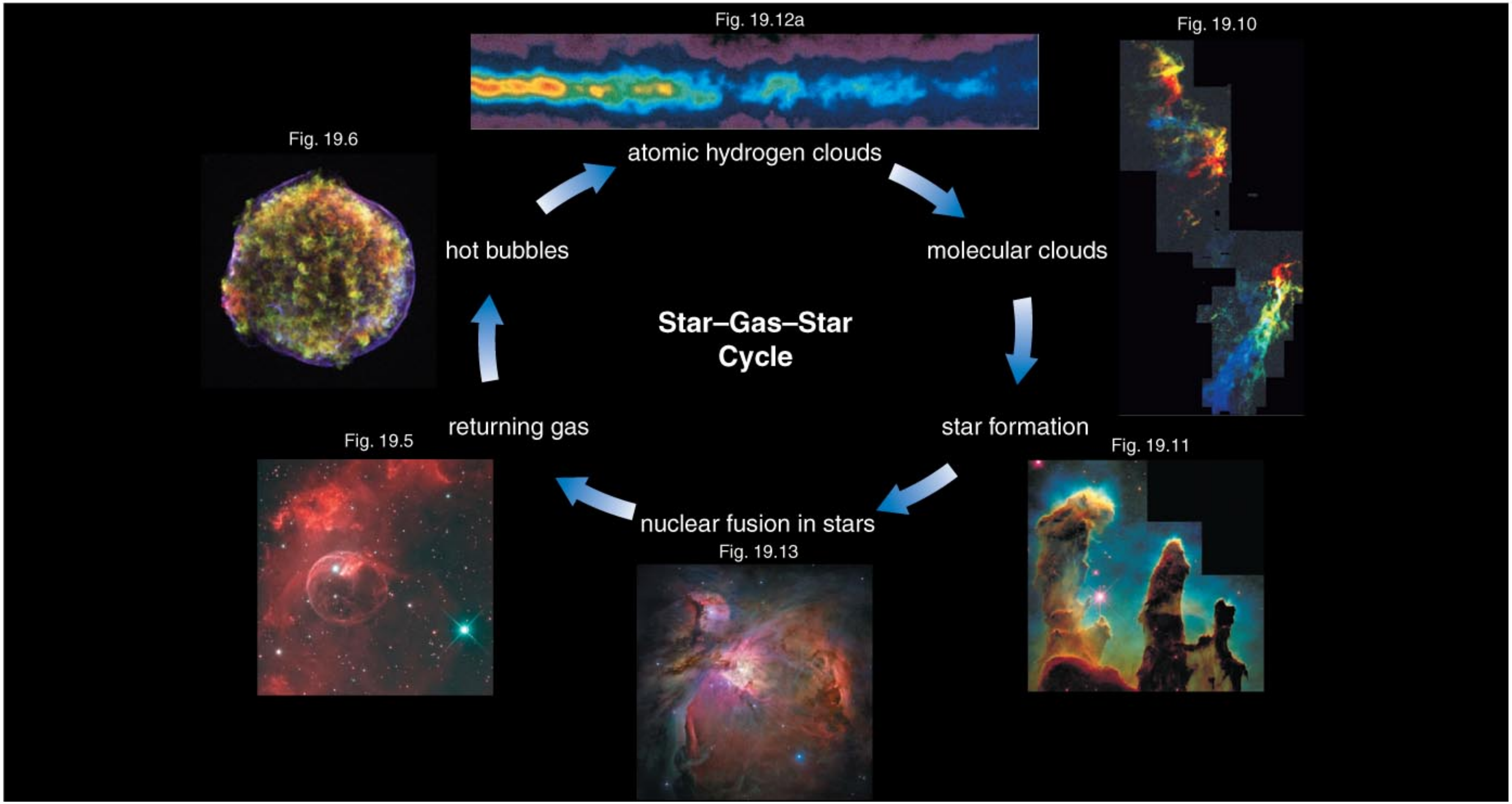
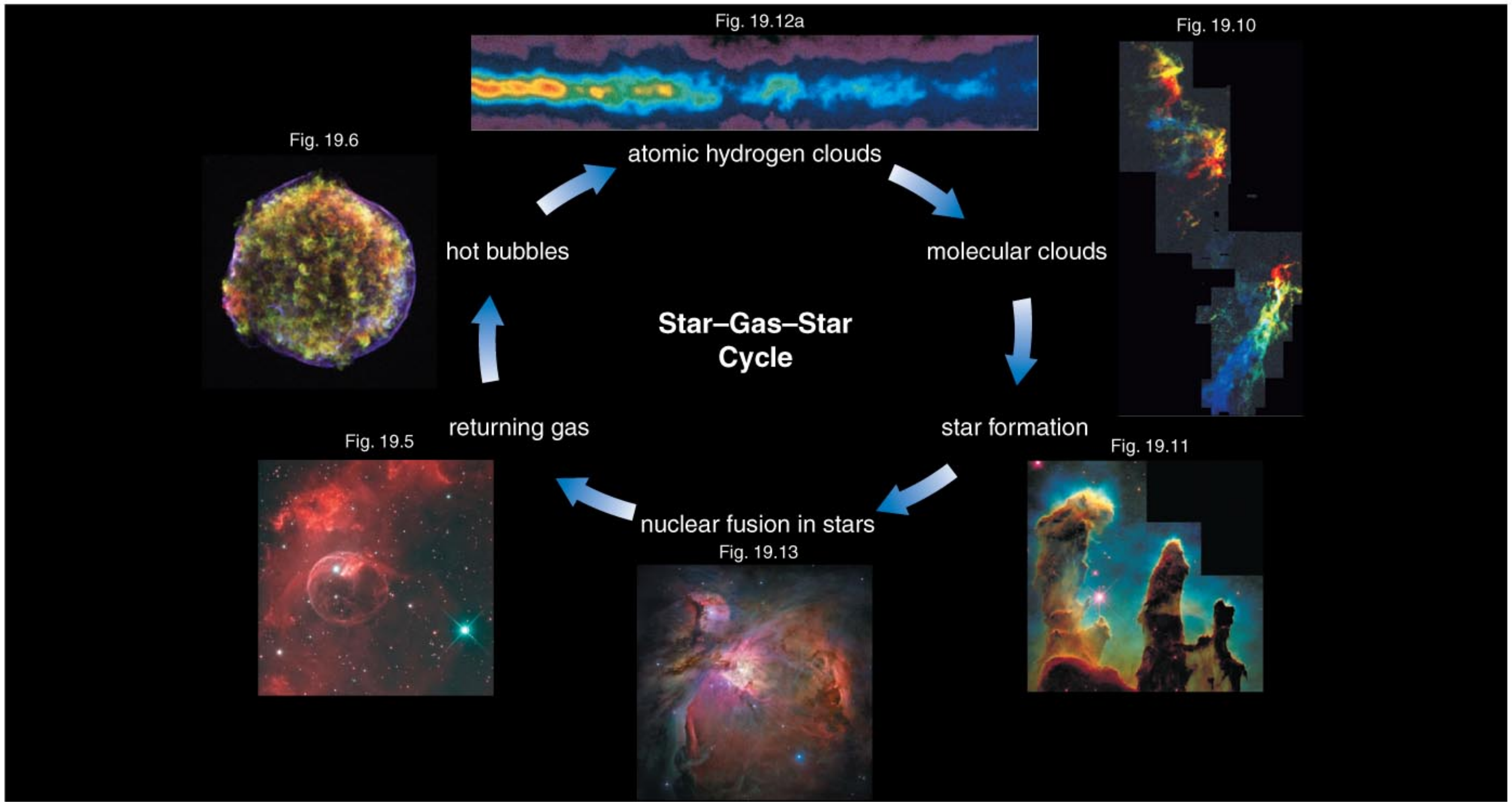
Lecture 21: Star Formation

Lamers & Levesque Ch. 12, 14.3, 30



How is gas recycled in our galaxy?



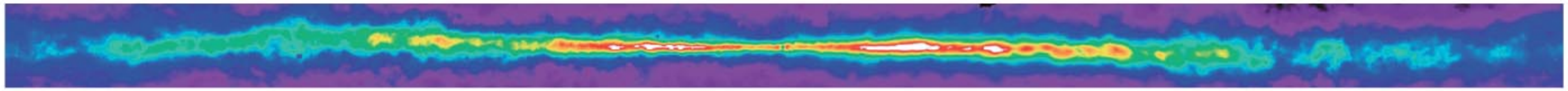
Star–gas–star cycle

Recycles gas from old stars into new star systems.

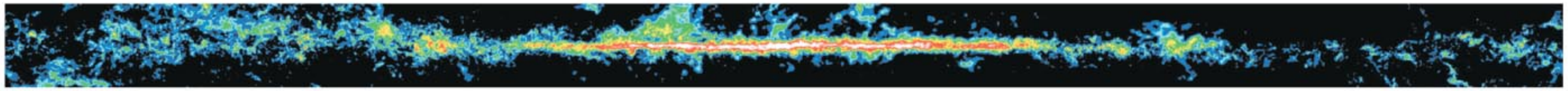
Summary of Galactic Recycling

Gas Cools

- Stars make new elements by fusion.
- Dying stars expel gas and new elements, producing hot bubbles (~10^6 K).
- Hot gas cools, allowing atomic hydrogen clouds to form (~100–10,000 K).
- Further cooling permits molecules to form, making molecular clouds (~30 K).
- Gravity forms new stars (and planets) in molecular clouds.



a 21-centimeter radio emission from atomic hydrogen gas.



