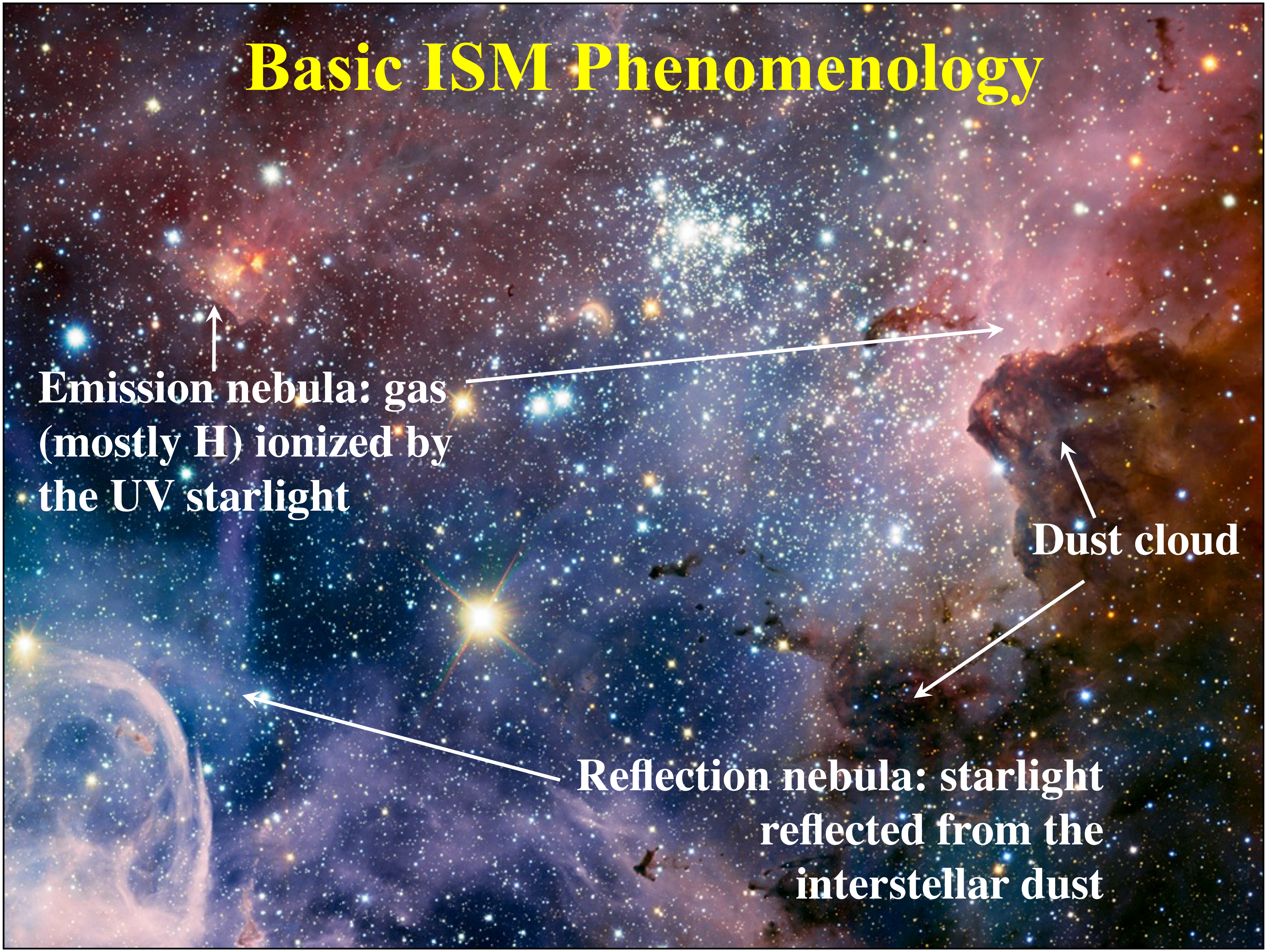

Ay 1 – Lecture 5
Interstellar Medium (ISM)
Star Formation
Formation of Planetary Systems

5.1 Interstellar Medium: General Properties

NGC 2174 (HST)

Interstellar Medium (ISM): A Global Picture

- "The stuff between the stars": gas and dust
- Generally concentrated in the Galactic disk
- Initially all of the baryonic content of the universe is a gas; and the baryonic dark matter probably still is
- Stars are formed out of the ISM, and return enriched gas to it via stellar winds, planetary nebulae, Supernovae - a cosmic ecology
- A complex physical system with many components and structures



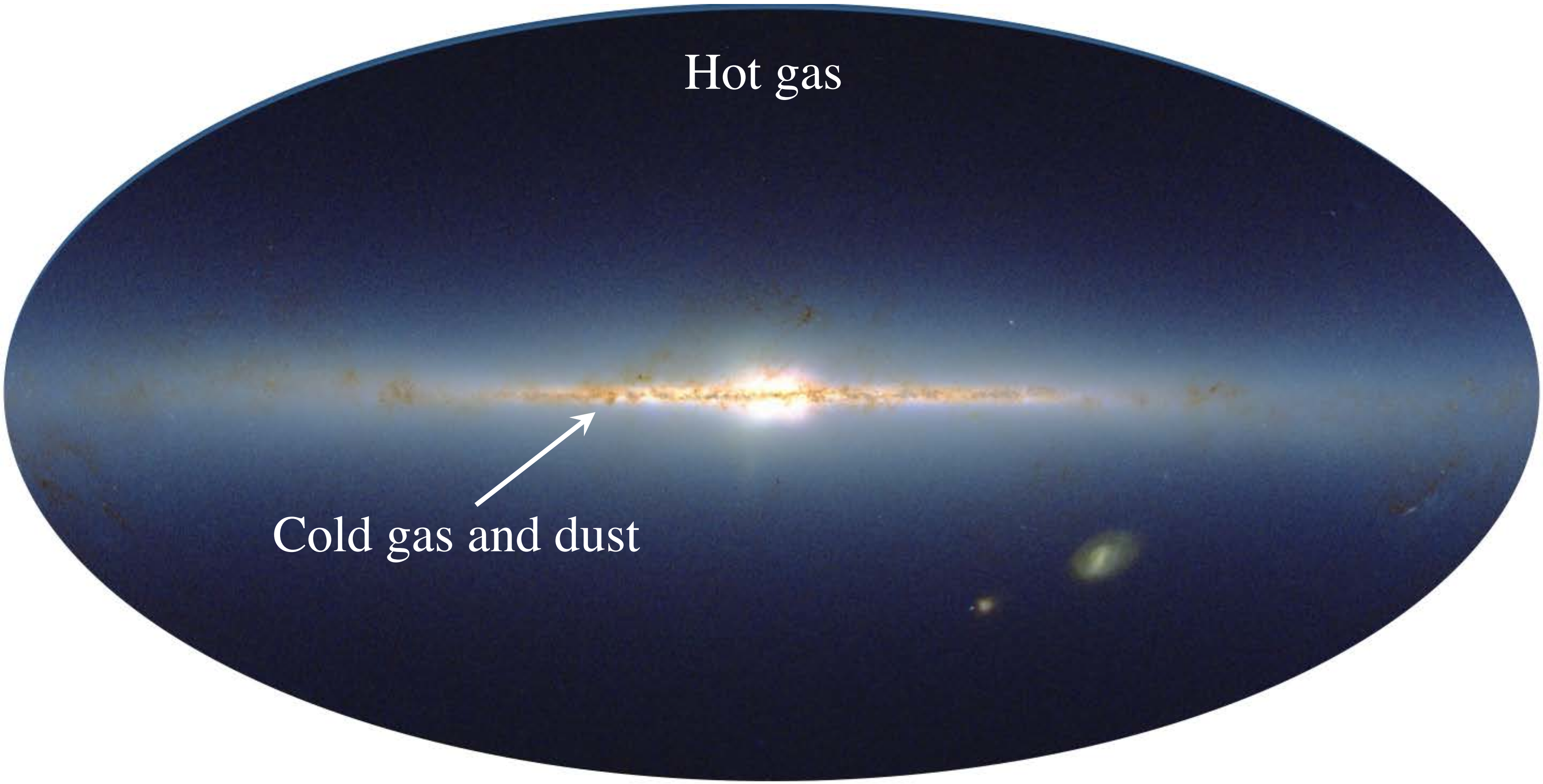
Basic ISM Phenomenology
Emission nebula: gas (mostly H) ionized by the UV starlight
Dust cloud
Reflection nebula: starlight reflected from the interstellar dust

Multi-Phase ISM

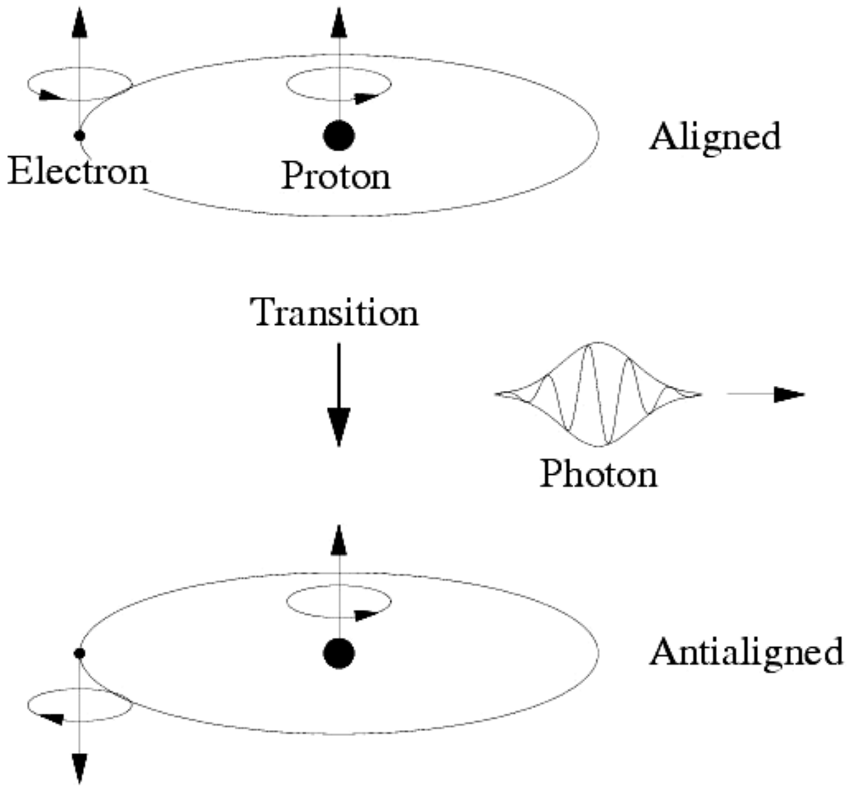
The ISM has a complex structure with 3 major components:

1. **Cold** ($T \sim 30$ - 100 K), dense ($n_{H\,I} > 10\ cm^{-3}$) atomic (H I) and molecular (H_2, CO, …) gas and dust clouds
   - ☆ Only ~ 1 - 5 % of the total volume, but most of the mass
   - ☆ Confined to the thin disk
   - ☆ Low ionization fraction ($x_{H\,II} < 10^{-3}$)
   - ☆ Stars are born in cold, dense clouds
2. **Warm** ($T \sim 10^3$-10^4 K) neutral & ionized gas, $n \sim 1\ cm^{-3}$
   - ☆ Energized mainly by UV starlight
   - ☆ Most of the total ISM volume in the disk
3. **Hot** ($T \sim 10^5$ - 10^6 K), low density ($n \sim 10^{-3}\ cm^{-3}$) gas
   - ☆ Galactic corona
   - ☆ Almost fully ionized, energized mainly by SN shocks

Where is the Gas?

