INTERSTELLAR MEDIUM

- Stefano Bovino -

Thermal processes in the ISM

ISM phases

$$A_v = \frac{N_{\mathrm{H}}}{2 \times 10^{21}} \,\mathrm{mag\,cm^{-2}}$$

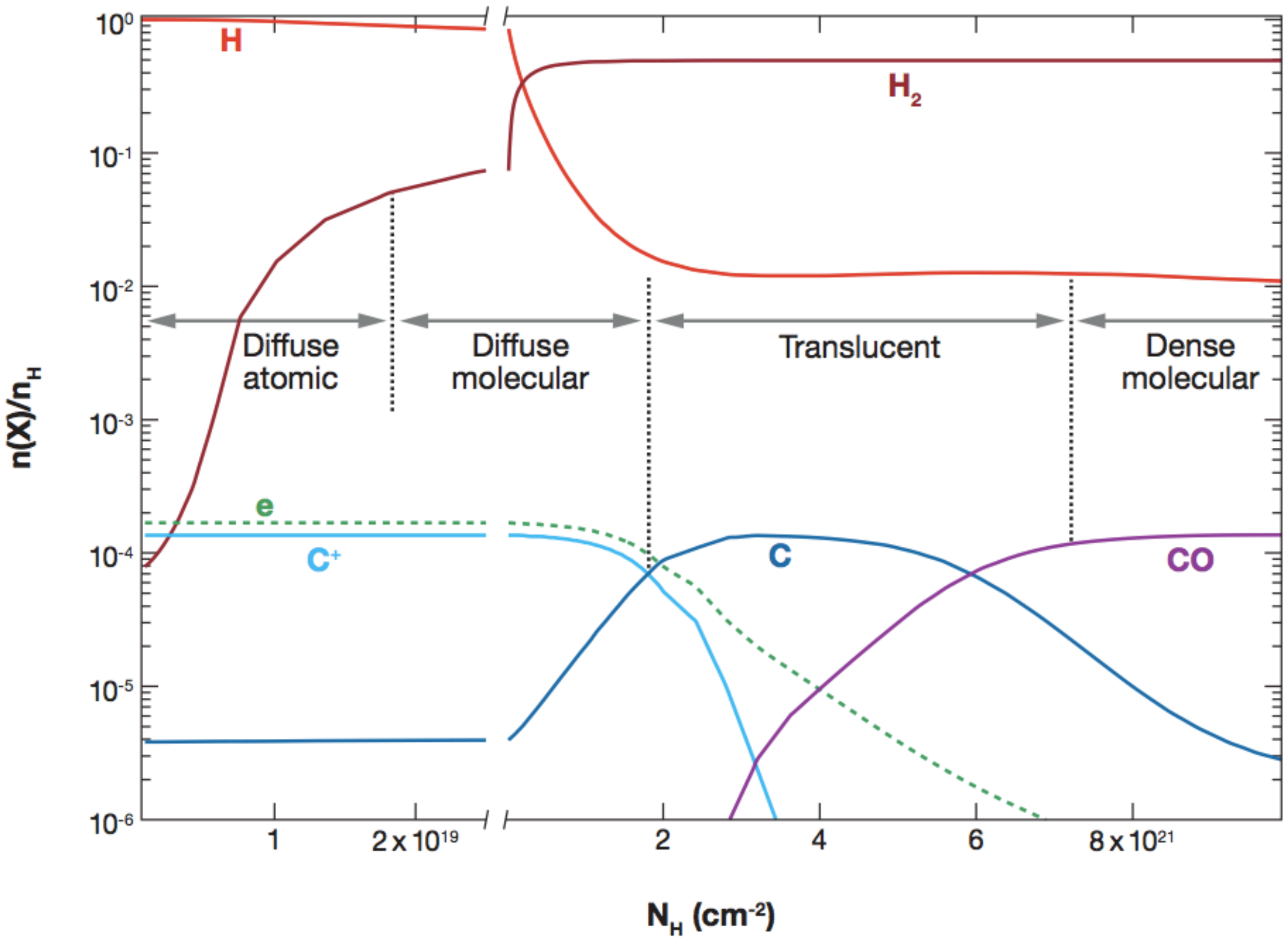
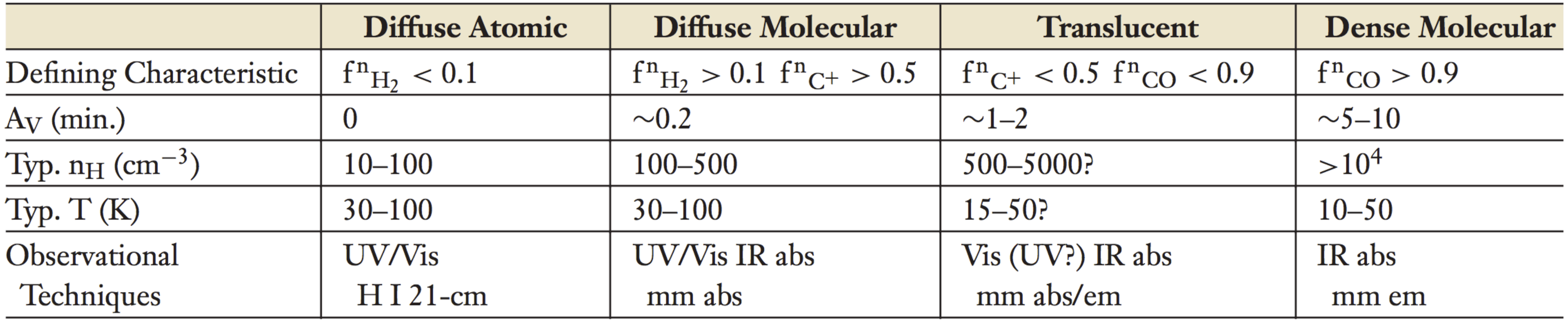
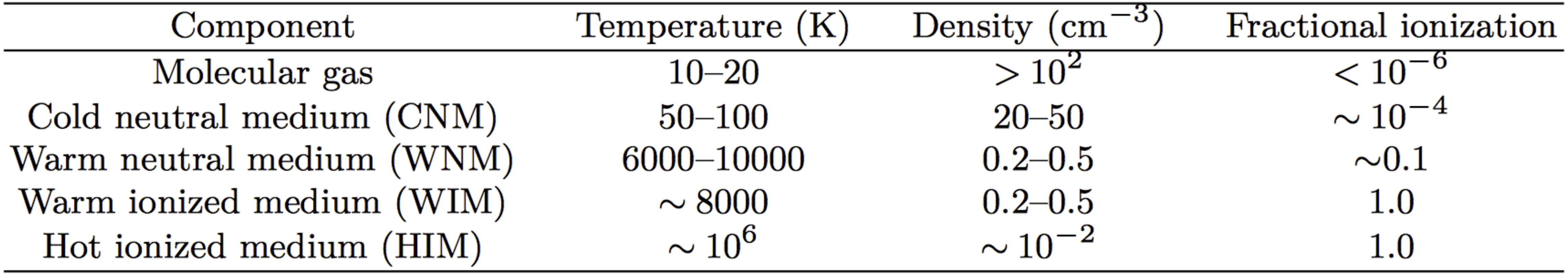


Table 1 Classification of Interstellar Cloud Types



	Diffuse Atomic	Diffuse Molecular	Translucent	Dense Molecular
Defining Characteristic	$f^n_{H_2} < 0.1$	$f^n_{H_2} > 0.1$ $f^n_{C^+} > 0.5$	$f^n_{C^+} < 0.5$ $f^n_{CO} < 0.9$	$f^n_{CO} > 0.9$
A_V (min.)	0	~0.2	~1–2	~5–10
Typ. n_H (cm^{-3})	10–100	100–500	500–5000?	$>10^4$
Typ. T (K)	30–100	30–100	15–50?	10–50
Observational Techniques	UV/Vis H I 21-cm	UV/Vis IR abs mm abs	Vis (UV?) IR abs mm abs/em	IR abs mm em

ISM phases



Component	Temperature (K)	Density (cm^{-3})	Fractional ionization
Molecular gas	10–20	$> 10^2$	$< 10^{-6}$
Cold neutral medium (CNM)	50–100	20–50	$\sim 10^{-4}$
Warm neutral medium (WNM)	6000–10000	0.2–0.5	$\sim$0.1
Warm ionized medium (WIM)	~ 8000	0.2–0.5	1.0
Hot ionized medium (HIM)	$\sim 10^6$	$\sim 10^{-2}$	1.0

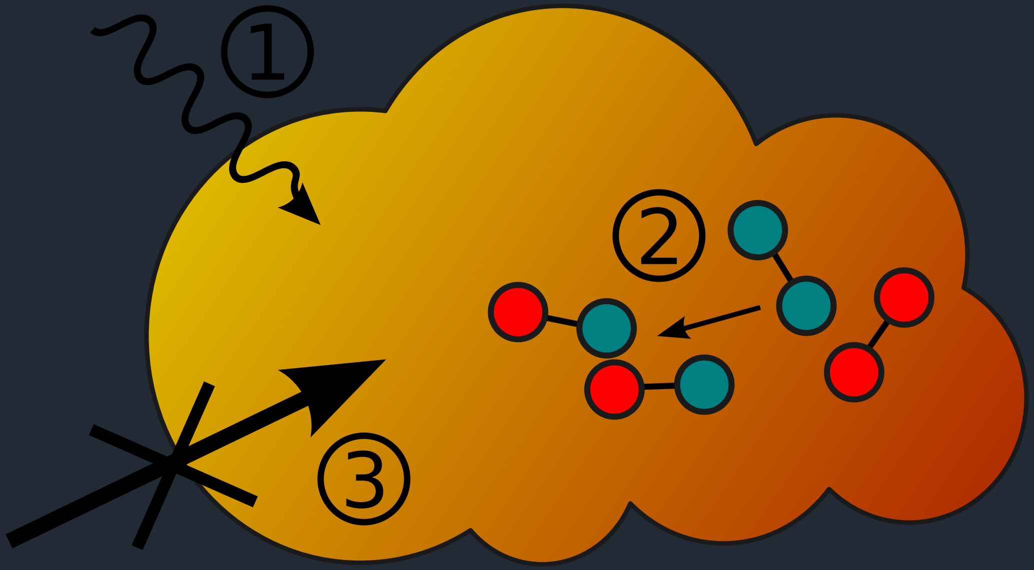
Adapted from Ferriére (2001), Caselli et al. (1998), Wolfire et al. (2003), and Jenkins (2013).

Thermal and pressure equilibrium produced when heating and cooling mechanisms in a region equilibrate at a particular temperature.

Phases are in equilibrium unless perturbed (by for instance radiation)

$$\mathscr{L} = n^2 \Lambda - n \Gamma$$

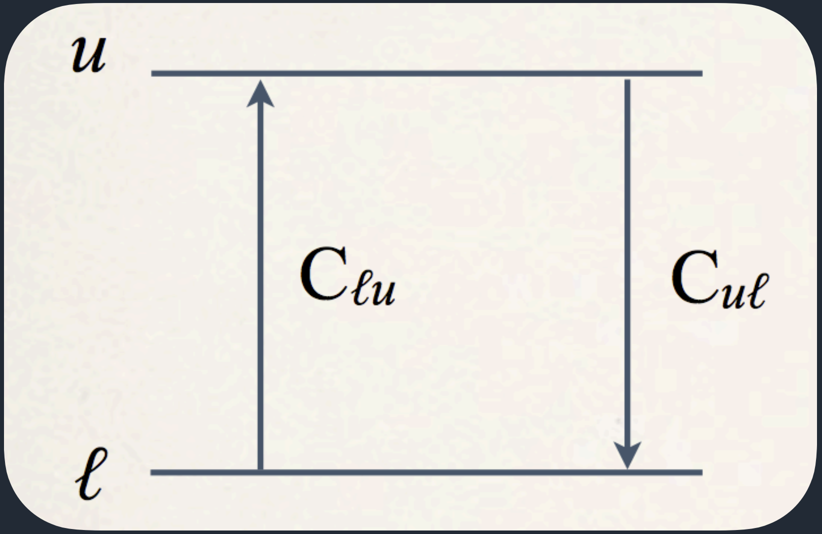
General concepts (1)



- We mean the transfer of kinetic energy to or from atoms, molecules and ions of the interstellar gas
- The principal heating is the removal of an electron from an interstellar species (gas or grain) by energetic particles or photons
- The heating is produced by the thermalization of these suprathermal electrons by elastic collisions with the gas

General concepts (2)

- Collisions force a Maxwellian distribution of velocities in the ISM
- Kinetic energy most useful characterization of the “temperature”
- Collisional de-excitation can transfer energy to the gas and heat it if the medium is dense (is less important in low-dense medium)



Main heating terms

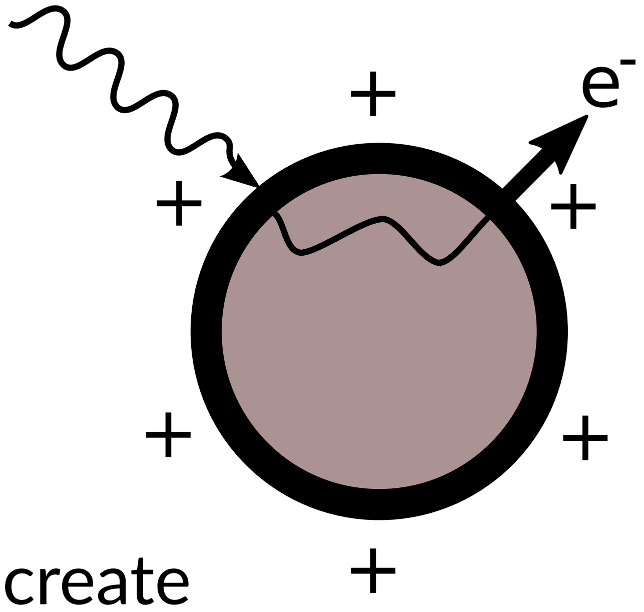
- Photoelectric heating
- Photoheating
- X-ray and CRs heating
- Gas-grain thermal exchange (heating/cooling)
- Chemical heating
- Hydrodynamical heating

Hydrodynamical heating (macroscopic)

- Gas can couple to macroscopic fluid motion
    - Turbulence (shock waves)
    - Viscous heating (e.g. ambipolar diffusion)
    - Gravitational (compressional) heating
    - Mechanical heating produced by stellar winds/SNe explosion

Photoelectric heating

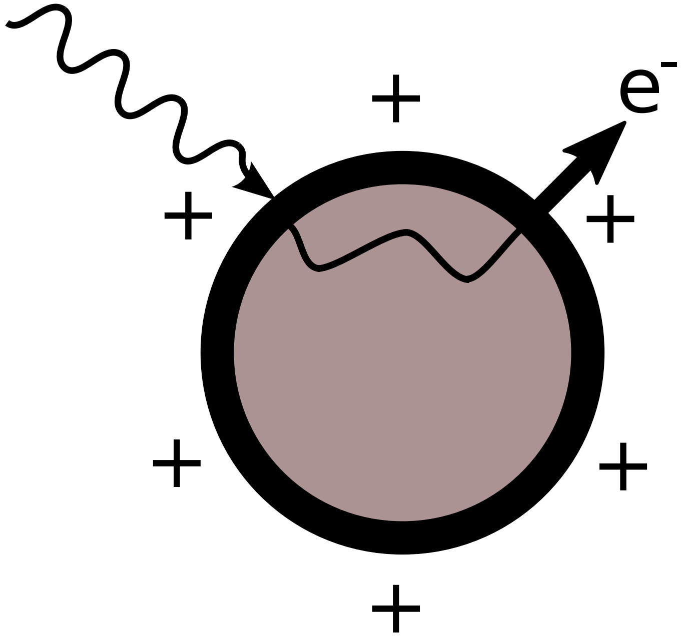
Photoelectric heating



- Most important heating process in the neutral ISM
    - Cold diffuse ISM
    - PAH and small dust grains
    - FUV photons (6-13.6 eV) absorbed by a grain will create energetic (several eV) electrons
    - Electrons then diffuse in the grain, lose energy through collisions
    - If they reach the surface with enough E they can escape