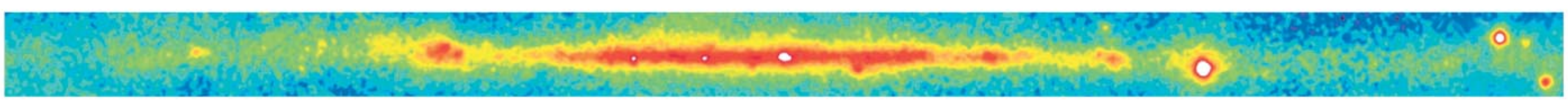
b Radio emission from carbon monoxide reveals molecular clouds.

c Infrared (60–100 μm) emission from interstellar dust.

d Infrared (1–4 μm) emission from stars that penetrates most interstellar material.

e Visible light emitted by stars is scattered and absorbed by dust.

f X-ray emission from hot gas bubbles (diffuse blobs) and X-ray binaries (pointlike sources).



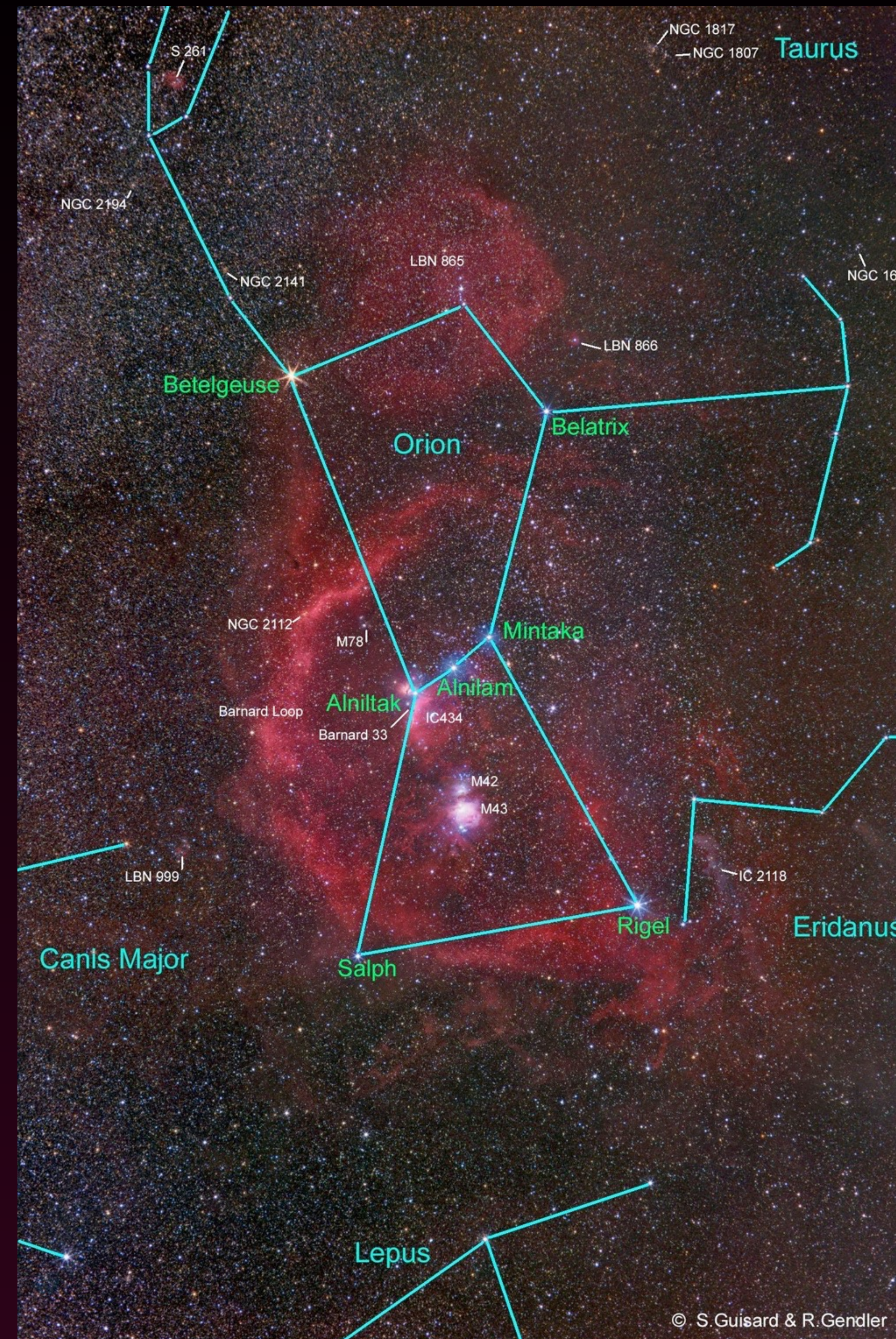
g Gamma-ray emission from collisions of cosmic rays with atomic nuclei in interstellar clouds.

We observe the star–gas–star cycle operating in Milky Way's disk using many different wavelengths of light.

Where do stars form?
Star-Forming Clouds

- Stars form in dark clouds of dusty gas in interstellar space.
- The gas between the stars is called the **interstellar medium.**

the Orion star-forming region



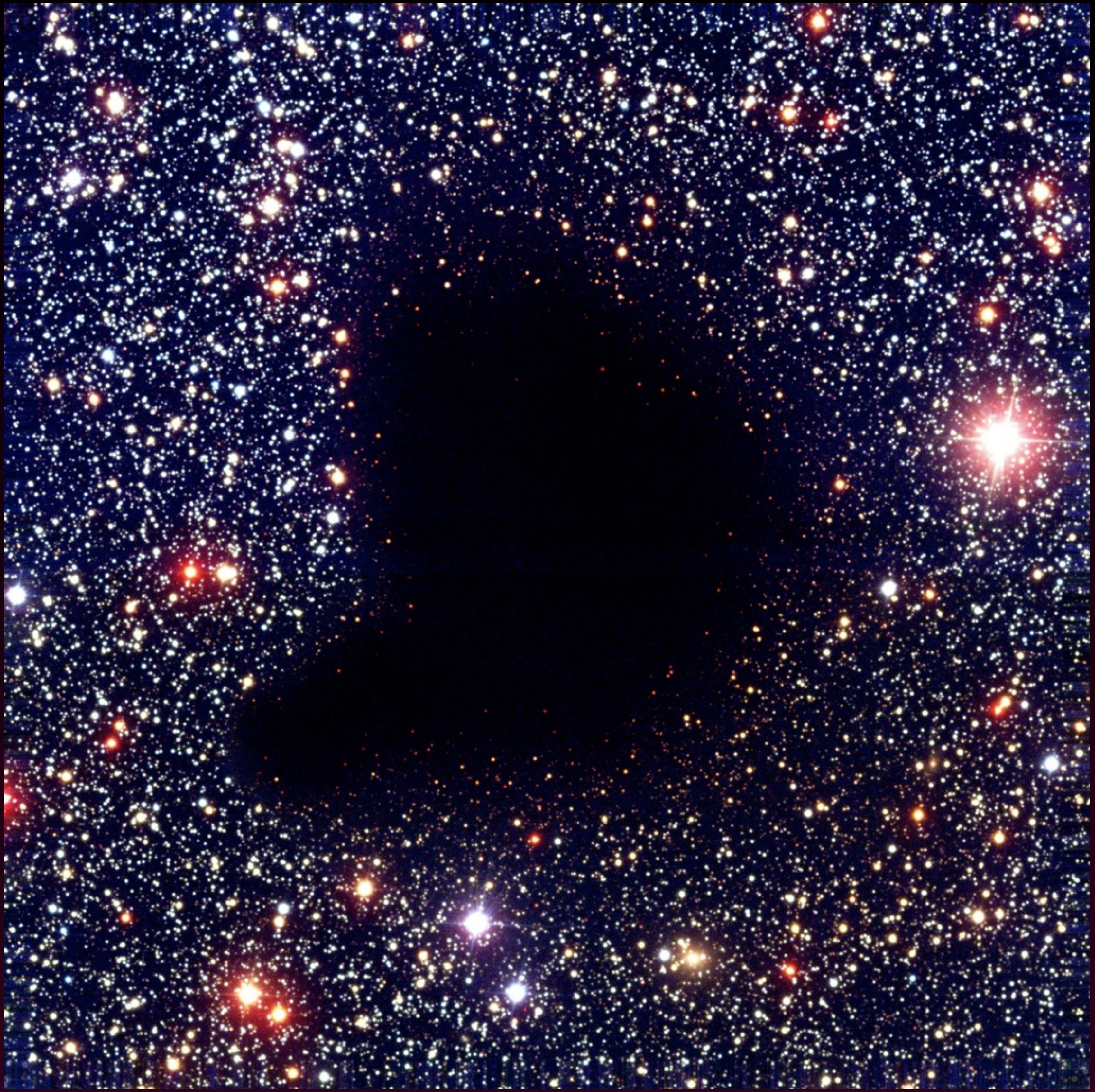
from http://apod.nasa.gov/apod/ap030207.html and
http://www.astrosurf.com/sguisard/Pagim/Orion_constellation-HRVB-50mm.html

