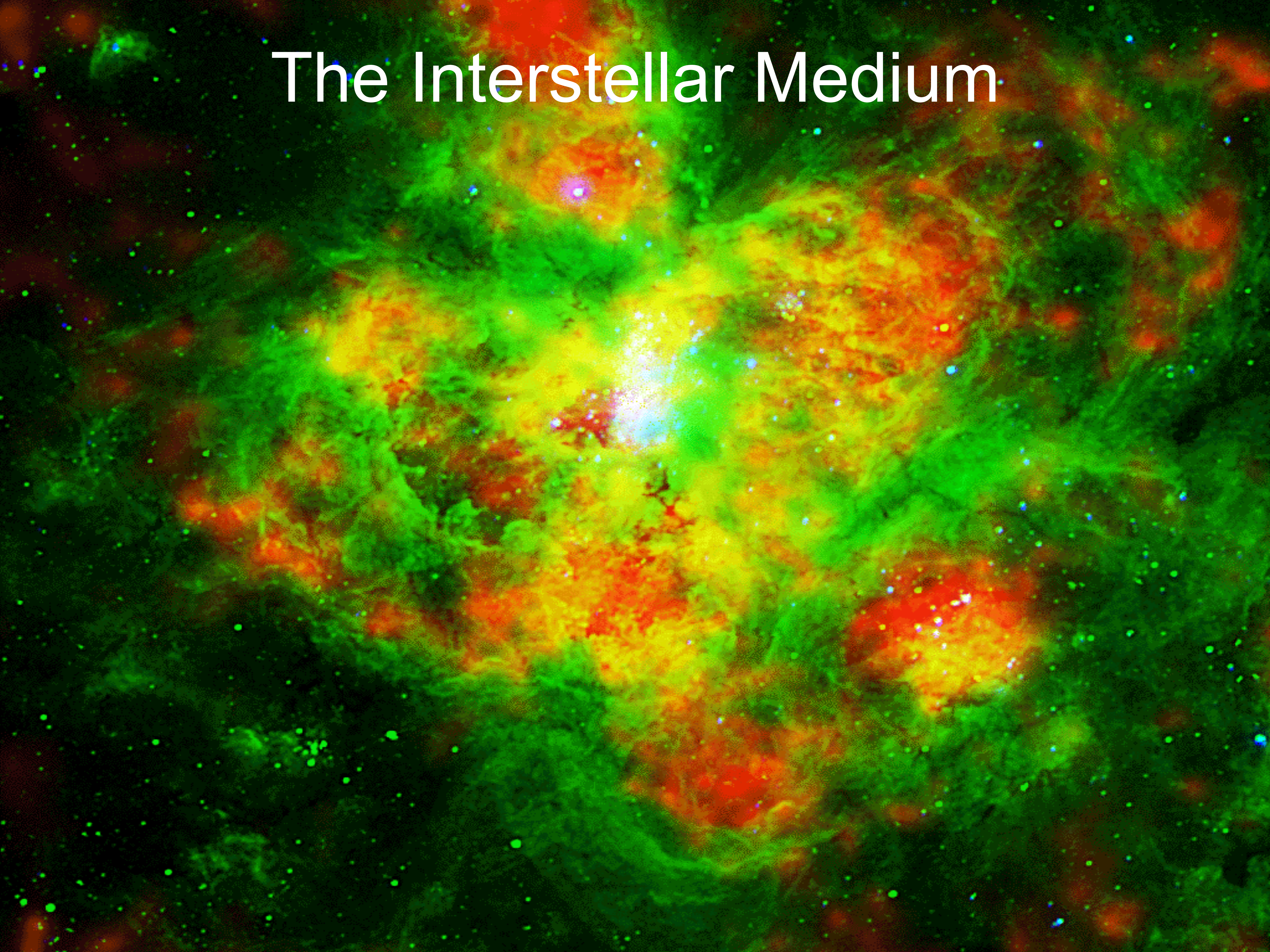
Announcements

Homework 3 is due this Thursday (Feb. 11) by start of class

The Interstellar Medium



The interstellar medium (ISM)

- Space between stars is not a complete vacuum.

- Why is the ISM important?
  - Stars form out of it
  - Stars end their lives by returning gas to it

- The ISM has
  - a wide range of structures
  - a wide range of densities (10^{-3}-10^{7} atoms/cm^3)
  - a wide range of temperatures (10 K - 10^7 K)

Overview of the ISM

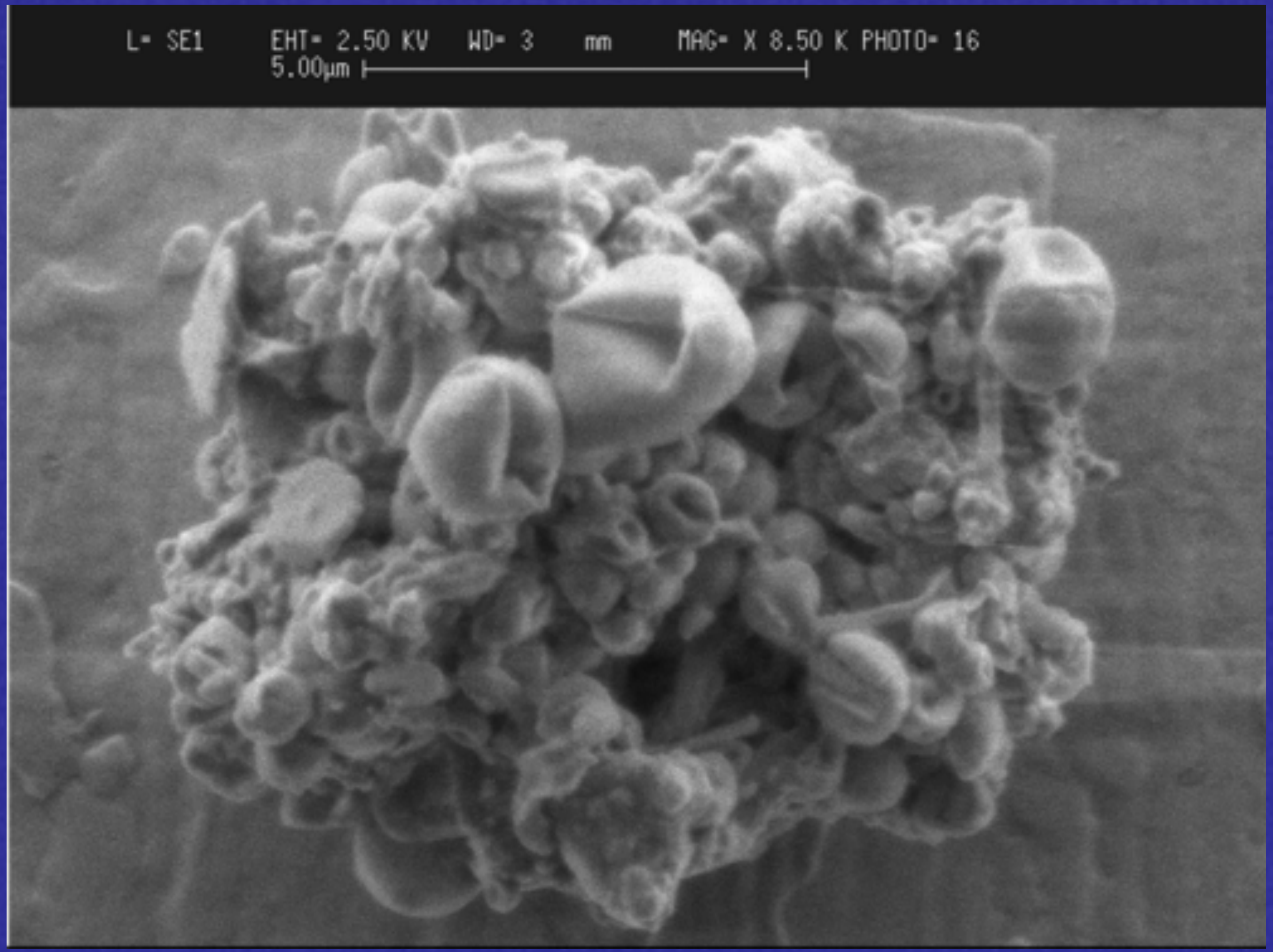
- The ISM is a multi-component, multi phase medium

- The *components* are gas and dust, with dust comprising 1-2% of the ISM mass.

- The *phases*, meaning different kinds of clouds of gas and dust – hot, warm, cold, dense, rarefied.

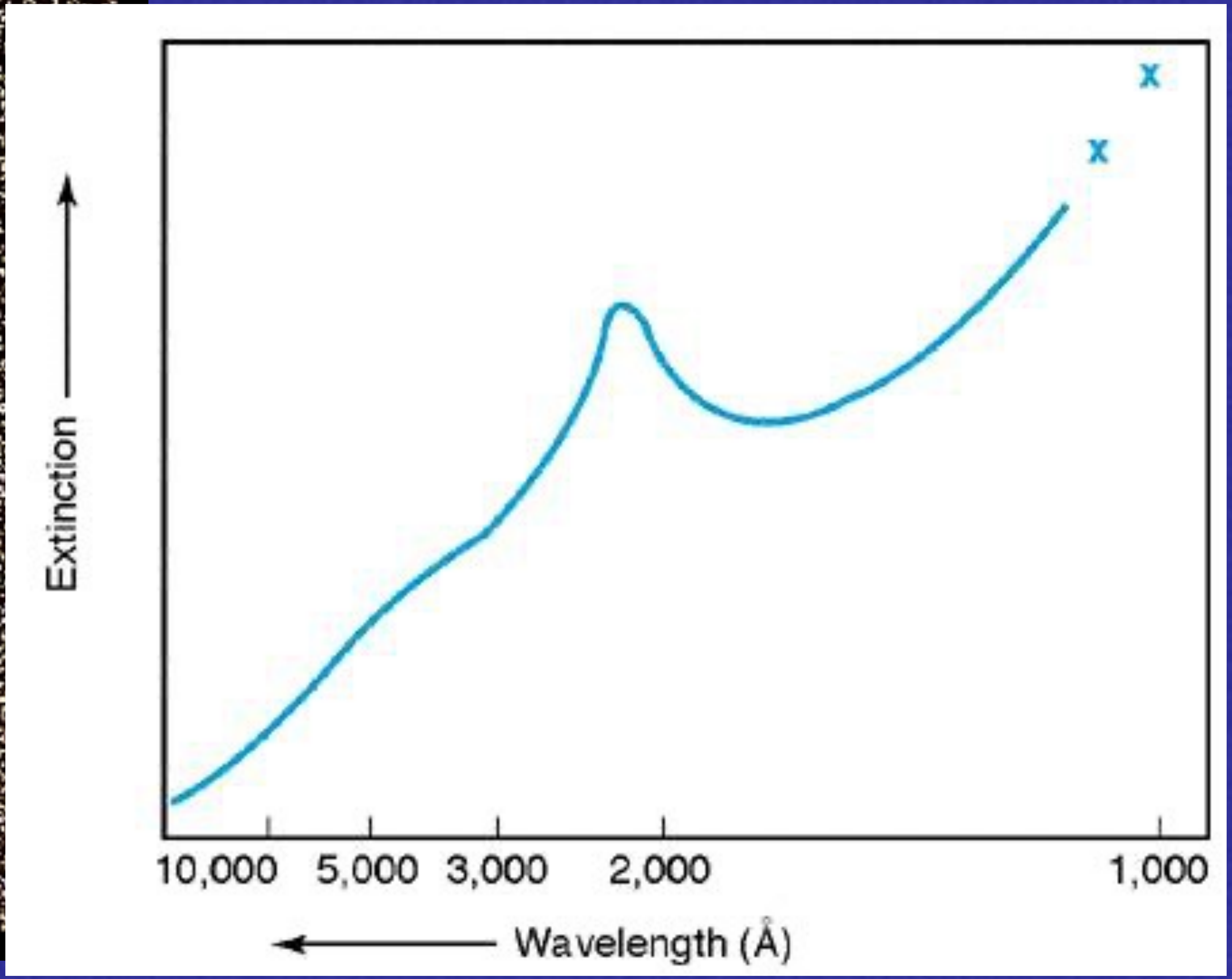
Dust particles

- Grains with carbon, graphite, silicates
- Particles of ~10^3 atoms, physical size d~10^{-7} m (range nm to µm)



- Cause interstellar extinction
- Cause reddening

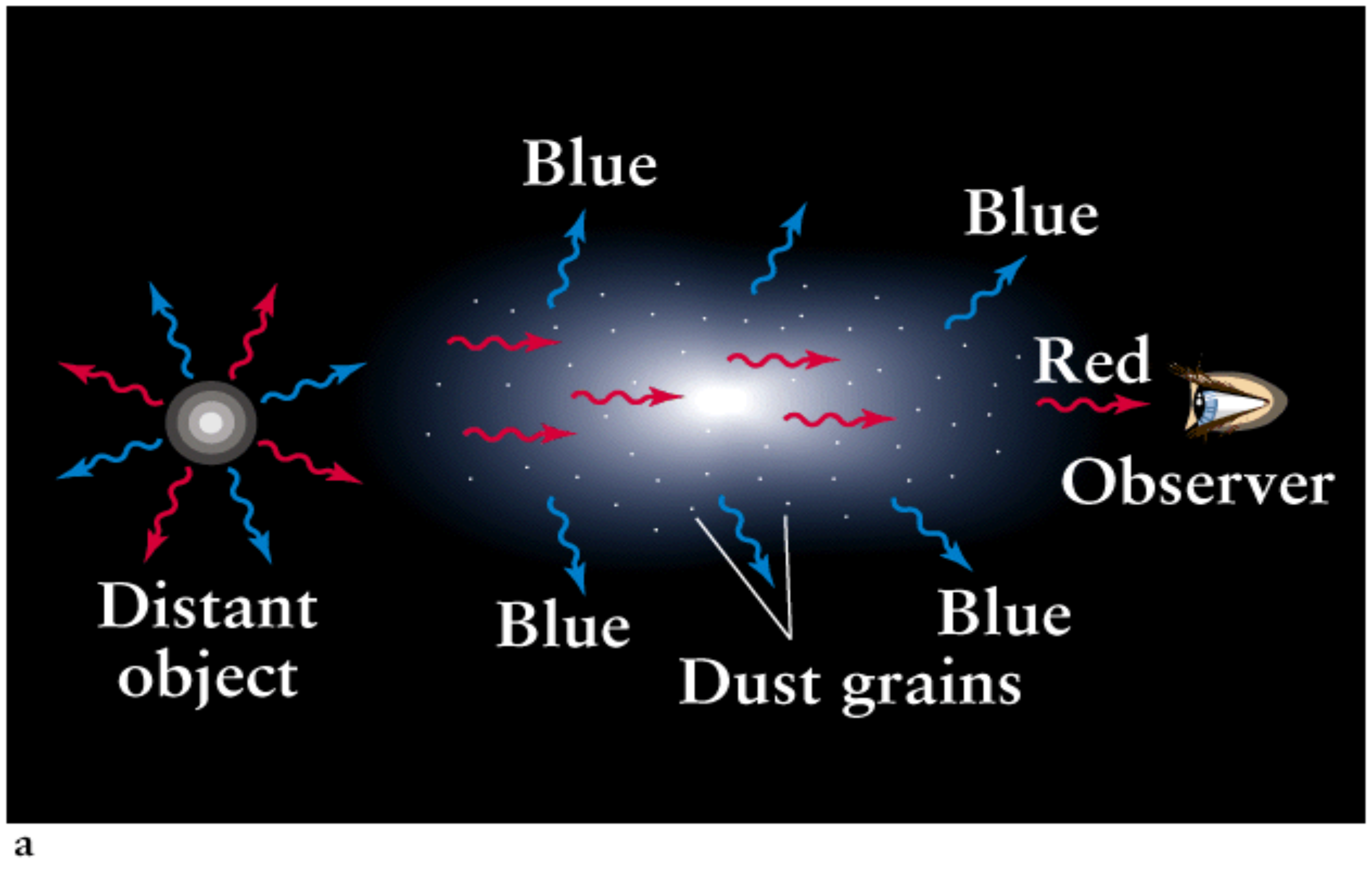
- Extinction is reduction in optical brightness
- Strong λ dependence on absorption and scattering
- Measure in magnitudes, A_V, at visible light



Orion at visible wavelengths

Orion at IR wavelengths (100μm): dust grains absorbs UV light and re-radiates in the IR!