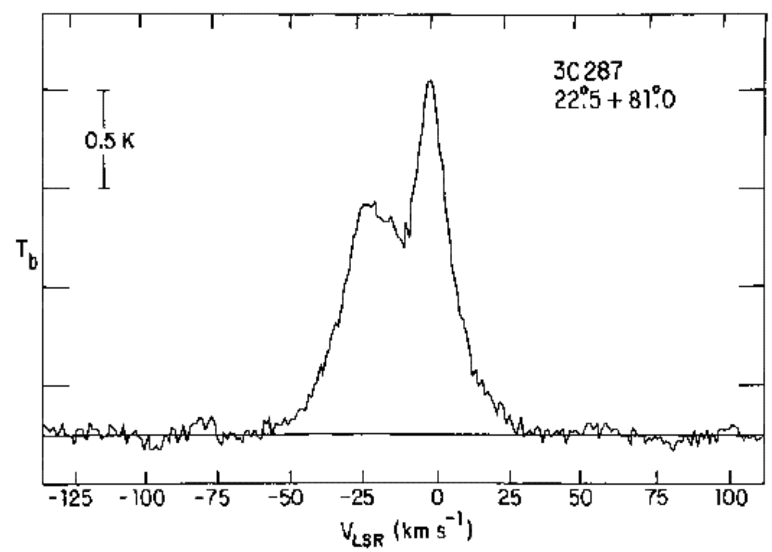


A Basic Tool: Spin-Flip (21 cm) Line of H I



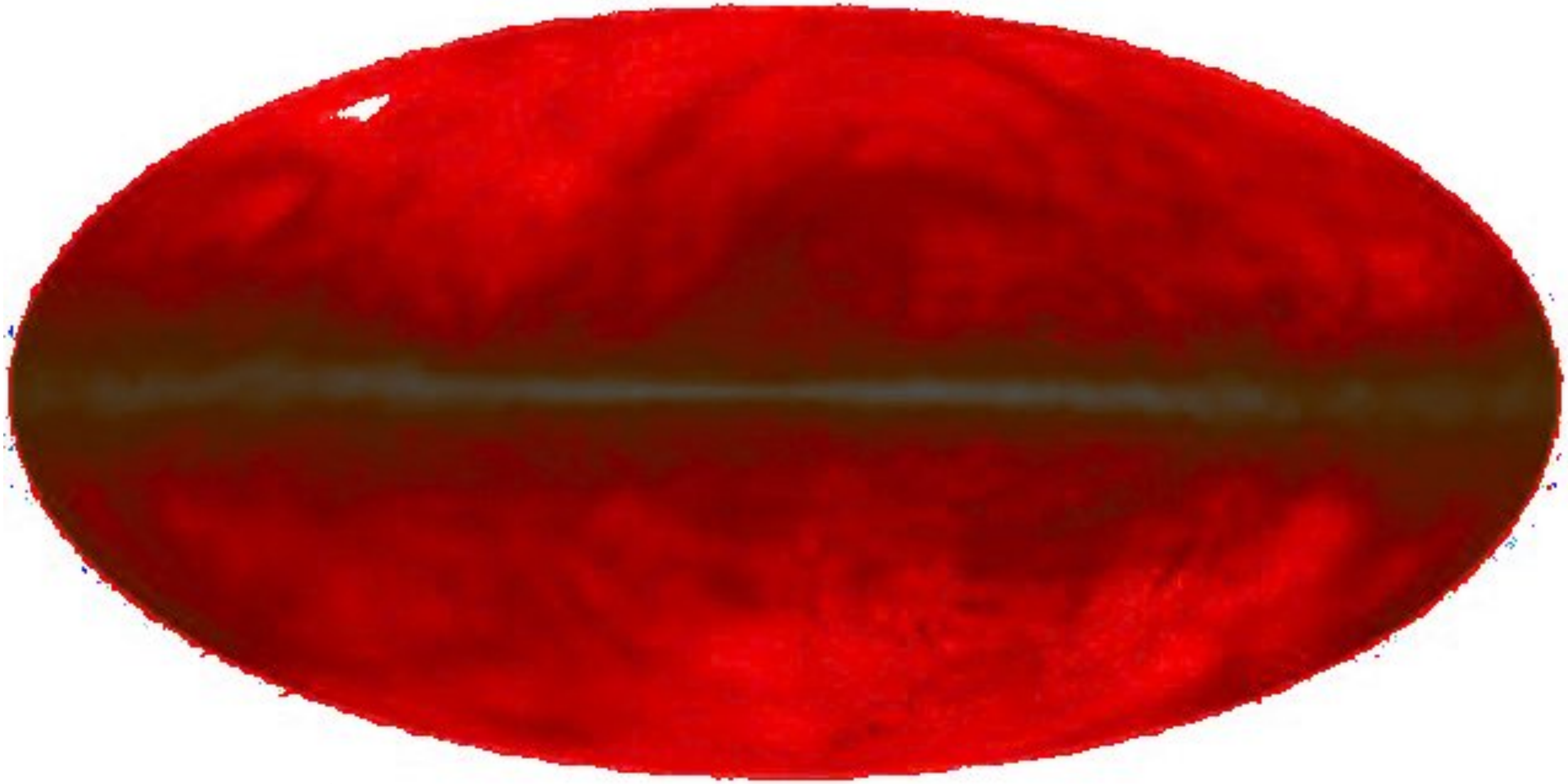
In emission generally originates from warm (T ~ 100 - 6000 K) ISM, which accounts for ~ 30 - 65% of the total ISM volume in the Galactic disk. In absorption, it probes a cooler ISM (can be also self-absorbed).

Typical line profile →



A major advantage: it is not affected by the dust absorption!

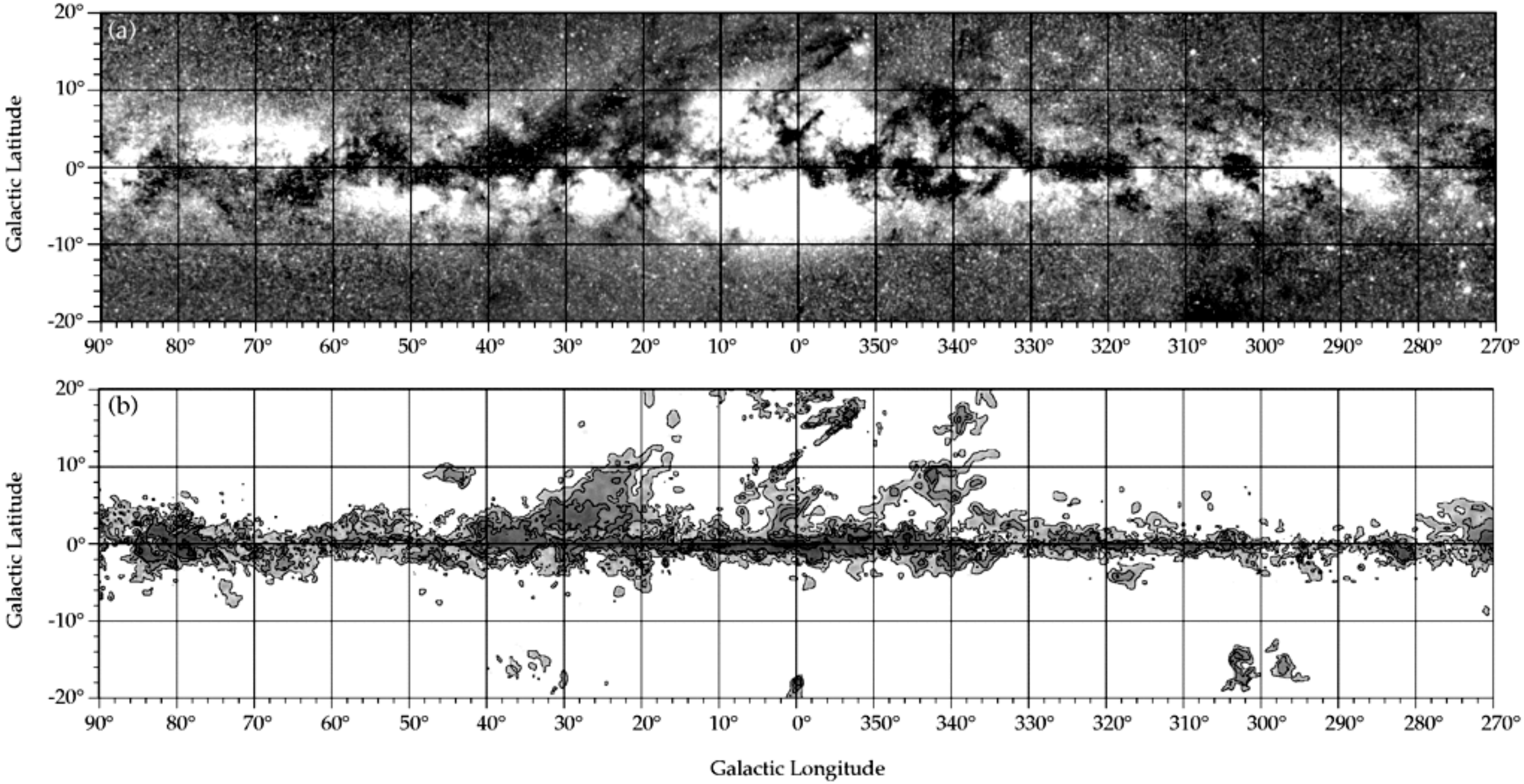
Global Distribution of H I in the Milky Way



Concentrated in the
Galactic Plane, but high-latitude features exist. These are believed to be remnants of SN and star formation driven shells and bubbles.

Milky Way:

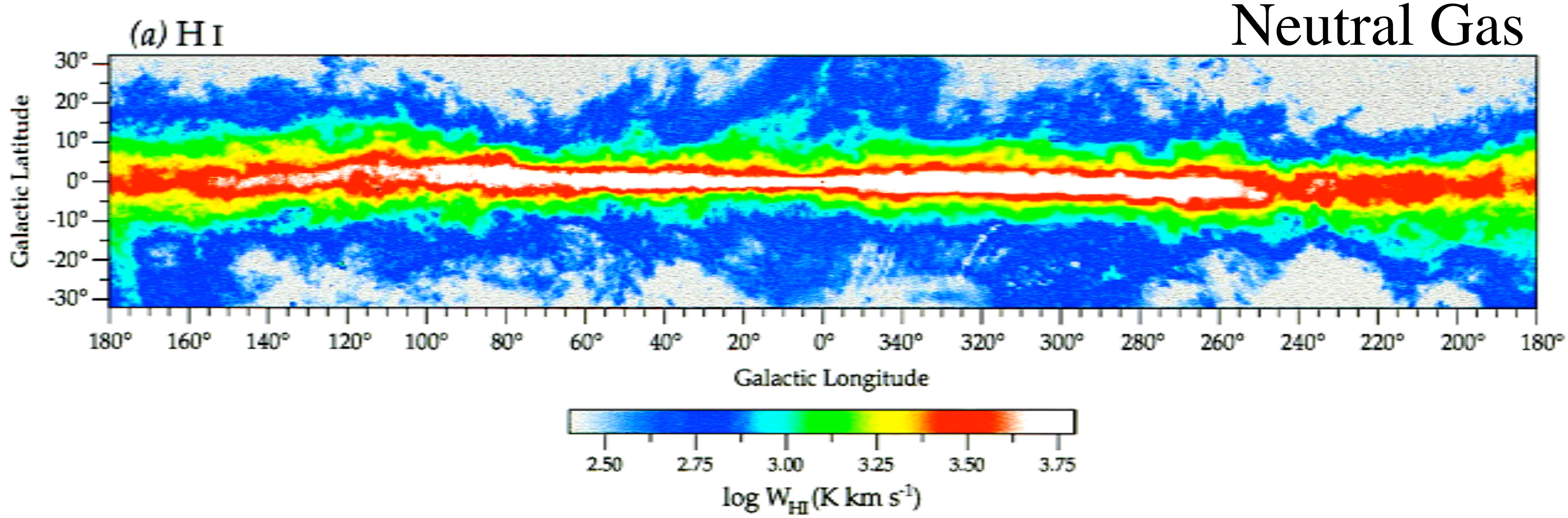
Visible Light (with obscuration from dust lanes)



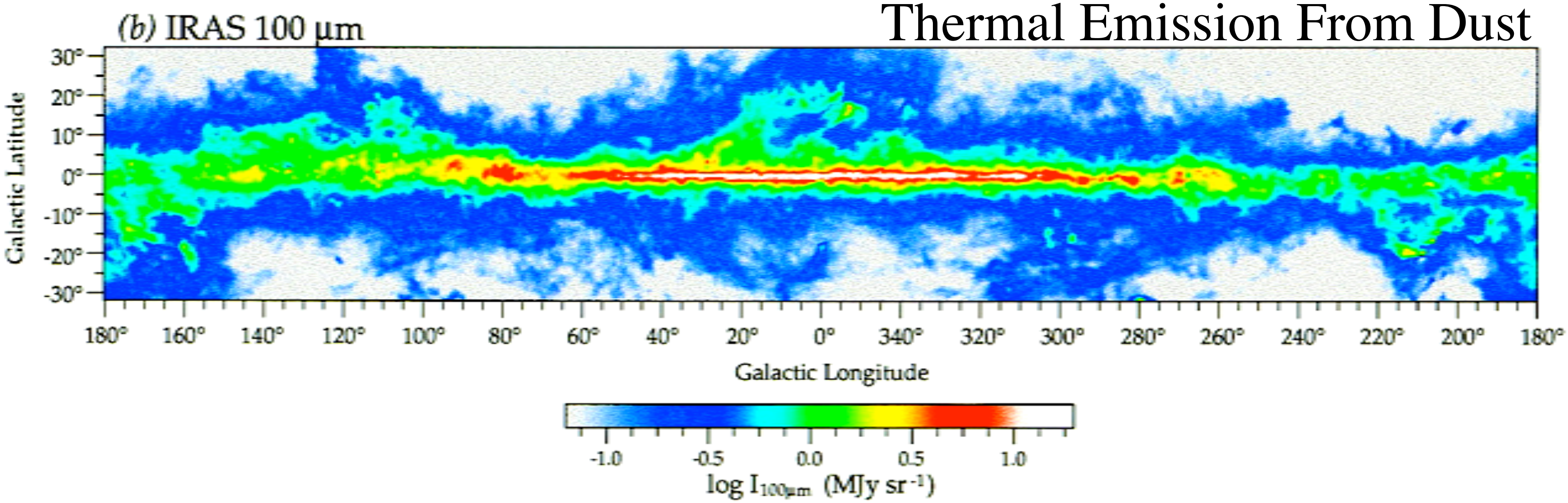
Molecular Gas (CO) - note correspondence with the dust lanes

