Gravitational collapse of gas

- Assume a gas cloud of mass M and diameter D

- Sound speed for ideal gas is $c_s = \sqrt{\gamma \frac{P}{\rho}} = \sqrt{\gamma \frac{nkT}{\rho}} = \sqrt{\gamma \frac{kT}{m}}$

- Time for sound wave to cross the cloud $t_{sound} = \frac{D}{c_s} == D\left(\frac{m}{\gamma kT}\right)^{1/2}$

- Time for free-fall collapse is $t_{ff} = \frac{1}{\sqrt{G\rho}}$

- Gravity beats pressure support when $t_{ff} < t_{sound}$

Gravitational collapse of gas

- Critical cloud size is then $t_{ff} = t_{sound} \rightarrow \frac{1}{\sqrt{G\rho}} = D\left(\frac{m}{\gamma kT}\right)^{1/2}$

This is the Jeans length

$$\lambda_J = \left(\frac{\gamma kT}{mG\rho}\right)^{1/2}$$

- Associated Jeans mass is $M_J = \frac{4}{3}\pi\left(\frac{\lambda_J}{2}\right)^3 \rho \rightarrow$

$$M_J = \frac{\pi}{6}\left(\frac{\gamma kT}{mG}\right)^{3/2} \rho^{-1/2}$$

Gravitational collapse of gas

- For a typical H_2 molecular cloud:

$$T = 10 - 100 \text{ K}$$
$$n = 10^2 - 10^6 \text{ cm}^{-3}$$
$$m = 3.34 \times 10^{-24} \text{ g}$$
$$\gamma \sim 1$$

- Associated Jeans mass is

$$M_J = 70 M_\odot \left(\frac{n}{10^3 \text{cm}^{-3}} \right)^{-1/2} \left(\frac{T}{10\text{K}} \right)^{3/2}$$

The Orion Nebula

Stars are born in giant gas clouds.

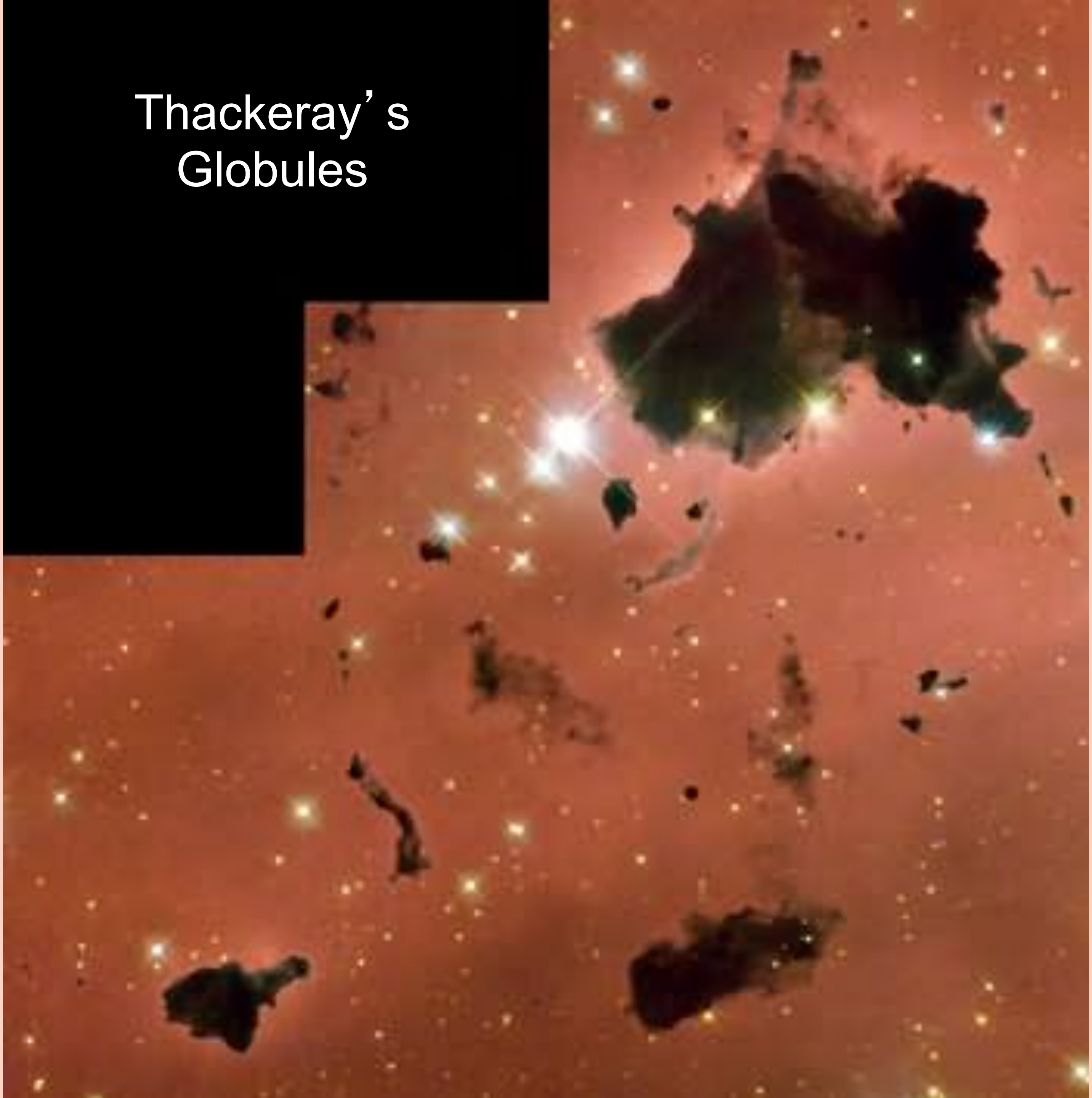
- If the cloud is too hot and not dense enough, it will never collapse. Pressure wins!
- If the cloud is cool and dense enough, it will collapse. Gravity wins!

The Stellar Womb

Stars are born deep in dark molecular clouds:

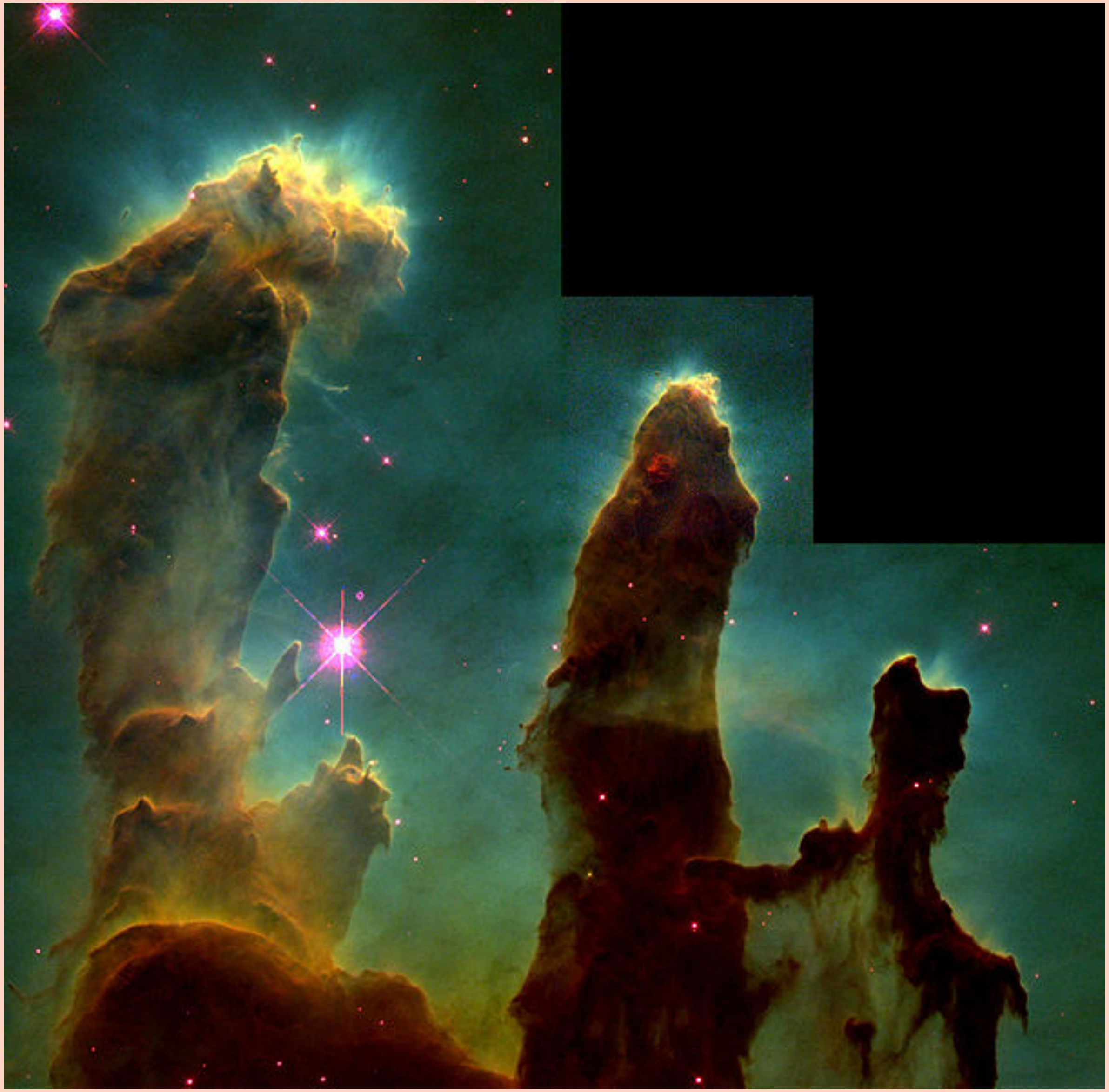
- cold (10 – 30 K), dense nebulae
- so cold that molecules (H_2 instead of atomic H) can exist
- dark because visible light cannot penetrate

