NTHUAC AstroRead

# Interstellar Medium

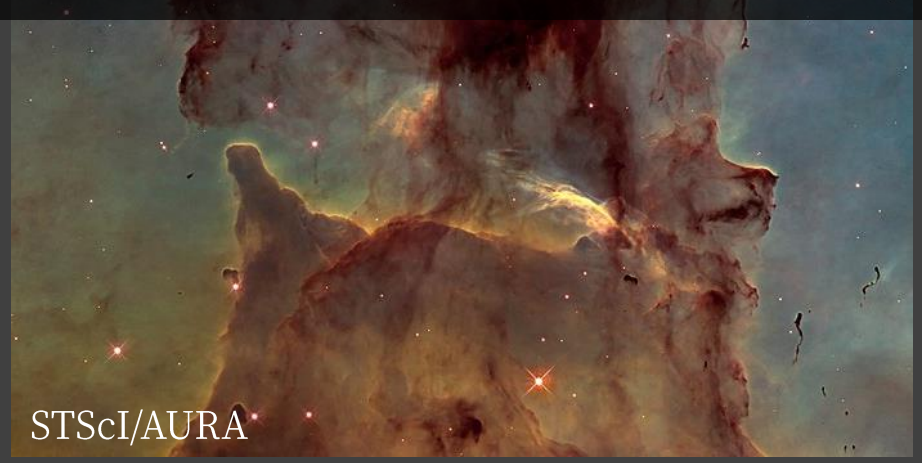
Yen-Hsing Lin (NTHU IoA) | 2023.10.24

陳子翔

They are **interstellar medium (ISM)**

Medium between stars (in a galaxy)

Rogelio Bernal Andreo



STScI/AURA

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ESO/Igor Chekalin

# Interstellar medium (ISM)

- Medium between stars, contains **gas** and **dust**.
- Role: fuel for star formation; emit/absorb/scatter radiation.
- Gas:
  - Matter in **gas** or **plasma** phase.
  - Mainly H, He, and some gas phase metals.
- Dust:
  - **Solid** grains and large organic molecules.
  - Made in Si, O, C, and other heavy elements.

# Types of gas by temperature/phase.


**Hot Ionized Medium (HIM) / Corona:**

Diffuse, fully ionized gas. Emit/absorb X-ray or far-UV.

**Warm Ionized Medium (WIM) / HII region:**

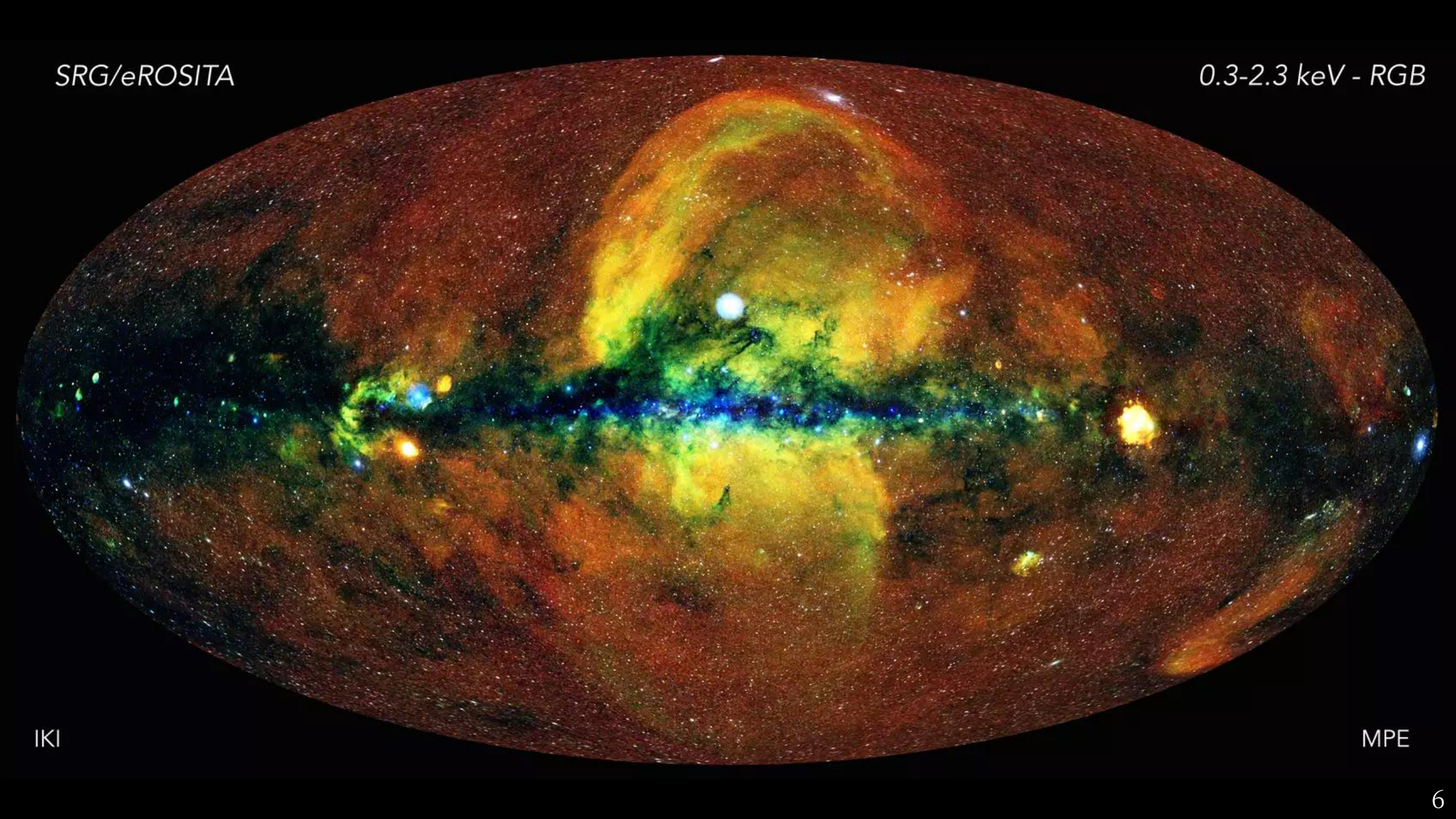
Diffuse, ionized gas. Emit atomic hydrogen lines (e.g. H$\alpha$).

**Warm/Cold Neutral Medium (WNM/CNM) / HI region:**

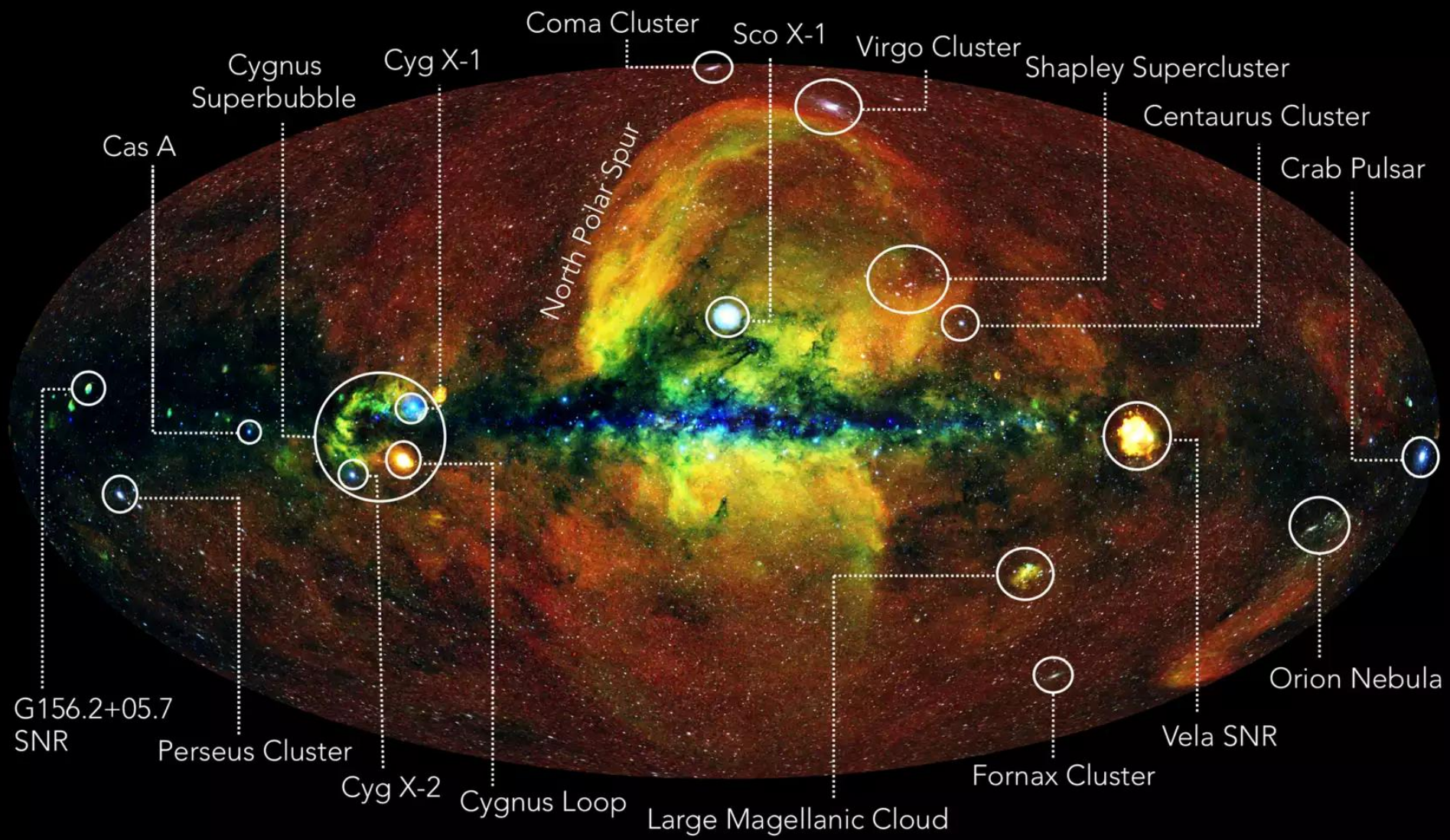
Somewhat dense, neutral gas. Emit 21 cm line or absorb atomic lines.

**Molecular cloud:**

Cold and dense molecular hydrogen ($H_2$). **Star formation** happens here.


