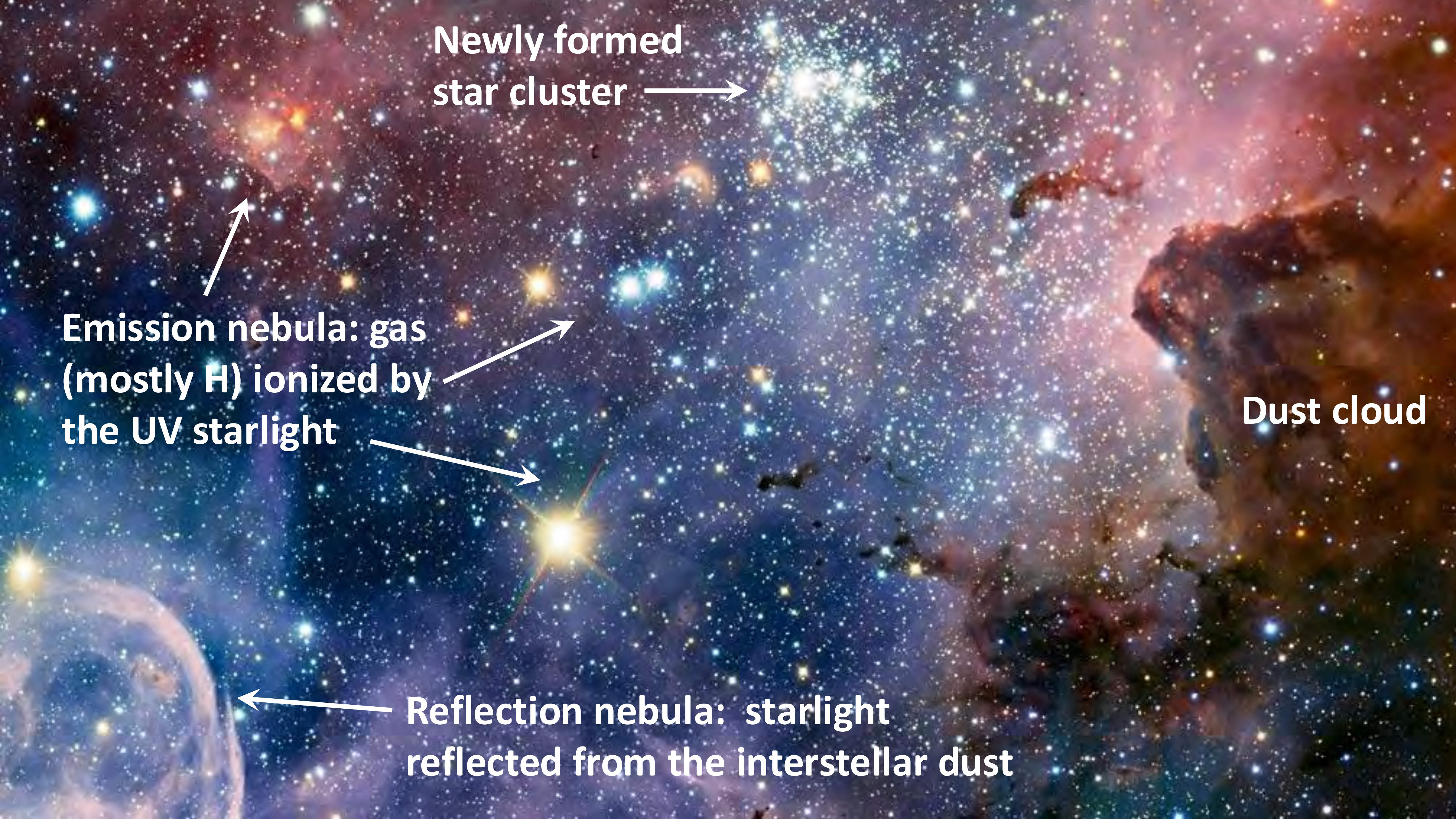
Interstellar Medium, Star and Planet Formation

Ay 1 – Lecture 5

Interstellar Medium (ISM): A Global Picture

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

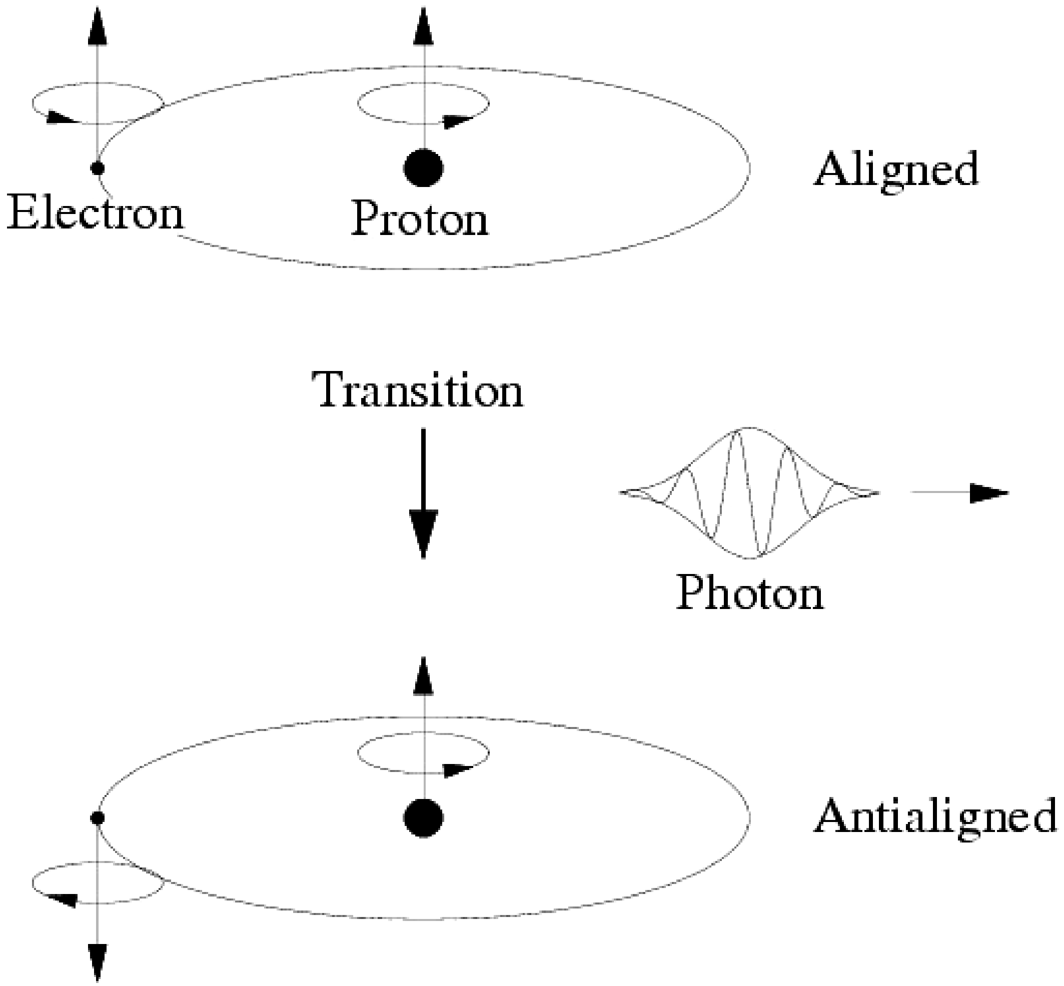

Newly formed star cluster
Emission nebula: gas (mostly H) ionized by the UV starlight
Dust cloud
Reflection nebula: starlight reflected from the interstellar dust

Multi-Phase ISM

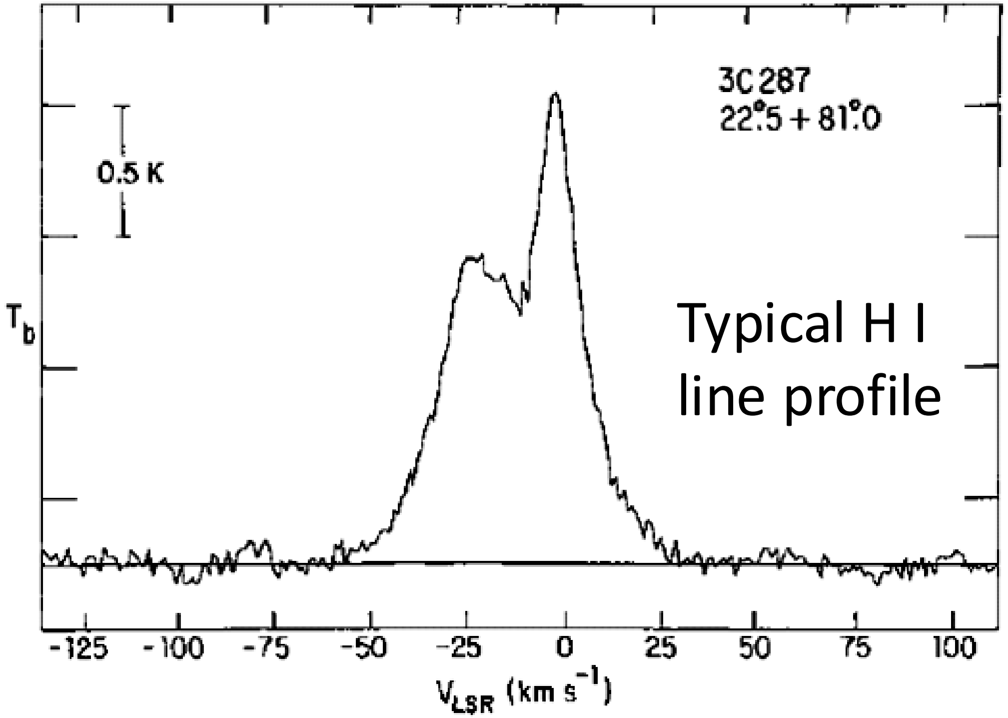
The ISM has a complex structure with 3 major components:

1. **Cold** (T ~ 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 (not to be confused with the dark matter halo)
   - Almost ***fully ionized***, ***energized mainly by SN shocks***

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

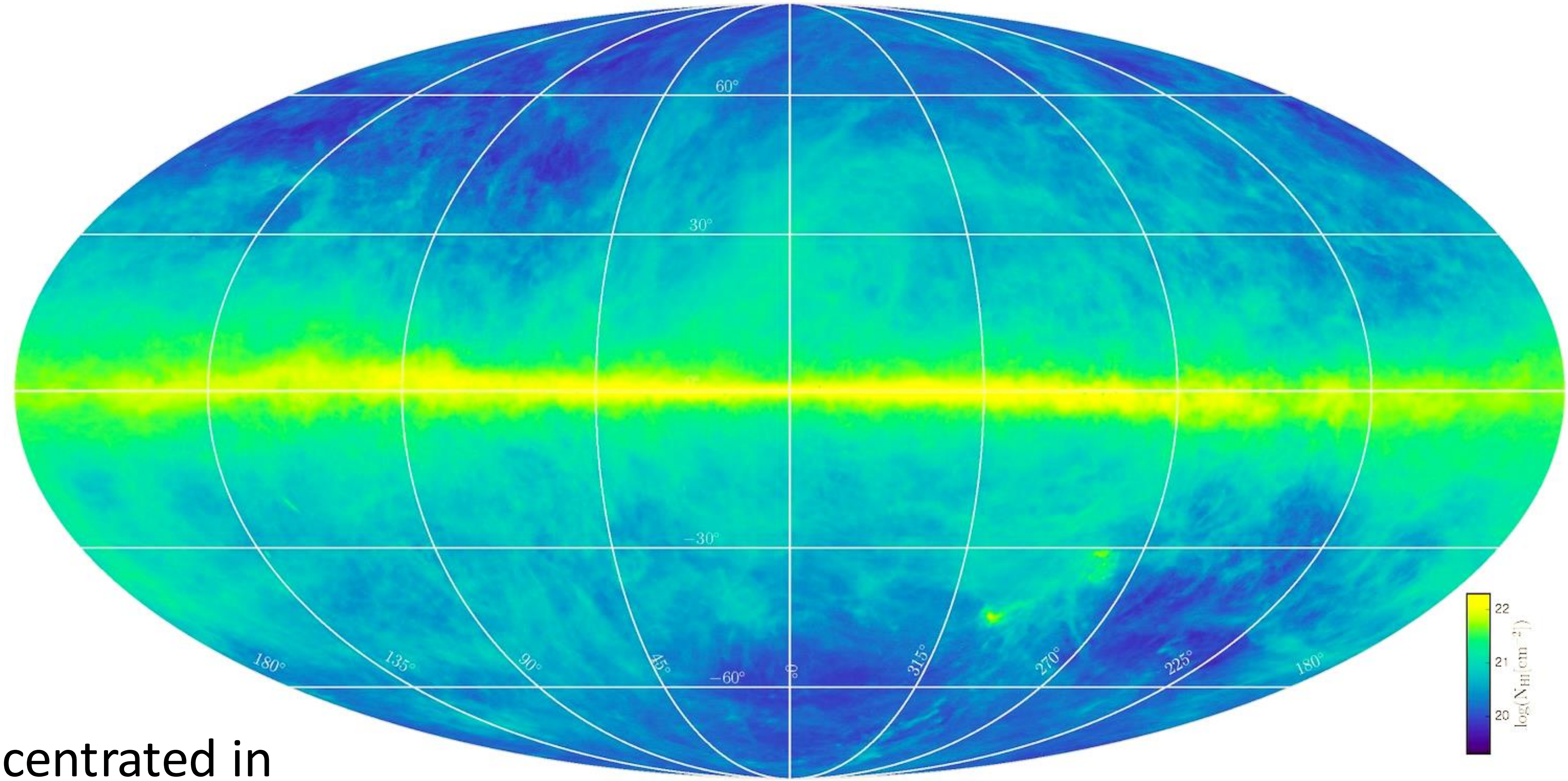


In emission generally originates from warm (T ~ 100 - 6000 K) ISM, which accounts for ~ 30 - 65% of the total ISM volume in the Galactic disk. In absorption, it probes a cooler ISM (can be also self-absorbed).



