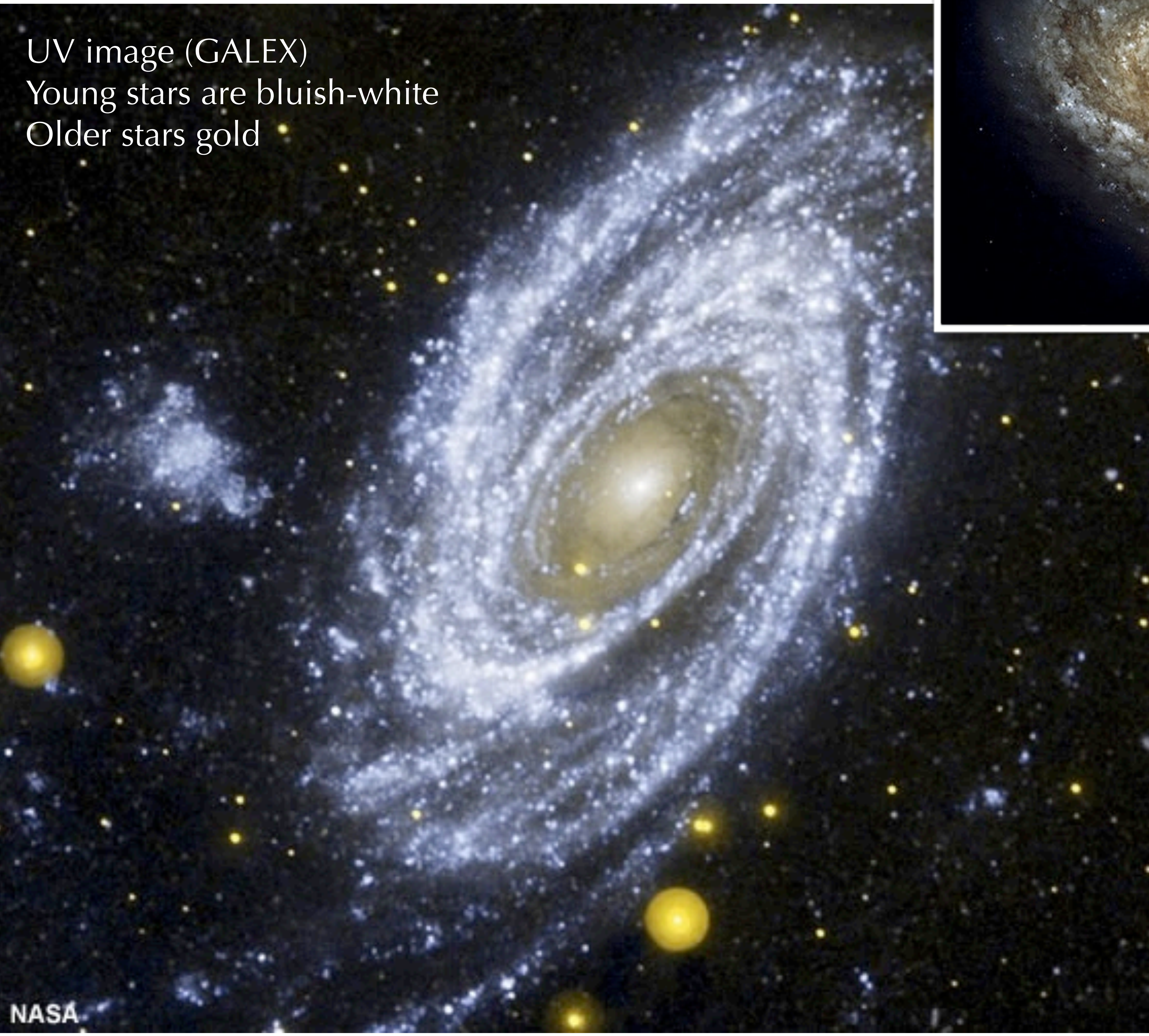
# Star Formation

Orion Nebula

# Where do stars form?





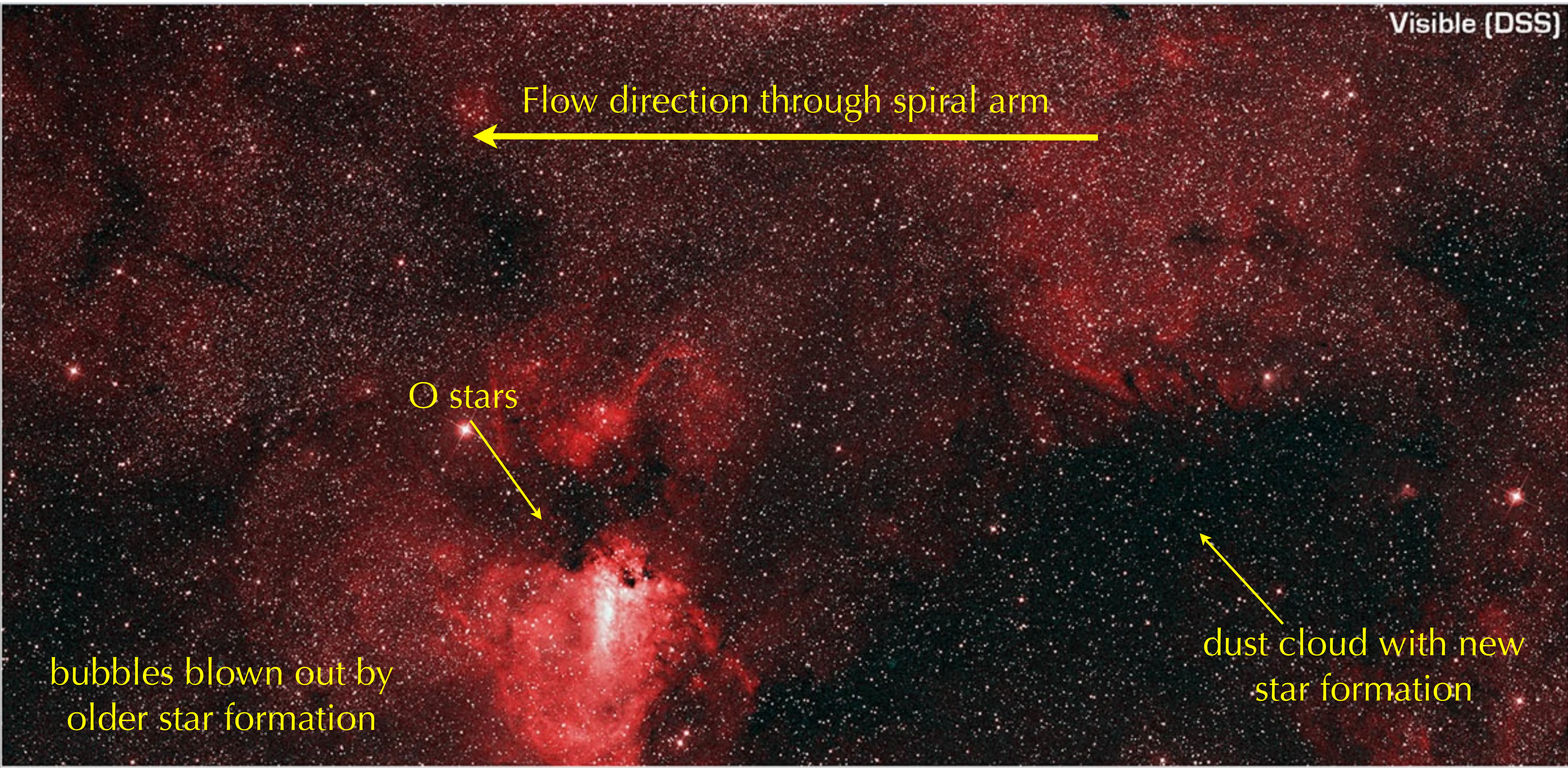
bulge of old stars, central black hole


disk of gas and stars

- Stars form in galactic disks
- Sun is a disk star
- Star formation concentrated in spiral arms


NASA/JPL-Caltech/
M. Povich (Penn State Univ.)