SRG/eROSITA
0.3-2.3 keV - RGB
IKI
MPE

# Navigating the eROSITA X-ray sky

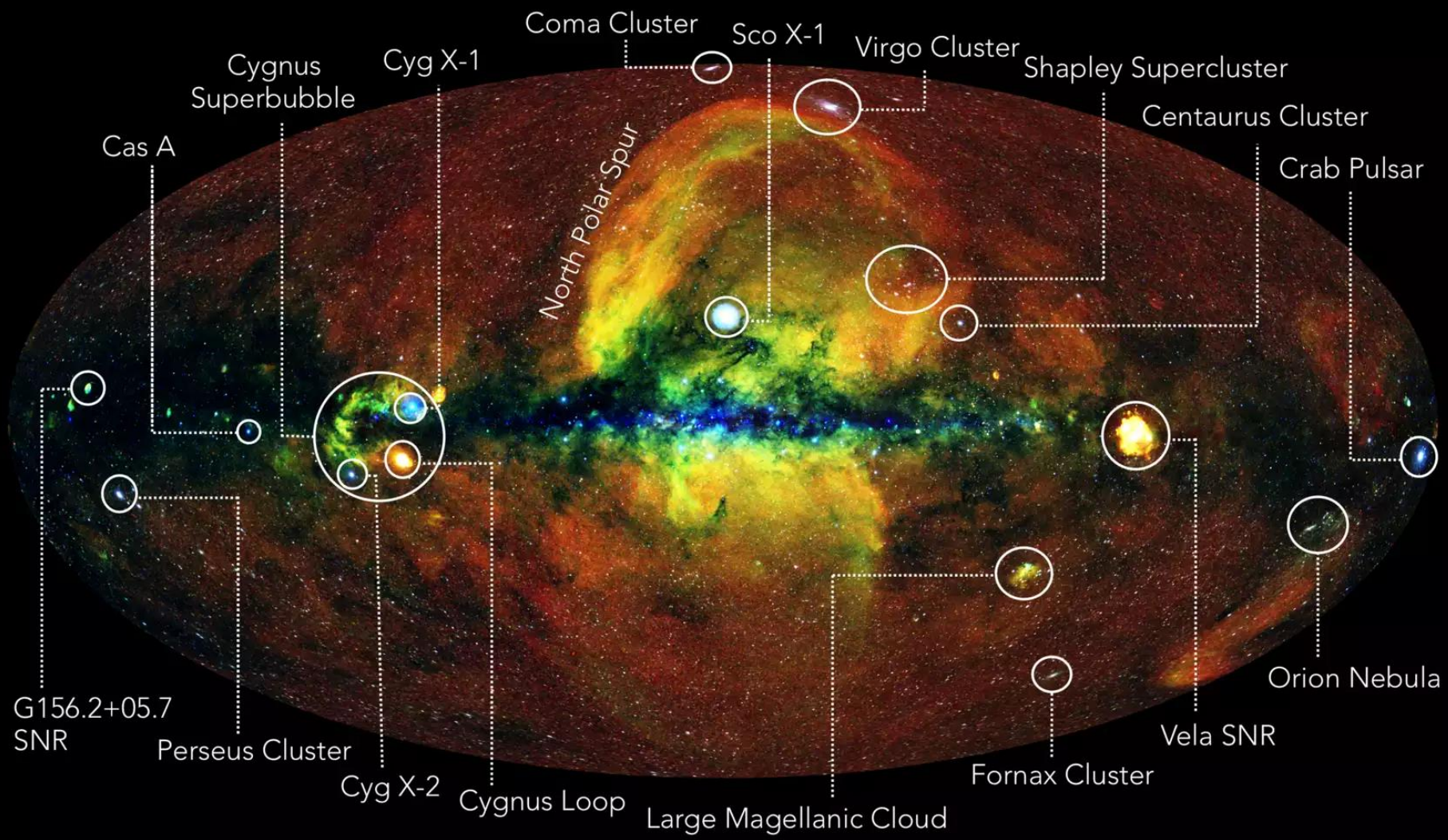



IKI

SRG/eROSITA 0.3-2.3 keV - RGB Map

MPE

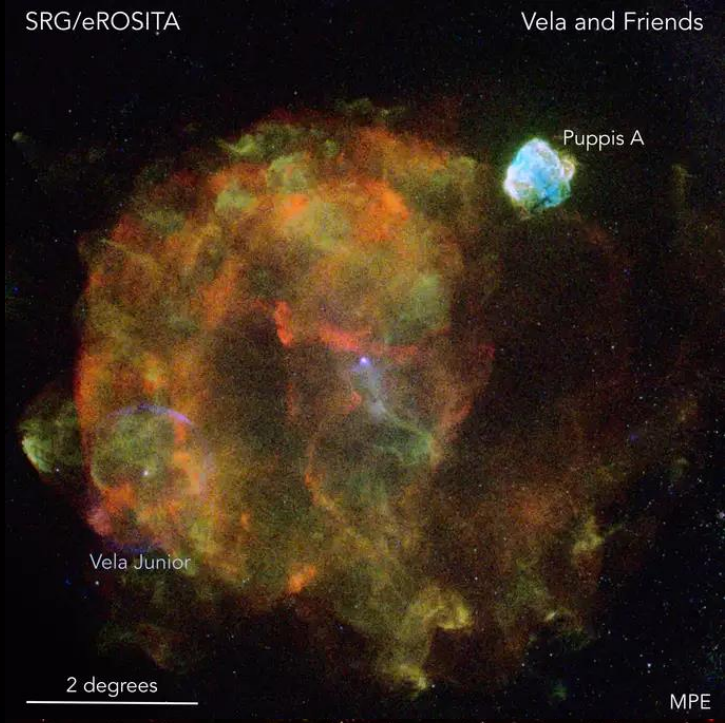
# Navigating the eROSITA X-ray sky

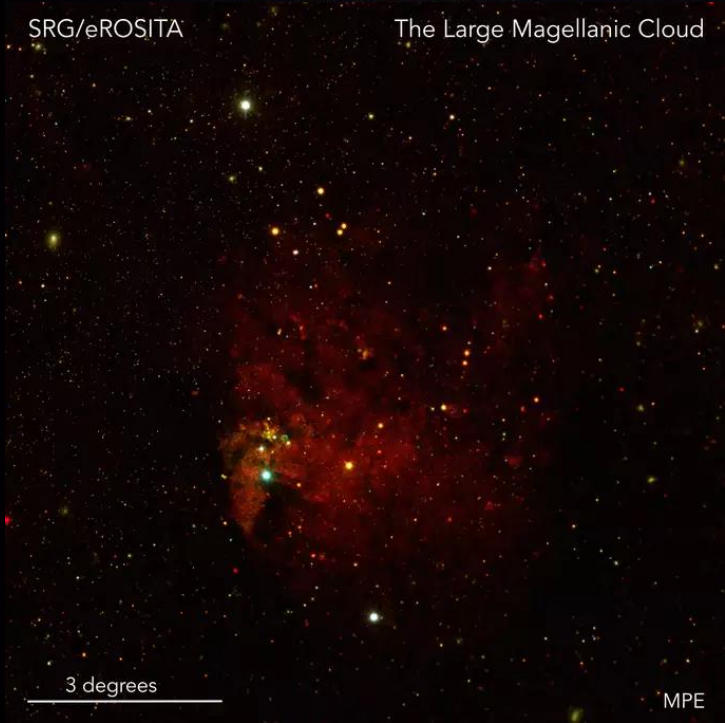



IKI

SRG/eROSITA 0.3-2.3 keV - RGB Map

MPE



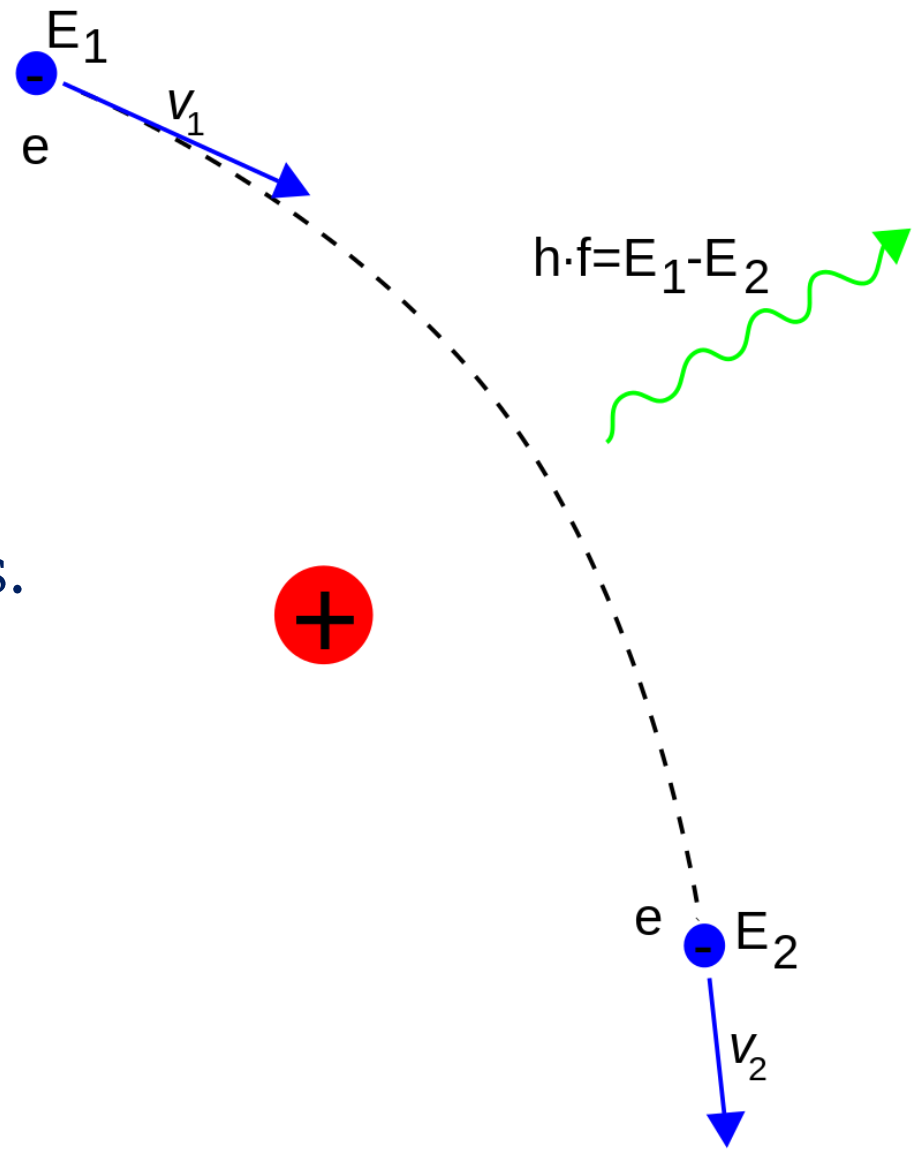



# Hot ionized medium

- Hot (> $10^6$ K) and diffuse (n < $10^{-3}$ $cm^{-3}$).
- Absorption/Emission in far-UV lines and X-ray.
  - Free-free emission:

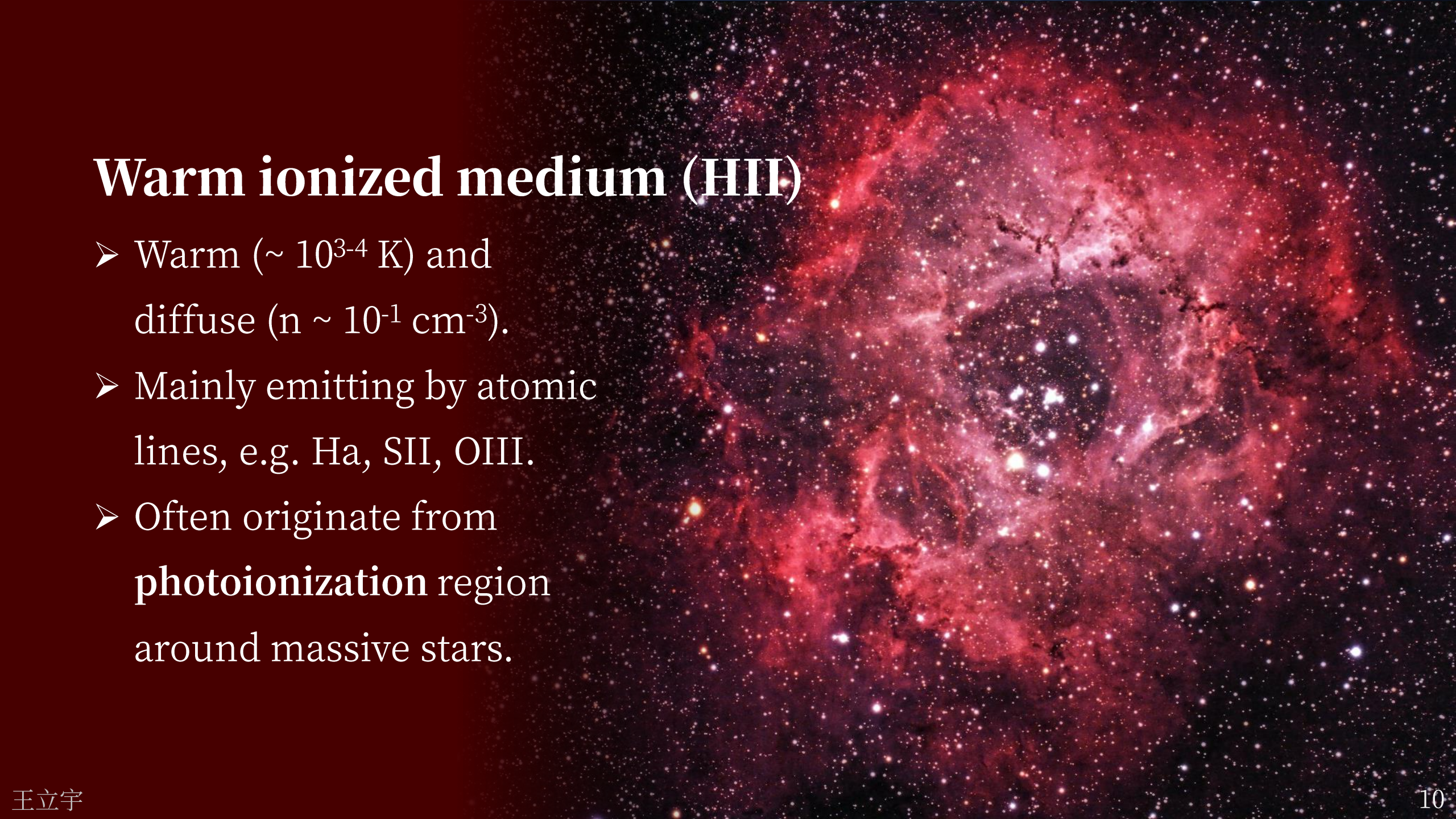
    Close encounter between electrons and ions.
  - Recombination:

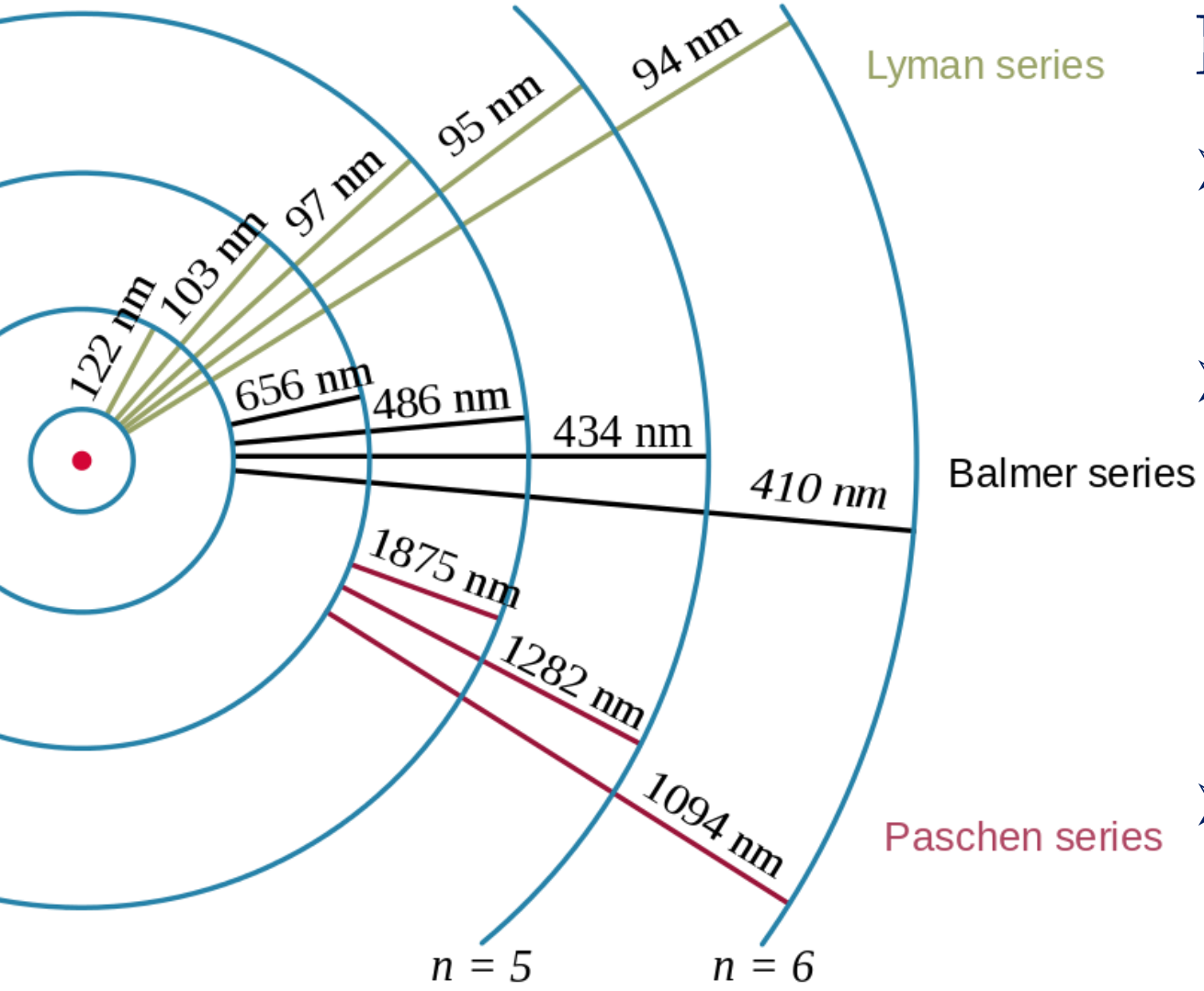
    Free electrons captured by ions, e.g. OVI.
- Often originate from **shocks** produced by **supernova explosion** or possibly **AGN jets**.



# Warm ionized medium (HII)

- Warm (~ $10^{3\text{-}4}$ K) and diffuse (n ~ $10^{-1}$ $cm^{-3}$).
- Mainly emitting by atomic lines, e.g. Ha, SII, OIII.
- Often originate from **photoionization** region around massive stars.





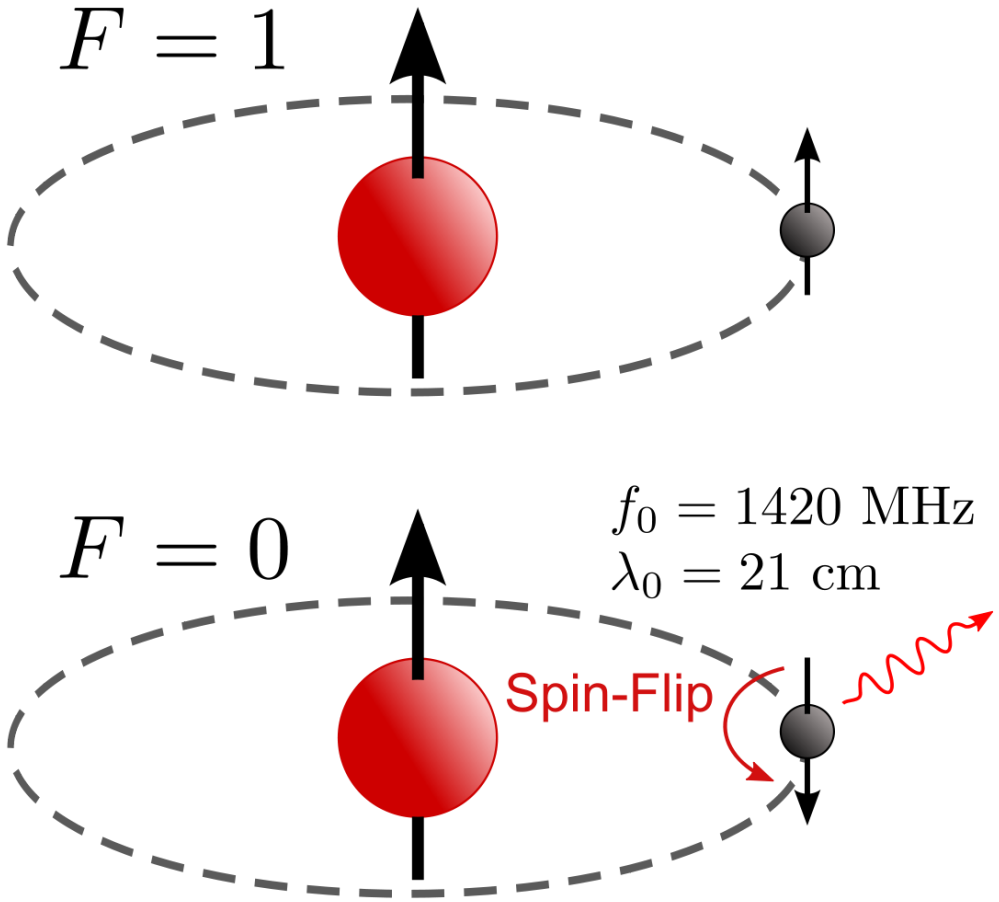

# Electron transition

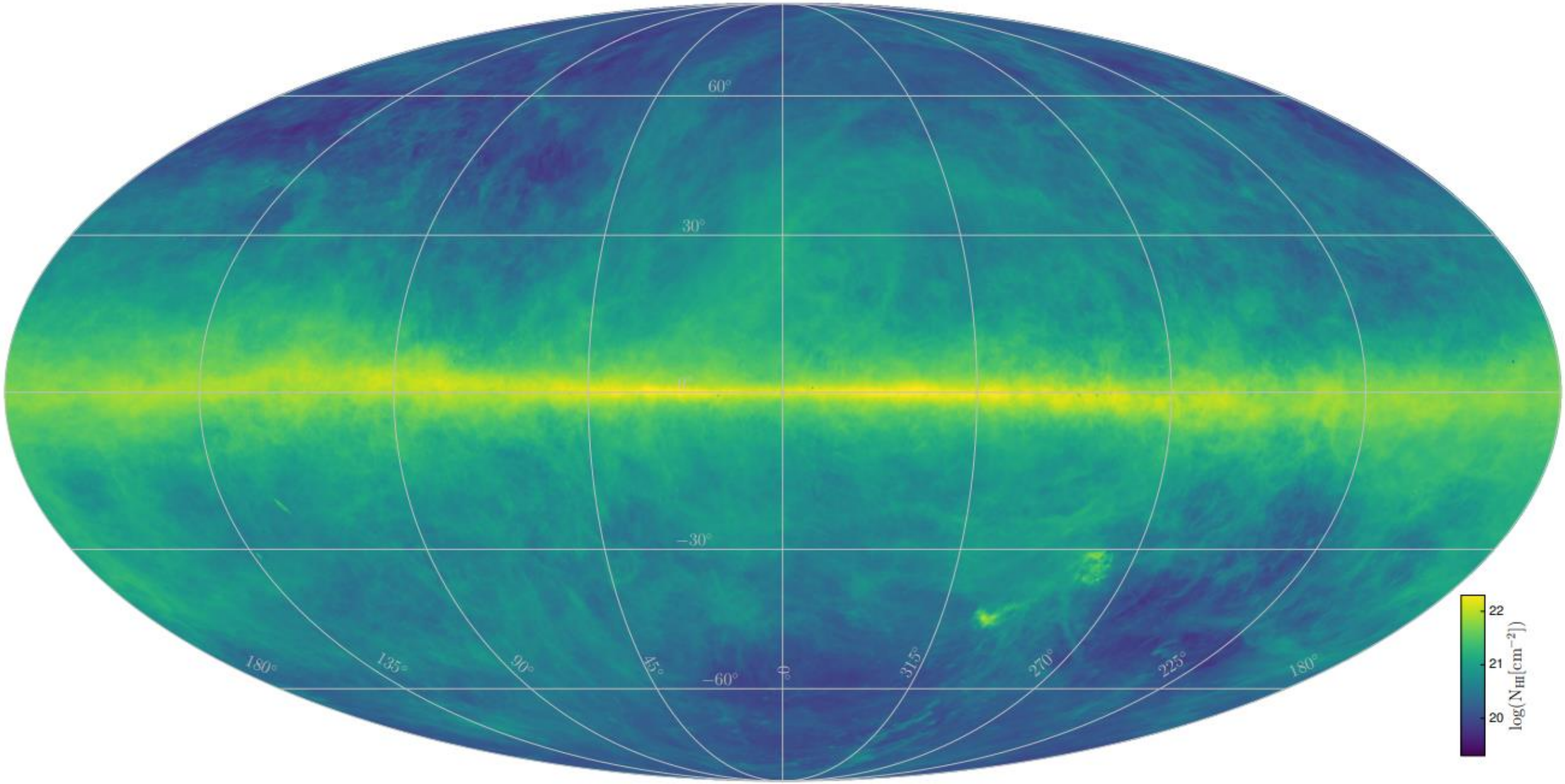
- H atom has energy state
  $E_n = -13.6/n^2$ eV
- Give rise to line series:
  - Lyman Series: n → 1 (UV)
  - Balmer Series: n → 2 (Optical)
  - Paschen Series: n → 3 (IR)
- Within one series, lines are named with Greek alphabet.

# Neutral medium (HI)

- Warm (~ $10^{2\text{-}3}$ K) and somewhat dense (n ~ $10^{0\text{-}1}$ $cm^{-3}$).
- Absorption/Emission:
  - Absorption: atomic lines
  - Emission: **21 cm line**

    Hyperfine structure of hydrogen atom; energy difference due to spin alignment.
- Occupy most of the mass and a large portion of space of ISM in the Milky Way.



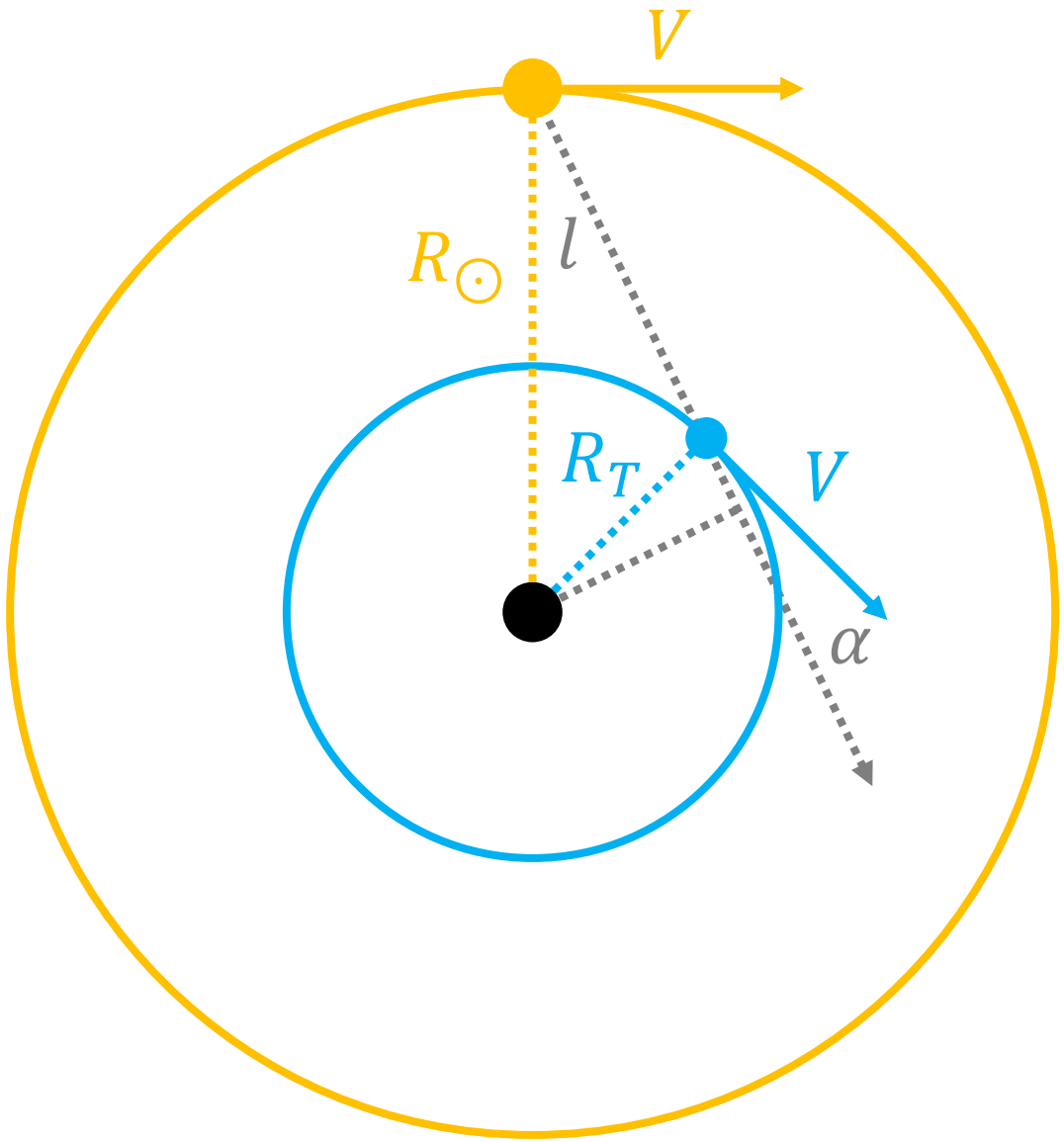



HI4PI. Bekhti et al. (2016).

