

Today's Topics

Wednesday, March 18, 2026 (Week 7, lecture 19) – Chapters 22, 23.

Sun-like stars: old age to death

- A. Main sequence to red giant.
- B. Planetary Nebulae.
- C. White Dwarfs.

Interlude 1 ESSAY is due on Monday, March 23 by 9:00 am on Gradescope

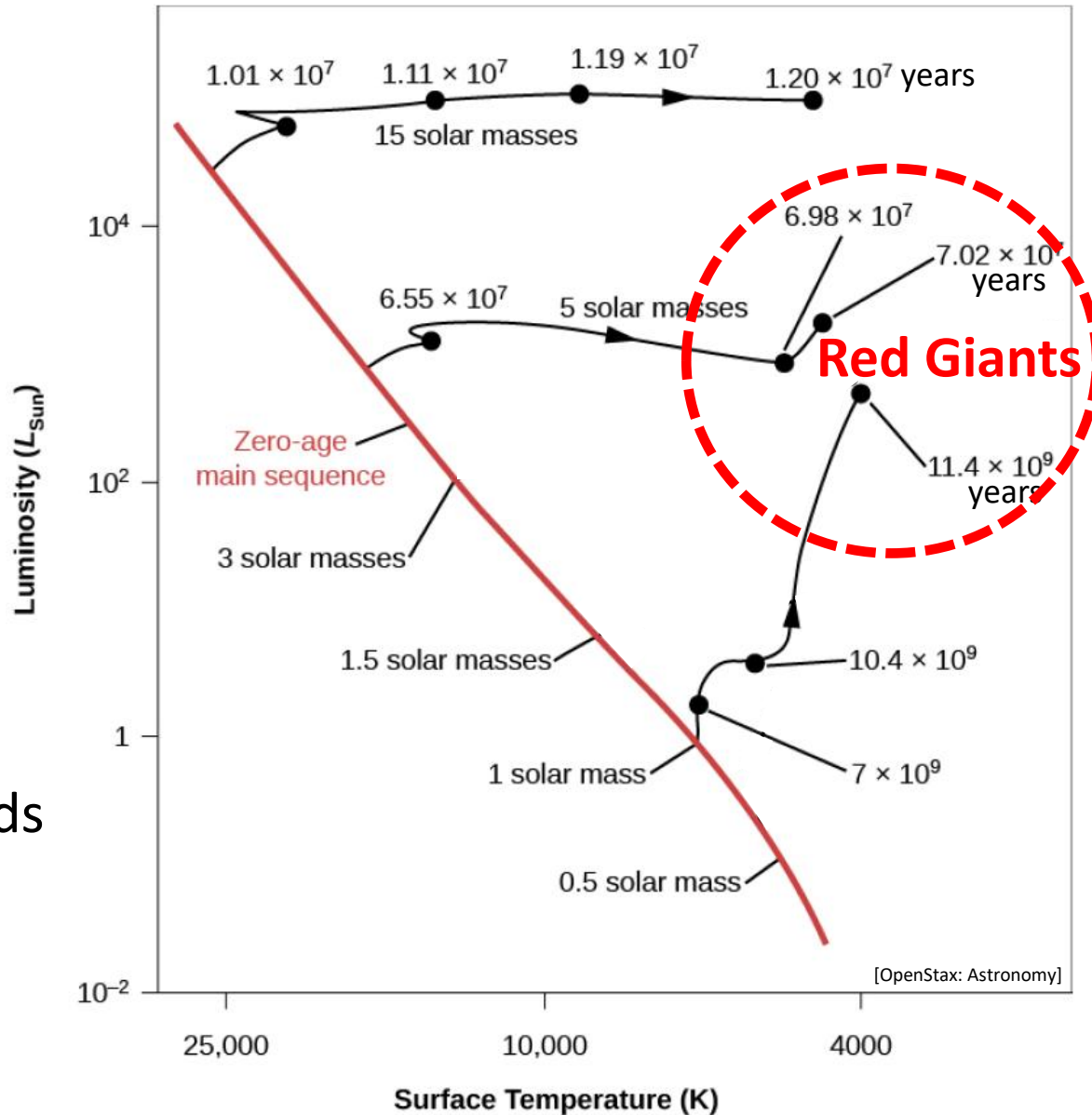
Stellar Evolution: on the H-R Diagram

Light stars (sun-like & smaller)

- Yellow and red color.
- cooler and dimmer.
- Long lived.
→ > 10 billion years.

Old age

Stars evolve quickly towards the upper right corner.
→ More luminous, but cooler.



Evolution of Sun-like Stars

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

white dwarf
(+ planetary nebula)

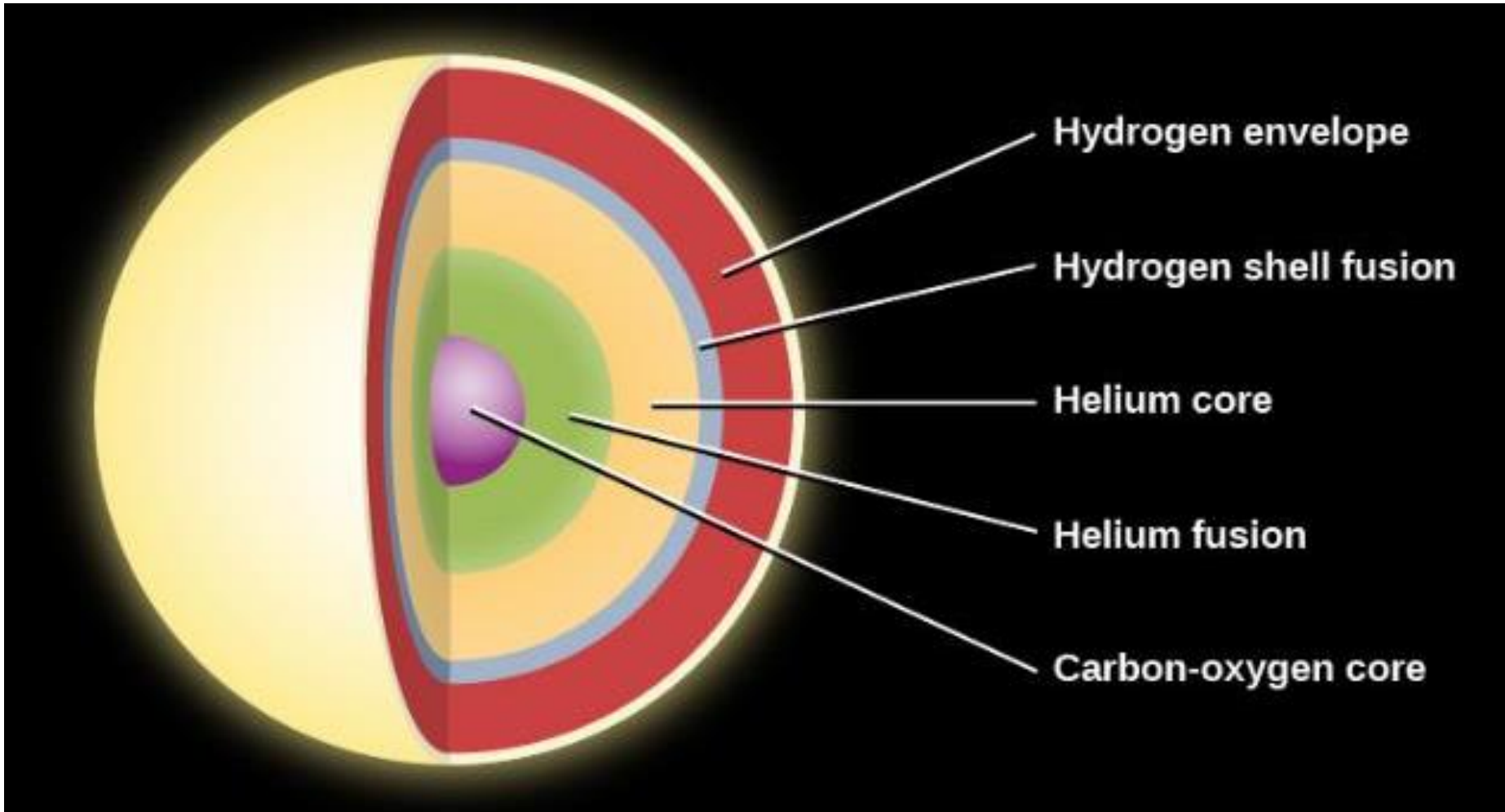
“forever”

