Chapter 7

Birth of stars

Birth of stars

7.1 Interstellar medium (ISM)

7.2 The Formation of Stars

7.1 Interstellar medium (ISM, 星際物質)

- ✓ ~ 75% hydrogen gas in various forms: neutral atomic hydrogen (H I), ionized hydrogen (H II), molecular hydrogen (H_2)
- ✓ ~ 24% helium
- ✓ a trace of "metal" (heavier elements such as C, O, Si)
- ✓ Dust grains of various sizes

7.1 Interstellar medium (ISM, 星際物質)

✓ *Interstellar extinction*: distant stars appear **dimmer** than they would if space were completely empty.

$(m-M)$: distance modulus

$$\boxed{\underbrace{m_\lambda - M_\lambda}_{(m-M)} = 5\log r - 5 + A_\lambda}$$

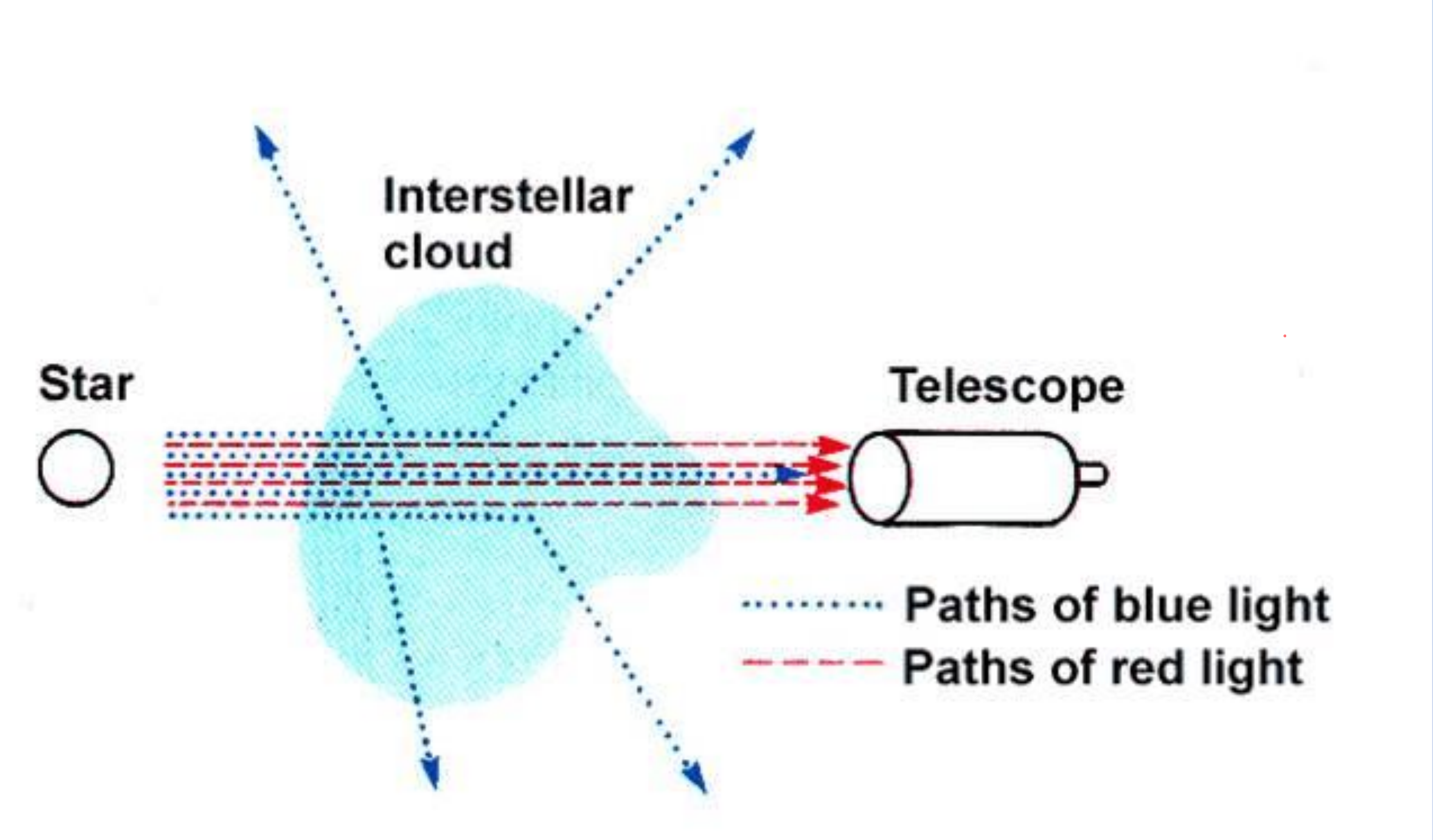
the effect is λ-dependent

distance (in pc)

extinction (a new term, +ve in sign)

On average, a star at 1000pc from Earth looks 2 magnitude dimmer than it should.

7.1 Interstellar medium (ISM, 星際物質)

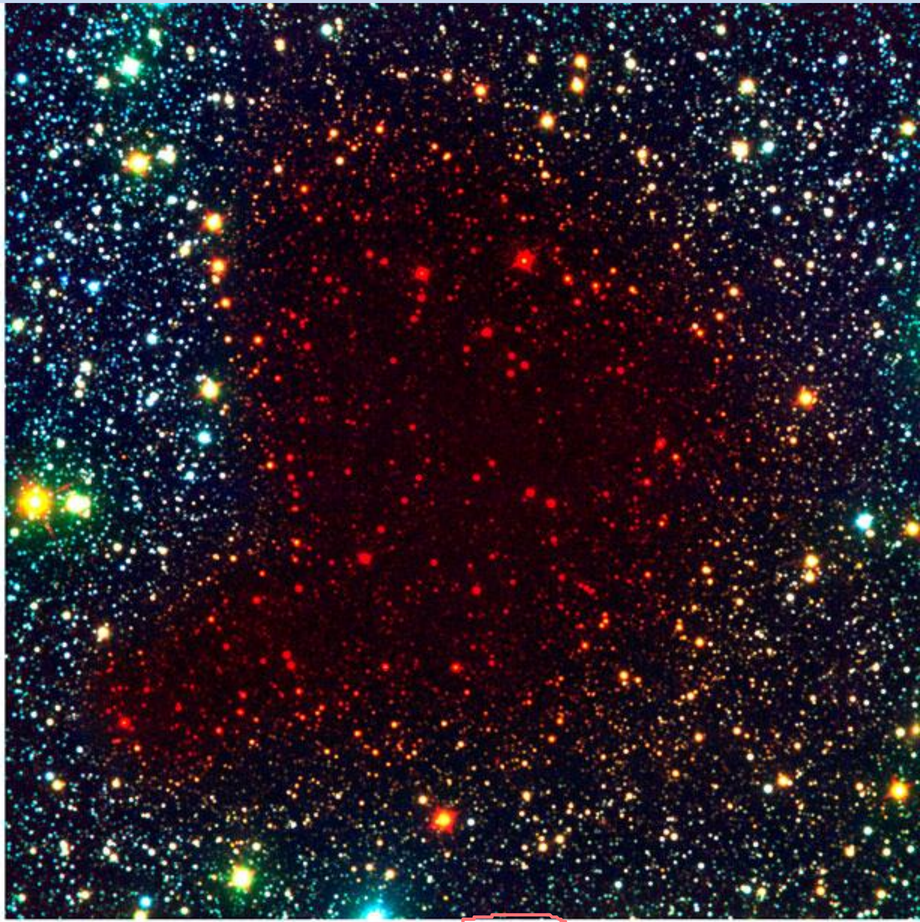


✓*Interstellar reddening*: interstellar media scatter more blue light than red light and stars become more reddish

the Barnard 68 cloud

Image: ESO

B, V, I visible



visible + IR B, I, K

7.1 Interstellar medium (ISM, 星際物質)

✓Average density of interstellar medium is very low, about a few particles per cm^3. (c.f., air we breathe ~ 10^{19} atoms per cm^3!)

✓*Nebula* (星雲): relatively high density clouds of gas and dust

Alnitak 參宿一
(獵戶座 ζ)

獵戶座 Orion

Orion Nebula 獵戶座大星雲 M42

Image: NASA, ESA


Alnitak (參宿一)


Horsehead Nebula 馬頭星雲
Image: CFHT/Coelum

7.1 Interstellar medium (ISM, 星際物質)

Emission nebula (發射星雲)

Image: NASA, ESA

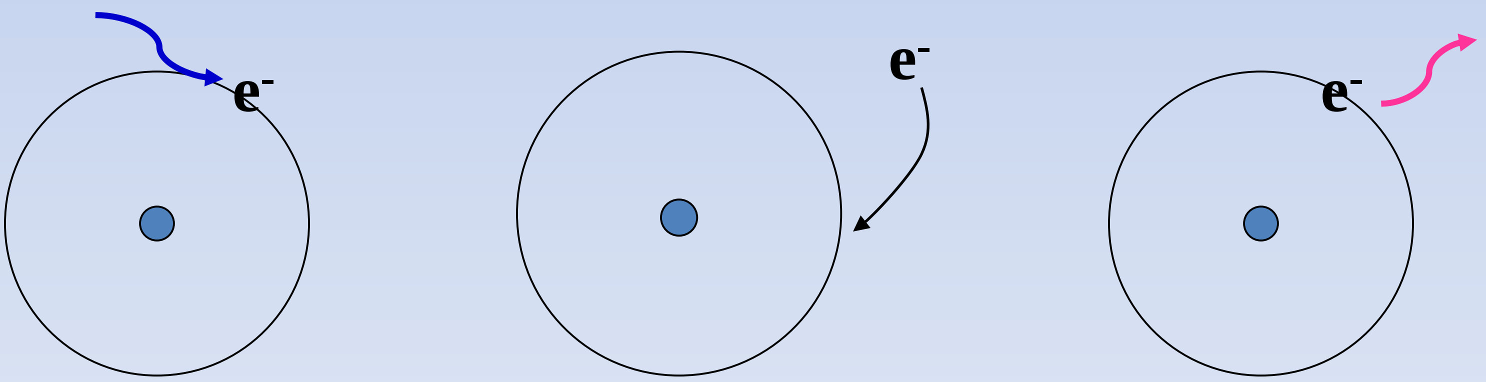
Orion Nebula (獵戶座大星雲), M42

450pc from us, mass ~ 300 $M_\odot$

7.1 Interstellar medium (ISM, 星際物質)

Emission nebula (發射星雲)

- ✓ Hydrogen gas is ionized by ultraviolet radiation from a nearby hot star.
- ✓ The ions emit light (mostly red in color) when the ionized gas recapture electrons, so appears *emission nebula* reddish.



ionized by UV

ultra violet

ionized gas recapture electrons, and light ($n=3 \rightarrow n=2$, reddish colour) emitted

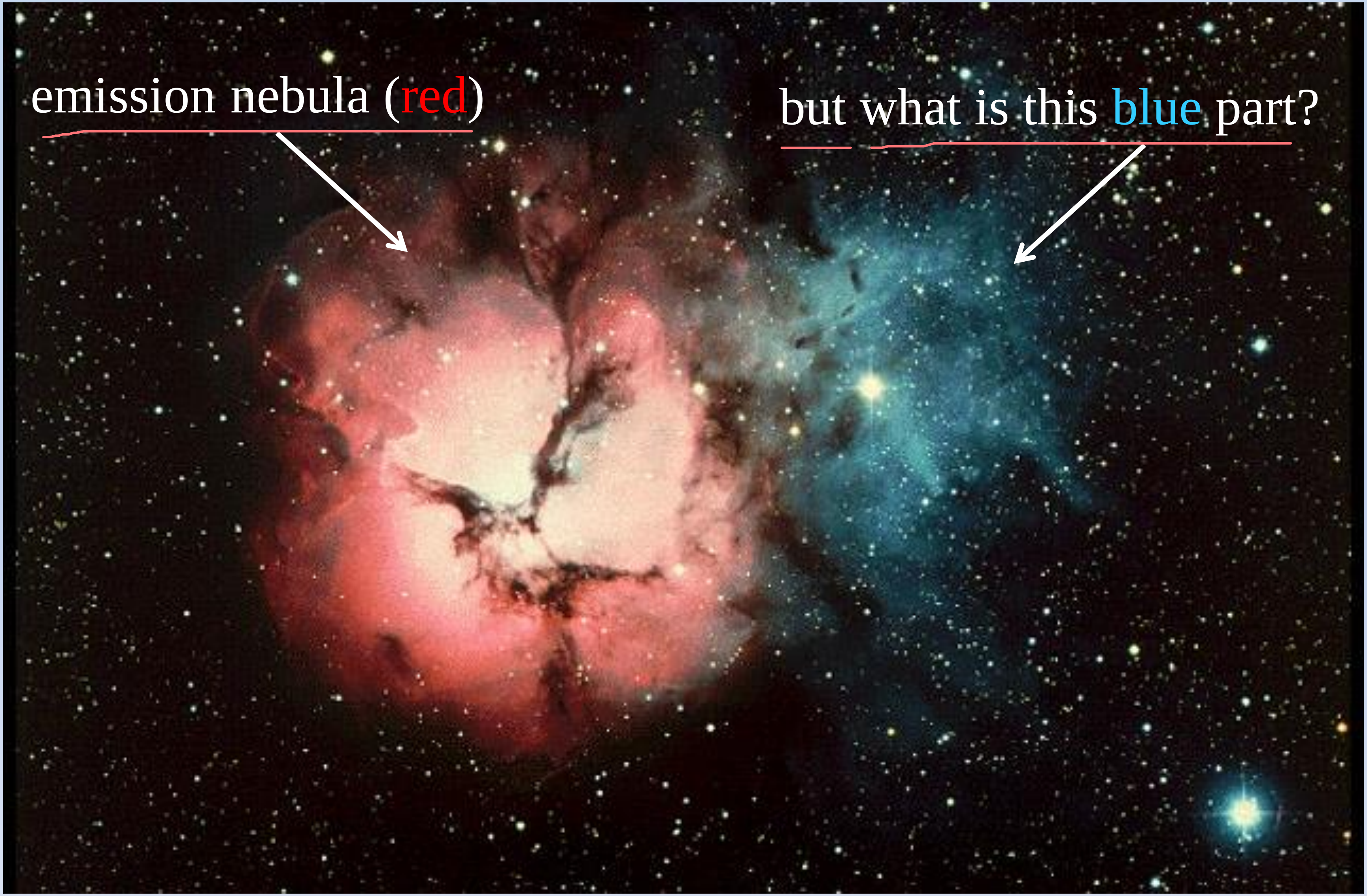
7.1 Interstellar medium (ISM, 星際物質)

Emission nebula (發射星雲)

- Temperature ~ 10,000 K;
- mass ~ 100 – 10,000 $M_\odot$; The nebula is spread over light-year across, so density only 100 – 1,000 atoms/cm^3 (c.f., air we breathe ~ 10^{19} atoms/cm^3 !)
- Note: H II for ionized hydrogen; H I for neutral hydrogen atoms. Hence emission nebula are also called H II regions.

