Week 13 Tuesday

Today's Agenda

- Project Examples
- Star formation
- Evolution of a low mass star
- Evolution of a high mass star
- Stellar Remnants intro

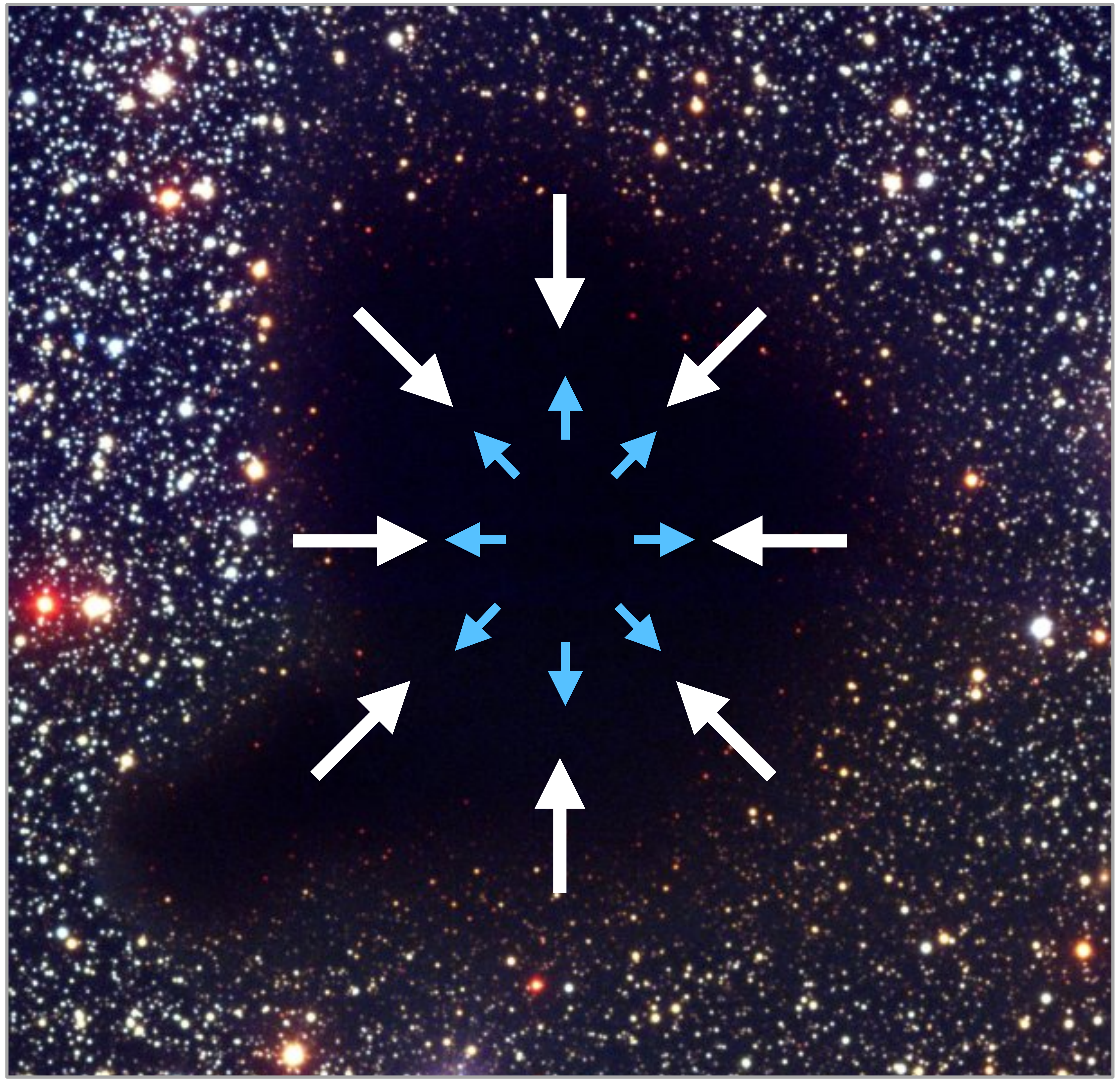
Announcements / Reminders

- Read Chapters 17 & 18
- HW 9 due Friday 1min before midnight

- HEAP talk at 4pm on Thursday
  - Dark Sector Visible Signals in Neutron Star Mergers
- Colloquium at 2pm on Friday
  - Cosmic Rays at Heliospheric Extremes: Recent Measurements by Voyager and Parker Solar Probe

“Star” —> undergoing fusion

Formed from clouds of gas that collapse due to self-gravity



Pressure in the gas can keep the cloud from collapsing
—> HSE

BUT, once a cloud of a given density and temperature reaches a critical size, it will collapse
—> Jeans length

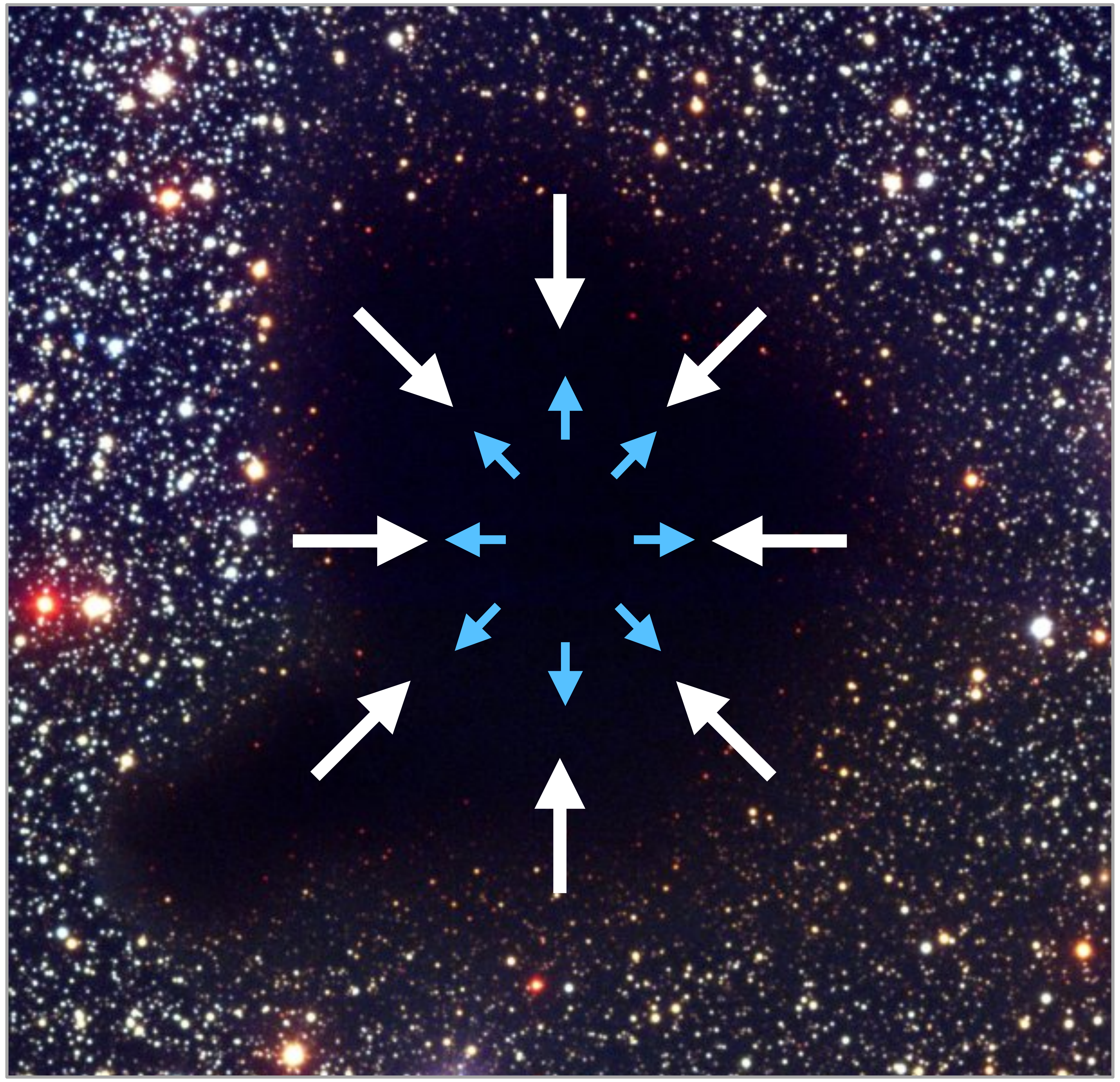
$$t_{\rm ff} < t_{\rm press} = \frac{r_0}{c_s}$$

$$t_{\rm ff} = \left(\frac{3\pi}{32 G \rho_0}\right)^{1/2} \qquad c_s = \left(\frac{\gamma k T}{\mu m_p}\right)^{1/2}$$

$$r_{\rm J} \approx 2000 \text{ AU} \left(\frac{T}{10 \text{ K}}\right)^{1/2} \left(\frac{\rho_0}{3 \times 10^{-15} \text{ kg m}^{-3}}\right)^{-1/2}$$

“Star” —> undergoing fusion

Formed from clouds of gas that collapse due to self-gravity



Pressure in the gas can keep the cloud from collapsing —> HSE

BUT, once a cloud of a given density and temperature reaches a critical size, it will collapse —> Jeans length

If density and size is determined, also have a critical mass —> Jeans mass

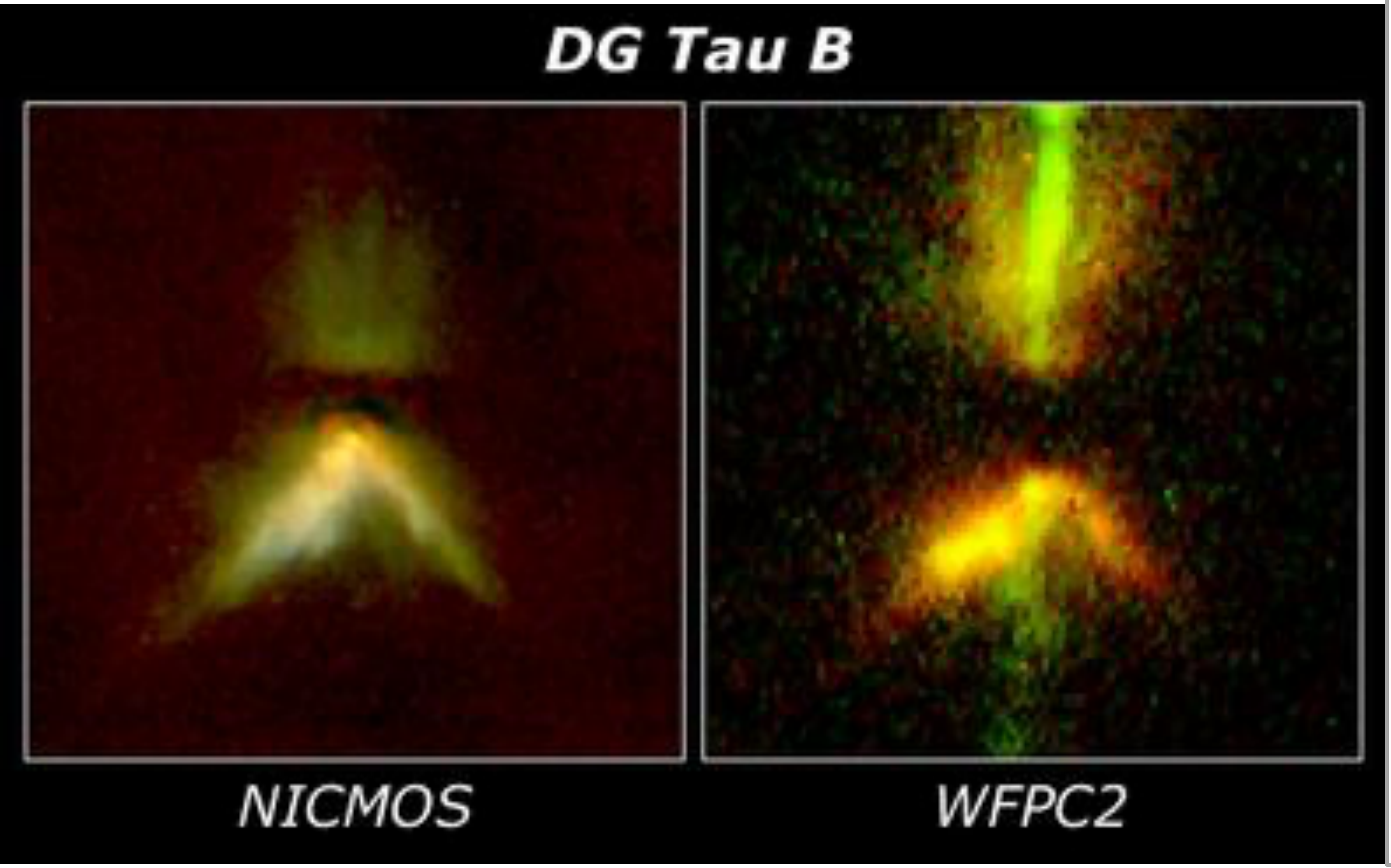
As a cloud collapses, density and temperature will change, causing the Jeans length and mass to shrink so the cloud fragments —> fragmentation

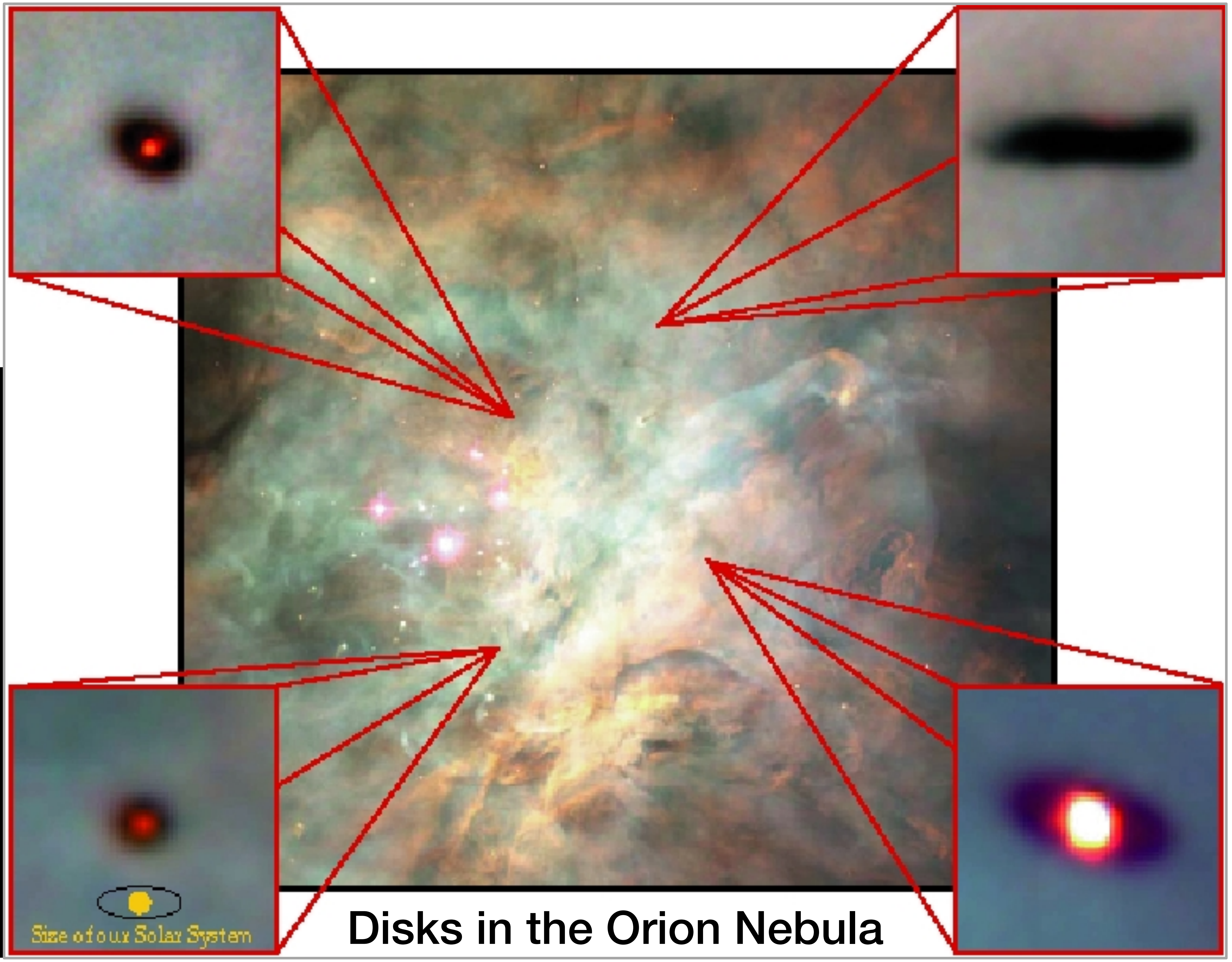
1 cloud produces many stars: a star cluster

Protostars form from an “accretion disk”