40,000 K \rightarrow 4,000 K

$\sim 1 \rightarrow 0.01$

~ 0.01

Structure of Red Giant Star before “Death”

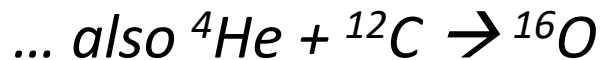


Helium Fusion

- At $T \approx 100,000,000$ K, helium nuclei begin to fuse.
- Fusion of two helium nuclei **does not produce a stable isotope:**
 ${}^4\text{He} + {}^4\text{He} \rightarrow {}^8\text{Be}$ (lifetime $\sim 10^{-16} - 10^{-17}$ s)

Triple alpha process (at 10^8 K)

Three helium nuclei can fuse simultaneously to produce carbon-12 (stable):

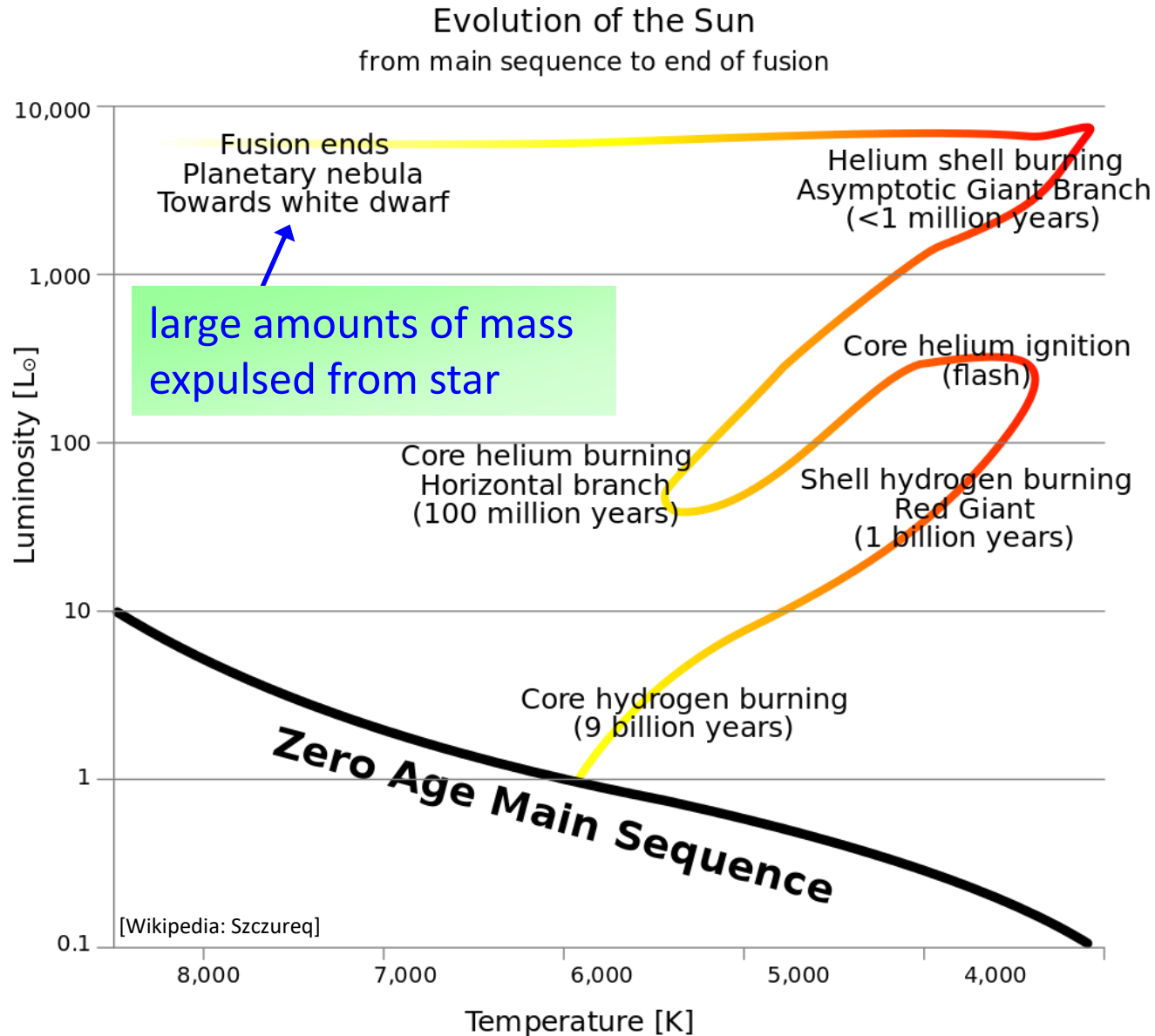


Helium Flash (for Sun-like stars)

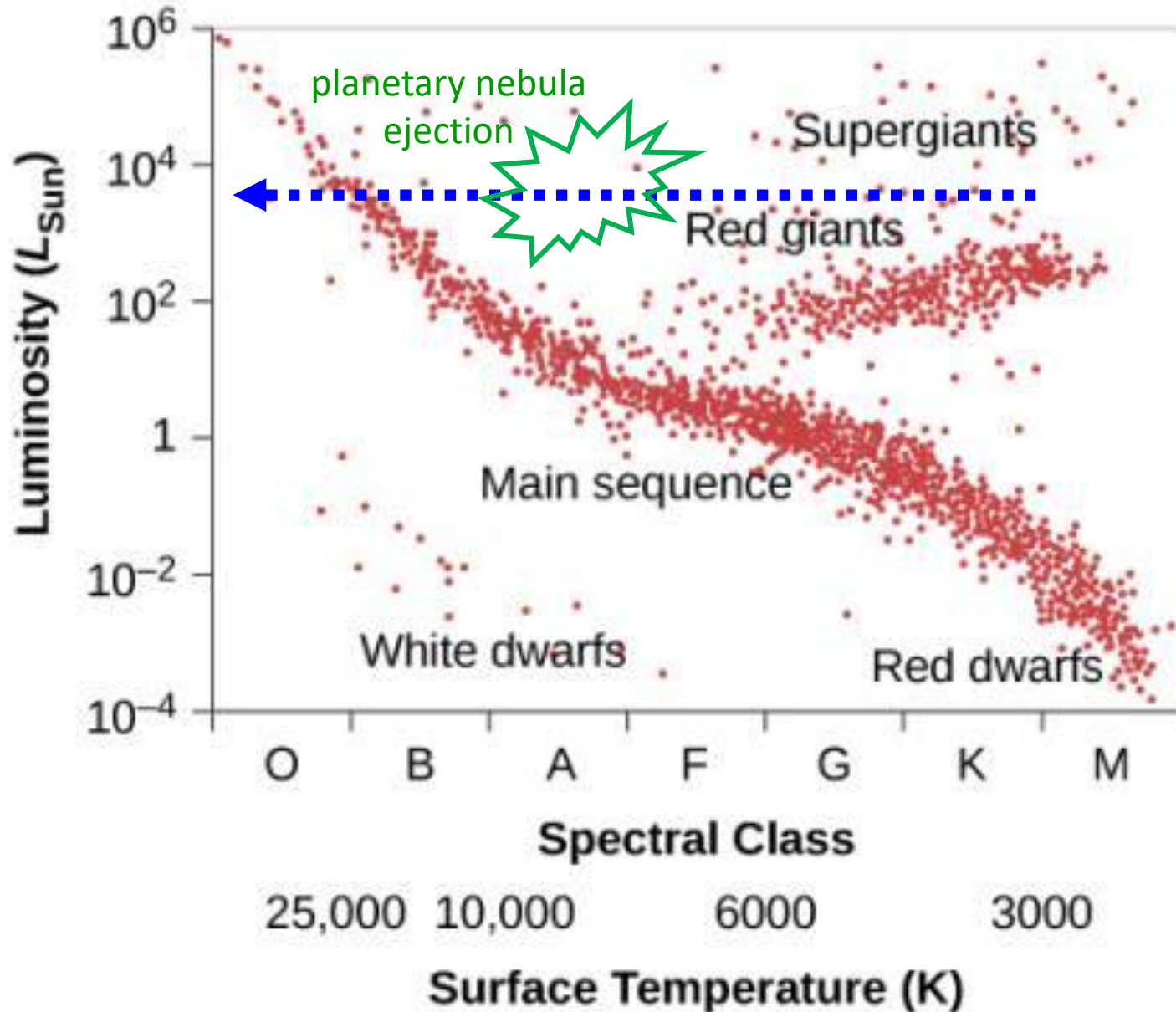
The fusion of helium into carbon happens very quickly (possibly in a few minutes).