- Interstellar reddening: Scattering will both dim and redden the starlight.
- This is Rayleigh-scattering, which is proportional to $1/\lambda^4$



- Thus, we need to be careful calculating distances to stars using the distance modulus:

$$m - M = 5\log d - 5$$

- If there is dust (and there will be) this becomes:

$$m - M = 5\log d - 5 + A$$

- where *A* is the amount of light absorption in magnitudes at the wavelength you are measuring brightness of star.

- Dust is seen as winding bands, or spherical clouds (Bok globules)
- Can also be detected via polarization

Rosette Nebula

- Dust is formed in low T regions (~<100K), since high T will cause collisions and sputtering of the grains => destruction of the grains.

- The surfaces of dust grains can act as a matrix to hold molecules close together, and allow chemistry to occur.

- These molecules are mostly hydrocarbon chains and other organic molecules (claims of protein, like DNA, seen in molecular cloud). This is the field of *cosmochemistry.*

The main ISM component: gas

- Interstellar gas is either neutral or ionized

- Ionized:
  - WIM, Warm Ionized Medium
  - HIM, Hot Ionized Medium

- Neutral:
  - WNM, Warm Neutral Medium
  - Cool NM
  - Cold NM

Review: what does “ionized” means?

Component	Phase	T(K)	$n(cm^{-3})$
Neutral	Cold (molecular)	10-50	10^3-10^7
	Cool (atomic)	100	1
	Warm	$8x10^3$	10^{-1}
Ionized	Warm	10^4	10^0-10^4
	Hot	$5x10^5$	10^{-3}

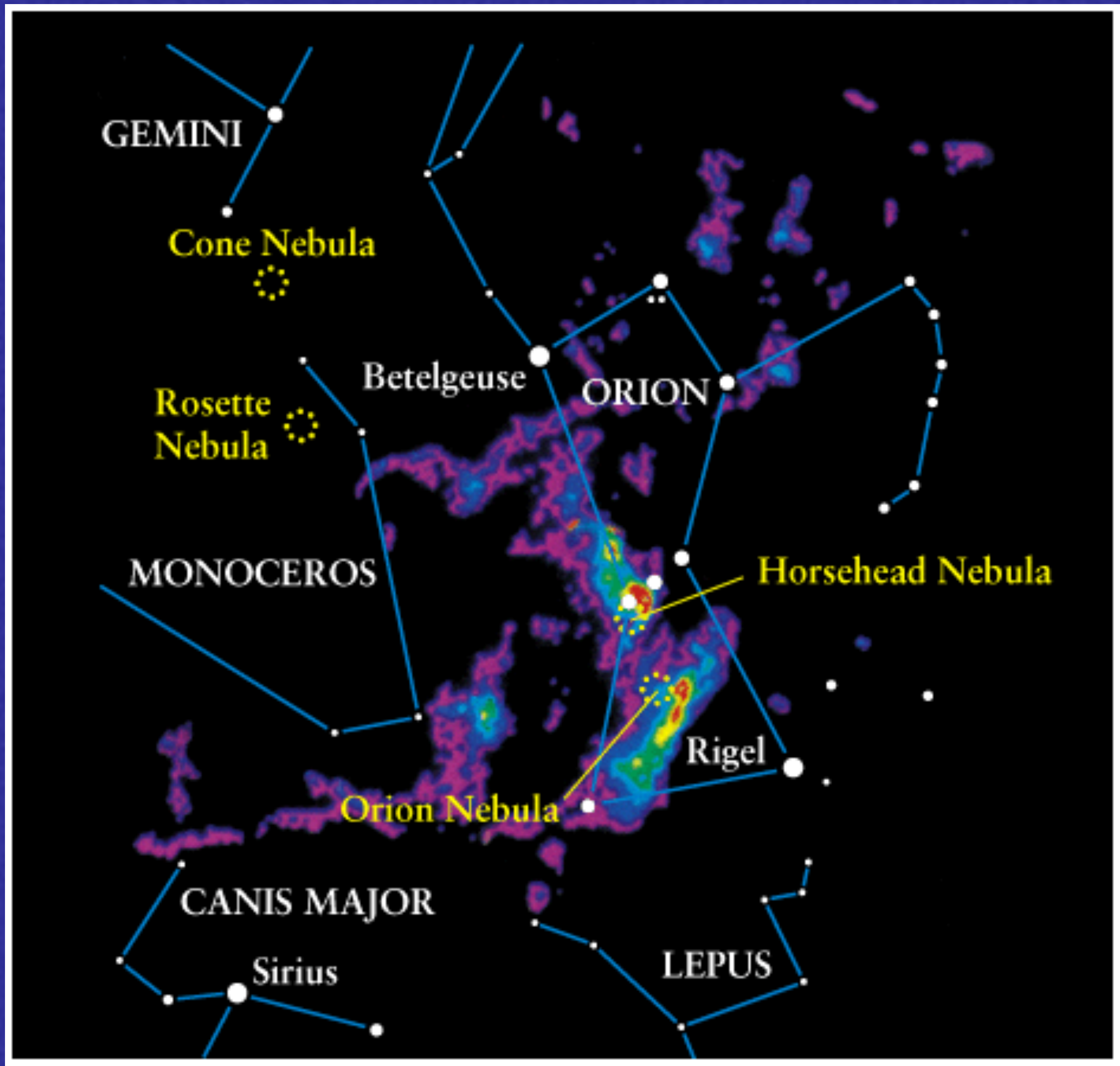
Molecular clouds

- Cold (~10 K), dense (10^3–10^7 molecules/cm3)
- Cloud masses: 10^3 - 10^6 $M_{\odot}$ (plenty of stars can form of this)
- Cloud sizes: a few to 100 pc
- In the Galaxy: ~5,000 molecular clouds
- Often buried deep within neutral atomic clouds

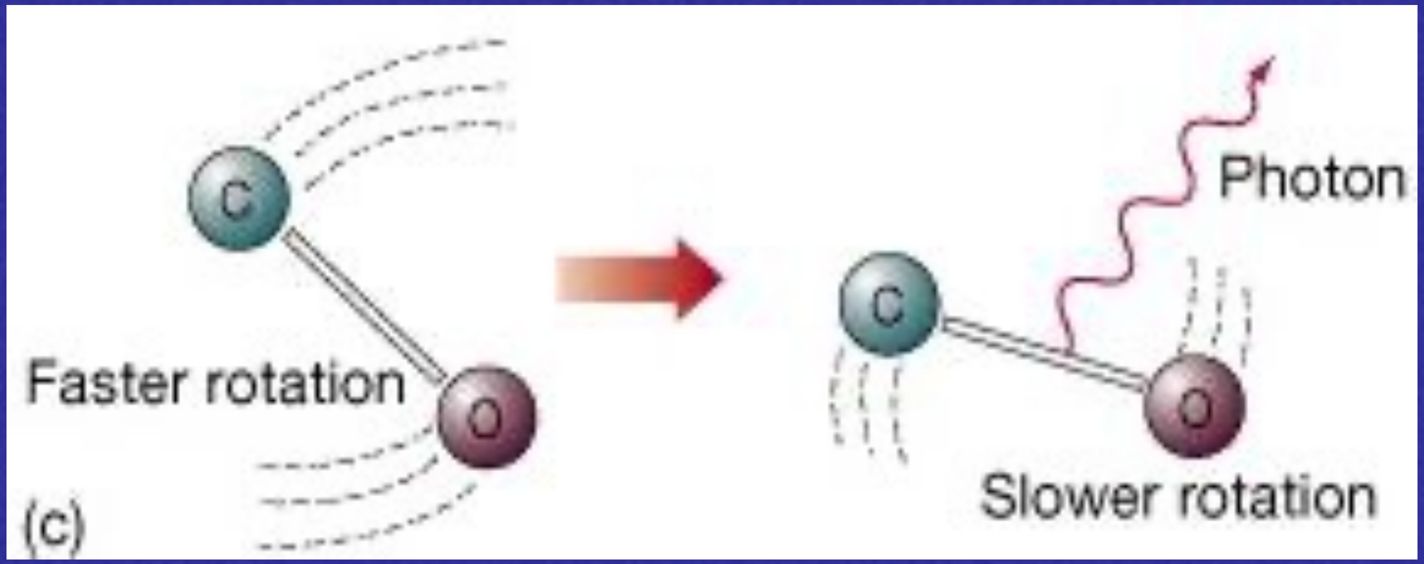
Molecular cloud seen as dark clouds in the optical

- Most abundant is H_2, but it has no allowed mm emission, so other "trace" molecules observed: CO, H_2O, NH_3, HCN etc.

- These molecules undergo rotational energy level transitions, emitting photons at mm λ



False color radio observations of CO in the Orion molecular cloud complex.



H_2 is symmetric - need atoms of different mass to produce rotational transitions.

Molecules in space

Over 140 molecules detected in space so far.

Examples:

- 2 atoms: H_2, CO, OH, CN
- 3 atoms: H_2O
- 6 atoms: CH_3OH
- 9 atoms C_2H_5OH
- 13 atoms: $HC_{10}CN$ (cyanodecapentayne)

Acetamide in SgrB2 (9 atoms) contains a bond that link amino acids together (building bocks of proteins).