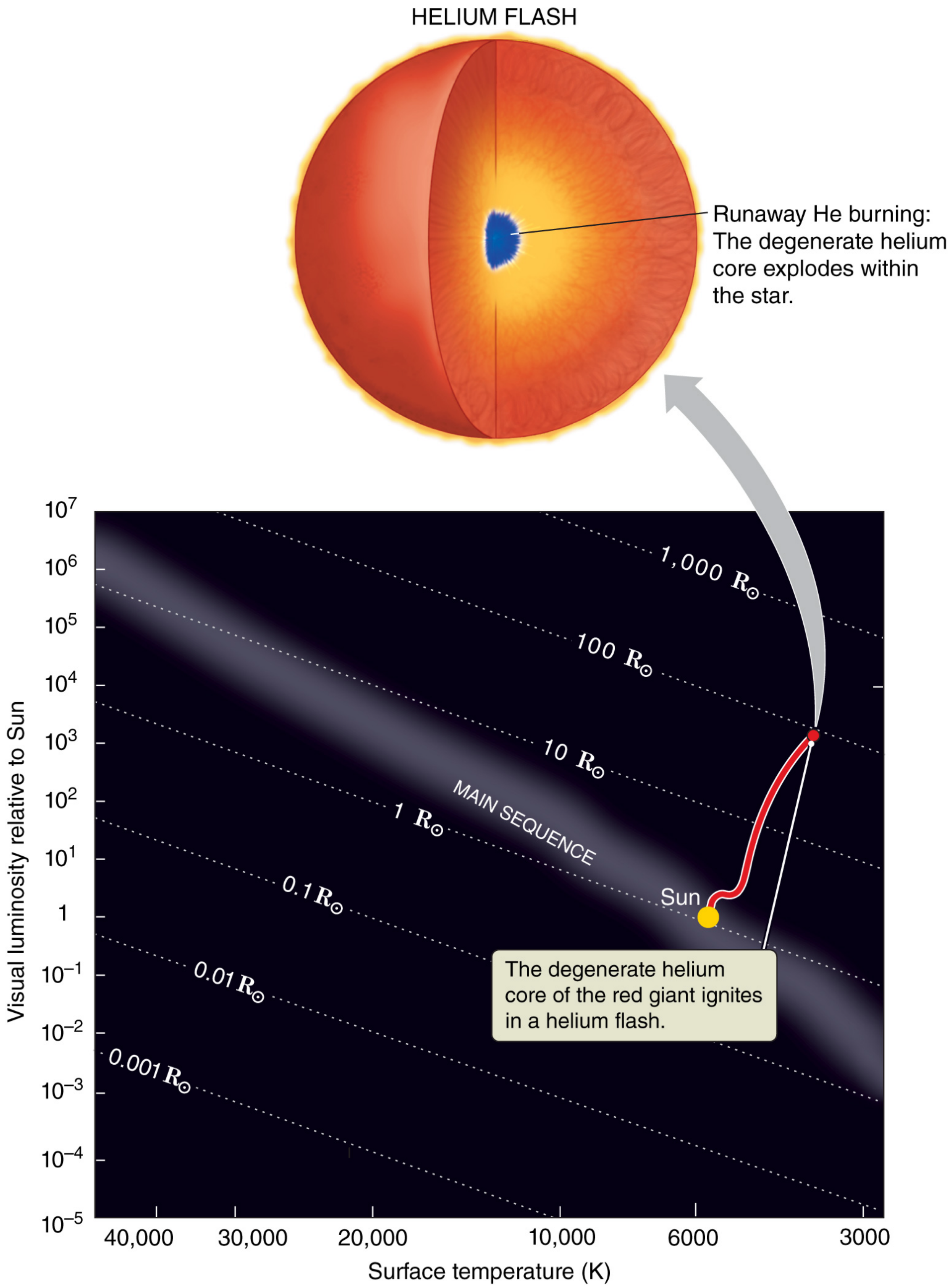
Angular momentum dissipated in the disk

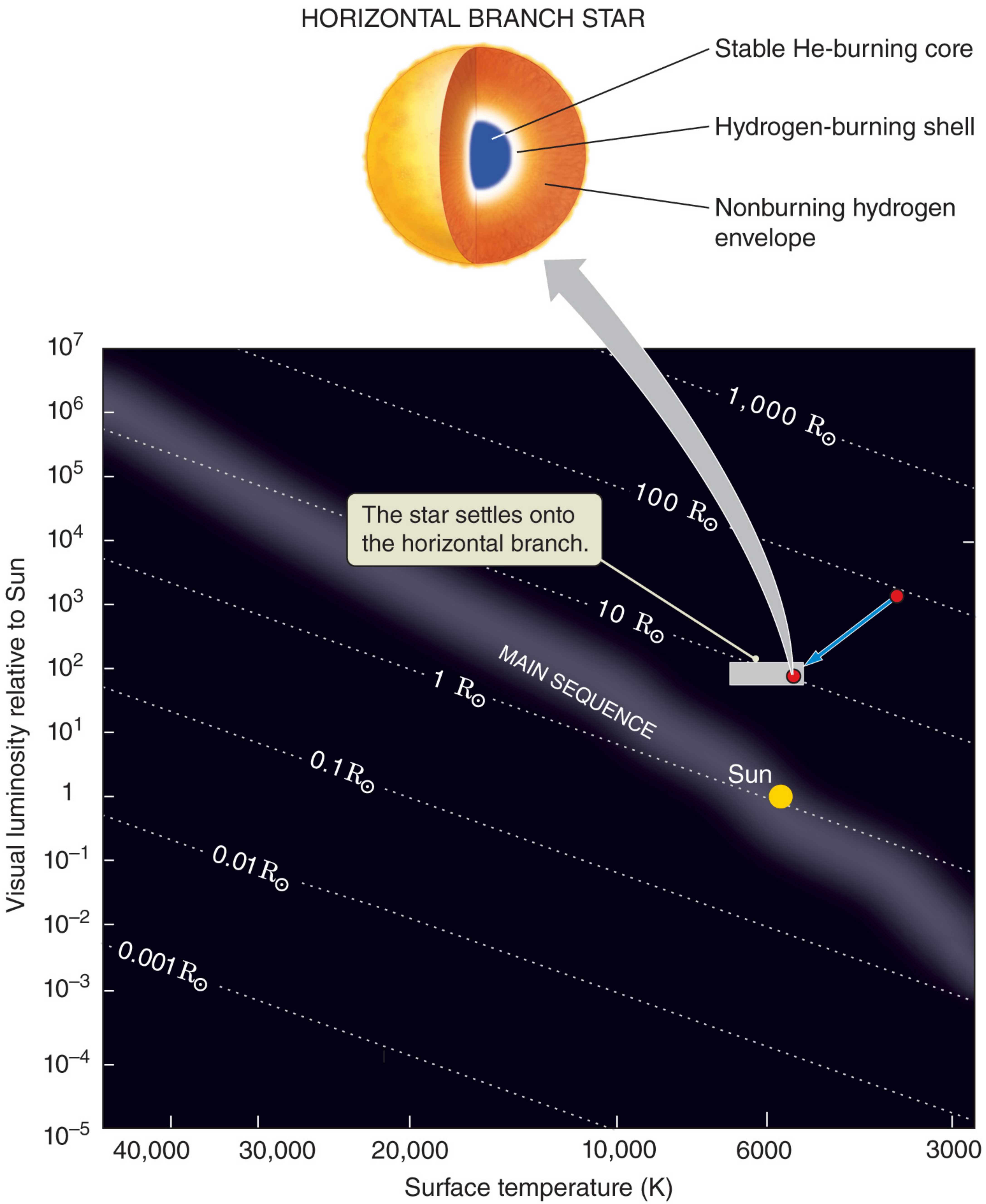
>99.9% of mass in the protostar, but planets with much less mass typically carry more angular momentum (which originates from the cloud)

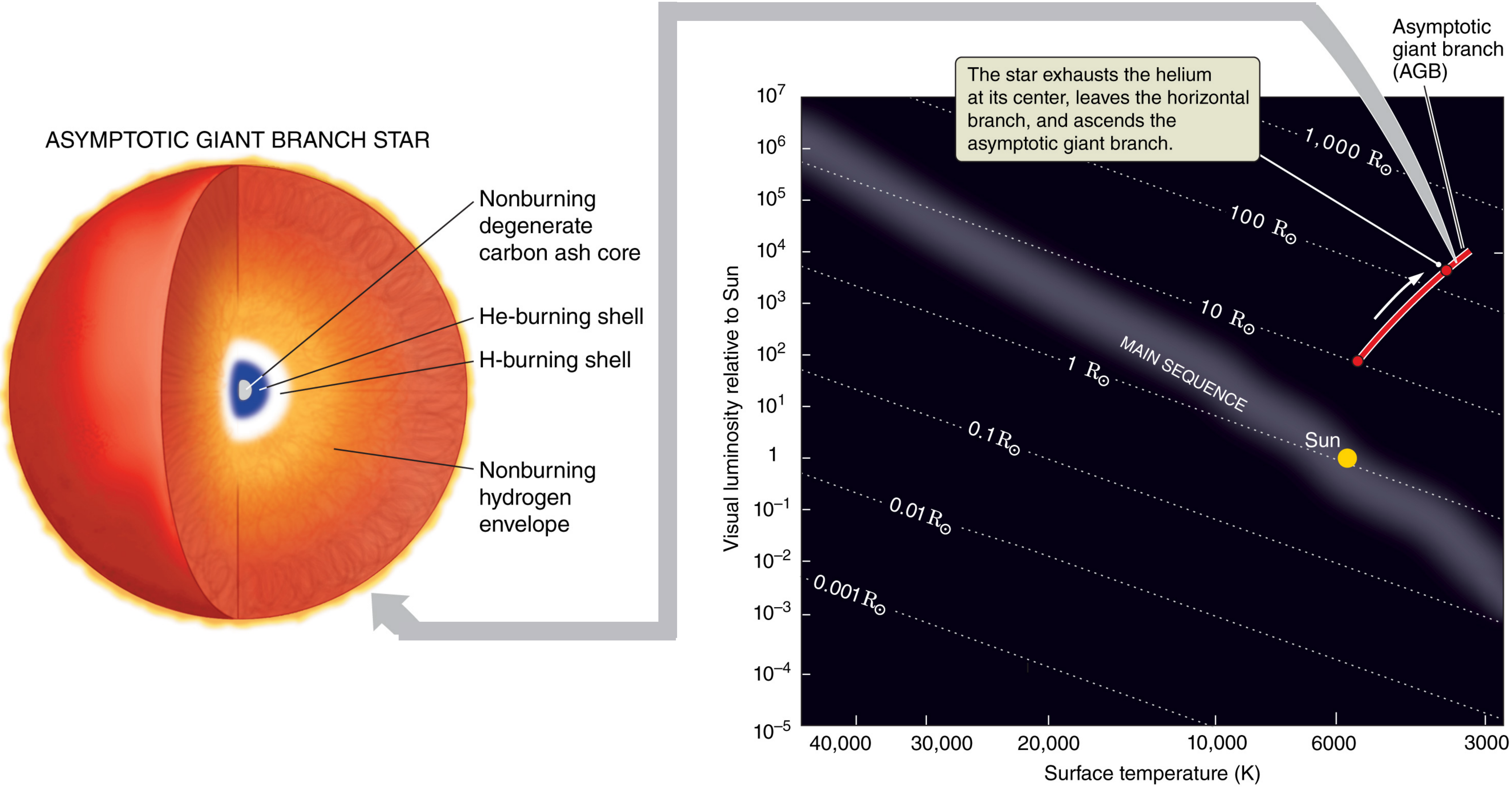


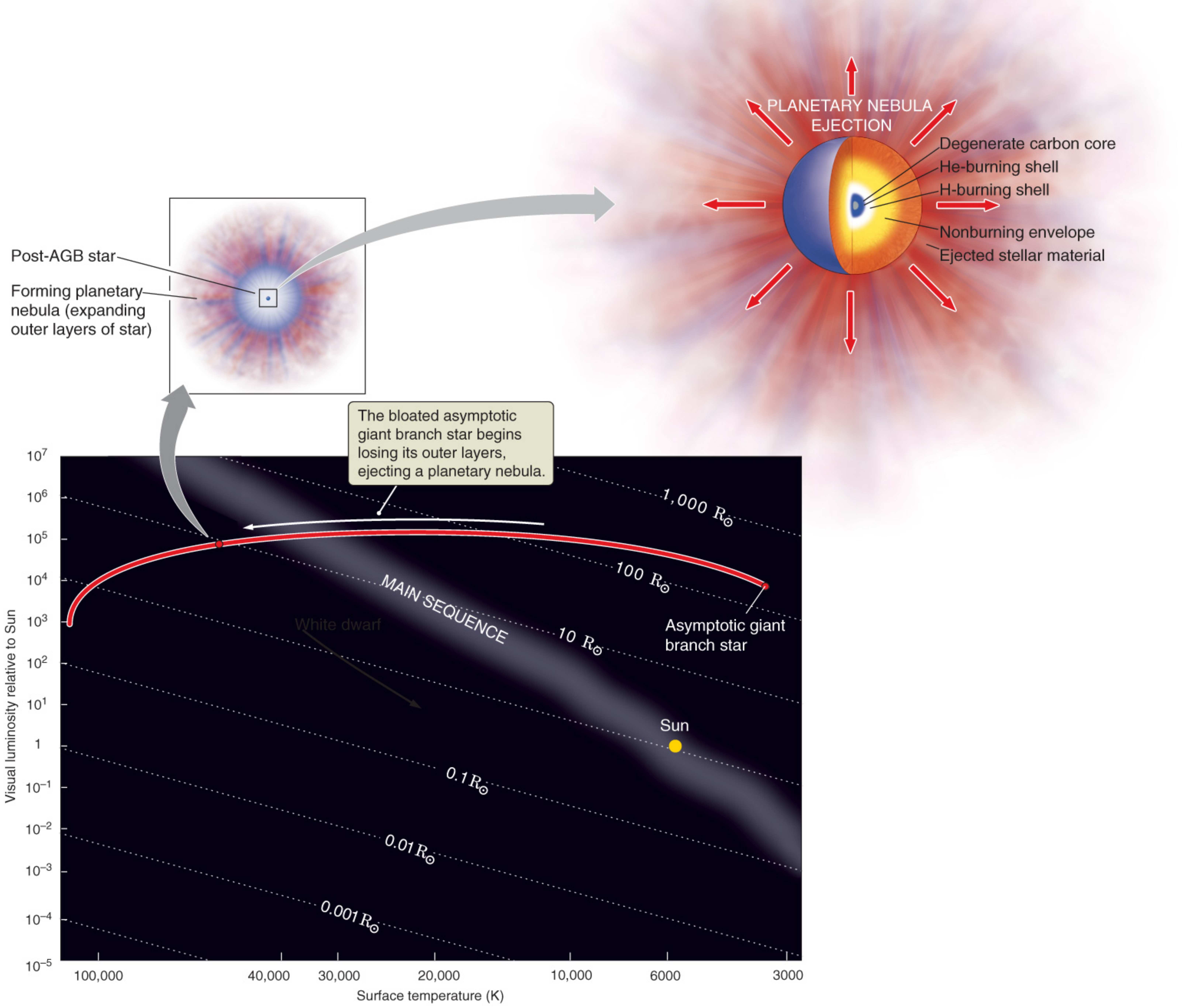


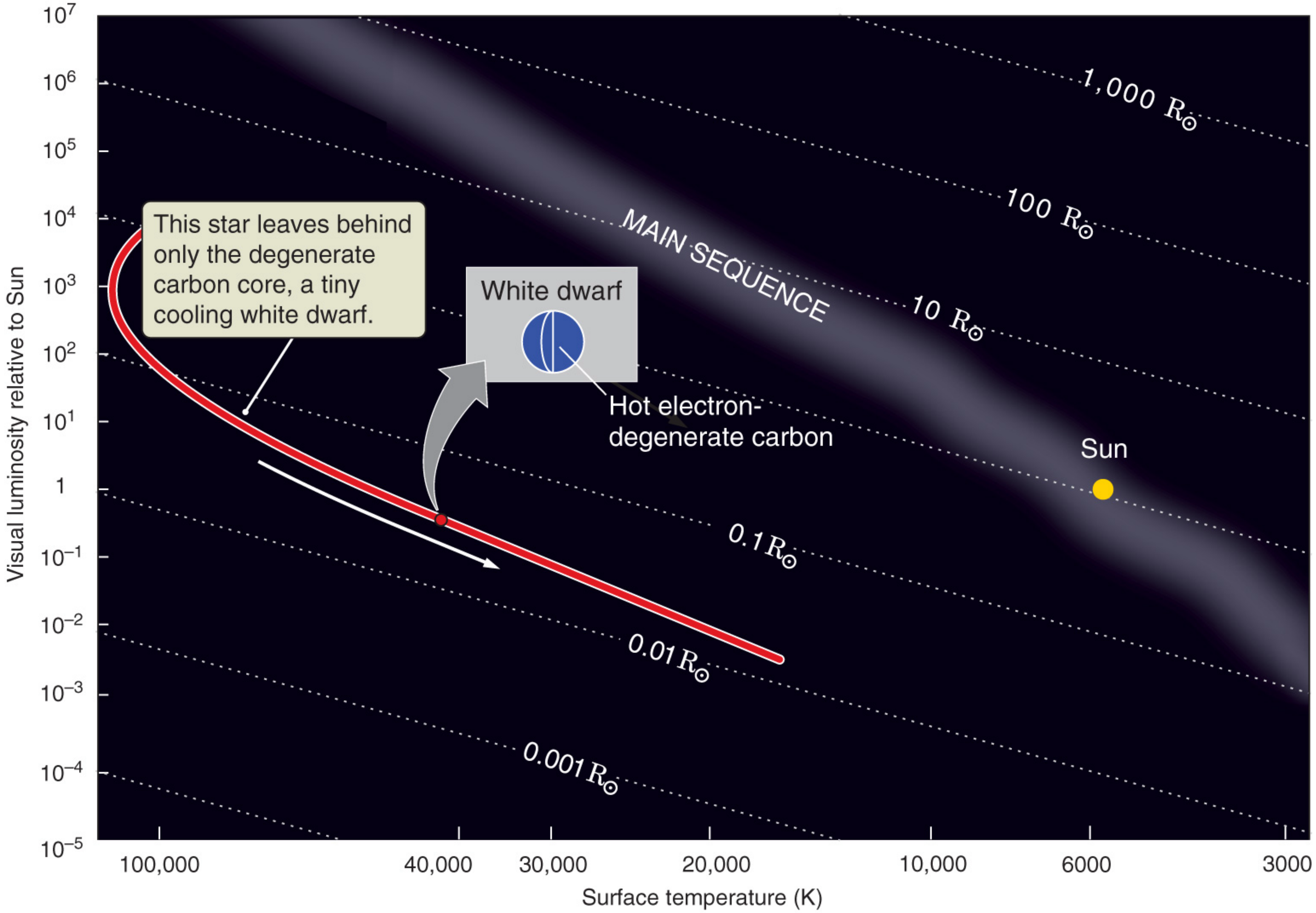
Disks in the Orion Nebula


HELIUM FLASH
Runaway He burning: The degenerate helium core explodes within the star.
The degenerate helium core of the red giant ignites in a helium flash.
Sun
MAIN SEQUENCE
1,000 R⊙
100 R⊙
10 R⊙
1 R⊙
0.1 R⊙
0.01 R⊙
0.001 R⊙
Visual luminosity relative to Sun
Surface temperature (K)
40,000
30,000
20,000
10,000
6000
3000


HORIZONTAL BRANCH STAR
Stable He-burning core
Hydrogen-burning shell
Nonburning hydrogen envelope
The star settles onto the horizontal branch.
Sun
MAIN SEQUENCE
1,000 R⊙
100 R⊙
10 R⊙
1 R⊙
0.1 R⊙
0.01 R⊙
0.001 R⊙
Visual luminosity relative to Sun
Surface temperature (K)
40,000
30,000
20,000
10,000
6000
3000

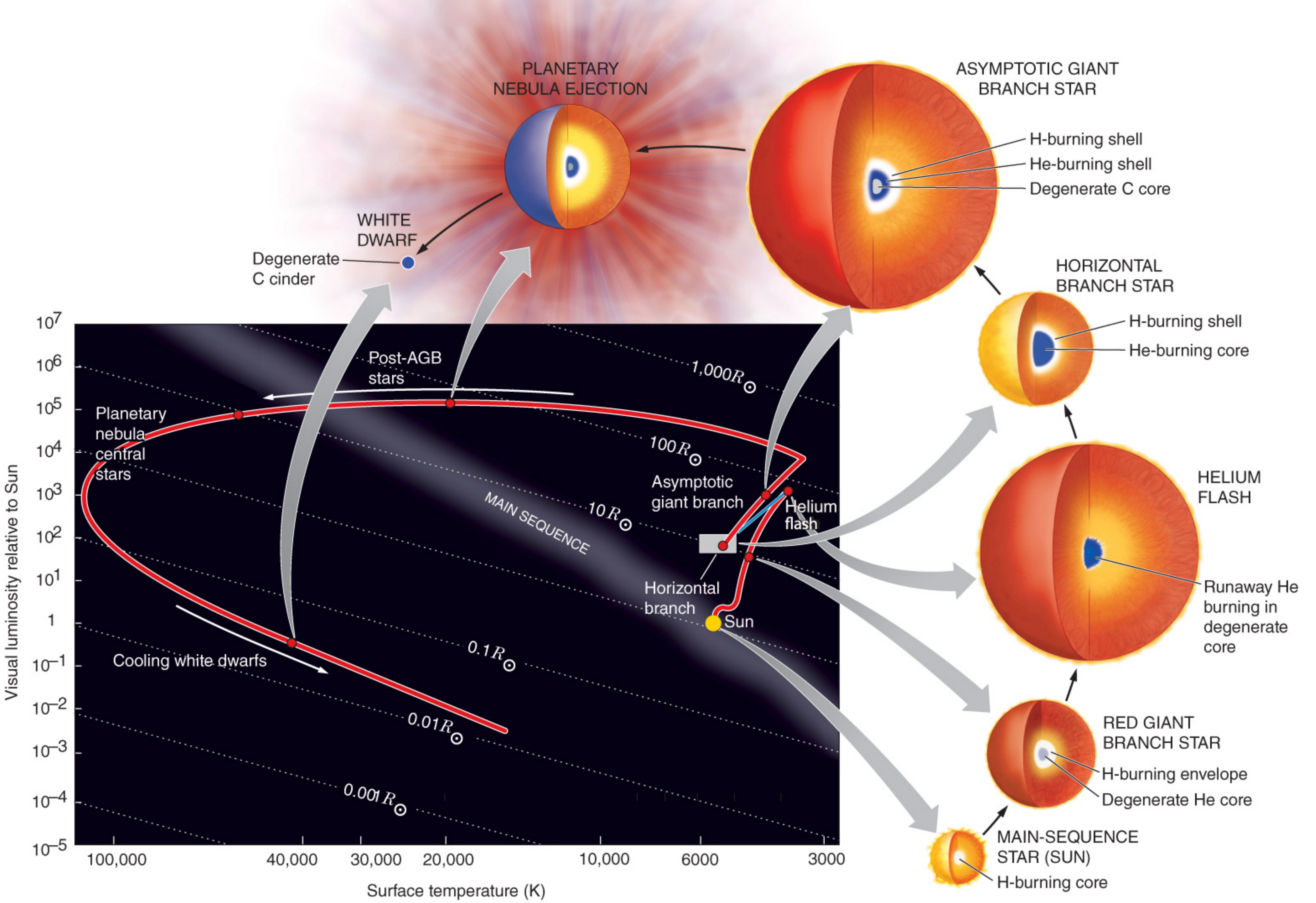

ASYMPTOTIC GIANT BRANCH STAR
Nonburning degenerate carbon ash core
He-burning shell
H-burning shell
Nonburning hydrogen envelope
The star exhausts the helium at its center, leaves the horizontal branch, and ascends the asymptotic giant branch.
Asymptotic giant branch (AGB)
1,000 R⊙
100 R⊙
10 R⊙
1 R⊙
0.1 R⊙
0.01 R⊙
0.001 R⊙
MAIN SEQUENCE
Sun
Visual luminosity relative to Sun
Surface temperature (K)
40,000
30,000
20,000
10,000
6000
3000