the Orion star-forming region

Orion and Horsehead nebulae from http://antwrp.gsfc.nasa.gov/apod/ap090310.html

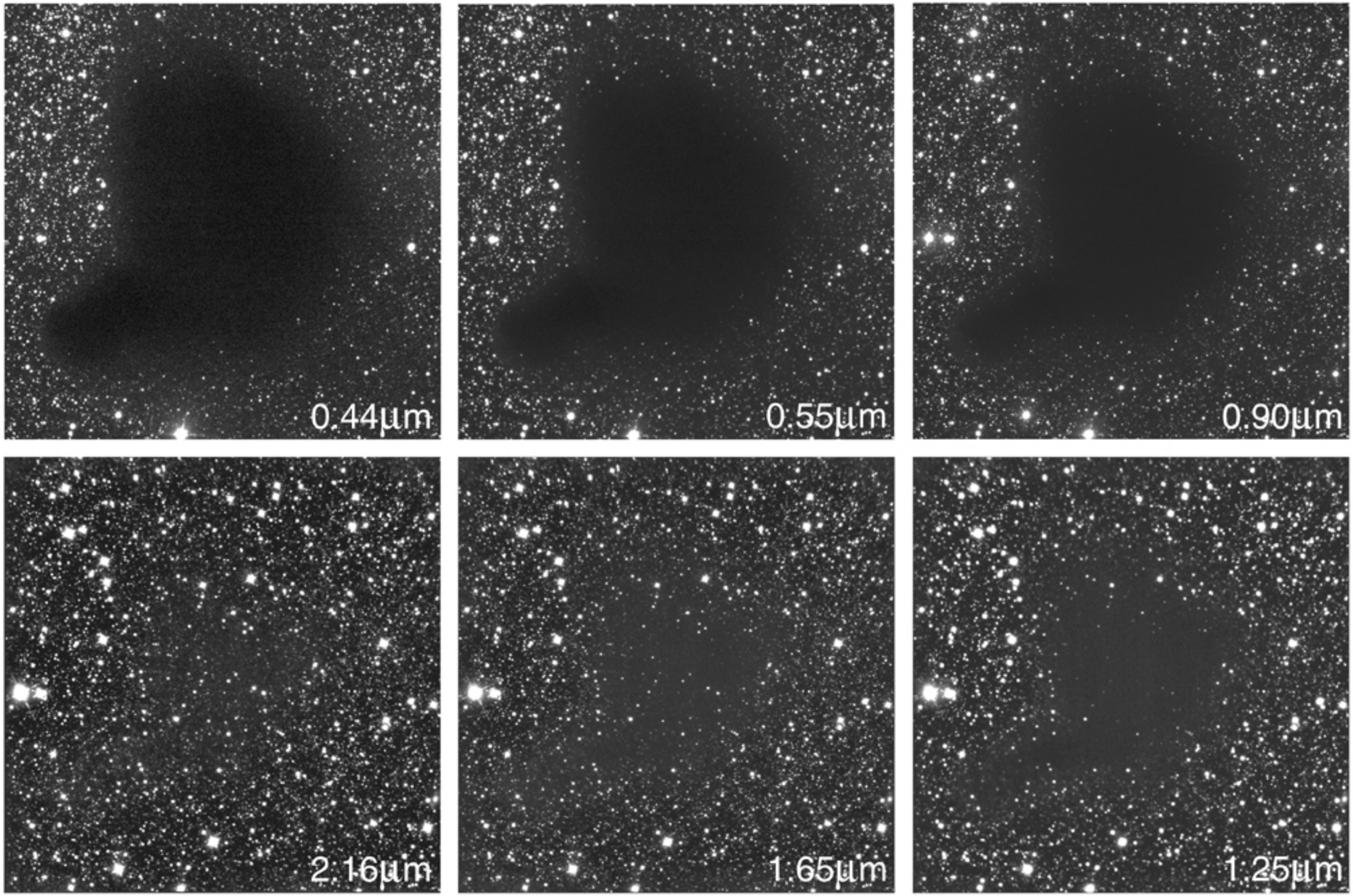
Hubble Space Telescope mosaic of the Orion Nebula and giant molecular cloud

Dark molecular clouds



dark cloud Barnard 68, from European Southern Observatory
http://www.eso.org/gallery/v/ESOPIA/Stars/phot-02a-01.tif.html

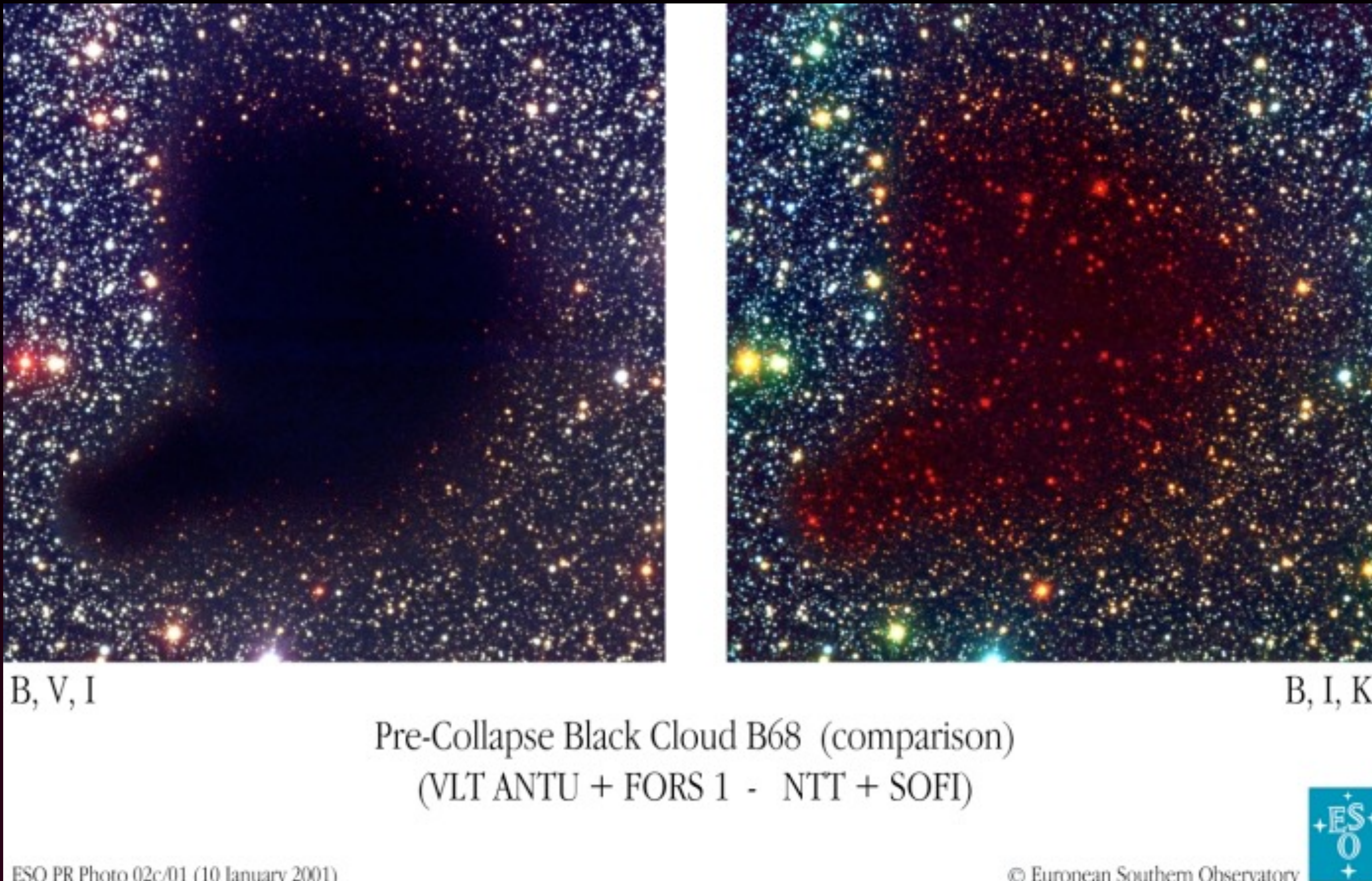
Dark molecular clouds



The Dark Cloud B68 at Different Wavelengths (NTT + SOFI)

ESO PR Photo 29b/99 (2 July 1999)

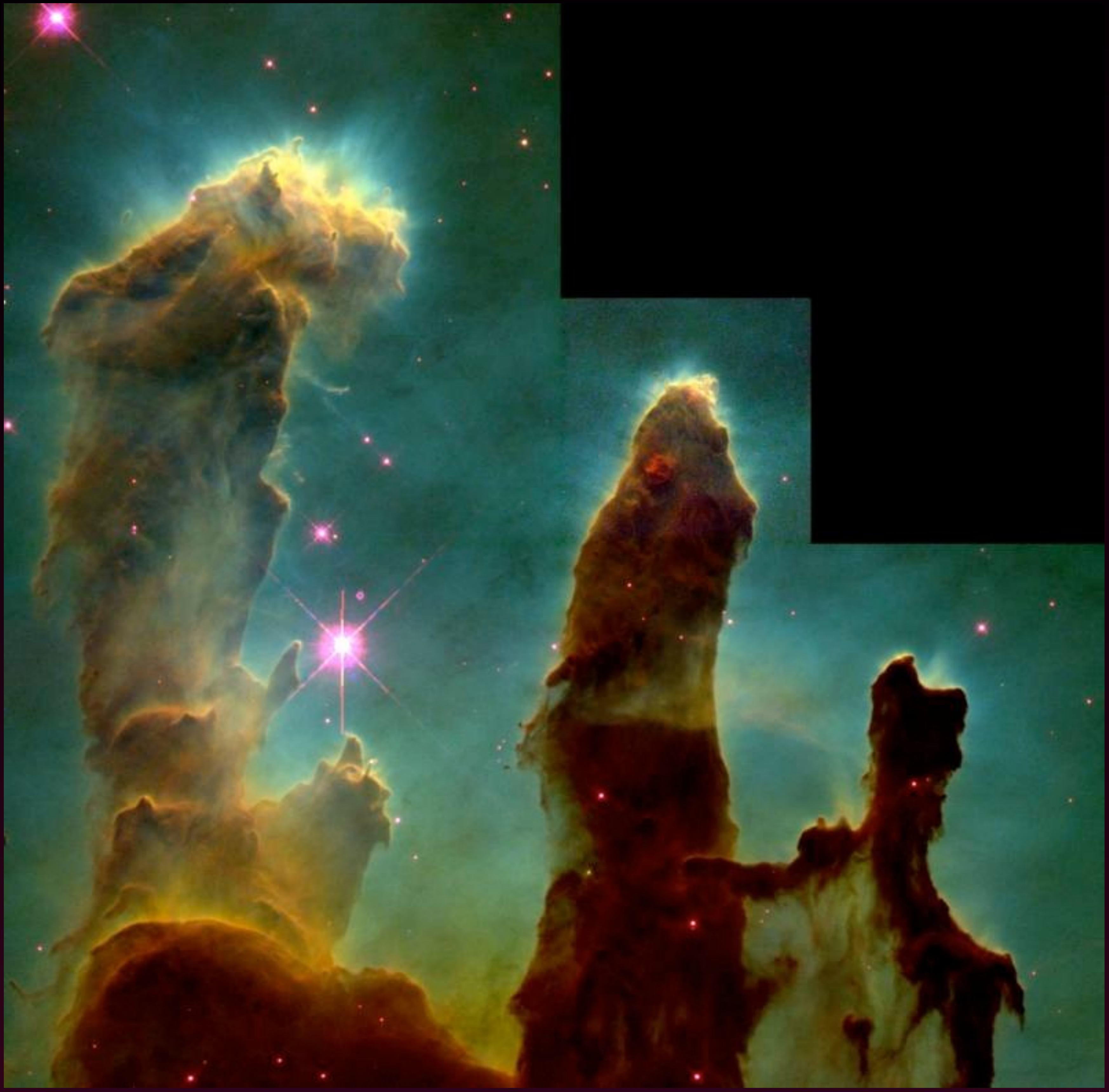
Dark molecular clouds: dust blocks the light