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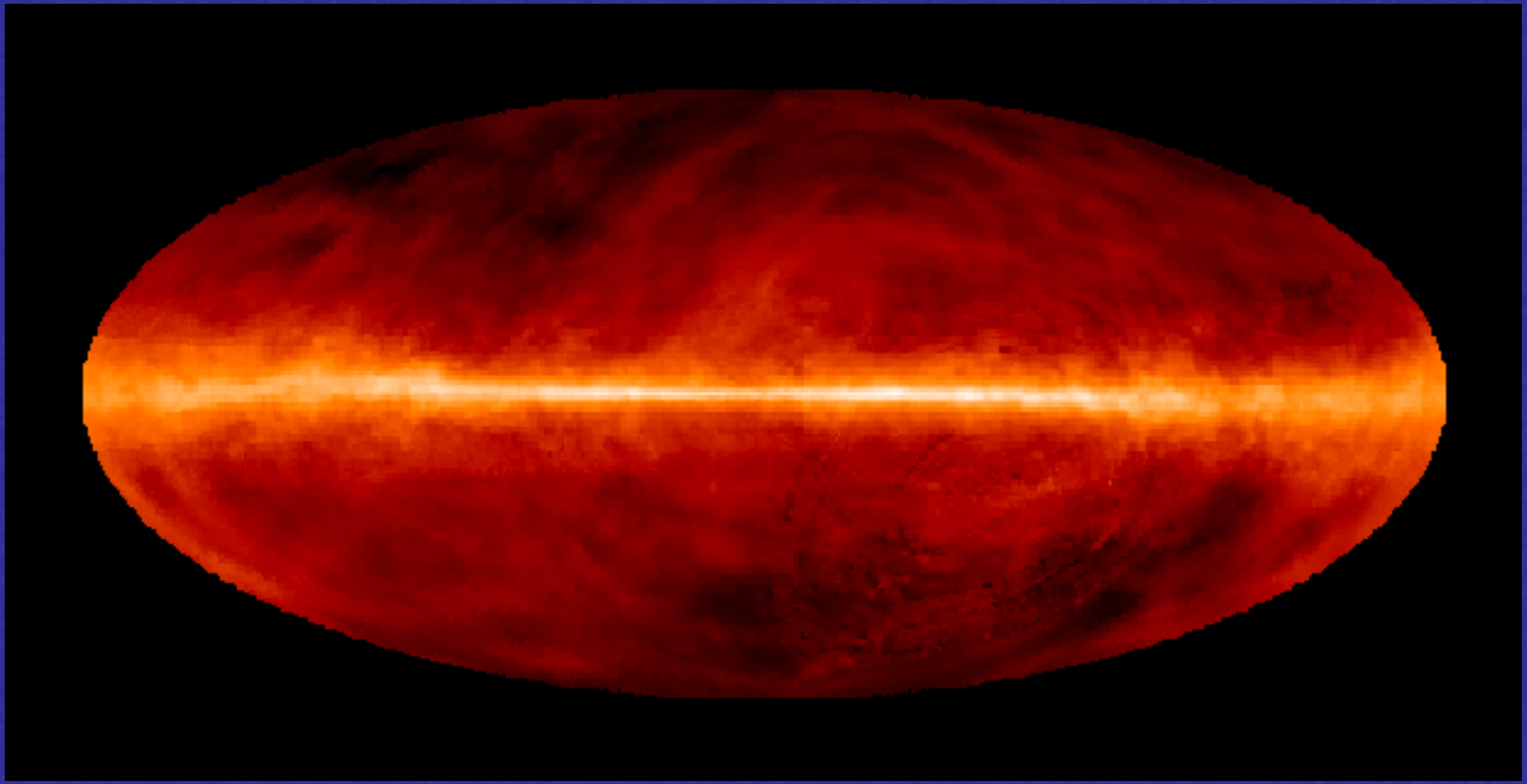
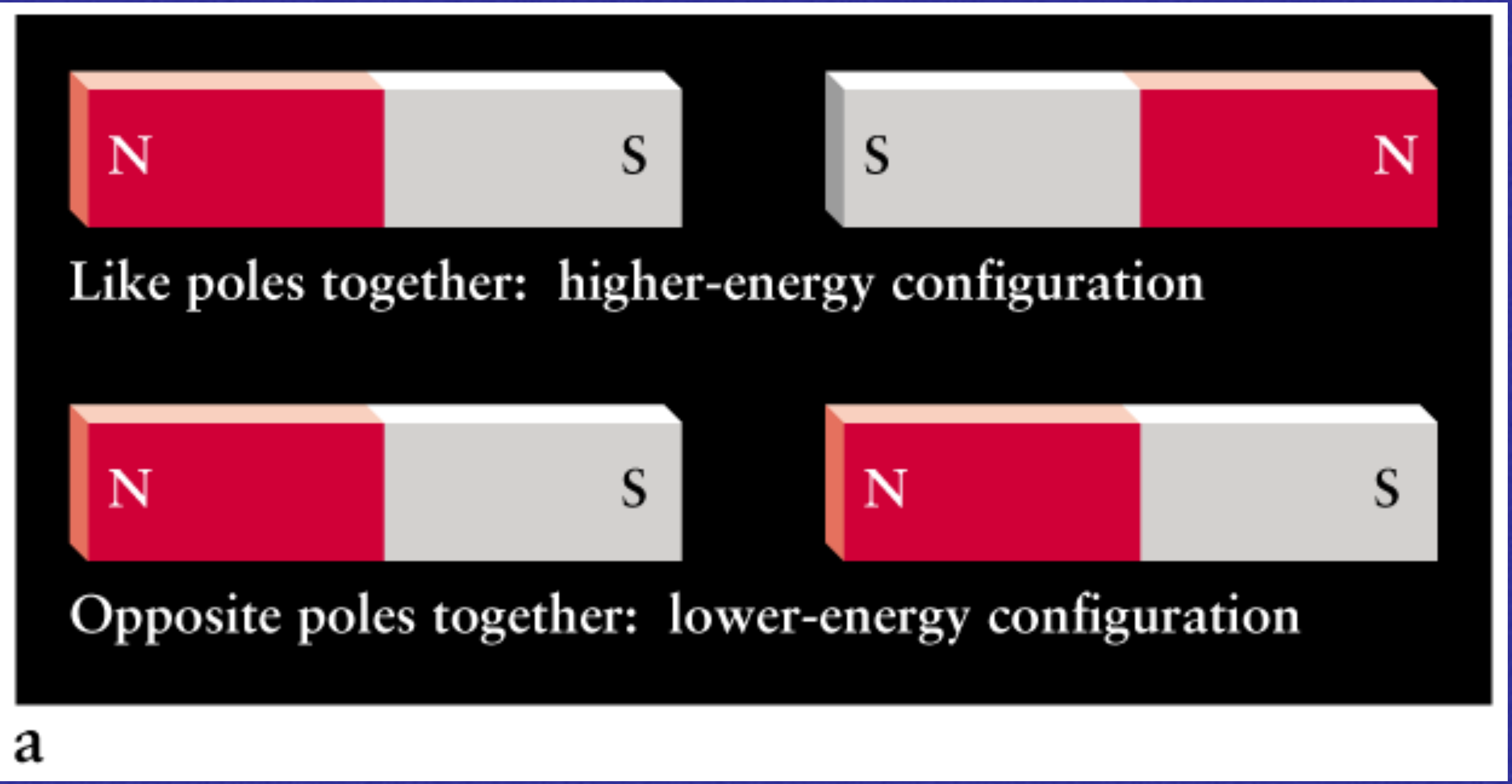
Atomic gas - HI

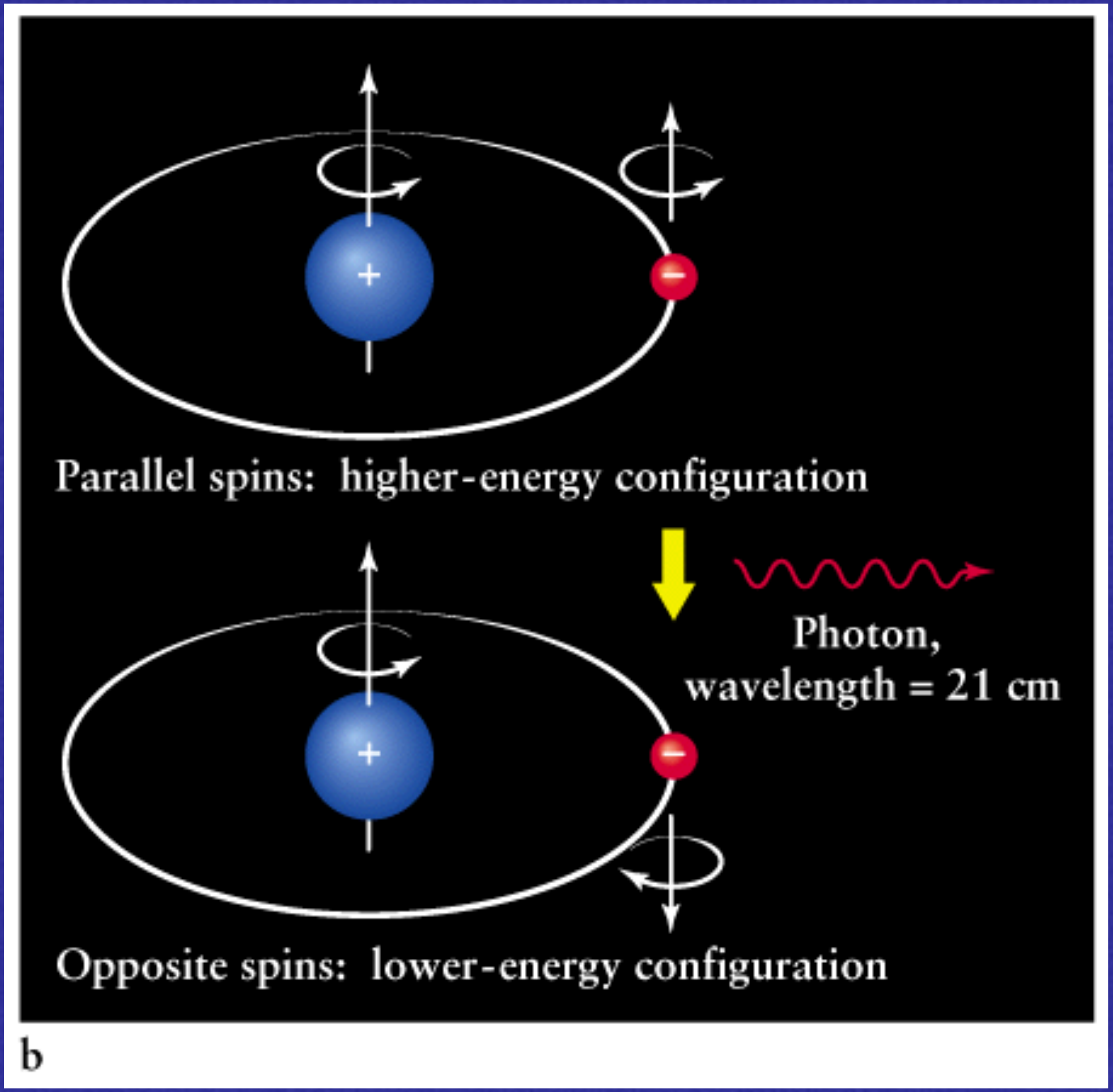
- Cool (and warm) atomic gas: T~100K (8000K), making up ~22% of the ISM
- 1-10 atoms/cm^3 (diffuse)
- Tenuous clouds filling a large part of the interstellar space
- No optical emission
- 2×10^9 $M_\odot$ in the Galaxy



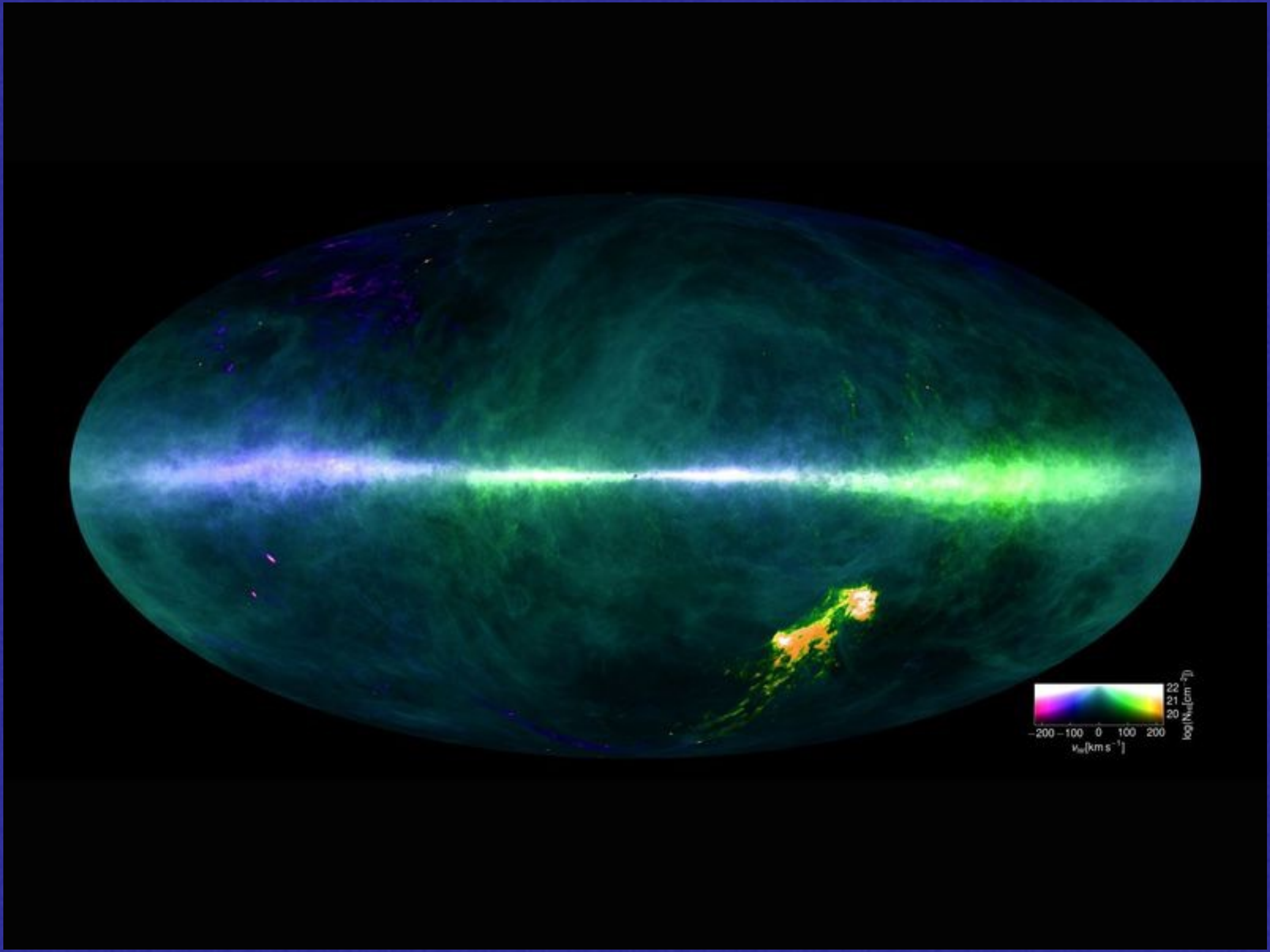
- Cold, neutral hydrogen with electrons in n=1 level still emits energy through the "spin-flip transition".
- How? Spinning electrons and protons are charged and act like magnets:



The spin-flip transition produces a 21-cm photon (1420 MHz).



21-cm (1420 MHz) map of neutral hydrogen in the Milky Way



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Emission nebulae - HII regions

- *nebula* = cloud (plural nebulae)
- ~5000/cm^3 (diffuse)
- T≅10^4 K (H essentially completely ionized)
- Sizes 1-20pc

Rosette Nebula

Hot, tenuous gas => emission lines (Kirchoff's laws)

- UV energies are required to ionize the atoms
- Provided by hot and massive O, B stars
- e^- quickly recombine with the p
- Dominant emission $H\alpha$, at $\lambda = 656$ nm. Color?

