Interlude 2 Papers
Space Art

If you make your own space art:

- Paper length is 4 pages (instead of 5).
- Art should incorporate some knowledge from the course.
- Quality of art will be graded Pass/Fail.

Papers are due in class on Friday, November 13 (last day of classes).

Today's Topics

Friday, October 30, 2020 (Week 10, lecture 29) – Chapters 22, 23.

Sun-like stars: old age to death

A. Main sequence to red giant.

B. Planetary Nebulae.

C. White Dwarfs.

Stellar Evolution: on the H-R Diagram

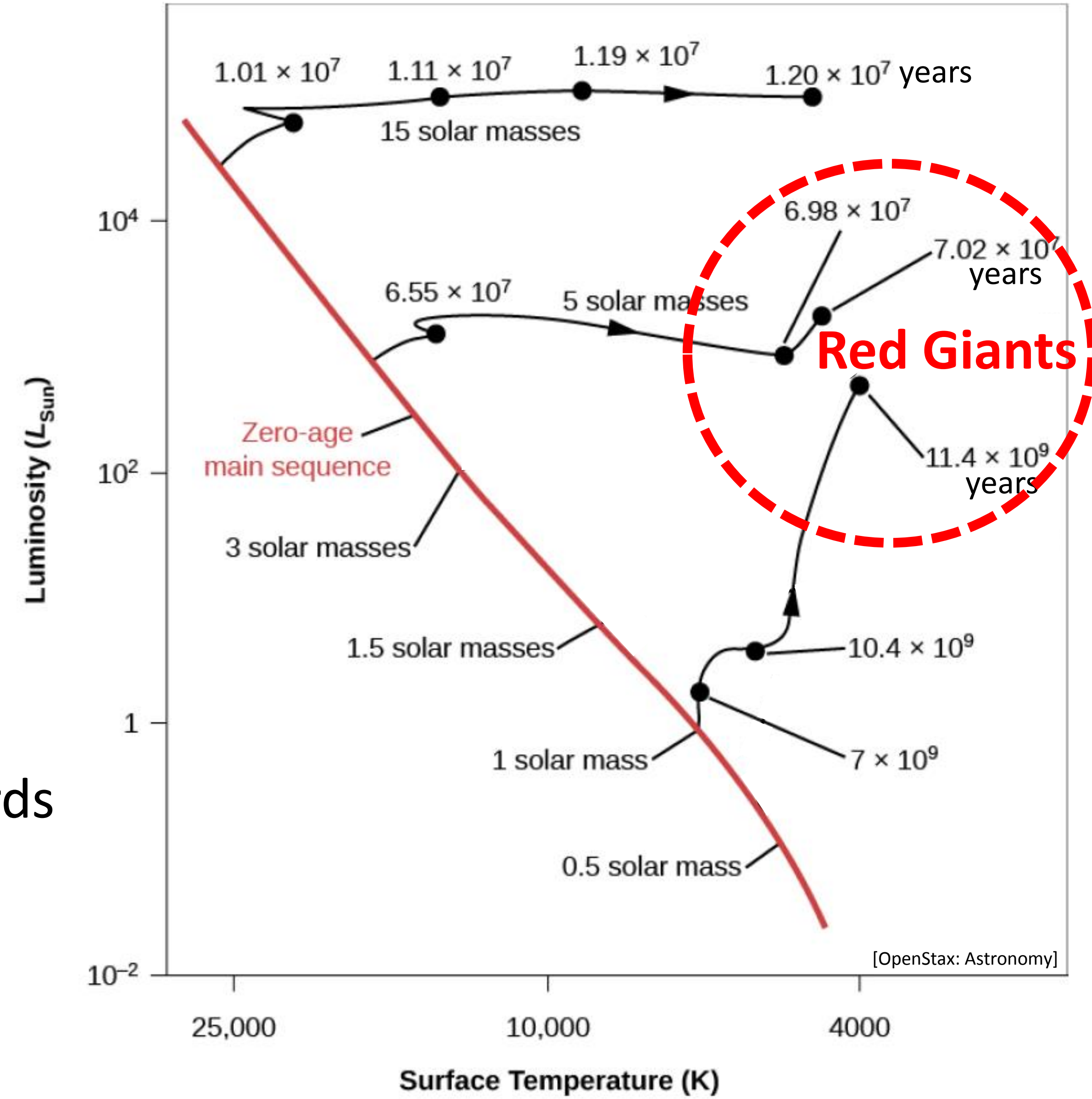
Light stars (sun-like & smaller

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

Old age

Stars evolve <u>quickly</u> 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 → 4,000 K	~ 1 → 0.01	~ 0.01

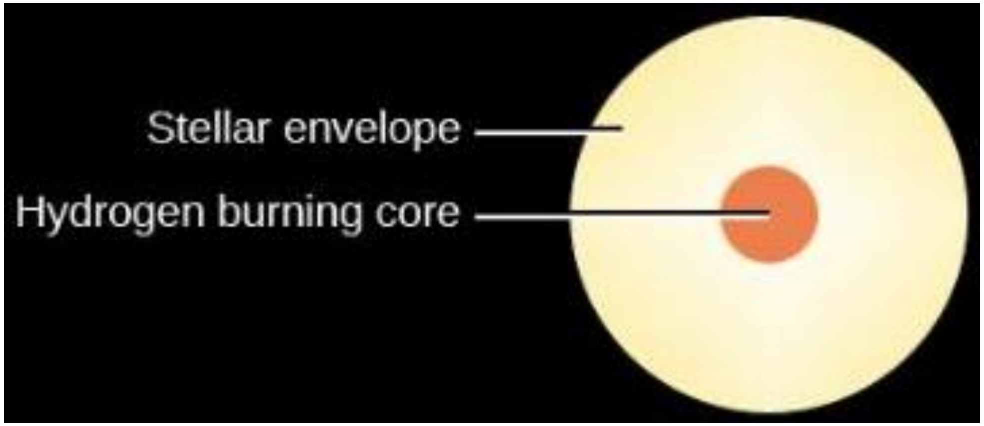
[OpenStax: Astronomy]

Becoming a Red Giant

1. Main sequence operation

Proton-proton fusion chain in core

4x Hydrogen → 1 helium



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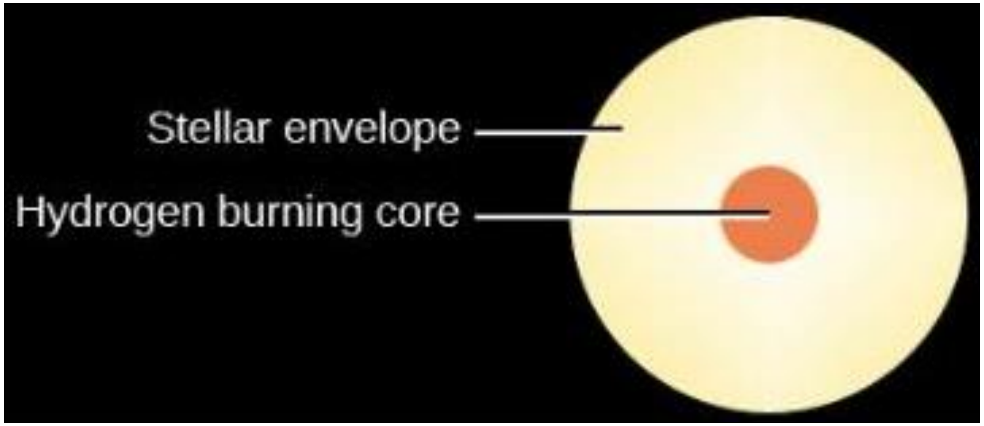
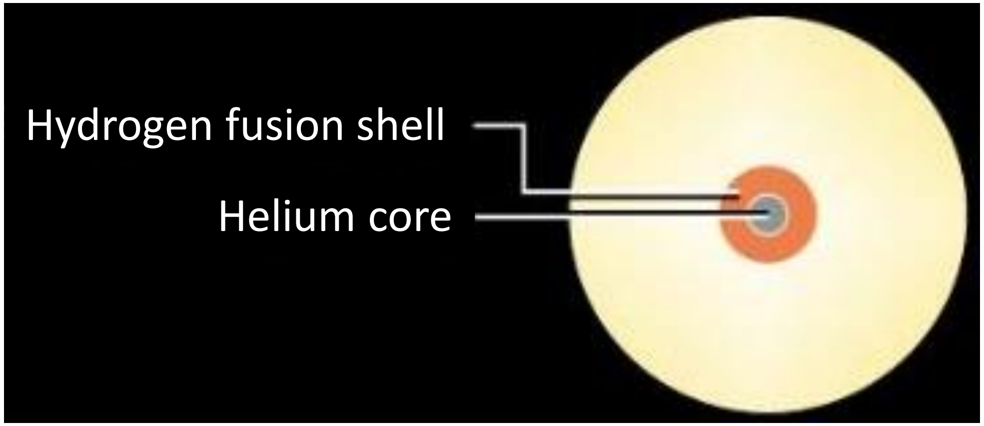


2. Core hydrogen exhausted

- Helium core begins to **contract**.
- Helium core **heats up**.
- Hydrogen just outside of helium core **begins fusion**.



