Week 11 Thursday

<u>Today's Agenda</u>

- ISM intro
- Group problem
- ISM outro
- Star formation
- Evolution of a low mass star

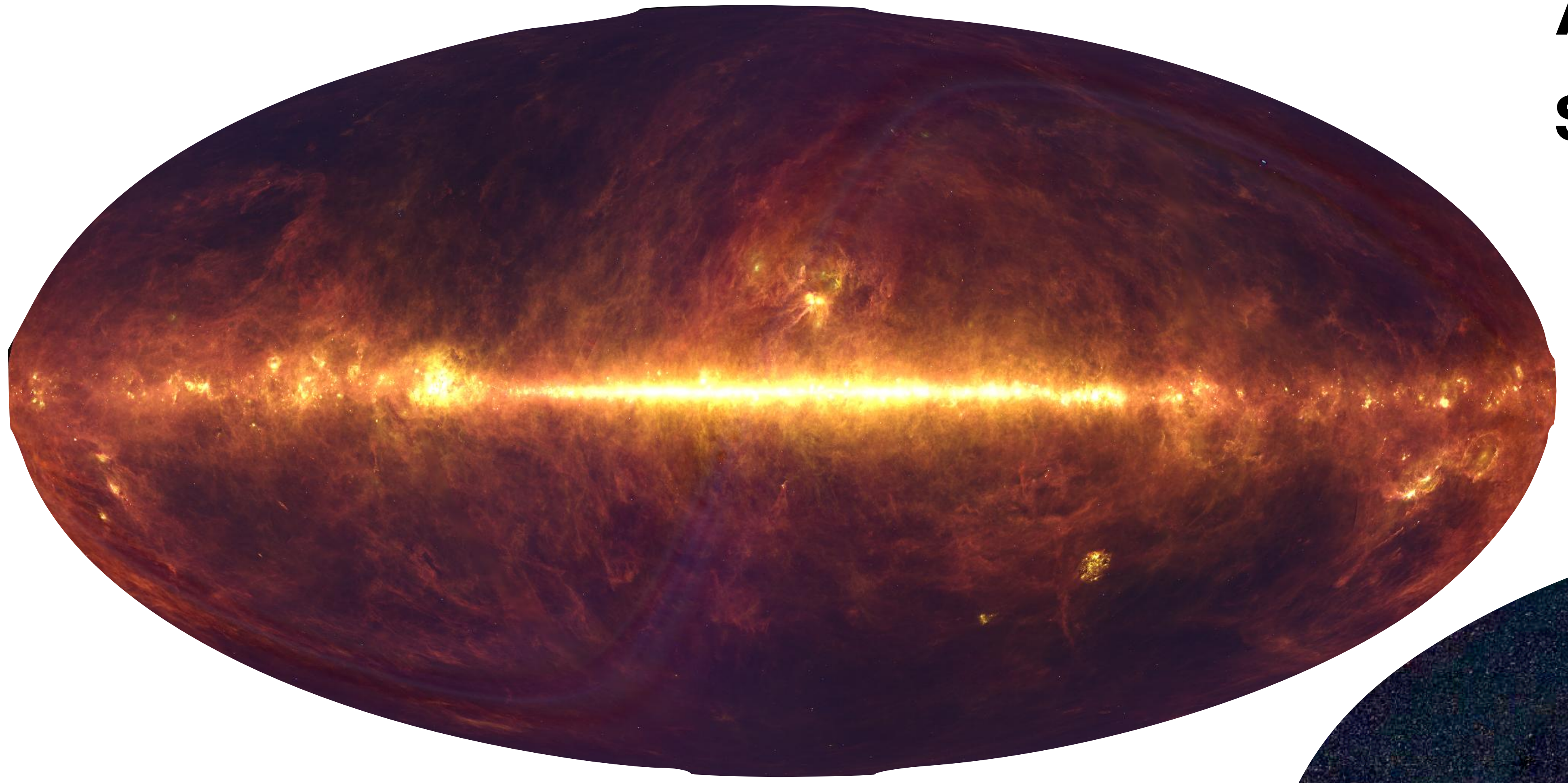
<u>Announcements / Reminders</u>

- HW 8 (& 7.3) due Friday 1min before midnight
- Read Chapters 17 & 18
- Midterm 2 next Thursday!!!!

- HEAP talk at 4pm on Thursday
  - CFTs Blueshift Tensor Fluctuations Universally 🤷‍♀️
- Colloquium at 2pm on Friday
  - Lithium-ion Batteries

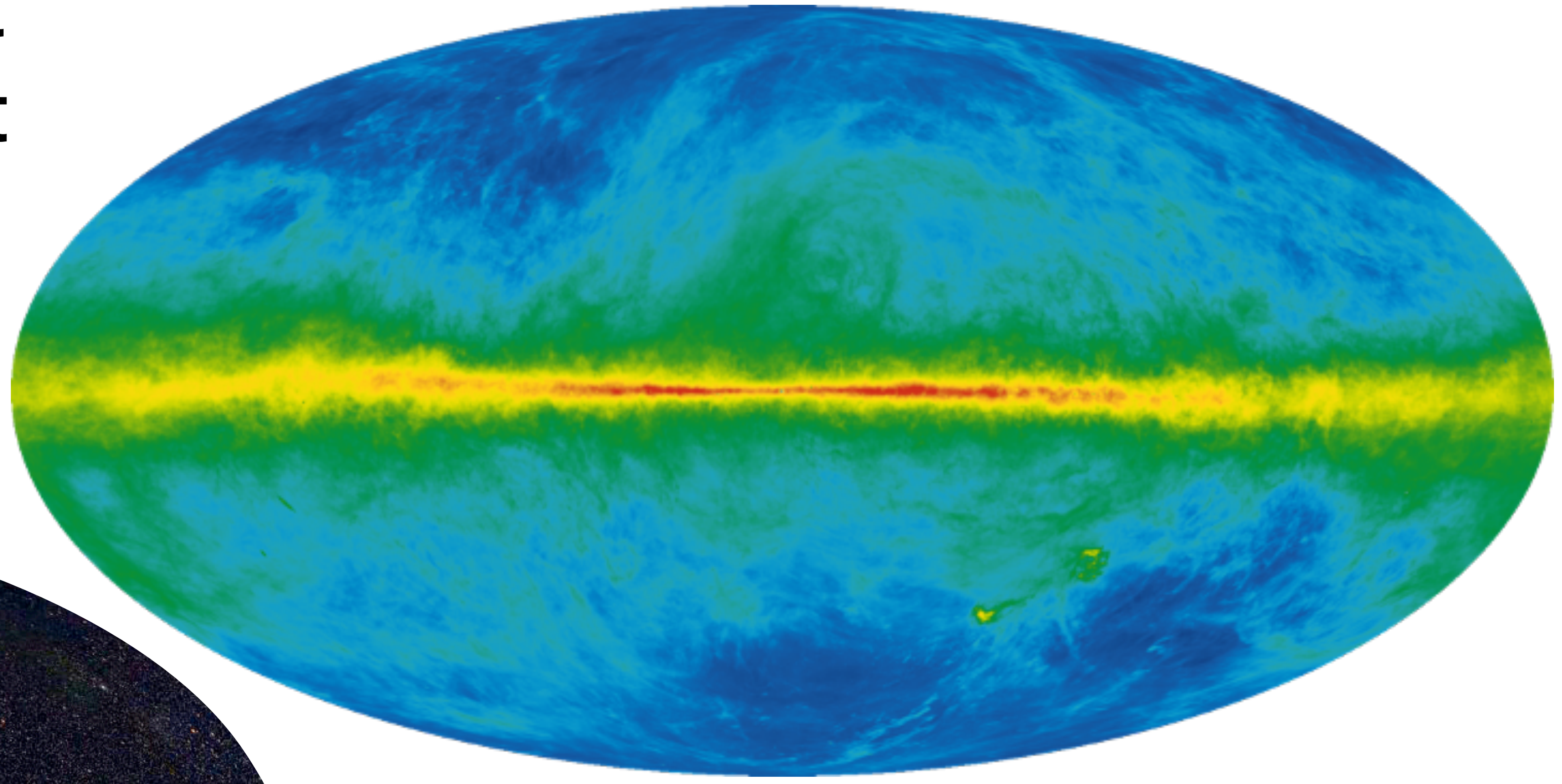
Interstellar Medium (ISM)

Hot Dust (far IR)



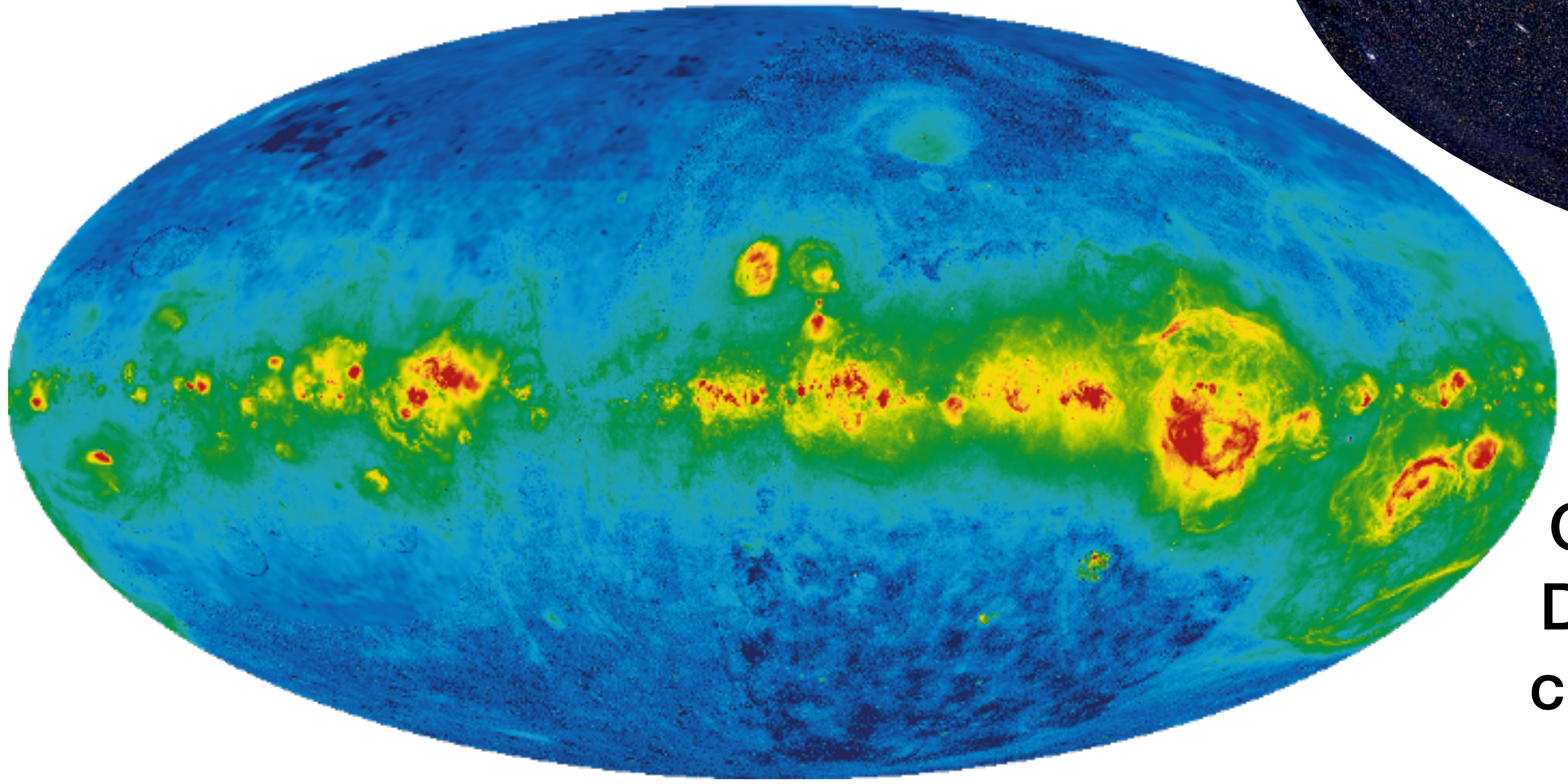
All the diffuse stuff in b/t stars and other compact objects in the MW

Neutral H (21cm; radio)

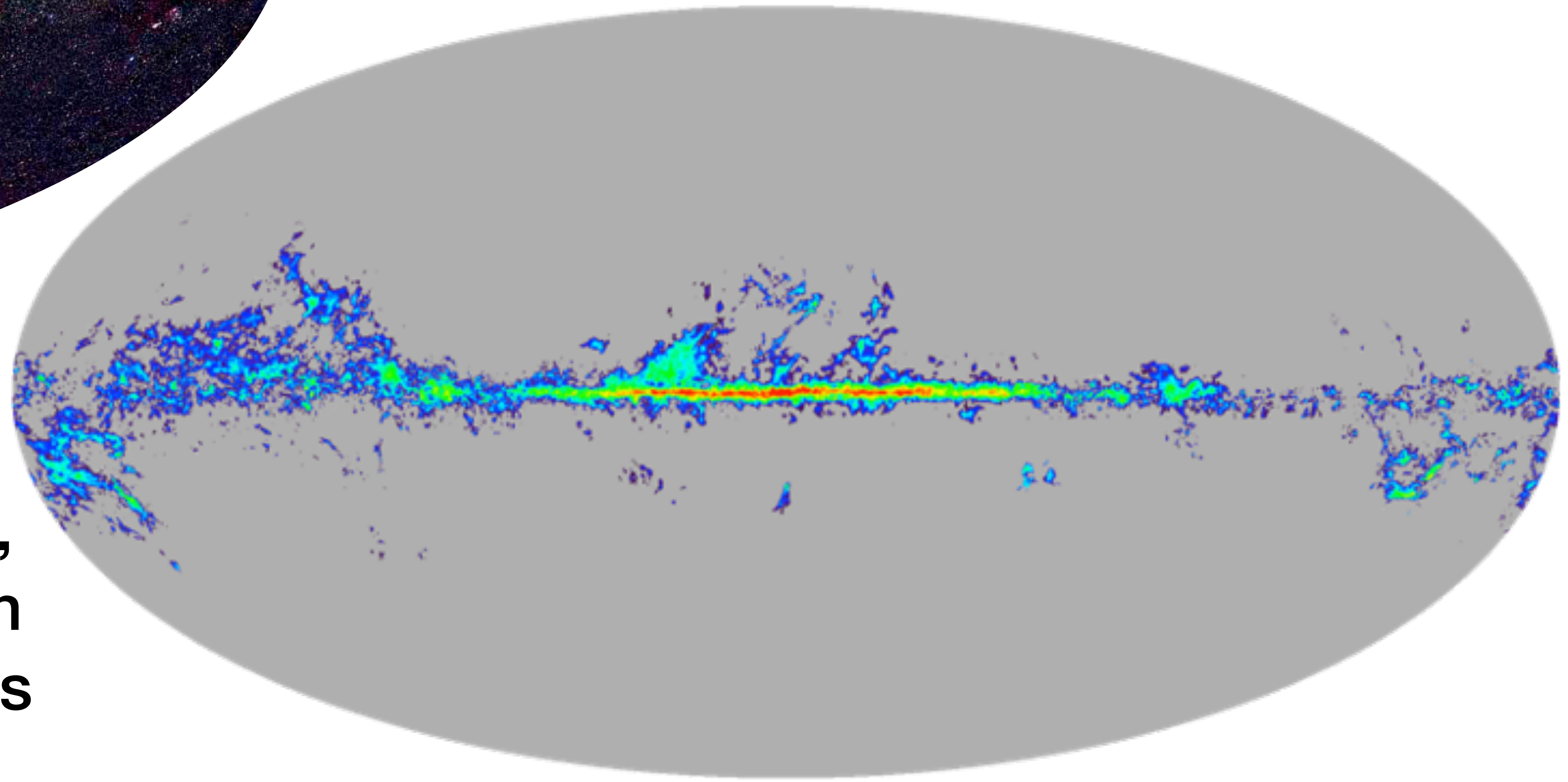


Stars (visible)