PLANETARY NEBULA
EJECTION
Degenerate carbon core
He-burning shell
H-burning shell
Nonburning envelope
Ejected stellar material
Post-AGB star
Forming planetary nebula (expanding outer layers of star)
The bloated asymptotic giant branch star begins losing its outer layers, ejecting a planetary nebula.
1,000 R⊙
100 R⊙
10 R⊙
0.1 R⊙
0.01 R⊙
0.001 R⊙
MAIN SEQUENCE
White dwarf
Asymptotic giant branch star
Sun
Visual luminosity relative to Sun
10^7
10^6
10^5
10^4
10^3
10^2
10^1
1
10^-1
10^-2
10^-3
10^-4
10^-5
100,000
40,000
30,000
20,000
10,000
6000
3000
Surface temperature (K)

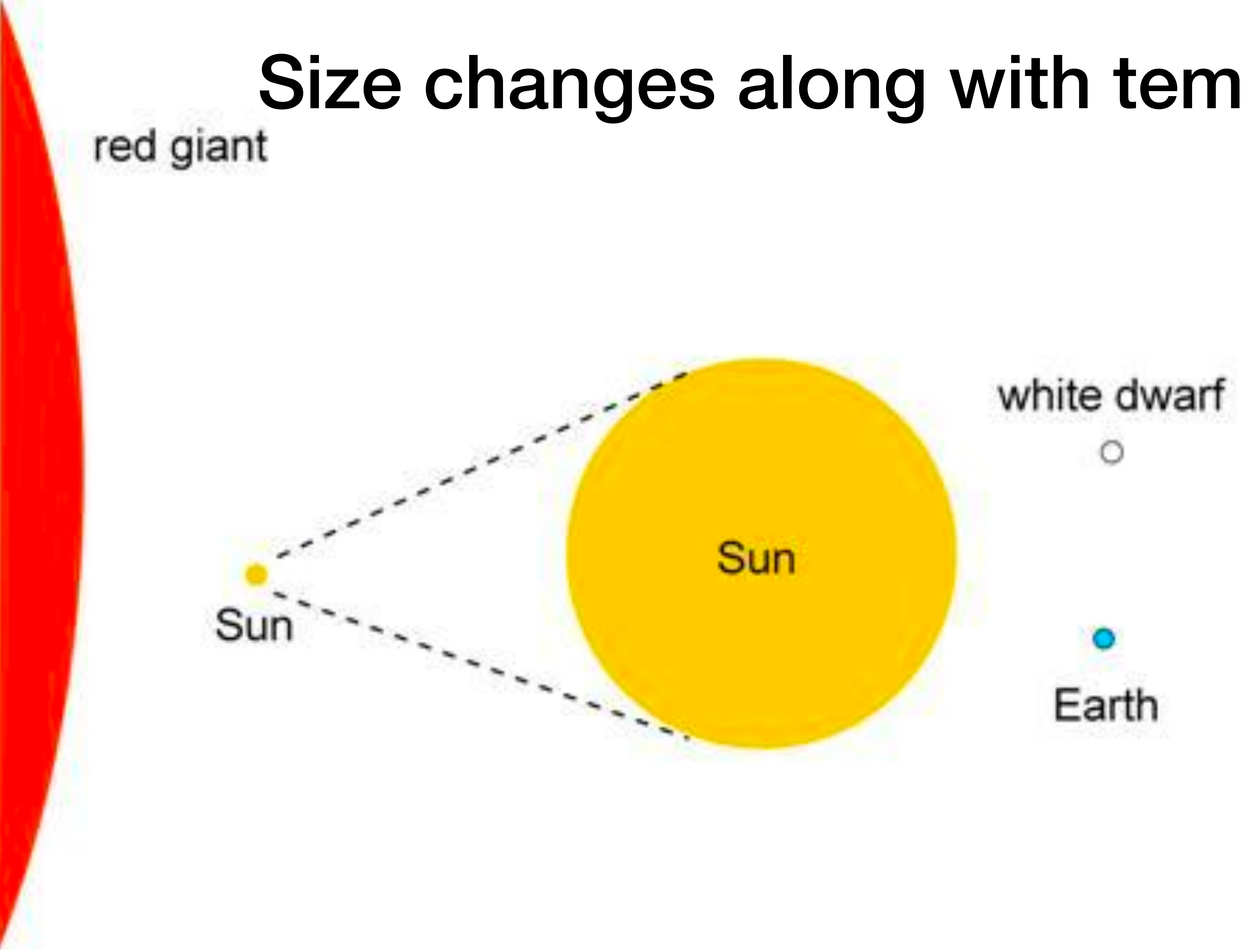


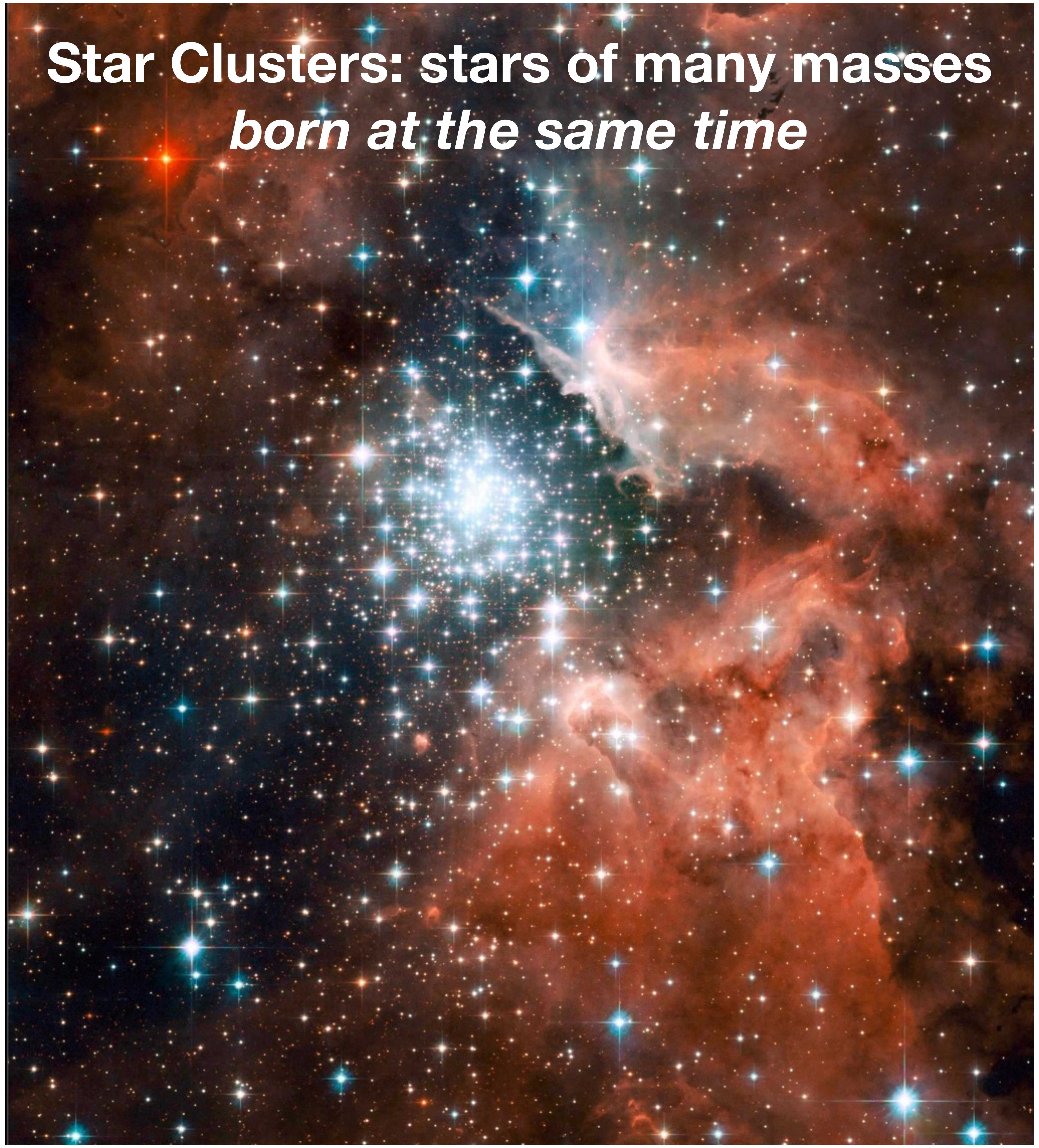
This star leaves behind only the degenerate carbon core, a tiny cooling white dwarf.
White dwarf
Hot electron-degenerate carbon
MAIN SEQUENCE
Sun
1,000 R☉
100 R☉
10 R☉
0.1 R☉
0.01 R☉
0.001 R☉
Visual luminosity relative to Sun
Surface temperature (K)
100,000
40,000
30,000
20,000
10,000
6000
3000

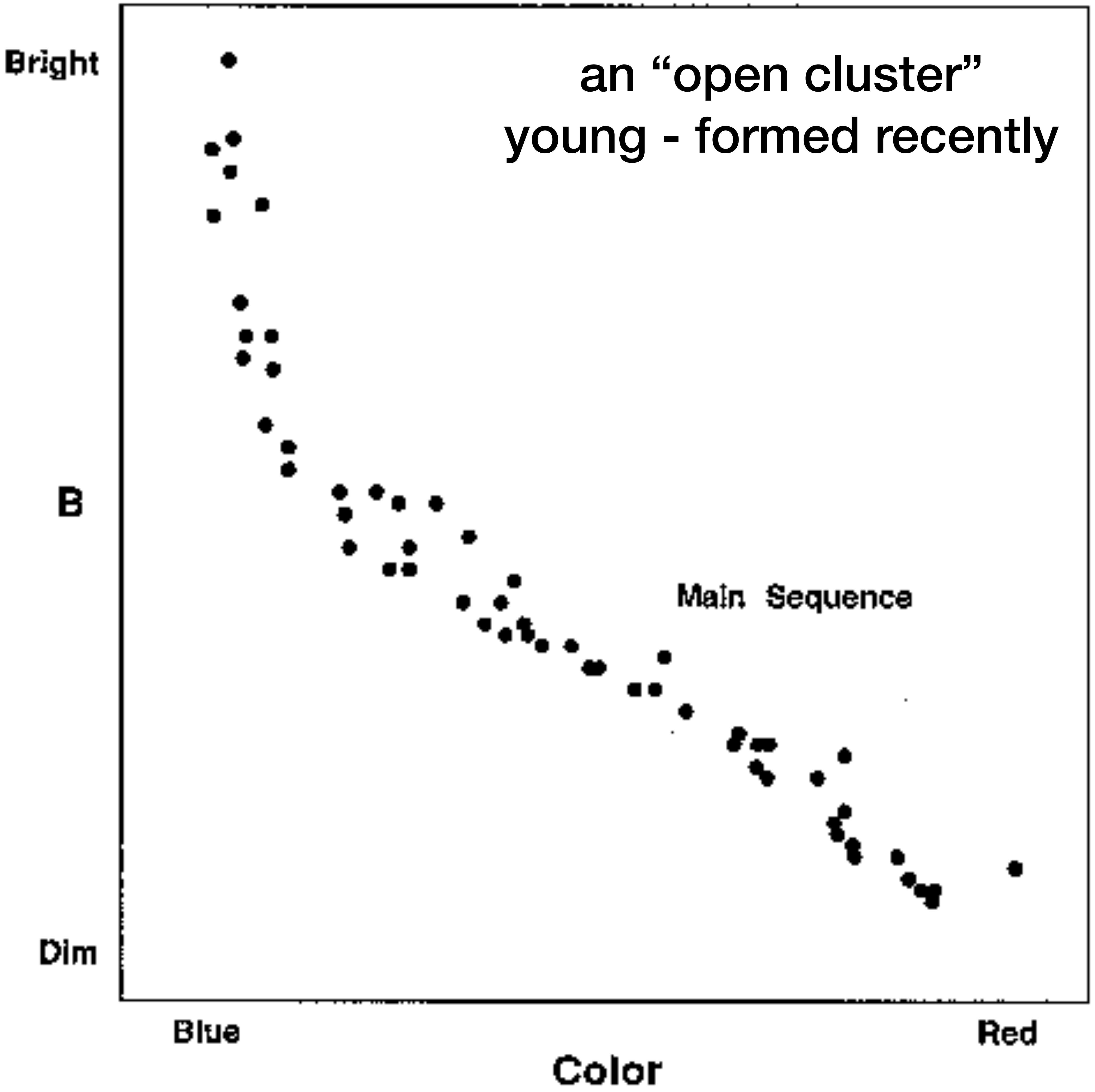
Again, this time with feeling!