# A small tangent……

How to probe the structure of the Milky Way?

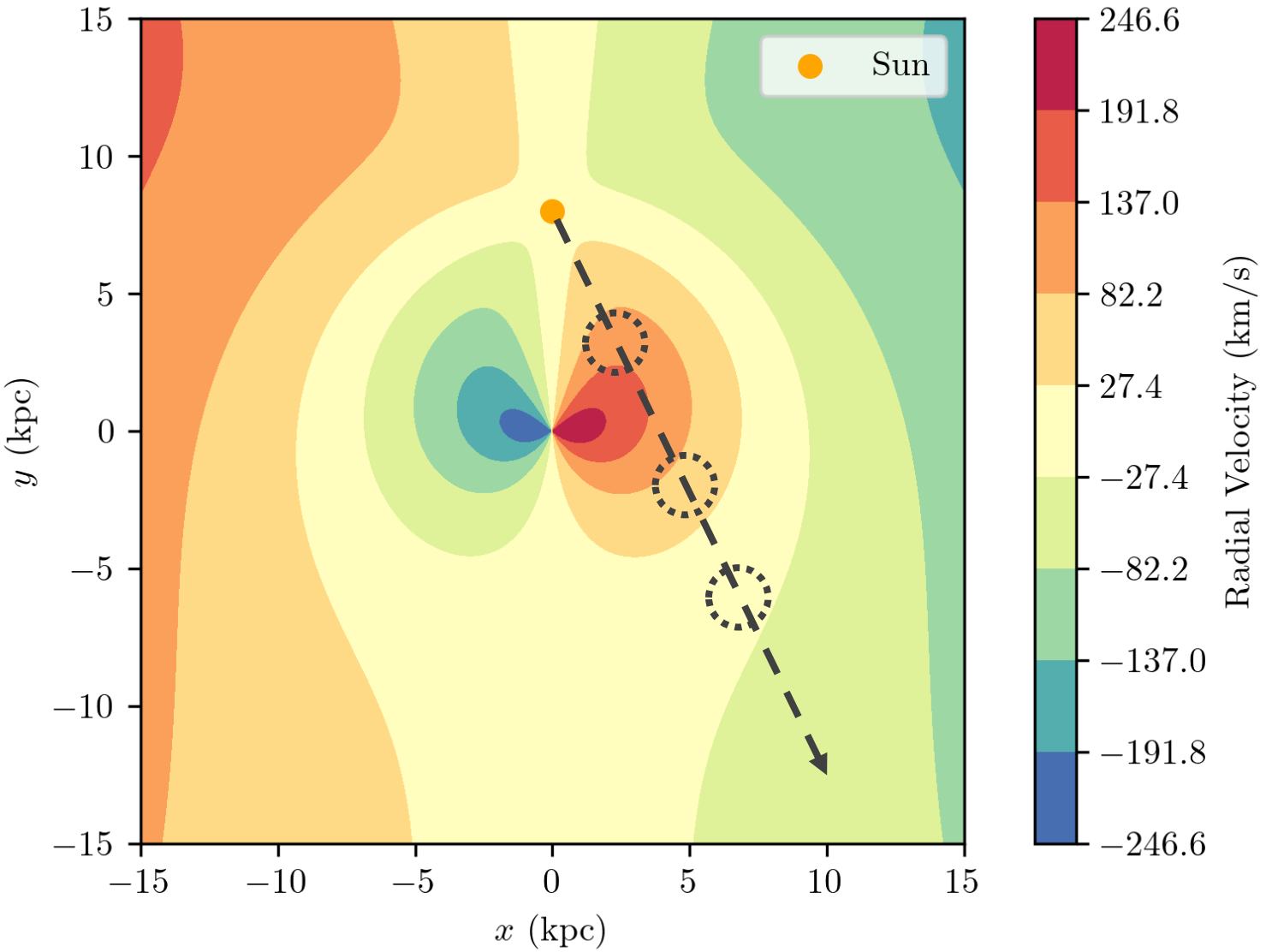
HI survey!

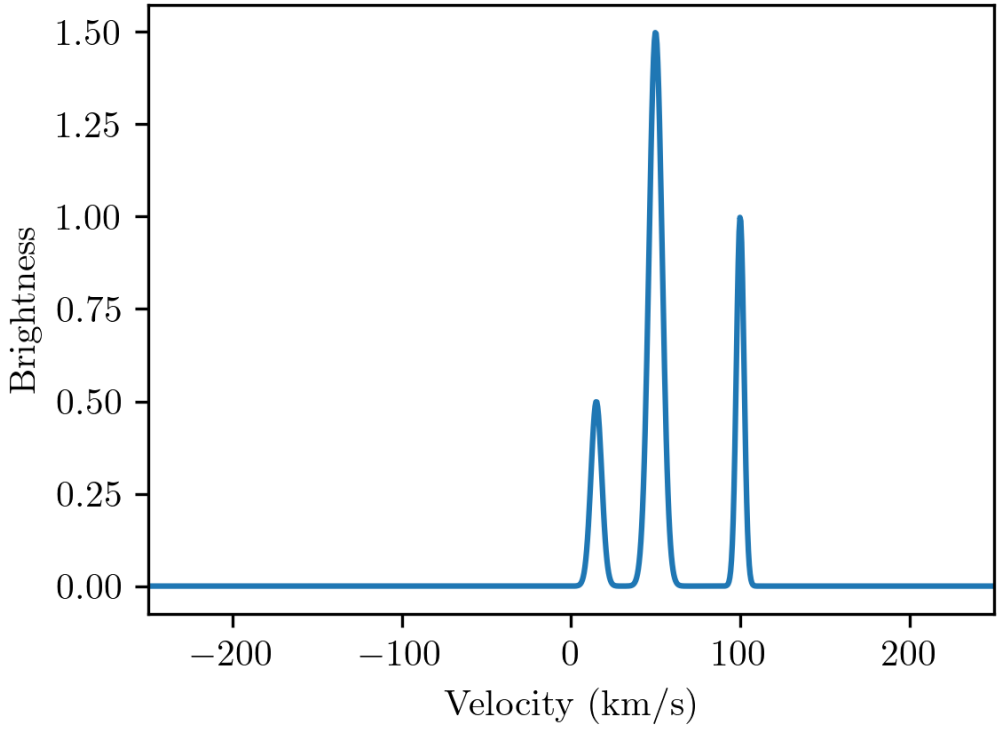



$$\begin{cases} V_r = V\cos(\alpha) - V\sin(\ell) \\ R_\odot \sin(\ell) = R_T \cos(\alpha) \end{cases}$$

$$V_r = V\left(\frac{R_\odot \sin(\ell)}{R_T}\right) - V\sin(\ell)$$
$$= V\sin(\ell)\left(\frac{R_\odot}{R_T} - 1\right)$$

# The Structure of MW

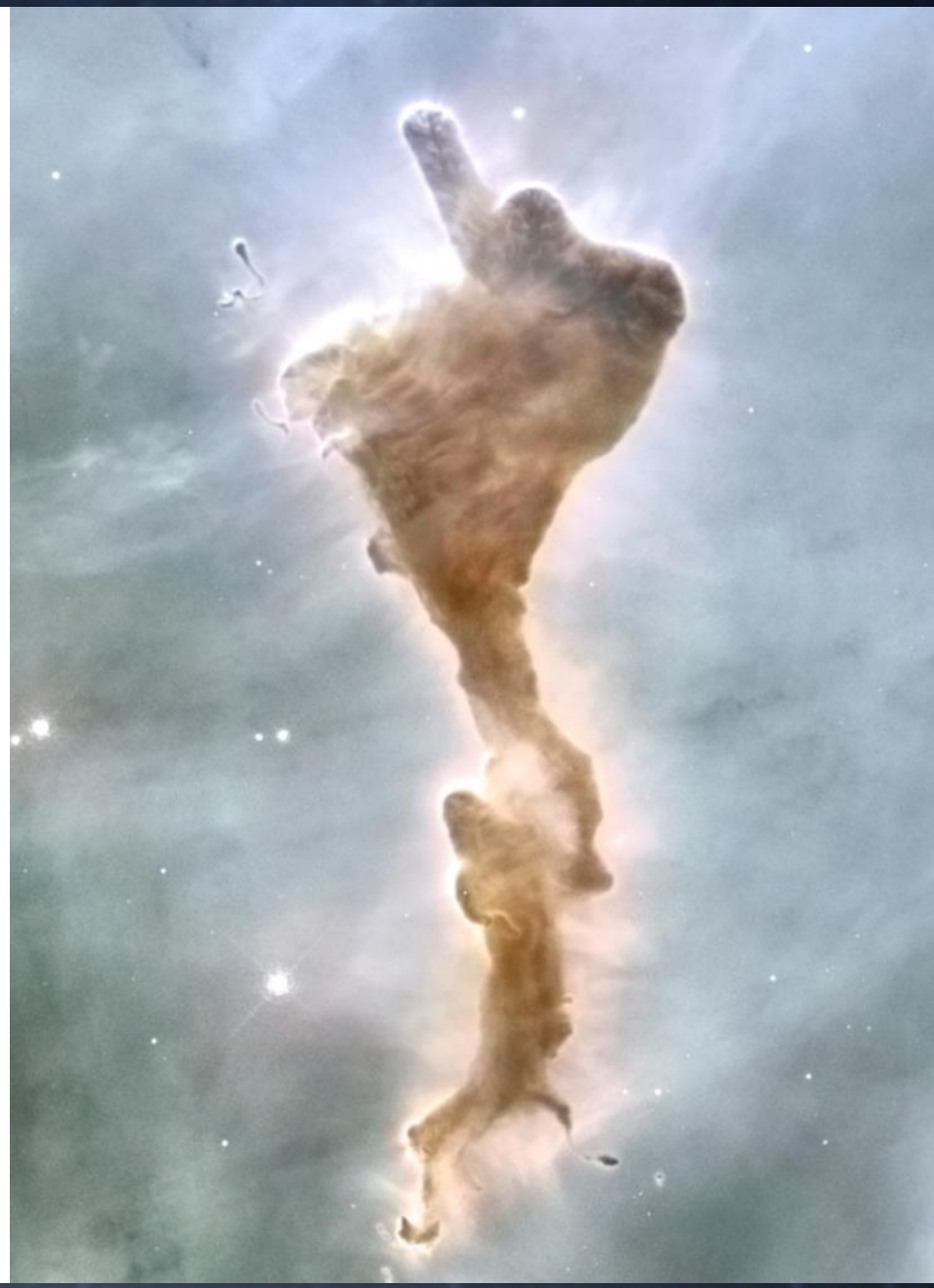



HI4PI. Bekhti et al. (2016).

# Molecular cloud

- Hydrogen exist in molecular form ($H_2$).
- Cold (10 – 20 K) and dense ($n > 10^3$ $cm^{-3}$).
- Small volume (~0.05%) but large mass fraction (~30%) in the Milky Way ISM.
- More complicated molecules can survive e.g. CO, $NH_3$, $CH_3OH$, etc.
- Usually dusty thus opaque in optical.
- Fuel for star formation.



Finger of God (Carina). Credit: HST

# Emission from molecules

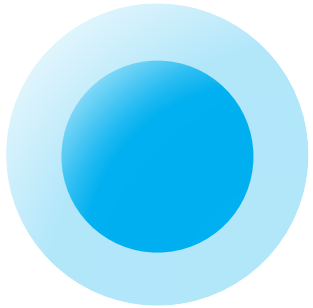
- Molecules usually emits with **rotational** or **vibrational** transitions.

  Yes, rotation and vibration are also quantized!

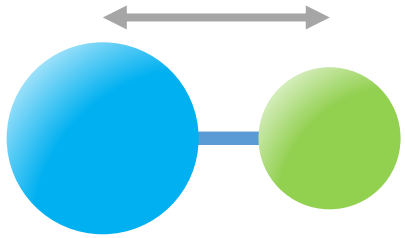
- $H_2$ itself is hard to observe because of its symmetric structure.

  You will learn it in quantum physics.

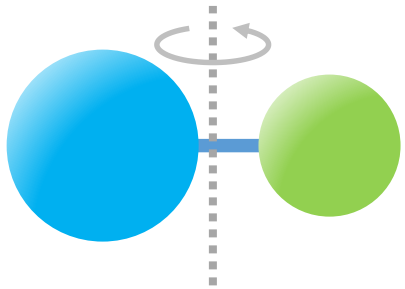
- Therefore $H_2$ is usually traced by CO rotational lines in Submm.