Red Giant Evolution from Sun-like Star



Planetary Nebula



Mass Loss: Planetary Nebula

- Over the course of its red giant phase, a Sun-like star is expected to **shed roughly 50% of its mass**. Gas speed \sim 20-30 km/s.
- This ejected mass becomes a **planetary nebula** with a **white dwarf** at its center.

(note: planetary nebula has nothing to do with planets)

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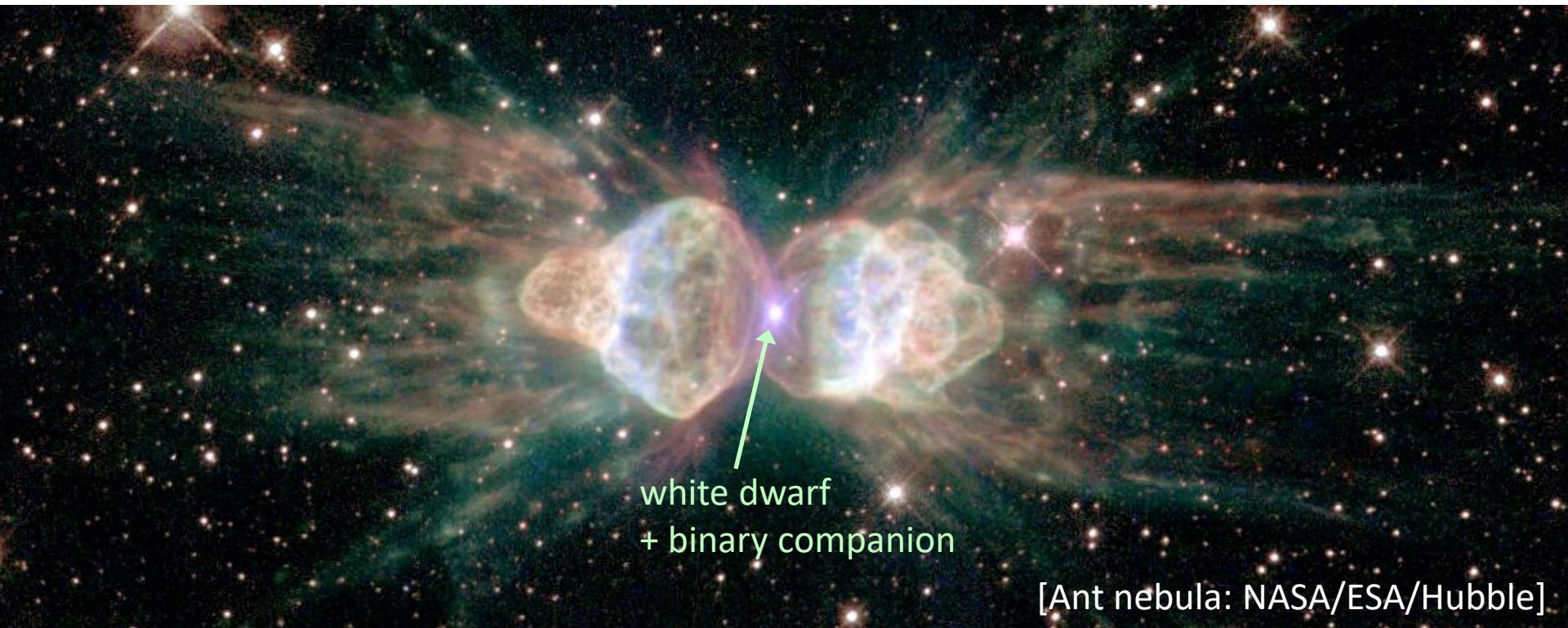
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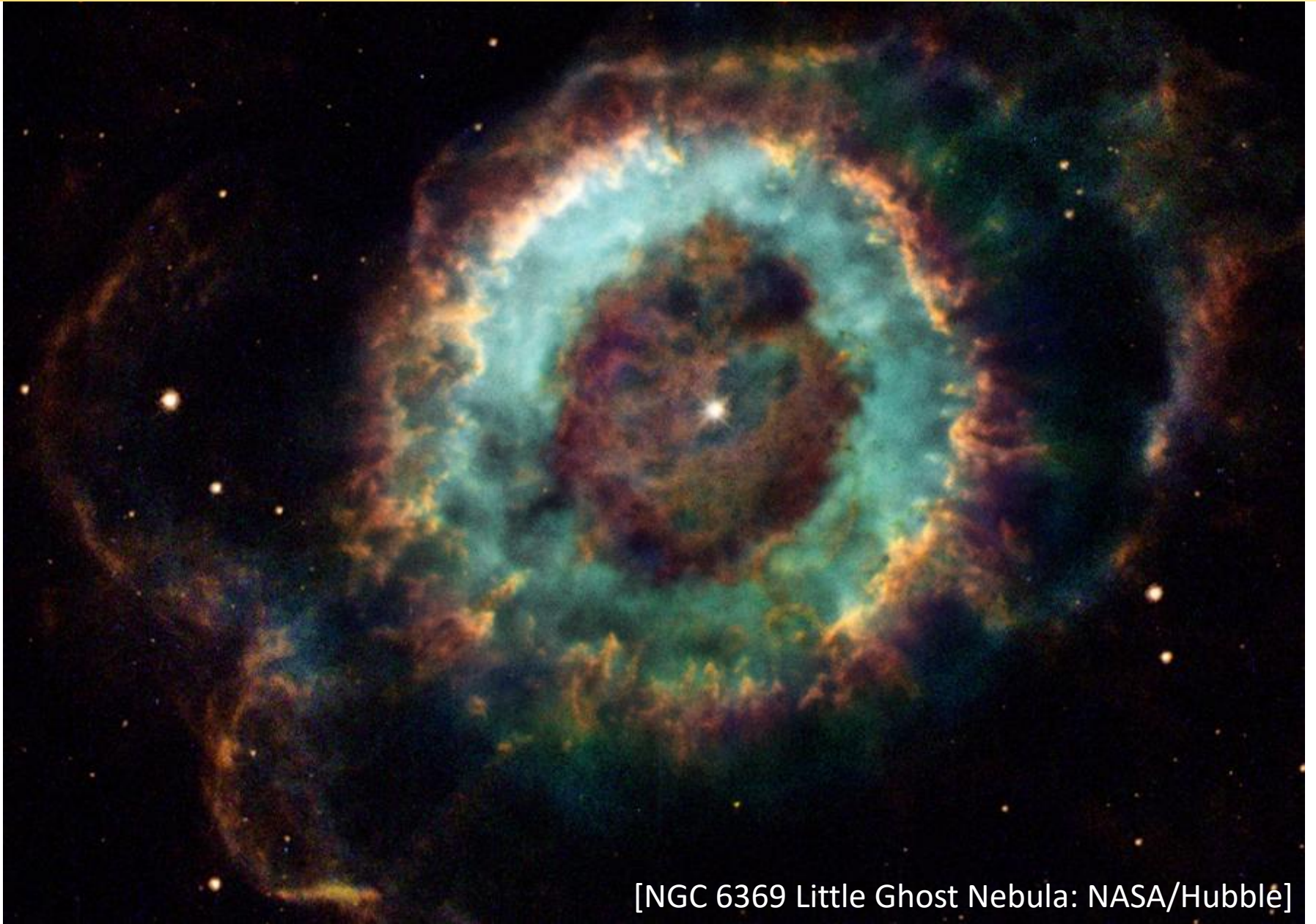
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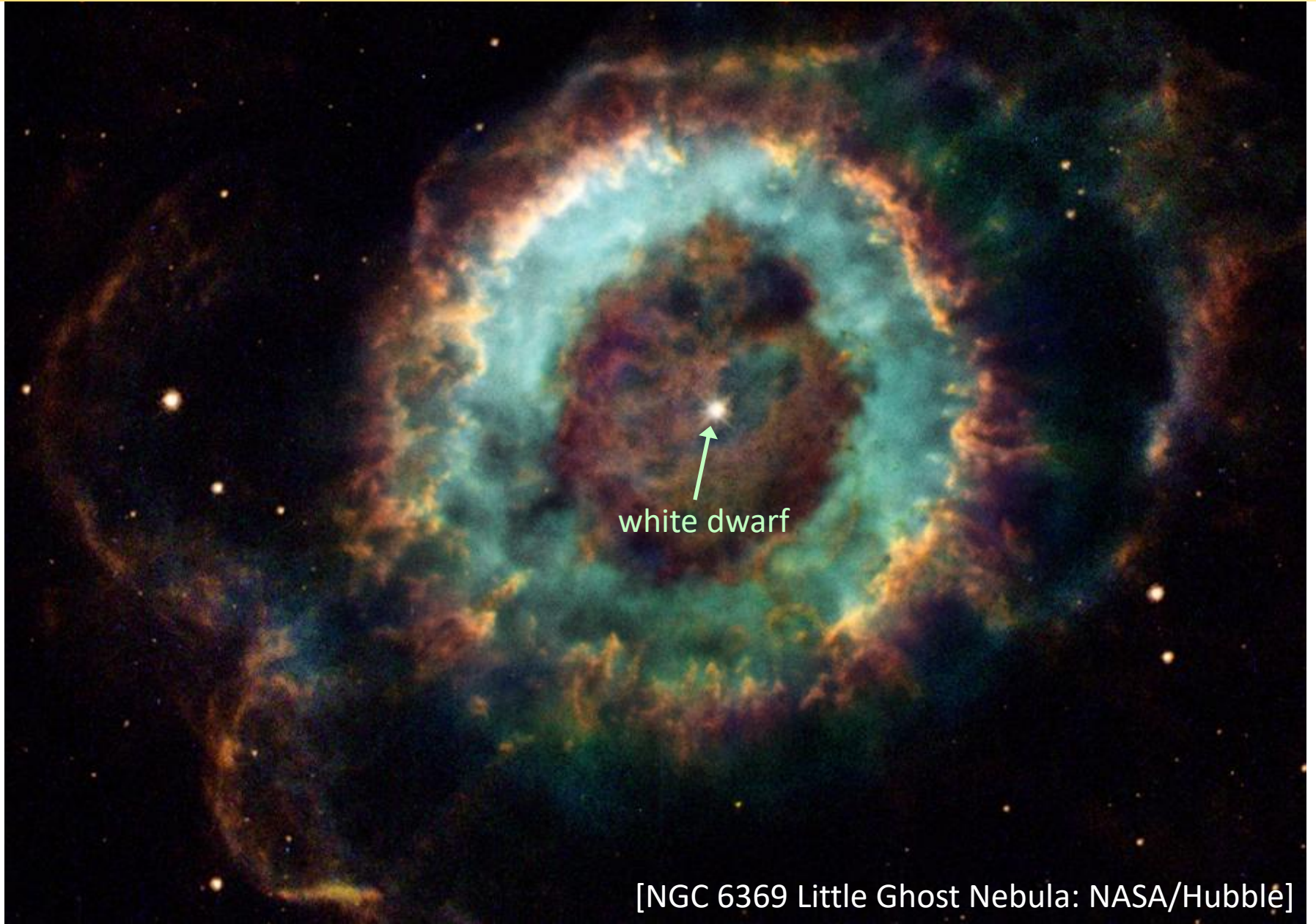


