Interstellar Medium (ISM)

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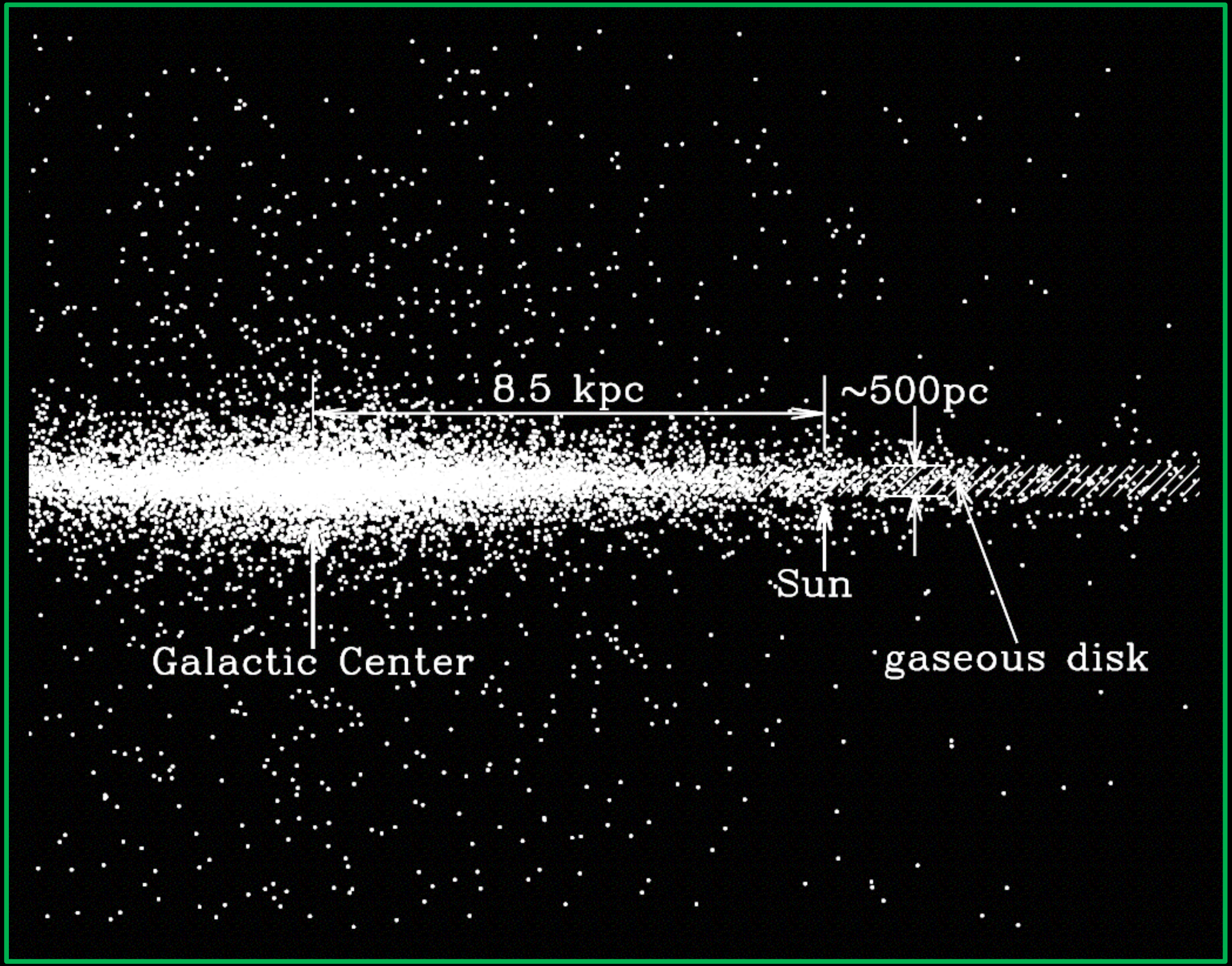
ASIAA summer student program

Interstellar medium is everything not in stars

- Galaxies are made of stars…

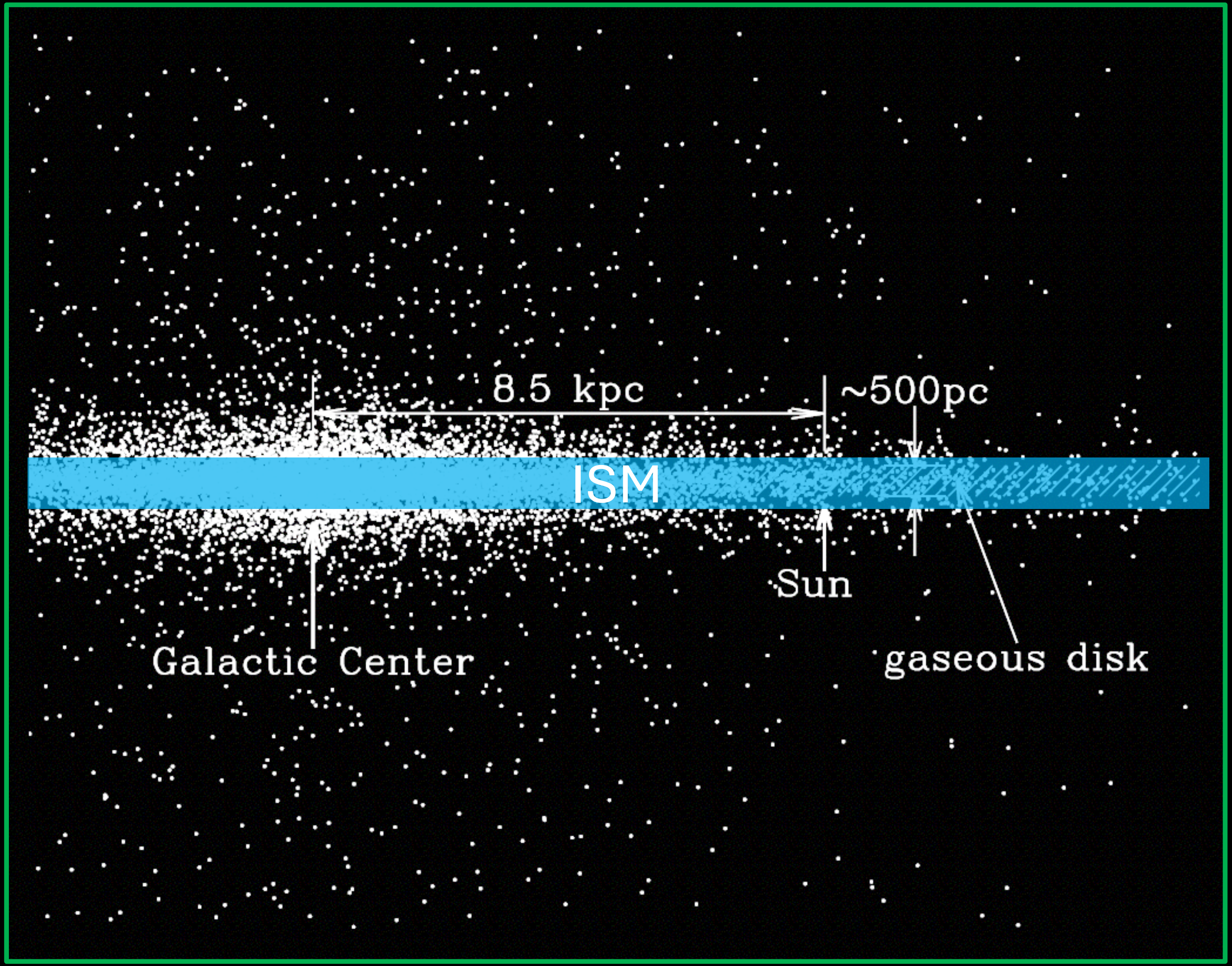


Interstellar medium is everything not in stars

- Galaxies are made of stars…

  AND the interstellar medium!

- The ISM is a mixture of gas, dust, and radiation distributed between the stars in a galaxy.

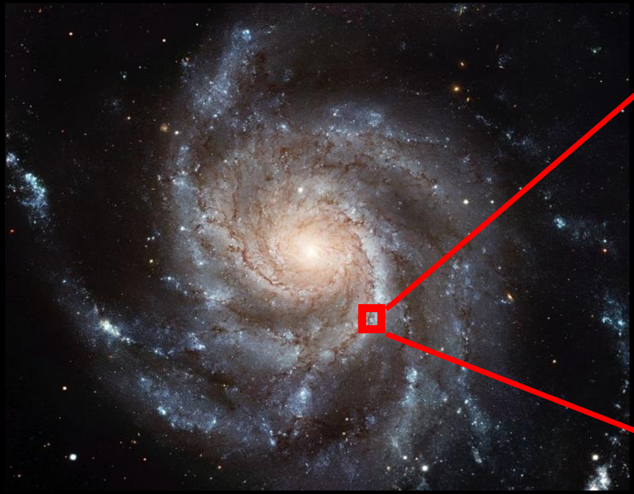


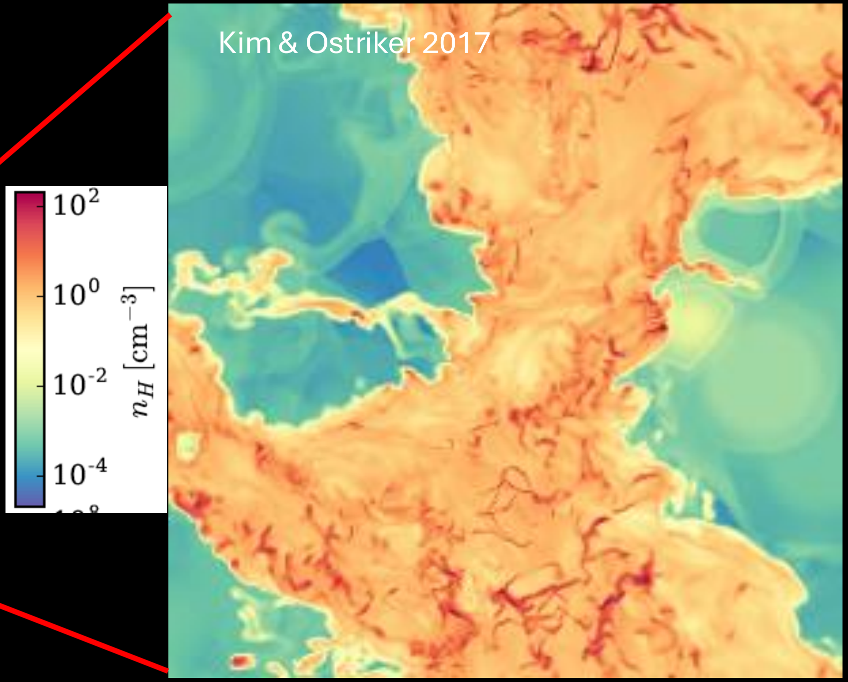
The Multiphase ISM

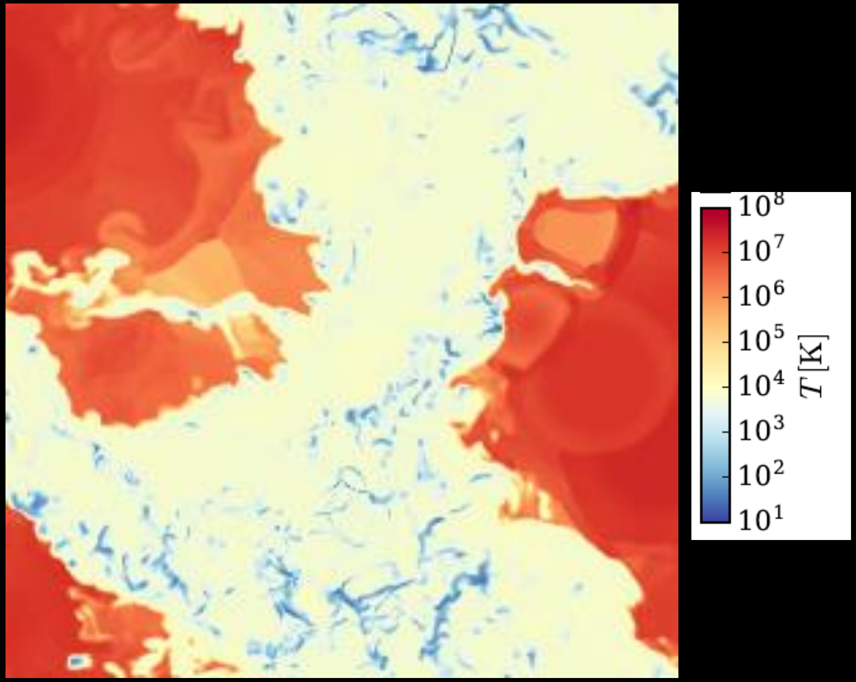
Five phases of ISM:

1. Warm neutral medium (WNM)
2. Cold neutral medium (CNM)
3. Hot ionized medium (HIM)
4. Warm ionized medium (WIM)
5. Molecular cloud (MC)

	MM	CNM	WNM	WIM	HIM
n (cm^{-3})	10^2 – 10^5	4–80	0.1–0.6	≈0.2 cm^{-3}	10^{-3}–10^{-2}
T (K)	10–50	50–200	5500–8500	≈8000	10^5–10^7
h (pc)	≈ 70	≈140	≈400	≈900	≥1 kpc
f_{volume}	< 1%	≈2–4%	≈30%	≈20%	≈50%
f_{mass}	≈20%	≈40%	≈30%	≈10%	≈1%



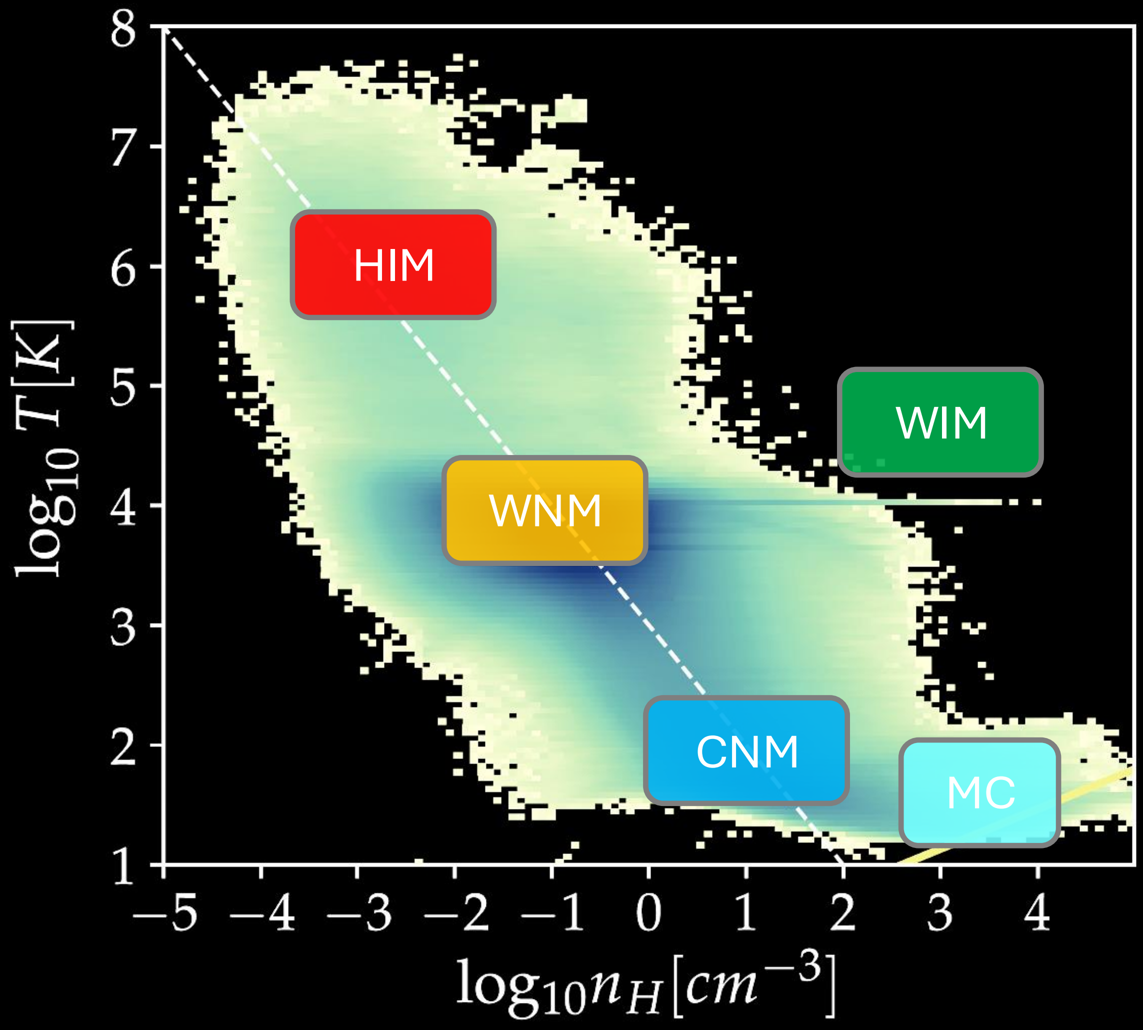




Multiphase ISM on a phase diagram

- The CNM, WNM, and HIM are roughly in **pressure equilibrium** (nT = constant).
  -> the classical three-phase ISM model

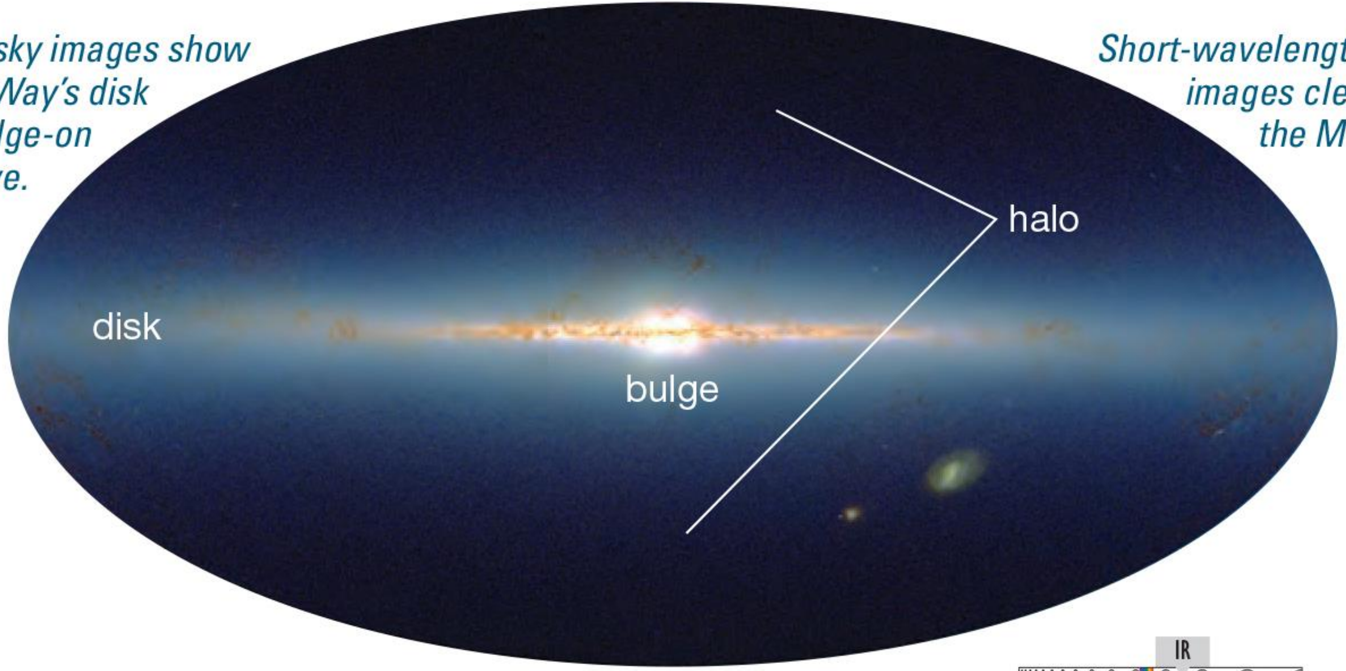
- MC and WIM are over-pressurized.



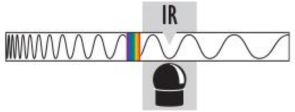
JWST Image of a nearby spiral galaxy (M74)

These all-sky images show the Milky Way's disk from an edge-on perspective.

Short-wavelength infrared images clearly show the Milky Way's starlight.