Spitzer Space Telescope: Star formation in the M17 nebula

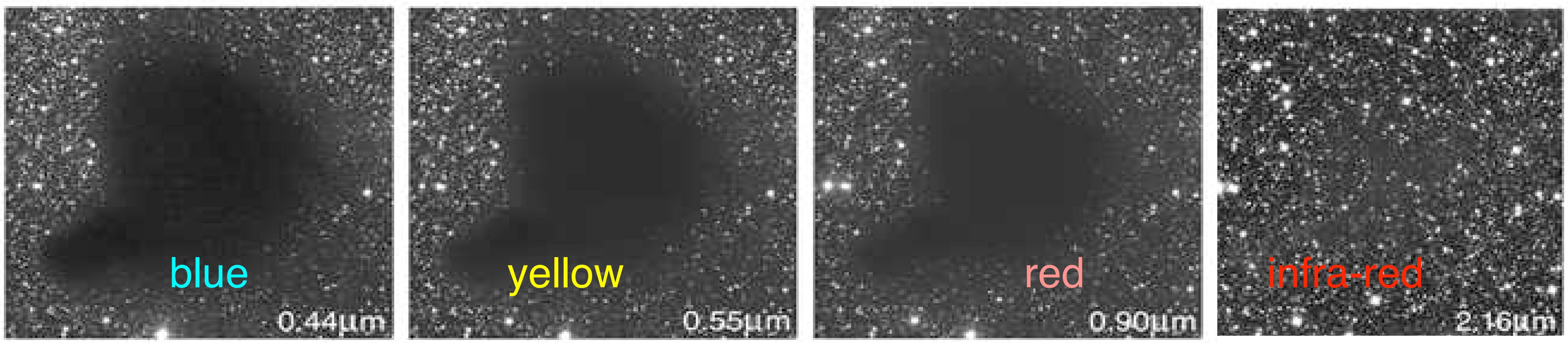



Spitzer Space Telescope: Star formation in the M17 nebula

NASA/JPL-Caltech/
M. Povich (Penn State Univ.)

# How much raw material in the Milky Way?

- Milky Way is ~$10^{10}$ years old, ~$10^{12}$ $M_\odot$
  - Dark matter ~90% (~$10^{12}$ $M_\odot$)
  - Stars ~10% (~$10^{11}$ $M_\odot$ - central black hole ~3 x $10^6$ $M_\odot$)
  - Interstellar medium ~1% (~$10^{10}$ $M_\odot$, mostly gas, ~1% dust)
- Interstellar medium
  - not smooth: clouds and cavities
  - regions of very cold (~ 10K), cold (~100K), warm ($10^4$ K) and very hot (~$10^6$K)
    - affected by nearby stars (stellar winds, supernovae, outflows)
  - average interstellar medium number density ~$10^6$ $m^{-3}$
    - best vacuum on Earth: n~$10^9$ $m^{-3}$
  - of relevance to star formation: giant molecular clouds, Bok globules