Milky Way

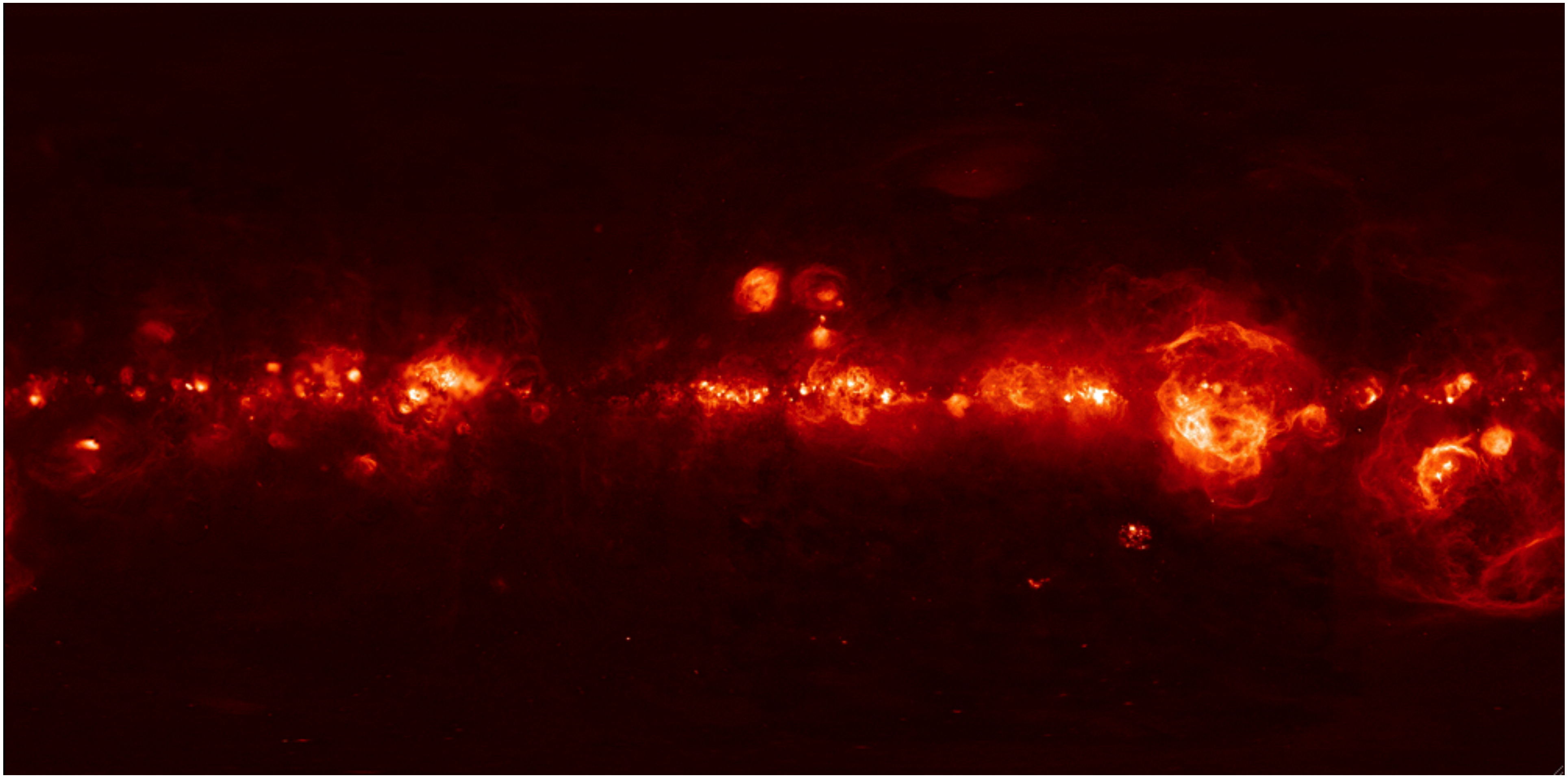
Neutral Gas



Thermal Emission From Dust



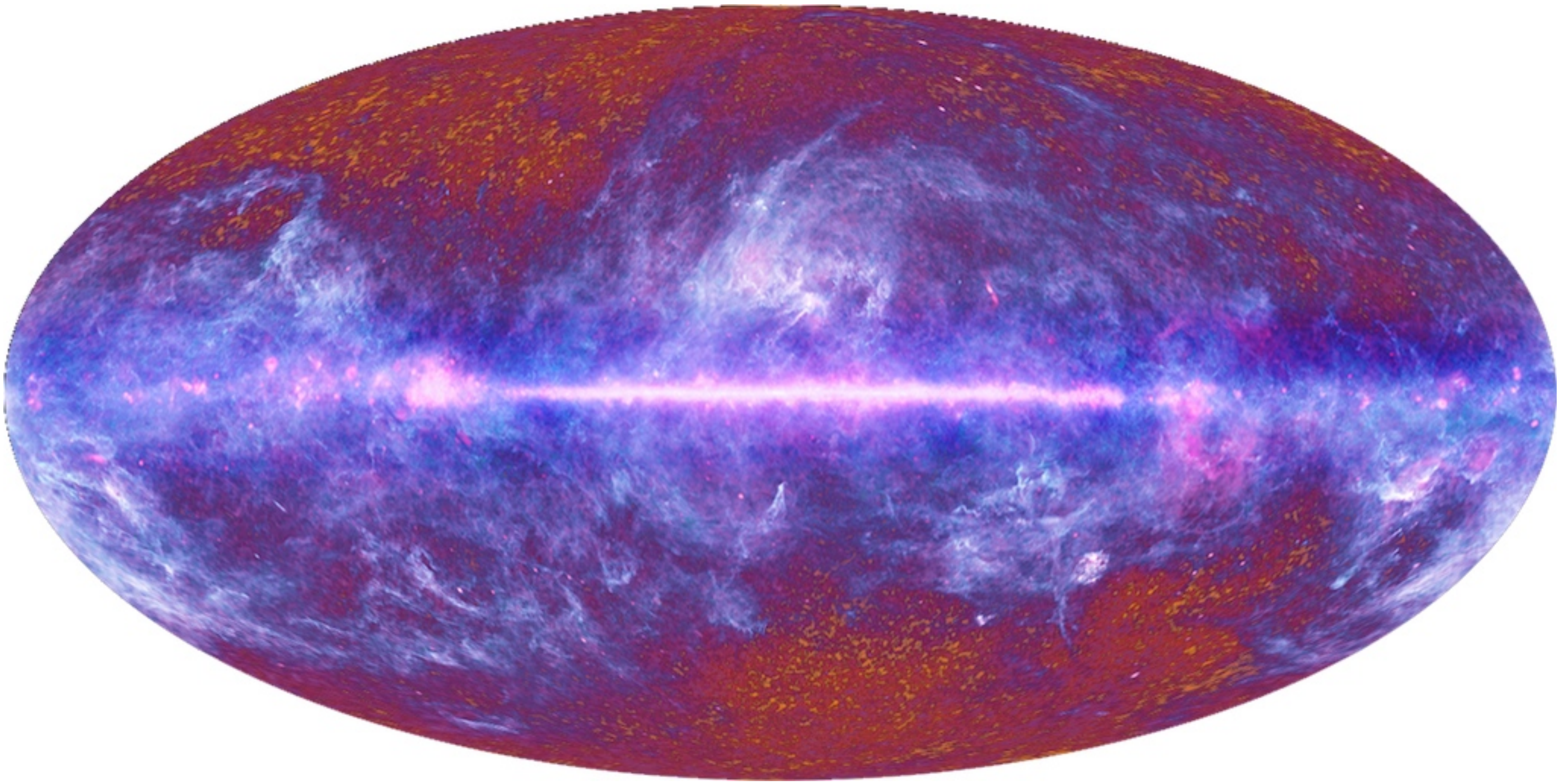
Composite Hα Image of the Galaxy (Warm/Ionized ISM)



(From D. Finkbeiner)

5.2 Interstellar Dust: Extinction and Reddening

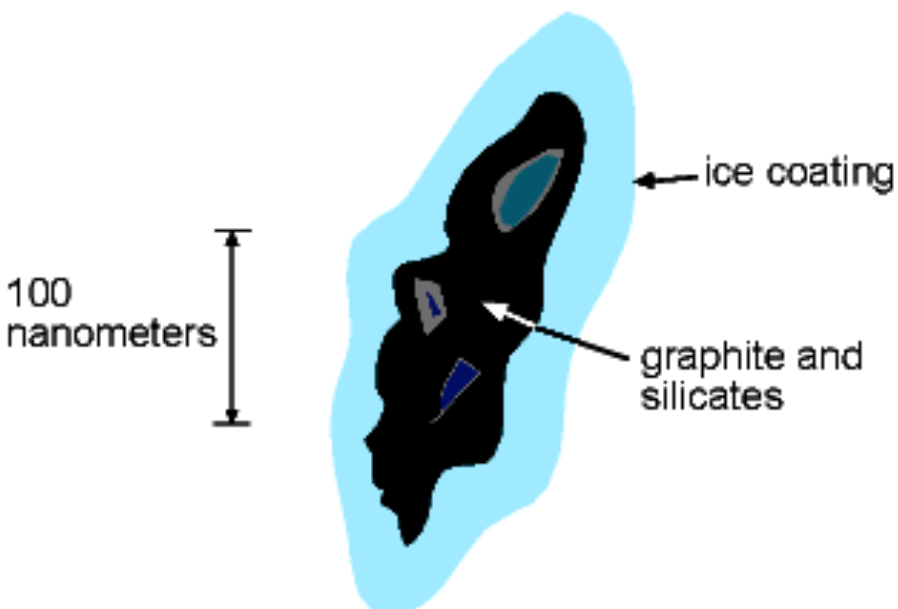
Galactic Dust Emission Map



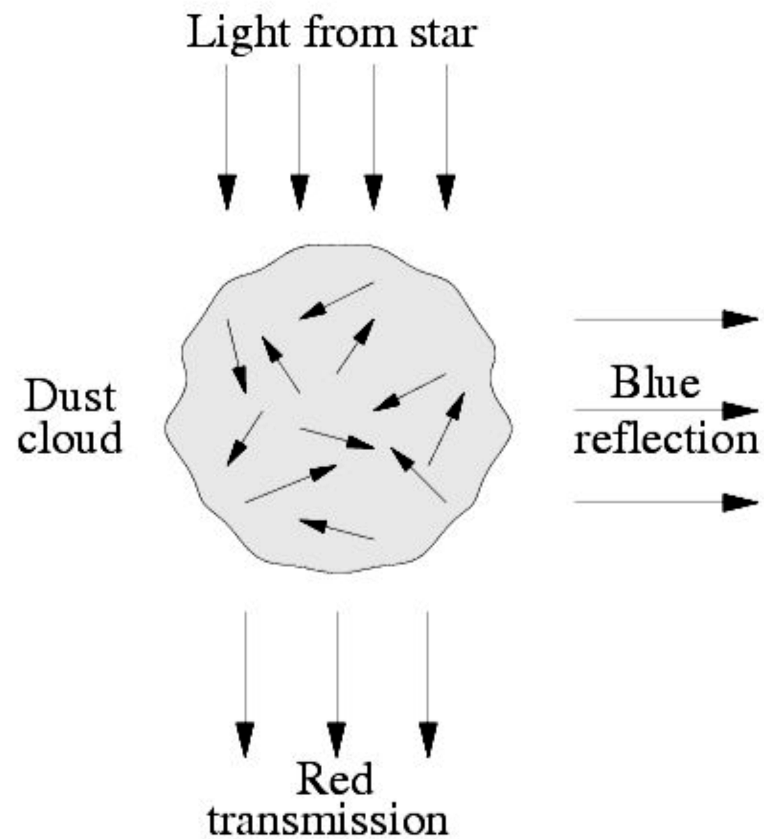
Planck

Interstellar Dust Grains

Probability of interaction with a photon increases for photons whose wavelength is comparable to or smaller than the grain size; longer wavelength photons pass through. Thus interstellar extinction = $f(\lambda)$. (Note: this breaks down for high-energy photons)

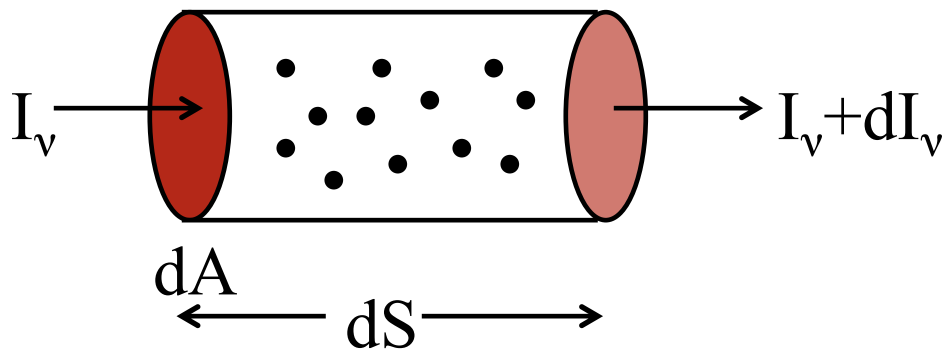


A typical dust grain (note the tiny scale!).



