INTERSTELLAR MEDIUM

- Stefano Bovino -

Molecular Clouds

Syllabus: this lecture

- Overview and historical sketch of the ISM
- The Milky Way's ISM and collisional processes
- The interstellar radiation field
- The Interstellar dust
- Chemistry of the ISM
- Heating & Cooling
- Cosmic rays
- **Molecular clouds**

Our Sun today

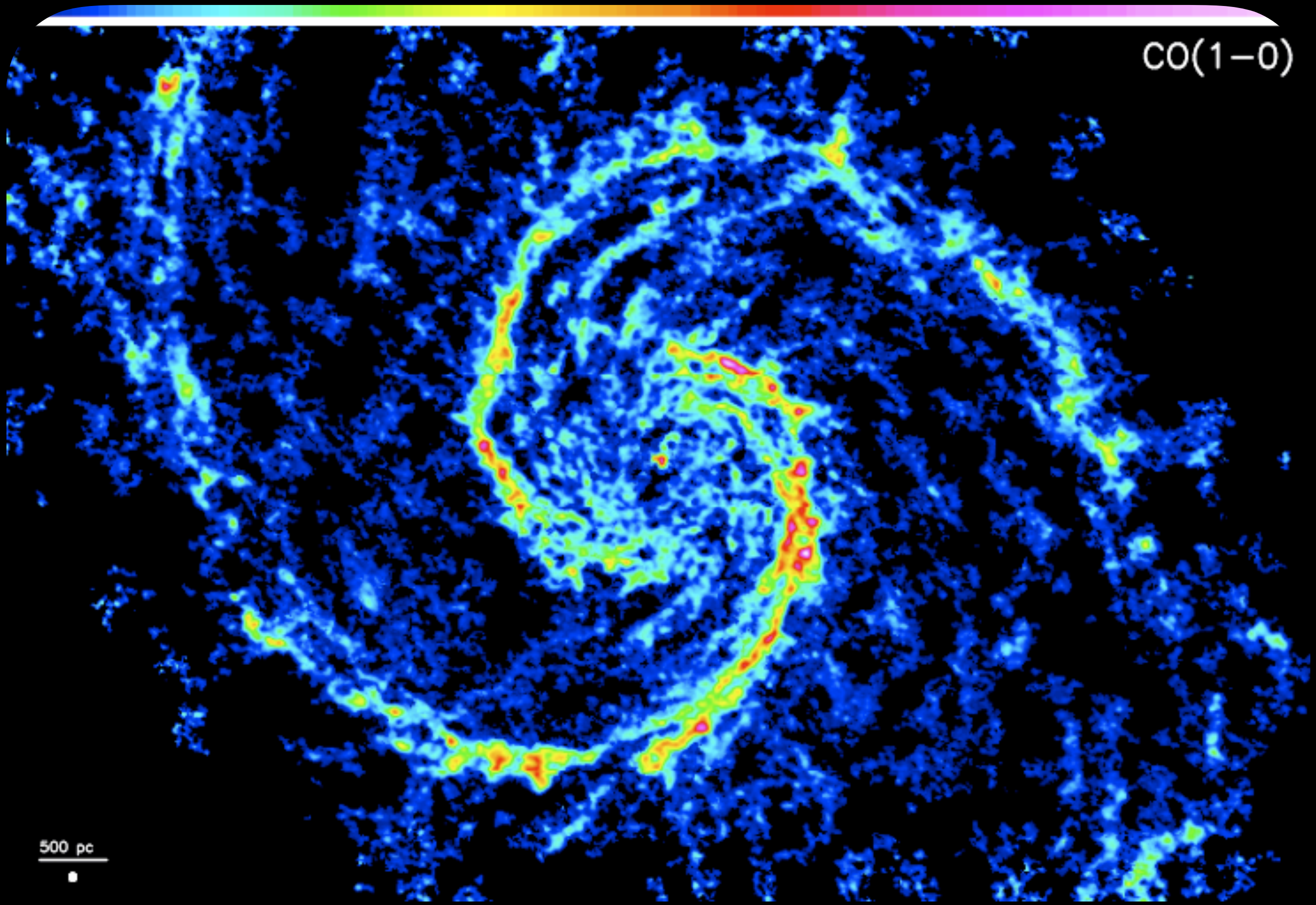
- 4.6 billion after he formed
- It is in **Hydrostatic Equilibrium:**
  - Pressure = Gravity
- It is also in **Thermal Equilibrium**
  - Energy which leaves the surface of the sun is replaced by the interior core energy (nuclear fusion)

How did it get this way?

Credits: NASA/Solar Dynamics Observatory/Joy Ng

Giant molecular clouds

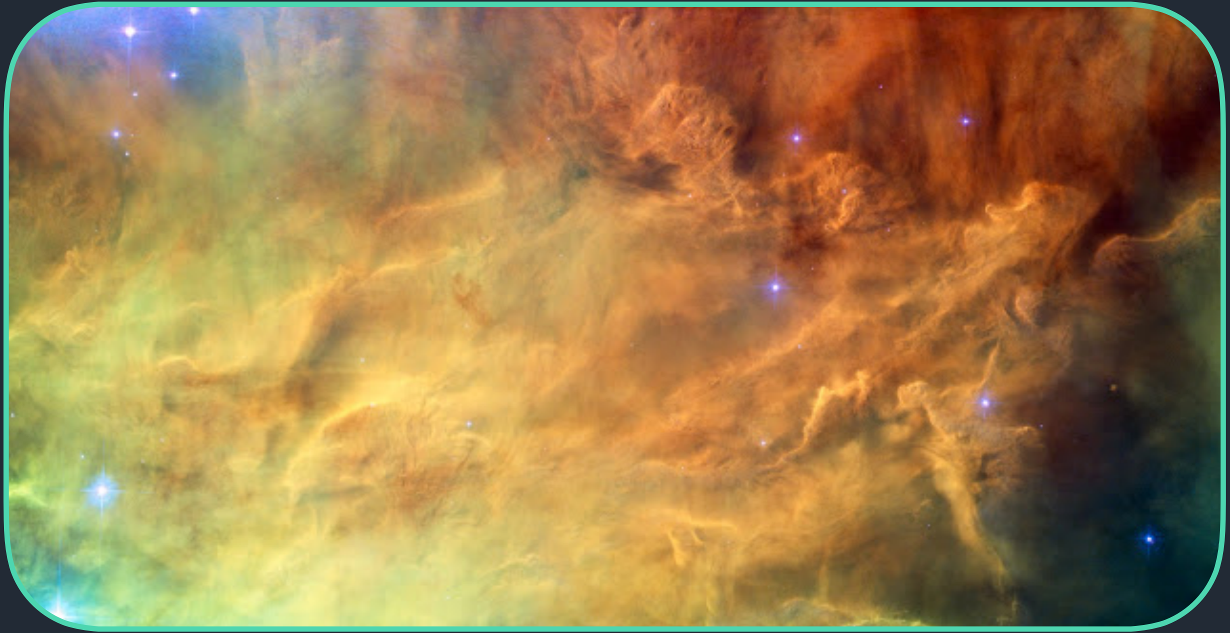
- In spiral galaxies molecular gas is constrained on the arms