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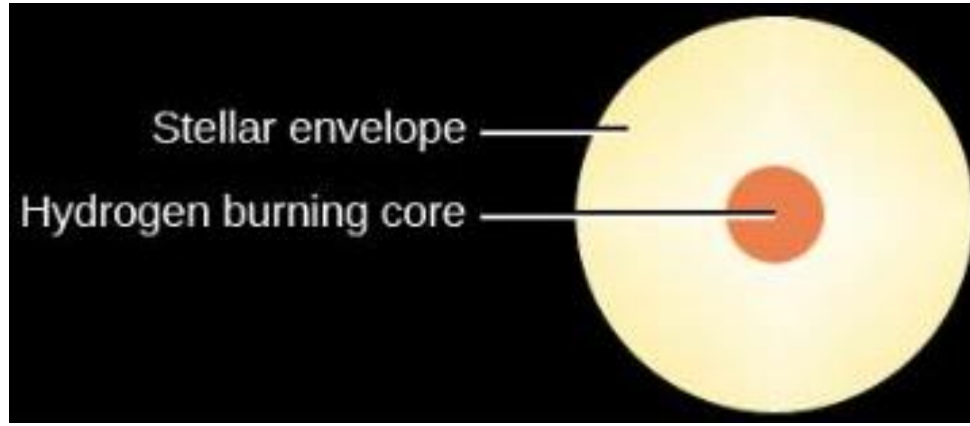

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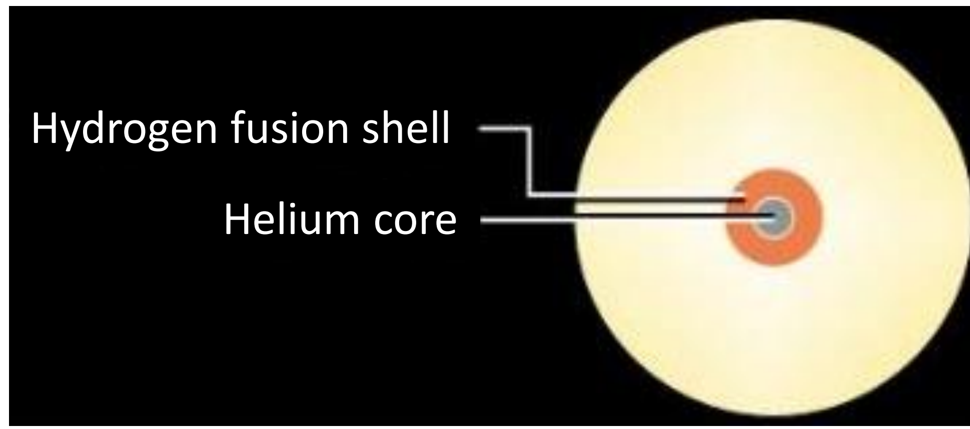
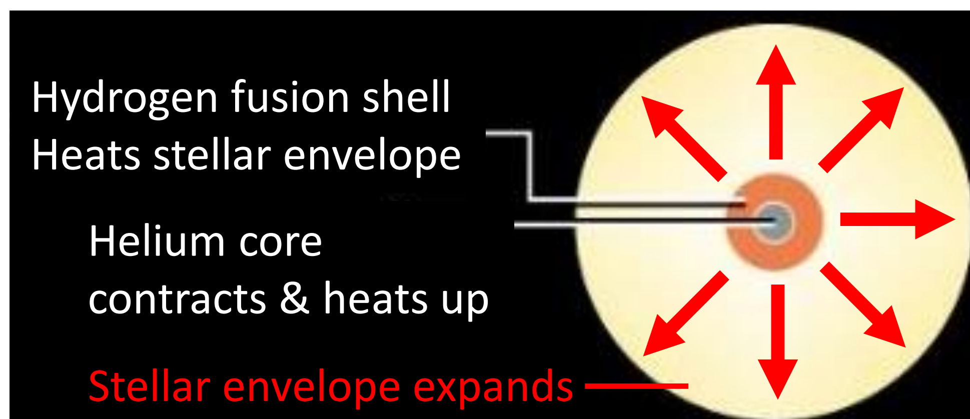


3. Expansion to red giant

- **Heat** from new hydrogen shell fusion is **significant** and heats up outer hydrogen in stellar envelope.
- Stellar envelope heats up and **expands** (outer layer then cools).
- **Helium core continues to contract and heat up**.



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**:
  $^{4}He + {}^{4}He \rightarrow {}^{8}Be$ (lifetime ~ 10^{-16} -10^{-17} s)

Triple alpha process (at 10^{8} K)
Three helium nuclei can fuse simultaneously to produce carbon-12 (stable):