Size changes along with temperature

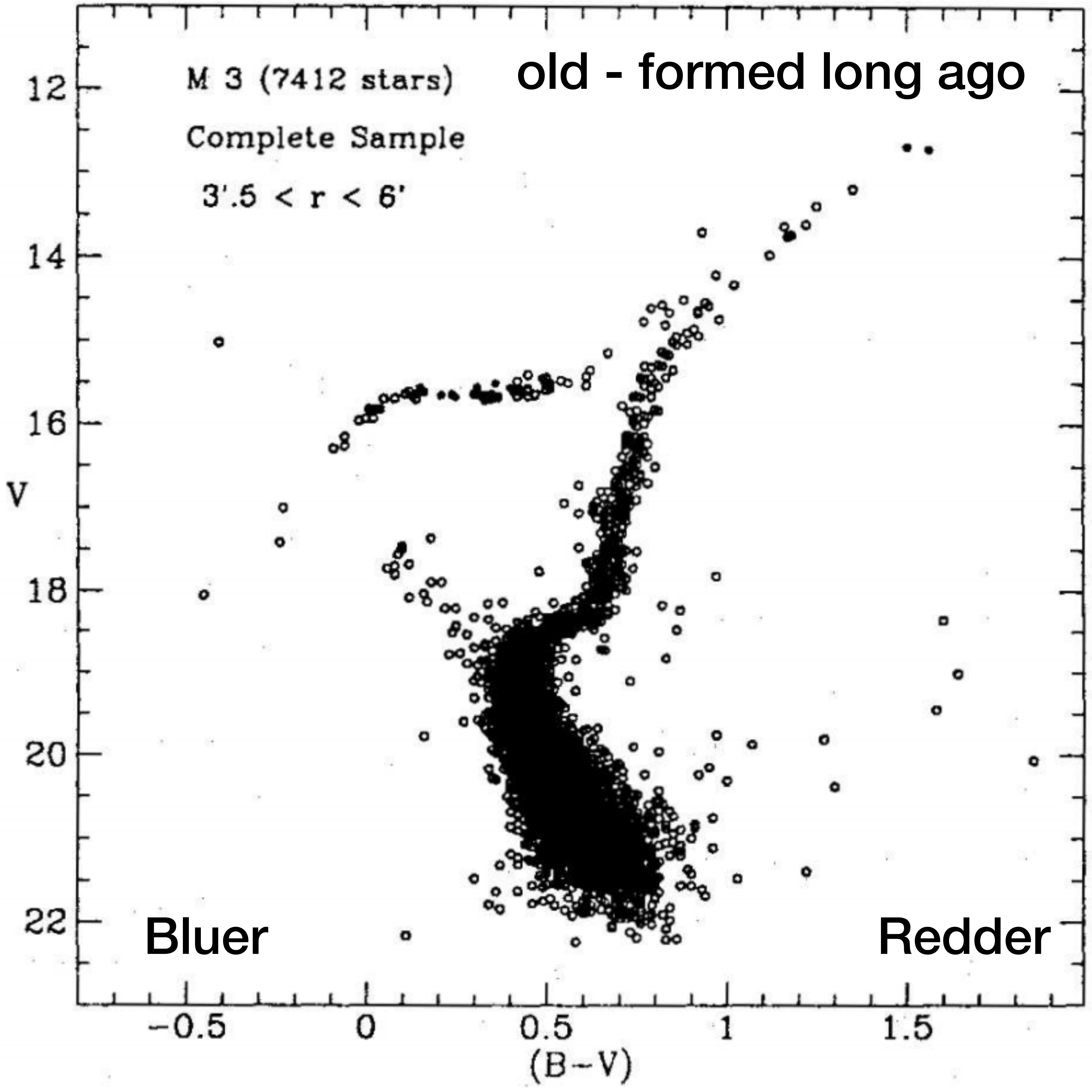






an “open cluster”
young - formed recently

Globular Cluster Color-Magnitude Diagram

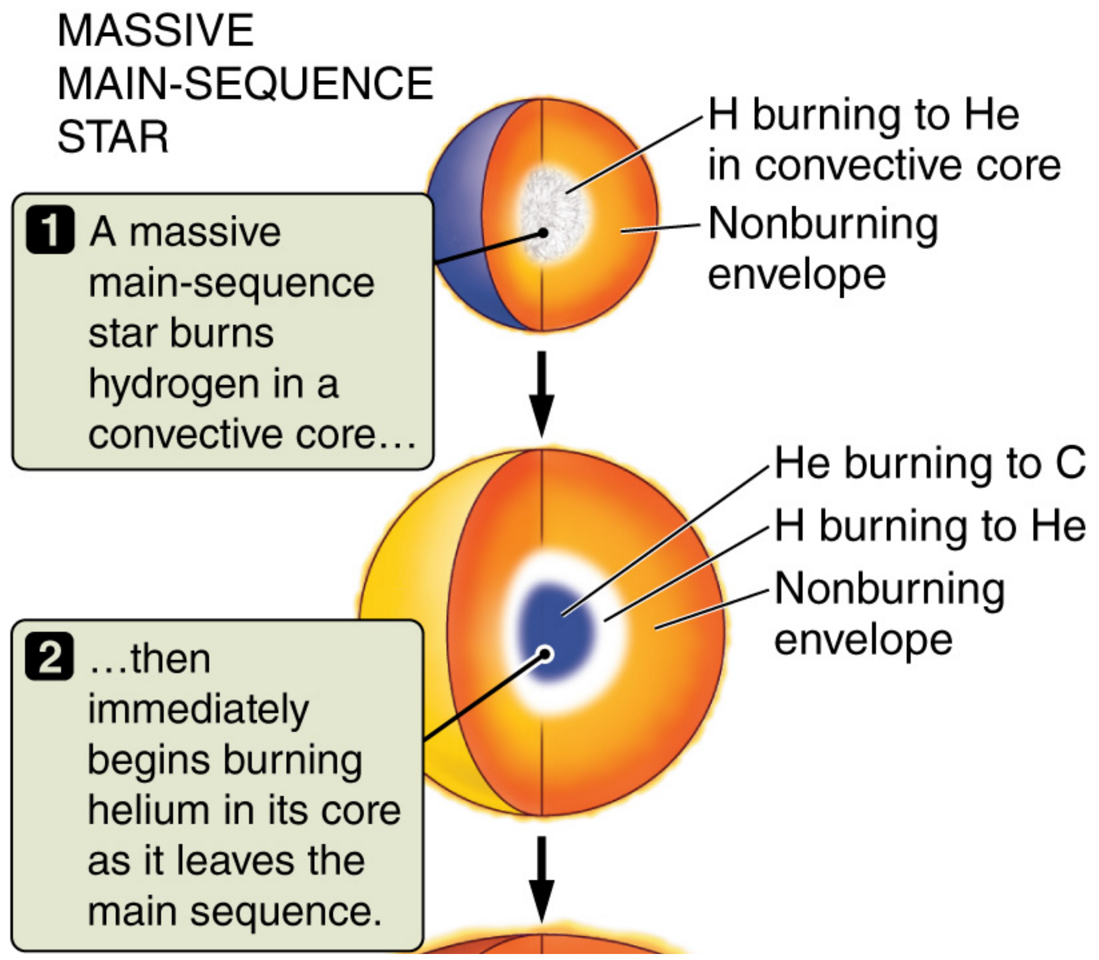


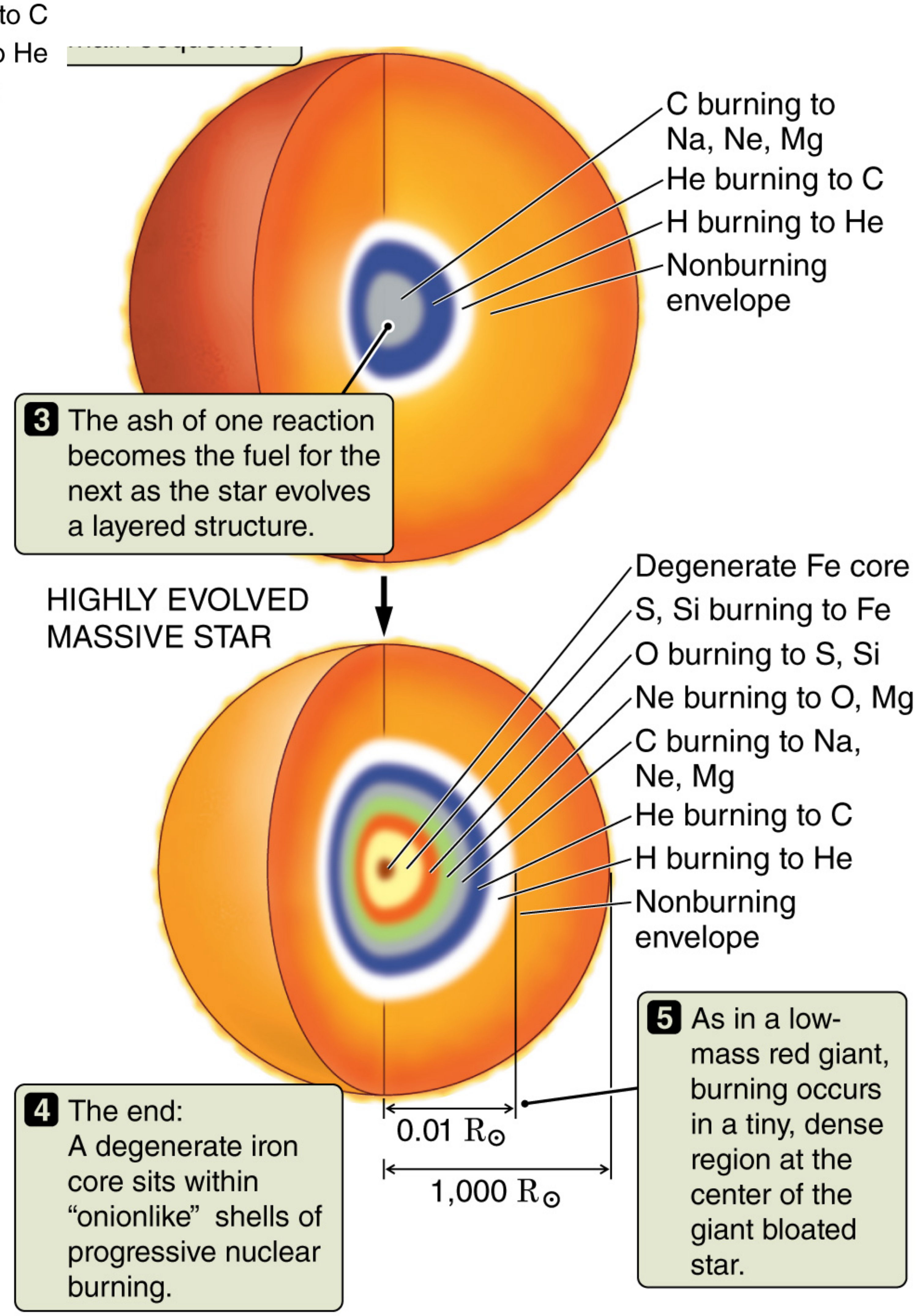
Brighter

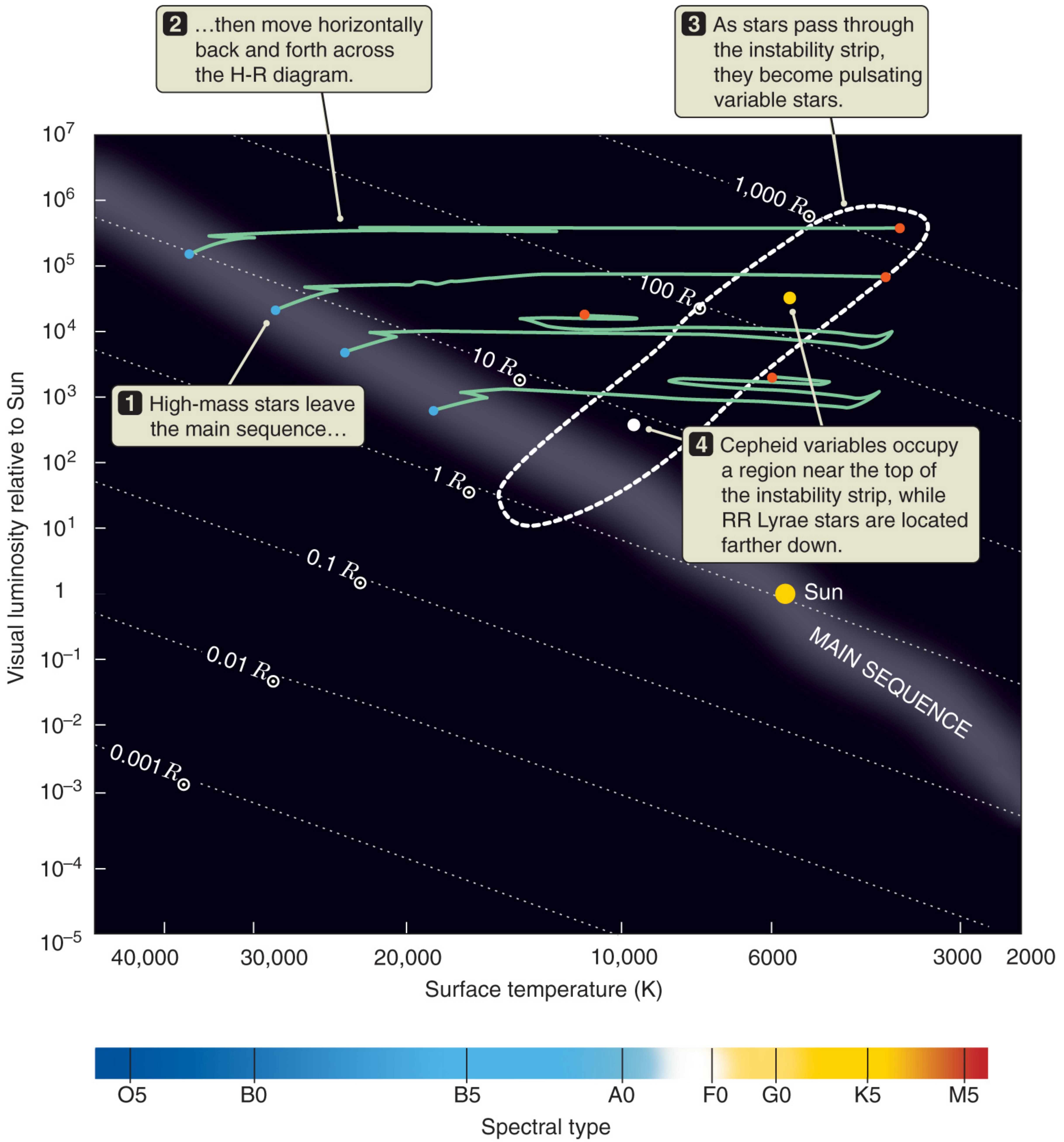
Fainter

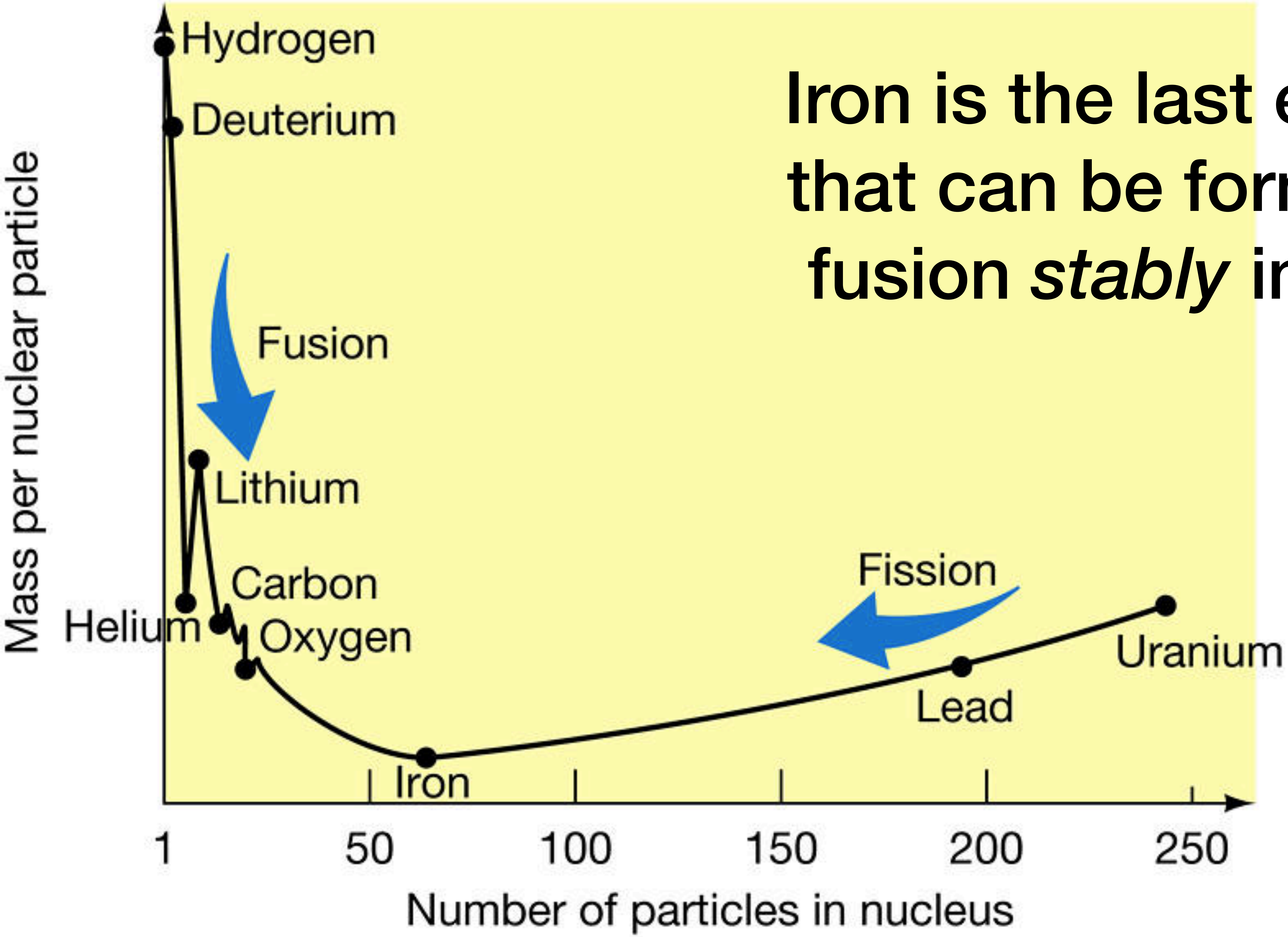
High Mass Stars = High Core Temps = CNO

Evolution of High Mass Stars



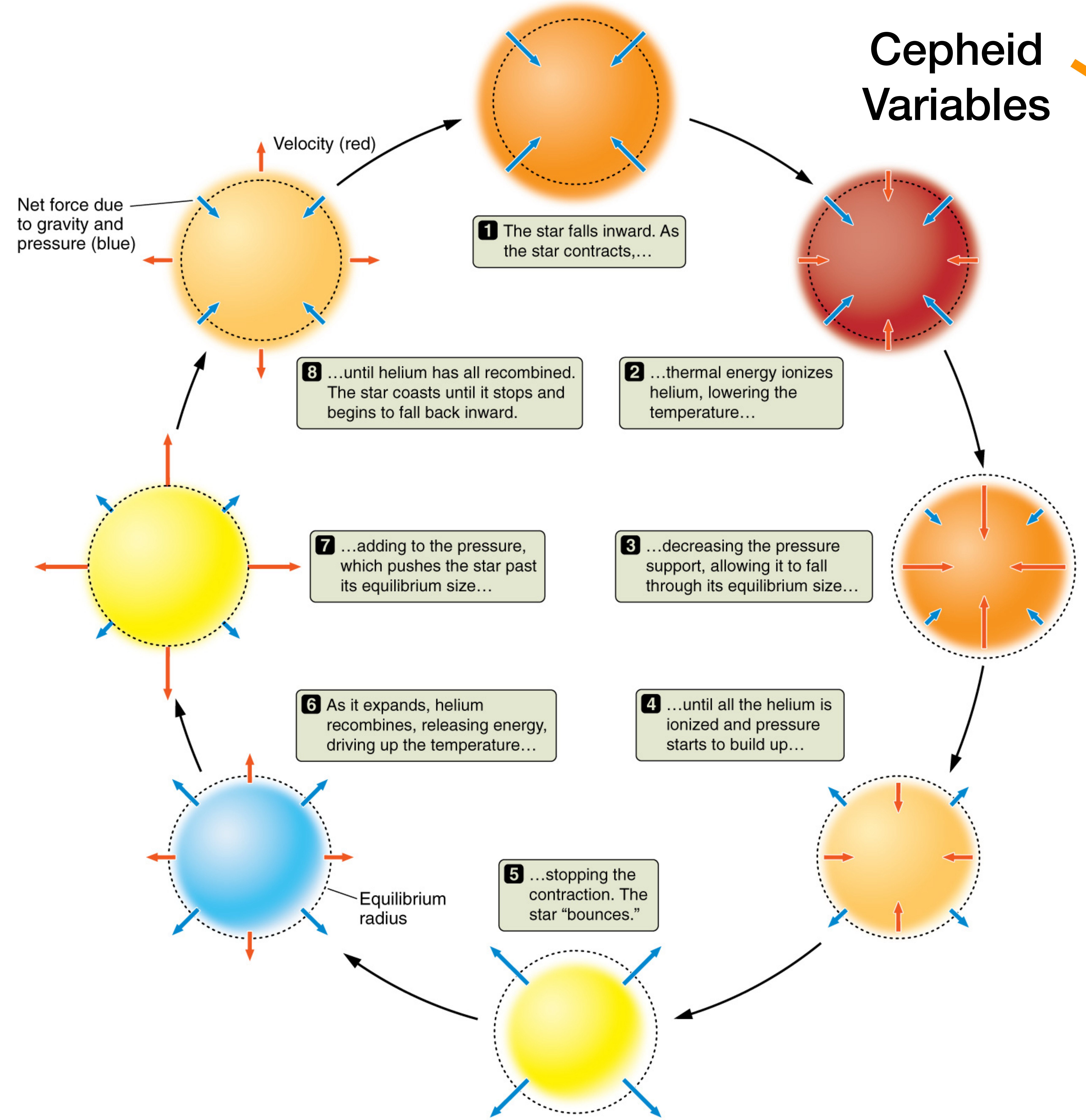


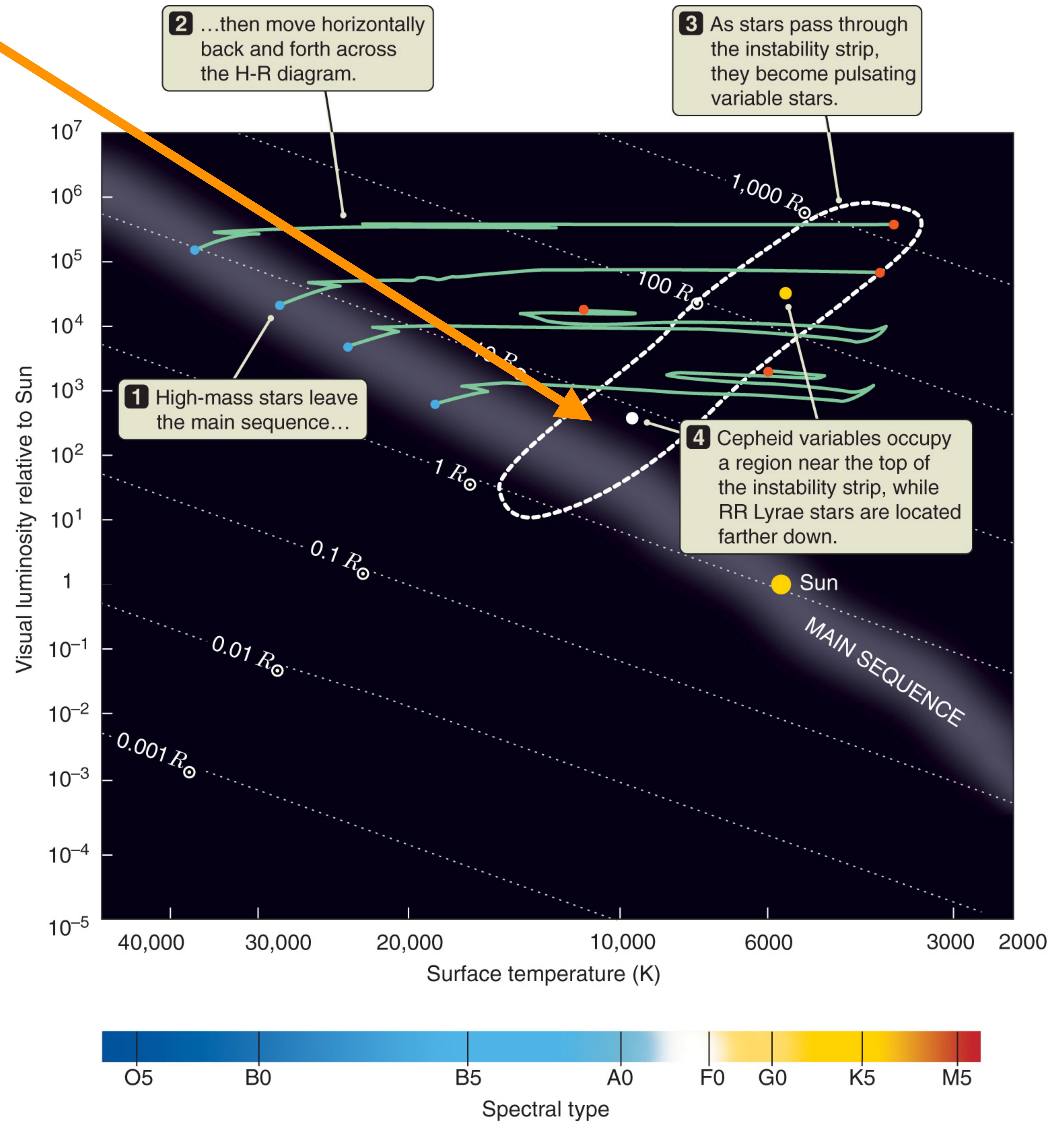




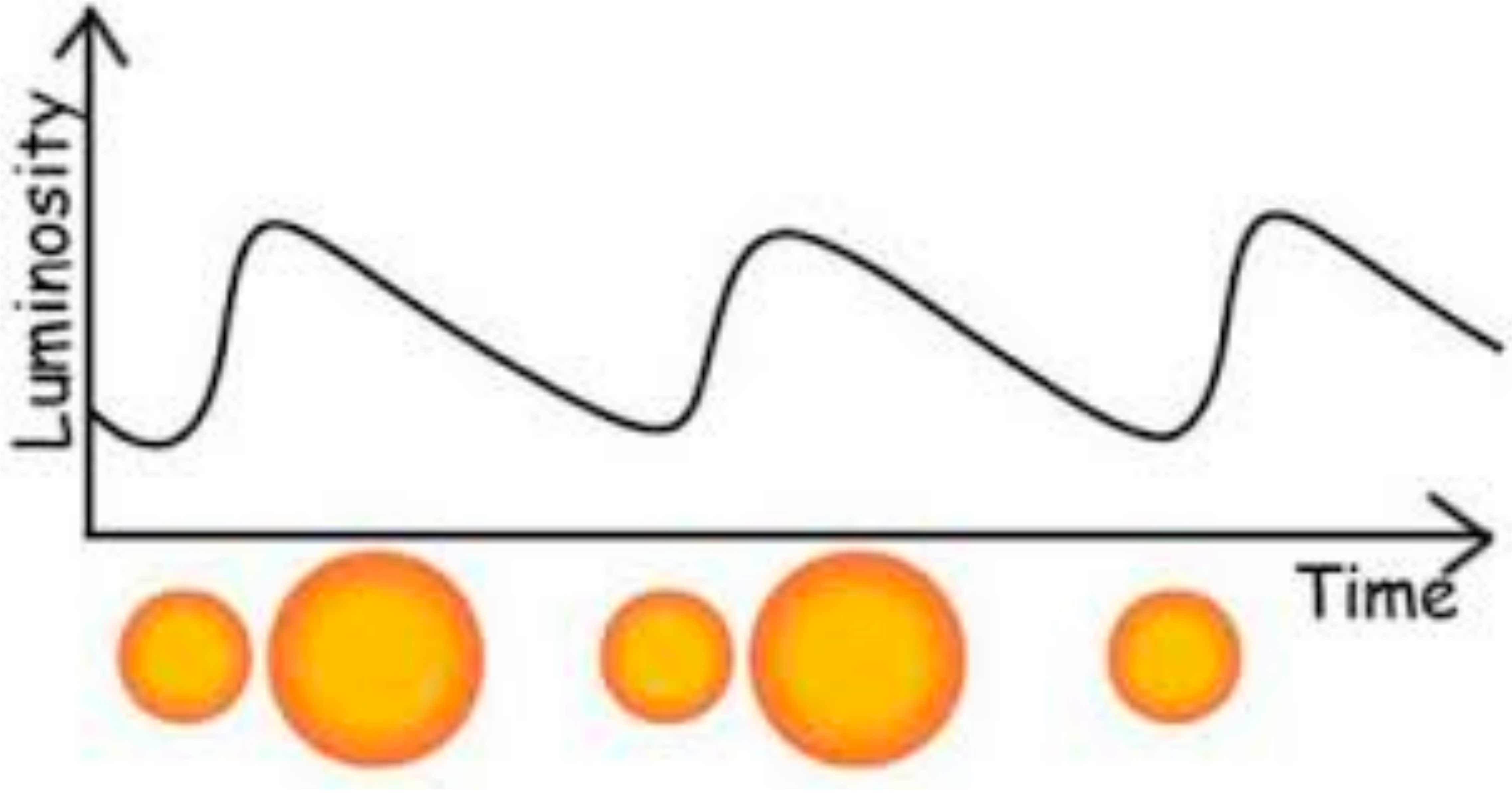
Iron is the last element that can be formed via fusion *stably* in a star

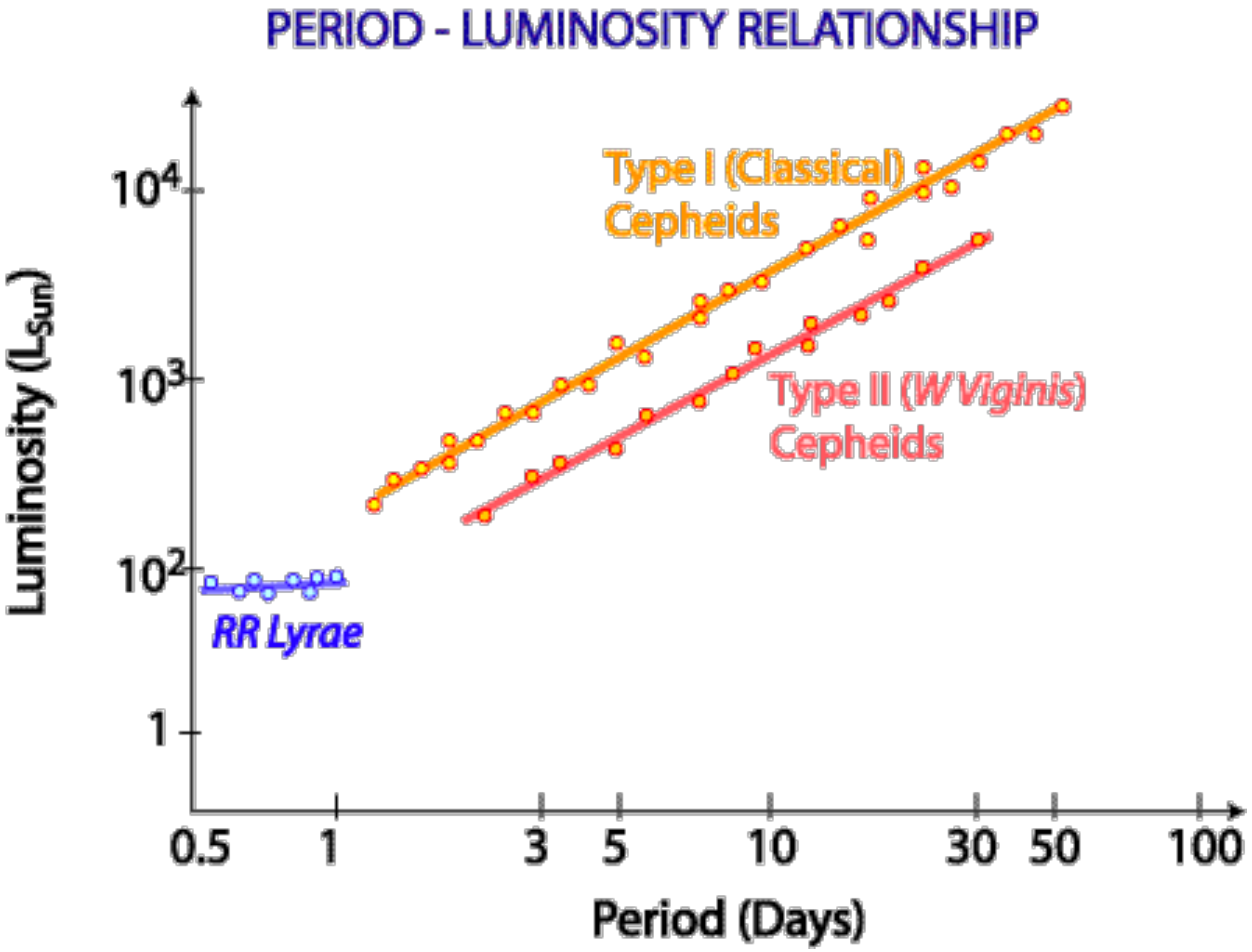
Cepheid Variables





A Cepheid's luminosity can be inferred





Empirically discovered by Henrietta Leavitt in 1912

$$\overline{M}_V = -2.76 \log(P/10 \text{ days}) - 4.16$$

$$\log(d/10 \text{ pc}) = 0.2(\overline{m}_V - \overline{M}_V)$$

Stellar Remnants: White Dwarfs, Neutron Stars, & Black Holes

Degeneracy Pressure

As stellar evolution proceeds, cores are supported by “degeneracy pressure” when there is no fusion to provide the necessary pressure to support the core against gravitational collapse.

—> acts as a “pressure floor”

Source of this pressure come from the rules of QM — Pauli exclusion & uncertainty principles

$$\Delta x \Delta p \geq \hbar$$

Material getting maximally compressed, so electron momentum/velocity driven by that compression, NOT the temperature of the material!

$$P_{\rm th} = n_e kT \sim n_e m_e v_{\rm th}^2 \quad \text{b/c} \quad v_{\rm th} \approx \sqrt{\frac{kT}{m_e}}$$