Absorption of Light

If the radiation travels through a medium which absorbs (or scatters) radiation, the energy in the beam will be reduced:



Number density of absorbers (particles per unit volume) = n
Each absorber has cross-sectional area = σ_ν (units cm^2)

If beam travels through dS, total area of absorbers is:

$$\text{number of absorbers} \times \text{cross-section} = n \times dA \times dS \times \sigma_\nu$$

Absorption of Light

Fraction of radiation absorbed = fraction of area blocked:

$$\frac{dI_\nu}{I_\nu} = -\frac{n\,dA\,ds\,\sigma_\nu}{dA} = -n\sigma_\nu ds$$

$$dI_\nu = -n\sigma_\nu I_\nu ds \equiv -\alpha_\nu I_\nu ds$$

↑

absorption coefficient (units cm^{-1})

The solution of this differential equation is:

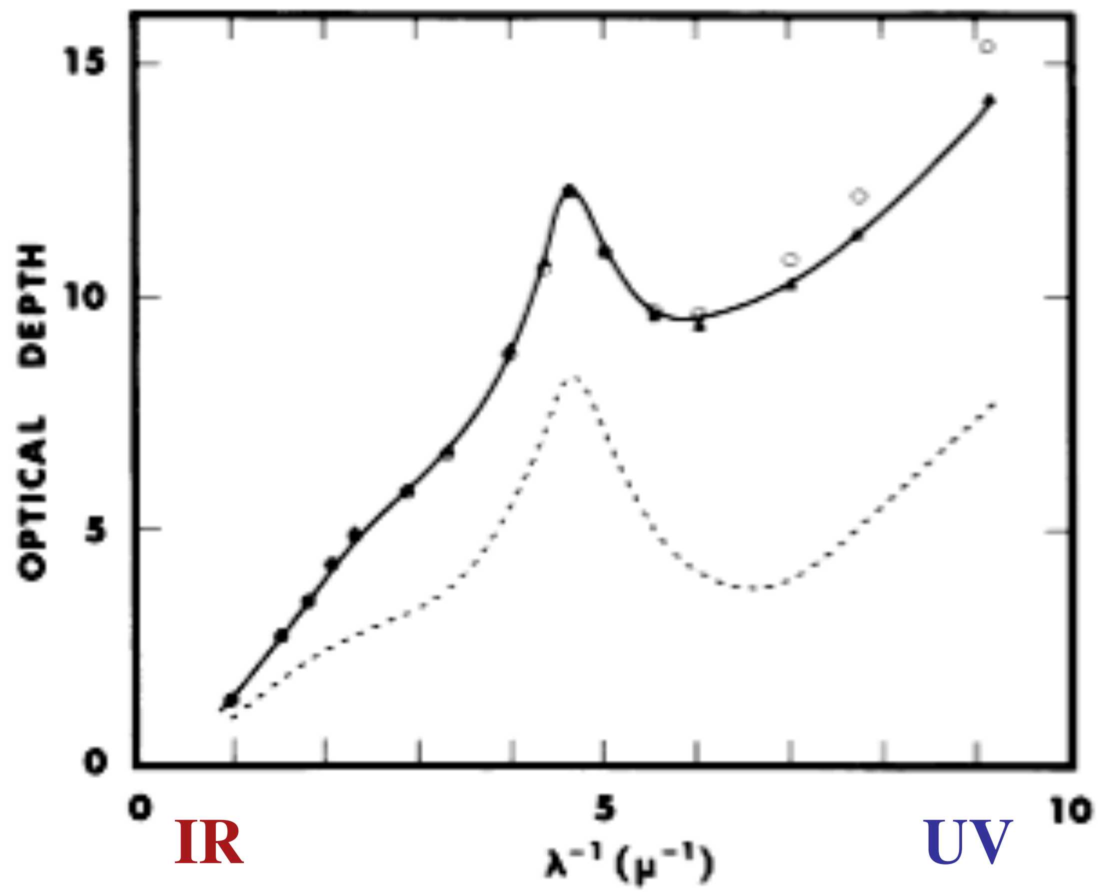
$$\int dI_\nu / I_\nu = \ln I_\nu = \int -\alpha \, dS = -\alpha S$$

$$I_\nu(S) / I_\nu(0) = \exp(-\alpha S)$$

Extinction is an exponential process

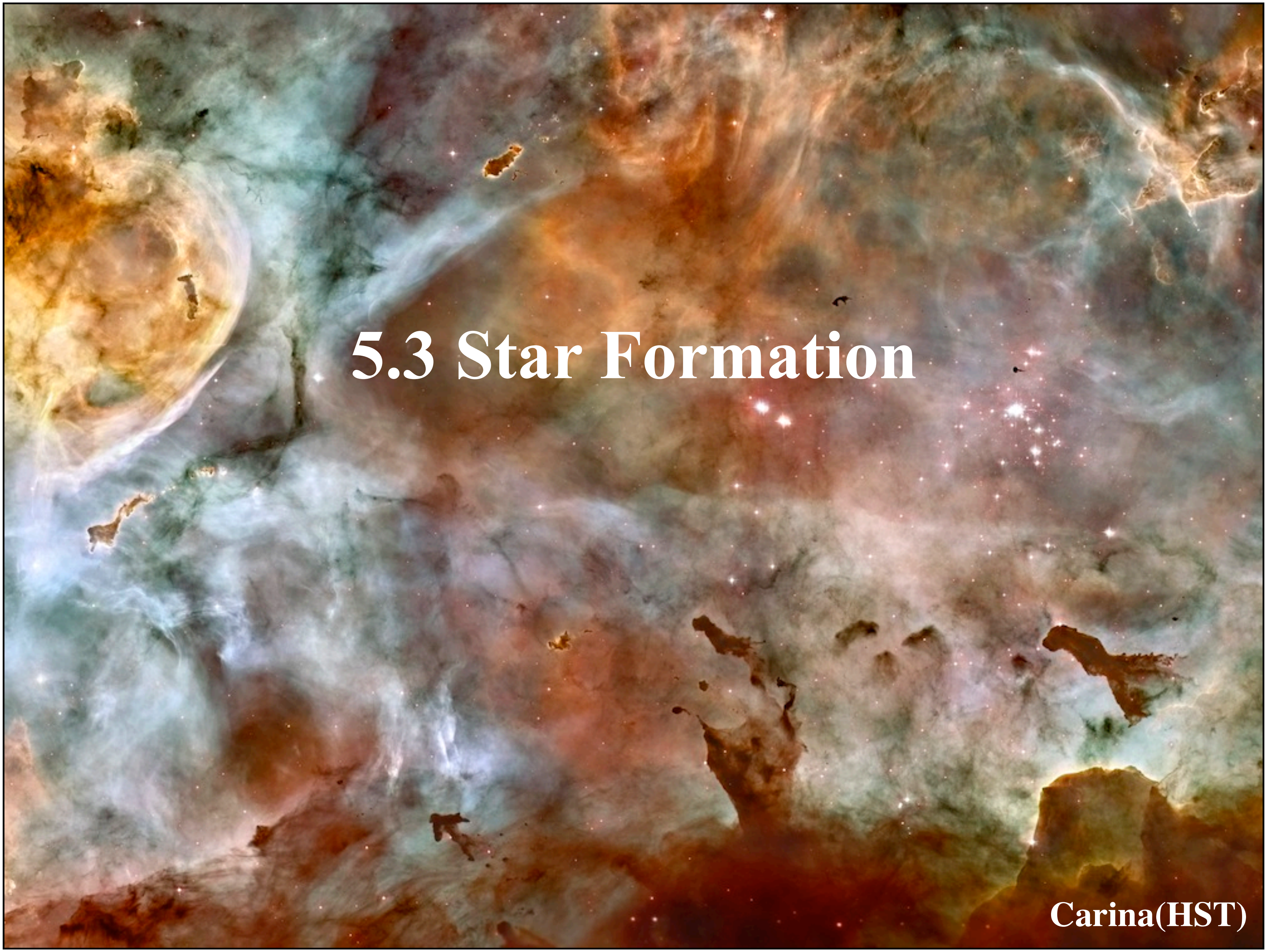
Interstellar Extinction Curve

Note: this is a log of the decrement! (i.e., just like magnitudes)

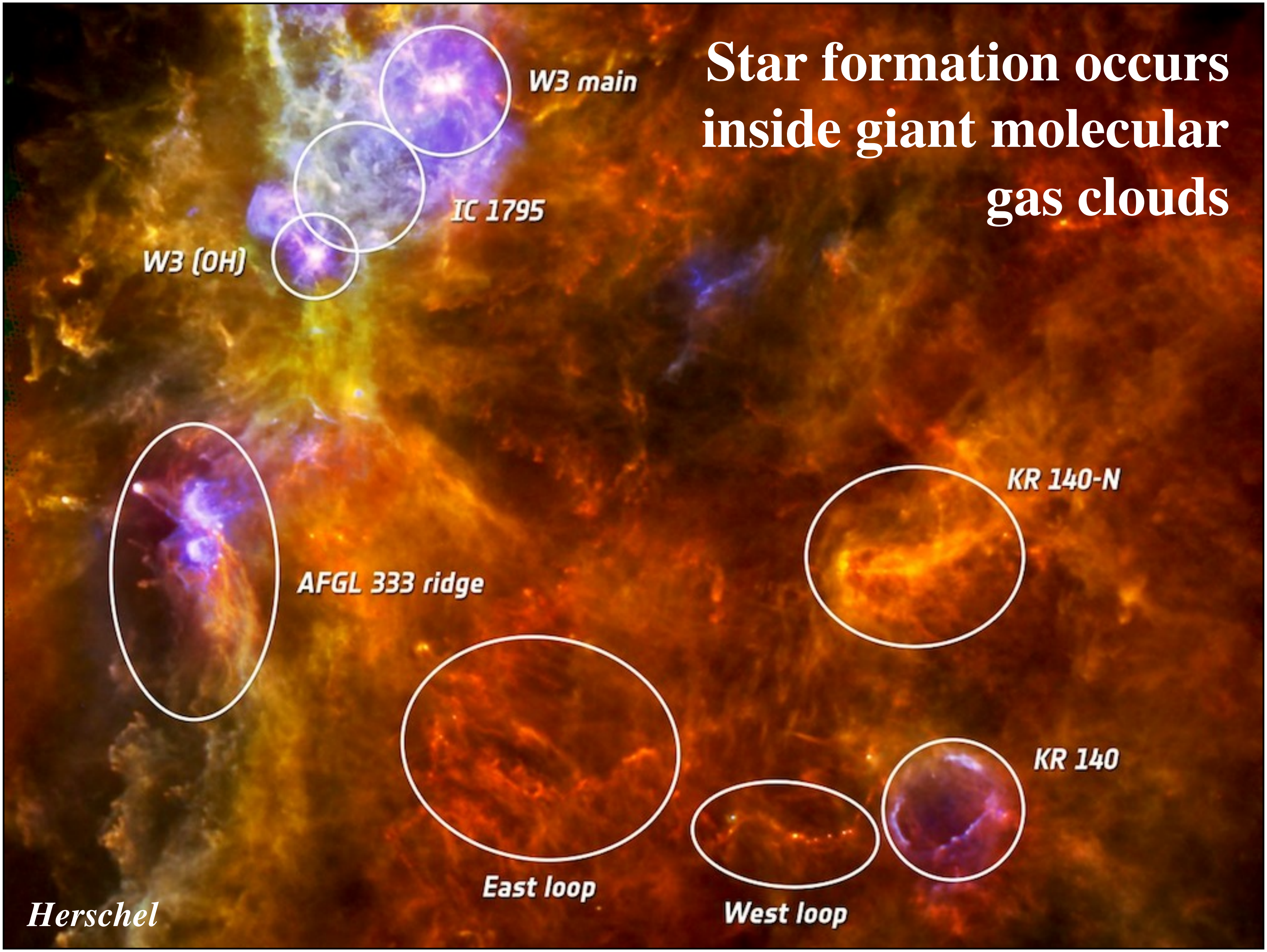


The bump at λ ~ 2200 Å is due to silicates in dust grains. This is true for most Milky Way lines of sight, but not so in some other galaxies, e.g., the SMC.