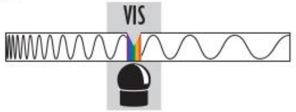


infrared (short wavelength)

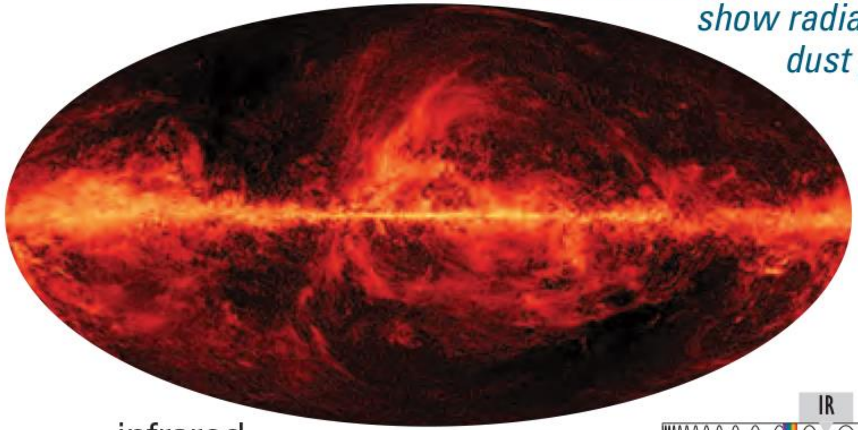


Dusty clouds in the disk block much of our galaxy's visible starlight.

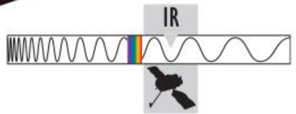
visible light



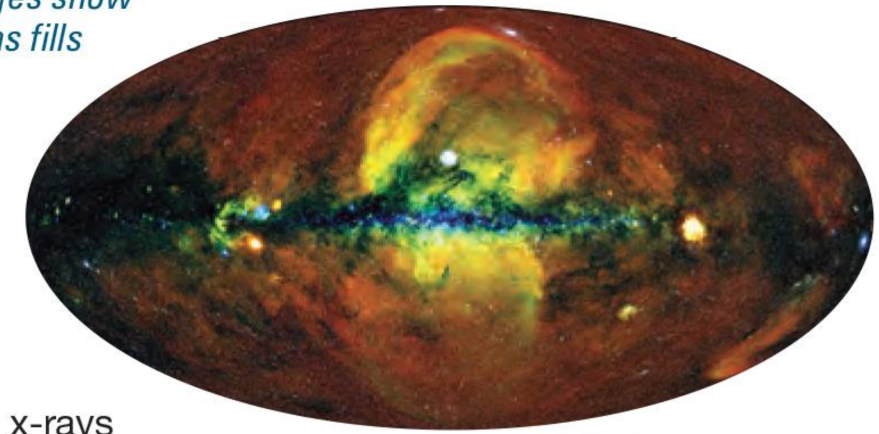
Long-wavelength infrared images show radiation from dust particles.



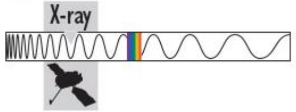
infrared (long wavelength)



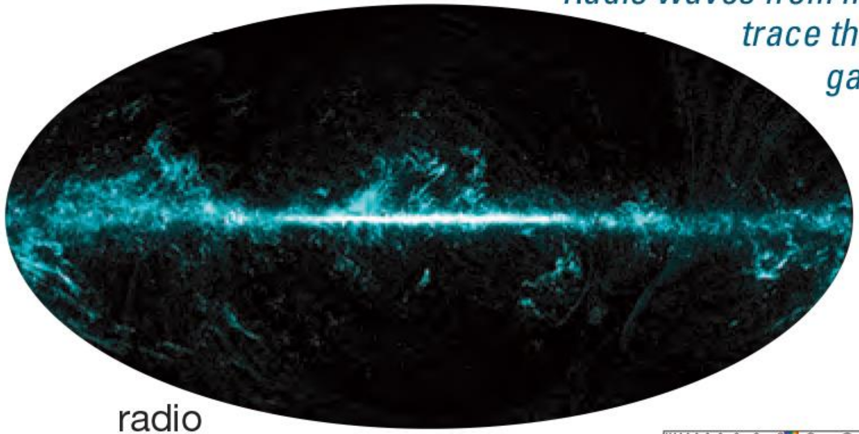
X-ray images show that hot gas fills the halo.



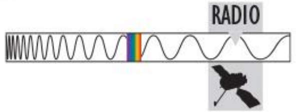
x-rays



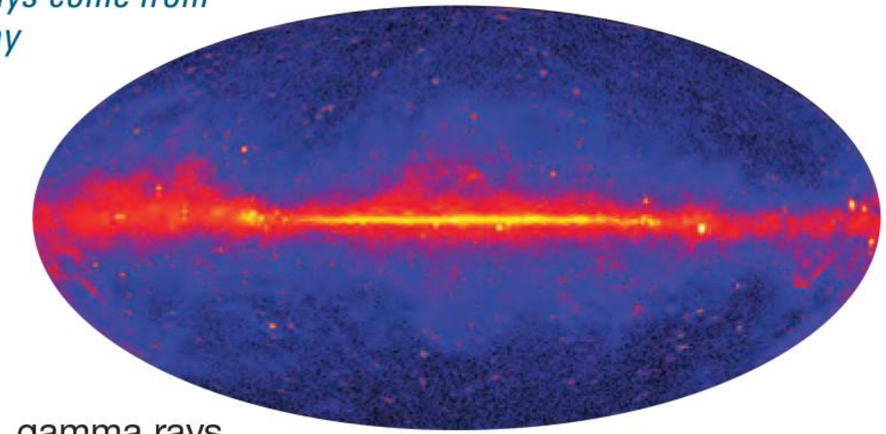
Radio waves from molecules trace the coldest gas clouds.



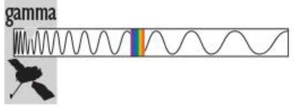
radio
(CO molecules)



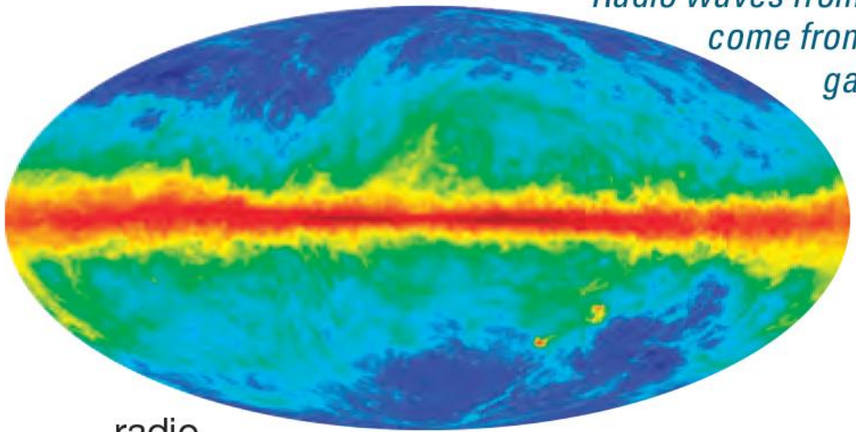
Gamma rays come from cosmic-ray collisions with gas atoms.



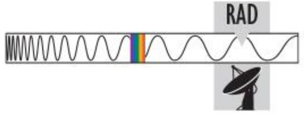
gamma rays



Radio waves from H atoms come from warmer gas clouds.



radio
(H atoms)



Each oval image shows the entire sky in the same way this world map shows the surface of a globe.

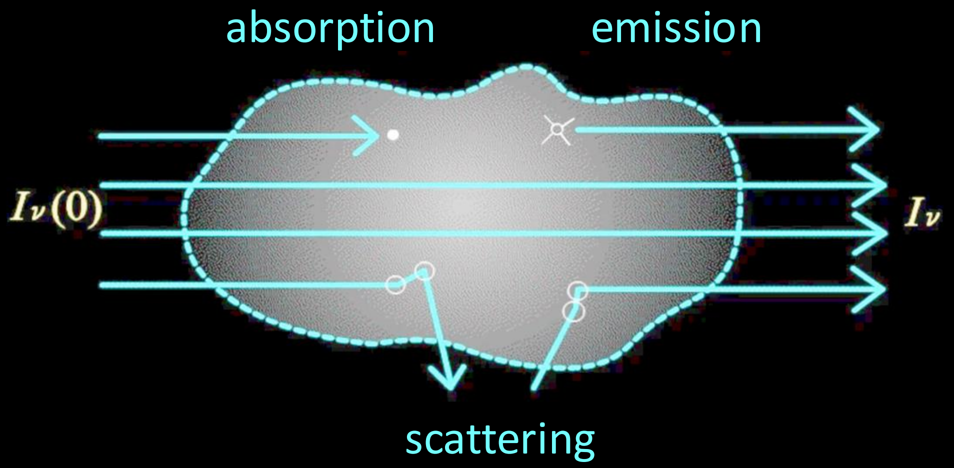
Crash Course on Radiative Transfer

Equation of radiative transfer (RT): $$\frac{dI_\nu}{ds} = -\alpha_\nu I_\nu + j_\nu$$

absorption coefficient:

$$\alpha_\nu = n\sigma_\nu = \rho\kappa_\nu$$

emissivity



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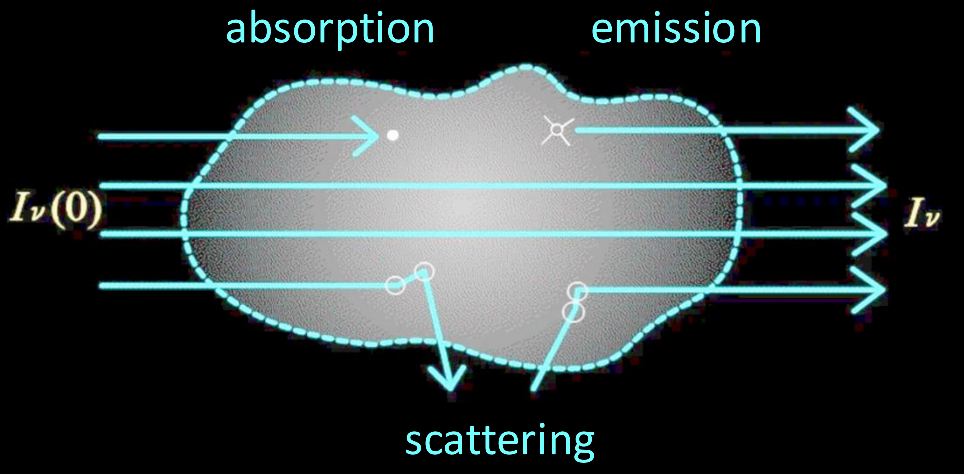

Define optical depth: $$\tau_\nu(s) = \int_{s_0}^{s} \alpha_\nu(s')ds'$$

$\tau_\nu \ll 1$ optically thin

$\tau_\nu \gg 1$ optically thick

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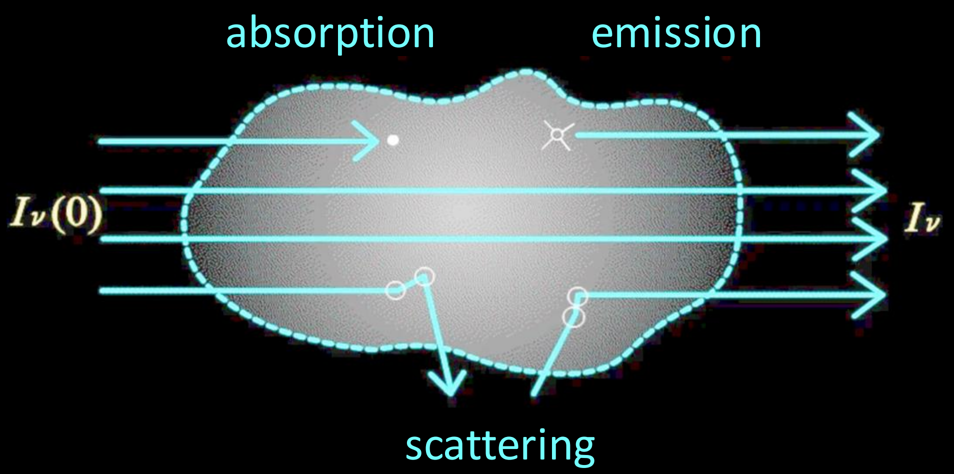

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Rewrite RT equation as: $$\frac{dI_\nu}{d\tau_\nu} = -I_\nu + S_\nu$$, where $S_\nu = \frac{j_\nu}{\alpha_\nu}$ is the source function

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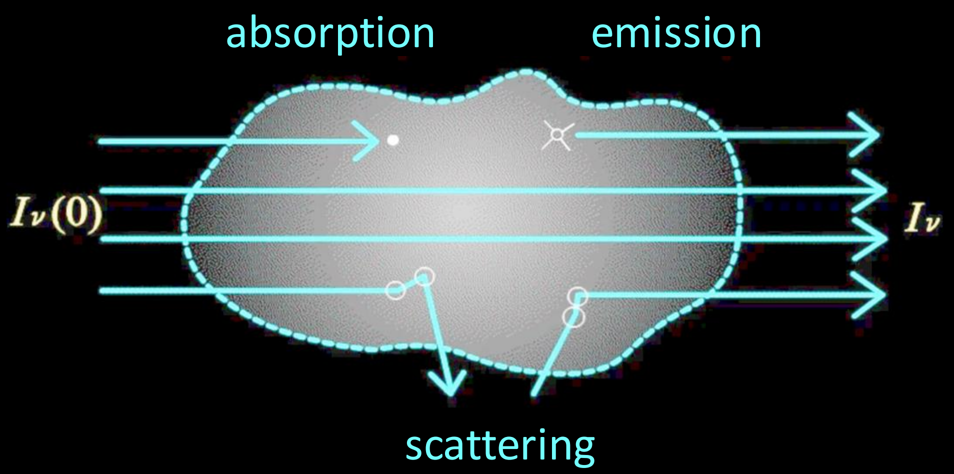

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Rewrite RT equation as: $\frac{dI_\nu}{d\tau_\nu} = -I_\nu + S_\nu$, where $S_\nu = \frac{j_\nu}{\alpha_\nu}$ is the source function

If $S_\nu = \text{const.}$ $\Rightarrow I_\nu(\tau_\nu) = I_\nu(0)e^{-\tau_\nu} + S_\nu(1 - e^{-\tau_\nu})$

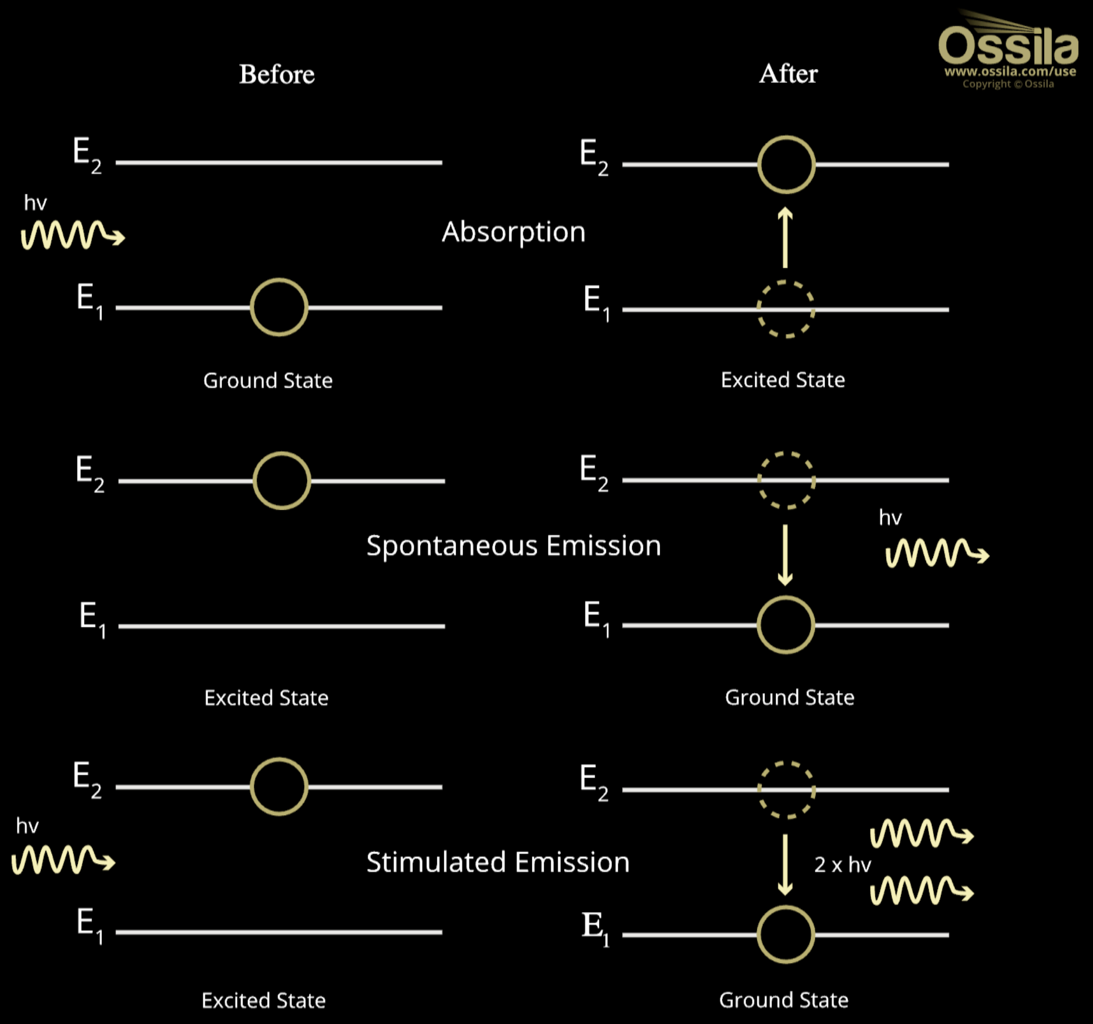
Einstein AB Coefficients

$$J_\nu = \frac{1}{4\pi}\int I_\nu d\Omega$$

- Consider a two-level system at local thermodynamic equilibrium (LTE):

$$\frac{dn_2}{dt} = 0 = -n_2 A_{21} - n_2 B_{21} J_\nu + n_1 B_{12} J_\nu$$

$$\Rightarrow J_\nu = \frac{A_{21}/B_{21}}{n_1 B_{12}/n_2 B_{21} - 1}$$



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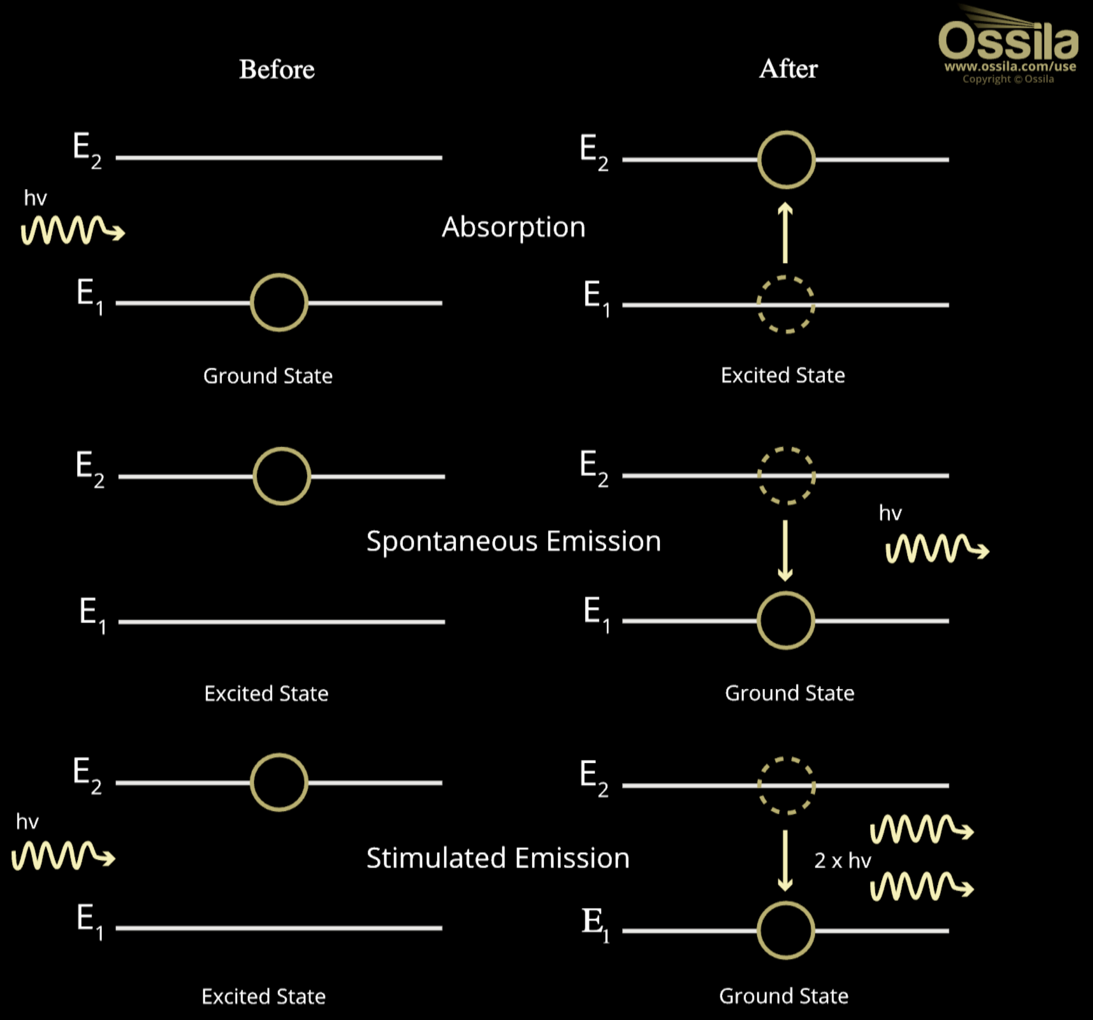
$$J_\nu = B_\nu(T) = \frac{2h\nu^3}{c^2}\frac{1}{e^{h\nu/kT} - 1}$$