Credits: Schinnerer et al. 2013

Giant Molecular Clouds

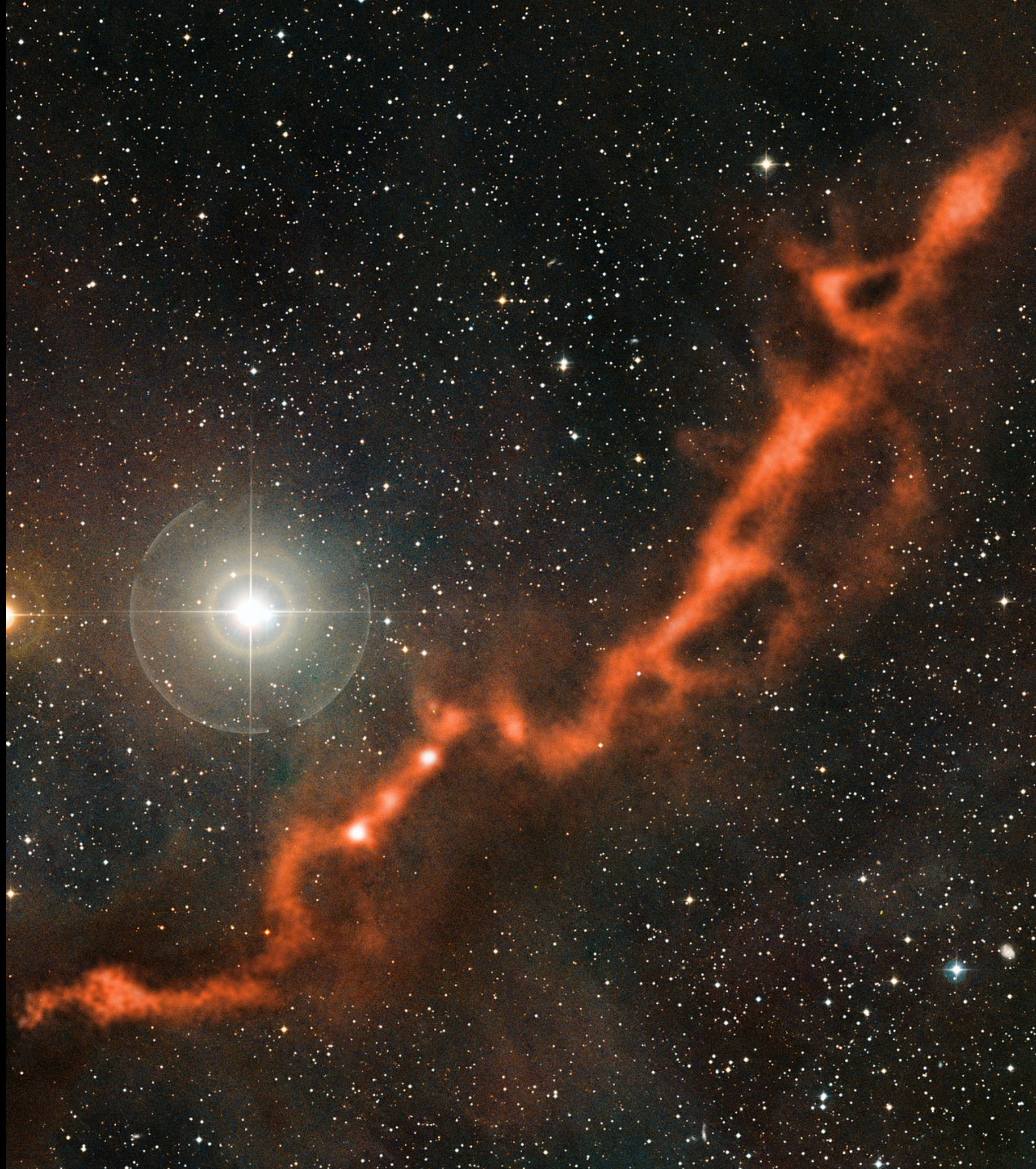
- Enormous regions out of which stars form
- Densest regions in the ISM
- Stars like the sun formed out of these regions
- Huge amount of cloudiness




Crédit: ESO

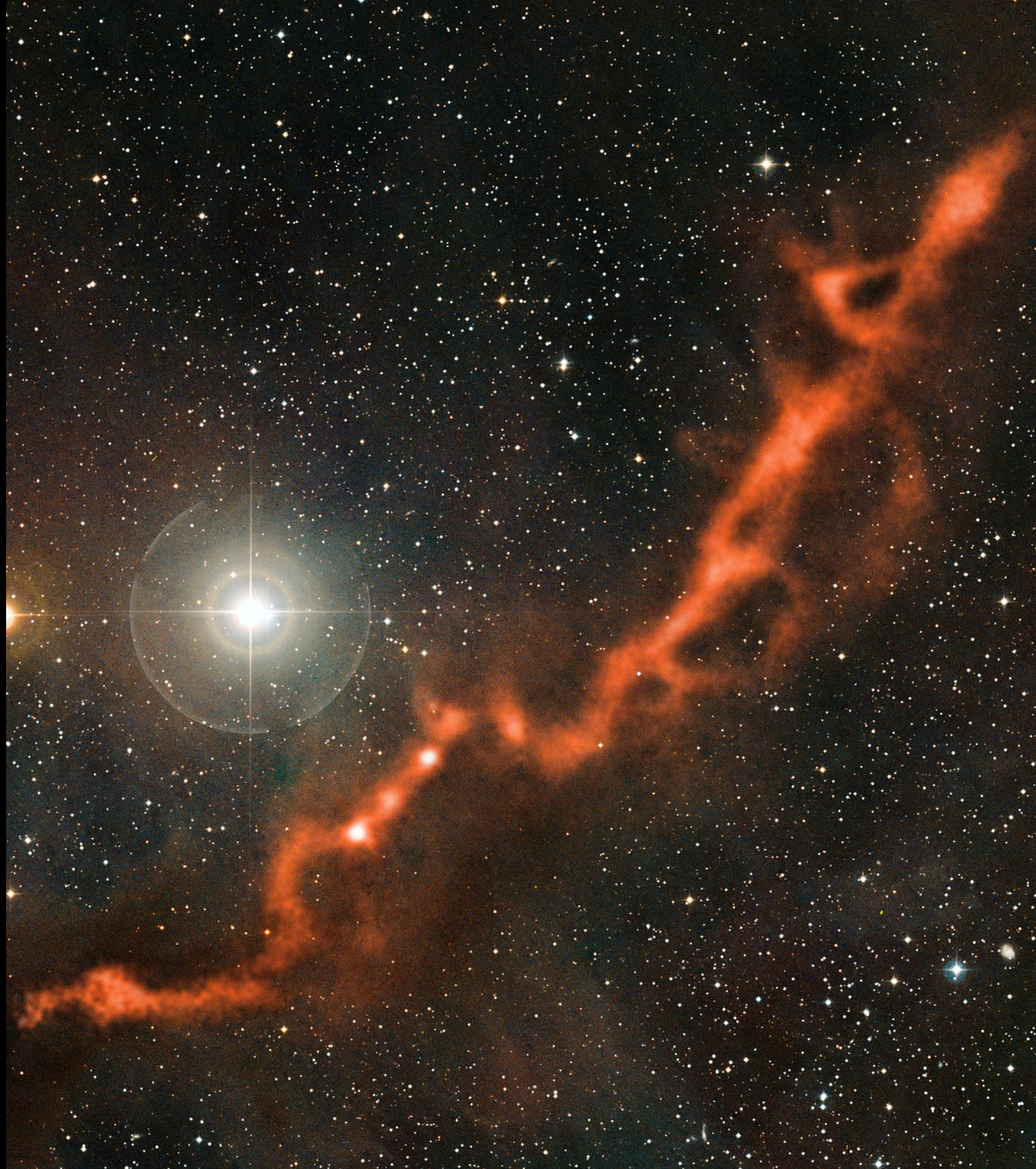
Giant Molecular Clouds

- Take up only 1% of the volume of the MW
- But they represent half the mass of the MW
- Typical sizes of 5-200 parsecs
- Masses between 10^3 - 10^7 solar masses
- Temperature: 10-30 K
- Cloud densities: 10^2 - 10^3 cm^{-3}