Photoelectric heating

- Energy should overcome the work function W of the grain
    - In solid-state physics work function is the thermodynamic work or energy required to remove an electron from a solid
- And the Coulomb potential (if grains are charged)



Photoelectric heating

- The ejected electrons (photoelectrons) bring energy of a few eV
  - Not enough to ionize or dissociate molecules
  - All the energy goes into heating

$$\Gamma_{\mathrm{PE}} = \boxed{\varepsilon_{\mathrm{GRAIN}}}\, n_{\mathrm{dust}} \sigma_{\mathrm{dust}}^{\mathrm{abs}} \chi$$

$$\epsilon_{\mathrm{grain}} \sim Y \left(\frac{h\nu - W - \phi_{\mathrm{c}}}{h\nu} \right)$$

Photoelectric heating

$$\Gamma_{\mathrm{PE}} = \varepsilon_{\mathrm{GRAIN}} n_{\mathrm{dust}} \sigma^{\mathrm{abs}}_{\mathrm{dust}} \chi$$

$$\chi = \frac{\int_{912}^{2050} \lambda \overbrace{u_\lambda}^{\text{photon energy density [erg/cm}^3\text{]}} d\lambda}{\int_{912}^{2050} \lambda u_\lambda^{Draine} d\lambda}$$

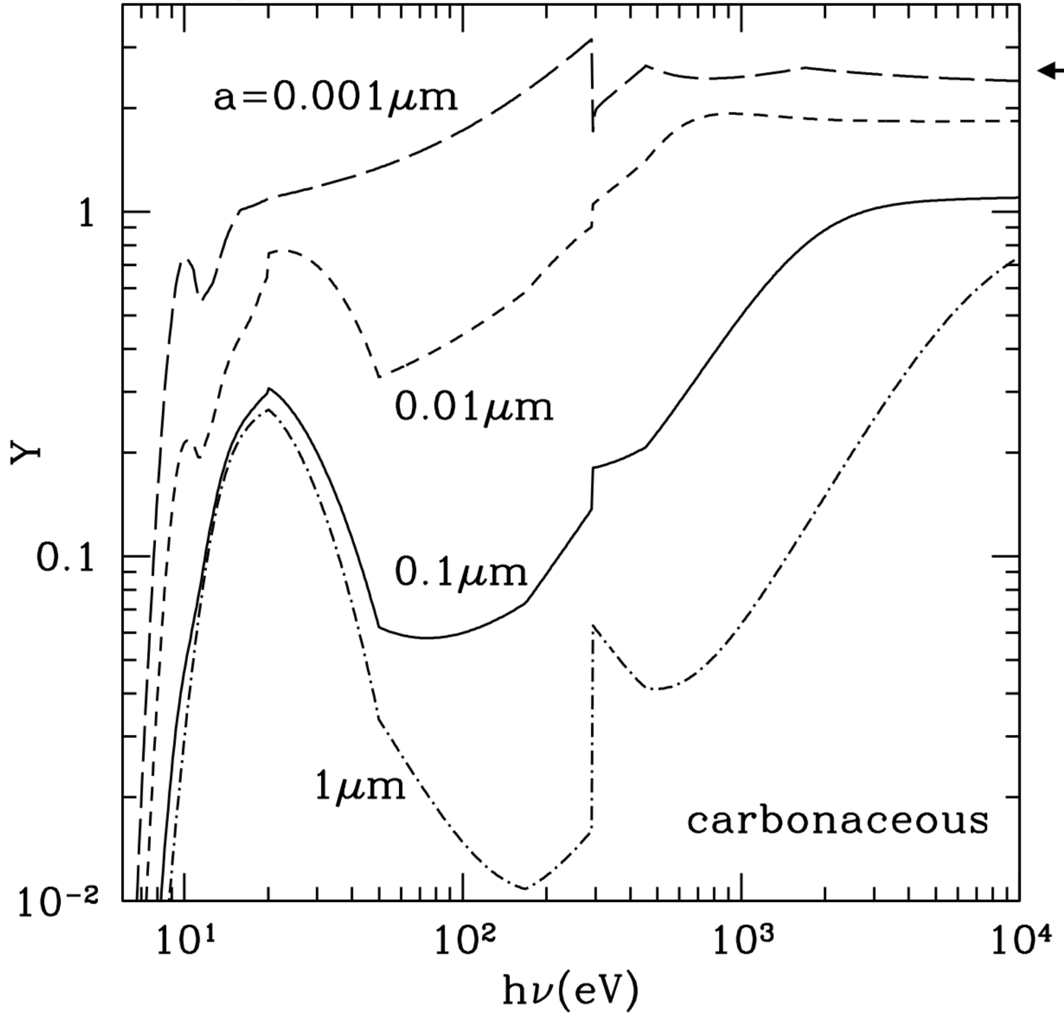
$$\epsilon_{\mathrm{grain}} \sim Y\left(\frac{h\nu - W - \phi_{\mathrm{c}}}{h\nu}\right)$$

W – work function of bulk dust material
Y – electron yield
$\varepsilon_{\mathrm{GRAIN}}$ – efficiency of heating
Φ_C – Coulomb potential of the dust grain
σ_{abs} – dust absorption cross section

- The strength of the radiation field
- The size distribution of the dust grains
- Yield: measures how many electrons escapes per photon
- The charge of the dust grains (Coulomb potential)

Photoelectric heating: Yield

Weingartner et al. (2006)



For small grains and
energetic photons,
more than 1 electron
can be ejected.

PE yield for uncharged carbonaceous grains of various sizes for different absorbed photon energies.

Photoelectric heating: Recombination

$$
\begin{aligned}
\mathrm{GR}^{+(n)} + \gamma &\rightarrow \mathrm{GR}^{+(n+1)} + \mathrm{e}^- \\
\mathrm{GR}^{+(n)} + \mathrm{e}^- &\rightarrow \mathrm{GR}^{+(n-1)} \\
\mathrm{GR}^{+(n)} + \mathrm{A}^+ &\rightarrow \mathrm{GR}^{+(n+1)} + \mathrm{A}
\end{aligned}
$$

$$\boxed{\Lambda_{rec} = 3.49 \times 10^{-30} T^{0.944} (\chi T^{1/2}/n_e)^{0.735 T^{-0.068}} n_e n_{\mathrm{H}}\ \mathrm{erg\,s^{-1}\,cm^{-3}}.}$$

Photoelectric heating

Charging parameter

$$\gamma = \left(\frac{G_0 T_{gas}^{1/2}}{n_e} \right)$$

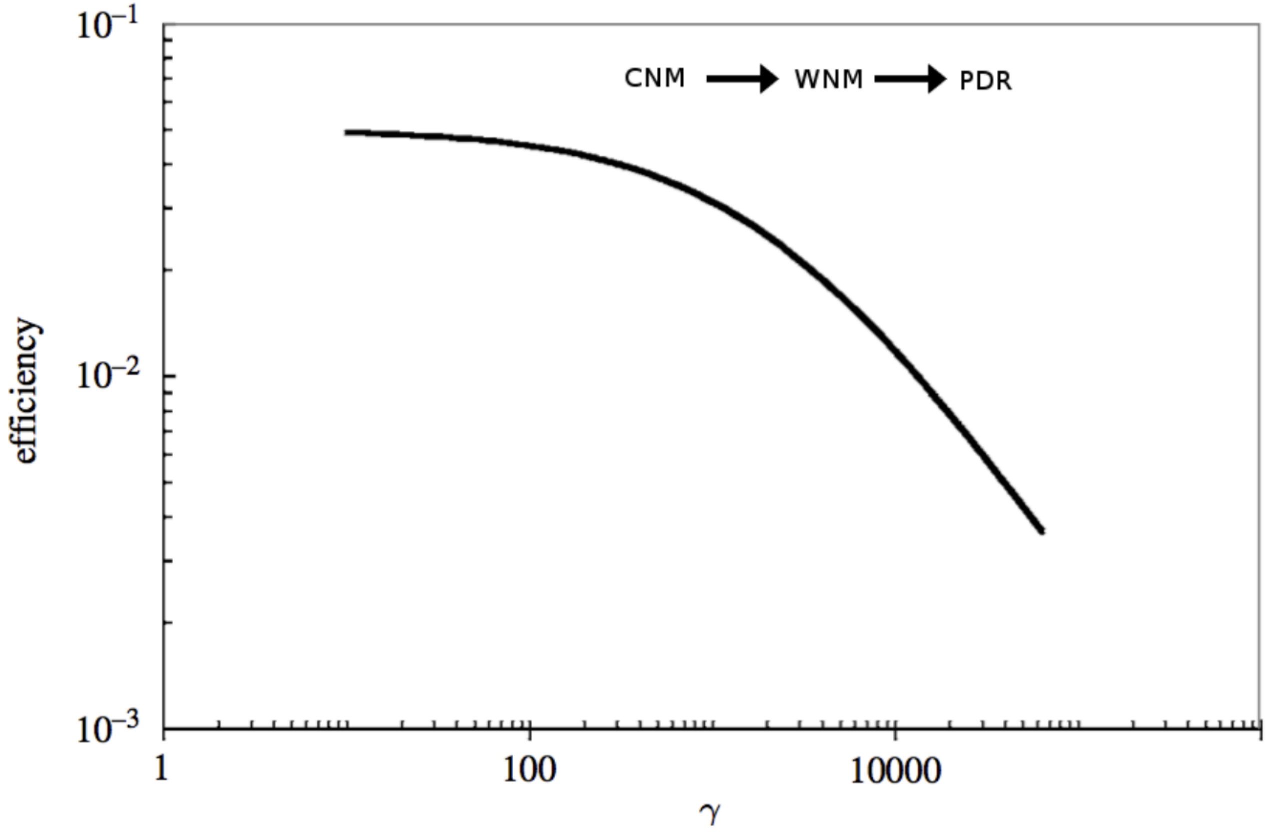
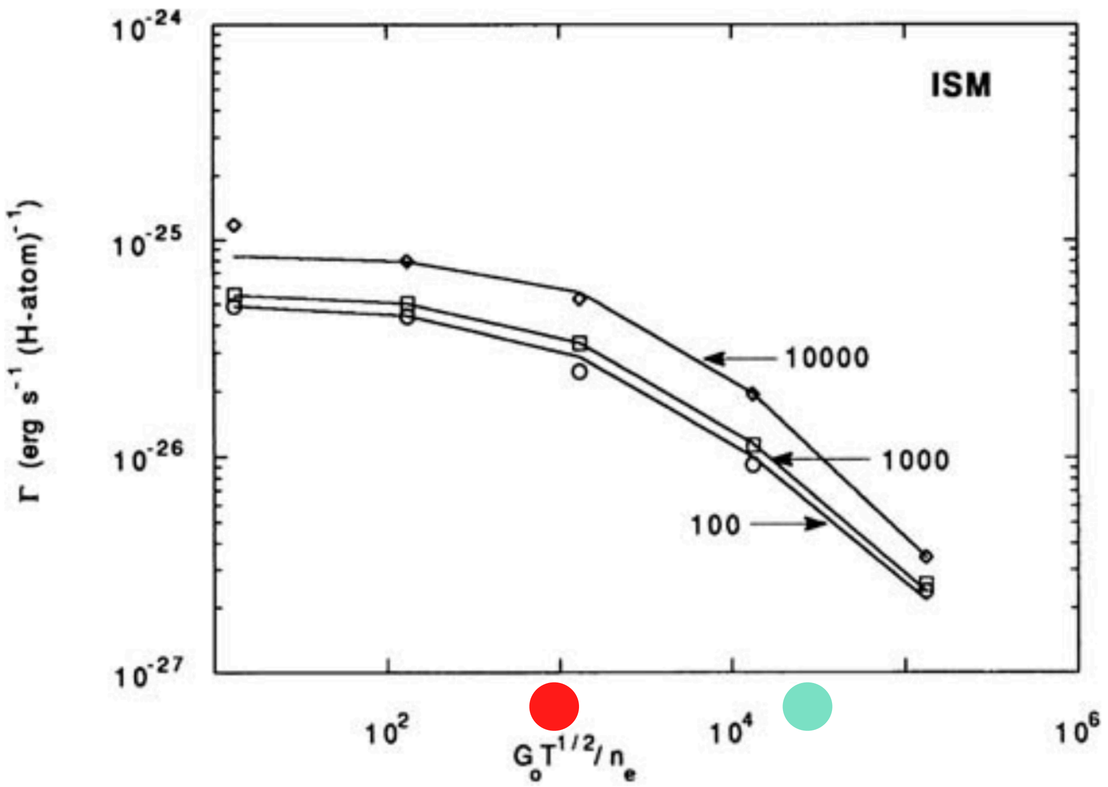
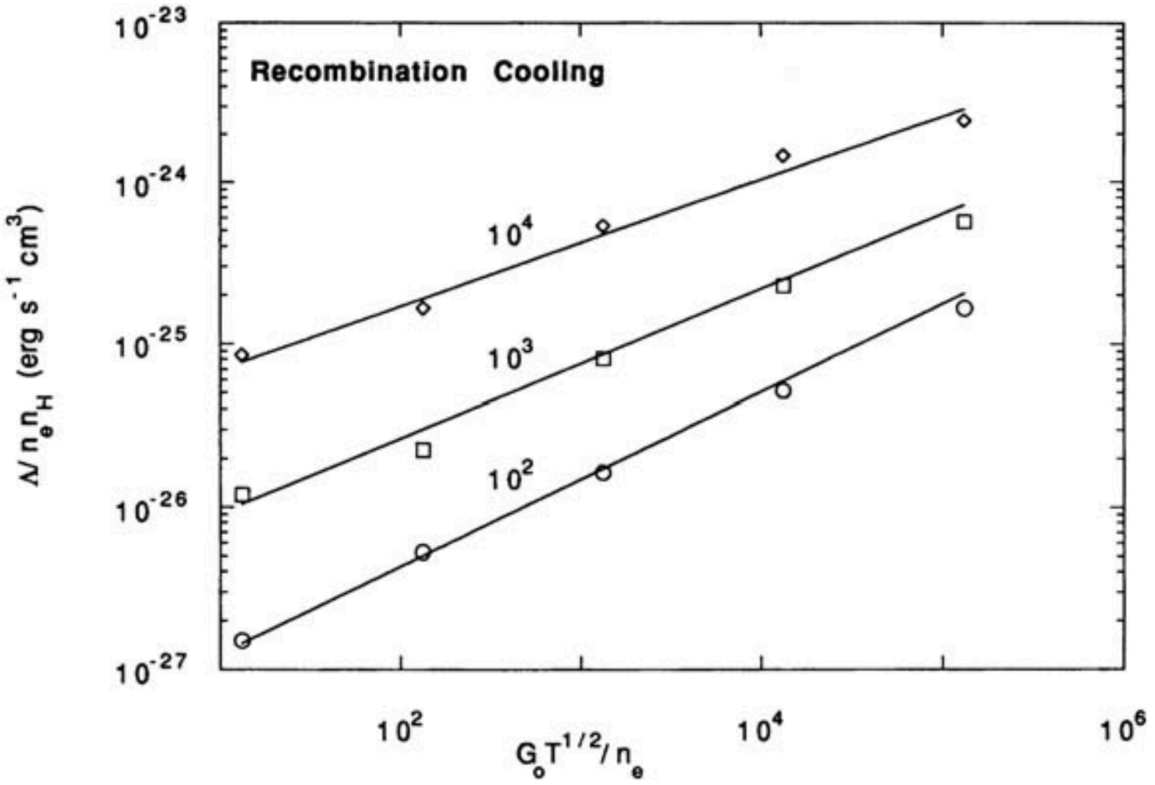