Rosette Nebula (麒麟座玫瑰星雲)

close-up of Rosette Nebula (麒麟座玫瑰星雲) shows the bright and hot stars



The Trifid Nebula (人馬座三裂星雲) Sagittarius M20

7.1 Interstellar medium (ISM, 星際物質)

Reflection nebula (反射星雲)

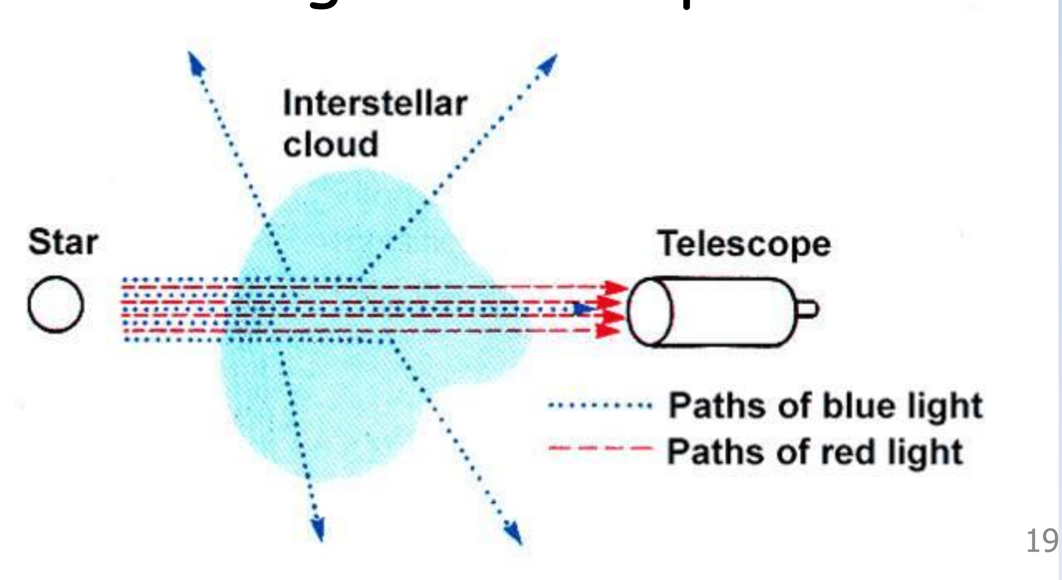
Taurus M45 (金牛座昴宿星團，七姊妹)

400 ly from us

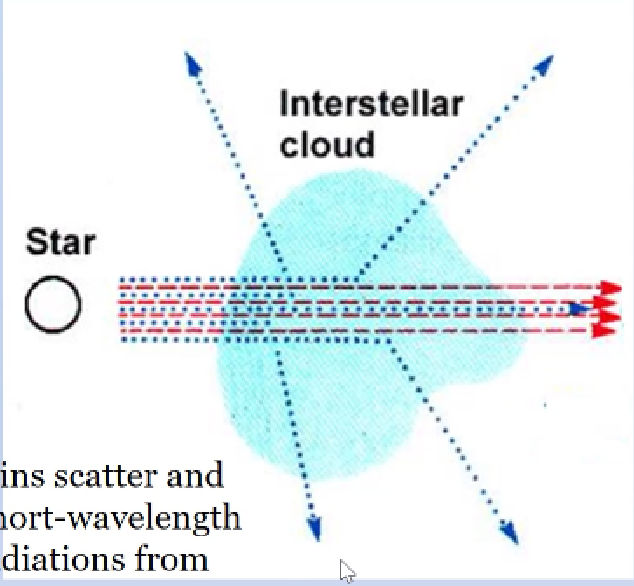
7.1 Interstellar medium (ISM, 星際物質)

Reflection nebula (反射星雲)

- ✓ Dust grains scatter and reflect short-wavelength (blue) radiation from other stars
- ✓ long-wavelength (red) radiation get through the dust without much scattering and absorption
- ✓ thus reflection nebula normally is relatively blue

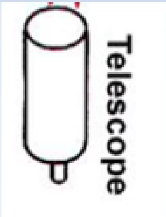


NGC 6726 in the Southern Crown (南冕座)



Long-wavelength (red) radiations get through the dust without much scattering and absorption

Dust grains scatter and reflect short-wavelength (blue) radiations from the stars



Thus, reflection nebula is always bluish.

7.1 Interstellar medium (ISM, 星際物質)

Dark nebula (黑暗星雲)

"holes in the heavens"

"a drop of ink on the luminous sky"

Barnard 86 in Sagittarius (人馬座)

Image: ESO

7.1 Interstellar medium (ISM, 星際物質)

Dark nebula (黑暗星雲)

- ✓ Dense region of dust grains that shields radiations from stars. Thus it is dark.
- ✓ temperature < 100 K
- ✓ H_2 inside the cloud exists without dissociation

But how can the H_2 be detected?

- ✓ Visible band is useful for observing emission and reflection nebulae, interstellar extinction and reddening, but not H_2! So, …

7.1 Interstellar medium (ISM, 星際物質)

Dark nebula (黑暗星雲)

- ✓ H_2 inside the cloud exists without dissociation

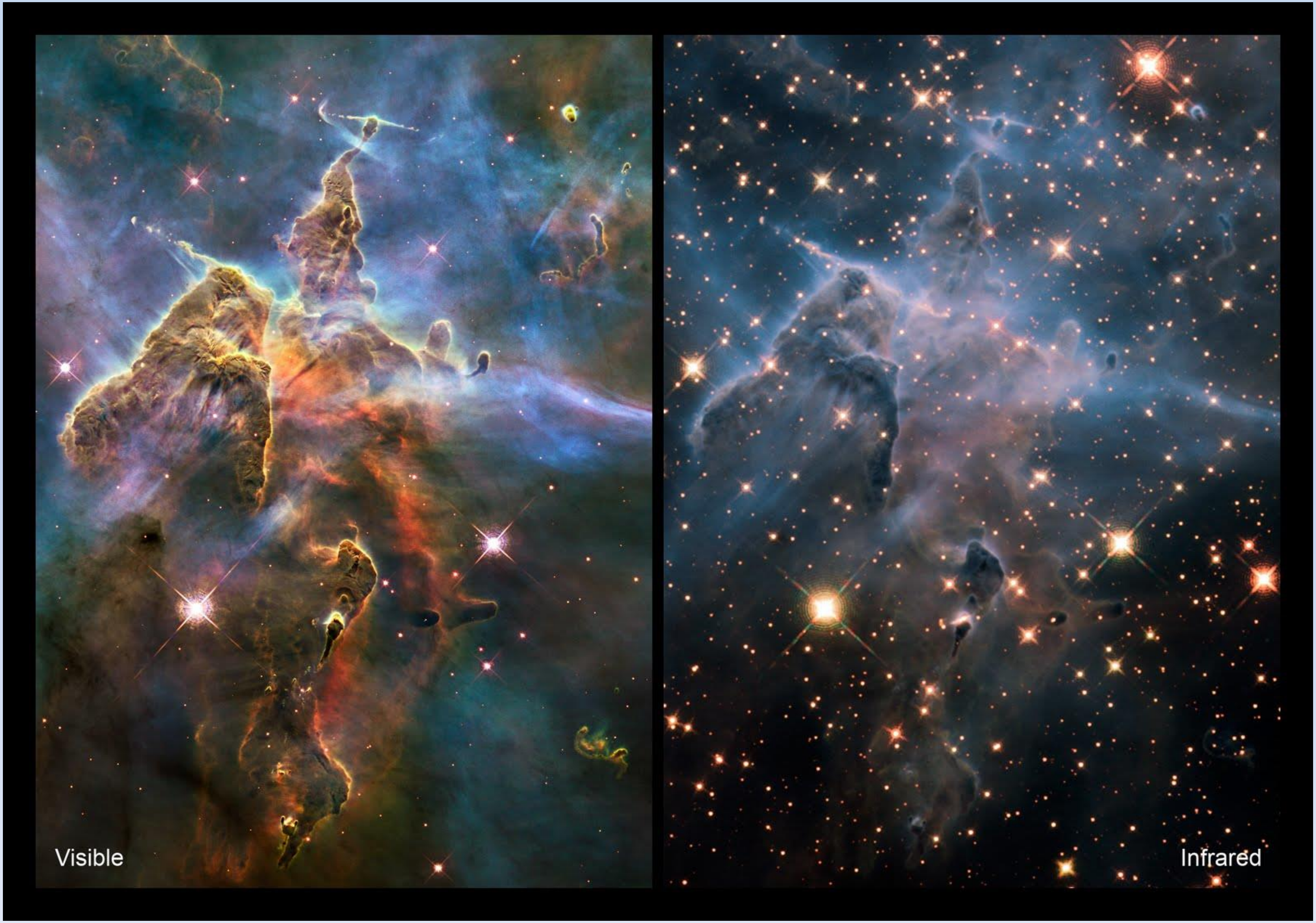
But how can the H_2 be detected?

- ✓ Visible-wavelength can observe emission, reflection nebulae, interstellar extinction and reddening, but not H_2!
- ✓ Radio waves can do..

- ✓ radio wave, IR, mm, sub-mm, …: nearly 100 types of atoms and molecules have been observed in these longer wavelength, e.g., H (21 cm), CO(2.6mm), C_2, CN, etc

star-forming region in the Carina Nebula

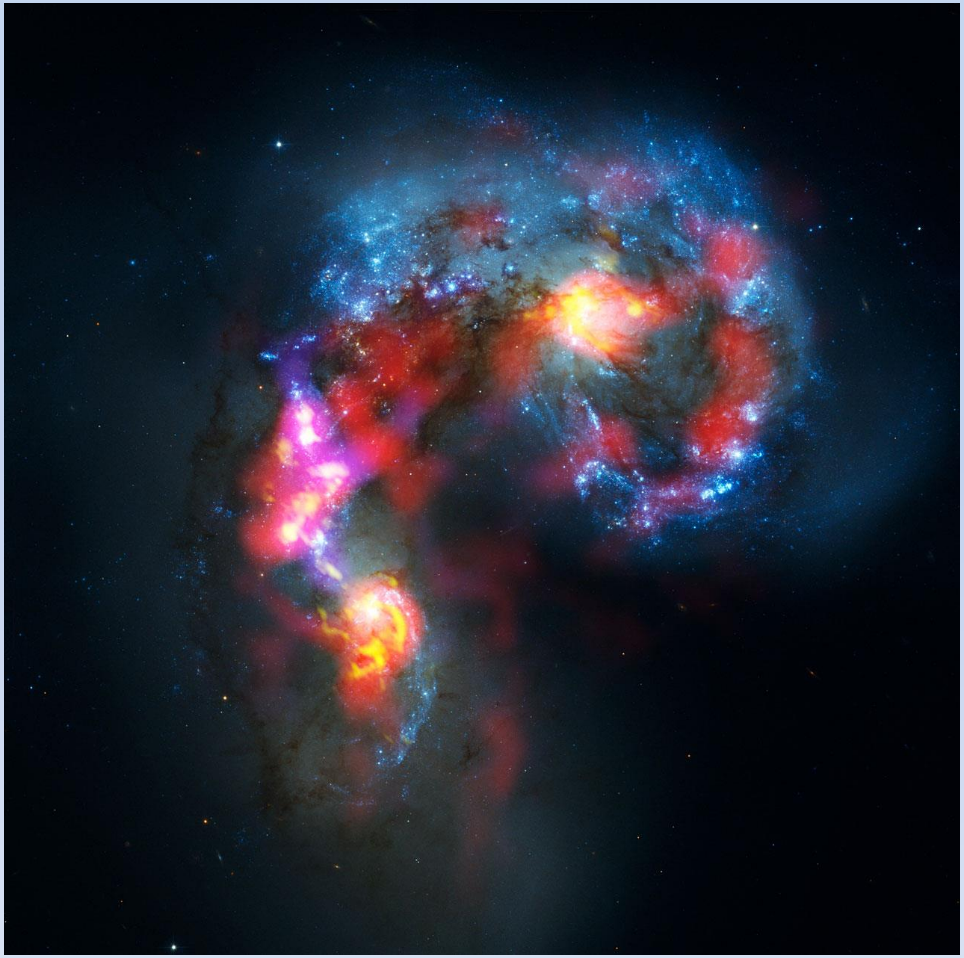
Image: NASA, ESA



Antennae Galaxies (觸鬚星系)

Hubble (optical)

Image: NASA, ESA



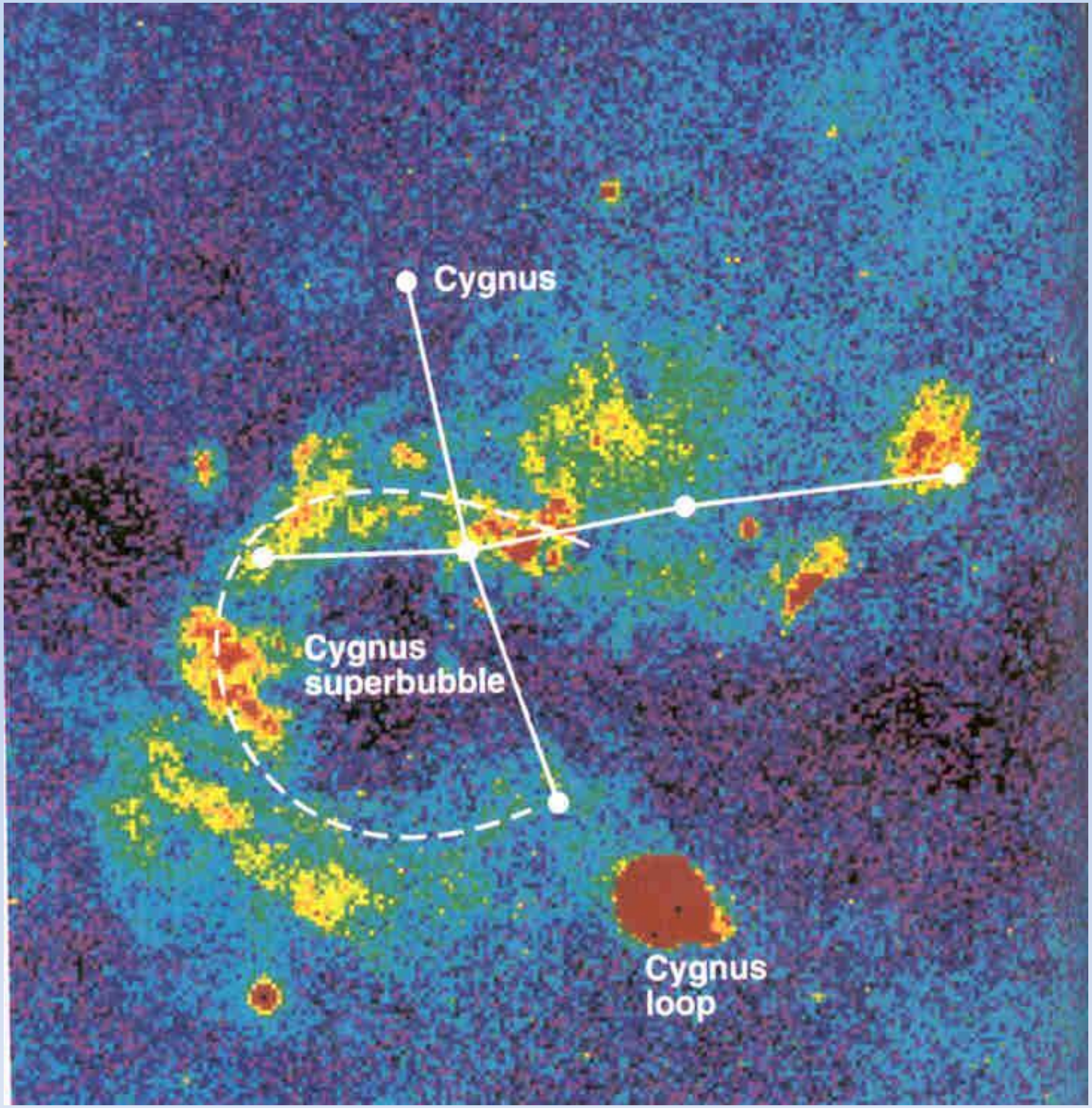
ALMA (mm & sub-mm) + Hubble (optical)

Image: ALMA, NASA, ESA

7.1 Interstellar medium (ISM, 星際物質)

Other EM wave observation

- ✓ X-ray observations: detects highly ionized coronal gas of very low density (10^{-3} particles/cm^3) and high temperature (10^5 K)
- ✓ originates in supernova explosions

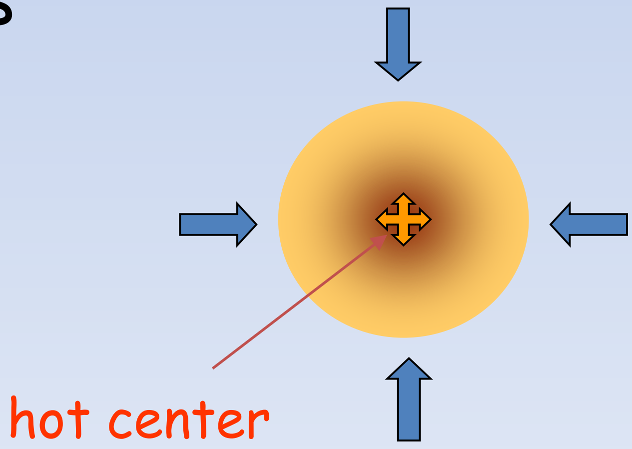


X-ray emission (yellow) of Cygnus (天鵝座)

