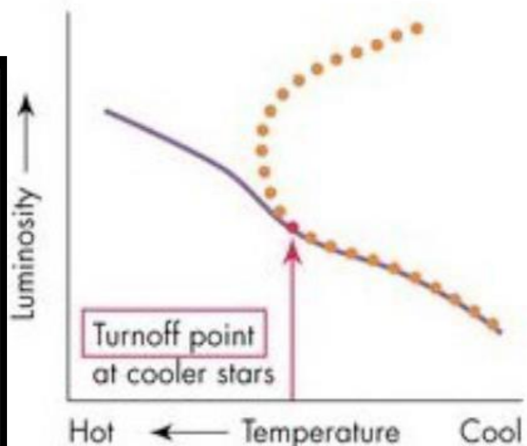
Numbers are ages

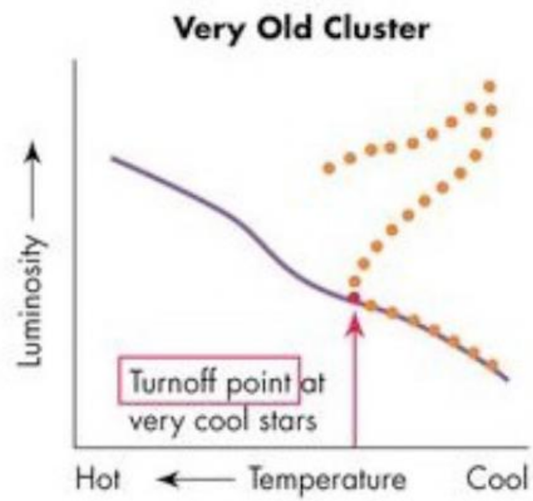

Very Young Cluster
Bright
Dim
Luminosity
Stars still contracting
Main sequence
Hot
Temperature
Cool


Young Cluster
All stars on main sequence
Luminosity
Hot
Temperature
Cool

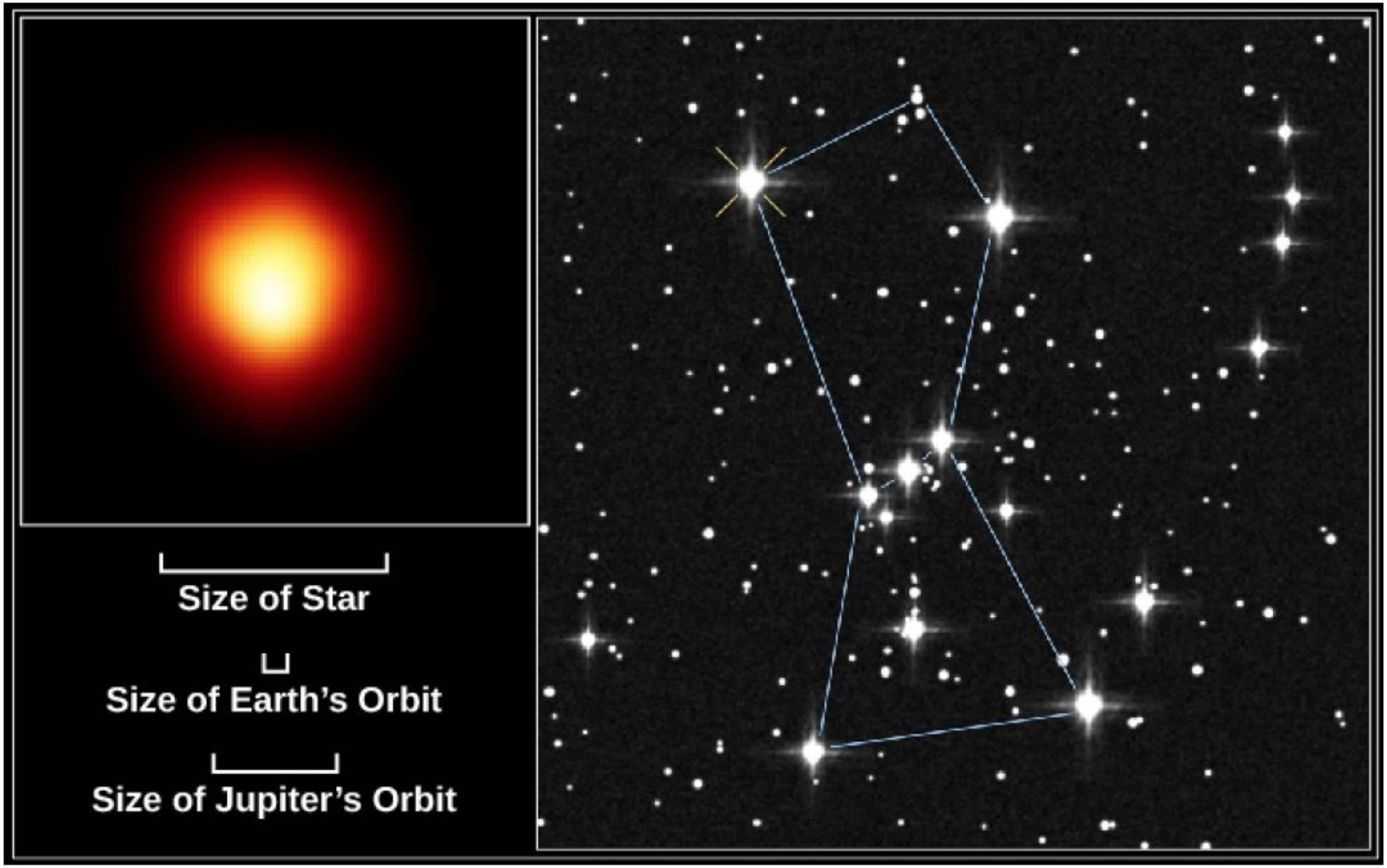

A few massive stars have evolved off main sequence
Luminosity
Turnoff point at hot stars
Hot
Temperature
Cool


SUPERGIANTS
GIANTS
MAIN SEQUENCE
WHITE DWARFS
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
Deneb
Rigel
Betelgeuse
Antares
Canopus
Polaris
Aldebaran
Arcturus
Pollux
Bellatrix
Spica
Achernar
Vega
Sirius
Procyon
Altair
Sun
Sirius B
Procyon B
Barnard's Star
Proxima Centauri
Wolf 359
DX Cancri


Luminosity
Turnoff point at cooler stars
Hot
Temperature
Cool


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

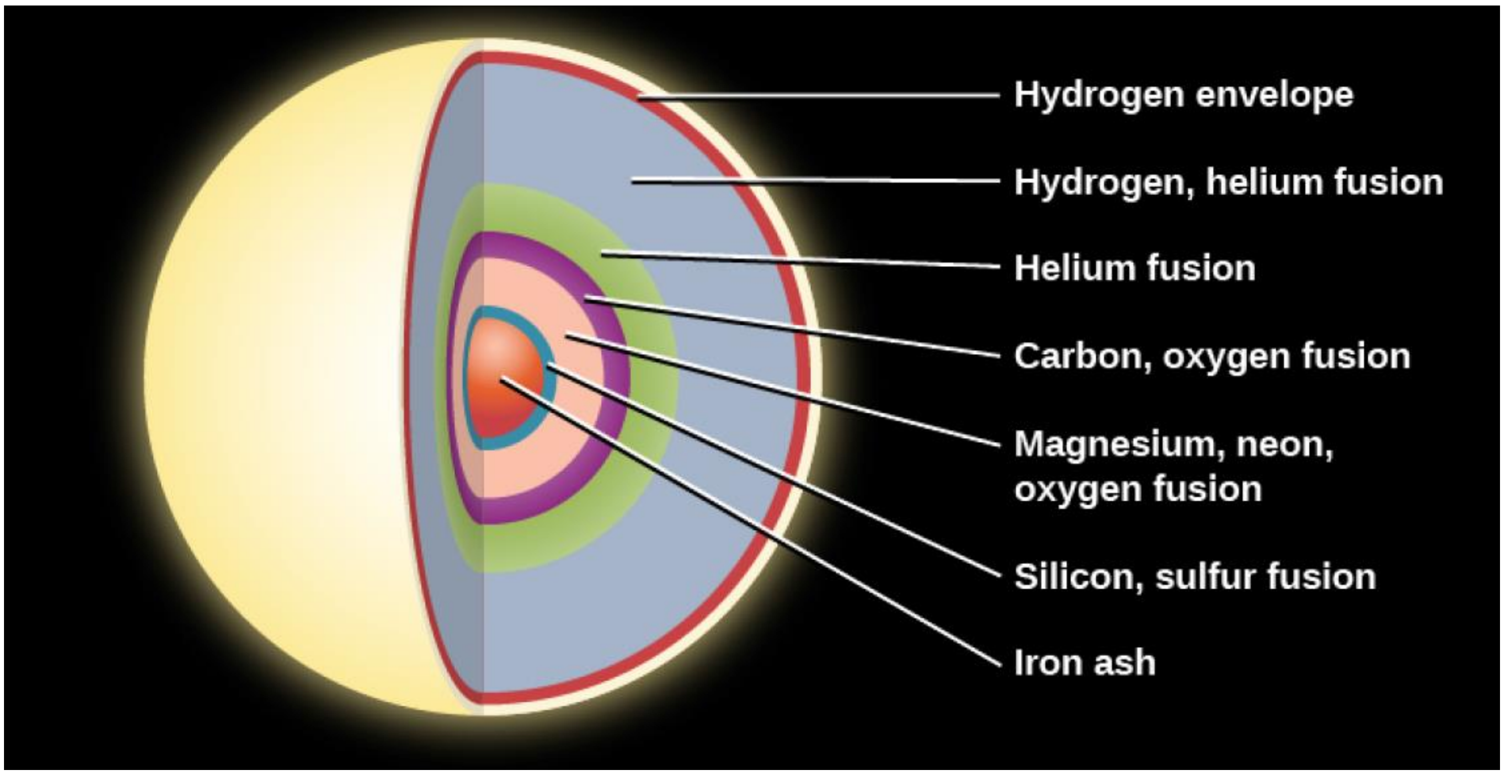
The supergiant star Betelgeuse



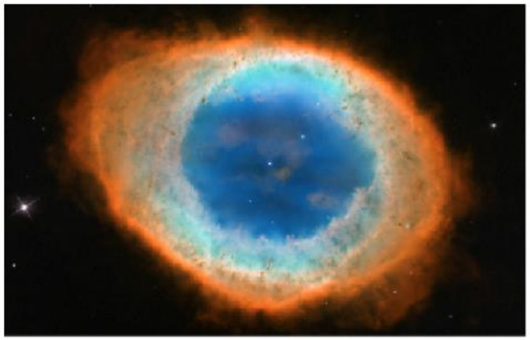
Comparing a Supergiant with the Sun

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

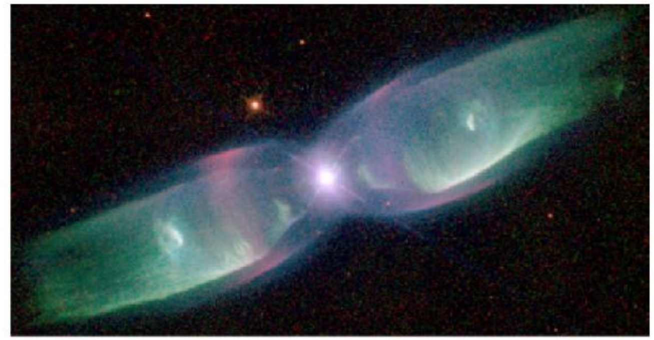
Planetary nebula: lost envelopes, only core is left; we see lost material