$$v_{\rm th} \approx \frac{\Delta p}{m_e} \sim \frac{\hbar n_e^{1/3}}{m_e} \quad \text{b/c} \quad \Delta x \sim V^{1/3} \sim n_e^{-1/3}$$

$$\boxed{P_{\rm degen} \sim n_e m_e (\Delta v)^2 \sim \frac{\hbar^2 n_e^{5/3}}{m_e}}$$

White Dwarfs

Leftover C core of a low mass ($M \sim 0.7\ M_\odot$) star

$$P_{\rm degen} \sim n_e m_e (\Delta v)^2 \sim \frac{\hbar^2 n_e^{5/3}}{m_e}$$ ⟵ Set these equal ⟶ $$P_{\rm c} \sim \frac{GM^2}{R^4}$$

$$n_e^{5/3} = \left(\frac{M}{m_p R^3}\right)^{5/3}$$

Solve for R

$$R \sim \frac{\hbar^2}{G m_e m_p^2}\left(\frac{M}{m_p}\right)^{-1/3} \approx 0.01 R_\odot \left(\frac{M}{0.7 M_\odot}\right)^{-1/3}$$

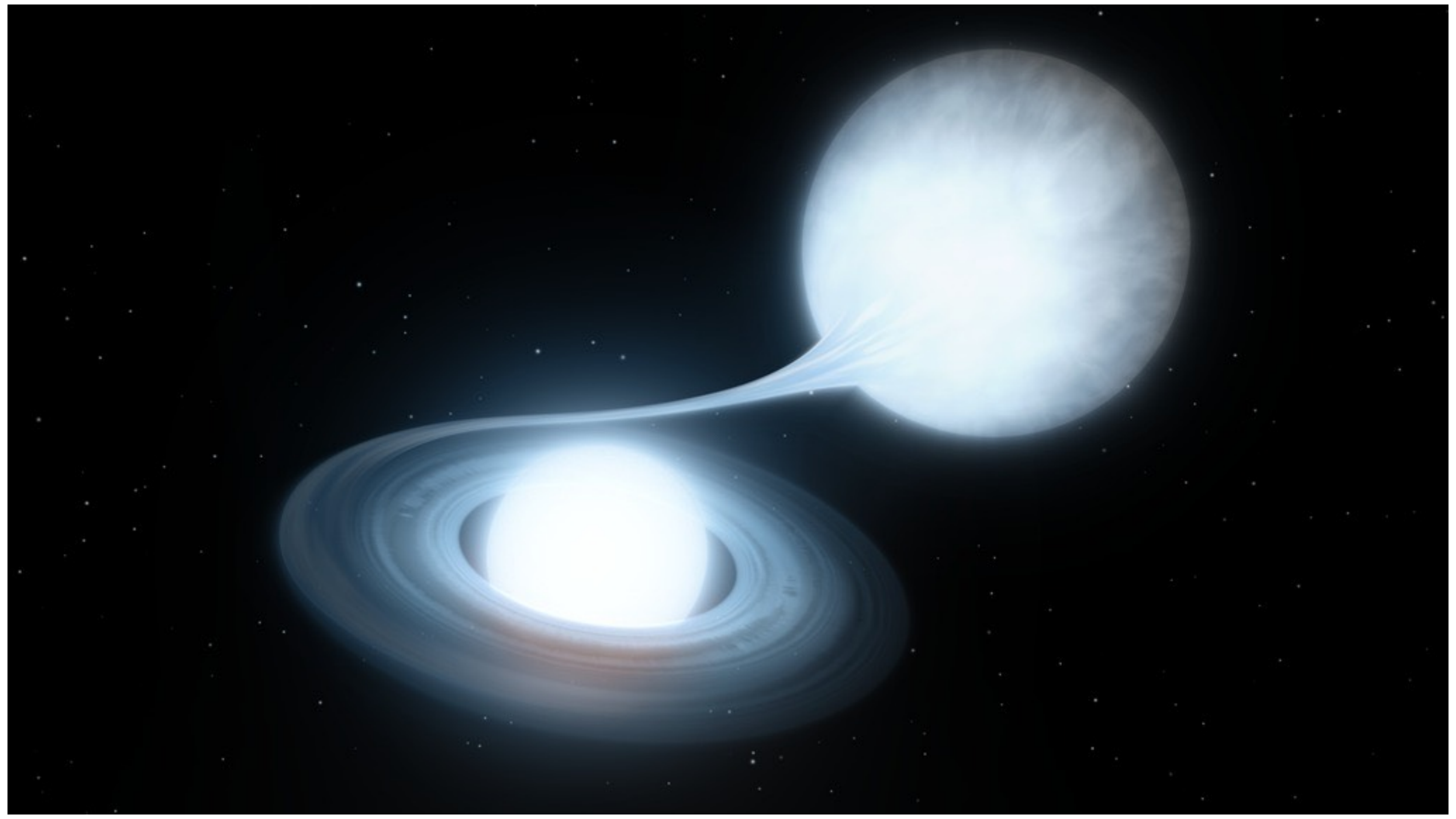
More massive WDs are smaller!

Why?

Also, because they have M~$M_{\rm sun}$ but are 100x smaller, their surface gravity is much stronger, producing strongly pressure-broadened absorption lines

Can a White Dwarf have any mass?

$$P_{\rm degen} \sim n_e m_e (\Delta v)^2 \sim \frac{\hbar^2 n_e^{5/3}}{m_e}$$



As a WD becomes more massive, the pressure has to increase — what will cause the pressure to max out?

$$\Delta v \sim c$$

$$M_{\rm Ch} \sim \left(\frac{\hbar^3 c^3}{G^3 m_p^4}\right)^{1/2} \sim 2M_\odot$$

Called the Chandrasekhar mass
Modern calculations give 1.4 M_{sun}

Initial mass of star	WD type
$M < 0.5M_\odot$	He
$0.5M_\odot < M < 5M_\odot$	C/O
$5M_\odot < M < 7M_\odot$	Ne/Mg

Neutron Stars are supported by neutron degeneracy pressure

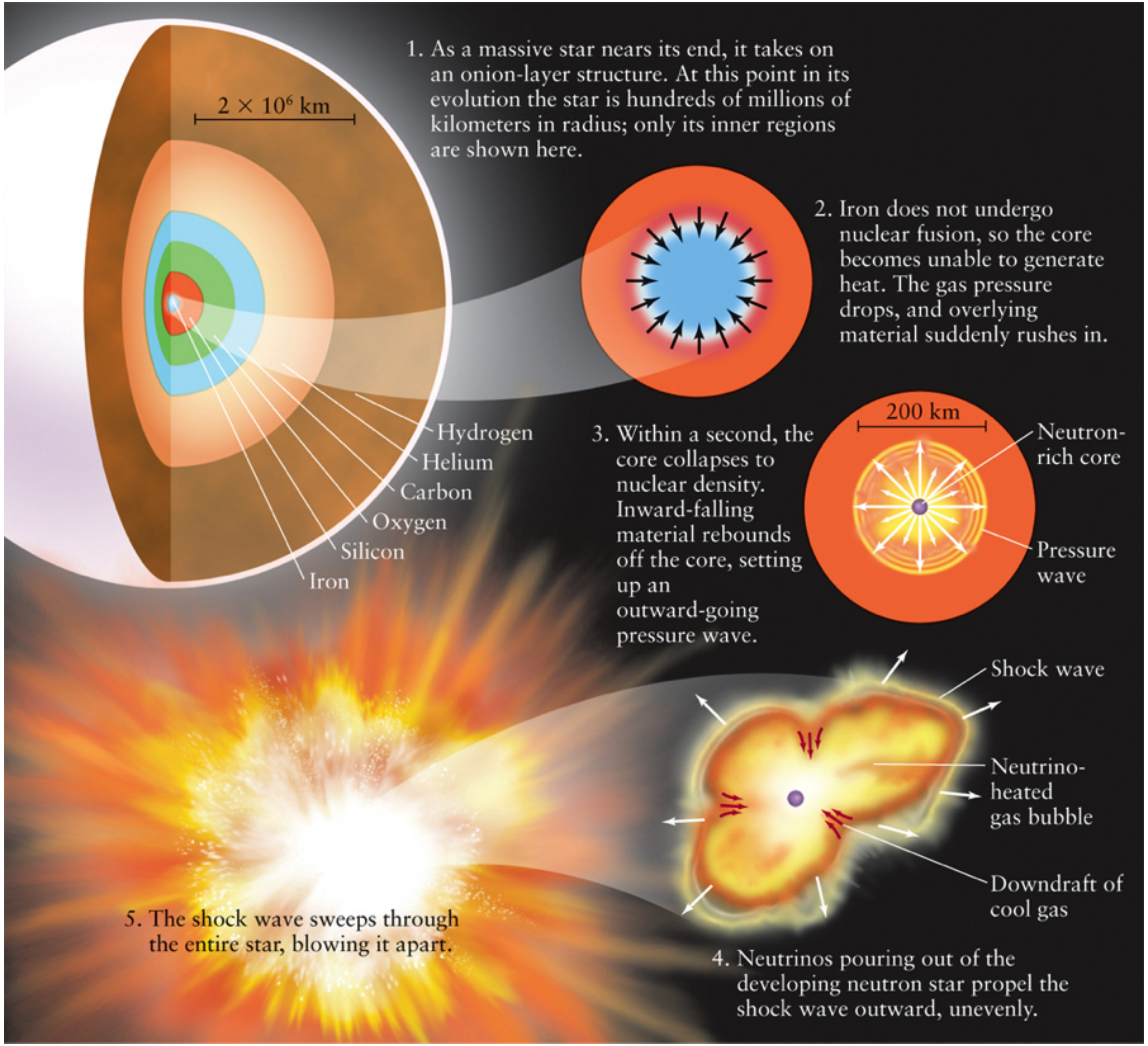
Supernovae!