Eagle Nebula

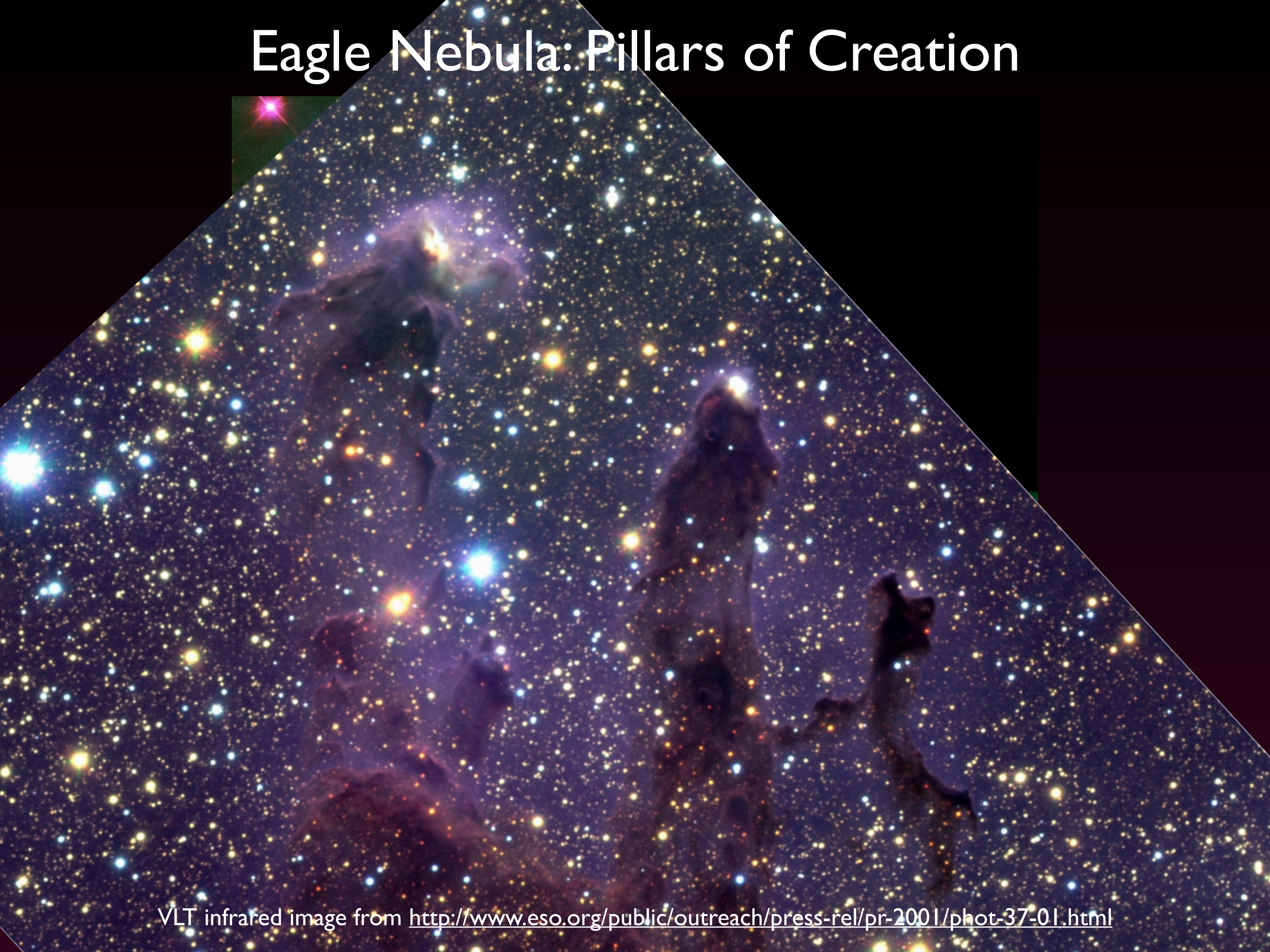
from KPNO and http://hubblesite.org/gallery/album/entire/pr2005012b/

Eagle Nebula: Pillars of Creation



HST optical image from http://hubblesite.org/gallery/album/pr1995044a

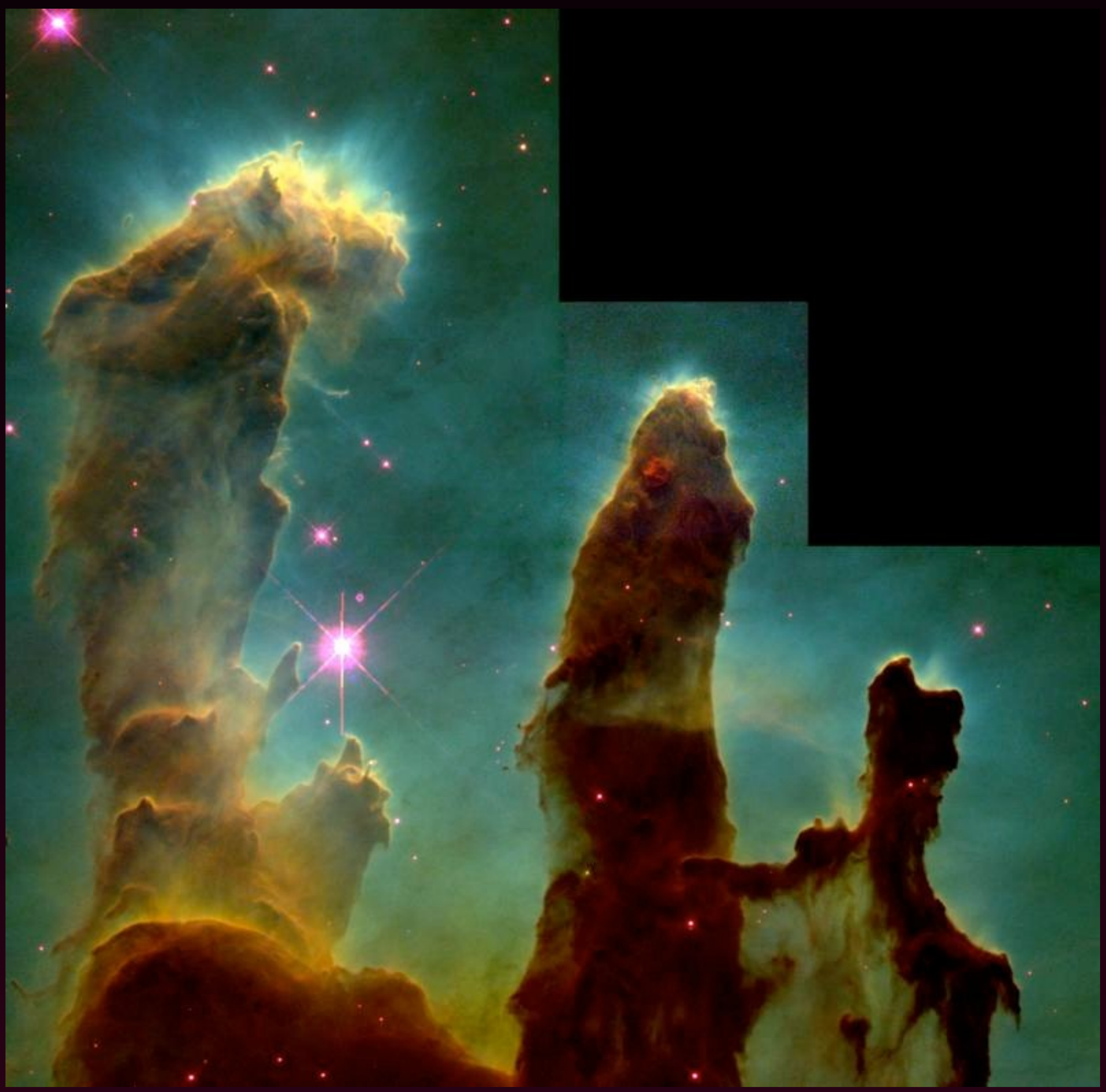
Eagle Nebula: Pillars of Creation



VLT infrared image from http://www.eso.org/public/outreach/press-rel/pr-2001/phot-37-01.html