Thackeray’s Globules



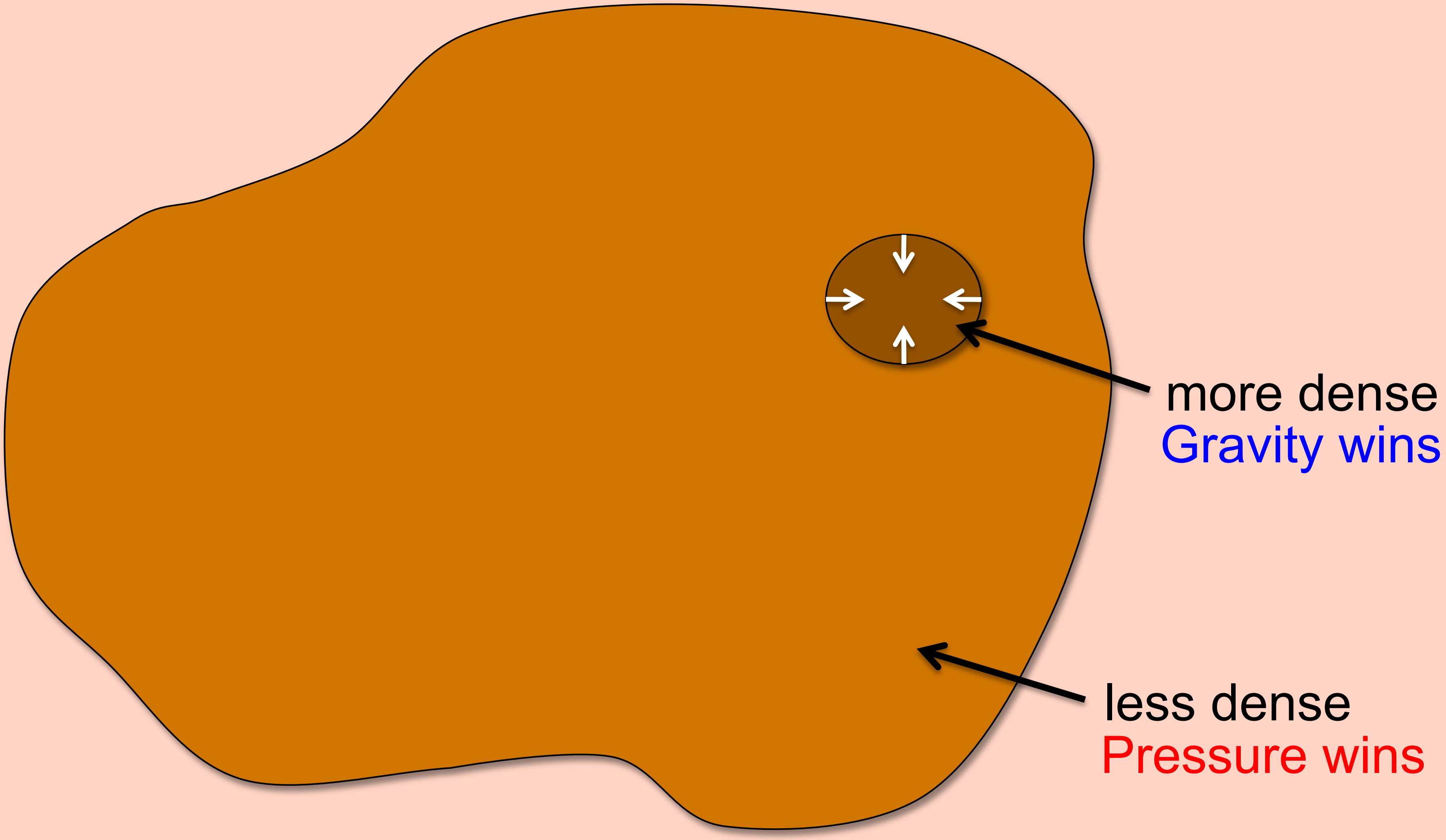
Stellar Gestation

- something happens to perturb part of a molecular cloud and make it begin to fragment
- as a core of gas collapses, it wants to heat up
- radiates away the excess heat and thus remains cool

