Week 12 Tuesday

Today's Agenda

- ISM outro
- Star formation
- Evolution of a low mass star
- Evolution of a high mass star

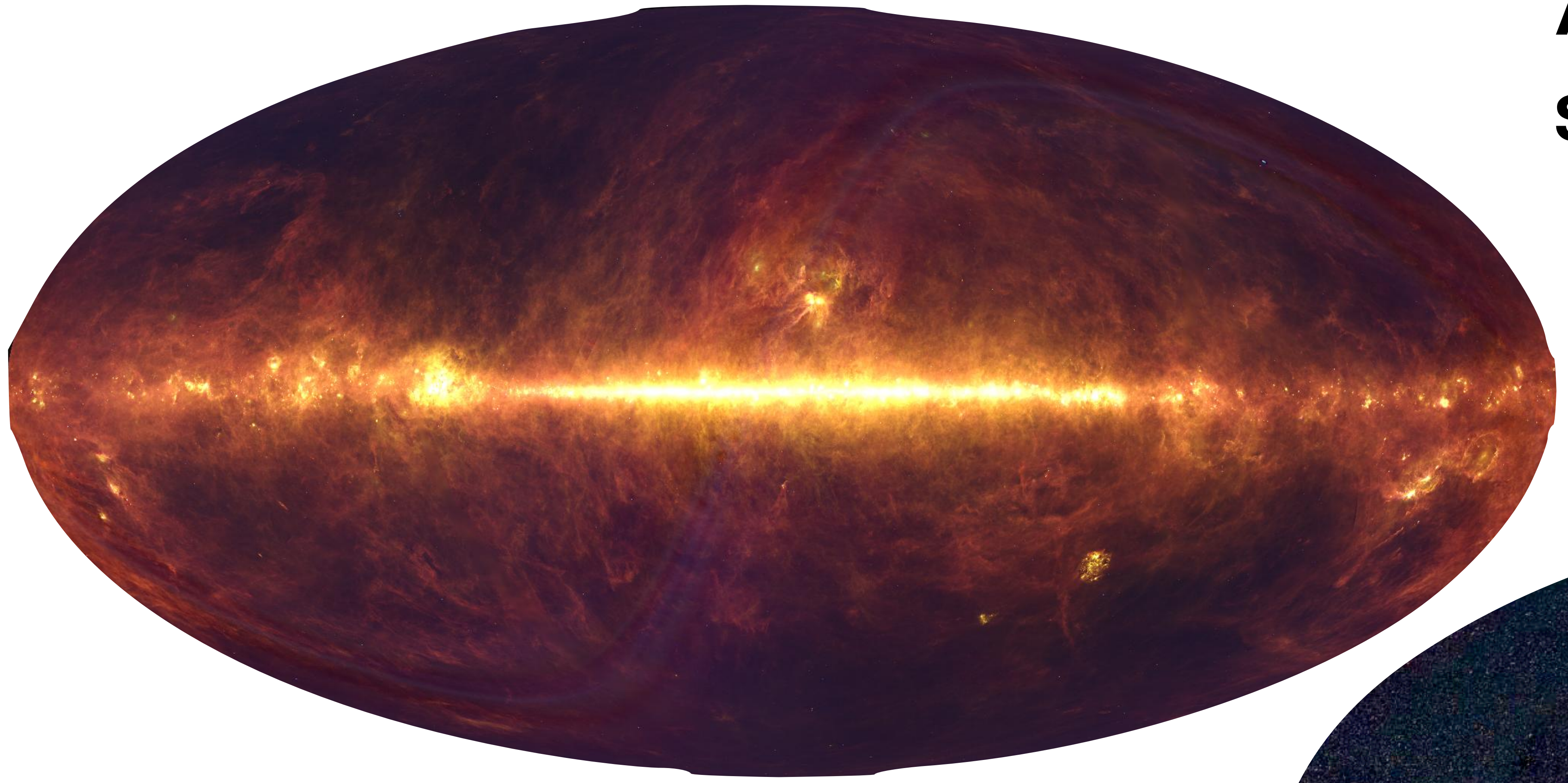
Announcements / Reminders

- Midterm 2 THIS Thursday!!!!
- HW 8.3 & Paragraph describing your project due Friday 1min before midnight

- HEAP talk at 4pm on Thursday
  - EFT Constraints from Neutrino Experiments
- Colloquium at 2pm on Friday
  - Emerging Frontiers at the Intersection Between Photon Sciences, Molecular Dynamics, and Light-Matter Interactions

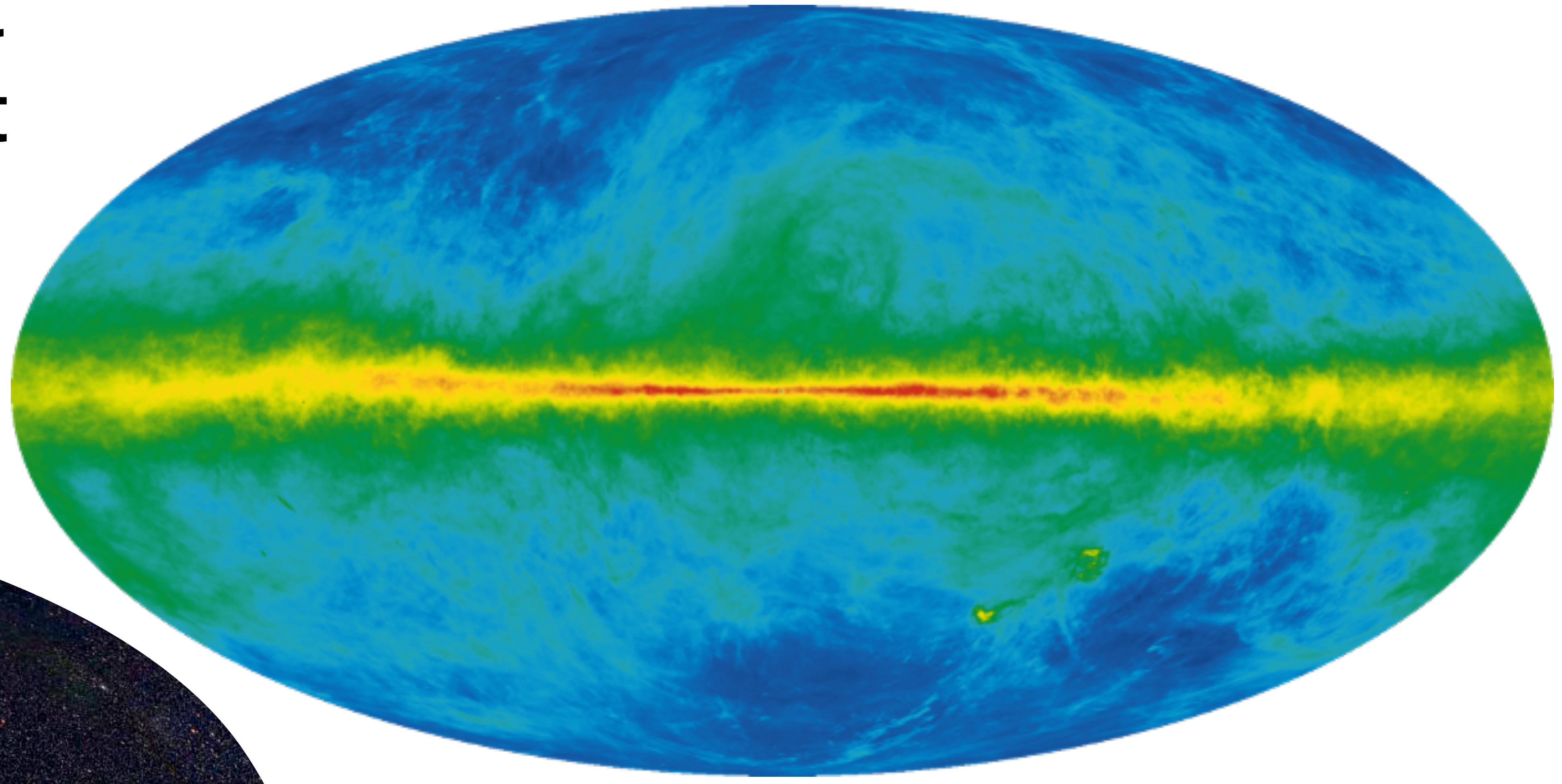
Interstellar Medium (ISM)

Hot Dust (far IR)

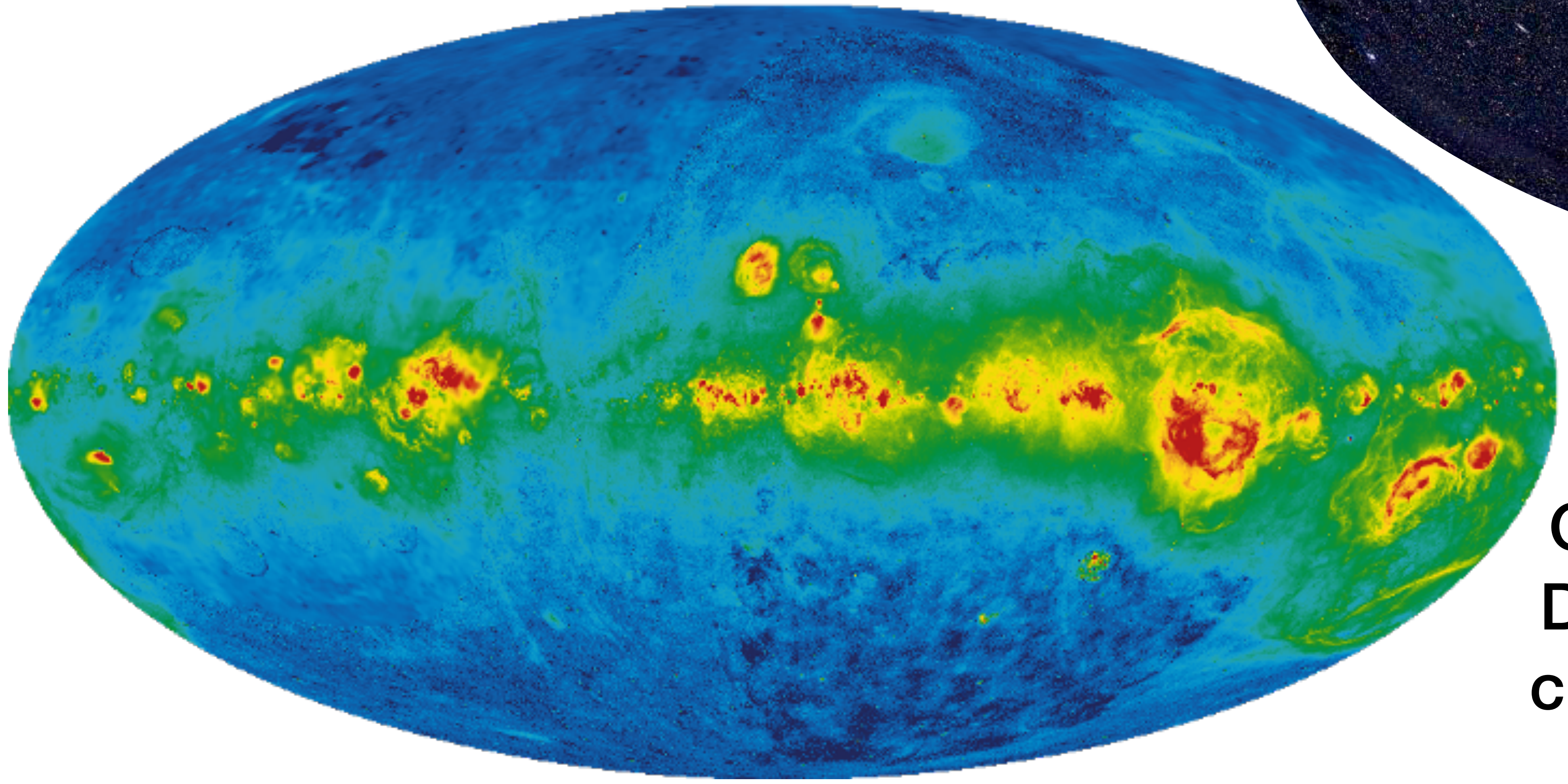


All the diffuse stuff in b/t stars and other compact objects in the MW

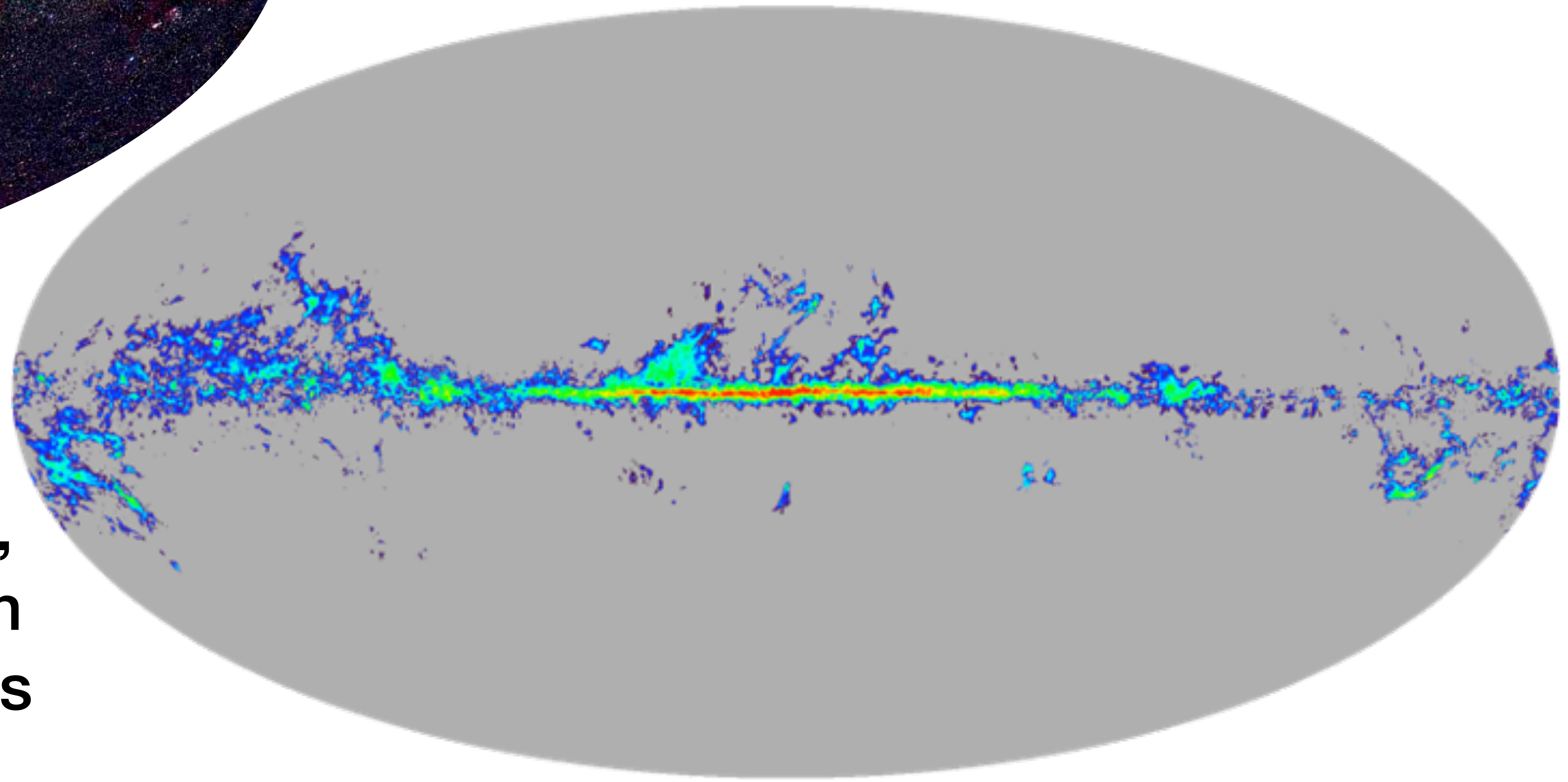
Neutral H (21cm; radio)