$$\frac{n_1}{n_2} = \frac{g_1}{g_2}e^{h\nu/kT}$$

at LTE



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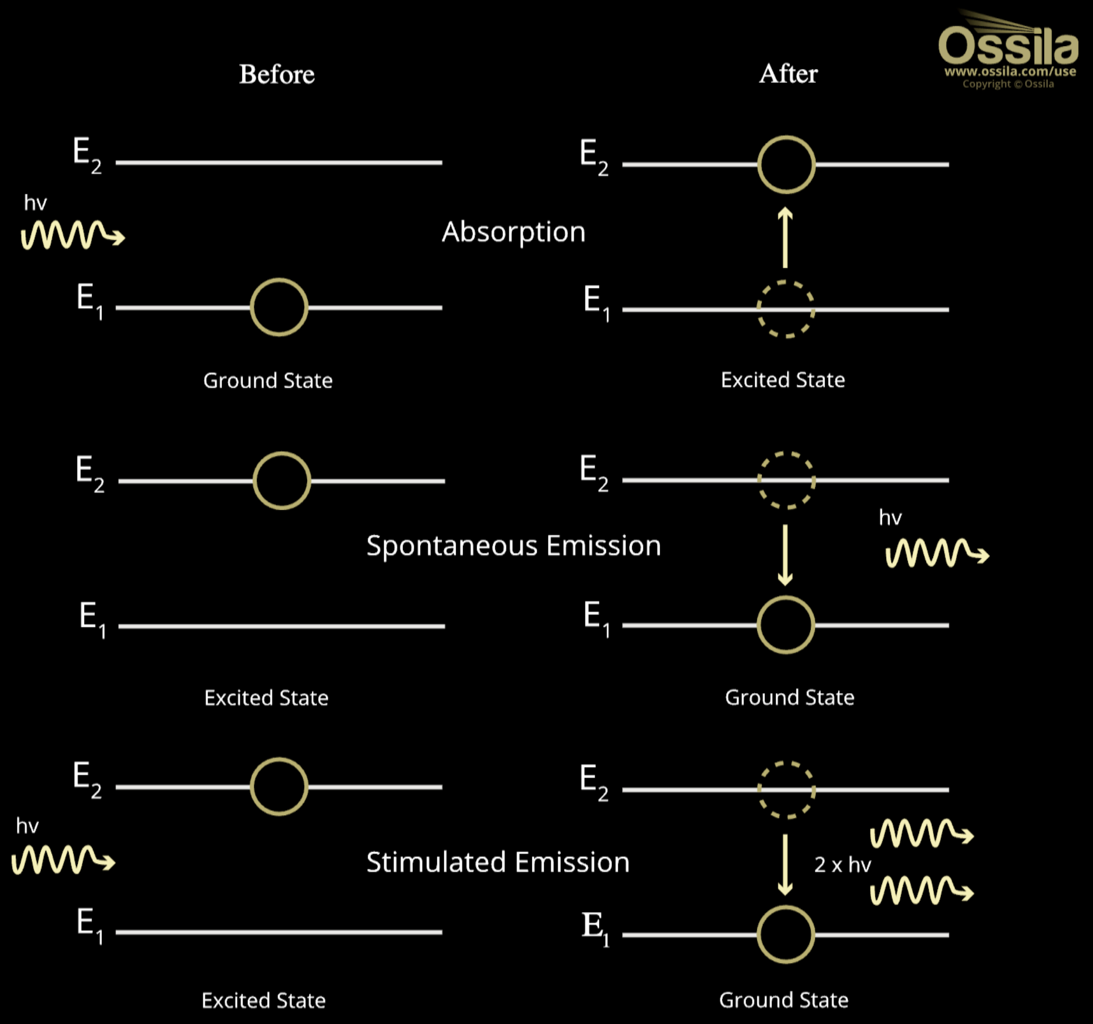
at LTE

$$\text{If } h\nu/kT \ll 1 \quad \Rightarrow \quad \frac{g_1}{g_2} B_{12} = B_{21}$$

$$\text{If } h\nu/kT \gg 1 \quad \Rightarrow \quad \frac{A_{21}}{B_{21}} = \frac{2h\nu^3}{c^2}$$

Einstein relation

only need to know one of the three (usually A_{21})



Line Radiative Transfer

We can define the photon occupation number $\langle n_\gamma \rangle = \frac{c^2}{2h\nu^3} J_\nu$ such that

$$\left(\frac{dn_1}{dt}\right)_{2\to 1} = n_2 A_{21}(1 + \boxed{\langle n_\gamma \rangle})$$ and

When $\langle n_\gamma \rangle \ll 1$, stimulated emission can be neglected!

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Absorption and emission in radiative transfer is controlled microscopically by the level population (n_1, n_2):

$$j_\nu = \frac{h\nu}{4\pi} n_2 A_{21} \phi(\nu)$$

$$\alpha_\nu = \frac{h\nu}{4\pi}(n_1 B_{12} - n_2 B_{21})\phi(\nu)$$

$$= \frac{h\nu}{4\pi} n_1 B_{12}(1 - \frac{n_2 g_1}{n_1 g_2})\phi(\nu)$$

$$= \frac{h\nu}{4\pi} n_1 B_{12}(1 - e^{-h\nu/kT})\phi(\nu)$$ at LTE

“Temperatures” in Astronomy

Brightness temperature (T_B):

$$B_\nu(T_B) = \frac{2h\nu^3}{c^2}\frac{1}{e^{h\nu/kT_B} - 1} = I_\nu$$

Antenna temperature (T_A):

$$T_A(\nu) \equiv \frac{c^2}{2k\nu^2} I_\nu$$

$T_B = T_A$ in the Rayleigh-Jeans limit

Excitation temperature ($T_{\rm exc}$):

$$\frac{n_u}{n_\ell} \equiv \frac{g_u}{g_\ell} \mathrm{e}^{-E_{u\ell}/kT_{\rm exc}}$$

Collisional Excitation

In the absence of external radiation (no absorption or stimulated emission), level population is controlled by collision:

$$\frac{dn_1}{dt} = \boxed{n_c n_0 k_{01}} - \boxed{n_c n_1 k_{10}} - \boxed{n_1 A_{10}} = 0$$

collisional excitation

collisional de-excitation

spontaneous decay

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collisional excitation

collisional de-excitation

spontaneous decay

From detailed balance: $k_{01} = \frac{g_1}{g_0} k_{10} e^{-E_{10}/kT}$

$$\Rightarrow \boxed{\frac{n_1}{n_0} = \frac{1}{1 + \frac{A_{10}}{n_c k_{10}}} \frac{g_1}{g_0} e^{-E_{10}/kT}}$$

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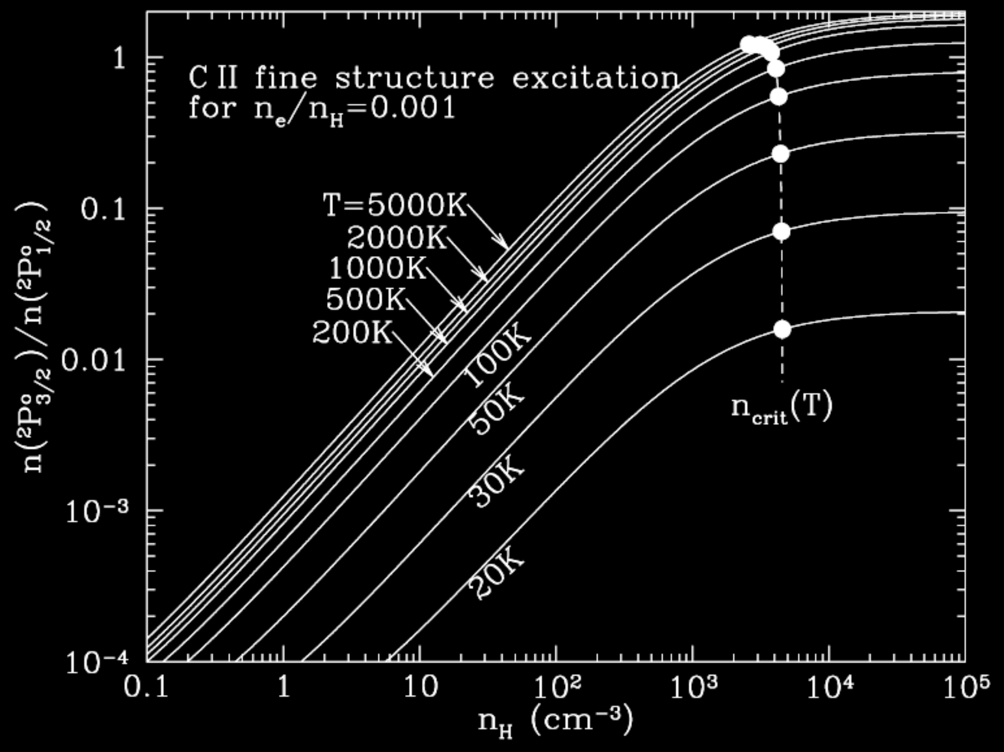
collisional excitation — collisional de-excitation — spontaneous decay

From detailed balance: $k_{01} = \frac{g_1}{g_0} k_{10} e^{-E_{10}/kT}$

$$\Rightarrow \boxed{\frac{n_1}{n_0} = \frac{1}{1 + \frac{A_{10}}{n_c k_{10}}} \frac{g_1}{g_0} e^{-E_{10}/kT}}$$

Define critical density: $\boxed{n_{\rm crit} \equiv \frac{A_{10}}{k_{10}}}$

If $n_c \gg n_{\rm crit} \Rightarrow \frac{n_1}{n_0} = \frac{g_1}{g_0} e^{-E_{10}/kT}$ Boltzmann distribution!



Collisional Excitation

When there is **external radiation** (need to including absorption and stimulated emission):

$$\frac{dn_1}{dt} = n_0 \left[n_c k_{01} + \langle n_\gamma \rangle \frac{g_1}{g_0} A_{10} \right] - n_1 \left[n_c k_{10} + (1 + \langle n_\gamma \rangle) A_{10} \right] = 0$$

- $n_c k_{01}$: collisional excitation
- $\langle n_\gamma \rangle \frac{g_1}{g_0} A_{10}$: absorption
- $n_c k_{10}$: collisional de-excitation
- 1: spontaneous decay
- $\langle n_\gamma \rangle$: stimulated emission

Collisional Excitation

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spontaneous decay: 1

collisional excitation: $n_c k_{01}$

absorption: $\langle n_\gamma \rangle \frac{g_1}{g_0} A_{10}$

collisional de-excitation: $n_c k_{10}$

stimulated emission: $\langle n_\gamma \rangle) A_{10}$

Collisional Excitation

When there is **external radiation** (need to including absorption and stimulated emission):

$$\frac{dn_1}{dt} = n_0 \left[n_c k_{01} + \langle n_\gamma \rangle \frac{g_1}{g_0} A_{10} \right] - n_1 \left[n_c k_{10} + (1 + \langle n_\gamma \rangle) A_{10} \right] = 0 \Rightarrow \frac{n_1}{n_0} = \frac{n_c k_{01} + \langle n_\gamma \rangle \frac{g_1}{g_0} A_{10}}{n_c k_{10} + (1 + \langle n_\gamma \rangle) A_{10}}$$

spontaneous decay: 1 (in $(1 + \langle n_\gamma \rangle) A_{10}$)

collisional excitation: $n_c k_{01}$

absorption: $\langle n_\gamma \rangle \frac{g_1}{g_0} A_{10}$

collisional de-excitation: $n_c k_{10}$

stimulated emission: $\langle n_\gamma \rangle) A_{10}$

Using

$$\begin{cases} k_{01} = \frac{g_1}{g_0} k_{10} e^{-E_{10}/kT} \\ \langle n_\gamma \rangle = \frac{1}{e^{h\nu/kT_B} - 1} \end{cases}$$

$$\Rightarrow \frac{n_1}{n_0} = \frac{1}{1 + \frac{n_c}{n}} \frac{g_1}{g_0} e^{-E_{10}/kT} + \frac{1}{1 + \frac{n}{n_c}} \frac{g_1}{g_0} e^{-E_{10}/kT_B}$$

Collisional Excitation

When there is **external radiation** (need to including absorption and stimulated emission):

$$\frac{dn_1}{dt} = n_0\left[n_c k_{01} + \langle n_\gamma\rangle \frac{g_1}{g_0} A_{10}\right] - n_1\left[n_c k_{10} + (1 + \langle n_\gamma\rangle) A_{10}\right] = 0 \quad \Rightarrow \frac{n_1}{n_0} = \frac{n_c k_{01} + \langle n_\gamma\rangle \frac{g_1}{g_0} A_{10}}{n_c k_{10} + (1 + \langle n_\gamma\rangle) A_{10}}$$

collisional excitation ($n_c k_{01}$); absorption ($\langle n_\gamma\rangle \frac{g_1}{g_0} A_{10}$); collisional de-excitation ($n_c k_{10}$); spontaneous decay (1); stimulated emission ($\langle n_\gamma\rangle A_{10}$)

Using
$$\begin{cases} k_{01} = \dfrac{g_1}{g_0} k_{10} e^{-E_{10}/kT} \\ \langle n_\gamma\rangle = \dfrac{1}{e^{h\nu/kT_B} - 1} \end{cases}$$

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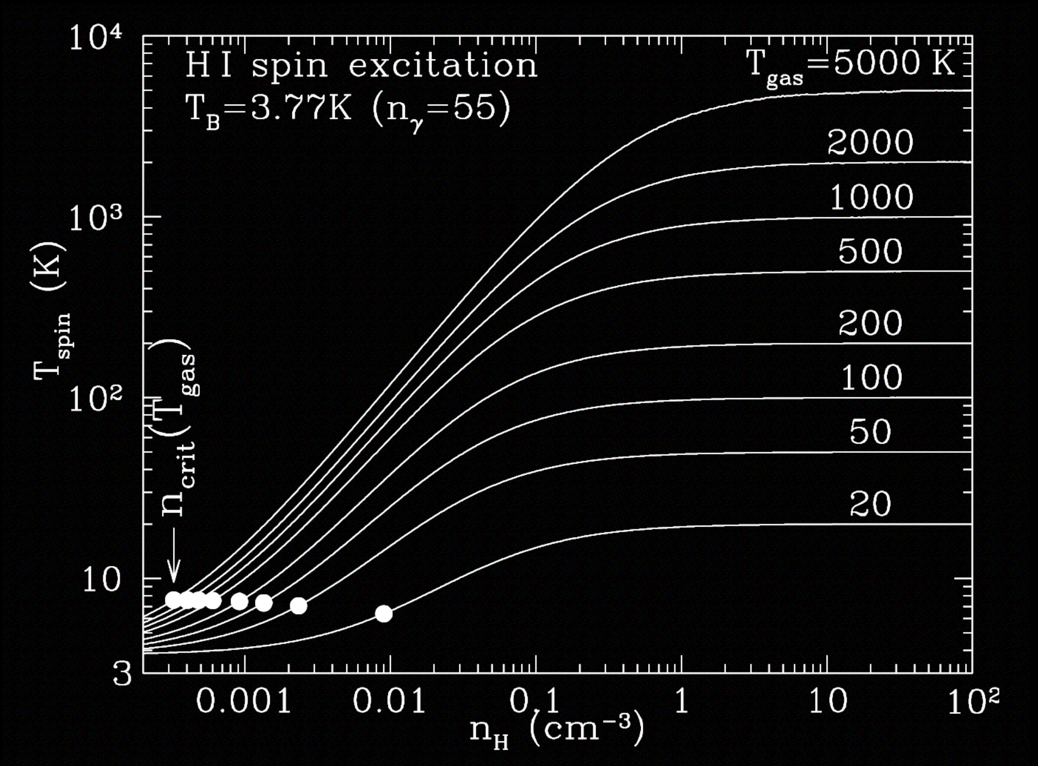
Critical density becomes: $n_{\rm crit} \equiv (1 + \langle n_\gamma\rangle) \frac{A_{10}}{k_{10}}$

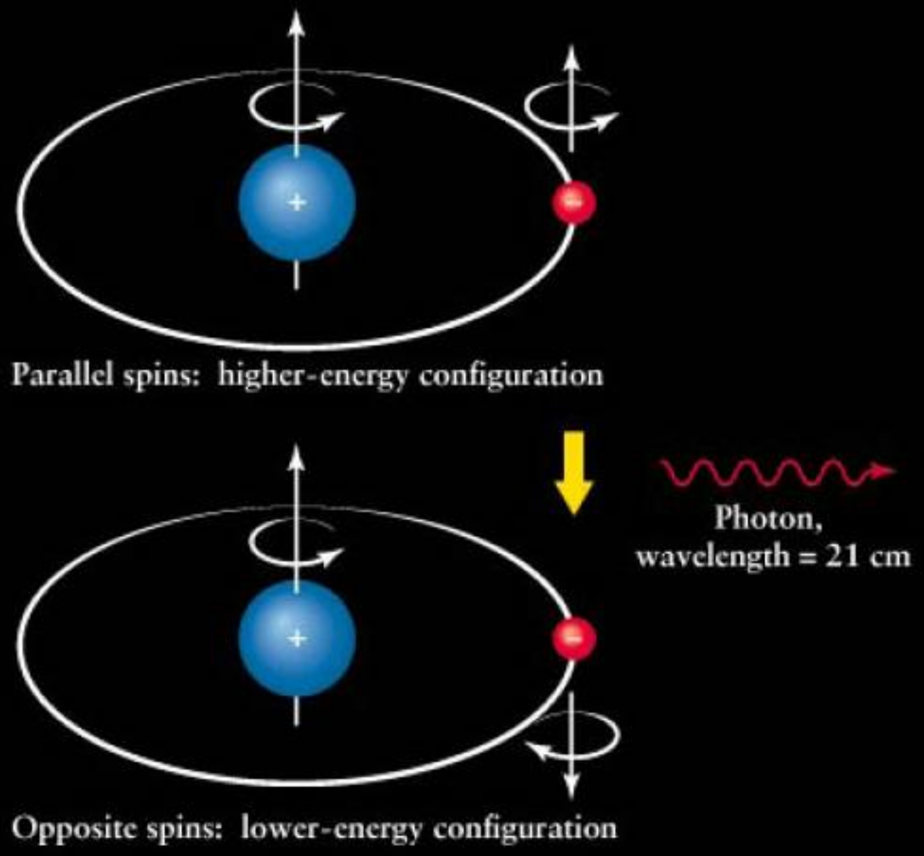
If $n_c \ll n_{\rm crit}$ $\Rightarrow$ radiation dominates $\Rightarrow$ Boltzmann distribution at T_B

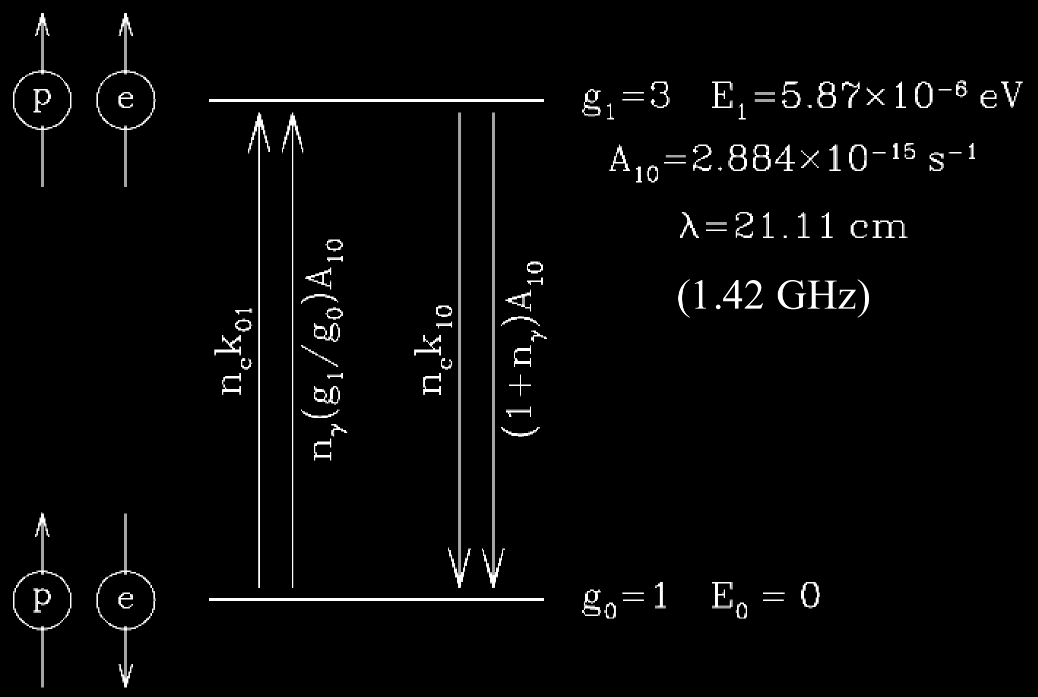
If $n_c \gg n_{\rm crit}$ $\Rightarrow$ collision dominates $\Rightarrow$ Boltzmann distribution at T