Eagle Nebula: Pillars of Creation

optical

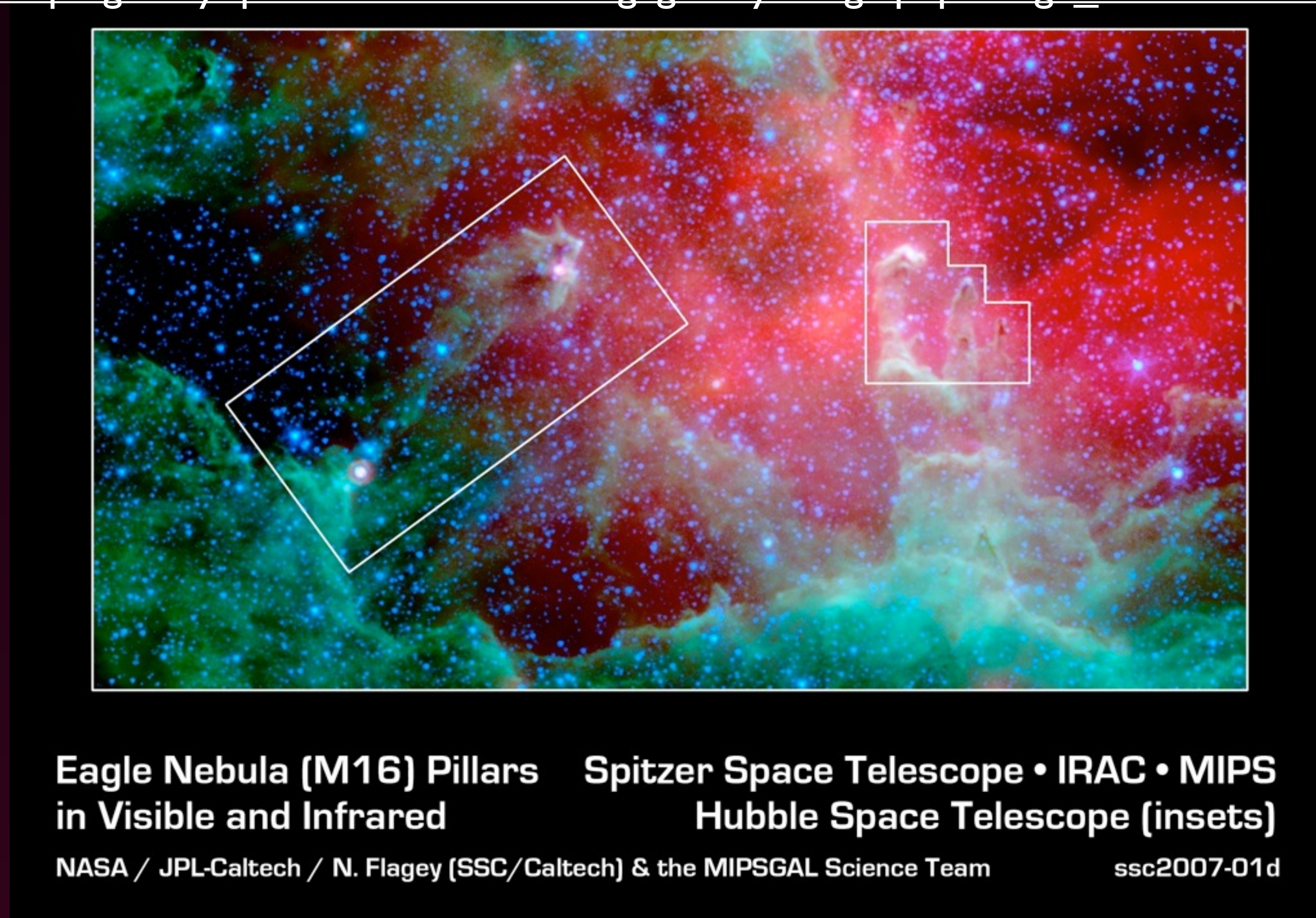


near-infrared

from http://hubblesite.org/gallery/album/pr1995044a
and http://www.eso.org/public/outreach/press-rel/pr-2001/phot-37-01.html

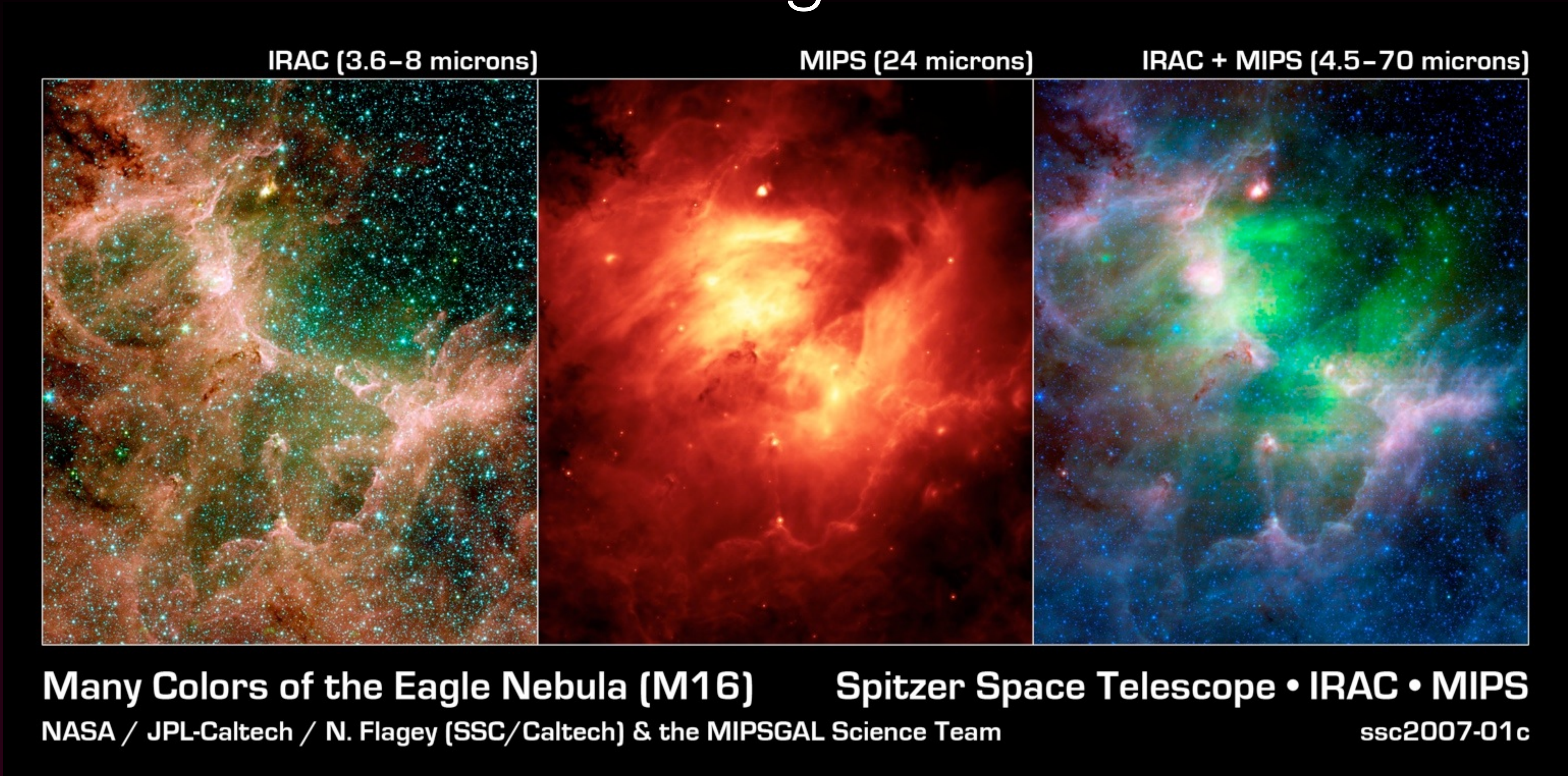
Eagle Nebula, farther into the infrared

from http://gallery.spitzer.caltech.edu/Imagegallery/image.php?image_name=ssc2007-01d



Eagle Nebula, farther into the infrared

JWST will be a huge advance here!

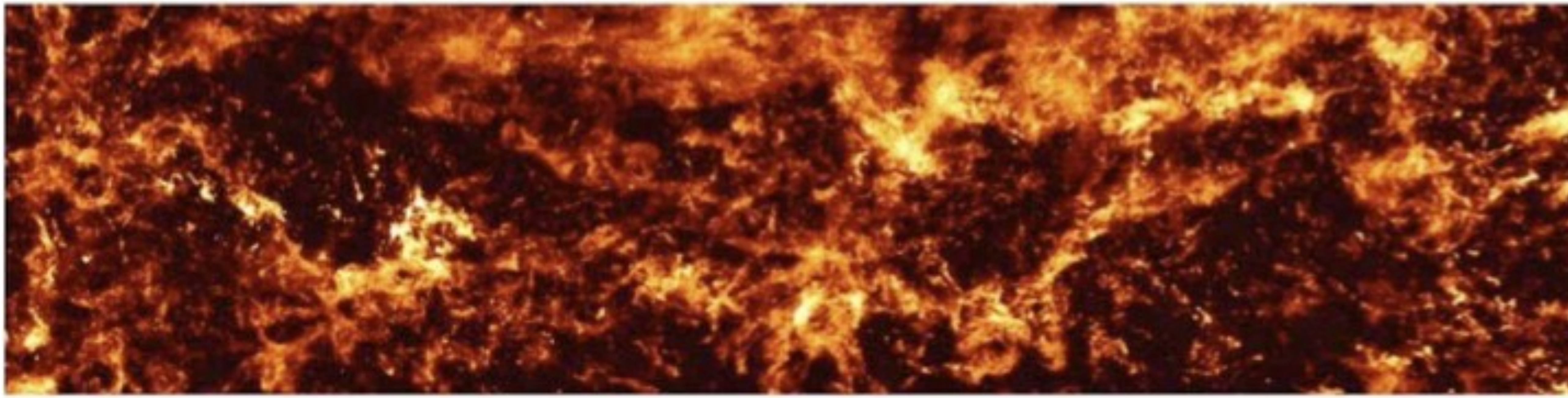


from http://gallery.spitzer.caltech.edu/Imagegallery/image.php?image_name=ssc2007-01c

the Orion star-forming region

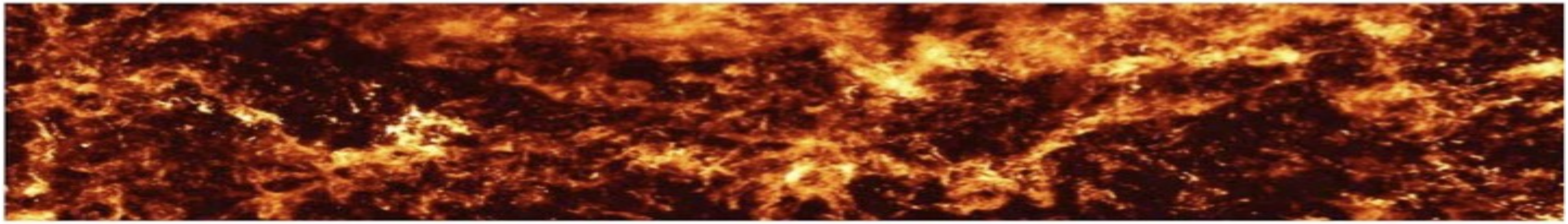
protoplanetary disks “proplyds” in the Orion Nebula from the Hubble Space Telescope

Molecular Clouds



- Most of the matter in star-forming clouds is in the form of molecules (H_2, CO, etc.).
- These *molecular clouds* have a temperature of 10–30 K and a density of about 300 molecules per cubic centimeter.