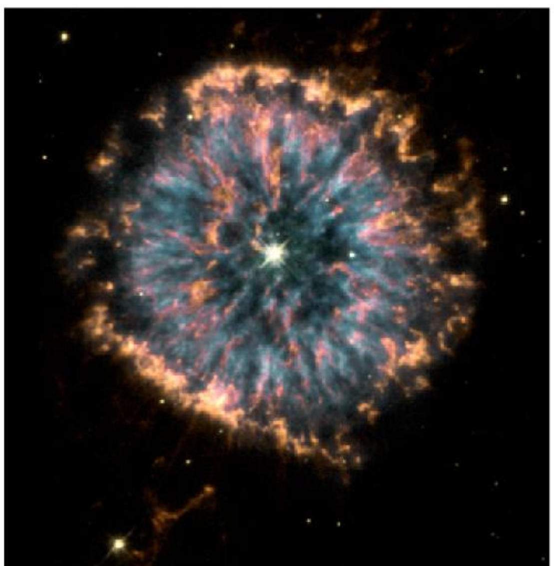
Planetary nebula: lost envelopes, only core is left; we see lost material



(a)

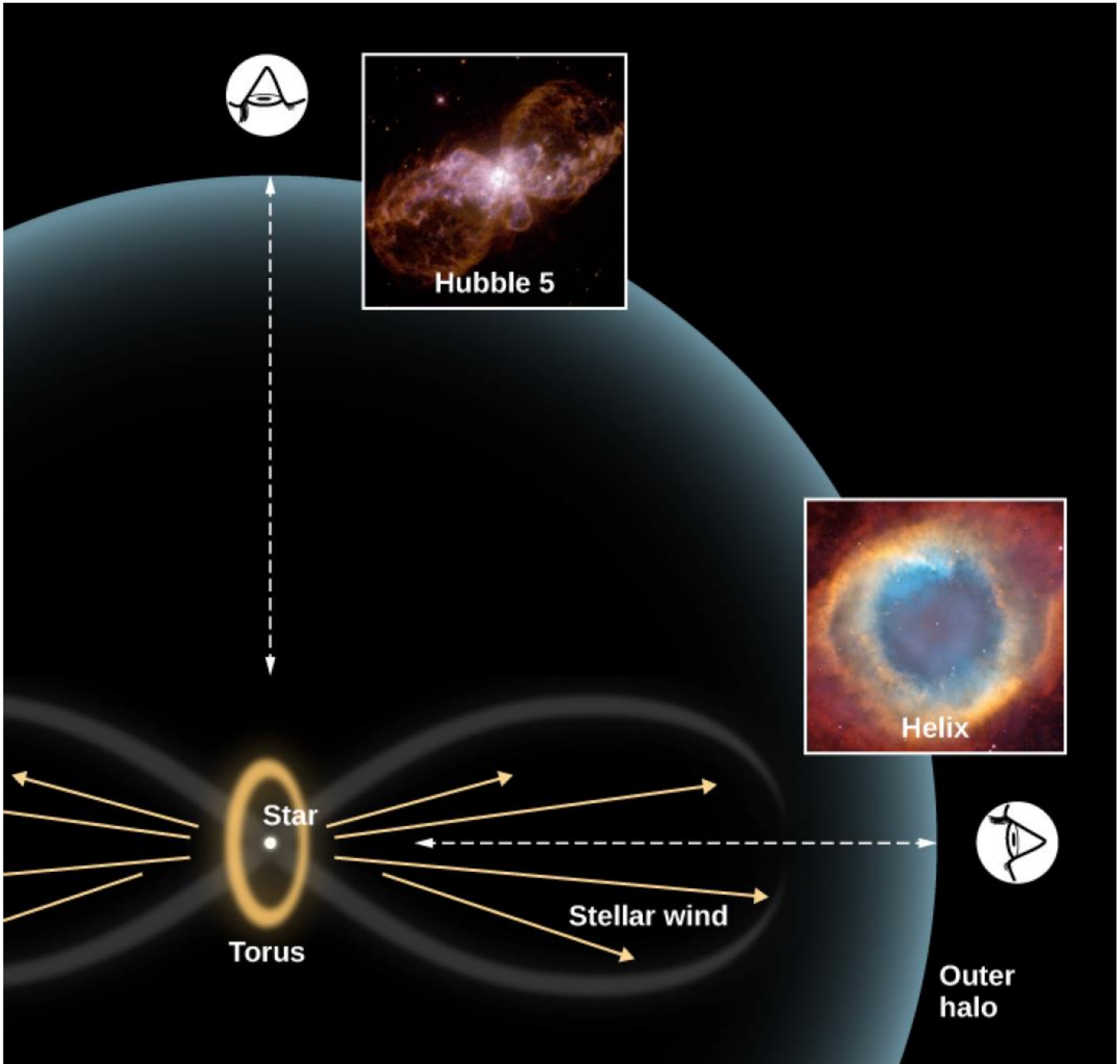


(b)



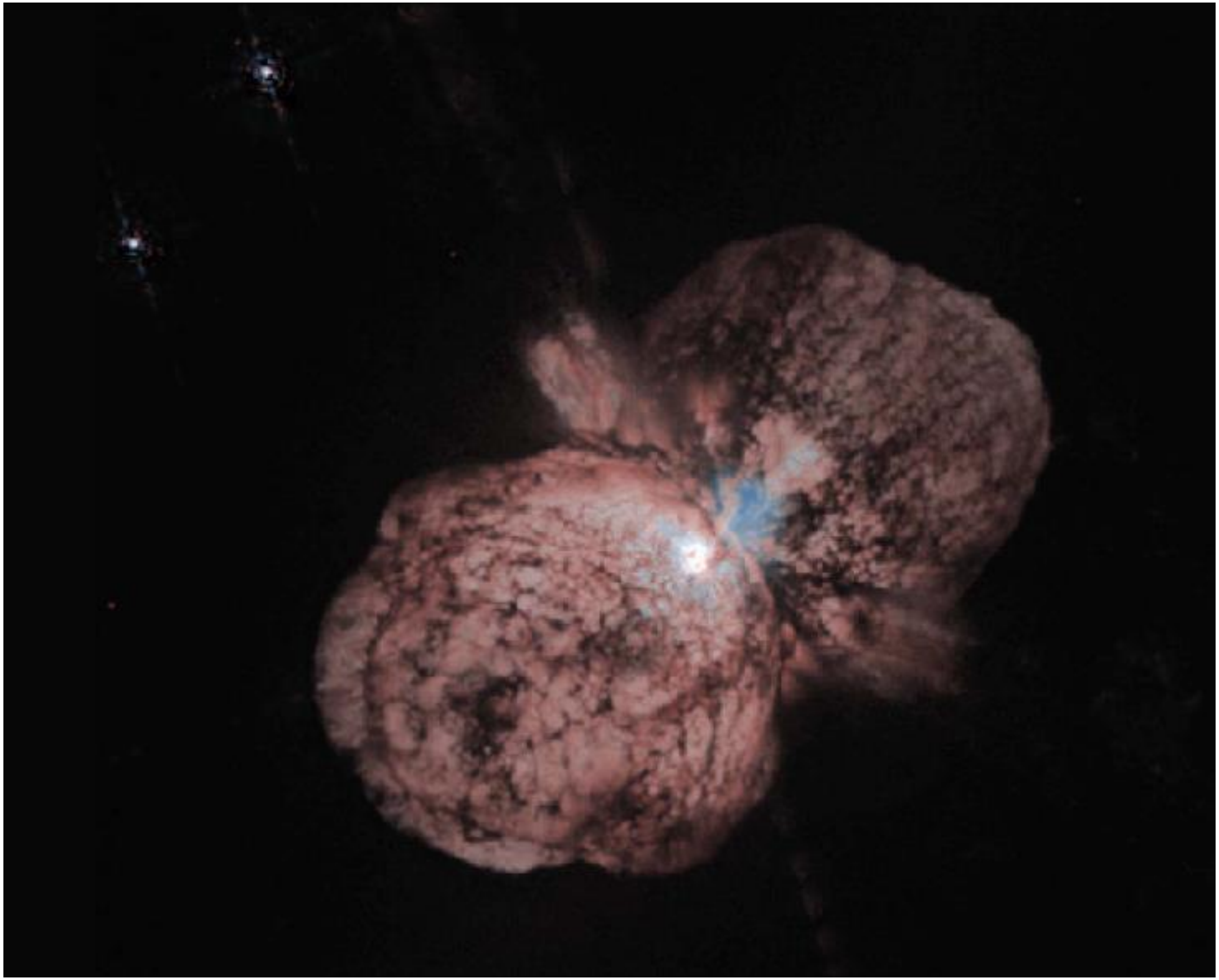
(c)

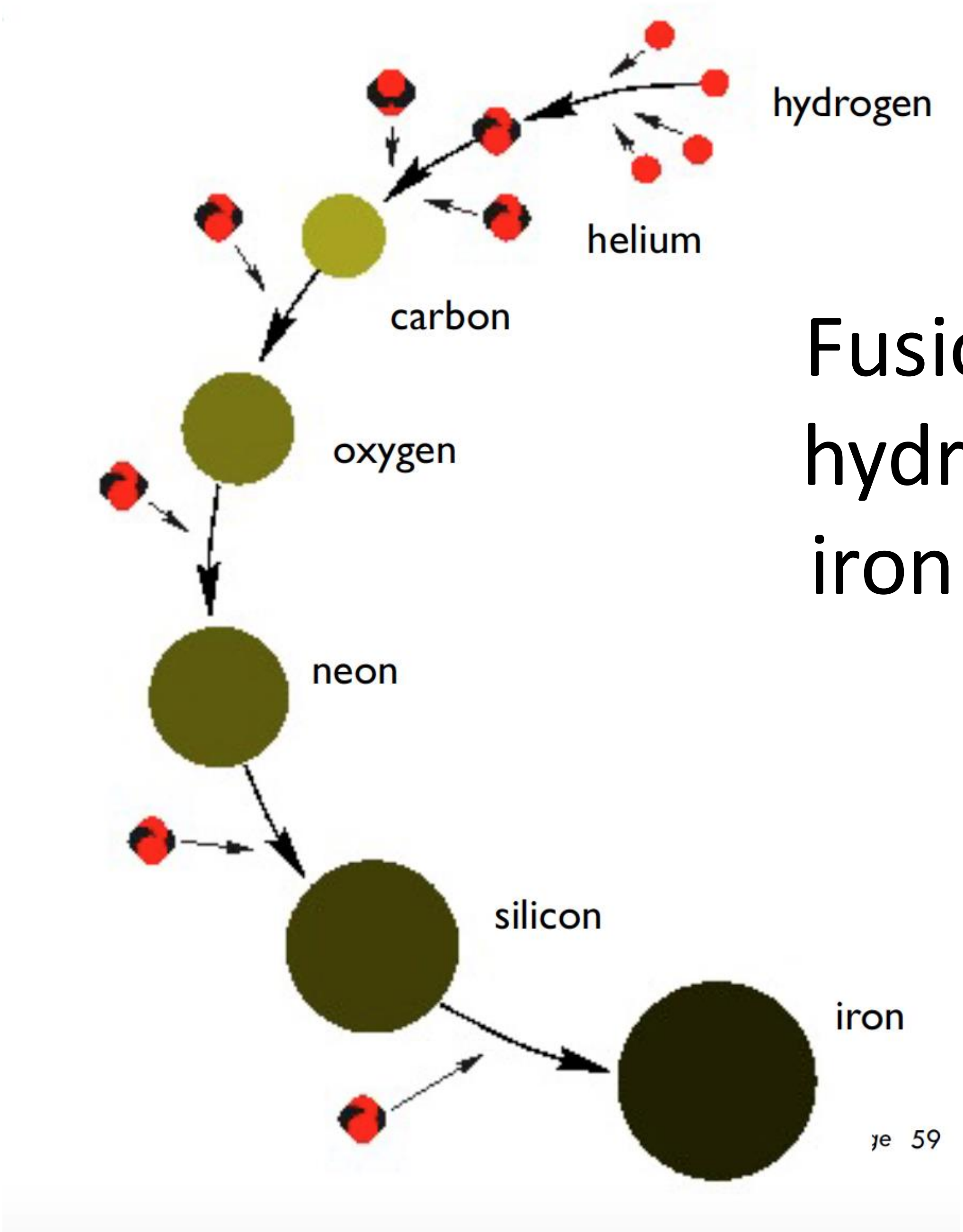
(d)