Lagoon Nebula

Tarantula Nebula

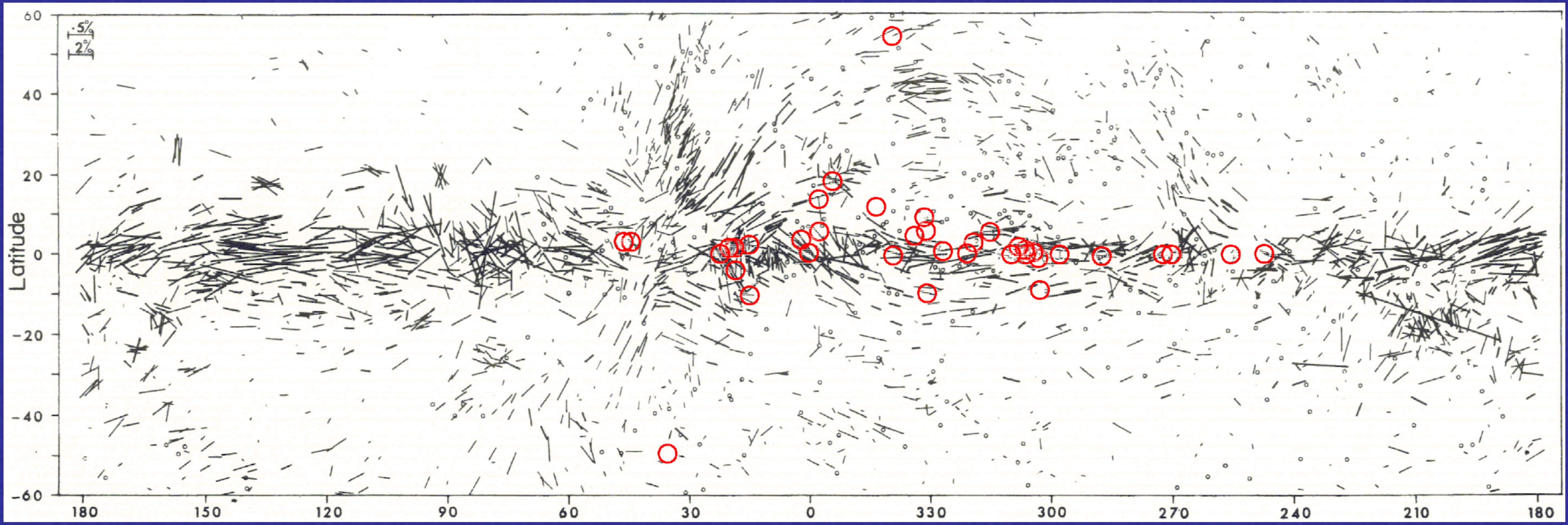
Reflection nebulae

- Blue color resulting from dust reflecting (scattering) light from nearby, bright hot stars
- Shorter wavelengths are most effectively scattered (why the sky is blue)

What kind of spectrum would you expect?

Other ISM components

- Hot gas X-ray emission; $T \cong 10^6$ K; very low density
- Cosmic Rays high energy particles, interact with B-fields $\Rightarrow$radio emission
- Magnetic fields 10^{-3}-10^{-6} of Earth's, widespread
- Supernova remnants radio, optical, x-ray
- Planetary Nebulae isolated objects – more later



.5%
2%
60
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Latitude
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270
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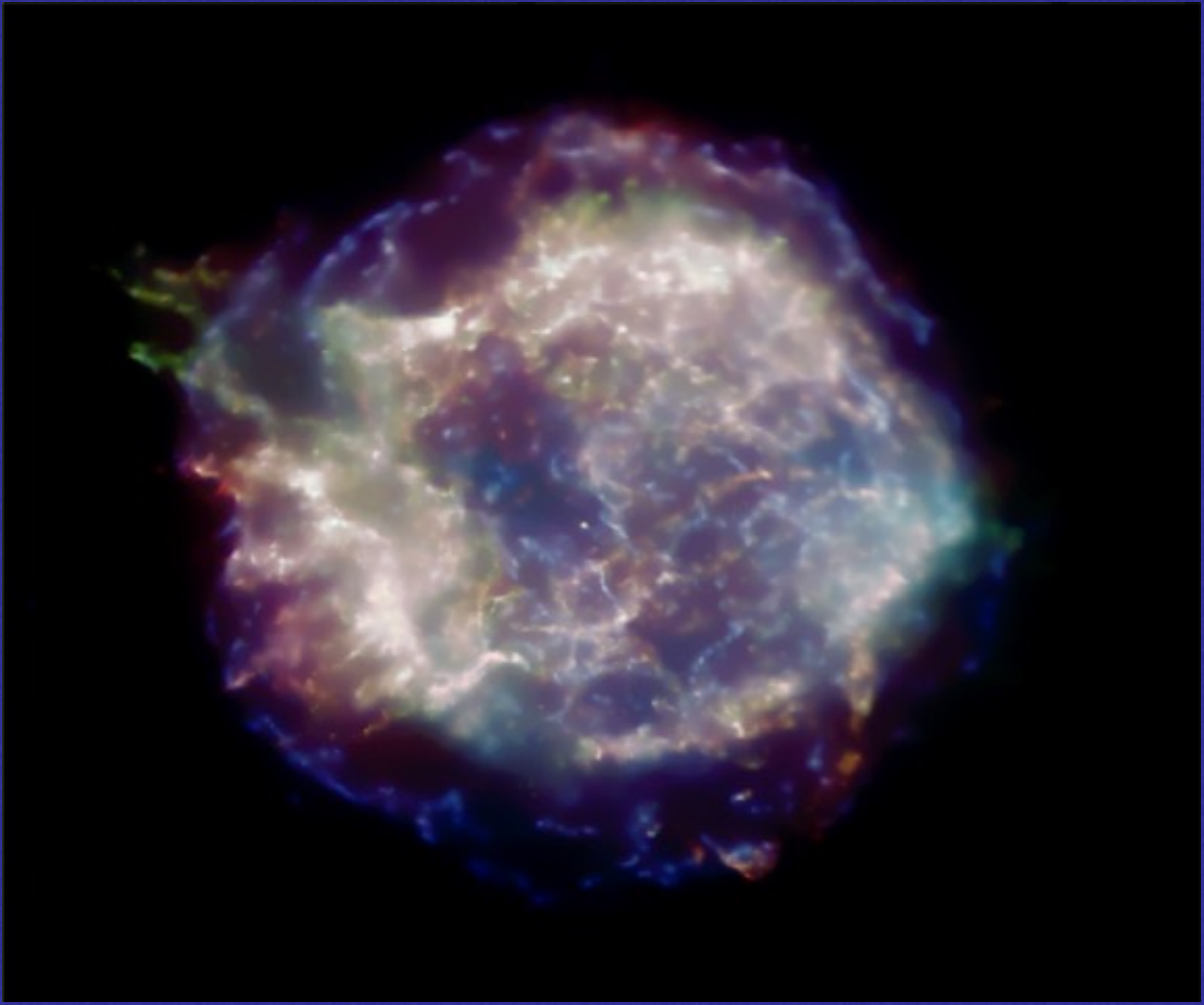
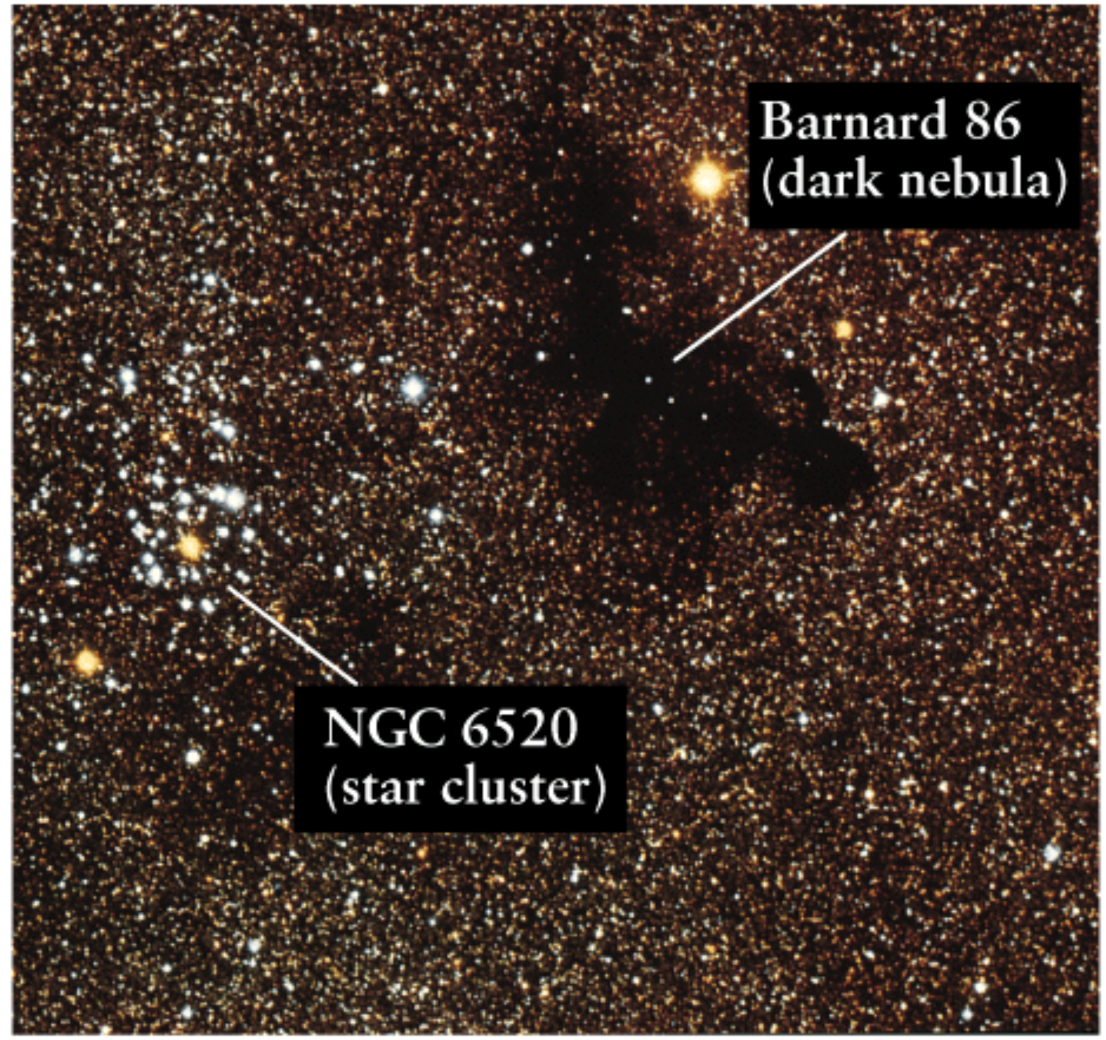
180



Planetary Nebula M2-9 HST • WFPC2
PRC97-38a • ST ScI OPO • December 17, 1997
B. Balick (University of Washington) and NASA

Which of these are involved with star formation?
-- HII regions, molecular clouds, dust clouds



Note that star clusters are usually seen in star forming regions


IR-View of "Pillars of Creation" at Centre of Eagle Nebula
(VLT ANTU + ISAAC)
ESO PR Photo 37b/01 (20 December 2001)
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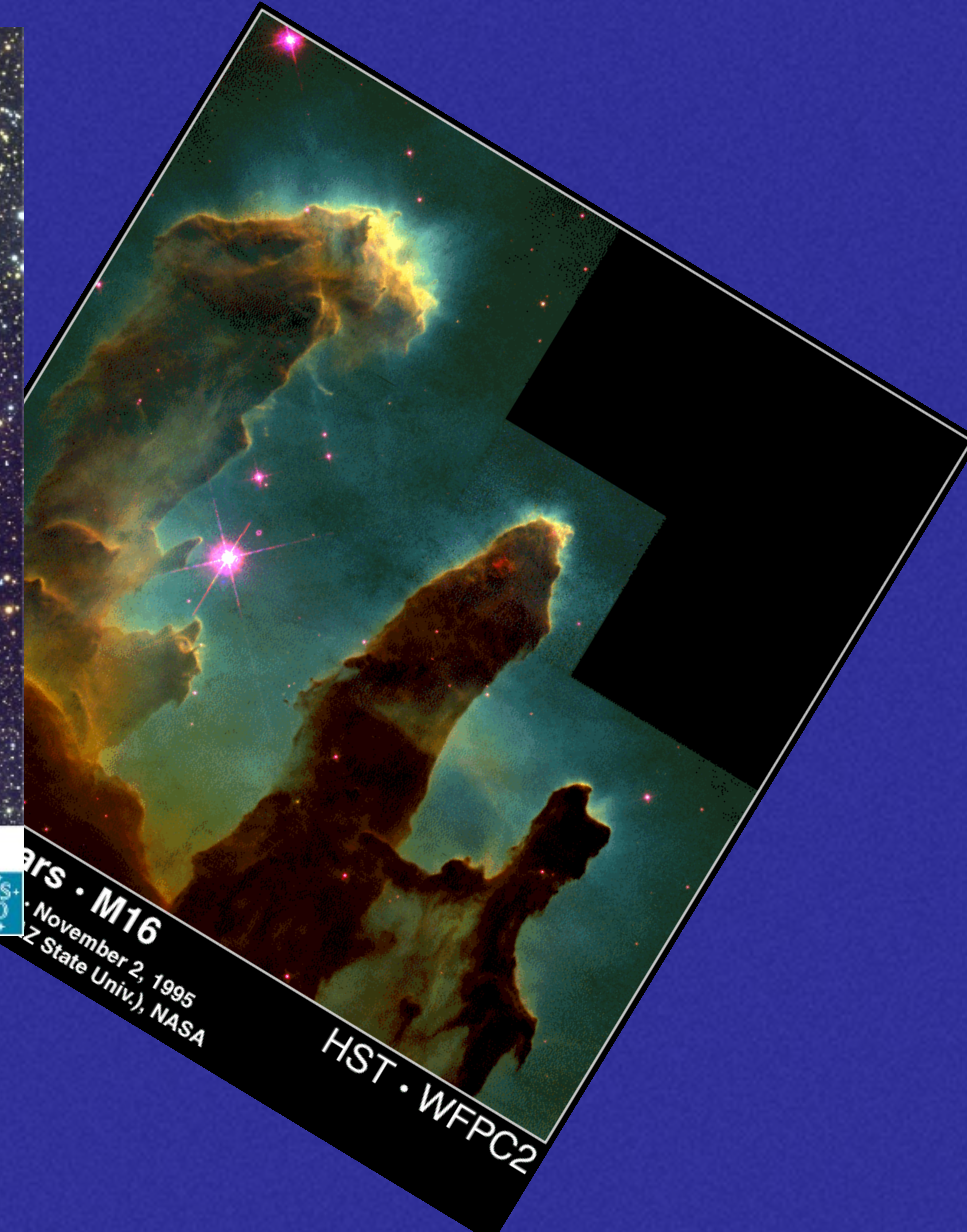
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November 2, 1995
Z State Univ.), NASA
HST · WFPC2

Star formation
Chapter 18

Star formation

- Gravitational collapse
  - Start with a collection of matter (e.g. a molecular cloud) somewhere in space and let gravity work on it. What happens?
  - Unless matter distribution perfectly uniform and infinite it will collapse eventually unless something stops it.