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



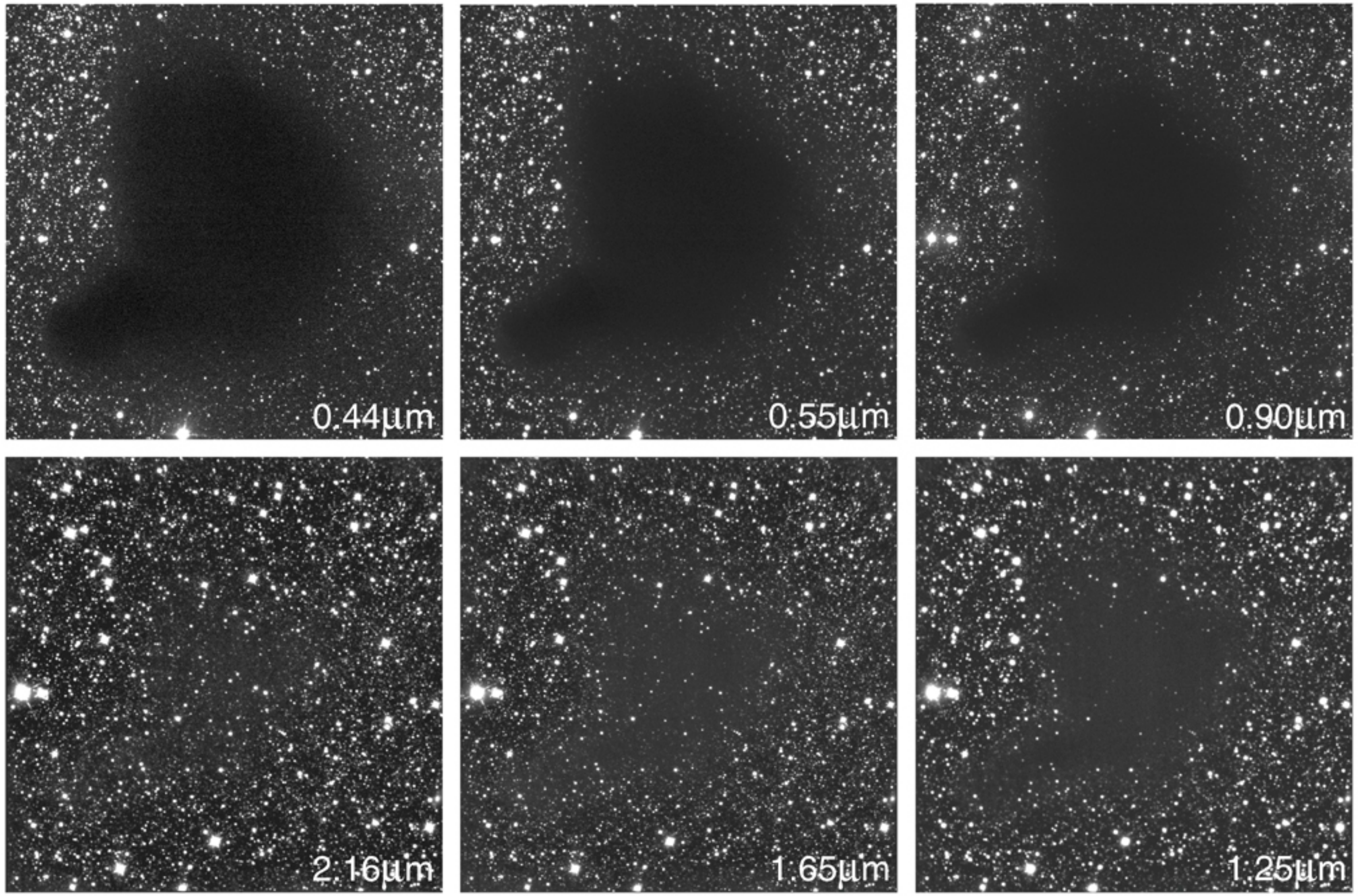
CO (2.6 mm; microwave)



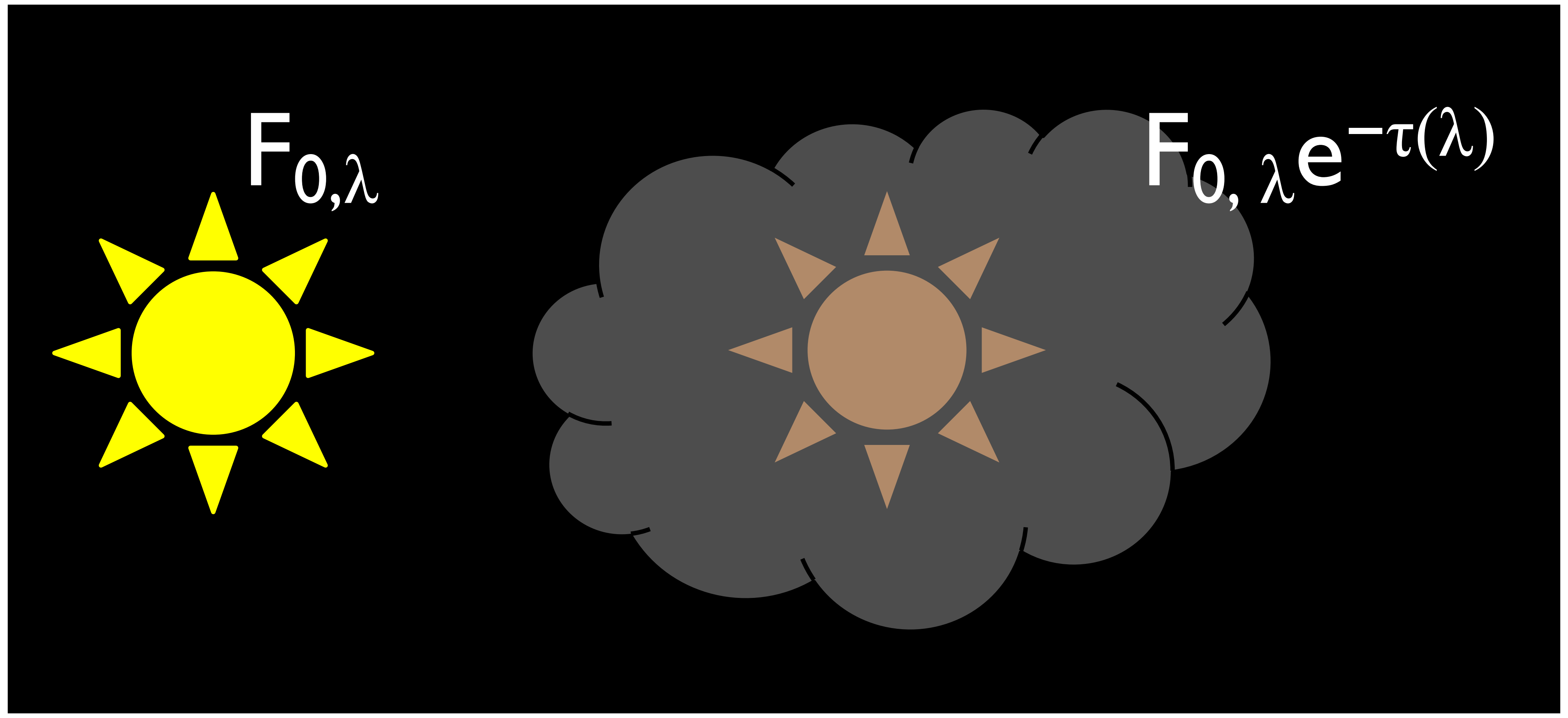
Gas (ionized, neutral, molecules), Dust (large molecules, singly or in clumps), & relativistic components (magnetic fields, cosmic rays)

Dust blocks starlight: Extinction

Barnard 68



Extinction messes up magnitudes AND colors



$$F_\lambda = F_{0,\lambda} e^{-\tau} = F_{0,\lambda} e^{-n\sigma r}$$

$$\begin{aligned} m_{\rm obs} &= C - 2.5\log(F) \\ &= C - 2.5\log(F_0) - 2.5\log(e^{-\tau}) \\ &= m_0 + 2.5\tau\log e \\ &= m_0 + 1.086\tau \end{aligned}$$

Correcting Magnitudes

$$m_{\rm obs}(\lambda) = m_0(\lambda) + A(\lambda)$$

$$\text{e.g.,}\ m_{V,{\rm obs}} = m_V + A_V$$
$$= V_0 + A_V$$

Correcting Colors

$$\begin{aligned} (B-V)_{\rm obs} &= (B-V)_0 + (A_B + A_V) \\ &= (B-V)_0 + E(B-V) \end{aligned}$$

$$R \equiv \frac{A_V}{E(B-V)} \approx 3.1$$

Group Problem

Imagine you observe 2 stars that have the same spectral (but not necessarily luminosity) type.

$$m_{V,1} = 15 \qquad m_{V,2} = 21$$

$$m_{B,1} = 15.5 \qquad m_{B,2} = 22.5$$

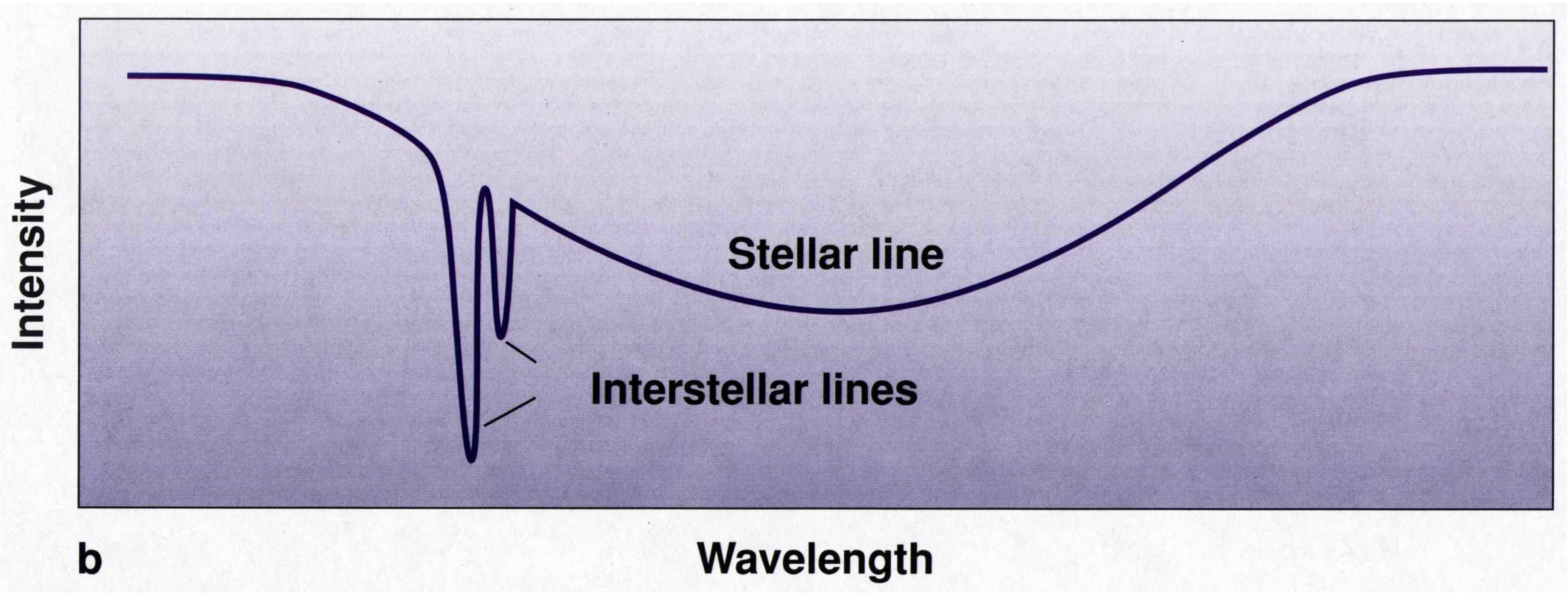
Assuming one of the stars has an $A_V = 0$, what is the extinction toward the other star?

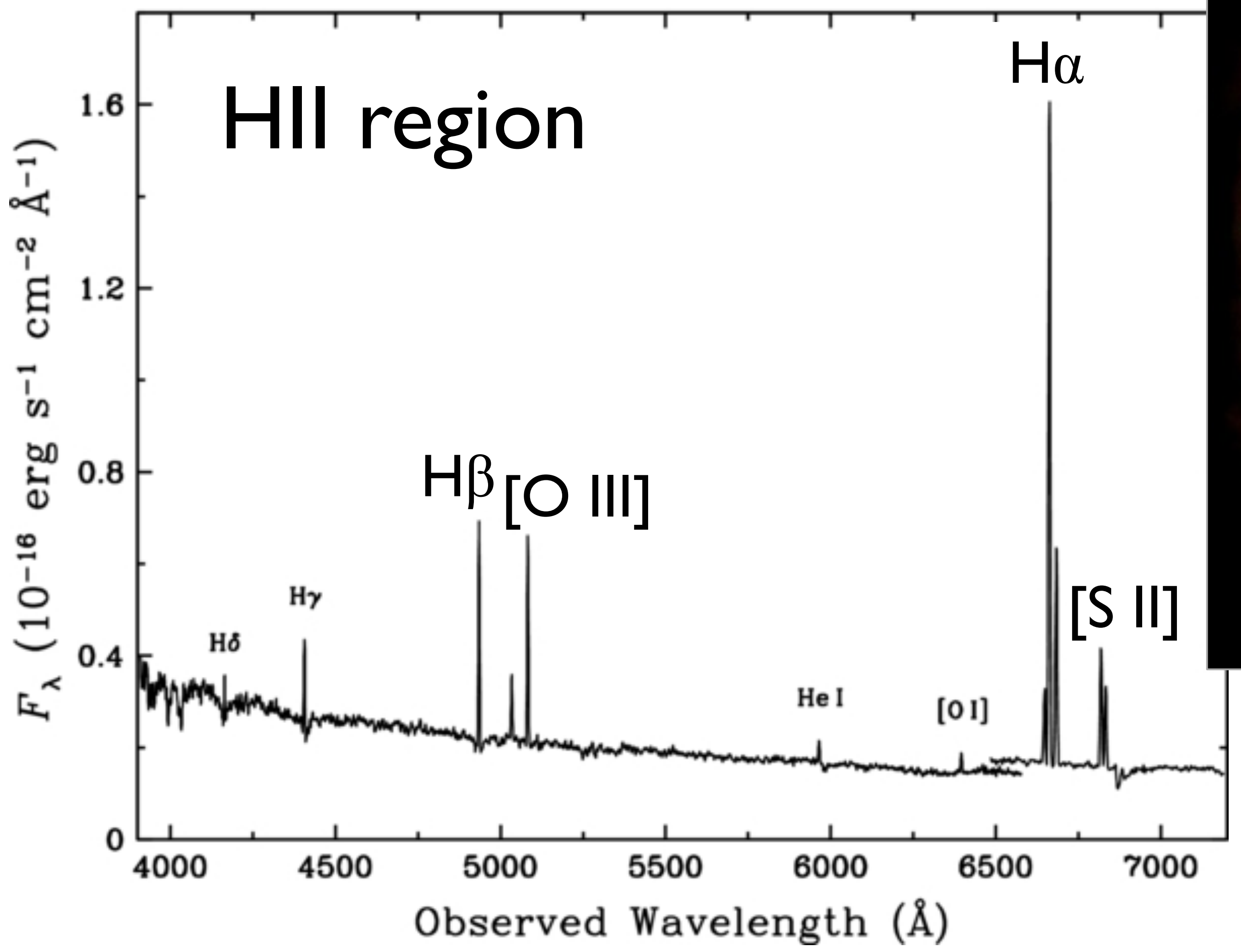
What is the optical depth toward that star in the B band?