Neutral Gas (HI)

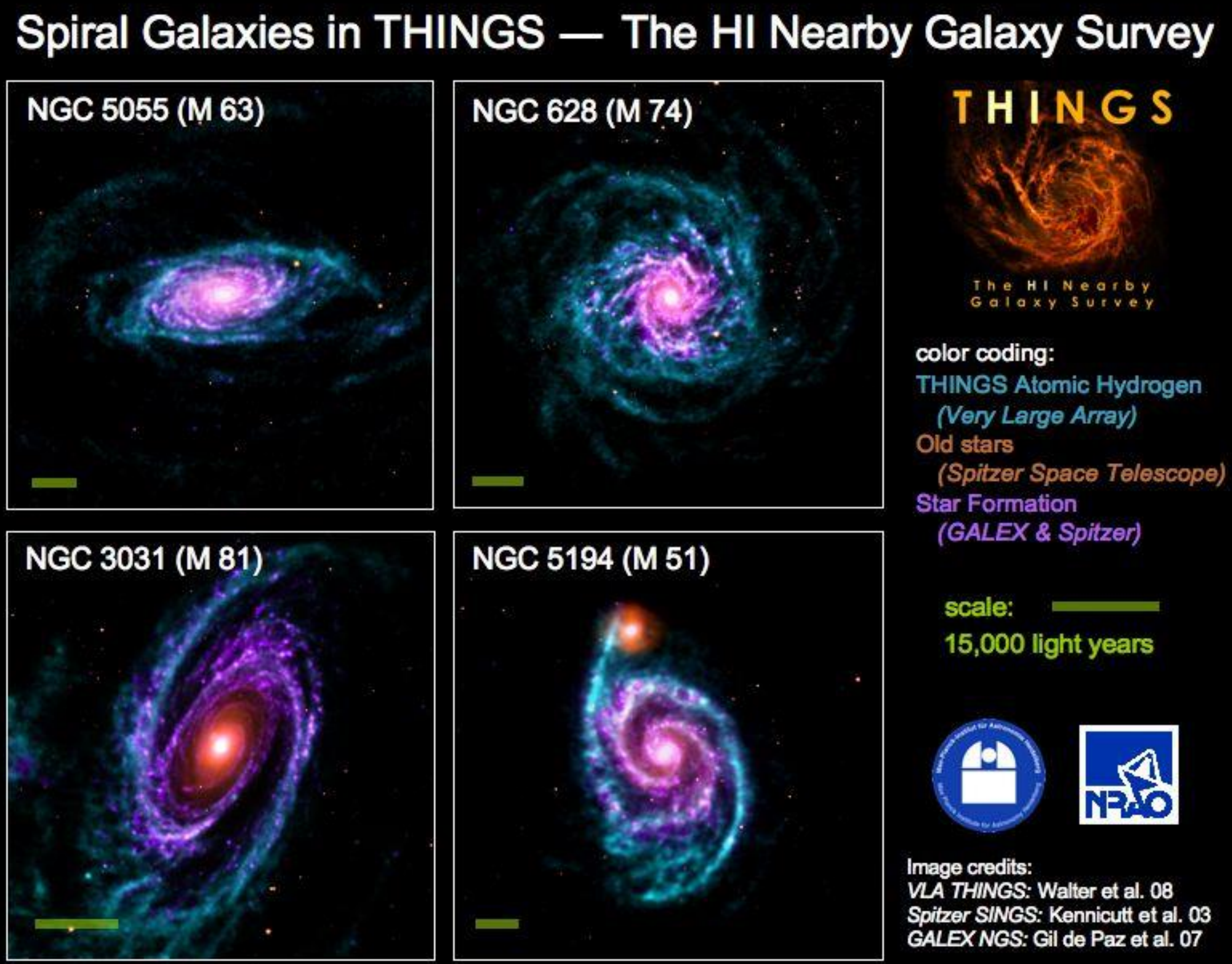
- Neutral atomic hydrogen gas (HI)
- Main tracer: the 21 cm line





Spatially Extended HI Disks

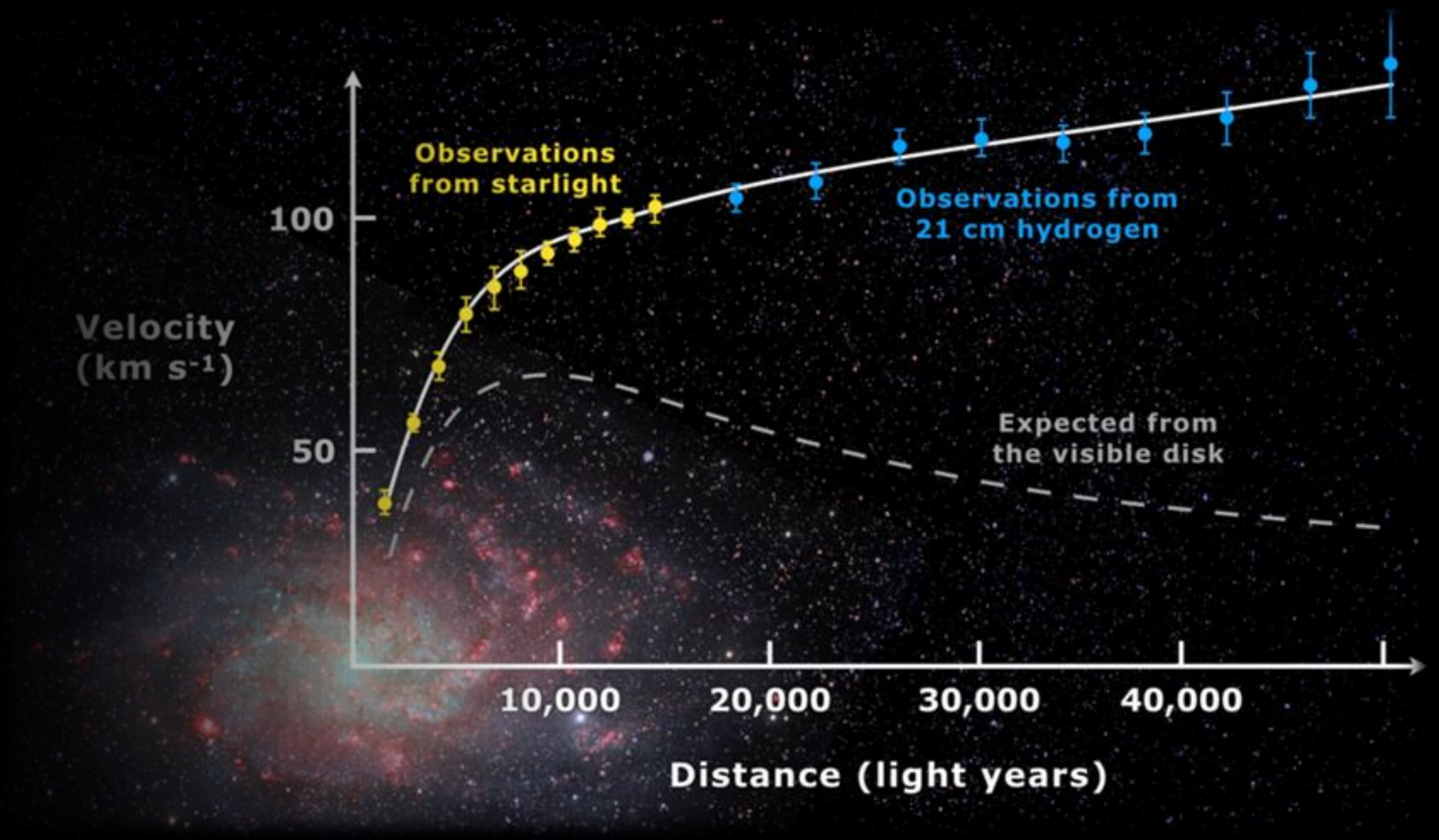
- The atomic gas is typically much more extended than the stellar disk in spiral galaxies .



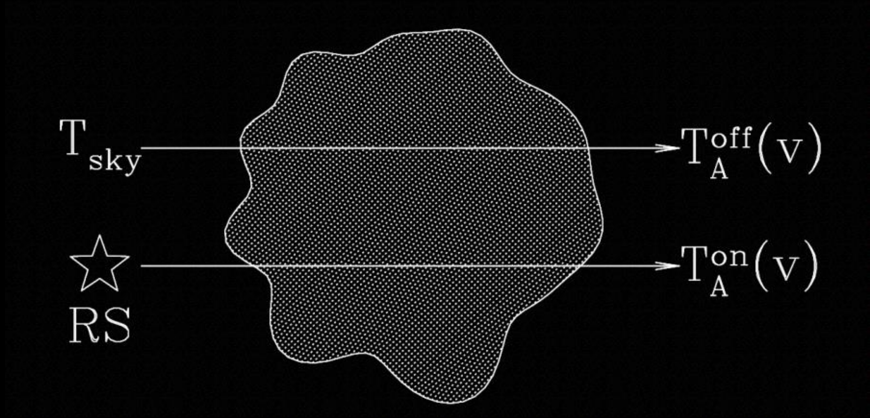
- Rotation velocity $v = \sqrt{\frac{GM}{r}}$, so by measuring the rotation velocity we can infer the underlying mass of the galaxy

Rotation Curves in 21 cm

- The 21 cm line allows for direct measurement of gas mass and rotation curves out to large radii, probing the dark matter.



Observational Evidence of the Two-phase ISM



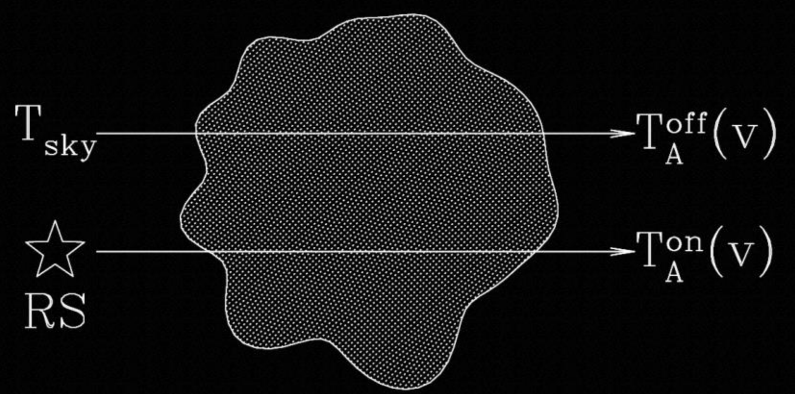
Observing 21 cm lines on and off a background source.

$$\alpha_\nu = \frac{h\nu}{4\pi} n_1 B_{12}(1 - e^{-h\nu/kT})\phi(\nu)$$

$$\approx \frac{3}{32\pi} A_{u\ell} \frac{hc\lambda_{u\ell}}{kT_{\rm spin}} n(\rm H\,I)\,\phi_\nu \propto \boxed{1/T_{\rm spin}}$$

absorption is more efficient in cold gas!

Observational Evidence of the Two-phase ISM



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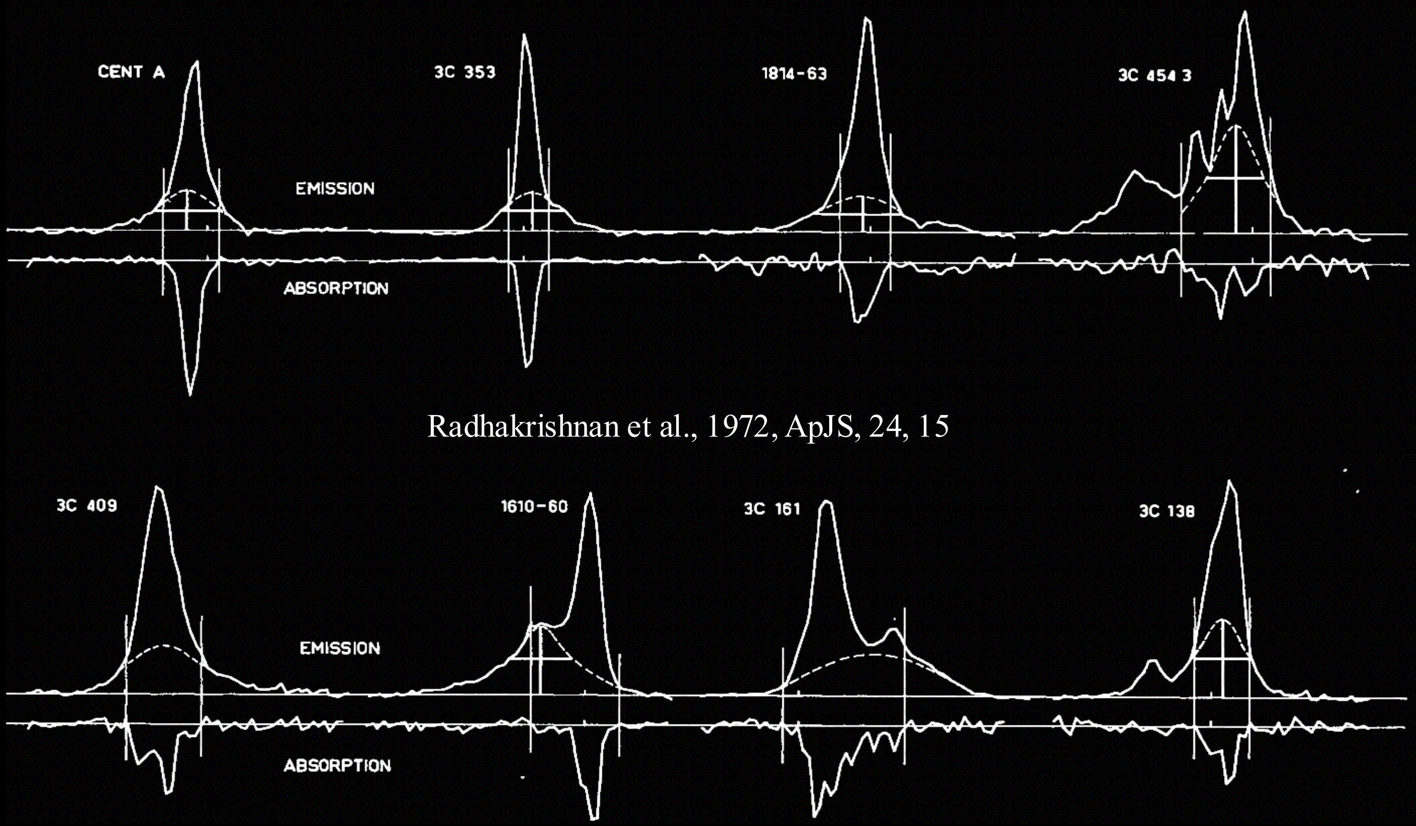


Radhakrishnan et al., 1972, ApJS, 24, 15

Emission is observed along every sightline,

but absorption is not.

=> discrete CNM clouds (absorption) +

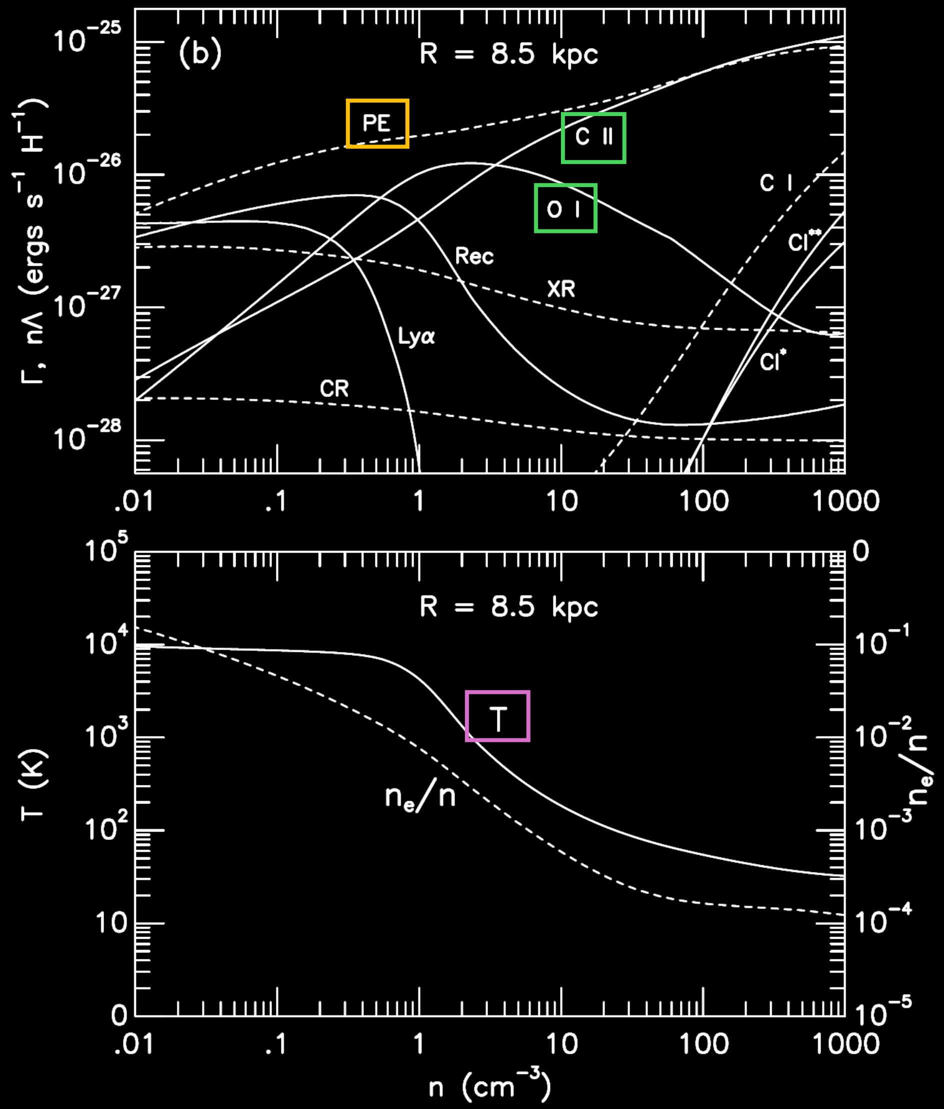
diffuse intercloud WNM (emission)!

Heating and Cooling Processes in the Neutral Gas

- Main heating processes:
  - FUV photoelectric effect on dust
  - cosmic ray ionization
  - X-ray ionization

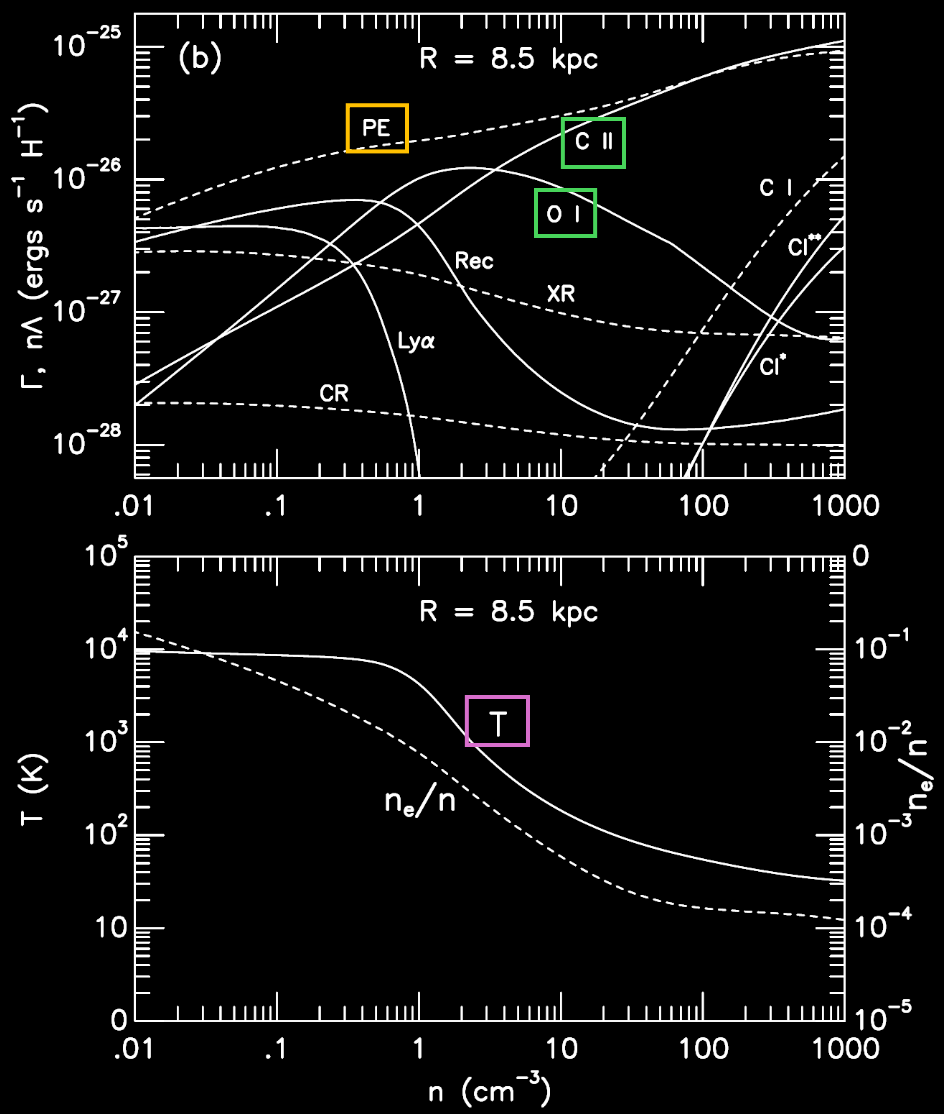
- Main cooling processes:
  - fine structure metal lines ([CII]158, [OI]63)
  - recombination
  - Lyman alpha transition

- Thermal equilibrium on the phase diagram is a classical "S-shape" curve.