Photo-electric heating efficiency

- Grain charge is a balance between photo-ionization and electron recombination
- Charge severely reduces the photoelectric heating

Photoelectric heating





CNM, G0=1, T=100, n~25 cm^{-3}, $x_e = n_e/n_H = 3 \times 10^{-4}$

WIM, G0=1, T=8000, n~0.25 cm^{-3}, $x_e = n_e/n_H = 10^{-2}$

Dense regions PE completely negligible, UV do not penetrate G0 ~ 0

PE dominates the medium

PE balanced by RC

Photoheating

- Ionizations of atoms induced by FUV radiation liberates electrons
- Energy of these photoelectrons is

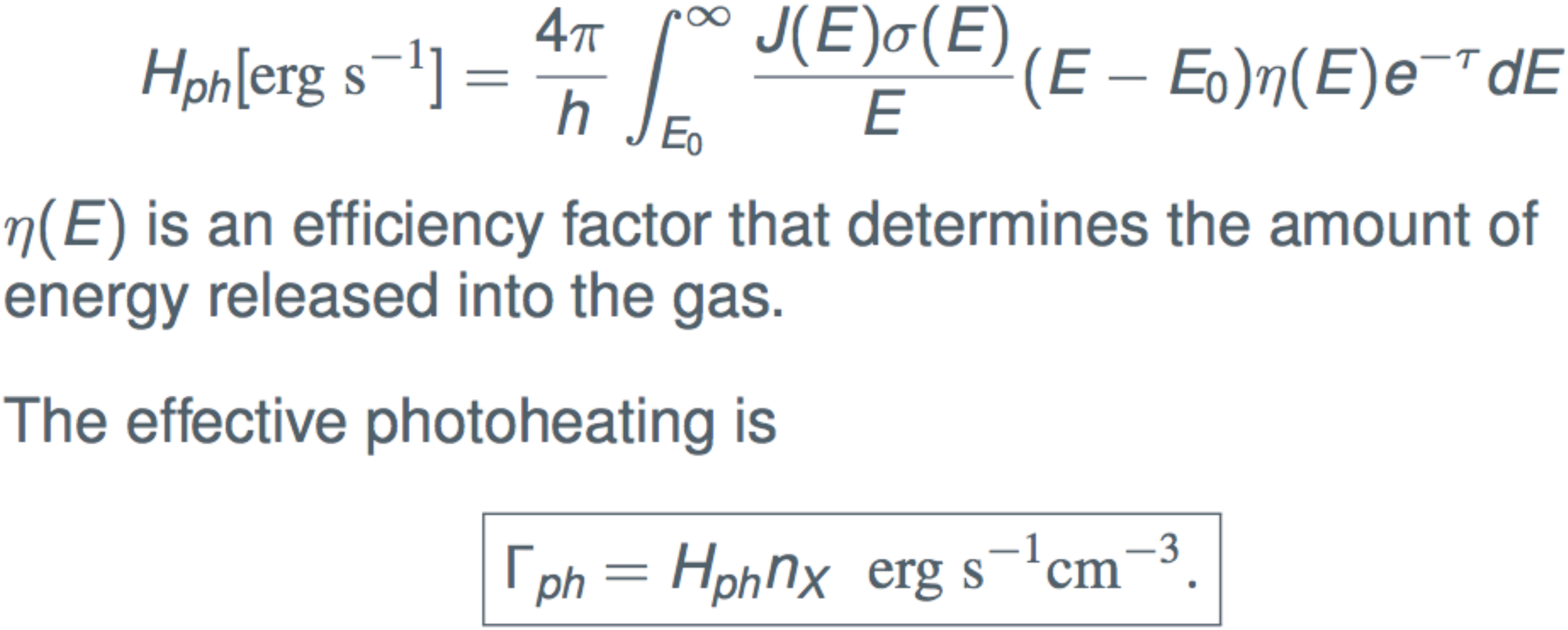
$$(h\nu - E_0).$$

$$\begin{aligned} \mathrm{A}^{+\mathrm{n}} \quad &+ \quad h\nu \rightarrow \mathrm{A}^{+(\mathrm{n}+1)} + \mathrm{e}^{-} \\ \mathrm{AB} \quad &+ \quad h\nu \rightarrow \mathrm{AB}^{+} + \mathrm{e}^{-} \end{aligned}$$

Photoheating

- It is mainly caused by
    - Atoms photoionization in HII regions (E > 13.6 eV)
    - Photoionization of large molecules and small dust grains in HI regions (E < 13.6 eV), carbon (IP: 11.2 eV, but negligible)
    - A different mechanism: molecules photodissociations in molecular regions $\mathrm{AB} \quad + \quad h\nu \rightarrow \mathrm{A} + \mathrm{B}$

Photoheating



$$H_{ph}[\mathrm{erg\ s^{-1}}] = \frac{4\pi}{h}\int_{E_0}^{\infty}\frac{J(E)\sigma(E)}{E}(E-E_0)\eta(E)e^{-\tau}dE$$

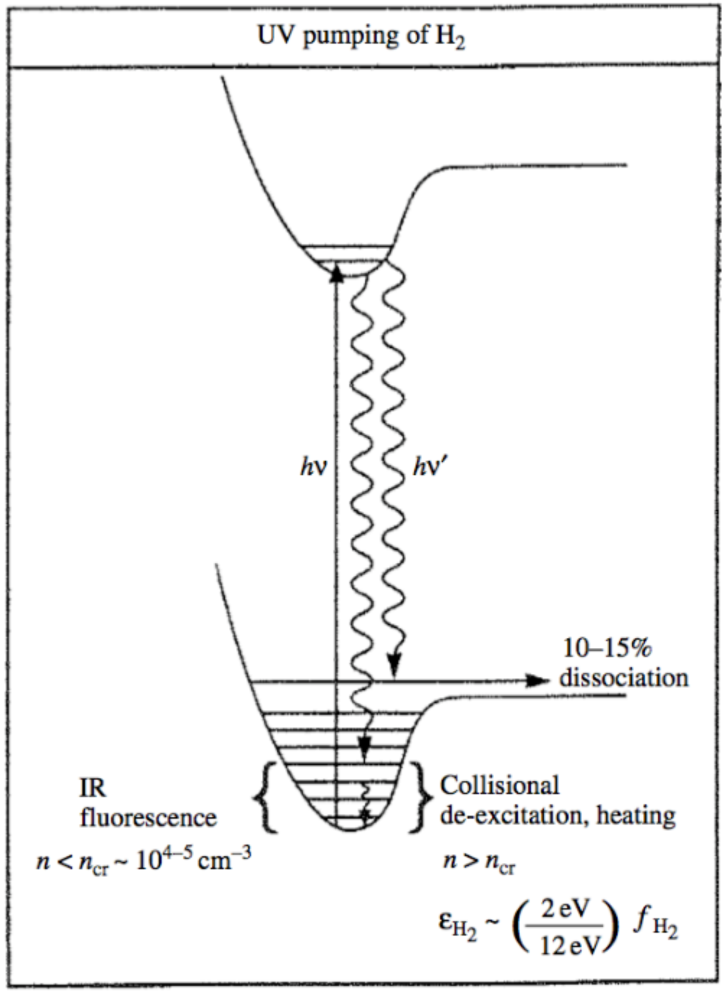
$\eta(E)$ is an efficiency factor that determines the amount of energy released into the gas.

The effective photoheating is

$$\boxed{\Gamma_{ph} = H_{ph}n_X \ \ \mathrm{erg\ s^{-1}cm^{-3}}.}$$

Photoheating (H_2 case)

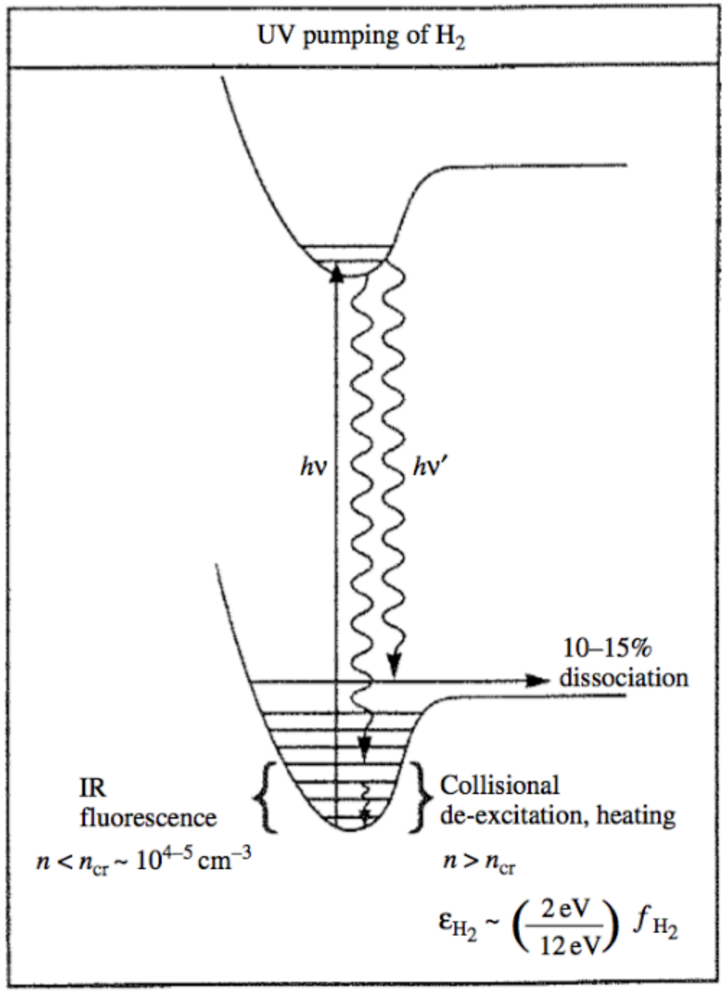
$$H_2 + h\nu \rightarrow H_2^* \rightarrow H + H$$



- Fragments carry away some of the photon energy as kinetic energy
- Collisional de-excitation of re-formed or in general excited H_2 molecules can de-excited and additionally heat the gas

Photoheating (H_2 case)

$$\boxed{\mathrm{H_2} + \mathrm{h}\nu \rightarrow \mathrm{H_2^*} \rightarrow \mathrm{H} + \mathrm{H}}$$



- Lyman-Werner bands (11.2-13.51 eV)
- 0.4 eV → 6.4×10^{-13} erg per dissociation (kinetic energy)
- 2.2 eV → 3.5×10^{-12} erg due to vibrational de-excitation

$$\boxed{\Gamma^{UV}_{pd_1} = 9R_{pd}(\mathrm{H_2})\{3.5 \times 10^{-12}\,[1 + n_{cr}/n]^{-1}\}n_{\mathrm{H_2}}}$$

$$\boxed{\Gamma^{UV}_{pd_2} = 6.4 \times 10^{-13} R_{pd}(\mathrm{H_2})\eta n_{\mathrm{H_2}}}$$

$$\boxed{\Gamma^{tot}_{pd} = \Gamma^{UV}_{pd_1} + \Gamma^{UV}_{pd_2}} \rightarrow \text{total heating}$$

- $\eta = 0.1$ (only 10% of the molecules dissociate)

X-ray

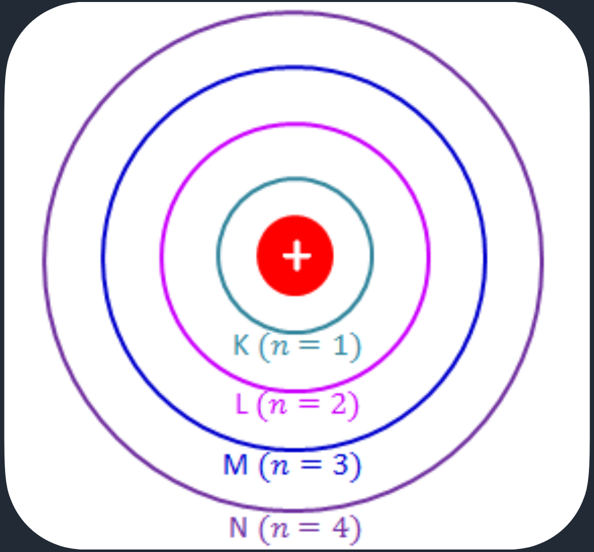
- Hot gas in the ISM ($T > 10^6$ K)
  - Its existence suggested by Spitzer as early as 1956
  - 1968: Bowyer diffuse emission in soft X-rays (< 1 keV)
  - 1974: Jenkins & Meloy and York observed O VI features (COPERNICUS satellite), establishment of the hot ISM phase
  - Inoue, Schnopper, Sanders interstellar X-ray lines OVII, OVIII

X-ray

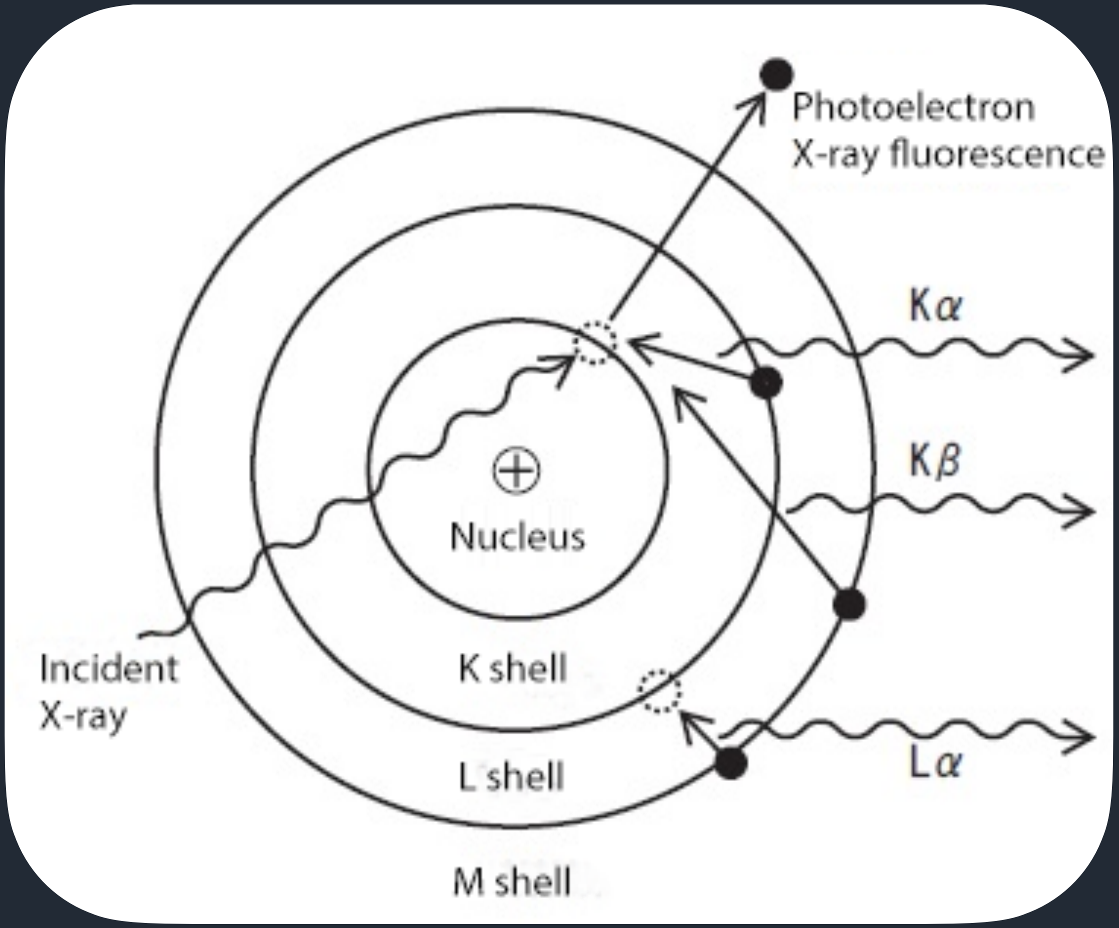
- This hot gas comes from SNRs and bubbles
- Shock-heated by stellar winds and blast waves by novae and SNe
- $T > 10^{5.5}$ K and $n \sim 0.004$ cm^{-3}
- Most of the ionization in this gas comes from collisions (O VI needs 114 eV)
- The suprathermal electrons thermalize very rapidly
- These electrons induce other ionization