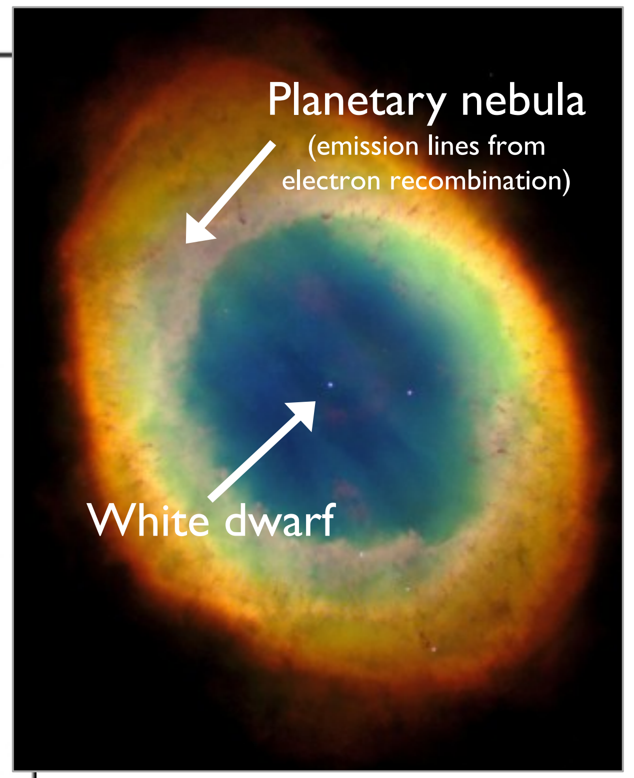
Assuming both stars have the same distance from us, what can you say about their luminosity classes?

Detection of gas is generally more direct

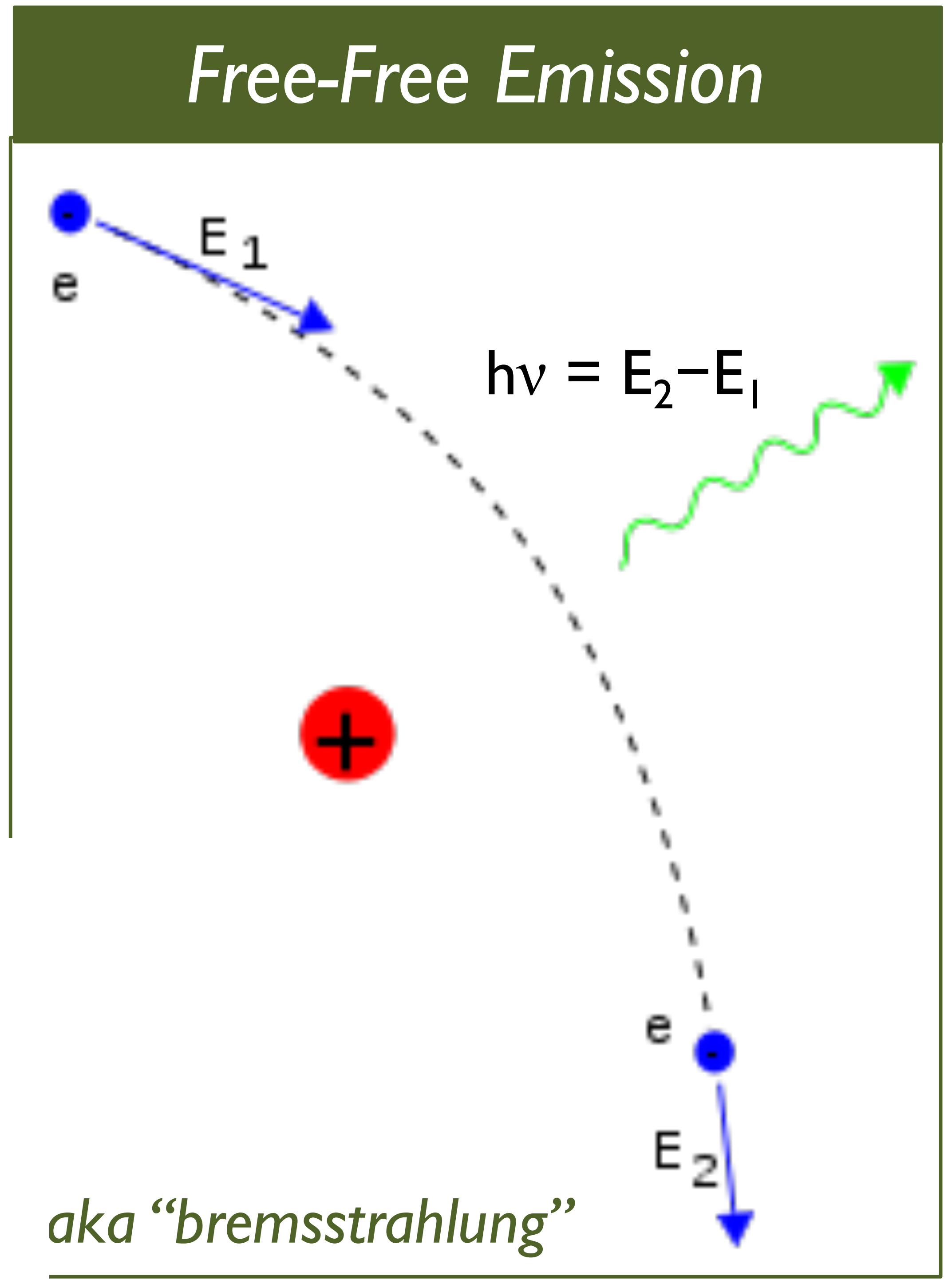
Absorption & Emission Lines (Kirchoff's laws)