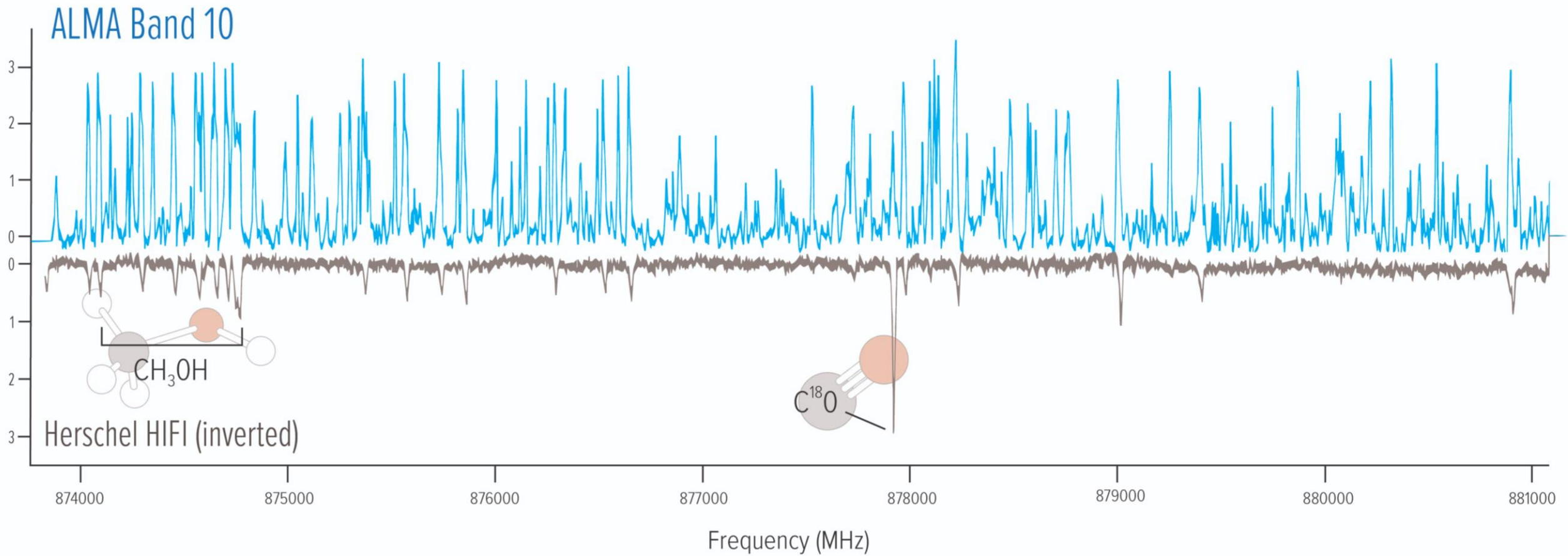
$$E_n \propto -\frac{1}{n^2}$$



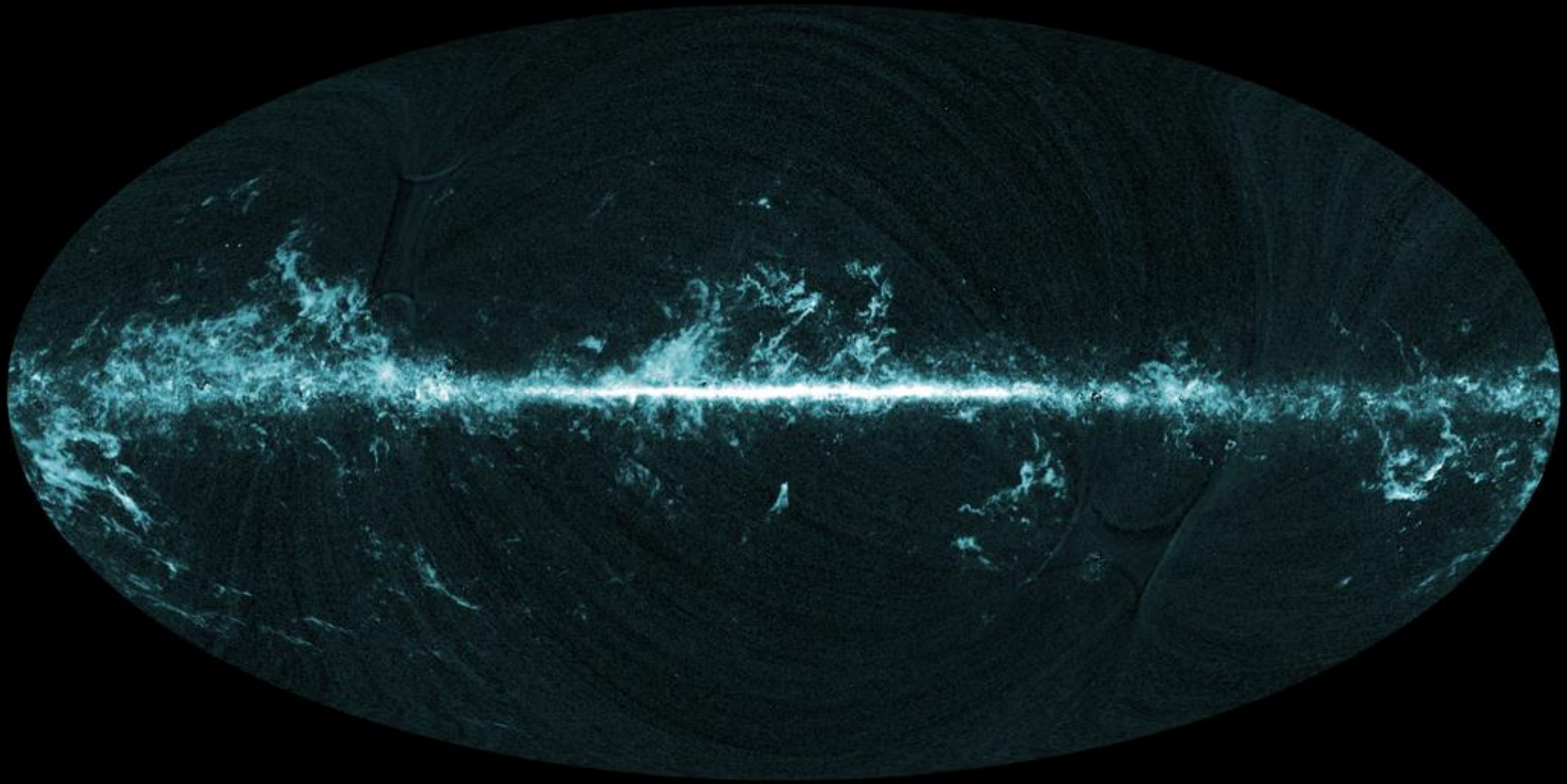
$$E_n \propto n + \frac{1}{2}$$



$$E_J \propto J(J+1)$$




Molecular clouds are often filled with rotational/vibrational spectral lines!