Hubble 5
Helix
Star
Torus
Stellar wind
Outer
halo

Eta Carina: what a 100 Msun star looks like

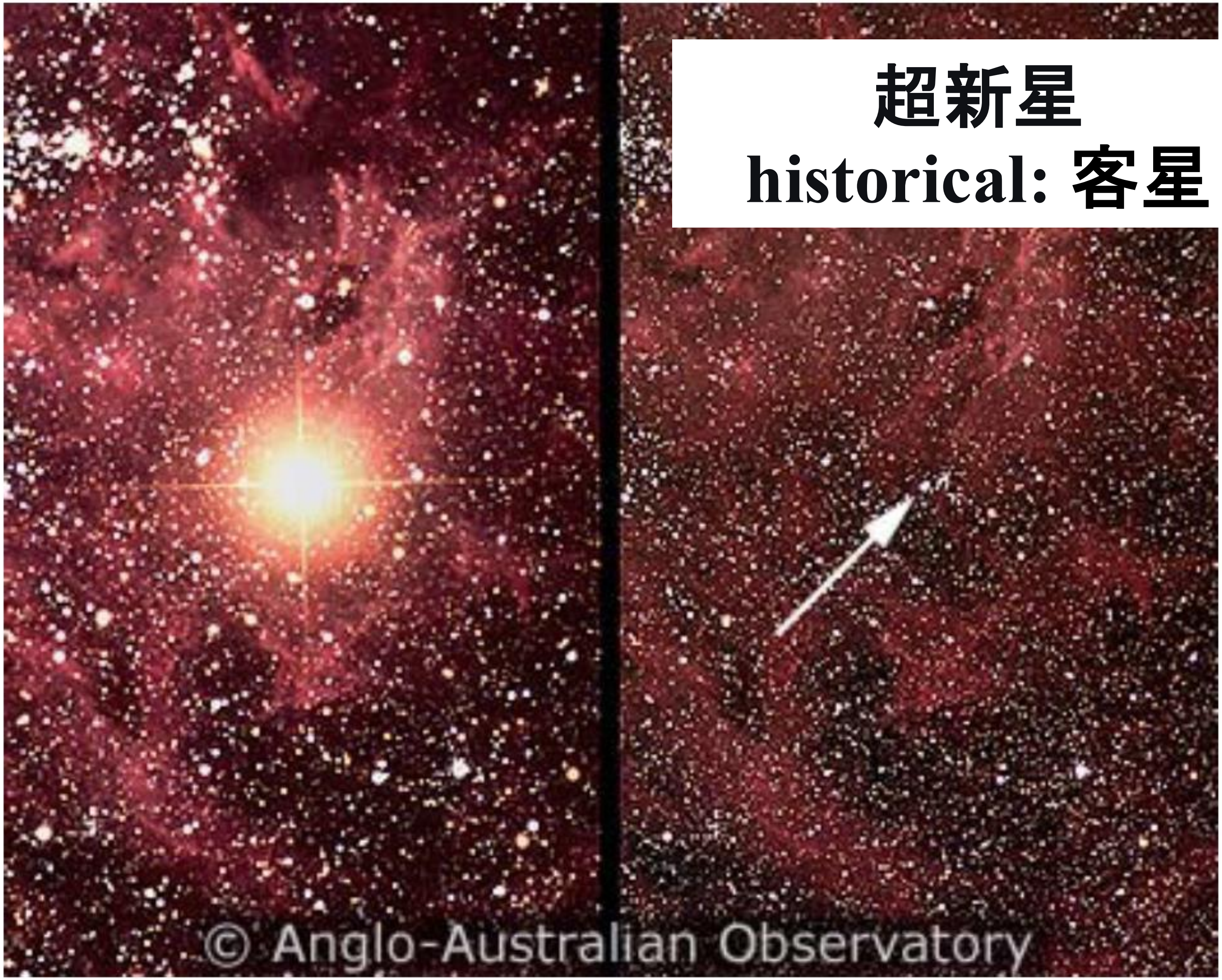




Fusion from hydrogen to iron in stars

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)

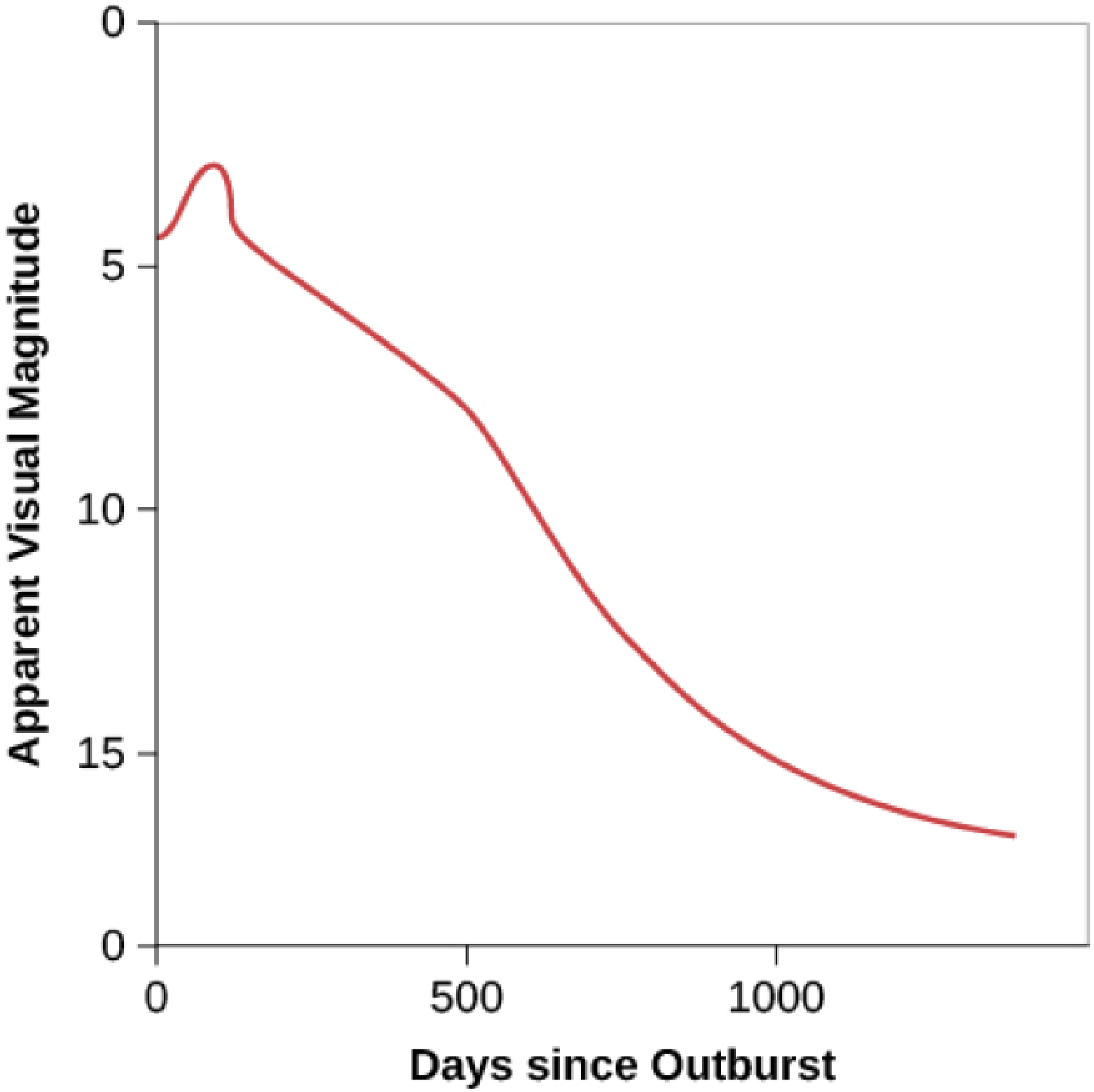


"On the Jisi day, the 7th day of the month, a big new star appeared in the company of the Ho star."

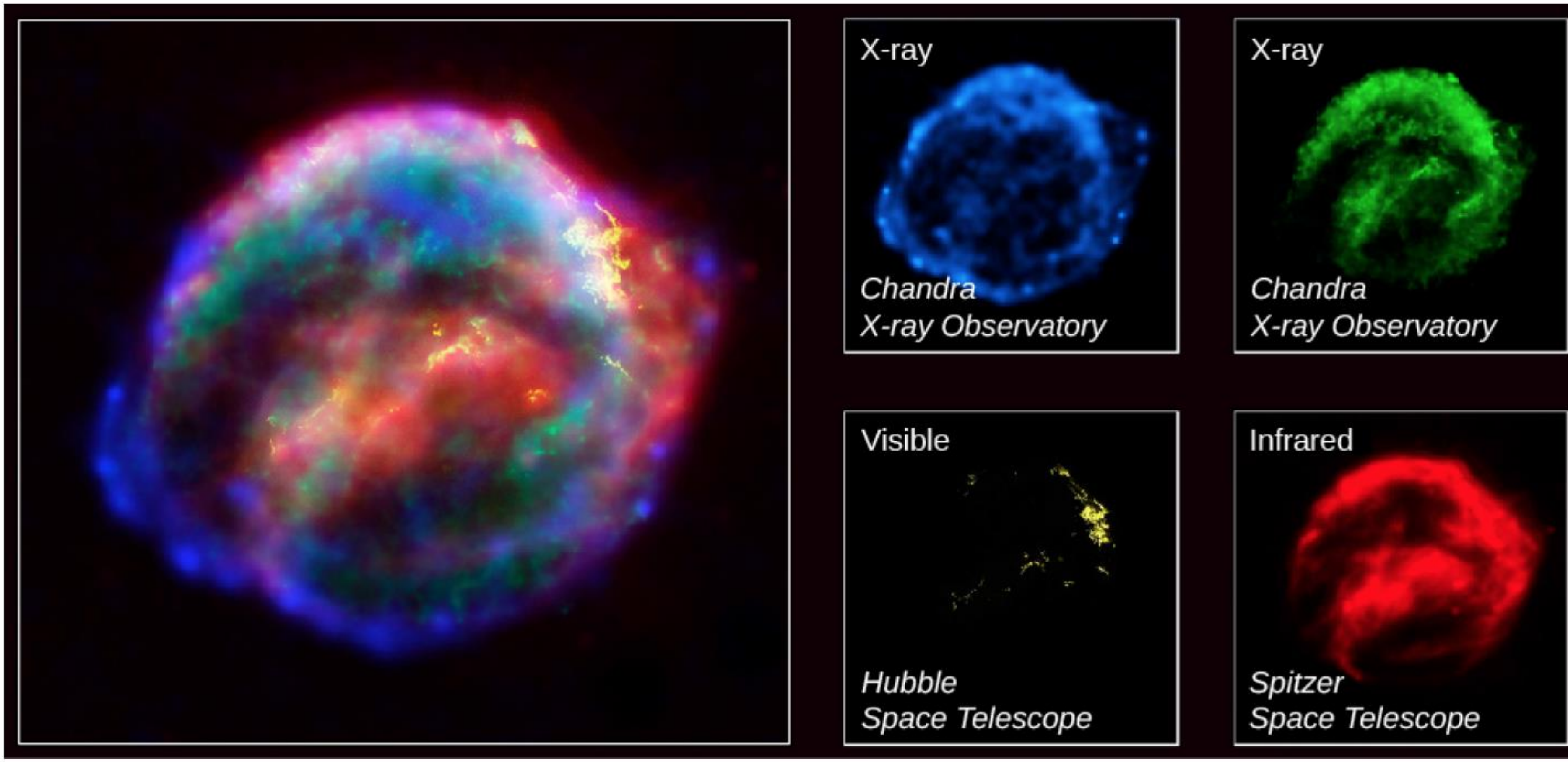
"On the Xinwei day the new star dwindled."

