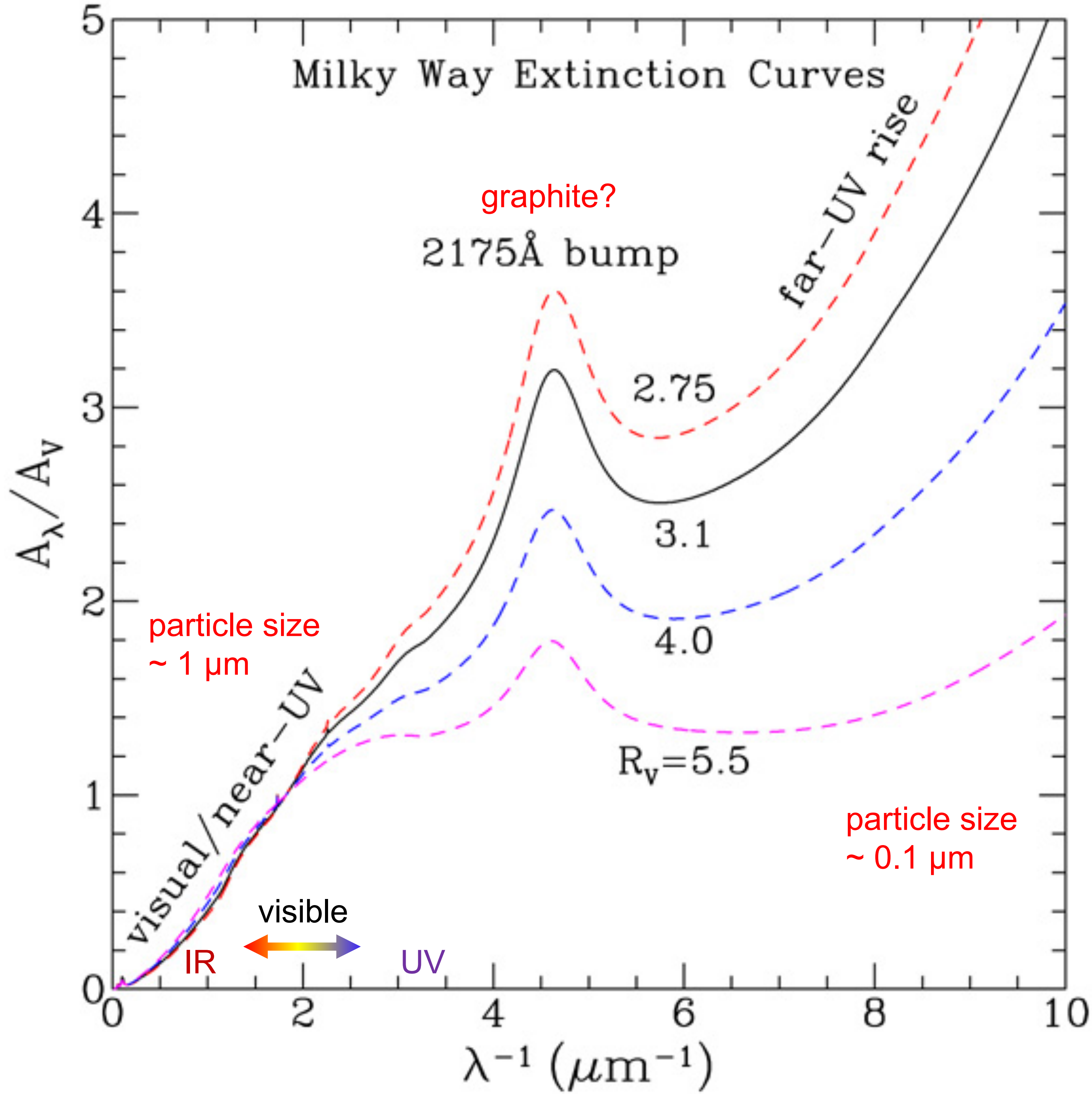