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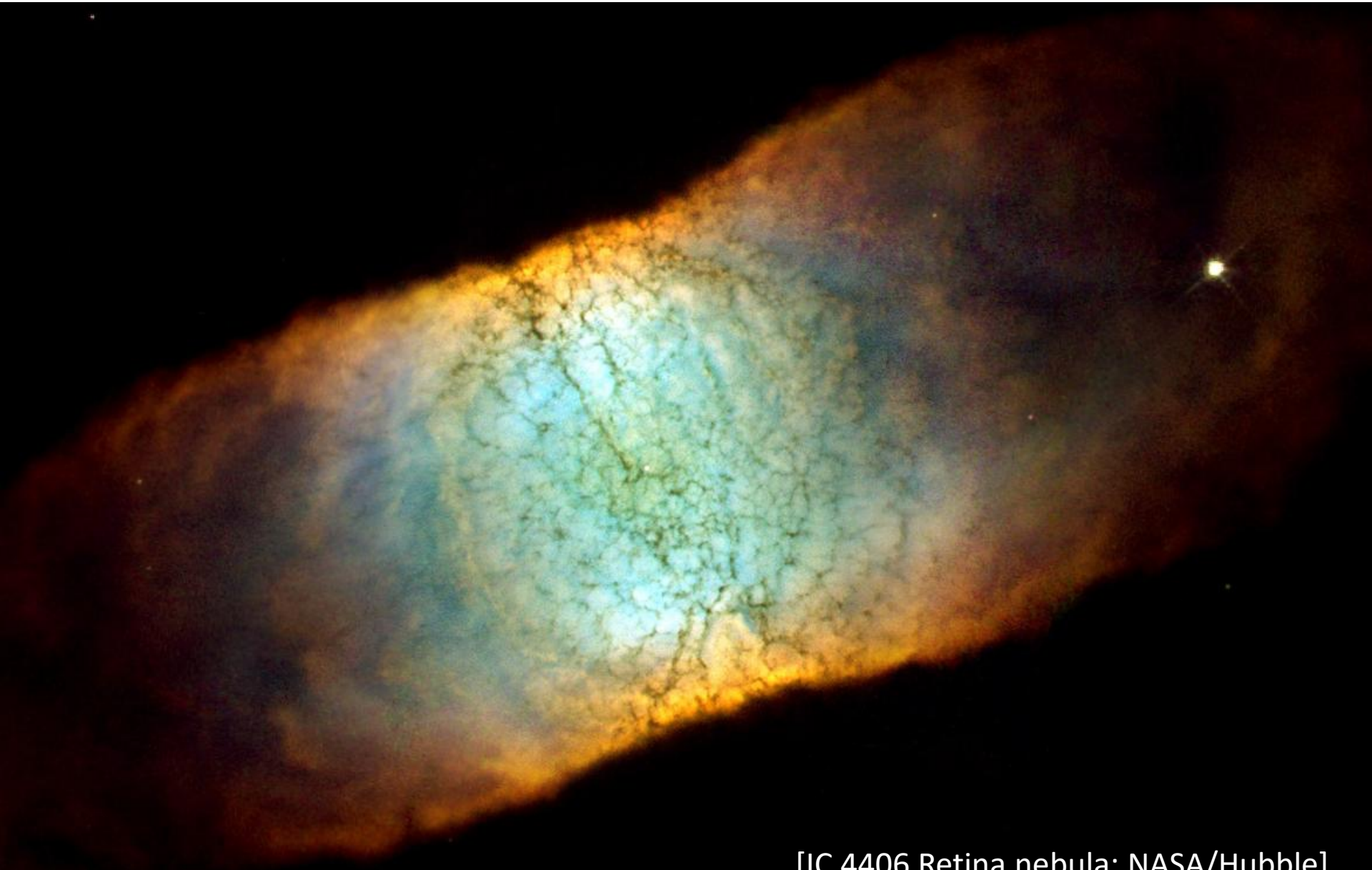
[NGC 6369 Little Ghost Nebula: NASA/Hubble]