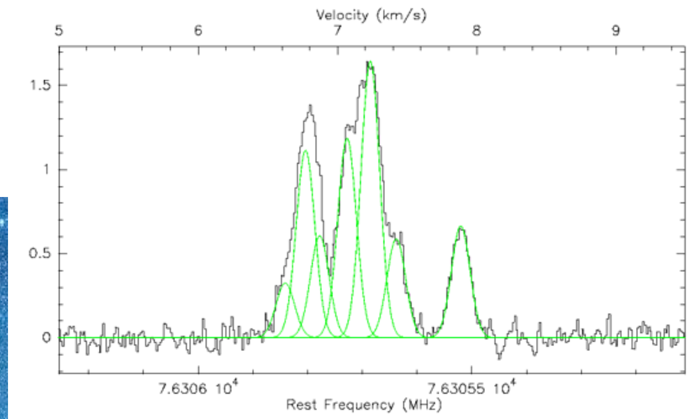
5.3 Star Formation

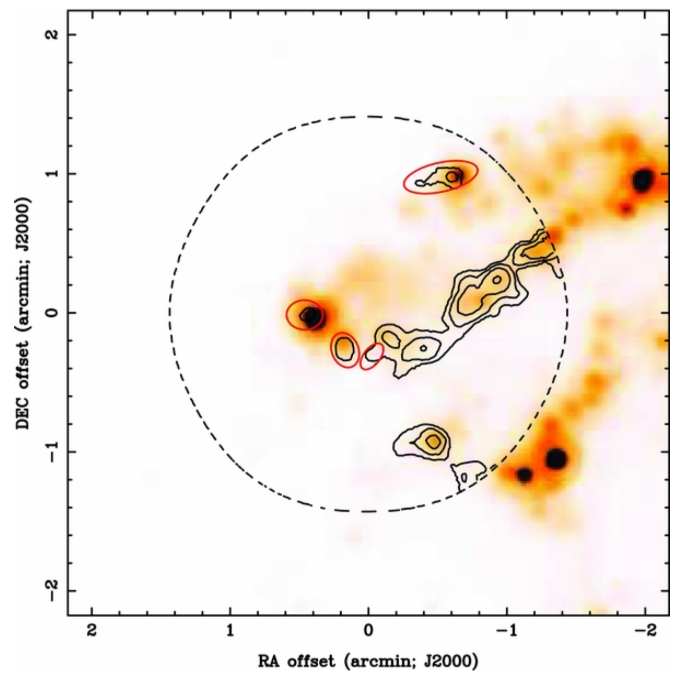


Carina(HST)

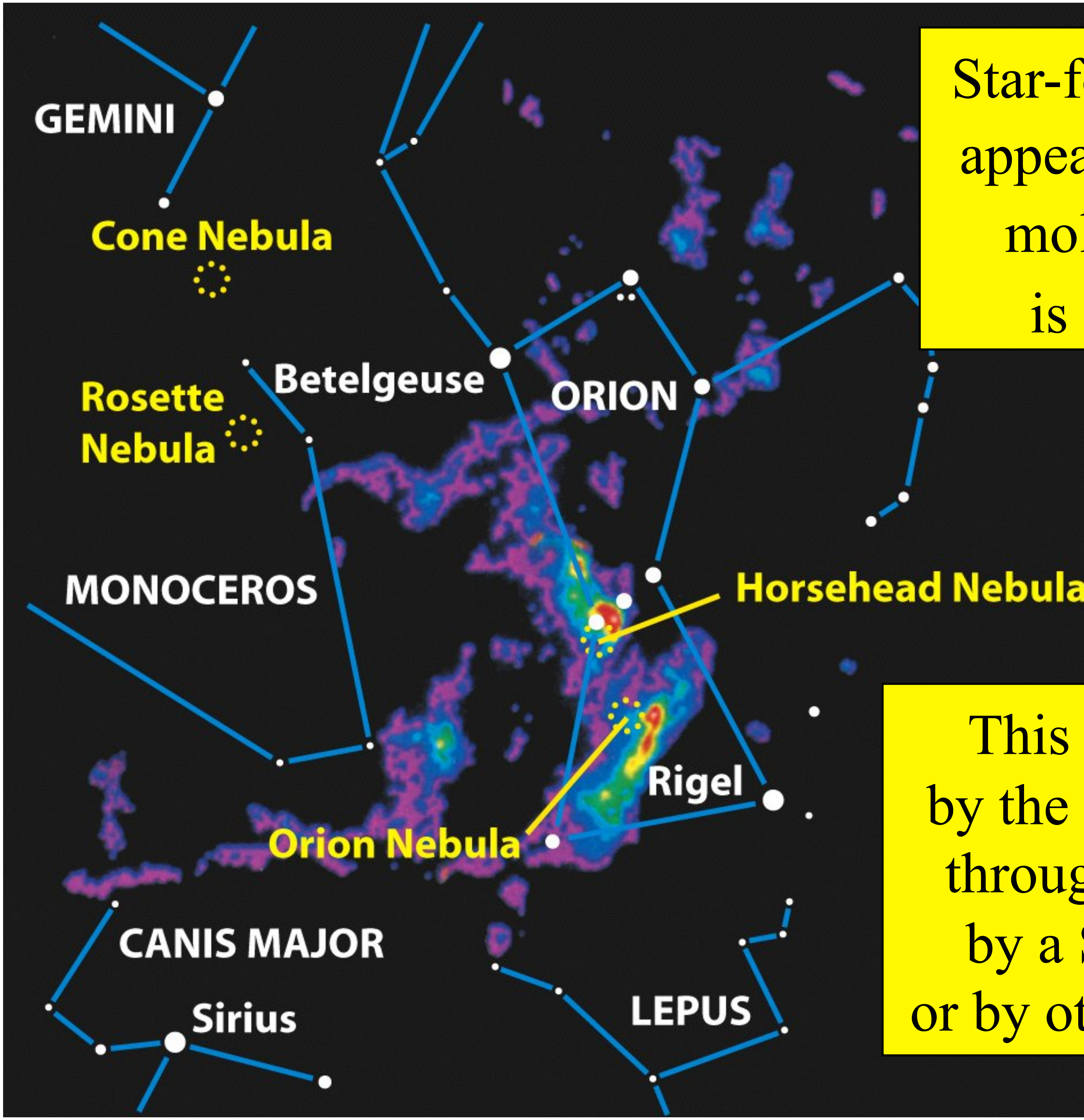

Star formation occurs inside giant molecular gas clouds
W3 main
IC 1795
W3 (OH)
AFGL 333 ridge
KR 140-N
KR 140
East loop
West loop
Herschel

Molecular Clouds are Typically Studied With the mm Interferometers, like CARMA or ALMA



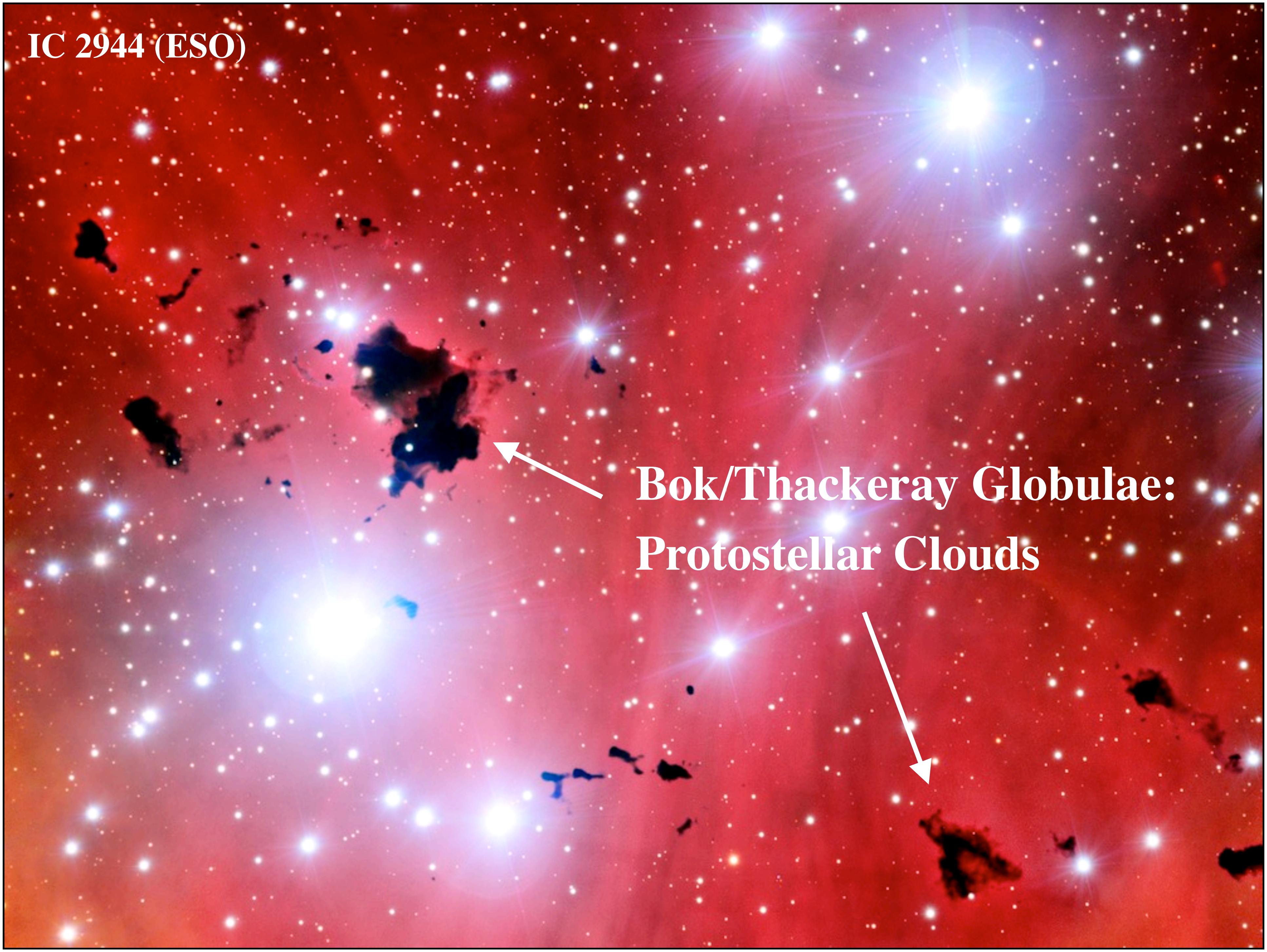


Some commonly found interstellar molecules: H_2, CO, NH_3, … some very complex organic molecules…



Star-forming regions appear when a giant molecular cloud is compressed

This can be caused by the cloud's passage through a spiral arm, by a SN explosion, or by other mechanisms

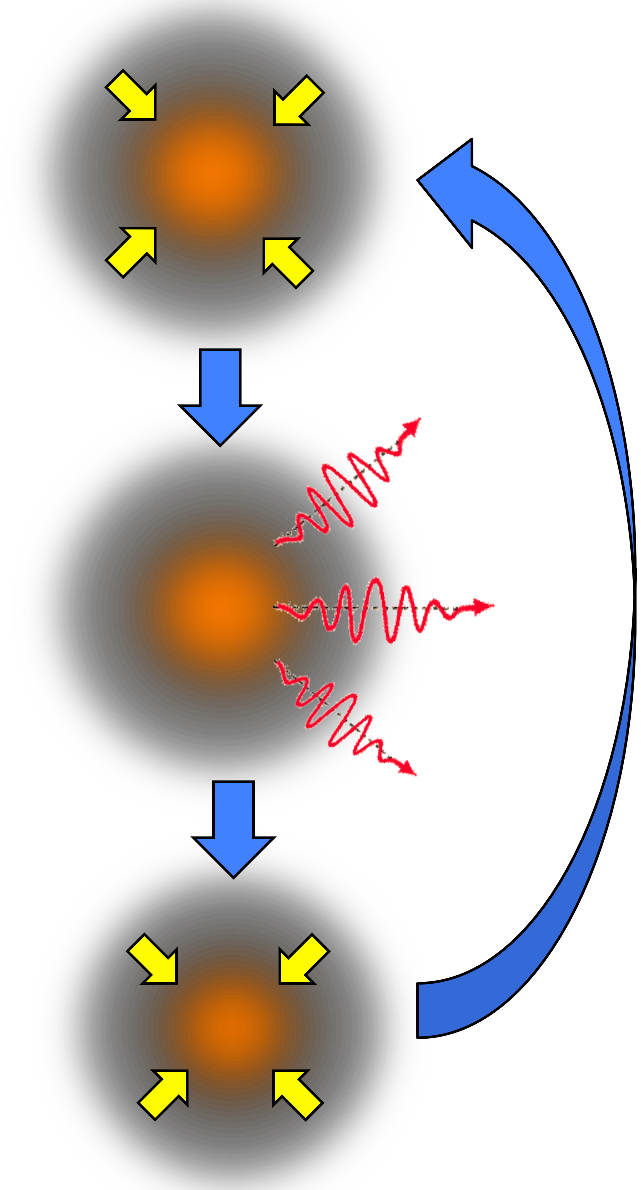

IC 2944 (ESO)
Bok/Thackeray Globulae:
Protostellar Clouds

Why Protostellar Clouds Collapse

Thermal pressure in the core balances the gravitational pressure

Heat escapes from the core, and the cloud shrinks a little as the kinetic energy is removed