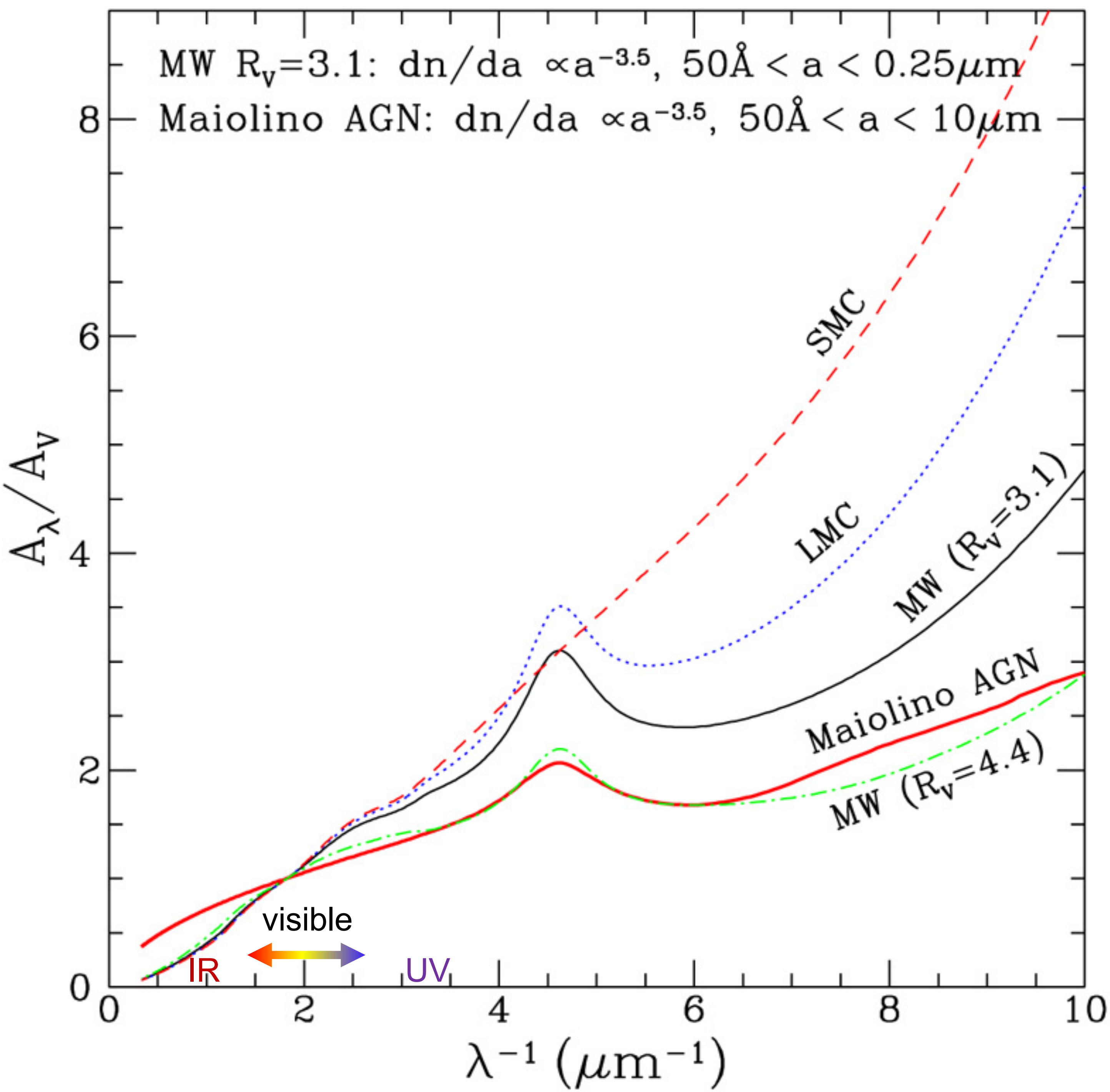
Interstellar Medium Phases