Giant Molecular Clouds

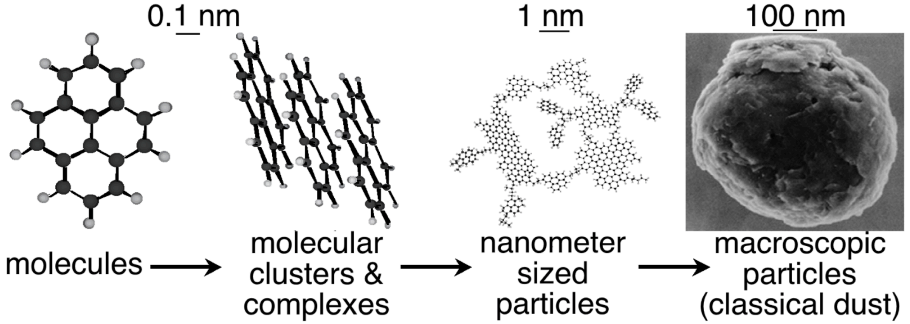
- Cloud densities: 10^2 - 10^3 cm^{-3}
- Inside clouds you have overdense regions called cores (n ~ 10^5 - 10^6 cm-3)
- This is a starting density of about 10^{20} times smaller than that of a star… from collapse is a long way to go.



Visible · WFC3 · 2015

T ~ 8-20 K, n > 10^4 cm-3

- Star-forming sites / self-gravitating
- Rich chemistry / main component H_2
- Ion-neutral reactions
- Gas-dust interaction

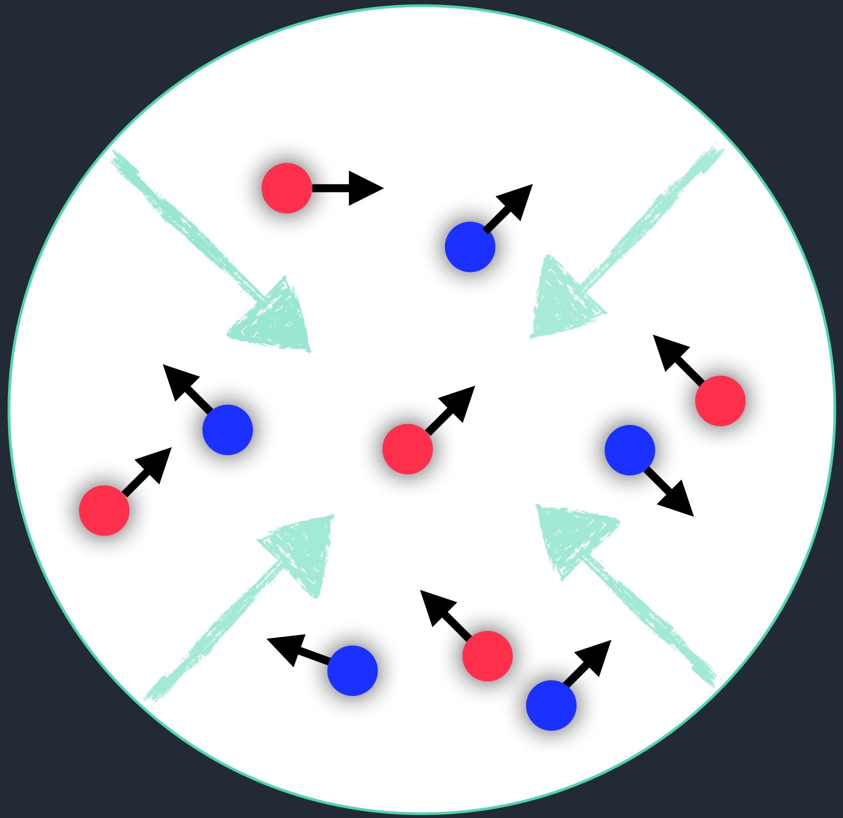


- Microscopic particles: atoms < size < clusters of molecules
  – Polycyclic Aromatic Hydrocarbons (PAHs): ~0.5–3nm (5–30 Å)
- Macroscopic particles: size >> molecules
  – Dust grains: > 3nm – 1cm

How the stars form?