- What can stop gravitational collapse?
  - Gas pressure (hitting the matter it is falling onto)
  - Radiation pressure (if matter becomes hot enough)
  - Magnetic pressure
  - Angular momentum (keeps stuff spinning instead of collapsing)

Under pressure: the ideal gas law

- To determine pressure we use the ideal gas law, $P=nkT$
- The core of the star formation problem is what happens to *P, n* and *T* when gravity acts.

- If two clouds co-exists with the same pressure *P* (*pressure equilibrium*), they are stable when pressures balanced.
- If pressures not balanced, the higher pressure region will compress the lower pressure region until pressure equilibrium is restored. Thus,

$$n_1T_1=n_2T_2$$

Are hot or cold clouds denser under the same pressure?

K-H heating: gravitational heating

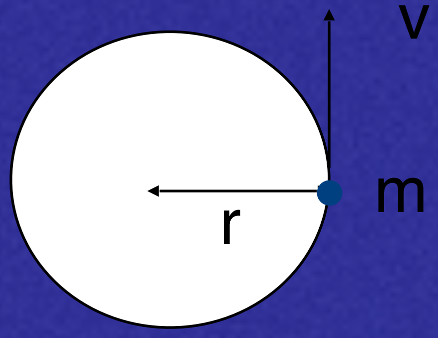
- Kelvin-Helmholtz contraction is contraction under gravity:
  - Gravitational potential energy converted into kinetic energy of the gas, which in turn converts into heat.
  - Recall: $E=mv^2/2 - GMm/r$
  - As cloud contracts, potential energy gets more highly negative to keep *E* the same, thus kinetic energy more highly positive.
  - Some heat radiated away at the surface of the cloud, the rest raises *T*
  - The more massive a cloud, the more potential energy available, the hotter it gets in the center.

Gravitational stability

- As a protostellar cloud collapses, it heats up, but it also gets more dense => increase in pressure $P=nKT$
- If the cloud is not dense enough for a given T (not cold enough for its density), the pressure wins and cloud will not collapse - the cloud is *gravitationally stable.*
- To continue a collapse, the cloud must lose heat, it must *cool*.
- Thermodynamics says heat flows from hot to cold. Three ways to transport heat:
  - Radiation
  - Convection
  - Conduction (some materials carry heat directly, like solid metals)
- Cooling of a cloud takes long time, since they are not very dense and therefore do not radiate efficiently (and do not convect at all).
- Very massive, cold clouds collapse easily - gravity is too strong.

Angular momentum

- Angular momentum, *L,* is a property of motion related to rotation about some point. Also related to the spin concept.
- *L* of a body of mass *m* moving at velocity *v* perpendicular to the line from the center to the body at distance *r* is *L=mvr.*



- *L* conserved in systems where only gravity is operating (friction can destroy *L*).
- Example: planets move faster in their elliptical orbits when closer to center of mass.

Spin up problem

- Rotation frequency f given by $f=v/2\pi r$ => $L=2\pi mfr^2$
- Thus, in a cloud collapse rotation gets amplified by the factor $f_2/f_1=(r_1/r_2)^2$
- Example: start with a cloud ~0.1pc in size and collapse it to the size of the Sun => $(r_1/r_2) = (3\times10^{15}m/7\times10^8m) = 4\times10^6$

  => $(r_1/r_2)^2=1.8\times10^{13}$, thus the cloud will spin up in rotation frequency by this factor! Even an extremely slowly spinning cloud (random motions) will be amplified into extreme rotation speeds - this is NOT seen!
- What does really happen? Gas friction causes it to form a spinning disk (*protostellar disks)*, which may be precursors for planetary systems formation.
- Binary stars can also form, as this is a way to store angular momentum

Magnetic fields

- Protostellar clouds have magnetic fields, and during the cloud collapse the magnetic field will be compressed and thus grow in strength.
  - Grows as inverse of volume: $B_2/B_1=(R_1/R_2)^3$

- B-field exerts a pressure, which is proportional to B^2: $P_2/P_1=(R_1/R_2)^6$.

- When cloud collapses by a factor 4×10^6, the magnetic pressure increases by a factor 4×10^{39}. Even initial tiny B-fields would grow to completely dominate any other pressure.

- However, stars are forming, and therefore there must be a removal of the B-field, along with the angular momentum, during a collapse.

- Done via magnetic diffusion, where the B-field (through action of small amounts of ionized gas) will diffuse out of the spinning cloud and drag along gas, removing angular momentum (cf. lecture of the Sun!).

Stages of star formation

- Start with a large, cold cloud: 0.1pc diameter, T~100 K, M=10-100$M_{\odot}$.
- First, gravity dominates and collapse is *free-fall* (like falling from the top of a building).
- As n and T increases, pressure begins to slow collapse. This is slower than free-fall, and outer gas is held up by a slower, inner gas core.
- K-H process converts gravitational energy to heat, and some radiated into space, rest heats up core.
- Outer parts spin-up to form a protostellar disk, slowing the collapse since protostar can only get new material through inner parts of disk (which has lost angular momentum from gas friction and magnetic diffusion).

- The protostar becomes hot enough to blow gas from the poles, and twisted B-fields help spew out gas in bipolar jets (v=200km/s).

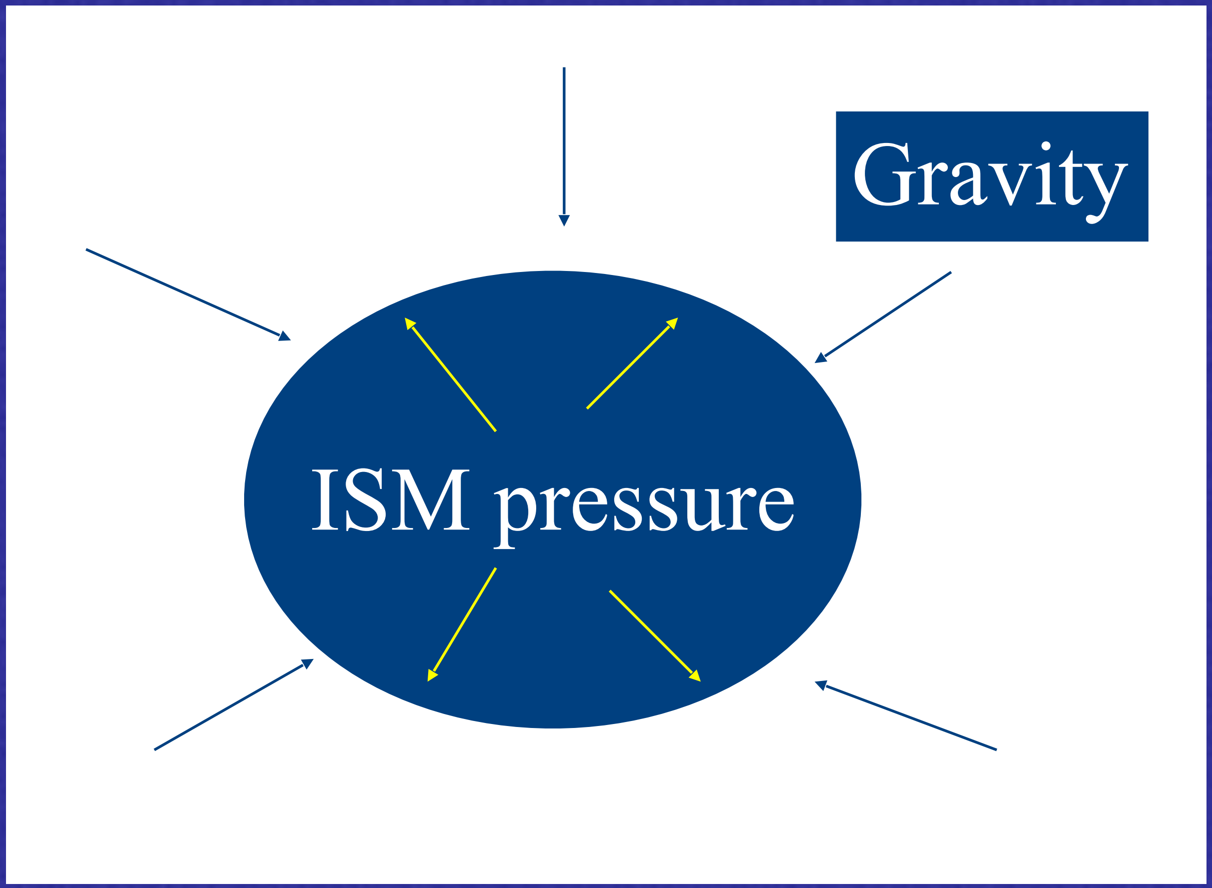
- Finally, protostar core hot enough to ignite nuclear fusion and becomes a star.

- At some point the luminosity is large enough to blow away most of the surrounding gas, and accretion stops. The star is now visible.

- Very little of the original cloud mass makes it into the star itself. Some of the protostellar disk remains, which might stay around long enough to form a planetary system.

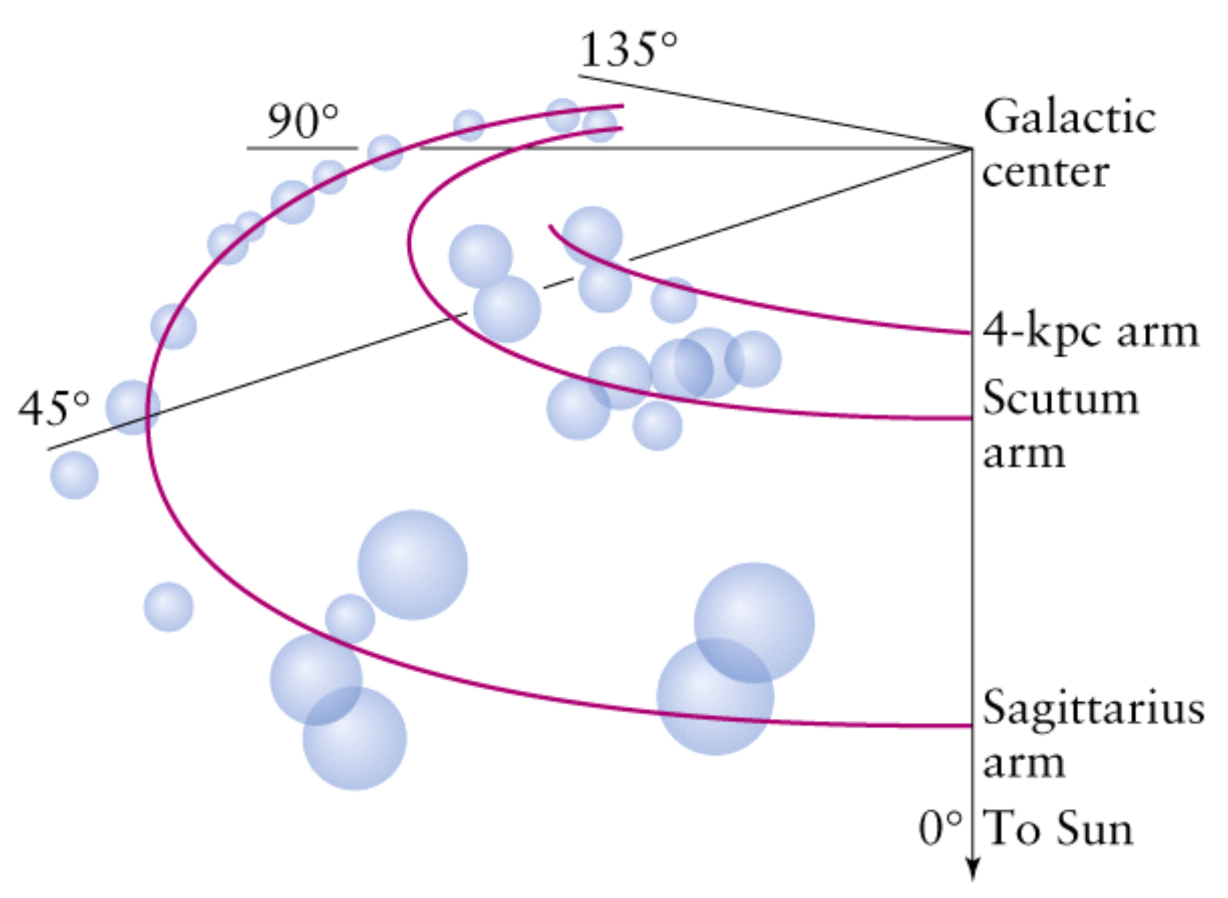
Stage 1: Cloud collapse

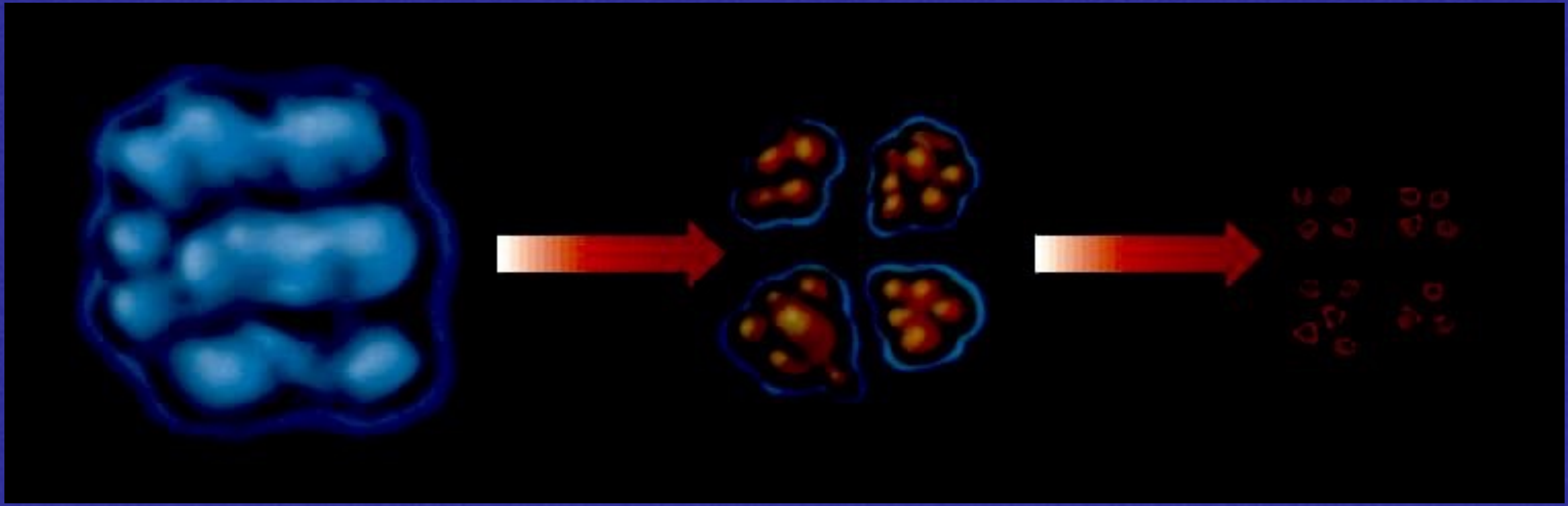
- Desired result: a star, with $n \sim 10^{24}$ cm^{-3}
- Resources: the interstellar medium (ISM), with $n \sim 10^5$ - 10^7 cm^{-3} (dense molecular clouds)
- Recall: a cloud withstands gravitation by its internal pressure