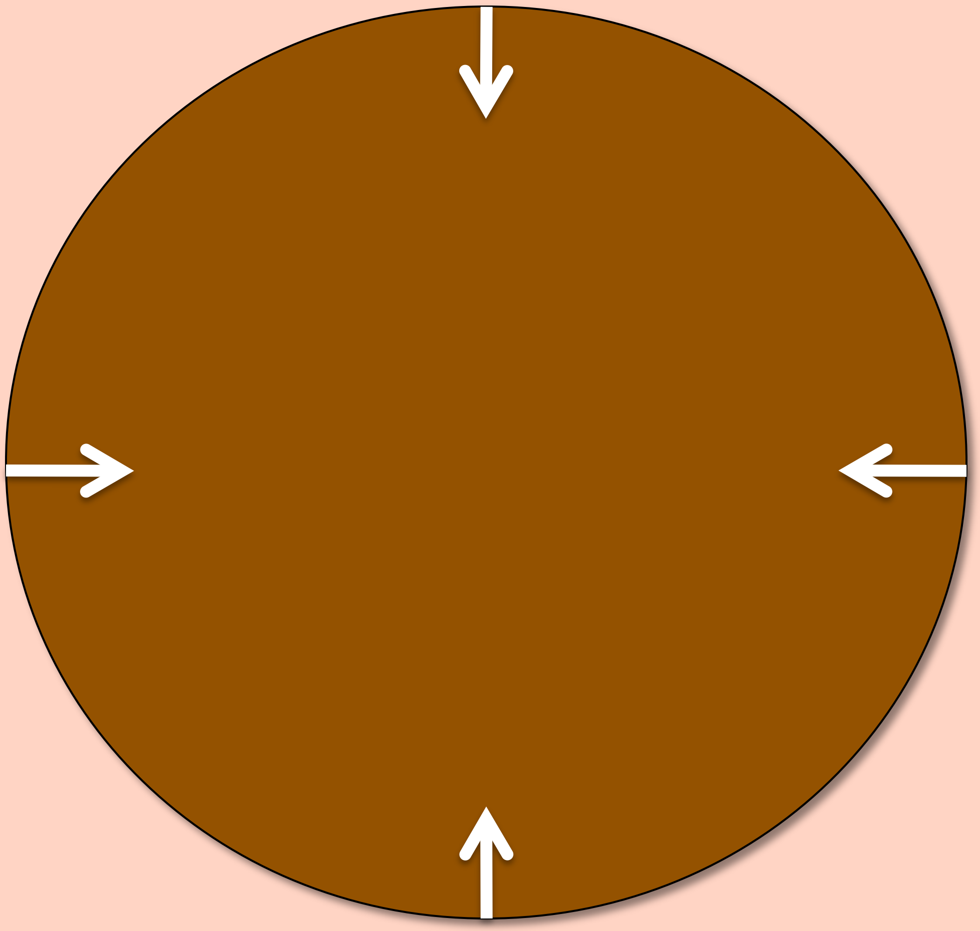


Eagle Nebula Pillars

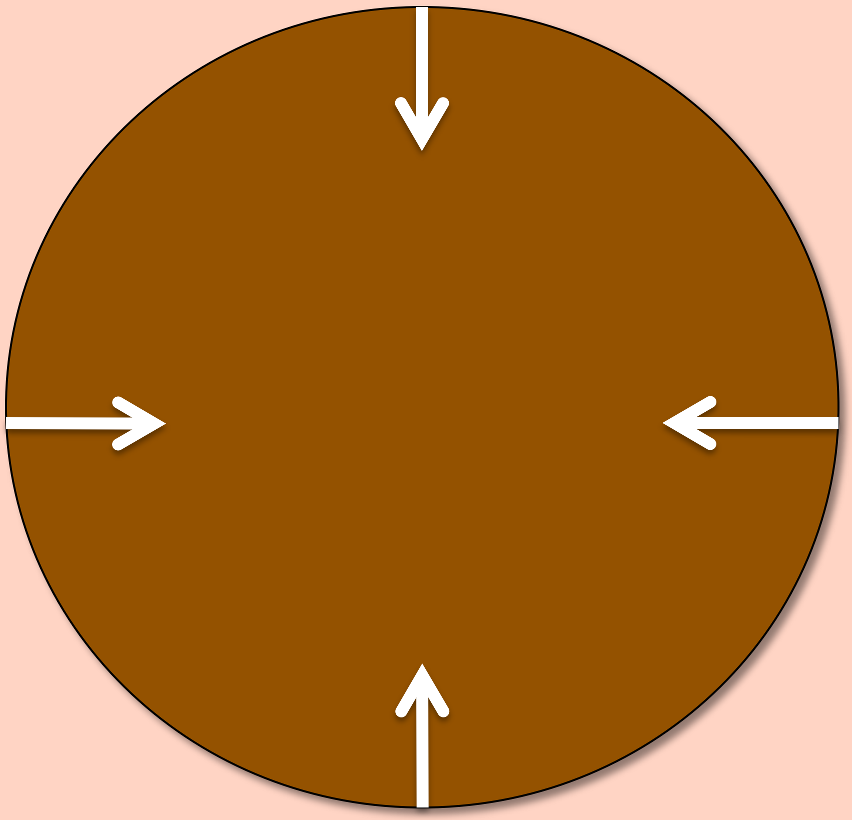
Giant Molecular Gas Cloud



Collapse of cold, unstable region

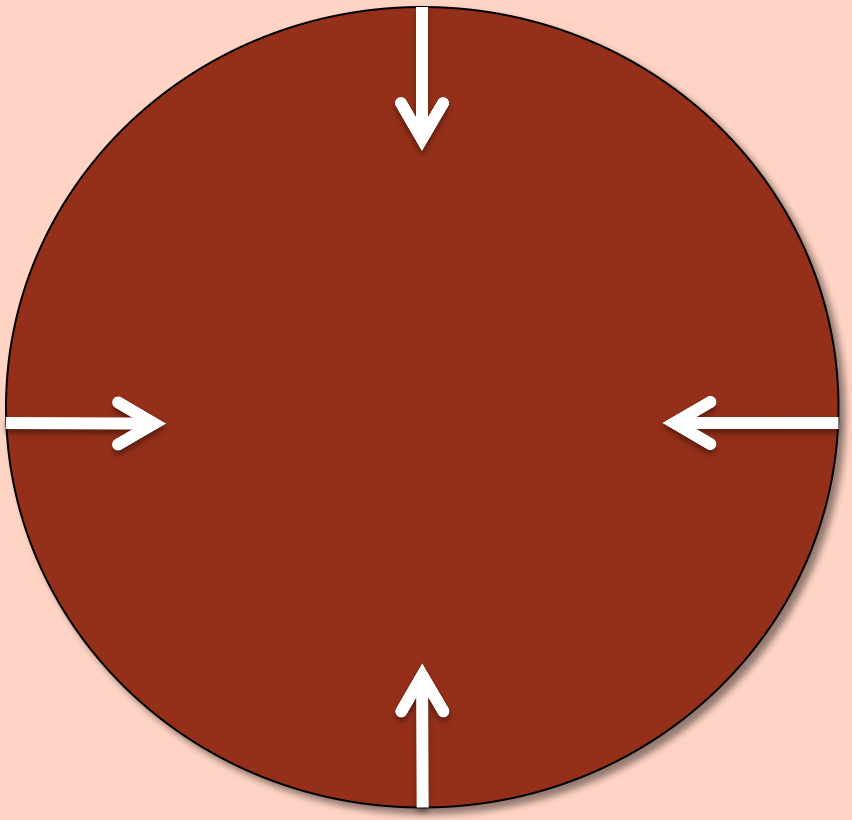


Collapse of cold, unstable region



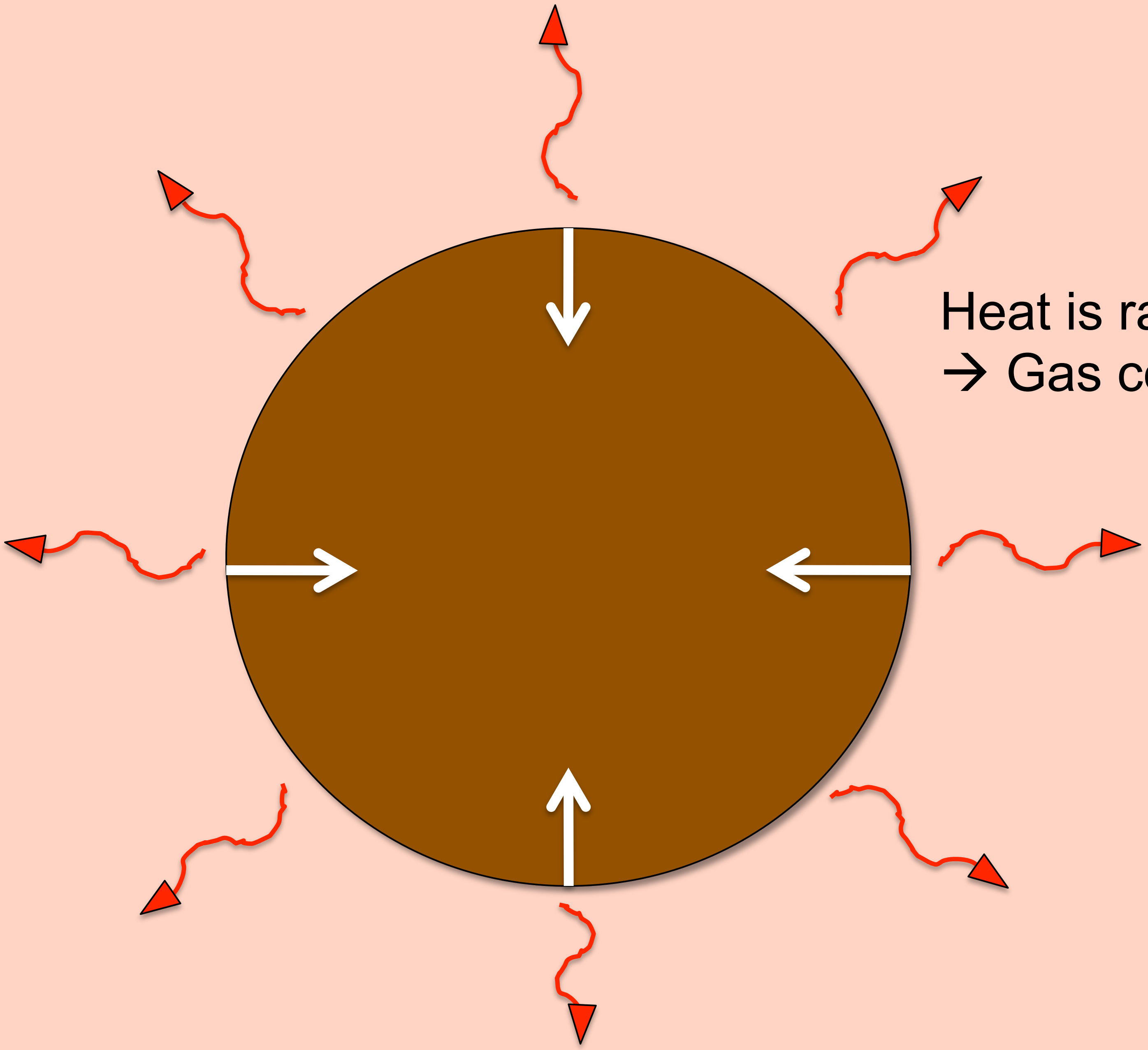
Gravity grows stronger

Collapse of cold, unstable region

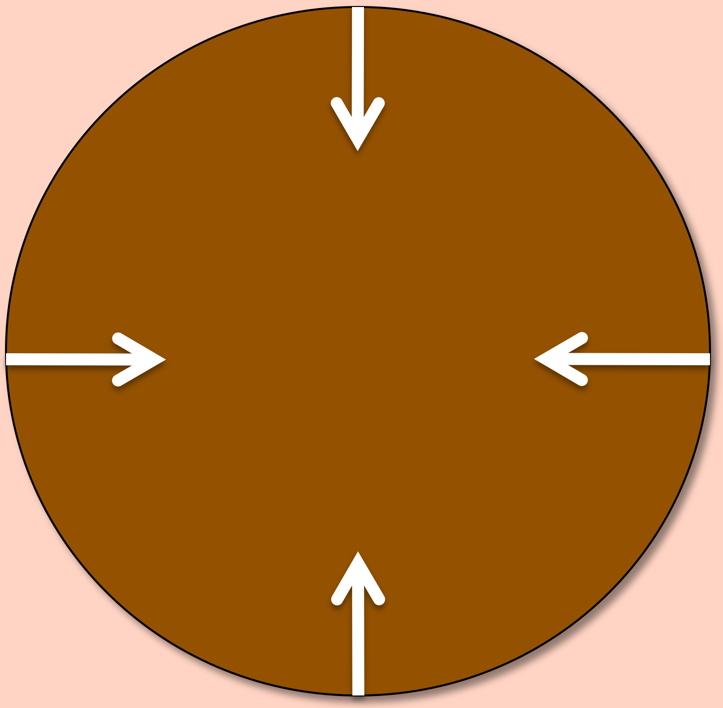


Gas starts to heat up

Collapse of cold, unstable region



Collapse of cold, unstable region



Denser →
Gravity grows stronger

Stellar Gestation

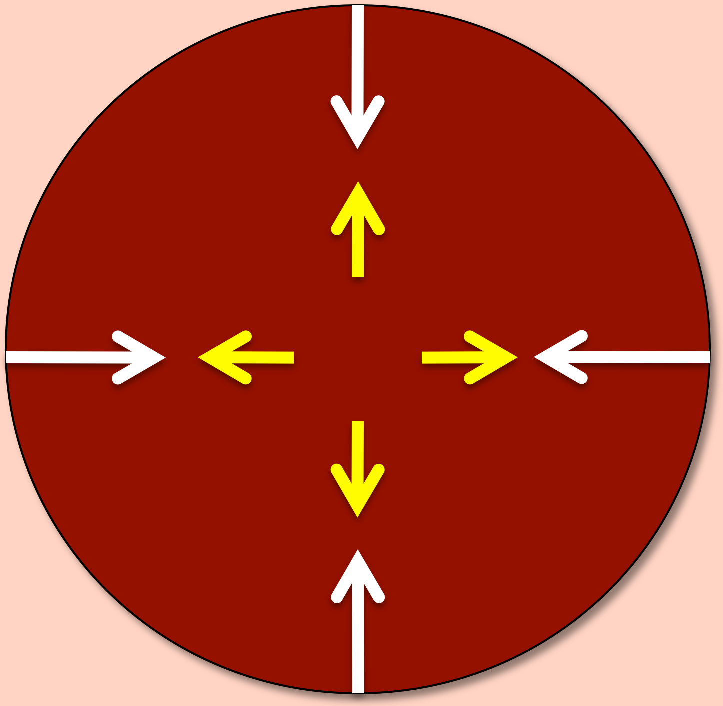
- gets smaller, denser, but not much hotter
- eventually, gas becomes opaque and light escapes less quickly → heats up and collapse slows down
- As it heats up, the emitted light moves toward the visible

Stellar Gestation

- bursts into view as a visible **protostar**
- hotter, denser, higher pressure
- but still contracting because gravity is stronger too

McNeil's nebula

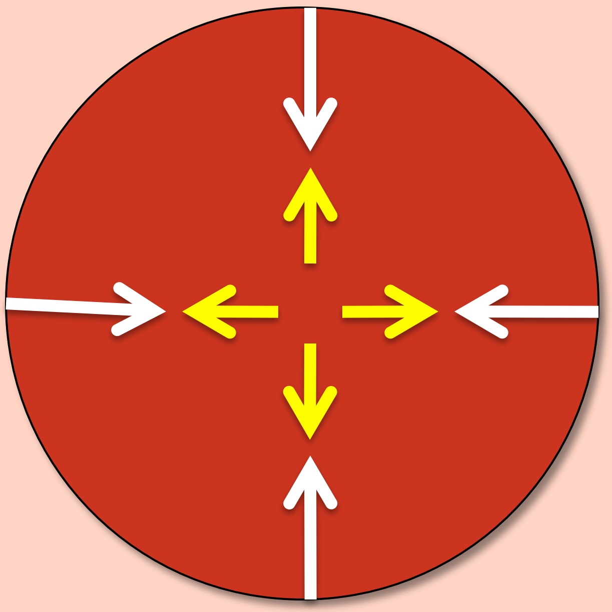
Collapse of cold, unstable region



Denser →
Gravity grows stronger

Hotter →
Pressure grows stronger

Collapse of cold, unstable region



Denser →
Gravity grows stronger

Hotter →
Pressure grows stronger

Stellar Gestation

- The protostar keeps on shrinking until internal pressure can resist gravity
- The protostar collapses until its core reaches 10^7 K in temperature and fusion starts.
- Fusion restores hydrostatic equilibrium.

Hubble's nebula

The Role of Mass

O stars are most massive (20-100 M_{sun})

- Enormous self-gravity, enormous compressive force

  need enormous pressure to resist gravity

- 10^7K core temperature is not enough

  Continue to compress due to gravity, despite fusion

- Compression → higher temperature
- Higher temperature → faster rate of fusion

  (larger number of protons have enough energy to fuse)

- Higher fusion rate → more pressure
- Equilibrium is reached at very high fusion rate

The Role of Mass

M stars are least massive (0.08-0.5 M_{sun})