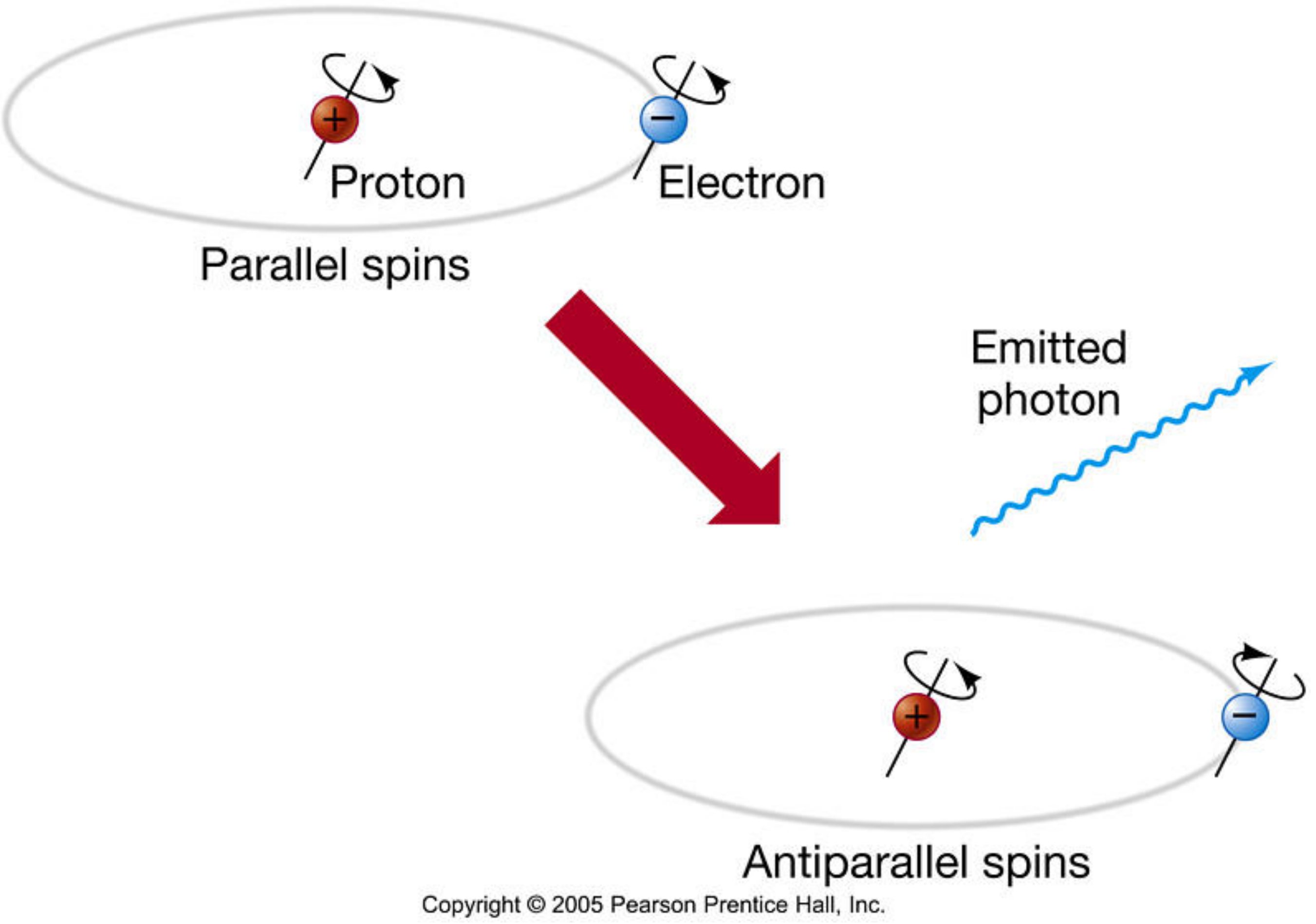




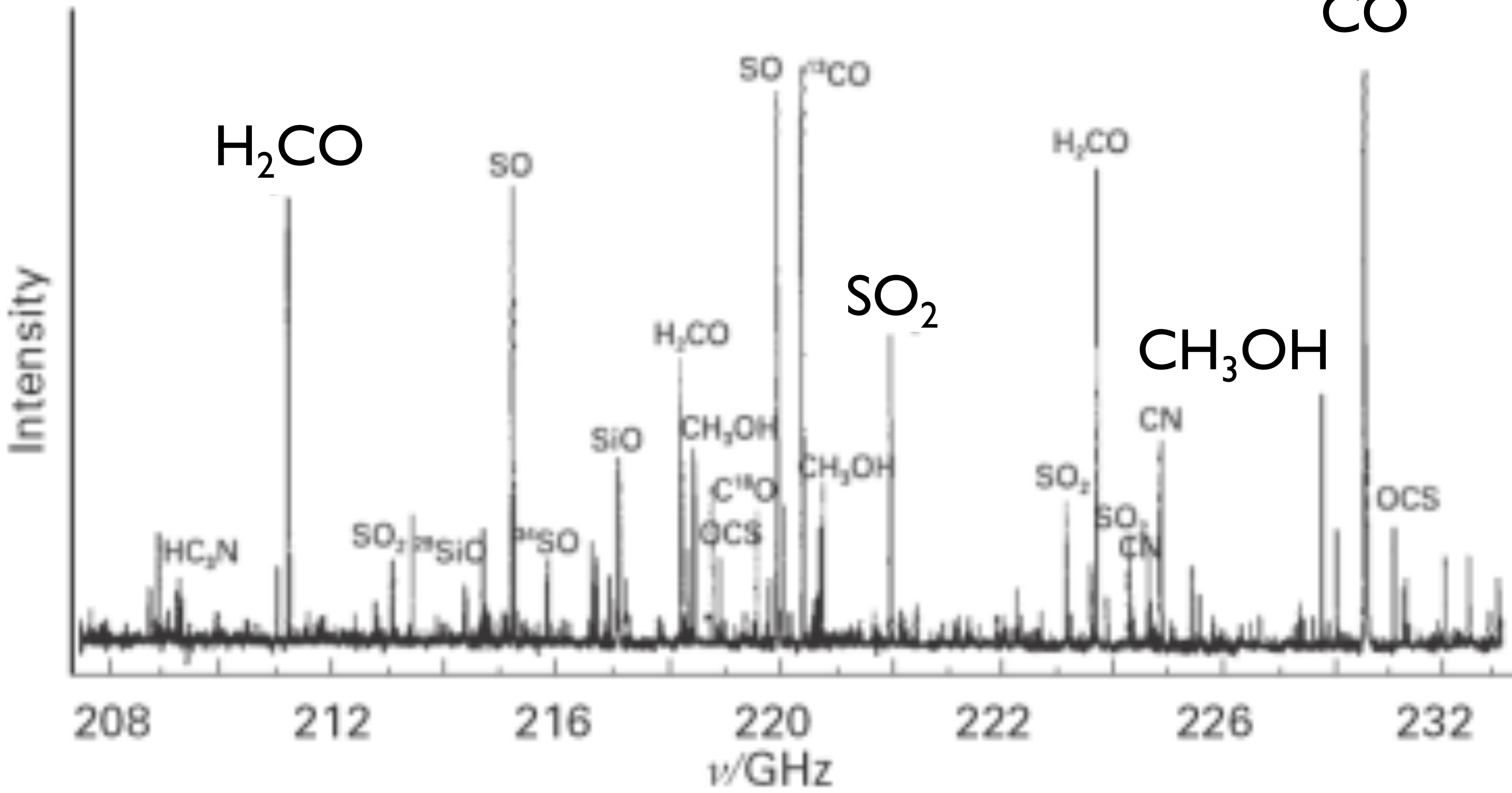
Radio continuum

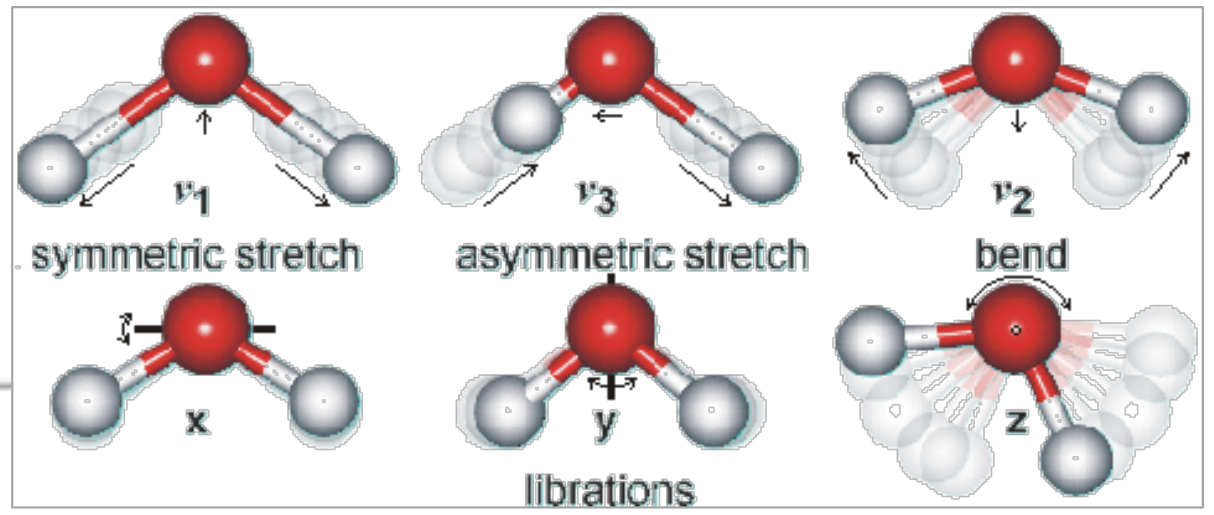


Neutral H "spin-flip": 21cm emission



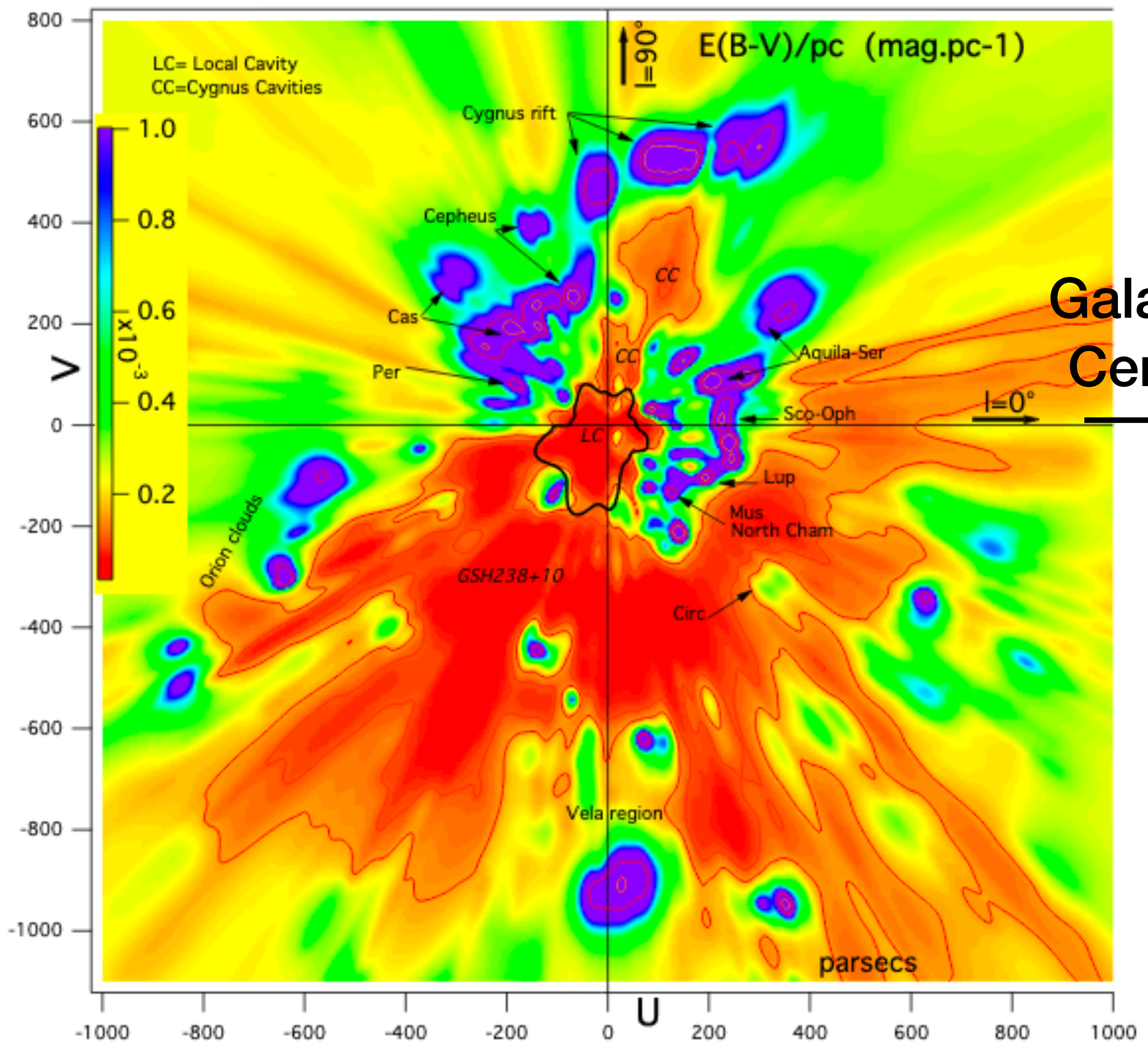
Molecule excitations (radio)





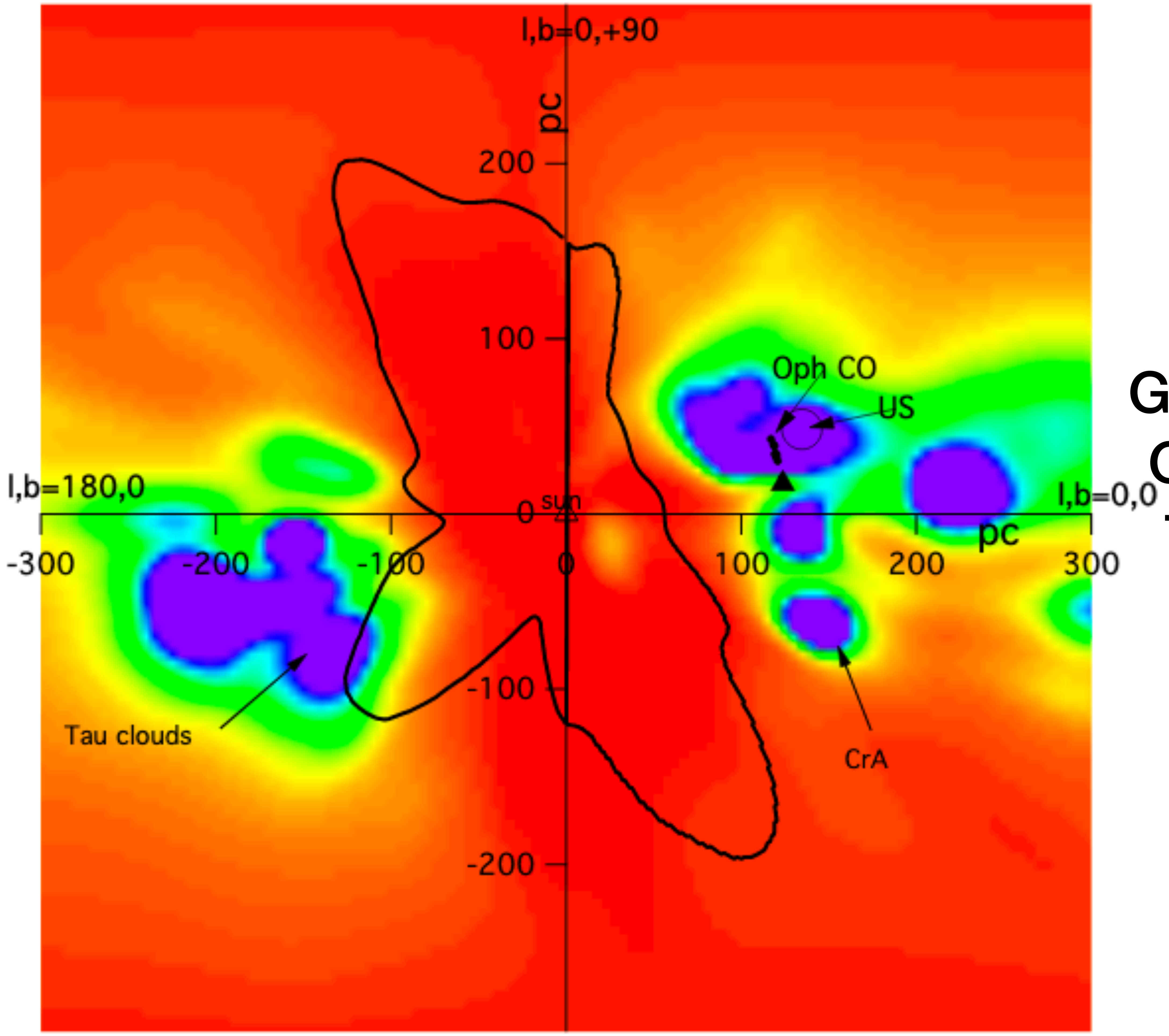
ISM also contains very hot gas heated by SNe

Face-on disk view



Galactic Center

Edge-on disk view

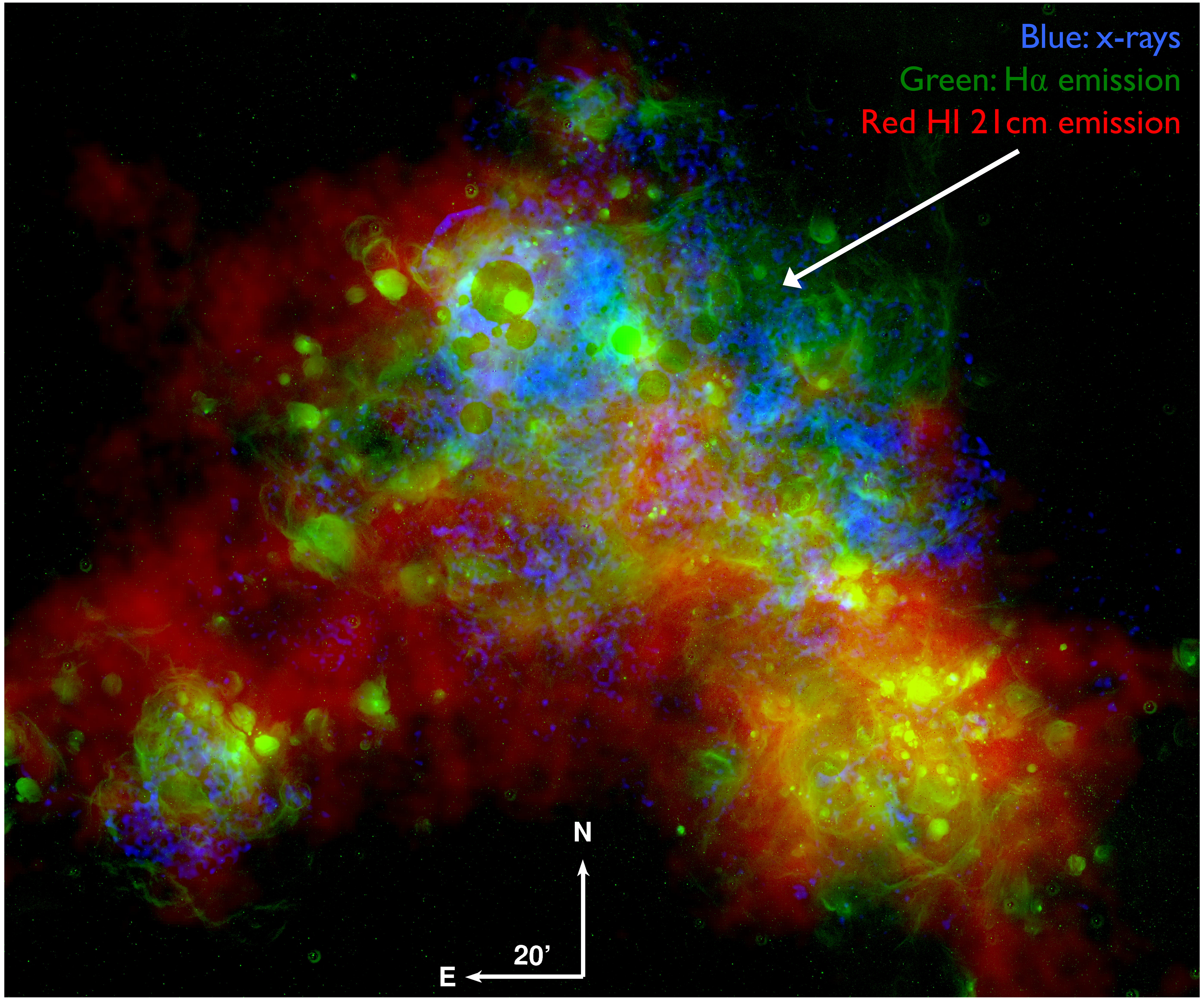


Galactic Center

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

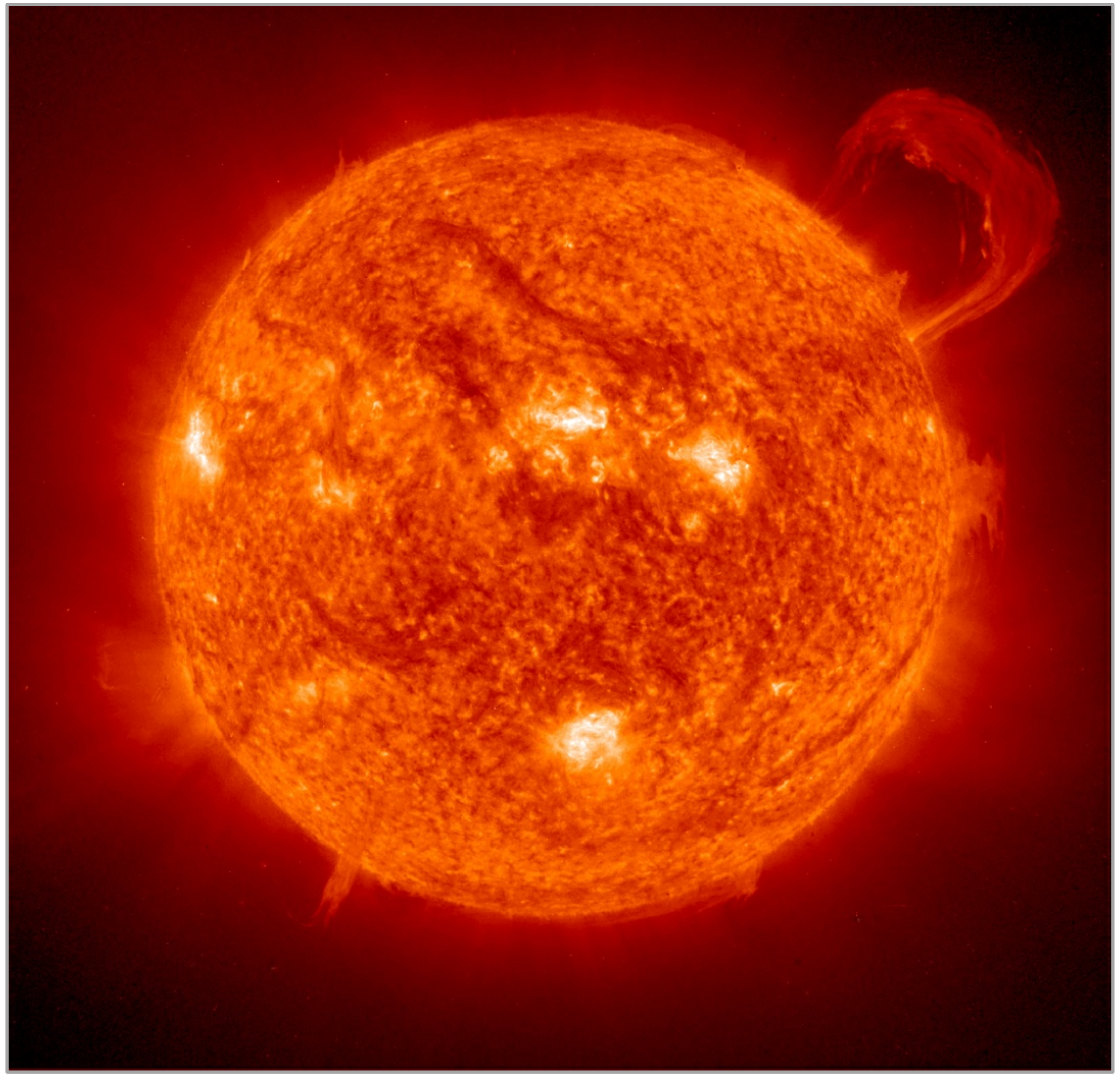
"Star" —> undergoing fusion

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

Density:

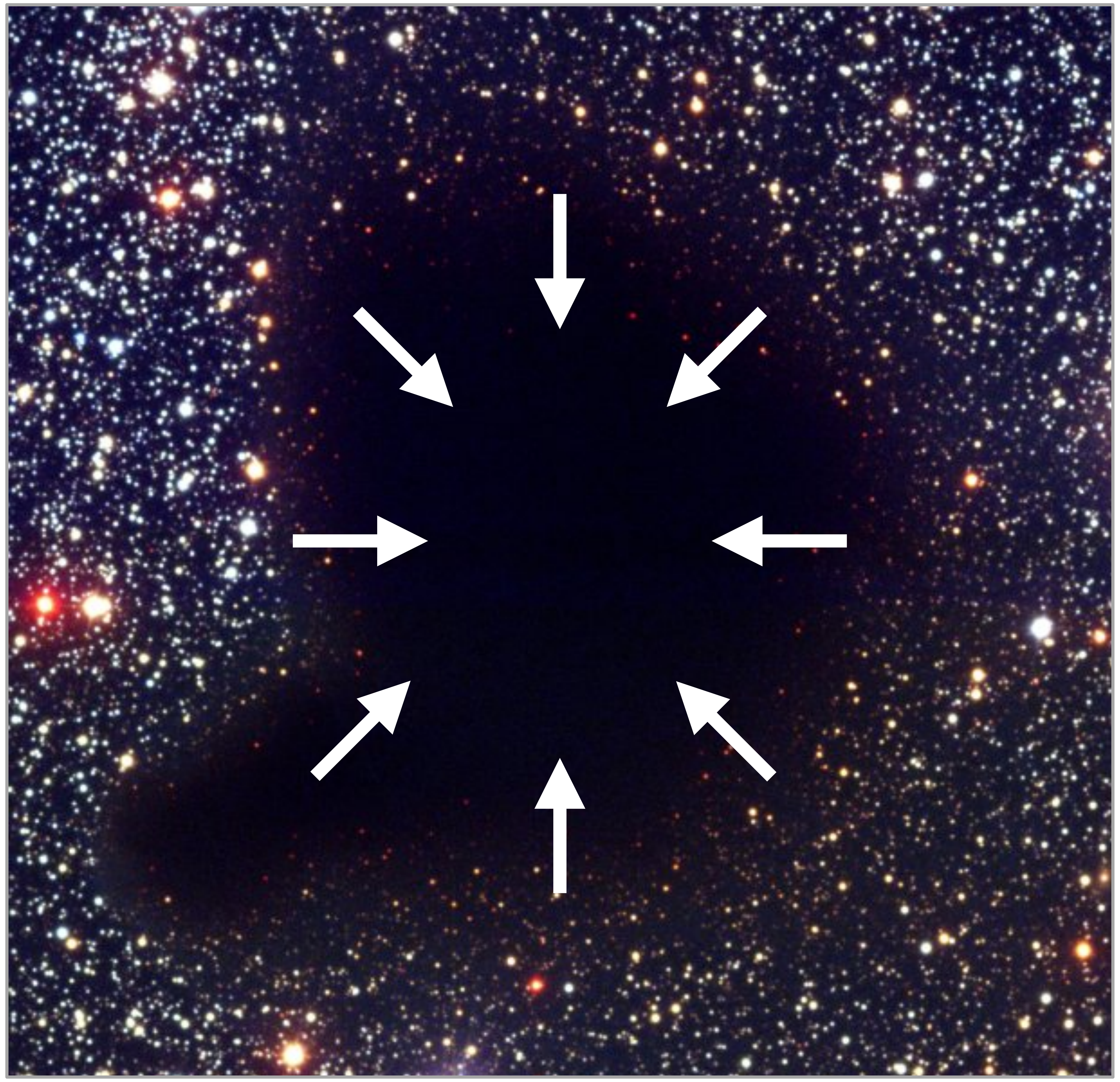
10^{-15} kg m^{-3}

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

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

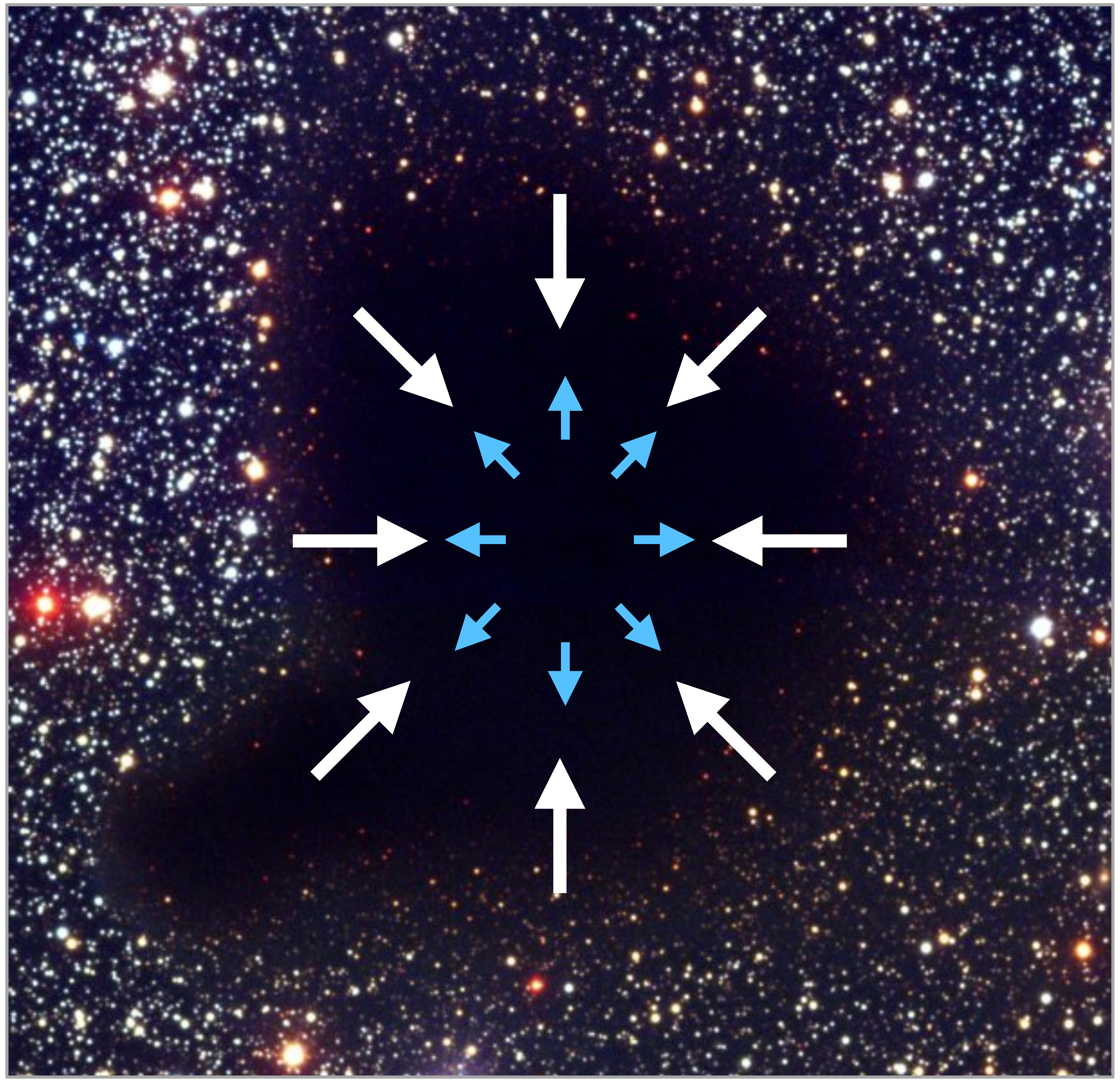
Halfway through the orbit, it reaches the center

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

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

"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

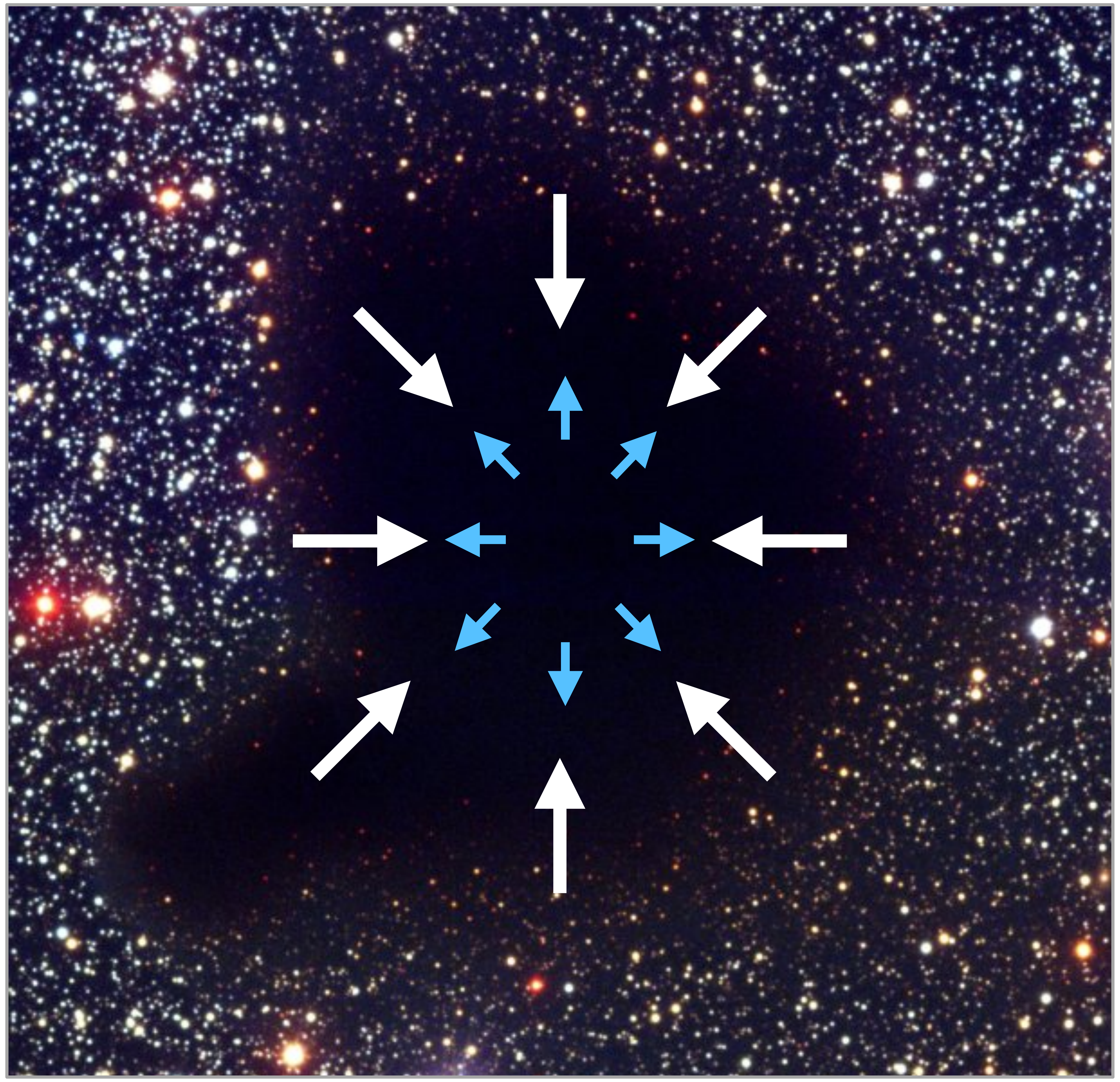
If density and size is determined, also have a critical mass —> Jeans mass