7.1 Interstellar medium (ISM, 星際物質)

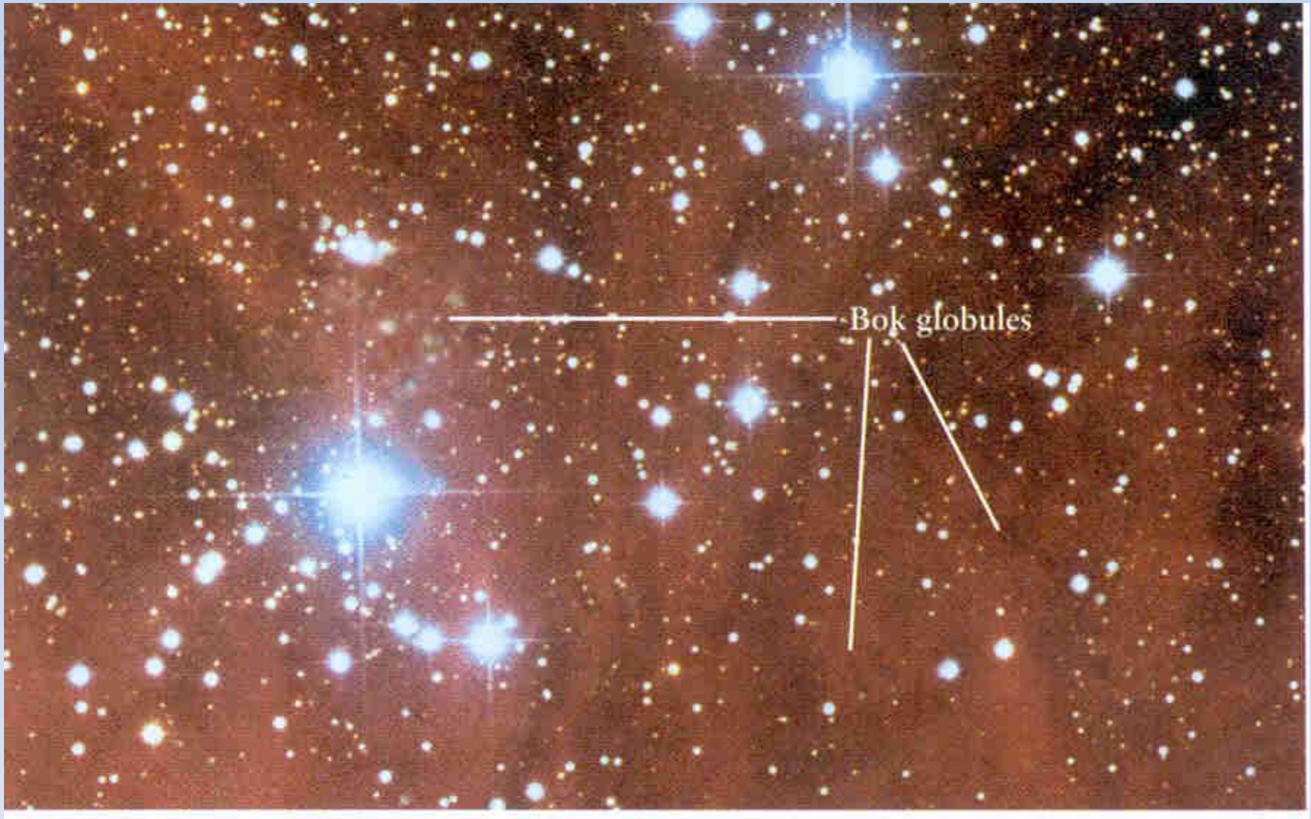
Bok globules (博克球狀體)

- ✓ small (<1 pc); massive (10-100 $M_\odot$) dark clouds of even higher density (10^4 to 10^9 particles/cm^3)
- ✓ Resembles the inner core of a dark nebula with the outer, less dense portions stripped away
  - ◆ Many contain infrared sources at the center; hence, may contain warm centers as it should be if contracting
  - ◆ possible star formation sites

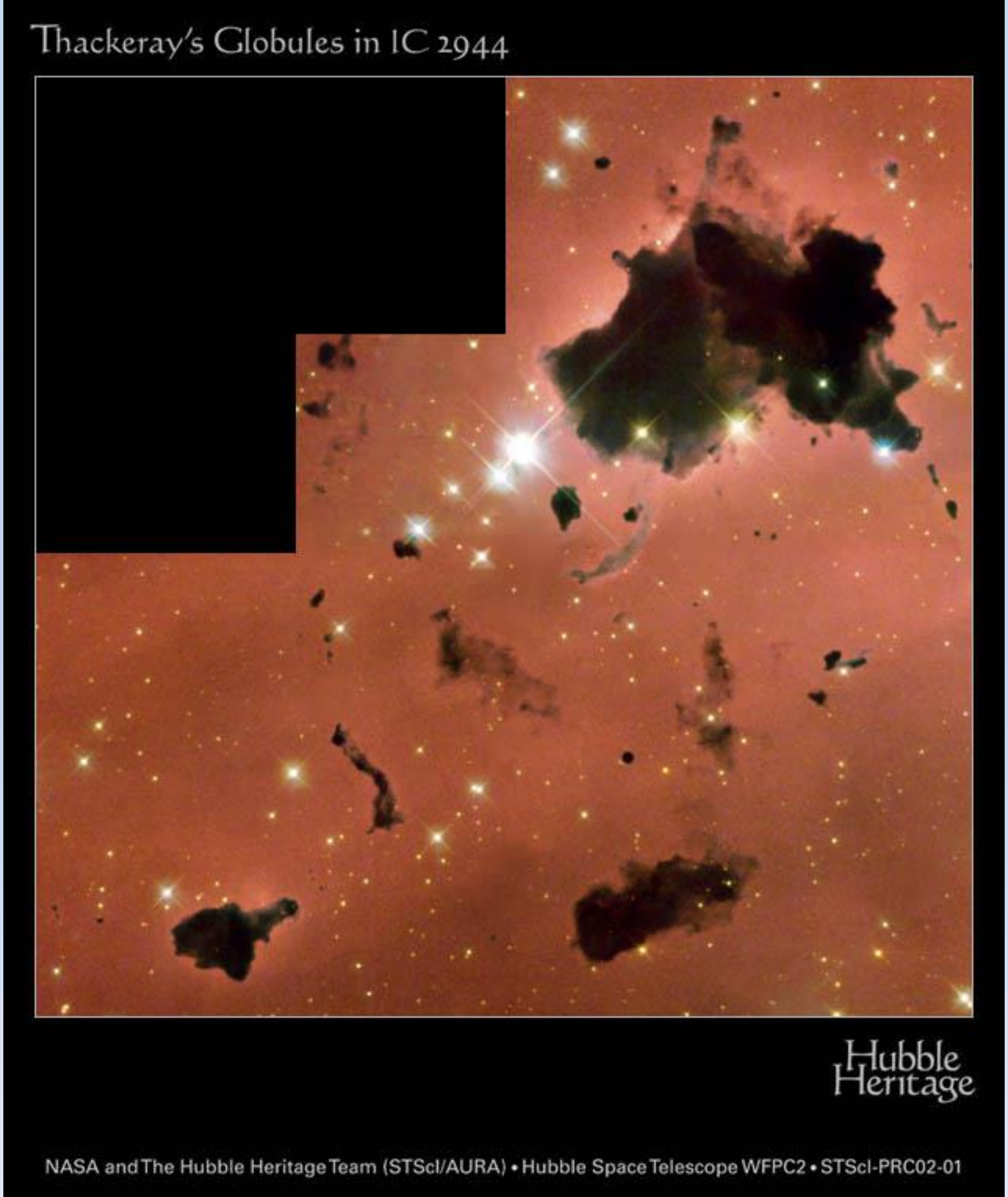


7.1 Interstellar medium (ISM, 星際物質)

Bok globules (博克球狀體)

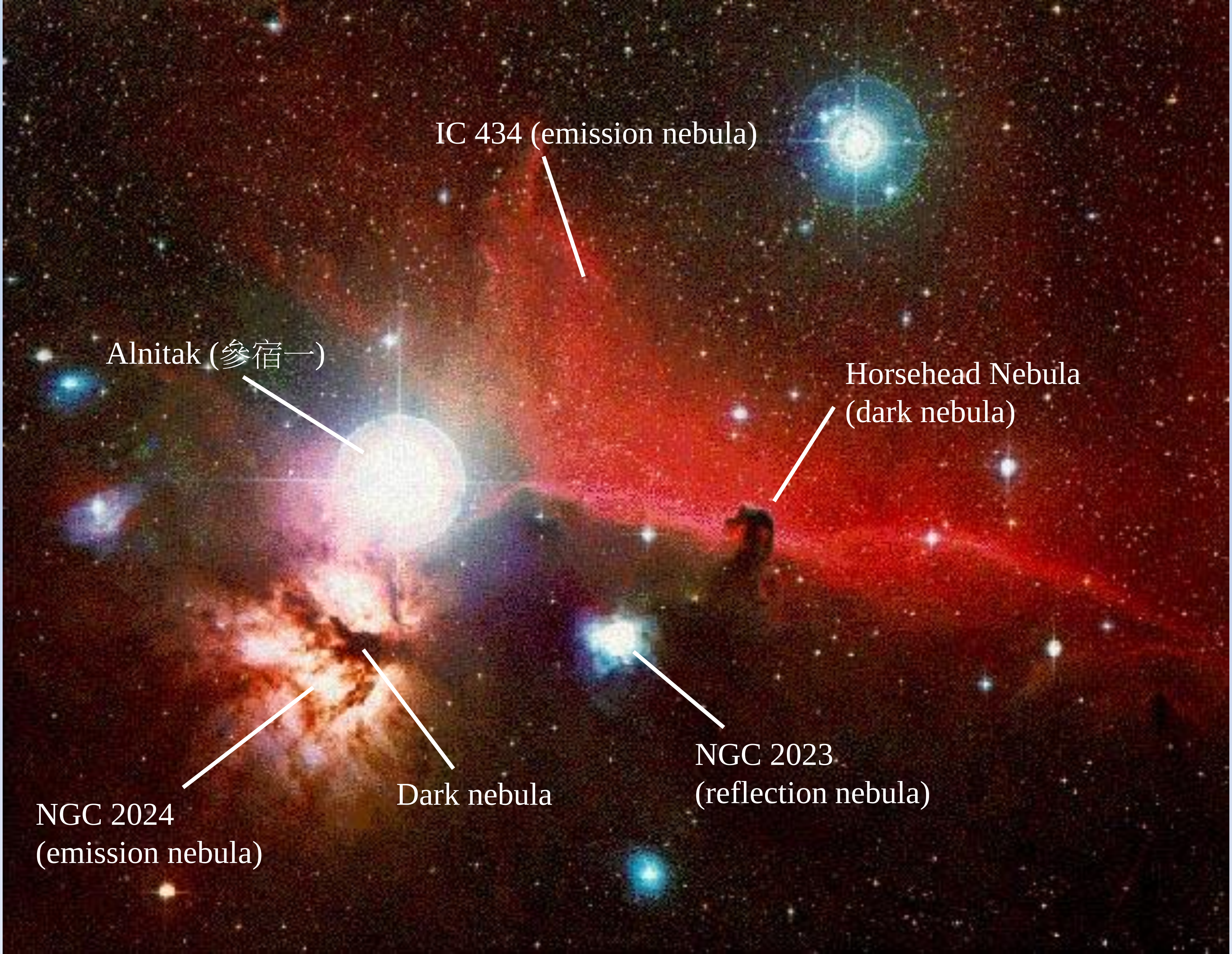


Foreground stars part of a cluster called IC 2944 in Centaurus (半人馬座)


Thackeray's Globules in IC 2944
Hubble Heritage
NASA and The Hubble Heritage Team (STScI/AURA) • Hubble Space Telescope WFPC2 • STScI-PRC02-01

Different types of nebulae exist near to each other

Image: CFHT/Coelum

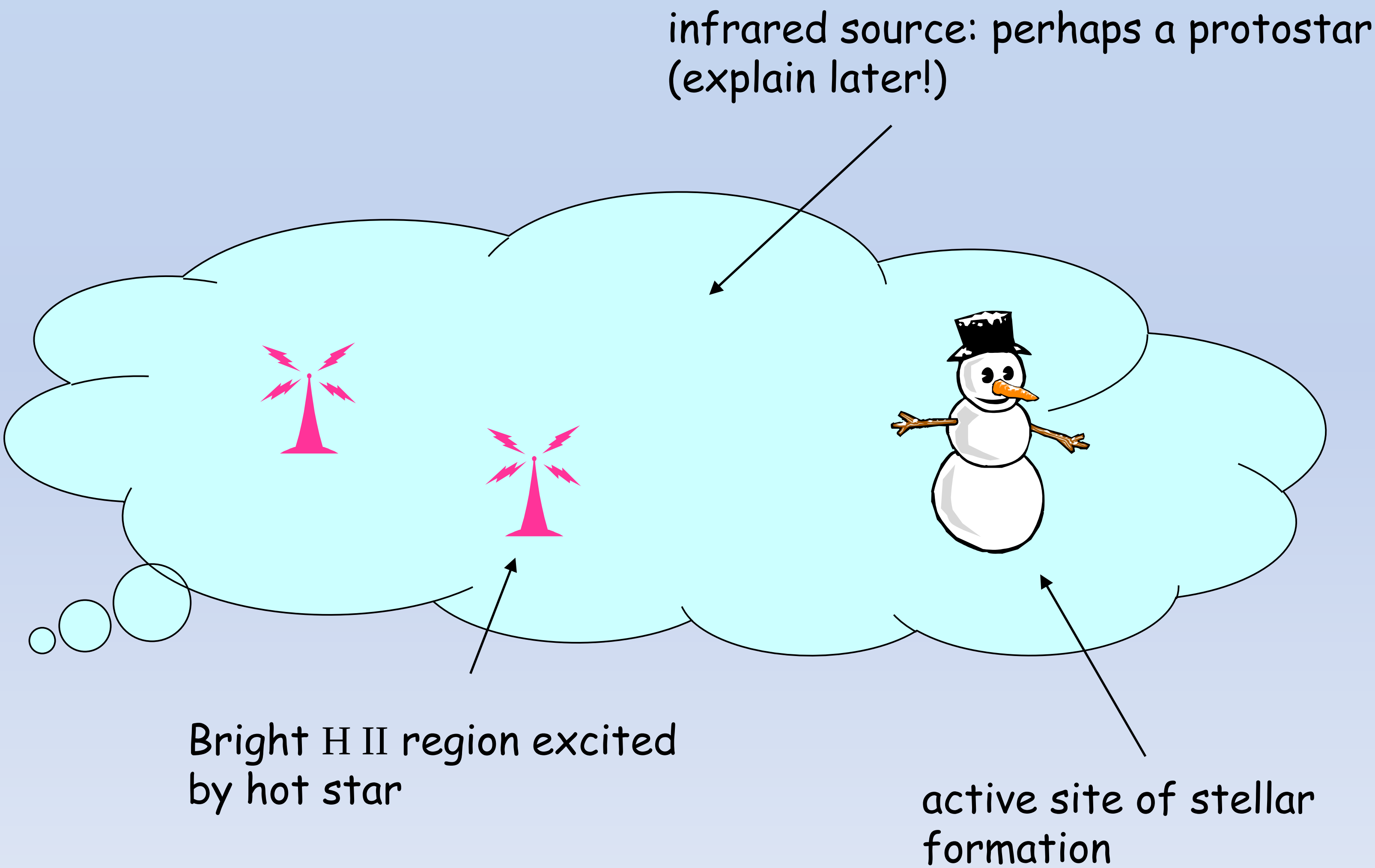

IC 434 (emission nebula)
Alnitak (參宿一)
Horsehead Nebula
(dark nebula)
NGC 2023
(reflection nebula)
Dark nebula
NGC 2024
(emission nebula)

7.1 Interstellar medium (ISM, 星際物質)

Giant molecular cloud (巨型分子雲)

- ✓ typically span over 15 - 100 pc, containing up to a million solar masses
- ✓ bright H II regions excited by hot stars
- ✓ Low-temperature (~15 K) and high-density (~10^6 - 10^8 particles cm^{-3}) regions
- ✓ infrared sources detected
- ✓ those cool regions may be sites of active star formation

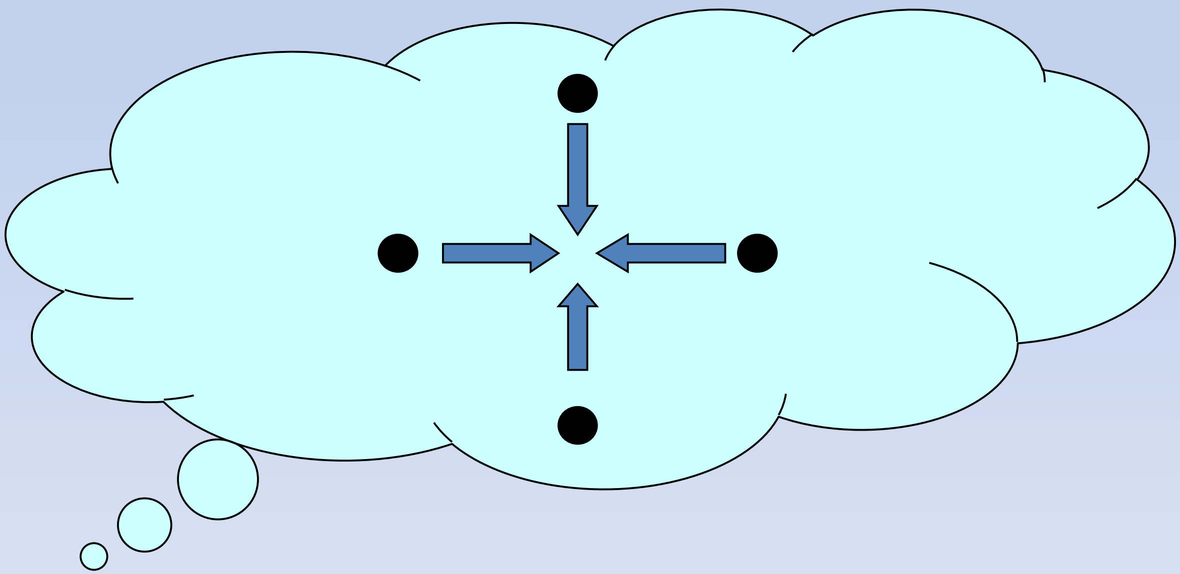
7.1 Interstellar medium (ISM, 星際物質)



A hypothesis predicts that the formation of a new star from a cloud takes about 0.15 - 100 million years. How can astronomers verify the hypothesis by observations?