X-ray fluorescence

- Multielectrons atoms have multiple shells
    - i.e. orbits
    - Correspond to a given principle quantum number n
    - n = 1, shell K, n=2 shell L, n=3, shell M



X-ray fluorescence



- When illuminated by X-ray photons atom produce X-ray absorption spectrum but not absorption lines
- The hole left in the K layer after an electron has been ejected can be filled by an electron from an outer layer
- This produce emission of a X-ray photon

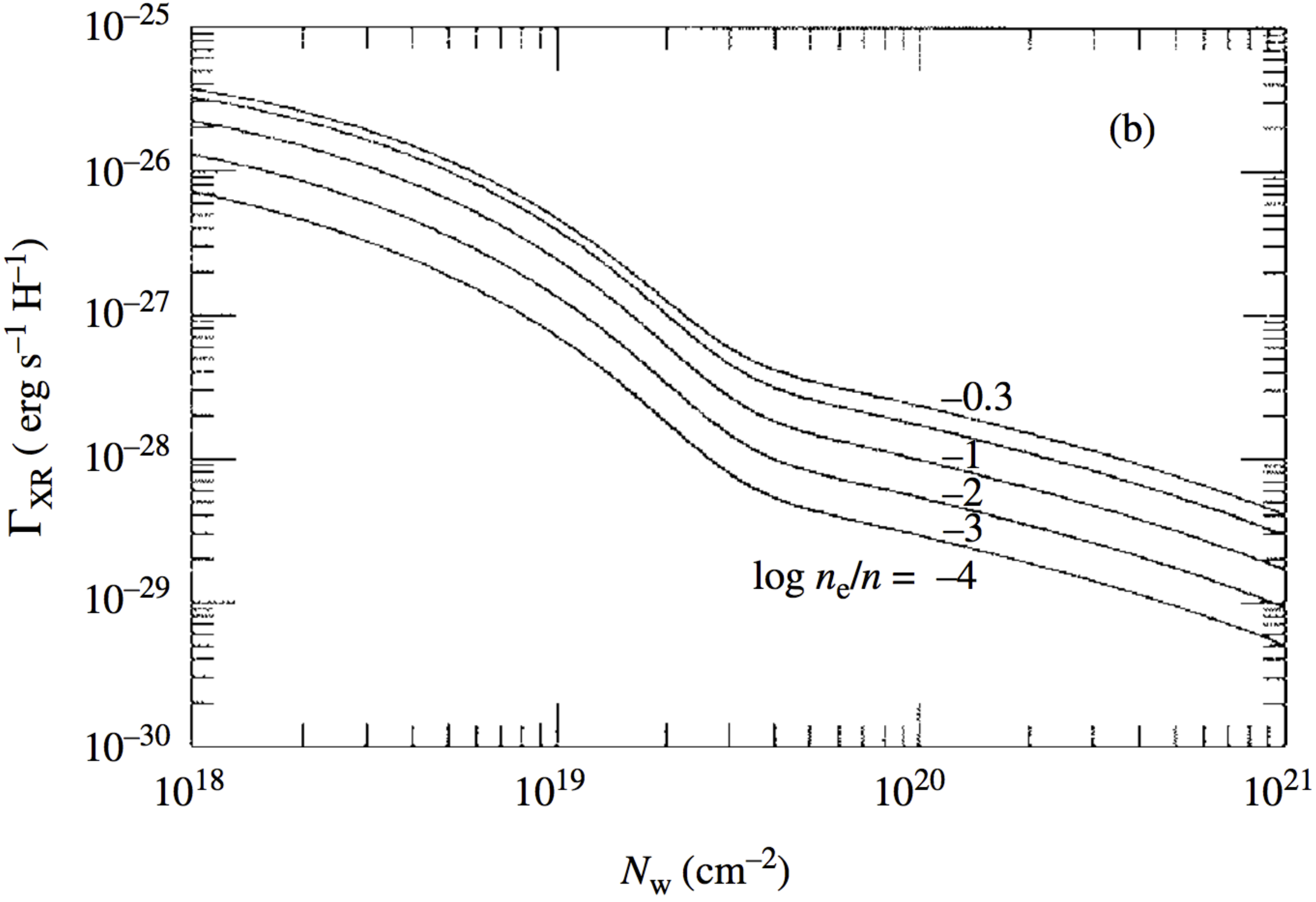
X-ray heating

- The primary photoelectrons emitted from K shells thermalize with the surrounding gas and heat the gas
- This photoelectrons can cause secondary ionization and liberate other electrons
- The secondary electrons represent an extra heating

X-ray heating

- Heating by X-ray radiation is not efficient for the cold atomic medium (relatively high column density)
- Very efficient for the warm, less dense atomic medium
- Completely neglected in MCs where soft X-rays cannot penetrate
- It is very efficient near to X-ray sources, SNRs and pre main-sequence stars

X-ray heating



Cosmic-rays

- Low energy CRs (~1-100 MeV) are most efficient in ionizing and heating the gas
- Every CR process releases ~ 35 eV of energy
    - Heating
    - Secondary ionization

Cosmic-rays

$$\boxed{\Gamma^i_{CR} = Qk_i^{cr} n_i} \rightarrow \boxed{\Gamma^i_{CR} = Q\alpha_i \xi_{cr} n_i}$$

- great uncertainty in the fraction of heating
- it varies depending on the environment (if neutral or ionized)
  - $Q = 7.7$ eV at 2 MeV → Glassgold & Langer 1973
  - $Q = 6.6$ eV at 2 MeV → Cravens & Dalgarno 1978
  - $Q = 6 - 35$ eV → Shull & van Steenberg 1985
  - $Q = 7.0$ eV → Stahler & Palla 2004
  - $Q = 20$ eV → Goldsmith 2001
  - $Q = 13$ eV → Glassgold, Galli, & Padovani 2012
- uncertainty also on ξ_{cr}
  - $\xi_{cr} = 1 - 2 \times 10^{-17}\ \mathrm{s}^{-1}$ → a kind of standard

Cosmic-rays

Photoheating

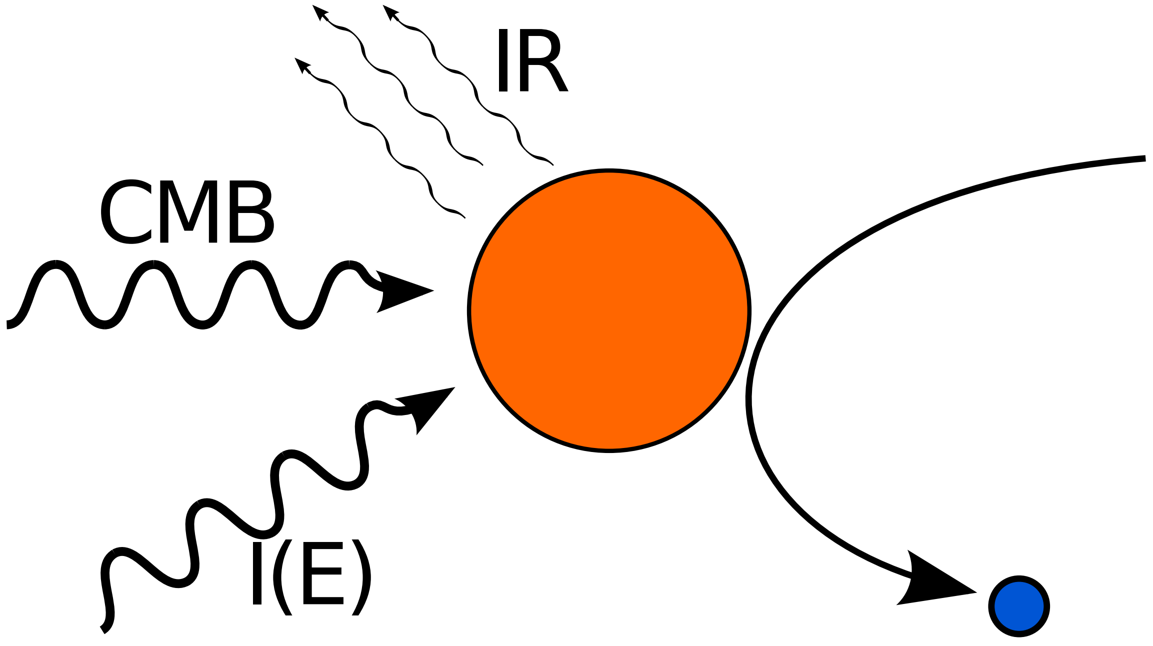
$$\boxed{\Gamma_{ph} = H_{ph} n_X \;\; \mathrm{erg\ s^{-1} cm^{-3}}.}$$

Cosmic ray heating

$$\boxed{\Gamma_{cr} \sim 3.2 \times 10^{-28} \frac{\zeta_{\mathrm{H}}}{10^{-17}} n_{\mathrm{H}} \;\; \mathrm{erg\ s^{-1} cm^{-3}}}$$

Gas-grain

- In the ISM dust and gas are not in thermodynamical equilibrium
- Quite often different temperatures



$$\Gamma_{\rm em} = \Lambda_{\rm g\rightarrow d} + \Gamma_{\rm CMB} + \Gamma_{\rm abs}$$

Gas-grain

- Mean flux of kinetic energy from gas which strikes the grain is $E = 2kT$ for a Maxwellian distribution
- Particles which struck the grain leave the grain with a different mean kinetic energy @ a temperature T_2 which is intermediate between T_d and T.

Gas-grain: accommodation coefficient

every collision gives to the gas a mean energy:

$$E = 2\alpha k(T_d - T_g) \longrightarrow \boxed{\alpha = \frac{T_2 - T_g}{T_d - T_g}}$$

how efficiently energy is shared between the dust and the gas

Accommodation coefficient of unity corresponds to a bouncing particle that has completely thermalized and leaves with $2kT_d$

Gas-grain: heating rate

$$\Gamma_{gas,grains} \simeq n_{\mathrm{H}} n_d \sigma_d \left(\frac{8kT}{\pi m_{\mathrm{H}}}\right)^{1/2} \alpha 2k(T_d - T) \text{ erg s}^{-1}\text{ cm}^{-3}$$

$$\tau_C = n_{\mathrm{H}} n_d \sigma_d v_{th}$$

it depends on

- nature of dust grains
- nature of colliders
- T_g and T_d

In literature

- $\alpha = 0.3$ fully molecular gas[4]
- $\alpha = 1$ common

Note: if gas warmer than dust (e.g. diffuse ISM or PDRs) this becomes a cooling process

Gas-grain: order of magnitudes analysis

$$n_d\sigma_d \simeq 1.5 \times 10^{-21} n_{\mathrm{H}}\ \mathrm{cm}^{-1}$$

$$\boxed{\Gamma_{gas,grains} \simeq 1.6 \times 10^{-33} n_{\mathrm{H}}^2 T^{1/2} (T_d - T)\ \mathrm{erg\,s^{-1}\,cm^{-3}},}$$

$$\boxed{\Gamma_{pe} = 10^{-24} \epsilon \chi n_{\mathrm{H}}\ \mathrm{erg\,s^{-1}\,cm^{-3}},}$$

@ 10 K and X = 1 $\Gamma_{gas,grains}/\Gamma_{pe} = 1.3 \times 10^{-7} n_{\mathrm{H_2}} (T - T_d),$

Gas-grain collisions are unimportant if the UV field is not very small

Gas-grain

- At high densities collisions between atoms/molecules and dust grains are frequent
    - Energy transfer is efficient
- In the neutral diffuse medium: grains always colder than gas
    - Can only cool it
    - Process inefficient because density is low

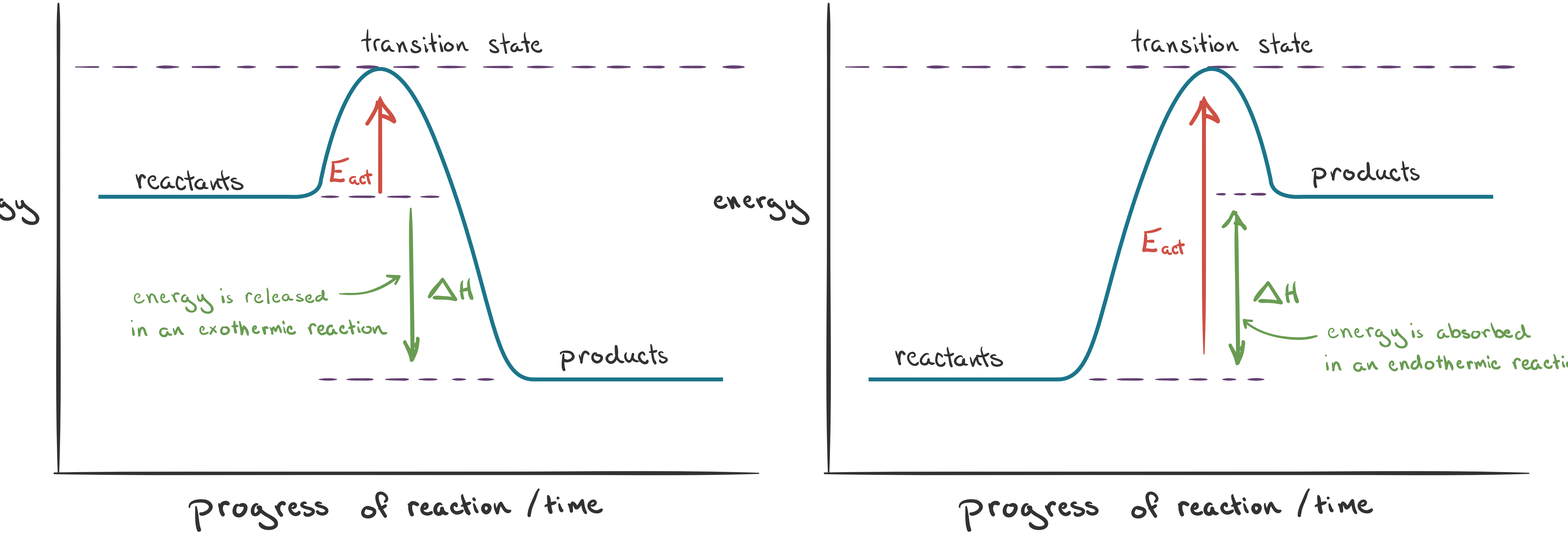
Gas-grain

- Heating of grains by the gas is unimportant in HII regions
  - These regions are dominated by UV radiation
- Diffuse ionized medium is also negligible
  - Because of the low-densities
- SNRs thermal exchange is dominant
  - Gas temperature high and density is larger