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

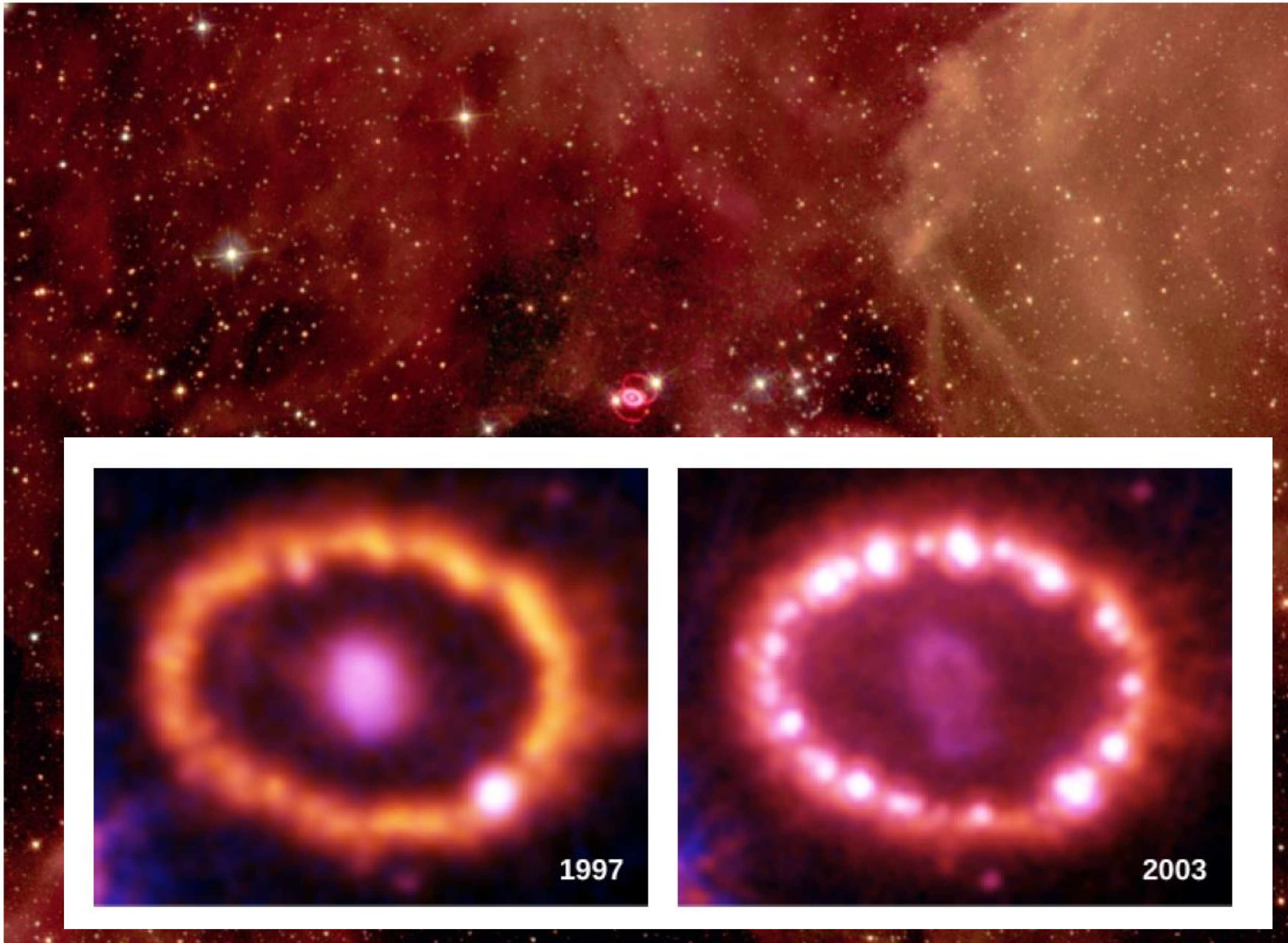


Supernova remnant

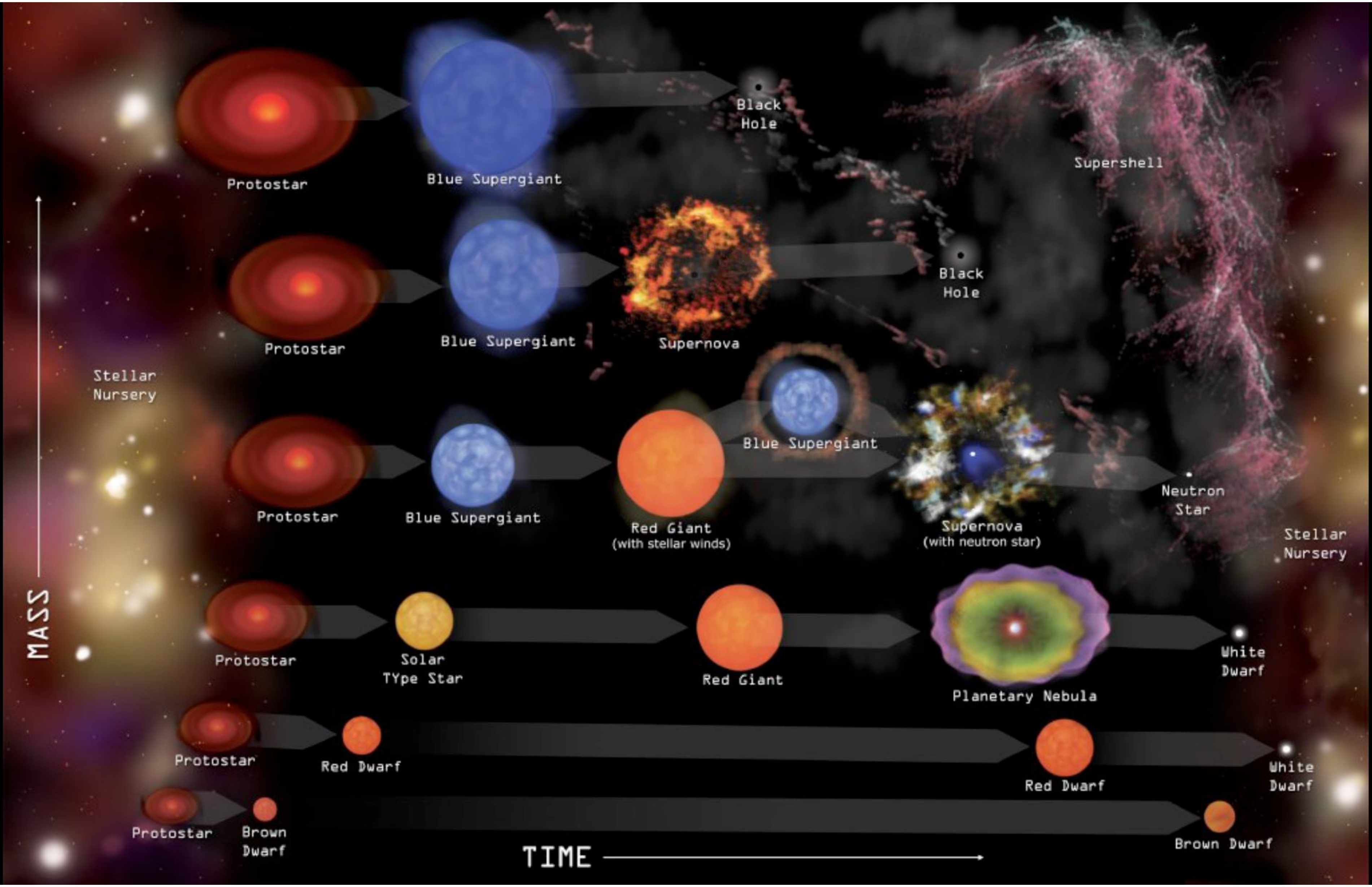


Supernova remnant

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



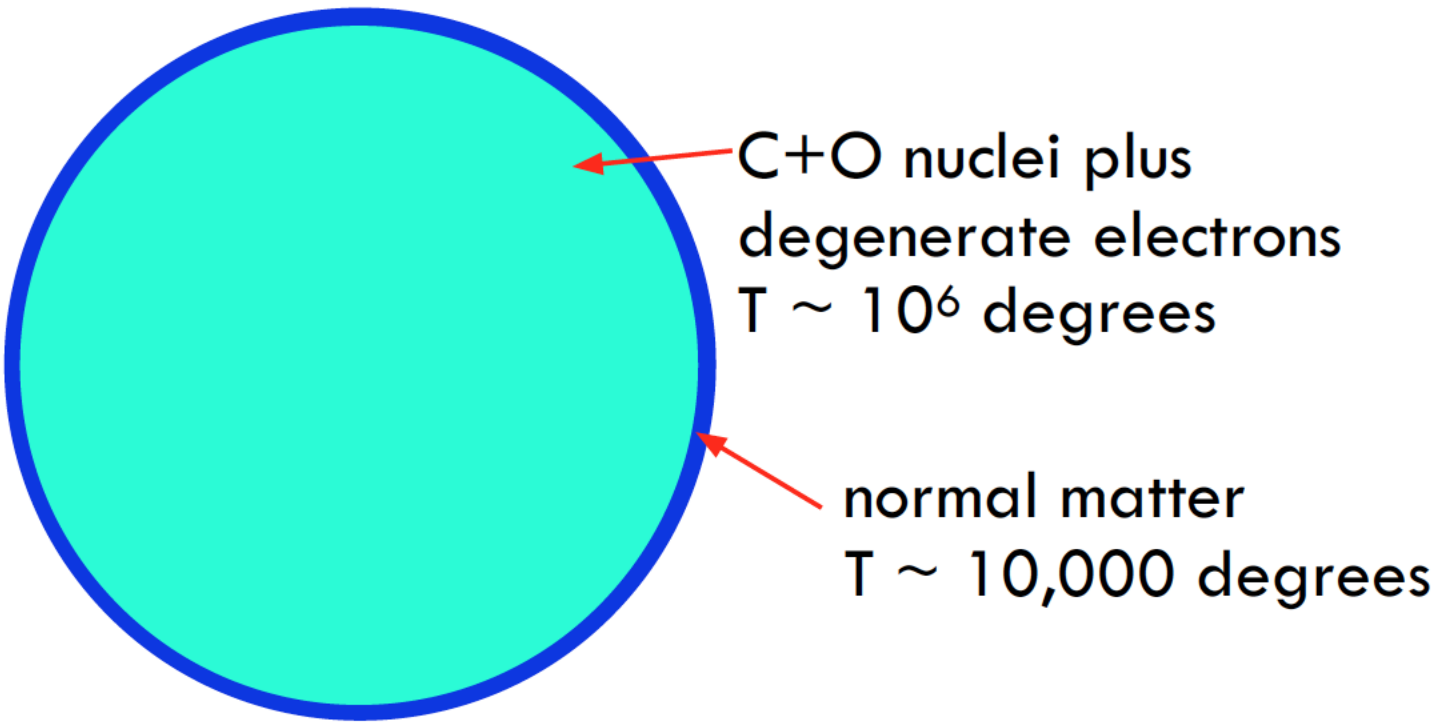
Protostar
Blue Supergiant
Black Hole
Supershell
Protostar
Blue Supergiant
Supernova
Black Hole
Stellar Nursery
Protostar
Blue Supergiant
Red Giant
(with stellar winds)
Blue Supergiant
Supernova
(with neutron star)
Neutron Star
Stellar Nursery
Protostar
Solar Type Star
Red Giant
Planetary Nebula
White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