phase	component	T (K)	n (cm^{-3})	M_{tot} ($M_\odot$)	scale (pc)
molecular cloud	cold	10 – 20	> 10^3	3 x 10^9	10 – 50
dust	cold/cool	—	~ 10^{-12} n_H	few x 10^7	
HI cloud	cool	100	20	6 x 10^9	100
HI cloud	warm	10^4	0.2		>1 kpc
corona/ bubble	hot	> 10^6	~ 10^{-3}	10^8	galaxy



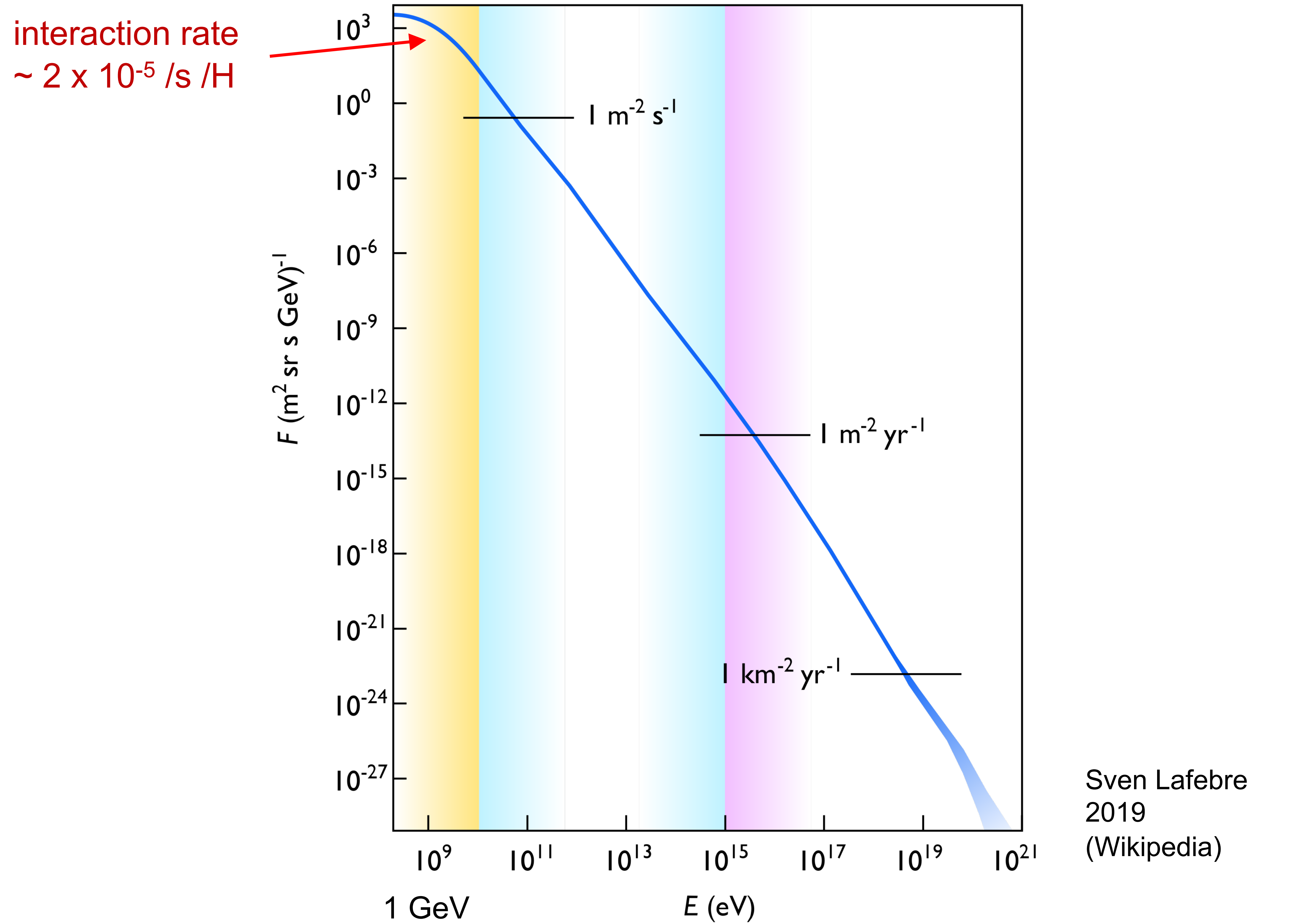
Li 2007 (AIP Conference Series)



Li 2007 (AIP Conference Series)