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

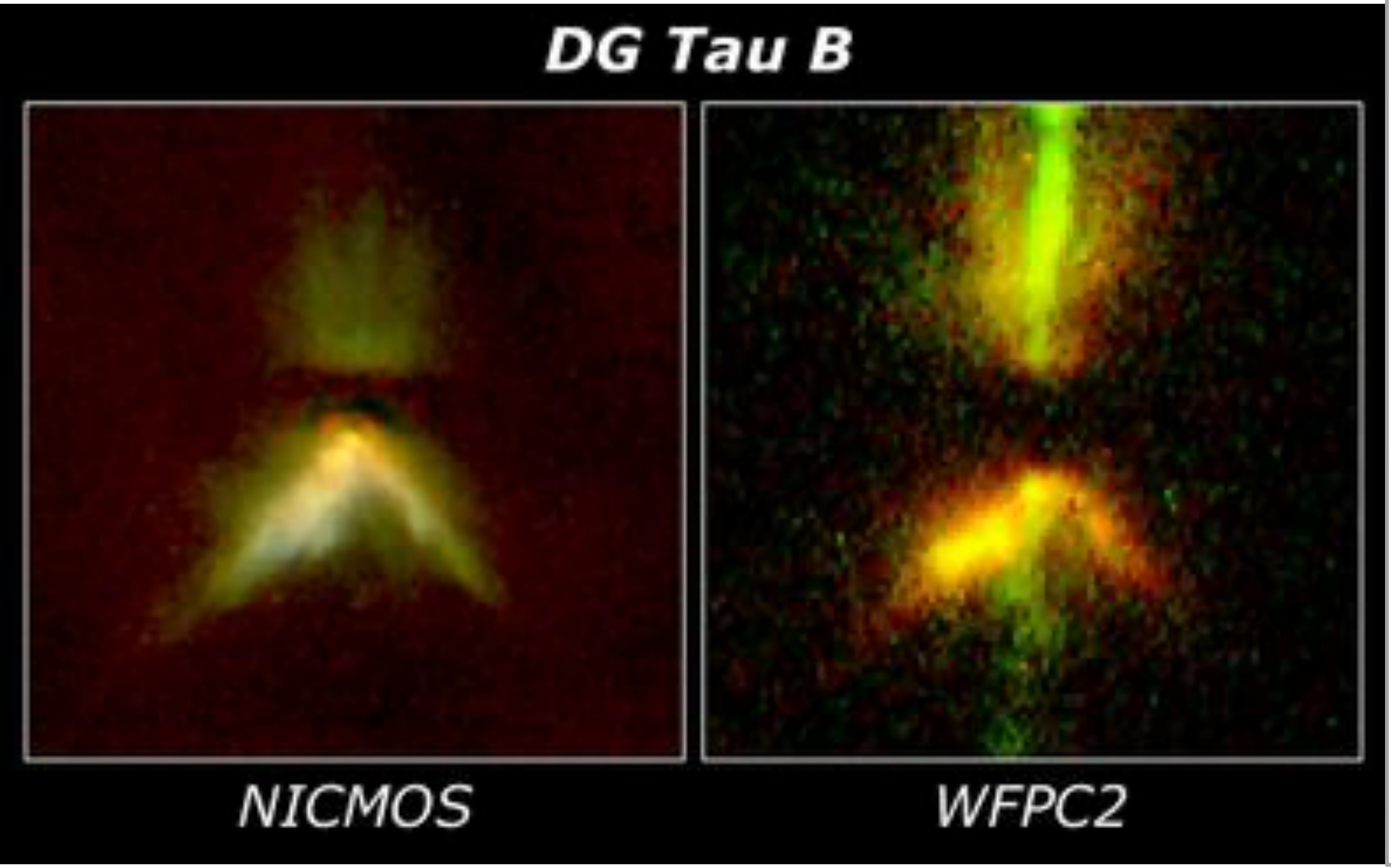
$$t_{\rm ff} < t_{\rm press} = \frac{r_0}{c_s}$$

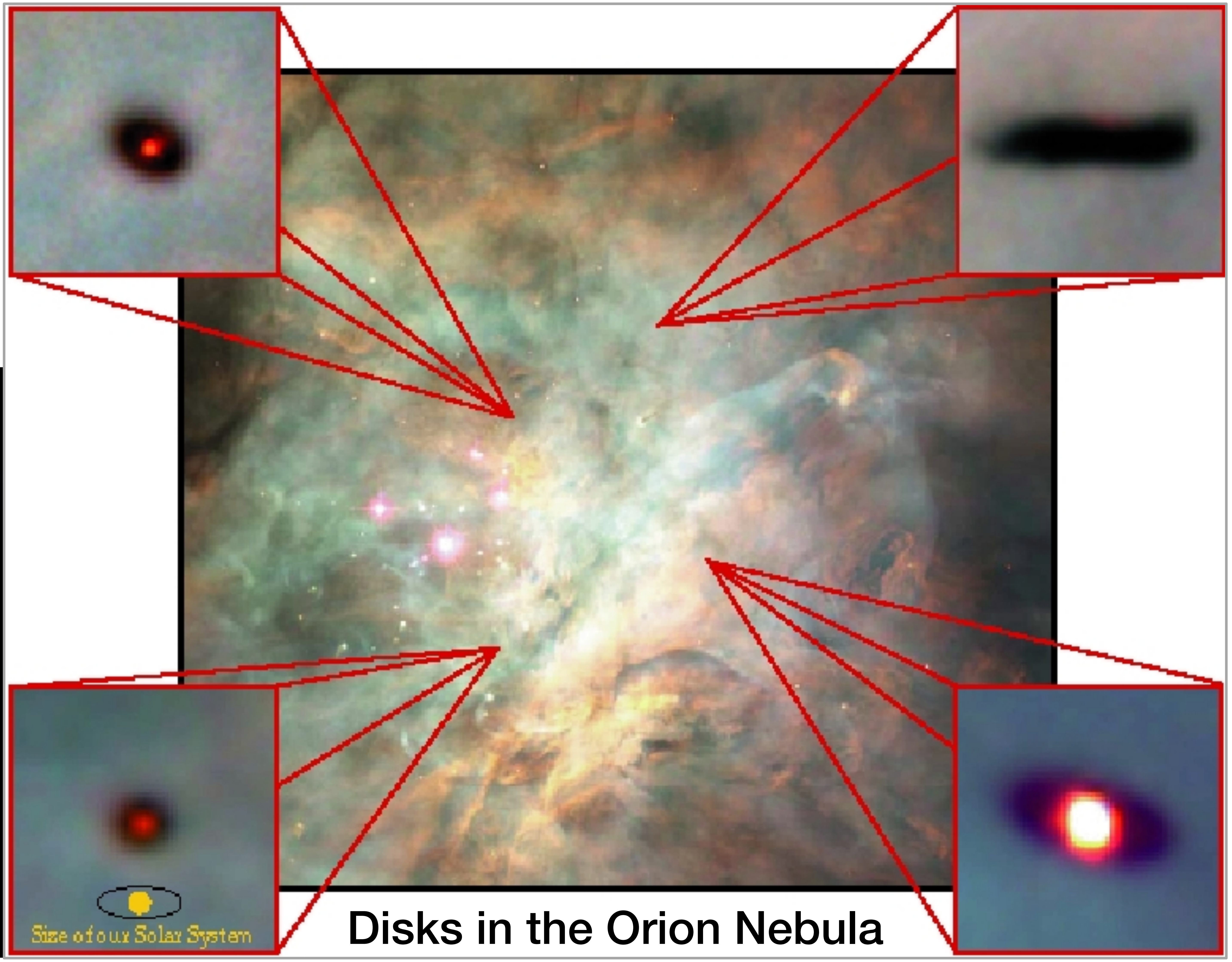
$$c_s = \left(\frac{\gamma k T}{\mu m_p}\right)^{1/2}$$

Protostars form from an "accretion disk"

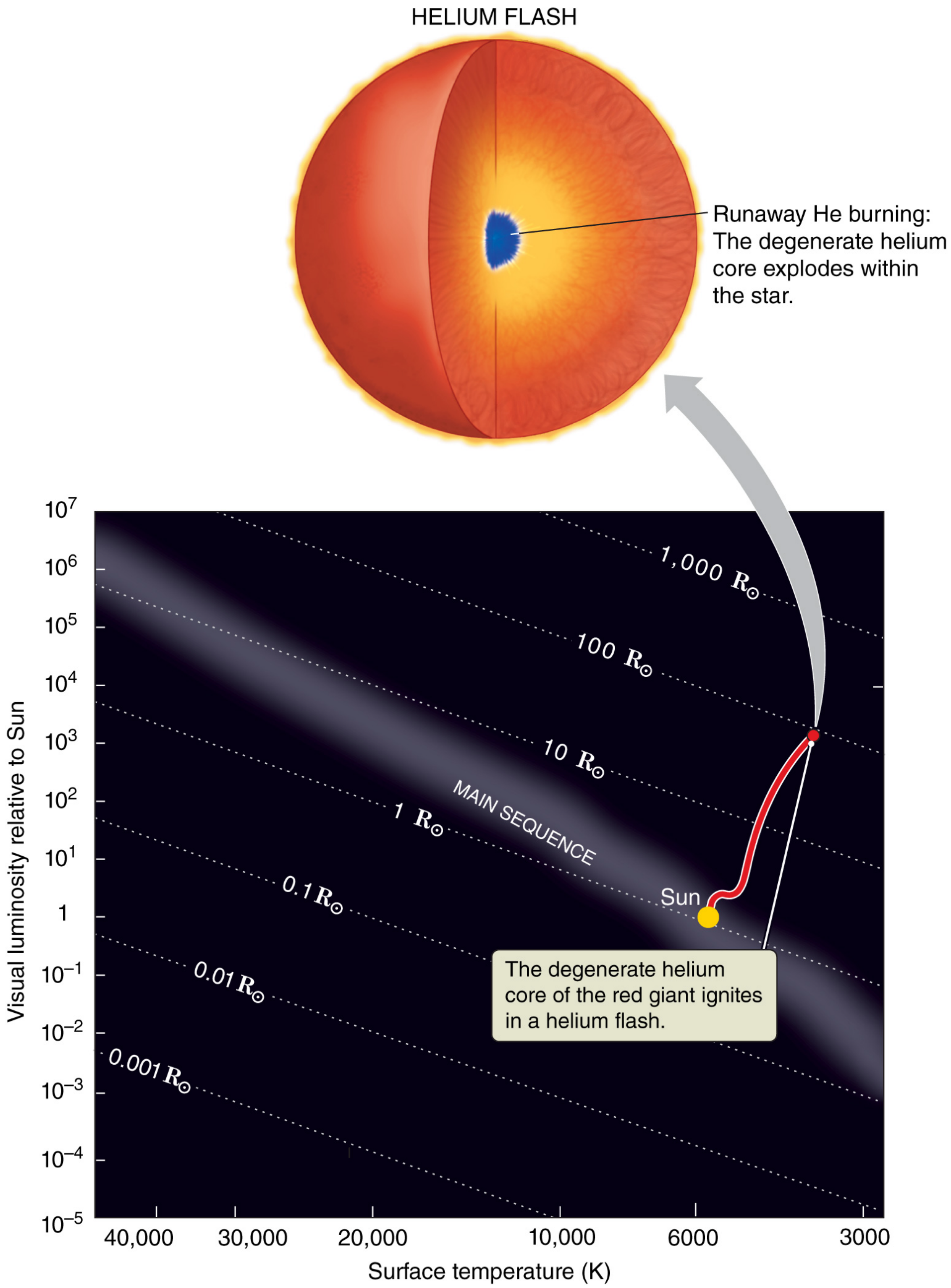
Angular momentum dissipated in the disk

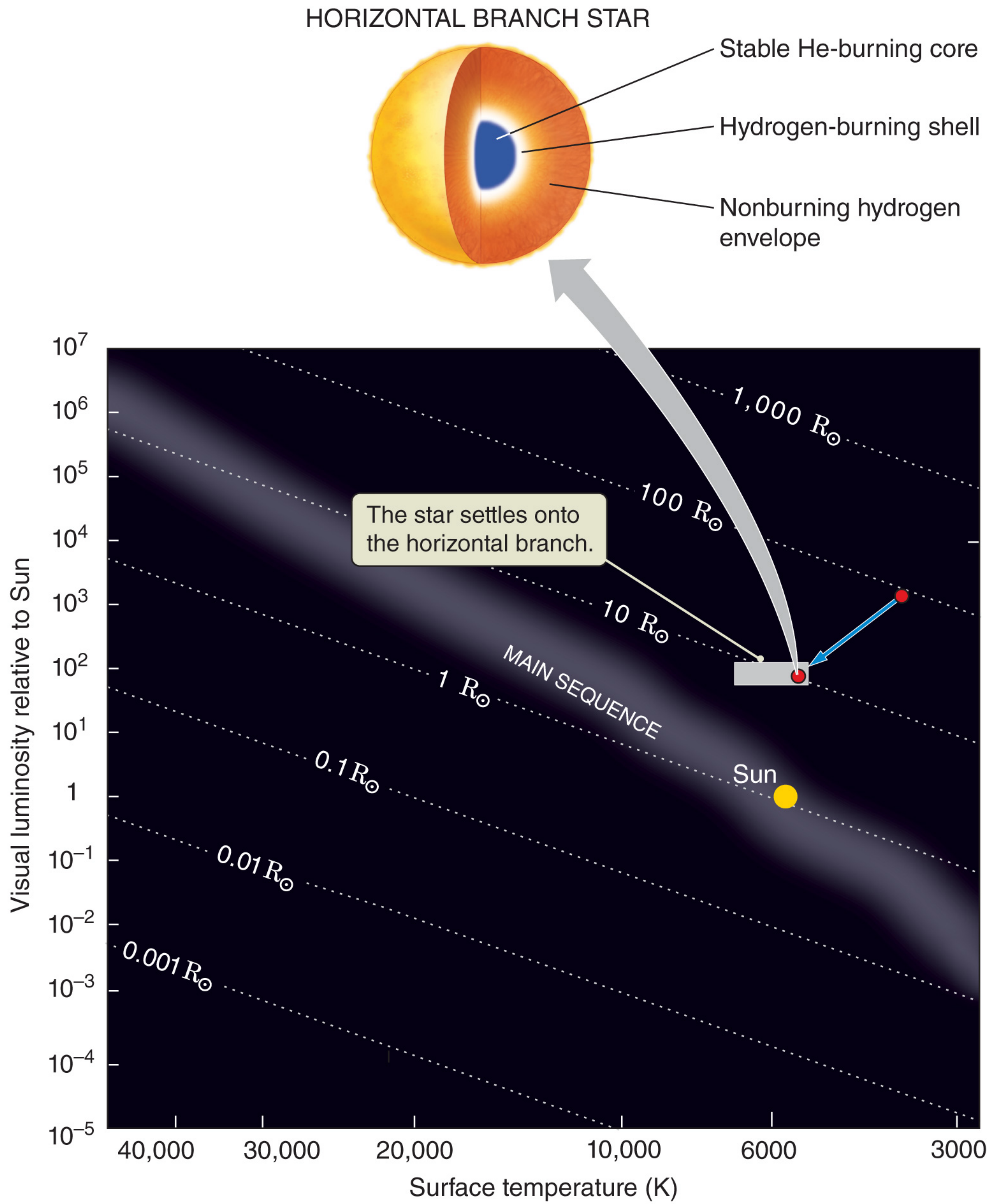
>99.9% of mass in the protostar, but planets with much less mass typically carry more angular momentum (which originates from the cloud)

