A brief of physical processes in the interstellar medium & in star formation

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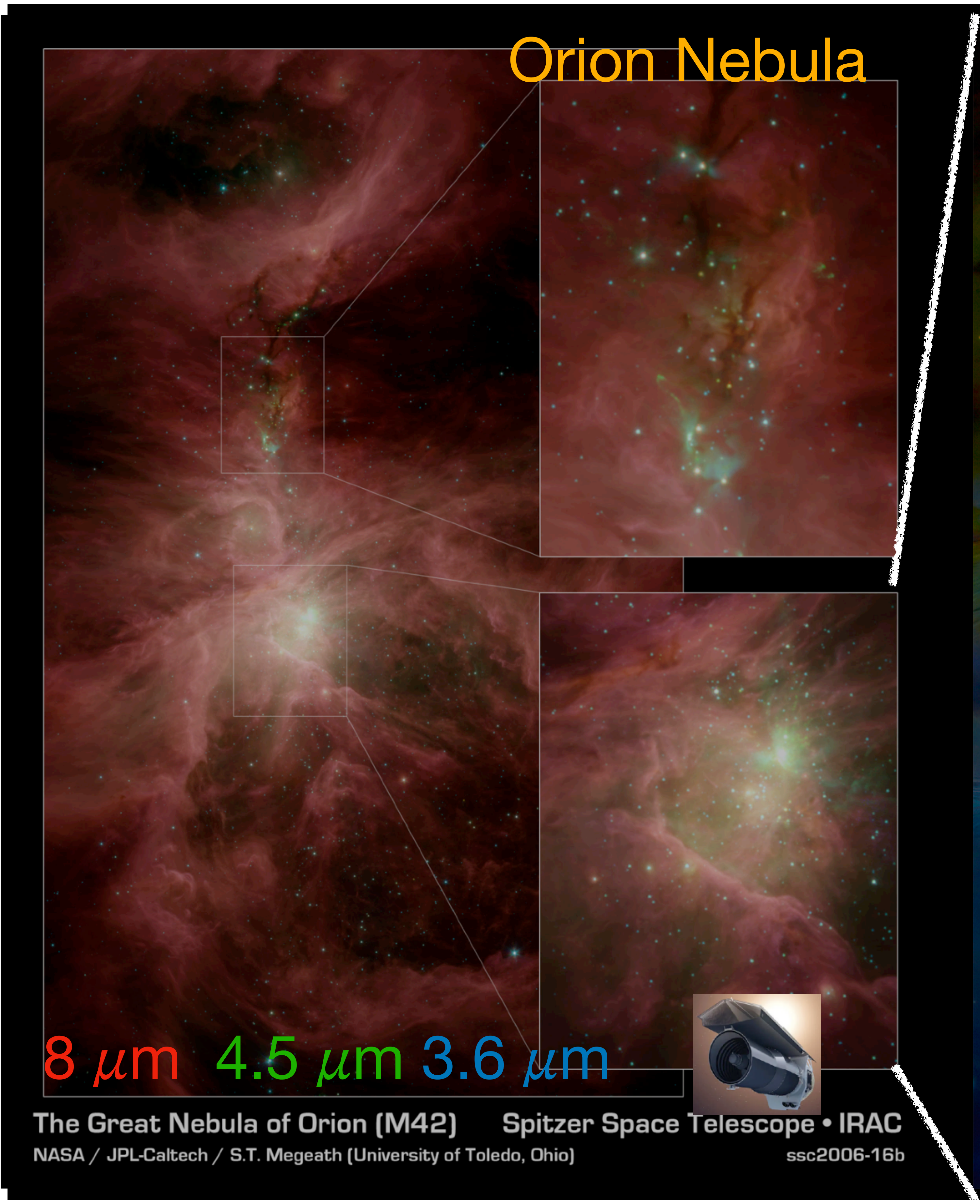
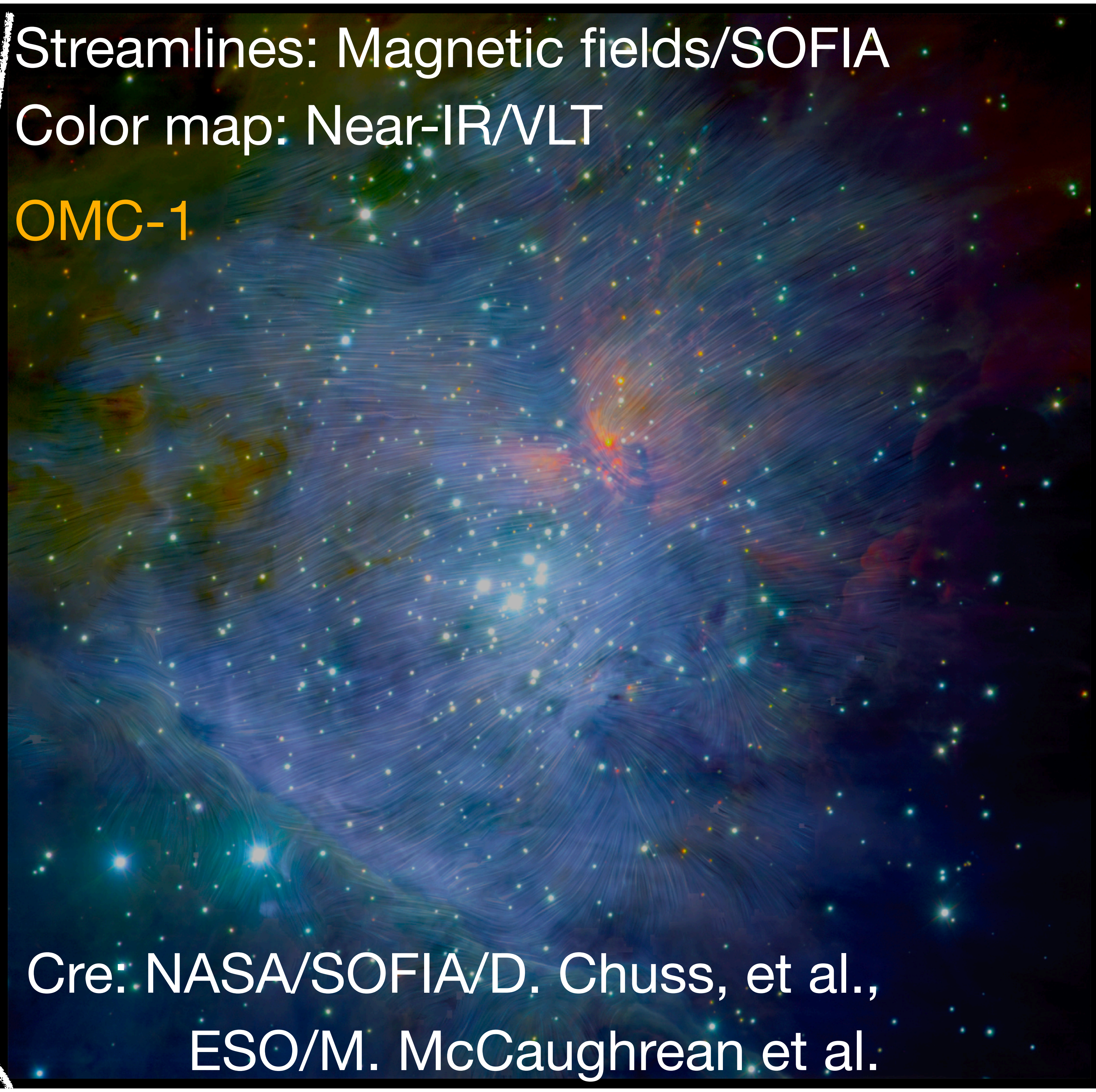
Outline