Why do stars form in molecular clouds?



- Most of the matter in star-forming clouds is in the form of molecules (H_2, CO, etc.).
- These *molecular clouds* have a temperature of 10–30 K and a density of about 300 molecules per cubic centimeter (which is a high density for the interstellar medium)

STARS FORM IF GRAVITY CAN OVERCOME PRESSURE:

HIGH DENSITY, LOW TEMPERATURE ENVIRONMENTS

Star Formation

Properties of the ISM

The interstellar medium consists of gas in different phases:

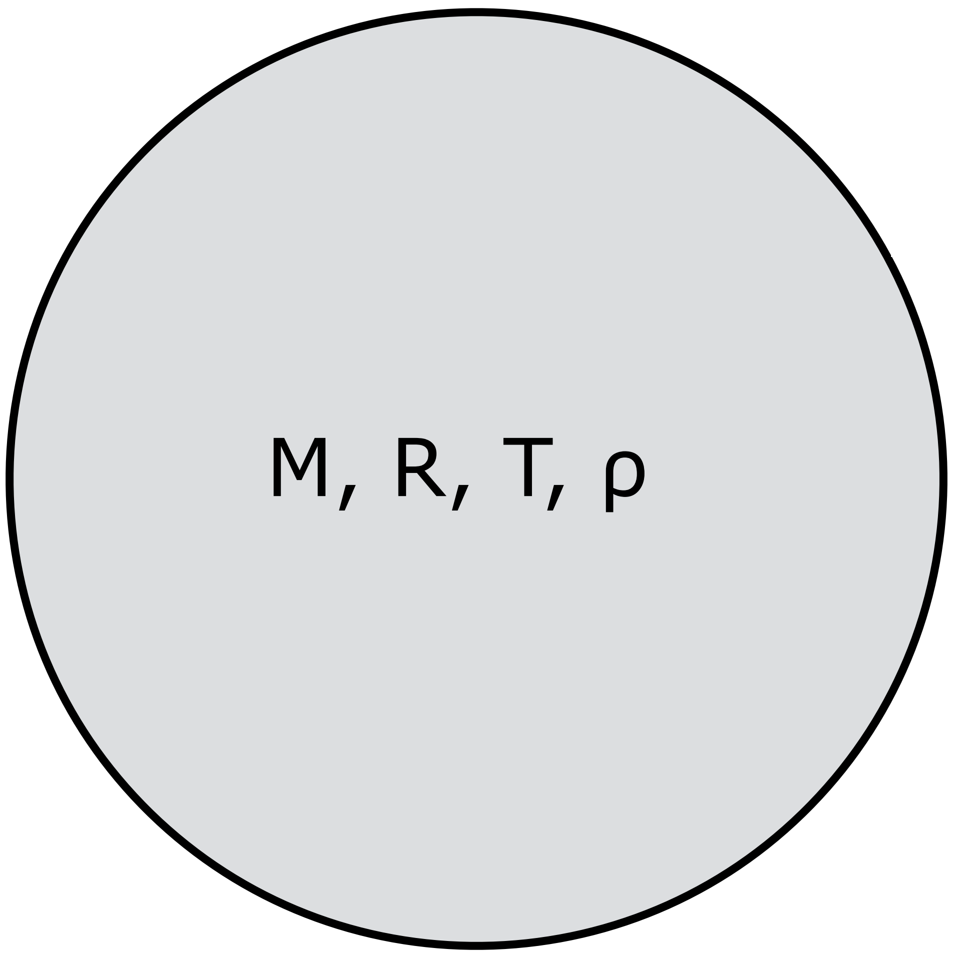
Component	T(K)	n (cm^{-3})	nT (K/cm^3)
Molecular clouds	$10 – 20$	10^3 - 10^4	$10^4 – 10^5$
Cold neutral gas	$50 – 100$	20 - 50	$10^3 – 10^4$
Warm neutral gas	$10^3 – 10^4$	0.2 - 0.5	10^3
Warm ionized gas	10^4	0.1 - 1	$10^3 – 10^4$
Hot gas	10^6 - 10^7	10^{-2} - 10^{-4}	$10^3 – 10^4$

The different components are (generally) in pressure equilibrium with their surroundings.

Star Formation

Jeans mass

Consider a spherical homogenous cloud:



$$E_{kin} = -\frac{1}{2}E_{pot}$$ with:

$$E_{kin} = (3/2)\ kT\ (M / \mu\, m_H)$$

$$E_{pot} = -\int_0^M \frac{Gm_r}{r}\, d\,m_r = -\frac{3}{5}\frac{GM^2}{R}$$

(assuming $r = (m_r/M)^{1/3}$ for constant ρ)

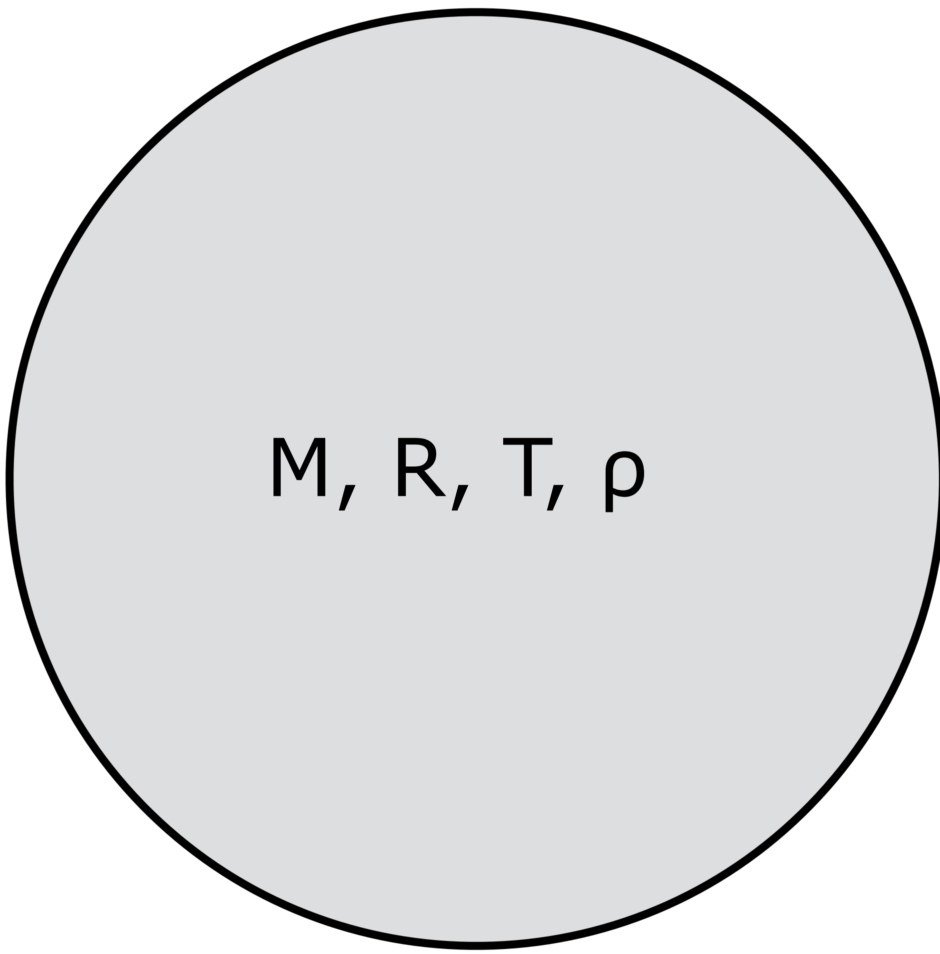
What condition do we need to meet for collapse?