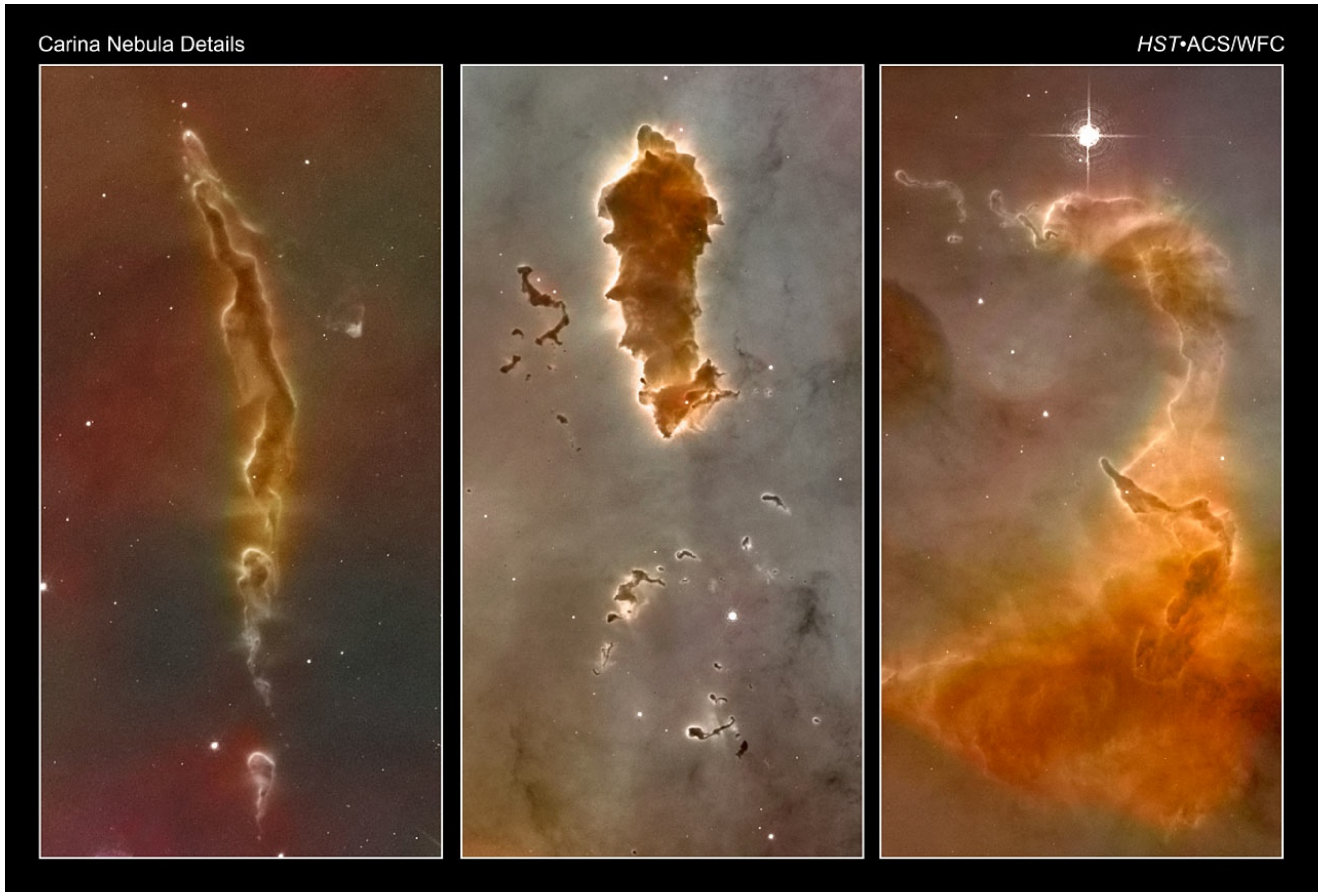



Dark cloud Barnard 68
shows scattering of starlight

# Stars form in dense, dusty gas

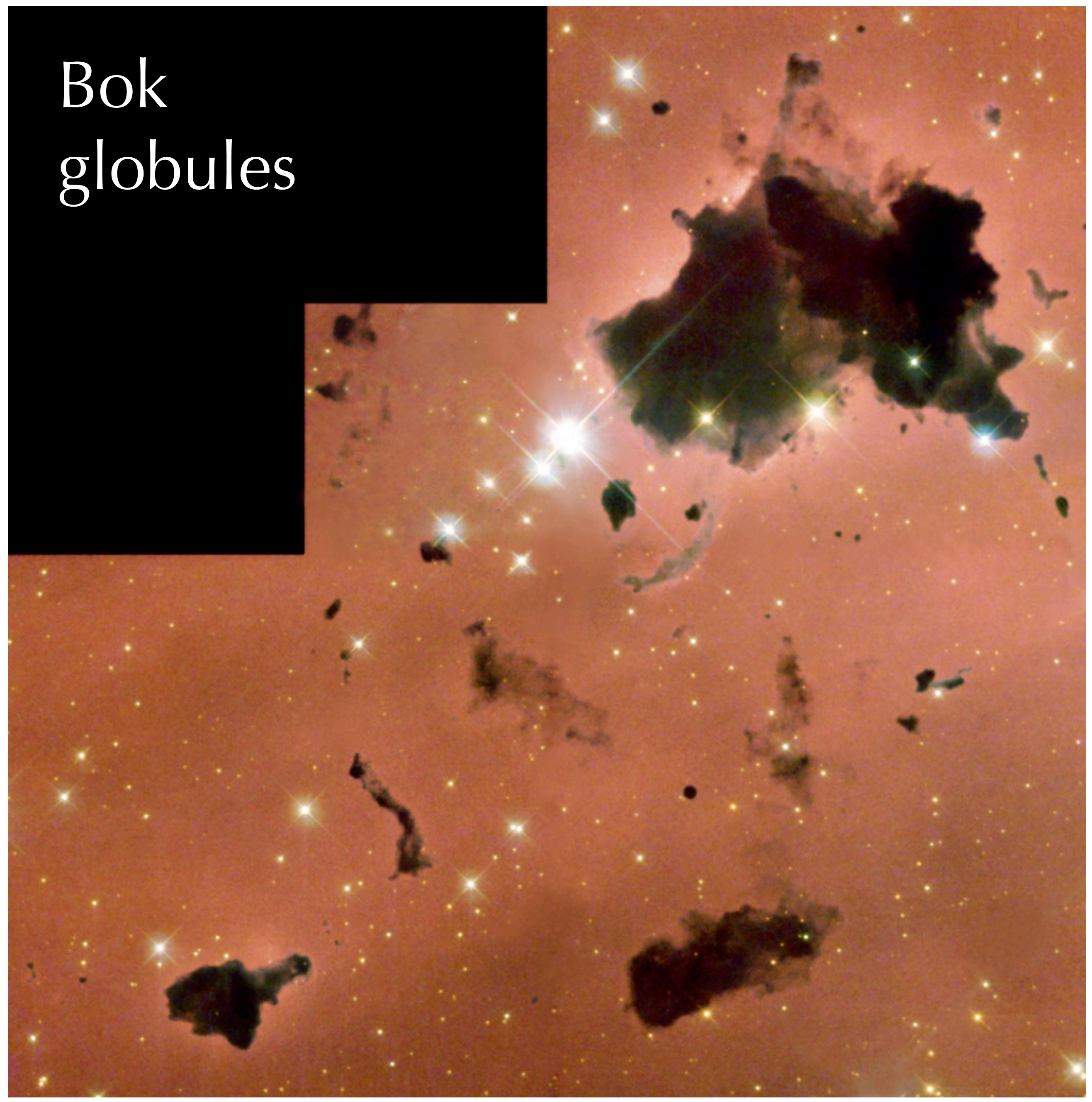
| | | | |
|---|---|---|---|
| Giant molecular cloud | ~50 pc | ~$10^5$ M$_\odot$ | ~$10^8$ m$^{-3}$ |
| Dense core of GMC | ~1 pc | ~100 M$_\odot$ | ~$10^{14}$ m$^{-3}$ |
| Bok globule | ~1 pc | ~10 M$_\odot$ | ~$10^{12}$ m$^{-3}$ |

Sun: ~$10^{-8}$ pc, ~$10^{32}$ m$^{-3}$




NASA, ESA, N. Smith (University of California, Berkeley), and The Hubble Heritage Team (STScI/AURA)

NASA



# Stars Form by Gravitational Collapse

- A necessary condition for gravitational collapse
- The Jeans criterion (1877-1946)
- Stable, gravitationally bound system satisfies the virial theorem $E_{\rm kin} + \frac{1}{2}E_{\rm pot} = 0$
- The cloud will collapse only if $E_{\rm kin} + \frac{1}{2}E_{\rm pot} < 0$

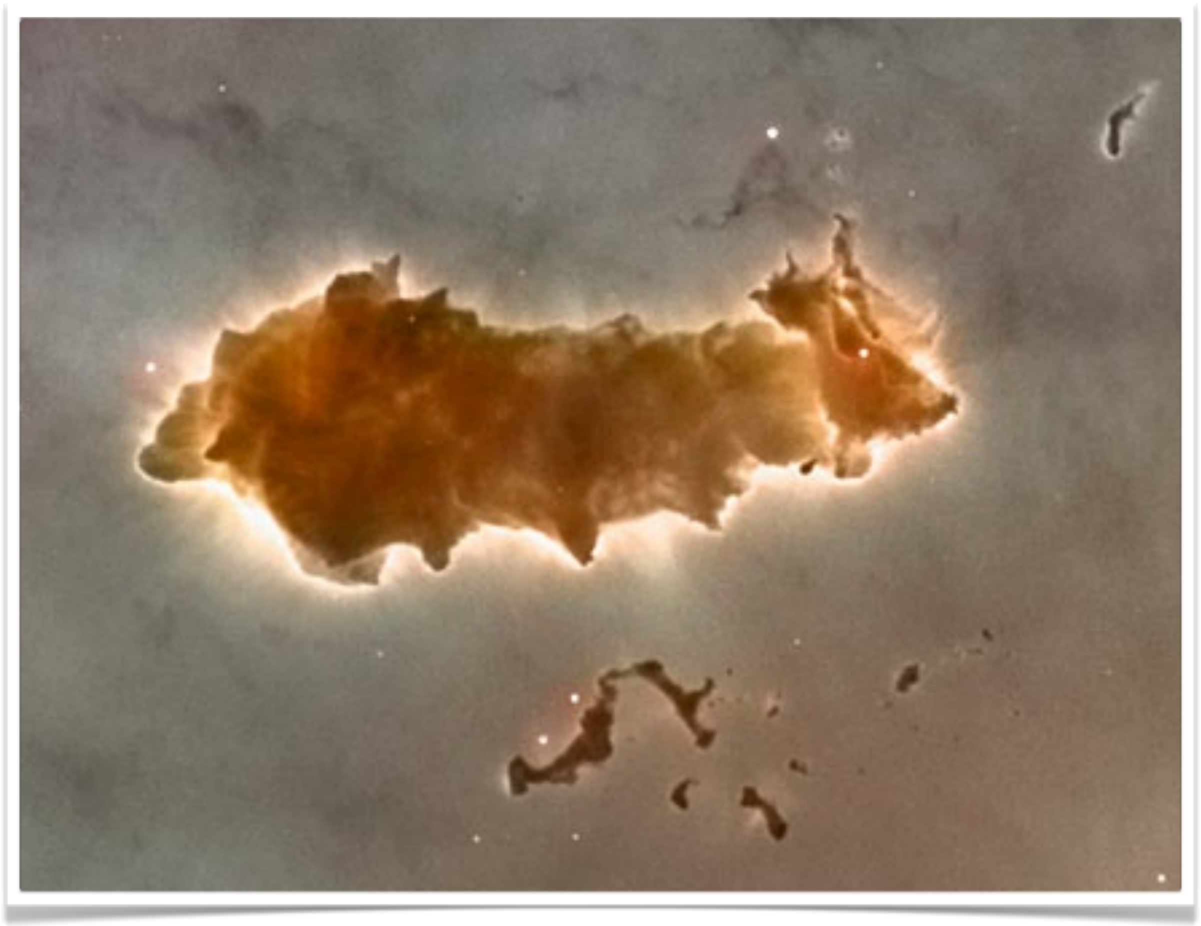
$$E_{\rm pot} = -\frac{3}{5}\frac{GM^2}{R} \qquad E_{\rm kin} = \frac{3}{2}NkT = \frac{3}{2}\frac{M}{\mu m_H}kT$$

$$E_{\rm kin} < -\frac{E_{\rm pot}}{2} \quad \longrightarrow \quad \boxed{M > M_J = \left(\frac{5kT}{G\mu m_H}\right)^{3/2}\left(\frac{3}{4\pi\rho}\right)^{1/2}}$$

"Jeans mass"

# Stars Form by Gravitational Collapse

Knowing the temperature and density of a cloud, we know the minimum mass it has to have in order to collapse under its own weight