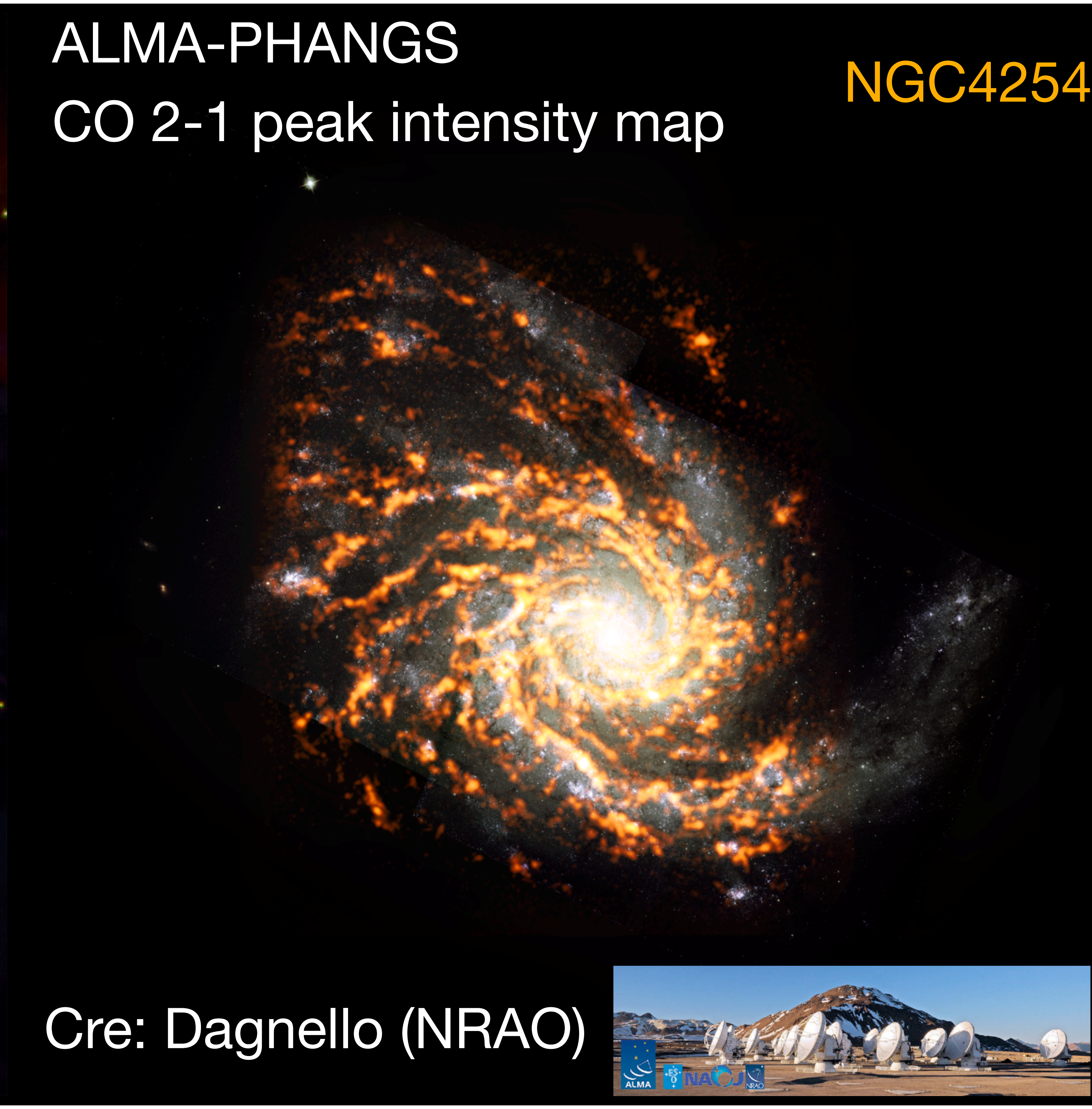
1. The interstellar medium (ISM) & its main constituents
2. Physical processes in interstellar gas
3. Physical processes in star formation: accretion and ejection processes

The Interstellar Medium

The Interstellar Medium







- Interstellar medium (ISM): everything in the space between stars.
- The ISM is comprised of gas, dust, cosmic rays, interstellar radiation (starlight and CMB), magnetic fields, dark matter, *interstellar objects, and spacecraft.*
- The ISM is filamentary, magnetized, and turbulent.

Composition of the ISM: phases of gas

Basics physical properties of these different phases

Component	Temperature (K)	Density (cm^{-3})	Ionization fraction	
Warm neutral medium (WNM)	10^4	~ 0.5	~ 0.1	HI gas (atomic)
Cold neutral medium (CNM)	100	20–50	10^{-4}	
Hot ionized medium (HIM)	10^6	0.01	1.0	fully ionized HII gas
Warm ionized medium (WIM)	10^4	~ 0.5	1.0	
Molecular gas	10–20	$\gtrsim 100$	$\ll 10^{-4}$	H_2, CO, …

- Atomic gas in the ISM: H (~70%*), He (28%*), and heavier elements (C, N, O, Si, Fe, … - for 2%*)
- Gas is found in a variety of chemical forms