Balmer line n=3->2 (656.3 nm)



CO (2.6 mm; microwave)

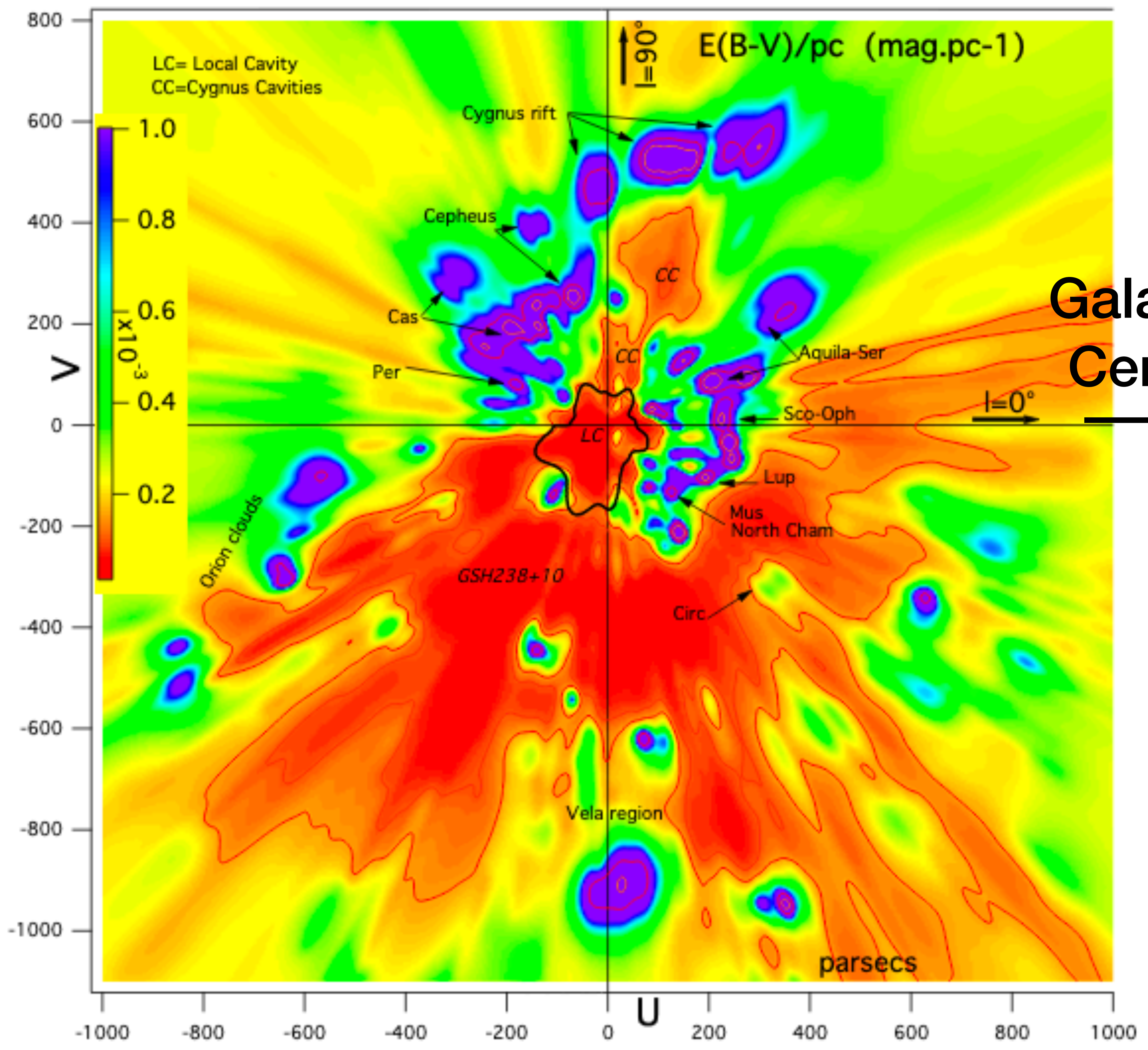


Stars (visible)

Gas (ionized, neutral, molecules), Dust (large molecules, singly or in clumps), & relativistic components (magnetic fields, cosmic rays)

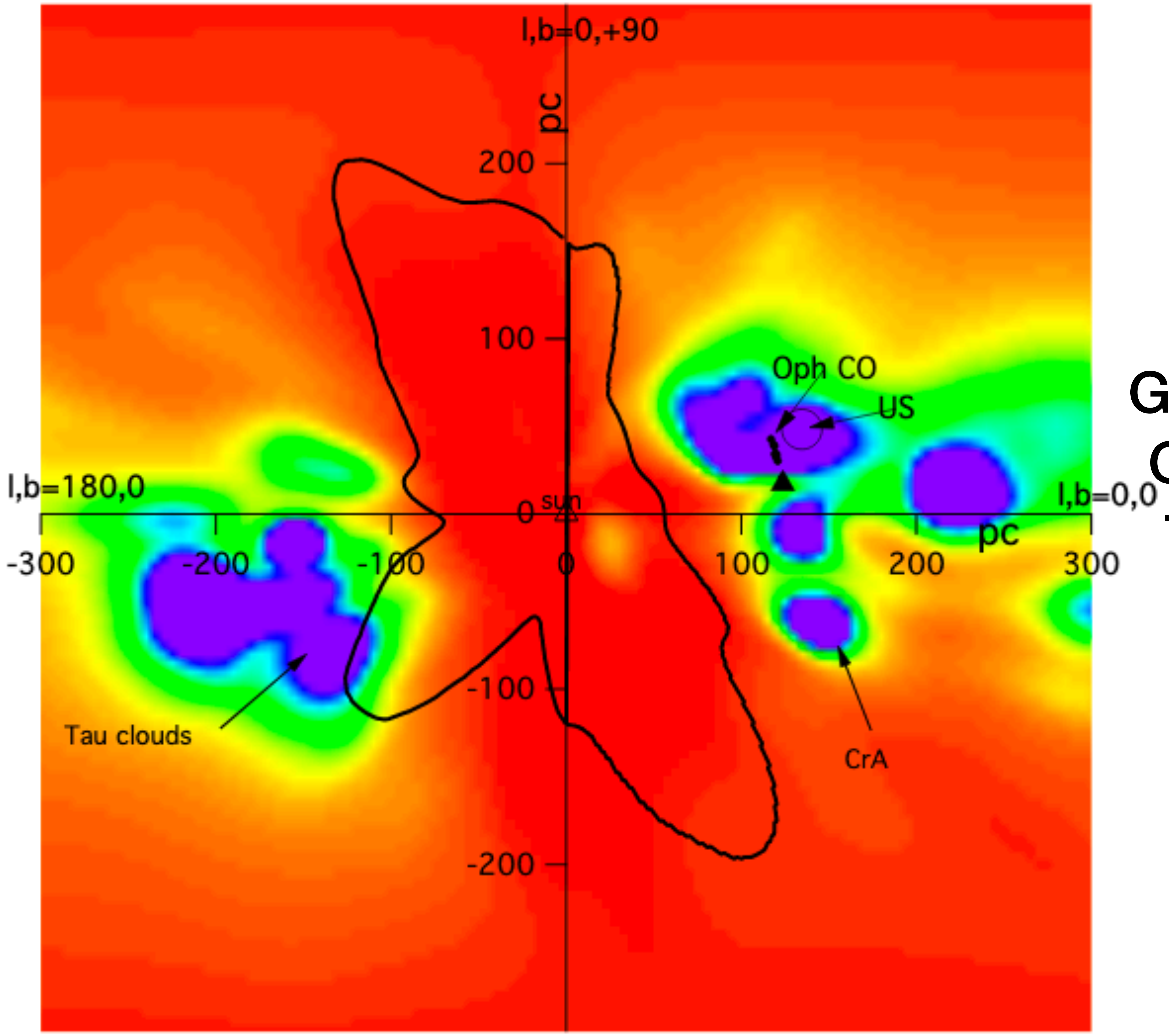
ISM also contains very hot gas heated by SNe

Face-on disk view



Galactic Center

Edge-on disk view

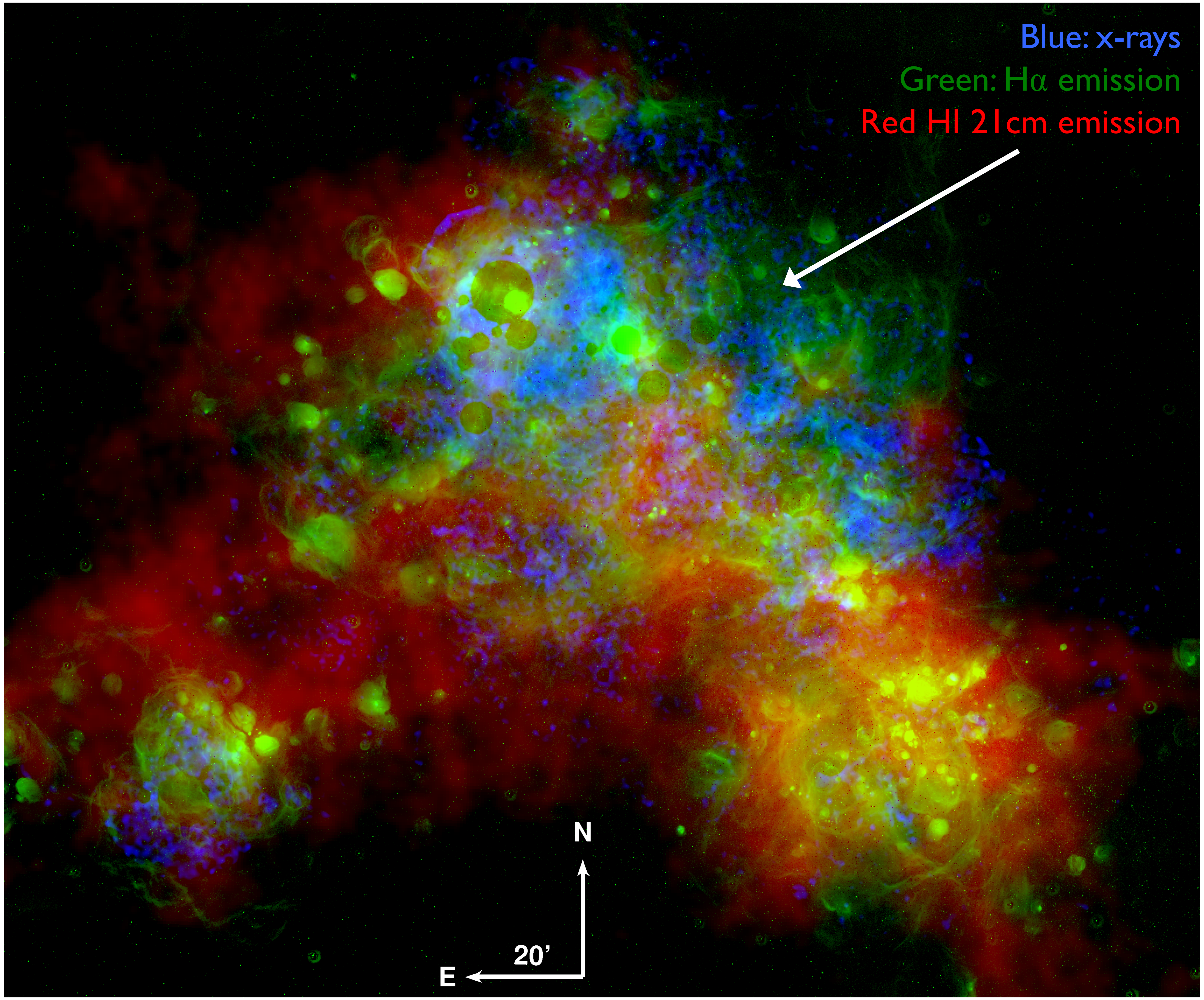


Galactic Center

All these gas "phases" are in pressure equilibrium

Cold Molecular Clouds:
$T \sim 10$ K, $n \sim 10^9$ m^{-3}
Cold Neutral Medium:
$T \sim 100$ K, $n \sim 10^8$ m^{-3}
Warm Neutral Medium:
$T \sim 7000$ K, $n \sim 10^5$ m^{-3}
Warm Ionized Medium:
$T \sim 10{,}000$ K, $n \sim 10^6$ m^{-3}
Hot Ionized Medium:
$T \sim 1{,}000{,}000$ K, $n \sim 10^4$ m^{-3}

$P \sim nkT \sim$ const.



Star Formation & Evolution

“Star” —> undergoing fusion

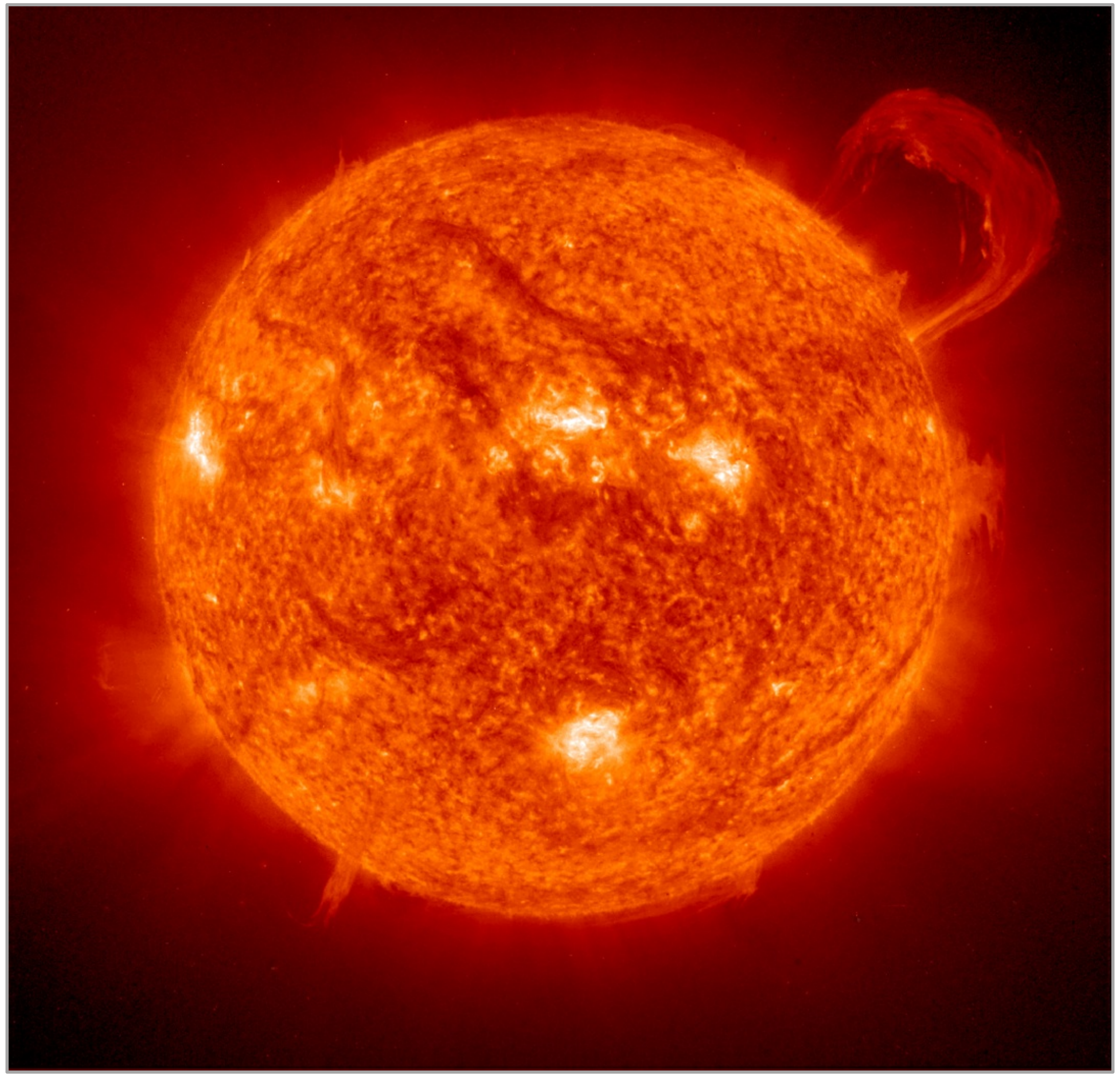
Formed from clouds of gas that collapse due to self-gravity