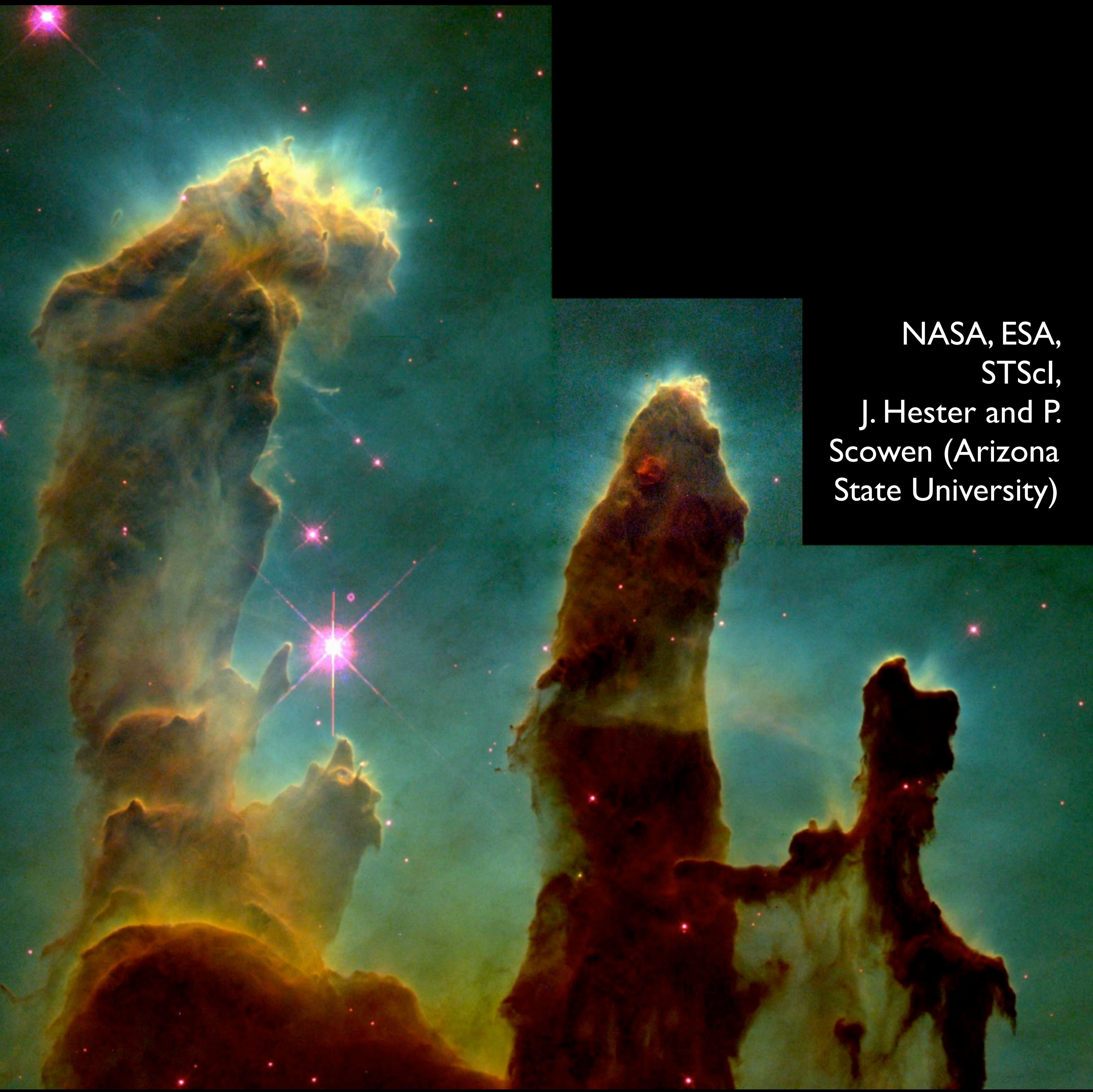
$$M_J \propto T^{3/2}\rho^{-1/2}$$

Hotter → more pressure support → need more mass

Denser → need less mass

| | | | |
|---|---|---|---|
| Diffuse hydrogen cloud, typically < $10^2$ $M_\odot$ | T ~ 50 K | n ~ 5 x $10^8$ $m^{-3}$ | $M_J$ ~ 1500 $M_\odot$ |
| GMC dense core, typically $10^2$ $M_\odot$ | T ~ 150 K | n ~ $10^{14}$ $m^{-3}$ | $M_J$ ~ 17 $M_\odot$ |
| Barnard 68 Dark cloud, ~ 3 $M_\odot$ | T ~ 10 K | n ~ $10^{12}$ $m^{-3}$ | $M_J$ ~ 3 $M_\odot$ |

- Eagle Nebula in Orion
- Massive stars evaporate clouds in which low mass stars are forming



NASA, ESA, STScI, J. Hester and P. Scowen (Arizona State University)


NASA, ESA, and The Hubble Heritage Team (STScI/AURA)


Jean-Charles Cuillandre (CFHT), Hawaiian Starlight, CFHT

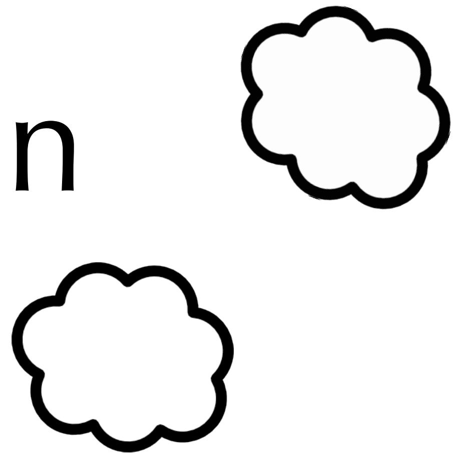
- Horsehead Nebula in Orion
- Dark molecular cloud silhouetted against bright nebula
- Young, massive B star (strong UV source)

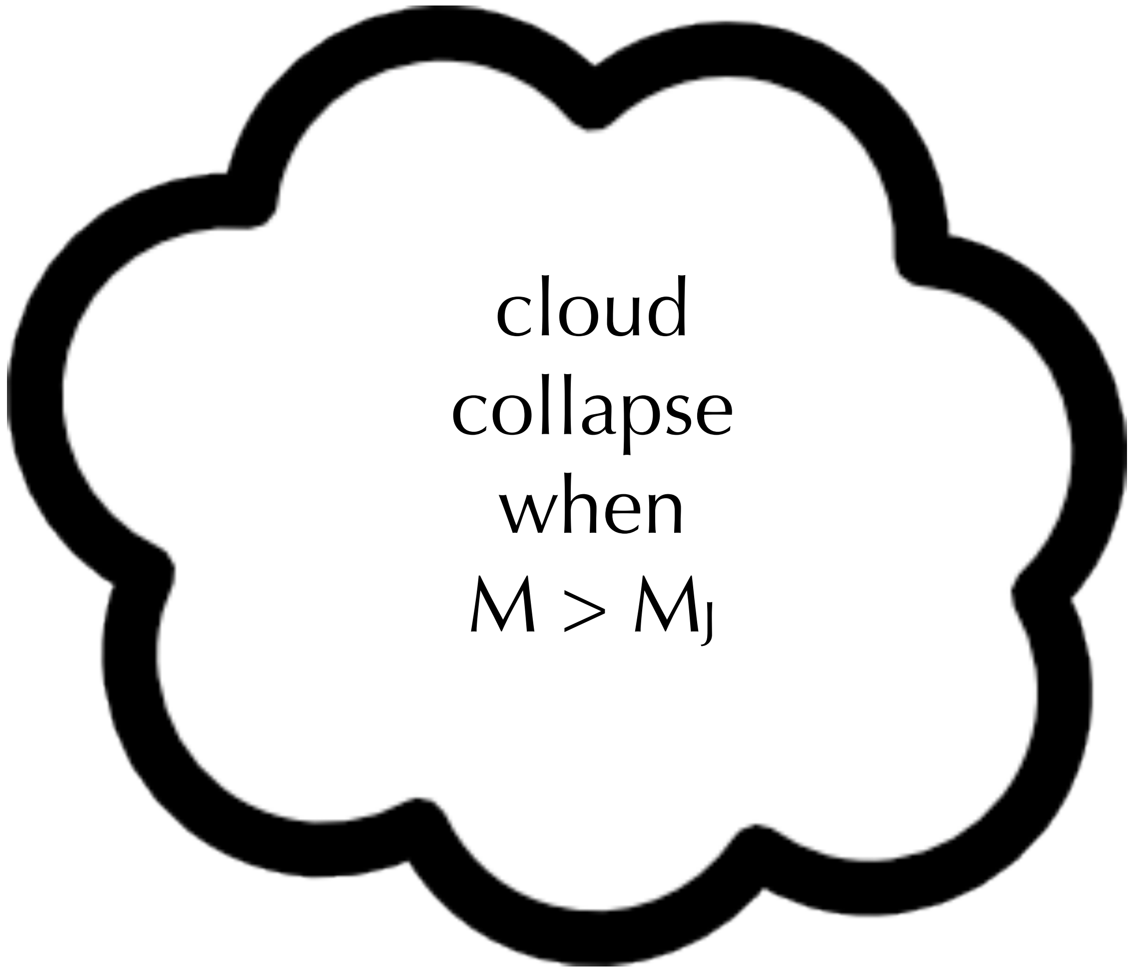
# What happens during collapse?