** by total mass*

Composition of the ISM: phases of gas

Table 1.3 Phases of Interstellar Gas

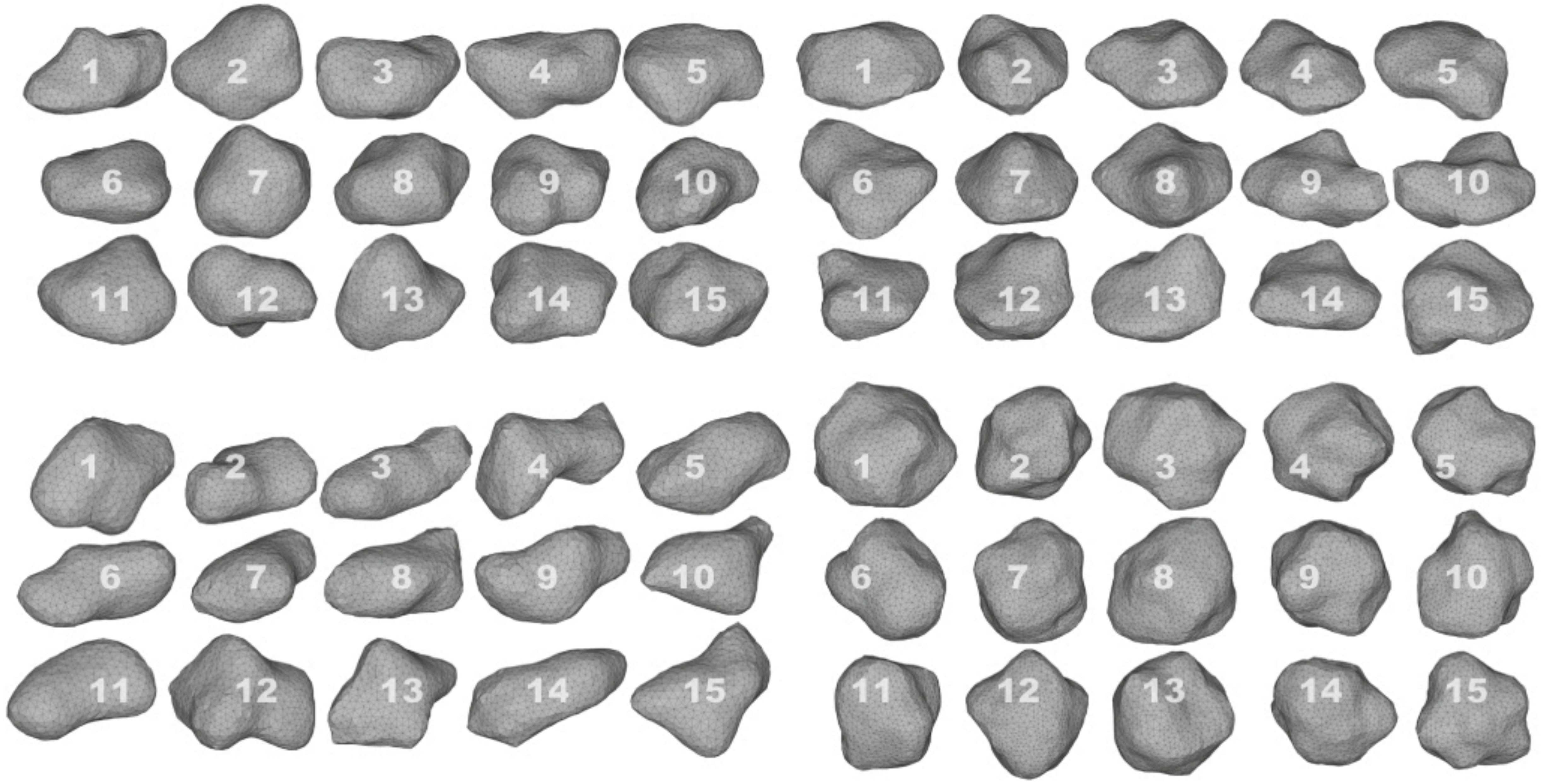
Phase	T(K)	n_H(cm^{-3})	Comments
Coronal gas (HIM) $f_V \approx 0.5?$ $\langle n_H \rangle f_V \approx 0.002\,\mathrm{cm}^{-3}$ ($f_V \equiv$ volume filling factor)	$\gtrsim 10^{5.5}$	~ 0.004	Shock-heated Collisionally ionized Either expanding or in pressure equilibrium Cooling by: ◇ Adiabatic expansion ◇ X ray emission Observed by: • UV and x ray emission • Radio synchrotron emission
H II gas $f_V \approx 0.1$ $\langle n_H \rangle f_V \approx 0.02\,\mathrm{cm}^{-3}$	10^4	$0.3 - 10^4$	Heating by photoelectrons from H, He Photoionized Either expanding or in pressure equilibrium Cooling by: ◇ Optical line emission ◇ Free–free emission ◇ Fine-structure line emission Observed by: • Optical line emission • Thermal radio continuum
Warm H I (WNM) $f_V \approx 0.4$ $n_H f_V \approx 0.2\,\mathrm{cm}^{-3}$	~5000	0.6	Heating by photoelectrons from dust Ionization by starlight, cosmic rays Pressure equilibrium Cooling by: ◇ Optical line emission ◇ Fine structure line emission Observed by: • H I 21 cm emission, absorption • Optical, UV absorption lines

Table 1.3 Phases of Interstellar Gas

Phase	T(K)	n_H(cm^{-3})	Comments
Cool H I (CNM) $f_V \approx 0.01$ $n_H f_V \approx 0.3\,\mathrm{cm}^{-3}$	~ 100	30	Heating by photoelectrons from dust Ionization by starlight, cosmic rays Cooling by: ◇ Fine structure line emission Observed by: • H I 21-cm emission, absorption • Optical, UV absorption lines
Diffuse H_2 $f_V \approx 0.001$ $n_H f_V \approx 0.1\,\mathrm{cm}^{-3}$	~ 50 K	~ 100	Heating by photoelectrons from dust Ionization by starlight, cosmic rays Cooling by: ◇ Fine structure line emission Observed by: • H I 21-cm emission, absorption • CO 2.6-mm emission • optical, UV absorption lines
Dense H_2 $f_V \approx 10^{-4}$ $\langle n_H \rangle f_V \approx 0.2\,\mathrm{cm}^{-3}$	$10 - 50$	$10^3 - 10^6$	Heating by photoelectrons from dust Ionization and heating by cosmic rays Self-gravitating: $p > p$(ambient ISM Cooling by: ◇ CO line emission ◇ C I fine structure line emission Observed by: • CO 2.6-mm emission • dust FIR emission
Cool stellar outflows	$50 - 10^3$	$1 - 10^6$	Observed by: • Optical, UV absorption lines • Dust IR emission • H I, CO, OH radio emission

Adapted from lecture by Thiem Hoang (KASI & UST)