Electron degeneracy pressure fails

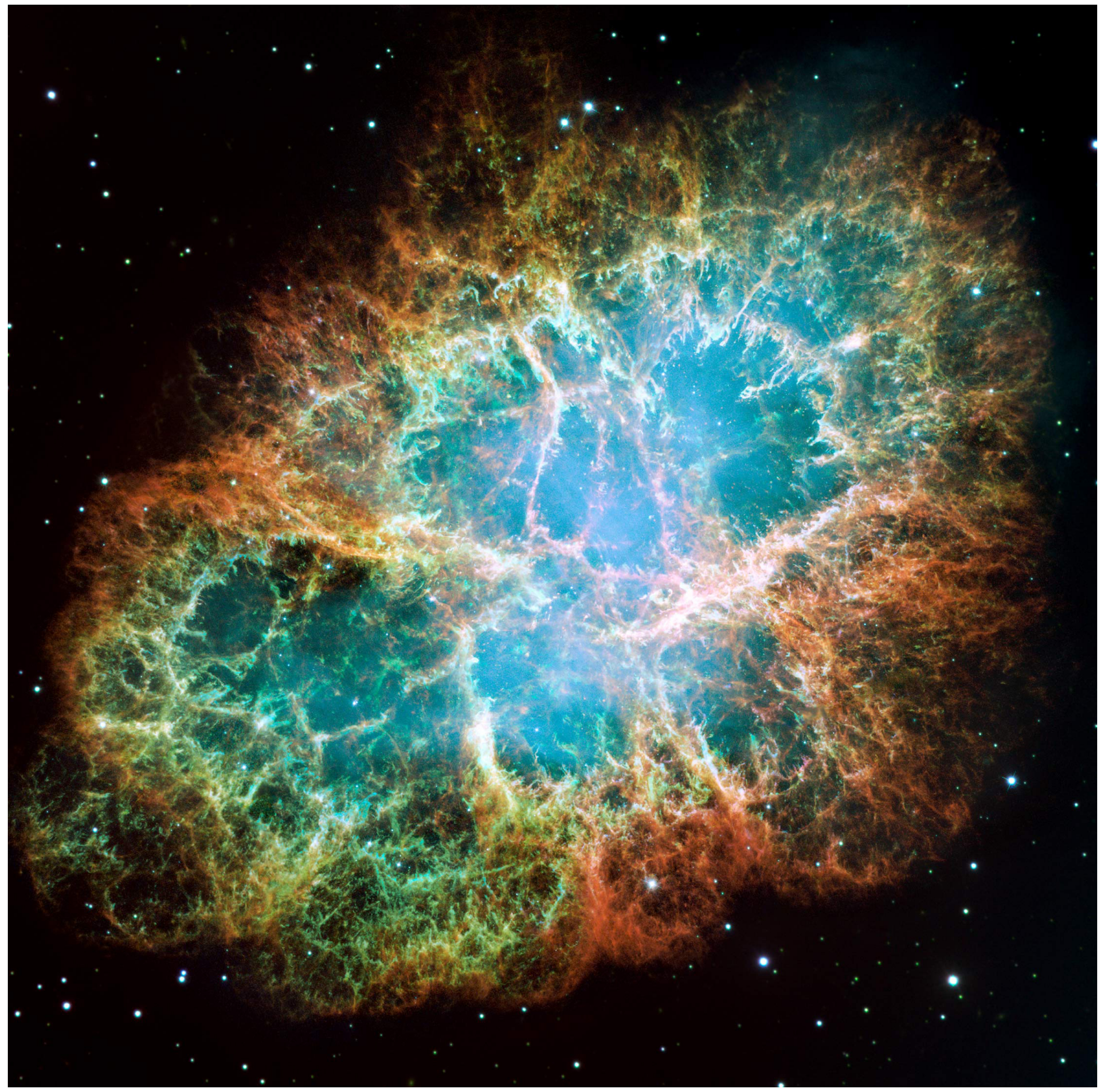
Electrons absorbed into protons in nuclei creating neutrons

$$p + e^{-} \rightarrow n + \nu_e$$

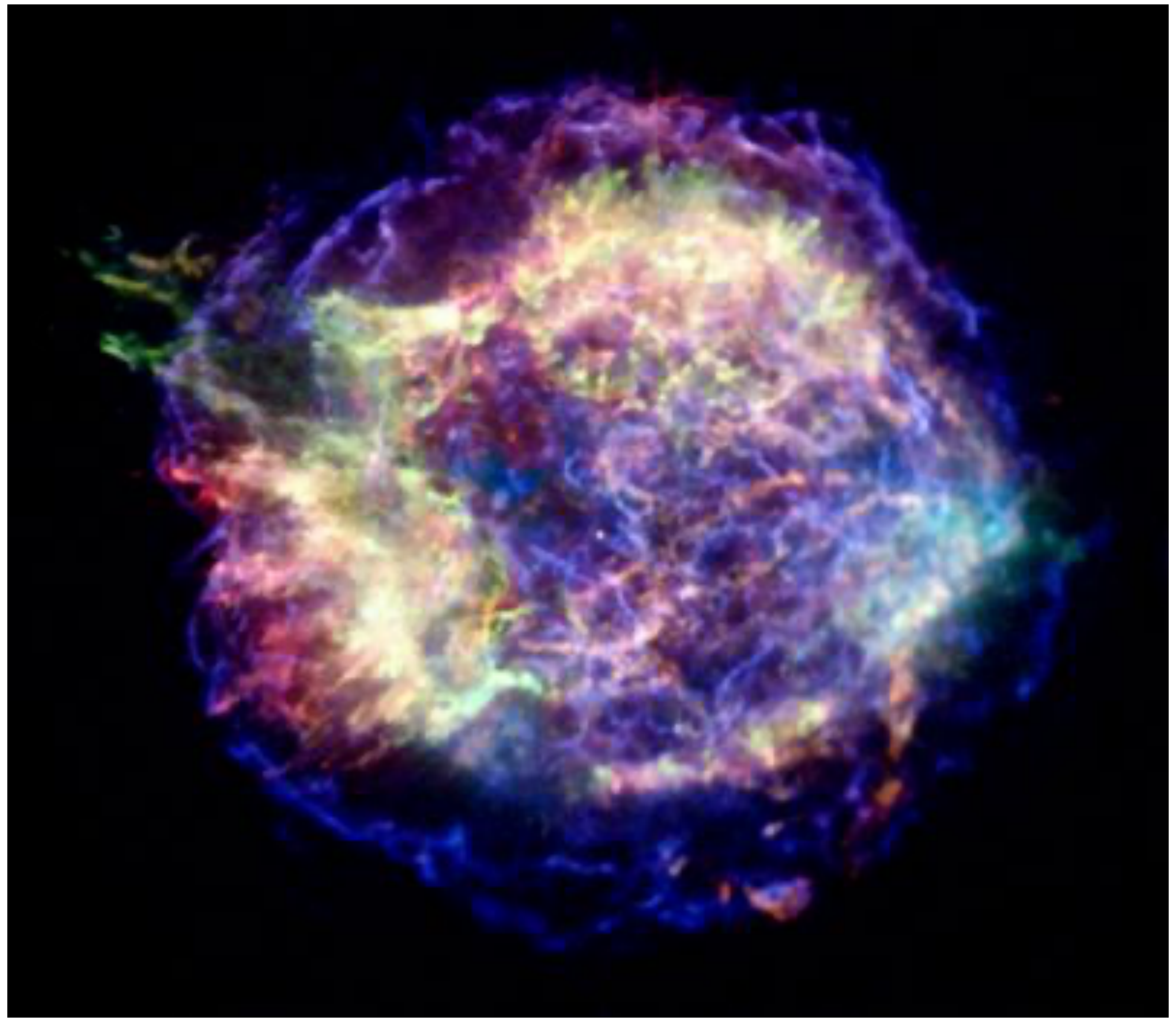
Outer layers bounce off of forming NS (or pressure wave), causing star to explode



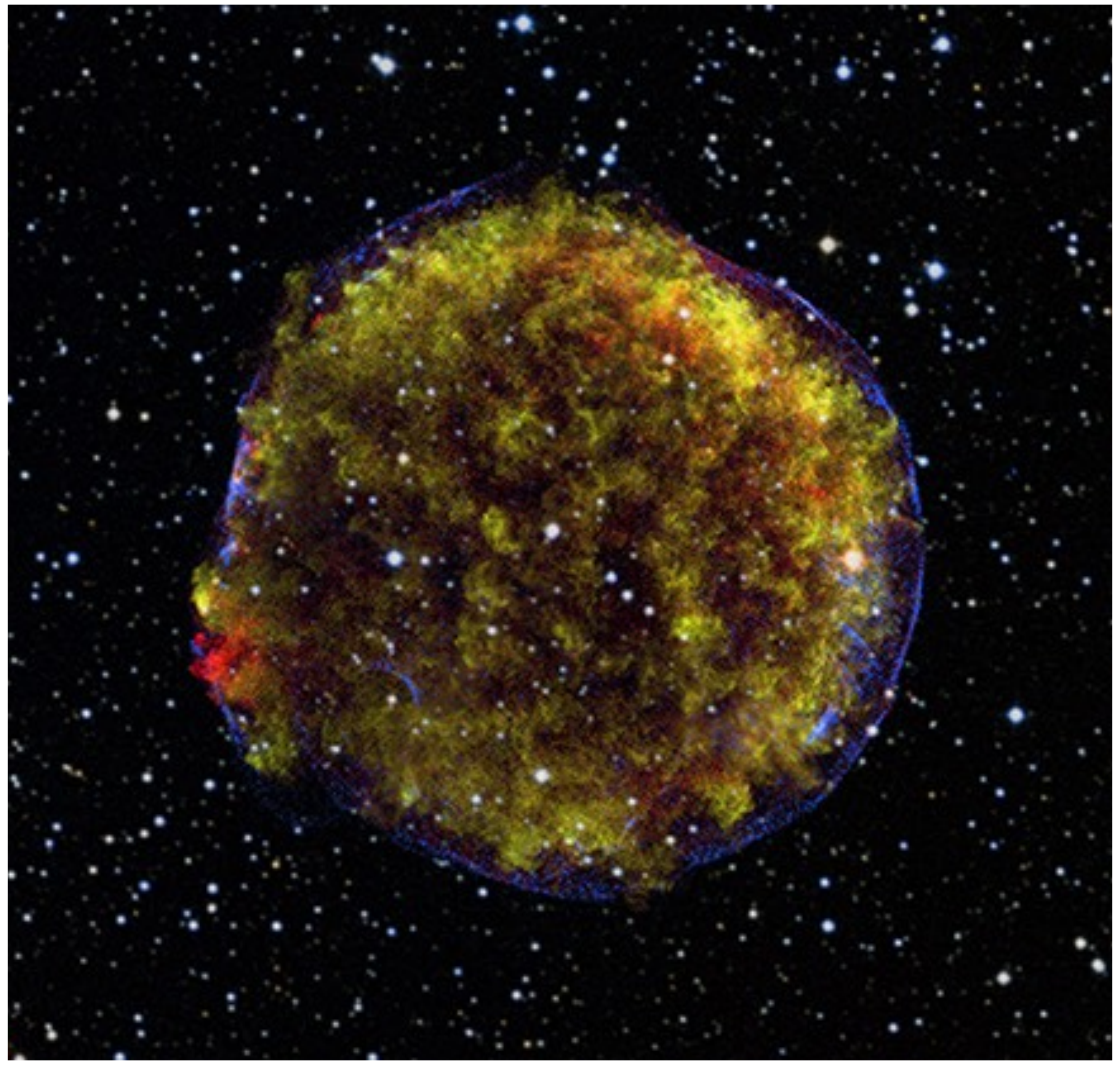
Historical SNe are now Supernova Remnants (SNRs)



Crab Nebula
1054

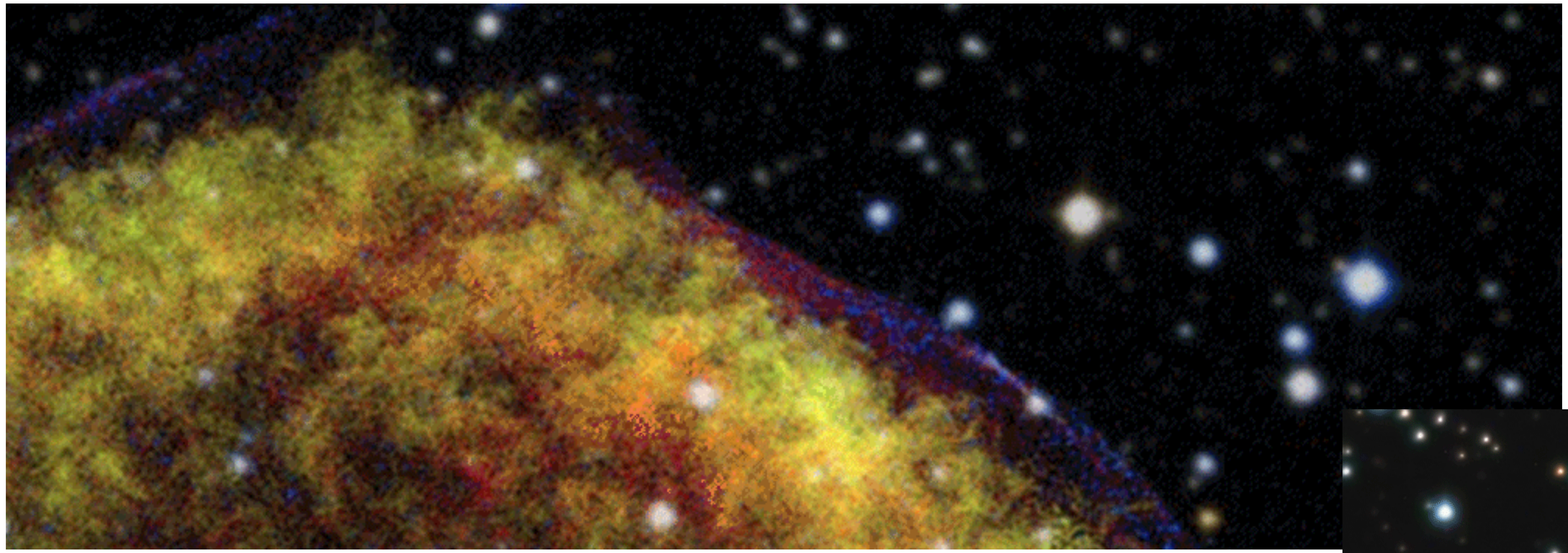


Cassiopeia A
~1680
(not clearly recorded)



Tycho SNR
1572

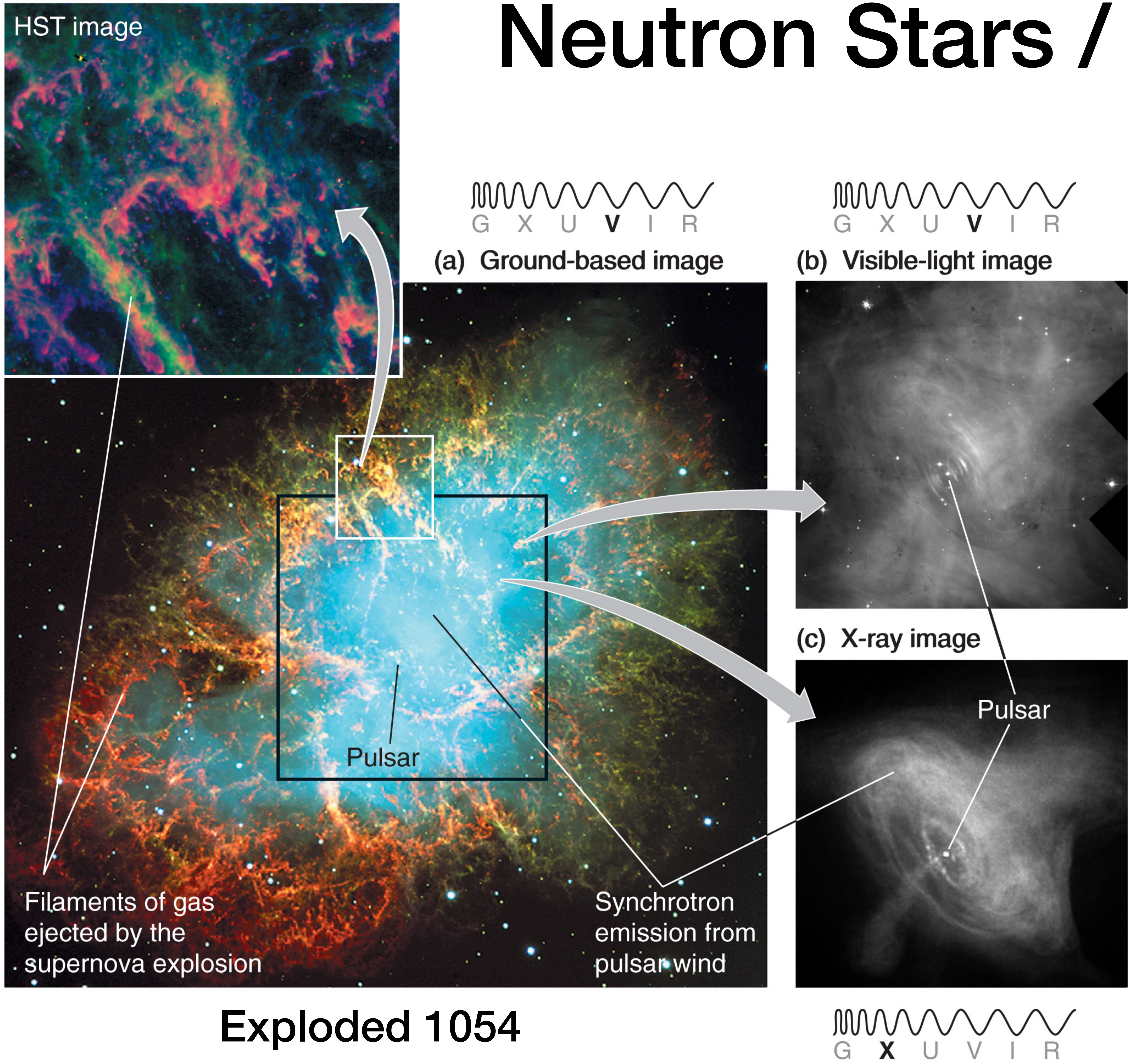
Can watch them expand!