Gas-grain

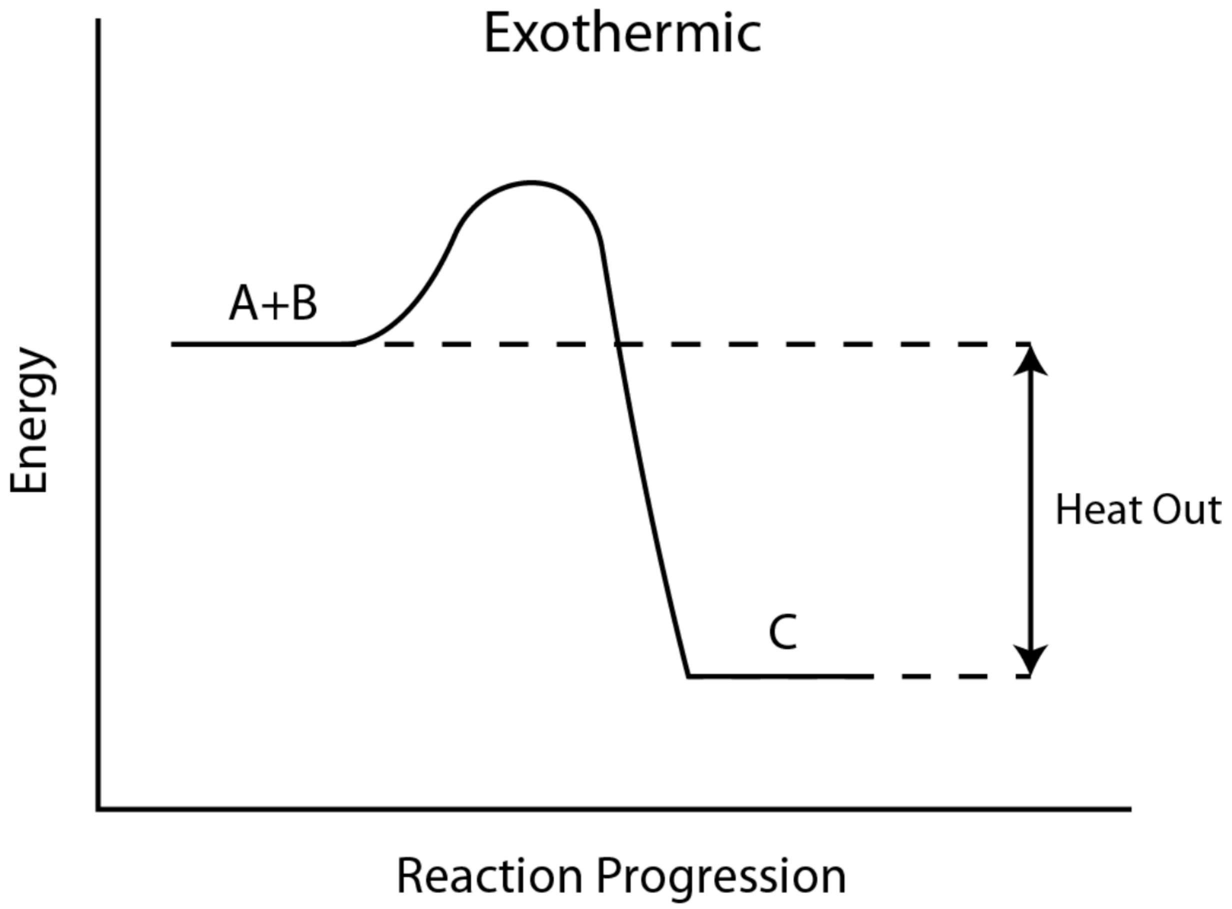
- Deep regions of GMCs grains are heated by IR radiation
    - IR radiation penetrates, grain temperature ~ 8 K
    - Grain can heat the gas if the density is large enough

Chemical heating



$$A + B \leftrightarrow C + D + \Delta E$$

Chemical heating



The energy can be released as:

- translation energy of the newly formed molecule

- ro-vibrational excitations

Heating occurs via:

- collisional de-excitations
- simple collisions

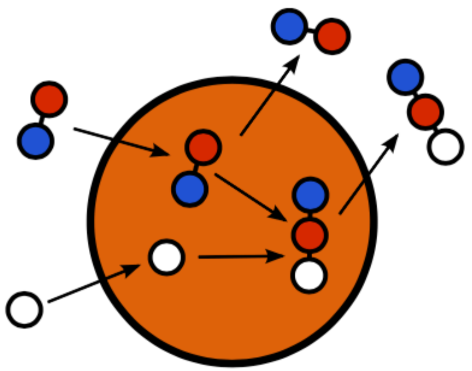
Chemical heating

$$A + B \xrightarrow{k_i} C + \Delta\mathrm{H}$$

$$\boxed{\Gamma_{chem} = k_i n_A n_B \epsilon_i \Delta\mathrm{H}}$$

$$\begin{aligned}
\mathrm{H^-} + \mathrm{H} &\rightarrow \mathrm{H_2} + \mathrm{e^-} + 3.53\ \mathrm{eV} \\
\mathrm{H_2^+} + \mathrm{H} &\rightarrow \mathrm{H_2} + \mathrm{H^+} + 1.83\ \mathrm{eV} \\
\mathrm{H} + \mathrm{H} + \mathrm{H} &\rightarrow \mathrm{H_2} + \mathrm{H} + 4.48\ \mathrm{eV} \\
\mathrm{H_2} + \mathrm{H} + \mathrm{H} &\rightarrow \mathrm{H_2} + \mathrm{H_2} + 4.48\ \mathrm{eV} \\
\mathrm{H} + \mathrm{H} + \mathrm{GR} &\rightarrow \mathrm{H_2} + \mathrm{GR} + 4.48\ \mathrm{eV}
\end{aligned}$$

Chemical heating: an example

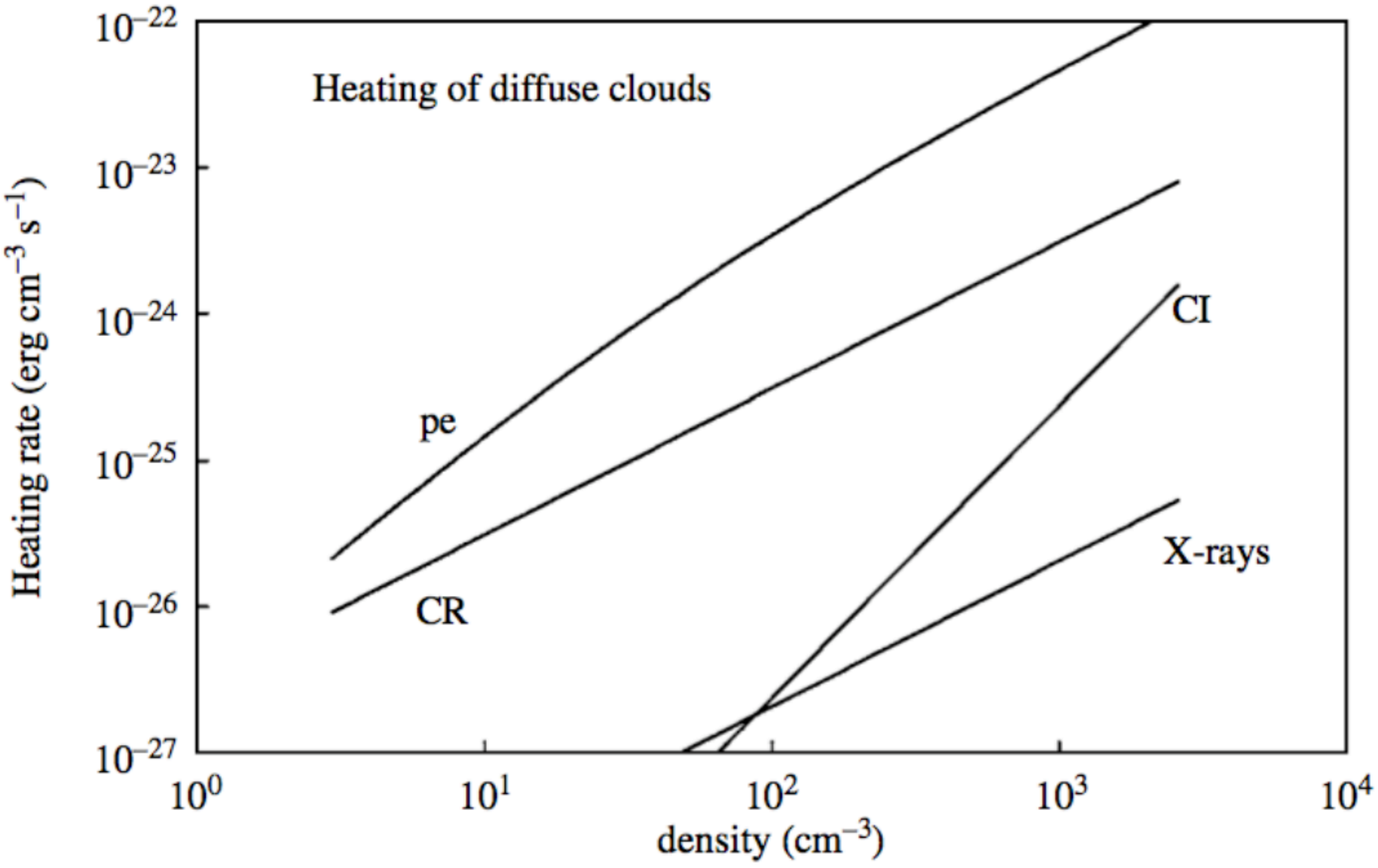


$$\boxed{\mathrm{H} + \mathrm{H} + \mathrm{GR} \rightarrow \mathrm{H}_2 + \mathrm{GR} + 4.48\ \mathrm{eV}}$$

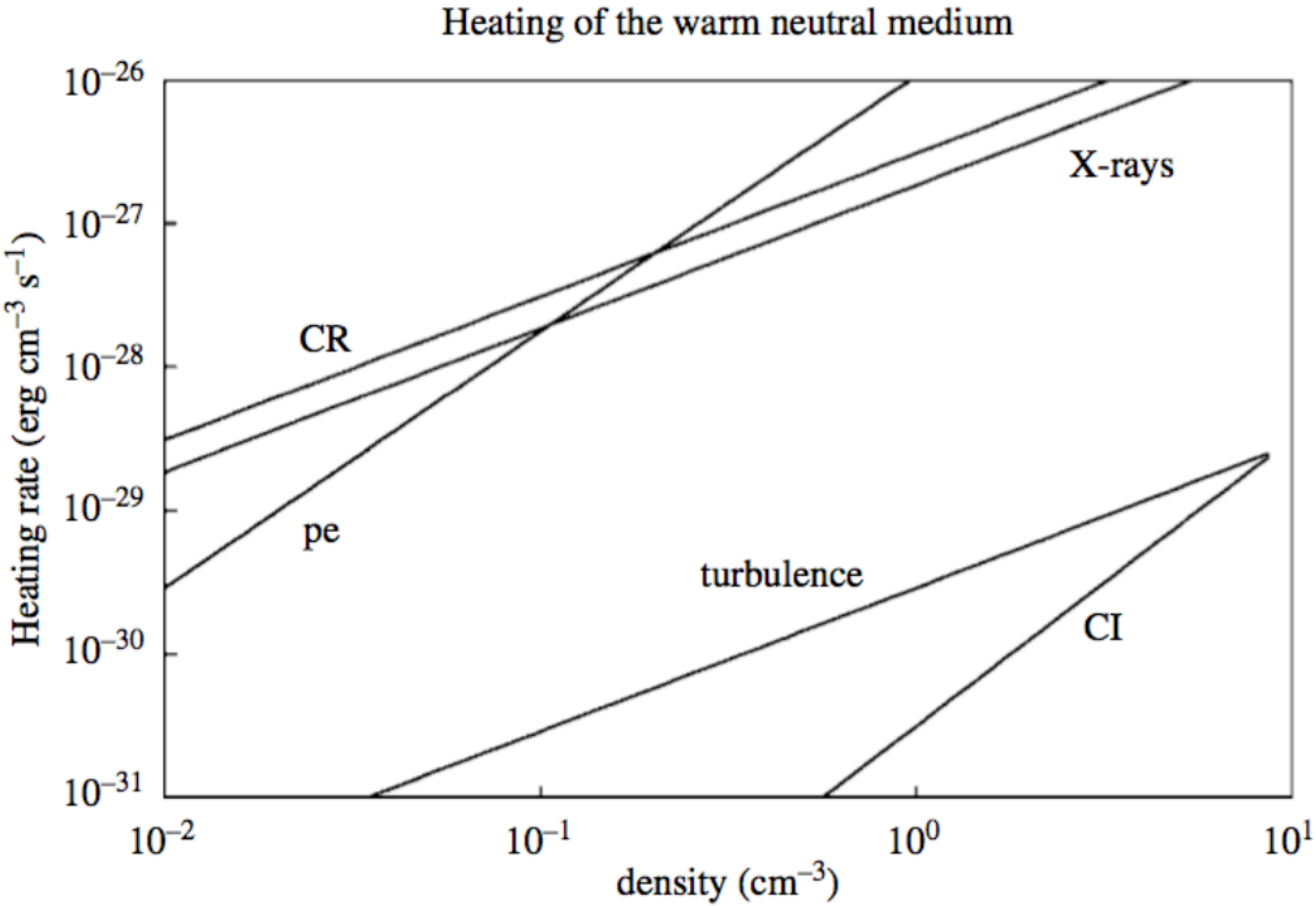
- most relevant process
- energy distributed as following
    - 0.2 eV as kinetic energy
    - 4.2 eV in roto-vibrational state of H_2
    - heating of grain negligible

$$\boxed{\Gamma^{d}_{\mathrm{H}_2} = R_f(0.2 + 4.2\epsilon) n_{tot} n_{\mathrm{H}}}$$