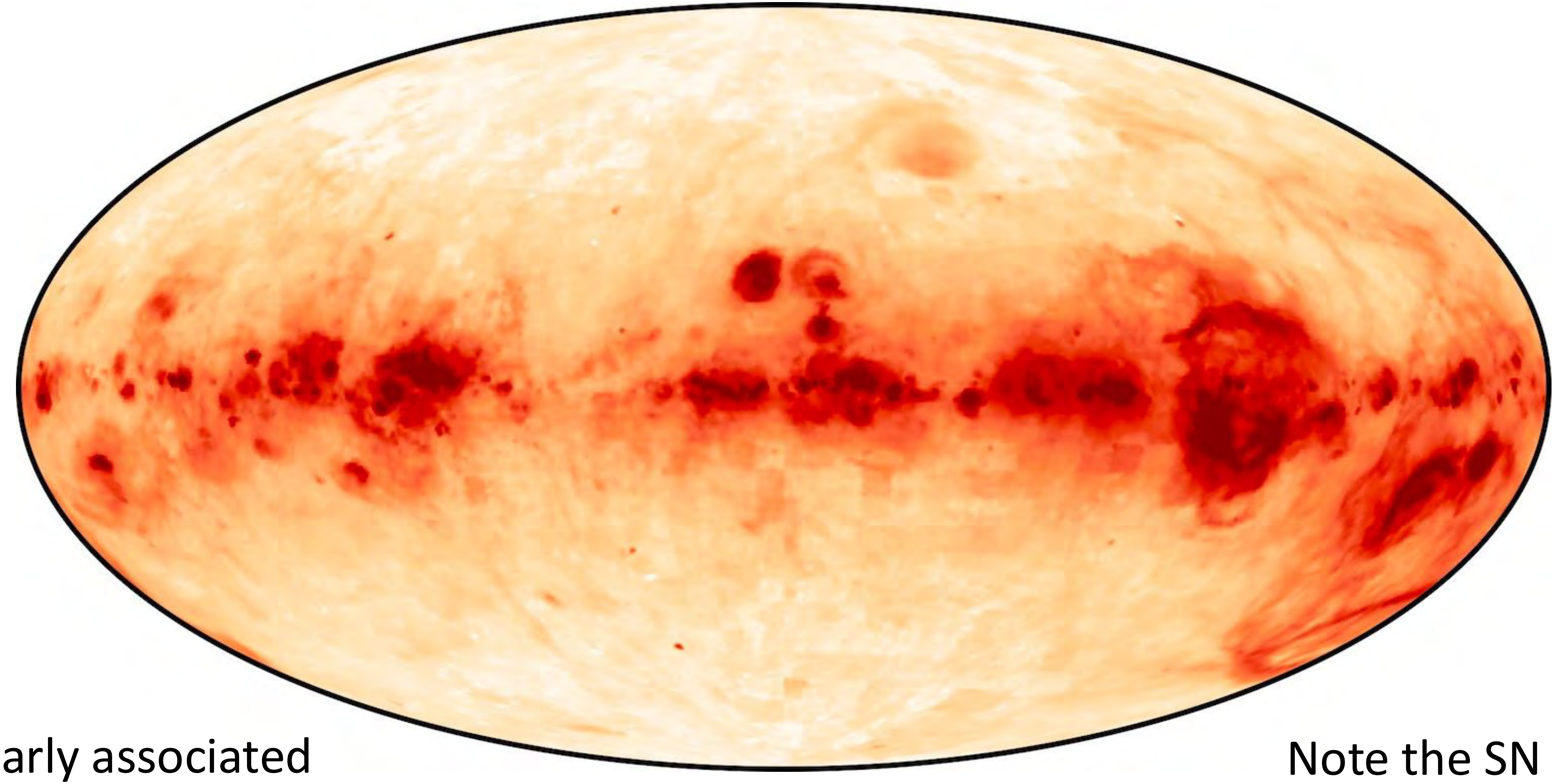
A major advantage: it is not affected by the dust absorption!

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.

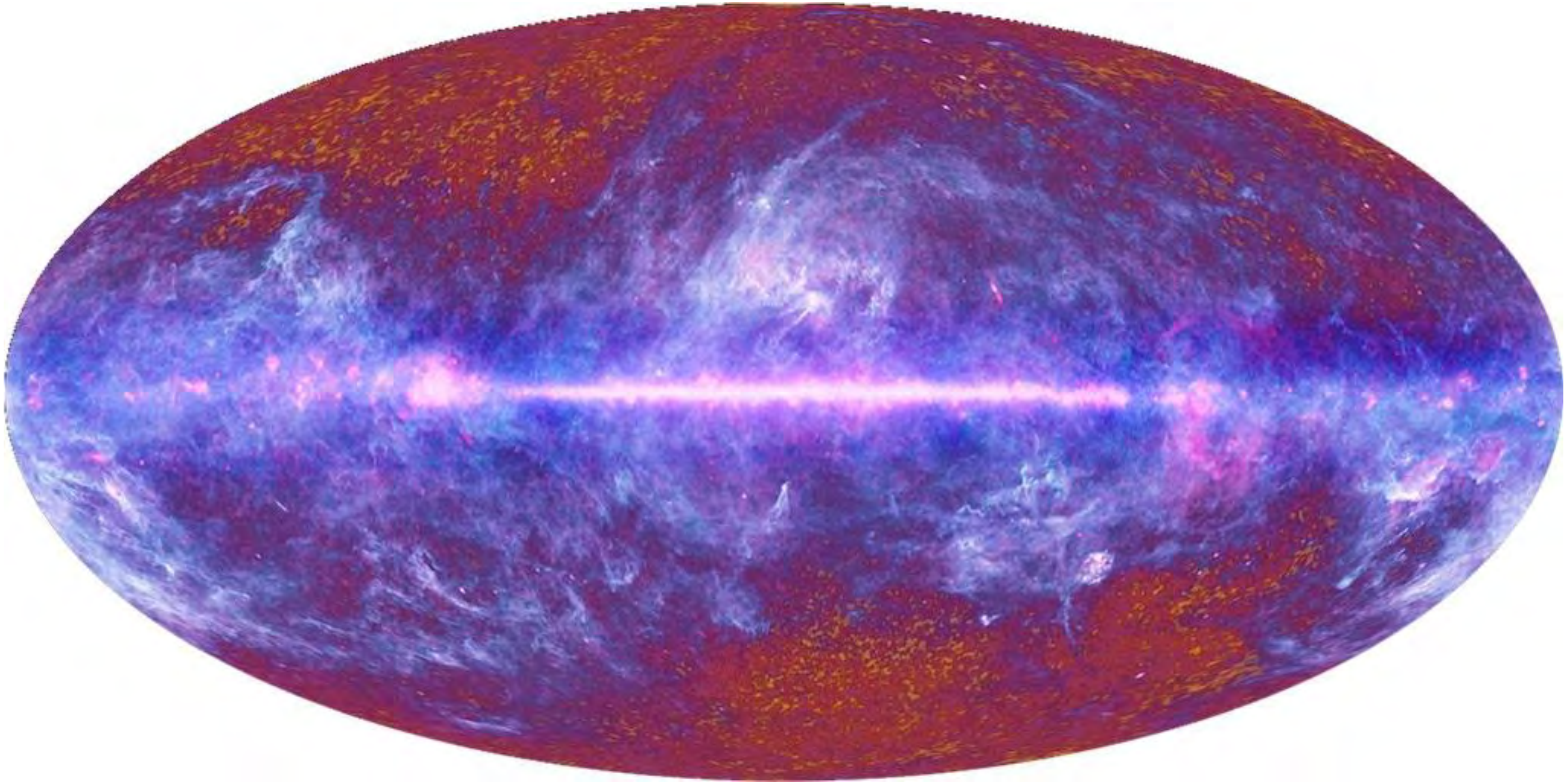
Distribution of (Ionized) H II in the Milky Way