- Weakest self-gravity, weakest compressive force

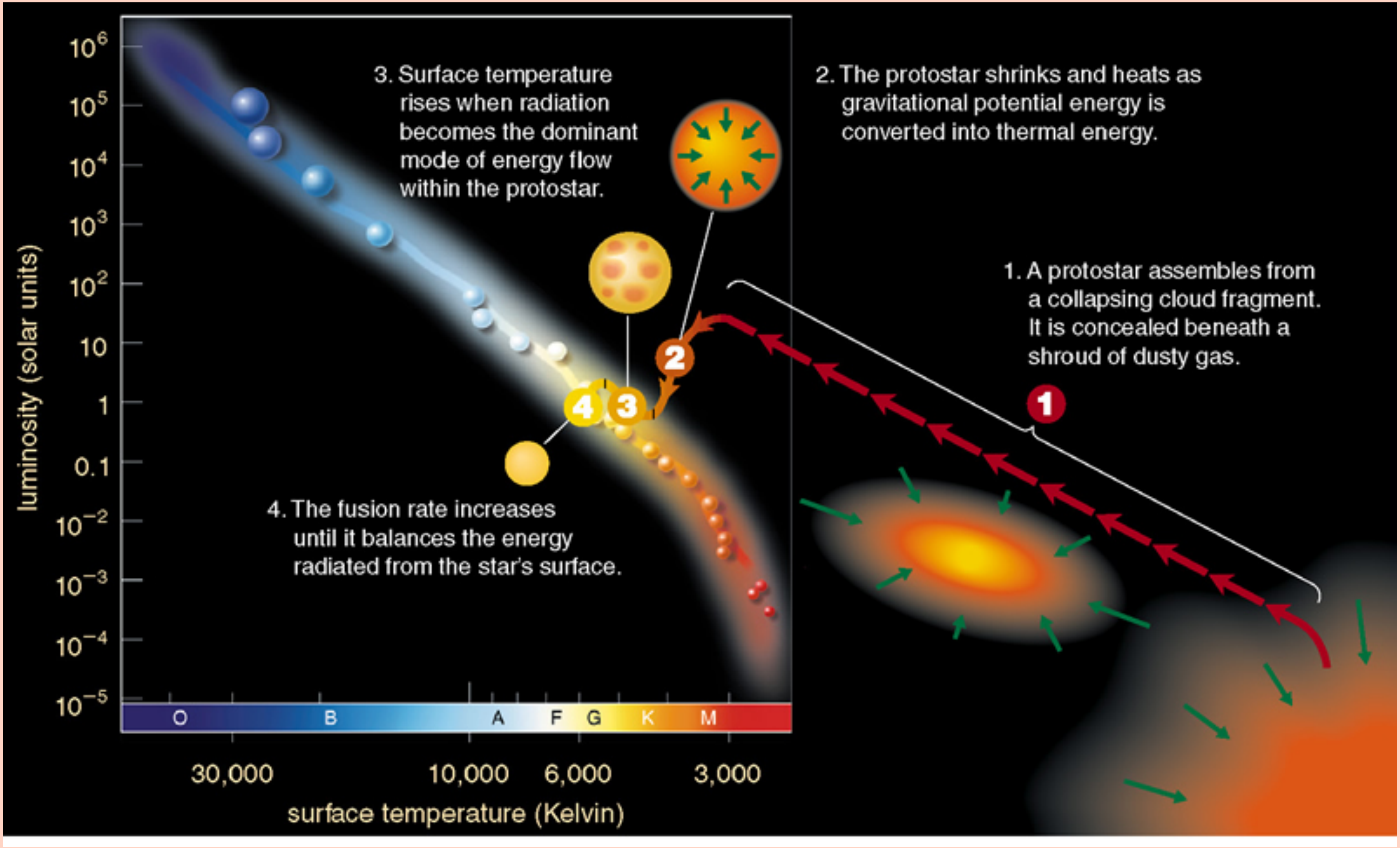
  need less pressure to resist gravity

- Pressure can balance gravity at lower temperature
- Lower temperature → lower rate of fusion
- Lower fusion rate → lower luminosity

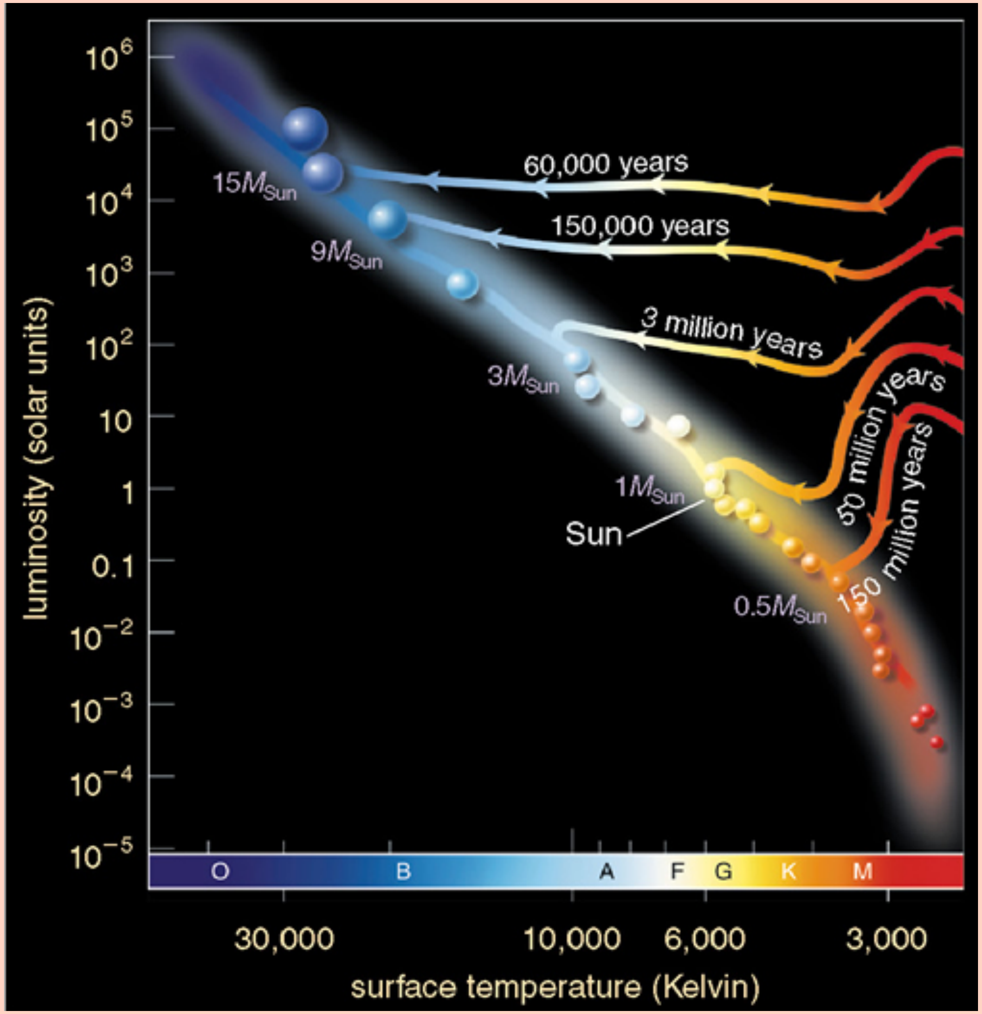
This is the origin of the Mass-Luminosity relation for Main Sequence stars.

$$L = M^{3.5}$$ (in solar units)

Stages of Star Formation on the H-R Diagram



Arrival on the Main Sequence

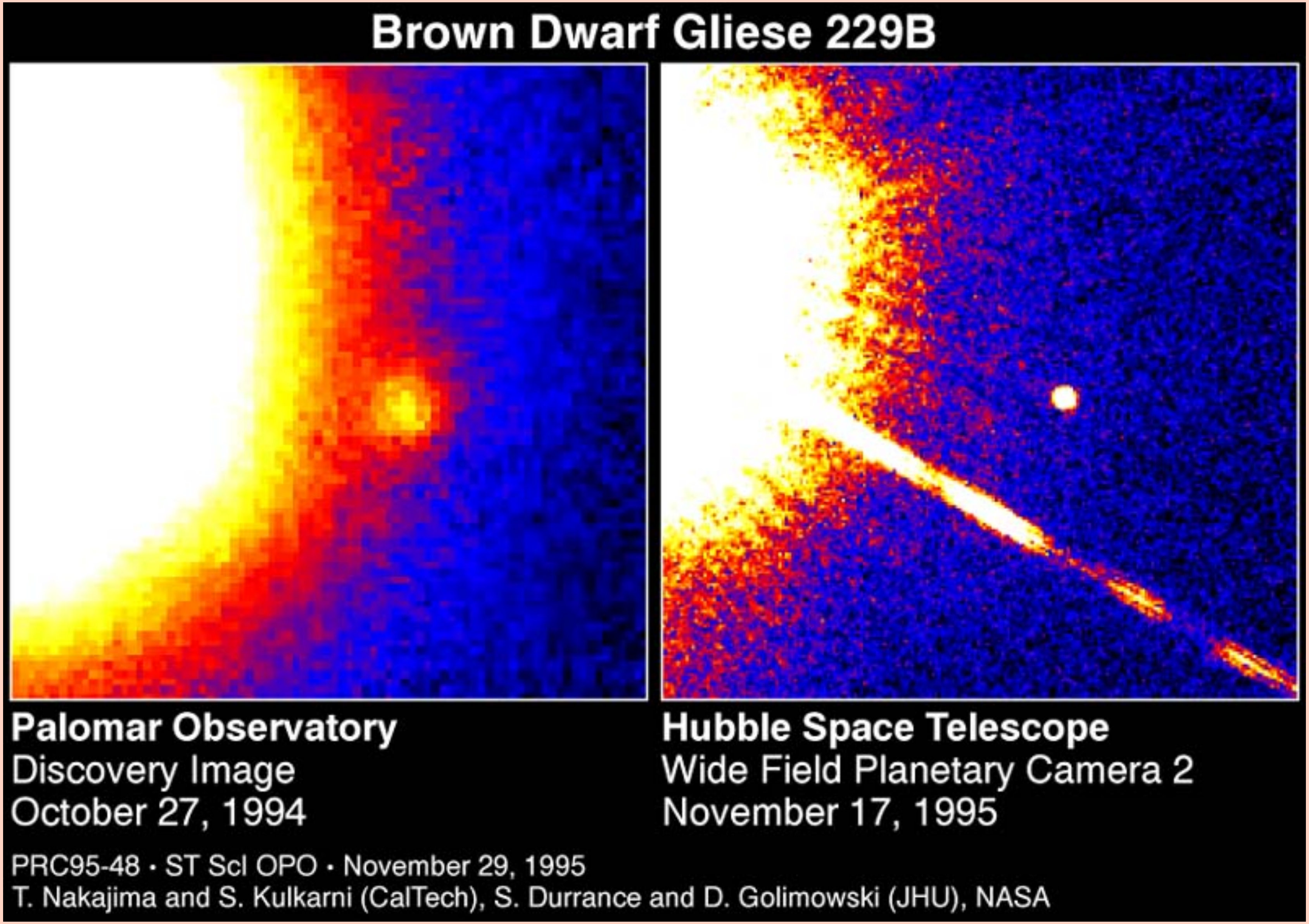


- The mass of the protostar determines:
  - how long the protostellar phase will last
  - where the new-born star will land on the MS
  - i.e., what spectral type the star will have while on the main sequence