Stellar Energy Budget

Source	Energy (J)
Stellar UV radiation, 20 $M_{\odot}$ star, lifetime ~ 3 Myr	4×10^{44}
Type II supernova	10^{44}
Wind, $\dot{M} \sim 5 \times 10^{-8}$ $M_{\odot}$/yr, v_{∞} = 1000 km/s, lifetime = 0.1 Myr	10^{46}
10^3 $M_{\odot}$ H cloud, v ~ 10 km/s, kinetic energy	10^{41}
10^3 $M_{\odot}$ H cloud, T ~ 100 K, thermal energy	2.5×10^{39}


interaction rate
~ 2 x 10-5 /s /H
1 m-2 s-1
1 m-2 yr-1
1 km-2 yr-1
F (m2 sr s GeV)-1
10^3
10^0
10^-3
10^-6
10^-9
10^-12
10^-15
10^-18
10^-21
10^-24
10^-27
10^9
10^11
10^13
10^15
10^17
10^19
10^21
1 GeV
E (eV)
Sven Lafebre
2019
(Wikipedia)

Cosmic ray heating

$CR + H_2 \rightarrow H_2^+ + e^-$ (30 eV) + CR

then

$e^- + H_2 \rightarrow 2H + e^-$ (-4.5 eV)

or

$e^- + H_2 \rightarrow H_2^* + e^-$

$H_2^* + H_2 \rightarrow 2H_2$ + energy

→ (Krumholtz 2010) net yield over all possible interactions ~ 7–20 eV

⟹ net heating rate Γ_{CR} ~ 10^{-34} W per H nucleus

⟹ ~ 10^{26} W in a 1000 $M_\odot$ molecular cloud core

Cooling dense molecular gas

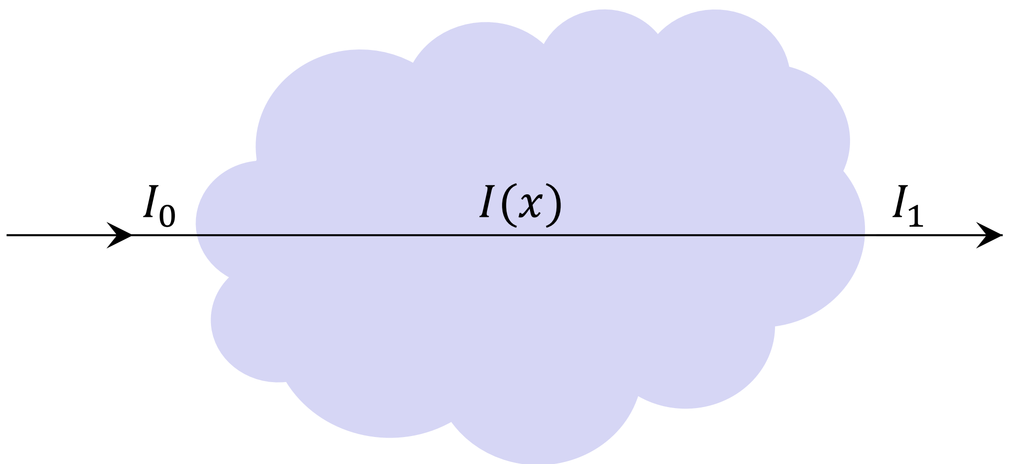
$T \sim 10$–20 K, $n > 10^3$ cm^{-3}

dust radiates as blackbody, $\lambda_{max} \sim 10$ μm (optically thin)
but dust is only in effective thermal contact for $n > 10^4$ cm^{-3}

molecular lines are more effective at lower n — CO is most important

lines may be optically thick, limiting total emission

Radiative Transfer



transfer equation

$$\frac{dI}{dx} = j - \alpha I$$

often write $j = \rho\epsilon,\ \alpha = \rho\kappa$ (emissivity and opacity)

→ assume here <u>constant</u> j and α, $I = I_0$ for $x = 0$

(1) α negligible: solution is $\quad I_1 = I_0 + \int j\, dx = I_0 + jx$

(2) j negligible: solution is $\quad I_1 = I_0 e^{-\int \alpha dx} = I_0 e^{-\alpha x} = I_0 e^{-\tau}$

(3) general solution is $\quad I_1 = I_0 e^{-\alpha x} + \frac{j}{\alpha}(1 - e^{-\alpha x})$

$$\rightarrow \frac{j}{\alpha} \text{ as } \tau = \alpha x \rightarrow \infty$$

effectively only see emission from within $\Delta x \sim 1/\alpha$ of surface

CO Cooling

Details depend on spatial and velocity structure; idealized calculation gives (Krumholtz 2010):

$$\Lambda_{CO} = \mathrm{x}_{CO}\,(2J+1)\,\frac{e^{-E_J/kT}}{Z}\,A_{J,J-1}\,\left(E_J - E_{J-1}\right)$$