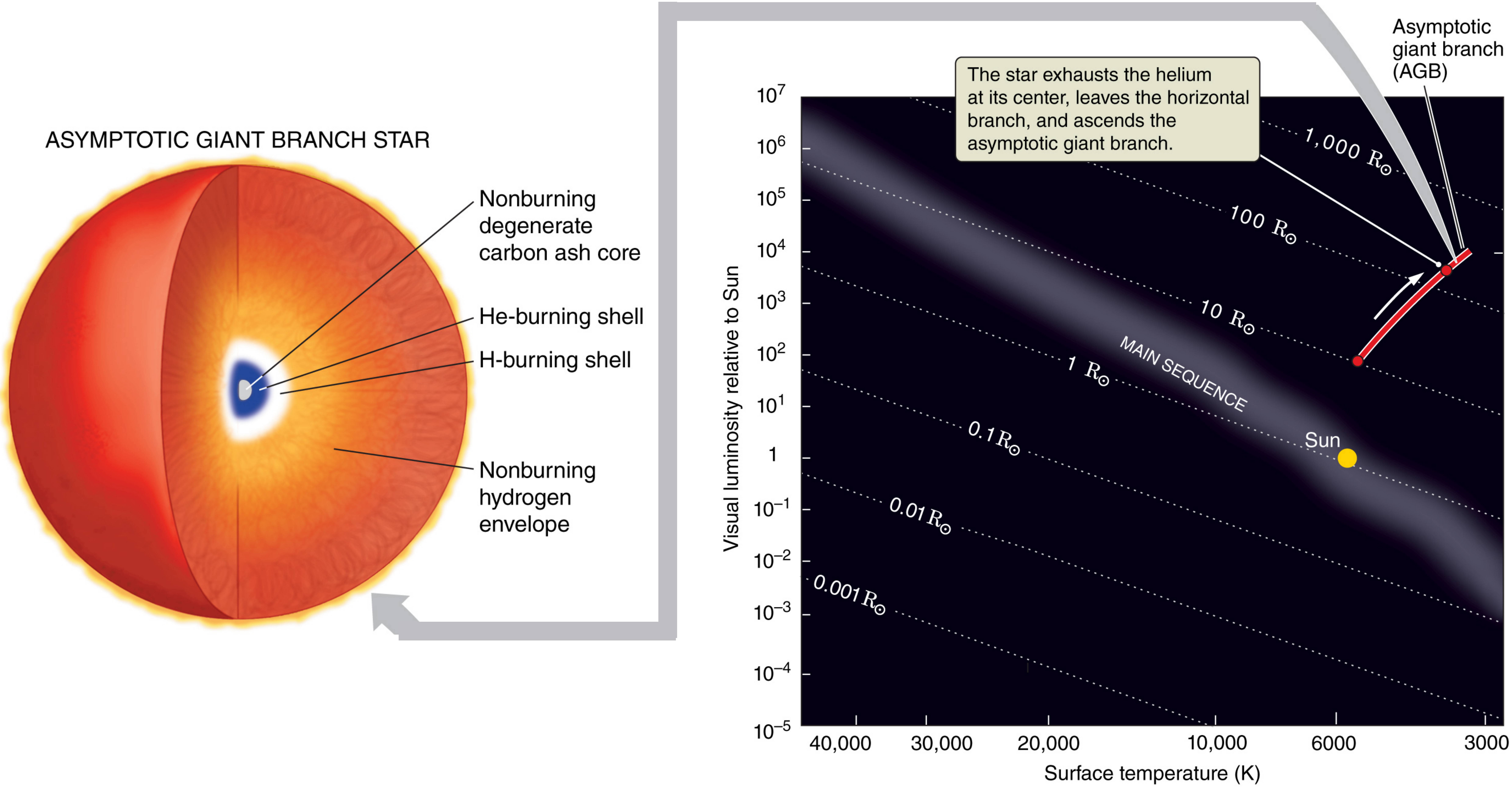




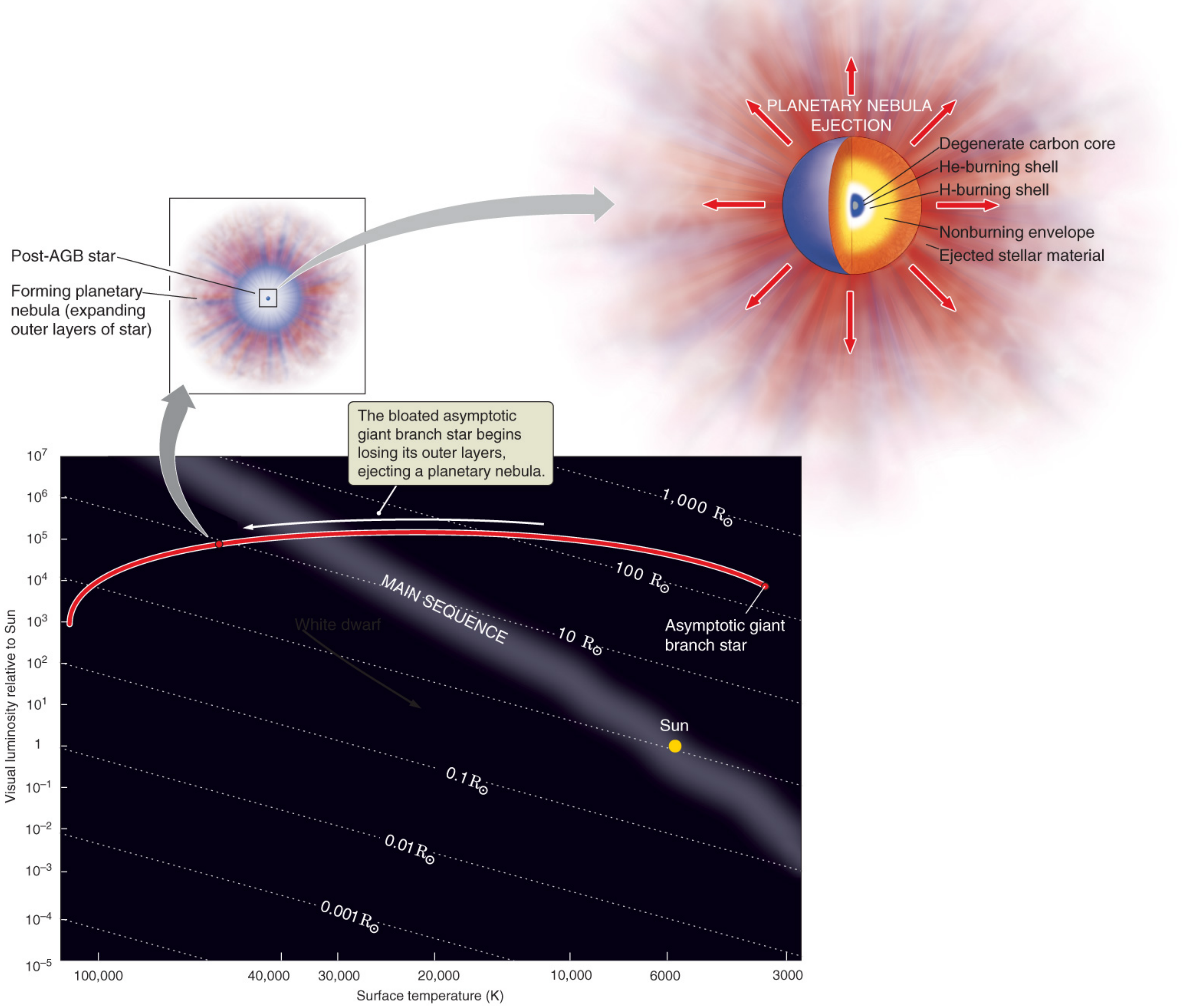
Disks in the Orion Nebula

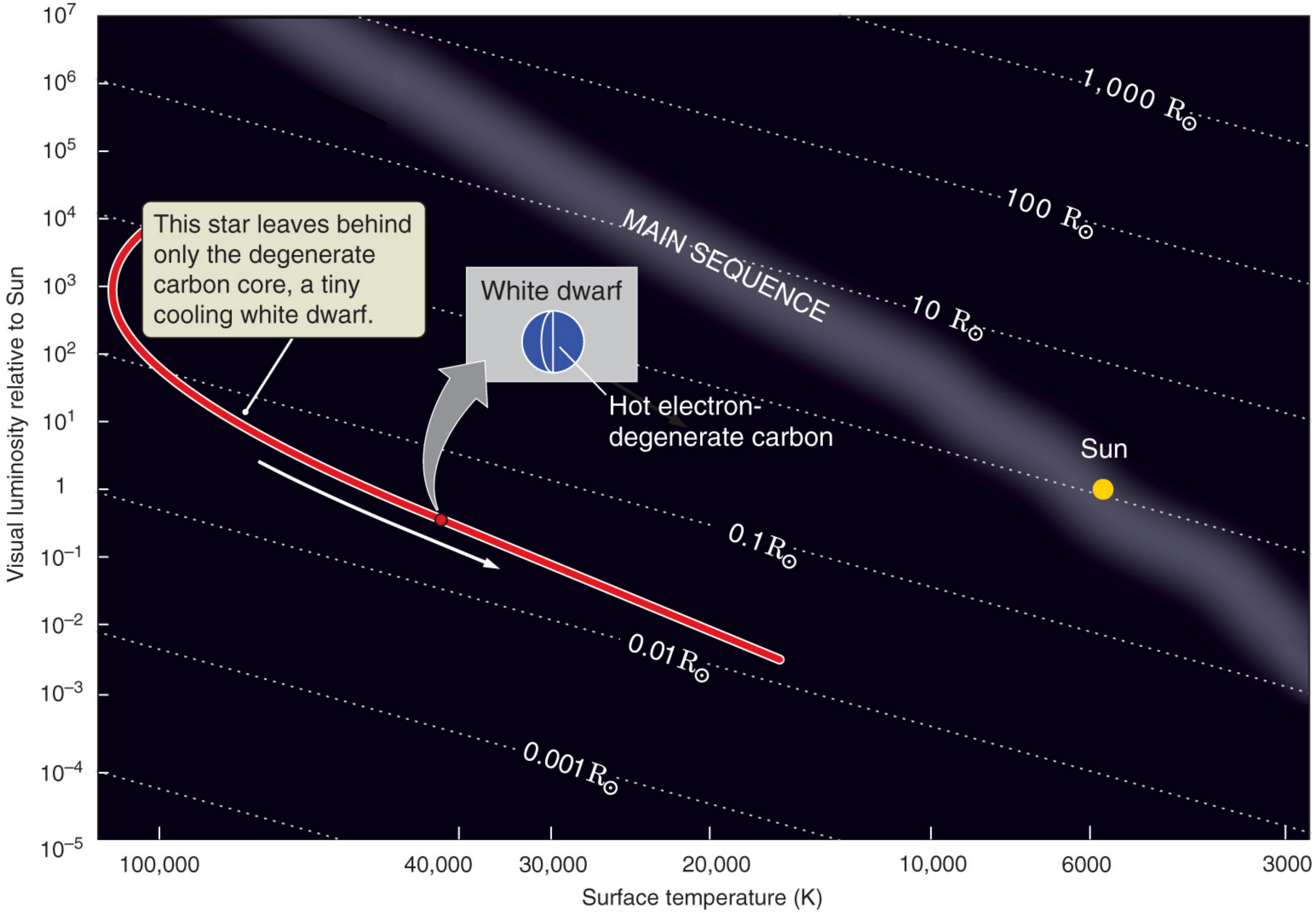

HELIUM FLASH
Runaway He burning: The degenerate helium core explodes within the star.
1,000 R☉
100 R☉
10 R☉
1 R☉
0.1 R☉
0.01 R☉
0.001 R☉
MAIN SEQUENCE
Sun
The degenerate helium core of the red giant ignites in a helium flash.
Visual luminosity relative to Sun
10^7
10^6
10^5
10^4
10^3
10^2
10^1
1
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
40,000
30,000
20,000
10,000
6000
3000
Surface temperature (K)


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
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)



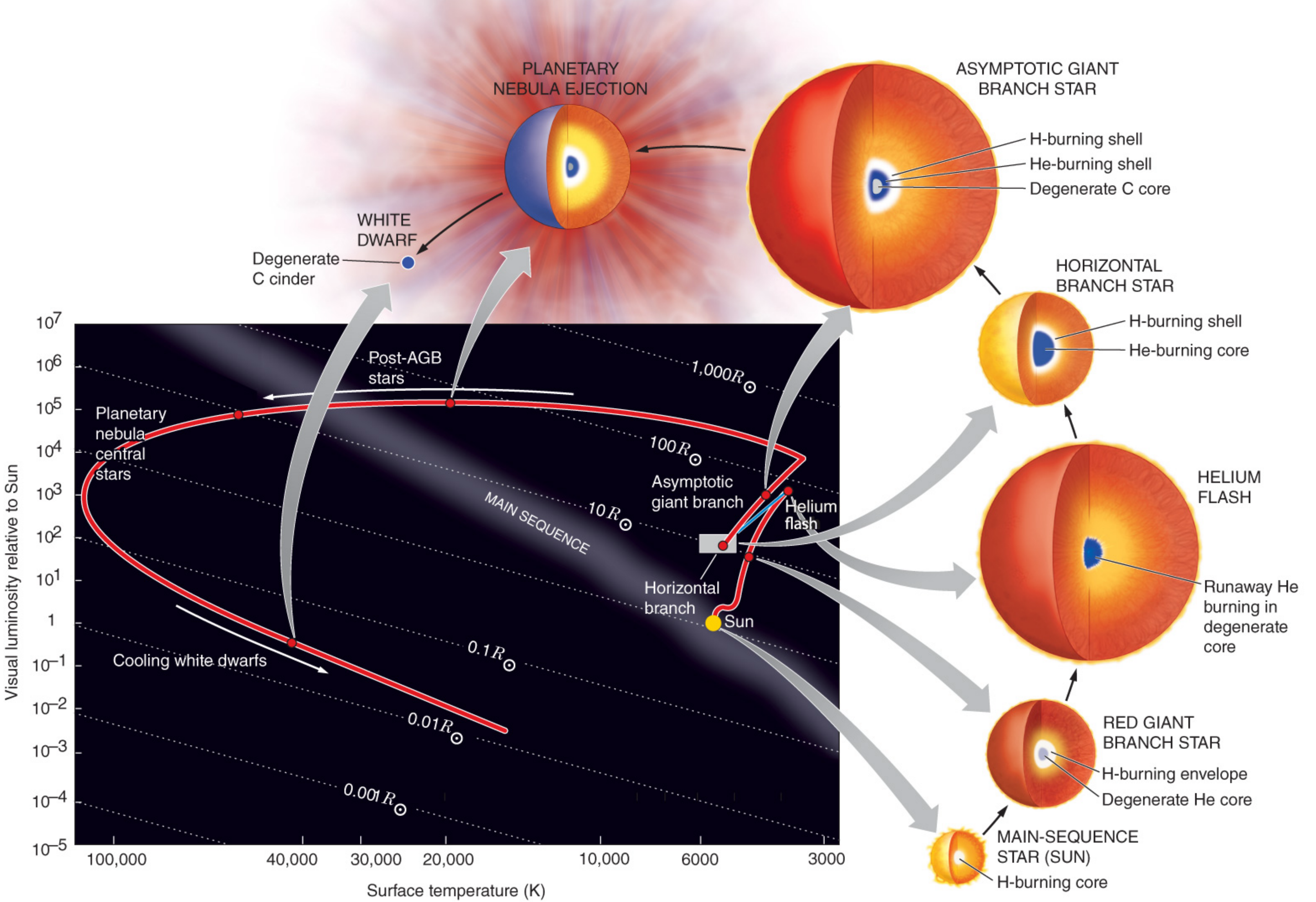
ASYMPTOTIC GIANT BRANCH STAR
Nonburning degenerate carbon ash core
He-burning shell
H-burning shell
Nonburning hydrogen envelope
Asymptotic giant branch (AGB)
The star exhausts the helium at its center, leaves the horizontal branch, and ascends the asymptotic giant branch.
1,000 R⊙
100 R⊙
10 R⊙
1 R⊙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