$E_{kin} < -\frac{1}{2}E_{pot}$ so $\boxed{M > M_J \equiv \frac{5kT}{\mu m_H} \cdot \frac{R}{G}}$ **Jeans mass**

Star Formation

Jeans mass

Consider a spherical homogenous cloud:



$$\boxed{M > M_J \equiv \frac{5kT}{\mu m_H} \cdot \frac{R}{G}}$$ **Jeans mass**

By substituting: $R = \left(\frac{3}{4\pi\mu m_H}\right)^{1/3} \left(\frac{M}{n}\right)^{1/3}$

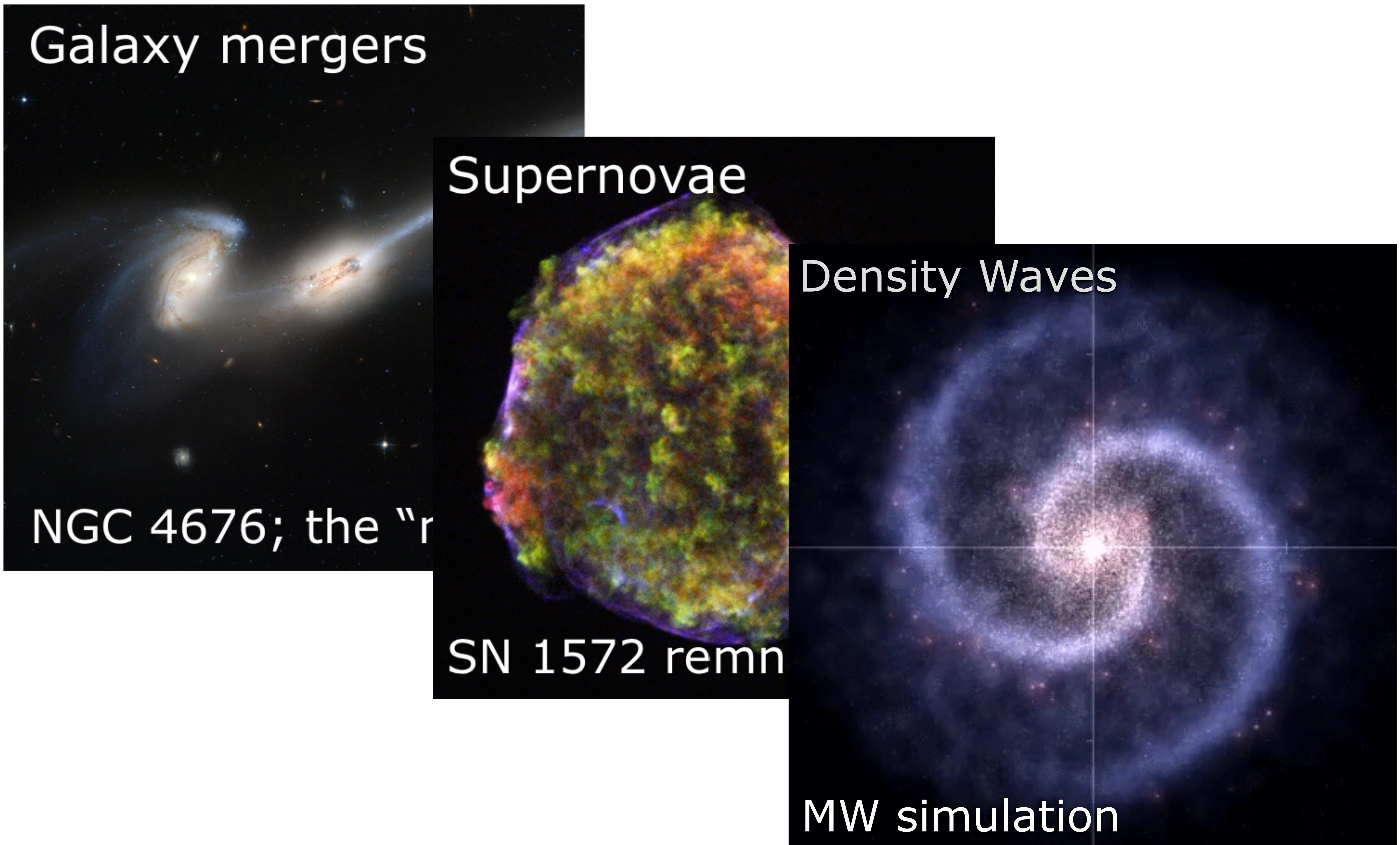
we get $M_J = \left(\frac{3}{4\pi}\right)^{1/2} \left(\frac{5k}{G\, m_H^{4/3}}\right)^{3/2} \left(\frac{T^3}{\mu^4 n}\right)^{1/2}$

so $\boxed{M_J \approx 100 \left(\frac{T^3}{\mu^4 n}\right)^{1/2} M_\odot}$

What might cause our cloud to exceed M_J?

Star Formation

Collapse of a molecular cloud



Star Formation

Other sources of pressure support can inhibit collapse:

turbulence
magnetic fields
cosmic rays

stellar feedback: winds + SN

Star Formation

Collapse of a molecular cloud

1. trigger kicks off process, cloud collapses when $M > M_J$

$$t_{ff} \approx (G\rho)^{-\frac{1}{2}} \approx 1.10^{8}(\mu n)^{-\frac{1}{2}} \quad yr$$

2. initial collapse is isothermal; cloud cools during collapse

Cooling by molecules: kinetic energy of molecules leads to temporary excitation, then de-excitation through emission of IR and sub-mm photons that escape the cloud

Cooling by dust: dust grains heat up through collisions and photon interactions and then emit as blackbodies with T<1000K, releasing IR photons that escape the cloud.

both of these are more efficient with more “metals”

Star Formation

Collapse of a molecular cloud

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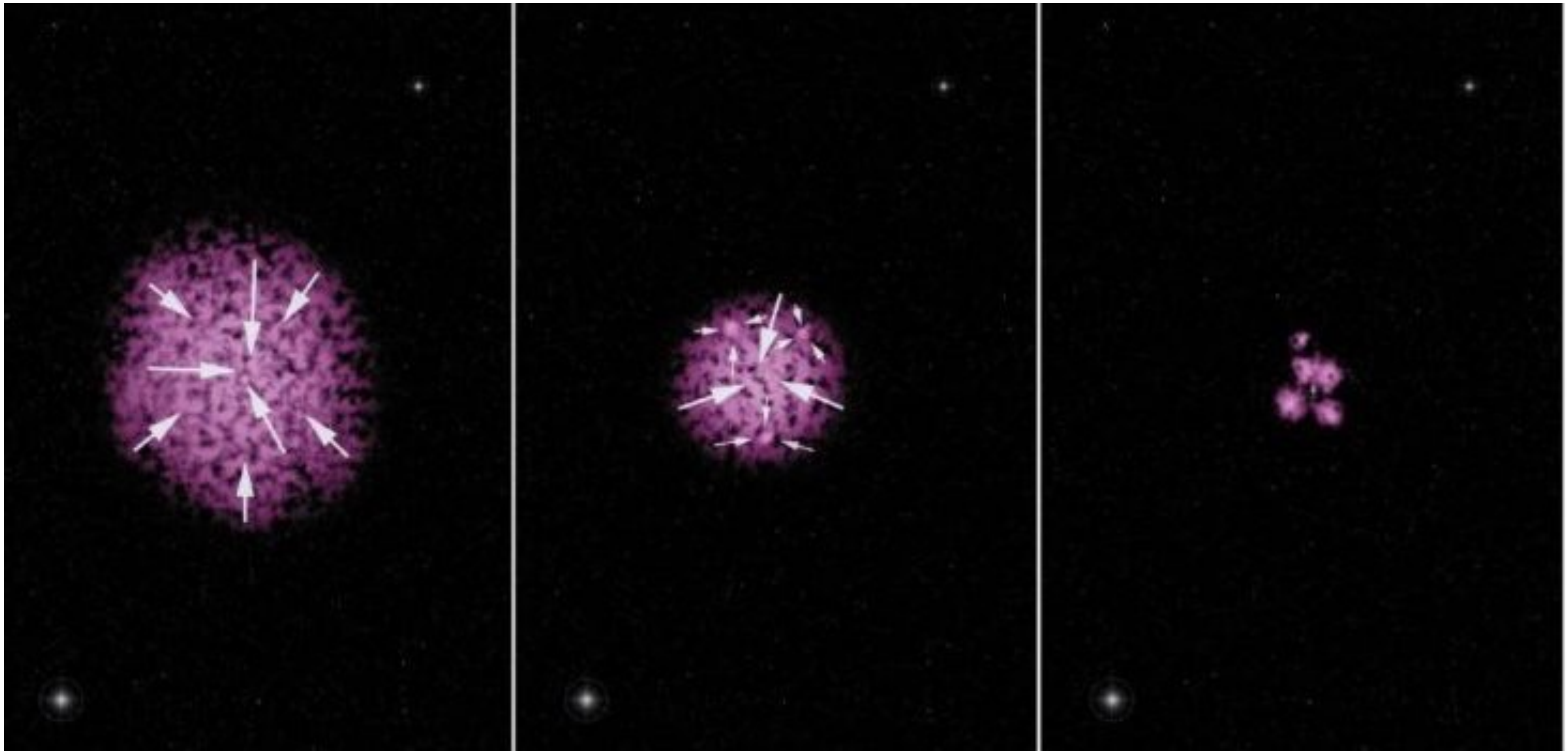

Star Formation

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3. clumps become opaque to IR; cooling switches off, collapse becomes adiabatic.

Star Formation

Collapse of a molecular cloud

3. clumps become opaque to IR; cooling switches off, collapse becomes adiabatic.