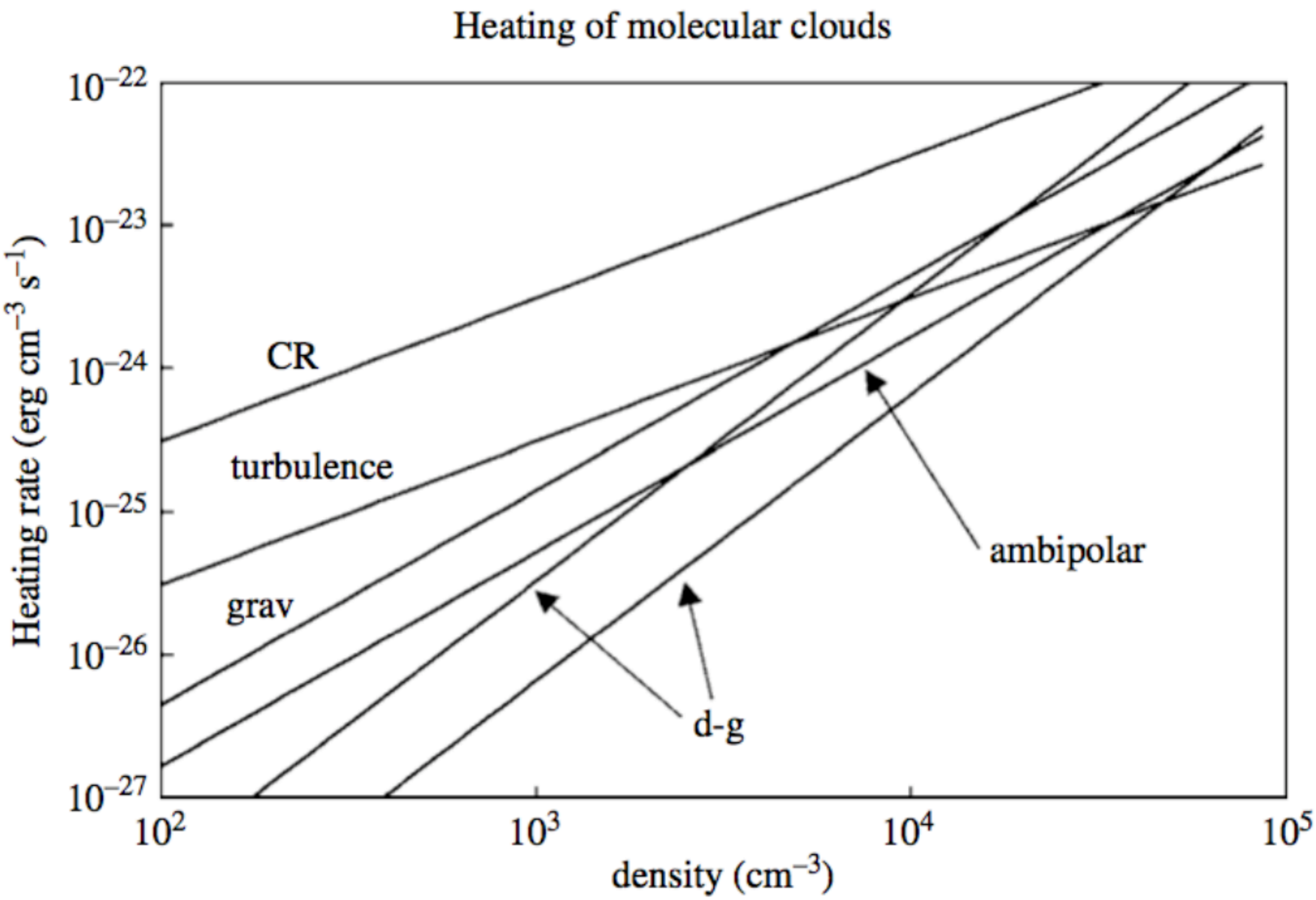
$T = 100$ K, $G_0 = 1$, $x_e = 1.2 \times 10^{-4}$



$T = 8000$ K, $G_0 = 1$, $x_e = 3 \times 10^{-3}$, $\xi_{cr} = 2 \times 10^{-16}$ s^{-1}



$T = 10$ K, no FUV/X-rays rad, $x_e = 1 \times 10^{-7}$



ISM phases

$$A_v = \frac{N_{\mathrm{H}}}{2 \times 10^{21}} \,\mathrm{mag\,cm^{-2}}$$

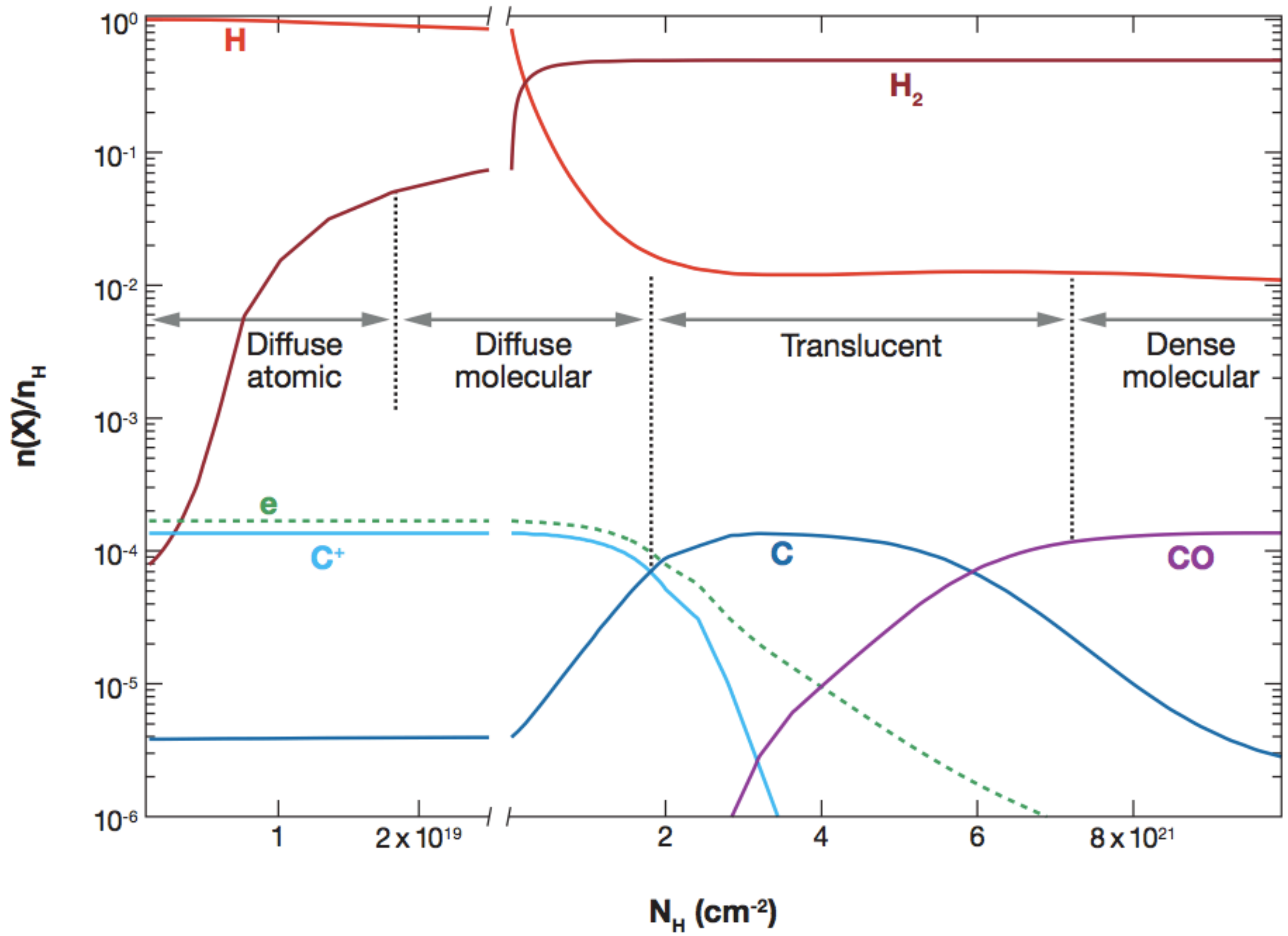


Table 1 Classification of Interstellar Cloud Types

	Diffuse Atomic	Diffuse Molecular	Translucent	Dense Molecular
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A_V (min.)	0	~0.2	~1–2	~5–10
Typ. n_H (cm^{-3})	10–100	100–500	500–5000?	>10^4
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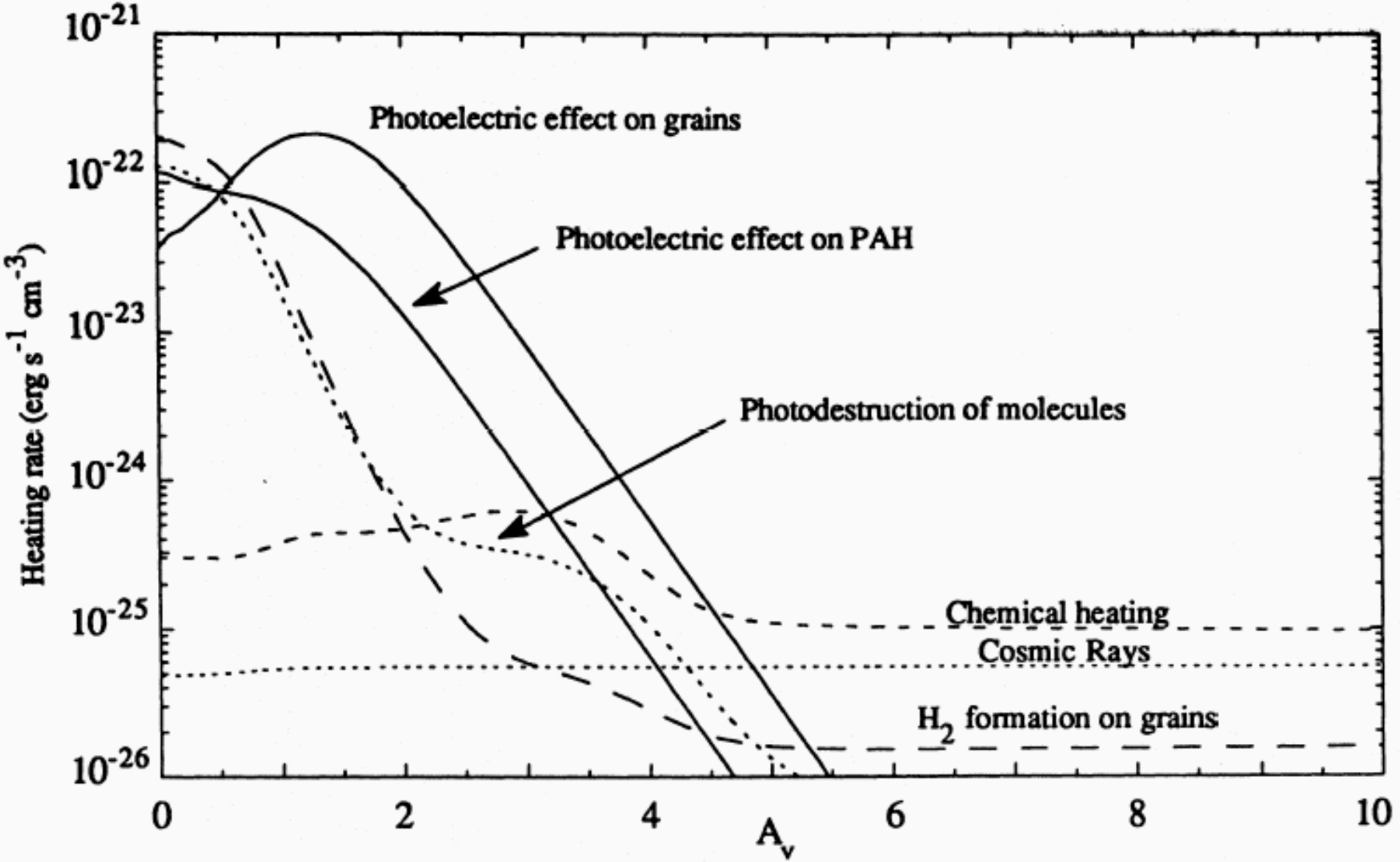
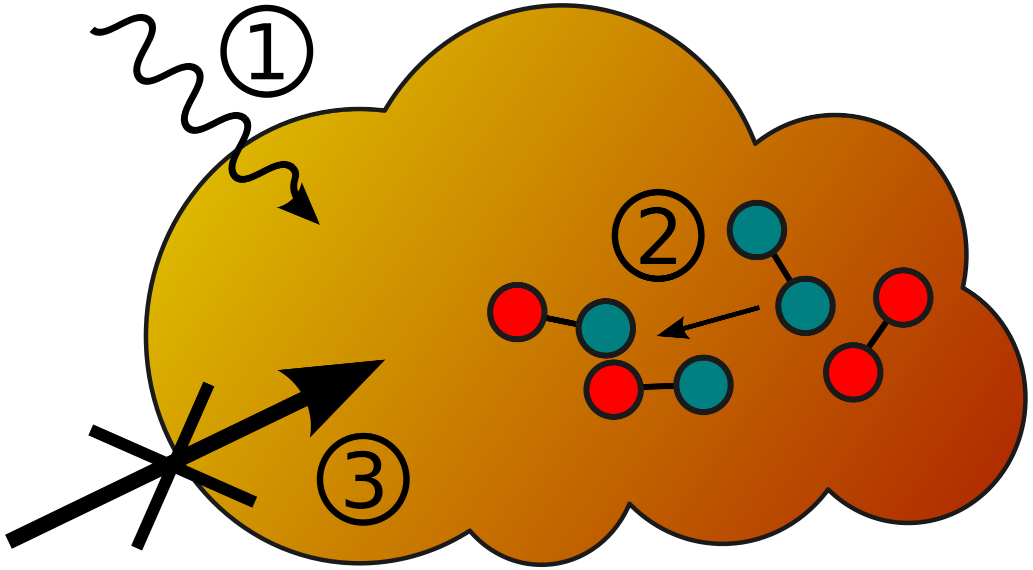
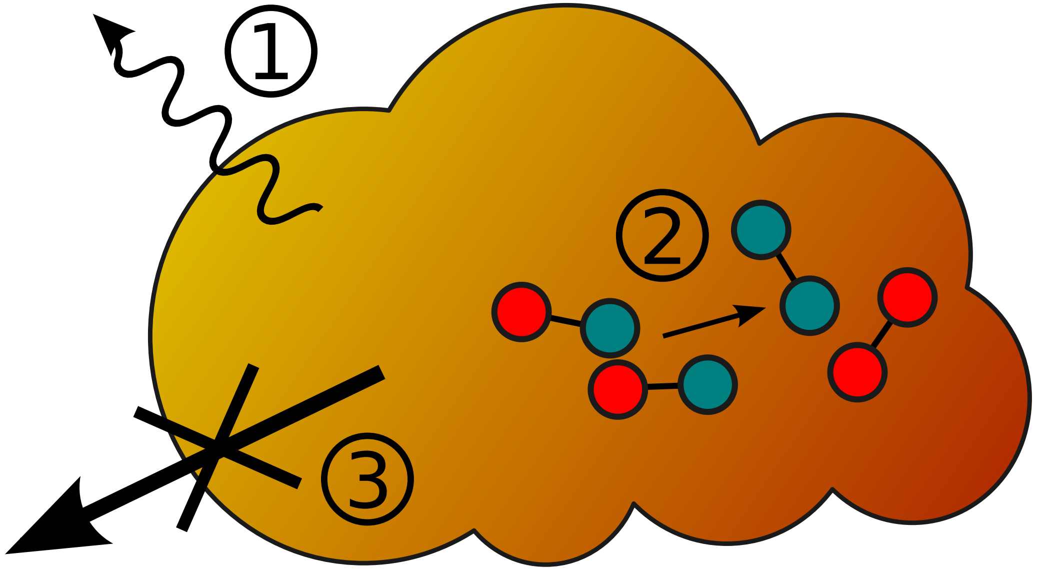

Photoelectric effect on grains
Photoelectric effect on PAH
Photodestruction of molecules
Chemical heating
Cosmic Rays
H_2 formation on grains
Heating rate (erg s^{-1} cm^{-3})
10^{-21}
10^{-22}
10^{-23}
10^{-24}
10^{-25}
10^{-26}
0
2
4
6
8
10
A_v

General concepts (1)