- First stage: free-fall (dynamical timescale)
  - gravity overcomes the pressure support
  - nearly free-fall collapse, $t \sim t_{dyn} \sim (G\rho)^{-1/2} \sim 10^3$ yr for dense core of GMC
    - center of the cloud higher density ➞ collapse faster ➞ central cusp
    - temperature of the cloud remains ~ constant (isothermal)
    - gravitational energy release is lost to the outside
      - this is possible as long as the cloud is still transparent to its own radiation
  - fragmentation occurs due to decreasing Jeans mass: $M_J \propto T^{3/2}\rho^{-1/2}$

The Cygnus Wall of Star Formation

# Cloud fragmentation






collapse is isothermal
(constant temperature)

↓

density increases

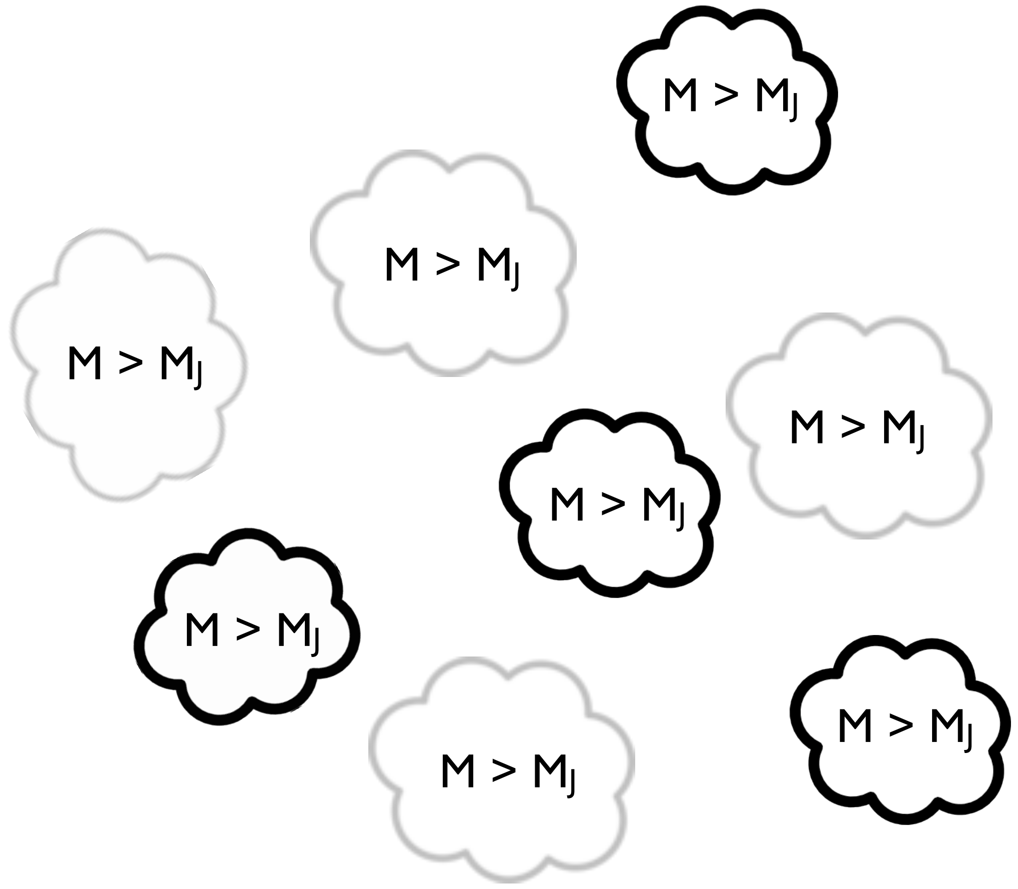
↓

Jeans mass decreases,

$$M_J \propto T^{3/2}\rho^{-1/2}$$

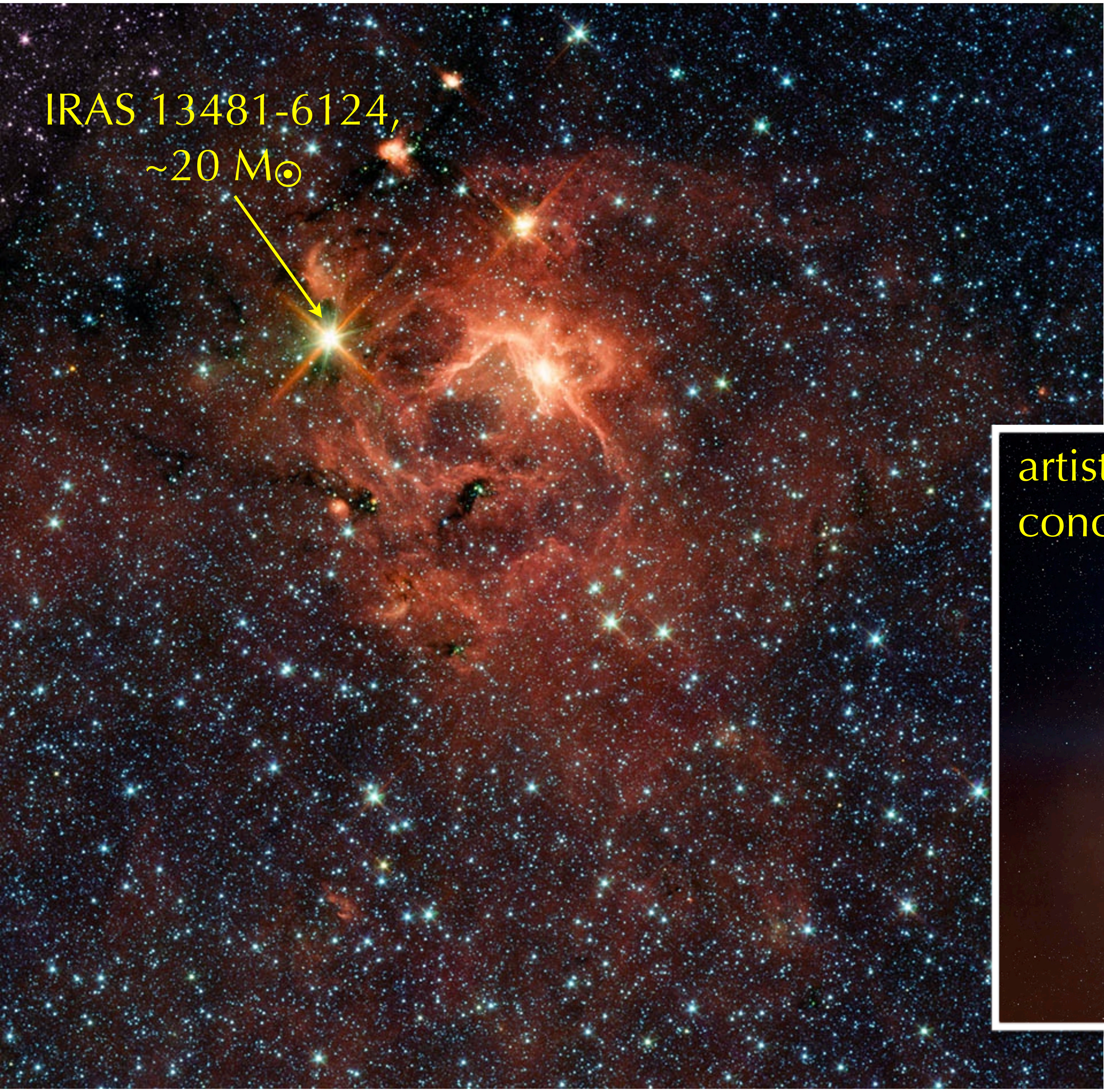
↓

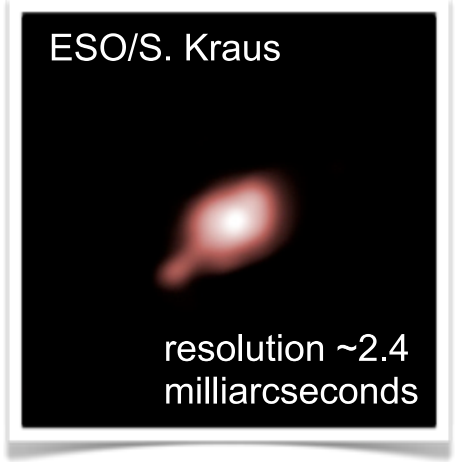
smaller parts of cloud
become unstable,
can collapse