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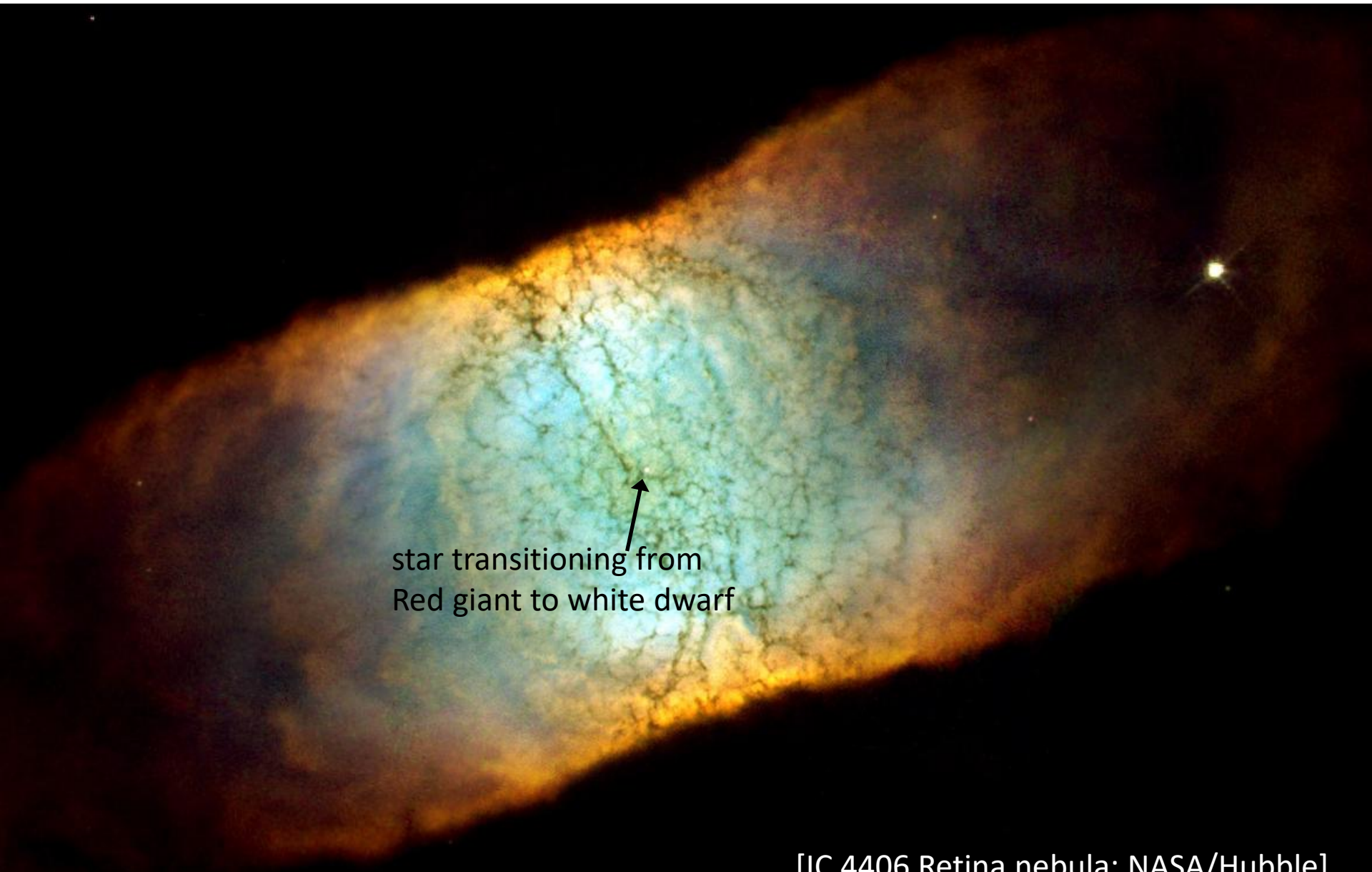
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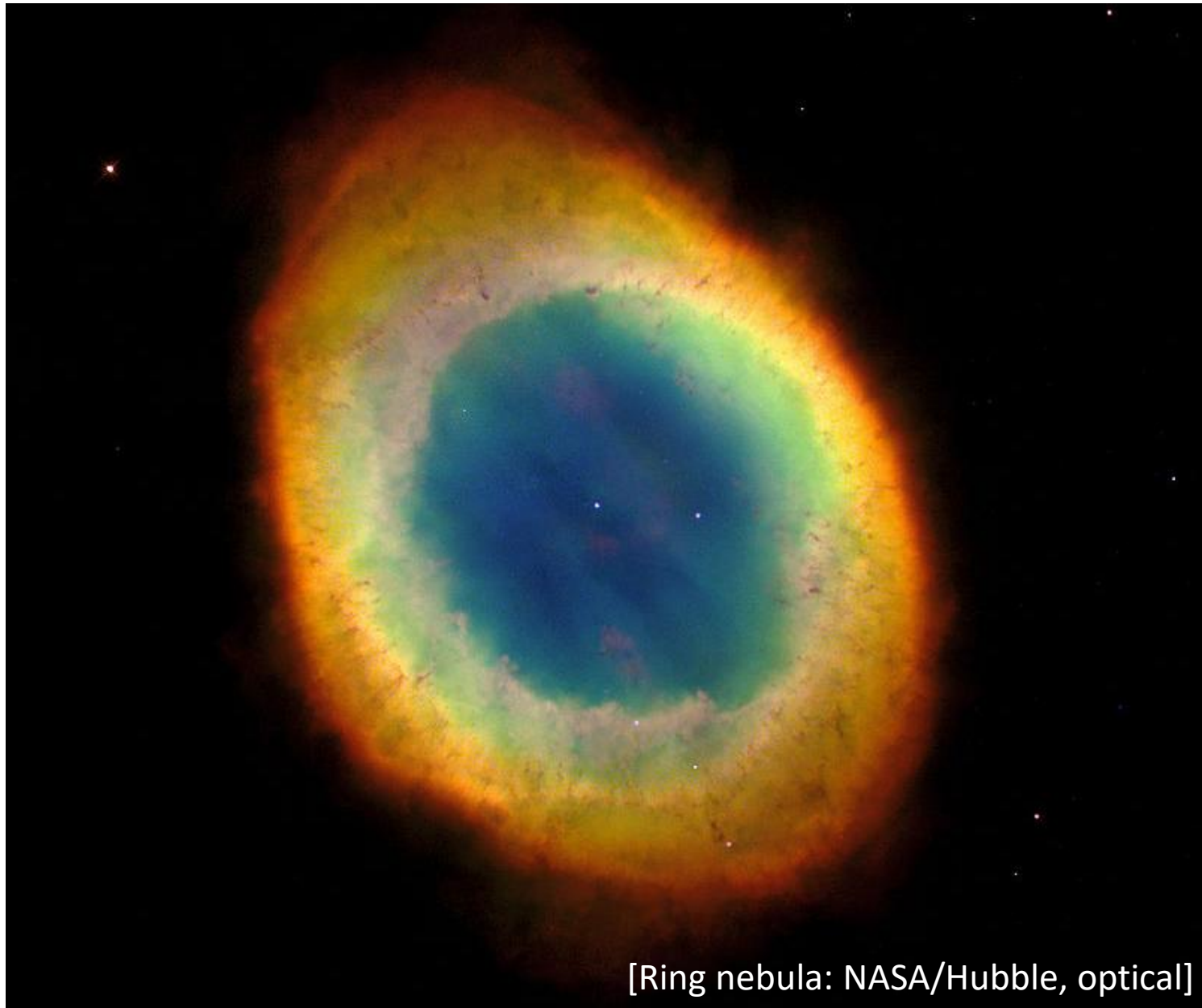
[IC 4406 Retina nebula: NASA/Hubble]