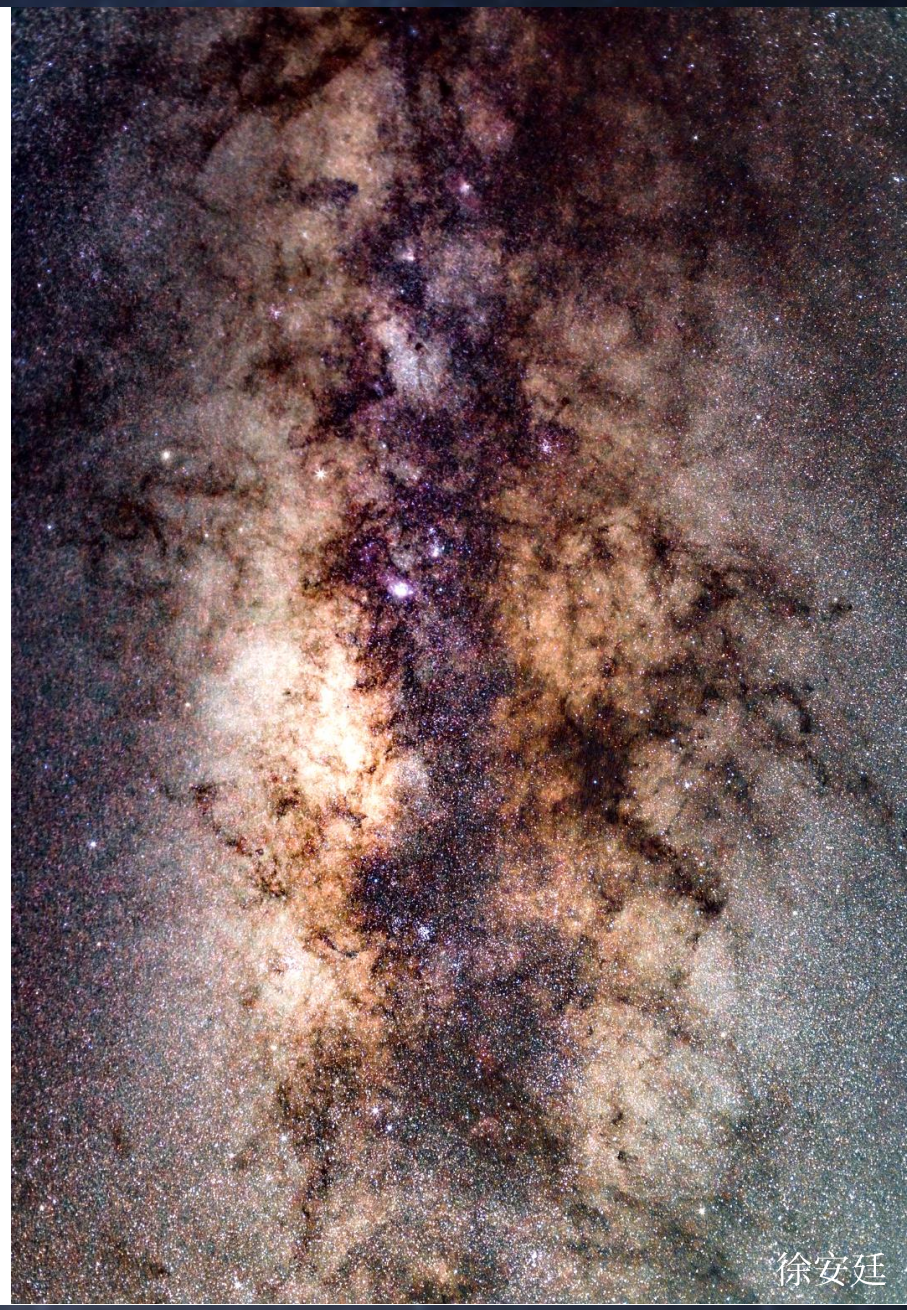
Planck 2013

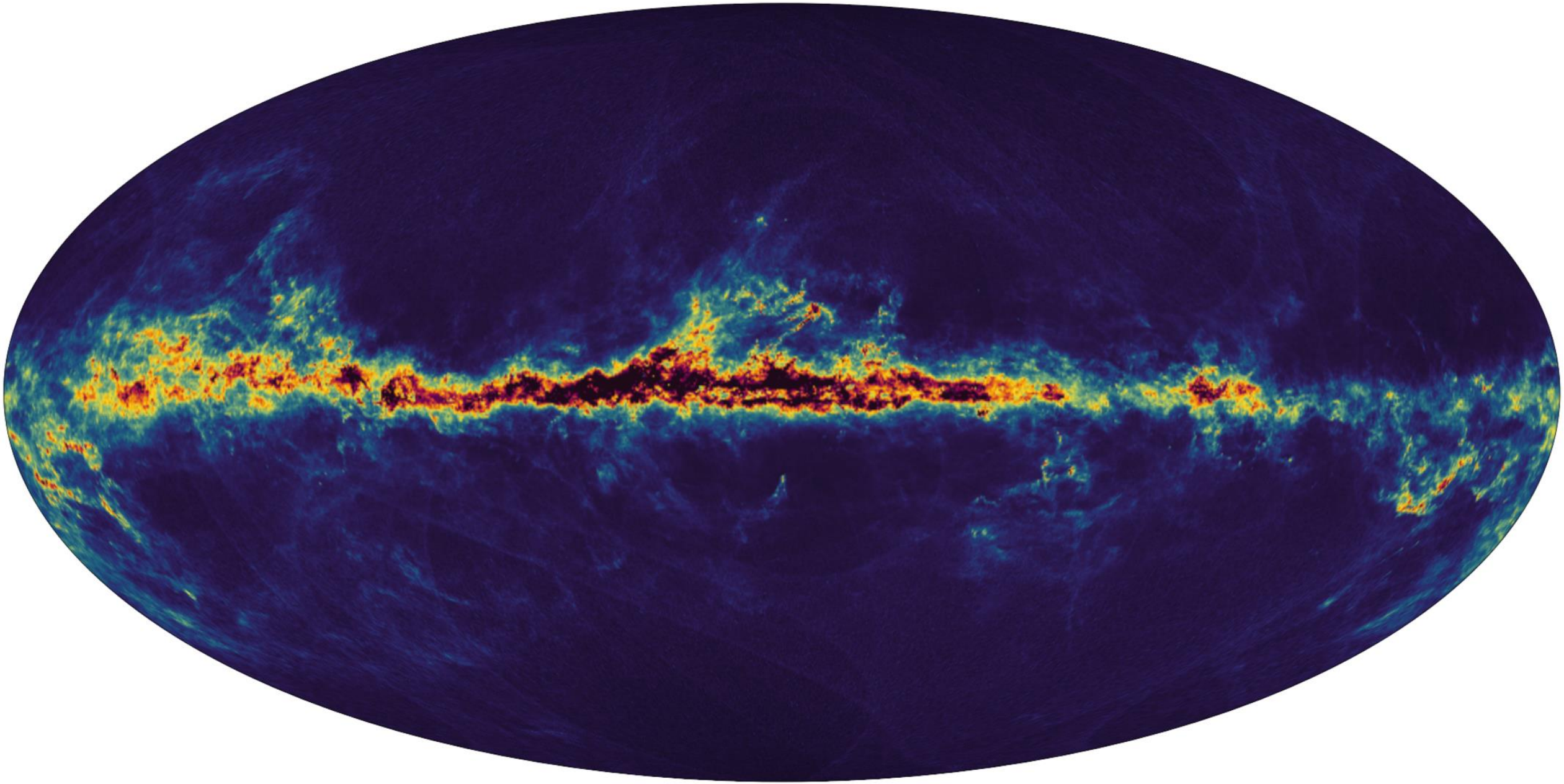
# Summary on GAS

| Types | n ($cm^{-3}$) | T (K) | $f_{mass}$ | $f_{volume}$ |
|---|---|---|---|---|
| MC ($H_2$) | $10^2$ - $10^5$ | 10 – 50 | ~ 20% | < 1% |
| NM (HI) | $10^0$ - $10^1$ | $10^2$ – $10^3$ | ~ 70% | ~ 30% |
| WIM (HII) | $10^{-1}$ | $10^3$ – $10^4$ | ~ 10% | ~ 20% |
| HIM (Corona) | < $10^{-3}$ | > $10^6$ | ~ 1% | ~ 50% |

# Dust

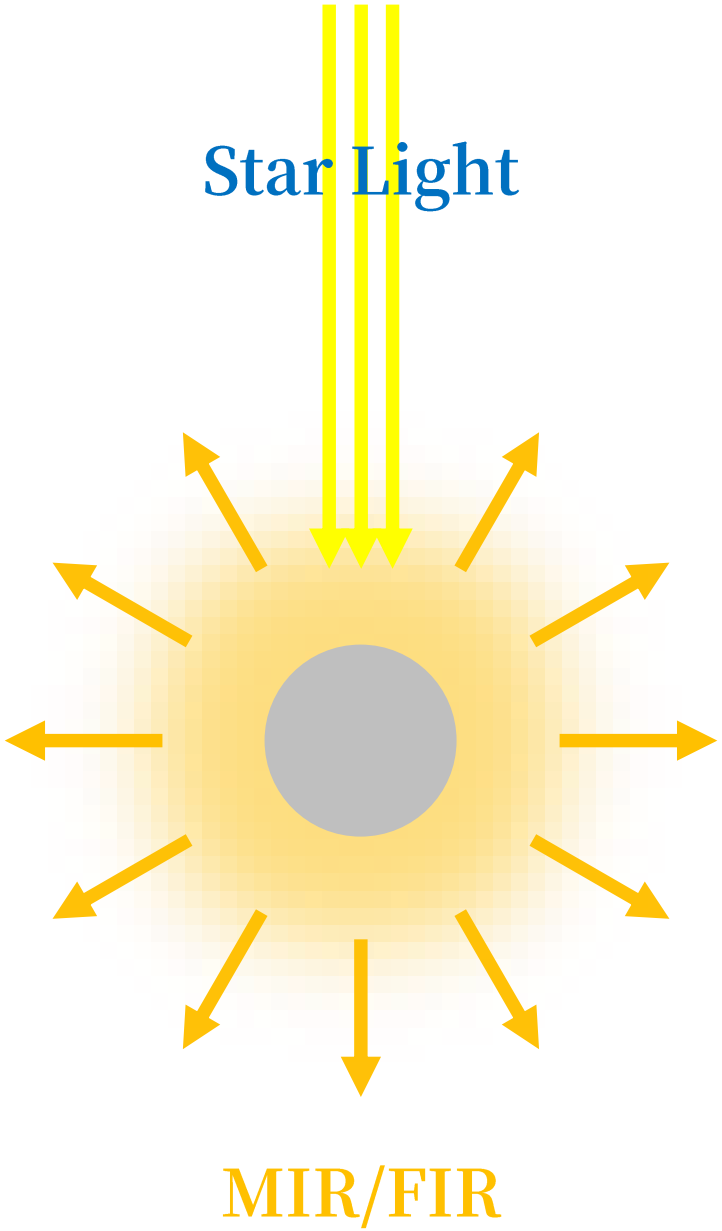
- Solid grains and large organic molecules made in Si, O, C. ~1% Molecular cloud mass.
- Role:
  - Absorb, scatter and re-emit radiation. Correction of **dust extinction** is crucial for correctly understand an object.
  - Enhance $H_2$ formation.
  - Material for forming planets and us.



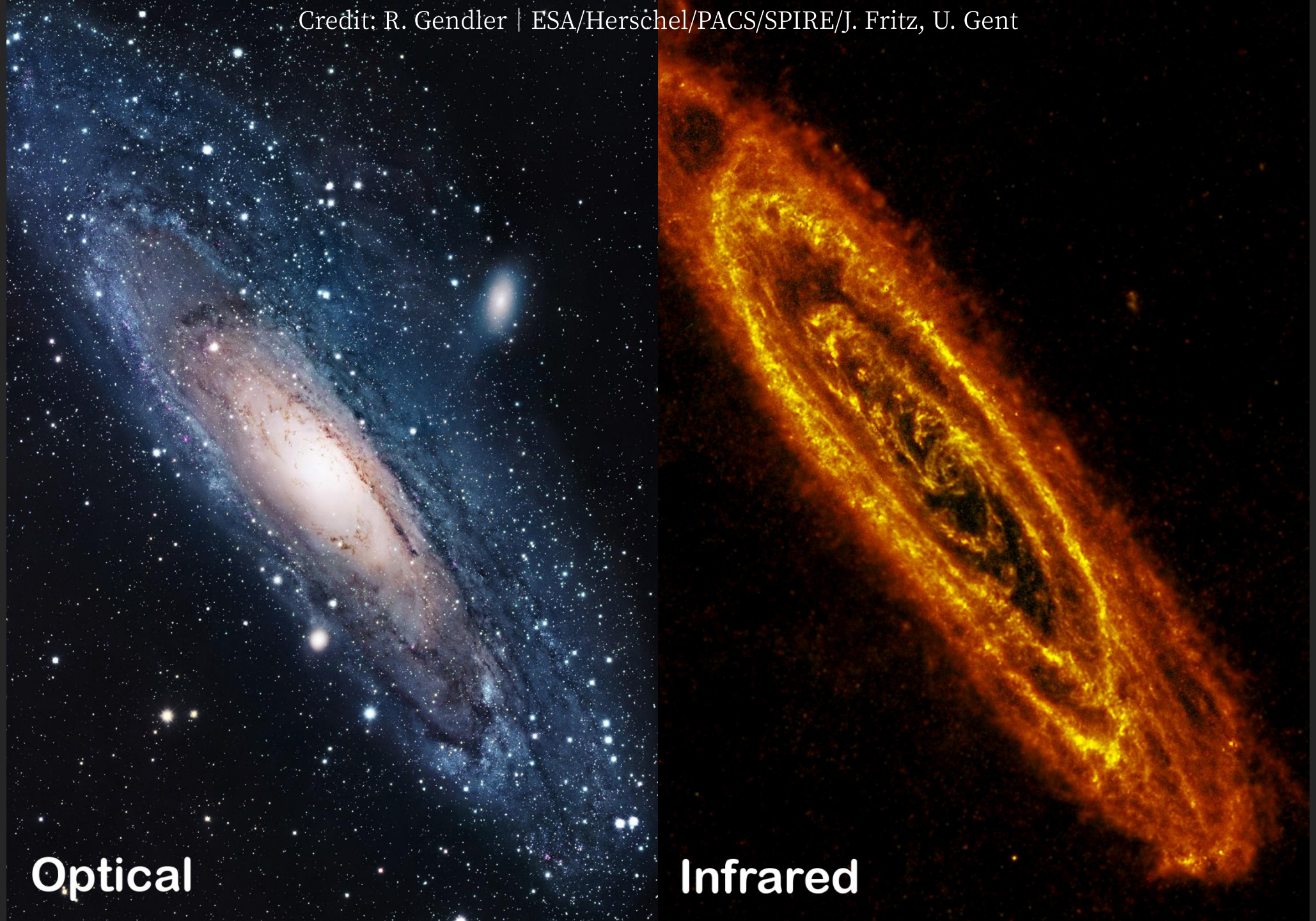


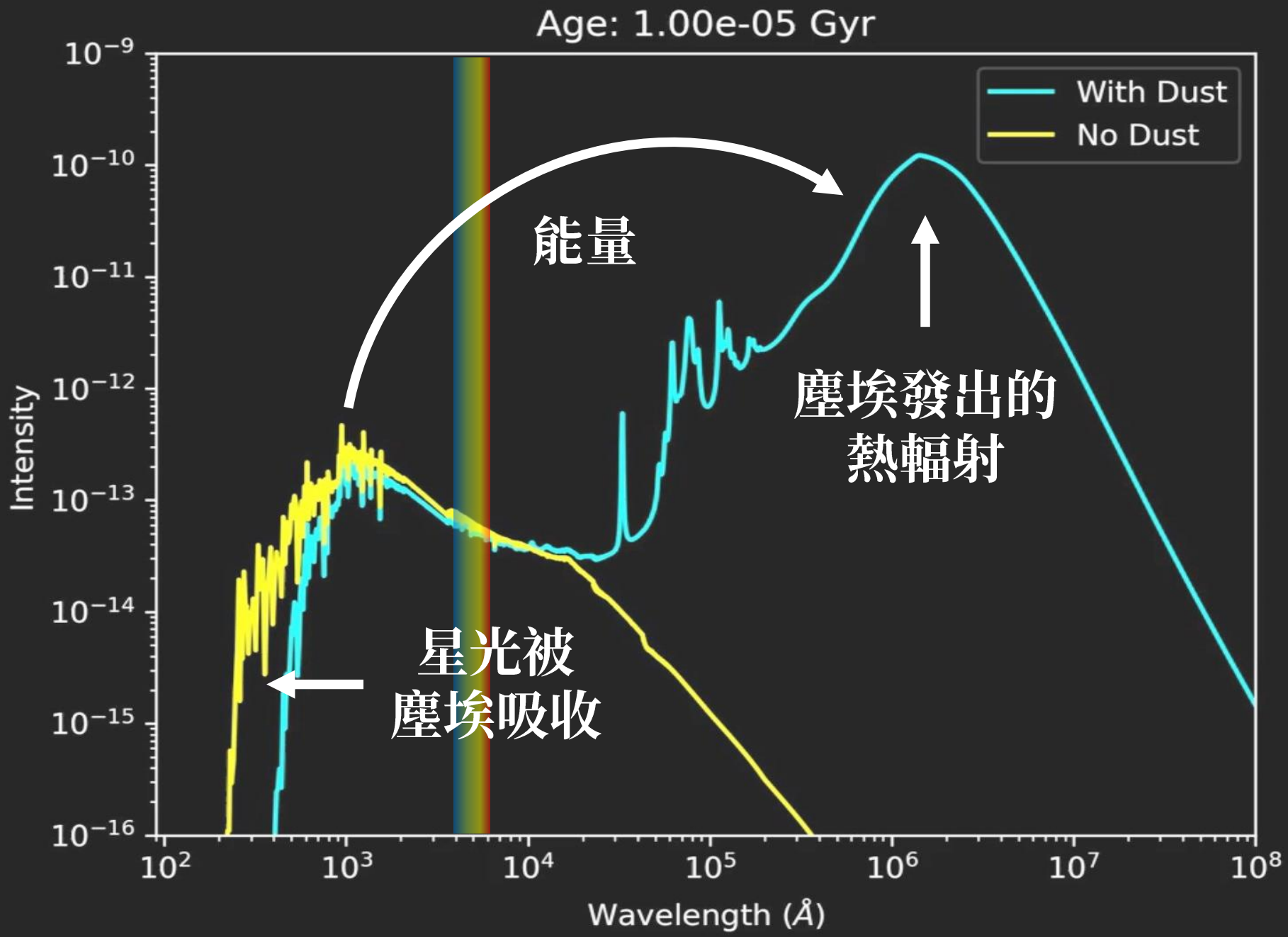
# Dust and radiation

- 3 processes can happen between light and dust (or any matter):
  - Absorption: Photon is eaten.
  - Scattering: Photon change direction.
  - Emission: New photon is created.
- Absorption + Scattering = Extinction
  Usually important in UV/Optical
- Emission usually happen in MIR/FIR/Submm.