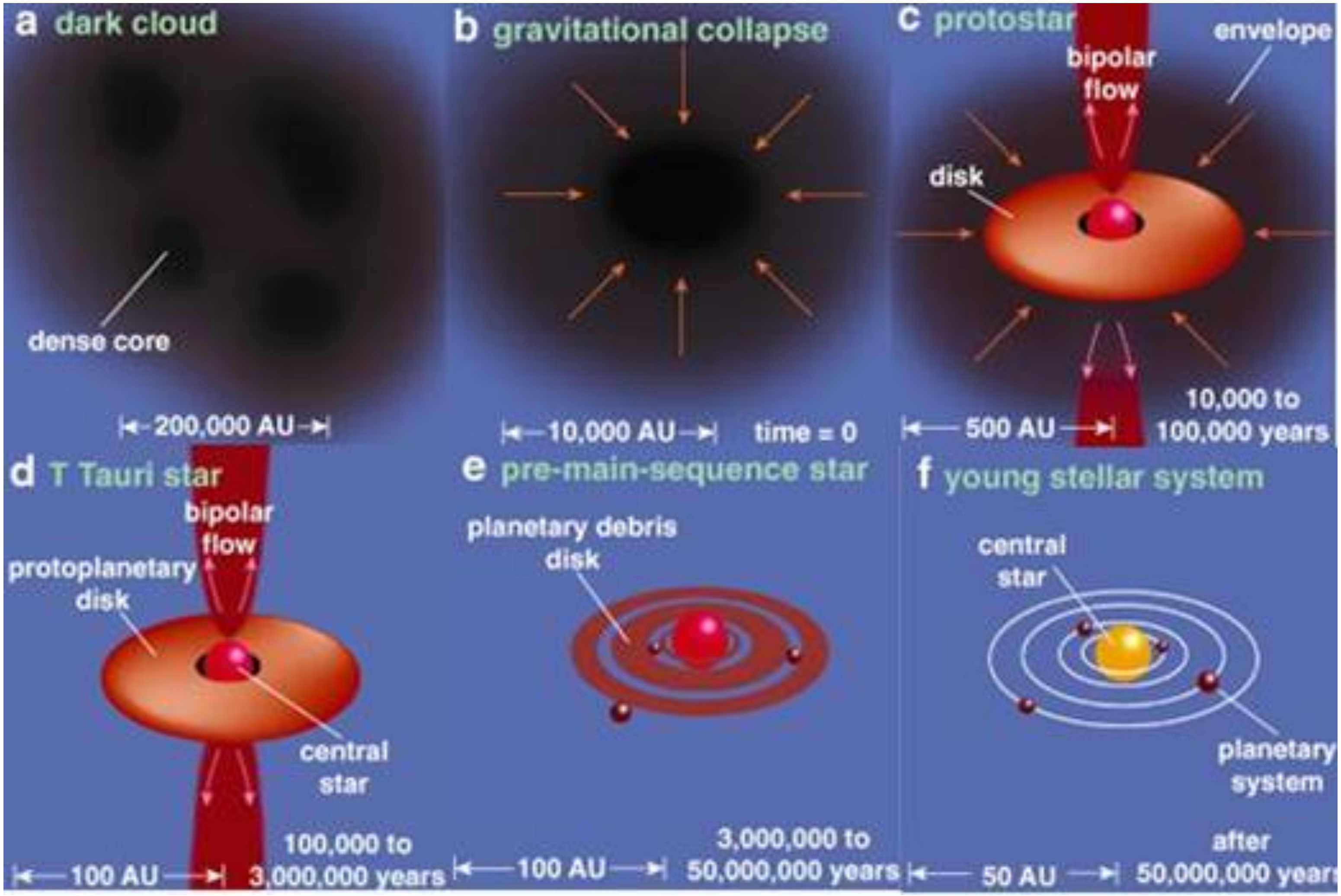
Missing the Main Sequence: Brown Dwarfs

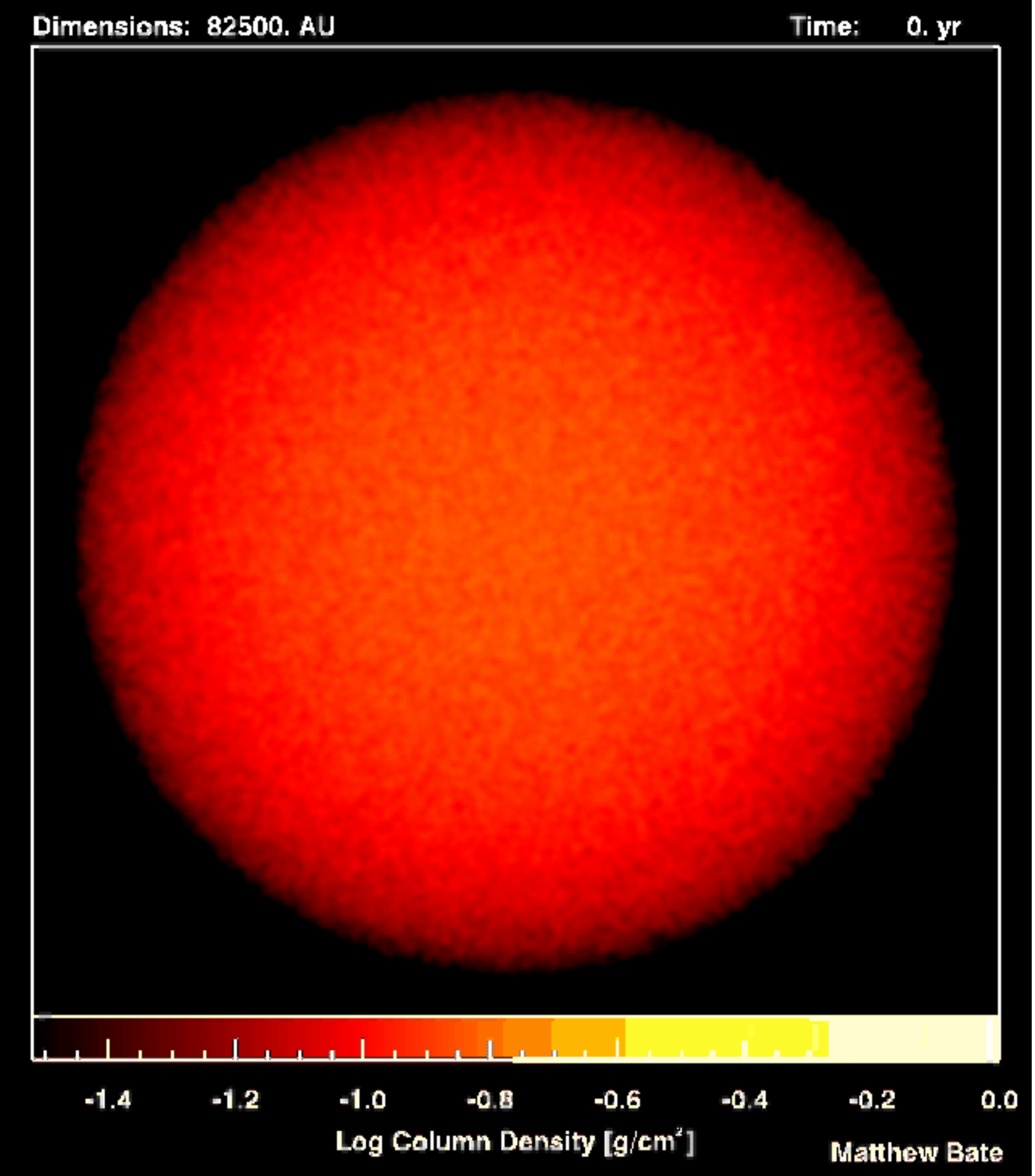
- If the protostar has a mass < 0.08 $M_{\odot}$:
  - It does not contain enough gravitational strength to reach a core temperature of 10^7 K
  - No proton-proton chain fusion reactions occur
  - The object never becomes a star
  - at 10^6 K, deuterium fusion begins (but there is not much deuterium) – hydrostatic equilibrium reached
  - this phase is short-lived

The First Brown Dwarf Discovery



Star Formation



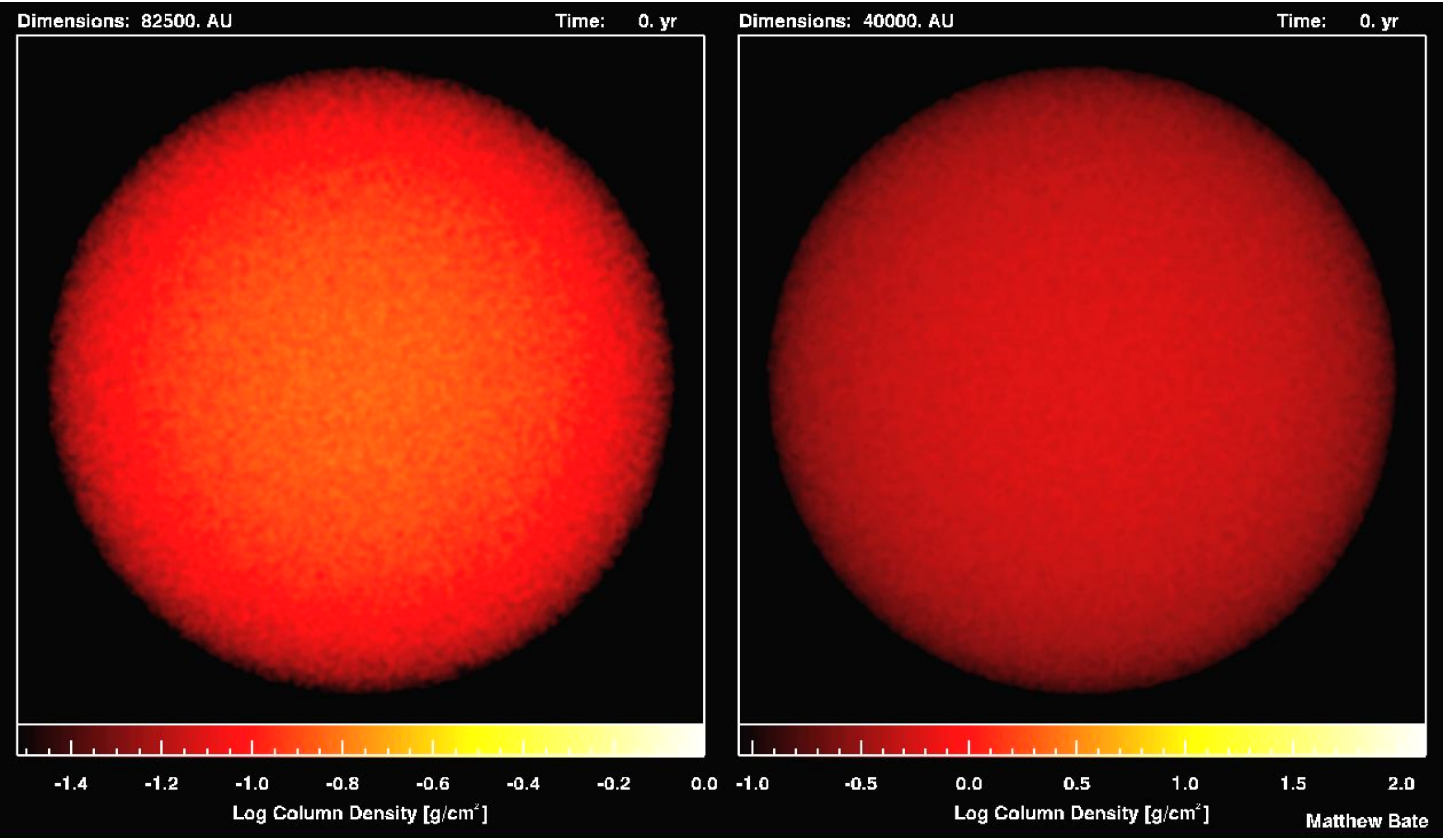


<u>Starting Inputs:</u>
Mass: 50 Msun
Diameter: 0.375 pc
Temperature: 10 K
Mean mol. Weight: 2.46
(Jeans mass = 1 Msun)
Time evolved = 266K years

Initial density and turbulence spectra.