Density:

10^{-15} kg m^{-3}

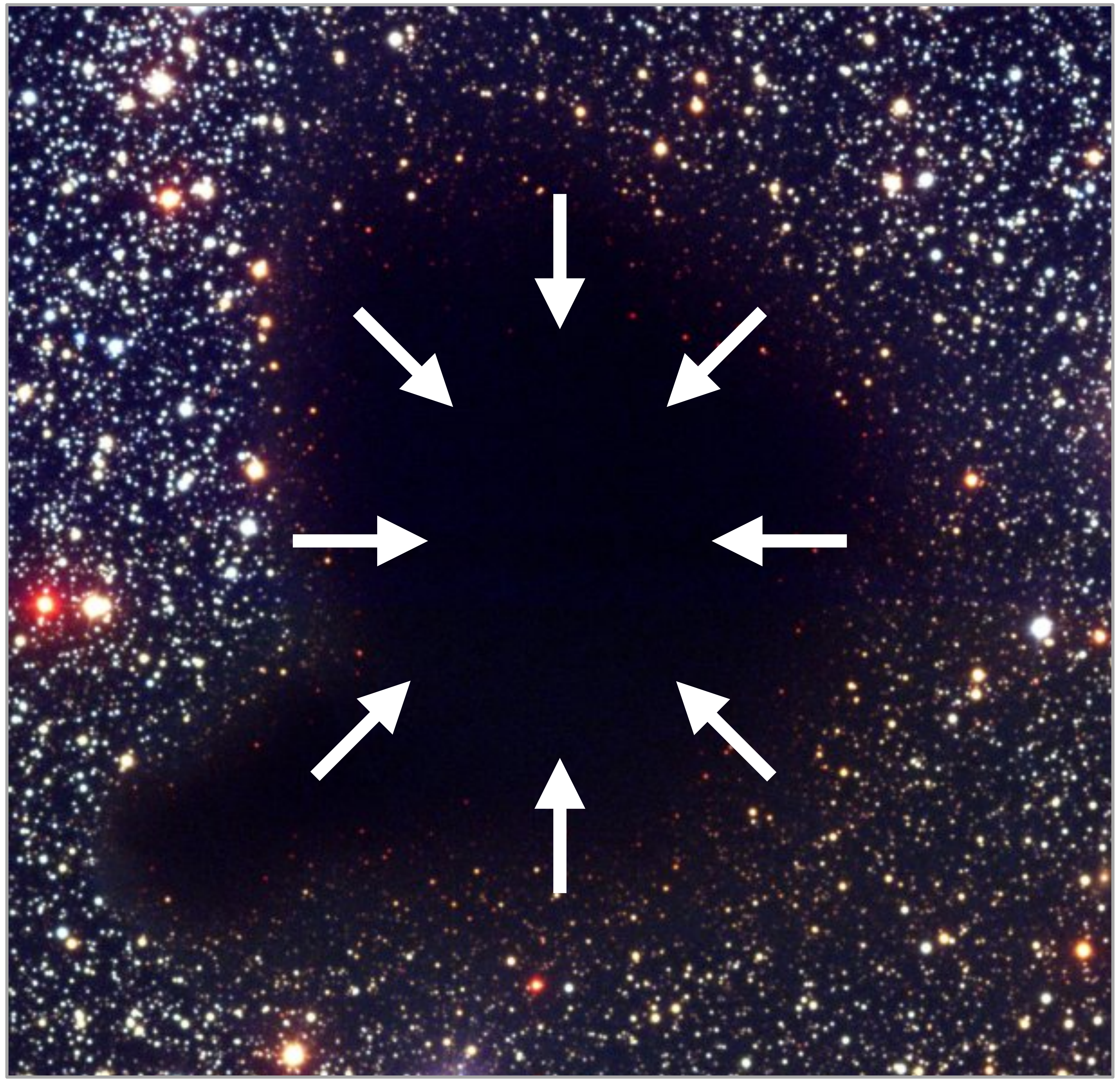
→

1400 kg m^{-3}



Forming a Star

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



Imagine a gas particle on an orbit with *e* = 1

$$P^2 = \frac{4\pi^2}{G}\frac{a^3}{M}$$

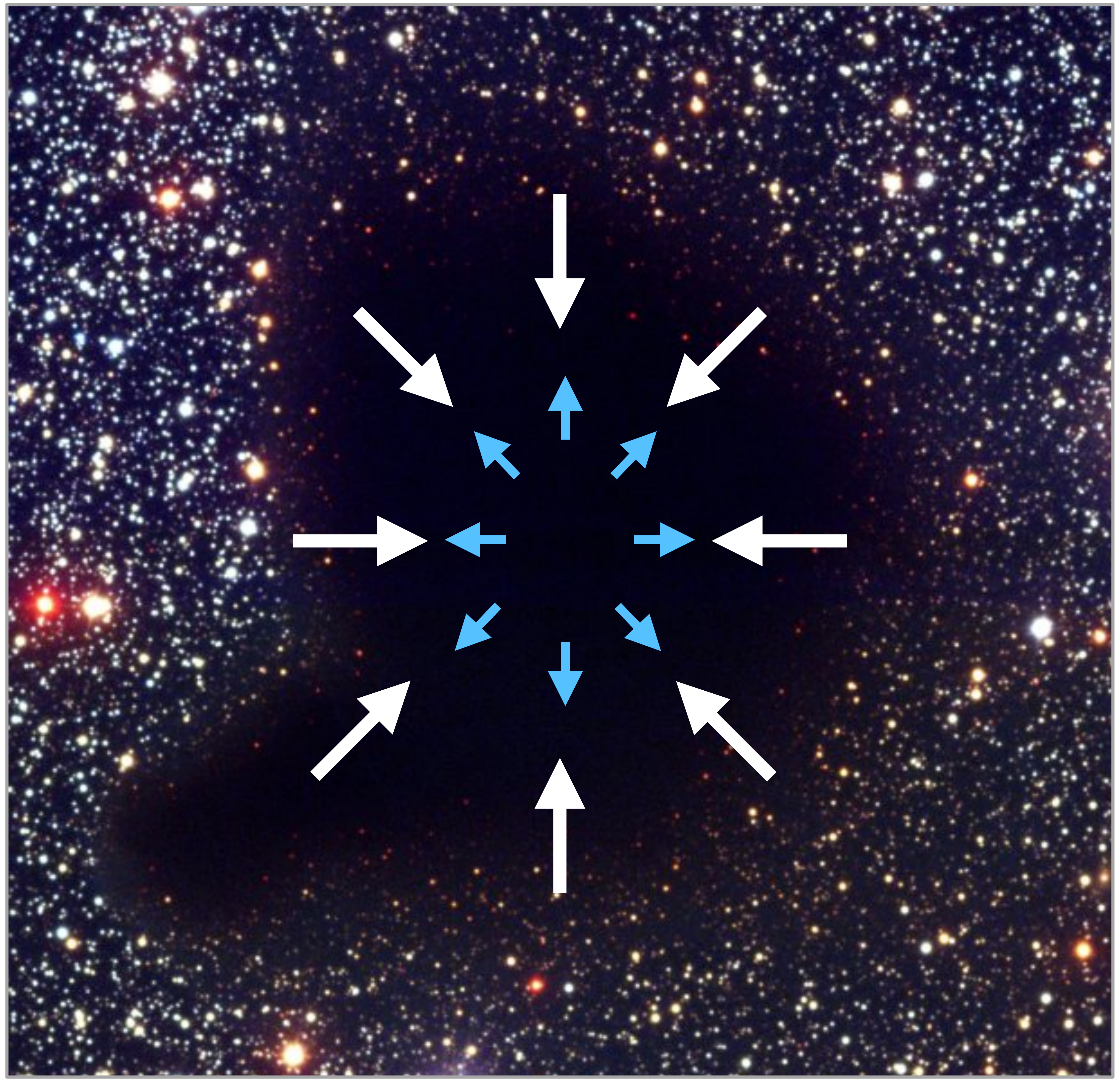
Halfway through the orbit, it reaches the center

$$t_{\rm ff} = \frac{P}{2} = \frac{2\pi}{2G^{1/2}}\frac{(r_0/2)^{3/2}}{M^{1/2}}$$
$$= \frac{\pi}{G^{1/2}}\frac{r_0^{3/2}}{(8\cdot 4\pi r_0^3\rho_0/3)^{1/2}}$$

$$t_{\rm ff} = \left(\frac{3\pi}{32G\rho_0}\right)^{1/2}$$

"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

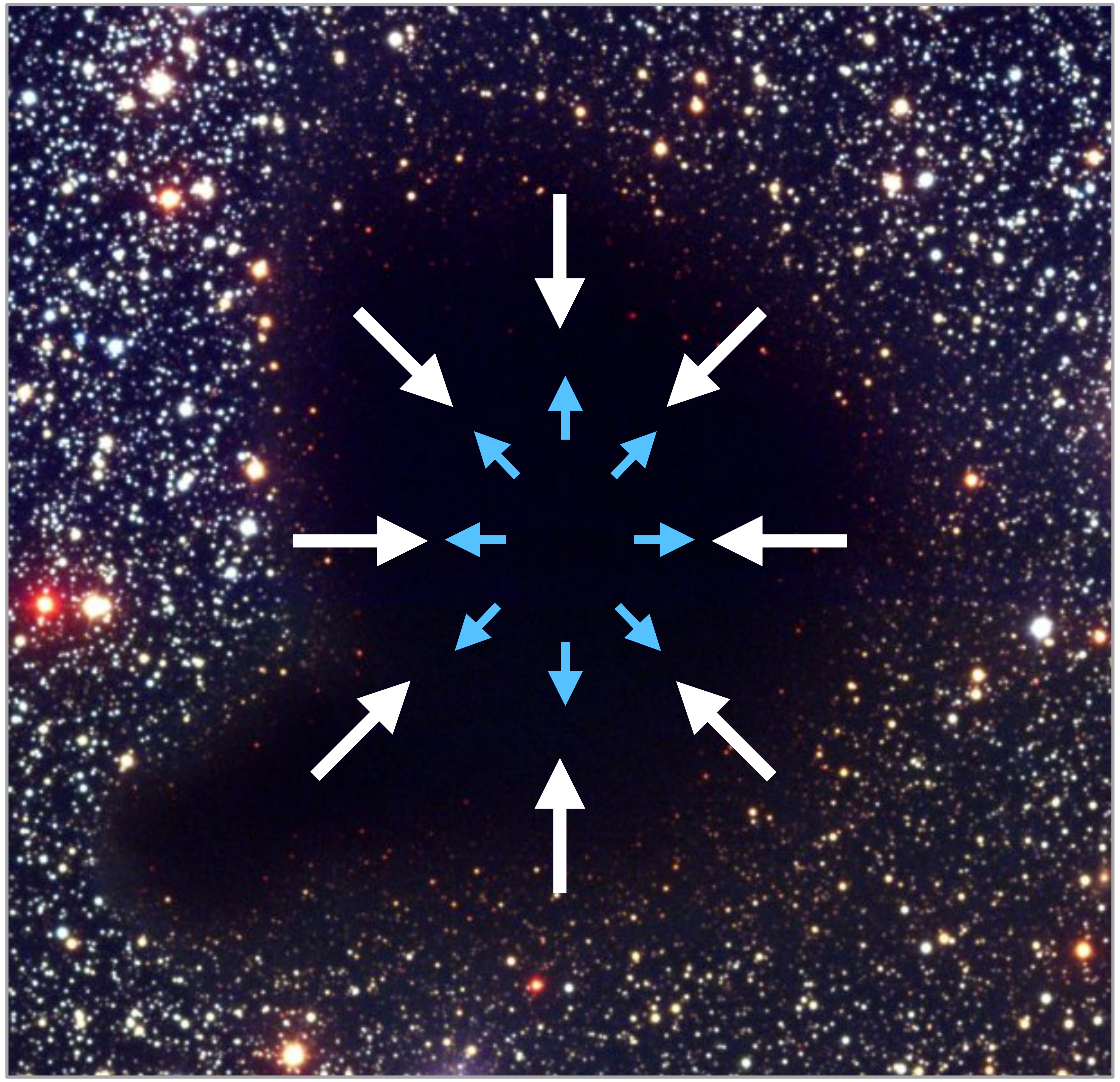
If density and size is determined, also have a critical mass —> Jeans mass

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

“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

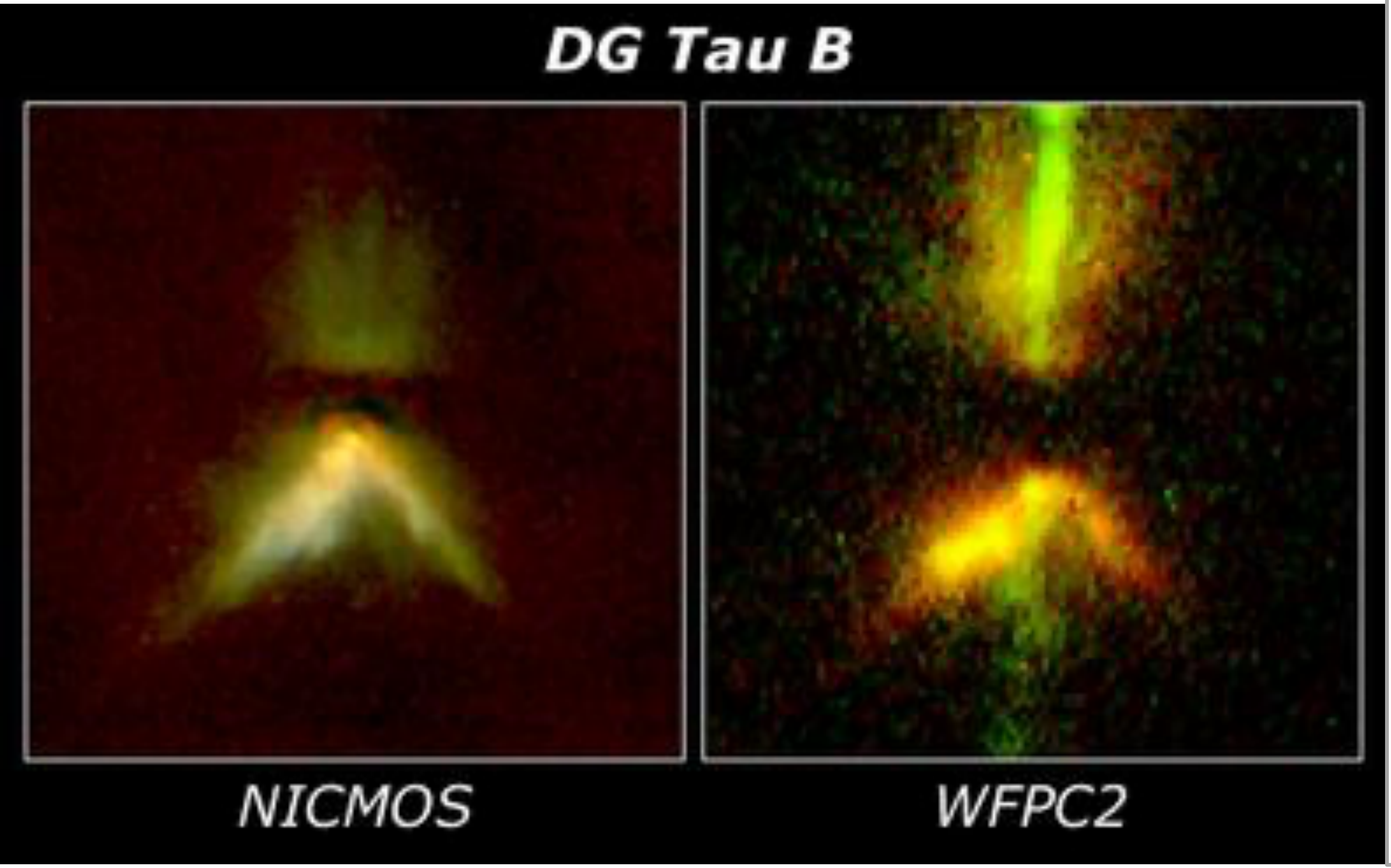
$$t_{\rm ff} < t_{\rm press} = \frac{r_0}{c_s}$$