Heating and Cooling Processes in the Neutral Gas

Ion	ℓ	u	E_ℓ/k (K)	E_u/k (K)	$\lambda_{u\ell}$ (μm)	$n_{H,crit}(u)$ $T = 100$ K (cm^{-3})	$n_{H,crit}(u)$ $T = 5000$ K (cm^{-3})
C II	$^2P^o_{1/2}$	$^2P^o_{3/2}$	0	91.21	157.74	2.0×10^3	1.5×10^3
C I	$^3P_0$	$^3P_1$	0	23.60	609.7	620	160
	$^3P_1$	$^3P_2$	23.60	62.44	370.37	720	150
O I	$^3P_2$	$^3P_1$	0	227.71	63.185	2.5×10^5	4.9×10^4
	$^3P_1$	$^3P_0$	227.71	326.57	145.53	2.3×10^4	8.4×10^3
Si II	$^2P^o_{1/2}$	$^2P^o_{3/2}$	0	413.28	34.814	1.0×10^5	1.1×10^4
Si I	$^3P_0$	$^3P_1$	0	110.95	129.68	4.8×10^4	2.7×10^4
	$^3P_1$	$^3P_2$	110.95	321.07	68.473	9.9×10^4	3.5×10^4



Why does [CII]158μm overtake [OI]63μm as the dominant cooling process in the CNM?

(1) Temperature is too low (collisional excitation)

(2) Density is too high (line becomes thermalized)

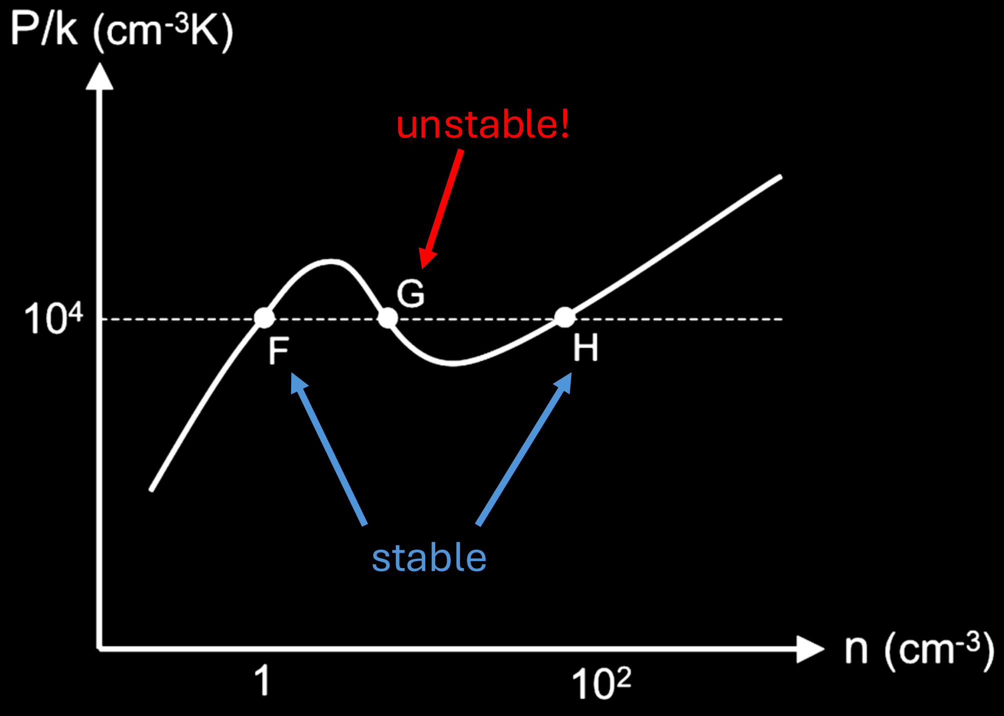
(3) Line becomes optically thick (only see the surface)

Thermal Instability

- For a given ISM pressure, thermal equilibrium allows 3 possible solutions (F, G, H). F & H are stable; G is unstable and suffers from **thermal instability**.

- Thermal instability: density decreases => net heating => density decreases further ($P \sim n\,T$) => even stronger heating => …

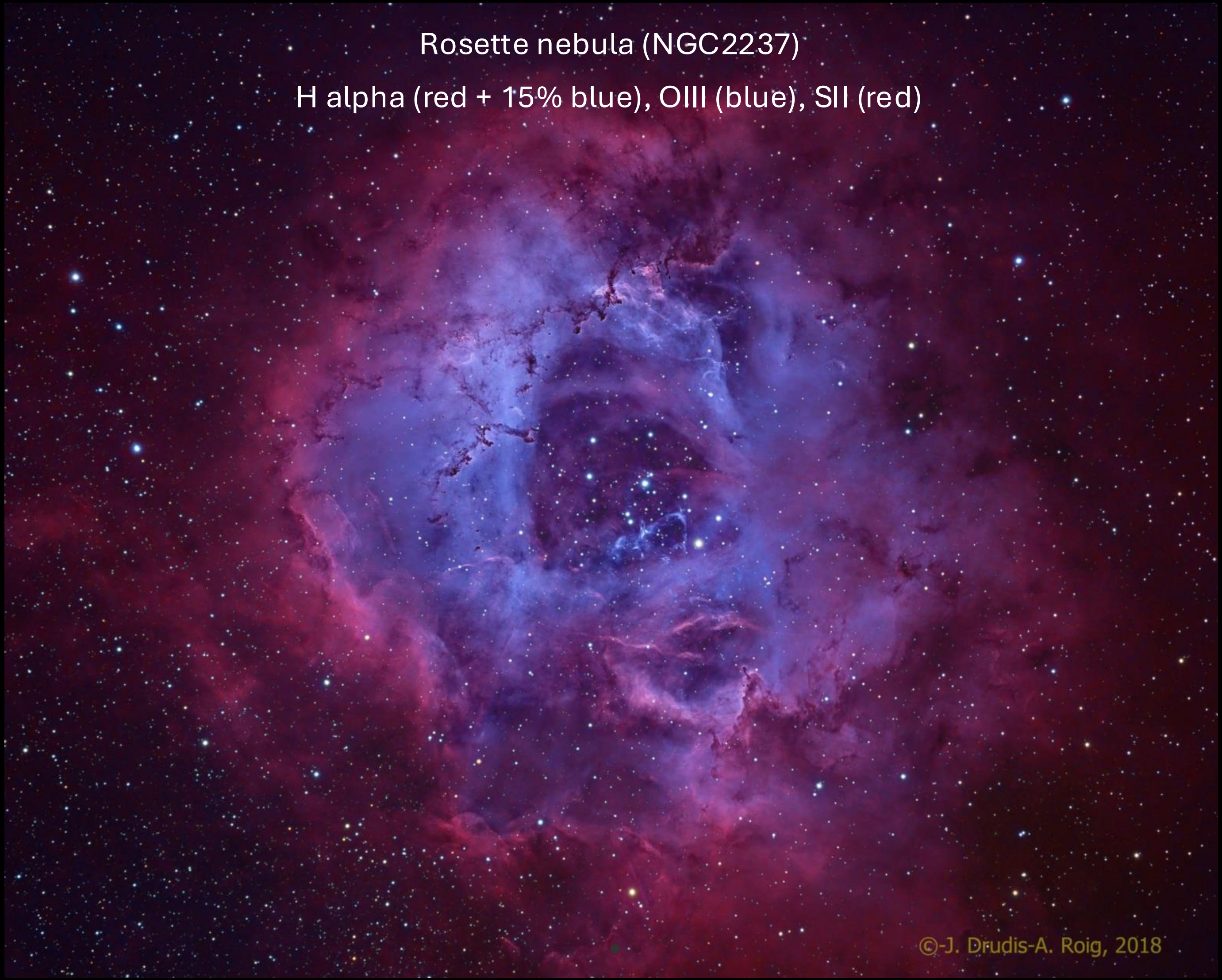
- Thermal instability naturally leads to 2 stable phases (WNM & CNM)!



WIM (HII region)

- Young, massive (OB) stars emit UV radiation energetic enough to ionize its ambient hydrogen (>13.6 eV).

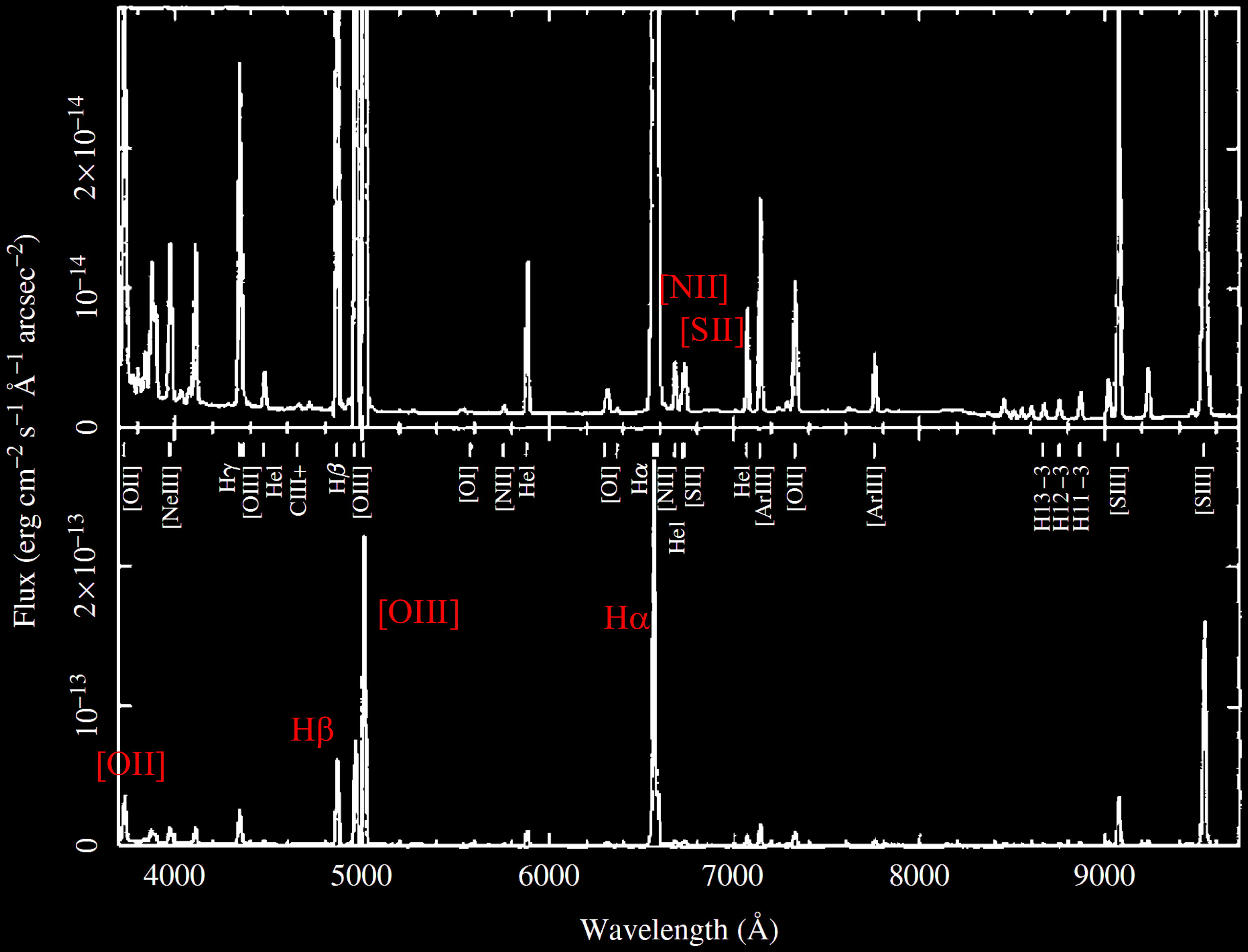
- Thermal balance:
  photoionization heating balancing recombination cooling.



Emission lines in the HII regions

- **Hydrogen recombination lines**
  - Hα (6563Å) (n=3->2)
  - Hβ (4861Å) (n=4->2)
  - …
  - radio recombination lines
    (e.g. H106α, n=107->106)

- **Forbidden metal lines**
  - [O III] (4959 Å, 5007 Å)
  - [O II] (3727 Å)
  - [N II] (6548 Å, 6584 Å)
  - [S II] (6716 Å, 6731 Å)



Hα is a widely used star formation tracer

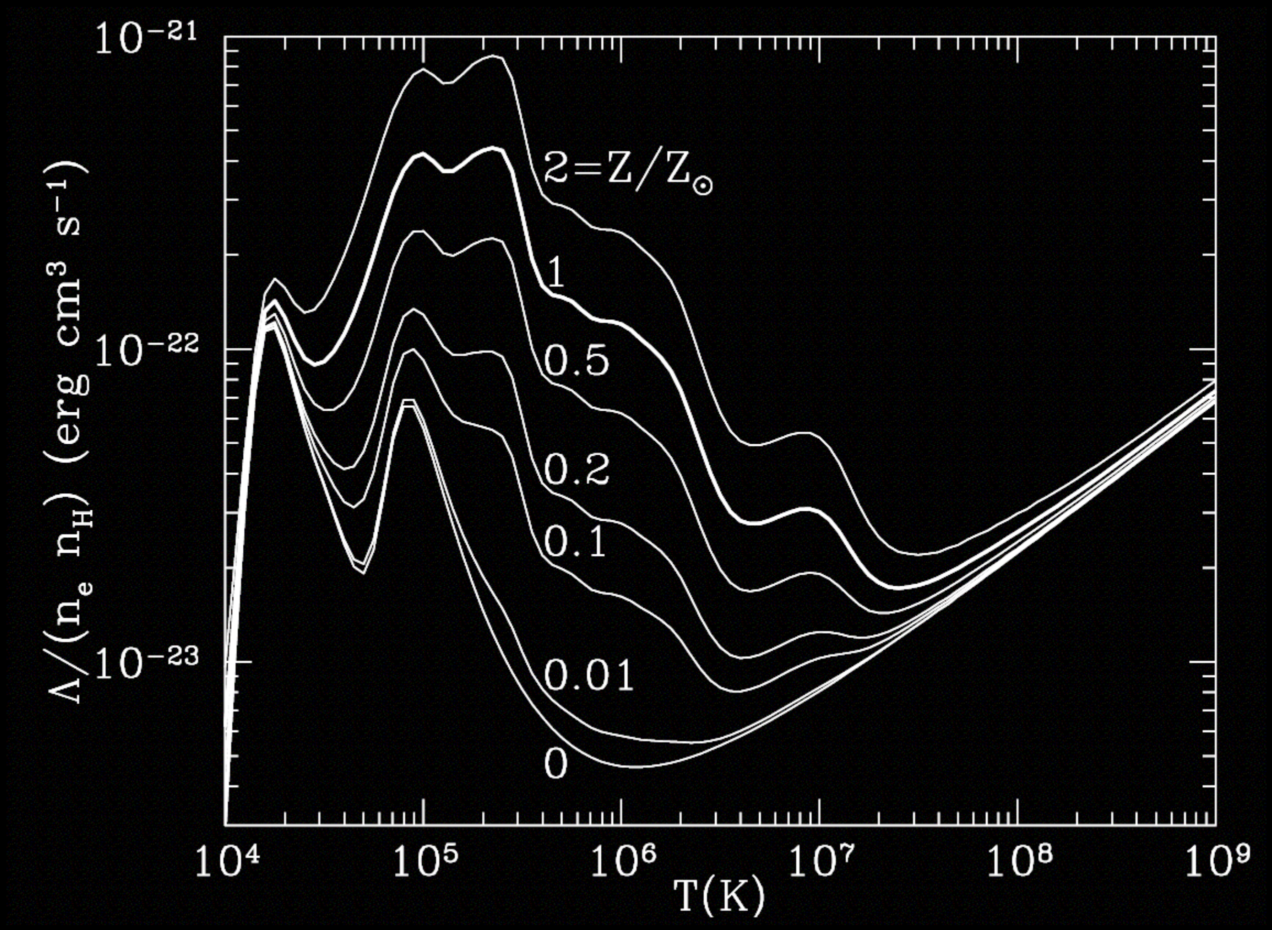
- Hα traces HII regions, which are indicators of young OB stars.

optical

Hα

Hot Ionized Medium

- Primarily driven by stellar feedback such as supernova blastwaves and stellar winds.
- Cooling is very efficient in hot gas.
- No heating mechanisms can balance cooling.
- However, transient hot gas can exist at the local minimum of the cooling function at $T \sim 10^6 - 10^7$ K.



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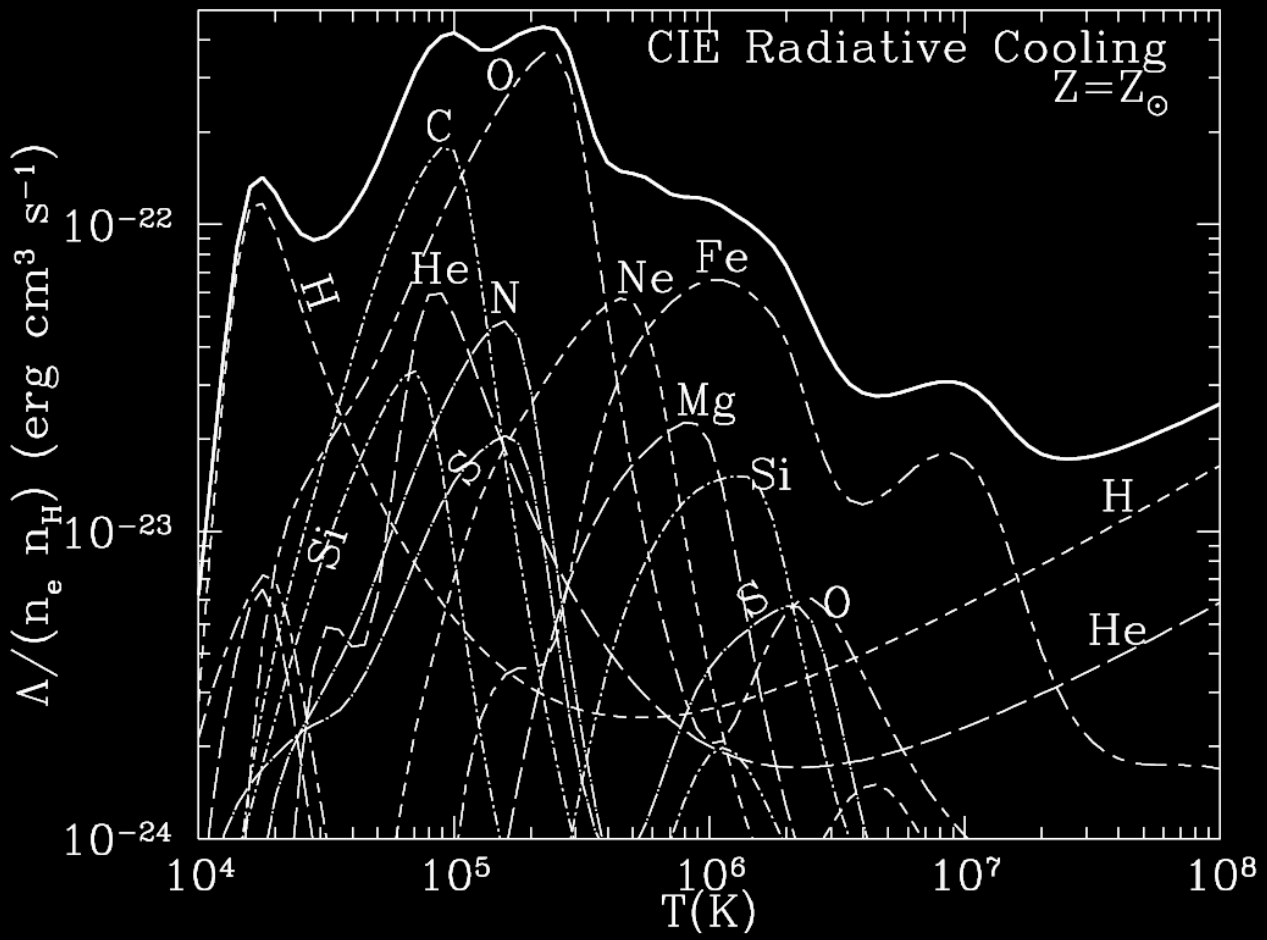


Dust

- Solid particles consist of metals (C, Si, O, Mg, Fe, ..)