- Internal pressure sources: gas pressure from internal heat, radiation pressure, plus pressure from embedded magnetic fields

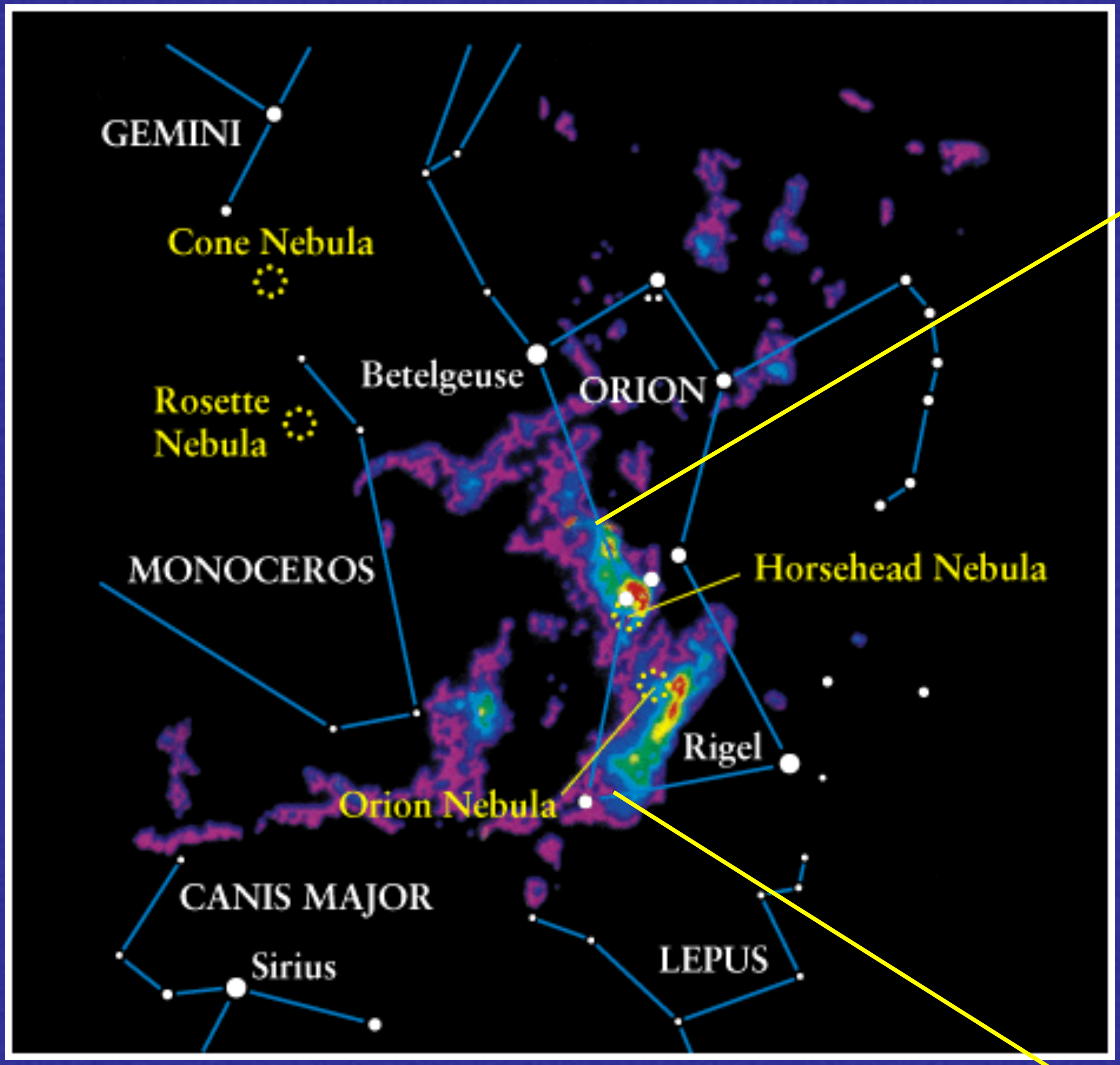
- A collapse (gravity>internal pressure) can be triggered by
  - Collisions with other clouds (cloud-cloud collisions)
  - Shocks from supernovas
  - Passage through a spiral arm in the Galaxy (density enhancement)

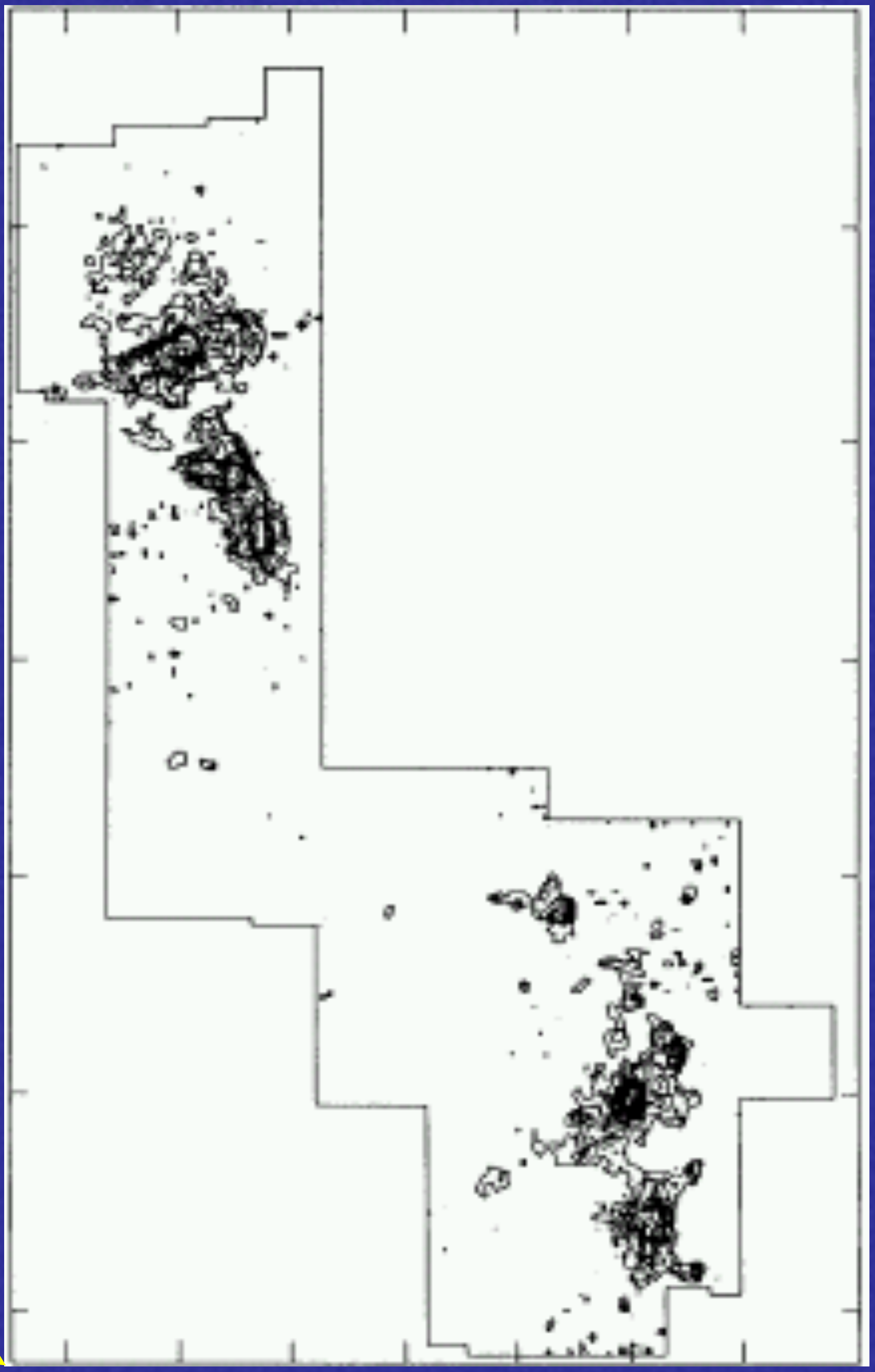




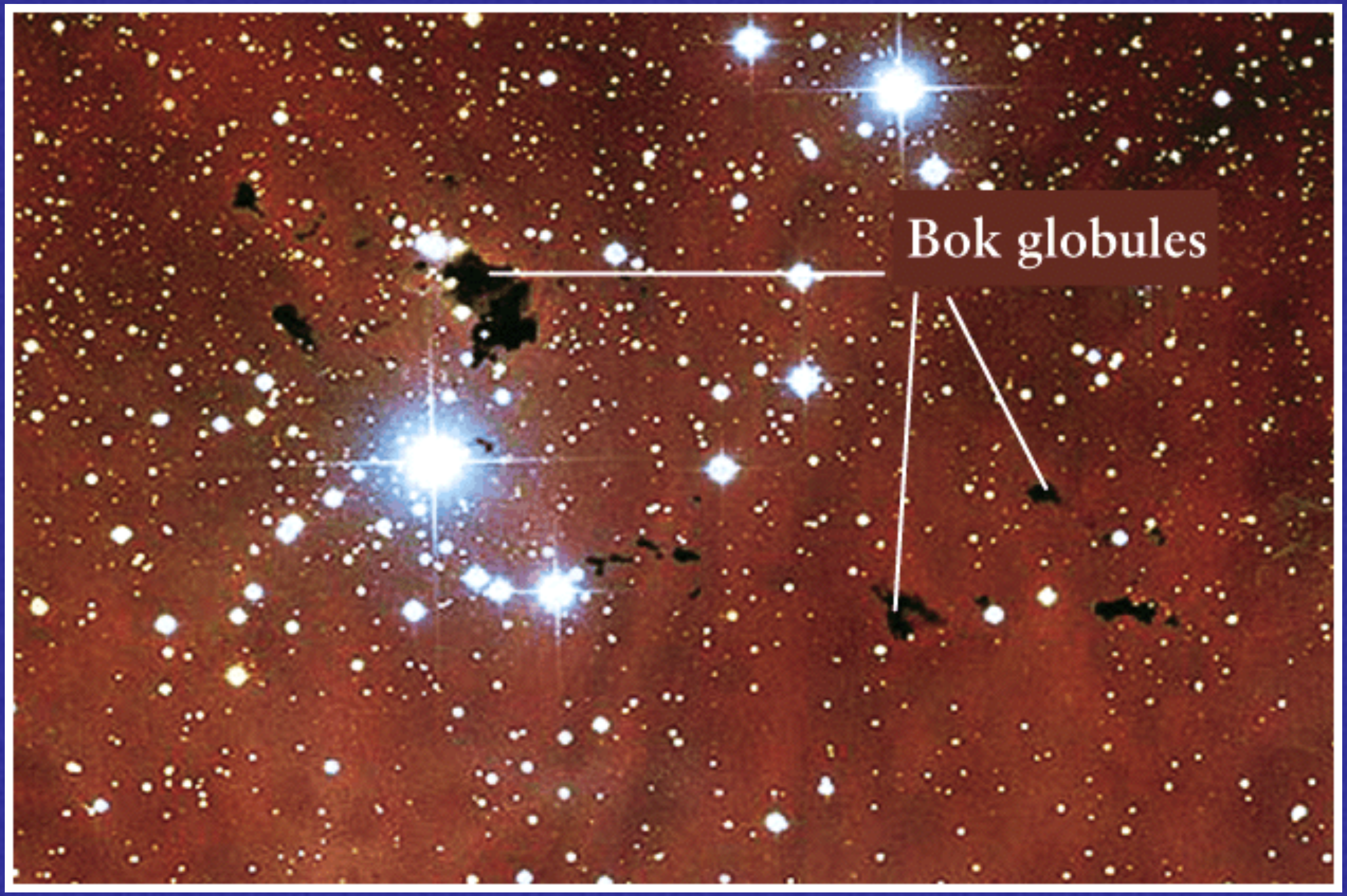
- Clouds are inhomogeneous - clumpy.
- Clumps start to collapse, densest clumps collapses first and fastest => fragmentation.
- 100s to 1000s of fragments may exist in one collapsing molecular cloud.

Fragments in Orion MC, about 1000 times denser than average gas in cloud.