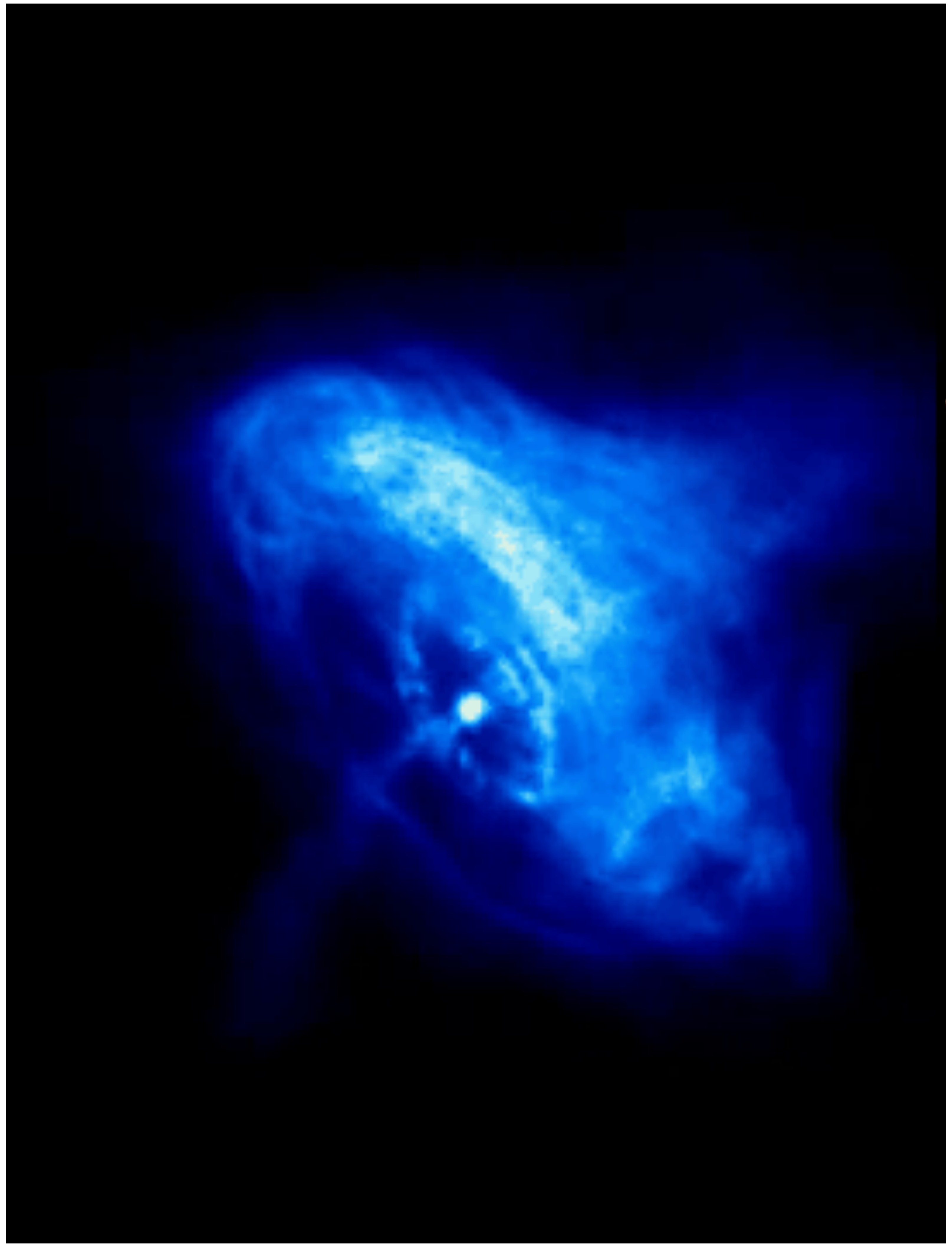
Tycho

Crab

Neutron Stars / Pulsars

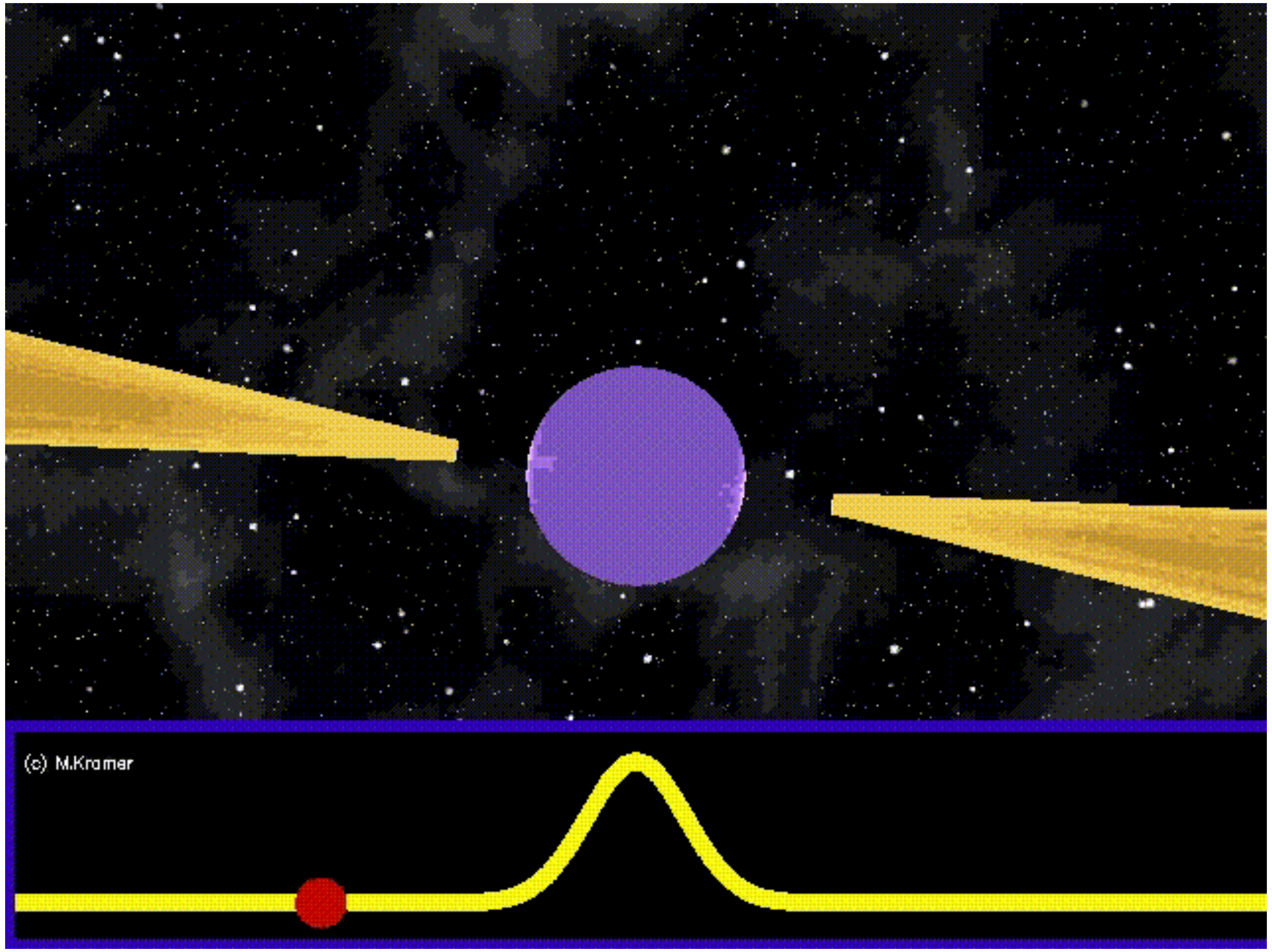


Exploded 1054



Pulsars emit pulses at all wavelengths

When formed, rotates with a period of ~ 10-100 ms



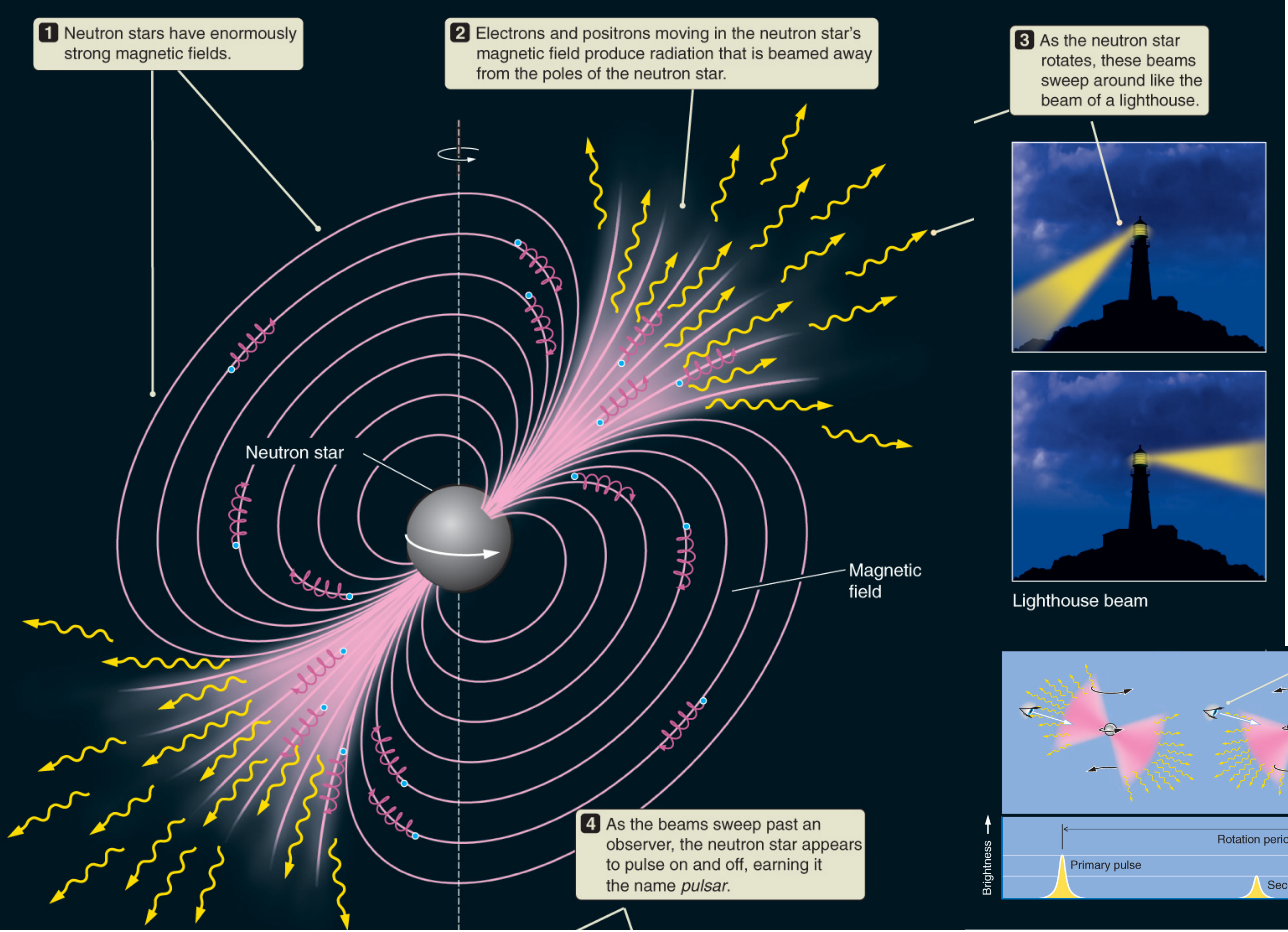
Realistic simulation of the magnetic field of a pulsar:

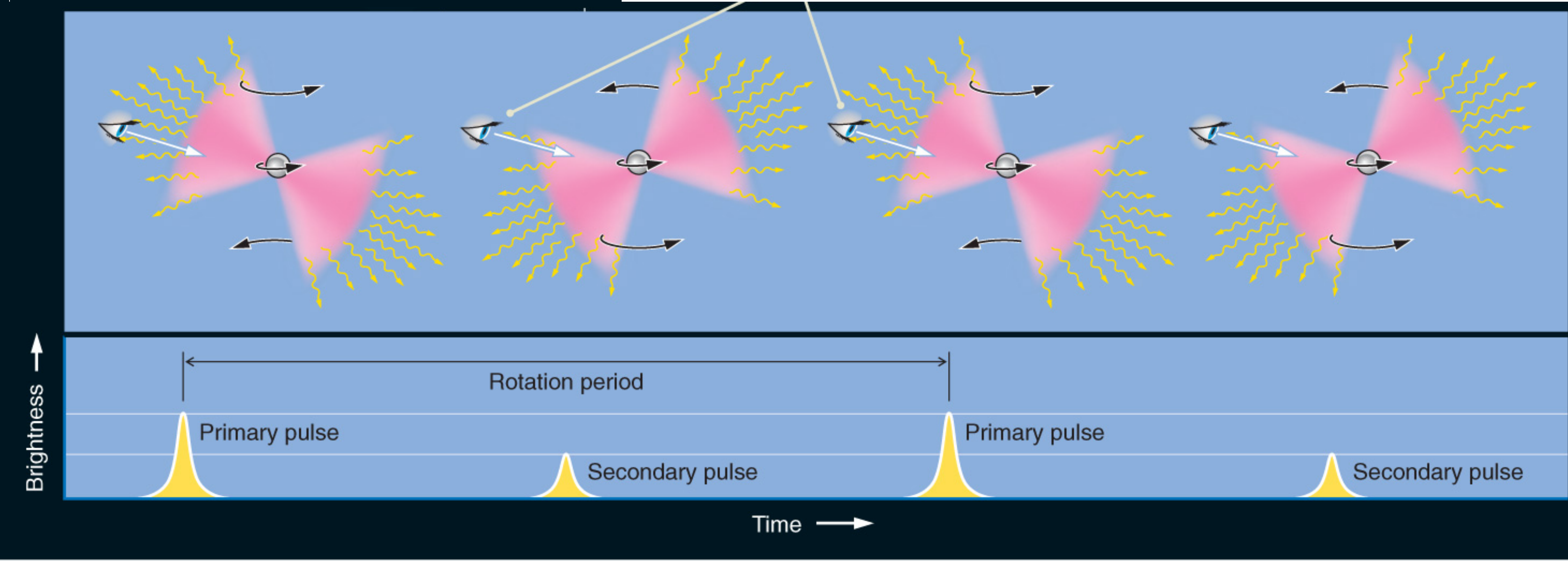
https://www.youtube.com/watch?v=jwC6_oWwbSE

Millisecond Pulsar:
https://www.youtube.com/watch?v=MPpDTvYL5ik

Black Widow Pulsar:

https://www.youtube.com/watch?v=-SoZ1xvCpMw





Neutron Stars are born with strong magnetic fields (get stronger as the core collapses)

Field accelerates electrons and positrons, which causes them to emit radiation across the spectrum

We see the beam once or twice each time the star rotates

Can a Neutron Star have any mass?

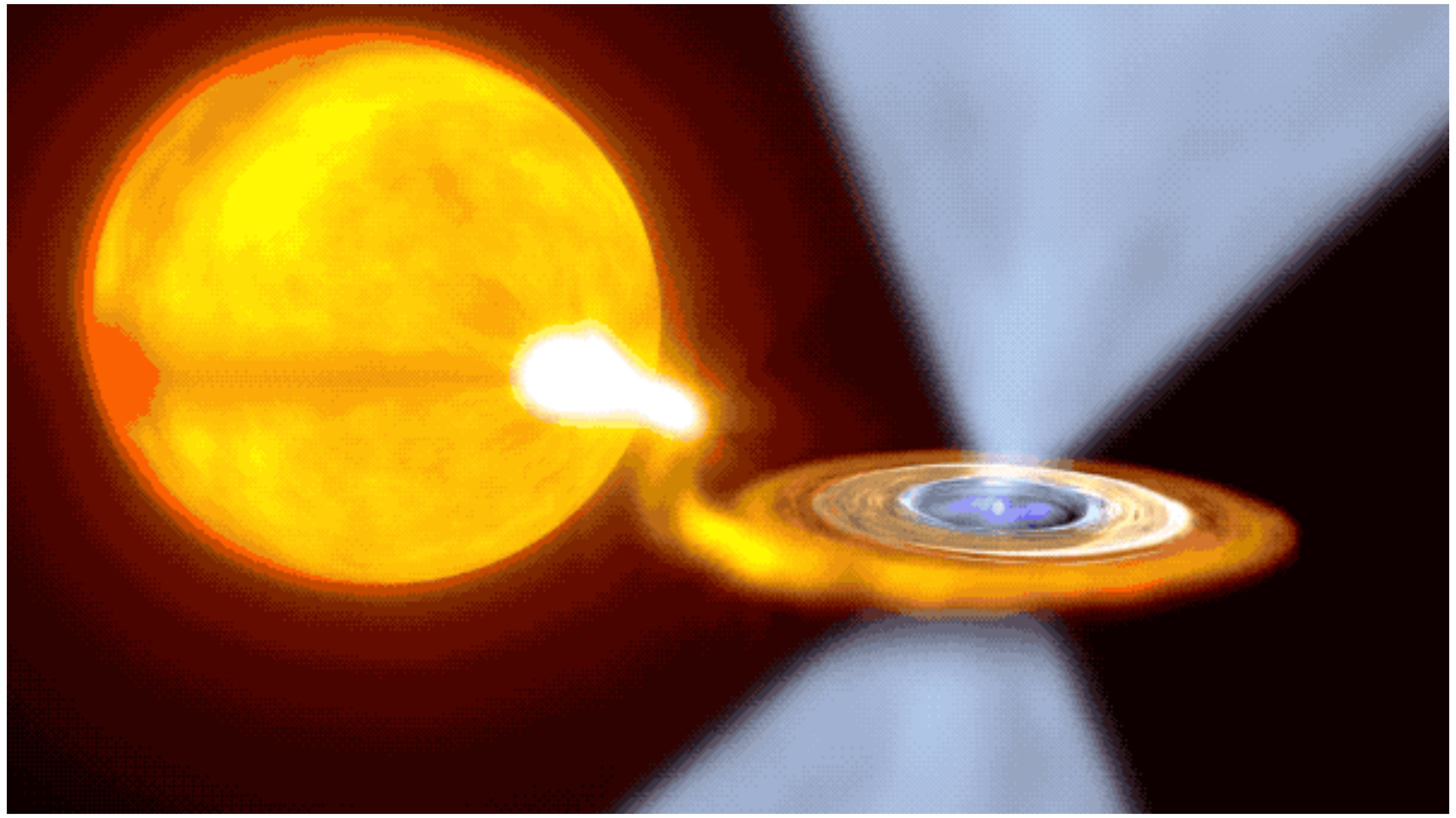
Neutron degeneracy pressure will also eventually fail

$$M_{\mathrm{max,NS}} \approx 3M_\odot$$

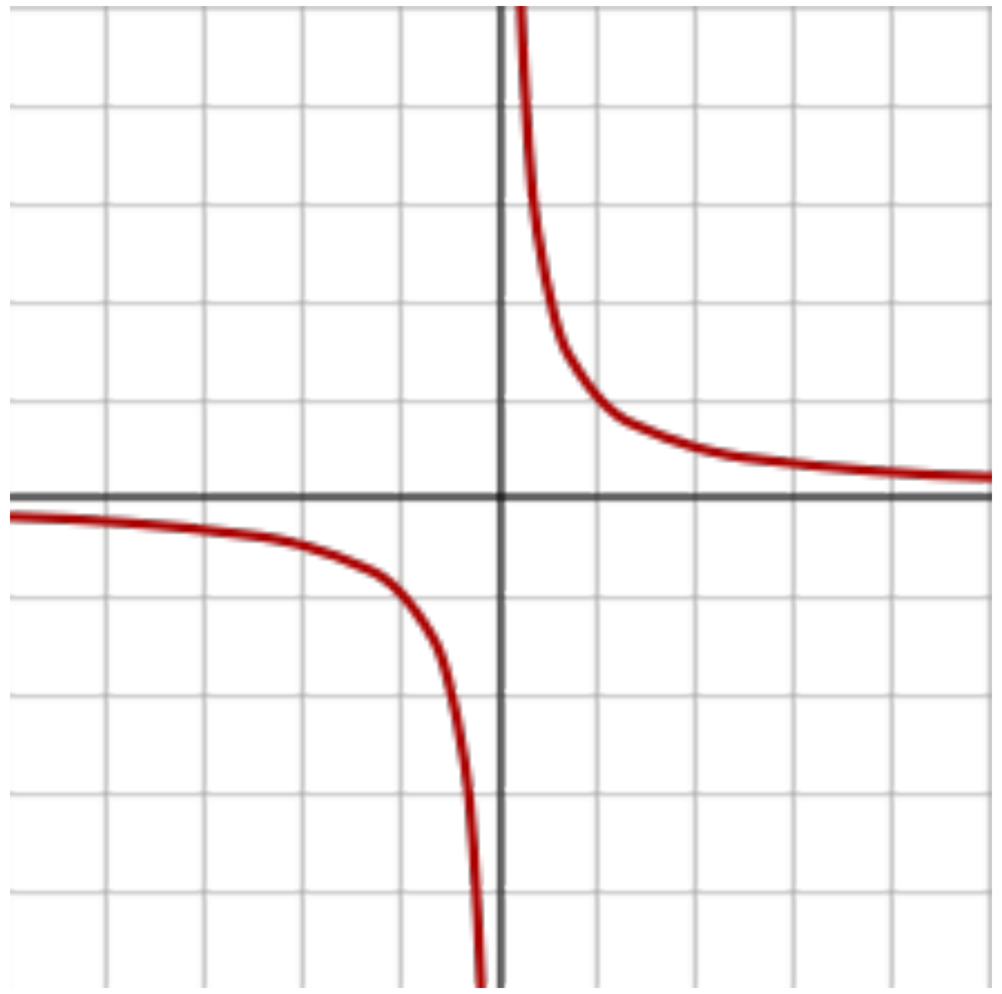
Once a NS reaches the critical mass, its collapse can no longer bed stopped. All of its mass will end up (as far as we know) in a single point at the center of the black hole, called the singularity.

Why is it called a singularity?

Roger Penrose won the Nobel Prize this year for mathematically proving that black holes must have singularities at their centers, *IF* general relativity is the correct theory of gravity.



$$f(x) = \frac{1}{x}$$



Black Holes

If the Sun suddenly collapsed and formed a black hole, what would happen to the Earth?

For a spherically symmetric object, its gravitational force (outside the object) is identical to that of an object with the same mass all at r = 0 —> exactly the case of a black hole!