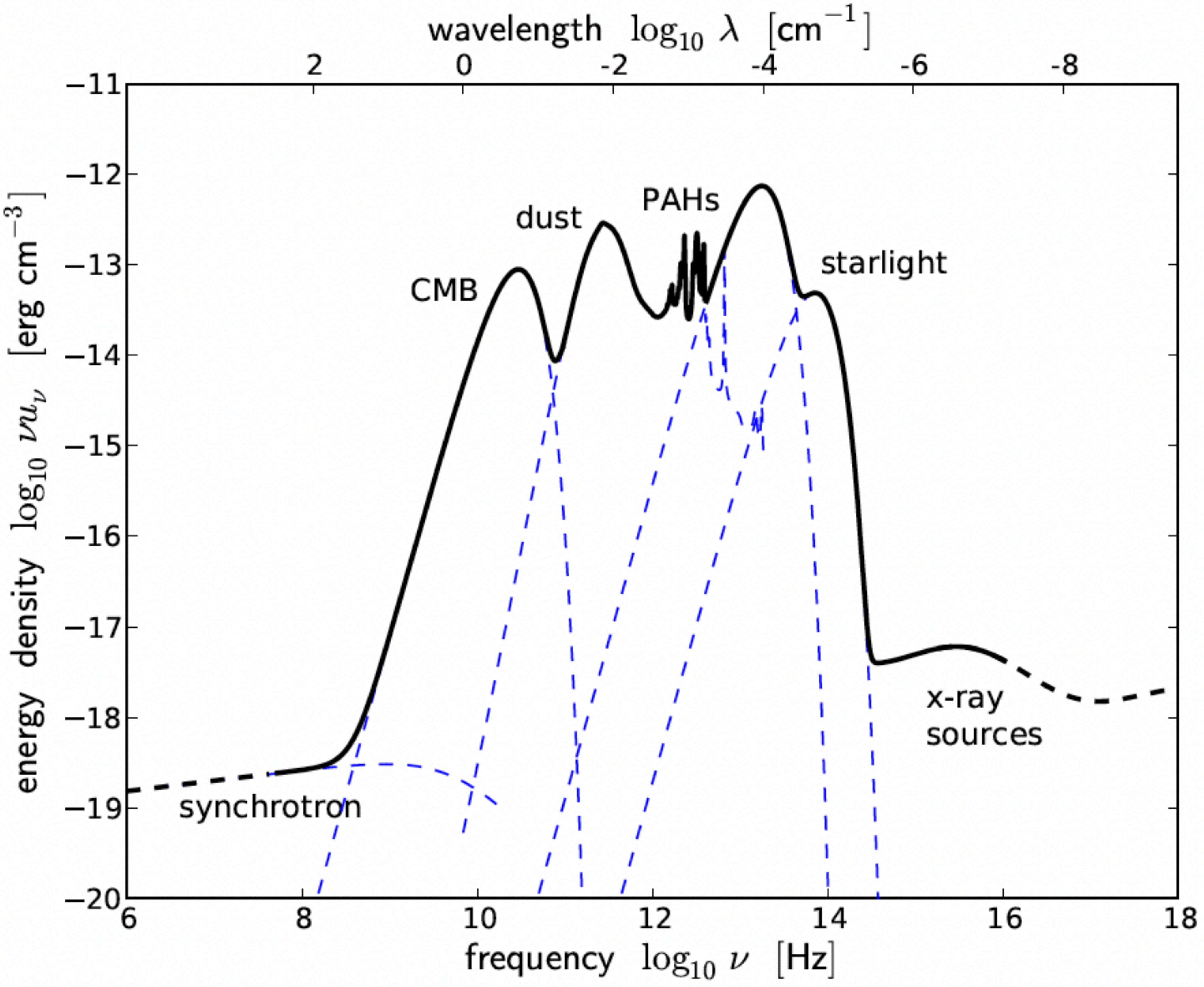
Composition of the ISM: dust (grains)



Herranen et al. 2019

- a mixture of primarily silicate and carbonaceous compounds, including polycyclic aromatic hydrocarbons (PAHs)
- have aspherical shapes & sub-micron sizes (~0.1 μm), but can significantly grow in dense gas of protoplanetary disks
- absorb or scatter starlight (energy) in the UV, optical, or near-IR range
- re-emit energy in longer wavelength, from far-IR to sub-mmm → thermal dust emission

Main sources of interstellar radiation field (ISRF)

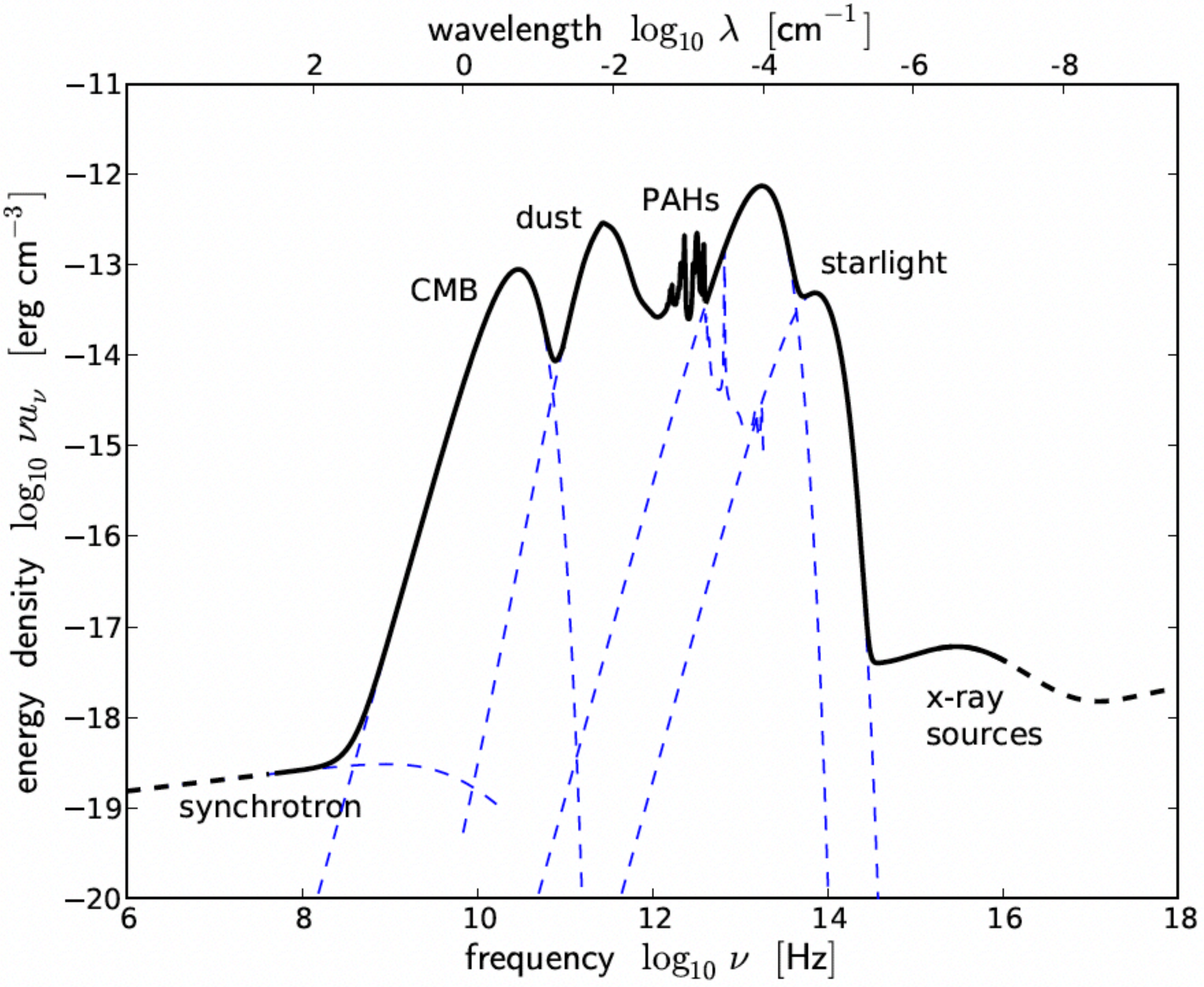


Klessen & Glover (2016)

- **Thermal emission from dust grains** heated by starlight (Far-IR to IR wavelength)
- **Starlight** from ionizing photons emitted by stellar photospheres (HI region, Photodissociation region - PDR)
- **X-ray emission** from hot plasma (10^5 - 10^8 K)
- **Emission from ionized plasma** (free–free, free–bound, and bound–bound transitions, 10^4 K)
- Cosmic microwave background (**CMB**) radiation (~2.73 K)
- **Galactic synchrotron radiation** from relativistic electrons

Q1: What which wavelengths the energy density of the ISRF is mainly in?