Clearly associated
with the star forming regions

Note the SN and
star formation driven shells and bubbles

Galactic Dust Emission Map

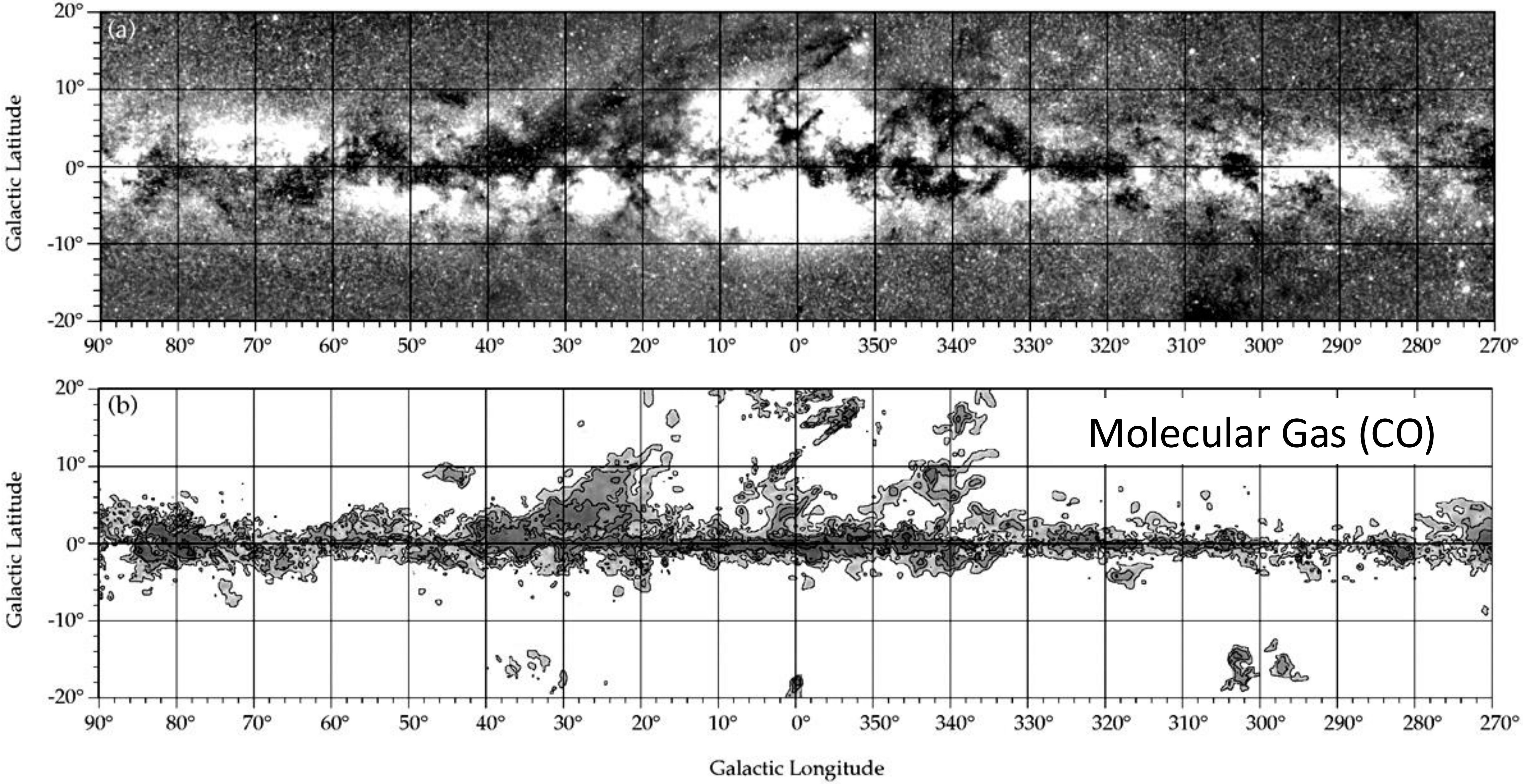


Mostly from the Galactic plane,
but also some at high Galactic latitudes

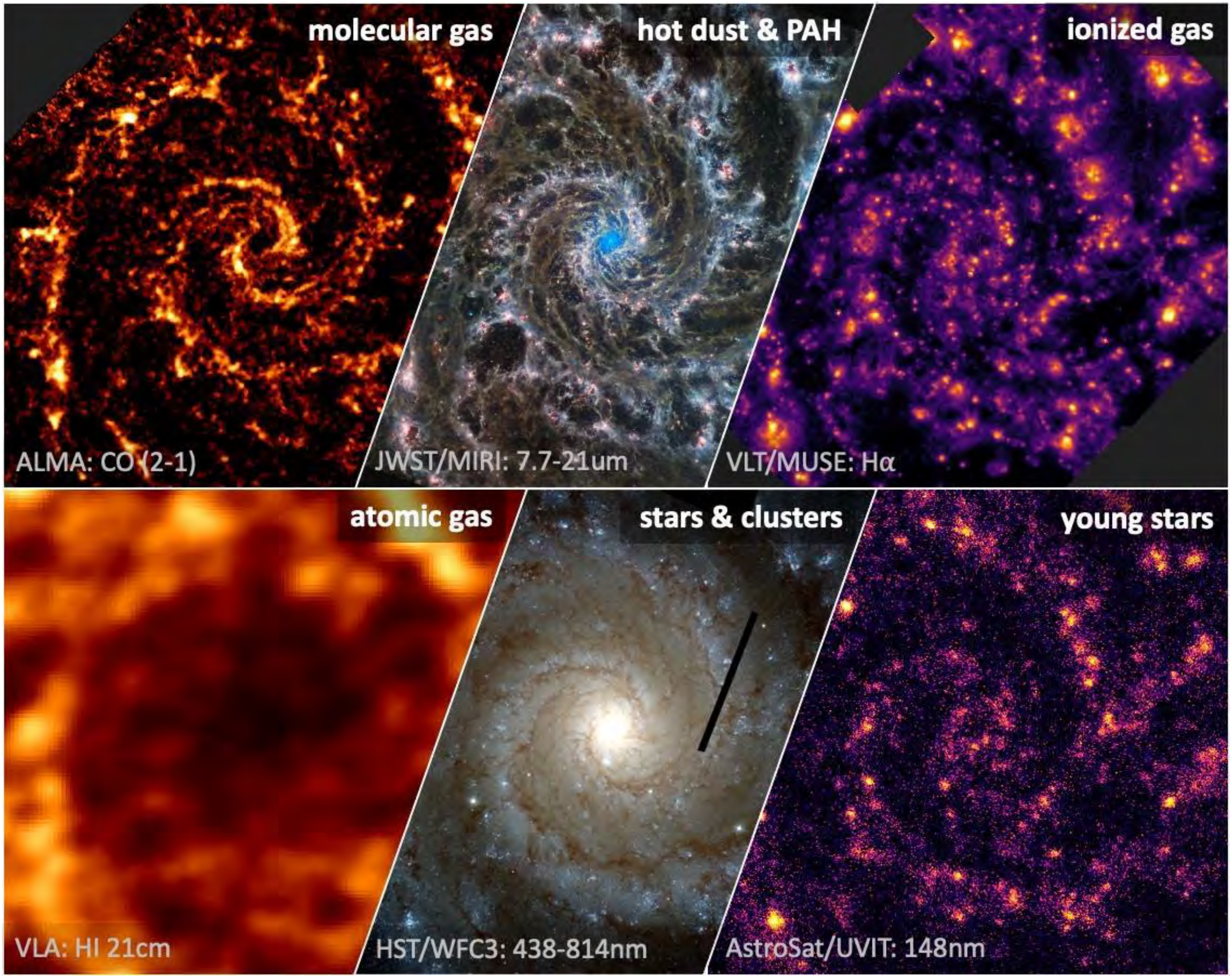
The S-like shape contains a
contribution from the Zodiacal dust

Molecular Gas Follows the Dust Distribution

Visible Light with the obscuration from dust lanes



Different ISM Components and Star Formation

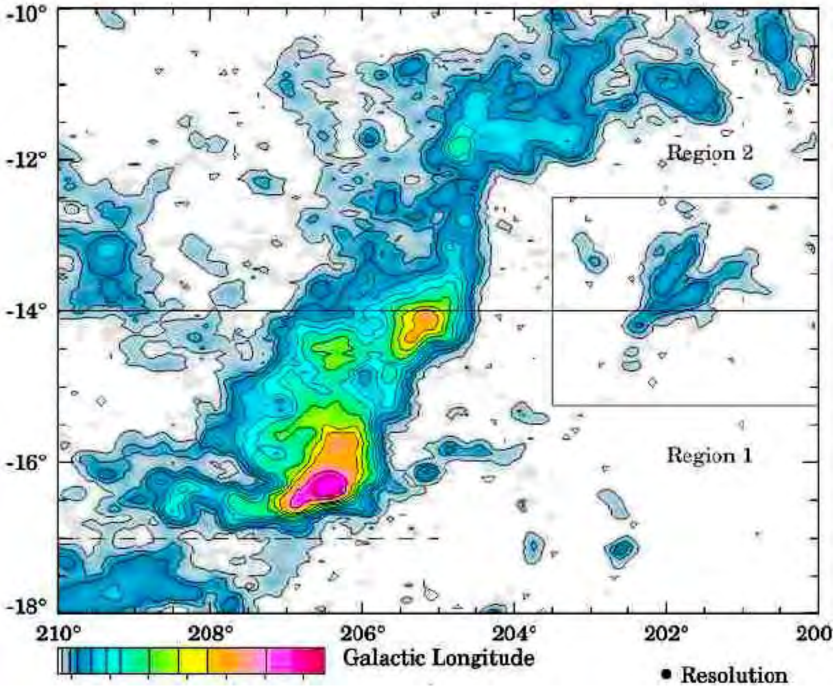


NGC 628

Interstellar Molecular Gas

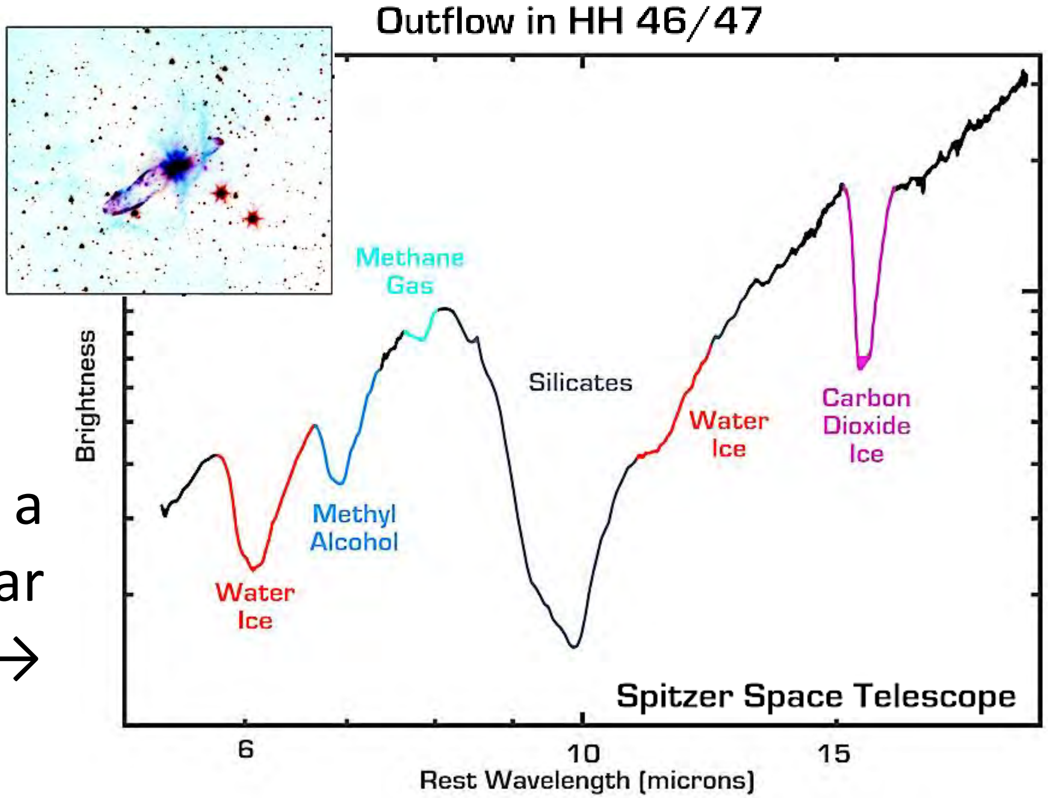
Generally studied using mm/sub-mm interferometers like ALMA, or mid/far-IR imaging from space

H_2 and CO are the most common, but to date, over 200 different molecule types have been found, including H_2O, many organic molecules,
up to amino acids



← CO map of Orion B molecular cloud

IR spectrum of a protostellar molecular outflow →



The Warm Interstellar Medium Is…

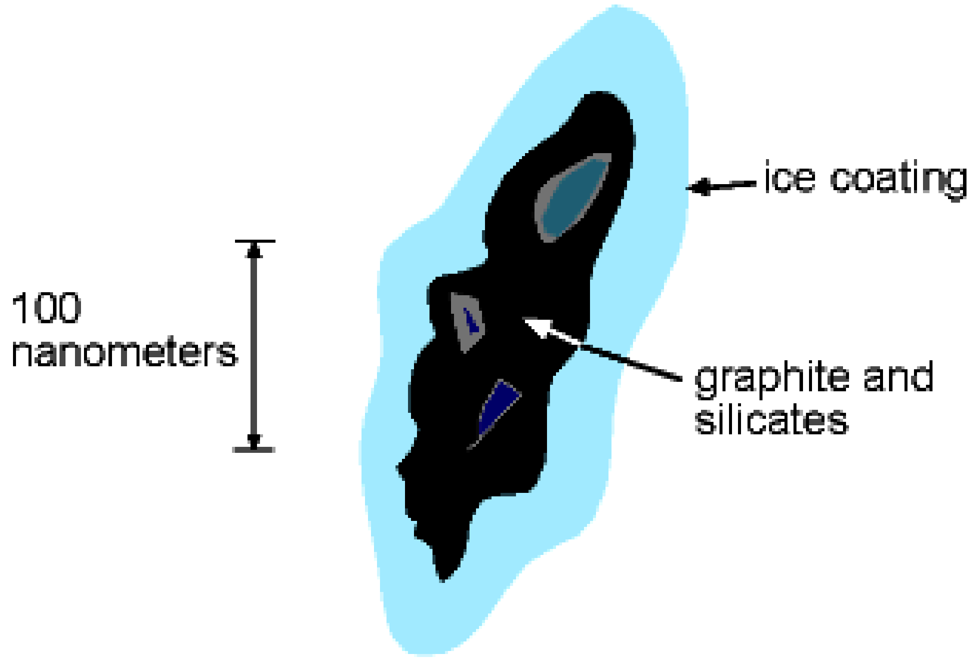
A. Inside molecular gas clouds
B. Has a temperature ~ million degrees
C. Mostly hydrogen
D. Makes pretty pictures
E. Mostly ionized
F. A friendly alien psychic

Interstellar Dust Grains

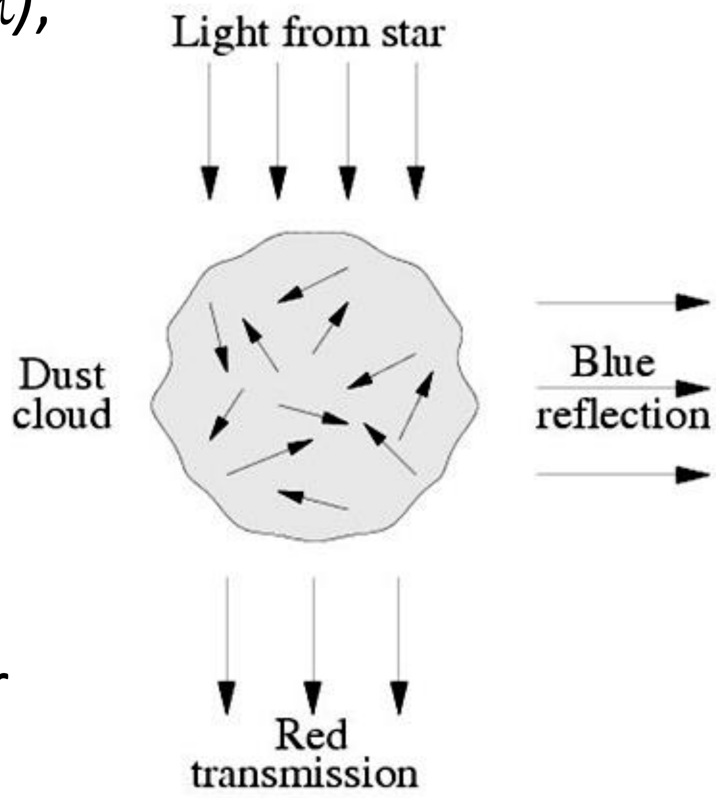
They are the cause of the **interstellar extinction**, and we have to *correct for that* to measure the true luminosities and colors of astronomical sources