The core heats up so that the thermal pressure balances the gravitational pressure



Basic Physics of Star Formation

Consider the forces acting on a protostellar cloud within a molecular cloud or its core:

- Gravity — act to collapse the cloud
- Pressure
- Magnetic fields
- Bulk motions

(Pressure, magnetic fields, bulk motions:) sources of support against collapse to form a star

If somehow we form a core in which gravity dominates over all other forces, collapse will occur on the dynamical or ***free-fall time***:

$$v_{esc} = \sqrt{\frac{2GM}{R}} \qquad \tau_{dyn} = \frac{R}{v_{esc}} = \sqrt{\frac{R^3}{2GM}} \sim \frac{1}{\sqrt{G\bar{\rho}}}$$

…for a cloud of mass M, radius R, and mean density ρ

The Jeans Mass

The *Jeans mass* is the minimum mass a cloud must have if gravity is to overwhelm pressure and initiate collapse:

$$M_J = \left(\frac{R_g}{\mu G}\right)^{3/2}\left(\frac{3}{4\pi}\right)^{1/2} T^{3/2}\rho^{-1/2}$$

R_g = Gas constant, *not* radius!   μ = mean molecular weight

Typical values for the molecular gas:

- $\rho \sim 10^{-19}$ g cm^{-3}
- T ~ 10 K

Use these numbers in the Jeans mass formula, and take μ = 2 for molecular hydrogen:

$$M_J = 7.6 \times 10^{32} \text{ g} \approx 0.4\, M_{sun}$$

The Jeans Mass

Can likewise define a characteristic length scale (the Jeans length), by eliminating mass rather than radius from the previous expression:

$$\frac{4}{3}\pi R^3 \rho = \frac{R_g}{\mu G} T R$$

$$R_J = \left(\frac{R_g}{\mu G}\right)^{1/2} \left(\frac{3}{4\pi}\right)^{1/2} T^{1/2} \rho^{-1/2}$$

For the same density / temperature as before, $R_J = 10^4$ AU

Free-fall timescale for a cloud of this density is:

$$\tau_{dyn} \approx \frac{1}{\sqrt{G\rho}} = 10^{13} \text{ s} = 4 \times 10^5 \text{ yr}$$

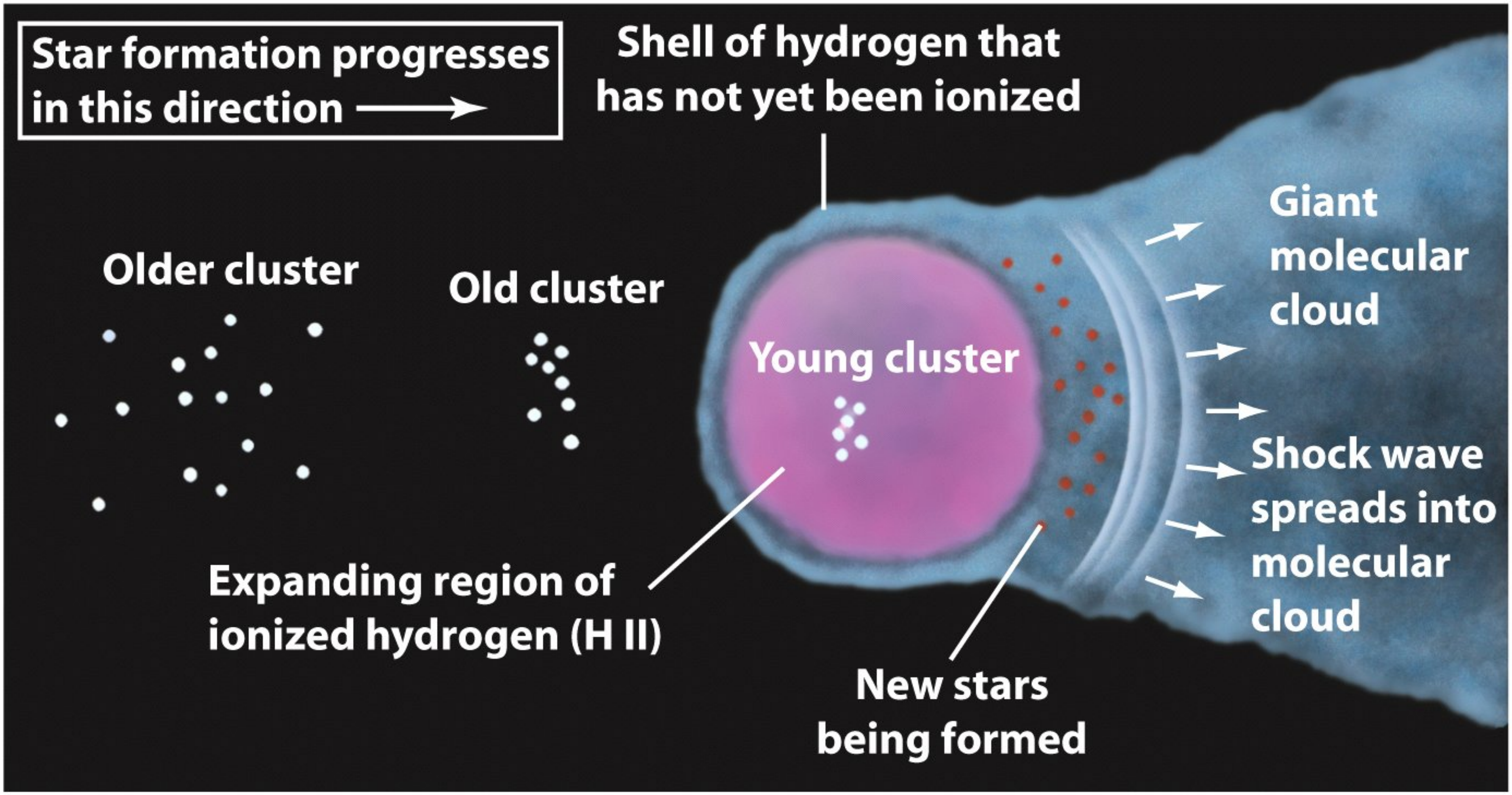
This is just barely shorter than the lifetimes of most massive stars

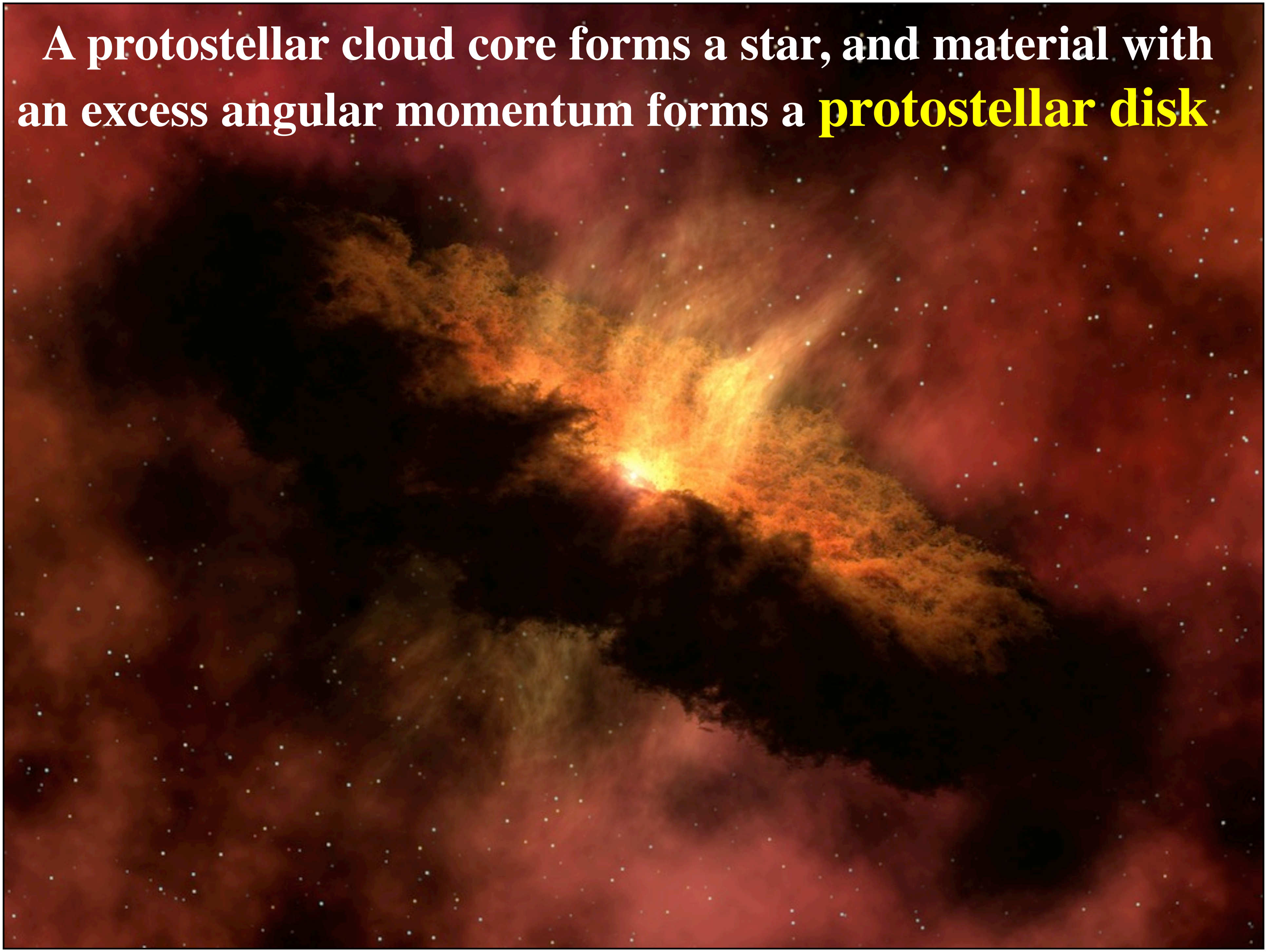

Most stars form in clusters or groups
NGC 2244 (HST)


Young stars ionize the gas and evaporate the dust
This stops the star formation
NGC 602 (HST)

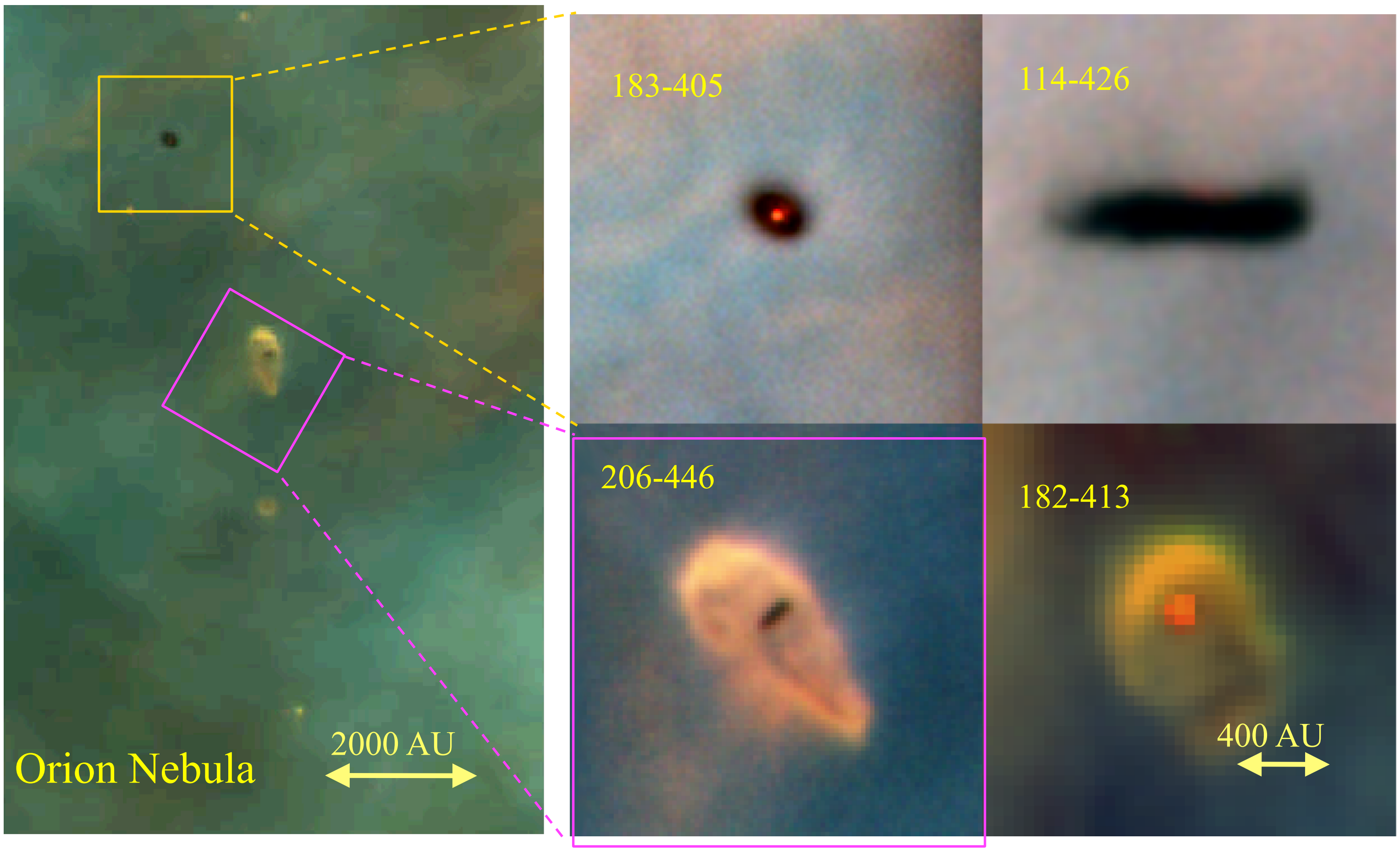

Supernovae are even more effective
in clearing out the gas and dust
NGC 2359 “Thor’s Helmet” (SSRO)