W - POTENTIAL ENERGY

T - KINETIC ENERGY



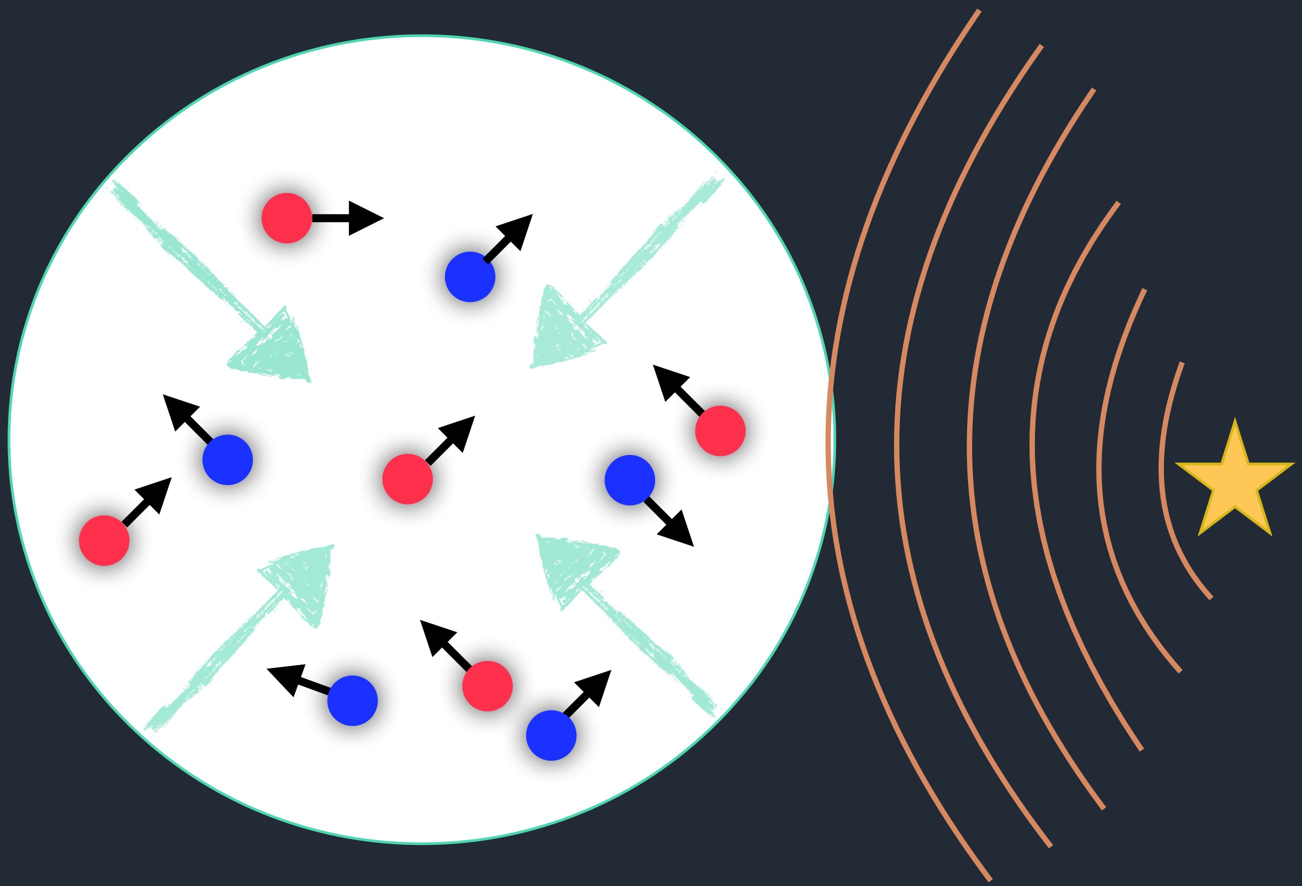
$$2T + W = 0$$

Giant Molecular Clouds

W - POTENTIAL ENERGY

T - KINETIC ENERGY

T_0 - EXTERNAL PRESSURE



$$2(T-T_0)+W=0$$

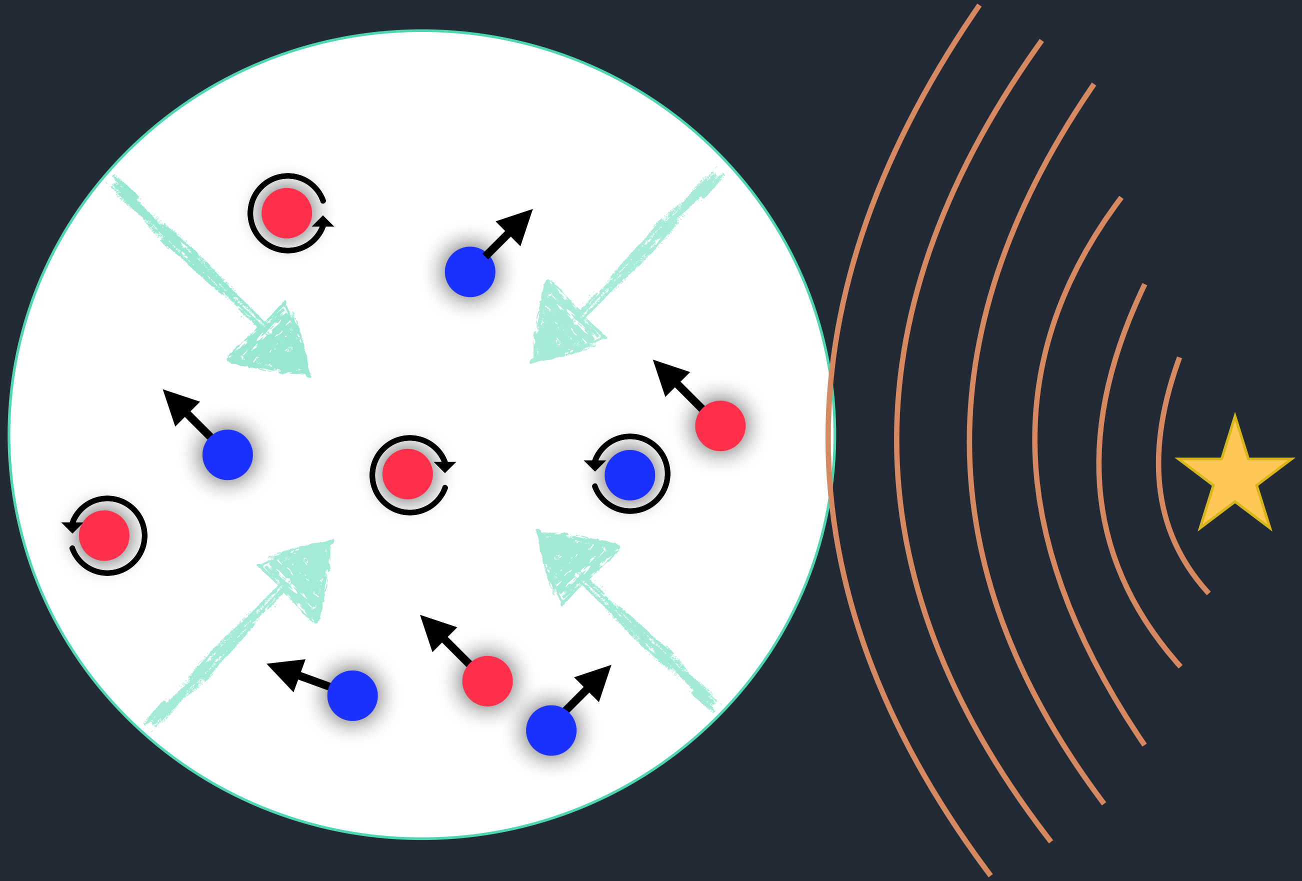
Giant Molecular Clouds

W - POTENTIAL ENERGY

T - KINETIC ENERGY

T_0 - EXTERNAL PRESSURE

T_t - TURBULENT KE



$$2(T_t+T-T_0) + W = 0$$

Giant Molecular Clouds

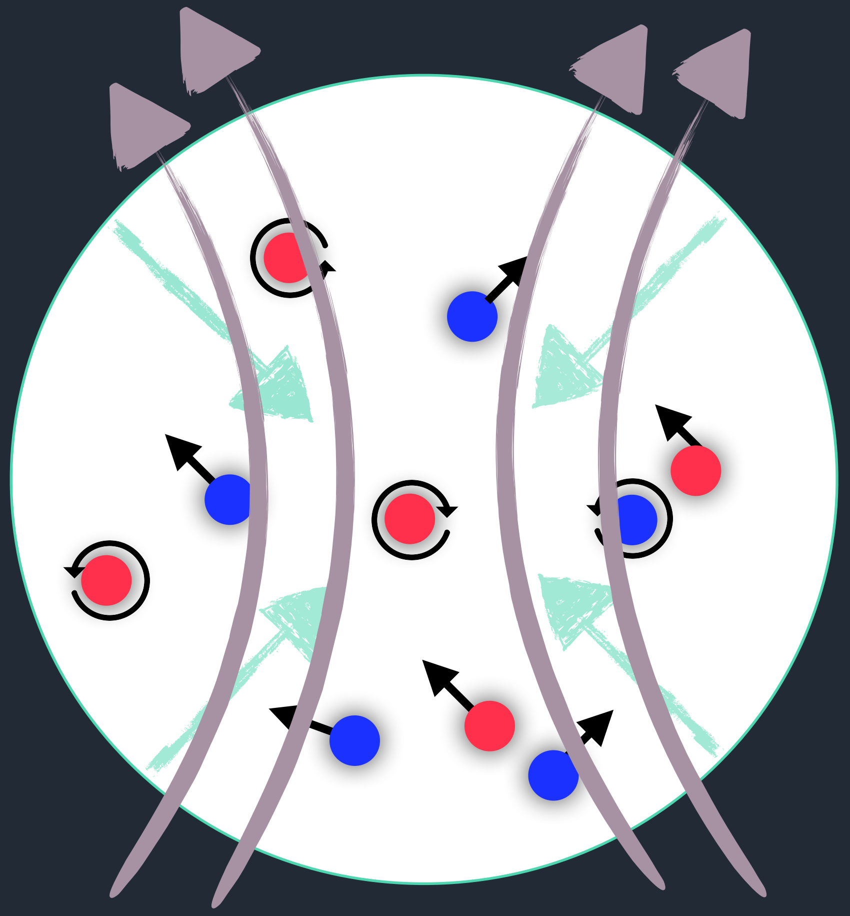
W - POTENTIAL ENERGY

T - KINETIC ENERGY

T_0 - EXTERNAL PRESSURE

T_t - TURBULENT KE

B - MAGNETIC PRESSURE



$$2(T_t+T-T_0) + W + B = 0$$

NASA / ESA / Hubble Heritage Team (STScI / AURA)