  - silicate dust (e.g. Mg_2SiO_4)

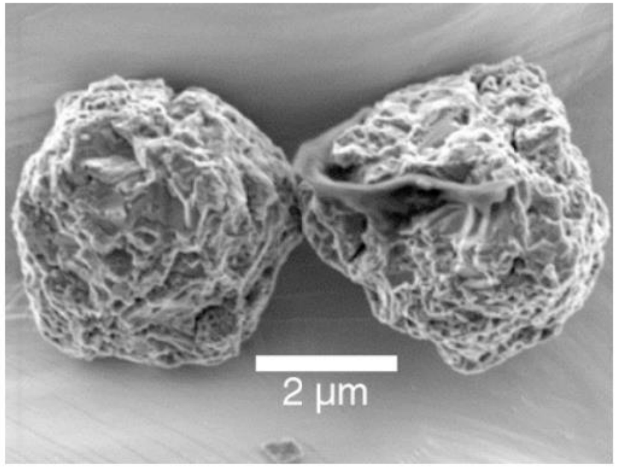
  - carbonaceous dust (graphite?)

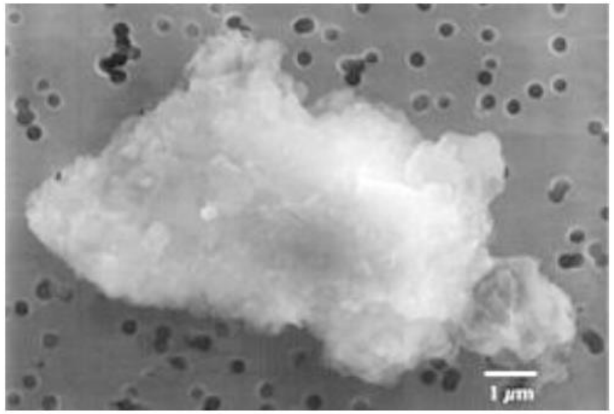
- Contribute ~1% of the ISM by mass in the Milky Way

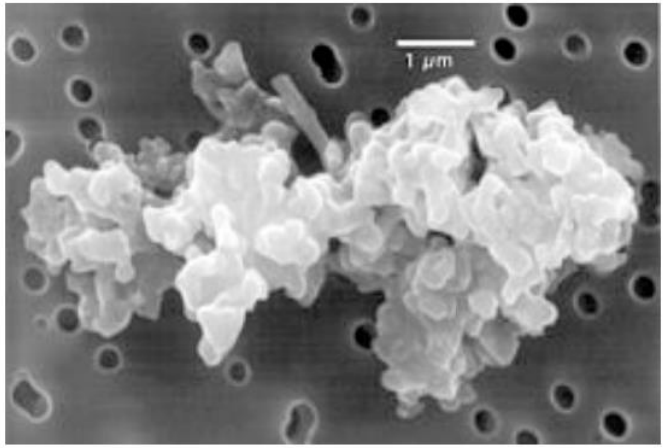
- Modify the radiation in two ways:

  - Extinction (absorption + scattering)

  - Thermal emission (FIR)





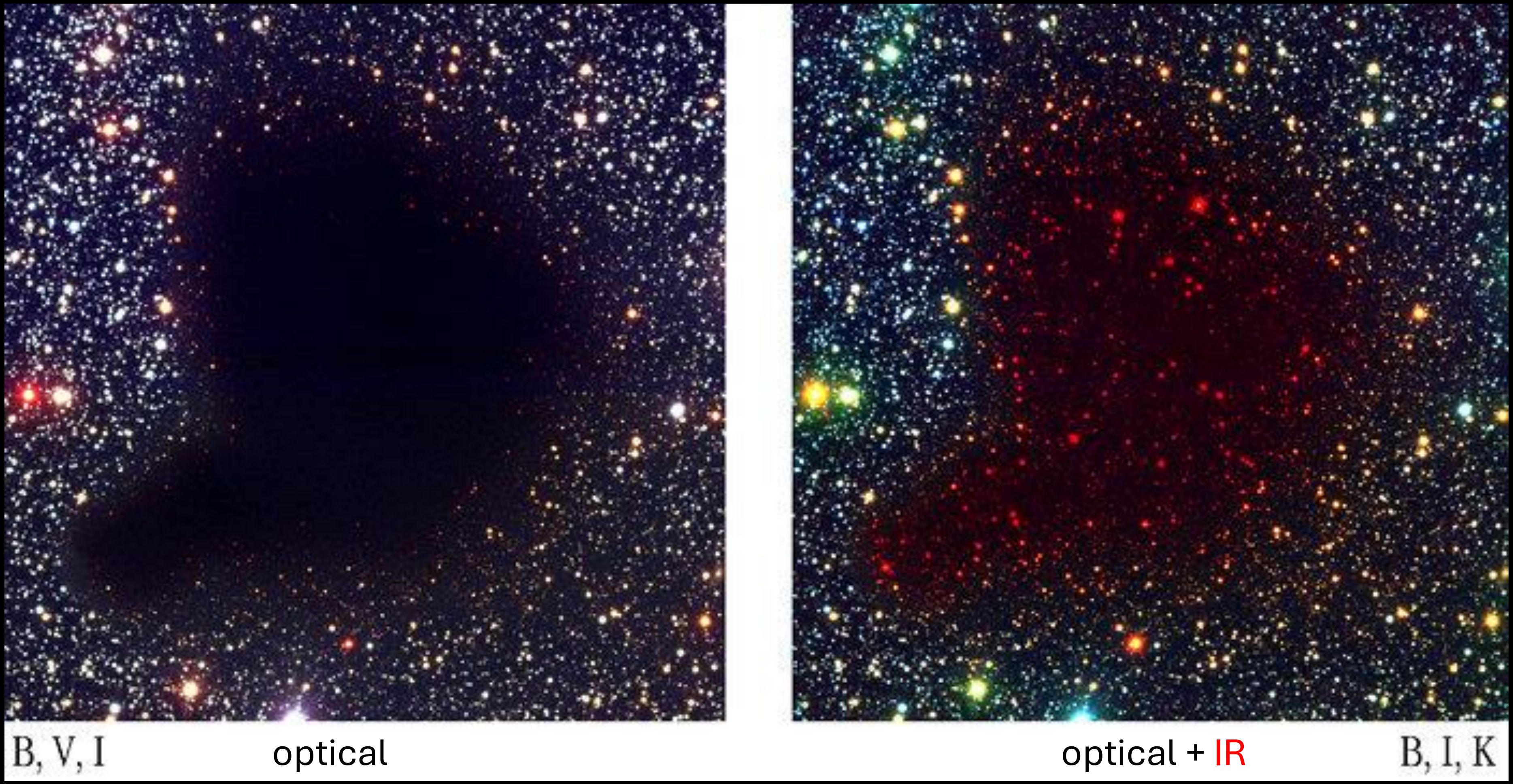


Dust Extinction

"Hier ist wahrhaftig ein Loch im Himmel!"

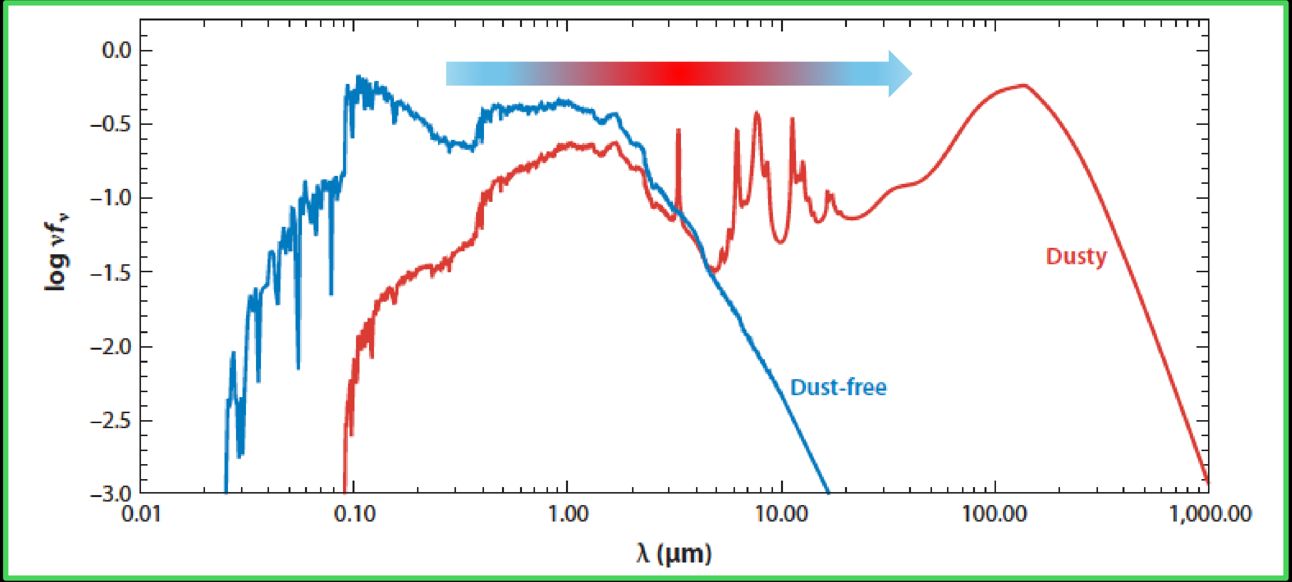
(Here truly is a hole in the sky!)

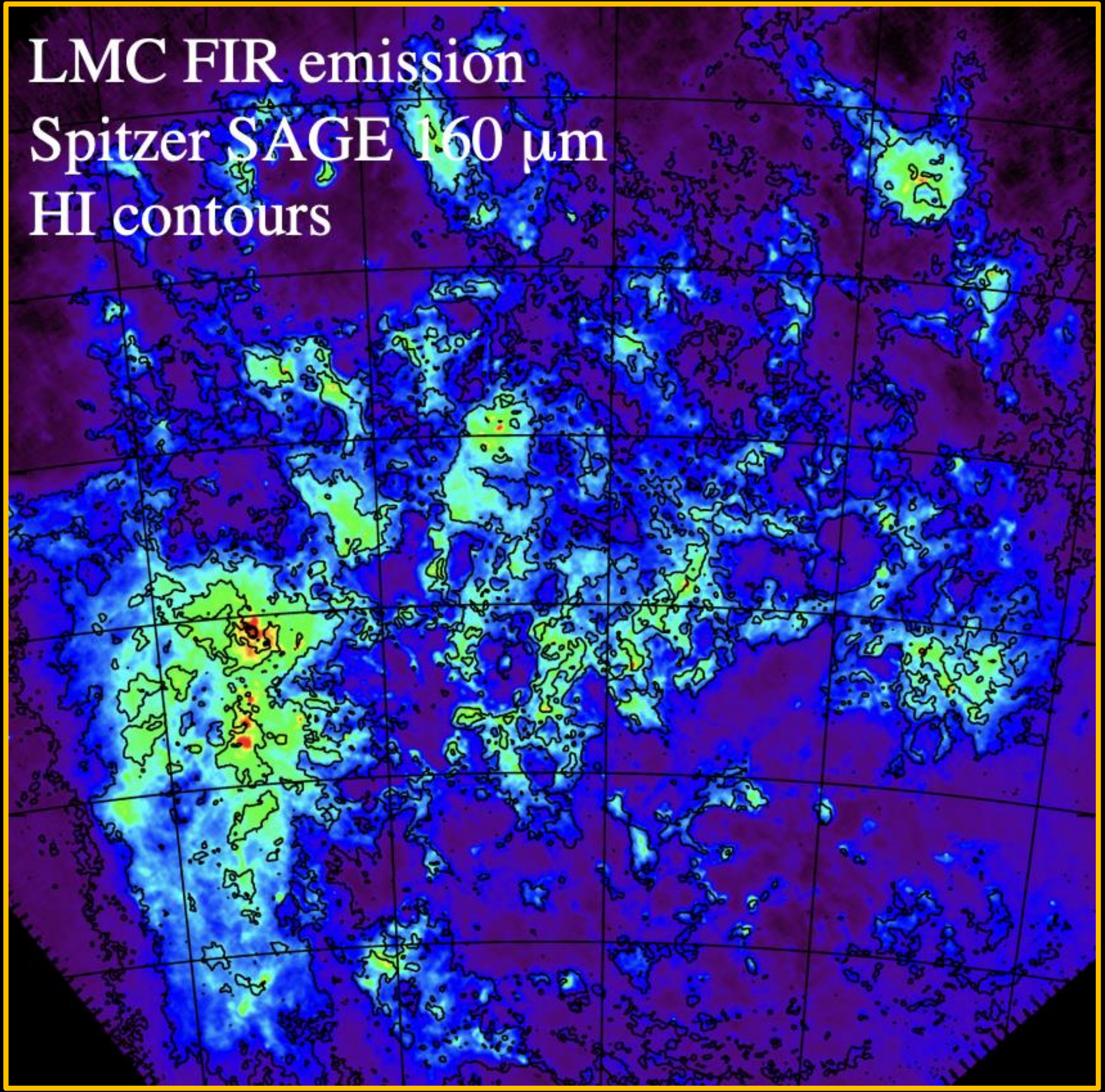
- William Herschel



Dust Emission

- Dust absorbs UV and re-emits in FIR.
- Emission roughly follows a modified blackbody radiation.





Molecular Clouds

- Molecular clouds are the densest gas where stars are formed.
- Composition: mostly molecular hydrogen (H_2)
- However, H2 cannot be directly observed in typical conditions of molecular clouds.

Molecular Clouds

What is the main reason for H_2 to emit radiation so inefficiently?

(1) Because H_2 molecule is symmetric

(2) Because the molecular weight of H_2 is too low

(3) Because H_2 lines are optically thick

(4) Because the critical densities of H_2 lines are too high

- Molecular clouds are the densest gas where stars are formed.
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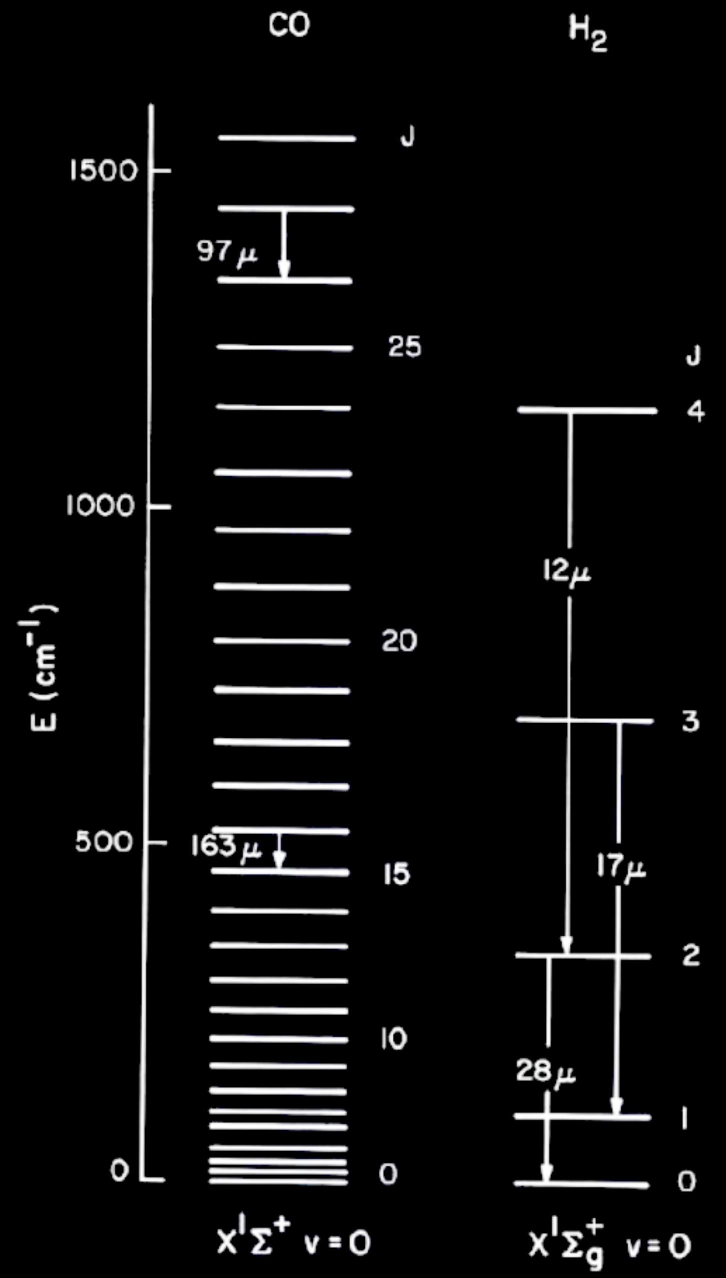
Molecular Clouds

$$E_J = \frac{\hbar^2}{2I} J(J+1)$$

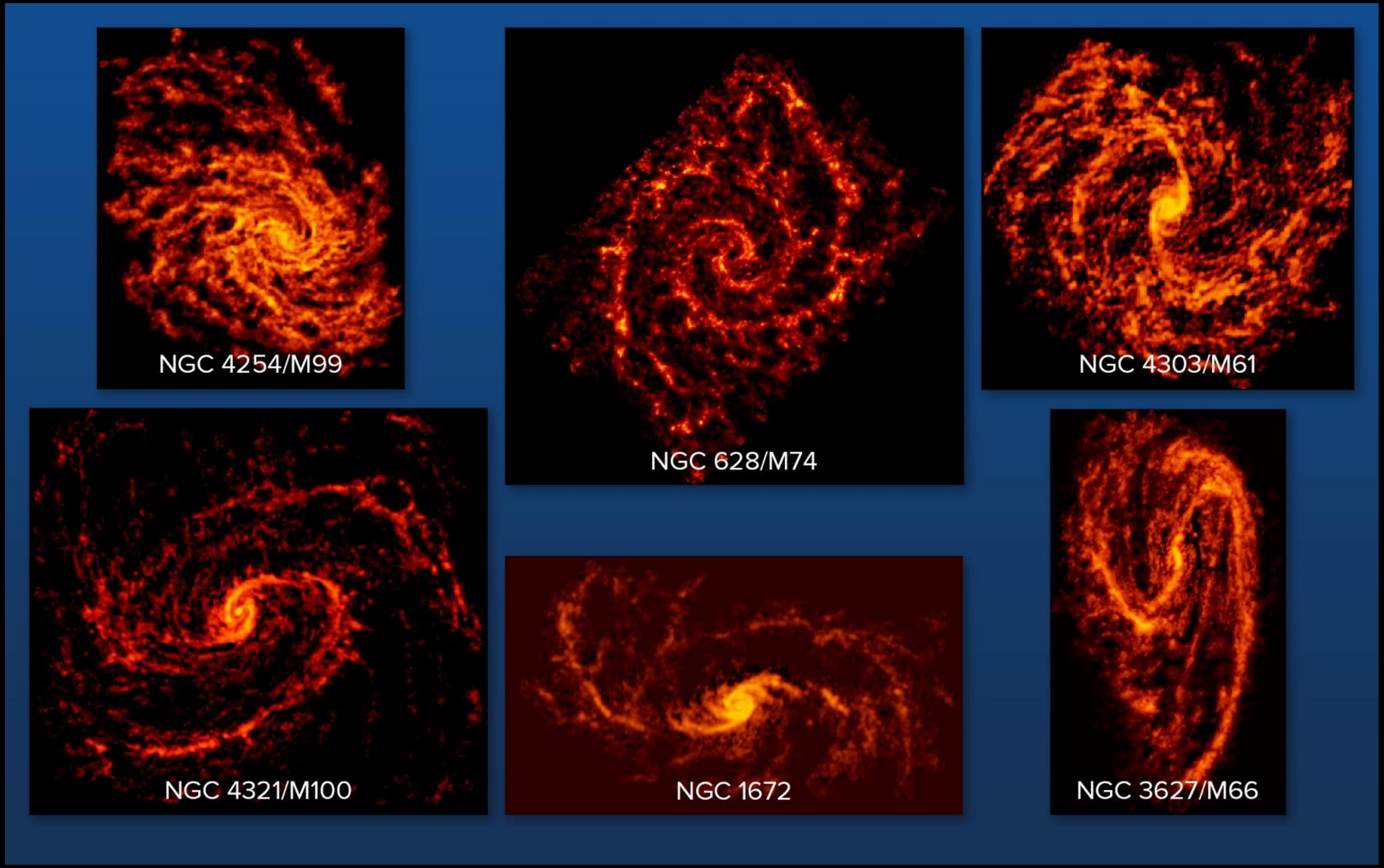
$$I = m\,r^2$$



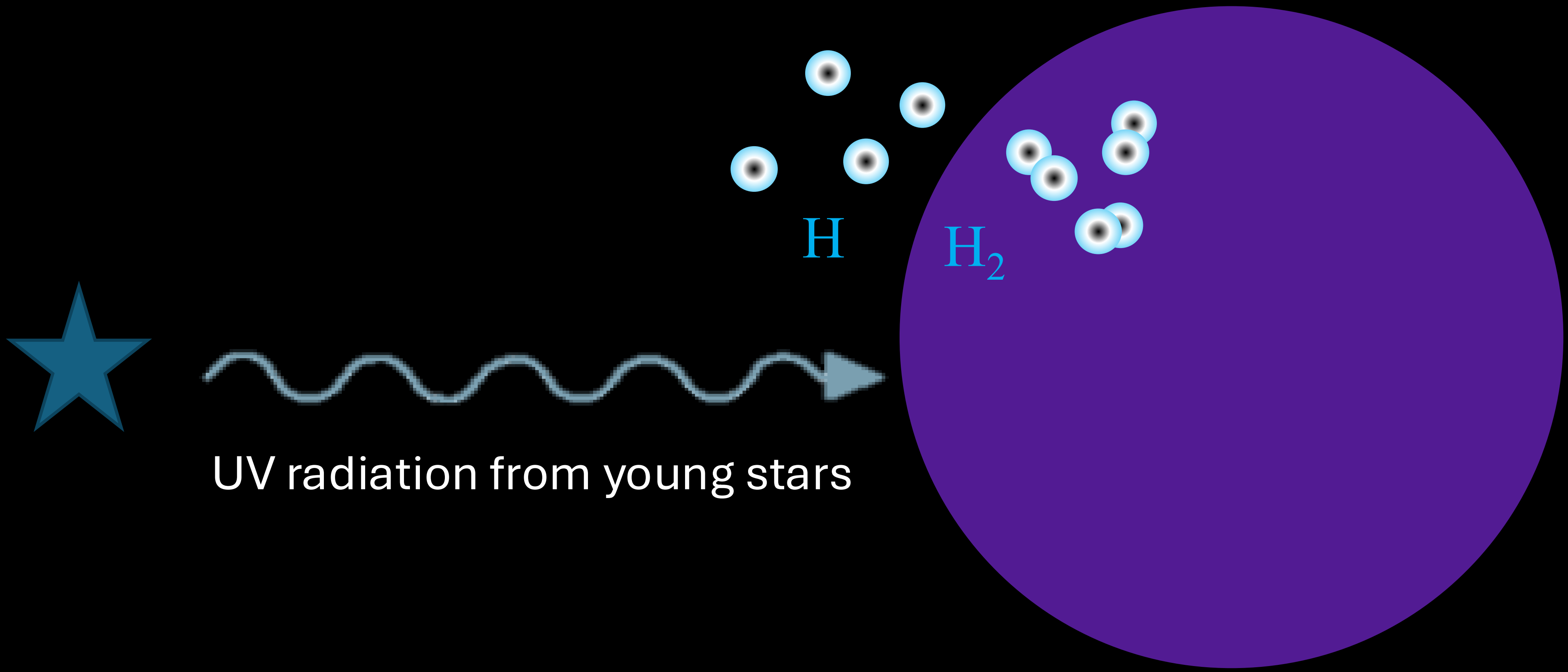
- Molecular clouds are the densest gas where stars are formed.
- Composition: mostly molecular hydrogen (H_2)
- However, H2 cannot be directly observed in typical conditions of molecular clouds.