Credit: R. Gendler | ESA/Herschel/PACS/SPIRE/J. Fritz, U. Gent

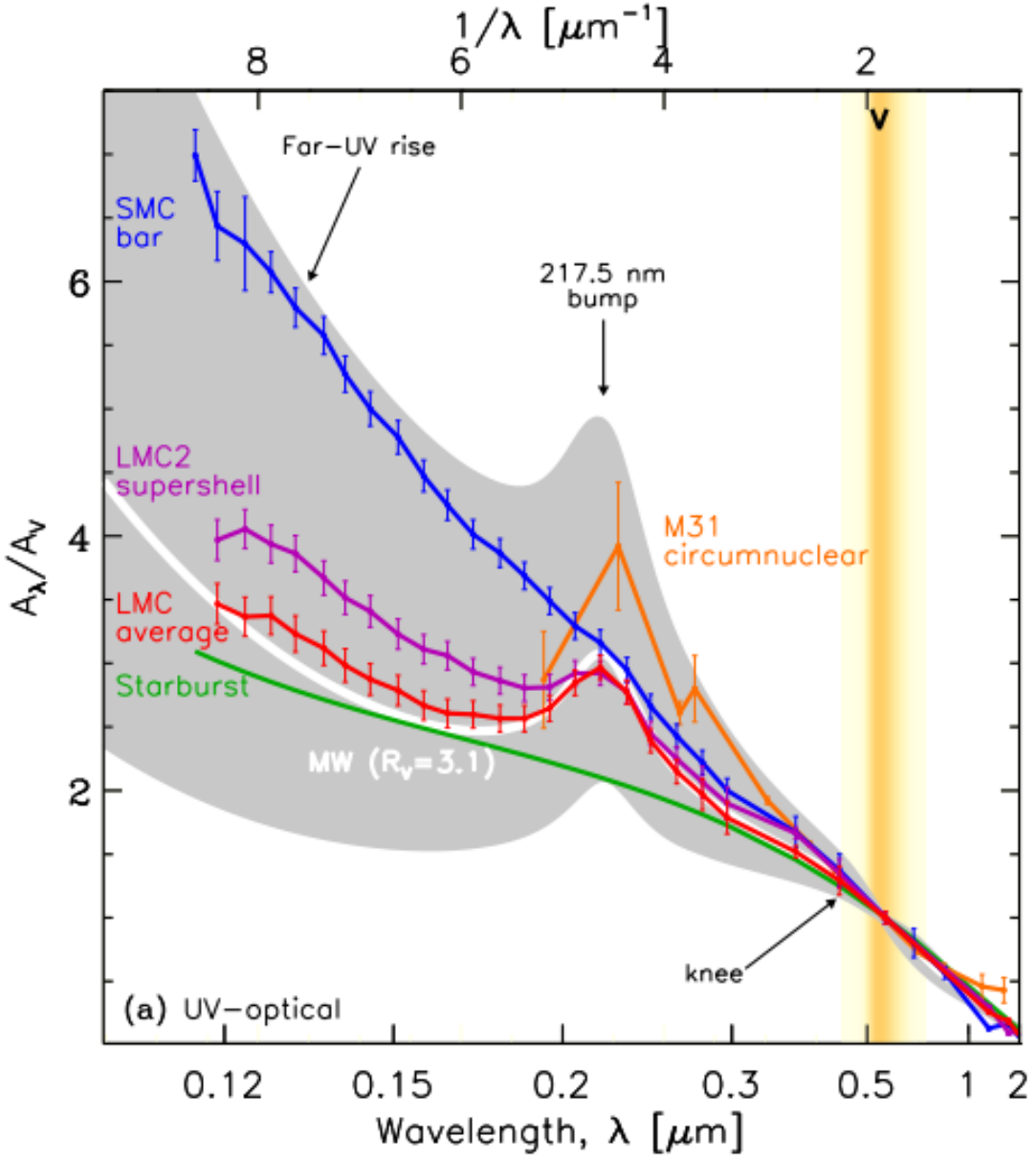





Made with FSPS by Lin Yen-Hsing

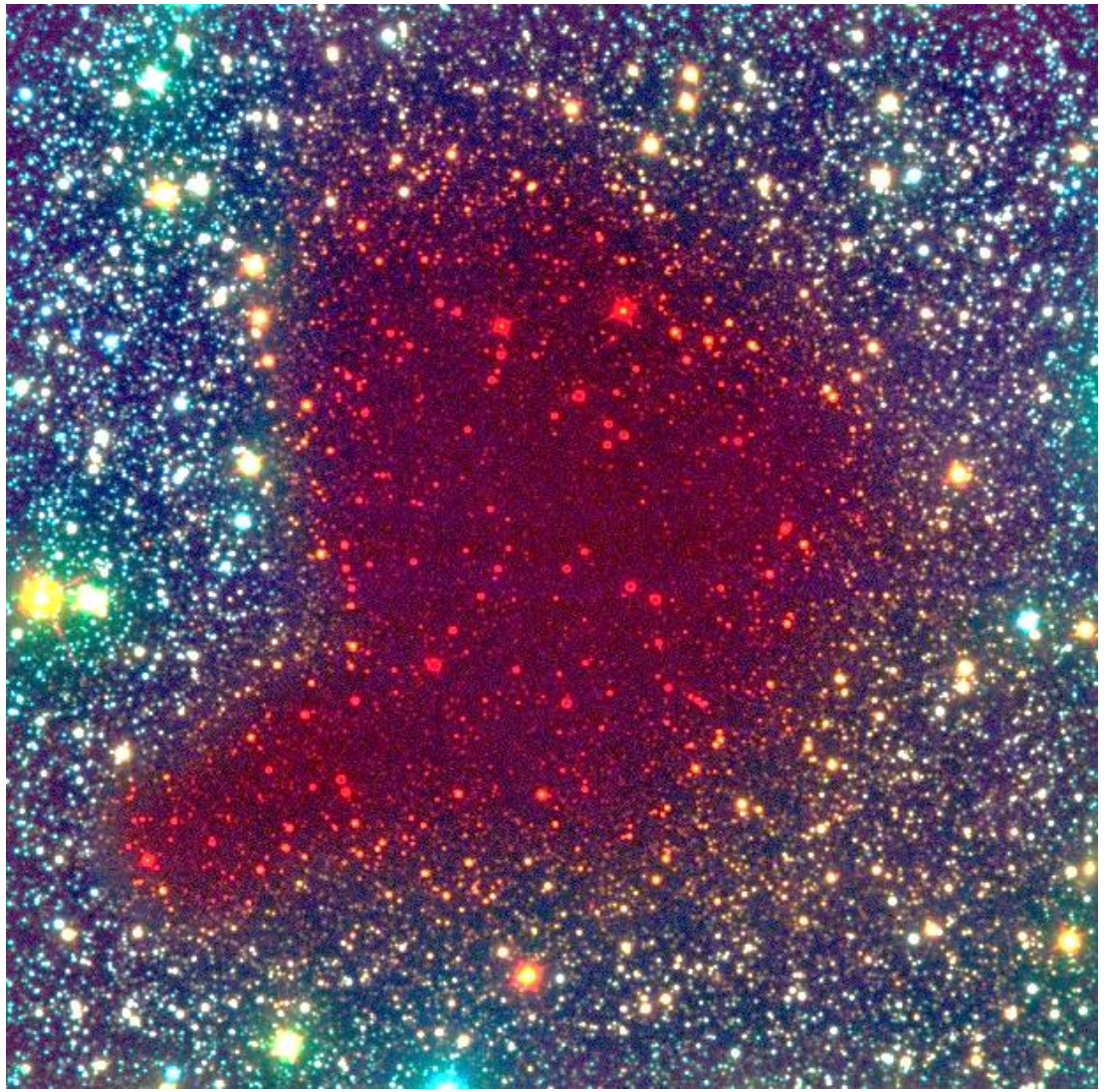
# Extinction

- Dust extinction can be described by Mie theory.
- Given the same amount of dust, short wavelength light (UV) gets extinguish more.
- The wavelength dependence of extinction cross section is called **extinction curve**.



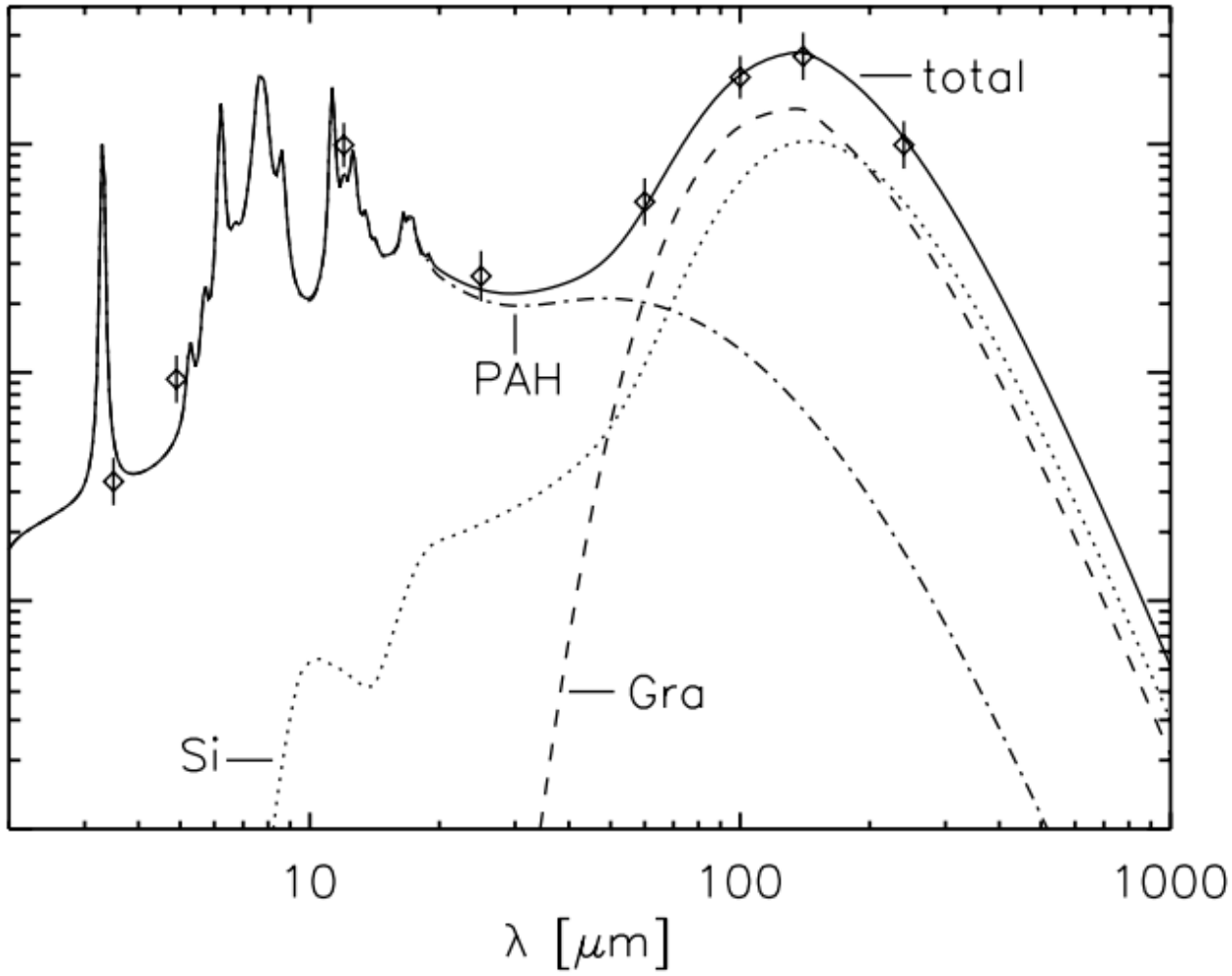
# Extinction and Reddening

- Short wavelength light is more easily extinguished.
- Object behind dust becomes redder → Reddening.
- Therefore, understand dust properties and correct for both **brightness** and **color** is important to correctly understand your target.