Visible · WFC3 · 2015

Infrared · WFC3 · 2015

Collapse of Giant Molecular Clouds

- A GMC is held up against its own gravity (W) by internal pressure:
  - Gas pressure from internal heat
  - Pressure from embedded magnetic field
- If W > internal pressure —> the entire cloud will start to collapse
- Possible ways to trigger the collapse
  - Cloud-cloud collisions
  - Shocks from nearby SNe explosions

Virial parameter

- There are a couple of useful "idelised" parameters that can be used to understand if a cloud is prone to collapse or not.

$$2(T_t+T-T_0) + W + B = 0$$

$$2T = |W|$$

$$\alpha_{\mathrm{vir}} = \frac{2\mathcal{T}}{|\mathcal{W}|}$$

Virial parameter

- We can define the viral parameter

$$\mathcal{W} = -\frac{3}{5}\frac{GM^2}{R}$$

$$\mathcal{T} \equiv \frac{3}{2}\bar{\rho}\sigma^2 V_{\mathrm{cl}}$$

$$\alpha_{\mathrm{vir}} \equiv \frac{2\mathcal{T}}{|\mathcal{W}|} = \frac{5\sigma^2 R}{|GM|}$$

Virial parameter

$$\alpha_{\mathrm{vir}} \equiv \frac{2\mathcal{T}}{|\mathcal{W}|} = \frac{5\sigma^2 R}{|GM|}$$

Velocity dispersion

Isothermal sound speed

Mach number

$$\sigma = c_s \mathcal{M}$$

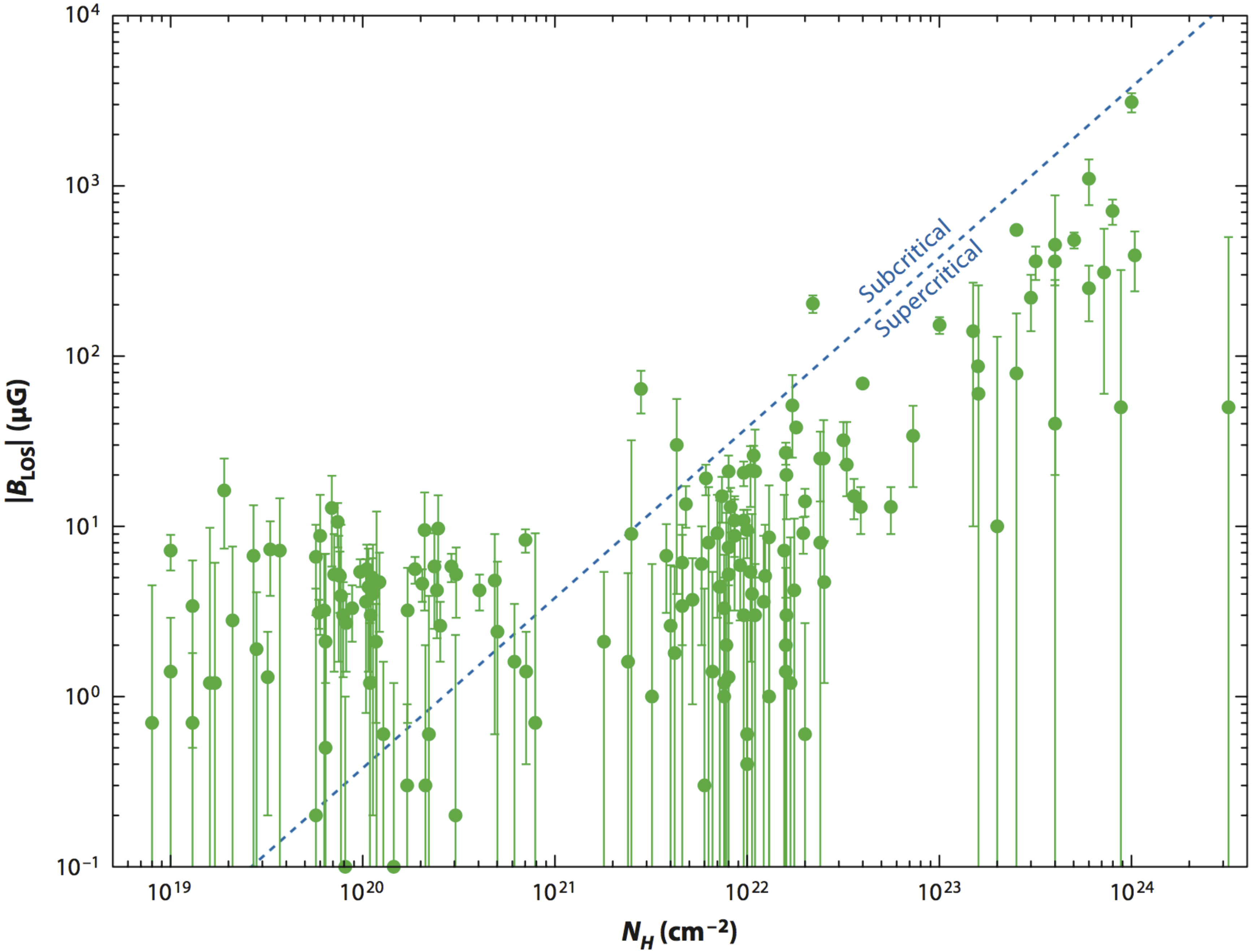
- If alpha > 1, cloud is *supervirial*, tend to diffuse back as kinetic energy dominates
- If alpha < 1 cloud is *subvirial*, gravity takes over and the cloud collapse
- If alpha = 1 cloud is in *virial equilibrium*