Mass Loss: Planetary Nebula



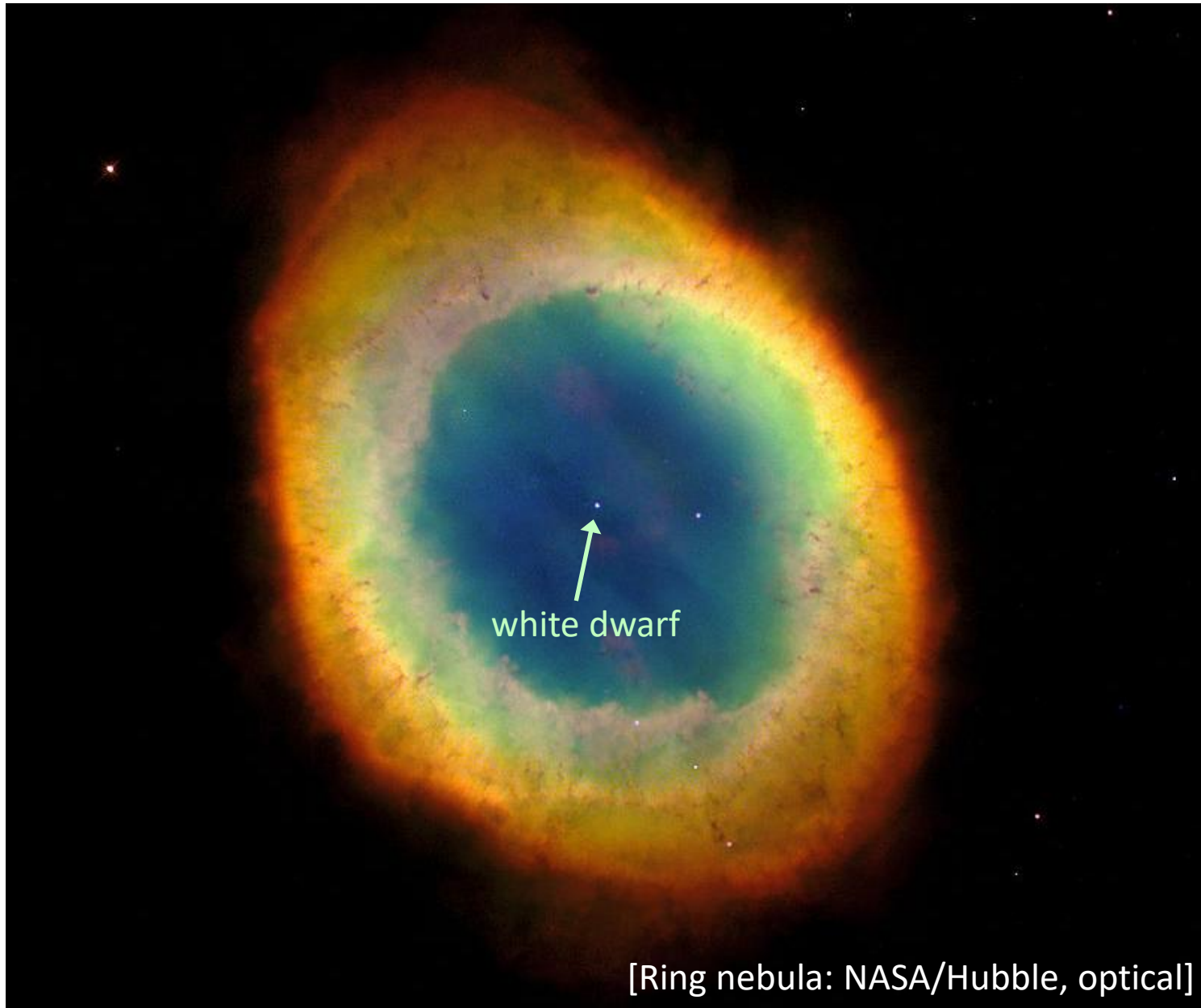
star transitioning from
Red giant to white dwarf

Mass Loss: Planetary Nebula



[Ring nebula: NASA/Hubble, optical]

Mass Loss: Planetary Nebula



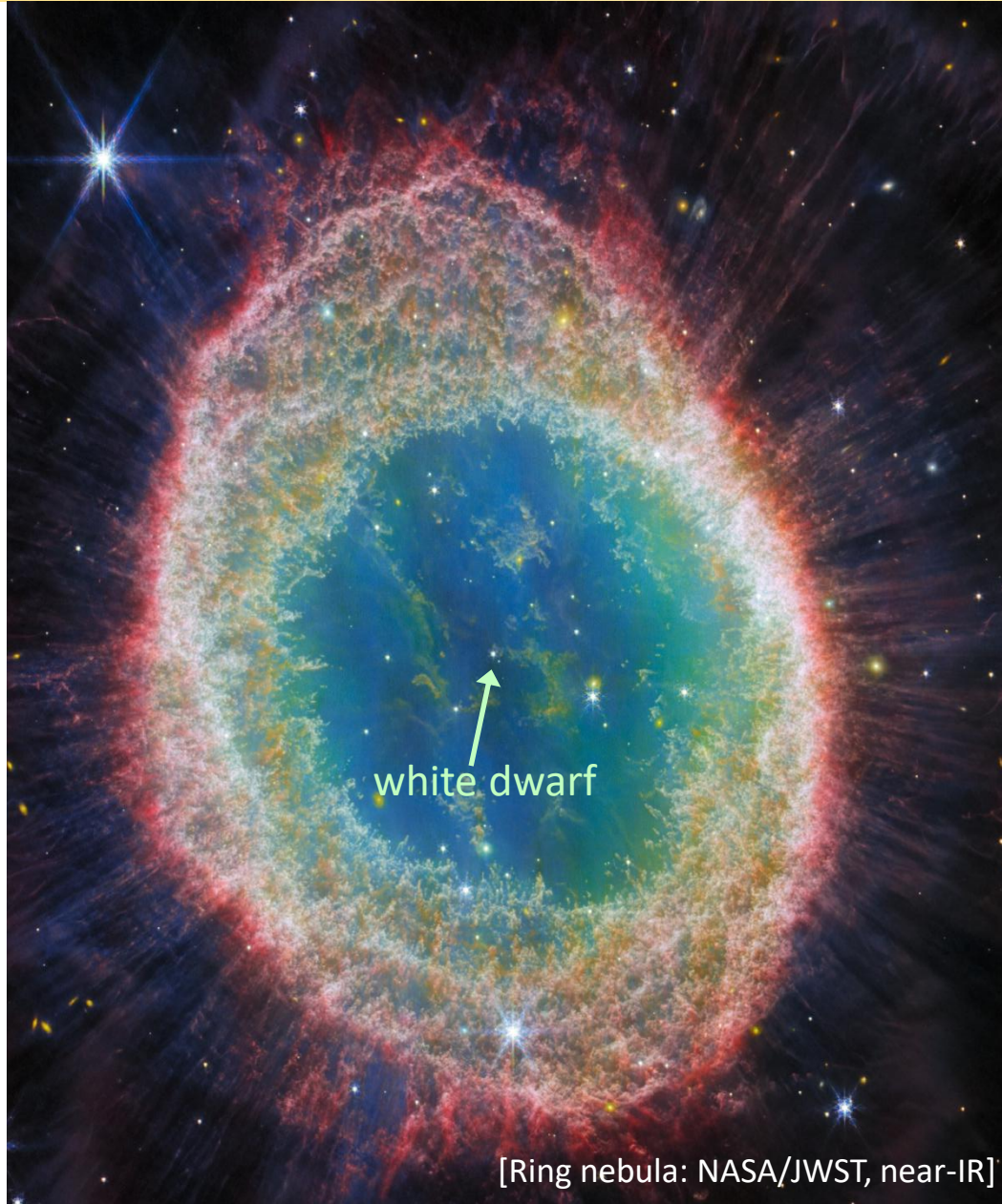
[Ring nebula: NASA/Hubble, optical]