Main sources of interstellar radiation field (ISRF)



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Most of the energy density of the ISRF is in IR (**thermal dust and CMB emission**), optical and UV (**starlight**) range → key role in regulating ISM's properties

Physical processes in interstellar gas

Collisional Processes

- Collisions: fundamental to the physics of the ISM
- Collisional rate: a rate at which a particle can collide with other particle of different masses
- Collisional rate coefficient ?

$$\left\langle \sigma_{AB} \nu \right\rangle = \left(\frac{8}{\pi \nu k_B T} \right)^{1/2} \langle \sigma \rangle, \text{ with } \langle \sigma \rangle = \int_0^\infty \frac{\sigma_{AB} E}{k_B T} e^{-E/k_B T} \frac{dE}{dT} \quad ?$$

Collisional Processes

- Assume a collision between 2 particles A and B, with masses of m_A and m_B, and density of n_A and n_B; B is at rest and A is moving with velocity of v toward B
- reduced mass: $\mu = m_A m_B/(m_A + m_B)$, reduced energy: $E = 0.5\mu v^2$
- Cross-section of collision: σ_{AB} as a function of v,
- Number flux of A: $J_A = n_A v$
- Collision rate of A with B: $J_A \sigma_{AB} = n_A \nu \sigma_{AB}(\nu)$
- Number of collisions per second per volume: $J_A \sigma_{AB} n_B = n_A n_B \nu \sigma_{AB}(\nu)$
- Integration over velo. distribution of A: $I = \int_0^\infty n_A n_B \nu \sigma_{AB}(\nu) f(\nu) d\nu$
- Collision rate per unit volume $I \equiv n_A n_B \langle \sigma v \rangle = n_A n_B k_{AB}$ $\quad$ (event/cm^3/s)
- Collisional rate coefficient: $k_{AB} = \langle \sigma \nu \rangle = \int_0^\infty \nu \sigma_\nu f(\nu) d\nu \quad (\mathrm{cm}^{-3}\mathrm{s})$
- Assume a thermal gas at temp. T, then the relative velocity will have Maxwelllian distribution:

$$f(\nu)d\nu = \left(\frac{\mu}{2\pi k_B T}\right)^{3/2} 4\pi\nu^2 e^{-\mu\nu^2/2k_B T} d\nu$$

- Using $f(\nu)d\nu = f(E)dE$, one gets: $k_{AB} = \langle \sigma \nu \rangle = \left(\frac{8k_B T}{\pi\mu}\right)^{1/2} \int_0^\infty \sigma_{AB}(E) \frac{E}{k_B T} e^{-e/k_B T} \frac{dE}{dT}$

Collisional Processes

- Collisional rate coefficient: $\langle \sigma_{AB} \nu \rangle = \left(\frac{8}{\pi \nu k_B T} \right)^{1/2} \int_0^\infty \frac{\sigma_{AB} E}{k_B T} e^{-E/k_B T} \frac{dE}{dT}$

- If B is much heavier than A: $m_A \ll m_B, \mu \approx m_A$
  - For e.g., election collides with atoms:

$$\langle \sigma_{AB} \nu \rangle = \left(\frac{8}{\pi \nu k_B T} \right)^{1/2} \langle \sigma \rangle, \text{ with } \langle \sigma \rangle = \int_0^\infty \frac{\sigma_{AB} E}{k_B T} e^{-E/k_B T} \frac{dE}{dT}$$

Physical processes in interstellar gas:

- Four basic types of collisional interactions:
    - between charged particles: (ions-ions, ions-electrons, and electrons-electrons)

      —> Coulomb field: $\sim r^{-1}$ —> use the “impact approximation”
    - between ions and neutral particles (atoms, molecules)

      —> induced-dipole potential: $\sim r^{-4}$ —> use exact results for scattering
    - between electrons and neutrals —> use experimental data
    - between neutrals —> effective “hard-sphere” radius

Physical processes in interstellar gas:

- Collisional Processes — interaction between gas and gas
- Radiative Processes — interaction between gas and radiation

Physical processes in interstellar gas:

Radiative Transfer Equation:

$$\boxed{\frac{dI_\nu}{ds} = -\alpha_\nu I_\nu + j_\nu,}$$

α_ν: absorption (attenuation) coefficient, j_ν: emission coefficient or emissivity

Emission coefficient: $j_\nu = \frac{1}{4\pi} n_u A_{ul} h\nu \phi(\nu)$

Absorption coefficient: $\alpha_\nu = n_l \sigma_{lu} - n_u \sigma_{ul} = -\frac{h\nu}{4\pi}(B_{lu} n_l - B_{ul} n_u)\phi(\nu)$