7.2 The formation of Stars

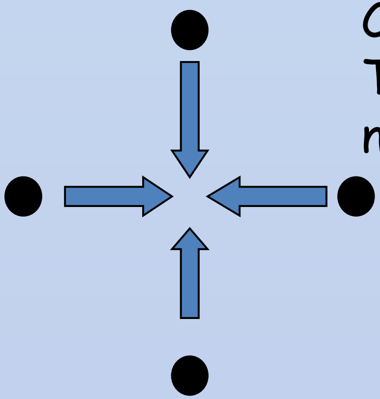
✓ Gravitational force causes gas clouds to contract and form stars



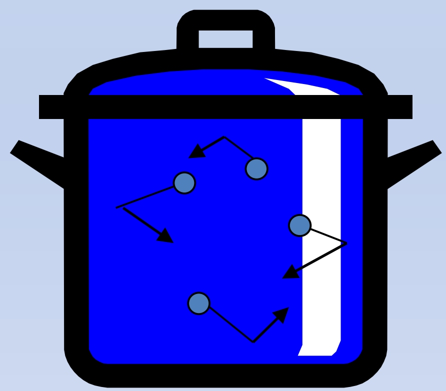
7.2 The formation of Stars

- As the cloud becomes smaller, the gravitational force becomes stronger (inverse-square force law).
- Particles fall faster and faster towards the centre; hence, temperature and pressure rise.
- Collisions between particles are more frequent.

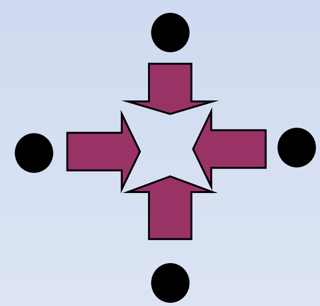
7.2 The formation of Stars



Clouds start to contract. Temperature and pressure not high.

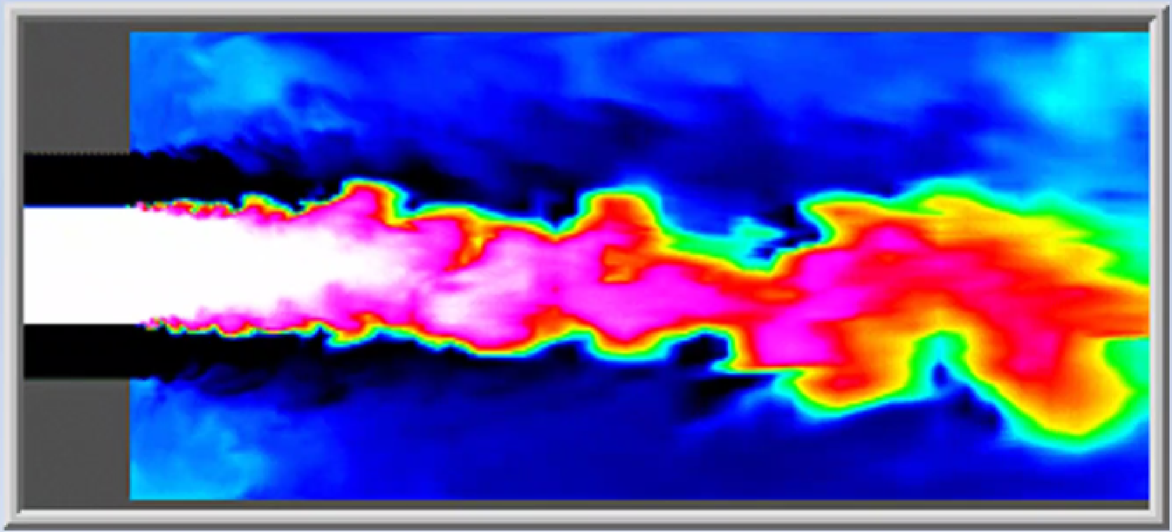


As particles closer, temp and pressure higher and higher. The particles in clouds move around rapidly



While gravity is stronger, thermal motion tends to expand the gas.

Apart from thermal motions, turbulence and rotational motions of the cloud (kinetic energies) tend to resist the contraction of the cloud.



[Turbulence flow.](http://abyss.uoregon.edu/~js/glossary/turbulent_flow.html)
http://abyss.uoregon.edu/~js/glossary/turbulent_flow.html

7.2 The formation of Stars

- ✓ Turbulence (湍流) and rotational motions also resist contraction.

7.2 The formation of Stars

Virial Theorem

- Condition for equilibrium under gravity:

$$2K = -U$$

达到这个平衡，那么星云不会再变化了

where K is the total kinetic energy;

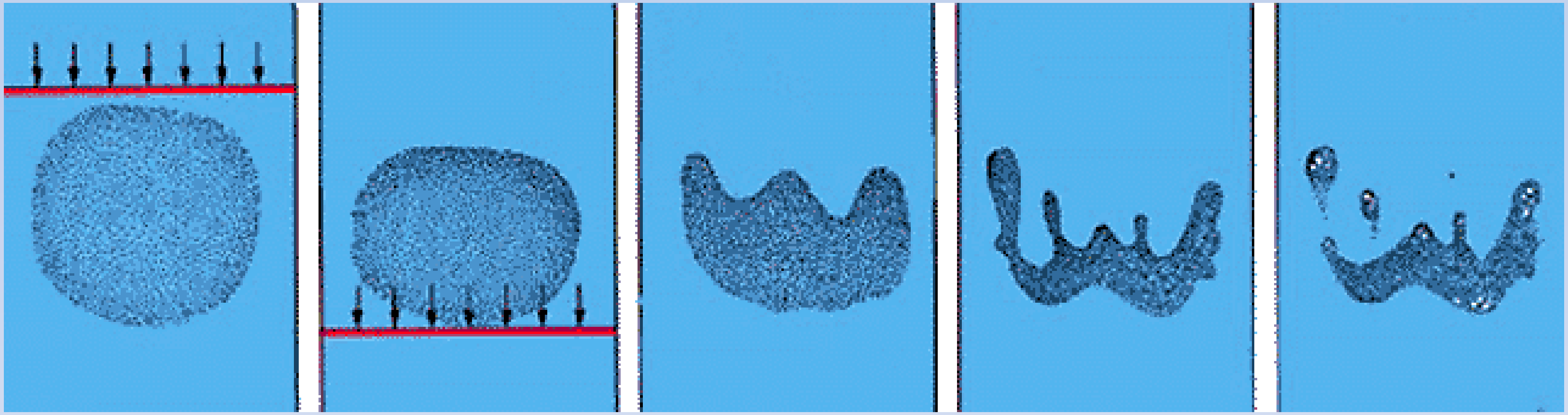
U is the gravitational energy of the gas clouds (-ve value)

- It is a simple form of the Virial Theorem.

7.2 The formation of Stars

Shock wave

✓ Most clouds would *not* contract under their own gravity.

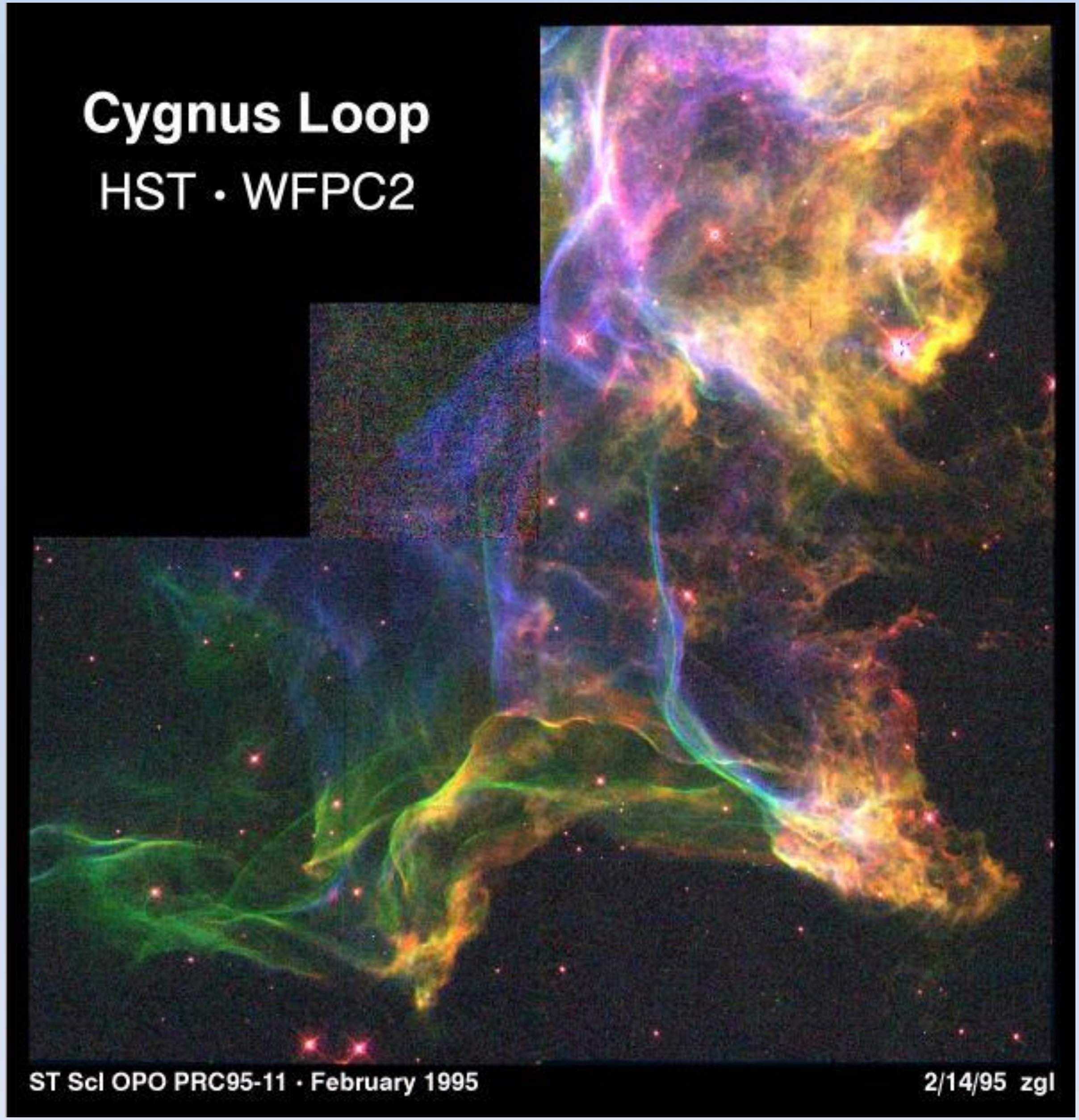


✓Shock waves trigger fragments formation, compressing some clouds to density high enough to form new stars.

冲击波的痕迹。

云层的破坏是由一些可能从左边移动的冲击波引起的。

Shock waves propagating from the left



7.2 The formation of Stars

Shock wave

Where does shock wave come from?

- ✓ Supernovae (超新星): exploding stars in the latest stage of stellar evolution.
- ✓ radiation pressure from hot, young stars
- ✓ collisions of molecular clouds or galaxies
- ✓ density waves generated by galactic rotations

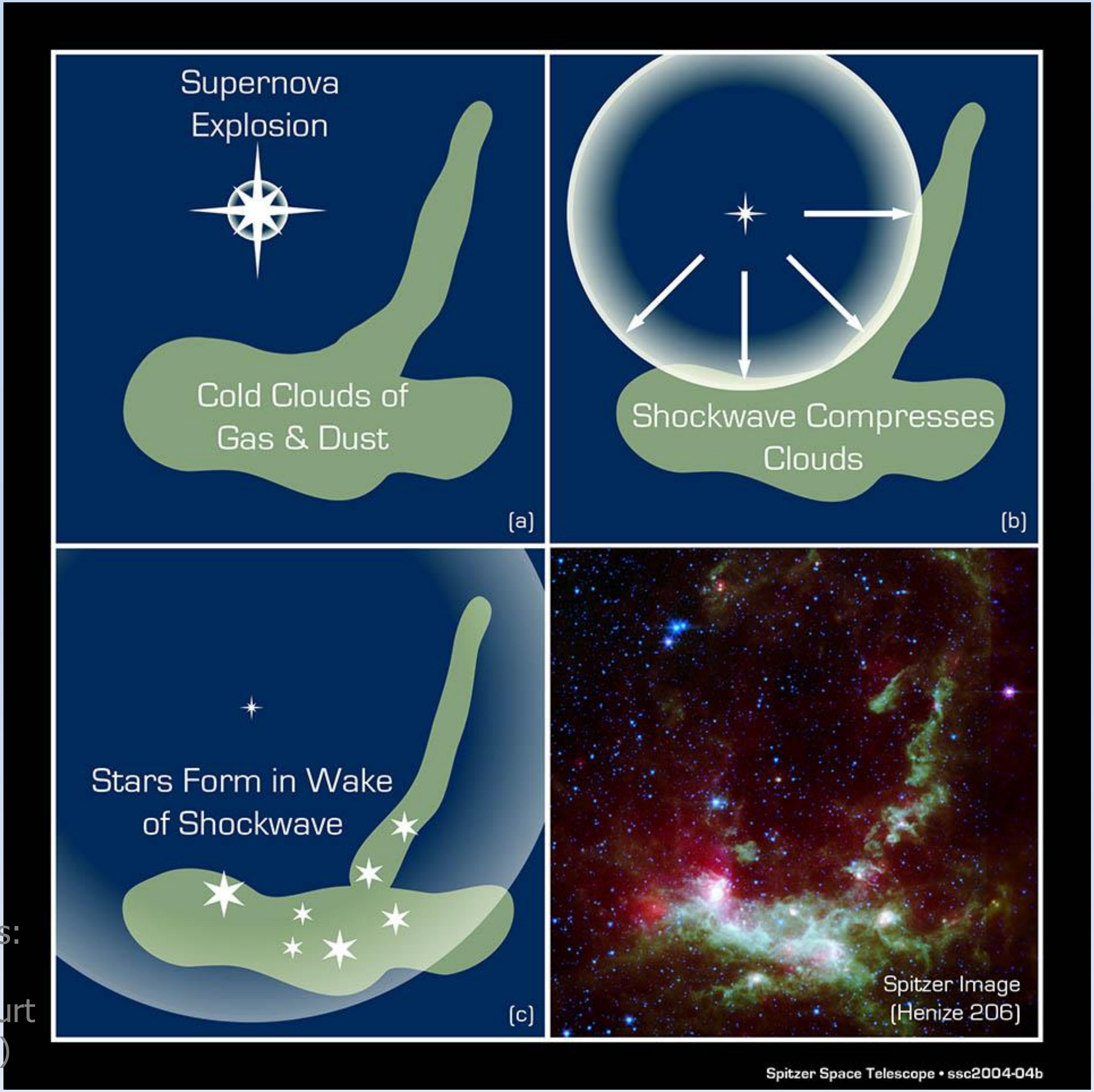
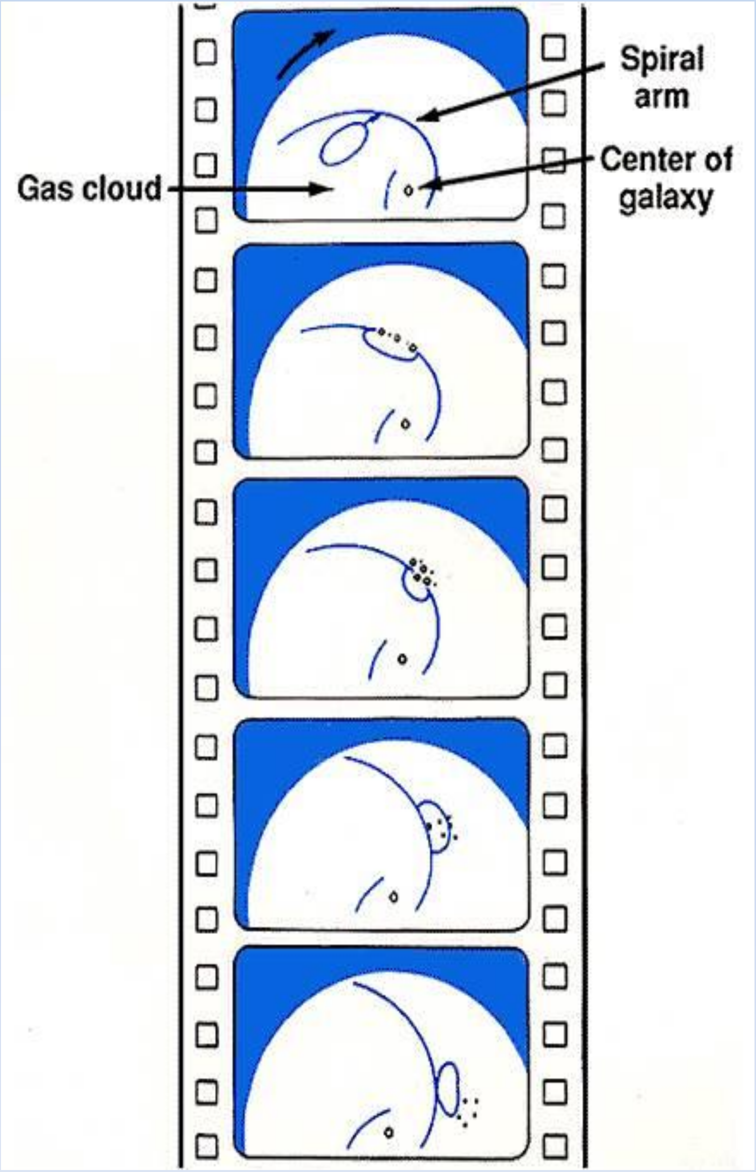
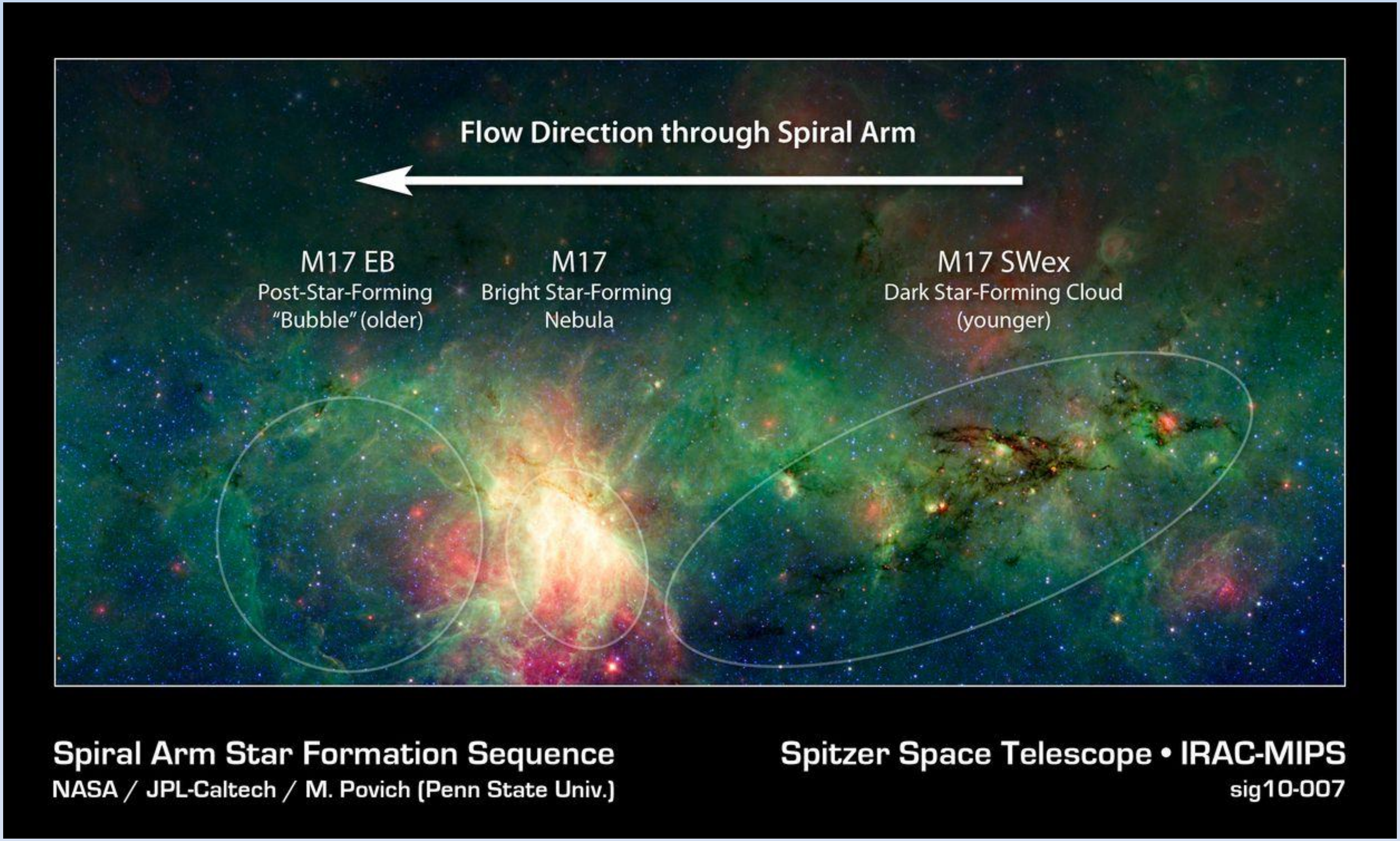