Mass-to-flux ratio

$$\mu = M/\Phi_B$$

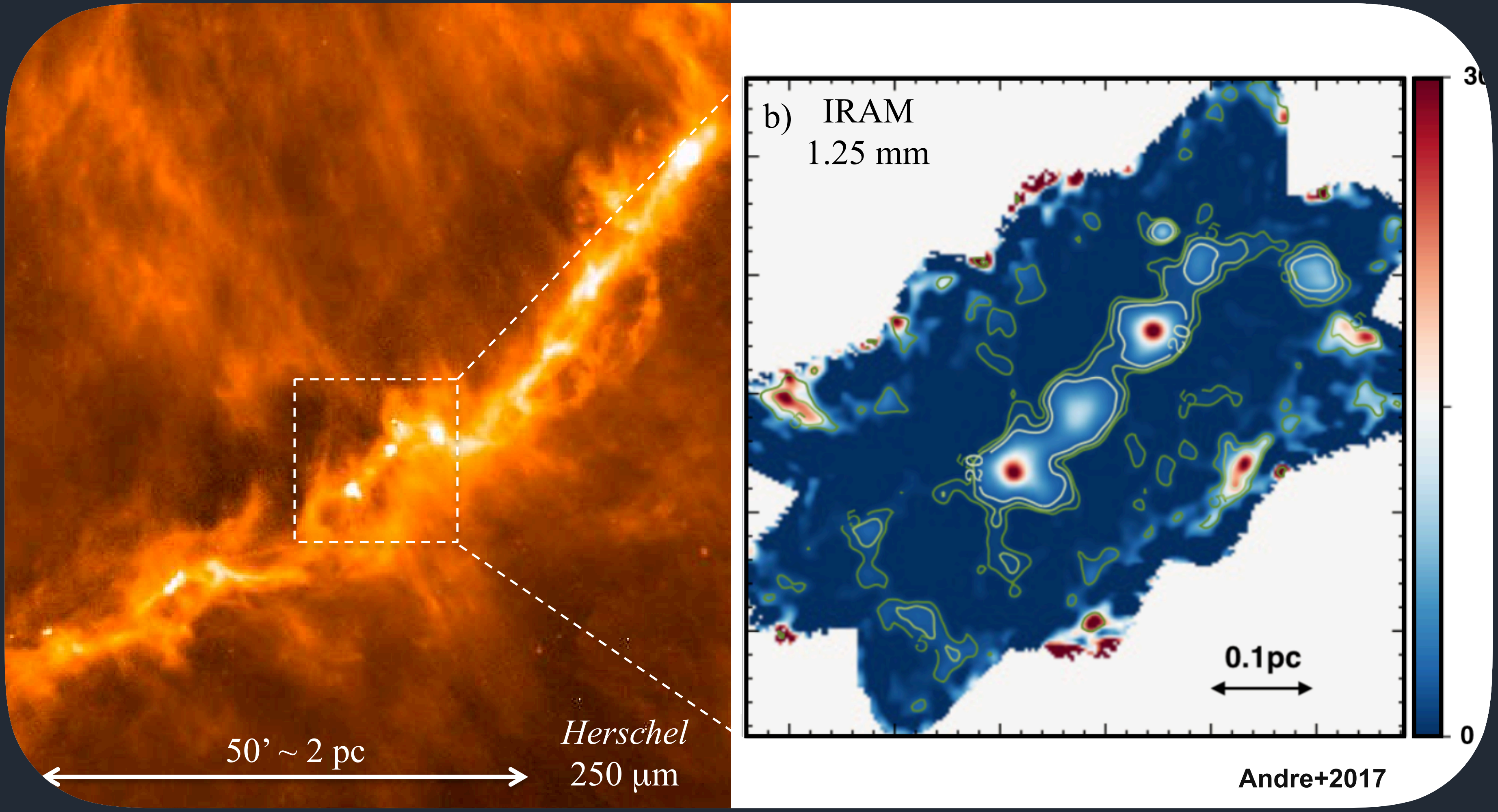
$$\mu_{crit} \equiv \left(\frac{M}{\Phi}\right)_{crit} = \frac{1}{2\pi\sqrt{G}}$$

- When $\mu/\mu_{crit} > 1$, $M > M_\Phi$, and magnetic force can not halt collapse. The cloud is then said to be *supercritical*.
- When $\mu/\mu_{crit} < 1$, $M < M_\Phi$, and the cloud is magnetically supported against collapse. The cloud is then said to be *subcritical*.
- When $\mu/\mu_{crit} = 1$, $M = M_\Phi$, and the cloud is in equilibrium.