— the adiabatic collapse and rise in T raises M_J to the mass of the clump

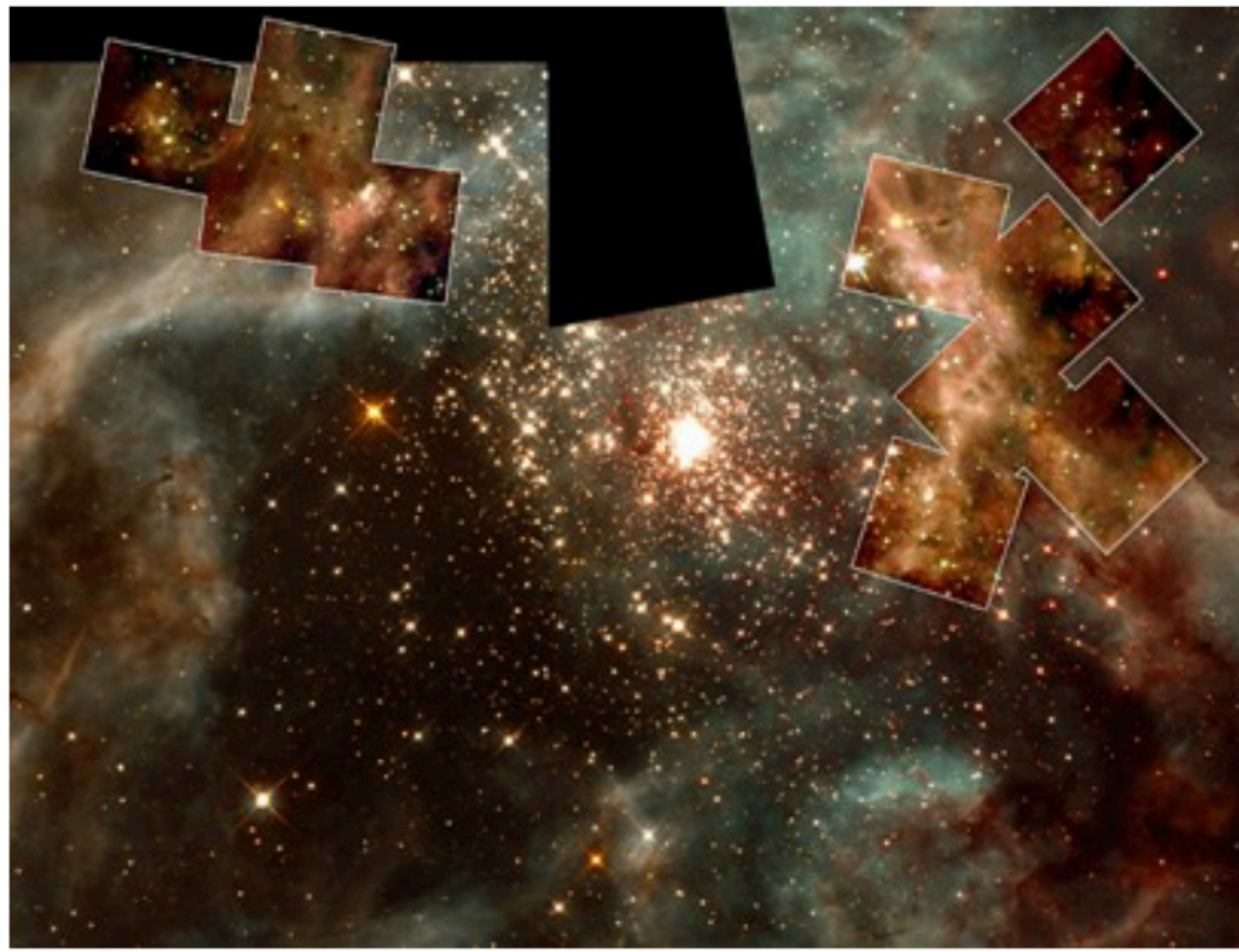
— starting at the center, the clump can now go back to hydrostatic equilibrium, ending the free-fall phase

— **we've made a proto-star!**

Star Formation: Fragmentation

- Clouds don't collapse to form one giant star. Stars tend to form in groups or clusters

$$M_J = \left(\frac{5kT}{G\mu m_H}\right)^{3/2}\left(\frac{3}{4\pi\rho}\right)^{1/2}$$



- As isothermal collapse progresses, the increase in density means the Jeans mass must decrease.
- Thus if the cloud has some density inhomogeneities, smaller clumps within the cloud may collapse later on.

from A. Davidson, https://slideplayer.com/slide/8767725/

Star Formation

Collapse of a molecular cloud

3. clumps become optically thick to IR; cooling switches off, collapse becomes adiabatic.

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4. proto-star contraction is still accelerated by cooling through dissociating H_2 and (later) ionizing H and He

Star Formation

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$$E_{dis} = \frac{M}{m_H}\left\{\frac{X}{2}x_{H2} + Xx_H\right\} = 1.3{\cdot}10^{58}\left(\frac{M}{M_\odot}\right)\ eV \approx 2\cdot10^{46}\frac{M}{M_\odot}\ \mathrm{ergs}$$

x_{H2} = 4.5 eV

x_H = **13.6 eV**

Star Formation

Collapse of a molecular cloud

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5. proto-star is eventually considered ionized and reaches hydrostatic equilibrium…

$$R/R_\odot \approx 100\ M/M_\odot$$

Star Formation

Collapse of a molecular cloud

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Now that it's back in H.E. we can estimate its mean internal temperature using the viral theorem:

$$\frac{3}{2}\frac{M}{\mu m_H}kT = \frac{A}{2}\frac{GM^2}{R} \ \rightarrow\ \bar{T} \approx \frac{A}{3}\frac{\mu m_H}{k}\cdot\frac{GM}{R}$$

Star Formation

Collapse of a molecular cloud

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Star Formation

Collapse of a molecular cloud

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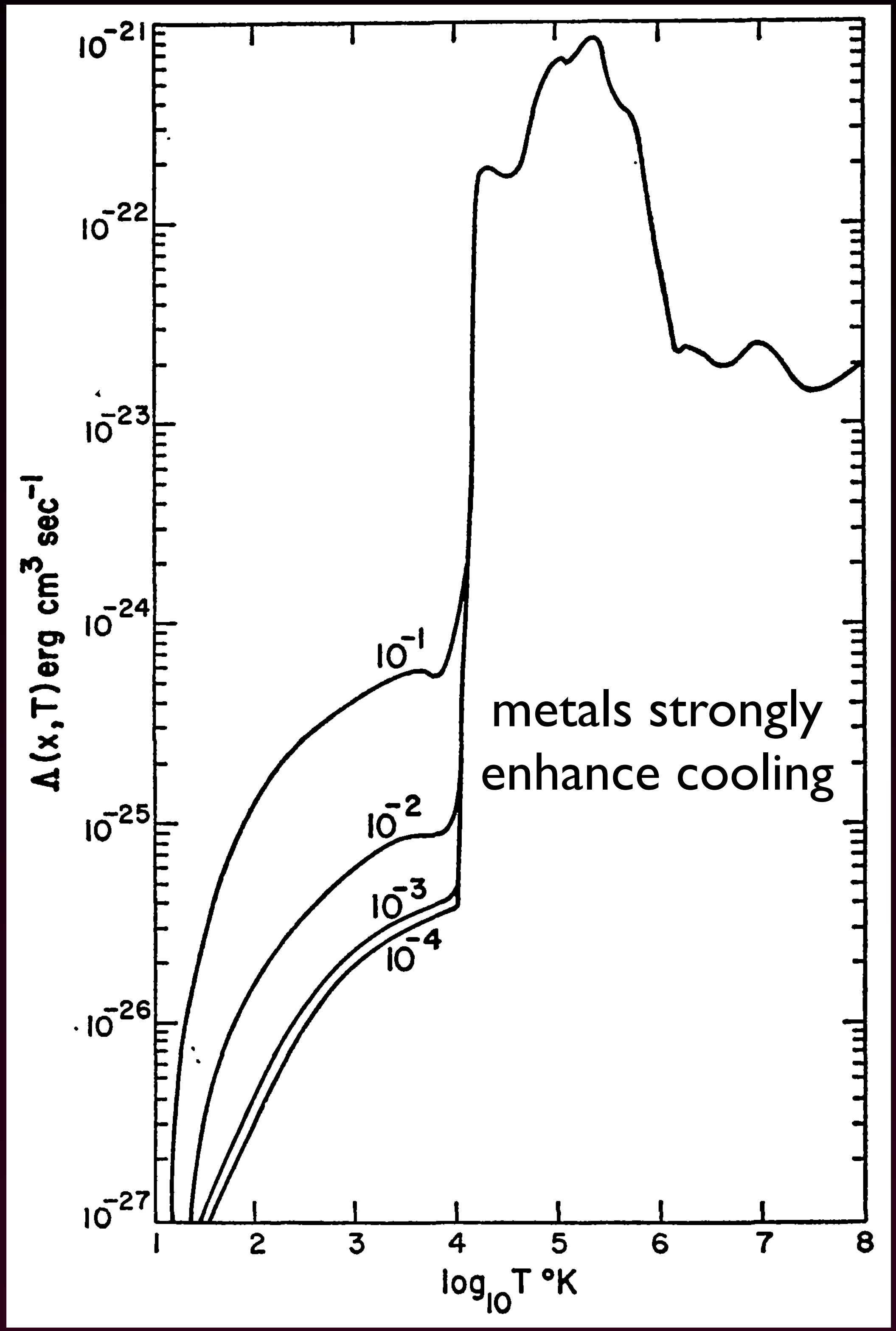
…proto-star is also fully convective.

Mean density is $\rho \sim 10^{-6}$ g cm^{-3}; at low T and ρ the opacity is very high and radiative energy transport is very inefficient with a high $|dT/dr|_{rad}$.

From the Schwarzschild criterion the star is convective!

cooling function



from Dalgarno & McCray 1972, ARAA, 10, 375

Star Formation

The early universe

We've demonstrated that cooling plays a crucial role in star formation, but in the early universe with low Z there was no dust and almost no molecules; only H_2 was available for cooling.

→ higher Jeans mass

→ more massive stars
"top-heavy" initial mass function
more supernovae
faster metal enrichment

For more, see Volker Bromm Richard B. Larson, 'The First Stars', Annual Review of Astronomy and Astrophysics 2004 42:1, 79-118

Star Formation

(timescales are for solar-mass objects)

Summary of star formation

Cloud collapse (t_{ff} ~ 10^5-10^7 yr)

Starts when cloud exceeds Jeans mass

Ends when H2 is dissociated and H is ionized

At the end, $\langle T \rangle \sim 10^5$ K, $R/R_\odot \sim 120 M/M_\odot$

today's lecture

Star Formation

(timescales are for solar-mass objects)

Summary of star formation

today's lecture

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Starts when cloud exceeds Jeans mass

Ends when H2 is dissociated and H is ionized

At the end, $\langle T \rangle \sim 10^5$ K, $R/R_\odot \sim 120 M/M_\odot$

next lecture, TUESDAY Apr 19:

Proto-star (t_{KH}~2×10^6 yr) (descending Hayashi track)

Starts when collapsing cloud is dissociated/ionized

Ends when core reaches radiative equilibrium

At the end, $\langle T \rangle \sim 10^6$ K, $R/R_\odot \sim 2.5 M/M_\odot$

Pre-MS (t_{KH}~7×10^6 yr) (T Tauri, Herbig Ae/Be)

Starts when proto-star core reaches radiative equilibrium

Ends when H-fusion starts (ZAMS)

no class on Friday Apr 15; PS #5 due Friday Apr 15, 11am