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, which is **reddening**. Thus interstellar extinction = $f(\lambda)$,

and it depends on the chemical composition of the grains (e.g., carbon vs. silicon)



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

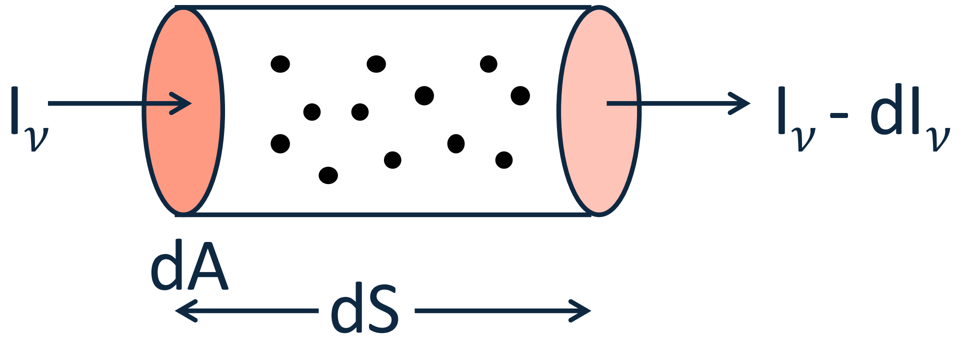


(Note: this breaks down for high-energy photons)

Absorption of Light

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

I_ν = input intensity at a frequency ν
dI_ν = flux decrement
dA = element of area
dS = element of the path length



Let number density of absorbers (particles per unit volume) = n
Each absorber has cross-sectional area = σ_ν (units cm^2)
The value of σ_ν depends on the material of the grains

If the beam travels through dS, the 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 (so it adds up really fast)

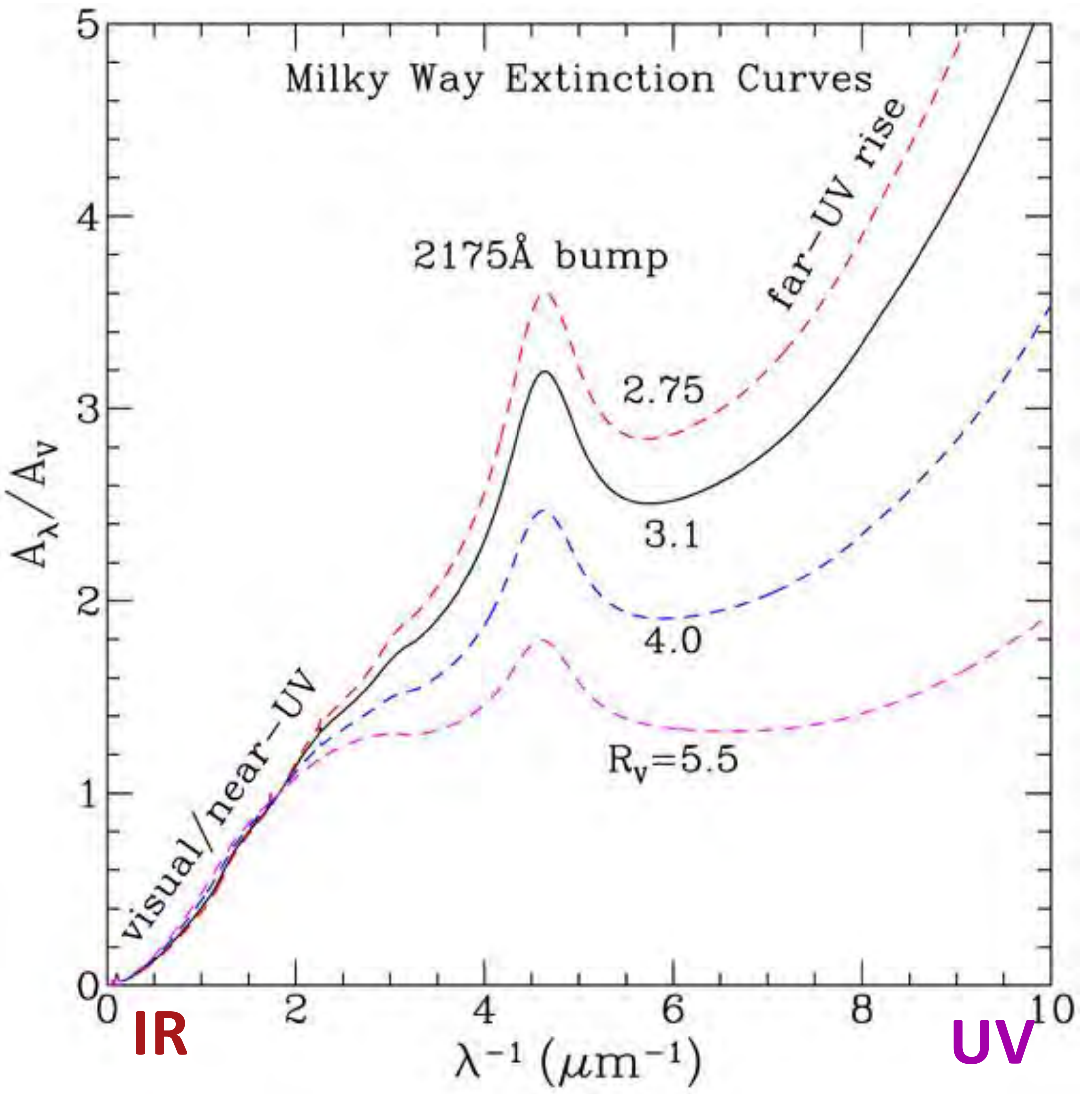
It is usually expressed in magnitudes

Interstellar Extinction Curve

It is really a family of curves that depend on the chemical composition of dust grains

Extinction is measured in magnitudes. For example, $A_V = 5$ means 5 magnitudes of extinction in the V band, i.e., dimming by a factor of 100

Note: this is the ratio of the extinction values at some wavelength λ and in the V band, and *both are in magnitudes*



Note the "inverted" axis, 1/wavelength

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 Small Magellanic Cloud

Interstellar Dust…

A. Grains are ~ 1 mm in size
B. Contains silicates, and organic molecules
C. Generally mixed with molecular clouds
D. Obscures shorter wavelengths more than the long ones
E. Obscures longer wavelengths more than the short ones

Stars Form in the Giant Molecular Gas and Dust Cloud

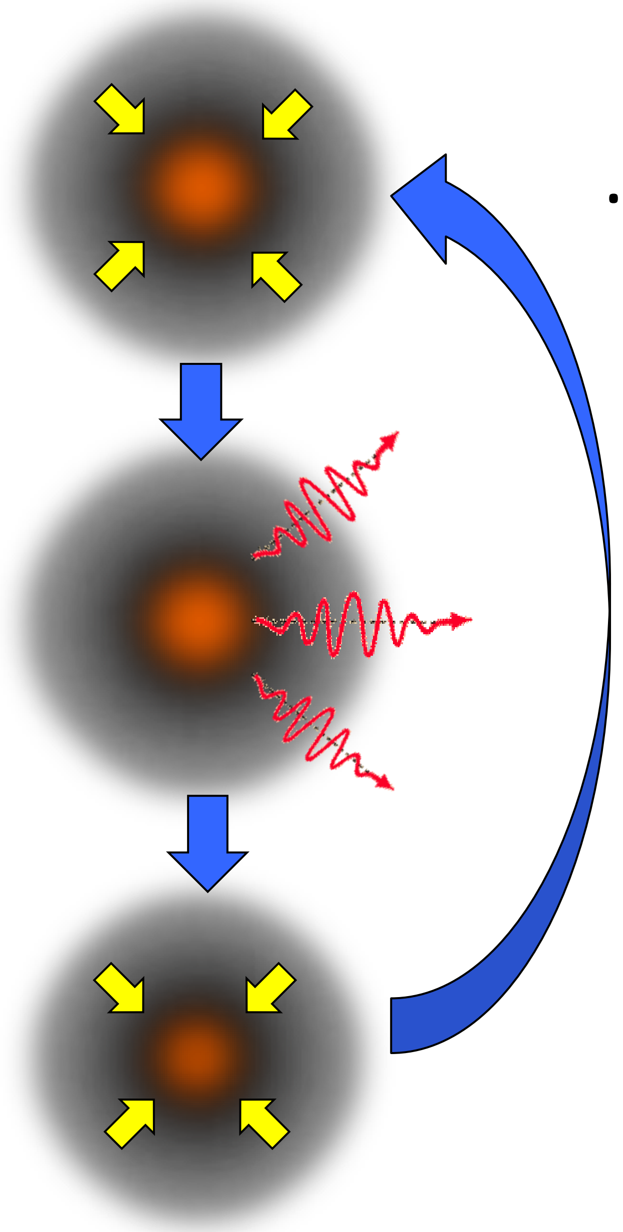

Bok/Thackeray Globulae:
Protostellar Clouds
IC 2944 (ESO)

Why Protostellar Clouds Collapse

Thermal pressure in the cloud 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



… and the feedback loop continues

The cycle stops when the thermonuclear reactions ignite in the core of the forming protostar

Basic Physics of Star Formation

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

- Gravity — acts to collapse the cloud to form a star
- Pressure
- Magnetic fields
- Bulk motions

$\left.\begin{array}{l}\text{Pressure}\\ \text{Magnetic fields}\\ \text{Bulk motions}\end{array}\right\}$ sources of support against gravity

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

Escape velocity is: $$v_{esc} = \sqrt{\frac{2GM}{R}}$$

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

…for a cloud of mass M, initial 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:

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

James Jeans

where *ρ* = mean density, *μ* = mean molecular weight,   T = temperature, and R_g is the gas constant, *not* radius!

Typical values for the molecular gas: $\rho \sim 10^{-19}$ g cm^{-3}, $T \sim 10$ K, $\mu \sim 2 – 20$

Using *μ* = 2 for molecular hydrogen: $M_J = 7.6 \times 10^{32}\ \mathrm{g} \approx 0.4 M_{sun}$

The corresponding spatial scale is the ***Jeans length***, $\lambda_J = \left(\frac{15 k_B T}{4\pi G \mu \rho}\right)^{1/2}$

where k_B is the Boltzmann constant

Clouds with $M > M_J$ or size $> \lambda_J$ **fragment and collapse**

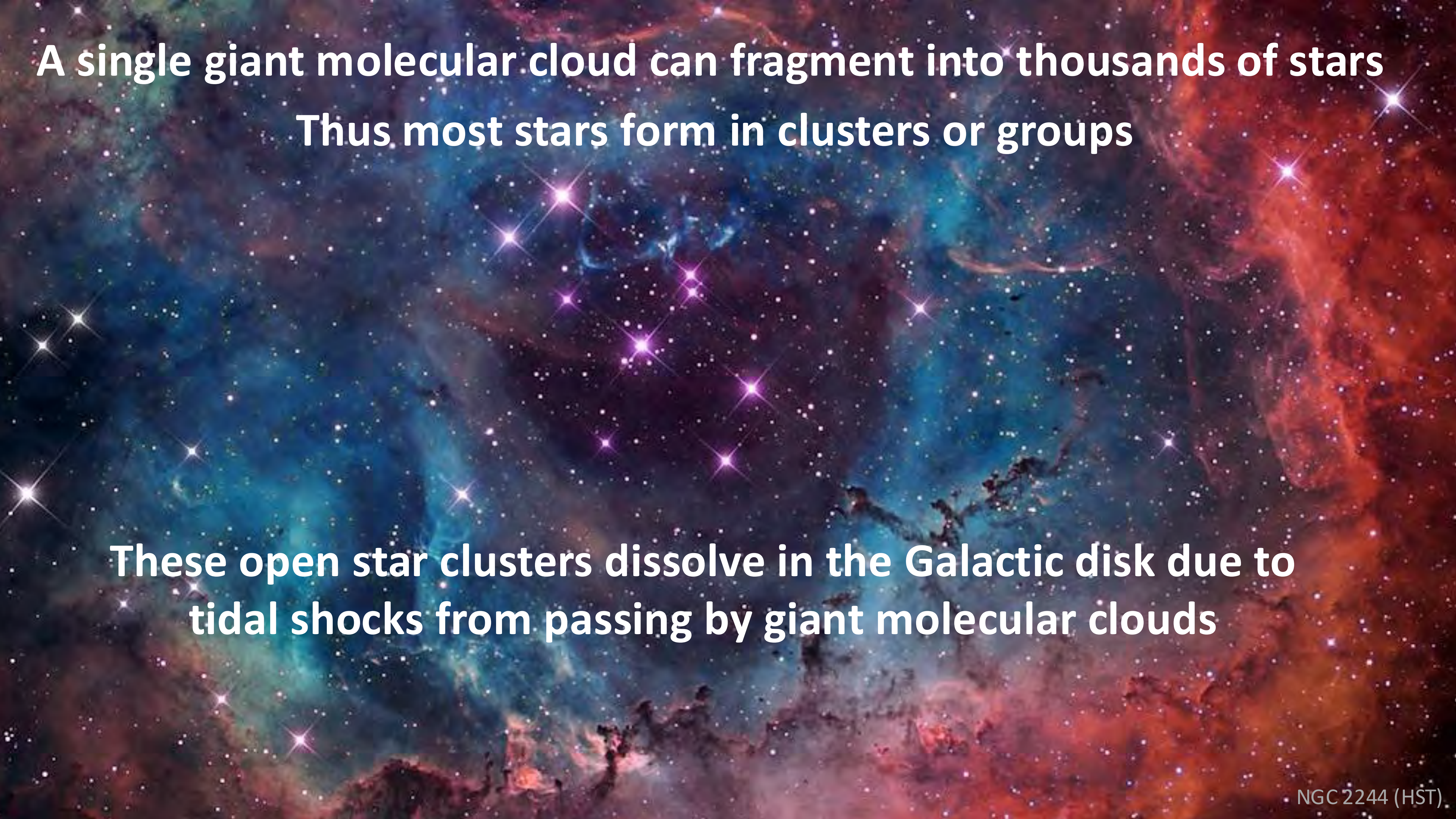
UV radiation from luminous young stars and their subsequent Supernova explosions dissipate the cloud