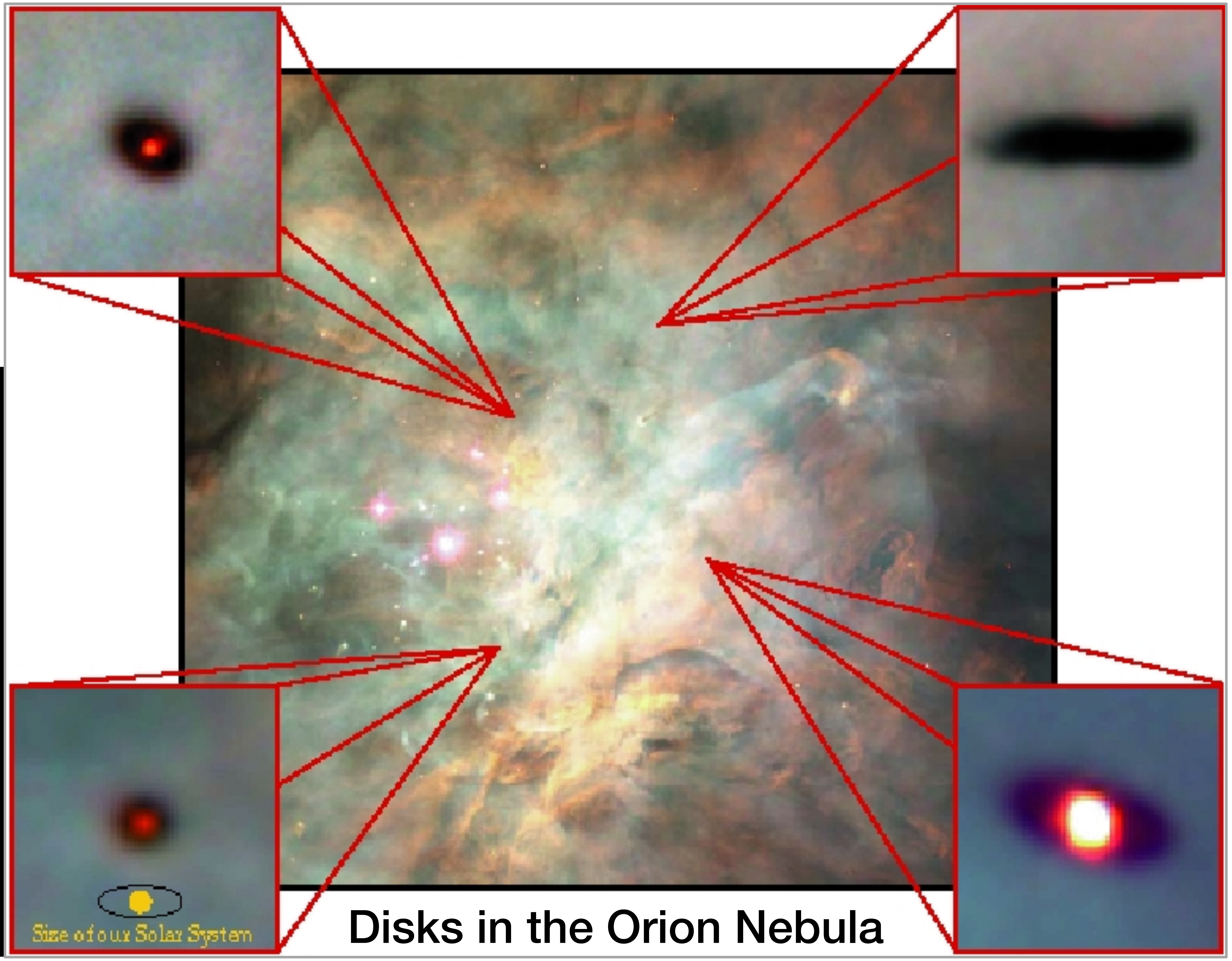
$$c_s = \left(\frac{\gamma k T}{\mu m_p} \right)^{1/2}$$

Protostars form from an "accretion disk"

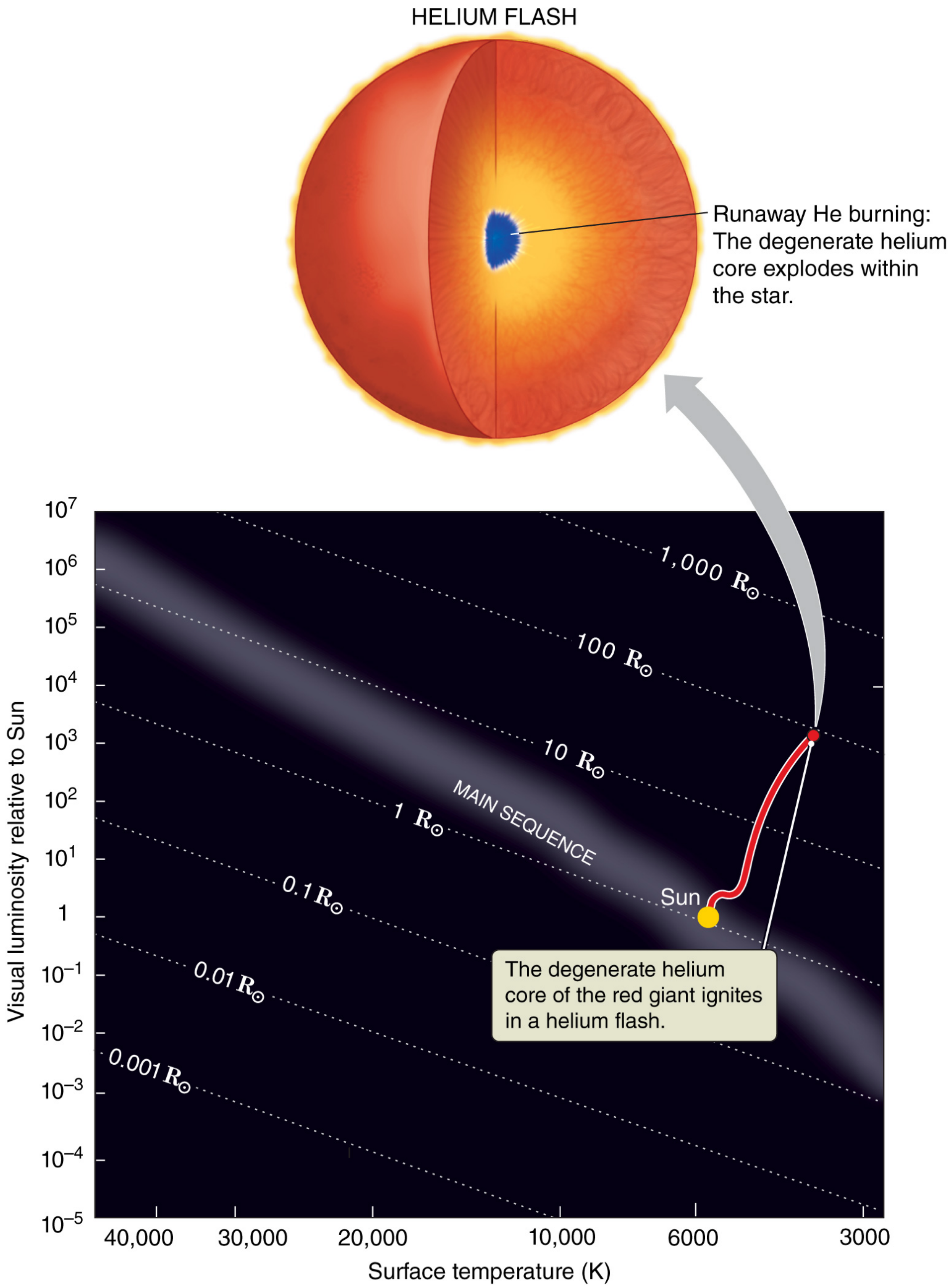
Angular momentum dissipated in the disk

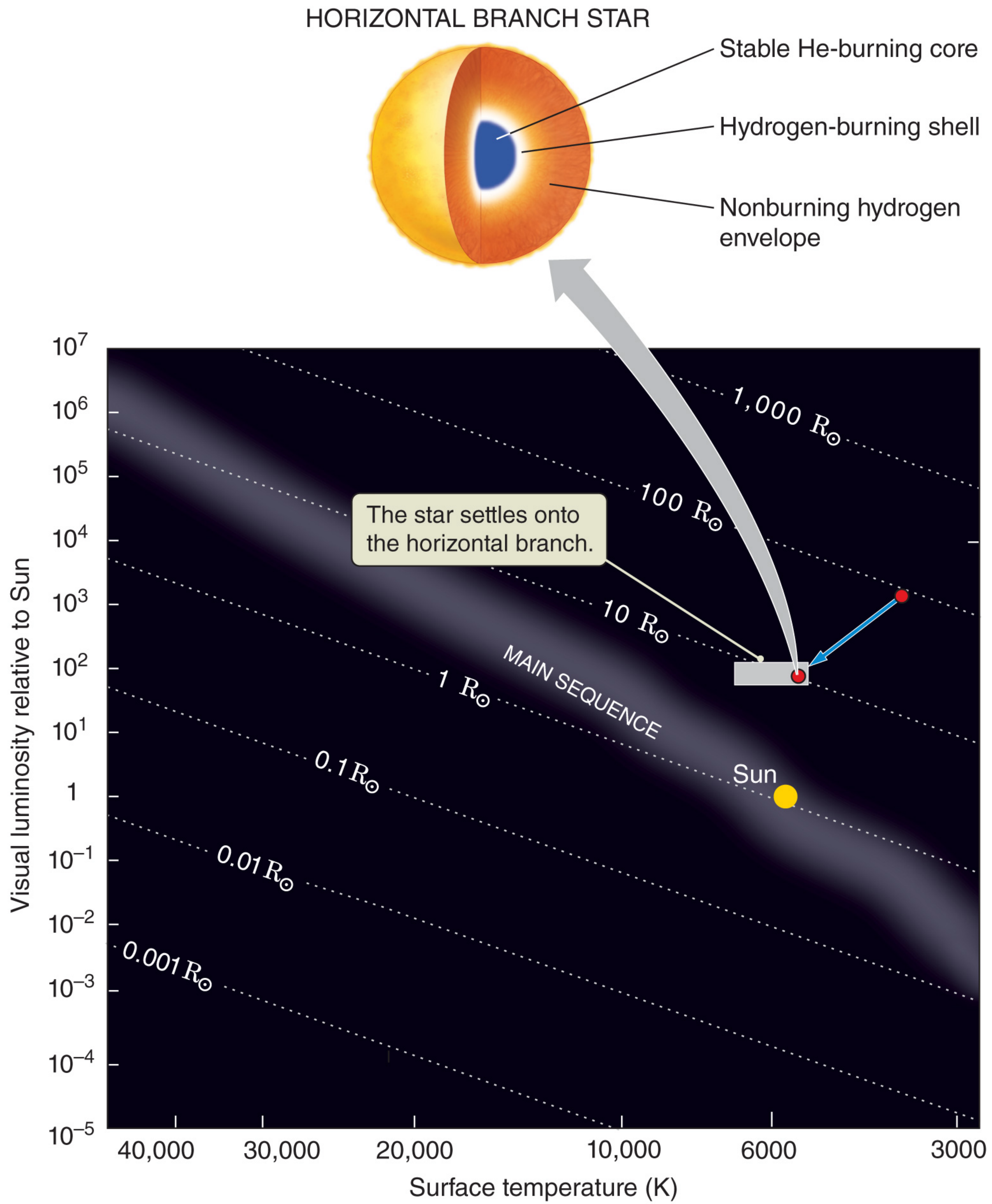
>99.9% of mass in the protostar, but planets with much less mass typically carry more angular momentum (which originates from the cloud)