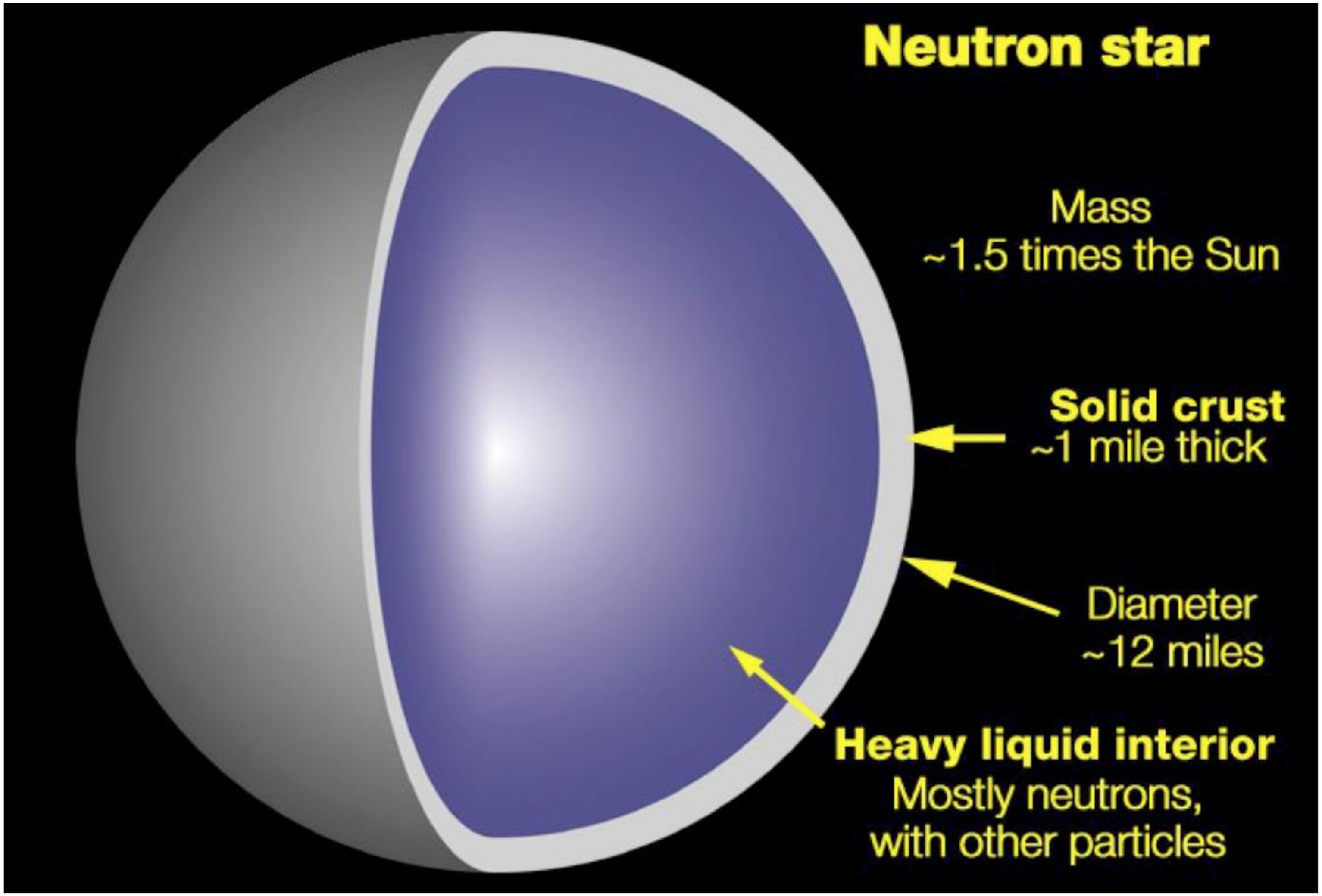
Property	White Dwarf	Neutron Star
Mass (Sun = 1)	0.6 (always <1.4)	Always >1.4 and <3
Radius	7000 km	10 km
Density	8×10^5 g/cm^3	10^{14} g/cm^3

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

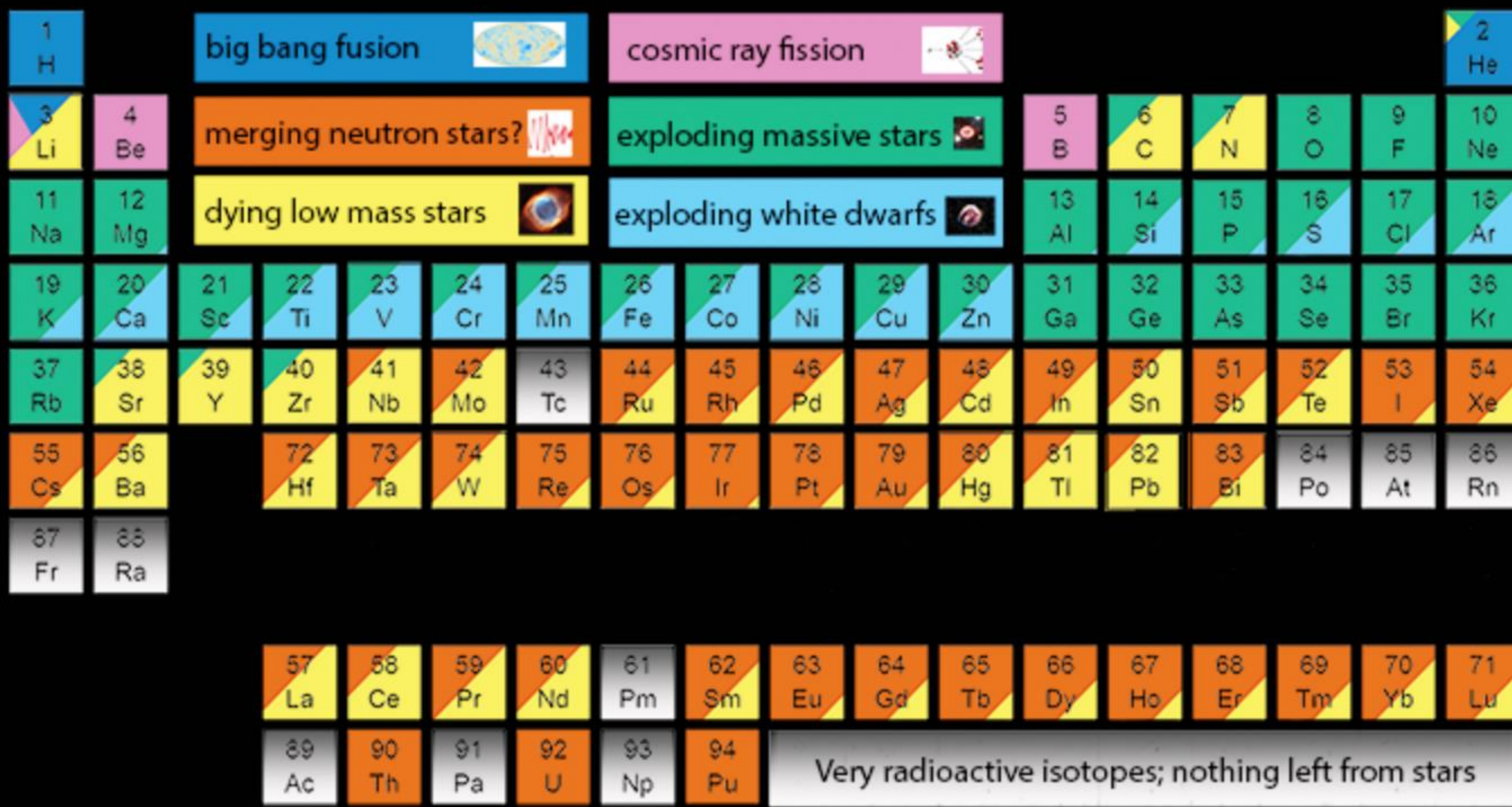
Sun: size 1.4×10^6 km

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



Graphic created by Jennifer Johnson
http://www.astronomy.ohio-state.edu/~jaj/nucleo/

Astronomical Image Credits:
ESA/NASA/AASNova

Interstellar medium

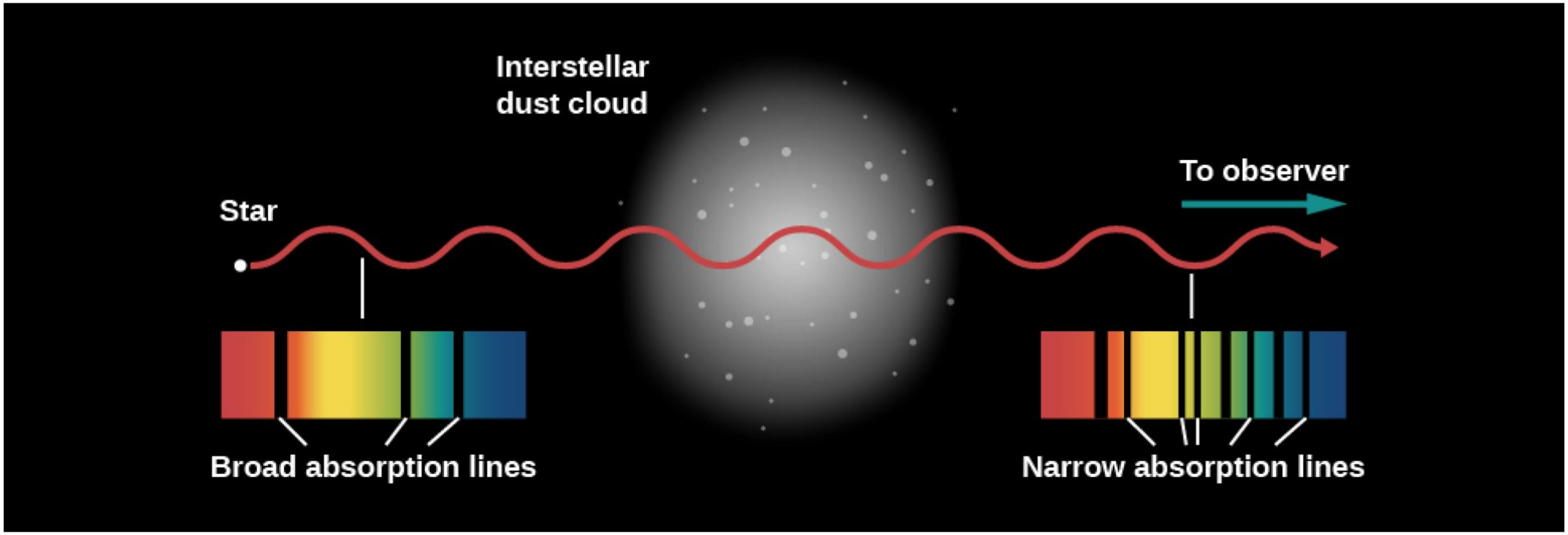
- Space is not quite empty
  - Hot interstellar medium: 10^{-4} ions per cm^3
  - In this room: 10^{19} molecules/cm^3
  - Best vacuum in lab: 10^{10} molecules/cm^3
- Some places are denser and colder
  - **Molecular clouds**, where stars form
  - Densities of 10^2-10^6 molecules/cm^3

Interstellar medium, supernova remnants

Intestellar medium: how to detect?