Mass Loss: Planetary Nebula



[Ring nebula: NASA/JWST, near-IR]

Mass Loss: Planetary Nebula



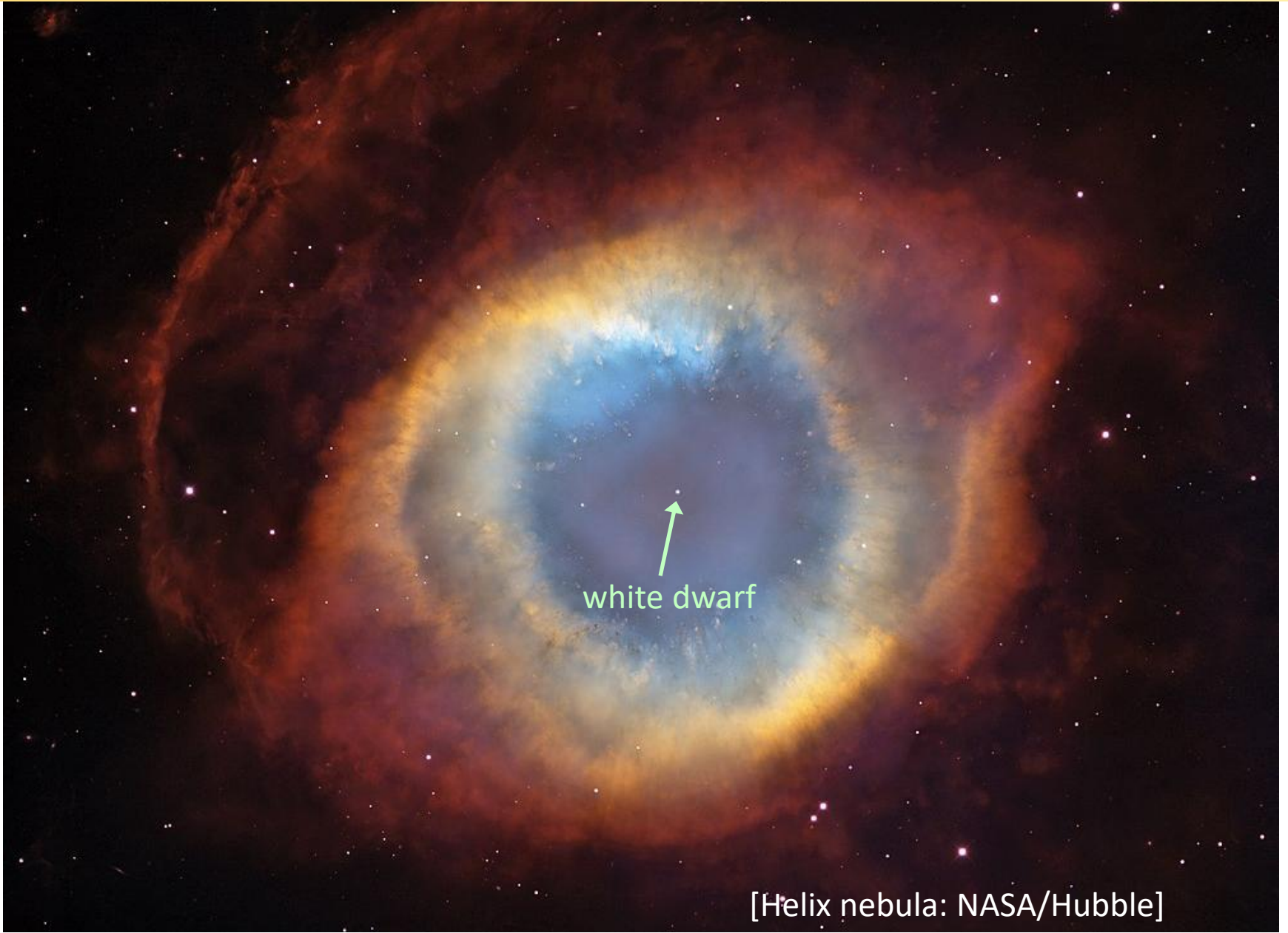
[Ring nebula: NASA/JWST, near-IR]

Mass Loss: Planetary Nebula



[Helix nebula: NASA/Hubble]

Mass Loss: Planetary Nebula



[Helix nebula: NASA/Hubble]

Mass Loss: Planetary Nebula



[M2-9 Twin Jet / Butterfly Wings Nebula: ESA/Hubble]

Mass Loss: Planetary Nebula



[NGC 6302 Butterfly Nebula: NASA/ESA/Hubble SM4 ERO Team]

Mass Loss: Planetary Nebula



white dwarf or soon-to-be white dwarf
(no binary companion)

$0.6 M_{\text{sun}}$, 200,000 K [Szyszka et al, *Astrophys. J.* 707, L32 (2009)]

[NGC 6302 Butterfly Nebula: NASA/ESA/Hubble SM4 ERO Team]