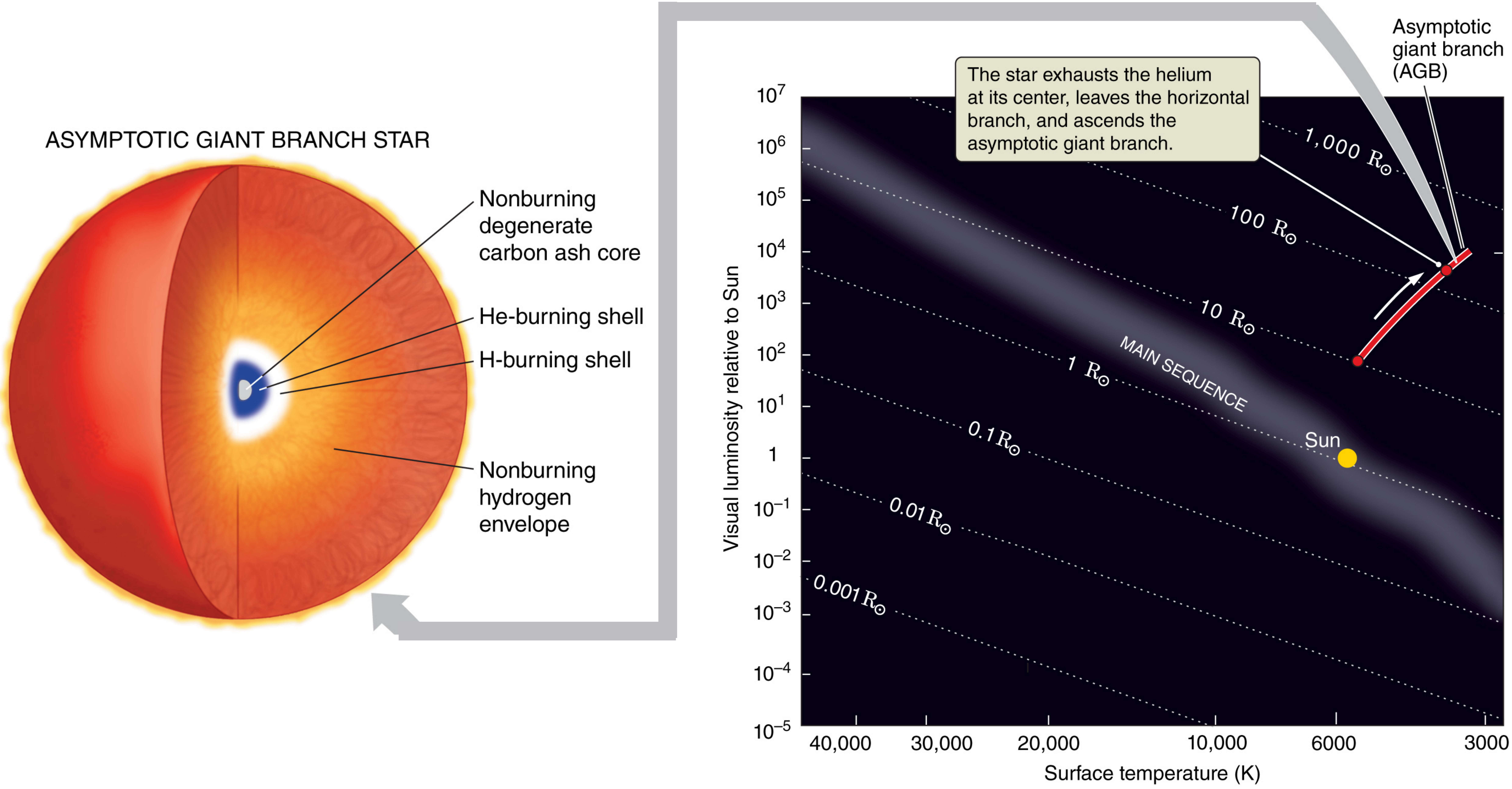


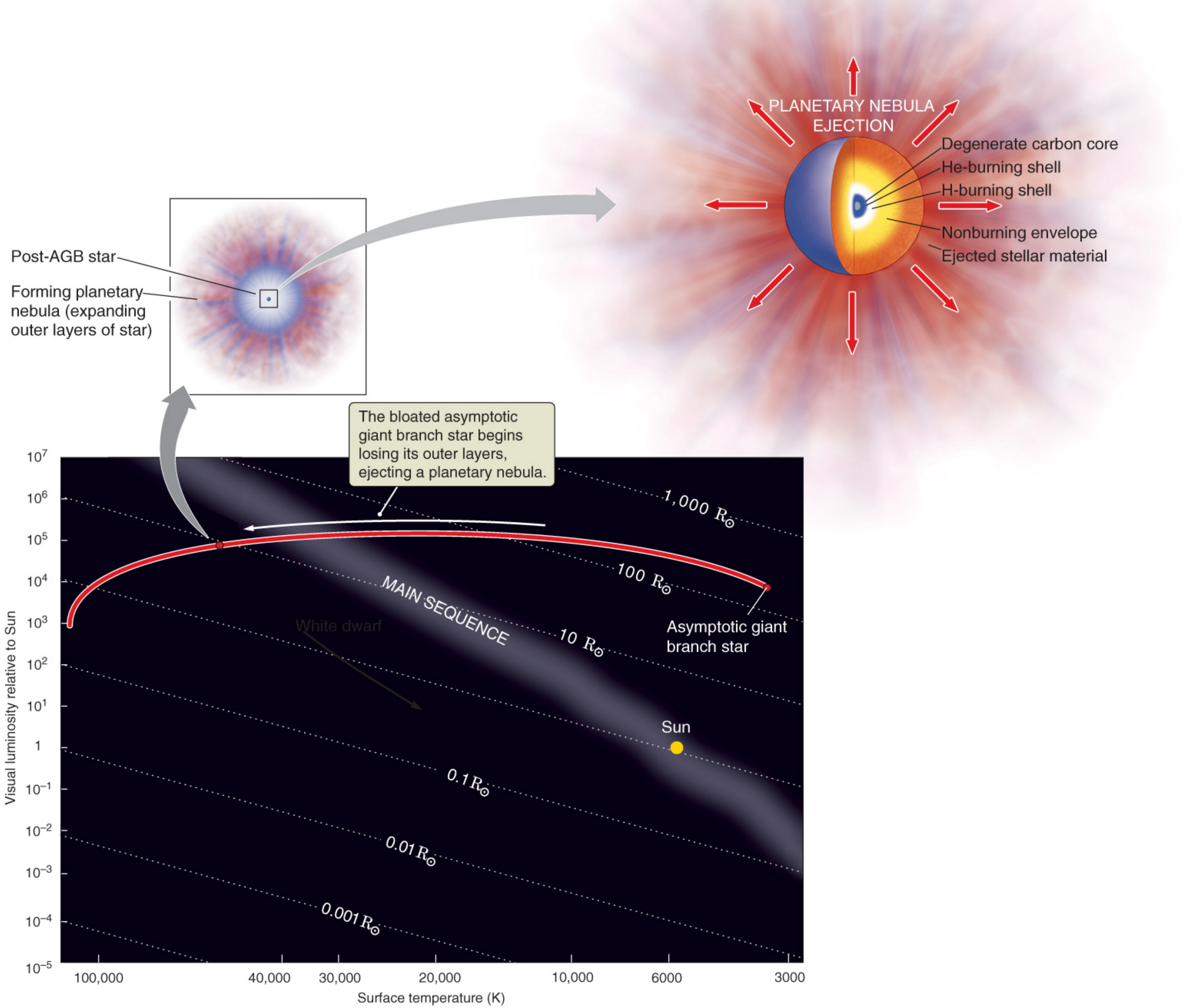


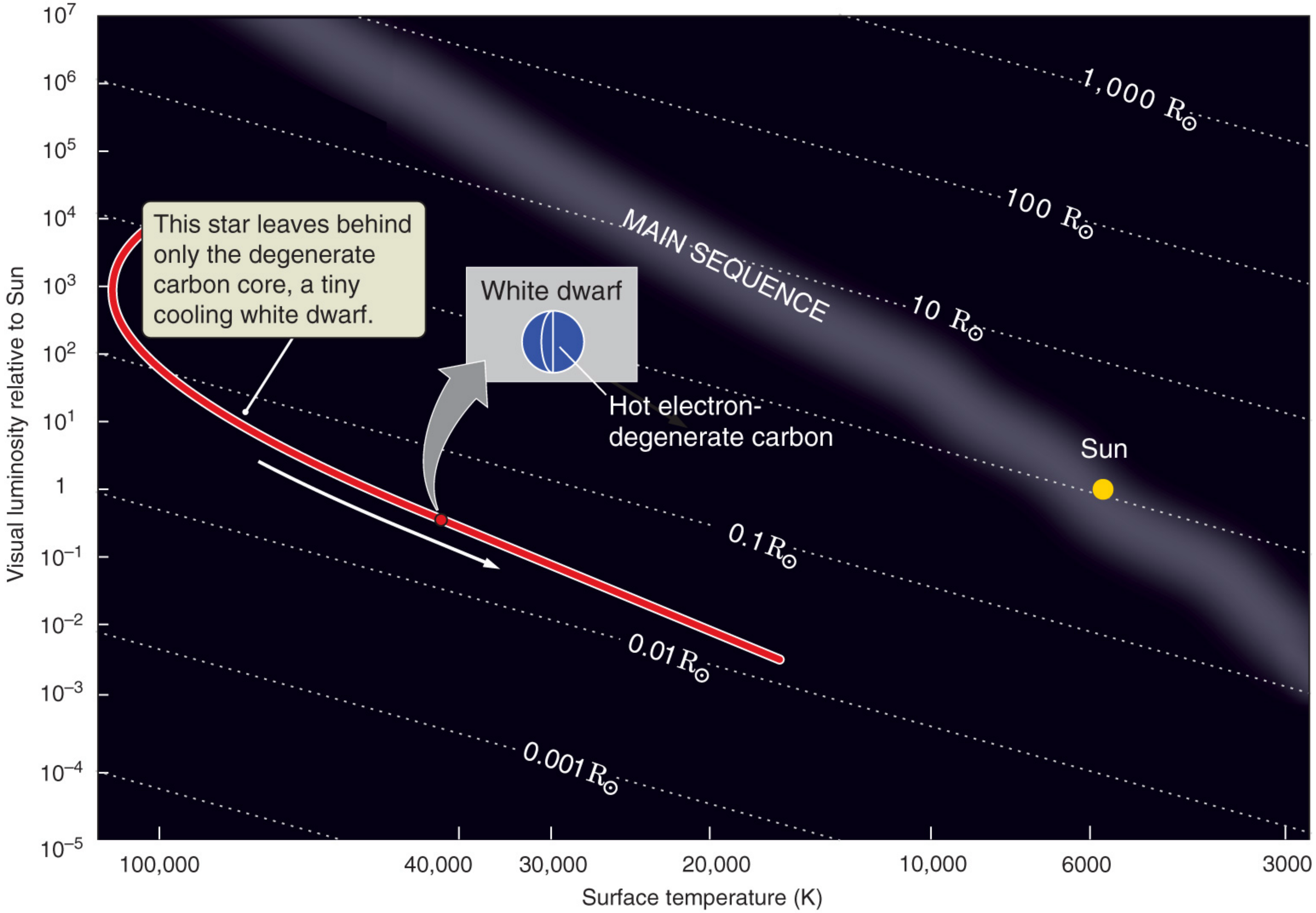
Disks in the Orion Nebula


HELIUM FLASH
Runaway He burning: The degenerate helium core explodes within the star.
1,000 R⊙
100 R⊙
10 R⊙
1 R⊙
0.1 R⊙
0.01 R⊙
0.001 R⊙
MAIN SEQUENCE
Sun
The degenerate helium core of the red giant ignites in a helium flash.
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.
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

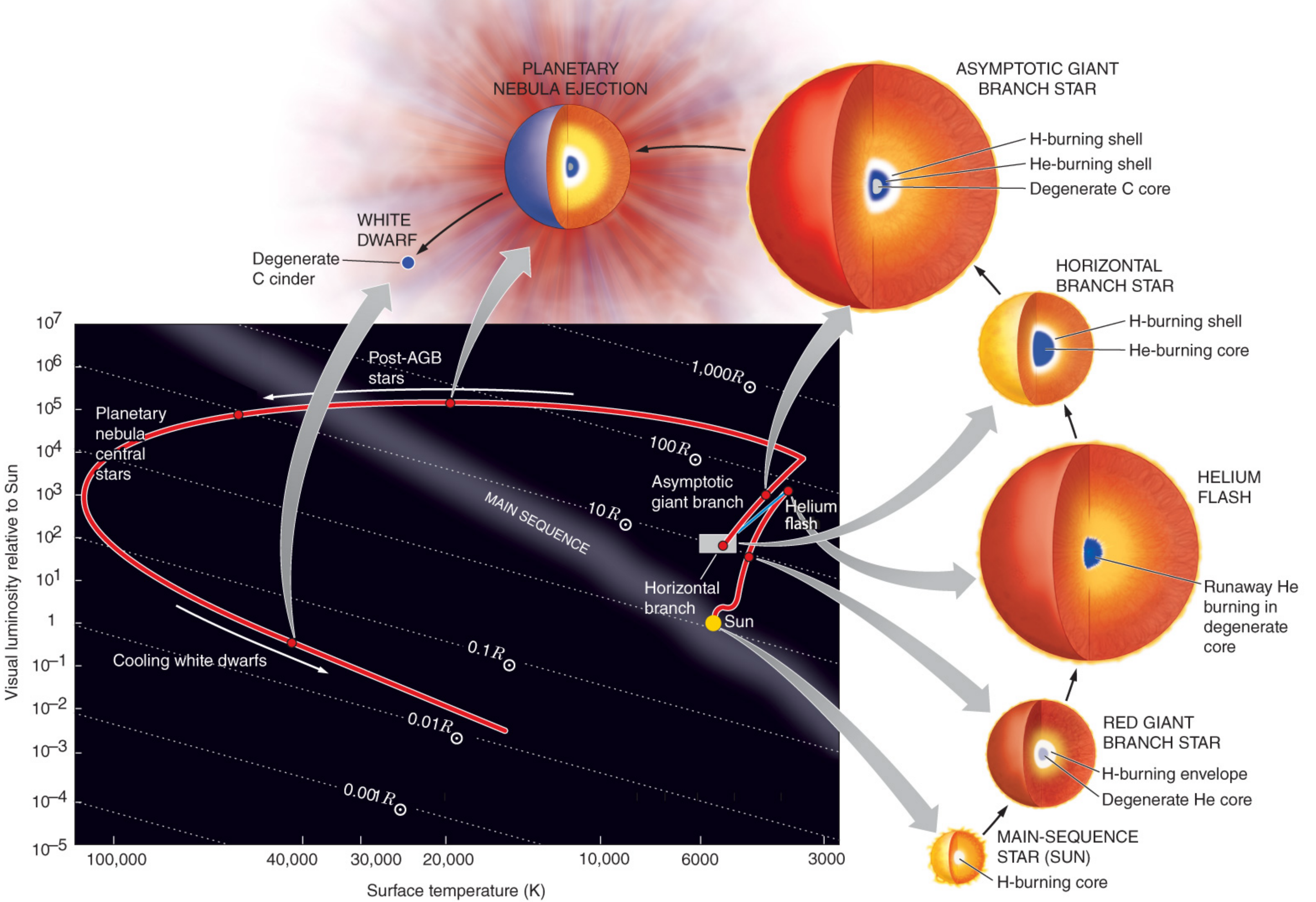

ASYMPTOTIC GIANT BRANCH STAR
Nonburning degenerate carbon ash core
He-burning shell
H-burning shell
Nonburning hydrogen envelope
The star exhausts the helium at its center, leaves the horizontal branch, and ascends the asymptotic giant branch.
Asymptotic giant branch (AGB)
1,000 R⊙
100 R⊙
10 R⊙
1 R⊙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


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⊙
MAIN SEQUENCE
White dwarf
Asymptotic giant branch star
Sun
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