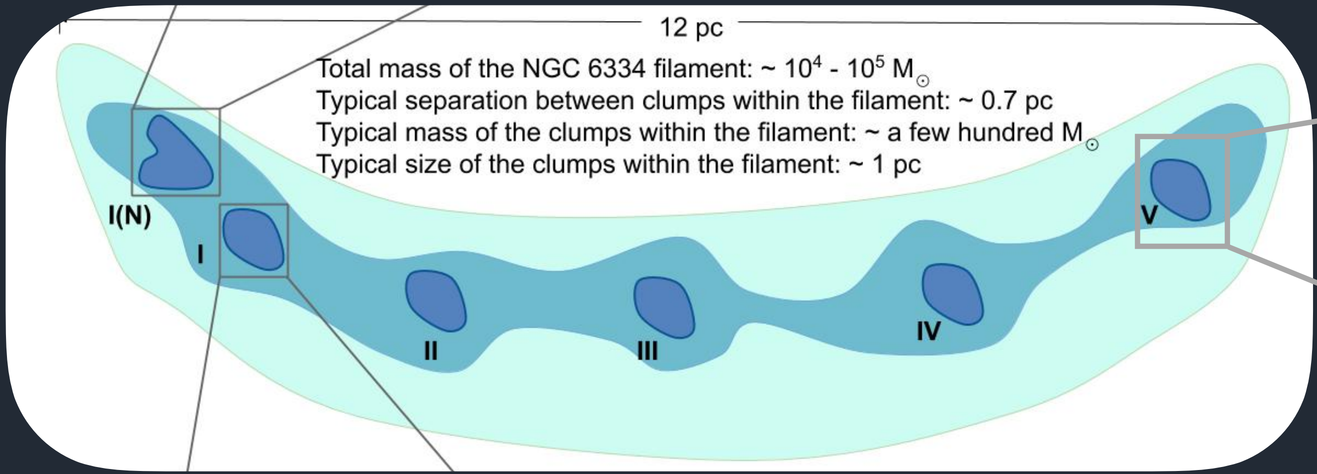
Credits: Crutcher et al. 2012

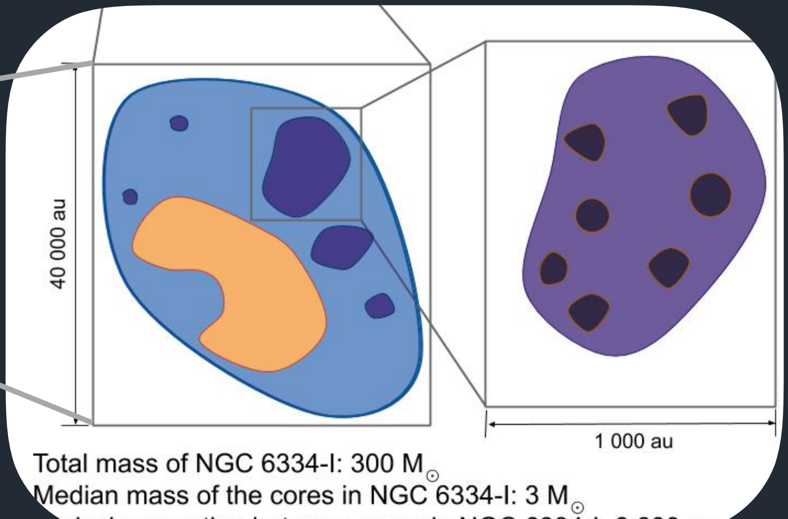
Giant Molecular Clouds: fragmentation



Hierarchical structure of GMCs

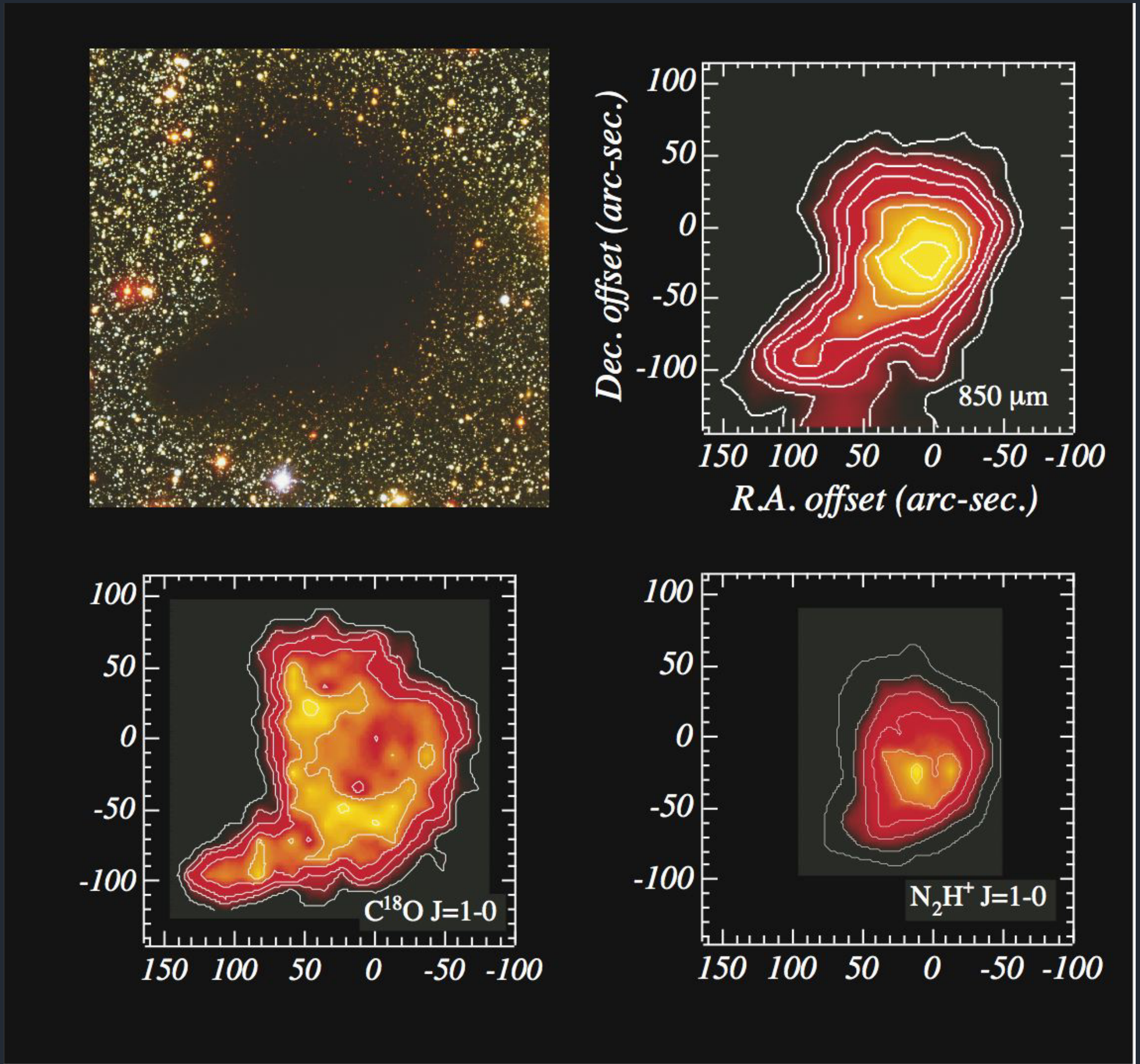
	Clouds[a]	Clumps[b]	Cores[c]
Mass ($M_\odot$)	$10^3 - 10^4$	50–500	0.5–5
Size (pc)	2–15	0.3–3	0.03–0.2
Mean density (cm^{-3})	50–500	10^3–10^4	10^4–10^5
Velocity extent ($km\ s^{-1}$)	2–5	0.3–3	0.1–0.3
Crossing time (Myr)	2–4	≈1	0.5–1
Gas temperature (K)	≈10	10–20	8–12
Examples	Taurus, Oph, Musca	B213, L1709	L1544, L1498, B68