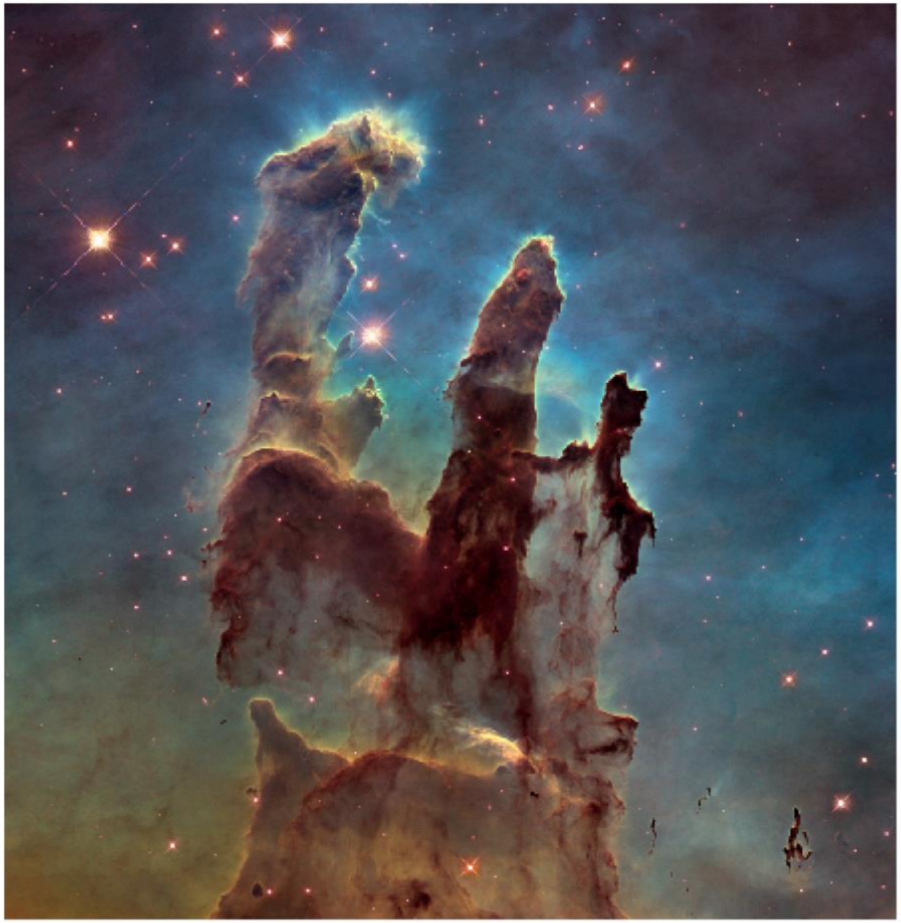
Absorption of photons by gas

Emission from gas/dust

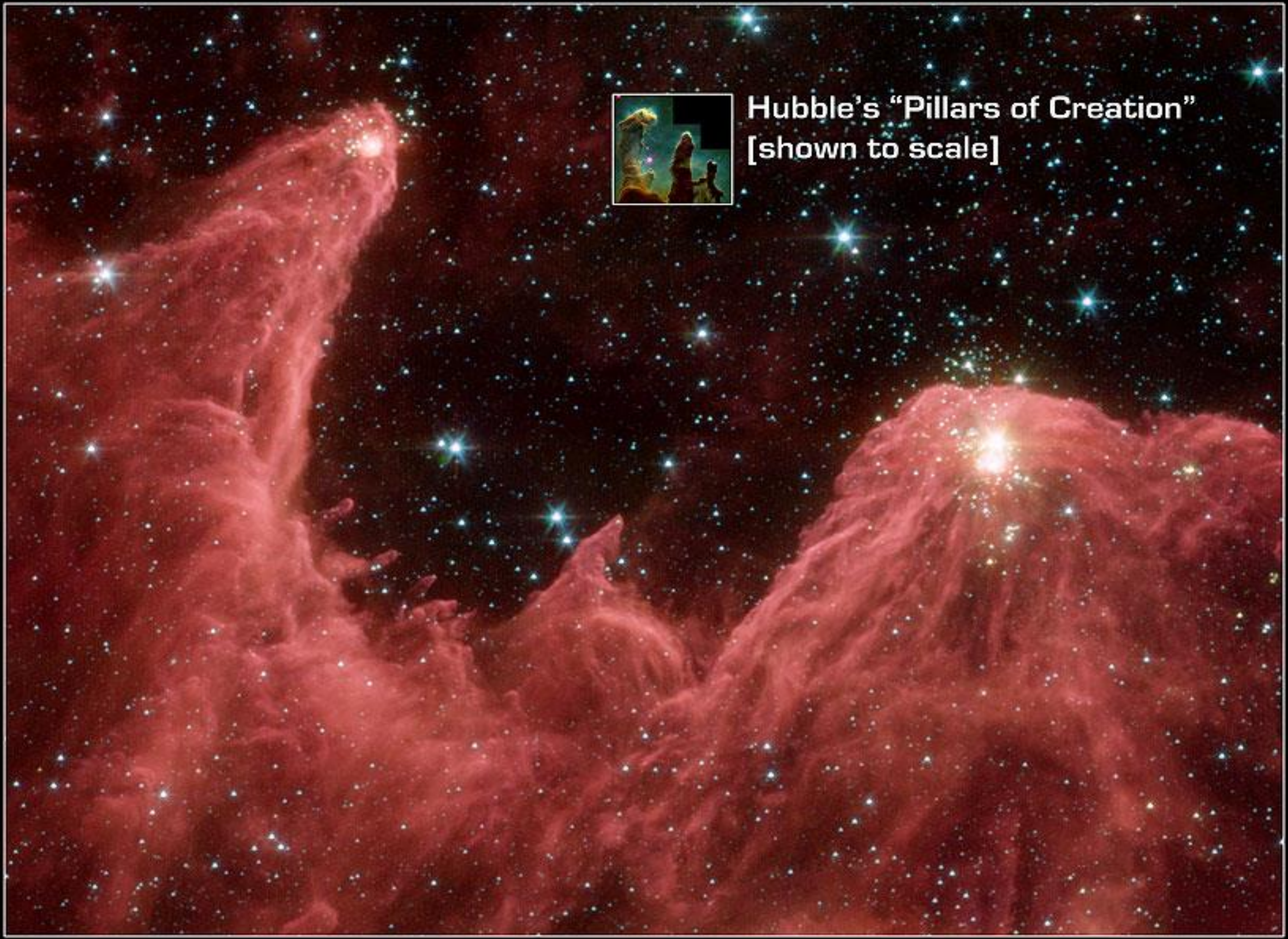



Orion Nebula
Largest nearby star-
forming region

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



Pillars of Creation:
Hubble Space Telescope (optical) on left
JWST (infrared) on right



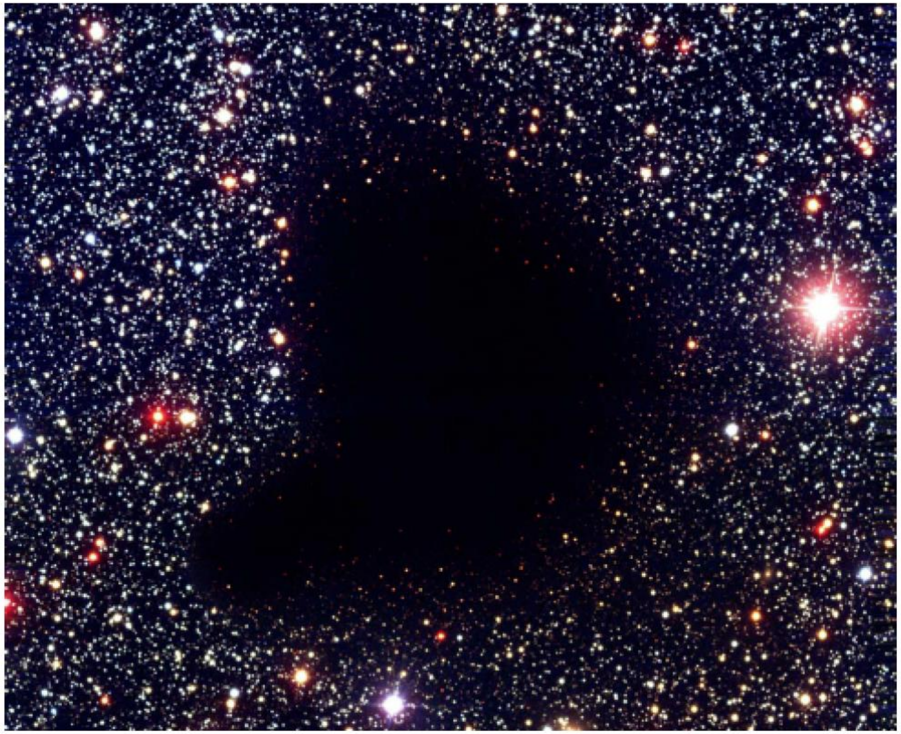
"Pillars" and "Mountains" of Star Formation

Spitzer Space Telescope • IRAC

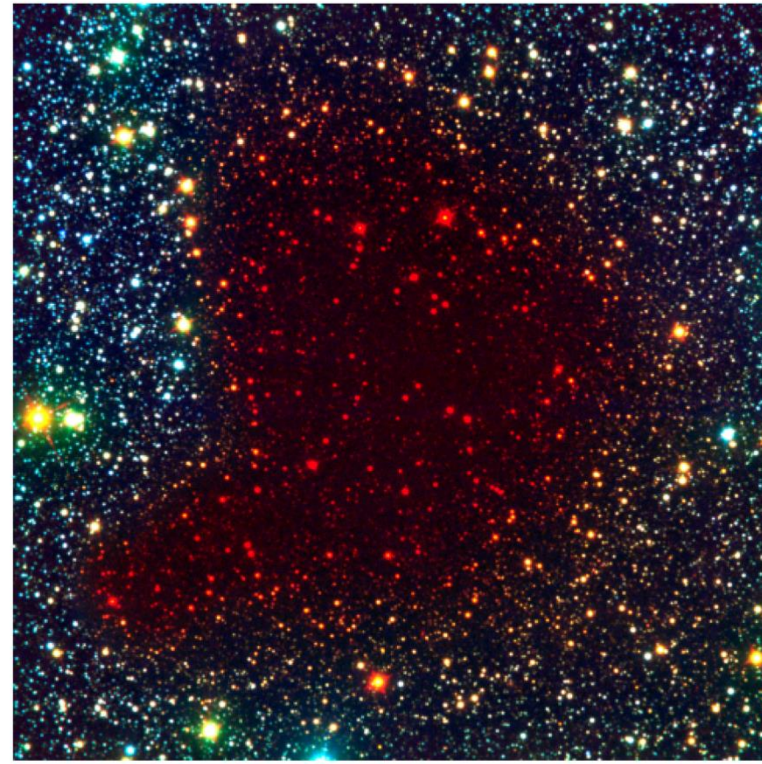
Inset: Hubble Space Telescope

NASA / JPL-Caltech / L. Allen (Harvard-Smithsonian CfA)