# What happens during collapse?

- Second stage: pre-main-sequence (thermal timescale)
  - further contraction, cloud becomes optically thick (heat not lost instantly)
  - free-fall and fragmentation stop, contracts slowly as heat diffuses out
    - $t_{KH} \sim E/L \sim 10^7$ yr for 1 $M_\odot$
      - longer or shorter for higher/lower mass stars?
    - strong stellar wind ($\sim 10^{-8}$ $M_\odot$/yr)
    - high angular momentum material forms disk
      - viscosity in the disk moves material inward
      - jets, stellar UV photons and winds disperse disk/cloud

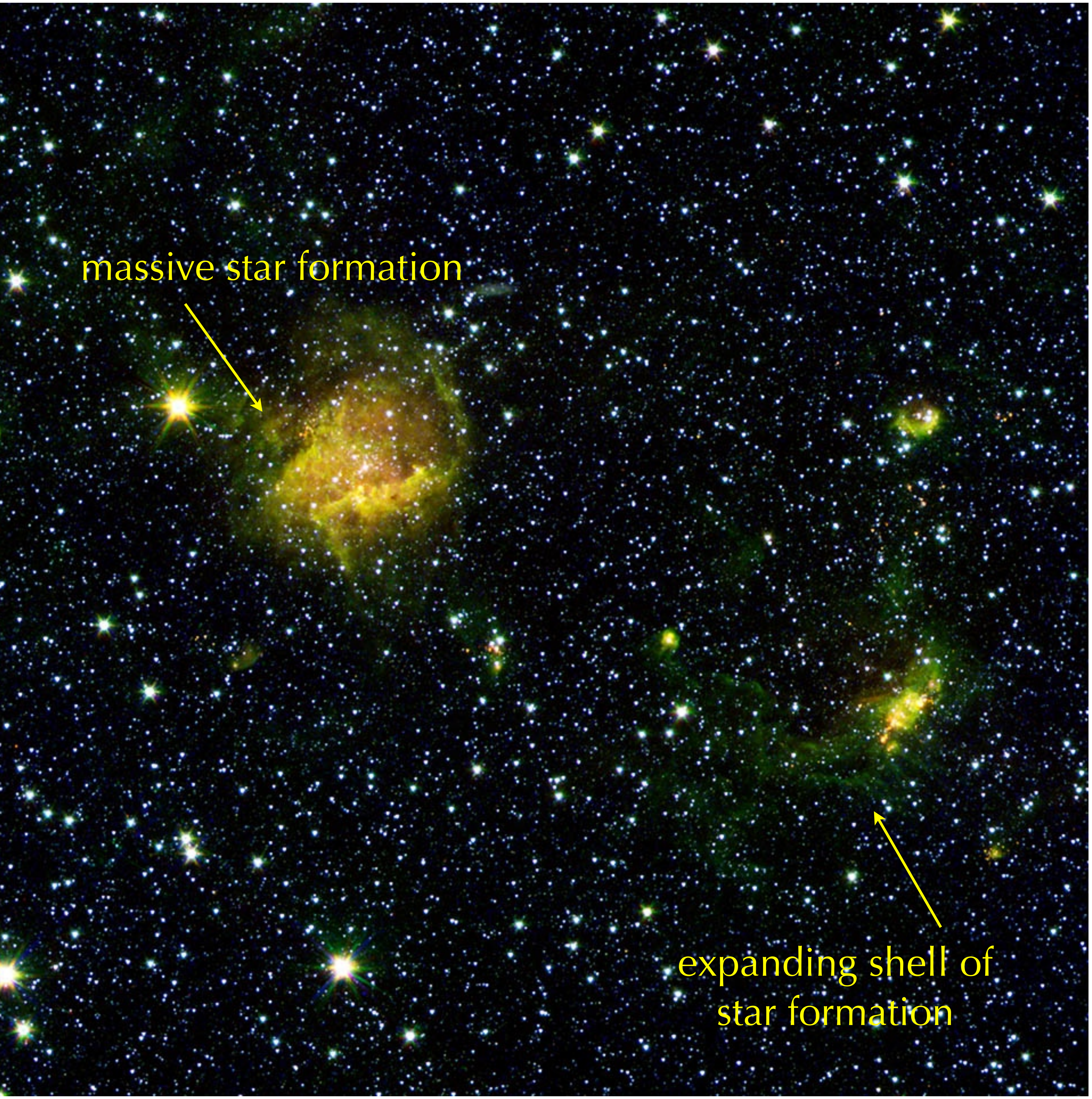




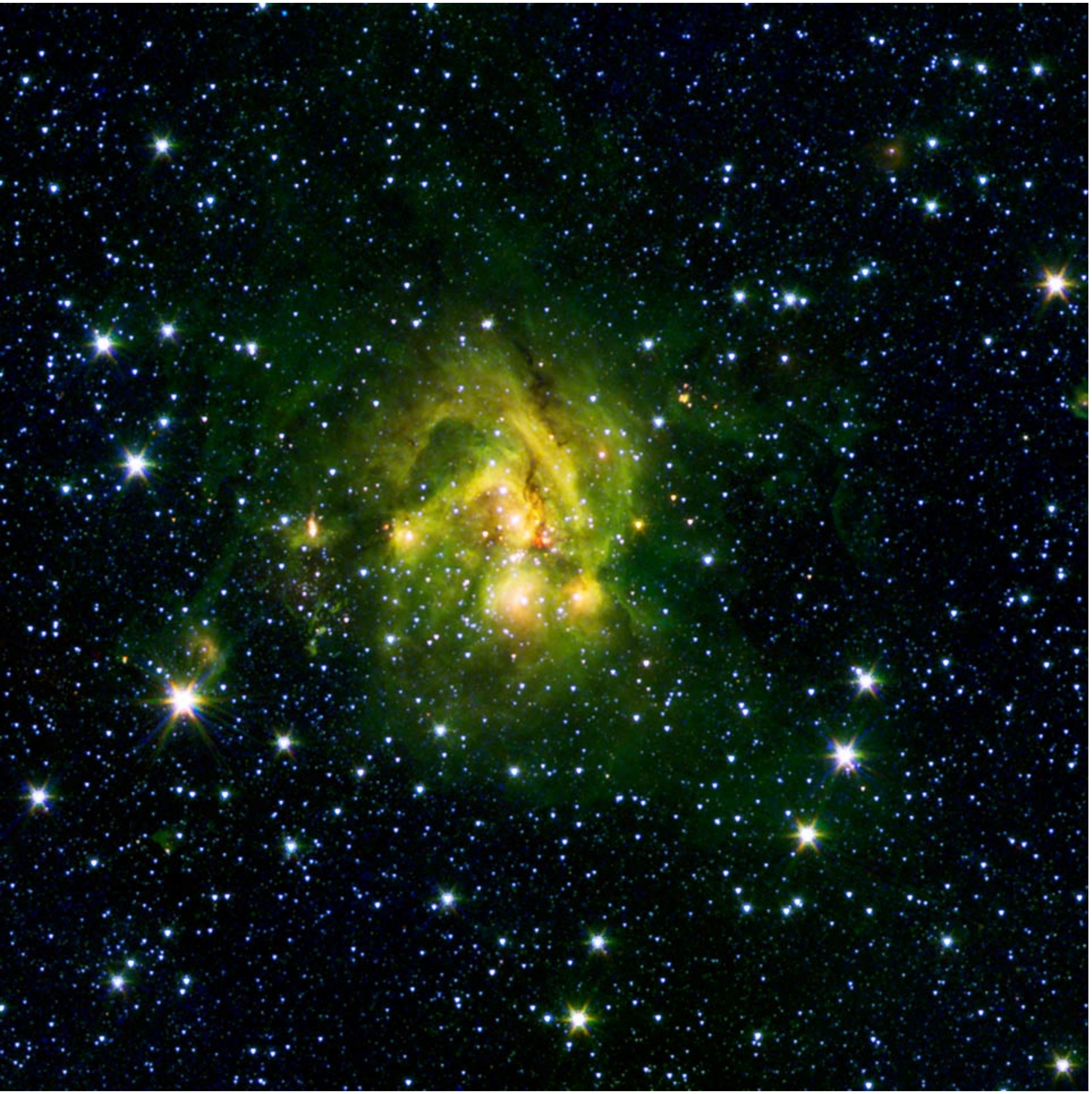
ESO/NASA/JPL-Caltech/S. Kraus

- Disk around a massive young star observed with European Southern Observatory Very Large Telescope Interferometer
- Massive stars form in the same way as less massive stars