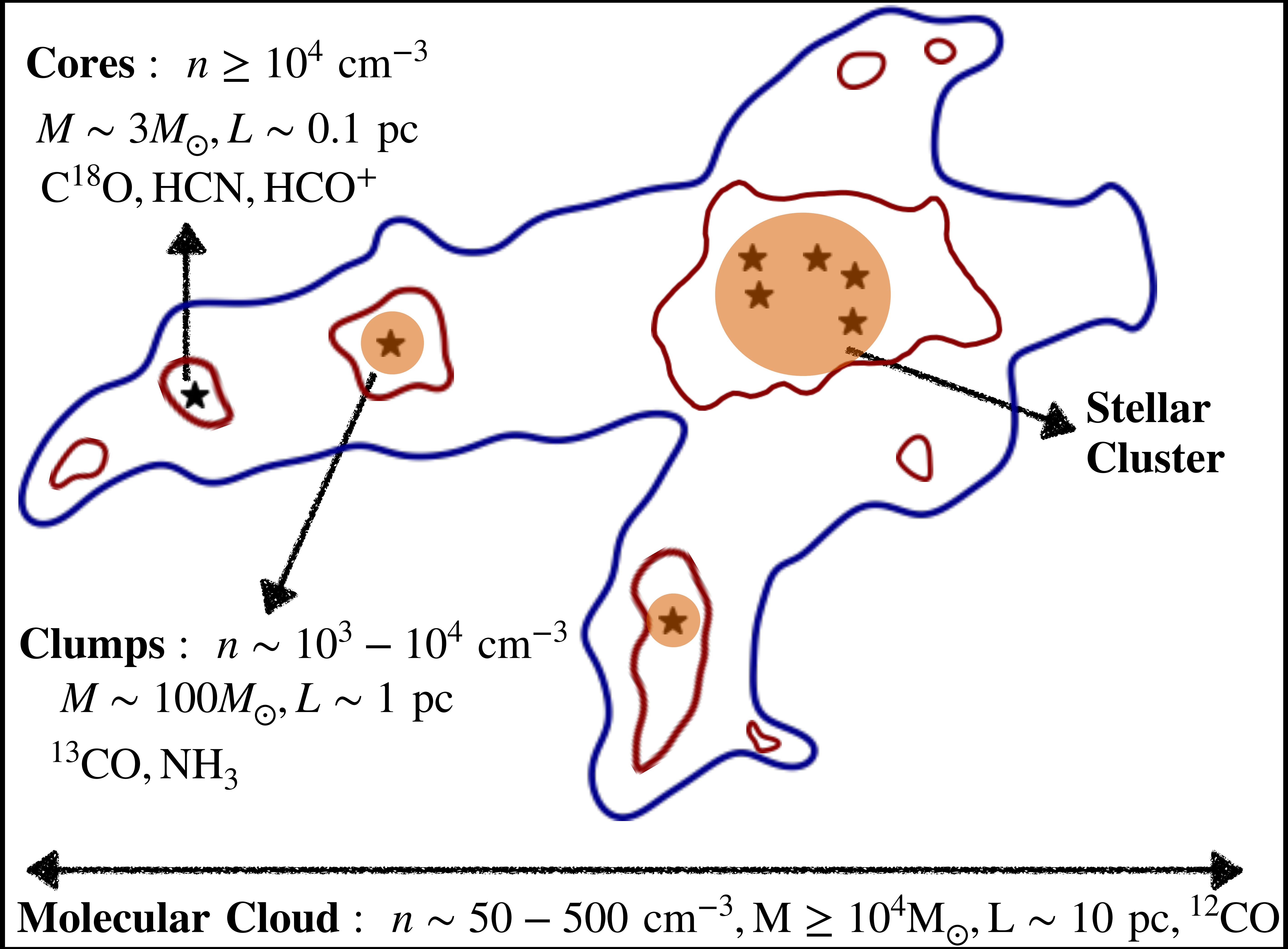
Source function:

$$S_\nu = \frac{j_\nu}{\alpha_\nu} = \frac{A_{lu} n_u}{(B_{lu} n_l - B_{ul} n_u)} = \frac{2h\nu^3}{c^2}\left(\frac{g_u n_l}{g_l n_u} - 1\right)^{-1},$$

Solution: $I_\nu = I_\nu(0) e^{-\tau_\nu} + \int_0^{\tau_\nu} e^{-(\tau_\nu - \tau')} S_\nu d\tau'$

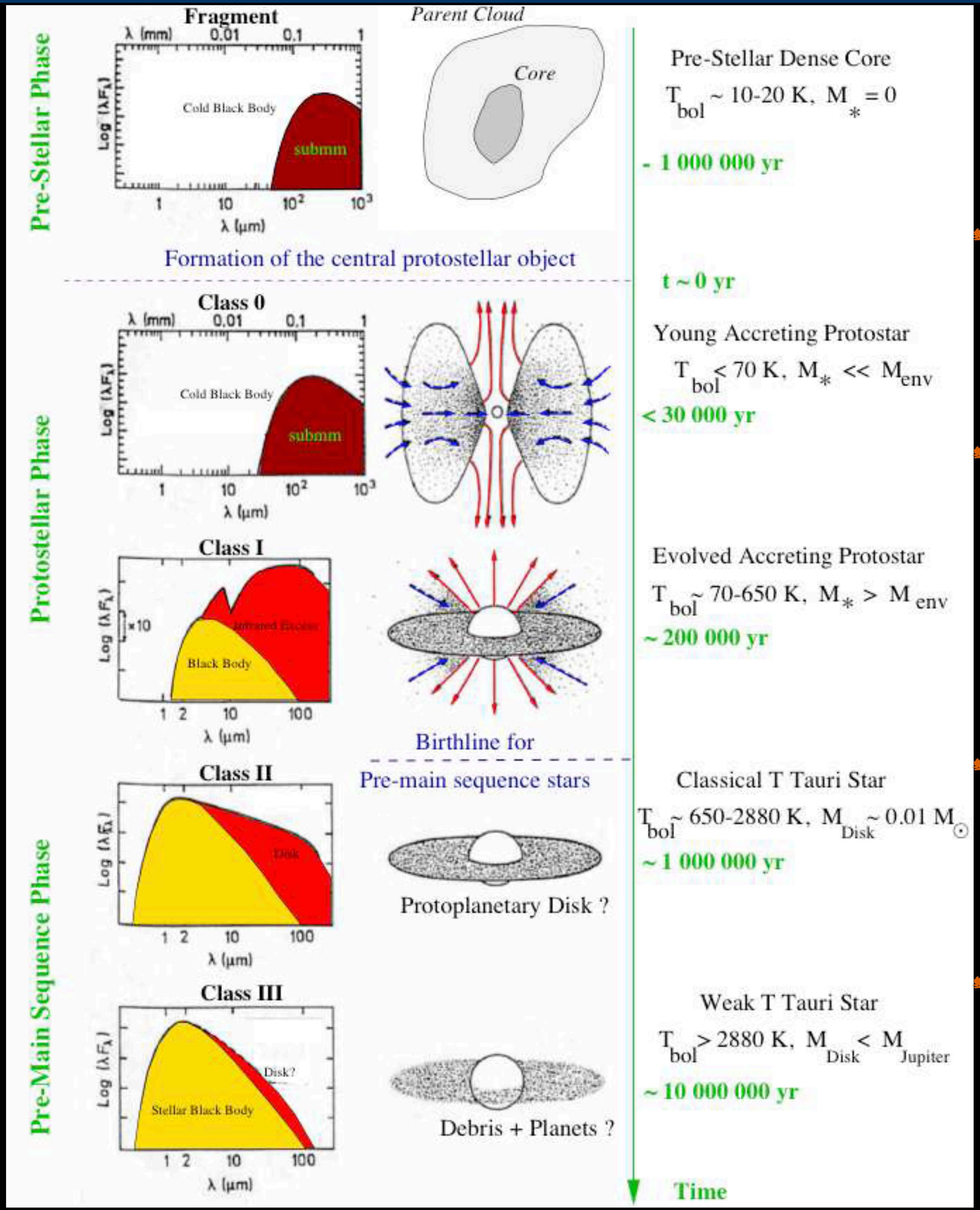
Physical processes in star formation

Molecular clouds – the stellar nurseries



- Stars like our Sun form in cold and dense parts of the molecular cloud, which consists of filaments, clumps, and dense cores