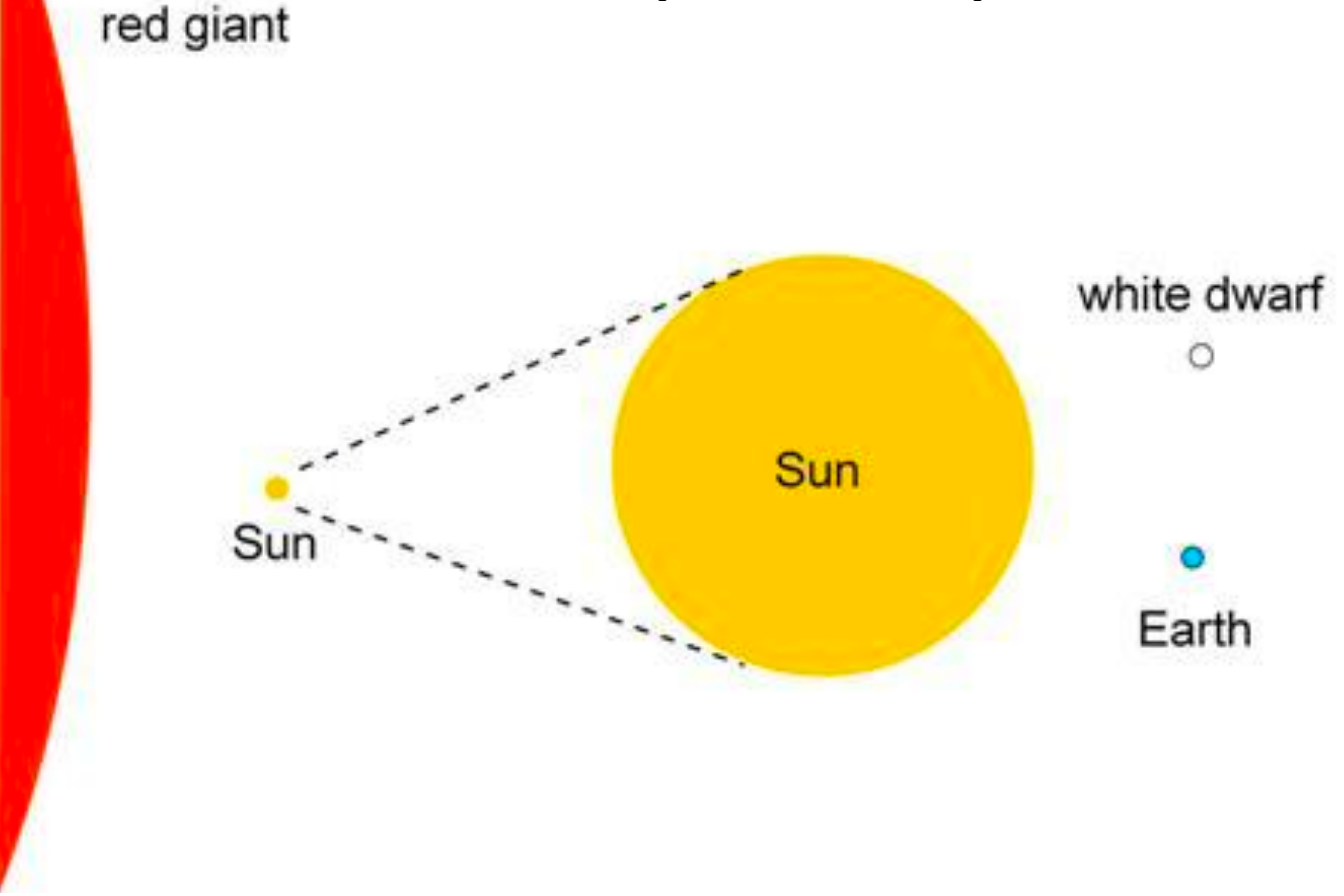


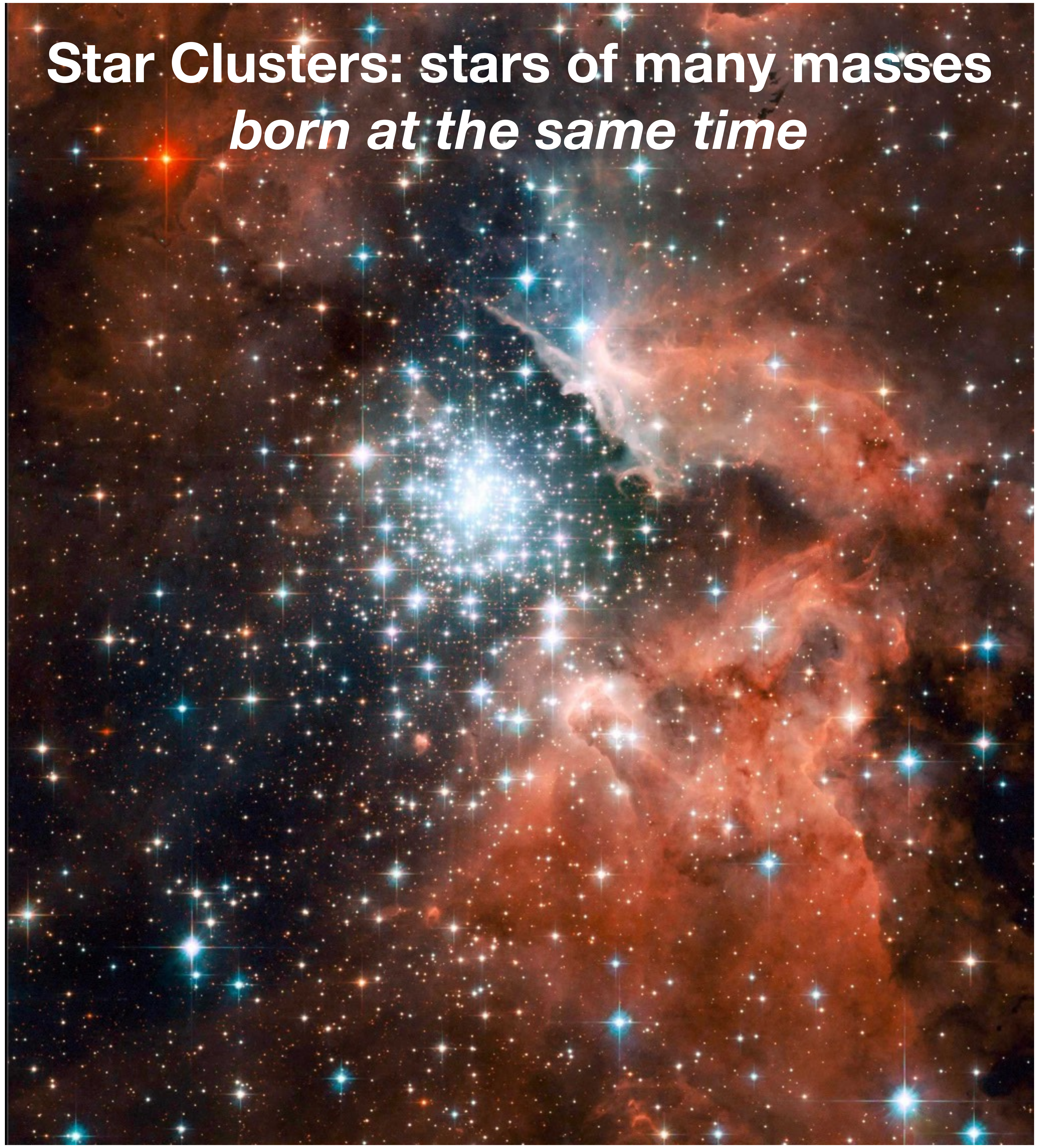
10^7
10^6
10^5
10^4
10^3
10^2
10^1
1
10^−1
10^−2
10^−3
10^−4
10^−5
Visual luminosity relative to Sun
100,000
40,000
30,000
20,000
10,000
6000
3000
Surface temperature (K)
1,000 R⊙
100 R⊙
10 R⊙
0.1 R⊙
0.01 R⊙
0.001 R⊙
MAIN SEQUENCE
Sun
This star leaves behind only the degenerate carbon core, a tiny cooling white dwarf.
White dwarf
Hot electron-degenerate carbon

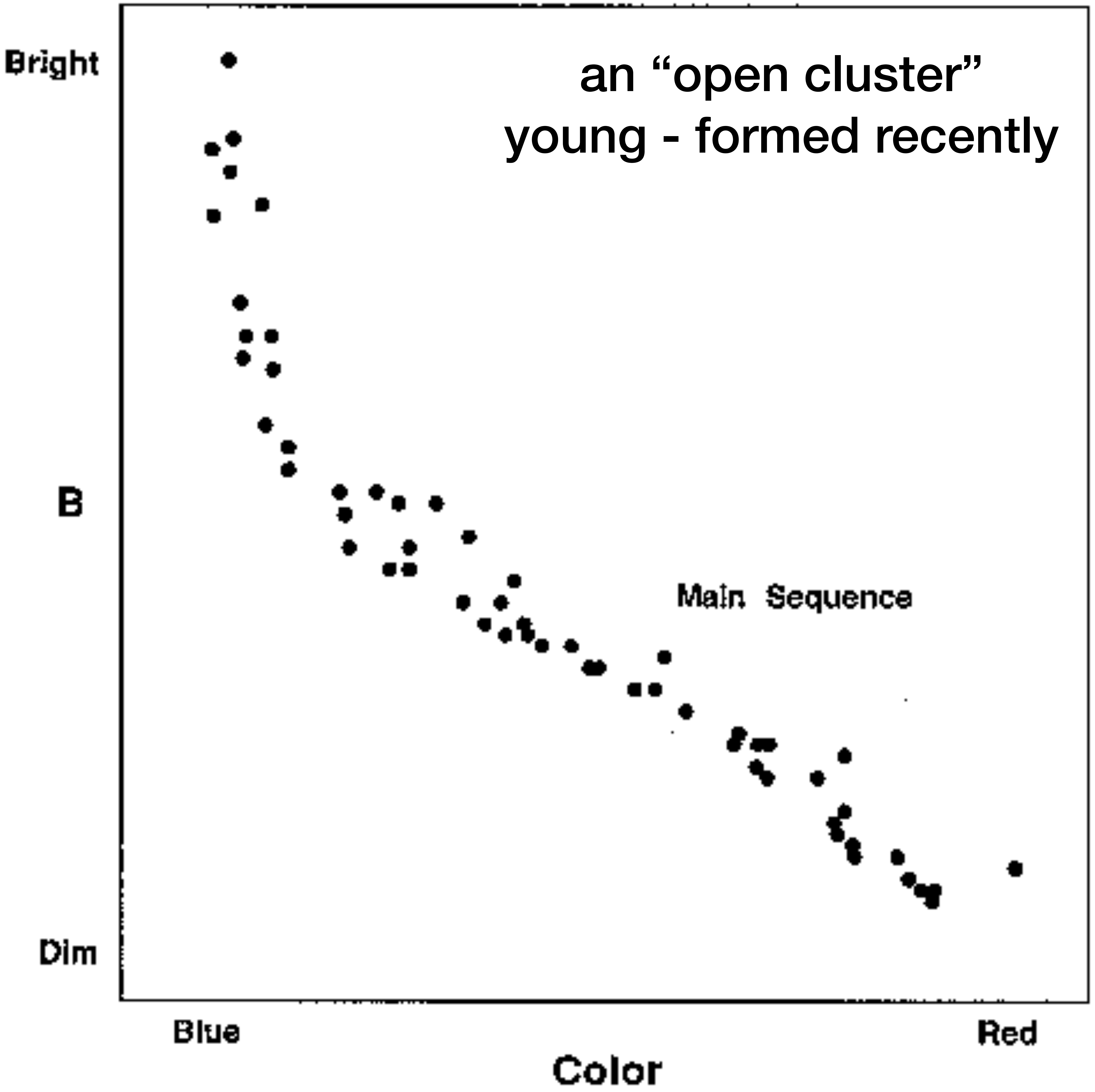
Again, this time with feeling!



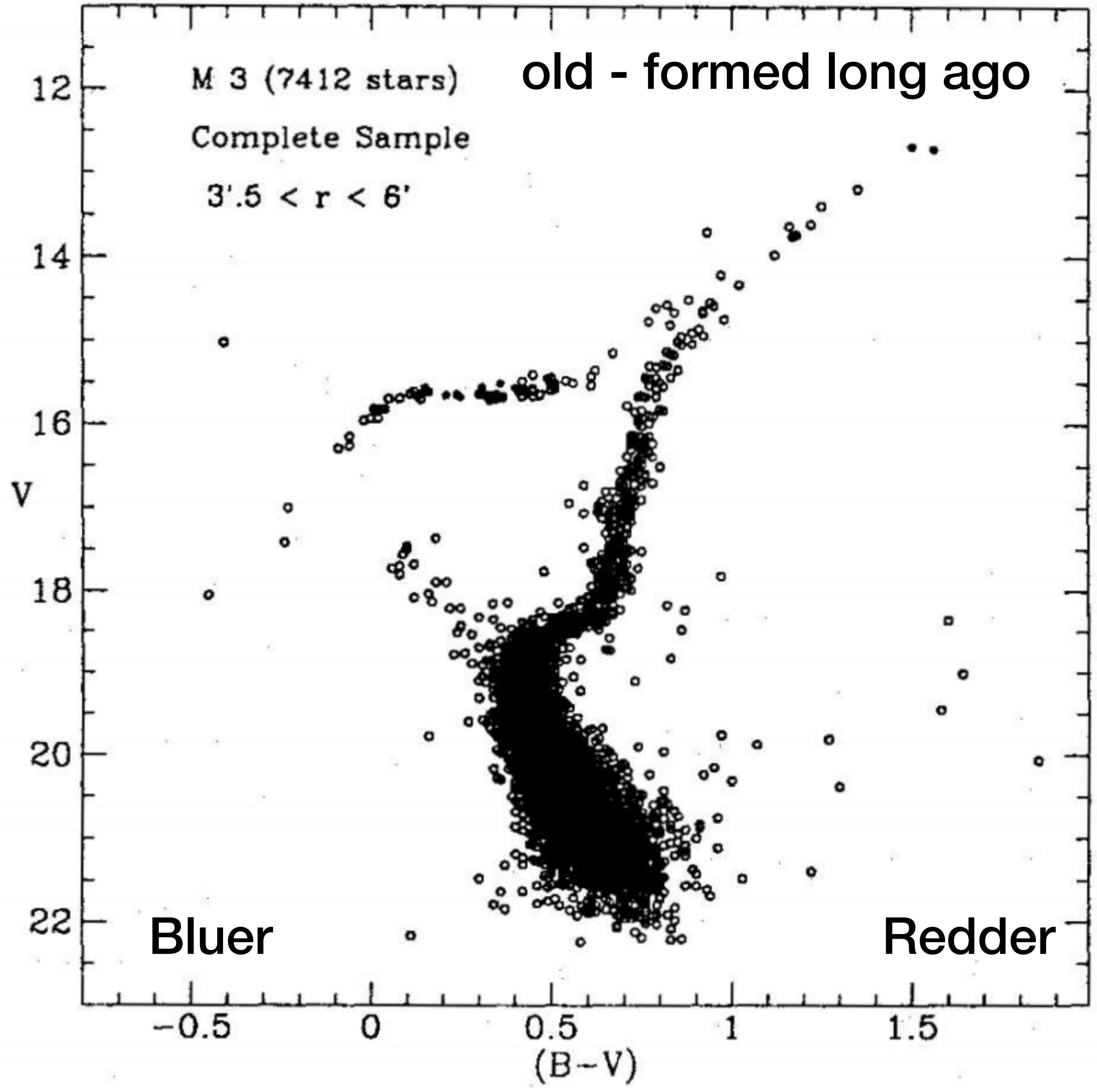
Size changes along with temperature




Star Clusters: stars of many masses
born at the same time


Bright
B
Dim
an "open cluster"
young - formed recently
Main Sequence
Blue
Red
Color