CO fraction · degeneracy · Boltzmann factor · decay rate · line energy

where

$$E_J = hBJ(J+1)$$

B = rotation constant

$$A_{J,J-1} = \frac{512\pi^4 B^3 \mu^2}{3hc^3}\,\frac{(J+1)^4}{2J+1}$$

μ = electric dipole moment

For $J = 5, T = 10\ K$, find

$$\Lambda_{CO} = 1.3\times10^{-34}\ \text{W / H nucleus}$$

balance with CR heating for T ~ 10 K, but quite temperature dependent

Table 2.5 Main processes that cool the interstellar gas

Temperature	*Cooling process*	*Spectral region*
$>10^7$ K	Free–free	X-ray
10^7 K $< T <$ 10^8 K	Iron resonance lines	X-ray
10^5 K $< T <$ 10^7 K	Metal resonance lines	UV, soft X-ray
8000 K $< T <$ 10^5 K	C, N, O, Ne forbidden lines	IR, optical
Warm neutral gas: $\sim$8000 K	Lyman-α, [OI]	1216 Å, 6300 Å
100 K $< T <$ 1000 K	[OI], [CII], H_2	Far IR: 63 μm, 158 μm
$T \sim 10-50$ K	CO rotational transitions	Millimeter-wave

Recombination

5000 K < T < 20000 K

$$\frac{dn_e}{dt} = -n_e^2\,\alpha(T)$$

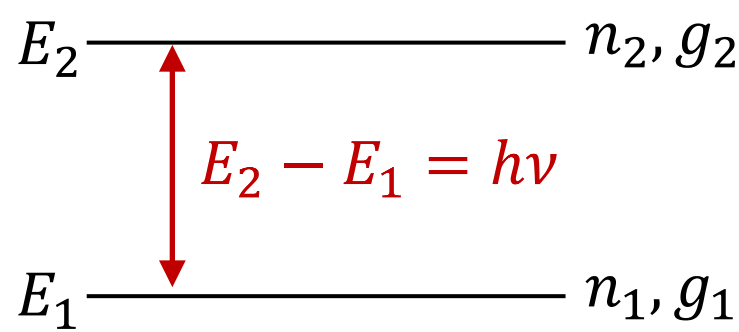
$$\alpha(T) = 2\times 10^{-13}\left(\frac{T}{10^4\mathrm{K}}\right)^{-3/4}\ \mathrm{cm^3 s^{-1}}$$

$$t_{rec} = \left|\frac{n_e}{dn_e/dt}\right| = 1500\ \mathrm{yr}\left(\frac{T}{10^4\mathrm{K}}\right)^{3/4}\left(\frac{n_e}{100\ \mathrm{cm^{-3}}}\right)^{-1}$$

denser regions cool <u>faster</u>

Atomic Lines

$$\frac{dI_\nu}{dx} = j_\nu - \alpha_\nu I_\nu$$



2-level atom

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

spontaneous emission — absorption — stimulated emission

$$\frac{A_{21}}{B_{21}} = \frac{8\pi h\nu^3}{c^3}$$

$$\frac{B_{21}}{B_{12}} = \frac{g_1}{g_2}$$

Atomic Lines

$$\frac{dI_\nu}{dx} = j_\nu - \alpha_\nu I_\nu$$

emission: $j_\nu = h\nu\, A_{21} n_2 \phi(\nu)/4\pi$

absorption: $\alpha_\nu = \frac{c^2}{8\pi\nu^2}\frac{g_2}{g_1}\, n_1 A_{21}\phi(\nu)\left(1 - e^{-h\nu/kT}\right)$

Table 2.5 Main processes that cool the interstellar gas

Temperature	*Cooling process*	*Spectral region*
$>10^7$ K	Free–free	X-ray
$10^7 \text{ K} < T < 10^8$ K	Iron resonance lines	X-ray
$10^5 \text{ K} < T < 10^7$ K	Metal resonance lines	UV, soft X-ray
$8000 \text{ K} < T < 10^5$ K	C, N, O, Ne forbidden lines	IR, optical
Warm neutral gas: ~8000 K	Lyman-α, [OI]	1216 Å, 6300 Å
$100 \text{ K} < T < 1000$ K	[OI], [CII], H_2	Far IR: 63 μm, 158 μm
$T \sim 10-50$ K	CO rotational transitions	Millimeter-wave