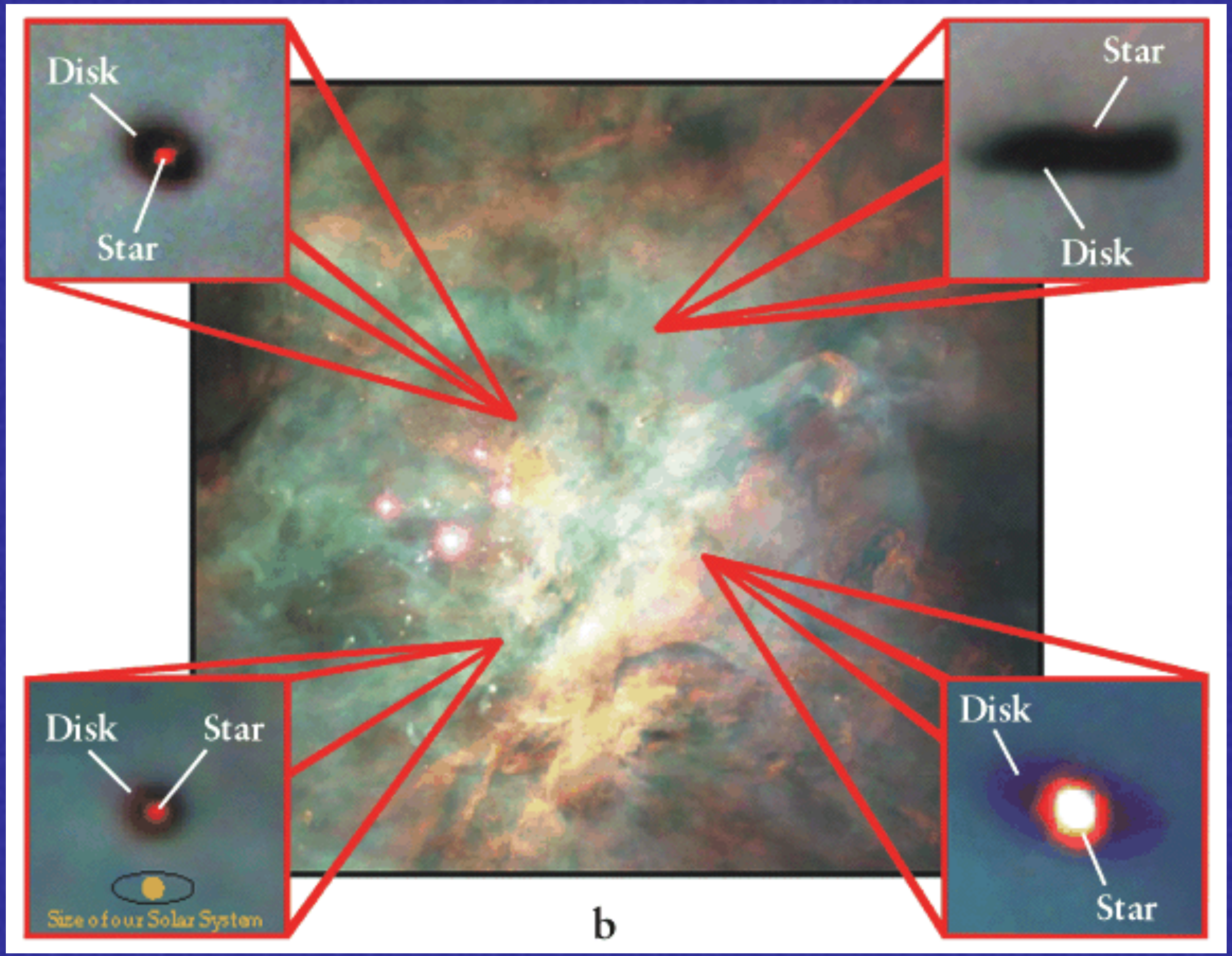


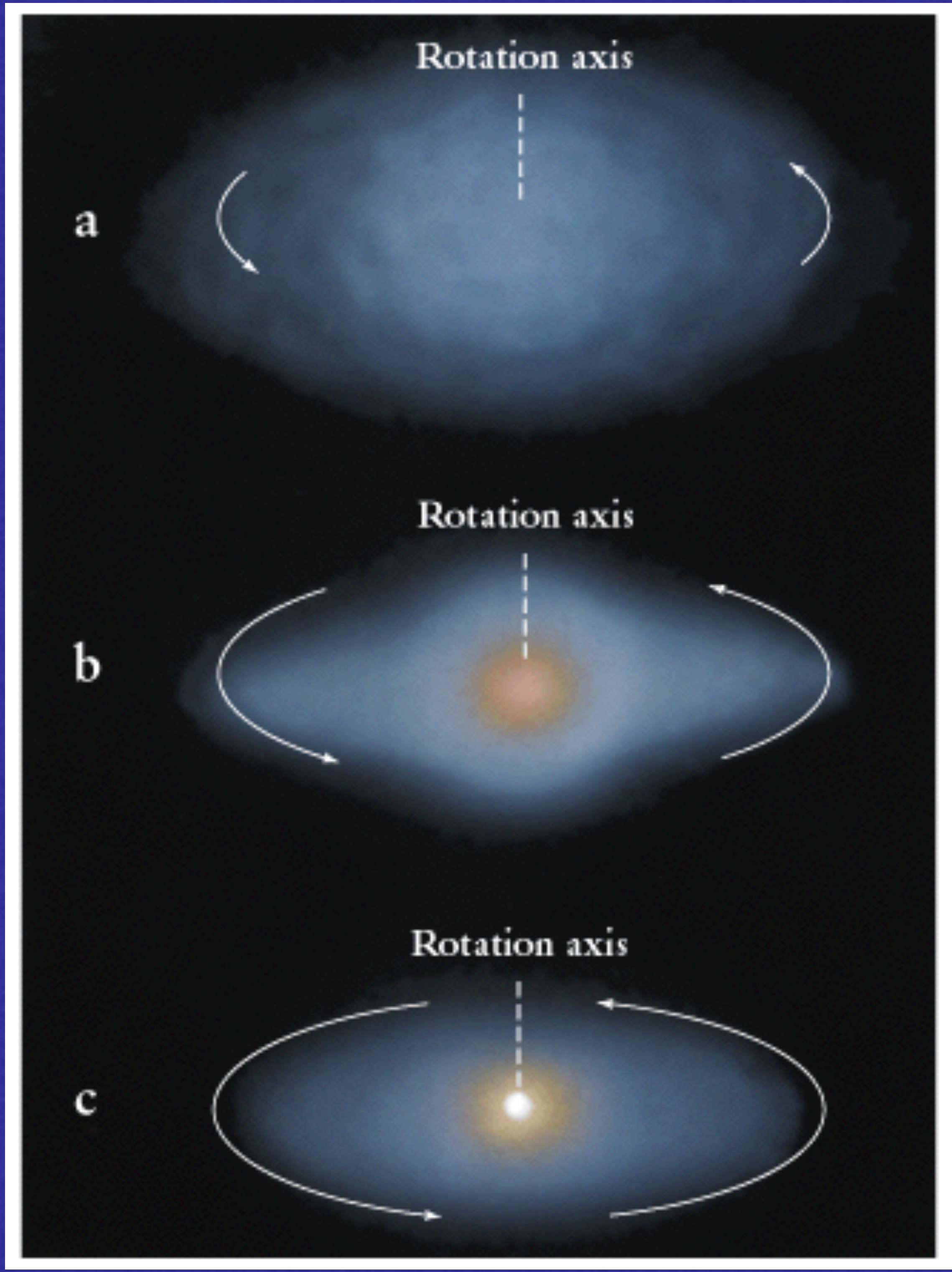
- Bok globules are good examples of very small fragments of dense gas.



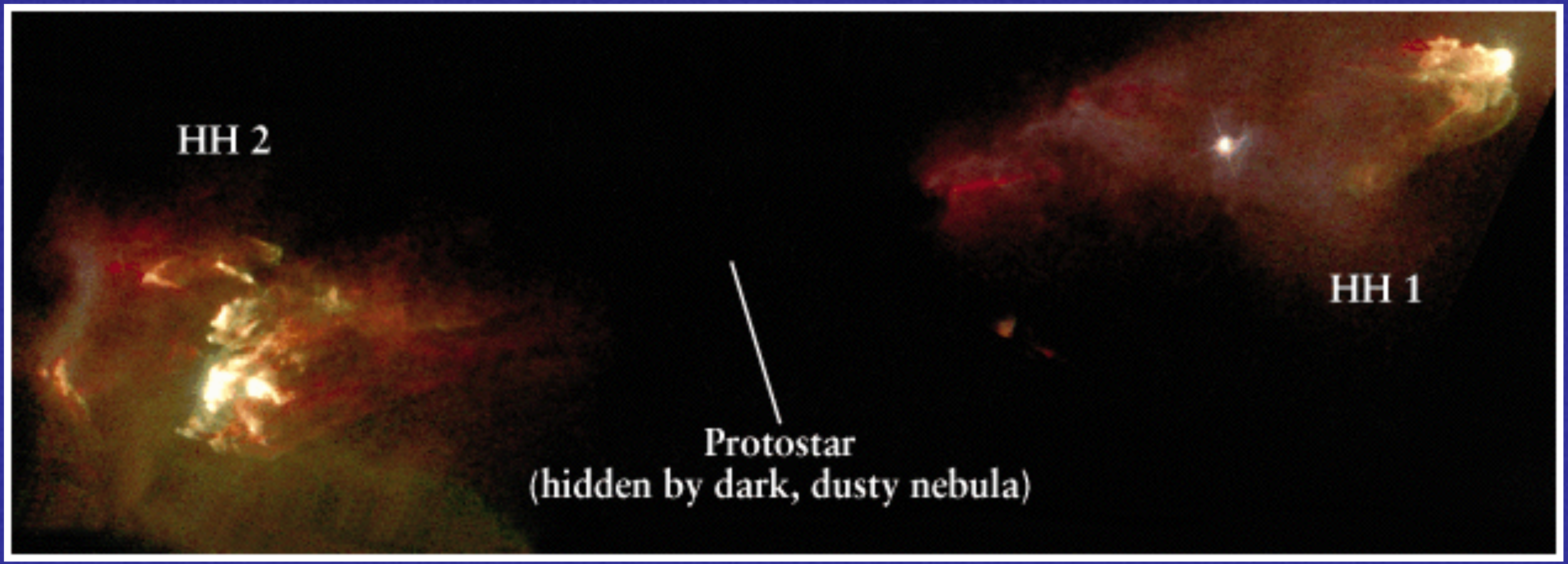
Stage 2: Clump to protostars

- Initial rotation and conservation of angular momentum will cause the formation of a protostar and a flattened disk



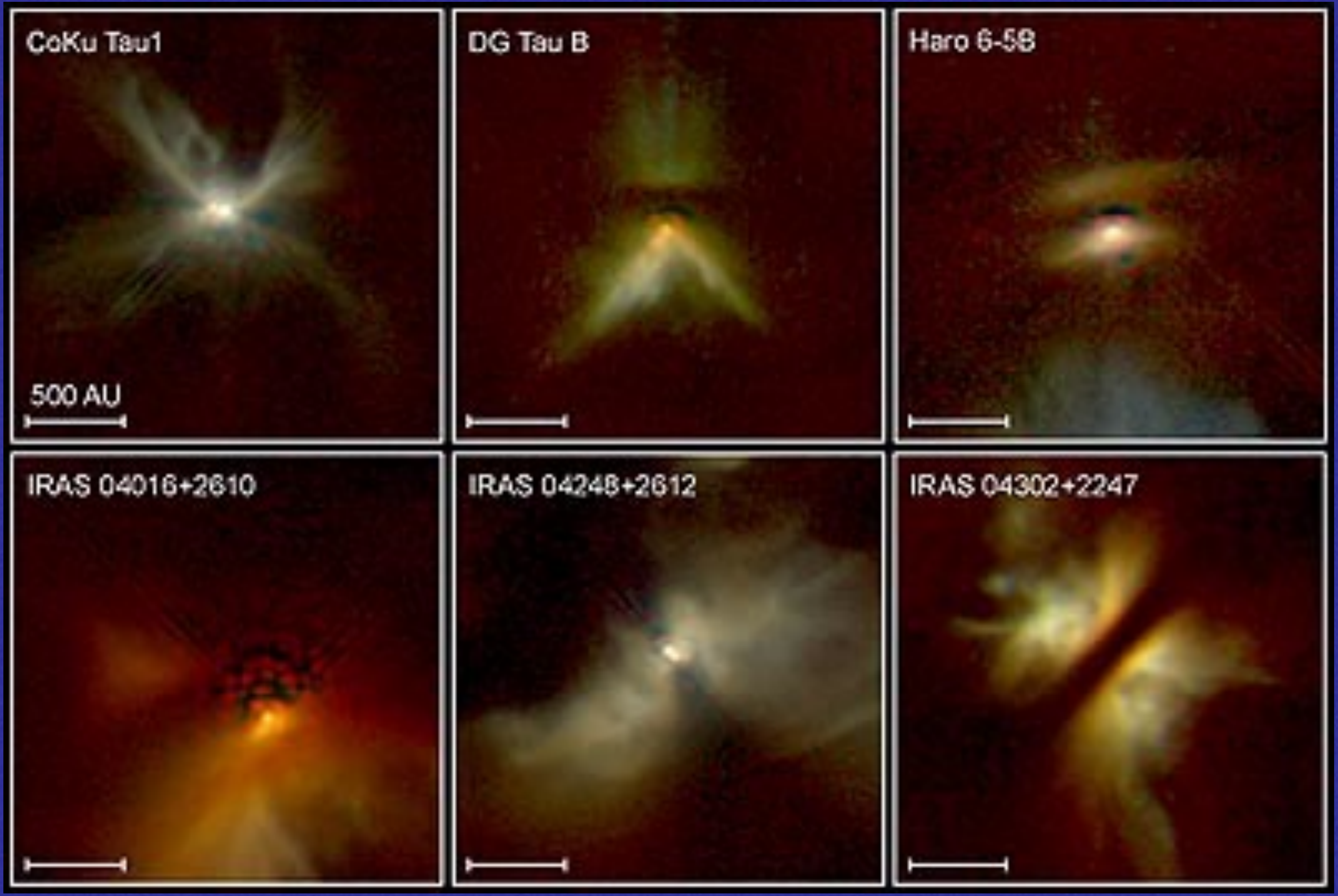


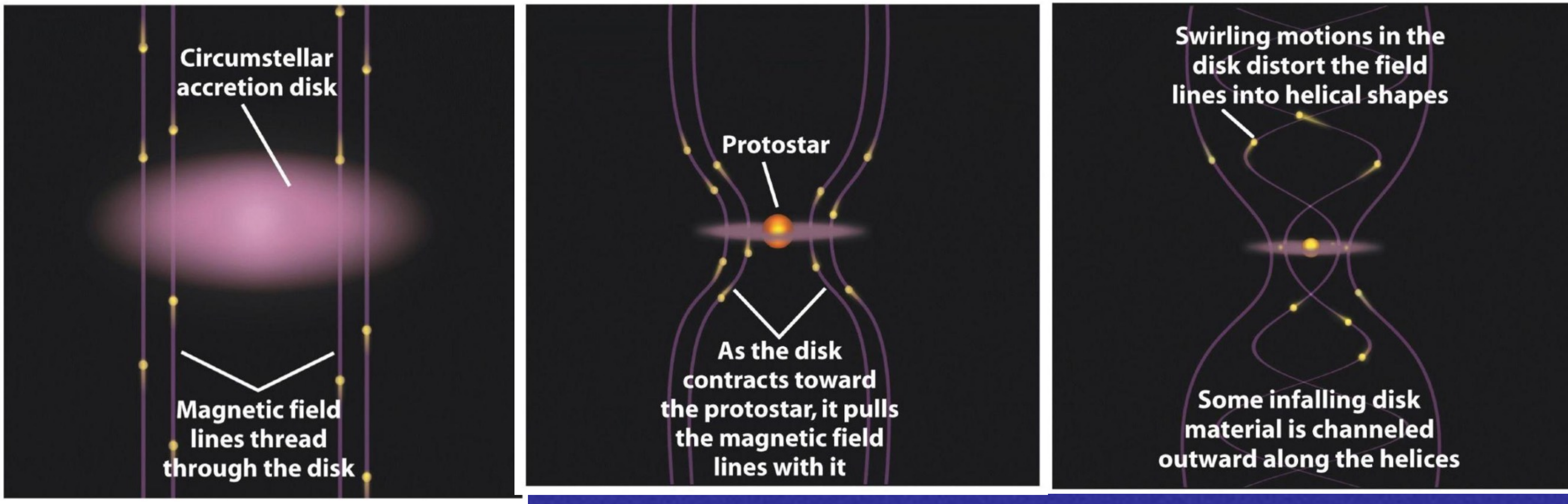
Some protostars (T Tauri types) eject gas, and create Herbig-Haro objects as ejected gas hits nearby ISM.