Heating



Cooling

Main cooling terms

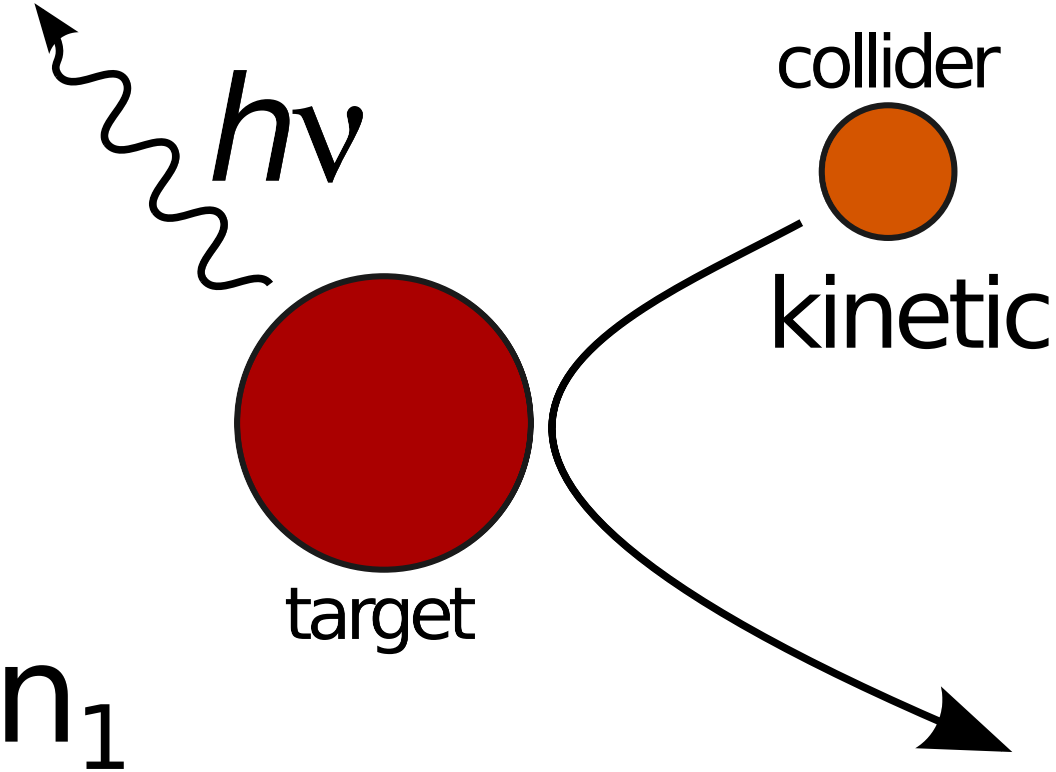
- The radiation observed from the ISM gas traces the primary cooling processes in the ISM
- We have two categories:
  - Radiative processes
  - Some of the inverse heating processes

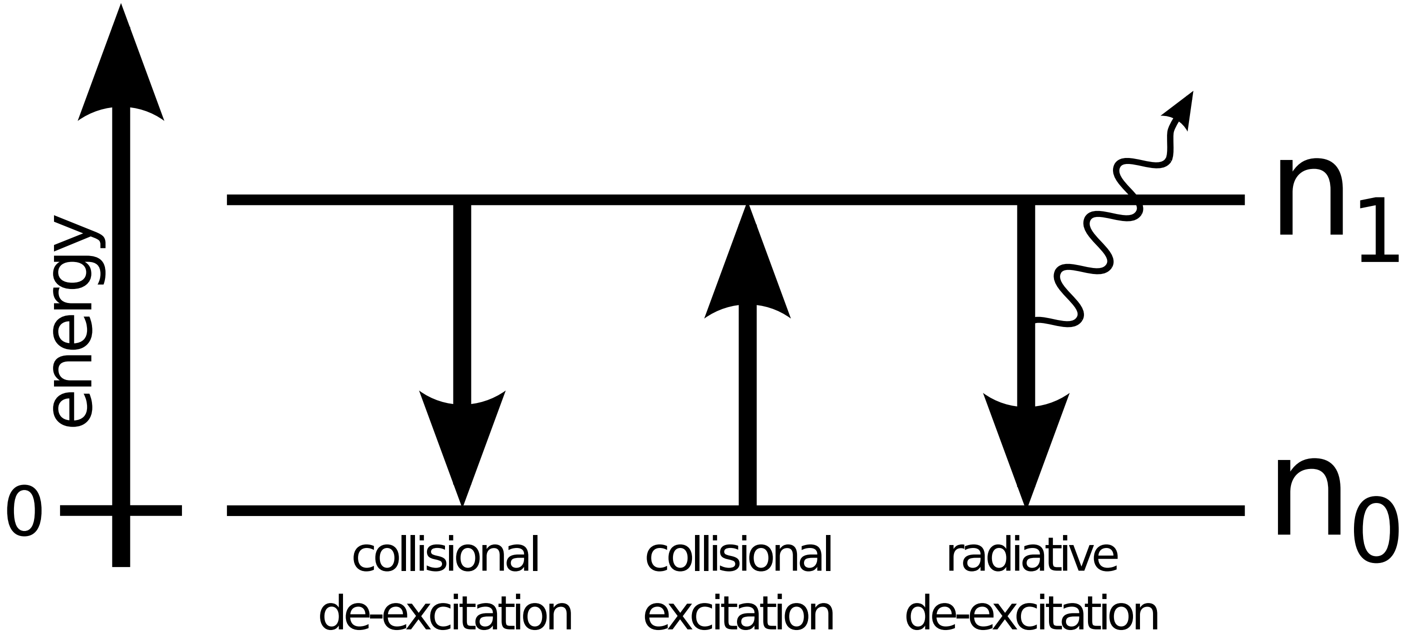
Main cooling terms

- **Collisional excitation**: free electron impact knocks a bound electron to an excited state: it decays, emitting a photon
- **Collisional ionization**: free electron impact ionizes a formerly bound electron, taking energy from the free electron
- **Recombination**: free electron recombines with an ion: the binding energy and the free electron’s kinetic energy are radiated away

Main cooling terms

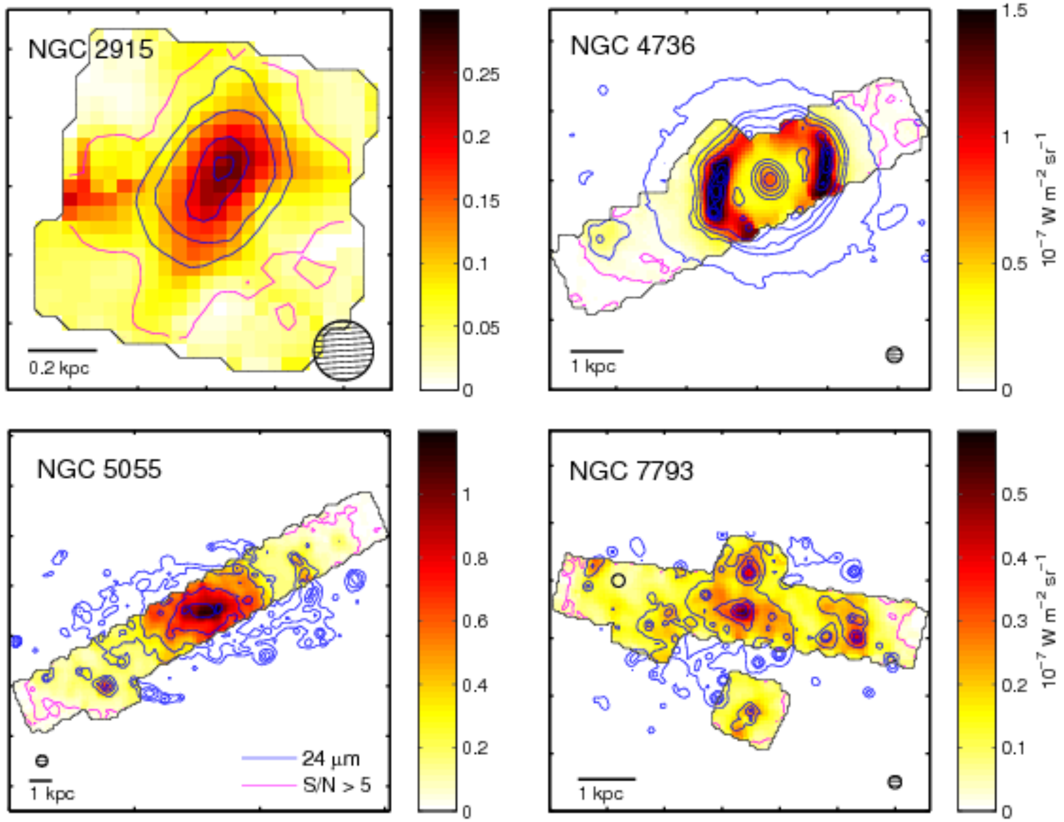
- Radiative processes:
  - Radiation by atoms/molecules/ions excited by collisions transfer part of the kinetic energy into radiation

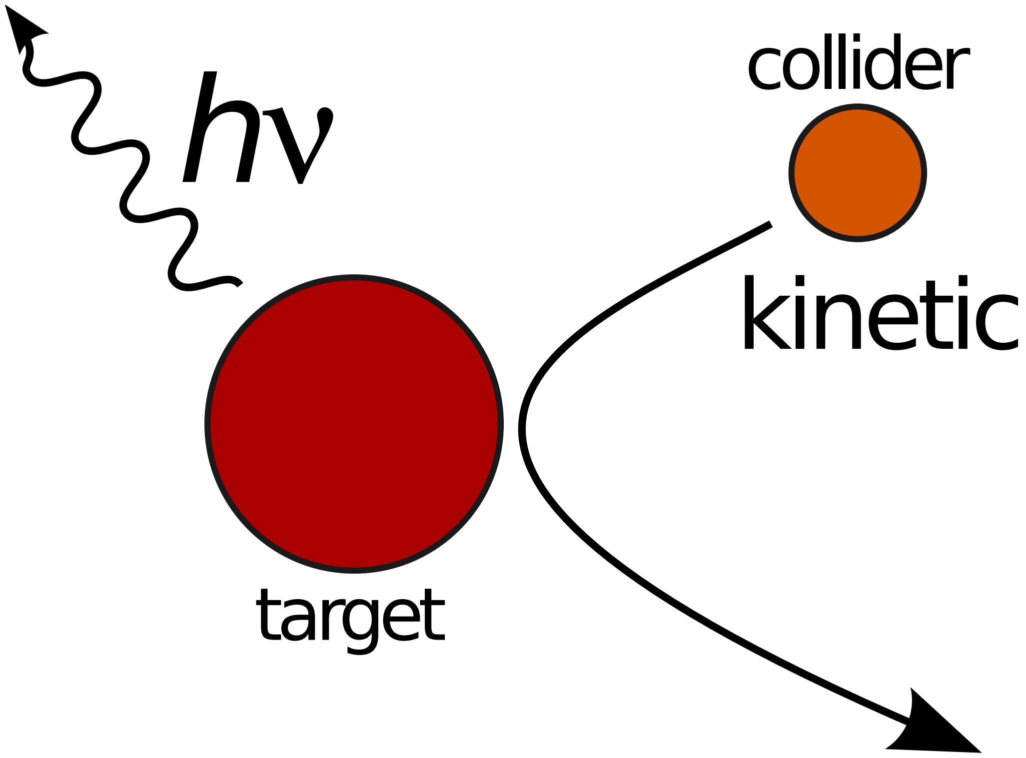




Radiative cooling

- Involves electronic, rotational and vibrational transitions
- It is the process through we observe atoms and molecules





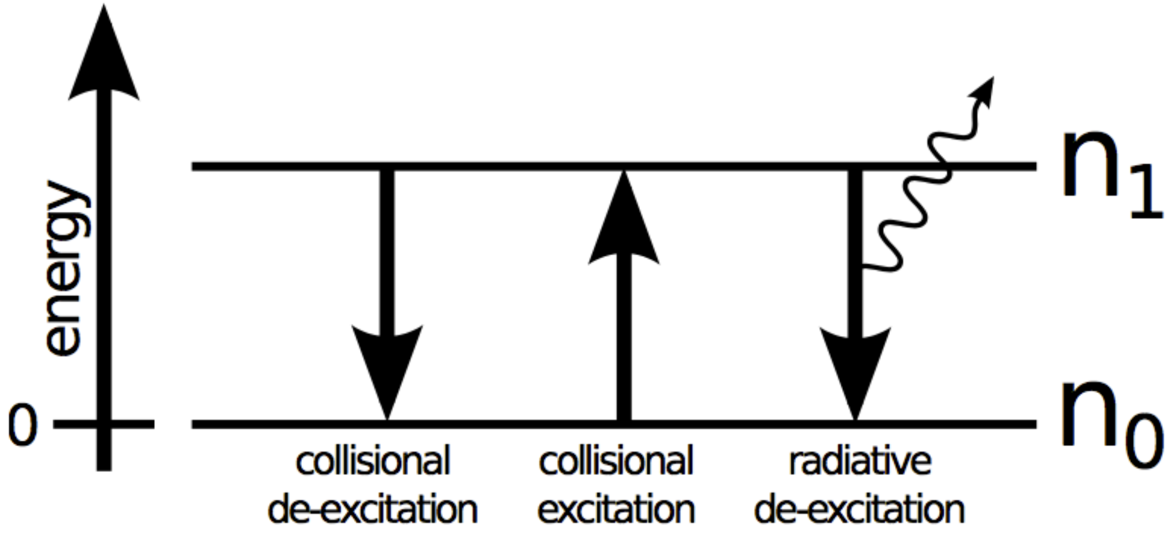
$h\nu$

collider

kinetic

target

Total cooling rate

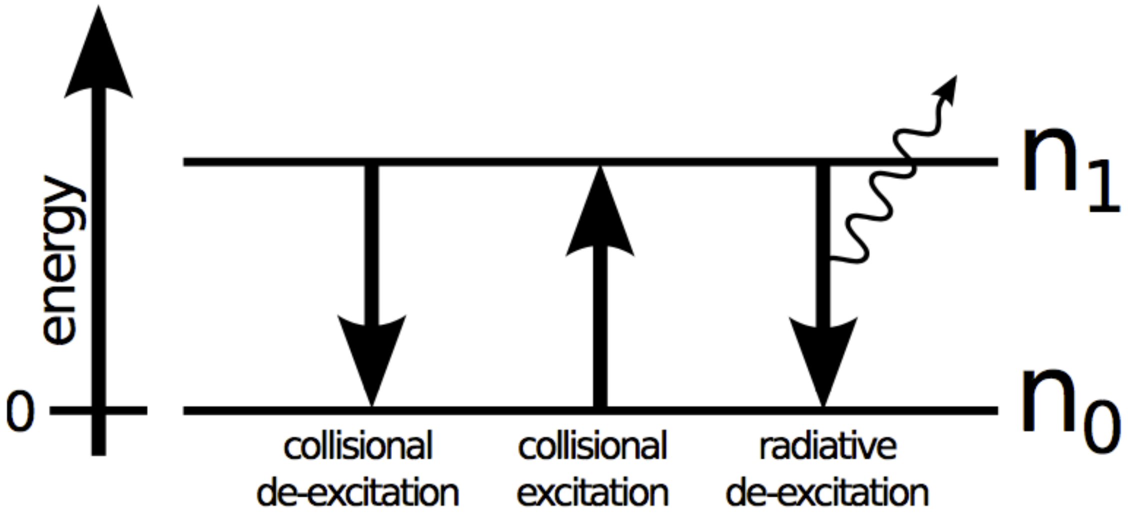


Total cooling

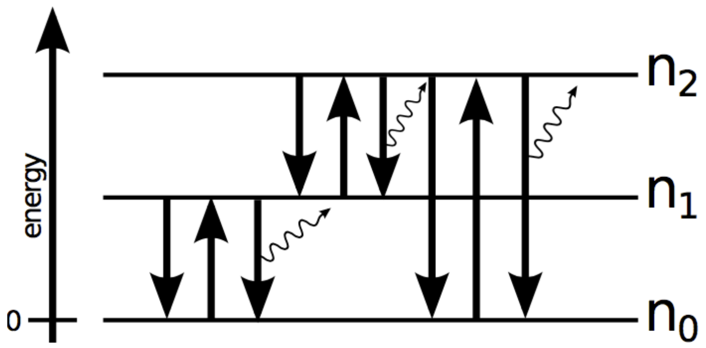
$$\Lambda_{\rm 2levels} = n_1 \Delta E_{10} A_{10} \text{ erg cm}^{-3}\text{ s}^{-1}$$