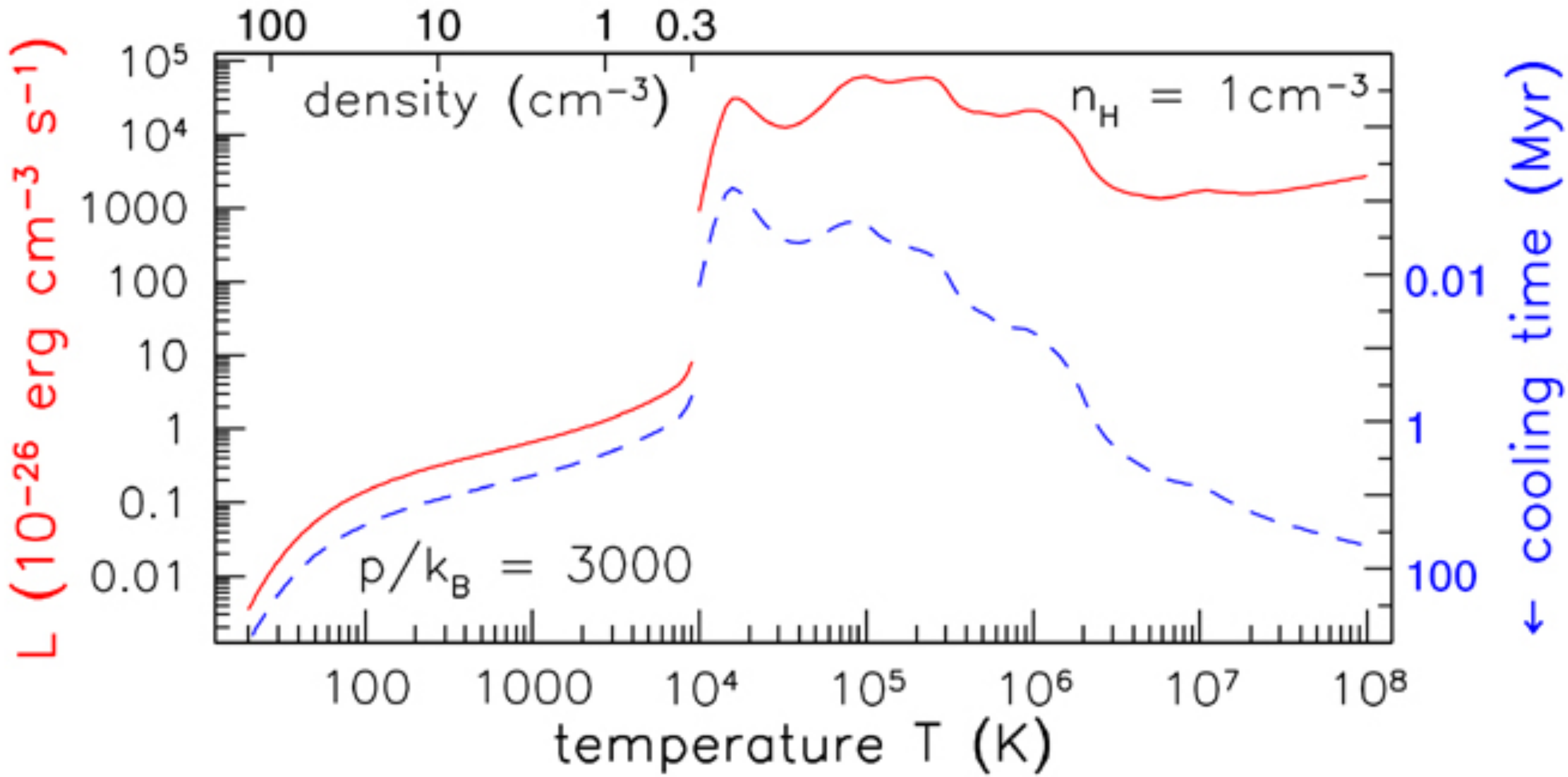


Fig 2.25 (Hensler, Wolfire) 'Galaxies in the Universe' Sparke/Gallagher CUP 2007