The escape speed for a BH is the same as usual then, but b/c we can get much closer to them, the escape speed can get really high

$$v_{\rm esc} = \left(\frac{2GM}{r}\right)^{1/2}$$

Set $v_{\rm esc}$ = c (speed of light)

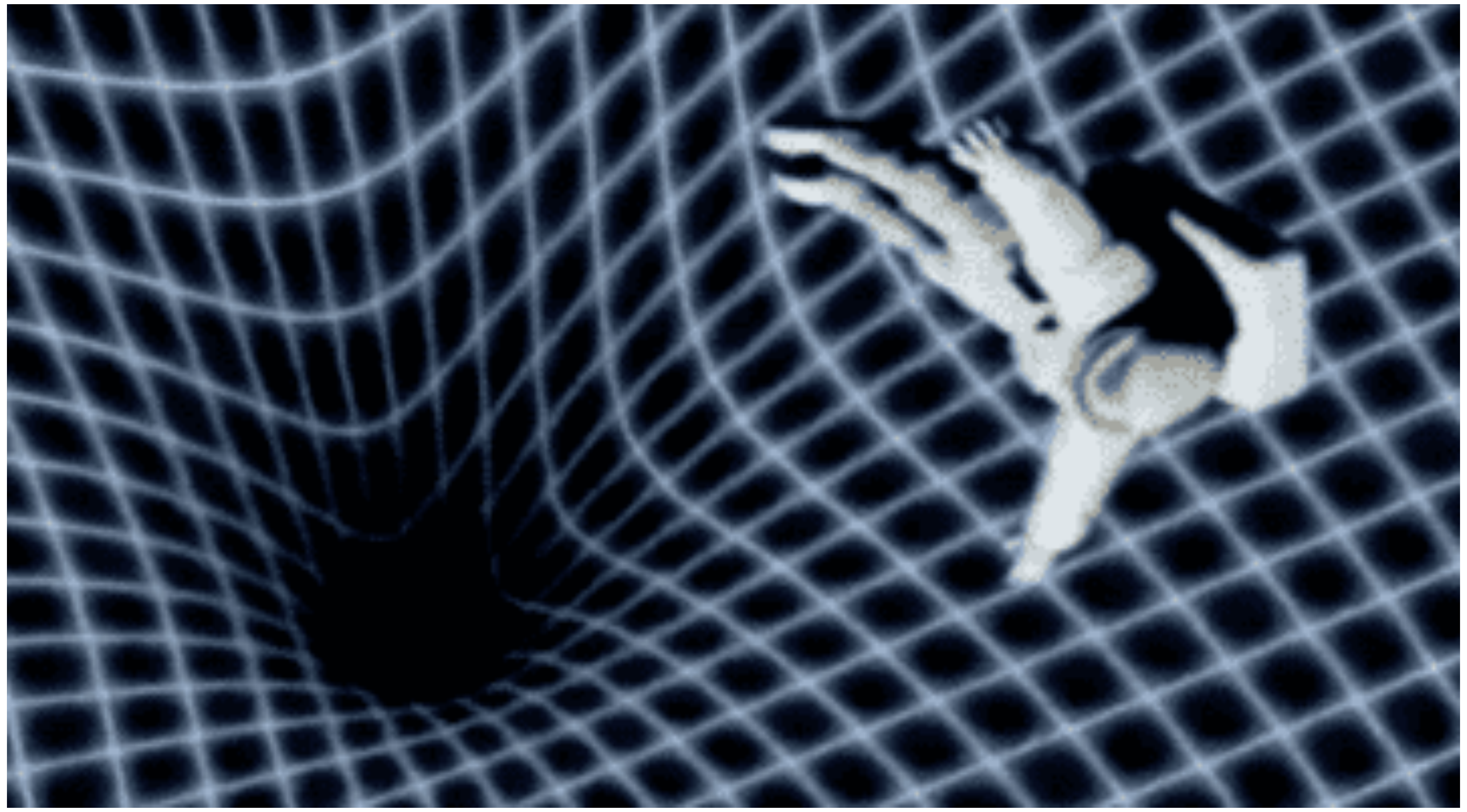
$$r_{\rm Sch} = \frac{2GM}{c^2}$$

<u>Schwarzschild radius</u>

The spherical surface defined by this radius is called the <u>event horizon</u>

Black Holes

Spaghettification



F_g changes so quickly with radius that gravitational tidal forces (the difference in F_g between your head and your feet) become strong enough to rip you apart as you fall towards a BH's singularity

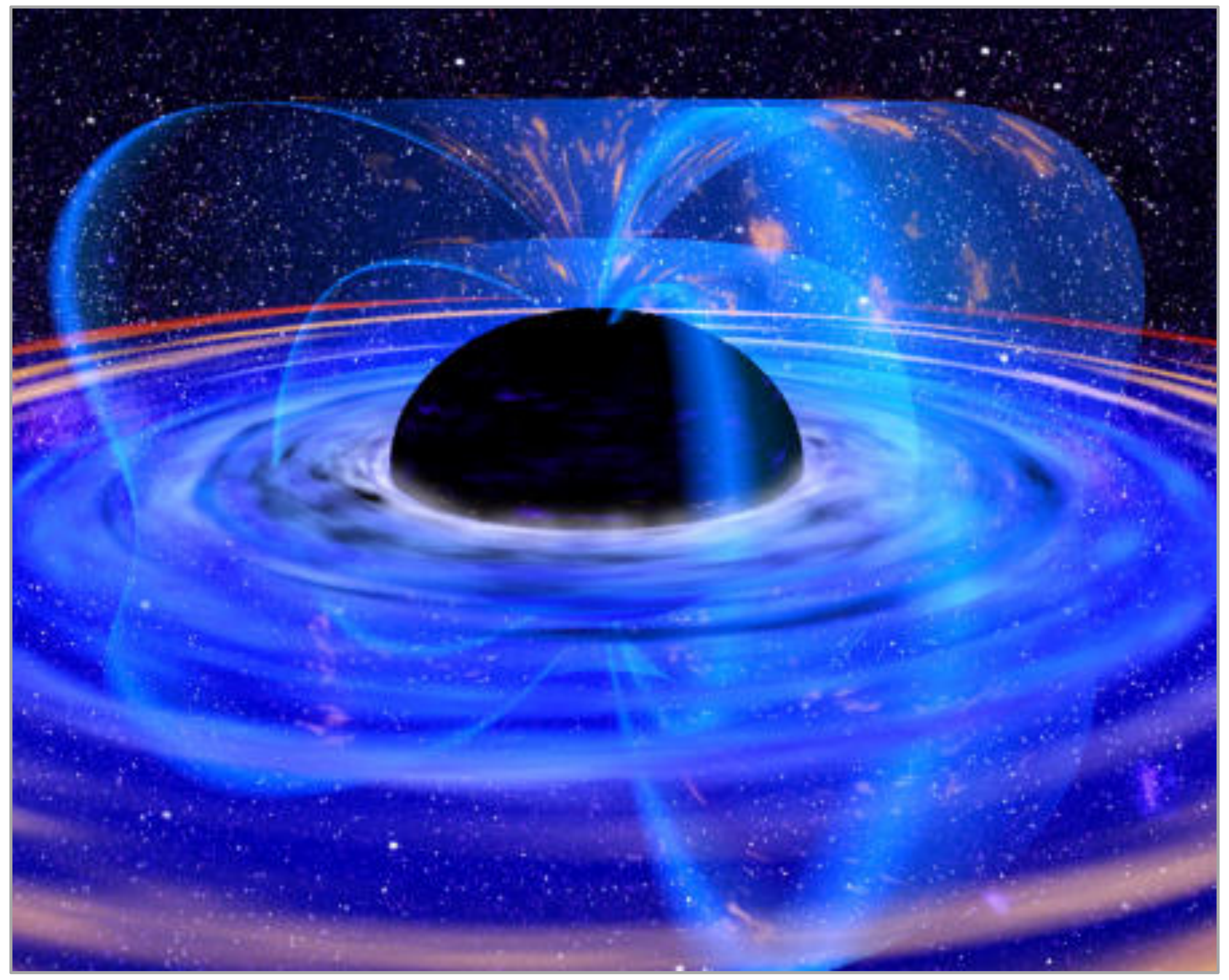
$$\Delta F \approx \frac{GMm}{r^3}\ell$$

Your mass (m)

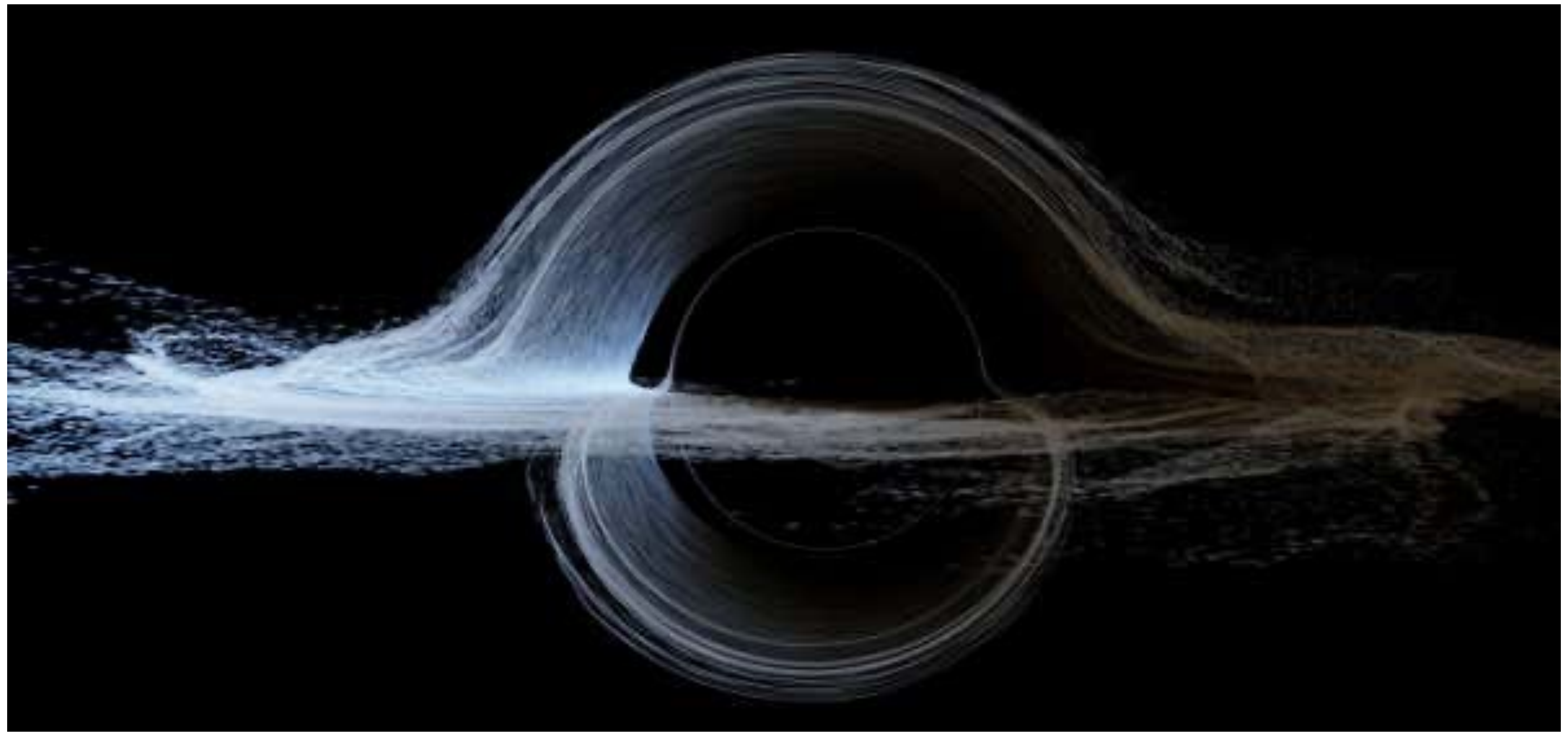
Your height (ℓ)

Other effects (e.g., explaining *Interstellar*)

BH with accretion disk (no gravitational lensing)



What it would actually look like



<u>Gravitational Lensing</u>

Light follows shortest path b/t 2 points, but space-time curved, so light rays are curved

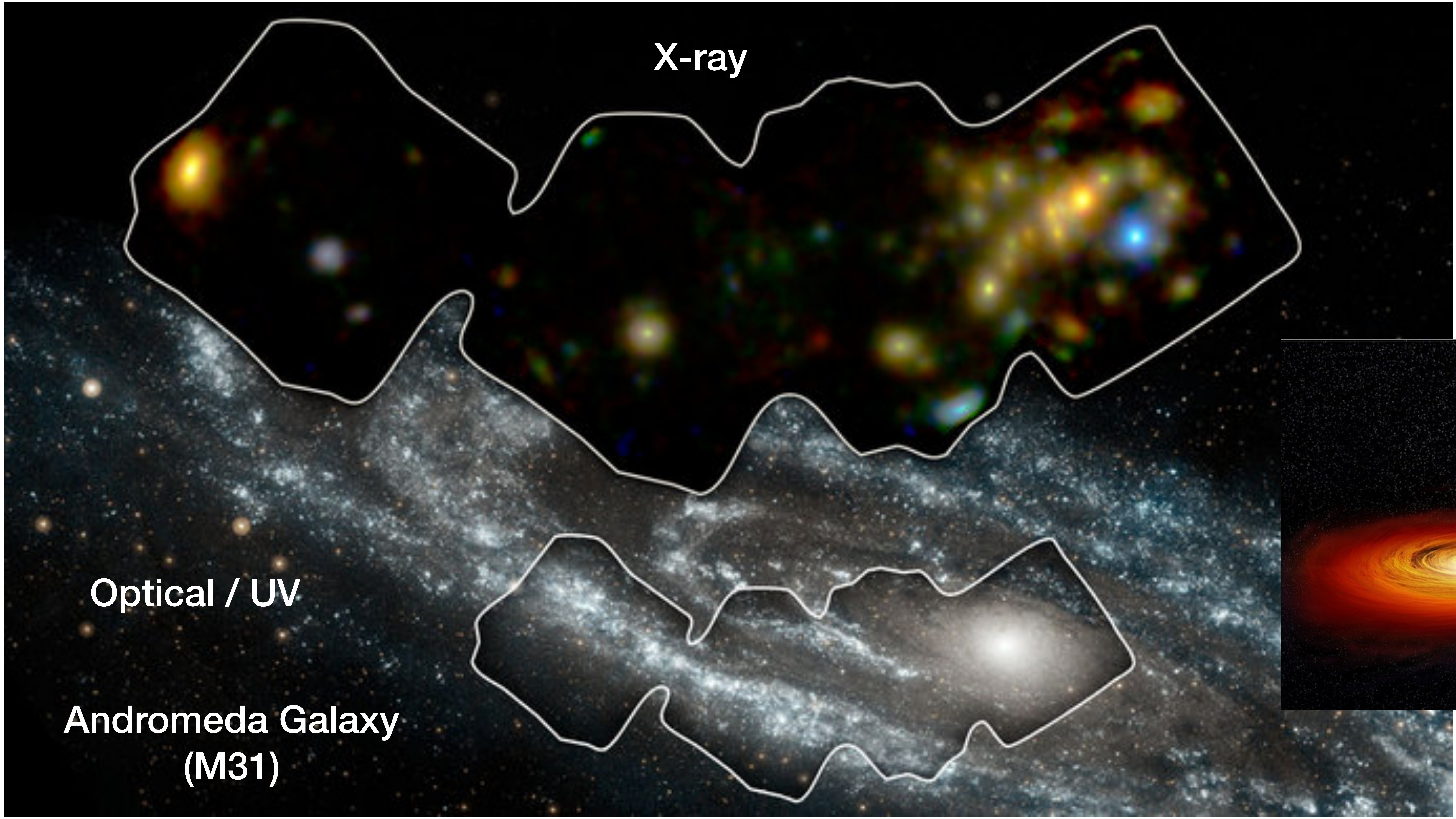
<u>Time Dilation</u>

Time passes slower the closer you are to a massive object (GPS satellite clocks "have more ticks" than our clocks in a given interval of time)

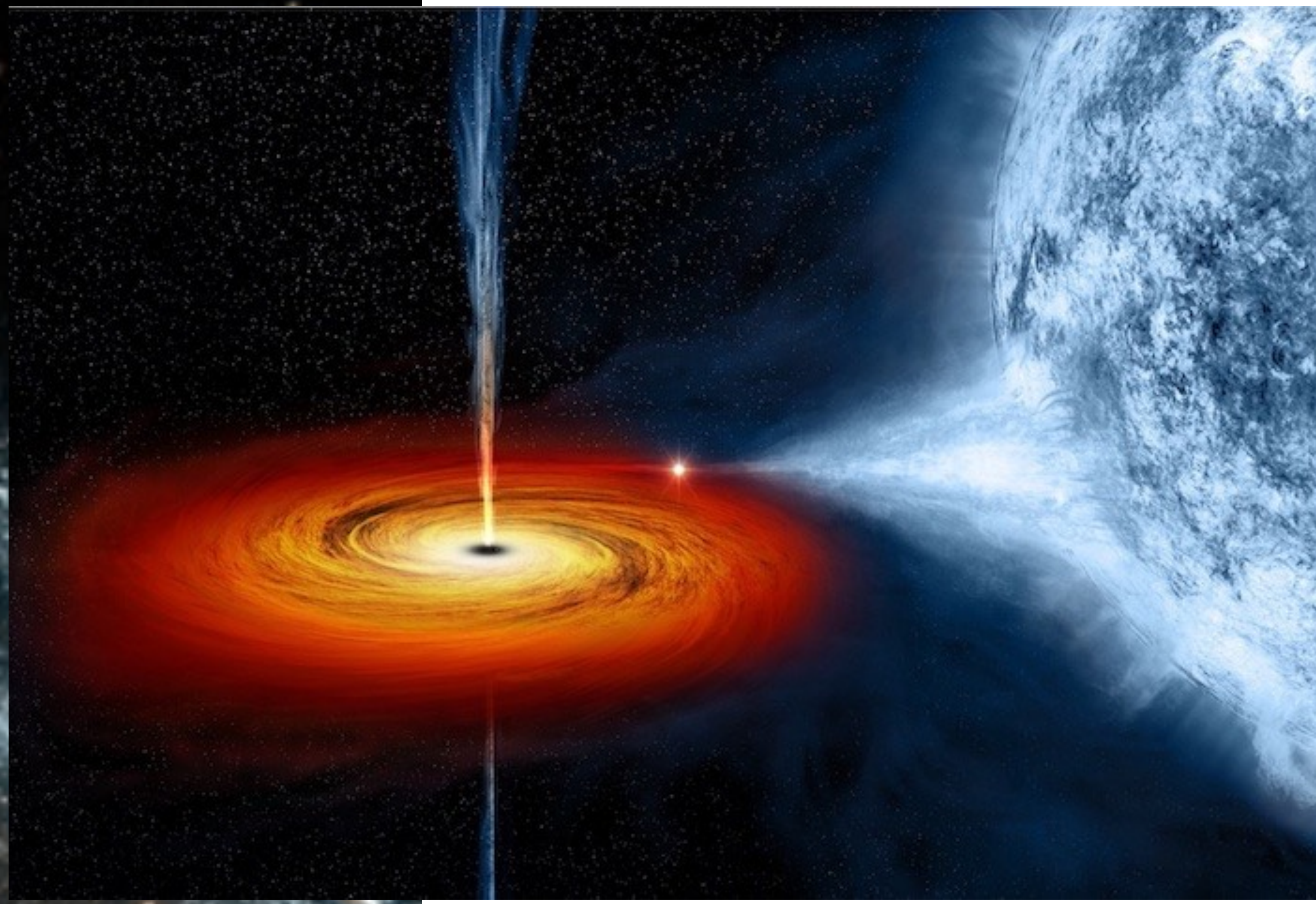
<u>Gravitational Redshift</u>

Light has to "climb out" of a gravitational potential well, losing energy — light with less energy has a longer wavelength (just outside the event horizon, light is nearly infinitely redshifted)

Observing real NSs and BHs



__X-ray Binaries__
Close binary stars where 1 star has exploded and is now accreting matter from its companion



Star's life determined mostly by its initial mass

White Dwarf:

$M < 7M_\odot$

Neutron Star:

$7M_\odot < M < 18M_\odot$

Black Hole:

$M > 18M_\odot$