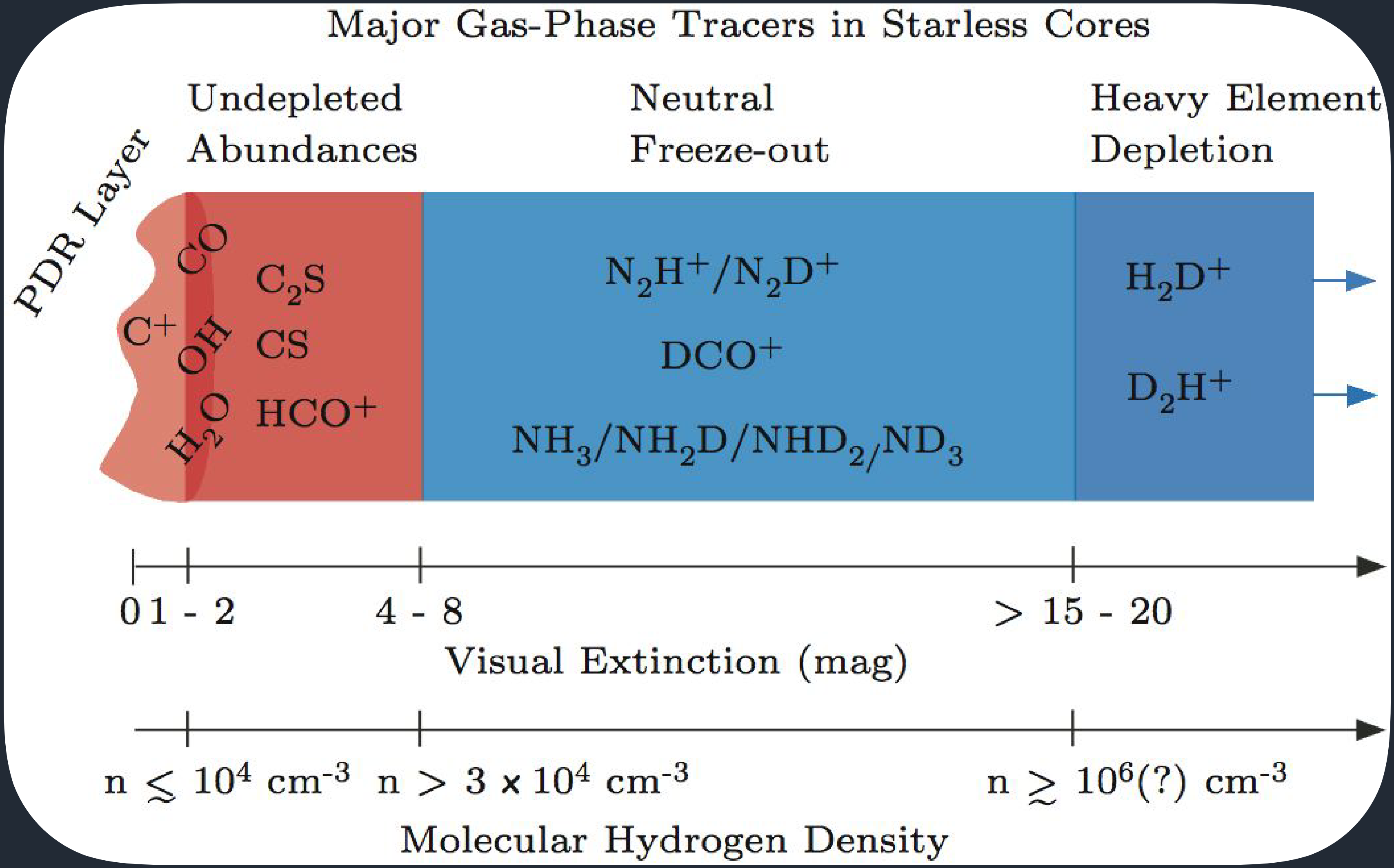


Sadaghiani+2019

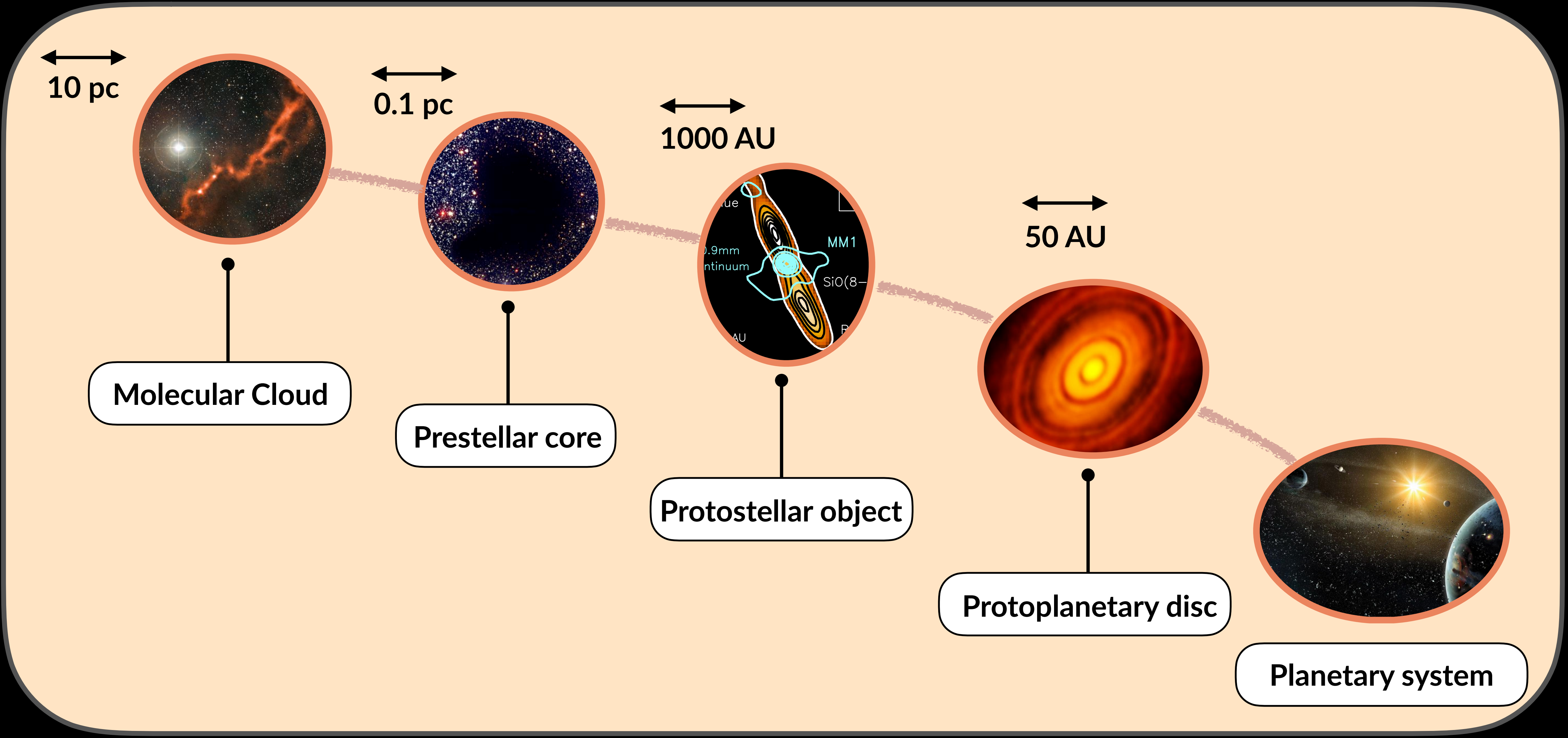
Dense cores


100
50
0
-50
-100
Dec. offset (arc-sec.)
850 µm
150 100 50 0 -50 -100
R.A. offset (arc-sec.)
C18O J=1-0
N2H+ J=1-0

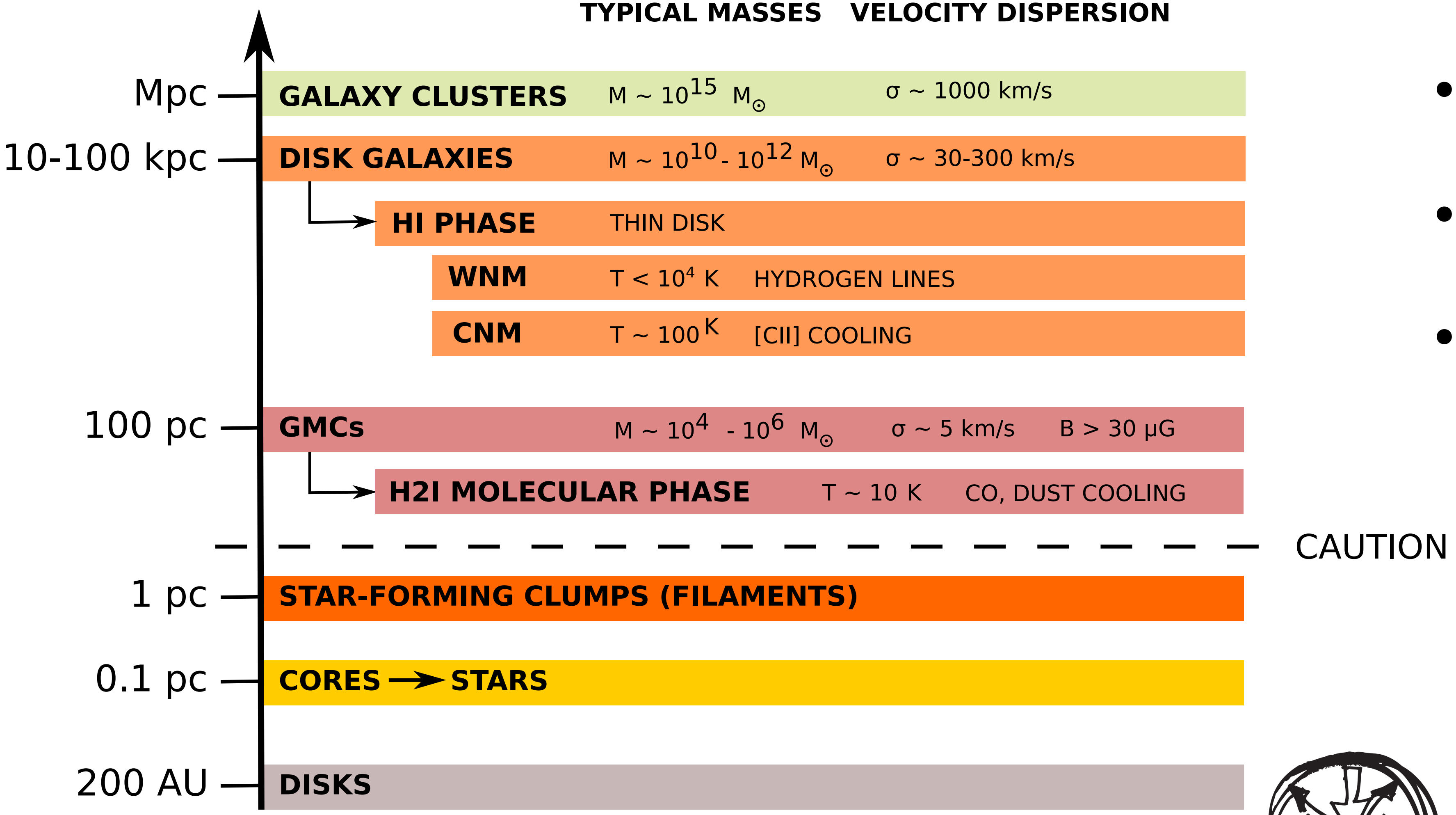
Chemistry at small scales



From stars to planets



Scales and Complexity



- **Multi-physics**
- **Multi-phase**
- **Multi-scale**