# Emission

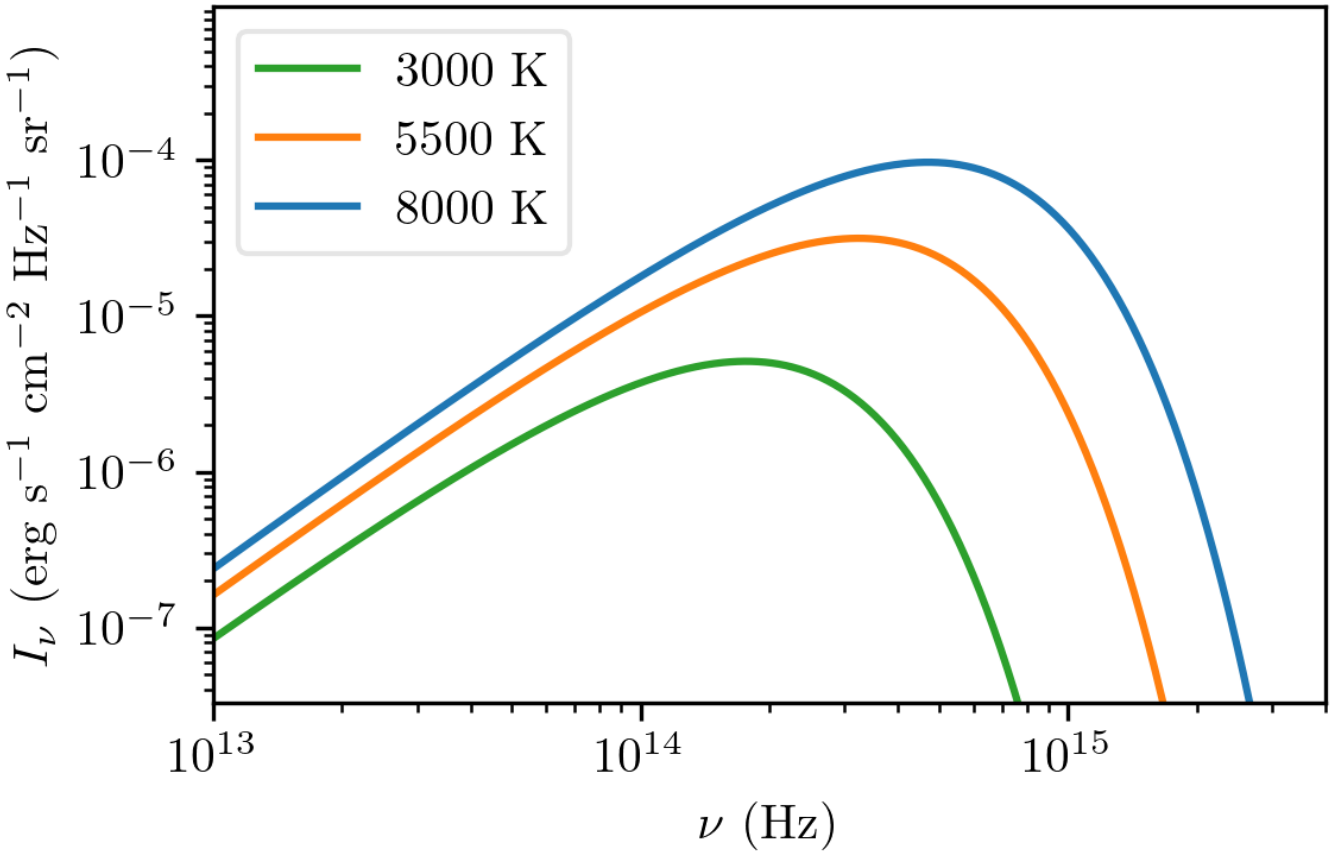
- Dust absorb photons and heat up.
- Heated dust emit the energy with **black body radiation**.
- Large molecule/small dust: **PAHs**, Polycyclic Aromatic Hydrocarbons.
  Creates emission lines in MIR wavelength.



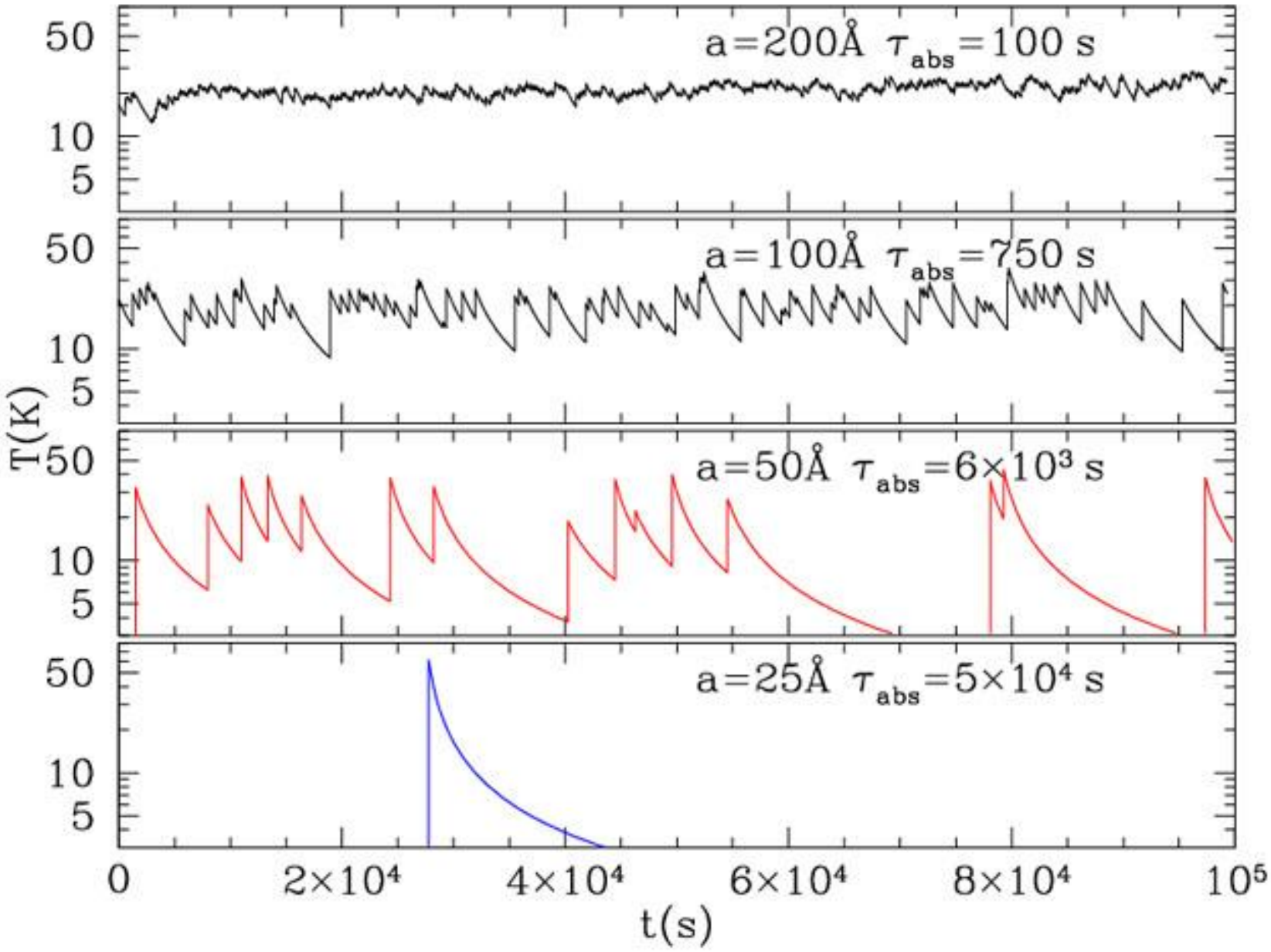

Galliano et al. 2018

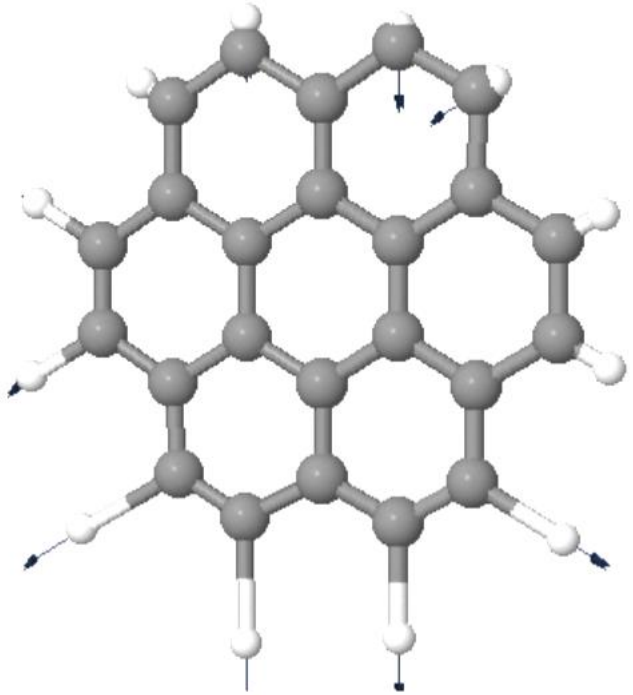
# Black body radiation

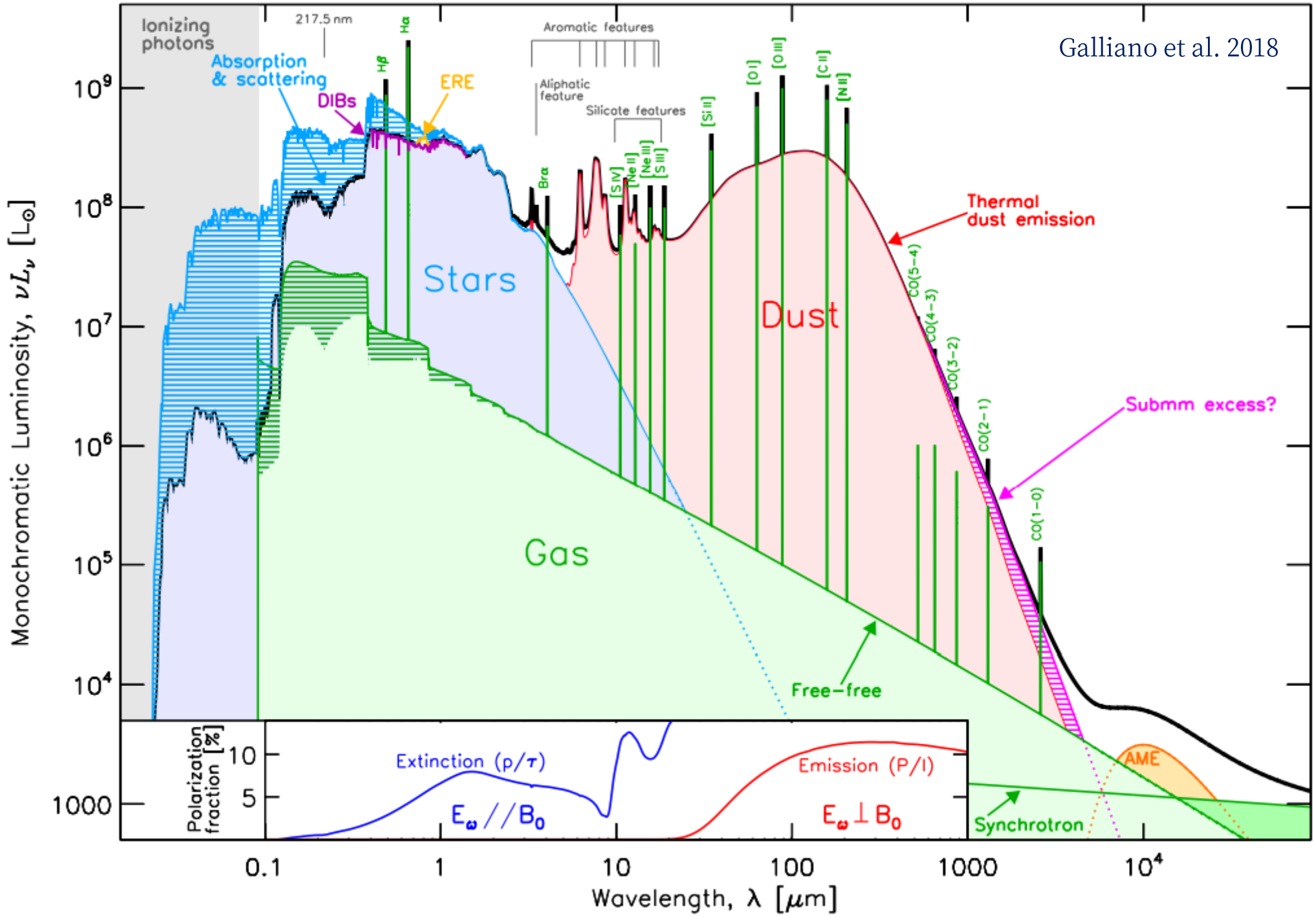
Matter in thermal equilibrium emits radiation with spectrum like this:




$$I_\nu \propto \frac{2h\nu^3}{c^2} \frac{1}{\exp\left(\frac{h\nu}{kT}\right) - 1}$$


a=200Å $\tau_{abs}$=100 s
a=100Å $\tau_{abs}$=750 s
a=50Å $\tau_{abs}$=6×10³ s
a=25Å $\tau_{abs}$=5×10⁴ s
T(K)
50
10
5
0
2×10⁴
4×10⁴
6×10⁴
8×10⁴
10⁵
t(s)




Galliano et al. 2018
Ionizing photons
217.5 nm
Absorption & scattering
DIBs
Hβ
Hα
ERE
Aromatic features
Aliphatic feature
Silicate features
Brα
[Si II]
[O I]
[O III]
[C II]
[N II]
[S IV]
[Ne II]
[Ne III]
[S III]
Stars
Dust
Gas
Thermal dust emission
CO(5–4)
CO(4–3)
CO(3–2)
CO(2–1)
CO(1–0)
Submm excess?
Free–free
Polarization fraction [%]
Extinction (p/τ)
$E_\omega // B_0$
Emission (P/I)
$E_\omega \perp B_0$
AME
Synchrotron
Monochromatic Luminosity, $\nu L_\nu$ [$L_\odot$]
Wavelength, λ [μm]

# Summary: ISM

- Medium between stars, contains **gas** and **dust**.
- Gas: H, He and gas-phase metals / molecules.

  Phase: Corona (HIM), HII (WIM), HI (Neutral Medium), Molecular Cloud.
- Dust: Solid grains and PAHs, eat UV/Optical and emit FIR/Submm.
- Radiative processes:
  - Free-free
  - Electron orbital / electron spin / rotational / vibrational transition
  - Black body radiation