This stops the star formation

NGC 2244 (HST)

A single giant molecular cloud can fragment into thousands of stars

Thus most stars form in clusters or groups



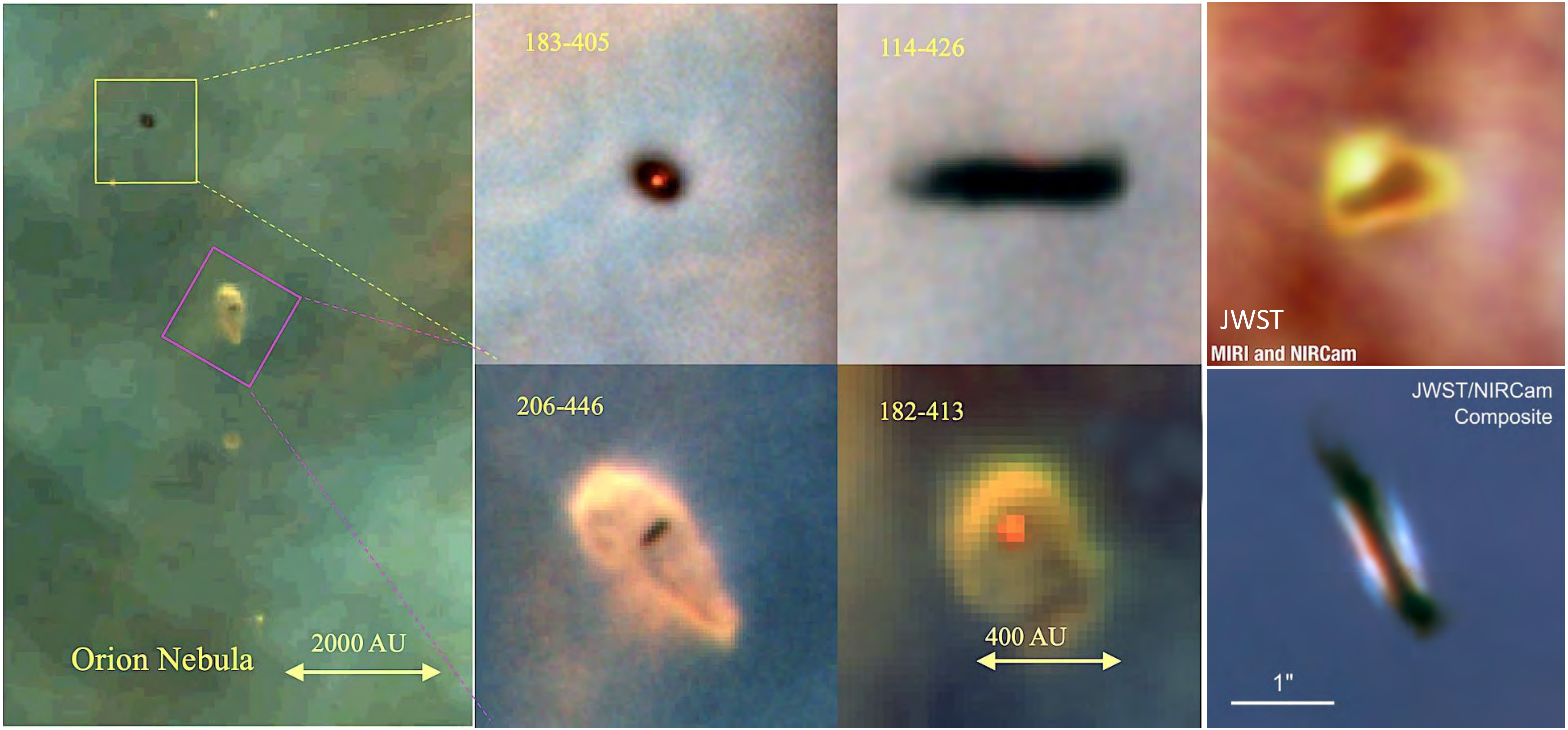
These open star clusters dissolve in the Galactic disk due to tidal shocks from passing by giant molecular clouds

NGC 2244 (HST)

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

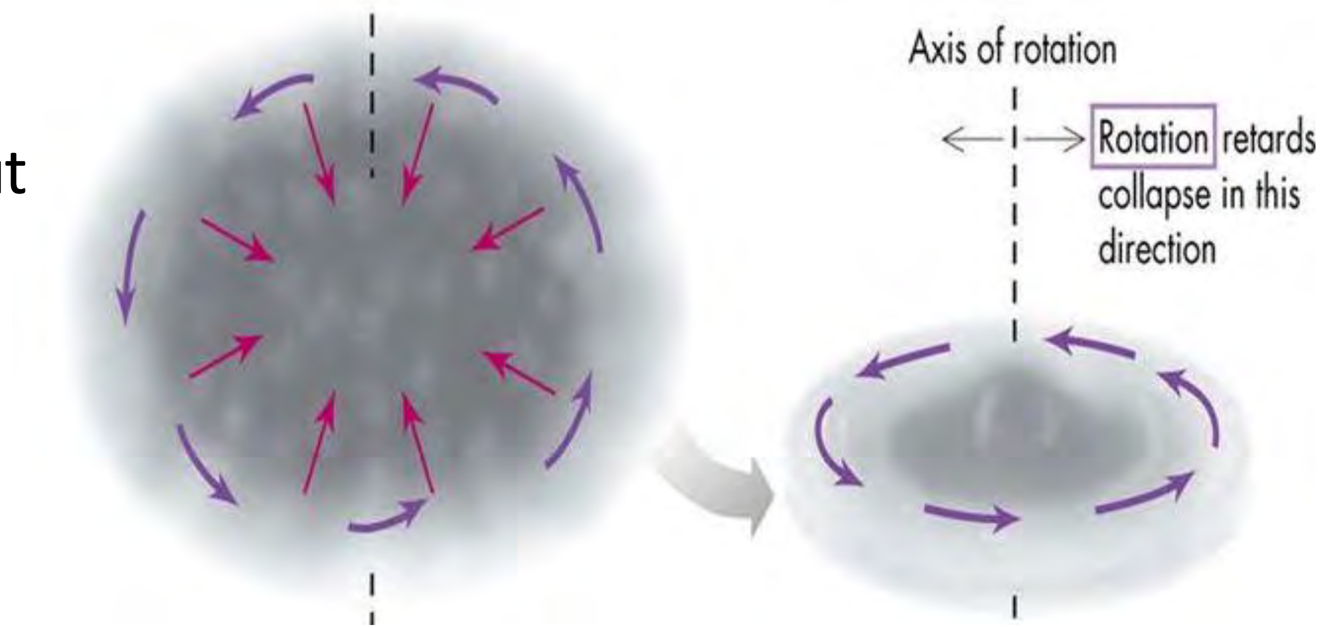
(Artist's conception)

Direct Images of Circumstellar Disks



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

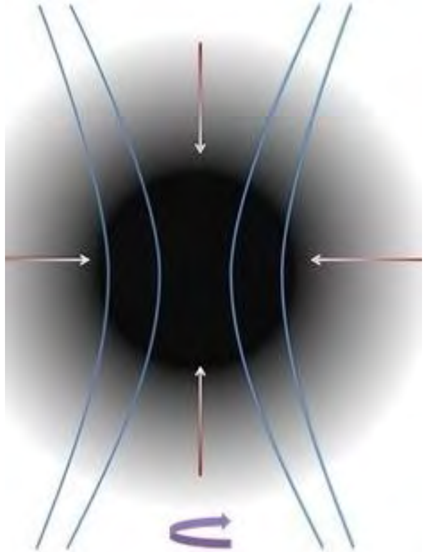
Why Disks?

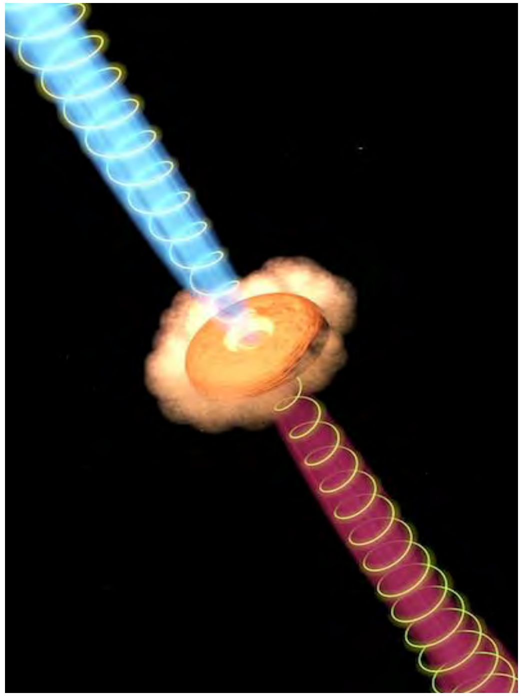


Because you can dissipate the energy, but cannot dissipate the angular momentum

The material with the excess angular momentum settles into a disk – the lowest energy configuration for a given angular momentum

Why Jets?