$$^{4}He + {}^{4}He + {}^{4}He \rightarrow {}^{12}C + 7.65\ \text{MeV}$$

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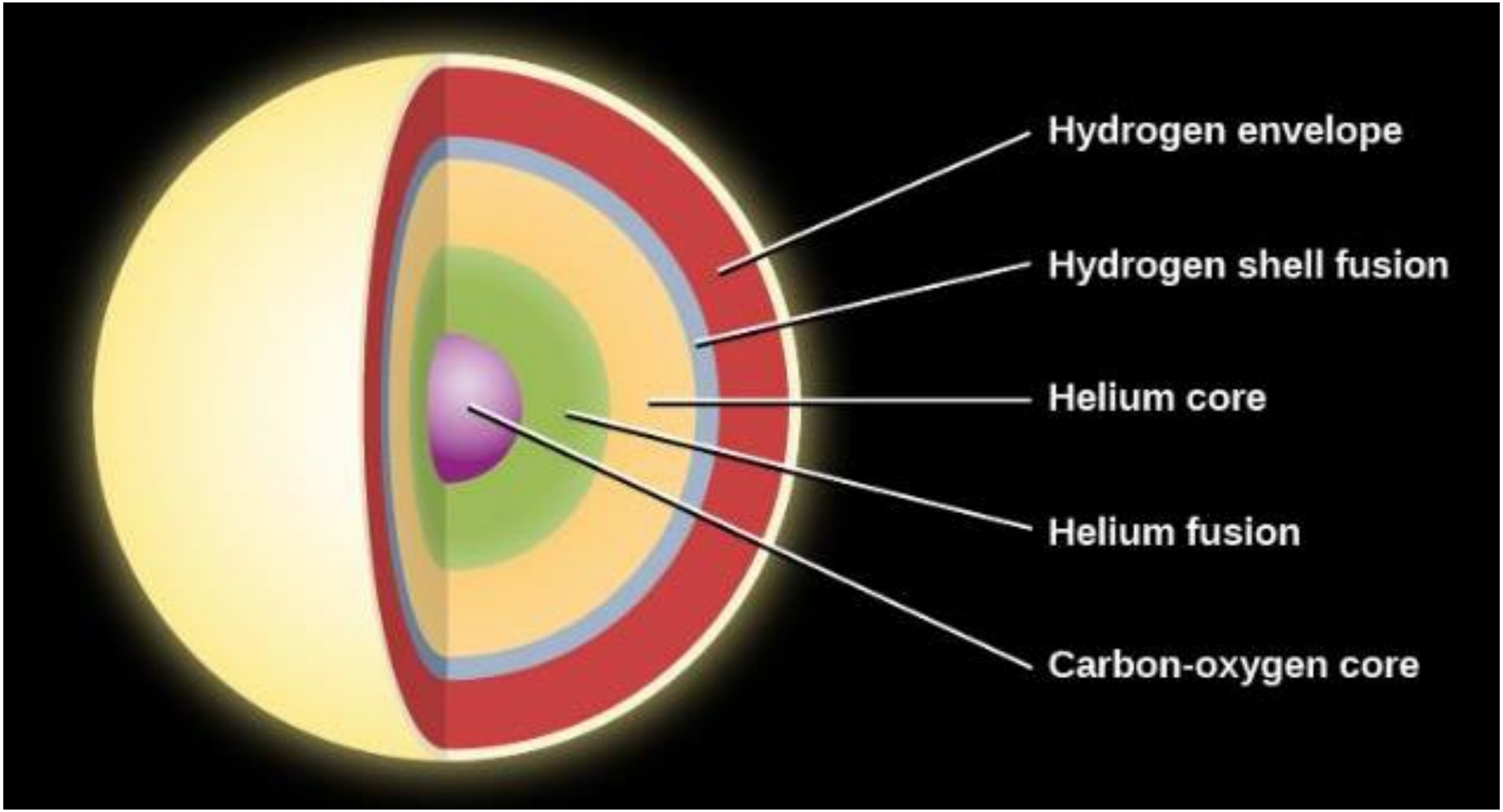
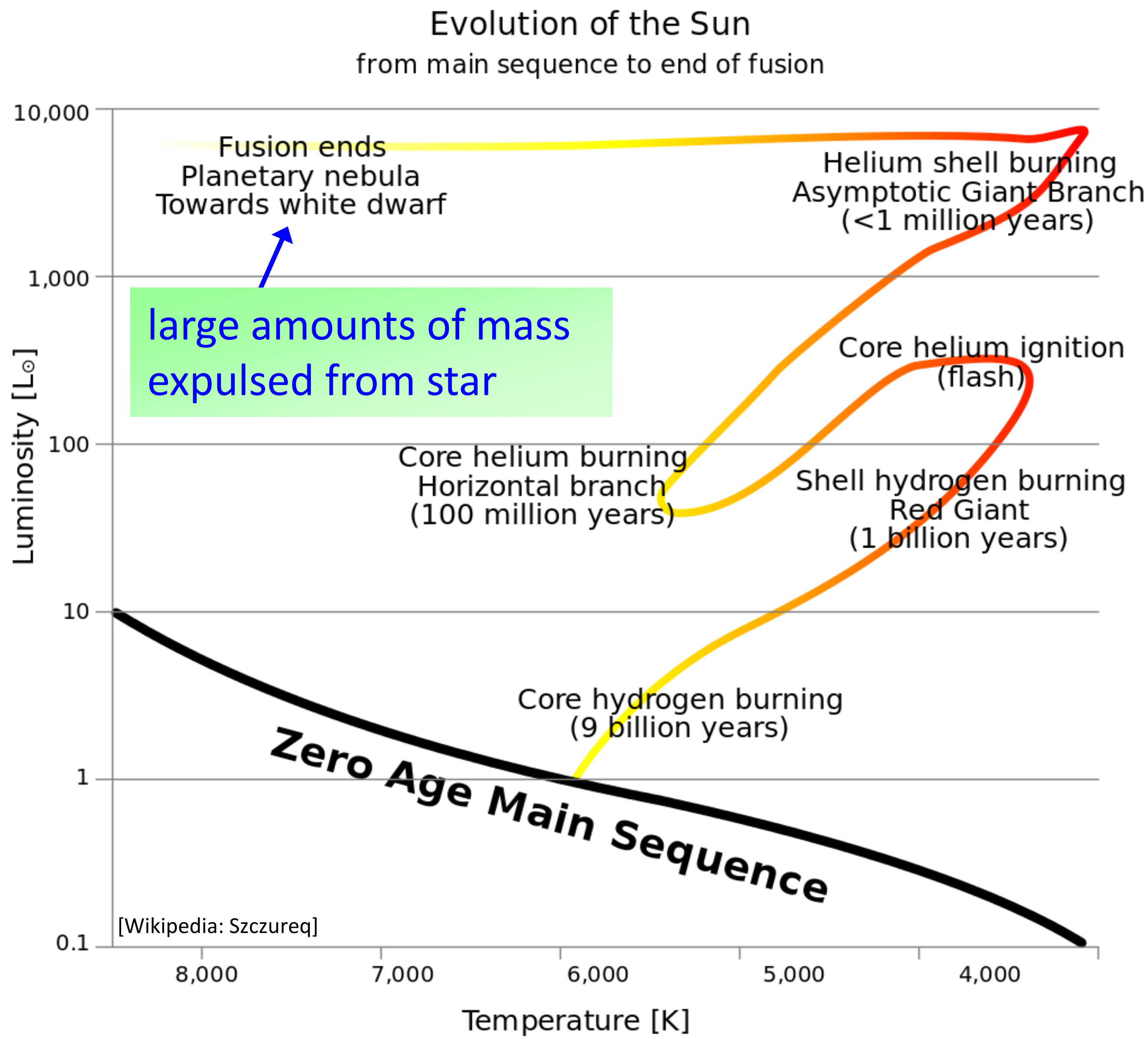
Helium Flash (for Sun-like stars)

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

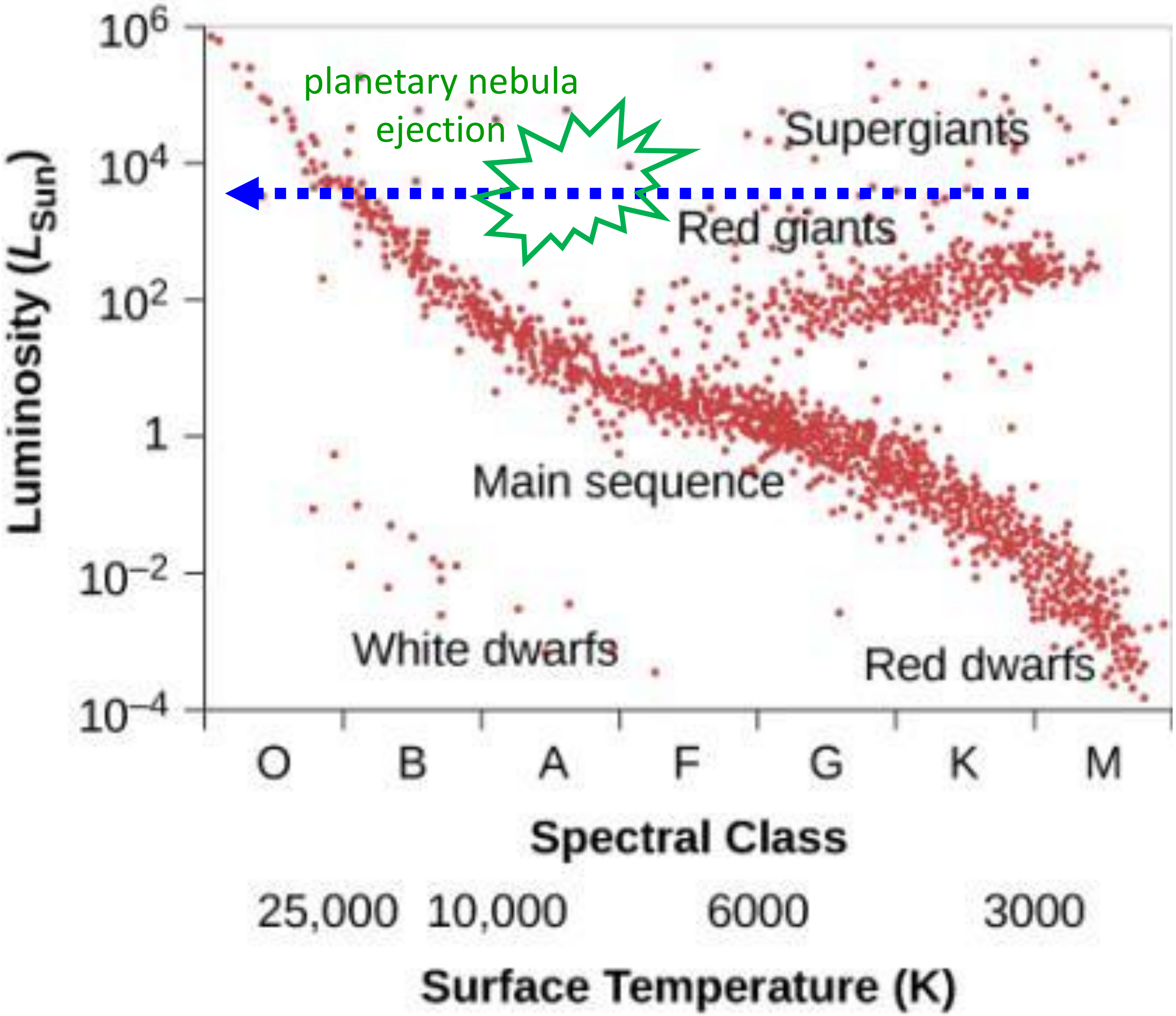
Structure of Red Giant Star before “Death”