Globular Cluster Color-Magnitude Diagram

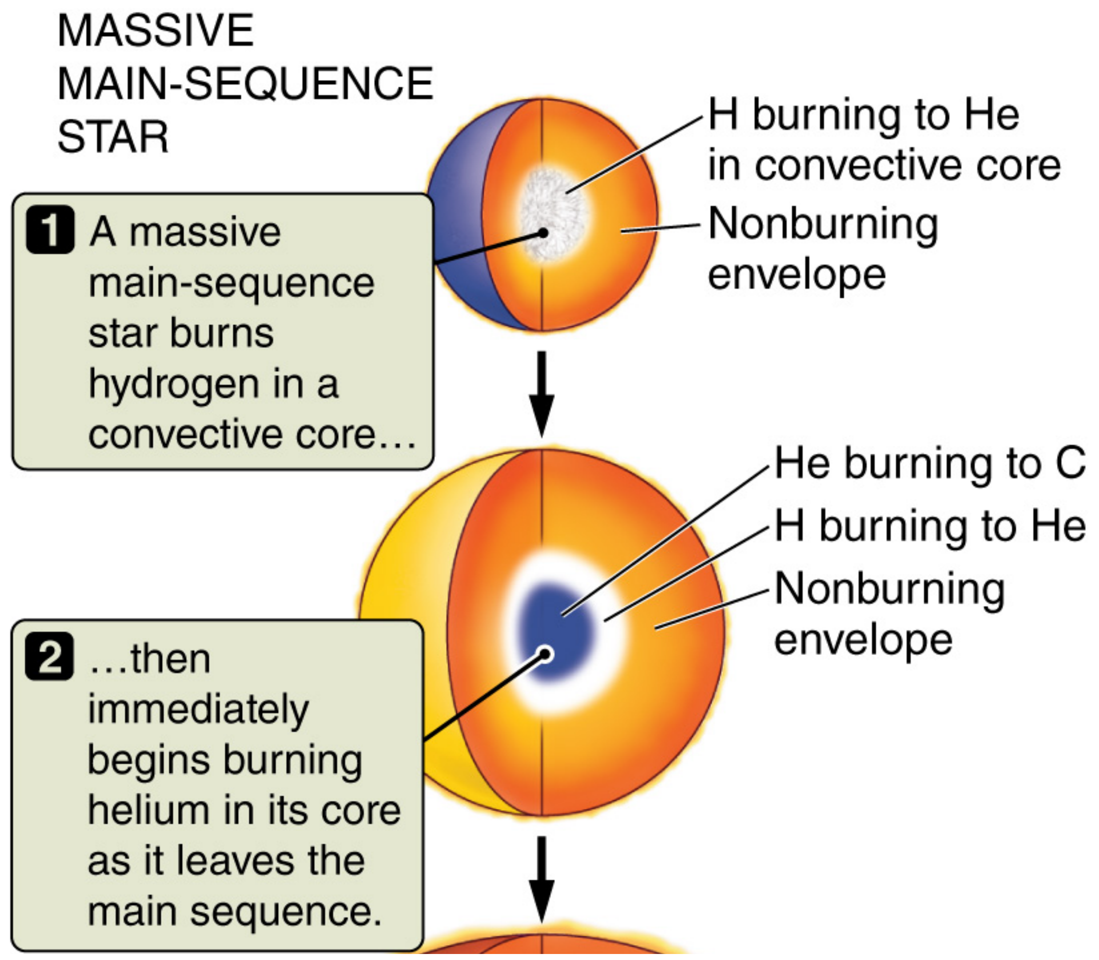


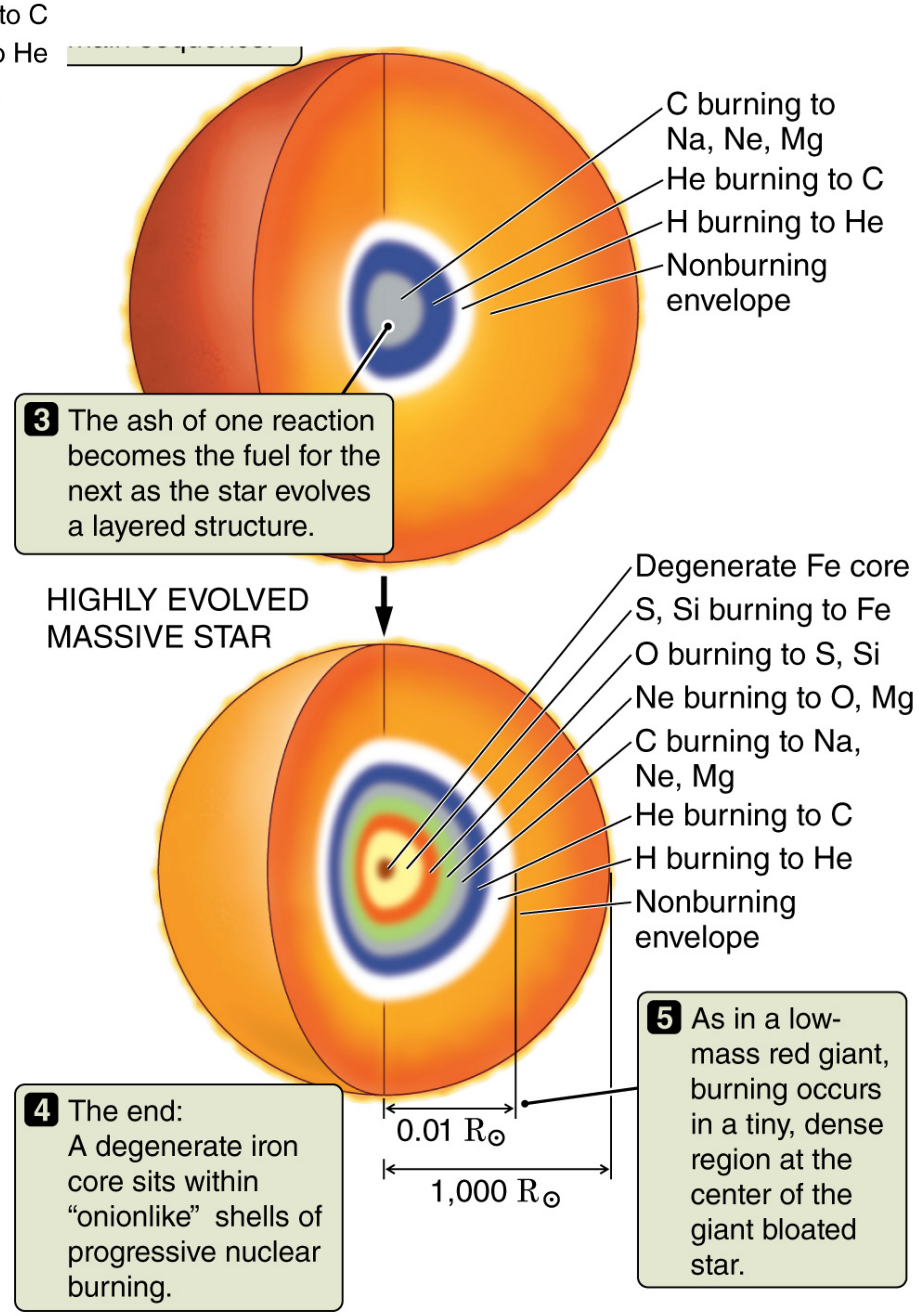
Brighter

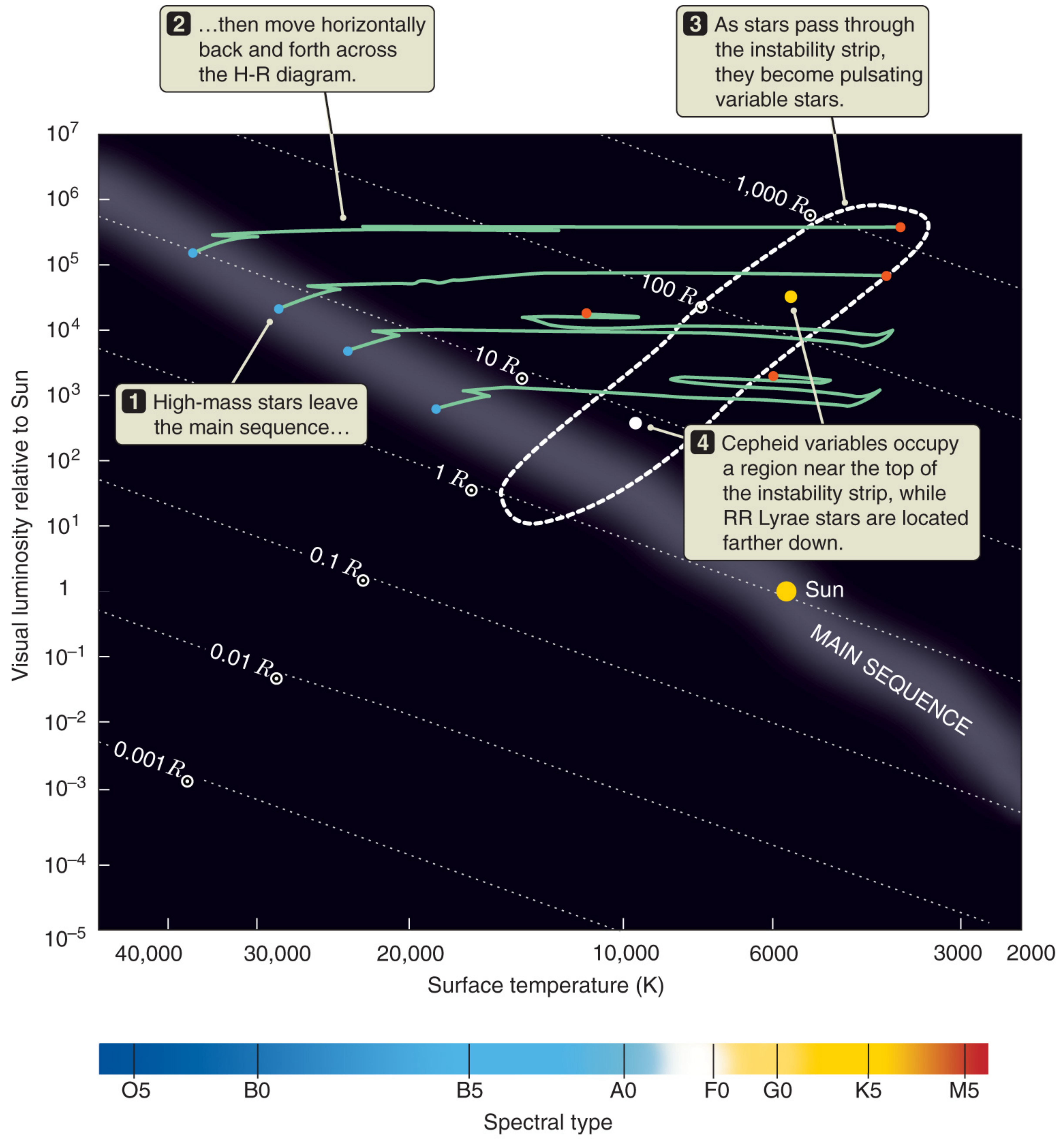
Fainter

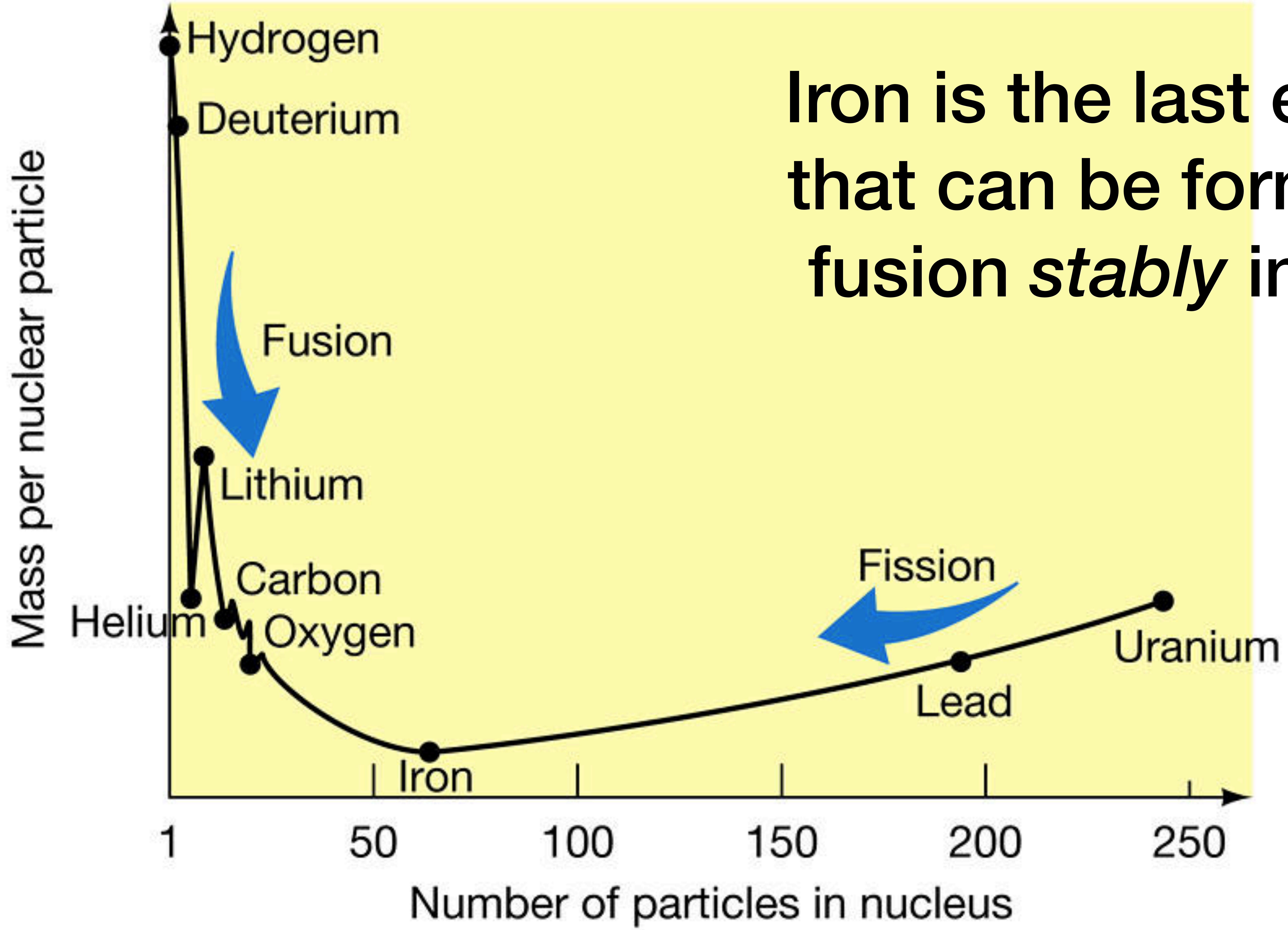
High Mass Stars = High Core Temps = CNO

Evolution of High Mass Stars



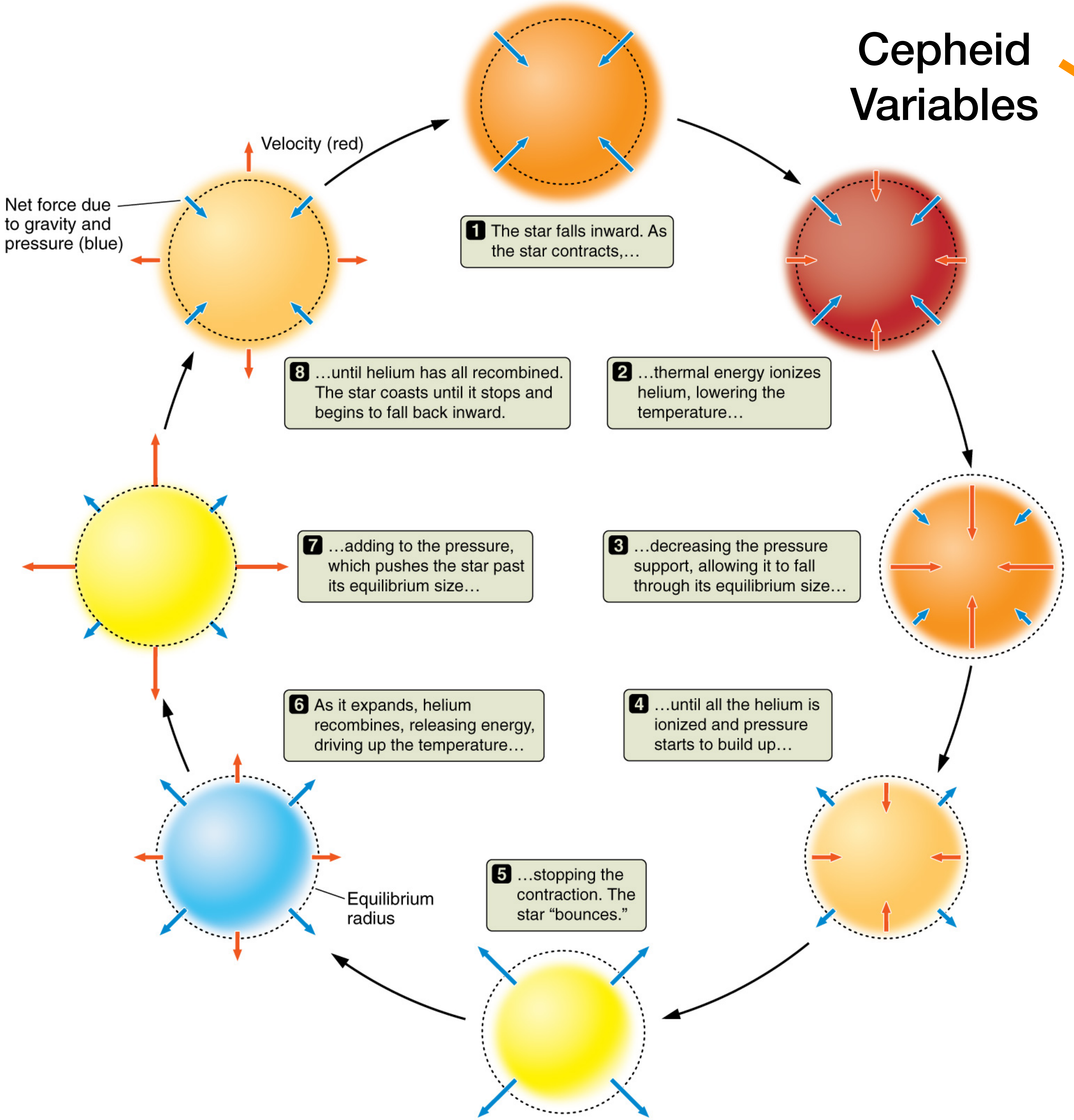


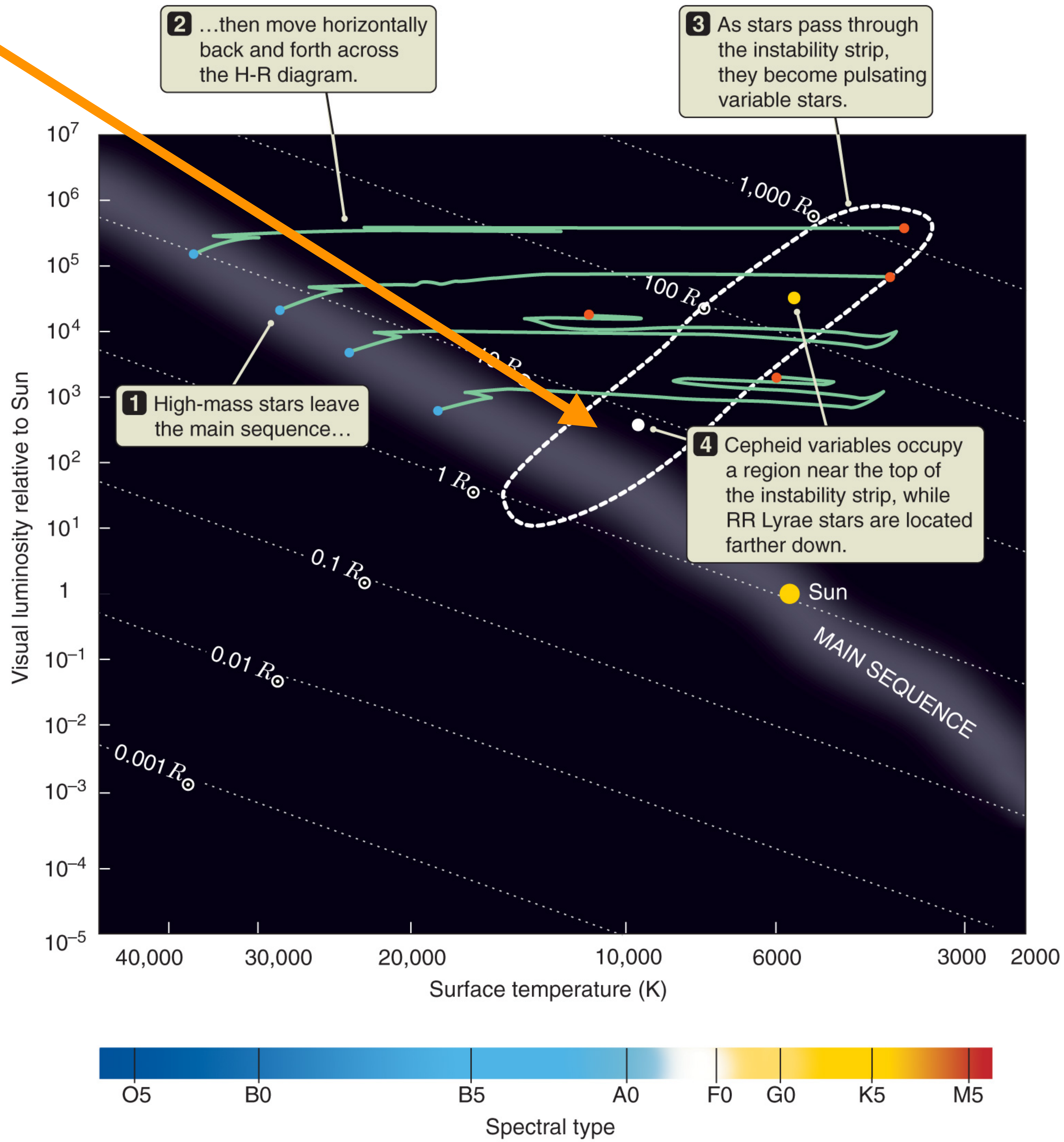




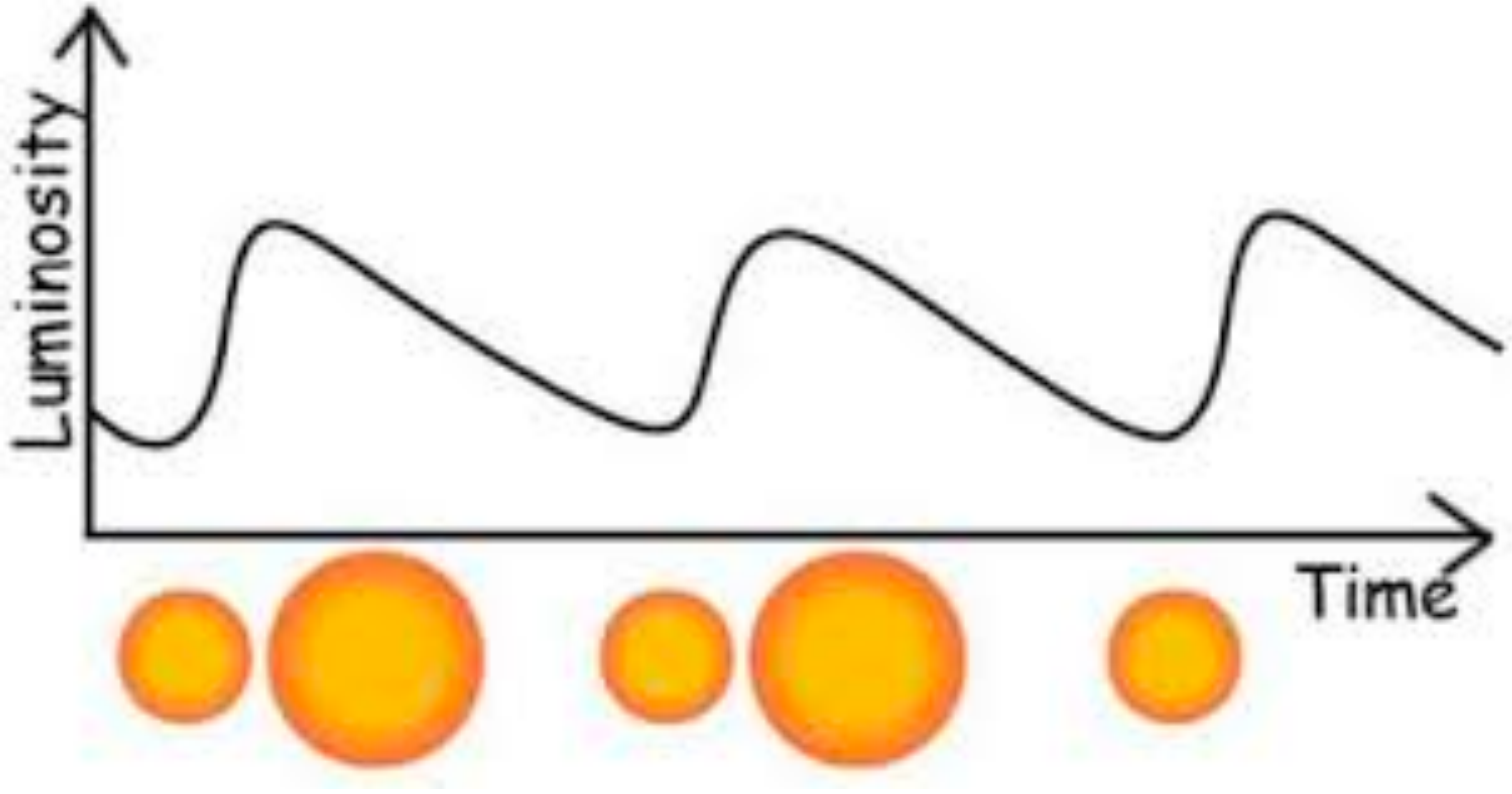
Iron is the last element that can be formed via fusion *stably* in a star

Cepheid Variables





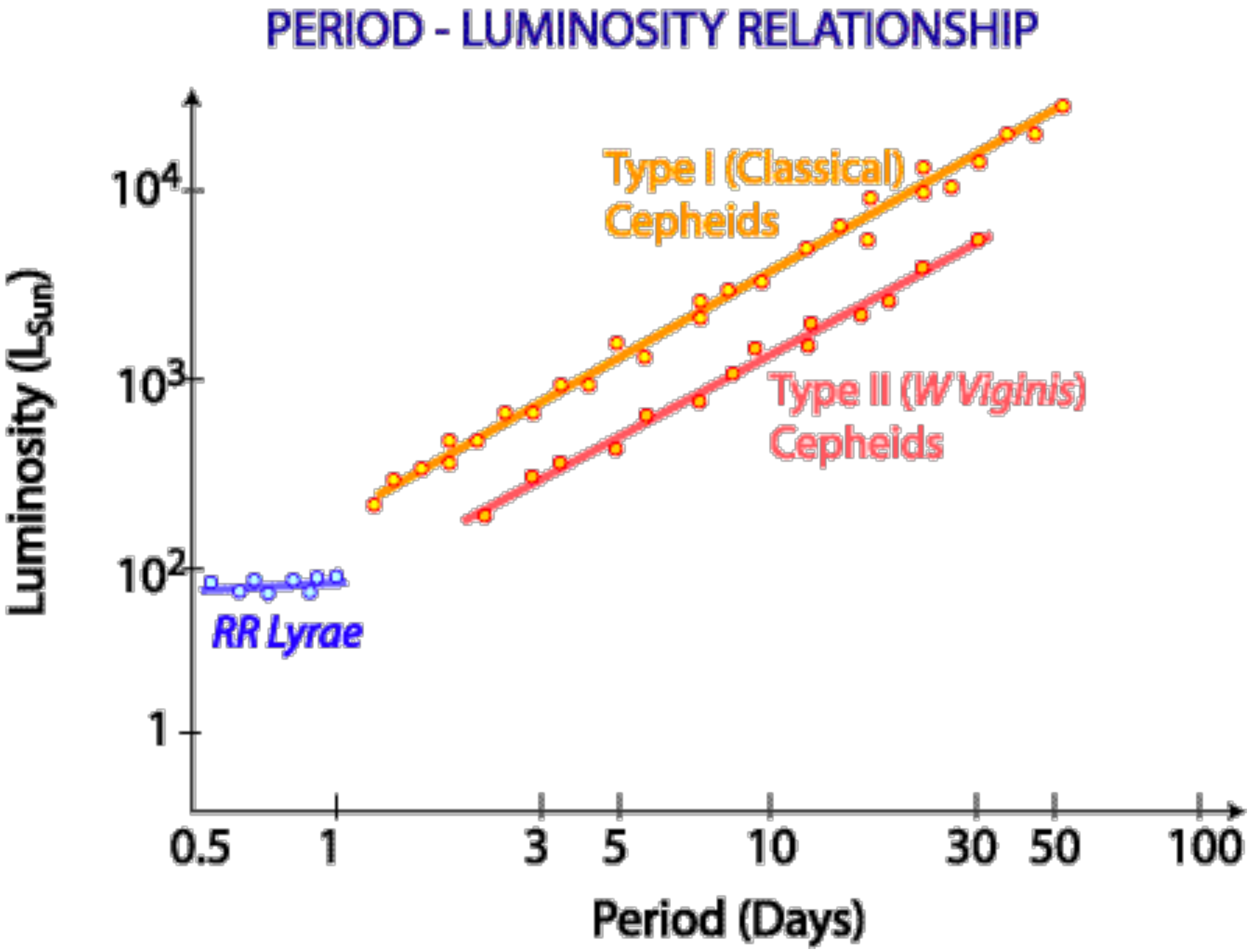
A Cepheid's luminosity can be inferred



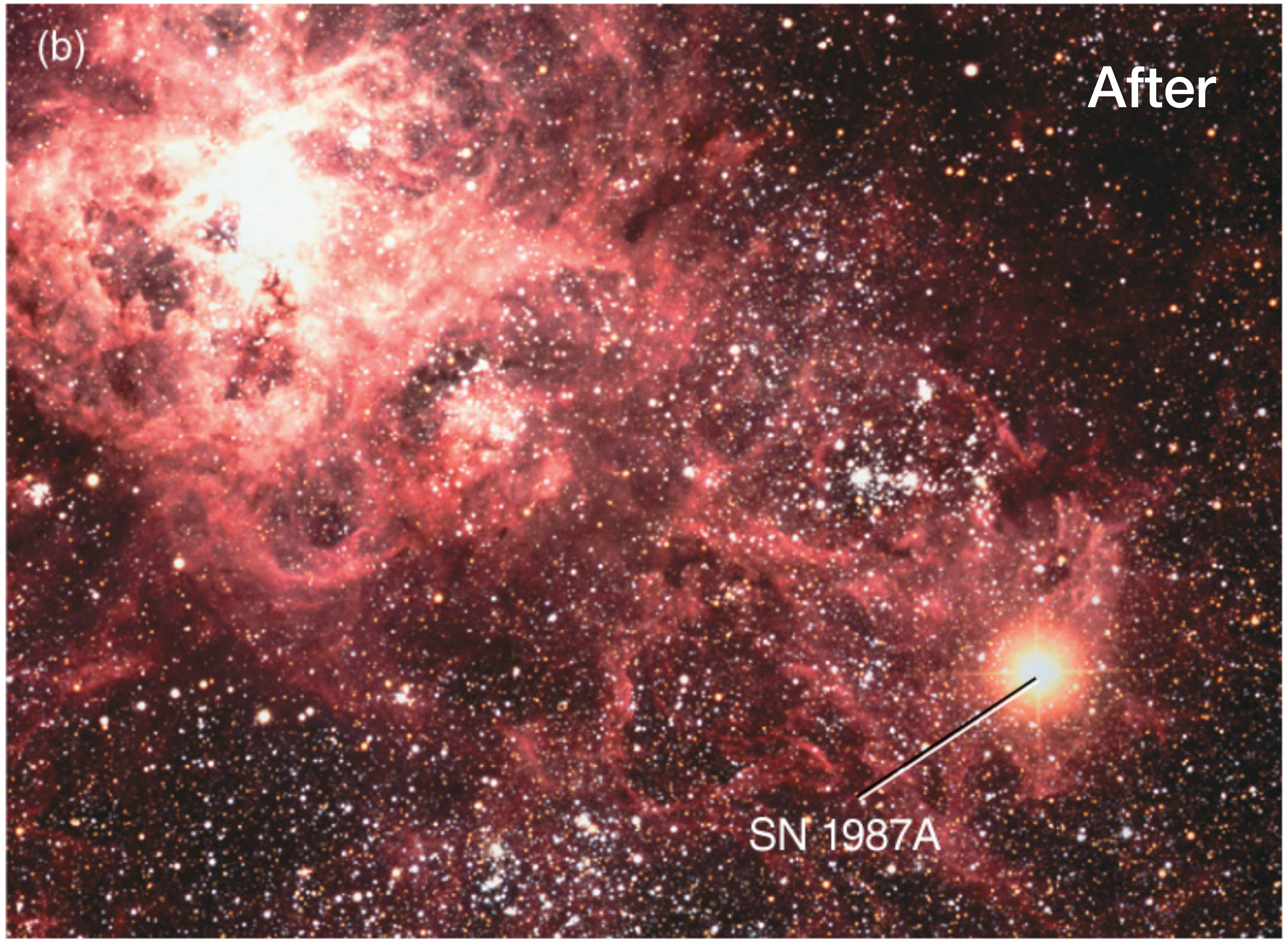
Empirically discovered by Henrietta Leavitt in 1912

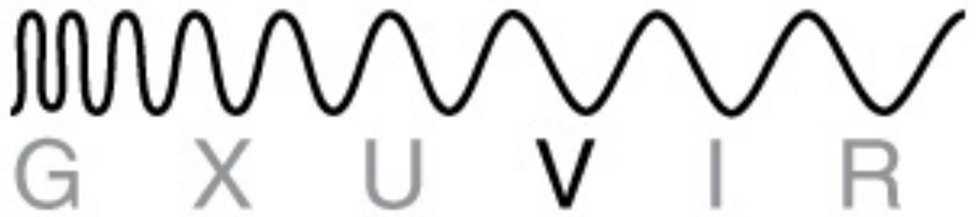
$$\overline{M}_V = -2.76 \log(P/10 \text{ days}) - 4.16$$

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



Type II Supernovae





Betelgeuse: Future Supernova

… were a supernova to go off within about 30 light-years of us, that would lead to major effects on the Earth, possibly mass extinctions. X-rays and more energetic gamma-rays from the supernova could destroy the ozone layer that protects us from solar ultraviolet rays. It also could ionize nitrogen and oxygen in the atmosphere, leading to the formation of large amounts of smog-like nitrous oxide in the atmosphere.

- Mark Reid, Harvard-Smithsonian CfA

430 light-years away (safe distance, unless it explodes as a gamma ray burst pointed at us)

May appear as bright as the full moon, visible during the day!