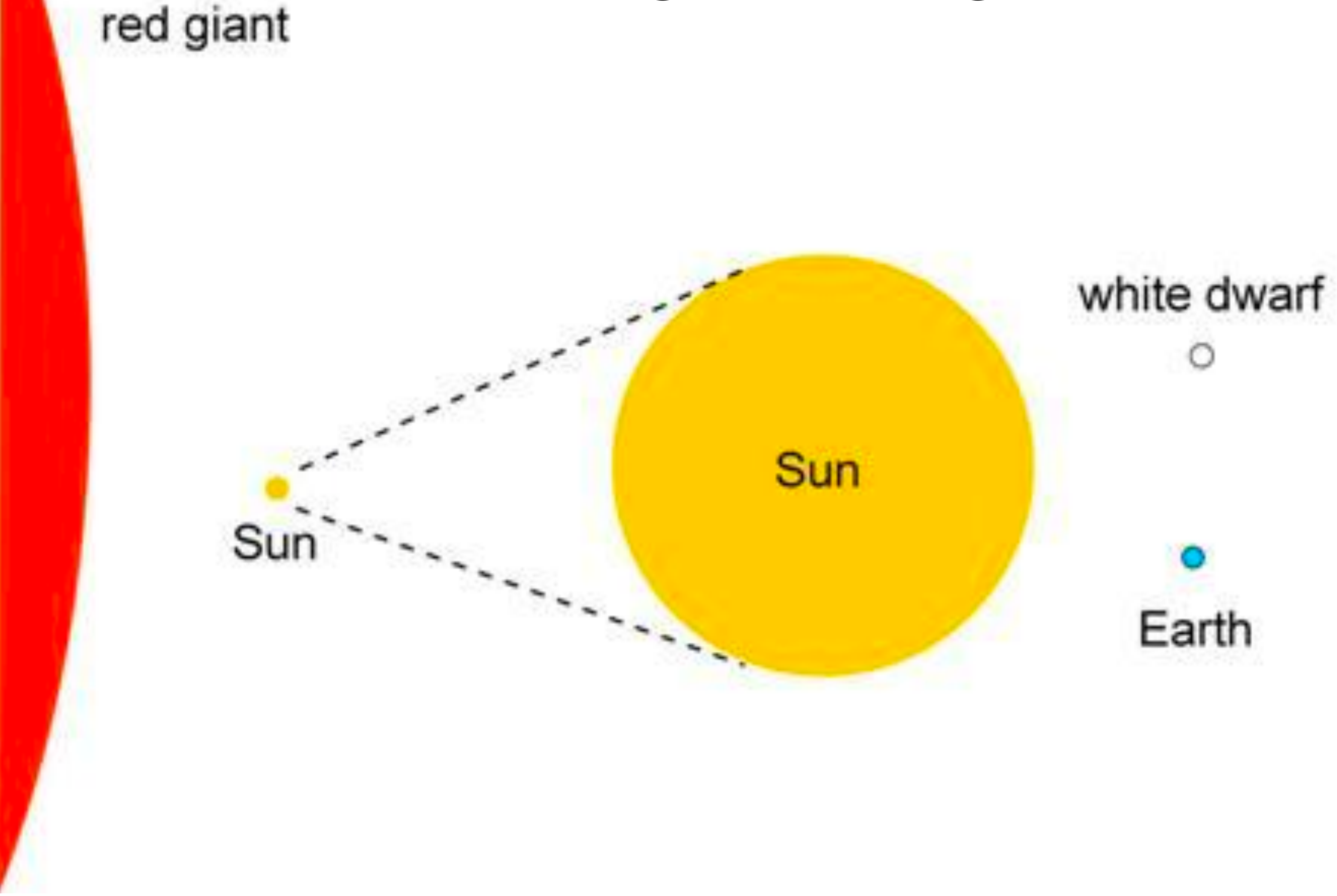


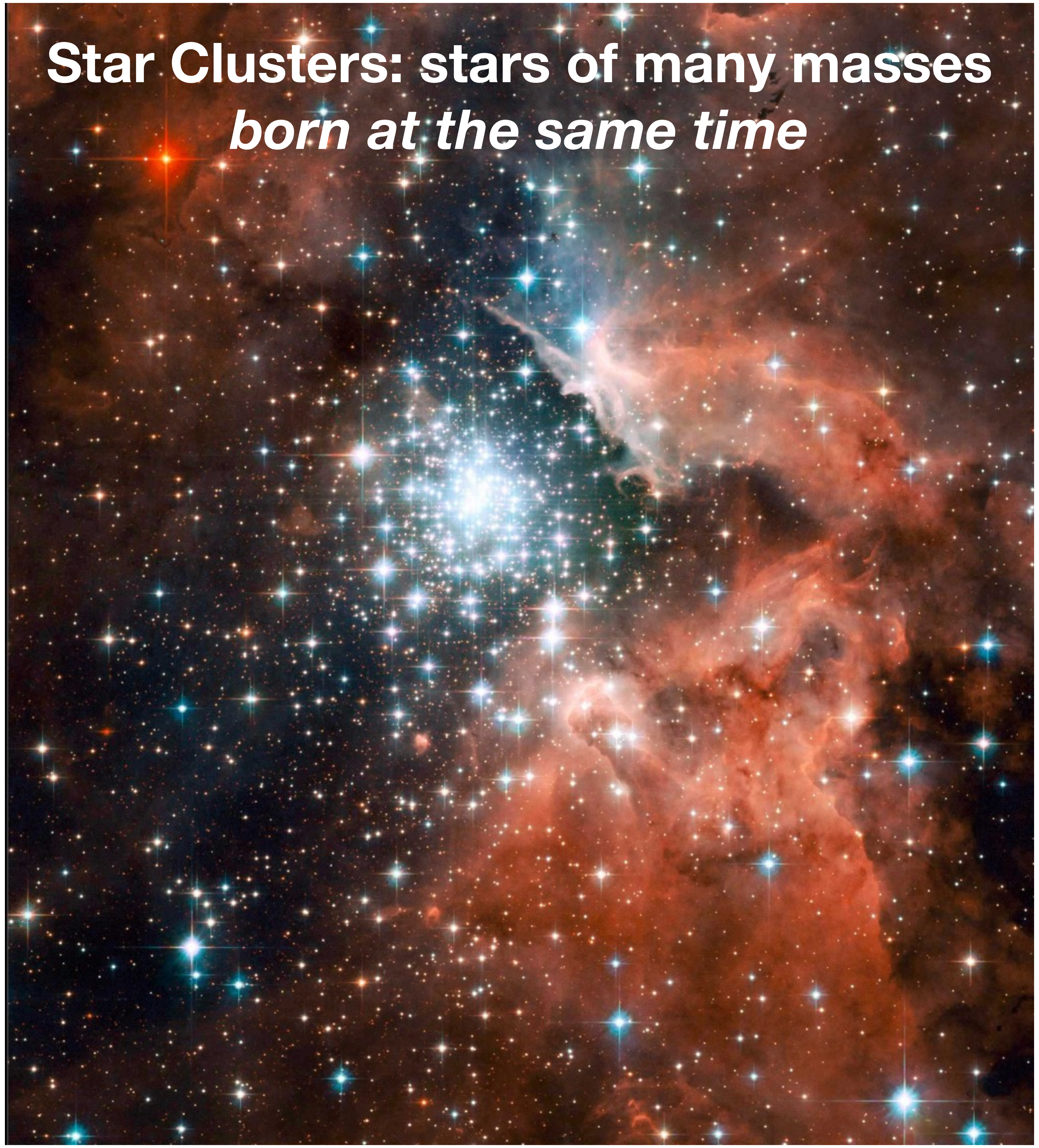
This star leaves behind only the degenerate carbon core, a tiny cooling white dwarf.
White dwarf
Hot electron-degenerate carbon
MAIN SEQUENCE
Sun
1,000 R⊙
100 R⊙
10 R⊙
0.1 R⊙
0.01 R⊙
0.001 R⊙
Visual luminosity relative to Sun
10^7
10^6
10^5
10^4
10^3
10^2
10^1
1
10^-1
10^-2
10^-3
10^-4
10^-5
100,000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

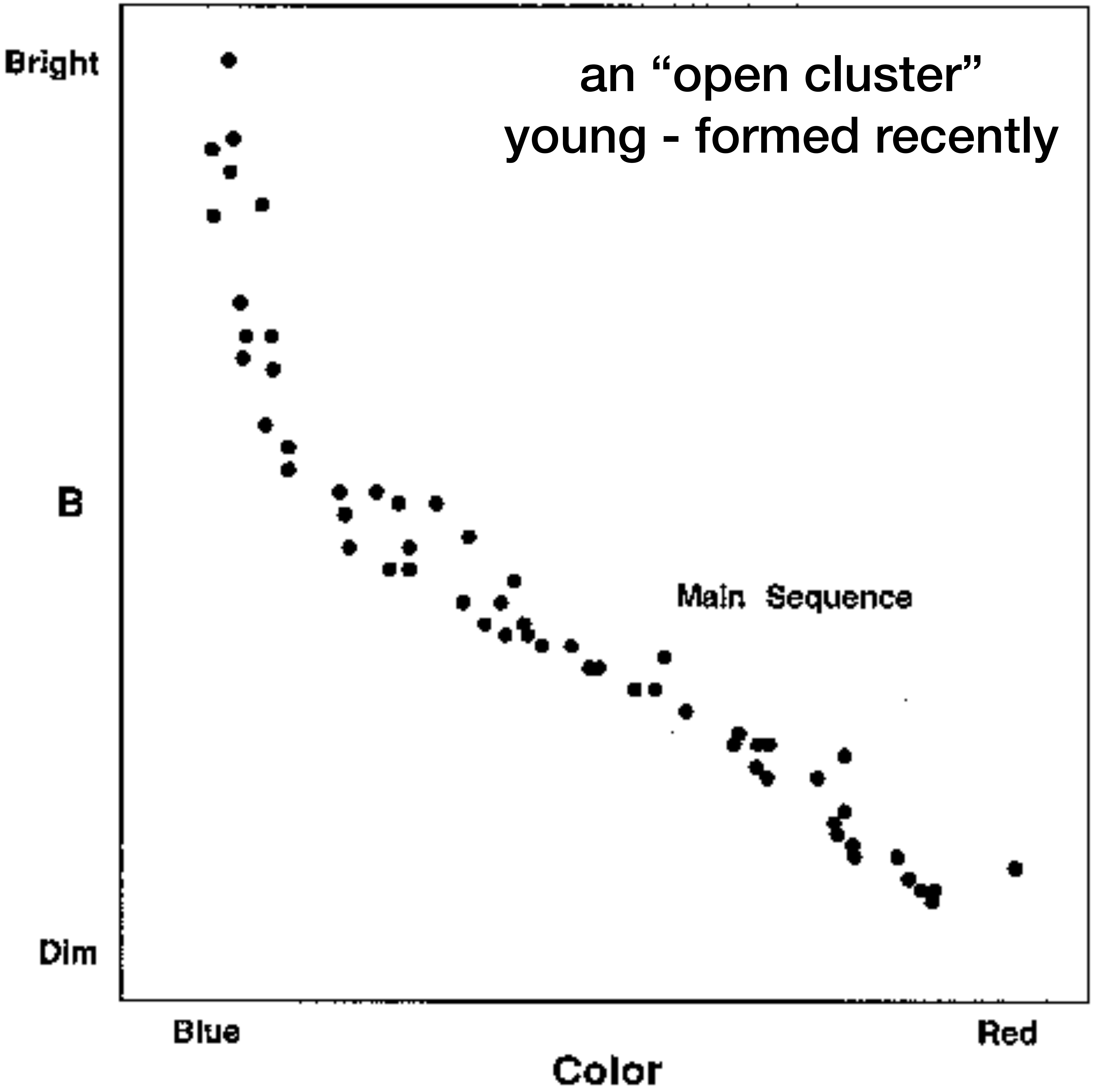
Again, this time with feeling!



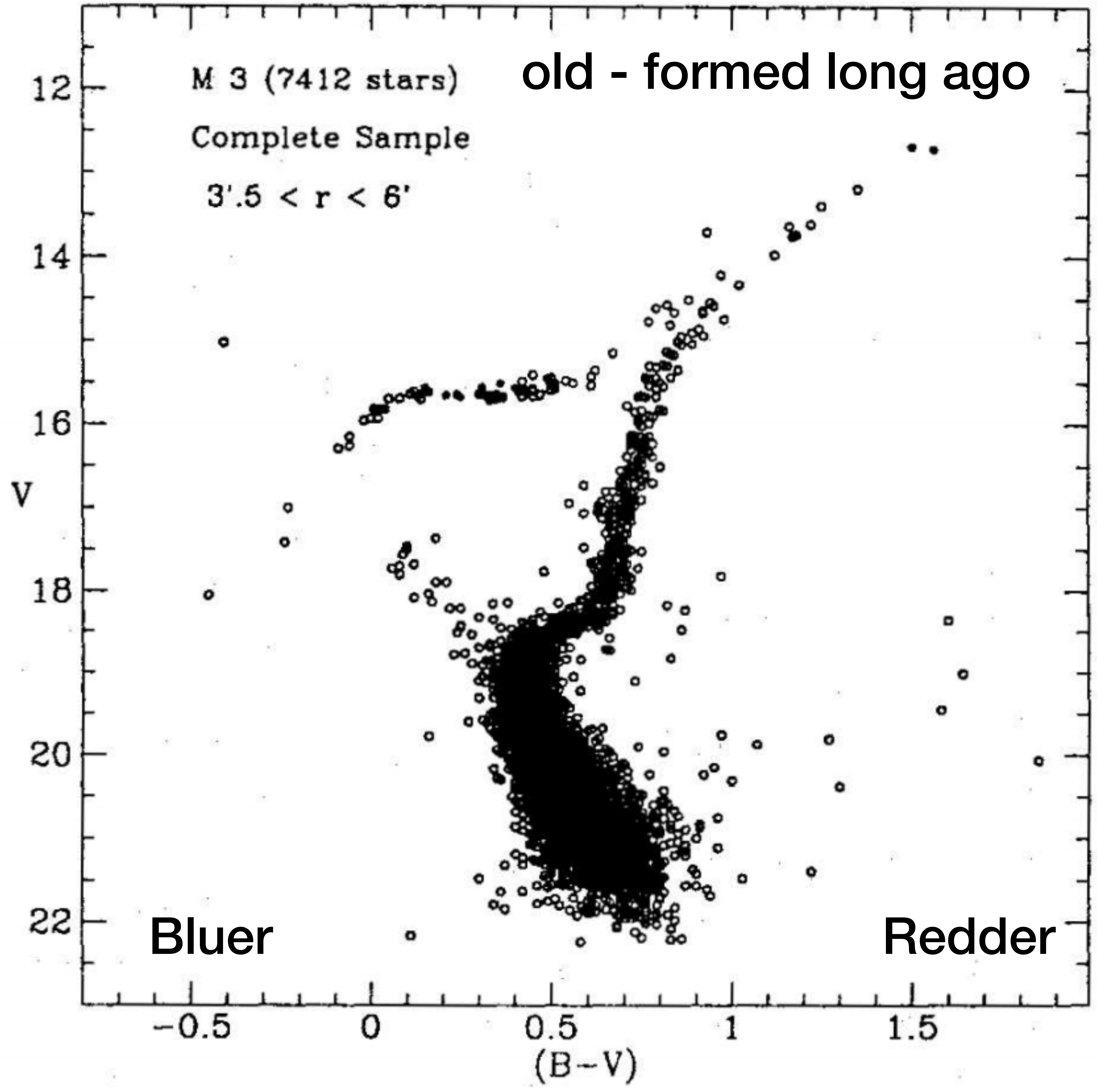
Size changes along with temperature




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


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

Globular Cluster Color-Magnitude Diagram



Brighter

Fainter