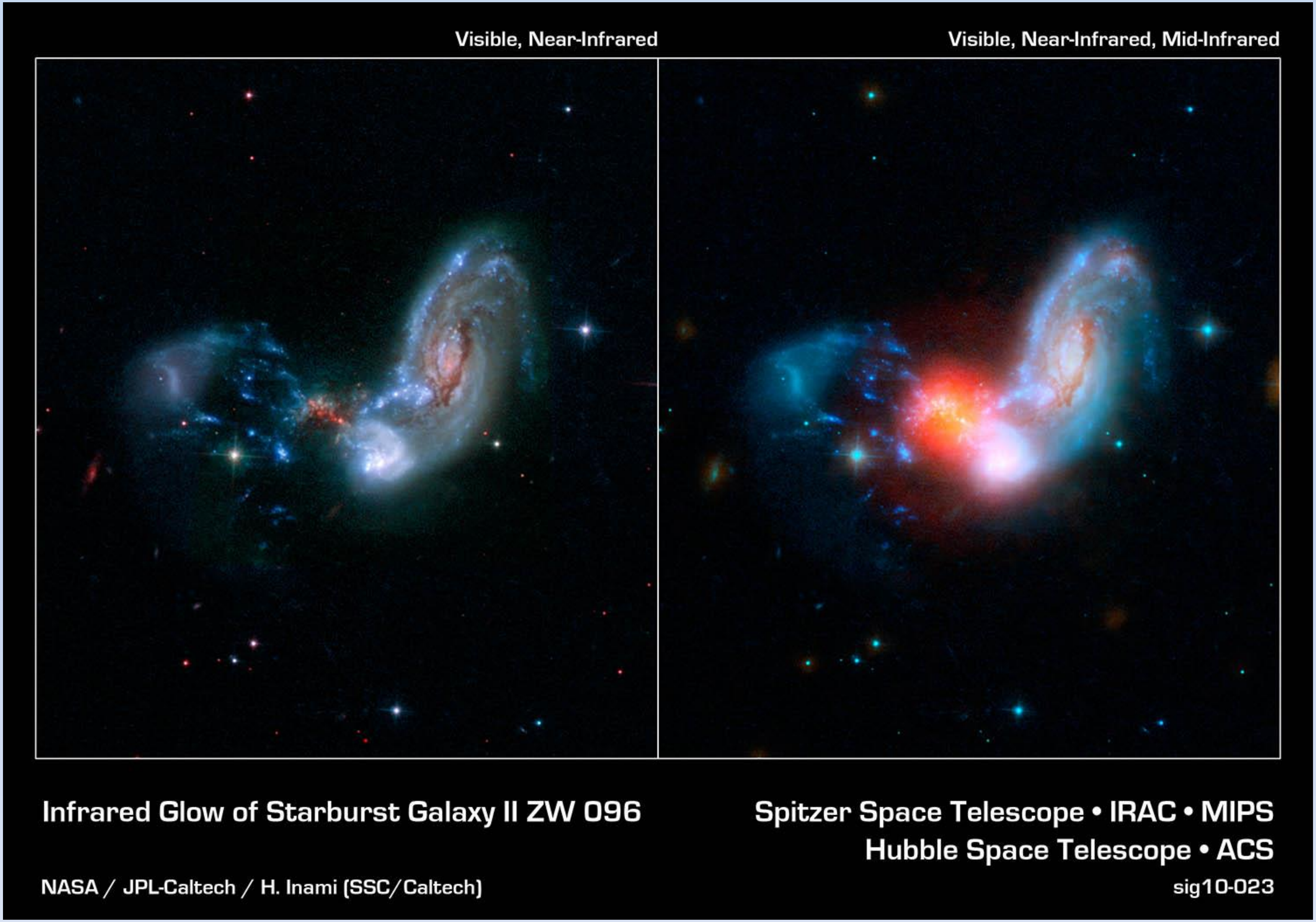
Image credits: NASA/JPL-Caltech/R. Hurt (SSC-Caltech)



Density wave creates spiral arms. Bulk motions of gas clouds in the spiral arms create stars.



Sagittarius M17 (人馬座 ω星雲). Clouds are shocked while passing through spiral arm.



Merging galaxies, known collectively as II Zw 096, leads to a lot of star forming activity within a short time.

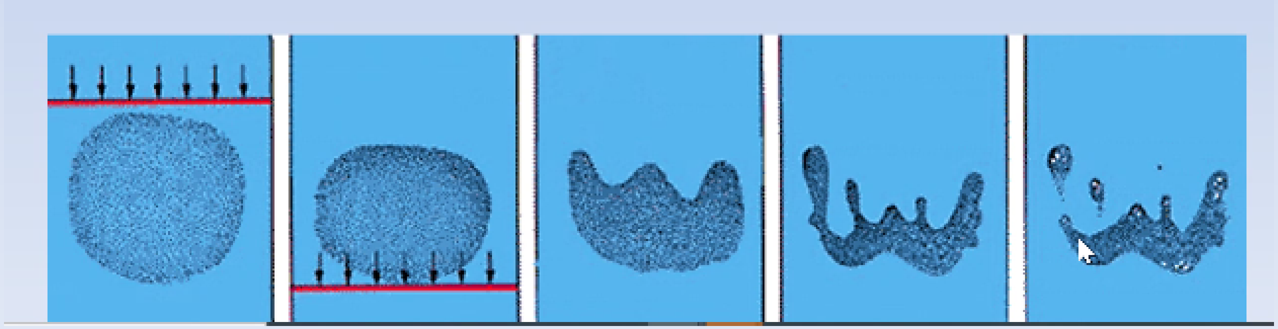
7.2 The formation of Stars

- ✓ As cloud starts to contract, the particles move faster and faster under gravity.
- ✓ Initially, density is low and thus not many collisions between particles at the initial phase of collapse.
- ✓ As density becomes higher. Temperature and pressure are increasing gradually

7.2 The formation of Stars

Fragmentation

- ✓ Instabilities in a large contracting cloud
- ✓ a large cloud fragments into many pieces, each forming a new star
- ✓ a group of young stars form at about the same time



7.2 The formation of Stars

M45 (七姊妹星團)

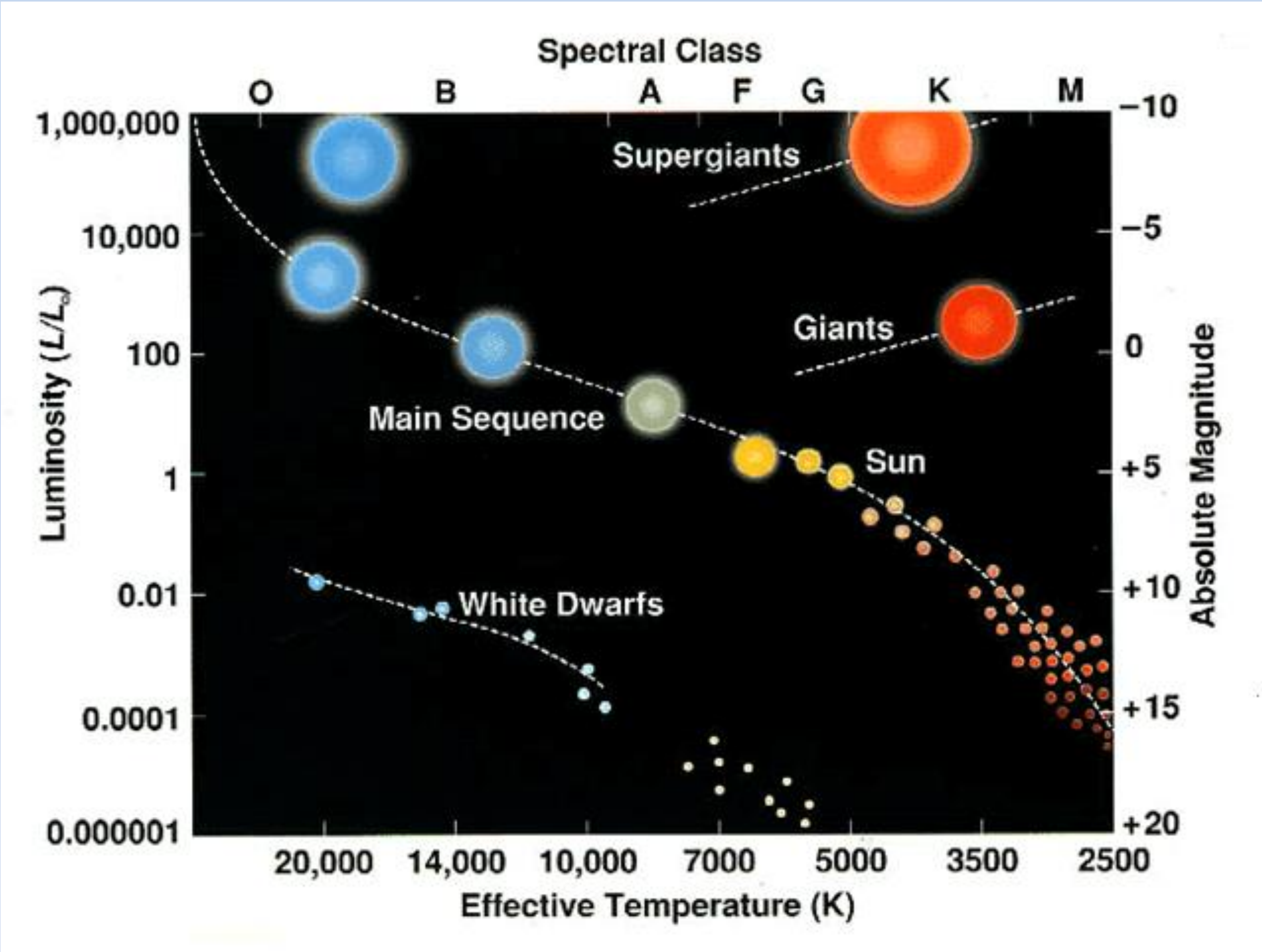
7.2 The formation of Stars

Protostar (原恆星)

- ✓ contracting gas cloud becomes hot enough to emit much infrared radiation, but not hot enough to ignite nuclear reaction
- ✓ Large size (bright) but low temperature, enters the upper-right area of the Hertzsprung-Russell (H-R) diagram

都是一个猜想

Remember?