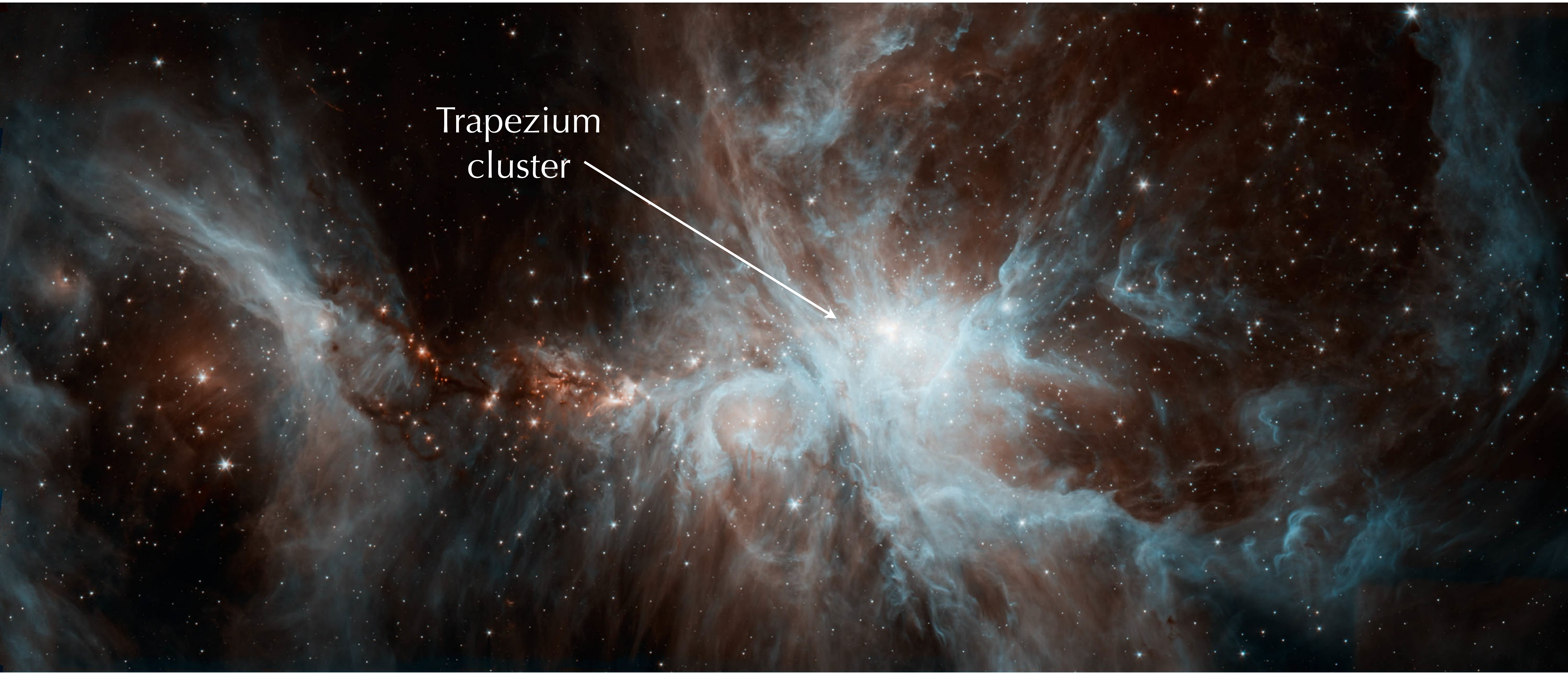

NASA/JPL-Caltech/2MASS/B. Whitney
(SSI/University of Wisconsin)

- Distant star forming region BG2107+49, 10 kpc away
- Spitzer Space Telescope + 2MASS (Two Micron All Sky Survey)
- Star formation triggers more star formation
- Red dots = young, forming stars cocooned in gas and dust



NASA/JPL-Caltech/2MASS/B. Whitney
(SSI/University of Wisconsin)

- “Shocked outflows”
- Gas outflow from a new star runs into the surrounding interstellar medium
- Spitzer Space Telescope + 2MASS (Two Micron All Sky Survey)

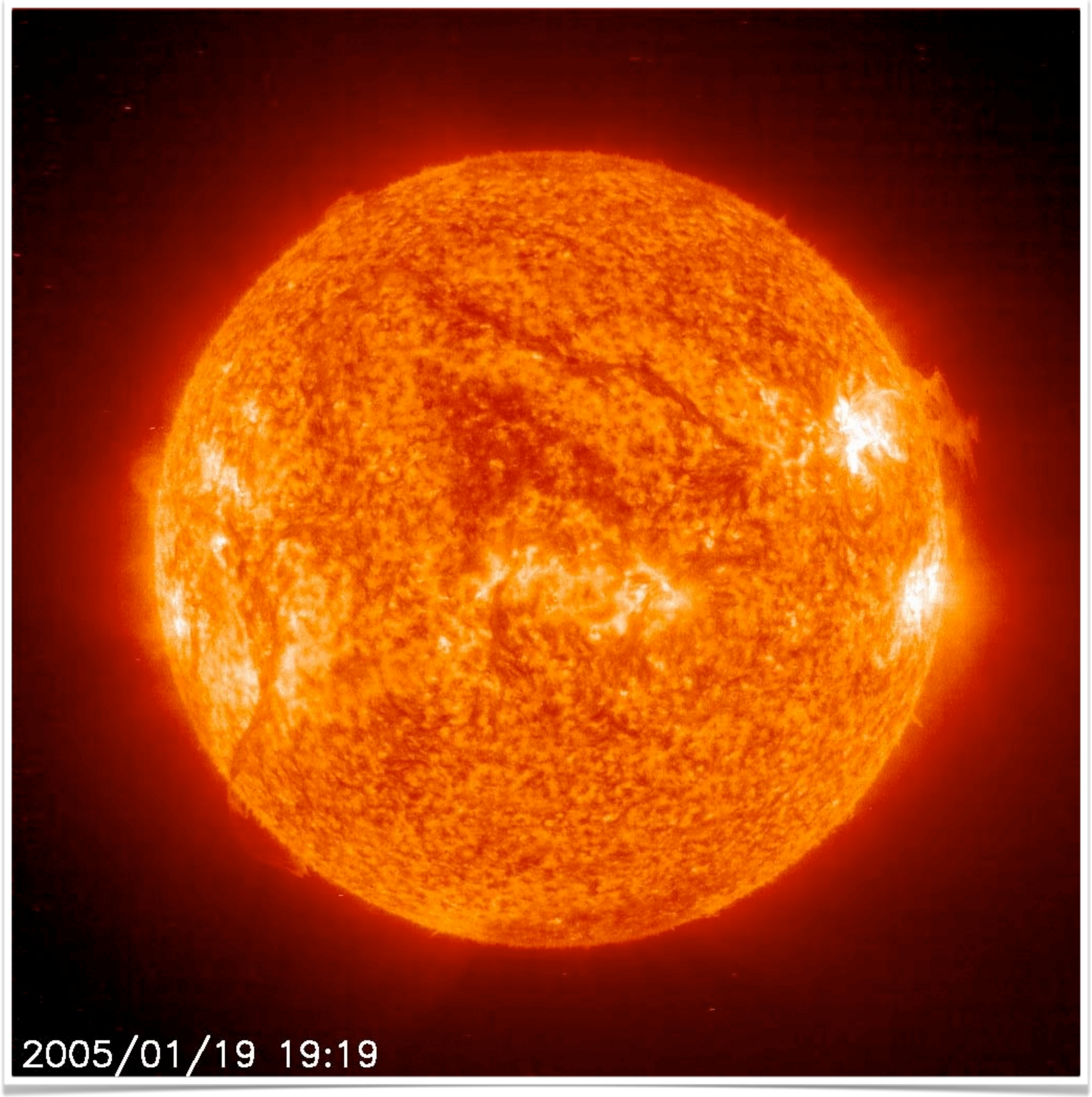



NASA/JPL-Caltech/J. Stauffer (SSC/Caltech)