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 ~ 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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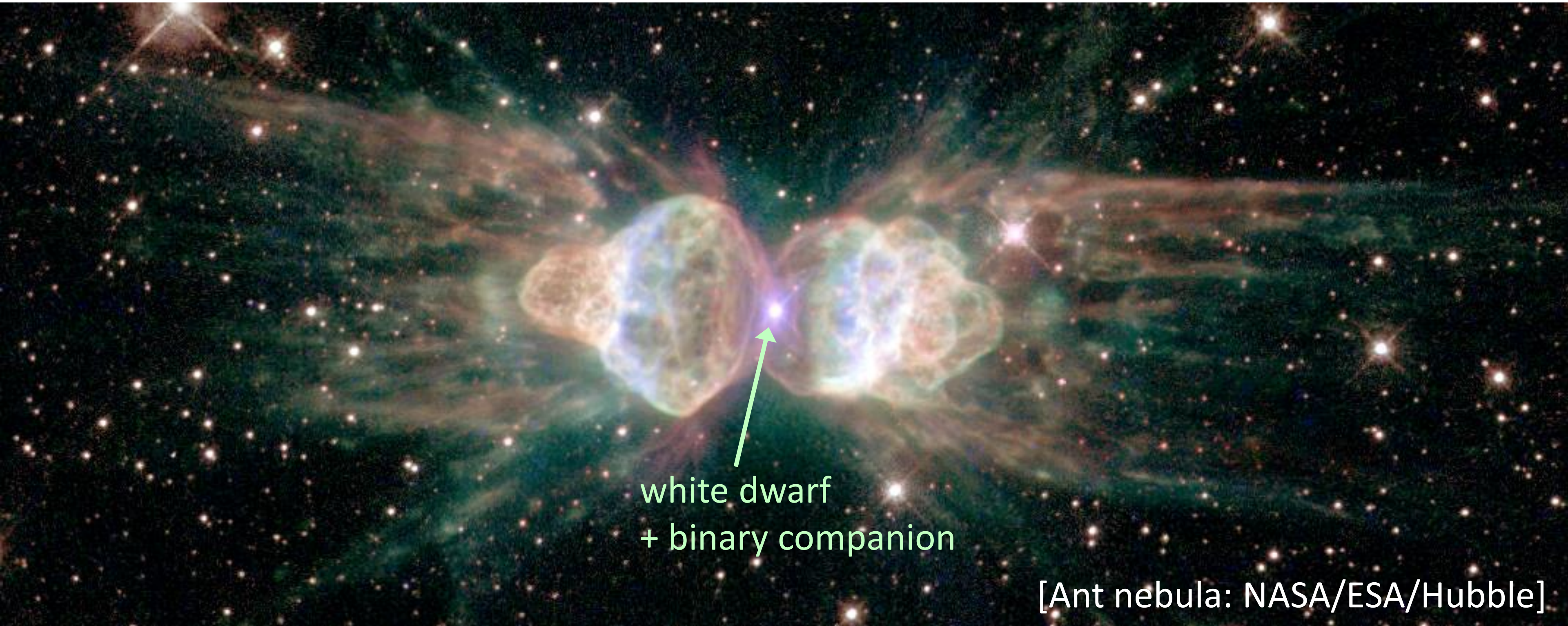

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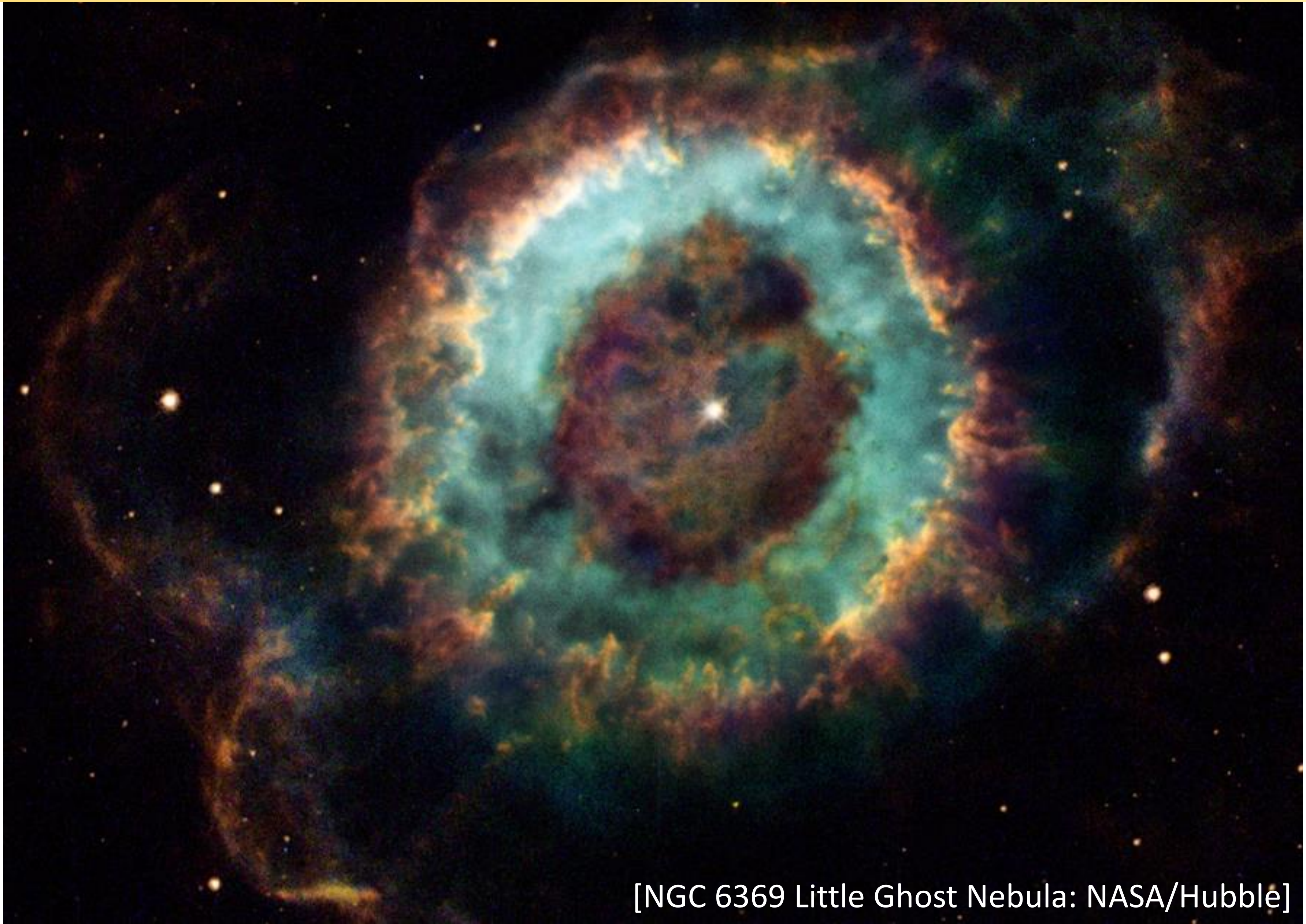

[NGC 6369 Little Ghost Nebula: NASA/Hubble]