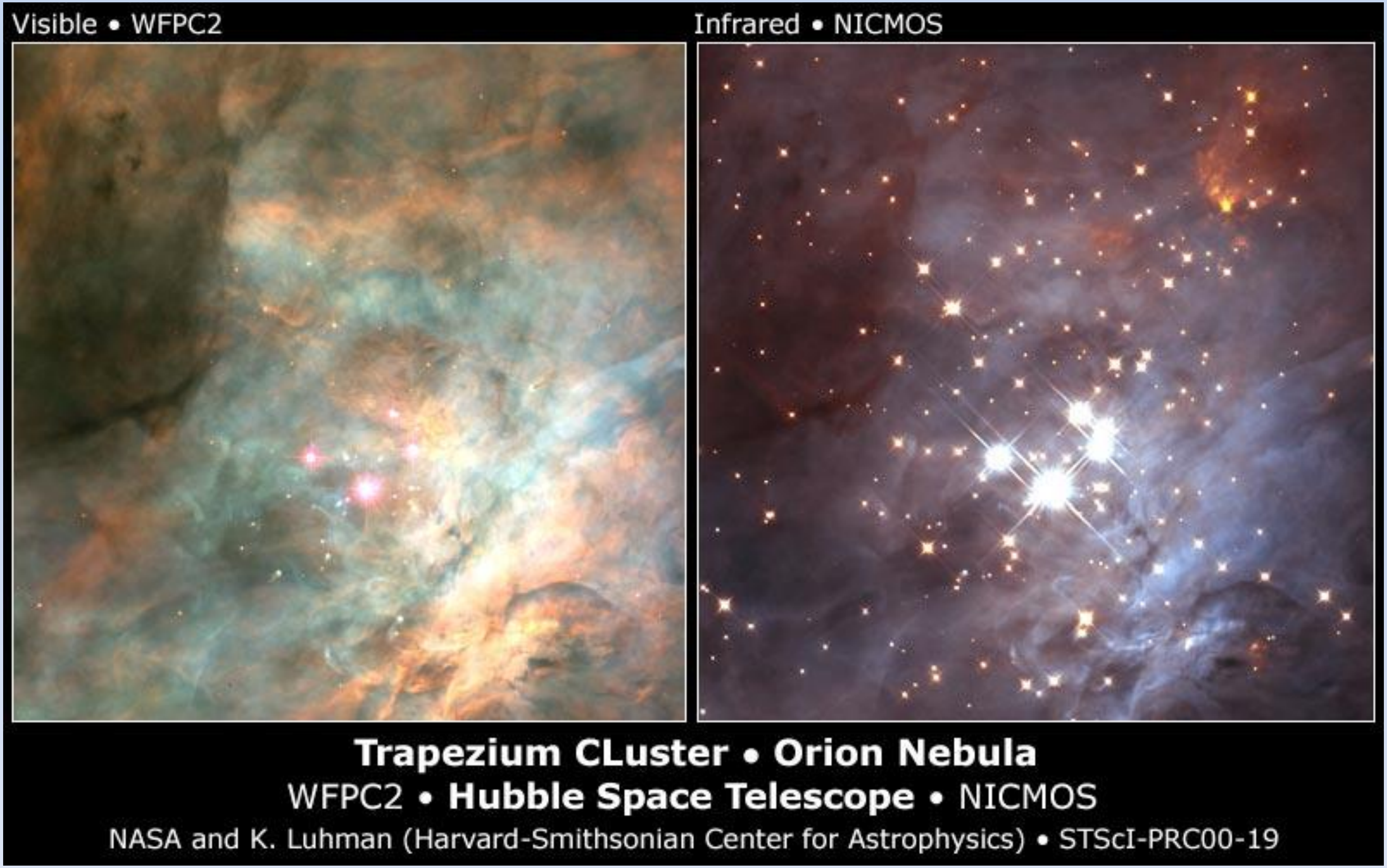


Spectral Class
O
B
A
F
G
K
M
1,000,000
10,000
100
1
0.01
0.0001
0.000001
Luminosity ($L/L_{\odot}$)
−10
−5
0
+5
+10
+15
+20
Absolute Magnitude
Supergiants
Giants
Main Sequence
Sun
White Dwarfs
20,000
14,000
10,000
7000
5000
3500
2500
Effective Temperature (K)

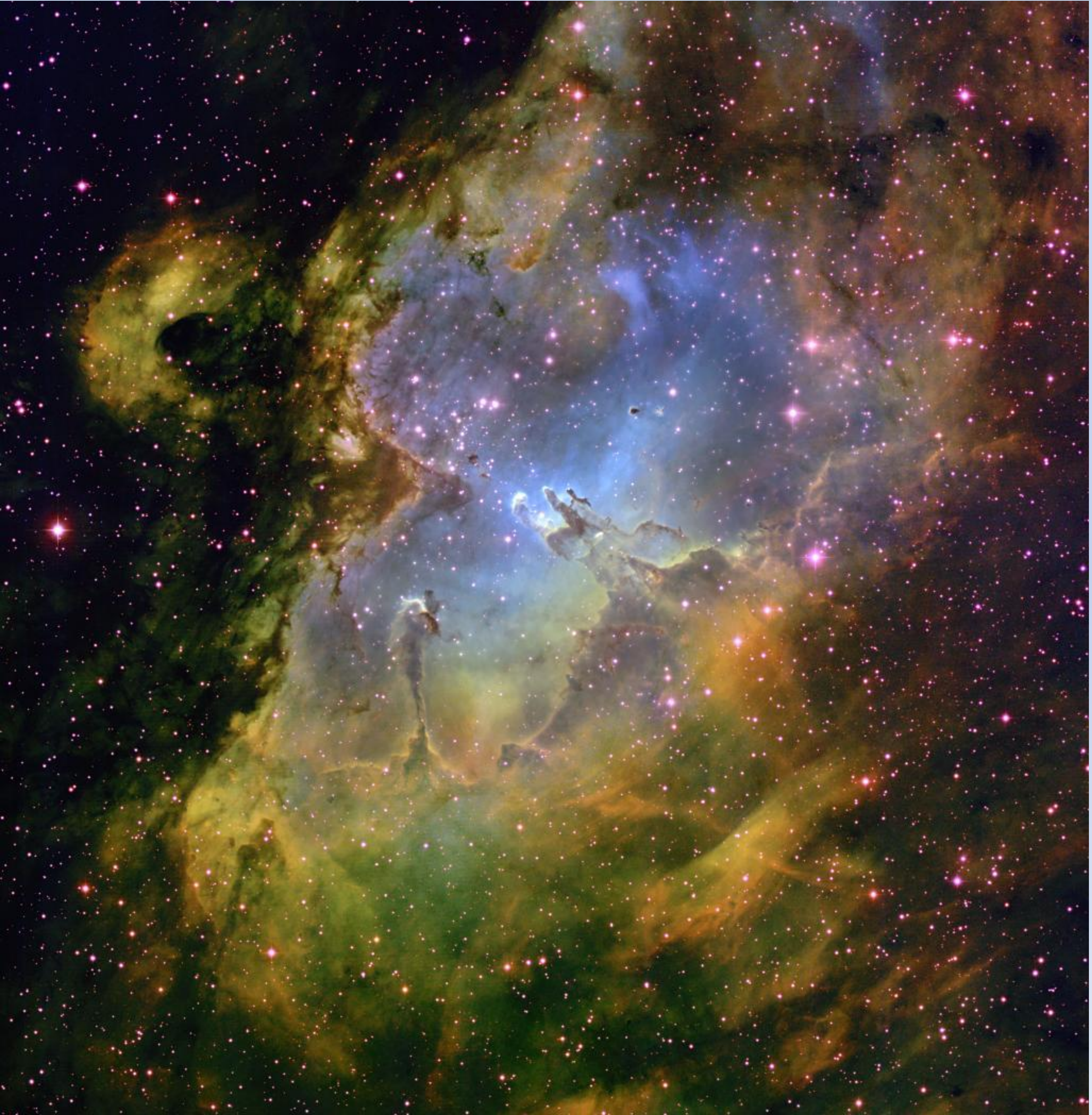
7.2 The formation of Stars

- ✓ as the clouds contracting, higher-density region at the centre (protostar taking their shape); enveloping clouds of colder gas of lower-density. They are called cocoons (繭).
- ✓ The cloud gas absorbing light from the protostar (inner region), re-radiating the energy as infrared radiation
- ✓ Therefore, IR sources detected in a giant molecular cloud may be protostar!

7.2 The formation of Stars

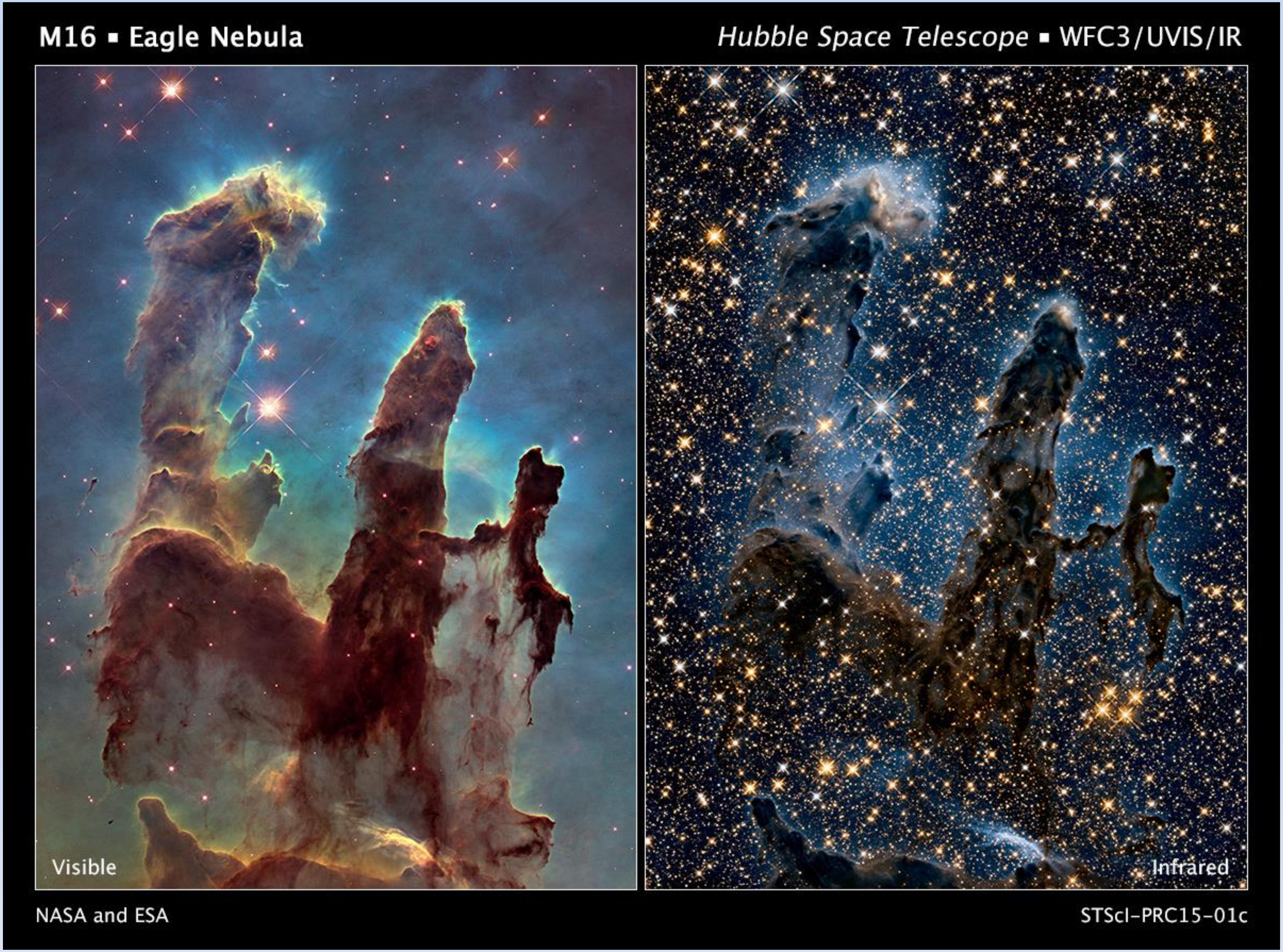


Optical and IR images look very different in this star-forming region.



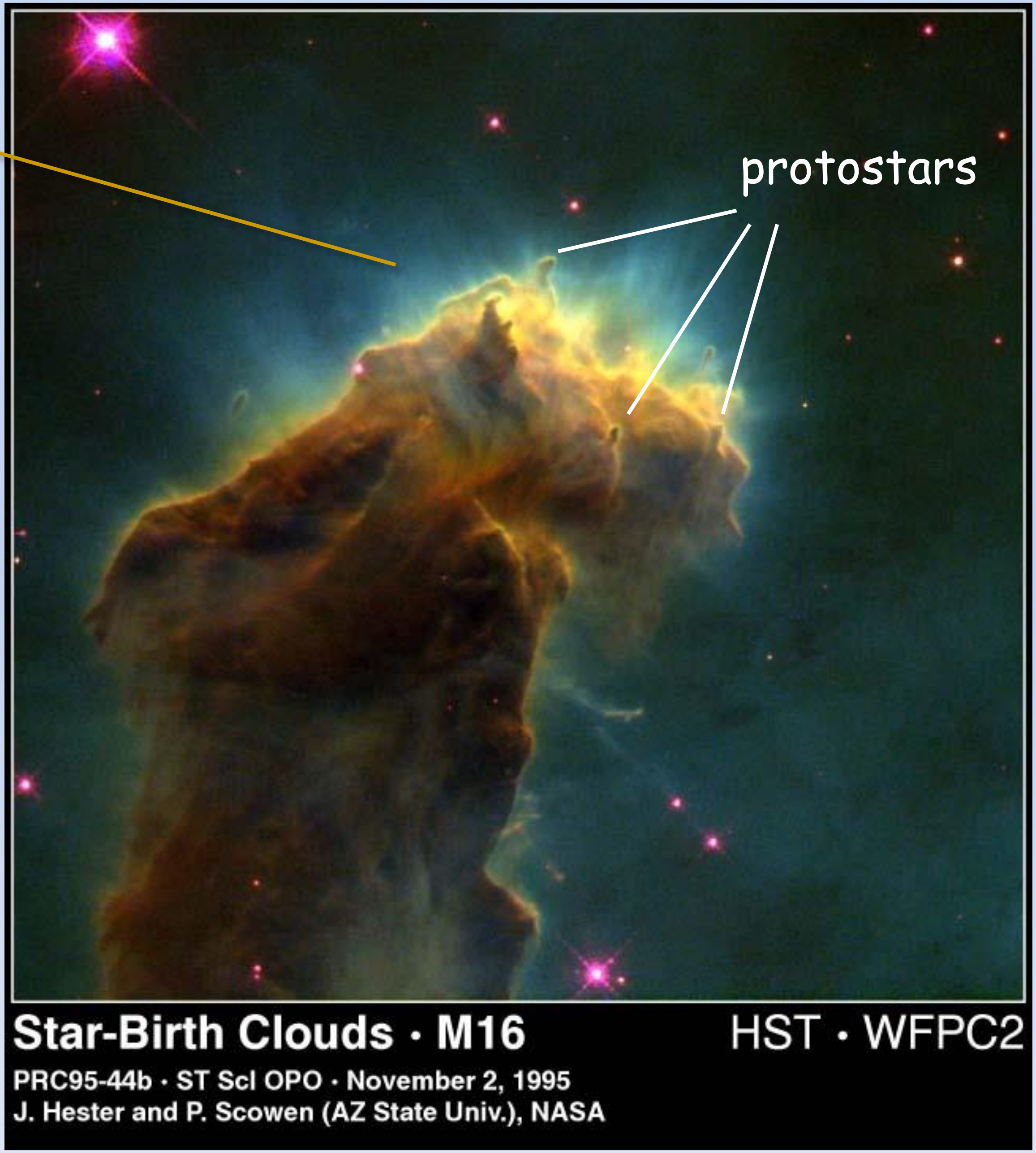
Dark nebula in Eagle Nebula (巨蛇座鷹星雲) M16

Image: T. A. Rector (NRAO/AUI/NSF and NOAO/AURA/NSF) and B.A. Wolpa (NOAO/AURA/NSF)

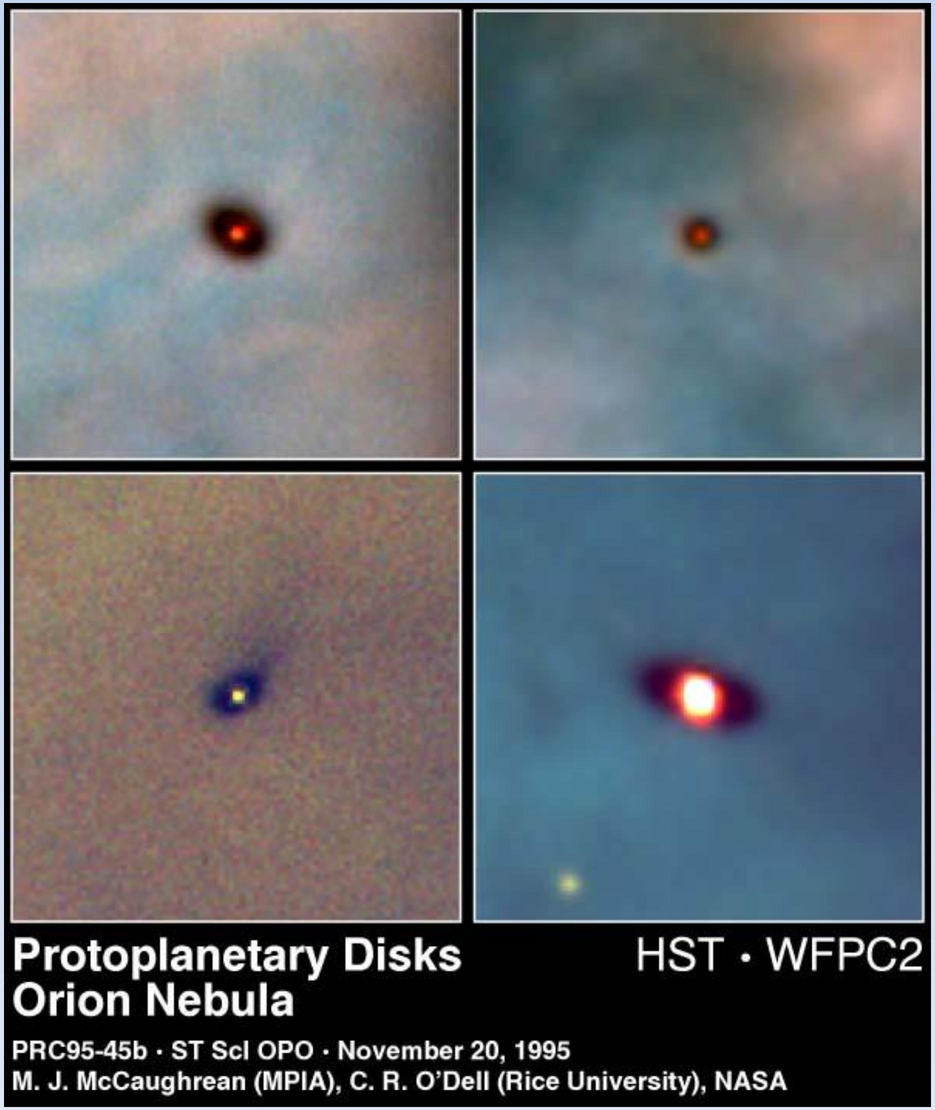


These pillars of life contain a lot of protostars.

photoevaporation: UV from young and hot stars heats and "boils" the gas away



7.2 The formation of Stars



- ✓As a cloud contracts, the gas and dust spin faster and flatten
- ✓A rotationally support structure
- ✓Planetary system is believed to form in such a *protoplanetary disk*.