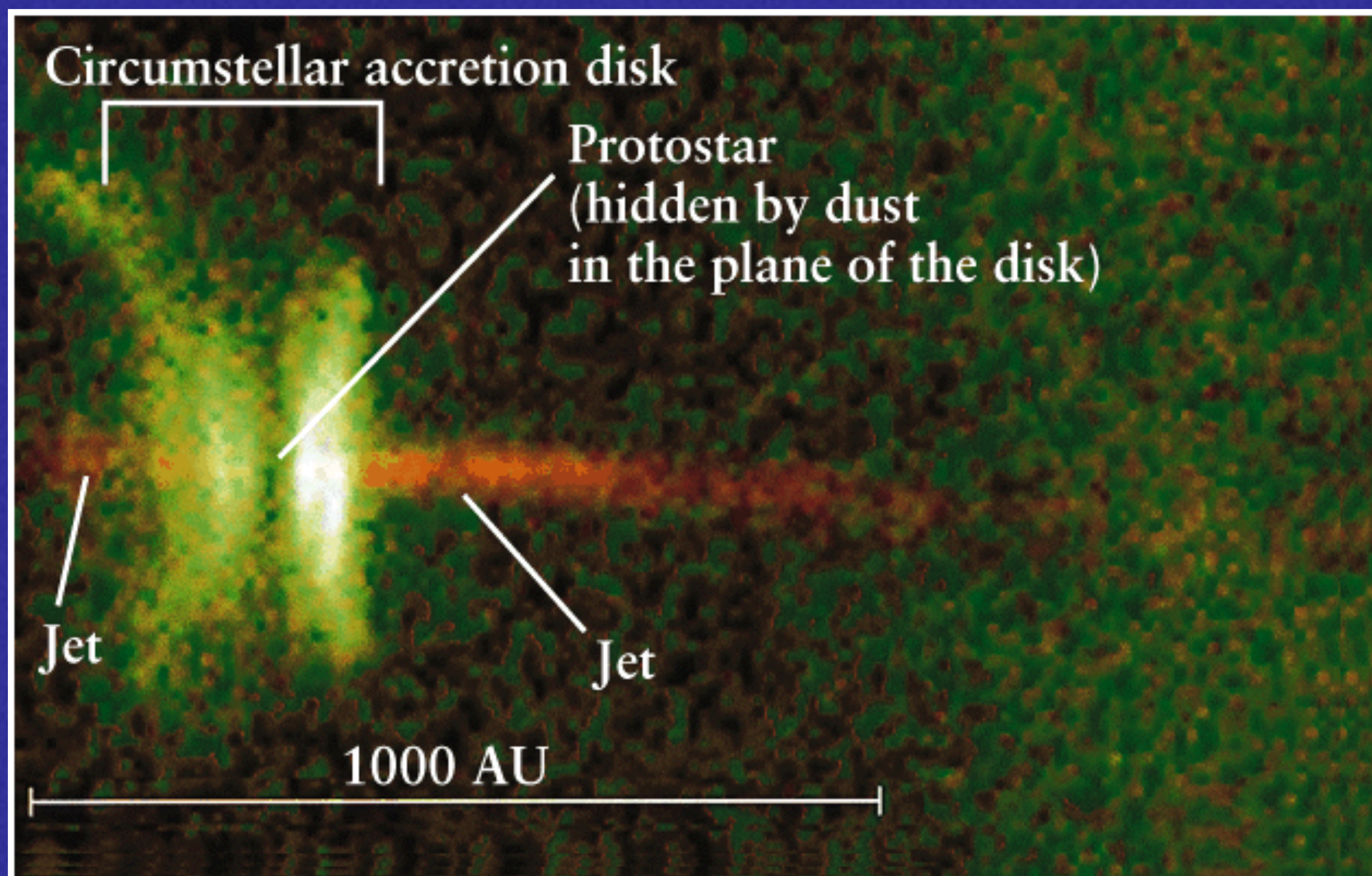


The protostar lies between ejected gas blobs, still embedded deep in the parent cloud.

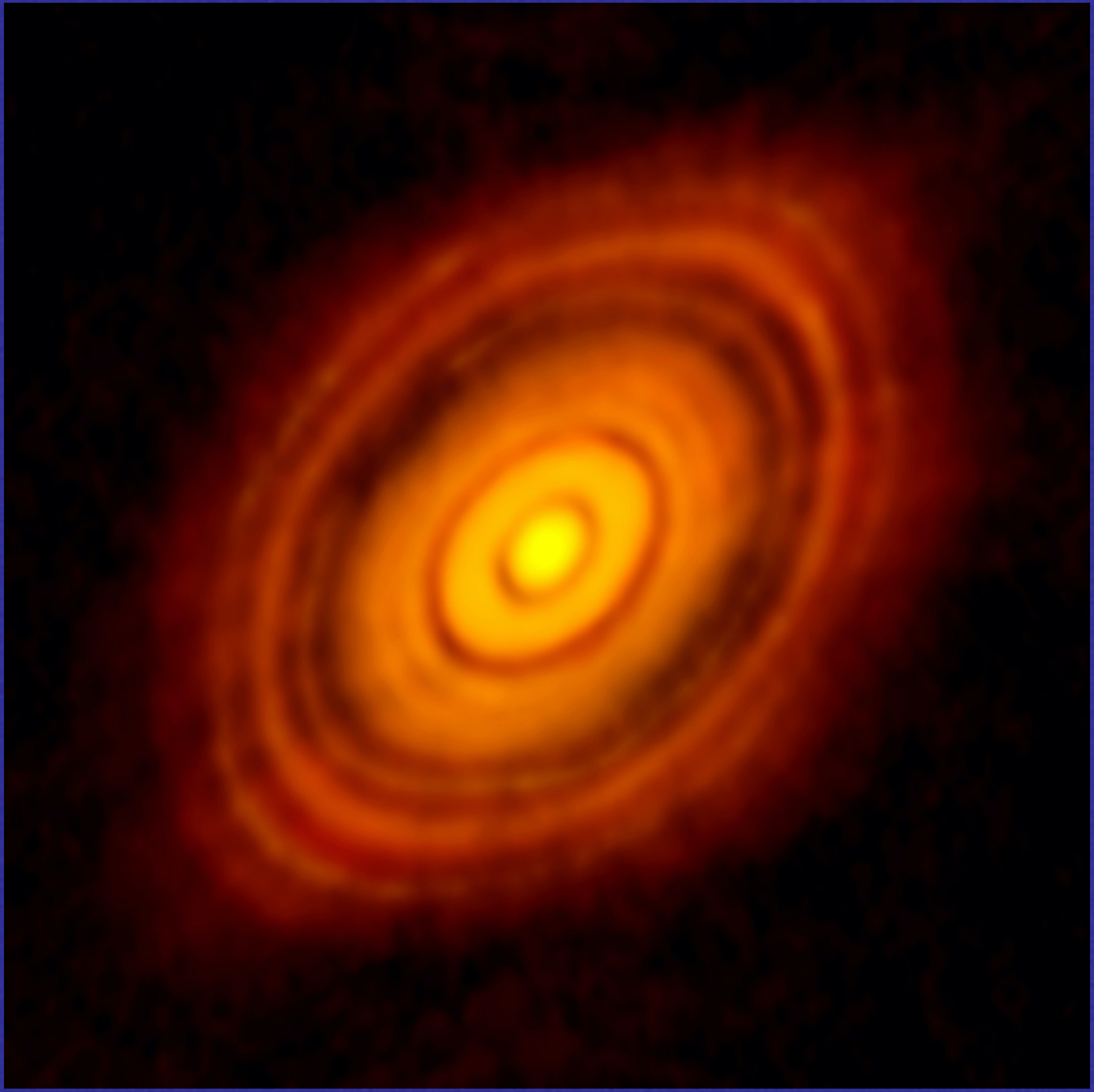
More Herbig-Haro objects. Note the equatorial dust.




Circumstellar accretion disk
Magnetic field lines thread through the disk
Protostar
As the disk contracts toward the protostar, it pulls the magnetic field lines with it
Swirling motions in the disk distort the field lines into helical shapes
Some infalling disk material is channeled outward along the helices


Circumstellar accretion disk
Protostar (hidden by dust in the plane of the disk)
Jet
Jet
1000 AU

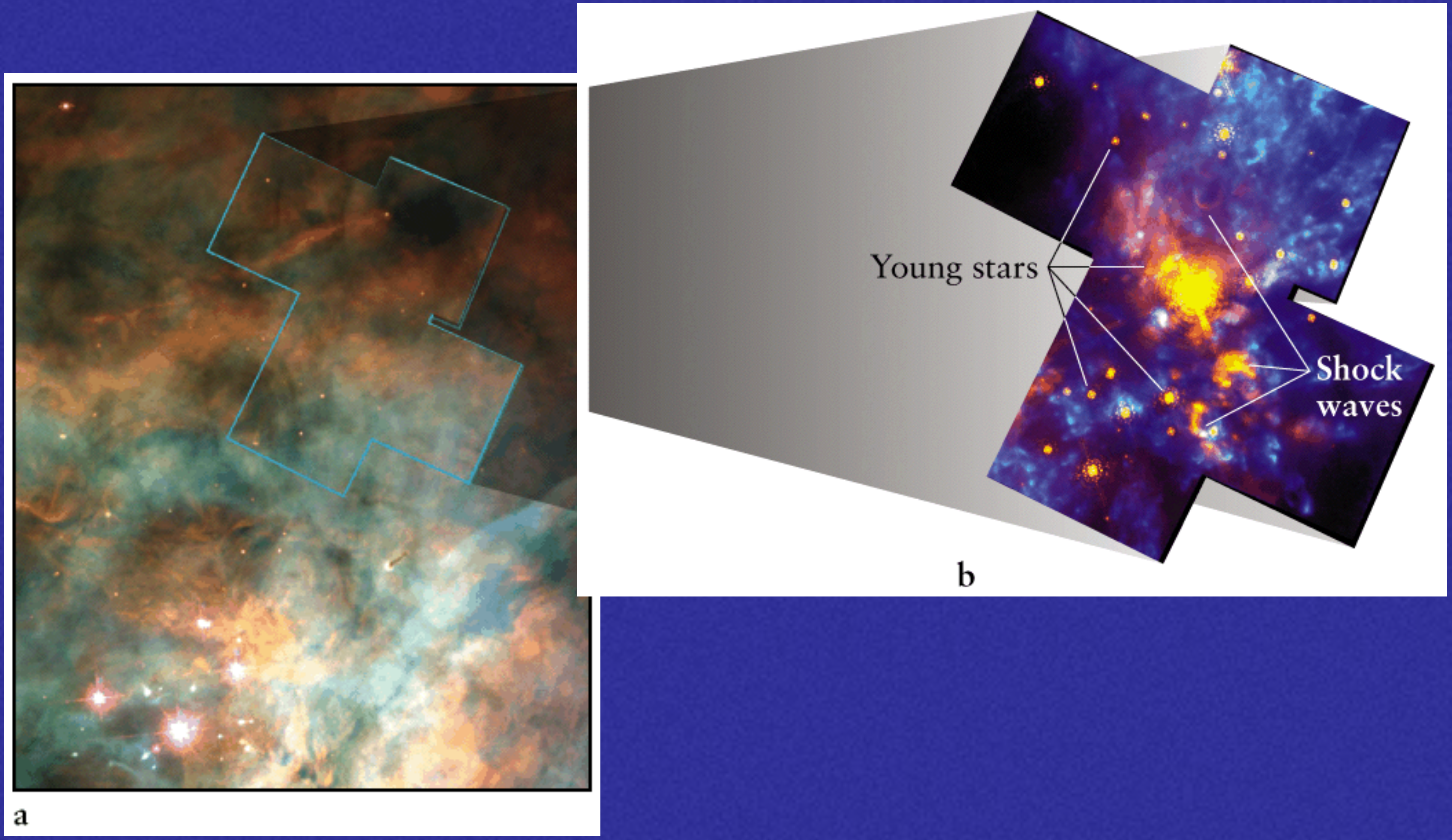
Proto Planetary Disks seen in the millimeter



HL Tau
< 2 Myr old

Gaps swept out by
planets formation

- During the protostar stage: at first low density, and no heating of the gas.
- As the protostar contracts, it will become less transparent => photons become trapped, and will heat the gas.
- This is the start of the protostar trying to reach hydrostatic equilibrium
- Hydrostatic equilibrium *almost* reached (but far from thermal!)
- Energy source gravitational contraction (Kelvin-Helmholtz contraction)
- Embedded in the parent gas cloud, and a short-lived phase (10^4-10^5 years) => hard to observe.



Orion: Visible (left) and IR (right)

Stage 3: Core ignition

- Eventually, the contracting protostar will become hot and dense enough in core for nuclear reactions to start (~a few million K).
- Enormous energy released, stopping gravitational contraction.
- The star enters the main sequence burning hydrogen to helium.