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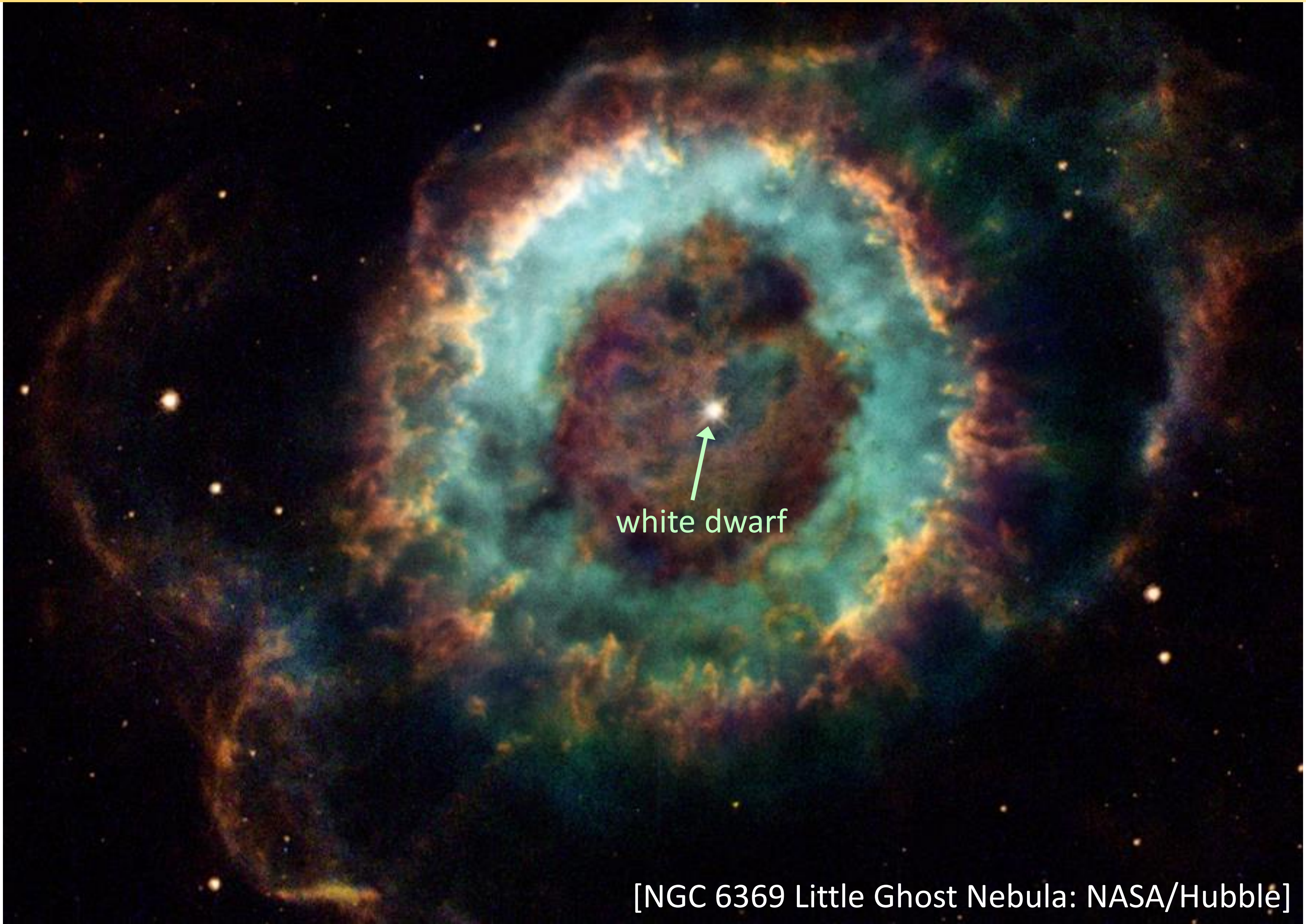

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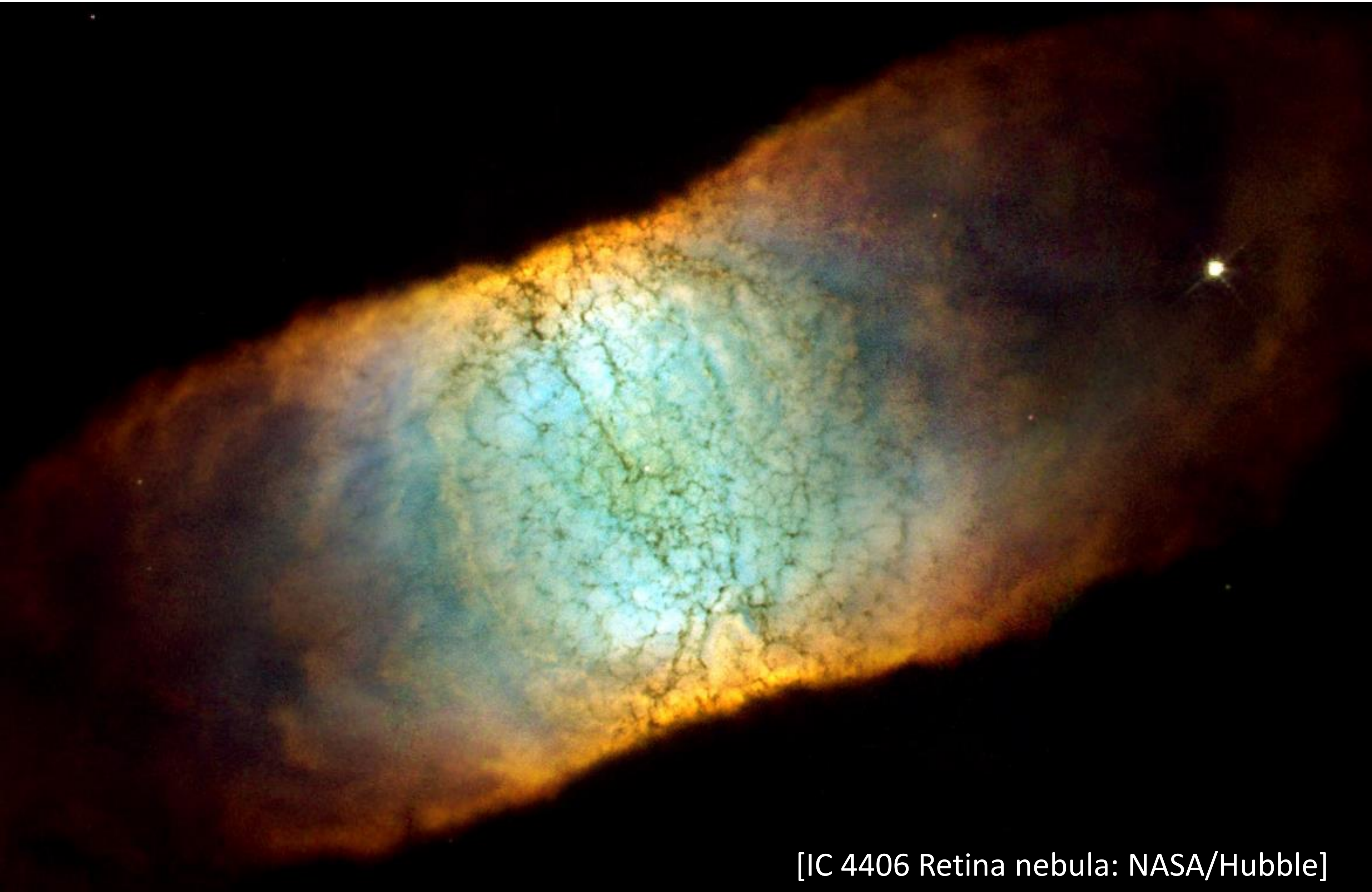

[IC 4406 Retina nebula: NASA/Hubble]