<u>Computing:</u>
SPH code, 3.5 M particles
100K CPU-hours on 64 CPUs (65 days)
Resolution: 1-5 AU

Bate, M. R., et al. (2002)



Original cloud

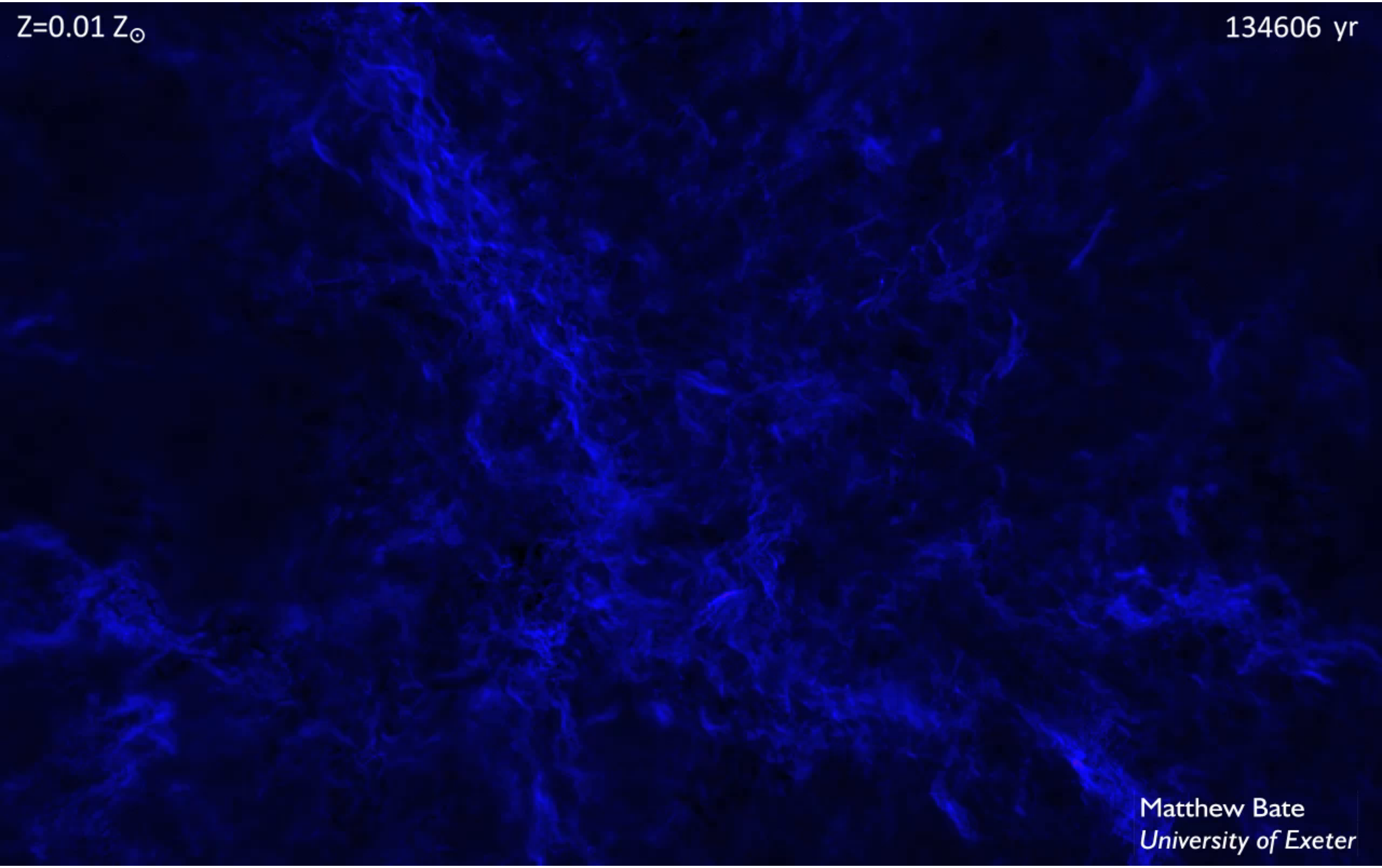
Denser cloud

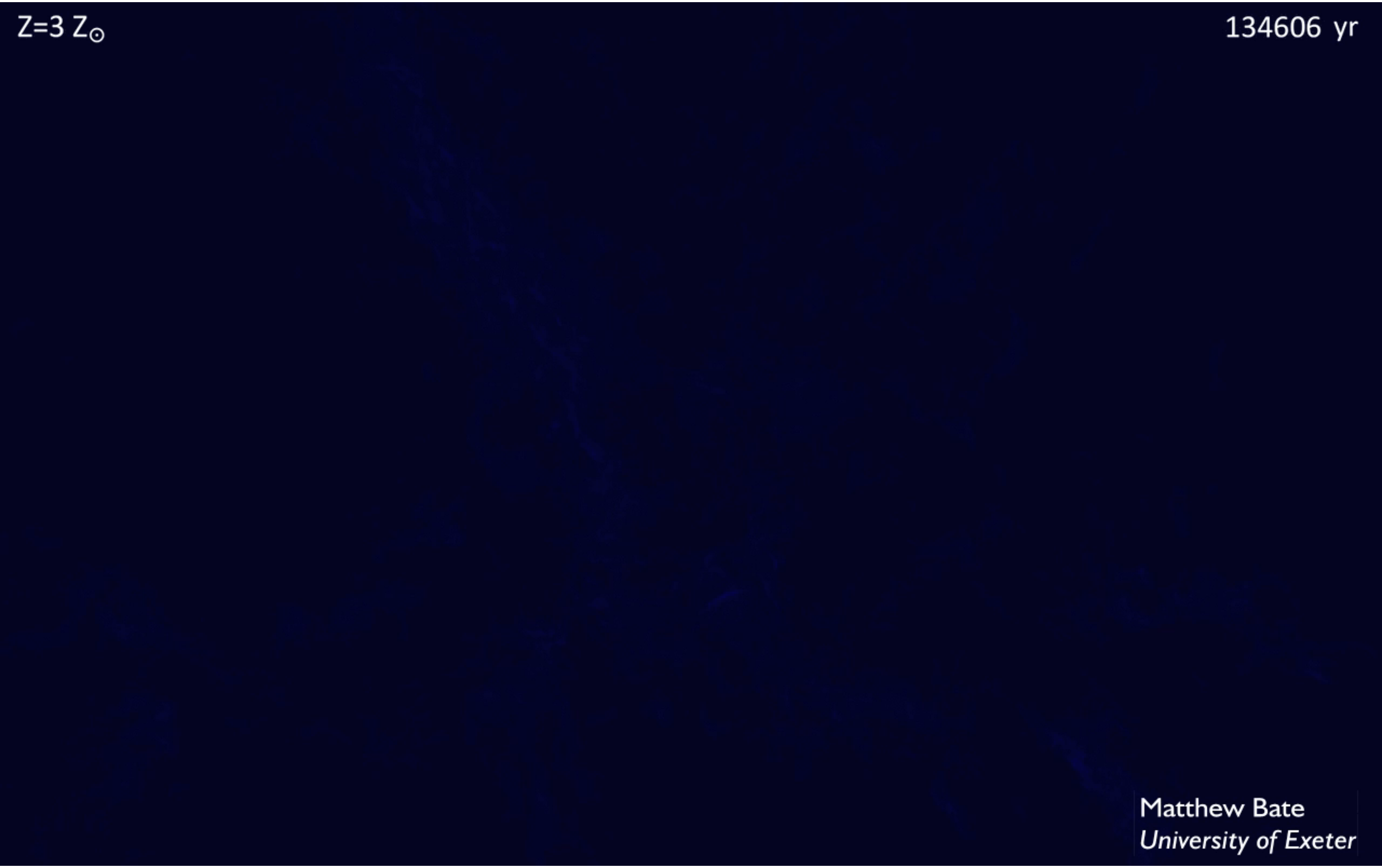

UK Astrophysical
Fluids Facility
Simulation: Matthew Bate, Exeter
Visualisation: Richard West, UKAFF

Star Formation

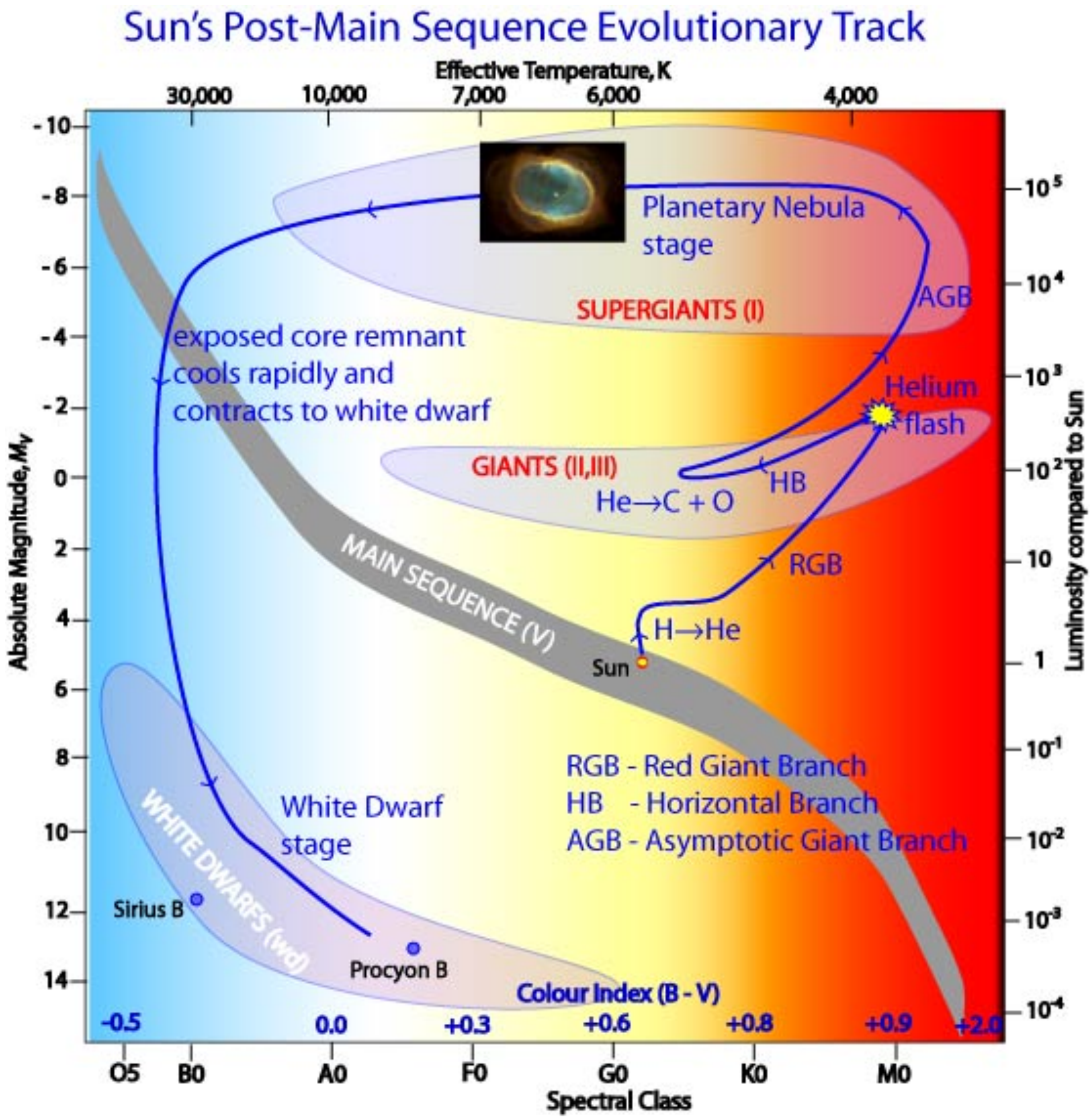
These simulations show:

- Star formation is a very chaotic and dynamic process
- Stars form so close together that they often interact before growing to full size
- Young stars compete for remaining gas with more massive stars
- About half the objects are kicked out of the cluster before they can grow enough to start fusion : brown dwarfs
- Many of the encounters btw. young stars and brown dwarfs strip the dusty disks off the stars suggesting planetary systems could be rare


Z=0.01 Z⊙
134606 yr
Matthew Bate
University of Exeter


Z=3 $Z_\odot$
134606 yr
Matthew Bate
University of Exeter

Evolution of the Sun



Stages in Evolution:

Hayashi track

Deuterium burning

Main Sequence

H → He in core

Red Giant Branch

He core, H → He in shell

Tip of the Red Giant Branch

Degenerate He core → He flash

Horizontal Branch

He → C,O in core, H → He in shell

Asymptotic Giant Branch

C,O core, He → C,O and H → He in shells

Planetary Nebula

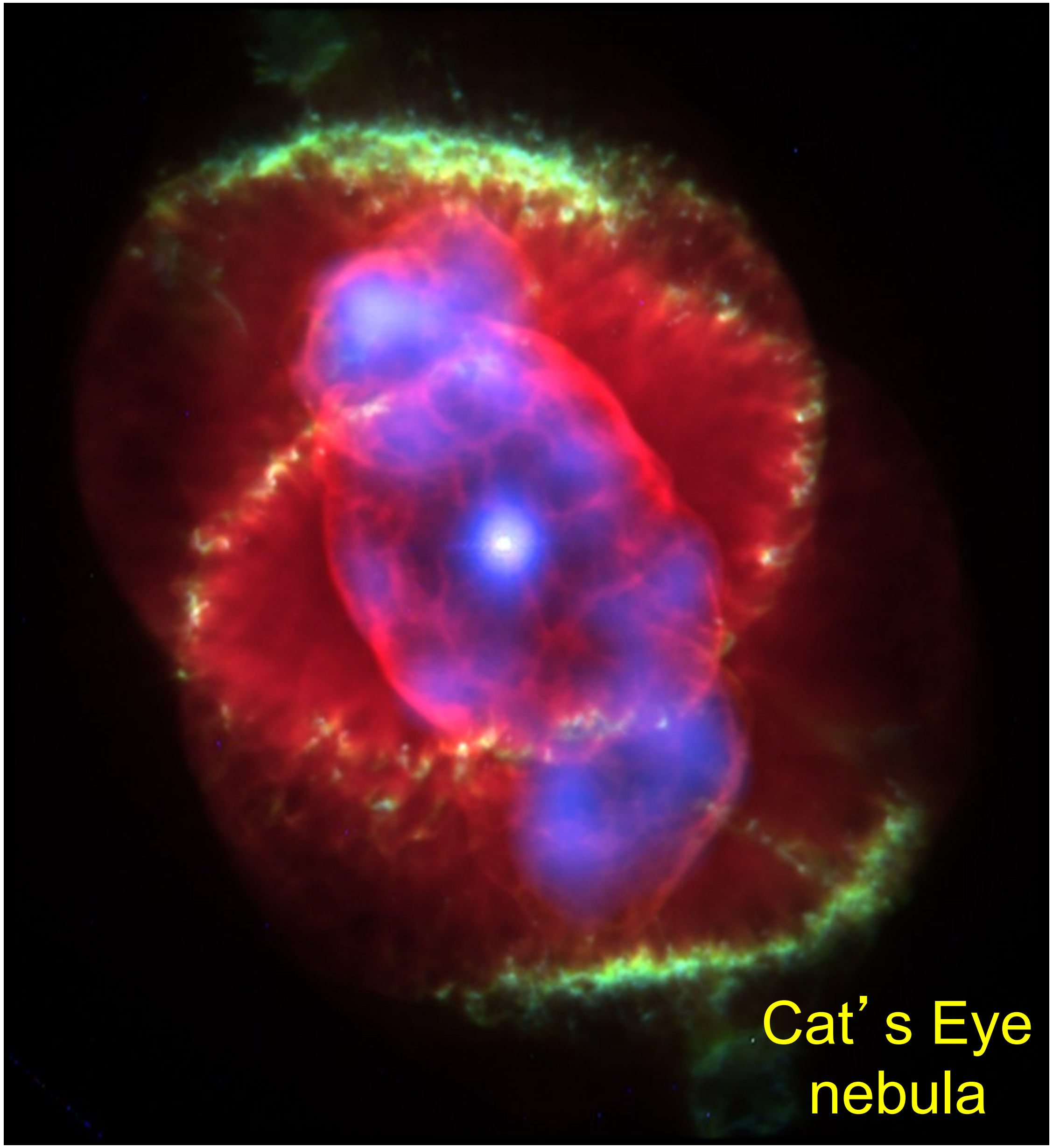
Not massive enough to burn C,O

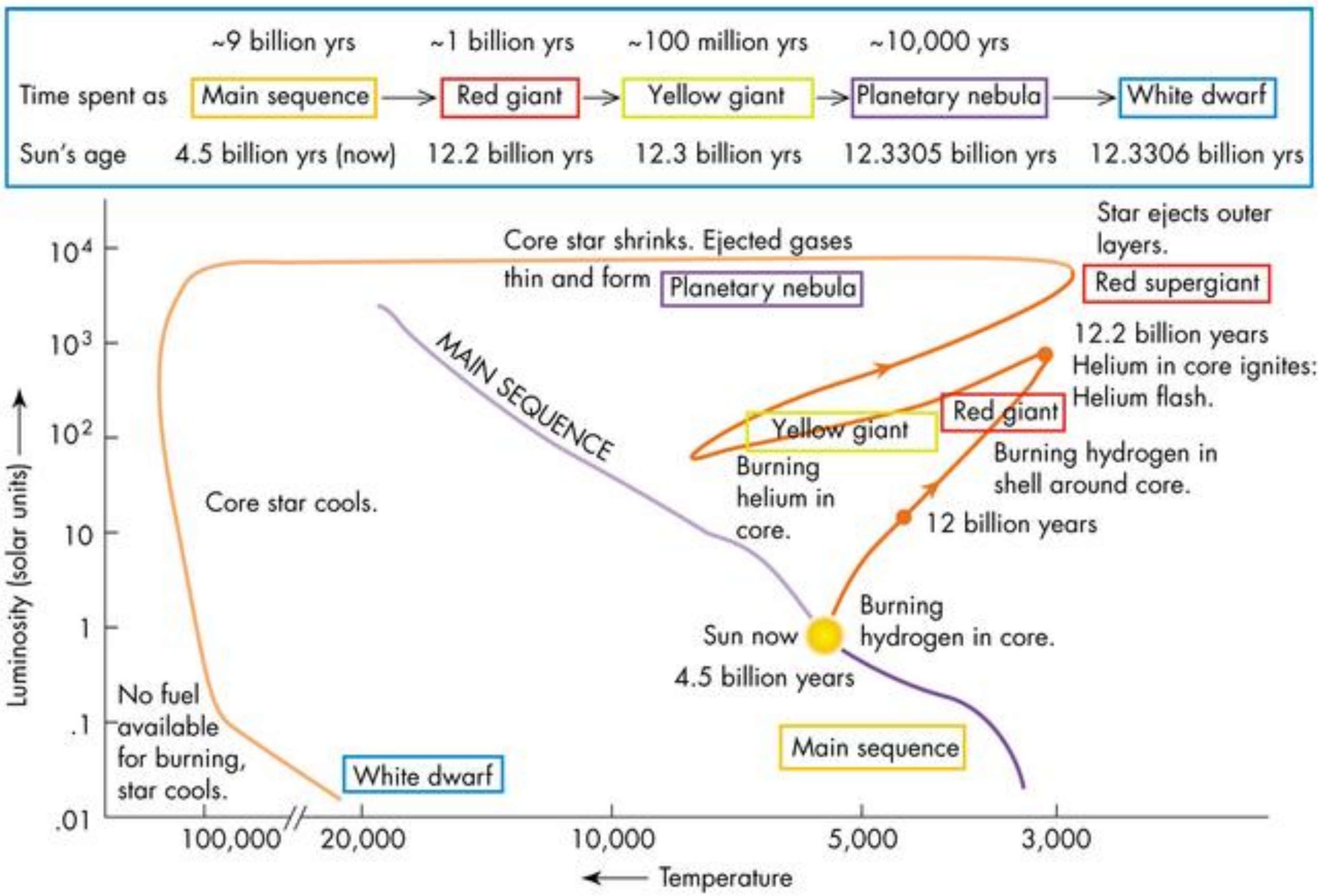
Sheds outer layers.