Occasionally we view such an object from the side.

an artist's conception:

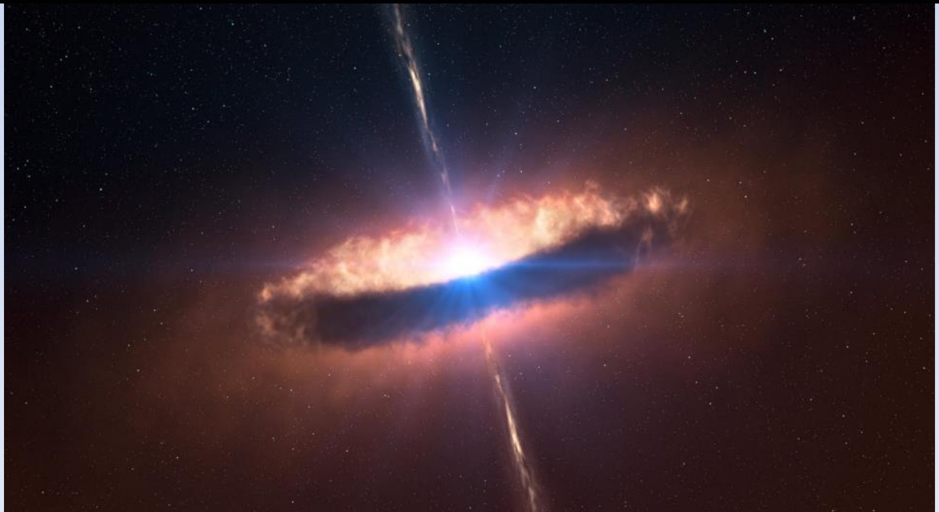
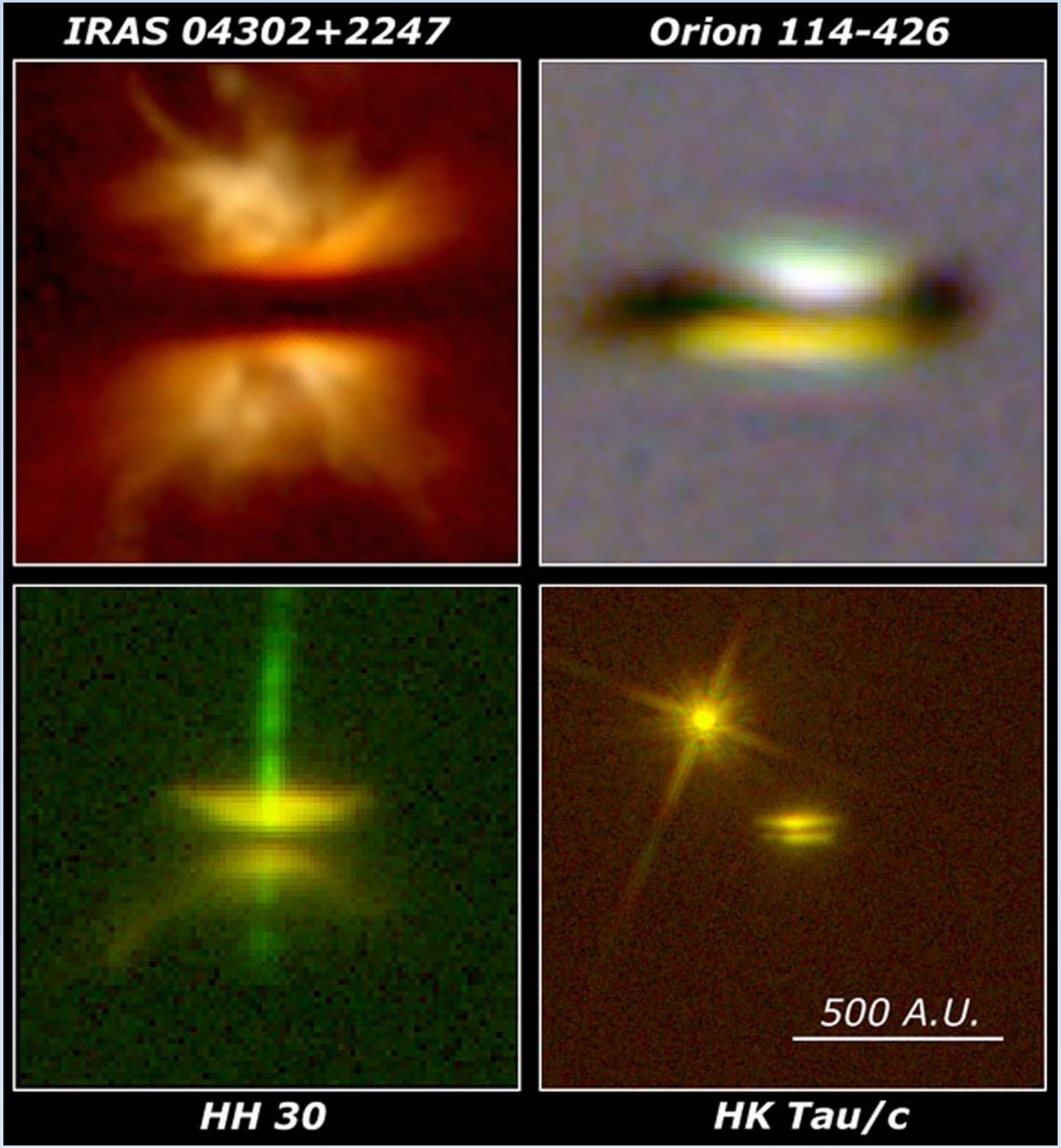


Image credits:
ESO / L. Calçada

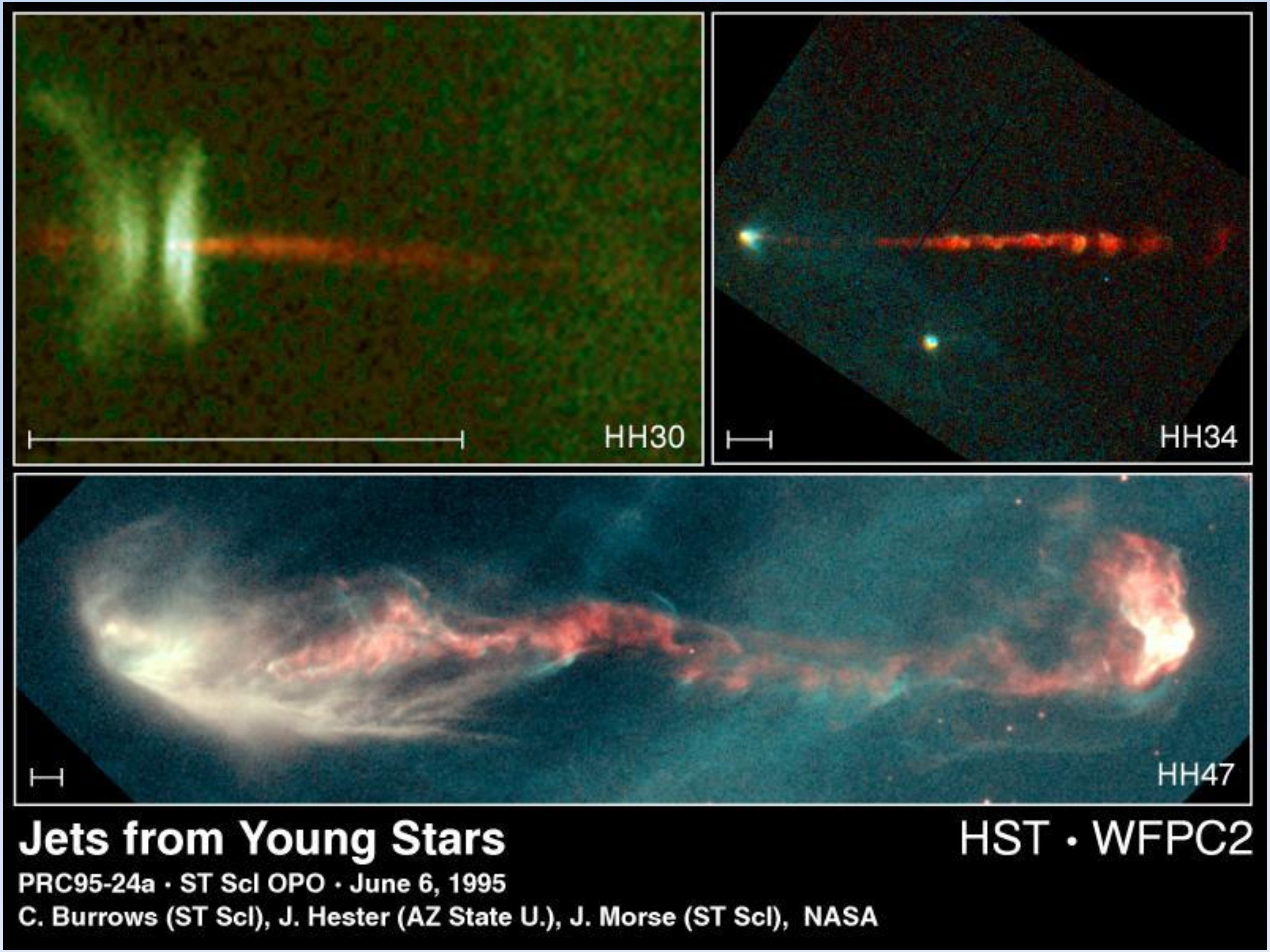


✓Depending on the mass and evolutionary stage, the images of the edge-on protoplanetary disks could look very different from one another.

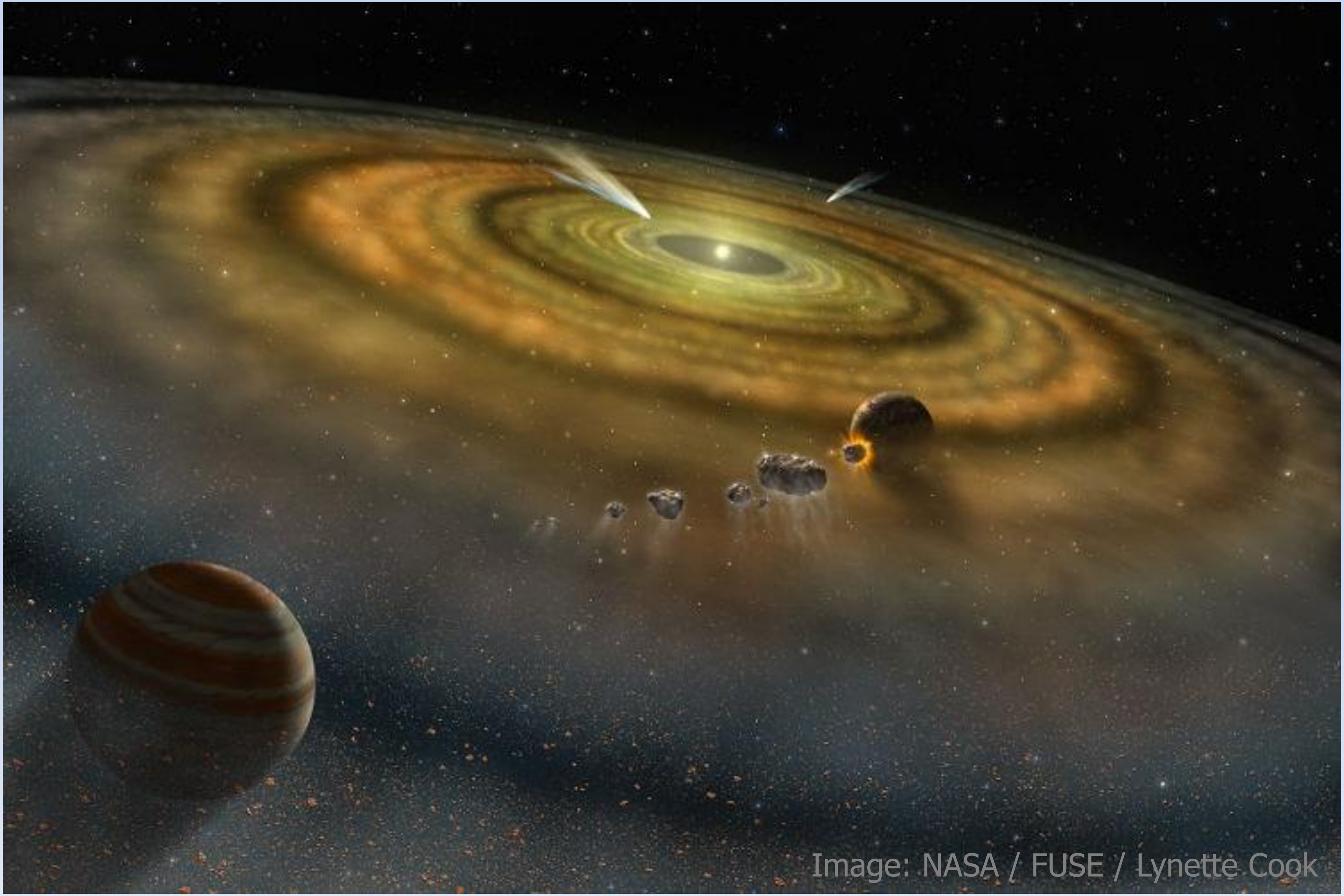
✓Sometimes jets of material are ejected along the axis.

Credits: HST photo (STScI-1999-05)

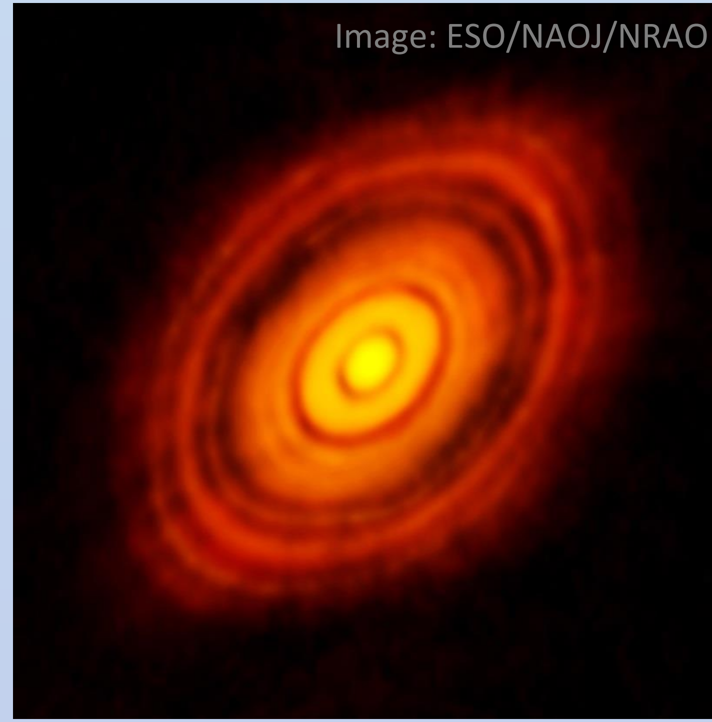
Some examples of gaseous jets ejected from newly forming stars.