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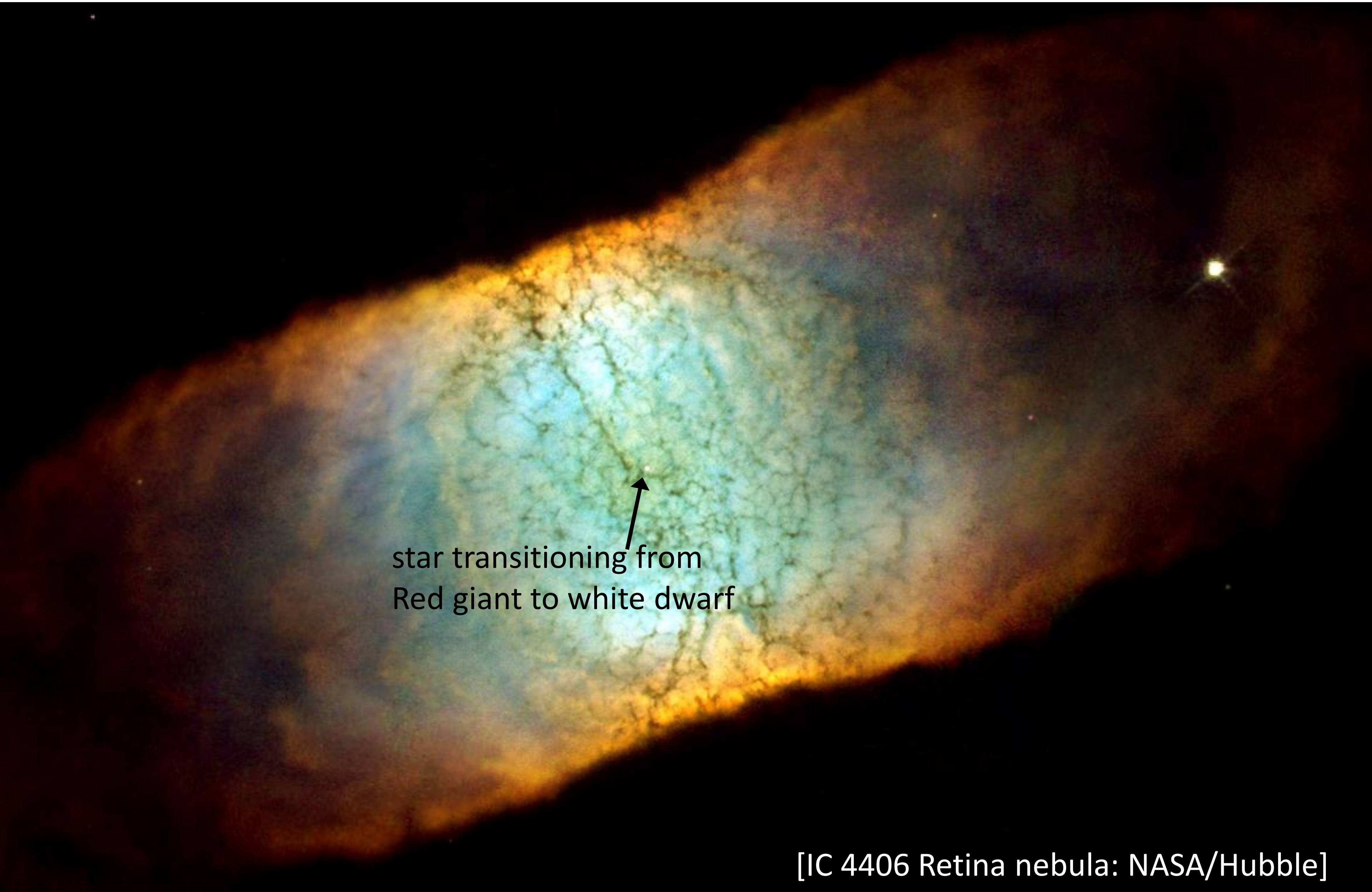

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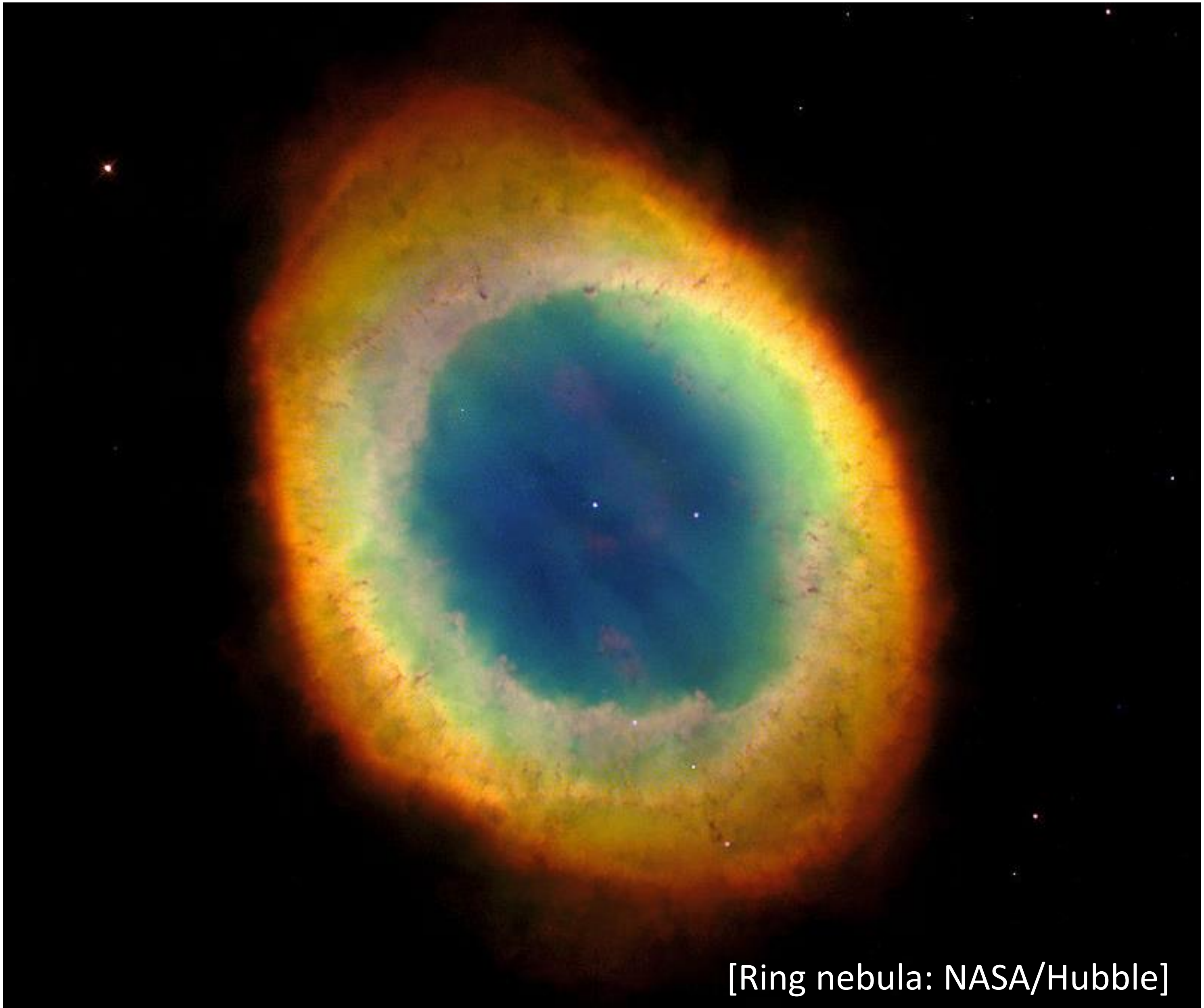

[Ring nebula: NASA/Hubble]