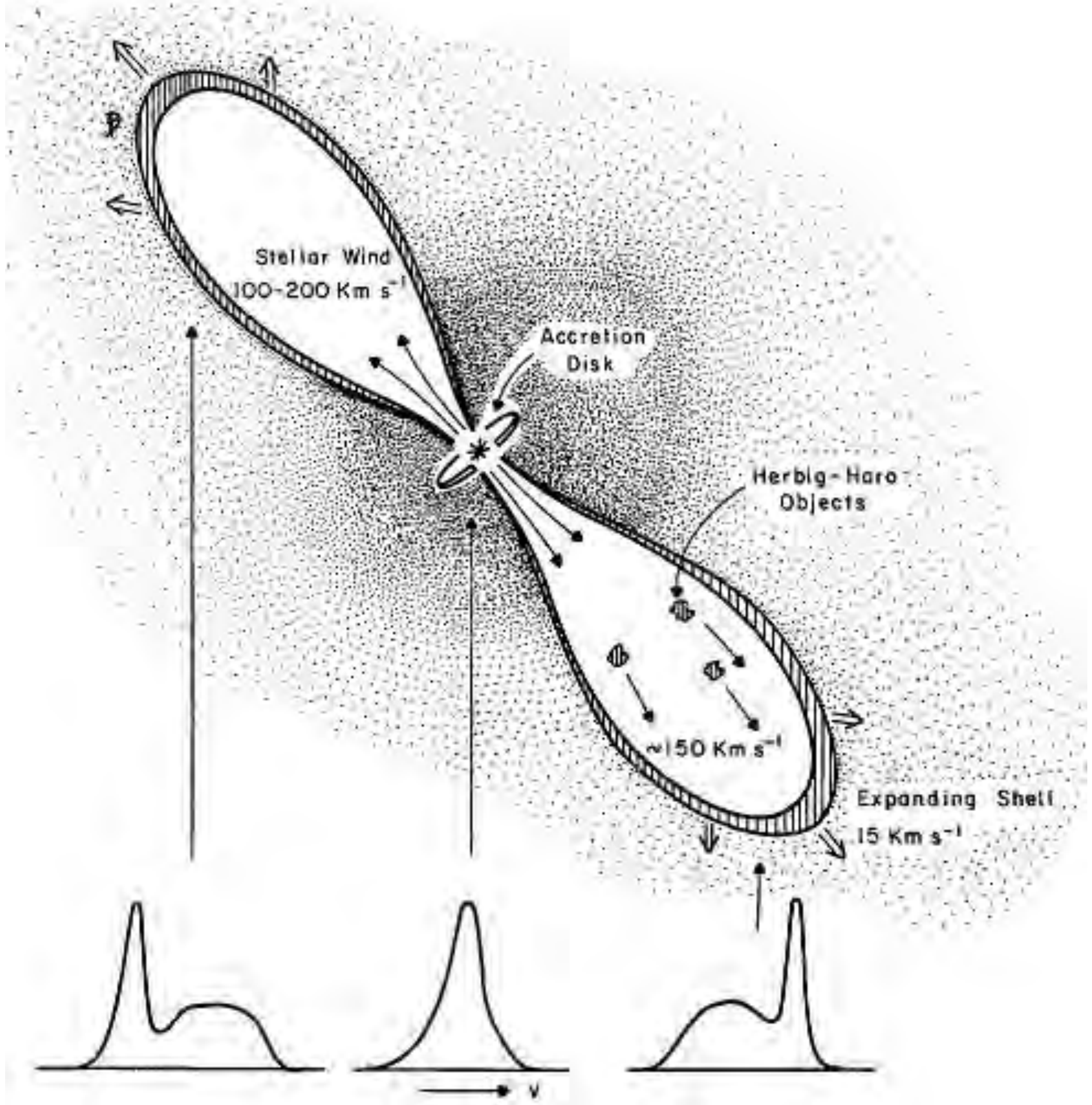




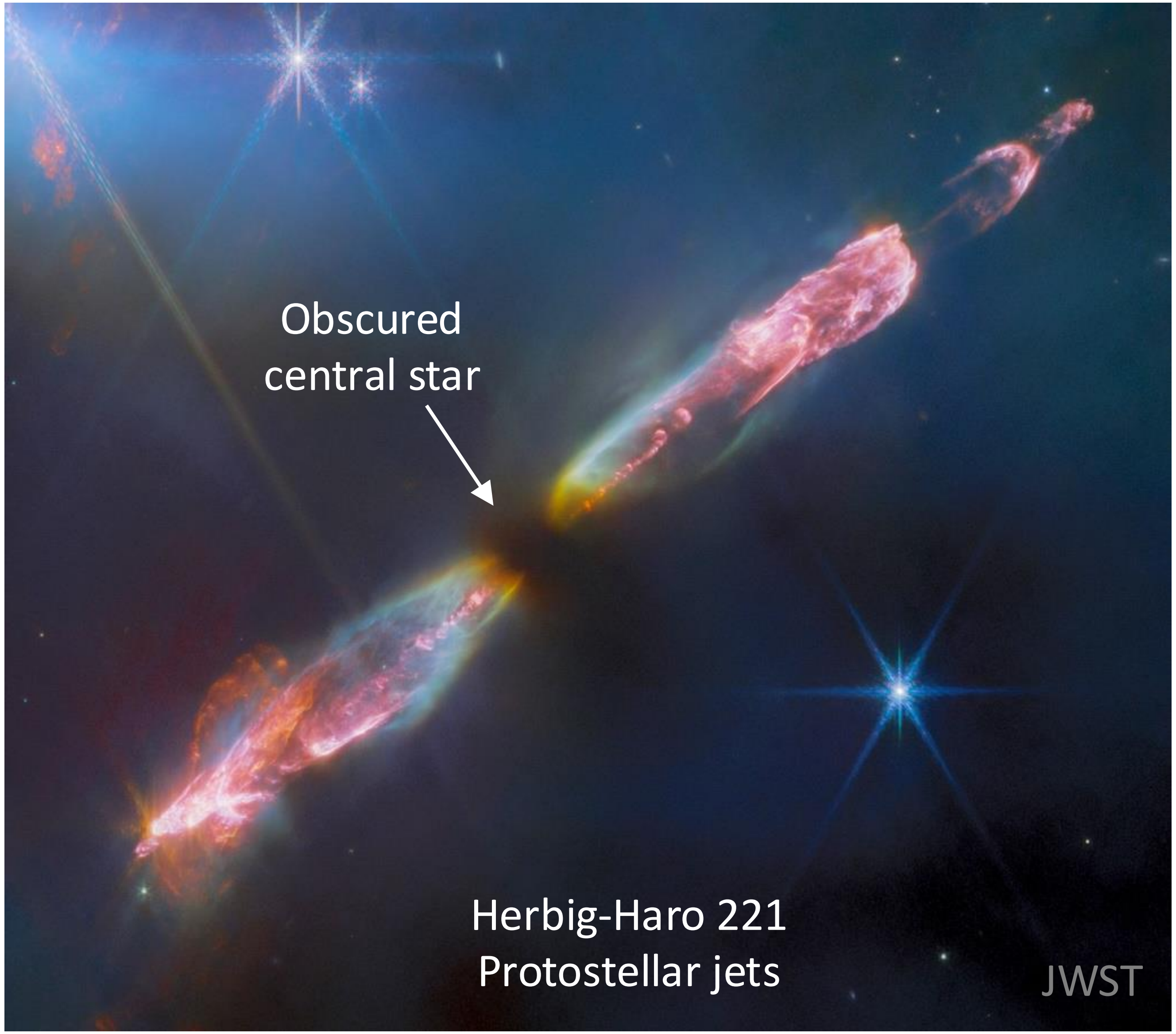
Magnetic fields are trapped in the plasma of the collapsing cloud and the disk

Disk rotation then winds up the field, making it even stronger – it then accelerates charged particles along the rotation axis, creating an outflow

Jets and Bipolar Outflows From Young Stars



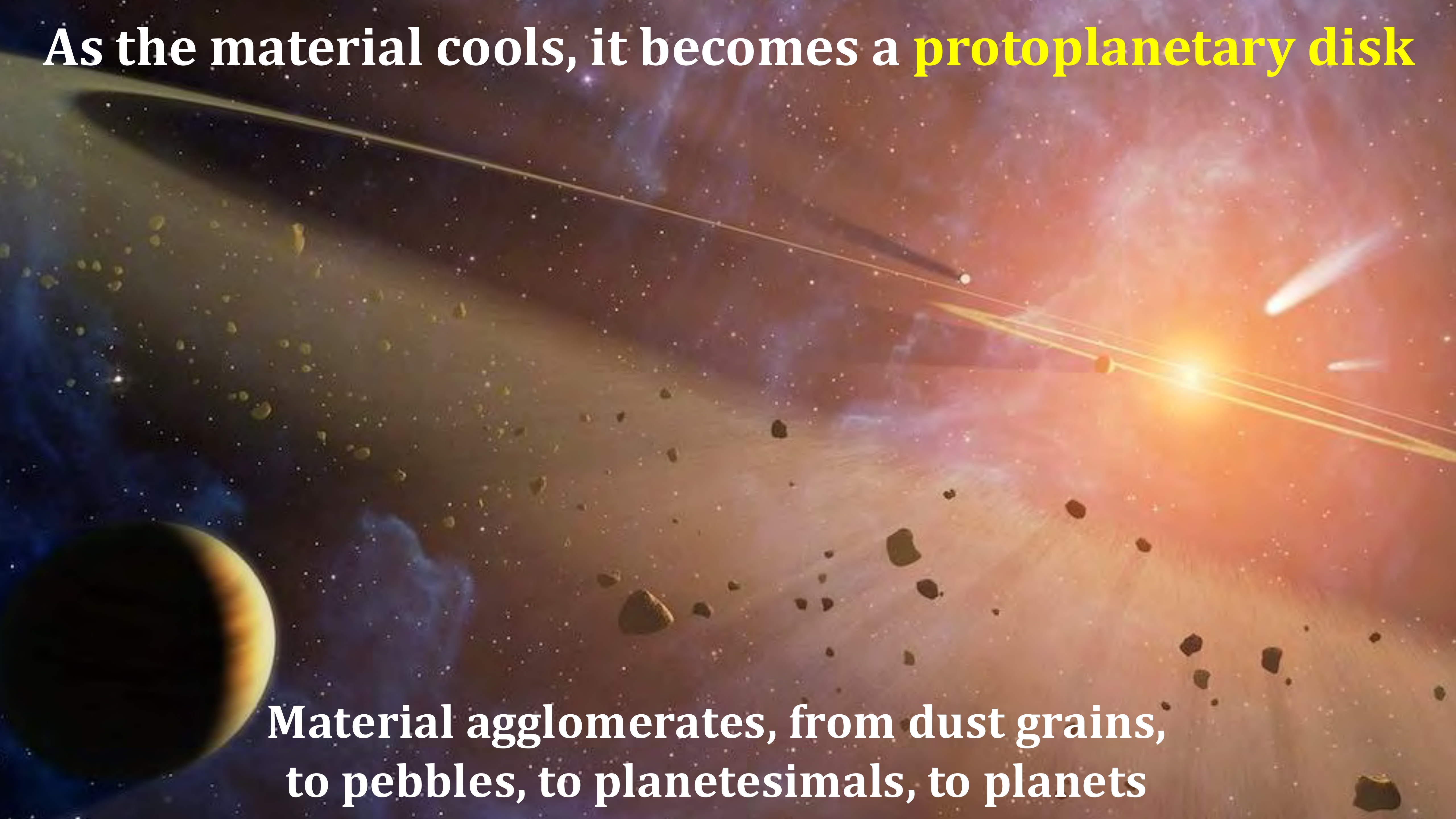
Observed line profiles



Young Stars …

A. Form from the warm interstellar medium
B. Ionize the gas near them
C. Generally come in clusters
D. Live long
E. Party hard

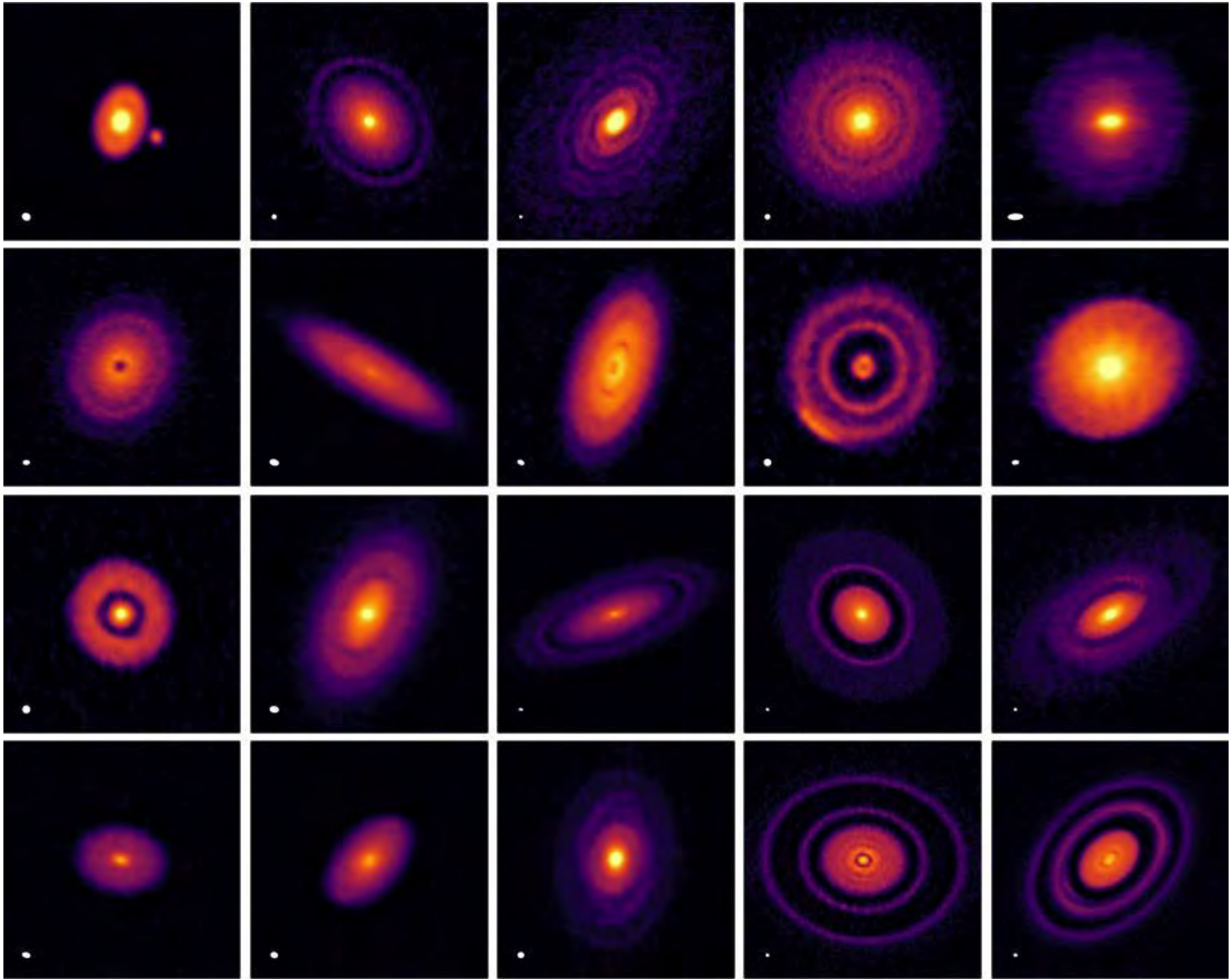
As the material cools, it becomes a protoplanetary disk