ssc2005-23b



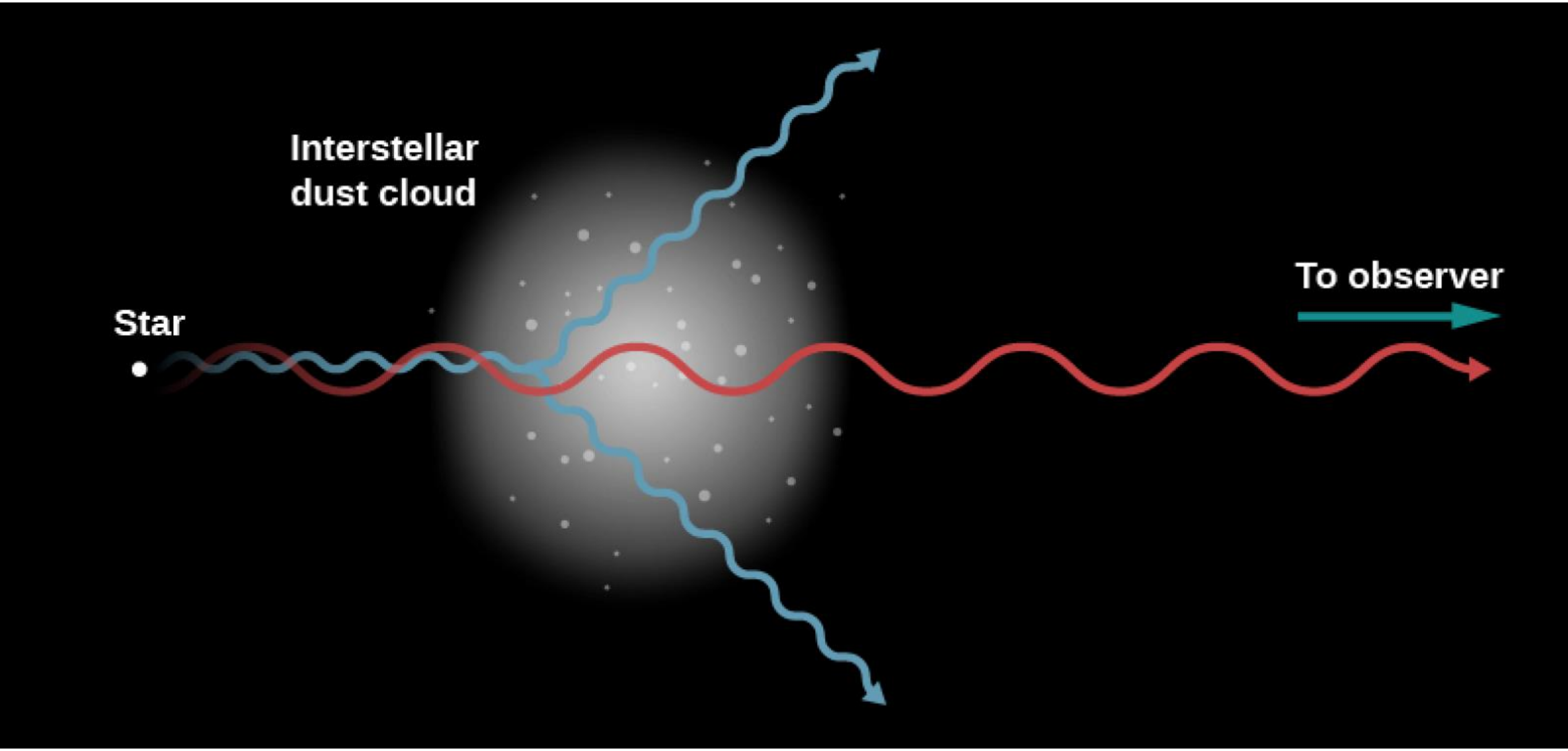
Optical



Near-infrared

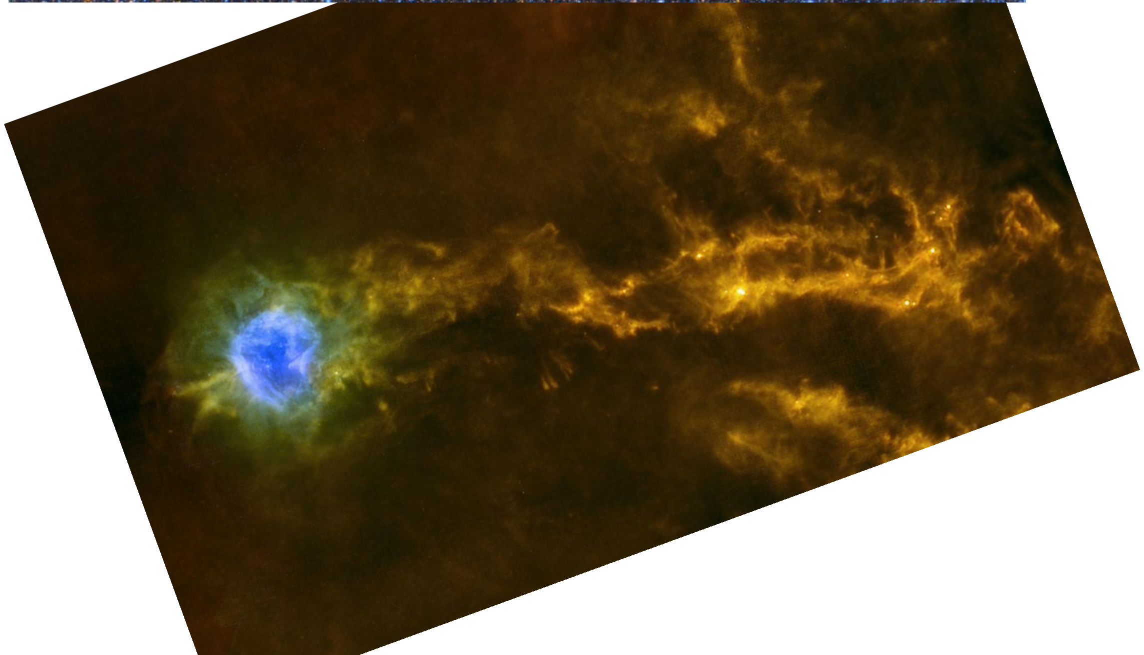
Barnard 68: very dusty!

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

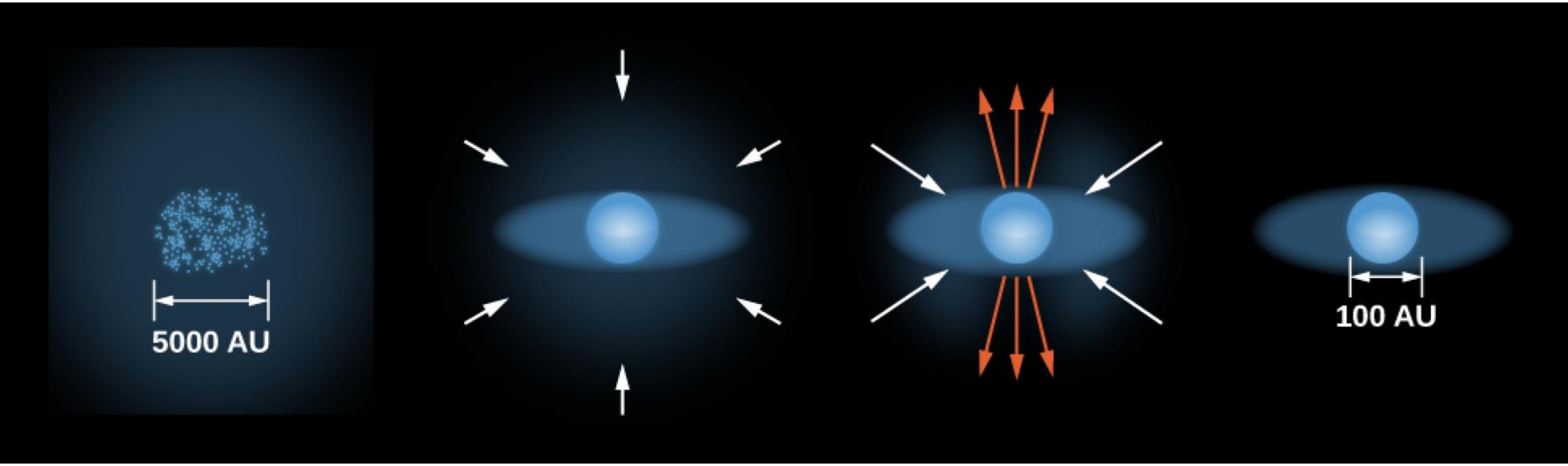


The same nebula can appear in both emission at short wavelengths and absorption at long wavelength

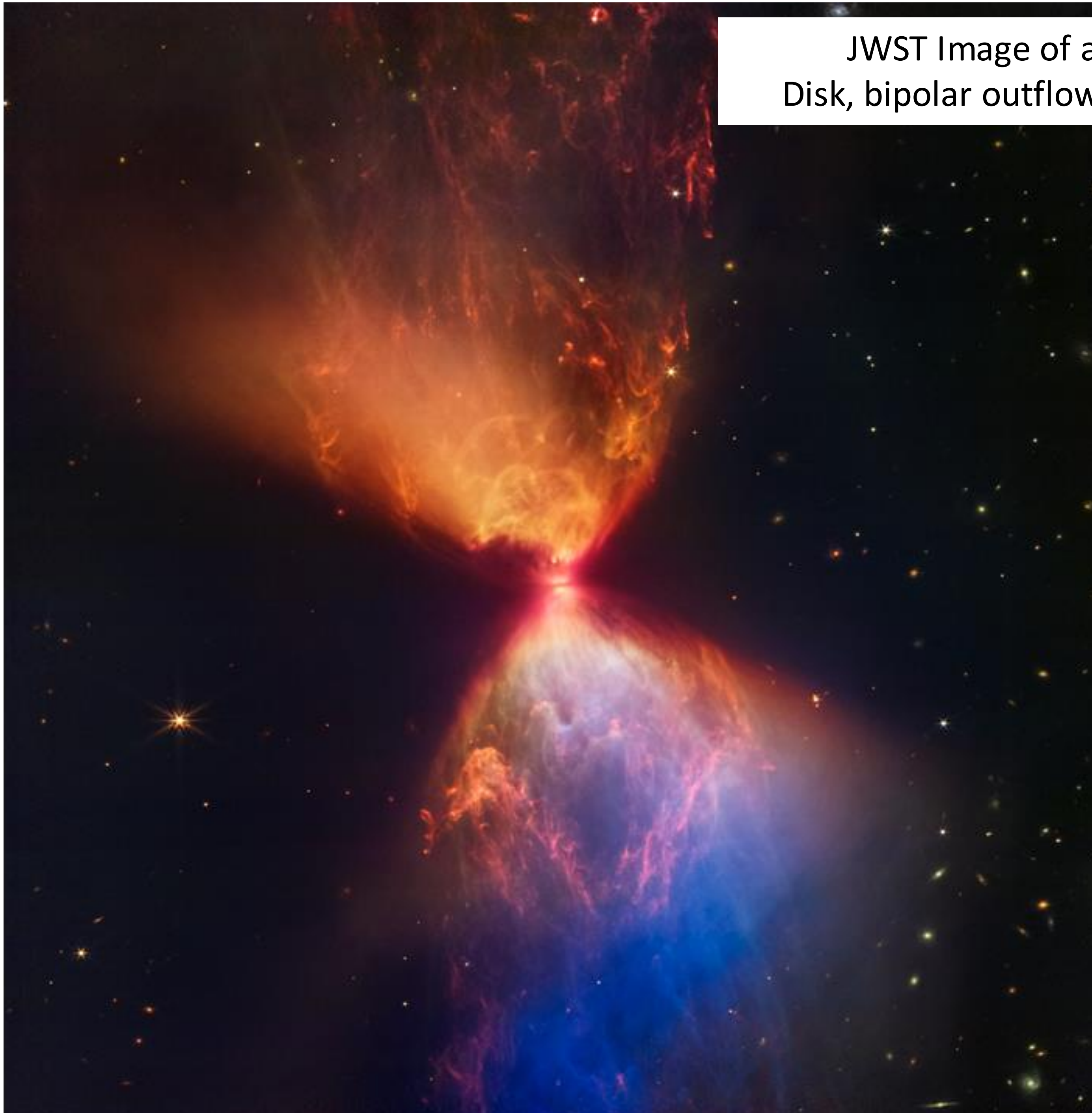
JWST image of Carina Nebula: hot stars ionize gas