CO as an observational tracer for H_2

- H_2 does not emit efficiently in molecular clouds (too cold).
- Observationally, we need a tracer for H_2 to infer its existence.
- Carbon monoxide (CO) is the most widely used tracer for H_2.



Chemistry: HI-H_2 transition



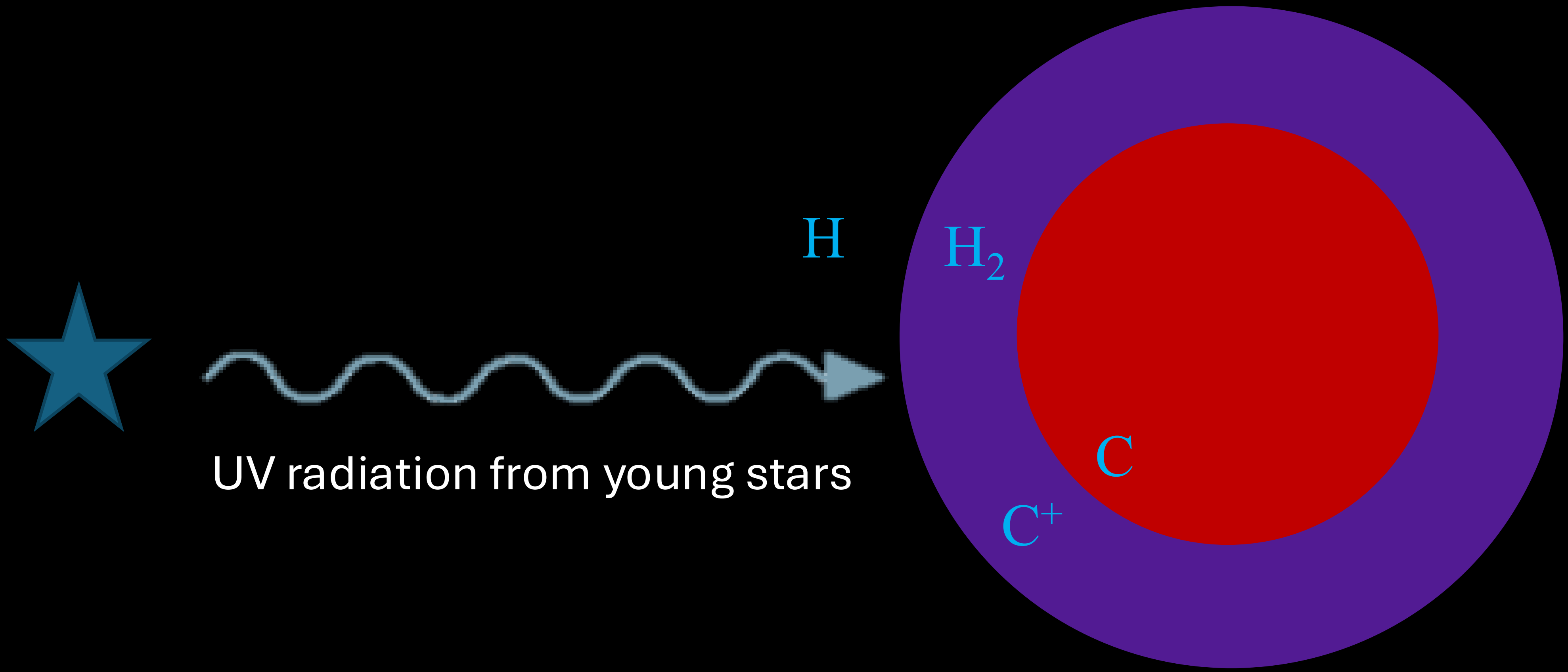
H_2 destruction: photodissociation

$$H_2 + h\nu \rightarrow H + H$$

H_2 formation: on surfaces of dust grains

$$H + H : \mathrm{dust} \rightarrow H_2$$

Chemistry: CII-CI transition



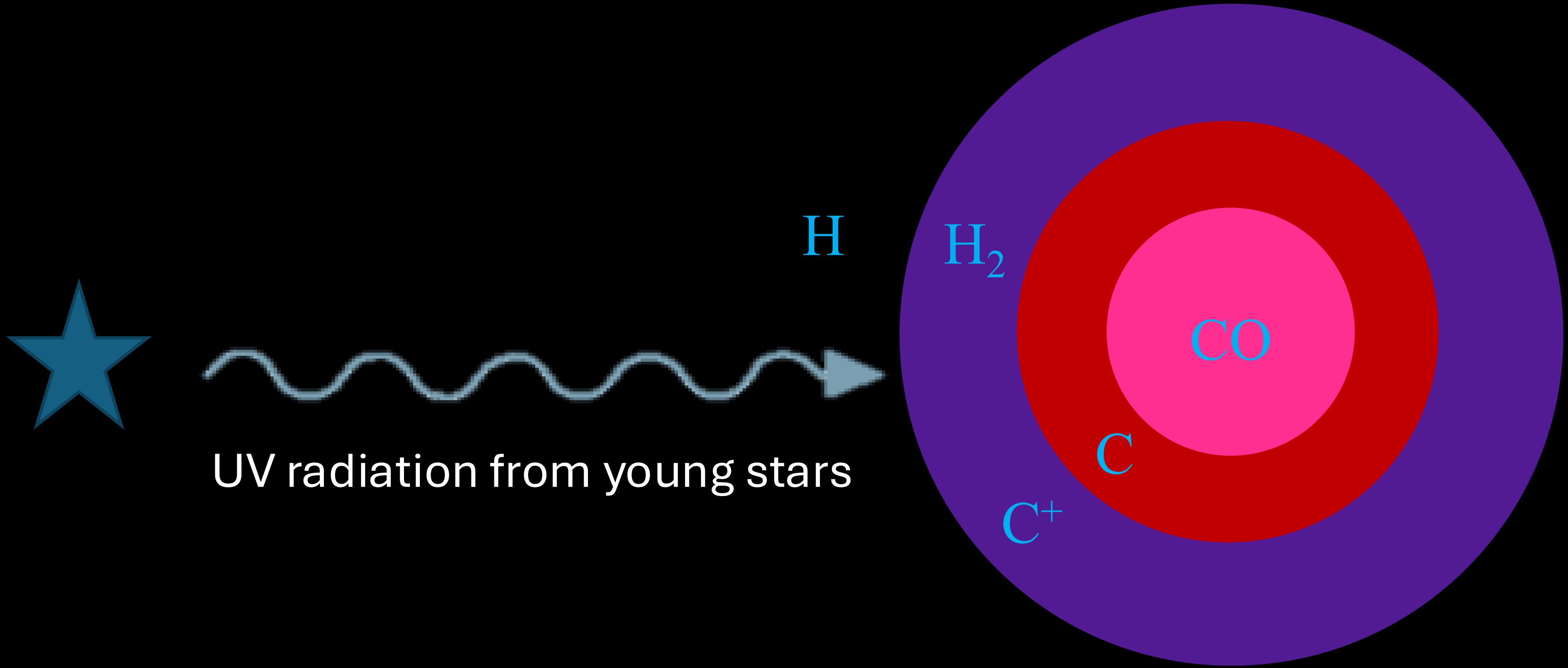
C destruction: photoionization

$$C + \gamma \rightarrow C^+ + e^-$$

C formation: recombination

$$C^+ + e^- \rightarrow C + \gamma$$

Chemistry: CI-CO transition



CO destruction: photodissociation

$$\mathrm{CO} + h\nu \rightarrow \mathrm{C} + \mathrm{O}$$

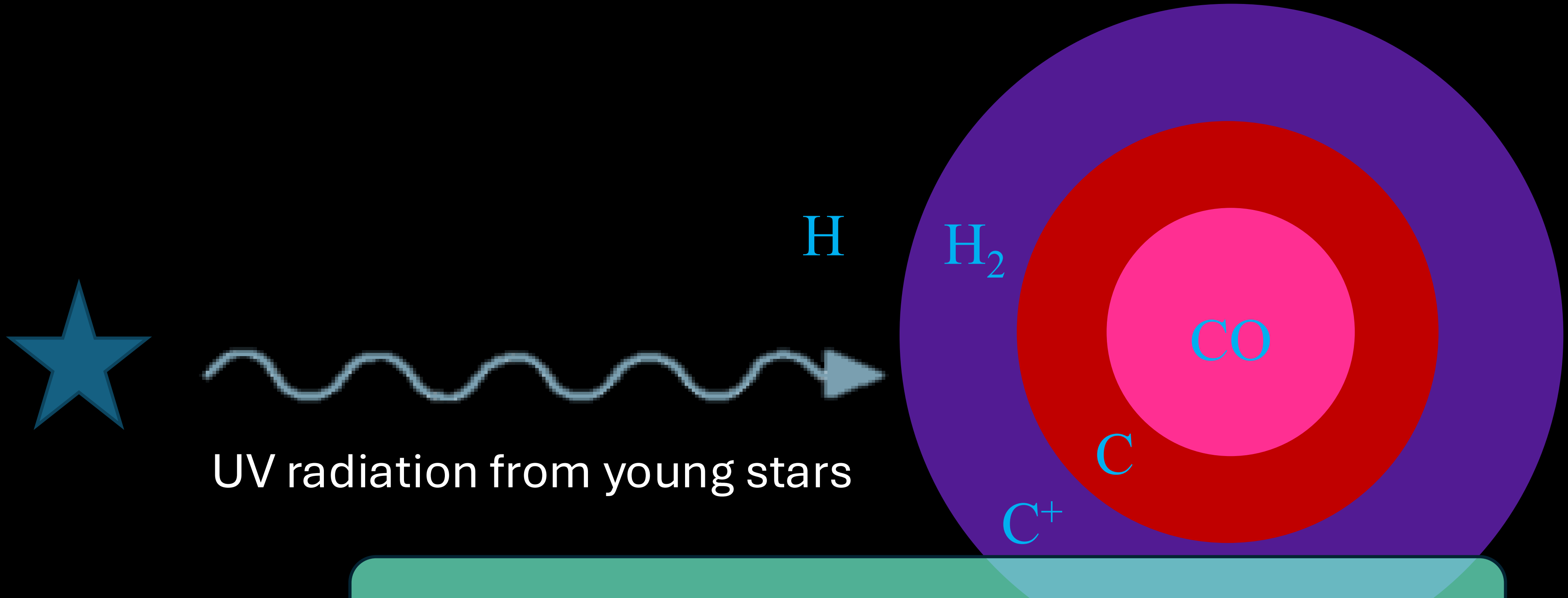
CO formation:
requires H_2!

$$\mathrm{C}^+ + \mathrm{H}_2 \rightarrow \mathrm{CH}_2^+ + h\nu$$

$$\mathrm{CH}_2^+ + e^- \rightarrow \begin{cases} \mathrm{CH} + \mathrm{H} & (25\%) \\ \mathrm{C} + \mathrm{H}_2 & (12\%) \\ \mathrm{C{+}H{+}H} & (63\%) \end{cases}$$

$$\mathrm{CH} + \mathrm{O} \rightarrow \mathrm{CO} + \mathrm{H}$$

Chemistry: CI-CO transition



CO is expected to trace H_2!

CO destruction: photodissociation

$$\mathrm{CO} + h\nu \rightarrow \mathrm{C} + \mathrm{O}$$

CO formation:
requires H_2!

$$\mathrm{C^+} + \mathrm{H_2} \rightarrow \mathrm{CH_2^+} + h\nu$$

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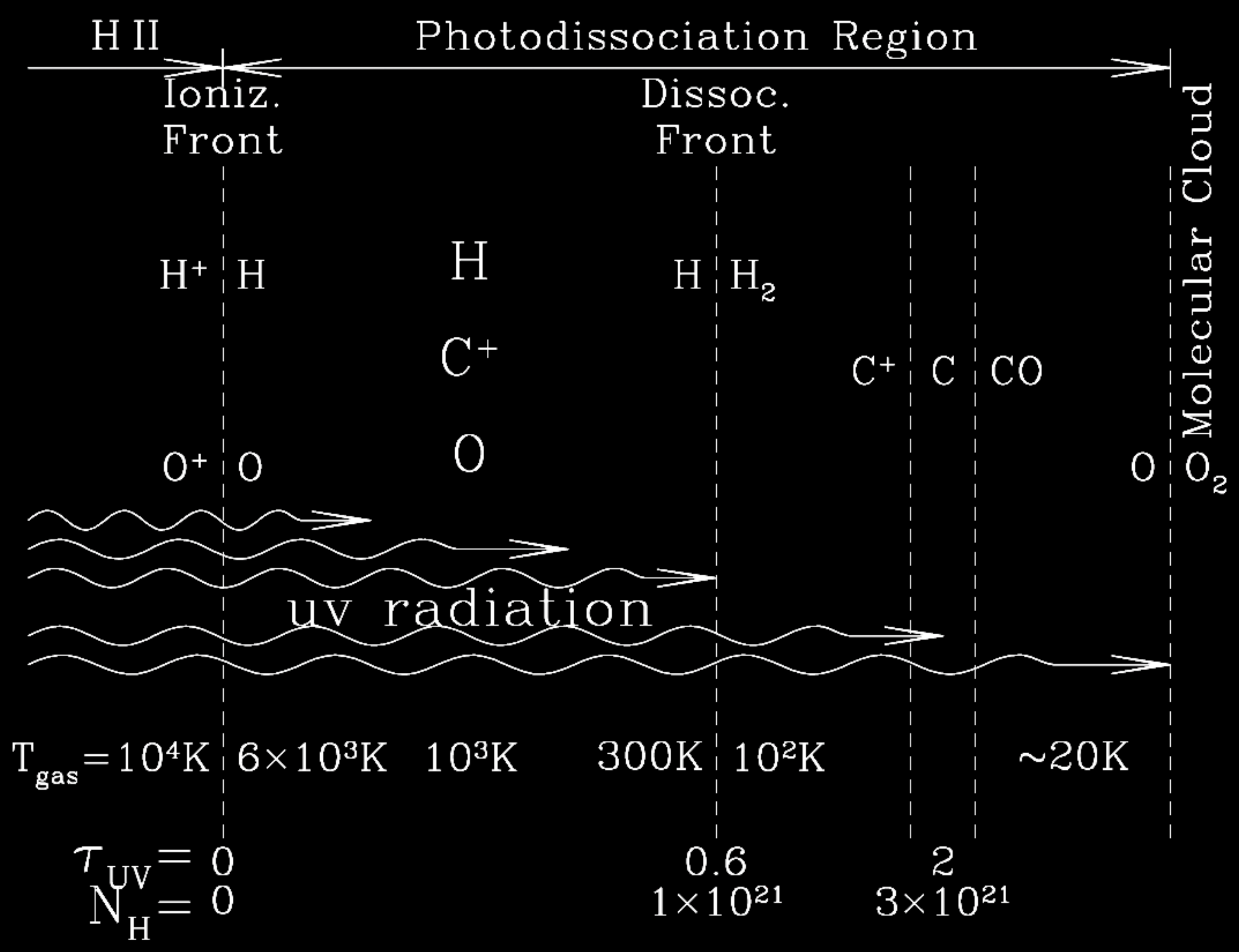
Structure of the photodissociation region



The CO-to-H_2 Conversion factor

- The CO(J=1-0) line is usually highly optically thick (τ κ1), i.e., we can only see the surface of the cloud.

- If so, how do we know how much H_2 is behind the surface?

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- The CO(J=1-0) line is usually highly optically thick (τ κ1), i.e., we can only see the surface of the cloud.

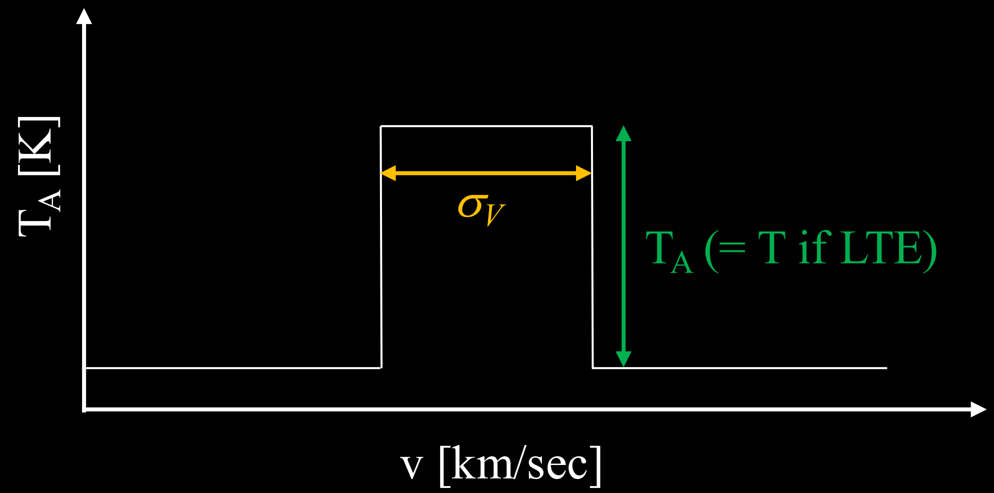
- If so, how do we know how much H_2 is behind the surface?

- virial equilibrium to the rescue!

$$\sigma_V = \sqrt{GM/5R}$$

- The CO linewidth gives us an estimate of the cloud mass!