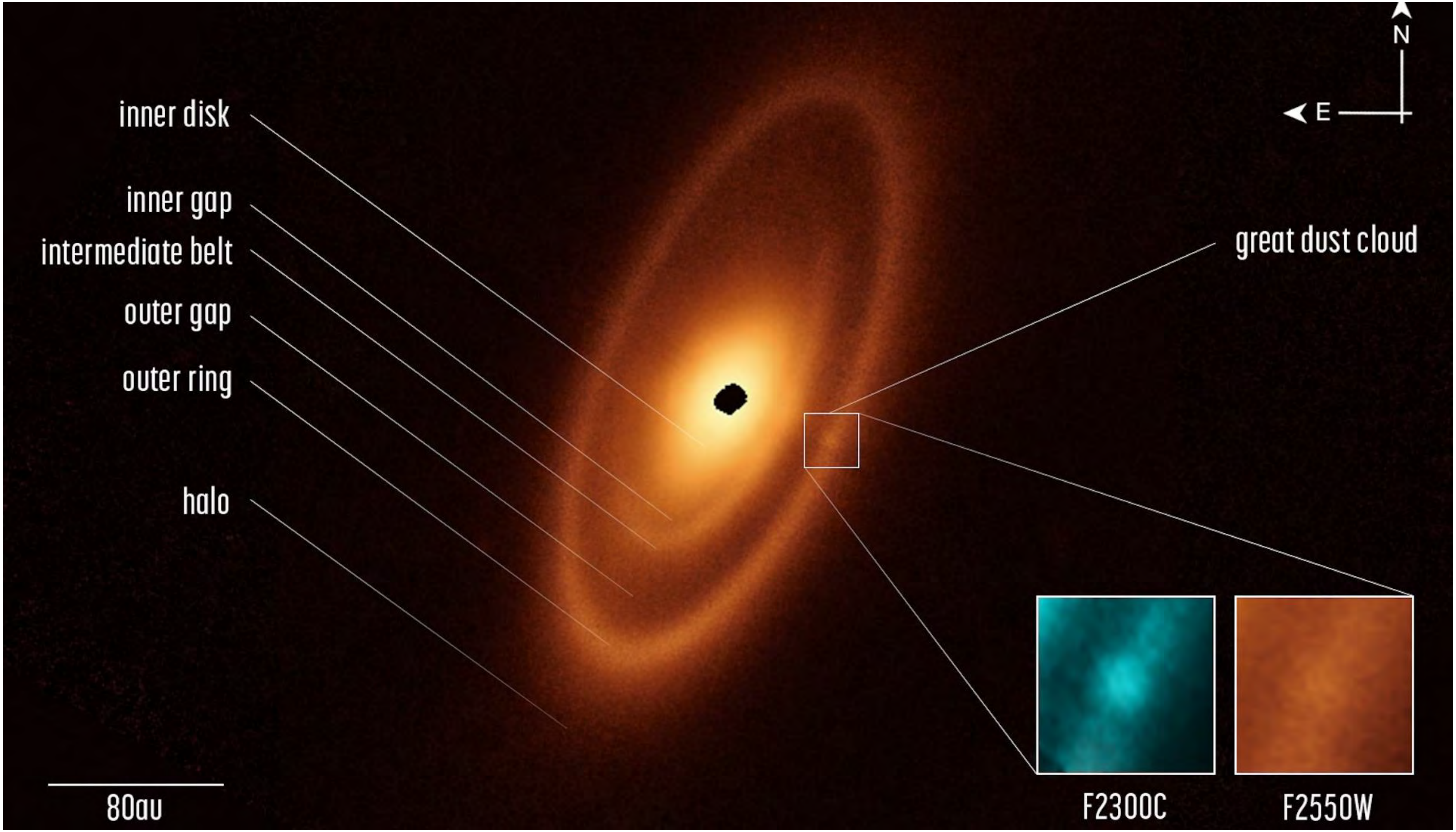
Material agglomerates, from dust grains,
to pebbles, to planetesimals, to planets

Protoplanetary Disks Observed by ALMA

The rings are gaps in the protoplanetary disks, cleared out by the newly formed planets



Protoplanetary Disk Around Fomalhaut Observed by JWST



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 eventually settles under gravity toward the midplane of the gas disk, due to the conservation of the angular momentum

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

Clearing of the Protoplanetary Disk

Four effects cleared the protoplanetary disk:

1. **Radiation pressure:** light from the parent star pushes against the leftover gas and smaller particles

2. **Stellar wind:** flow and ejections of ionized plasma push dust and gas hydrodynamically

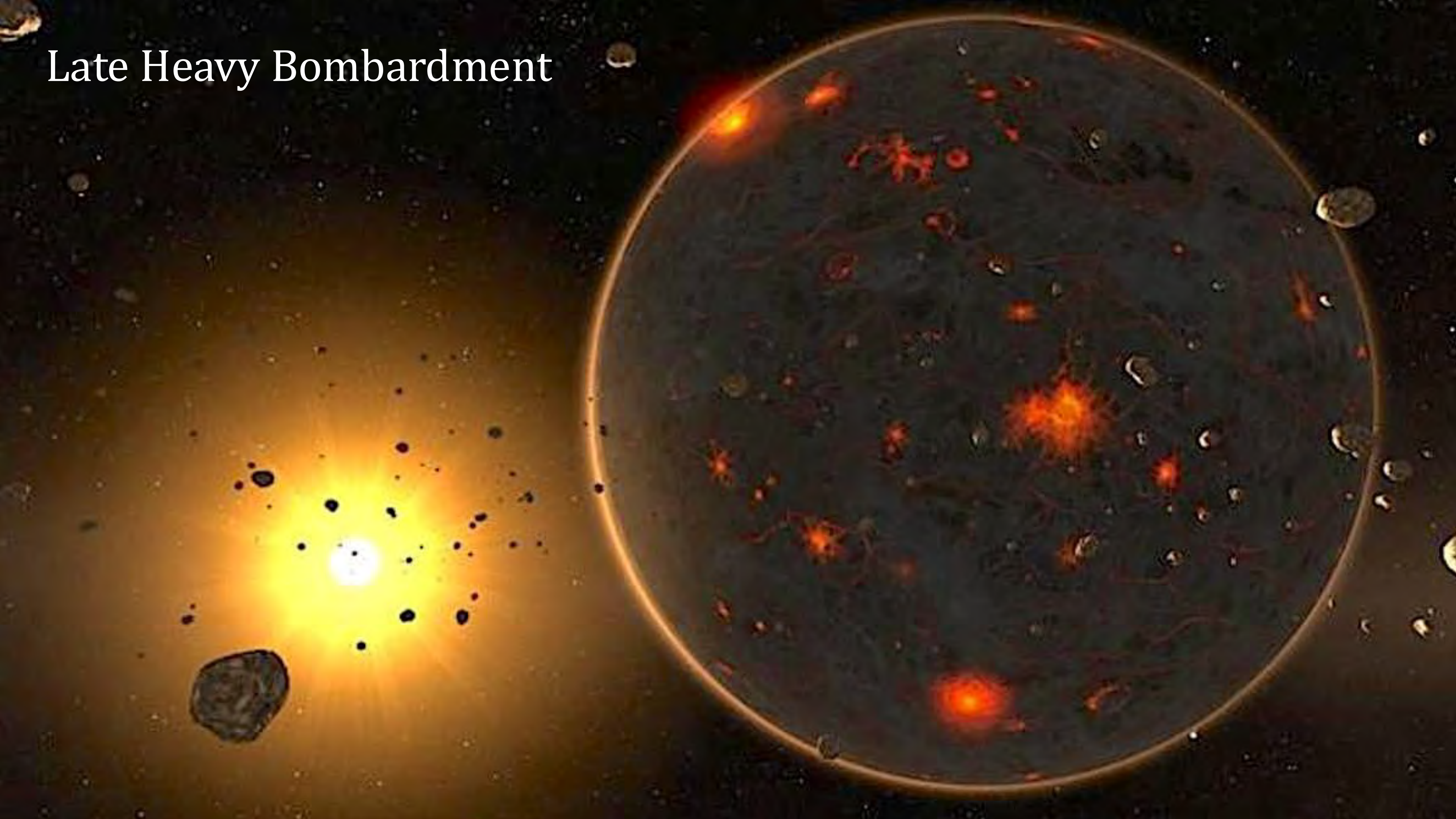
3. **Sweeping of space debris in the disk by the planets:** as the young planets go around in their orbits, they scoop any material in the similar orbits. This is the origin of the rings/gaps we see in protoplanetary disks

   This was also the era of the **Heavy Bombardment** as the young planets and their moons were bombarded by the swept rocks and planetesimals bombarded by meteorites. This was when the impact craters were formed, roughly 4 billion years ago in our Solar system

4. **Ejection of material from the system by close encounters with planets**

   This is still going on, mostly due to the interactions with Jupiter

Late Heavy Bombardment



Planetary Morphology Gradient

A consequence of the temperature gradient in the protoplanetary disk

High temperature	Low temperature
Rocky planetesimals	Rocky and icy planetesimals

Snow (frost) line at r ~ 3 au

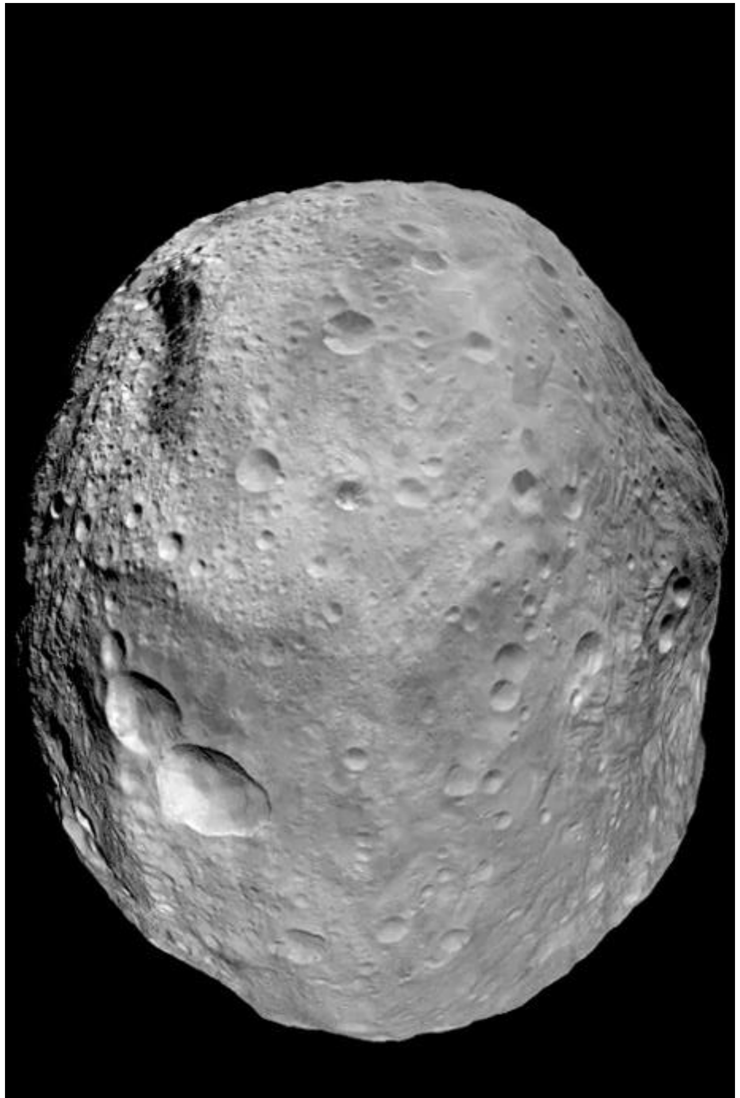
- Surface density of planetesimals is larger beyond the snow line, in parts of the disk cool enough for ice to be present
- Higher surface density → more rapid formation of planets
- In the outer Solar System, planets grew to ~20 M_{Earth} while gas was still present, captured gas to form gas giants
- In the inner Solar System, most of the gas was swept

Thus:

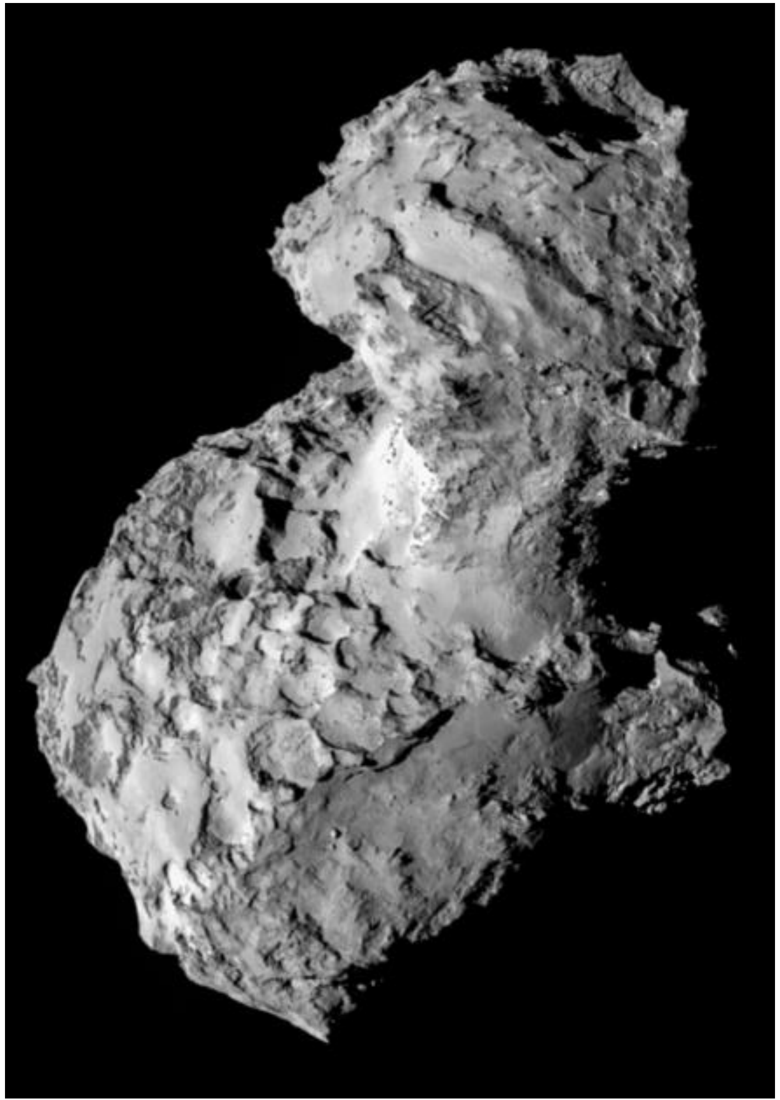
Rocky planets — Gas giants — Icy dwarf planets — Comets

Asteroids, comets, and Kuiper belt objects are leftover planetesimals

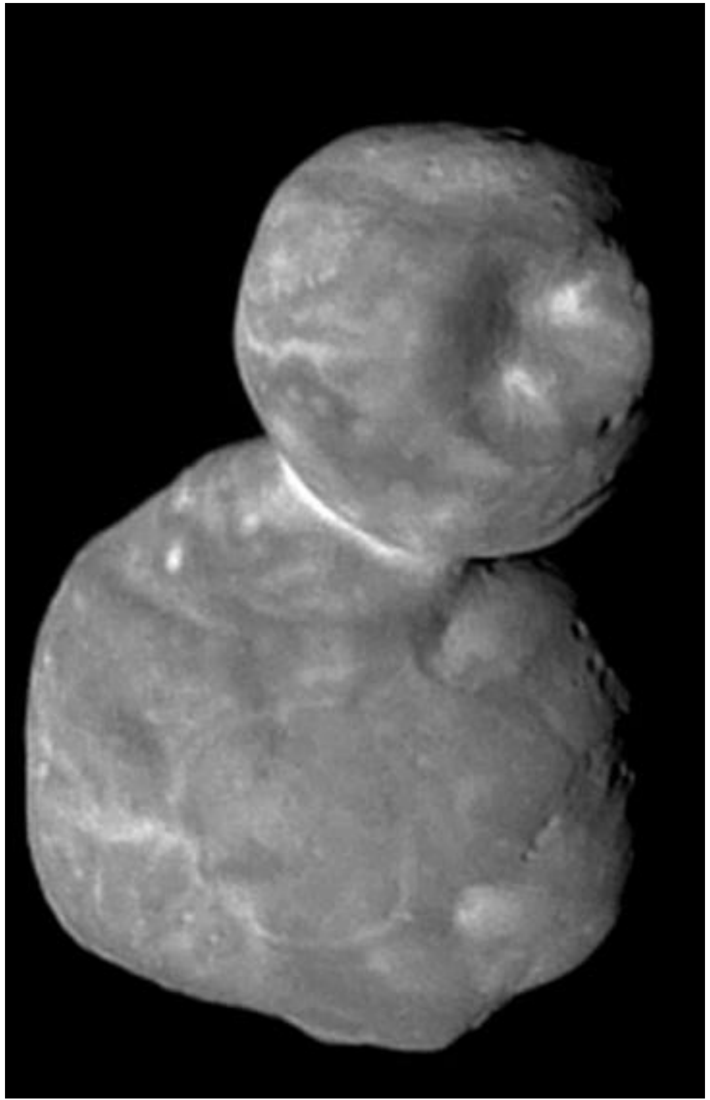
Asteroid Vesta
Dawn mission, NASA



Comet 67P/Churyumov–Gerasimenko
Rosetta mission, ESA



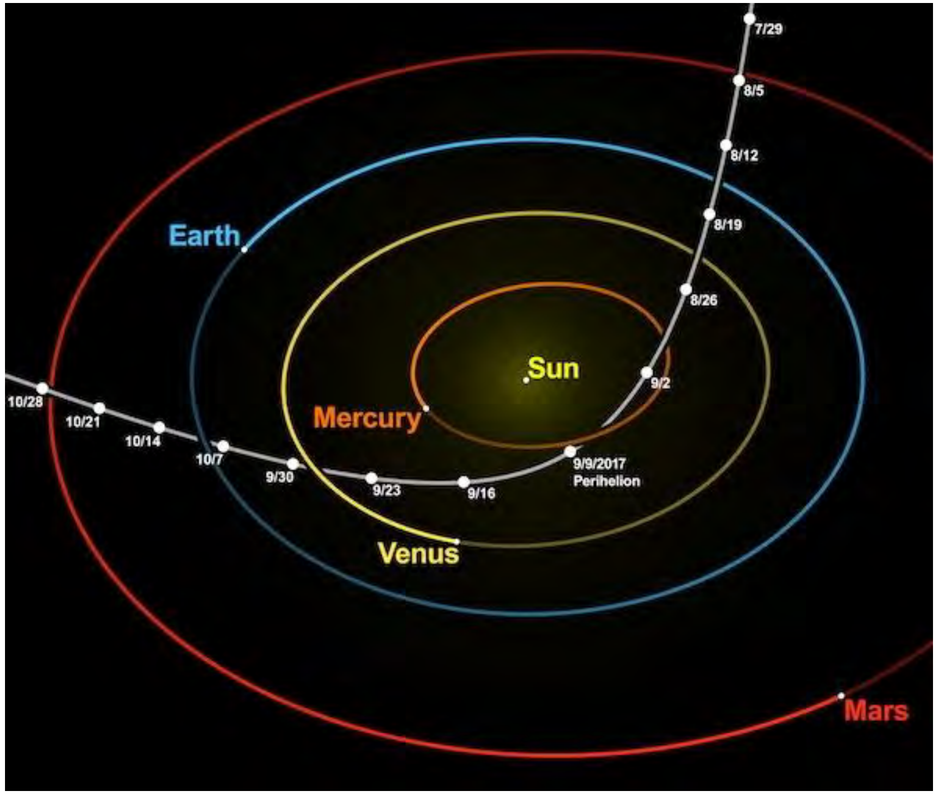
KBO Arrokoth
New Horizons, NASA



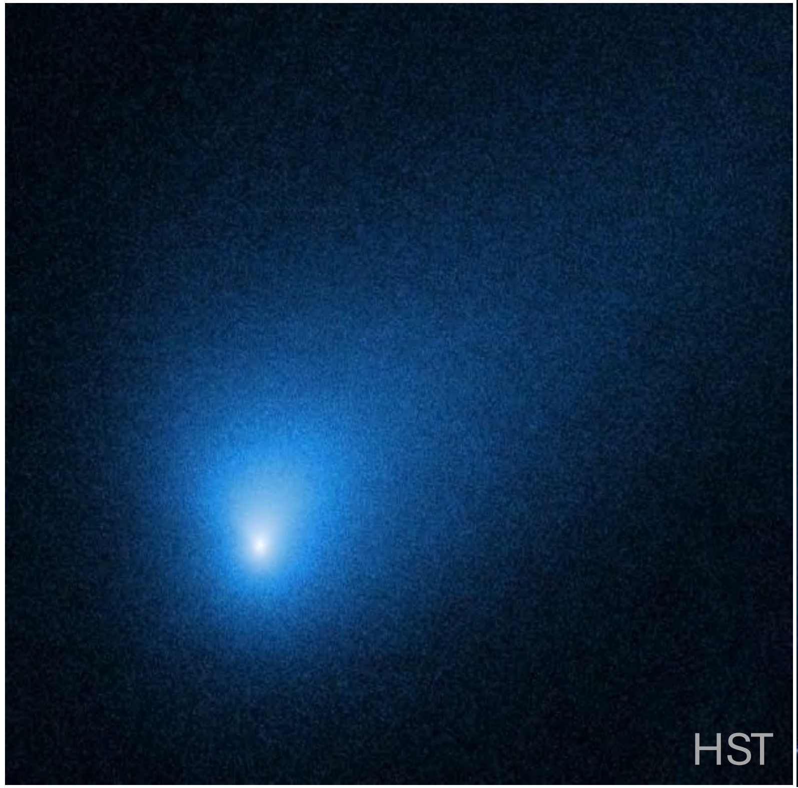
Some planetesimals are ejected from their parent protoplanetary disks, and become ***interstellar comets or asteroids***

They are a natural byproduct of star and planet formation

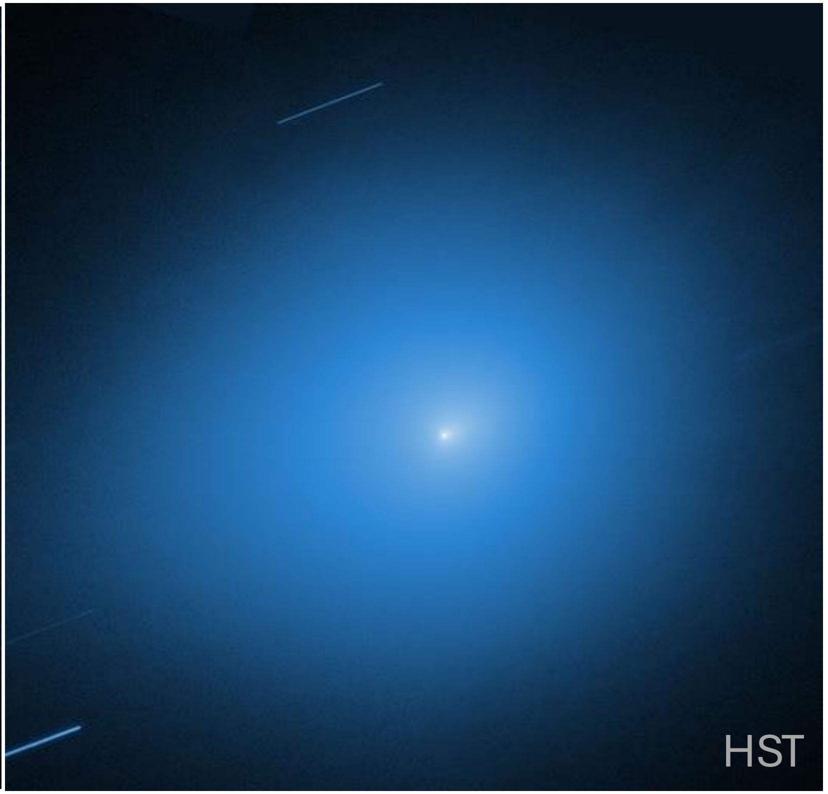
Hyperbolic orbit of 1I/‘Oumuamua



2I/Borisov



3I/ATLAS



Free-floating planets in Orion

Planets Form…

A. From the leftover gas and dust of star formation
B. Thanks to the conservation of the angular momentum
C. Around most stars
D. In disks
E. In discos

Key Concepts in This Lecture

- Major ISM components: **cold**, atomic and molecular gas and dust, concentrated in the Galactic plane, from which stars and planets form; **warm,** ionized by young stars in star forming regions; and **hot**, as a Galactic spheroidal corona, ejected and heated by SNe
- **21cm spin-flip line of neutral hydrogen** is a significant tool to study the ISM
- **Dust** causes **interstellar extinction**, mainly at the short wavelengths. The process is exponential with the path length
- Stars form in **giant molecular and dust clouds**. Protostellar clouds collapse under their self-gravity, until thermonuclear reactions ignite in their core. Young, massive stars then ionize and clear out the remaining ISM, leaving a young star cluster
- **Angular momentum** conservation leads to a **protoplanetary disk**, in which planets form by agglomeration, dust $\longrightarrow$ pebbles $\longrightarrow$ planetesimals $\longrightarrow$ planets, which then sweep the leftover material along their orbits
- Heavier elements lead to the formation of **rocky planets** closer to their star, while volatile materials condense and form **gas giants** further away from the star

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