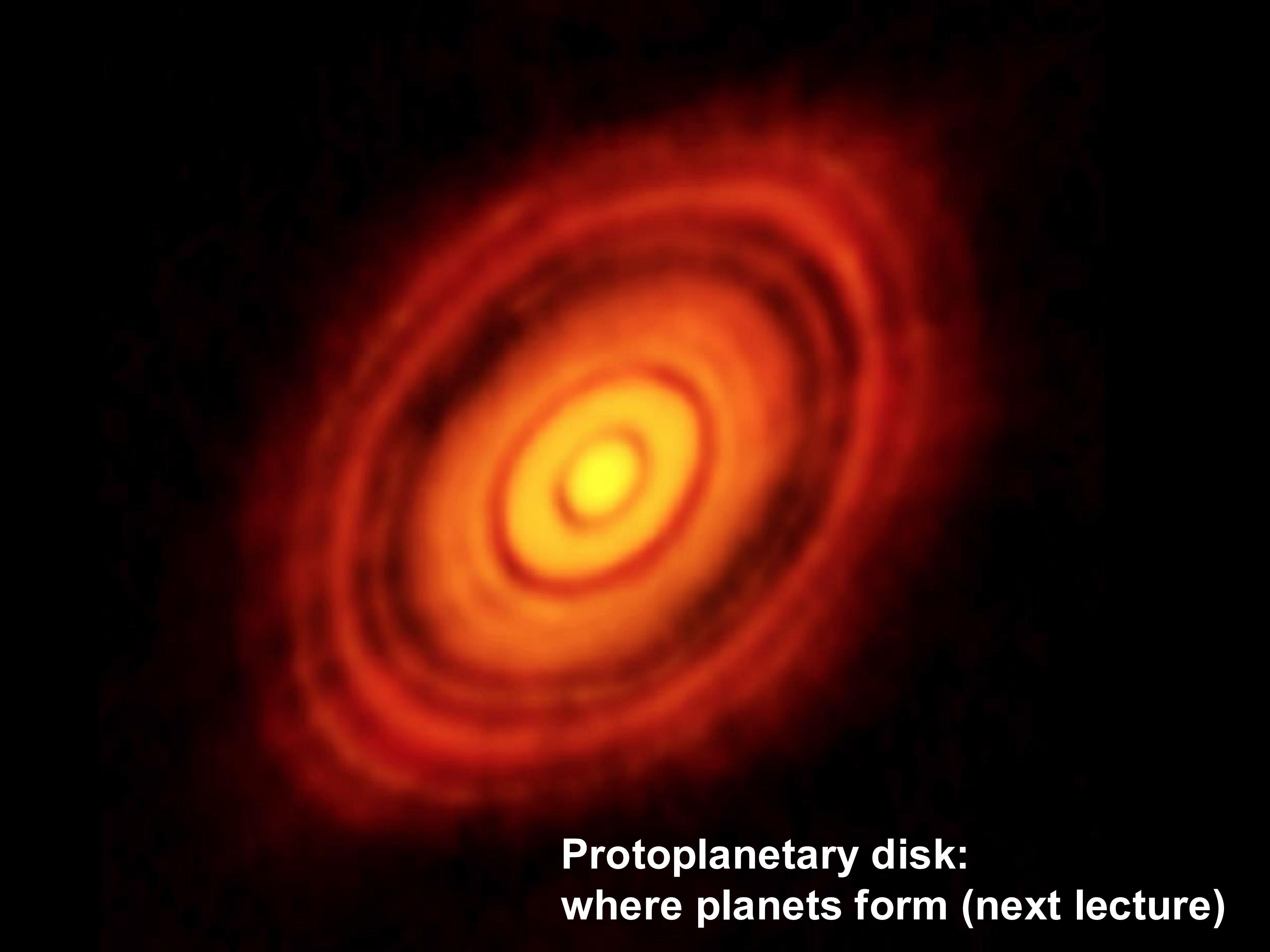
Steps of star formation:

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

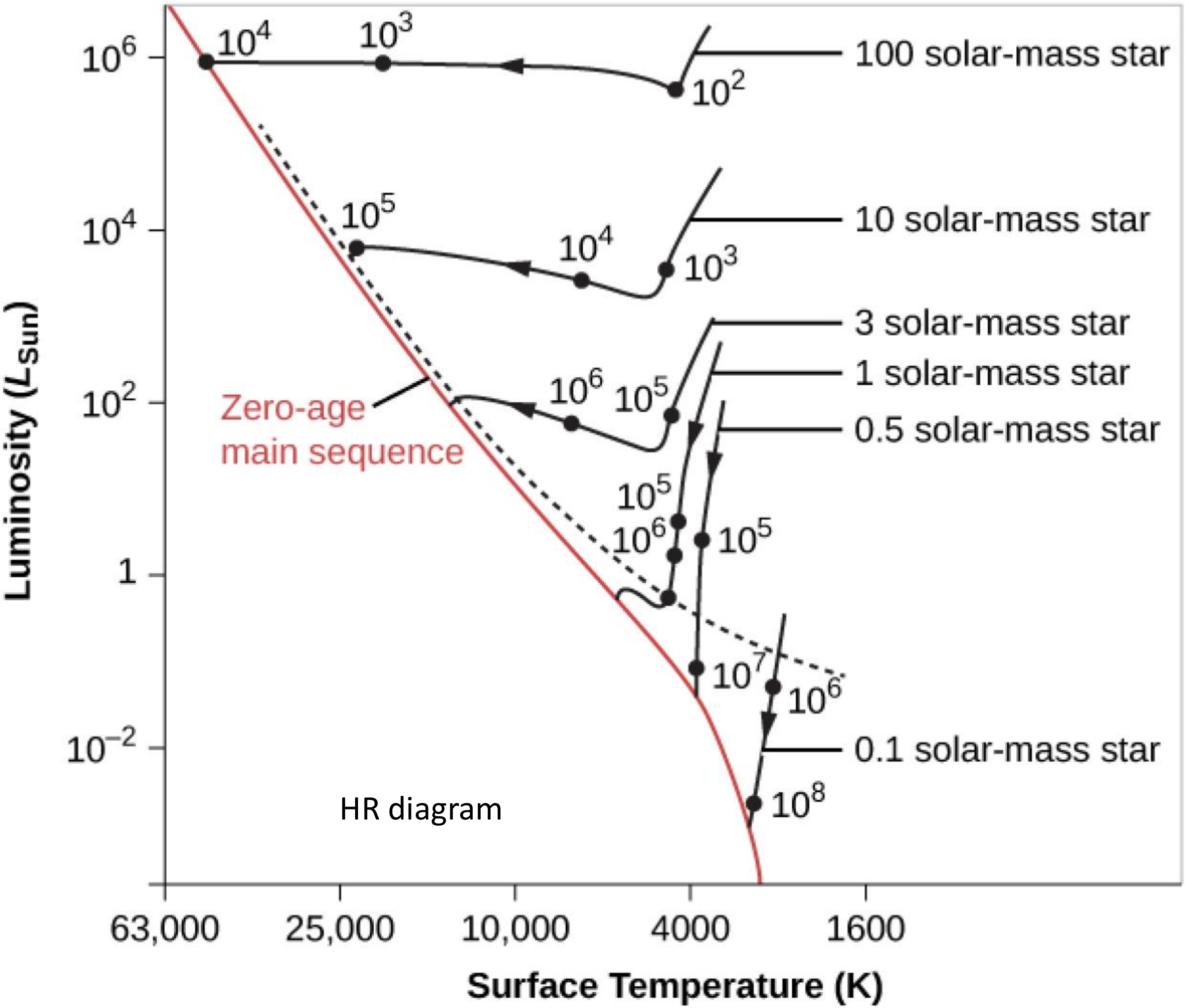


JWST Image of a Protostar:
Disk, bipolar outflow, and envelope





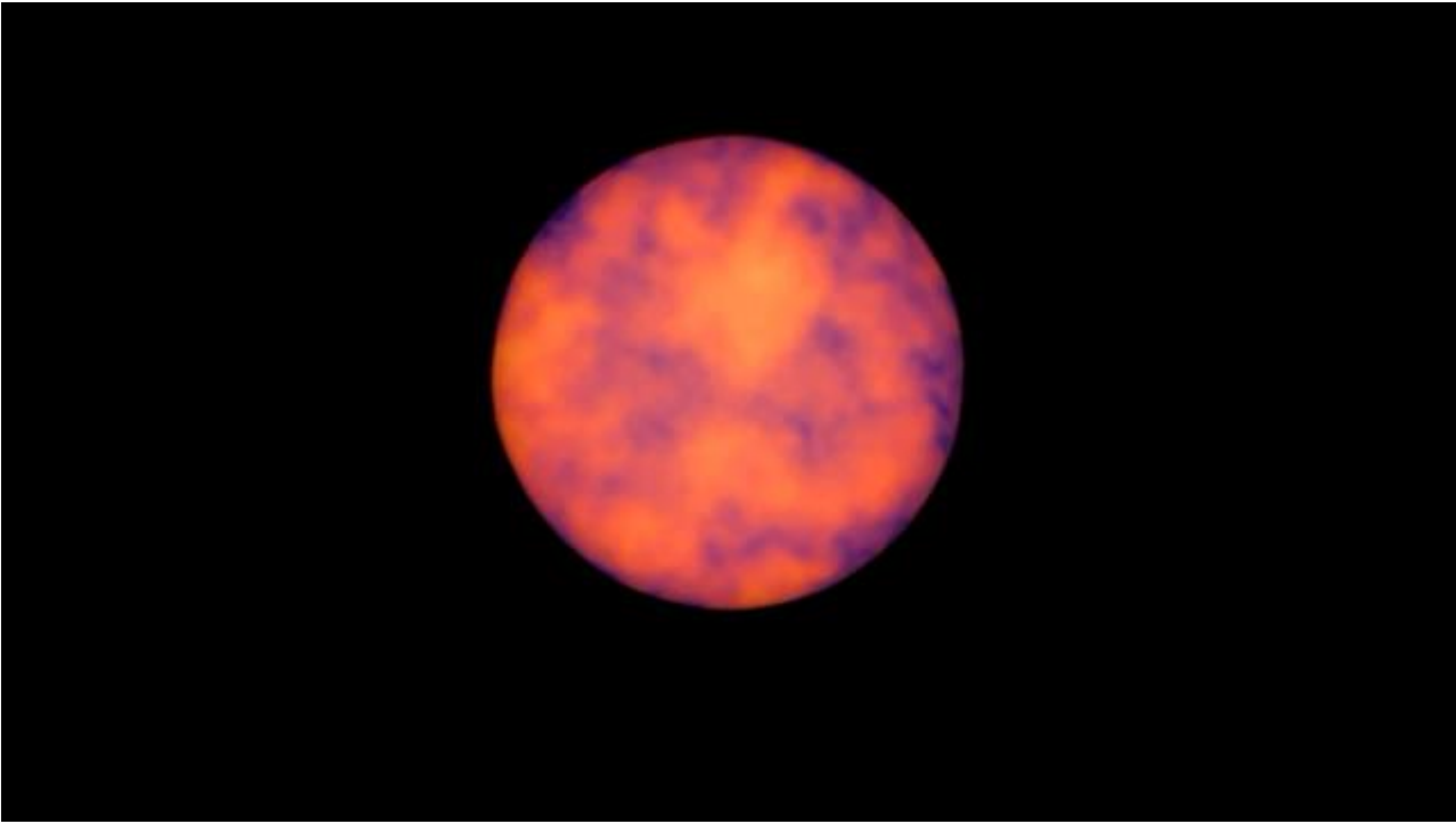
Protoplanetary disk:
where planets form (next lecture)



Luminosity (L_{Sun})
10^6
10^4
10^2
1
10^{-2}
Surface Temperature (K)
63,000
25,000
10,000
4000
1600
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
10^4
10^3
10^2
10^5
10^4
10^3
10^6
10^5
10^5
10^6
10^5
10^7
10^6
10^8

HR diagram

Simulation of a star-forming region: STARFORGE (Michael Grudic)



Next week: EXOPLANETS!