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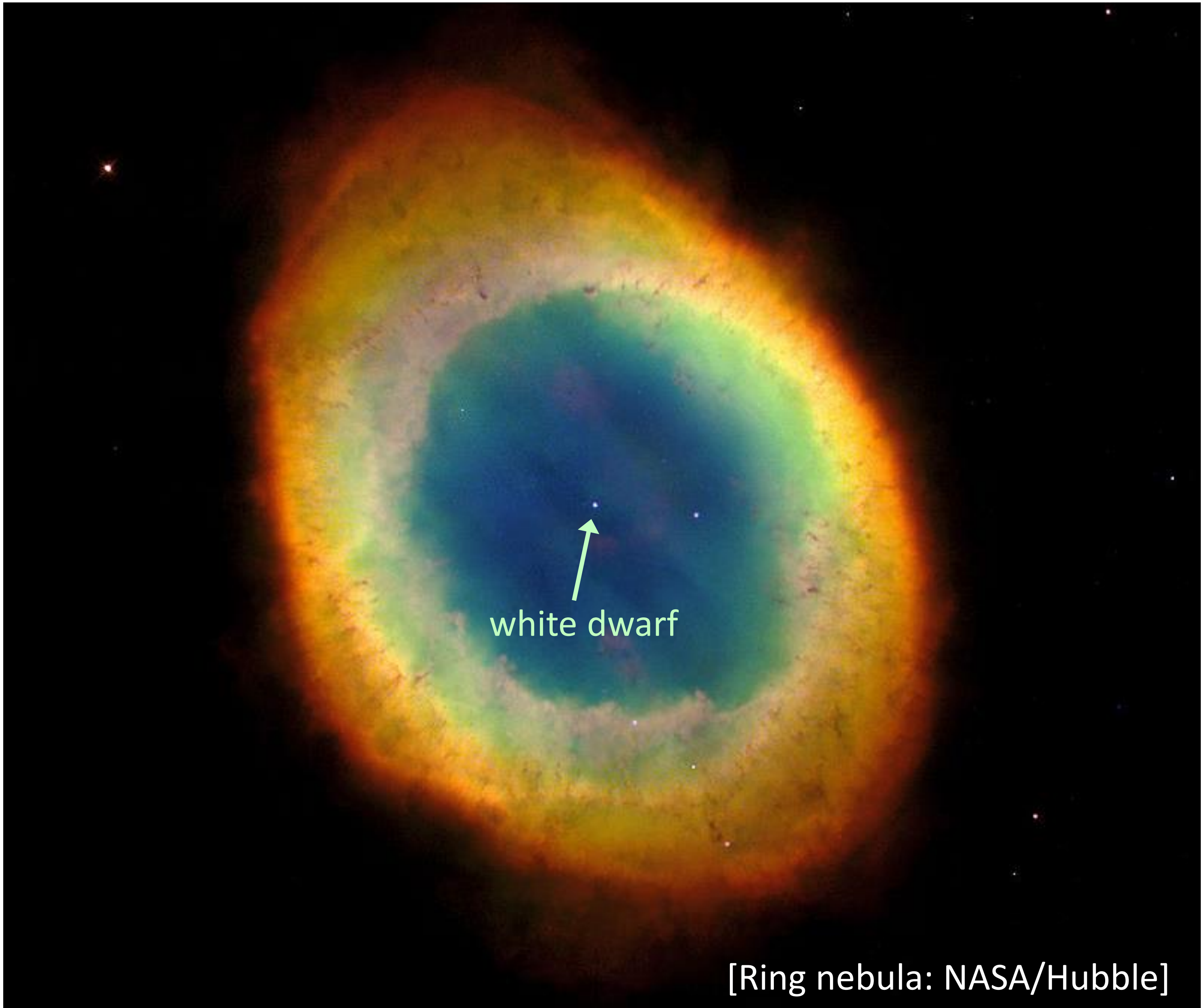

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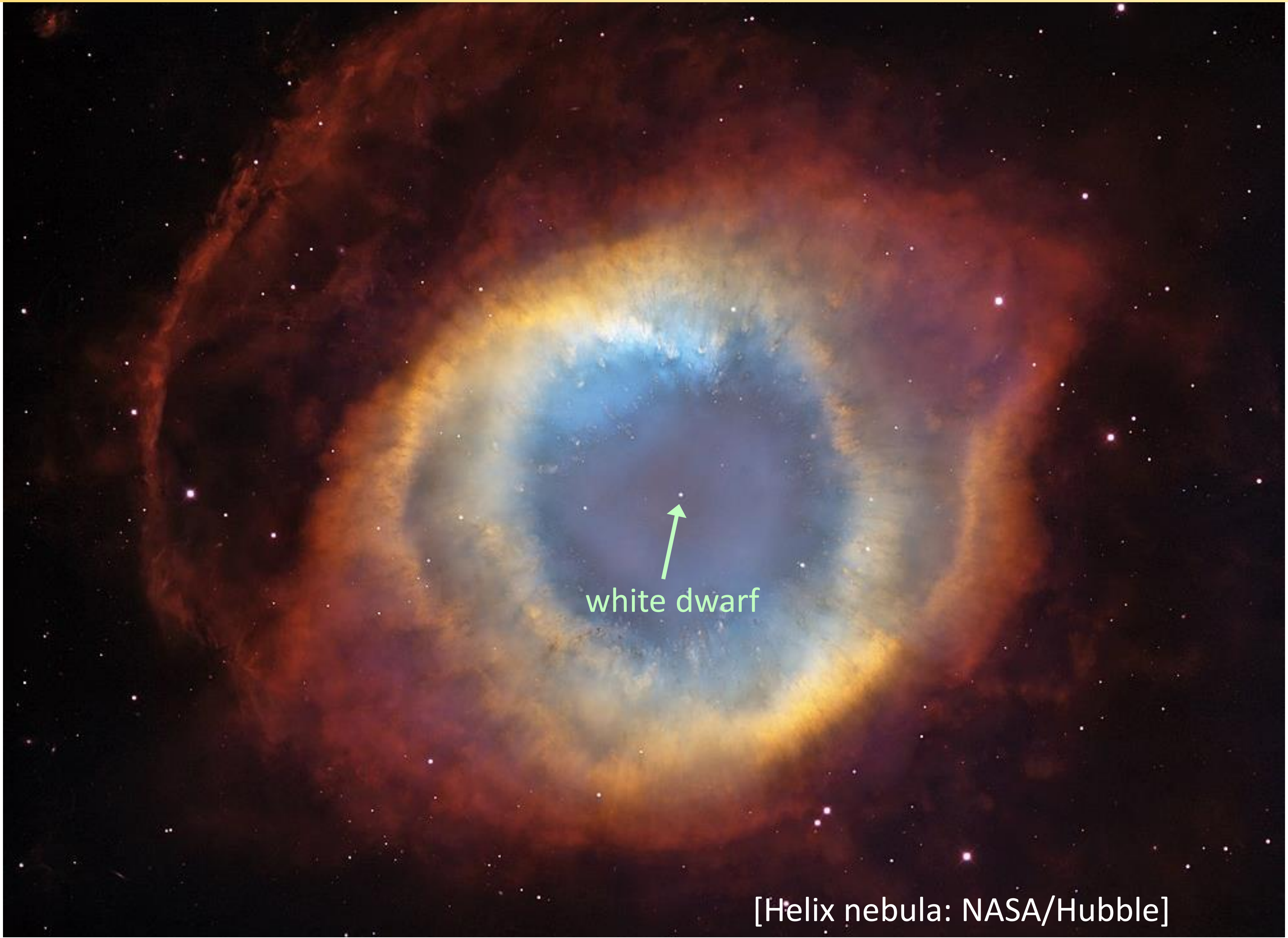