Evolutionary sequence of a low-mass star



- Gravitational fragment forms dense core

- Material accretes onto the forming star
- Collimated jets

- Wide-angle outflows dissipate the envelope
- Mass of the star increases, and an embedded disk is formed

- No envelope left, evolution within the gas-rich protoplanetary disk

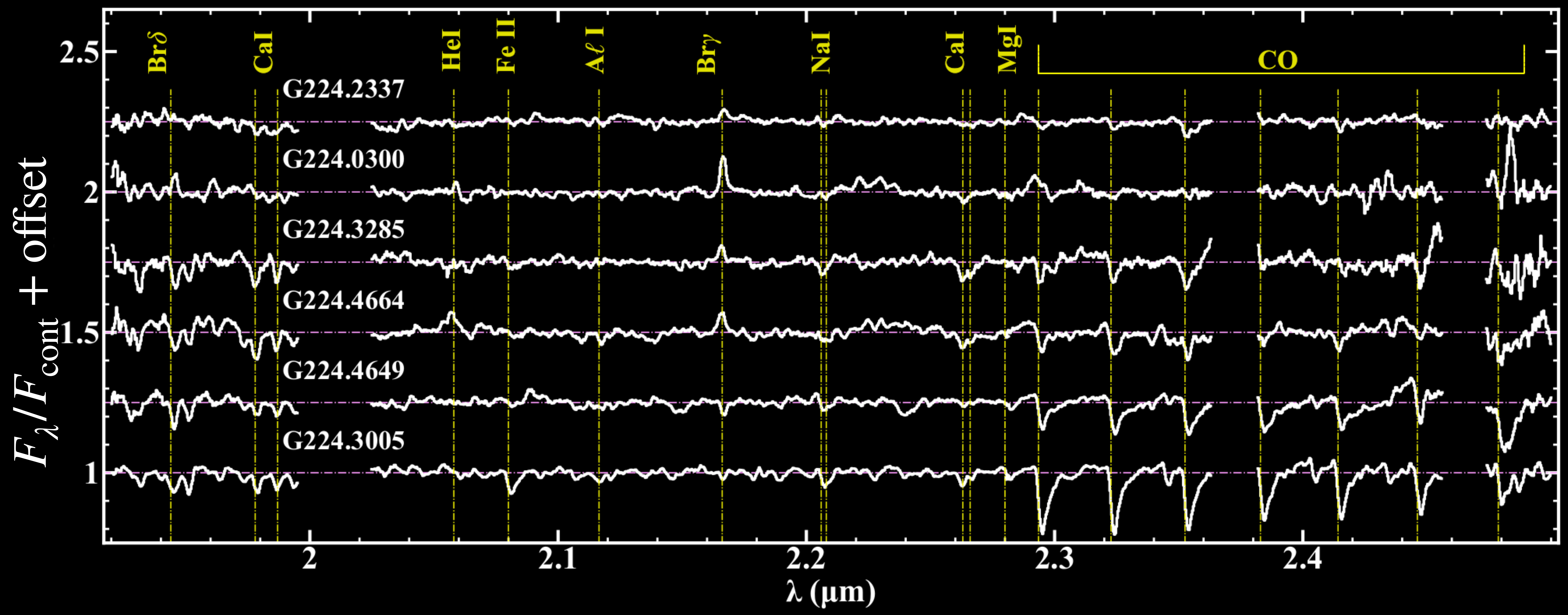
- Planet formation inside the dust-rich disk, lack of accretion

André 2002

- Mass accretion rate: a key quantity to study evolution of pre-main sequence stars
- Jets and outflows: signature of star formation in earliest stages

Near-IR spectroscopy of YSOs

Lê+, in prep.

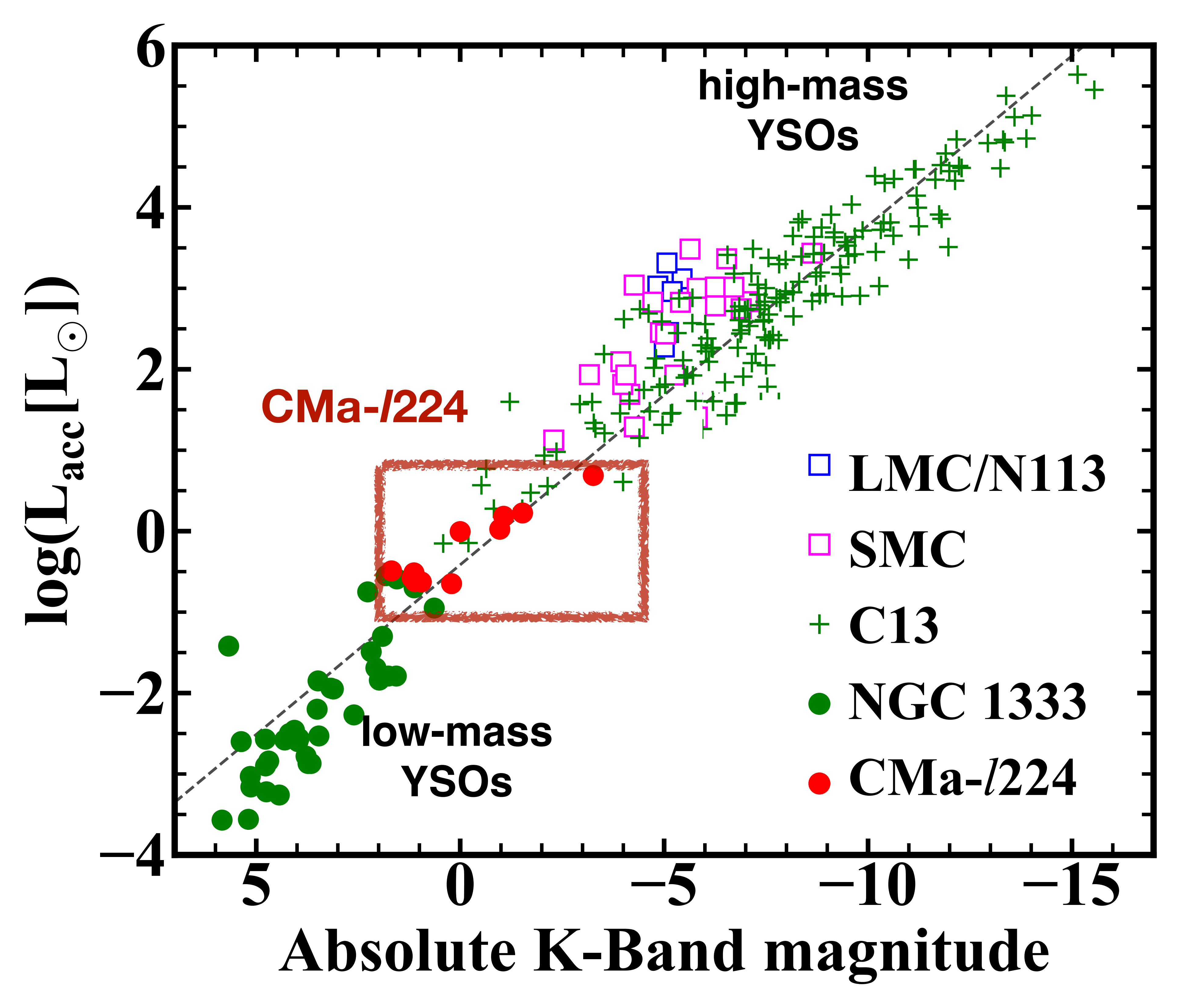


- SpeX spectra of YSO candidates cover the range of 0.8–2.5 μm
- sources show the typical signatures of YSOs (H Brγ, H Paβ, and/or CO bandhead)
- calculated from empirical relation with line luminosity of H Brɣ and/or H Paβ