Young Stars Eat Their Molecular Clouds …



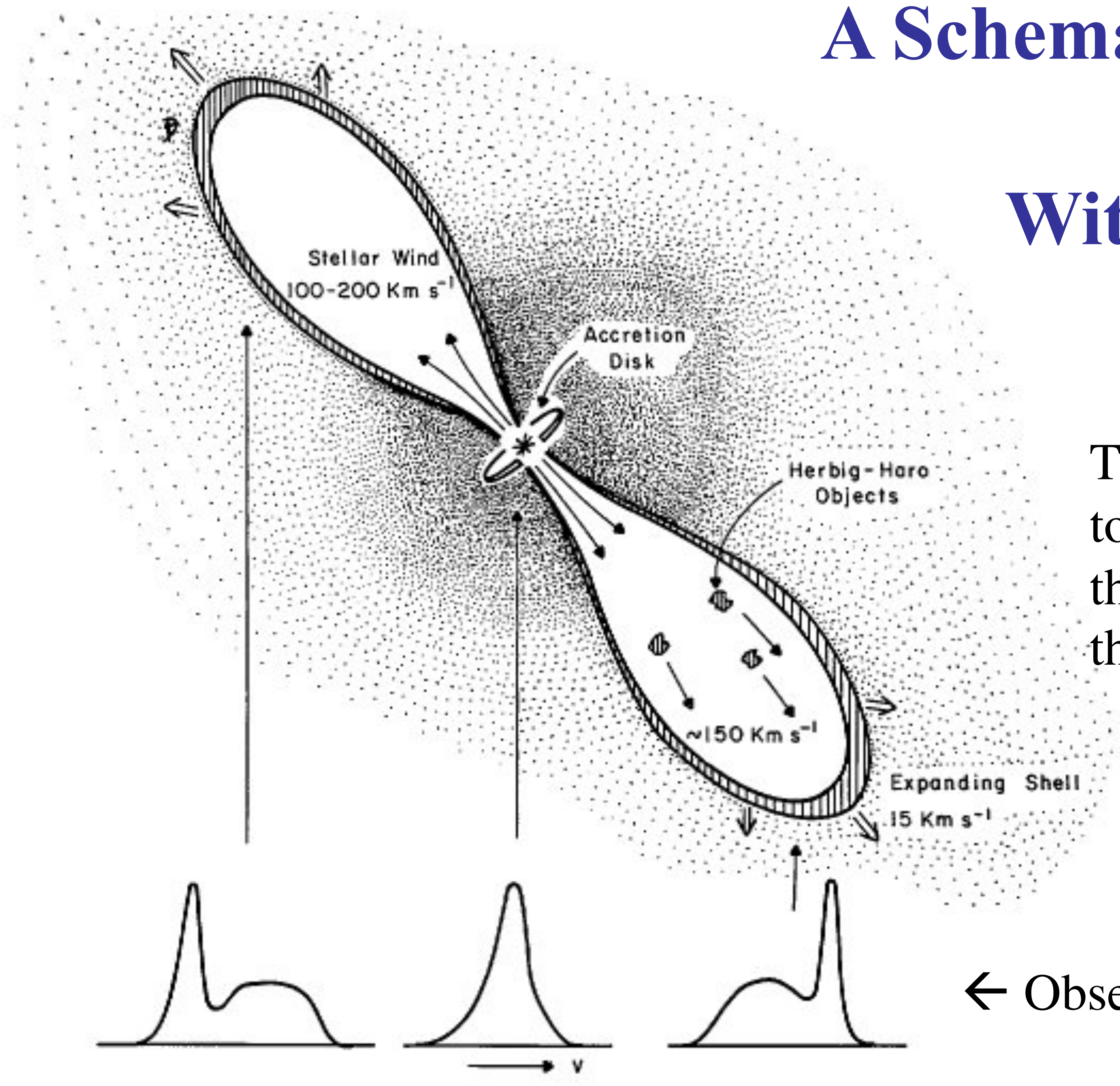

A protostellar cloud core forms a star, and material with
an excess angular momentum forms a protostellar disk

Direct Images of Circumstellar Disks



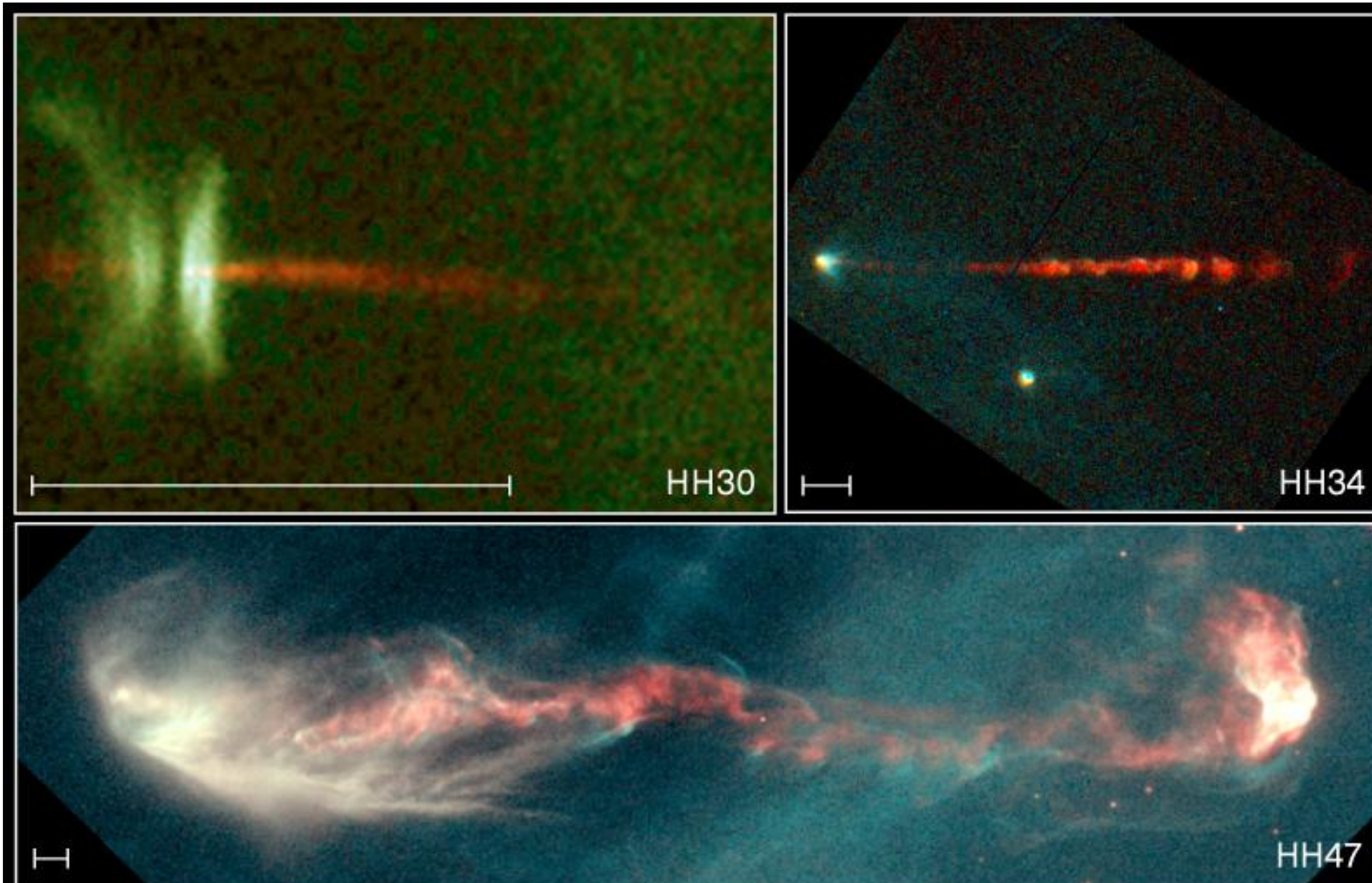
From HST.   O’Dell & Wen 1992, McCaughrean & O’Dell 1996