Mass Loss: Planetary Nebula

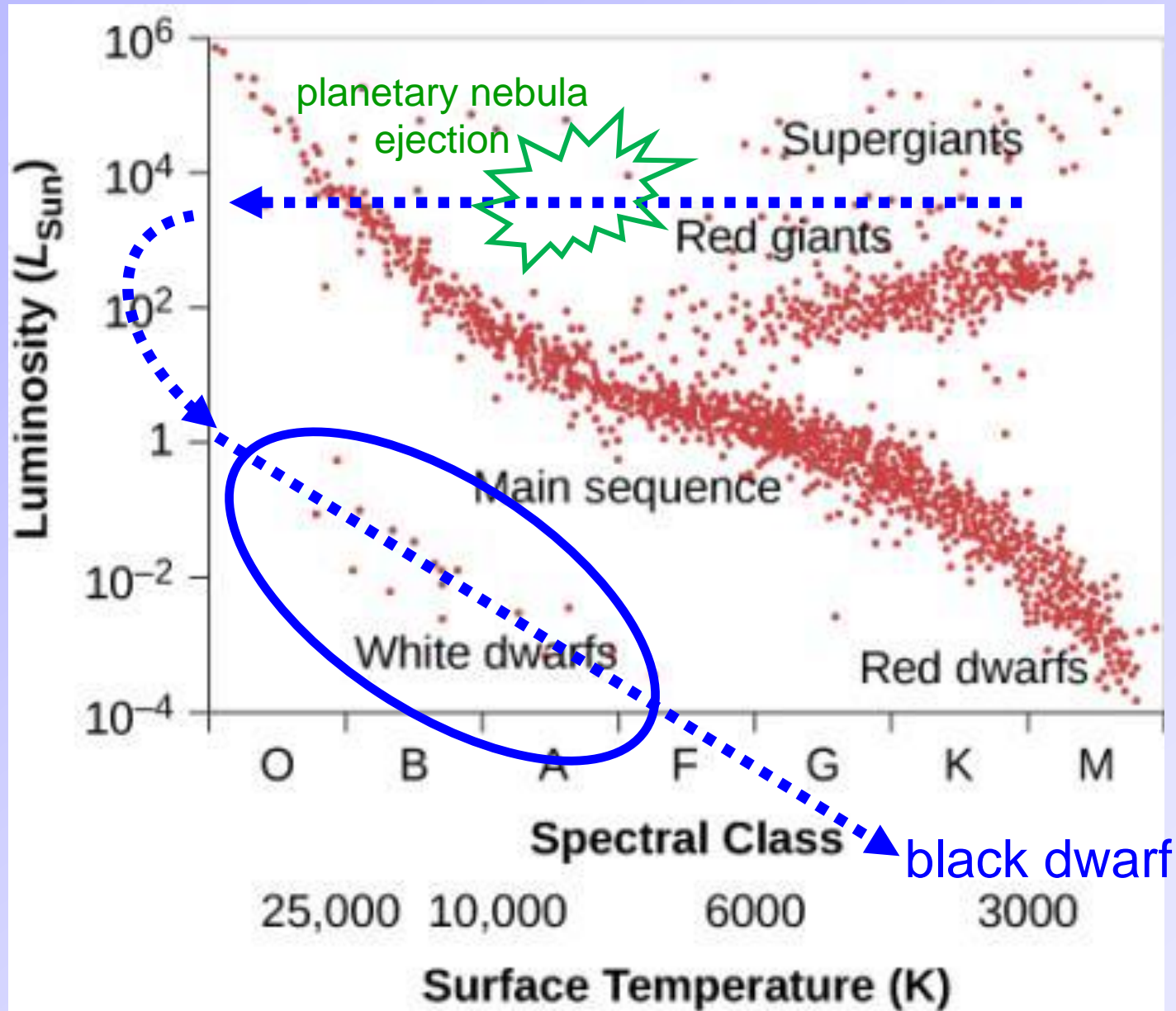


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White Dwarfs

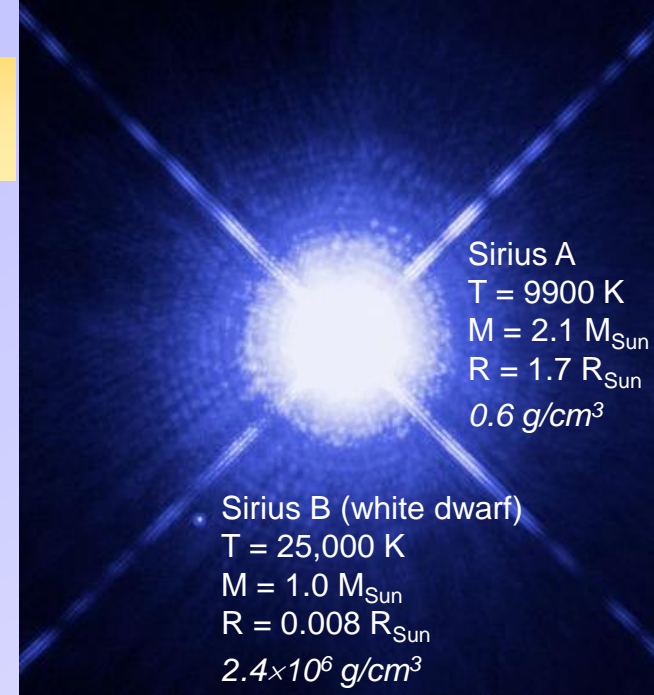


PolEv Quiz: PolEv.com/sethaubin

White Dwarfs

White dwarf

- “Ember” of dead star.
- Does not produce any energy of its own.
 - No fusion
- Starts out “white hot” and cools down to a black dwarf.
- Cools by emitting blackbody radiation.
- Heavier white dwarfs are smaller !!!

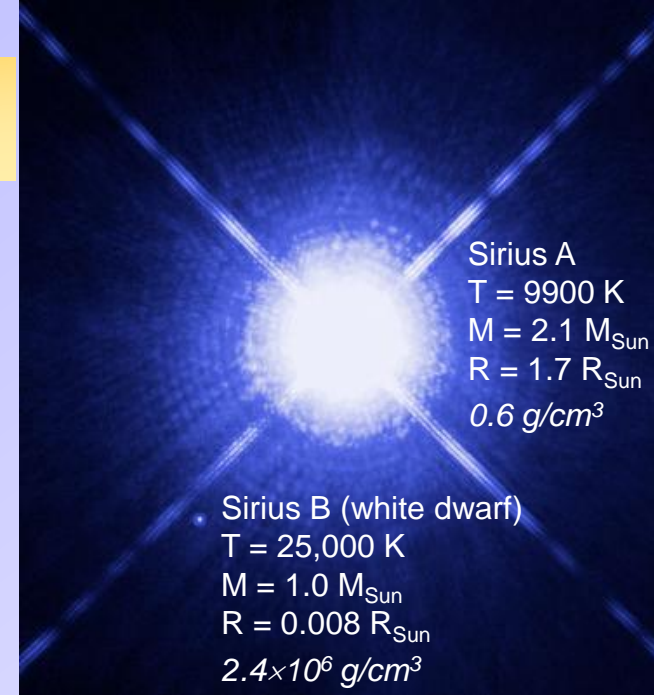
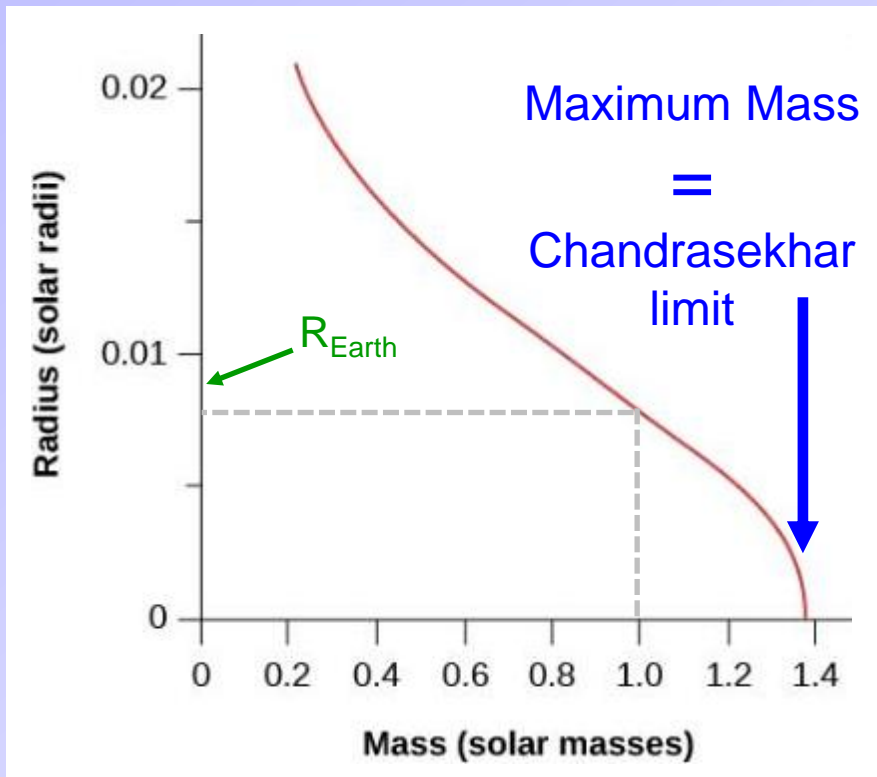


[NASA, ESA, H. Bond (STScI), and M. Barstow (University of Leicester)]

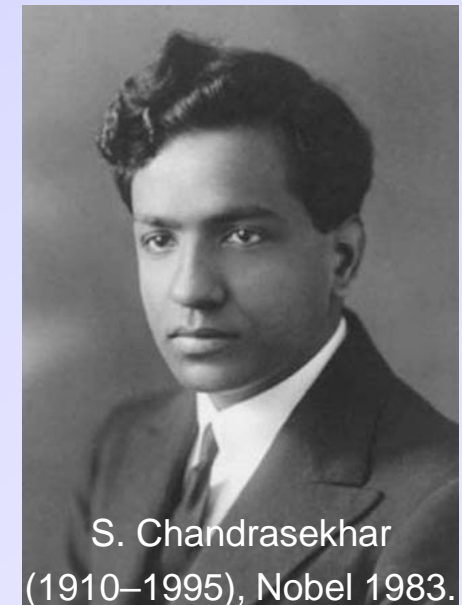
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White Dwarfs

- A white dwarf is dense enough that ***gravity & pressure are strong enough to overwhelm the electric repulsion*** between nuclei and electrons, but ...
- Gravity is counteracted by quantum “**Pauli pressure.**”
- the Pauli exclusion principle for electrons: you cannot have more than one electron per quantum state (location or velocity).
 - Same principle prevents electrons from piling up in the ground state orbital of atoms.

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White dwarf crystallization

Below ~ 4,000 K, the electric force between nuclei is strong enough to make an ordered arrangement of nuclei, i.e. “**nuclear crystal.**”

- The **core** of the white dwarf **crystallizes.**
- Some asteroseismology evidence.