$\log(L_{acc}) = -0.7 + 0.9\,[\log(L_{Br\gamma}) + 4]$ (Calvet+2004)

$\log(L_{acc}) = 1.8 + 1.03\,\log(L_{Pa\beta})$ (Muzerolle+1998)

Accretion luminosities



Lê+, in prep.

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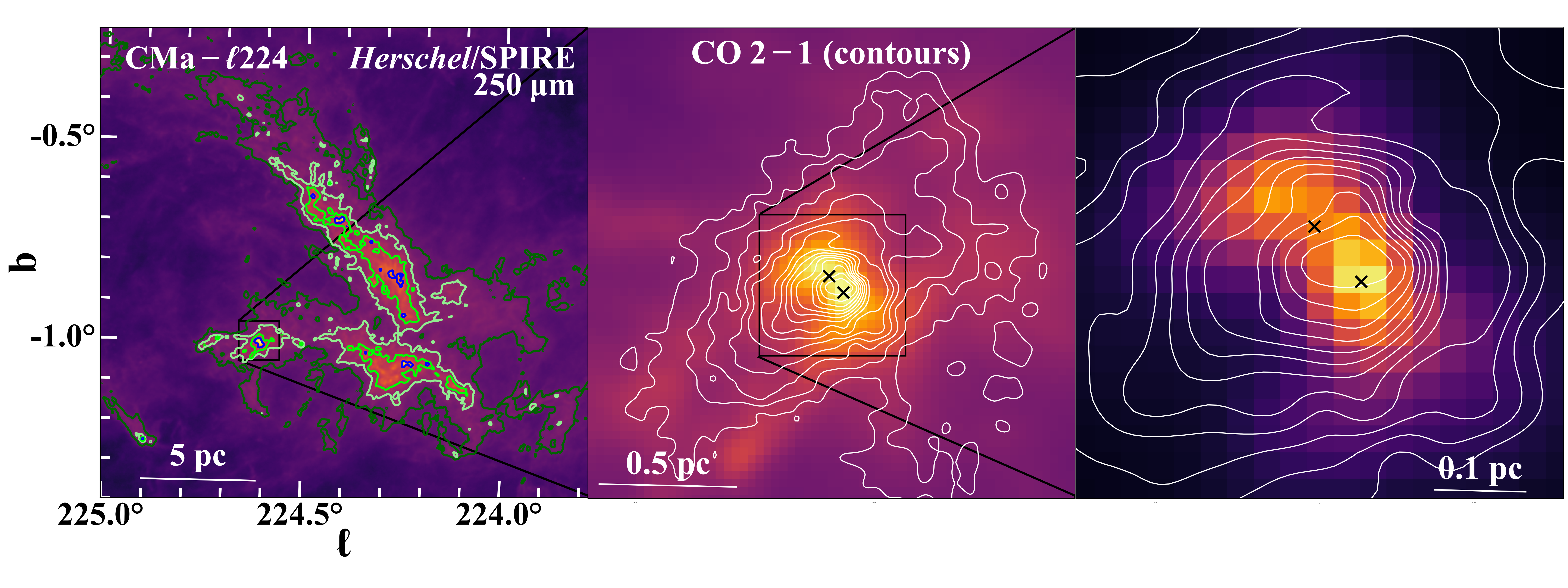
Gaskinematics: low–*J* CO lines

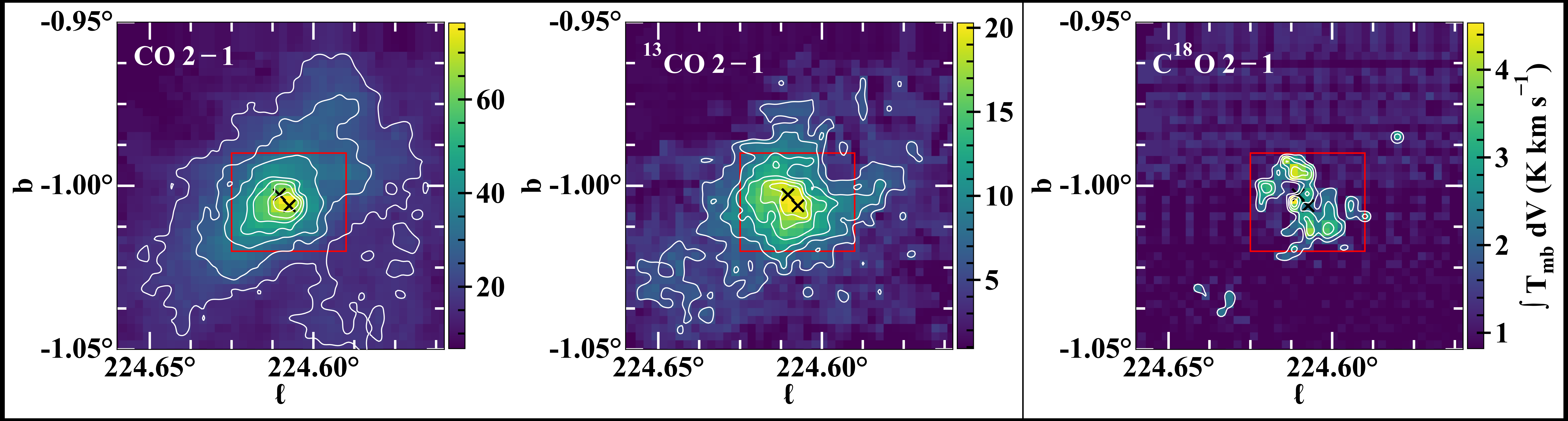
Lê + in prep., APEX PI 230 (OGHReS, König +2021)



- Integrated line intensities of CO 2–1 show relatively low-density gas associated with the filament in the CMa–*l*224 region
- SPIRE 250 *µ*m on 0.1 pc scales shows the region observed with FIFI-LS

Maps of CO 2–1 isotopologues

Lê + in prep., APEX PI 230 (OGHReS, König +2021)



- ^{12}CO 2-1 is extended perpendicular to the far-IR and C^{18}O line emission; traces either the filament or some outflows