CO spectrum:



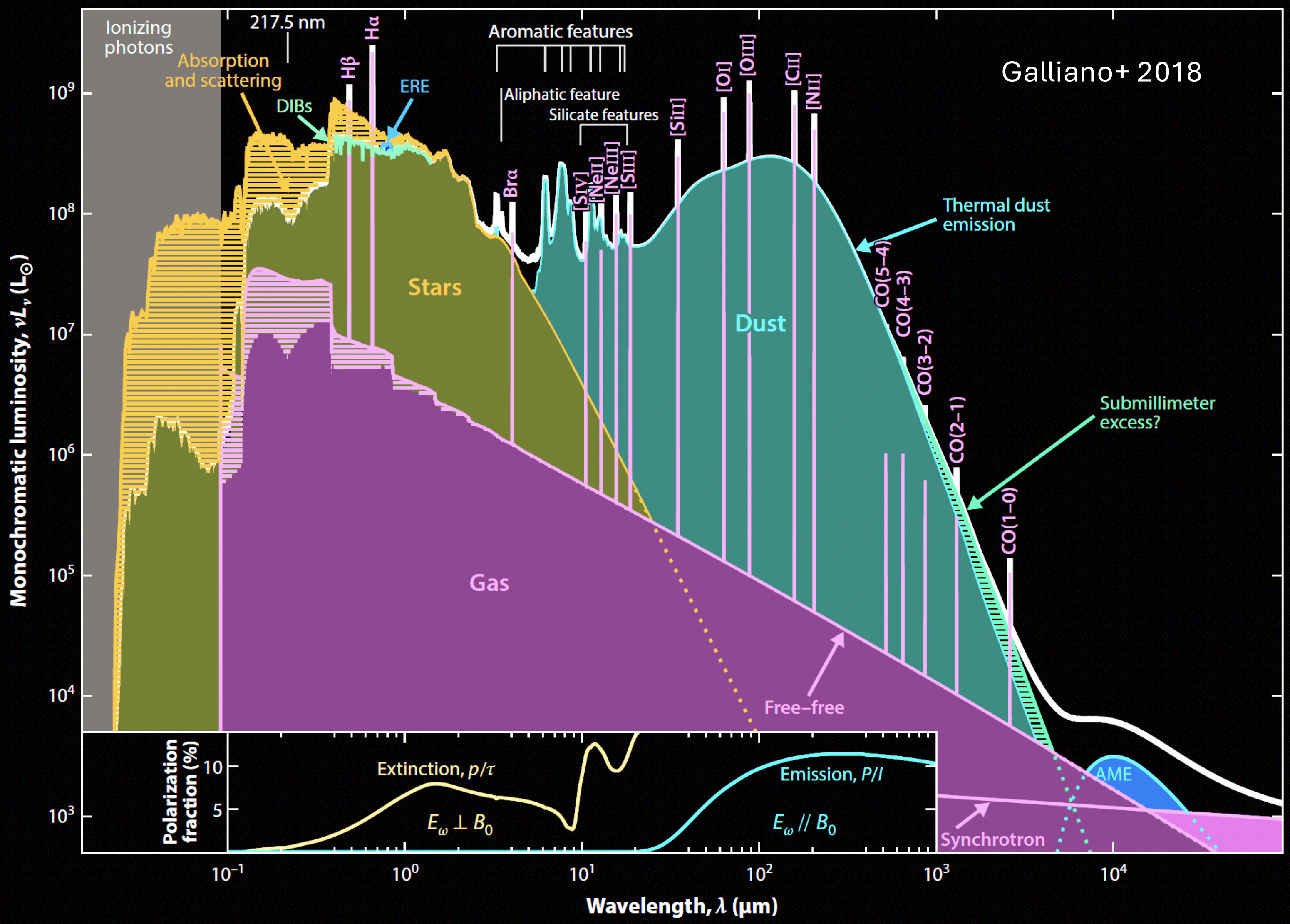
In the Milky Way

$$X_{CO} \equiv \frac{N_{H_2}}{W_{10}} = 2 \times 10^{20}\ \mathrm{cm}^{-2}\ (\mathrm{K\ km\ s}^{-1})^{-1}$$

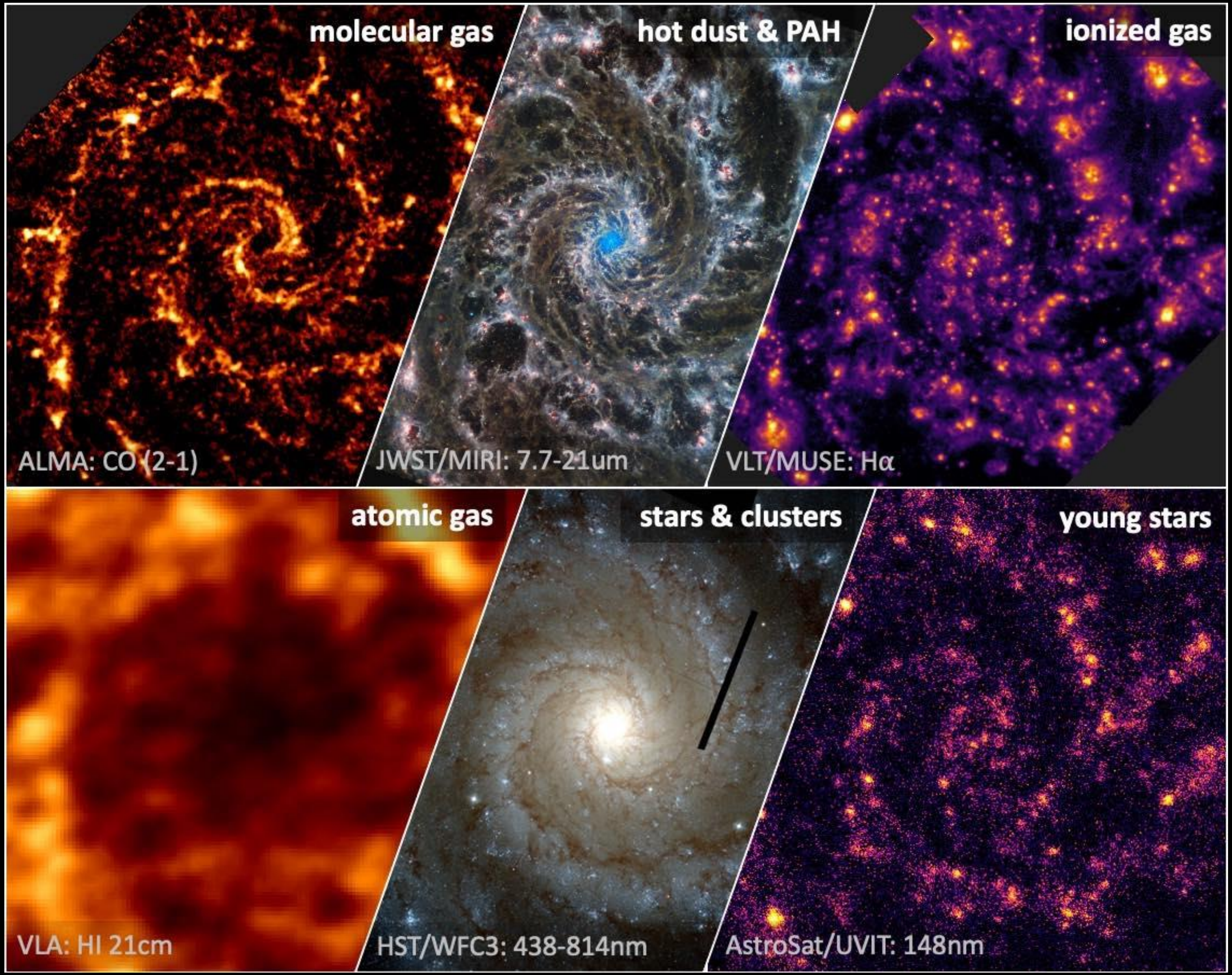
Put it all together

- WNM & CNM: HI 21 cm and FIR fine-structure lines ([CII, [OI], ...)
- WIM (HII regions): recombination lines (Hα, Hβ, □), optical lines ([NII], [OII], [SII], ...), FIR fine-structure lines ([OIII])
- Dust: FIR continuum and extinction
- Molecular clouds: CO rotational lines
- HIM: X-ray

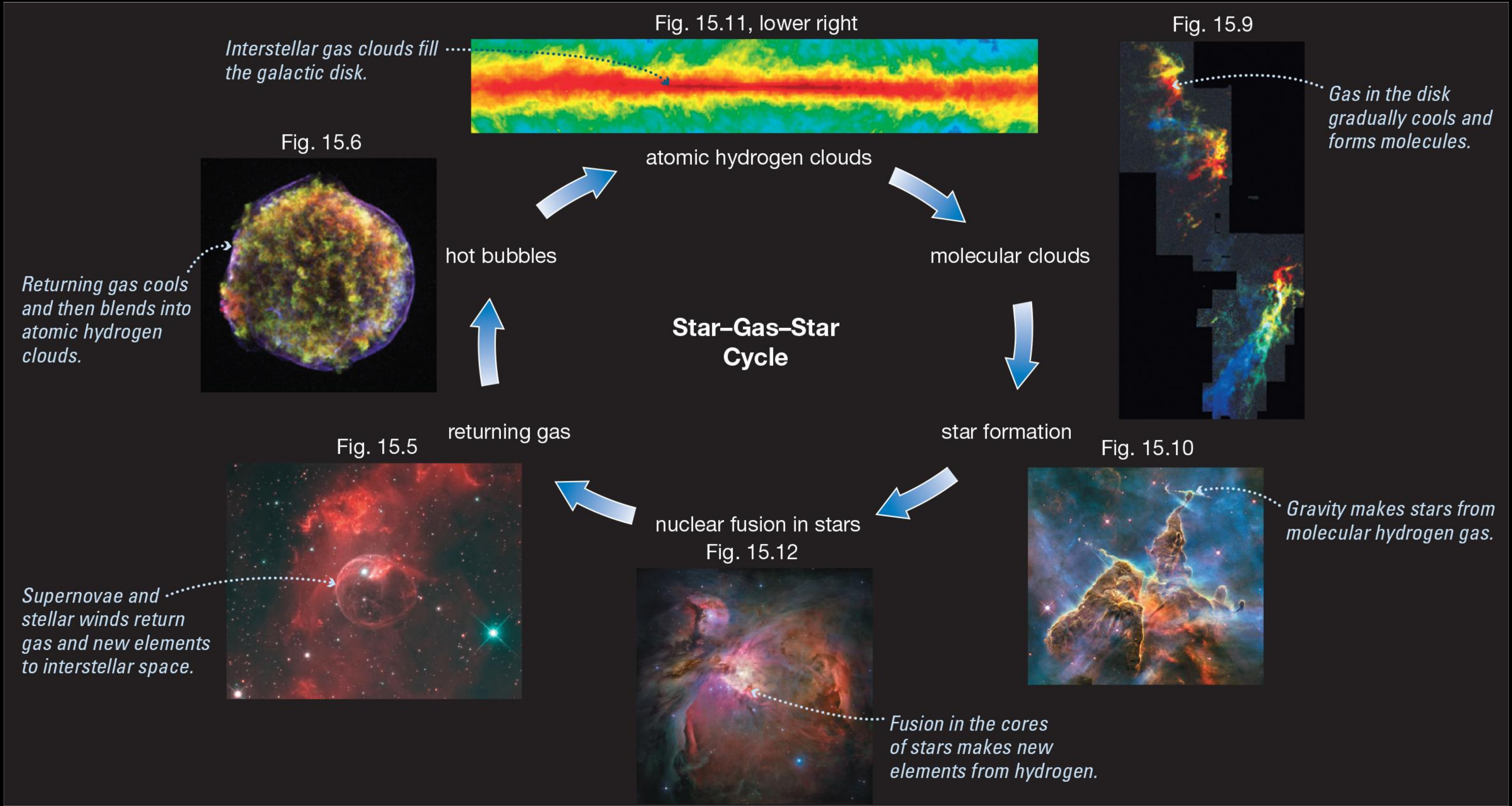
Spectral energy distribution of a typical star-forming galaxy



Multiwavelength view of the ISM



Lifecycle of the Interstellar Medium



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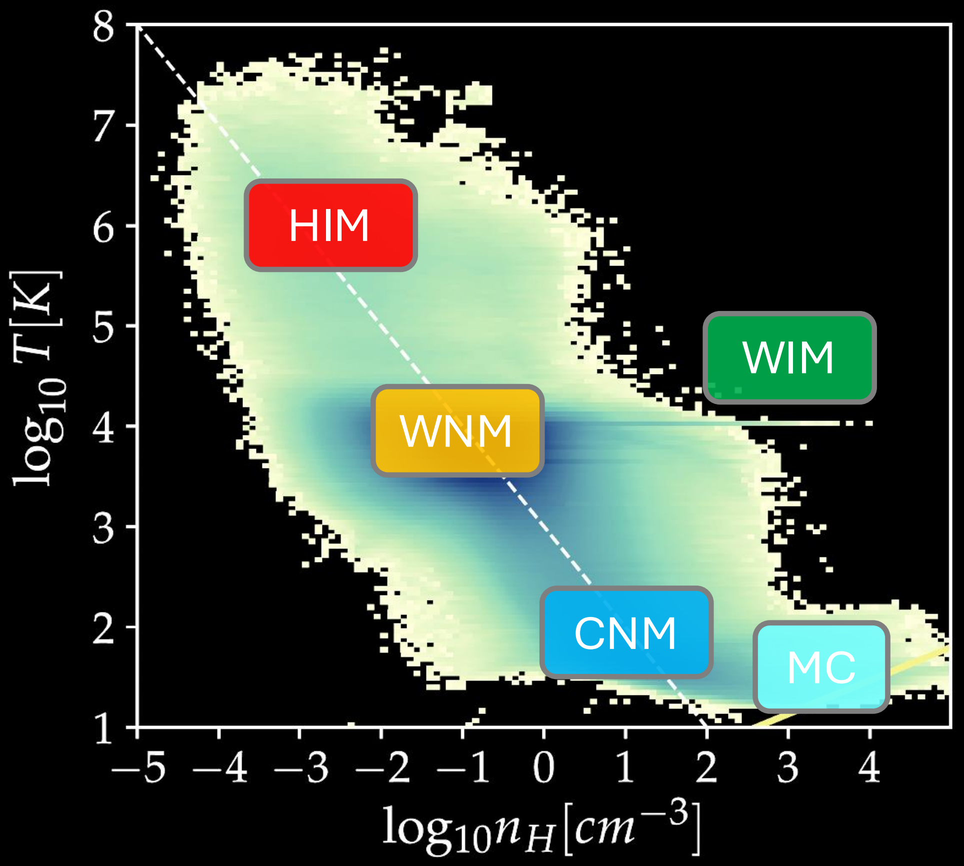
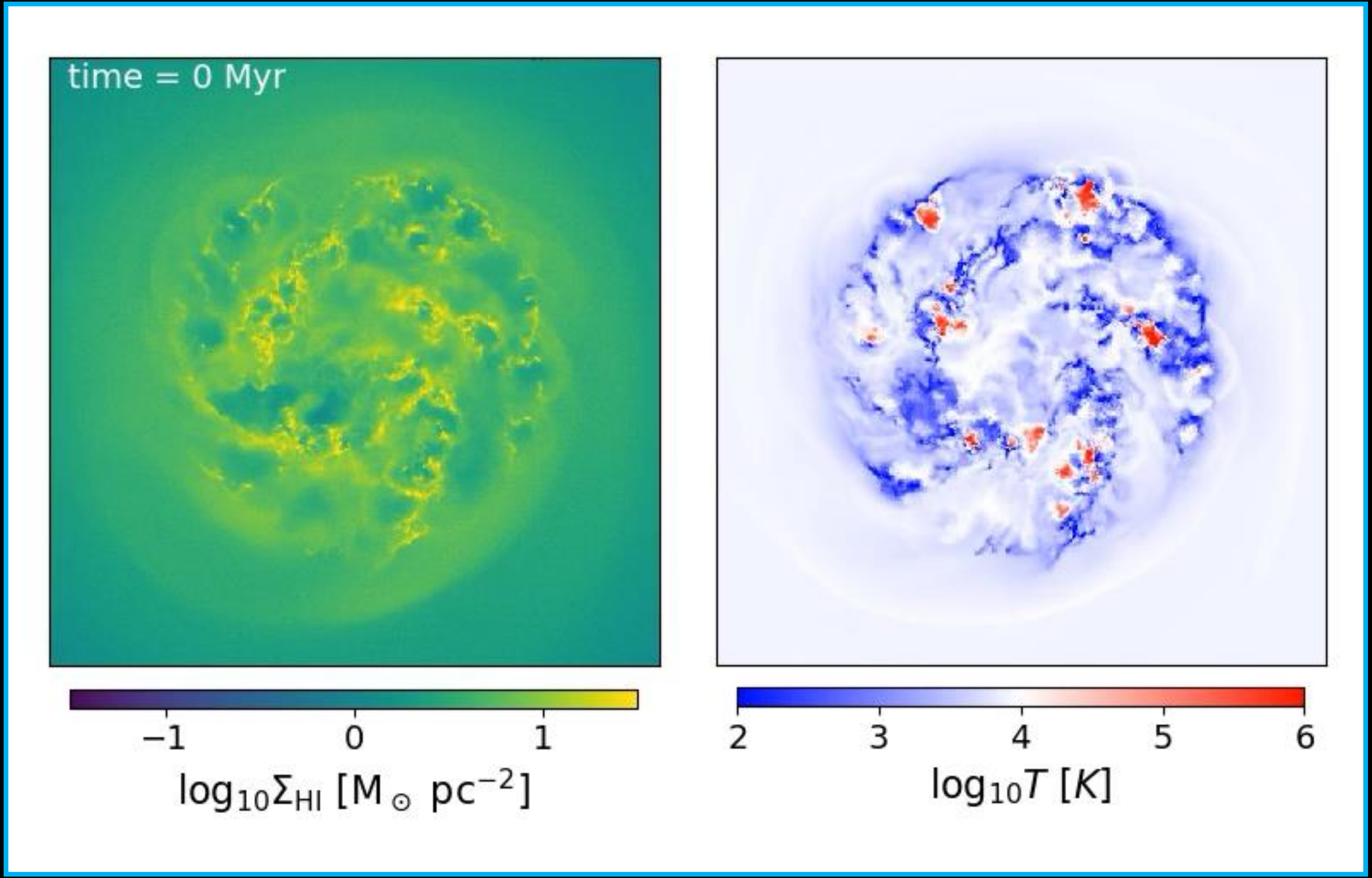




Summary of the multiphase ISM

- Warm neutral medium (WNM) and cold neutral medium (CNM):

  - main tracer: HI 21cm line, FIR fine-structure lines ([CII] & [OI])

  - thermal instability -> two stable phases

- Warm ionized medium (WIM): HII regions around massive stars

  - recombination lines (Hα, Hβ, …) and forbidden lines ([OIII], [SII])

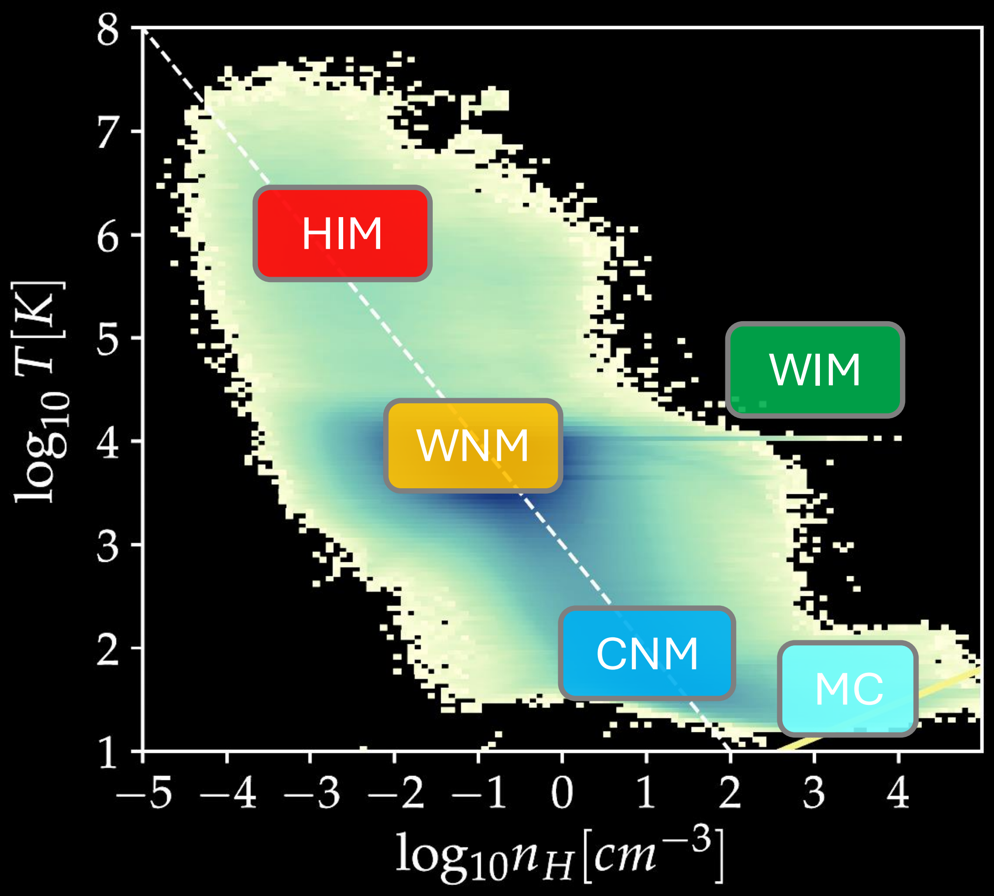
- Molecular clouds (MC): site for star formation

  - H_2 most abundant but invisible -> traced by CO rotational lines

- Hot ionized medium (HIM):

  - driven by strong shocks (stellar winds or supernovae)

- Dust: convert UV to FIR



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