White Dwarf

Degenerate C,O

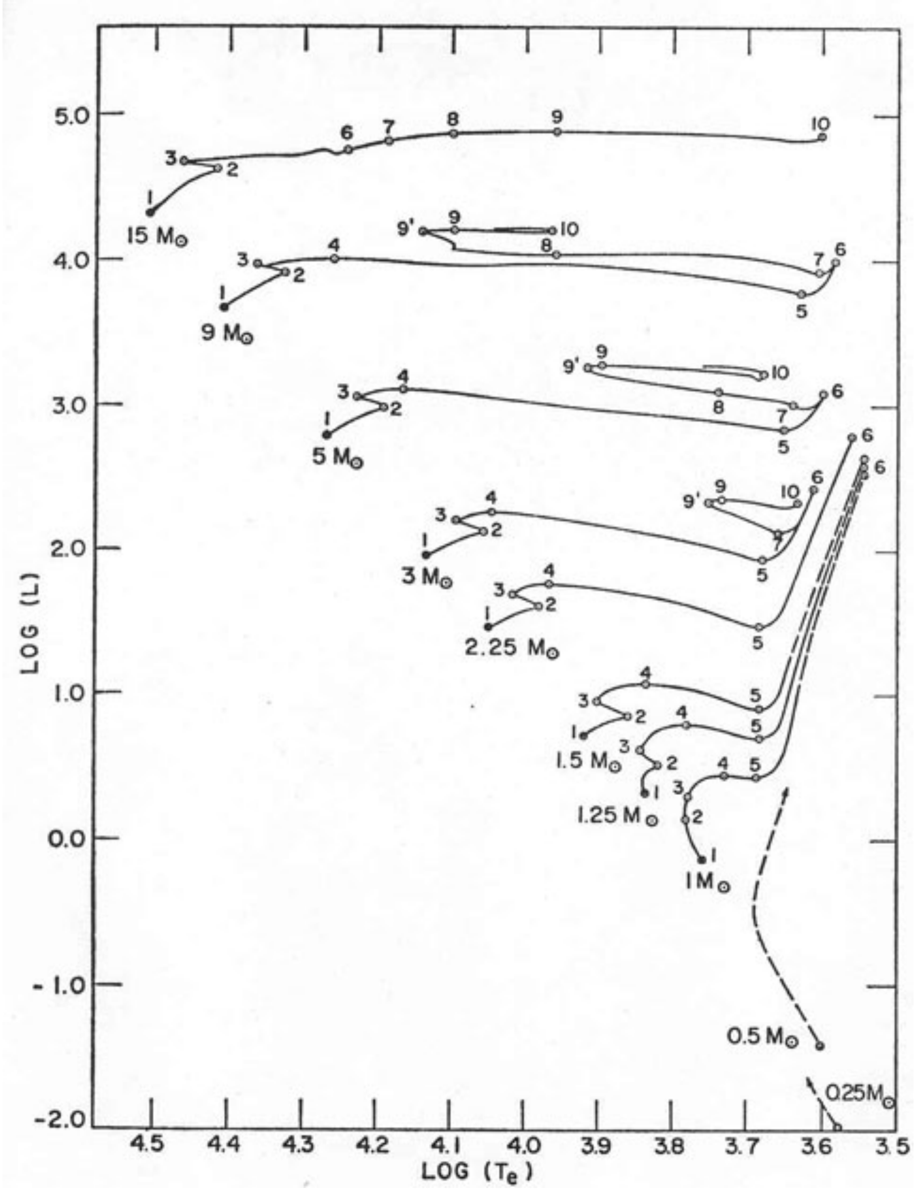
Planetary Nebulae



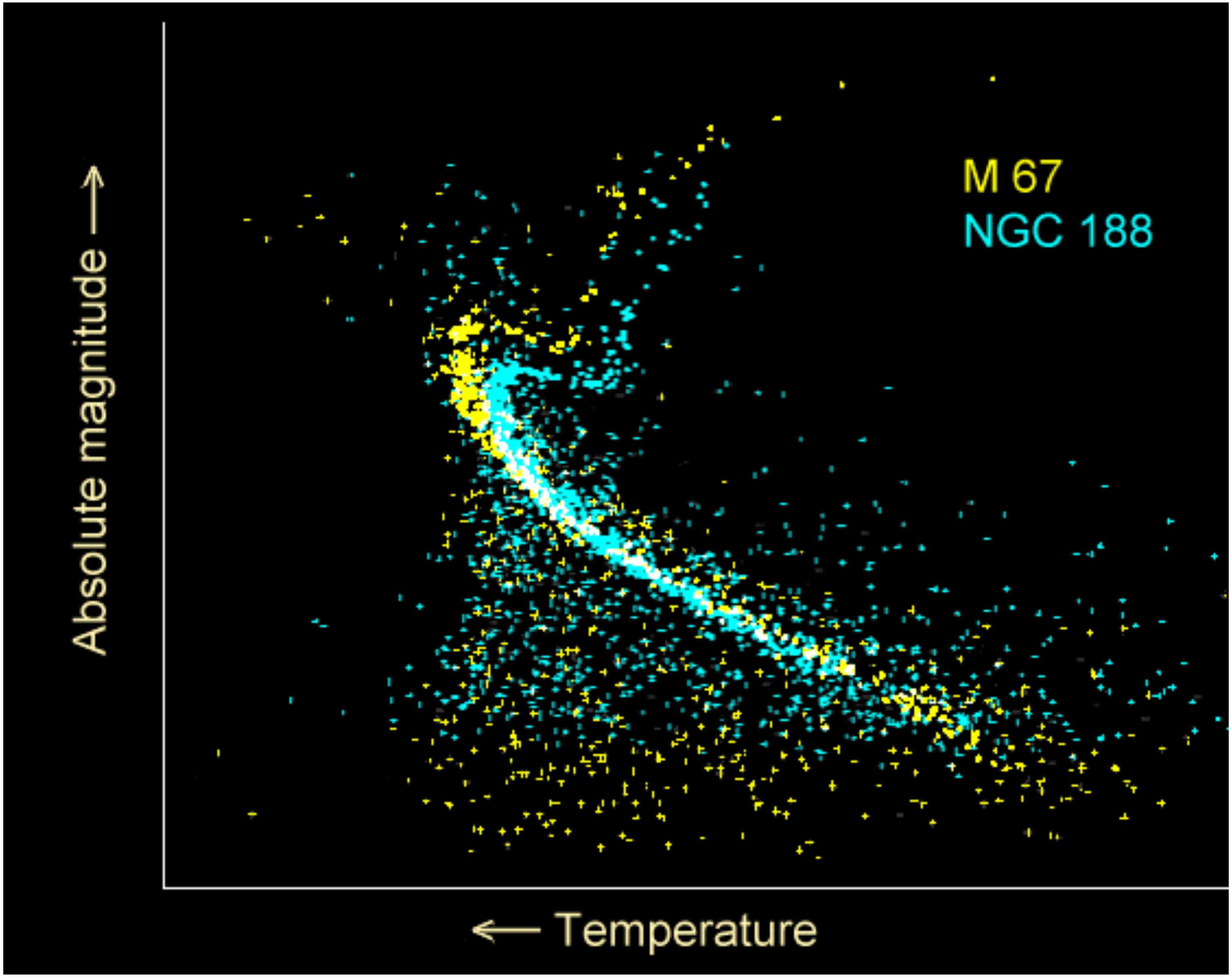


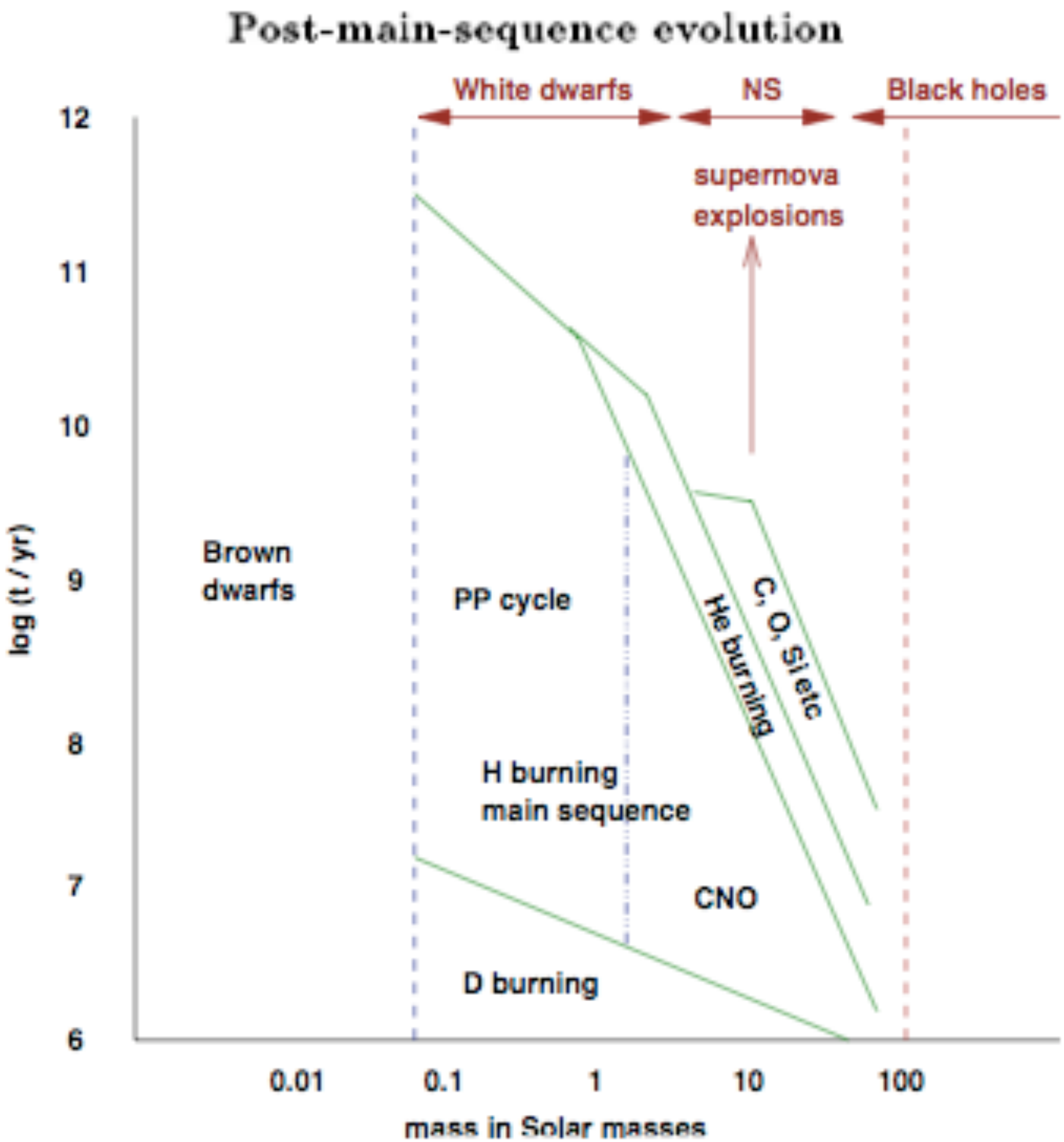
~9 billion yrs
~1 billion yrs
~100 million yrs
~10,000 yrs
Time spent as
Main sequence
Red giant
Yellow giant
Planetary nebula
White dwarf
Sun's age
4.5 billion yrs (now)
12.2 billion yrs
12.3 billion yrs
12.3305 billion yrs
12.3306 billion yrs
Core star shrinks. Ejected gases thin and form
Planetary nebula
Star ejects outer layers.
Red supergiant
12.2 billion years
Helium in core ignites: Helium flash.
MAIN SEQUENCE
Red giant
Yellow giant
Burning helium in core.
Burning hydrogen in shell around core.
12 billion years
Core star cools.
Burning hydrogen in core.
Sun now
4.5 billion years
No fuel available for burning, star cools.
White dwarf
Main sequence
Luminosity (solar units)
10^4
10^3
10^2
10
1
.1
.01
100,000
20,000
10,000
5,000
3,000
Temperature

Post - Main Sequence Evolution



Main Sequence Turn-off





Post-main-sequence evolution
White dwarfs
NS
Black holes
supernova
explosions
12
11
10
9
8
7
6
log (t / yr)
Brown
dwarfs
PP cycle
He burning
C, O, Si etc
H burning
main sequence
CNO
D burning
0.01
0.1
1
10
100
mass in Solar masses

MASS	FUSION	REMNANT
$M < 0.08 M_\odot$	No fusion	Brown Dwarf
$0.08 M_\odot < M < 0.5 M_\odot$	Central H burning Formation of degenerate core No He burning	He White Dwarf
$0.5 M_\odot < M < 2 M_\odot$	Central H burning Helium flash	CO White Dwarf
$2 M_\odot < M < 8 M_\odot$	Central H burning He ignites in non-degenerate core	CO White Dwarf
$8 M_\odot < M < 20 M_\odot$	Numerous burning phases Type II supernova	Neutron Star
$20 M_\odot < M < 50 M_\odot$	Numerous burning phases Type II supernova	Black Hole
$M > 50 M_\odot$	Numerous burning phases Hypernova/Collapsar	Black Hole