- Spitzer Space Telescope: Star formation in the Orion nebula
- Radiation and wind from massive stars blows away gas and dust

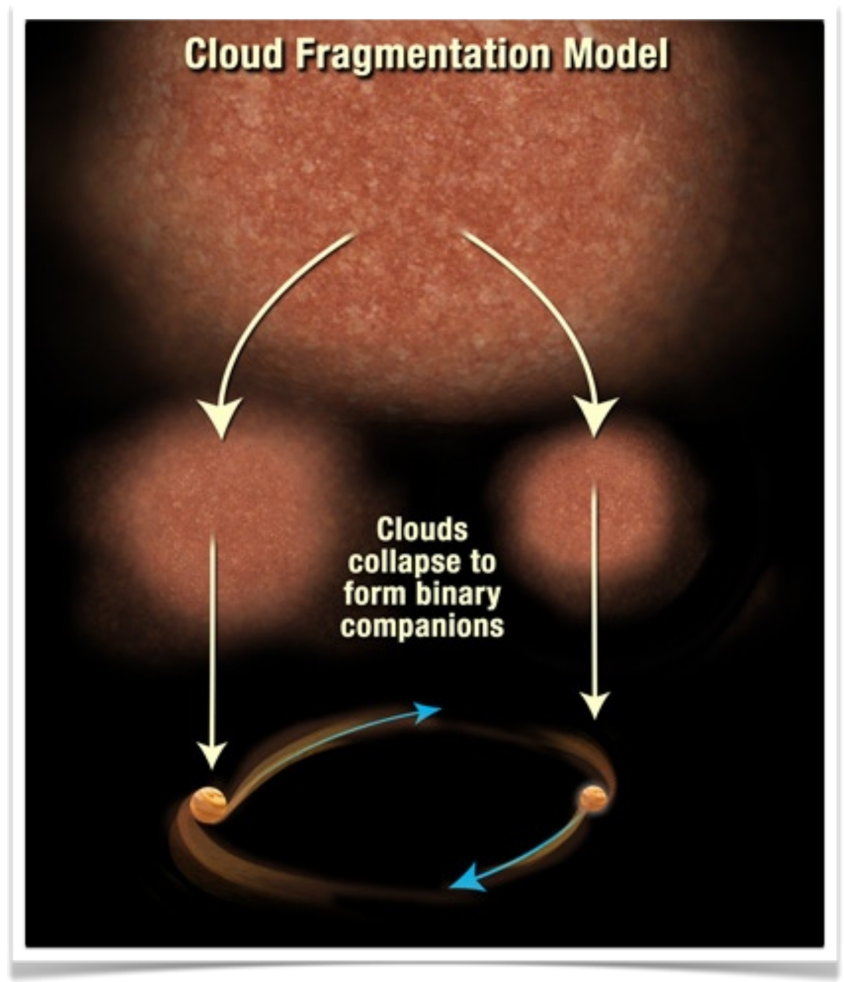
# What happens during collapse?

- Third stage: main-sequence stars (nuclear timescale)
  - central temperature so hot that H burning starts, $t \sim t_{nuc} \sim Mc^2/L$



# Distribution of stellar masses

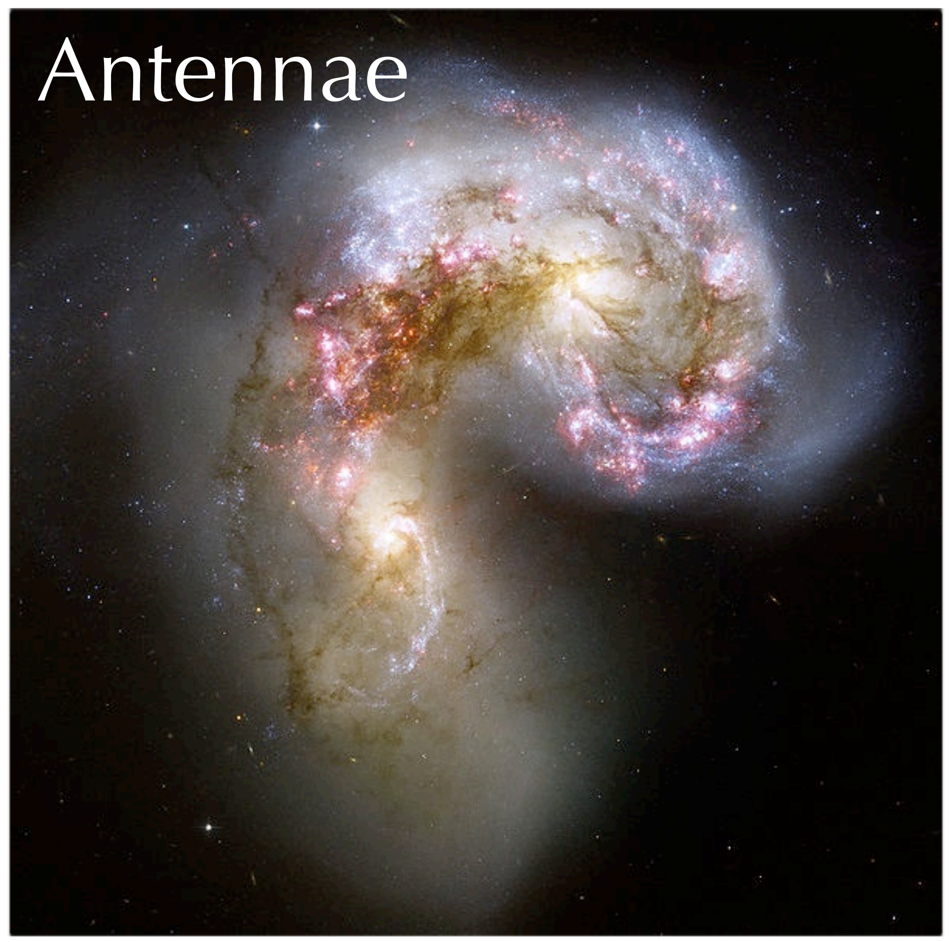
- Star formation tends to form low mass stars
- Final stellar mass is not the initial $M_J$
- Fragmentation
  - Isothermal collapse phase, T constant, $\rho$ increases ➞ $M_J$ decreases
  - An initially collapsing cloud can fragment ➞ lighter stars
  - Fragmentation stops when isothermal phase stops
- Angular momentum
  - $d \sim 1$ pc ➞ $d \sim 10^{-8}$ pc
  - forming binary stars, triple stars....
- Observed:
  - 20 times as many stars $< 1\ M_\odot$ than $> 1\ M_\odot$ (to $0.1\ M_\odot$)
  - Average mass of a star $\sim 0.3\ M_\odot$
  - Distribution of stellar masses is called the initial mass function (IMF)




NASA, ESA, and A. Feild (STScI)

# Star formation in galaxies

- The Milky Way is forming stars at a rate of ~1 $M_\odot$/yr
- Each star takes ~$10^6$ yr to mature to main sequence
- $10^{10}$ $M_\odot$ of gas, turned into stars at ~1 $M_\odot$/yr, can last $10^{10}$ yrs
  - Star formation can last longer - why?
- Some galaxies form stars at much higher rates, > 100 $M_\odot$/yr
  - "starburst galaxies"




NASA, ESA, and the Hubble Heritage Team (STScI/ AURA)-ESA/Hubble Collaboration


NASA, ESA and the Hubble Heritage Team STScI/AURA). Acknowledgment: J. Gallagher (University of Wisconsin), M. Mountain (STScI) and P. Puxley (NSF)

starbursts triggered by galaxy-galaxy collisions