Mass Loss: Planetary Nebula

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

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

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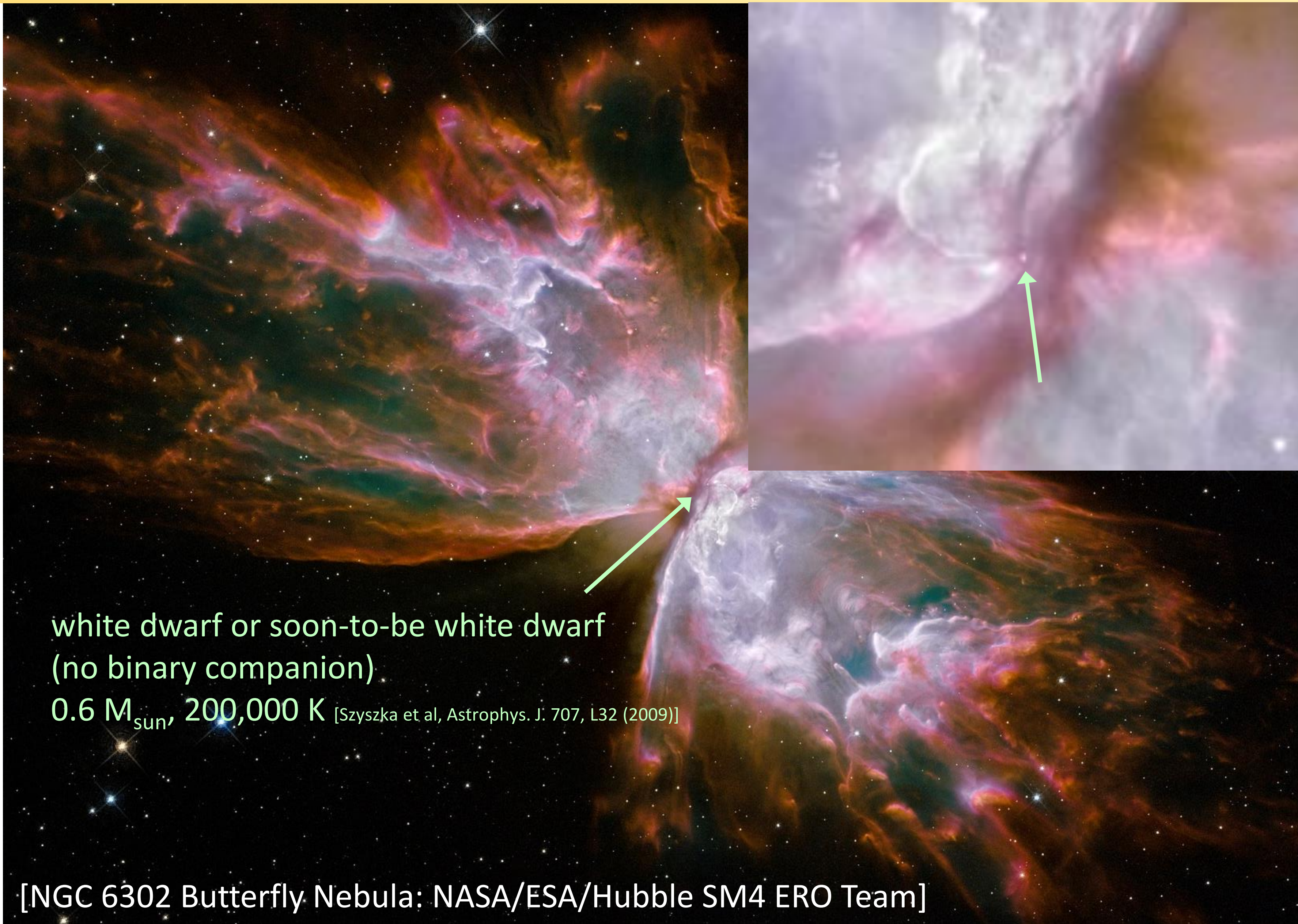
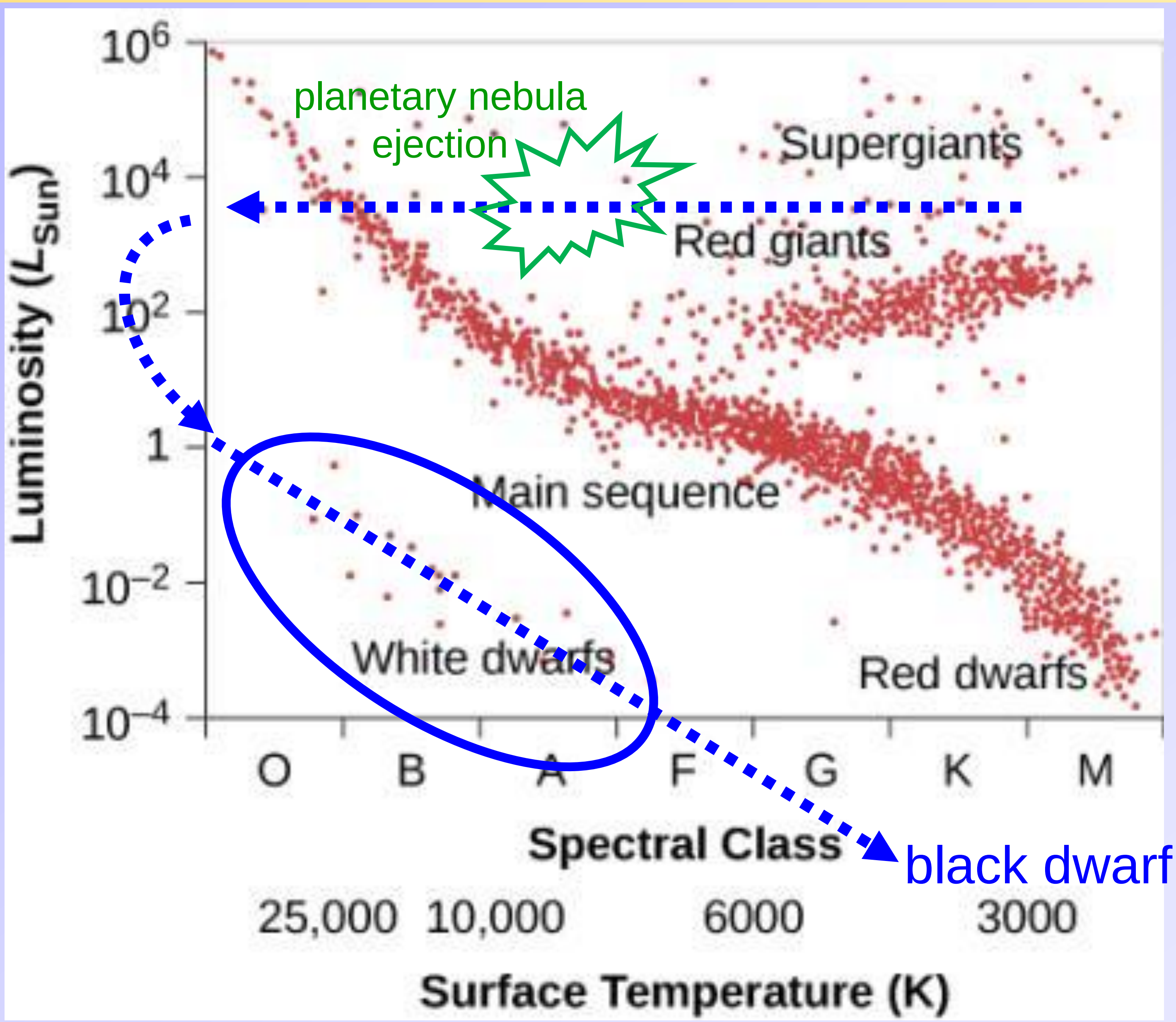


[NGC 6302 Butterfly Nebula: NASA/ESA/Hubble SM4 ERO Team]

White Dwarfs



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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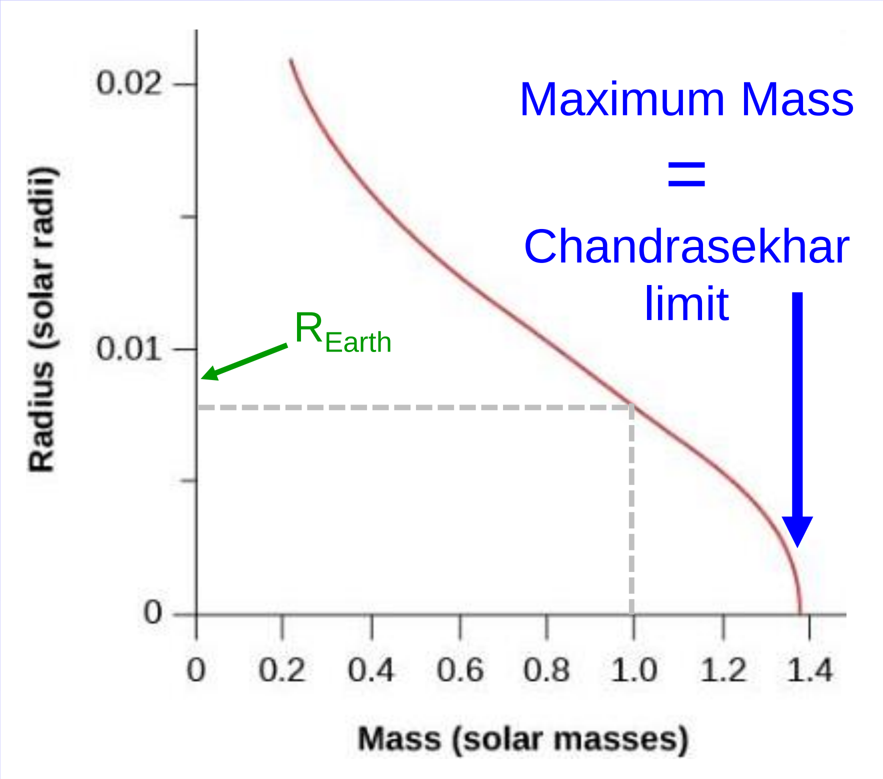

S. Chandrasekhar (1910–1995), Nobel 1983.

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."**
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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 asteroseimology evidence.