A Schematic View of a Protostar With a Bipolar Outflow



The outflows are due to the magnetic field that is threaded through the disk

← Observed line profiles



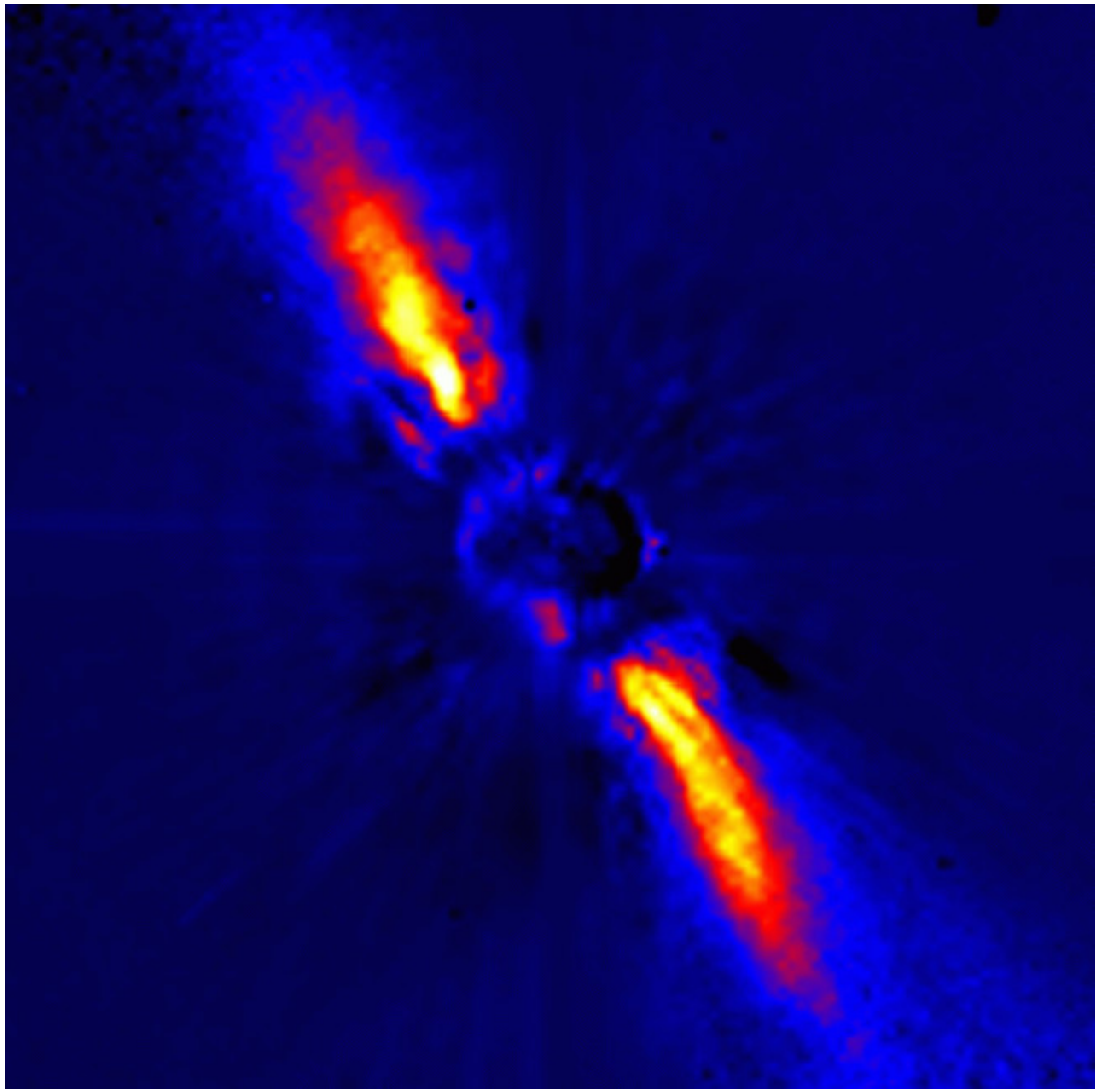
Jets from Young Stars HST • WFPC2

PRC95-24a • ST ScI OPO • June 6, 1995

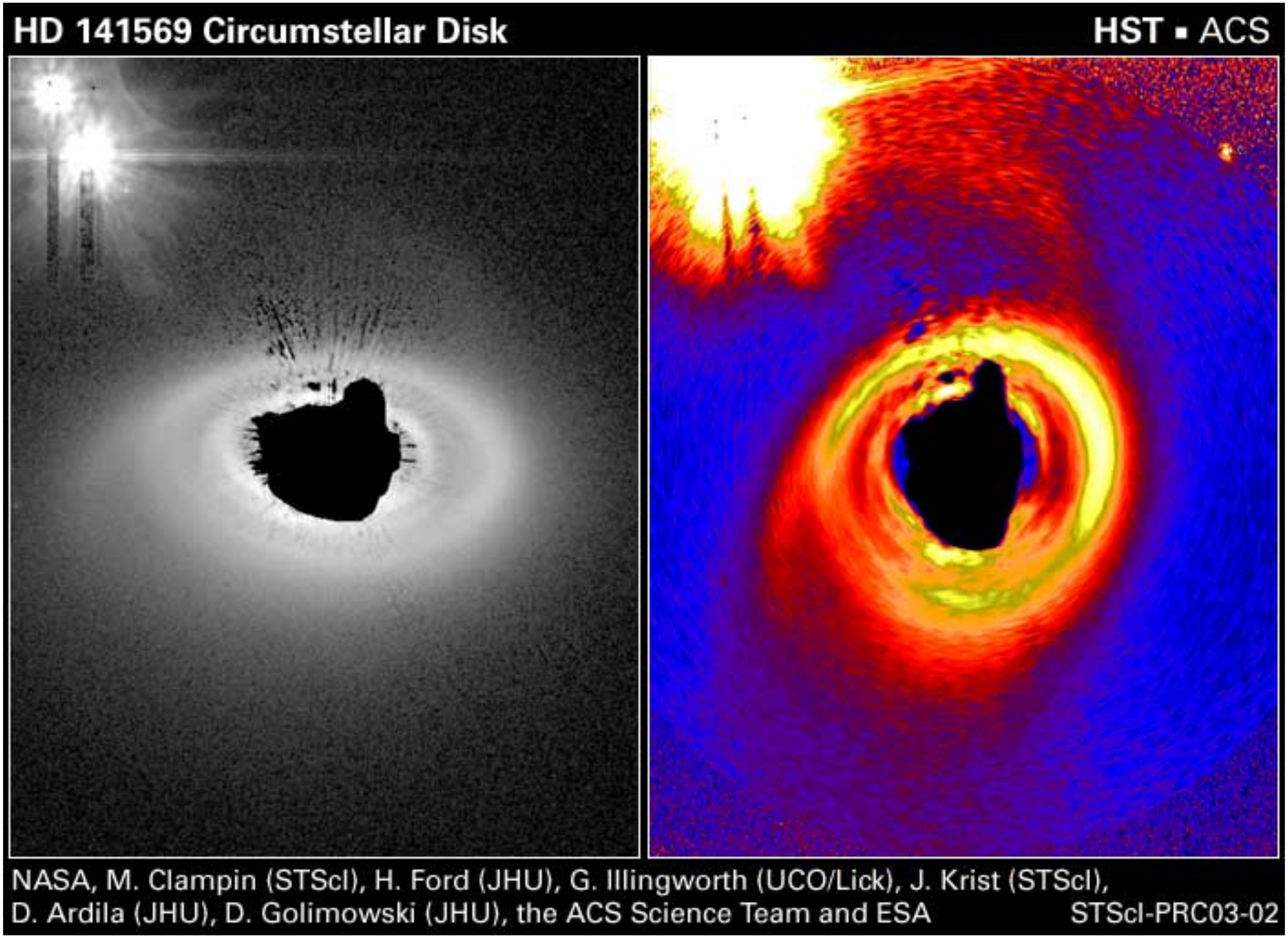
C. Burrows (ST ScI), J. Hester (AZ State U.), J. Morse (ST ScI), NASA

5.4 Formation of Planetary Systems

Beta Pictoris: Planetary Debris Disk



Older, mostly dust disk:



Formation of Planetary Systems

Protoplanetary disks contain dust - micron sized solid particles formed for example in the stellar winds of some stars.

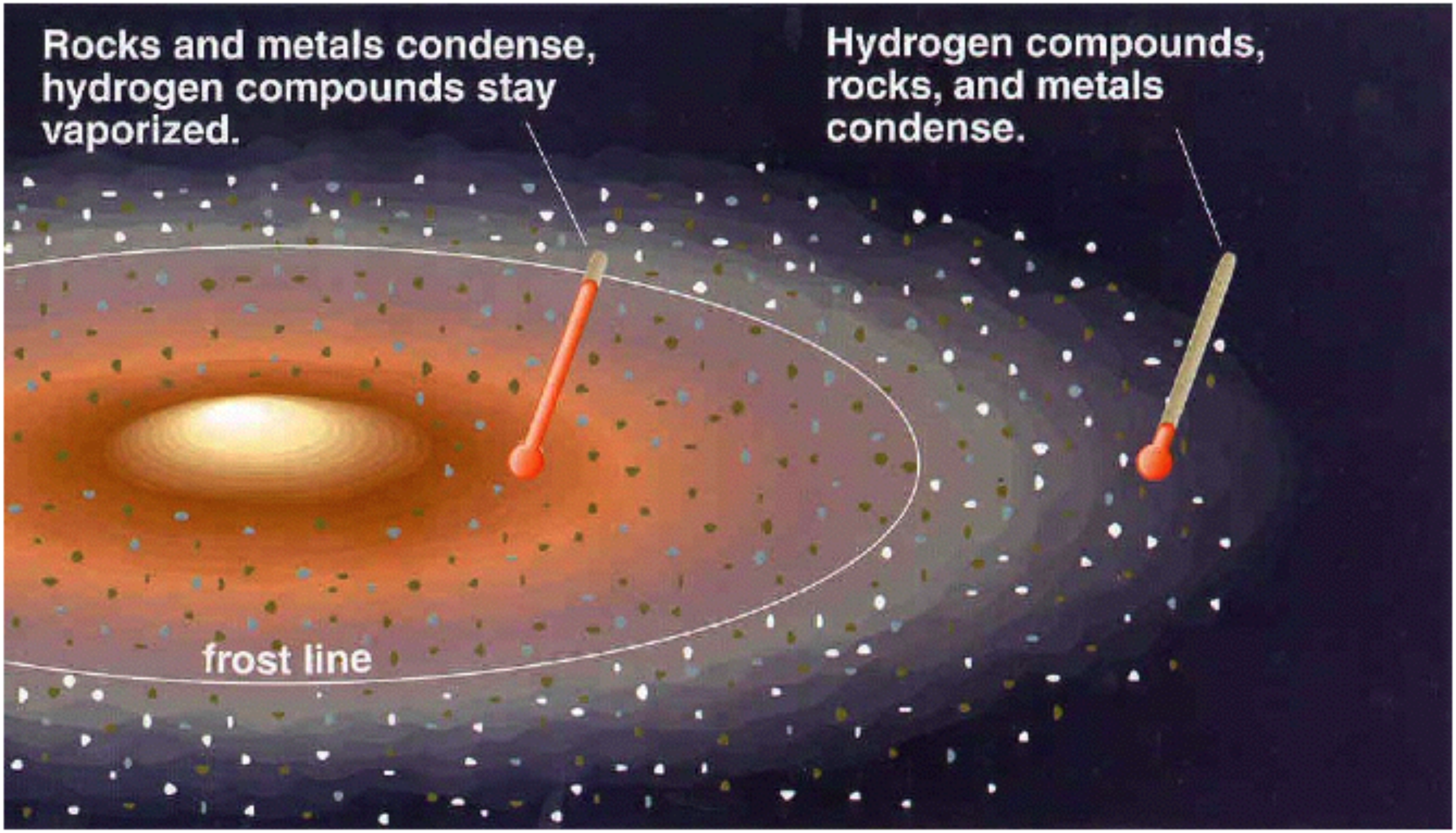
Initially the dust is uniformly mixed with the gas in the disk, but over time it will settle under gravity toward the midplane of the gas disk.

Collisions between particles lead to growth:

- Initially because particles are "sticky" - dissipate energy of relative velocity on impact
- Eventually because bodies become large enough that their own gravity attracts other bodies

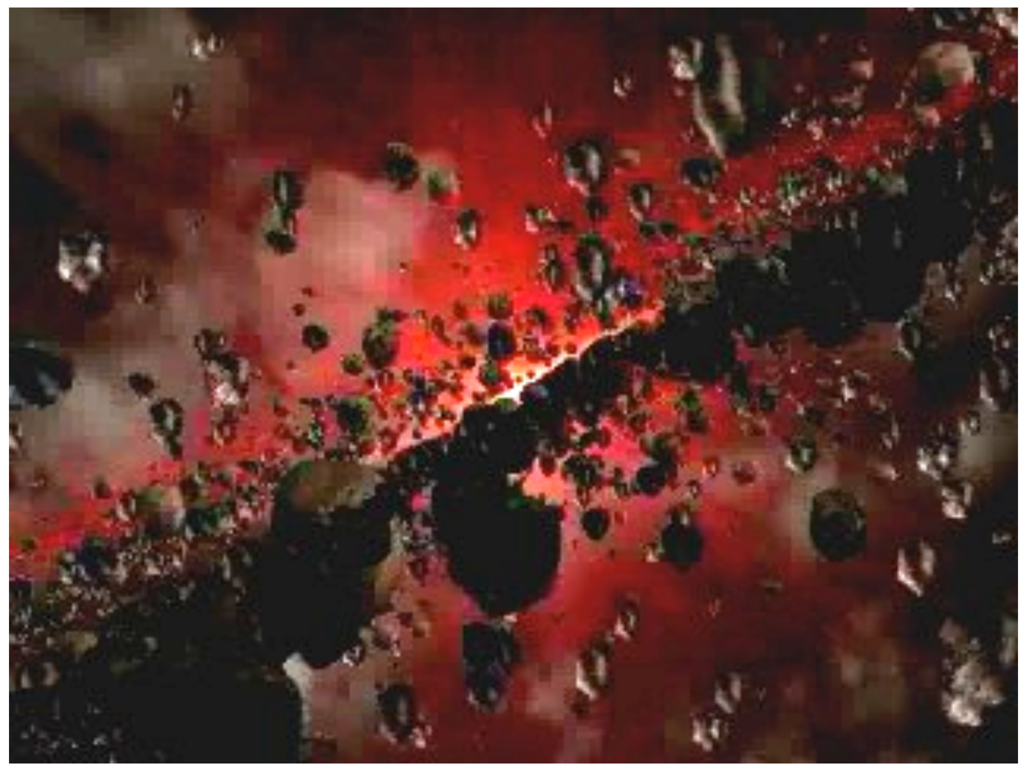
Dust	→	**Pebbles / rocks**	→	**Planetesimals**	→	**Planets**
microns		cm - m		km		10^3 km

Temperature Variations in the Solar System



Planet Building

- Jovian planets began as aggregating bits of rock and ice that reached 15 Earth masses and began to capture large amounts of He & H
- Terrestrial planets have very little H & He because their low masses can't keep these gases from evaporating
- The comets are just remains of the icy planetesimals that Jupiter threw out far into the Solar system. They are fossils of the early Solar system

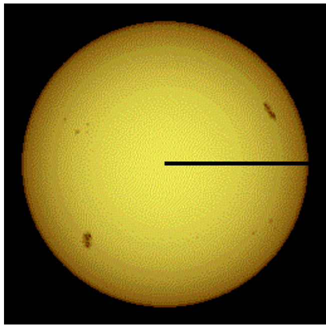


Clearing the Protosolar Nebula

Four effects cleared the nebula:

1. **Radiation pressure**-light streaming from the sun pushed against the particles of the solar nebula.
2. **The solar wind**—flow of ionized H helped push dust and gas out of the nebula.
3. **Sweeping of space debris by the planets**—the moons and planets are constantly getting bombarded by meteorites. **Heavy bombardment**—was a period when the craters were formed roughly 4 billion years ago.
4. **Ejection of material from the solar system by close encounters with planets**

Traditionally, understood this as resulting from a temperature gradient in the protoplanetary disk:



High temperature	**Low temperature**
Rocky planetesimals	Rocky and icy planetesimals

Snow (frost) line at r ~ 3 au

- Surface density of planetesimals is larger beyond the snow line, in parts of the disk cool enough for ice to be present
- Higher surface density → more rapid formation of planets
- In the outer Solar System, planets grew to ~20 M_{Earth} while gas was still present, captured gas to form gas giants
- In inner Solar System, no gas was captured
- All circular orbits as formed from a circular disk