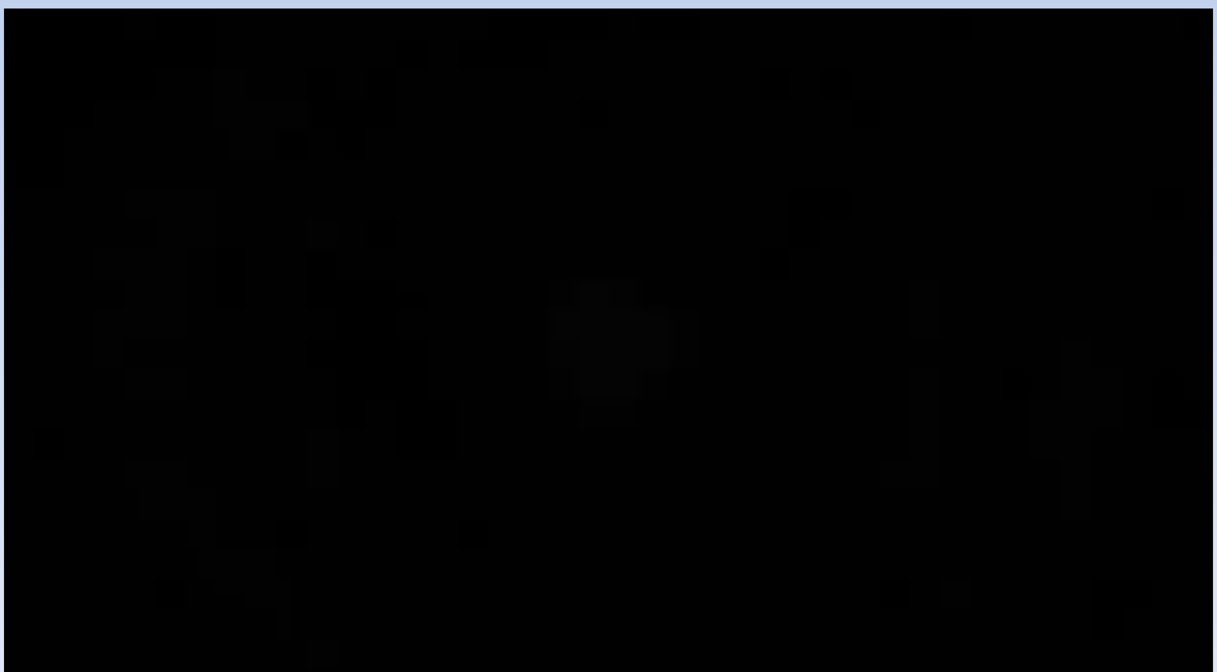


An artist's conception of the planet formation process in a protoplanetary disk around a young star



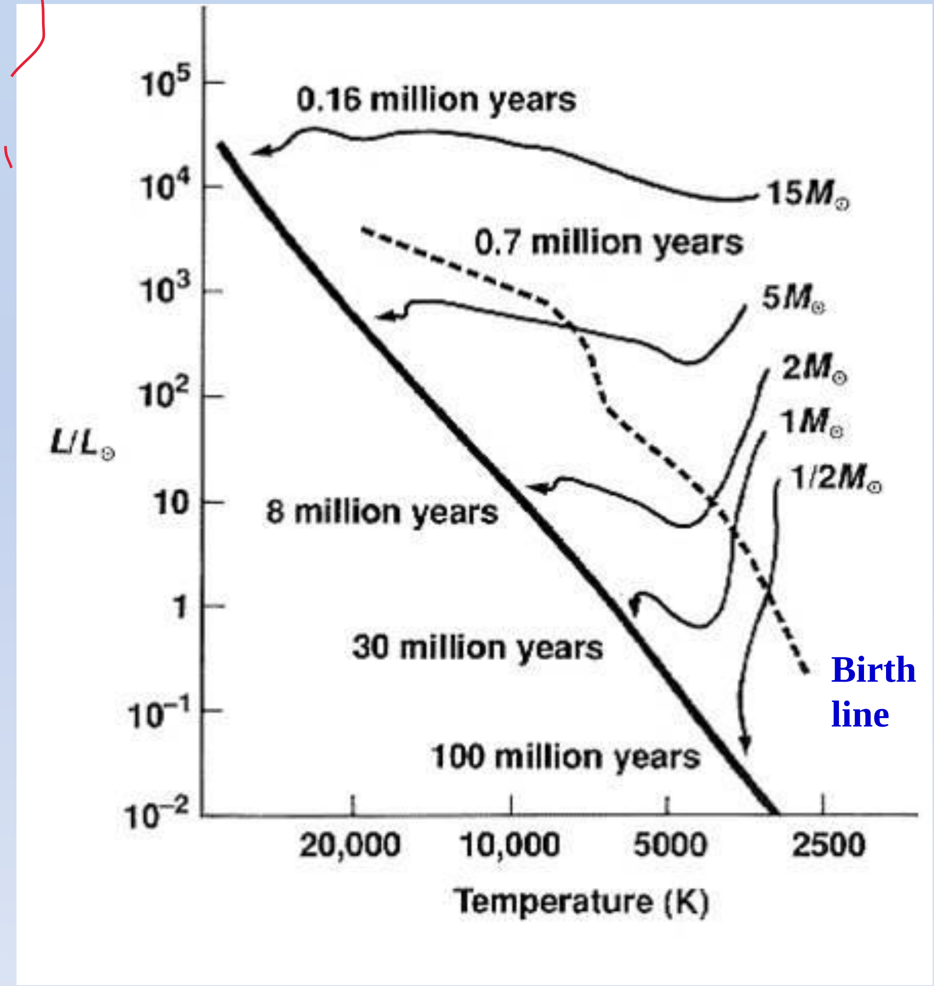
✓ A 2014 observation was able to resolve a planet-forming disk for the first time. The concentric and bright rings, separated by gaps, are similar to what one expects from the theory.





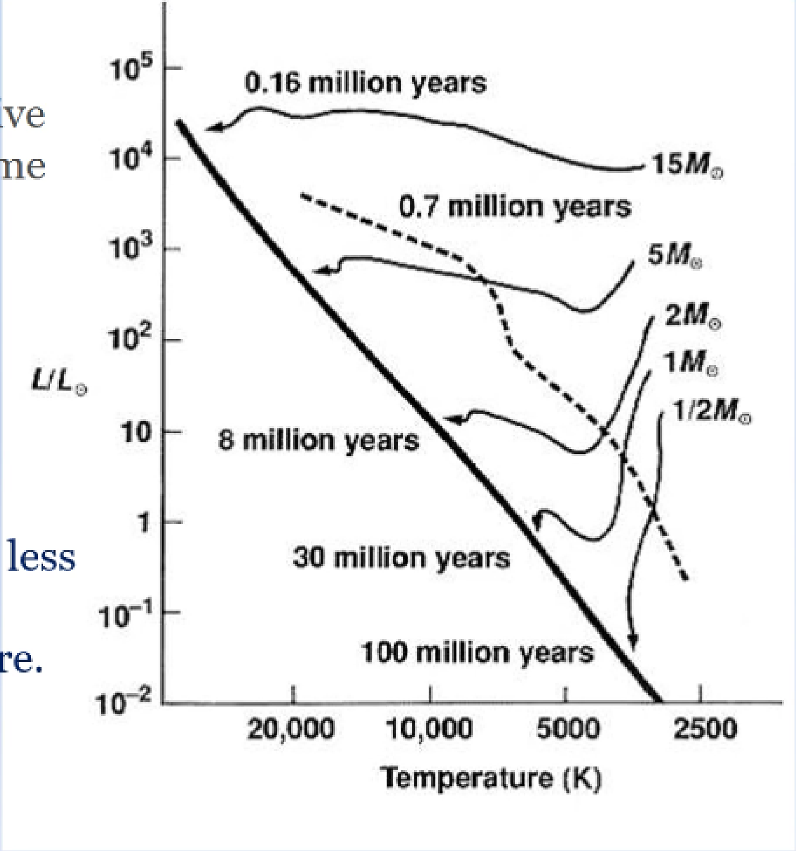
7.2 The formation of Stars

- ✓ when a protostar becomes hot enough, its radiation vaporizes and pushes away the cocoon.
- ✓ the star becomes visible. It is at the *birth-line* in the H-R diagram.



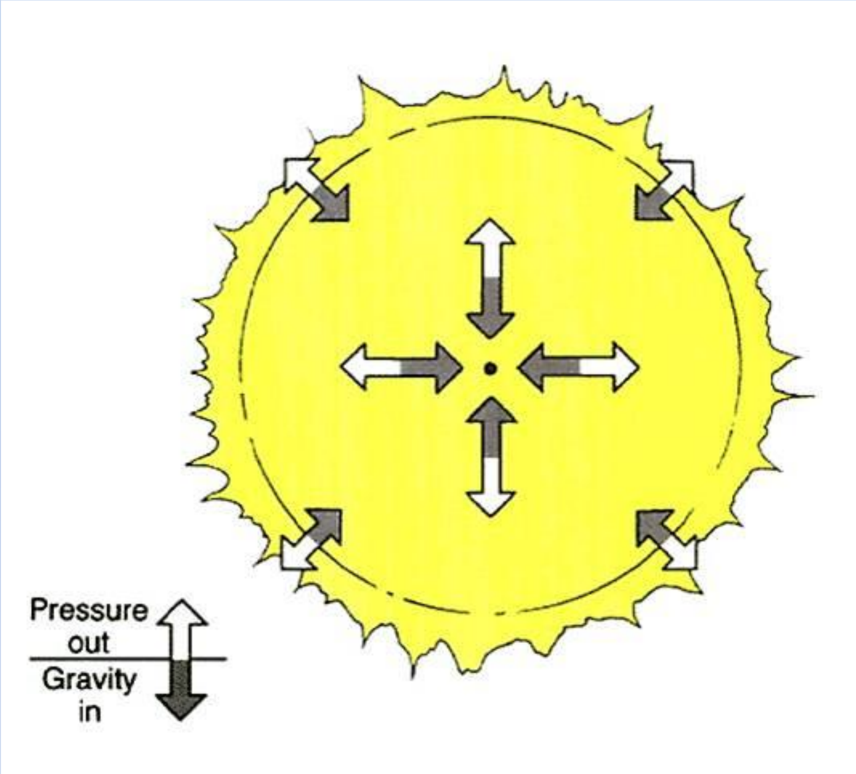
Note: more massive stars takes less time to enter the main sequence. Why?

The gravity of a massive star is so large that it takes less time to attain the fusion temperature.



7.2 The formation of Stars

- ✓ When the central temperature is high enough $> 10^7$ K,
- ✓ nuclear fusion ignites at the core and produces energy, and
- ✓ temperature of the star increases rapidly.

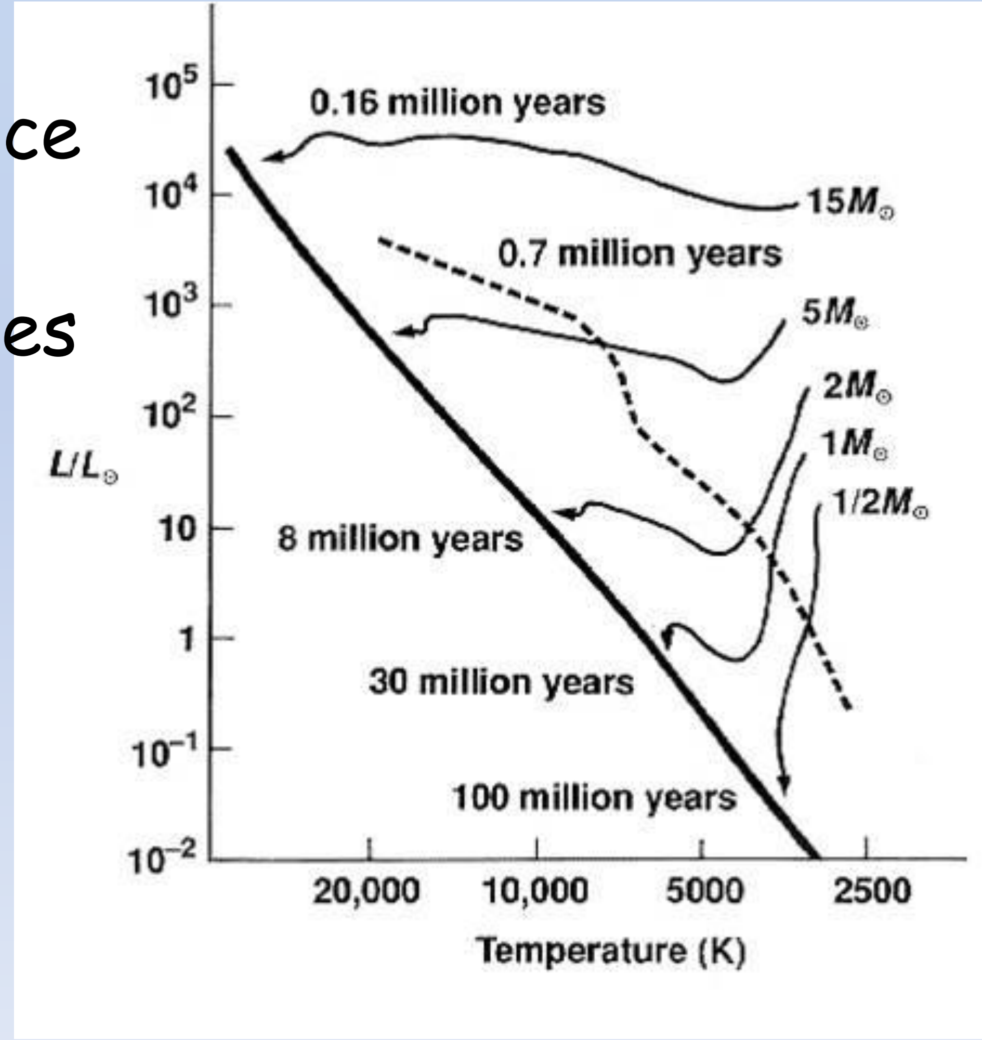


- ✓ Thermal and radiation pressures balance the gravitational force, and
- ✓ contraction of gas stops.

7.2 The formation of Stars

- ✓ enters the main sequence (主星序)
- ✓ more massive stars takes less time to enter

质量越大，越容易形成star



7.2 The formation of Stars

Do all protostars enter main sequence?

- ✓Upper mass limit of main-sequence stars:

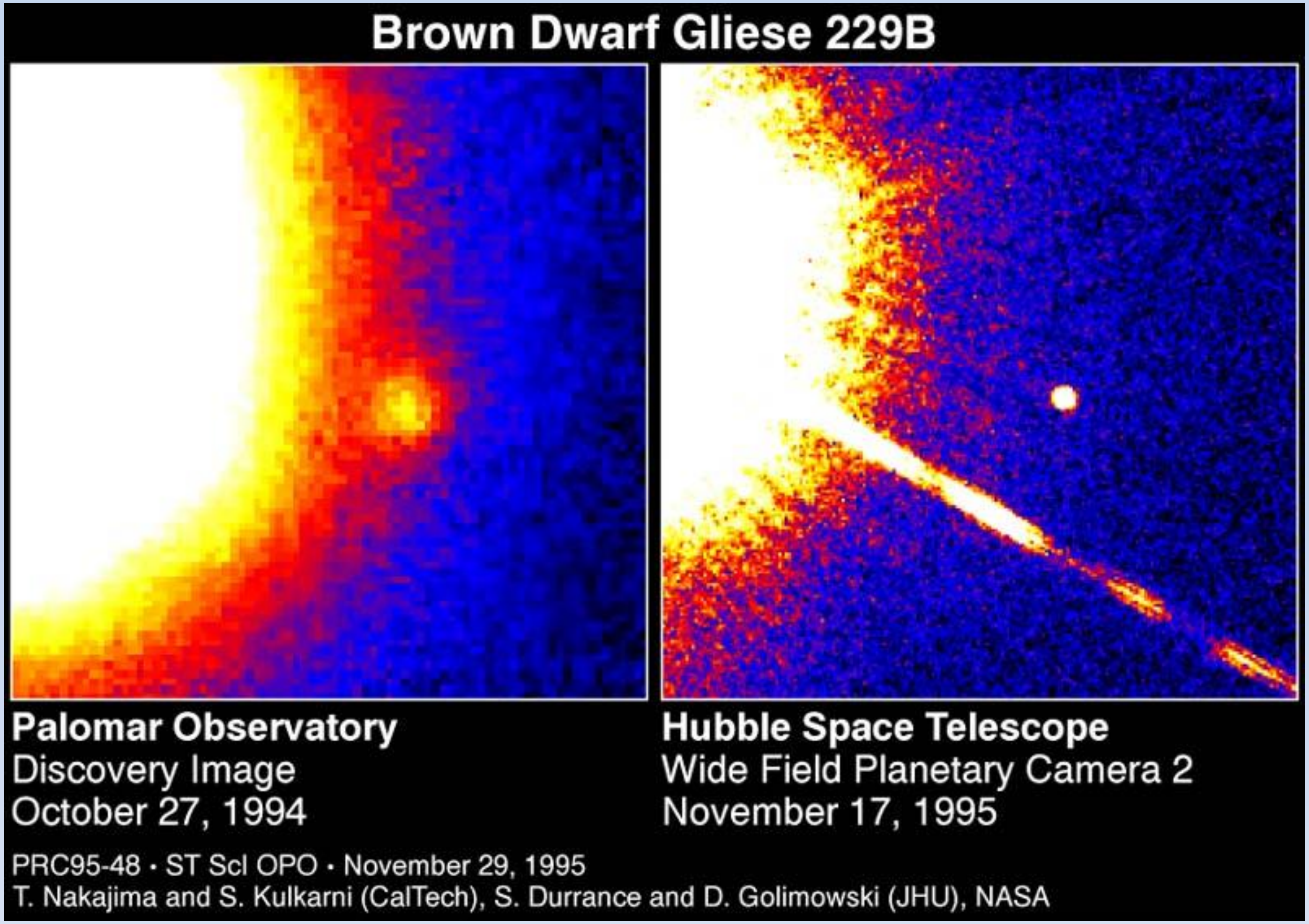
  $M > 100\ M_{\odot}$: unstable, fragments into smaller pieces finally

- ✓Lower mass limit:

  infrared radio

  $M < 0.08\ M_{\odot}$: core not hot enough to start hydrogen fusion, and emits IR radiation – the object is known as a ***brown dwarf*** (棕矮星). It is <u>not</u> a main-sequence star.

7.2 The formation of Stars



This brown dwarf is about 20 to 50 times the mass of Jupiter