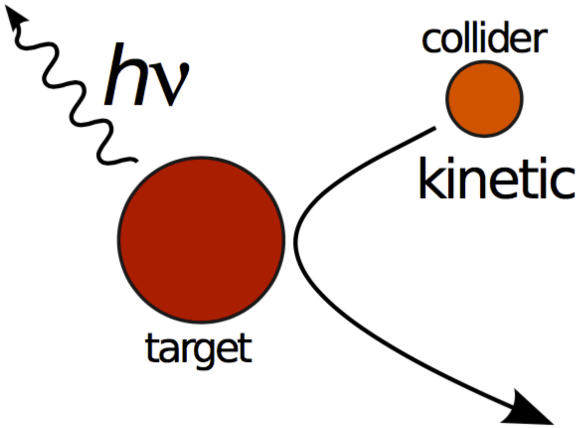
Two levels cooling

1. Ignore radiation induced processes
2. Assume statistical equilibrium
3. Optical thin conditions: photon can escape



Multilevels cooling





general expression (N levels)

$$\dot{n}_i = n_i\left(\sum_{j<i}A_{ij}+\sum_{i\neq j}\sum_{k}n_{ck}C_{ij}^{(k)}\right)+\left(\sum_{j>i}n_jA_{ij}+\sum_{i\neq j}n_j\sum_{k}n_{ck}C_{ji}^{(k)}\right)$$

$$\Lambda(n,T)=\sum_{i}n_i\sum_{j<i}\Delta E_{ij}A_{ji}$$

Main coolants

- Fine structure line cooling is almost everywhere in the ISM the dominant physical process
- Efficient cooling by fine structure lines needs
    - High element abundance
    - A fine structure level close to the fundamental level

Main coolants

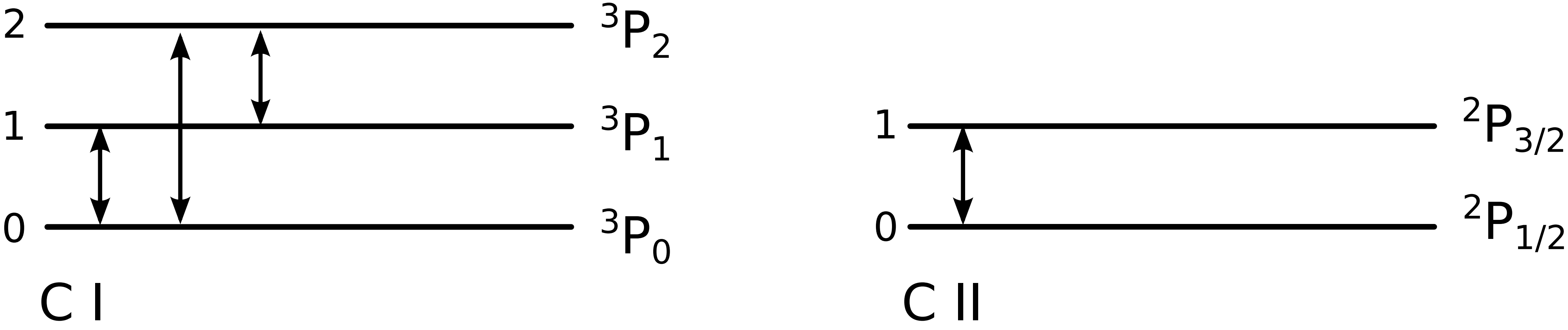
- In neutral regions CII and OI dominate
  - In the low temperature only upper fine structure of CII (91.2 K), line intensity @ 158 micron.
  - OI first fine-structure level is @ 228 K, WNM
- In ionized regions OII, OIII, NII, NIII, NeII and NeIII
  - Excitation by electron collisions with ions / Lyman alpha (H)

Main coolants

- $T > 10^4$ K
    - Lyman series of hydrogen atoms excited by electrons
    - Allowed transitions
    - Electrons abundance decays with temperature
- $T < 10^4$ K
    - Other lines, forbidden lines
    - Critical densities ~ 10^2-10^6 cm^{-3}
    - Important in WNM and CNM

Main coolants: molecular gas

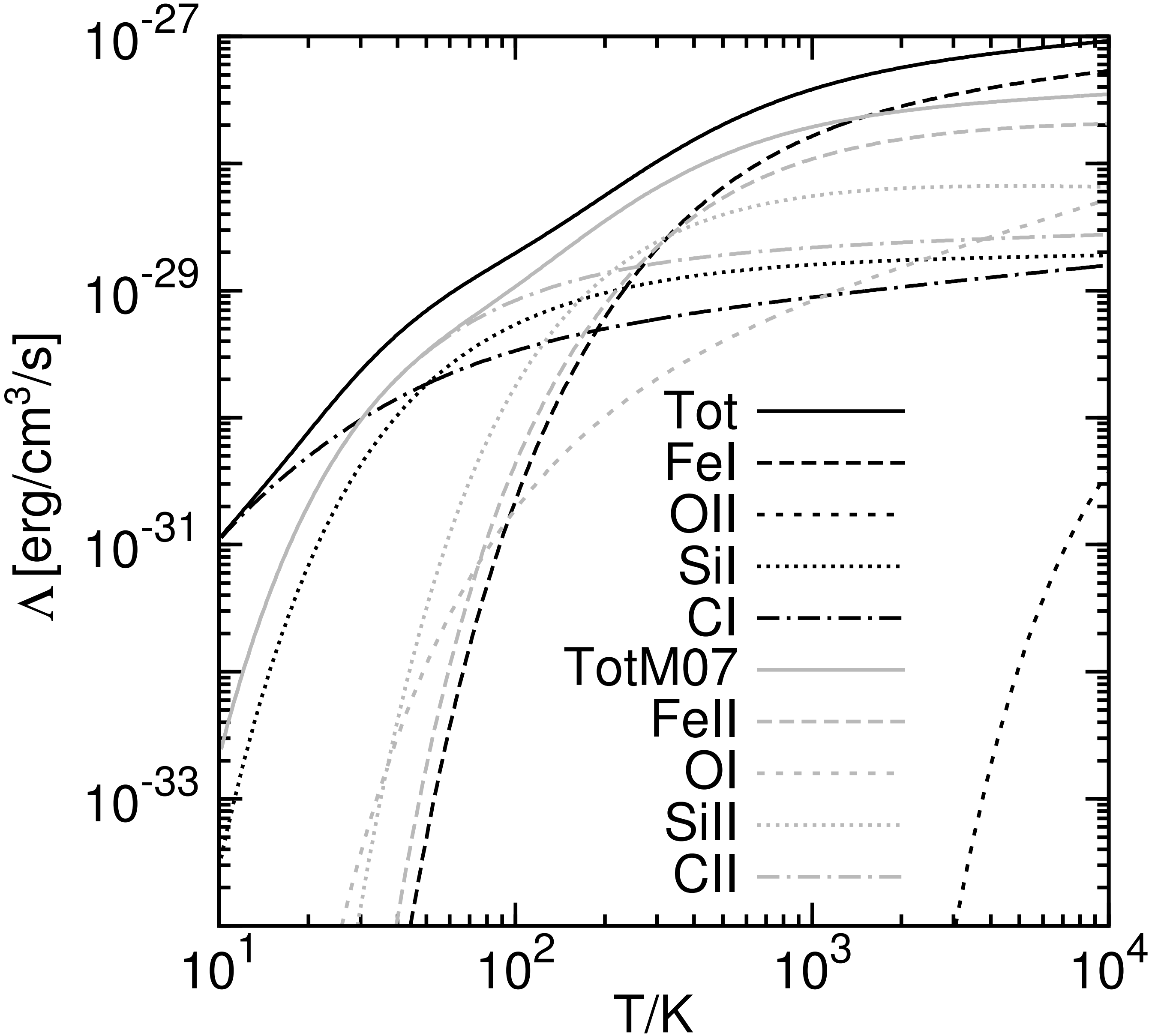
- The most important: rotational emission lines of CO
- Also the emission line of the CI fine-structure line 23.4 K



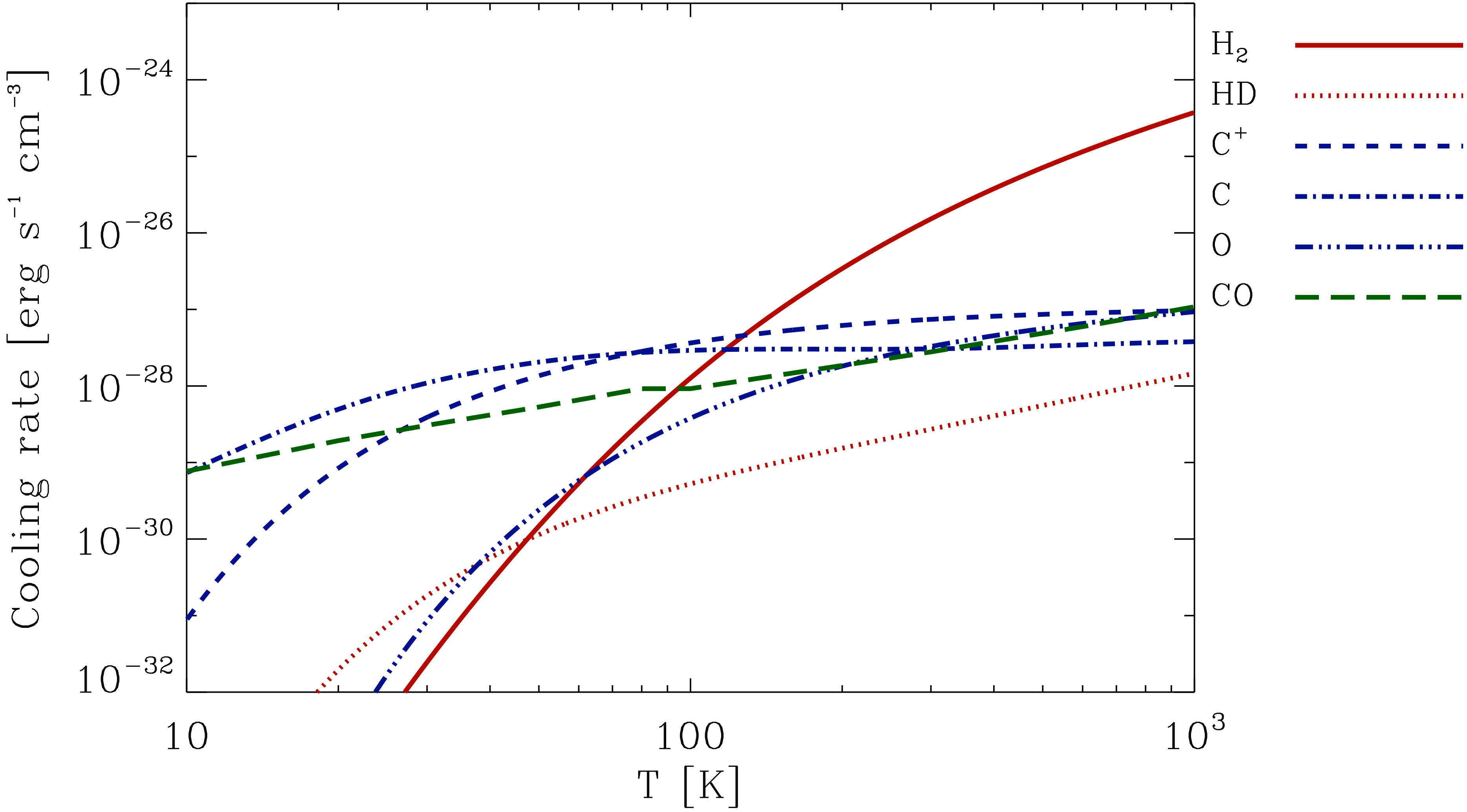
Requirements for cooling

- High frequency of collisions
- Amount of exchanged energy less than the thermal (kinetic) energy of the gas
- High probability of energy exchange
- Excitation energy transported via photons
- Photons emitted by the excited atom/ion before the next particle collision happens + photons leave the gas without any absorption

Cooling rate

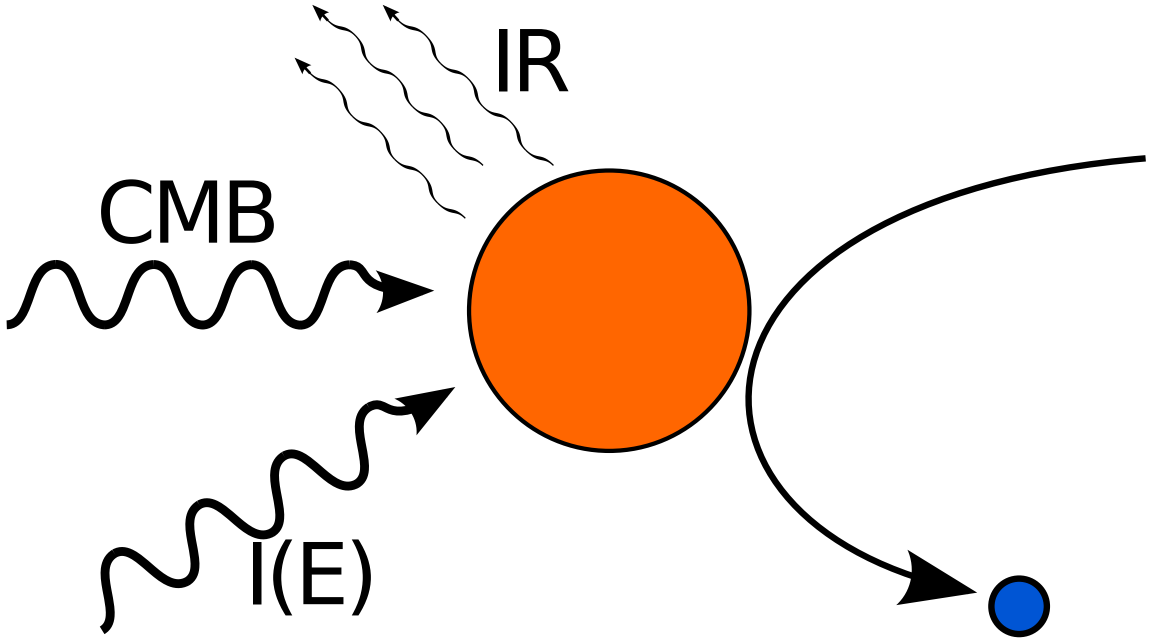


Cooling rate



Gas-grain

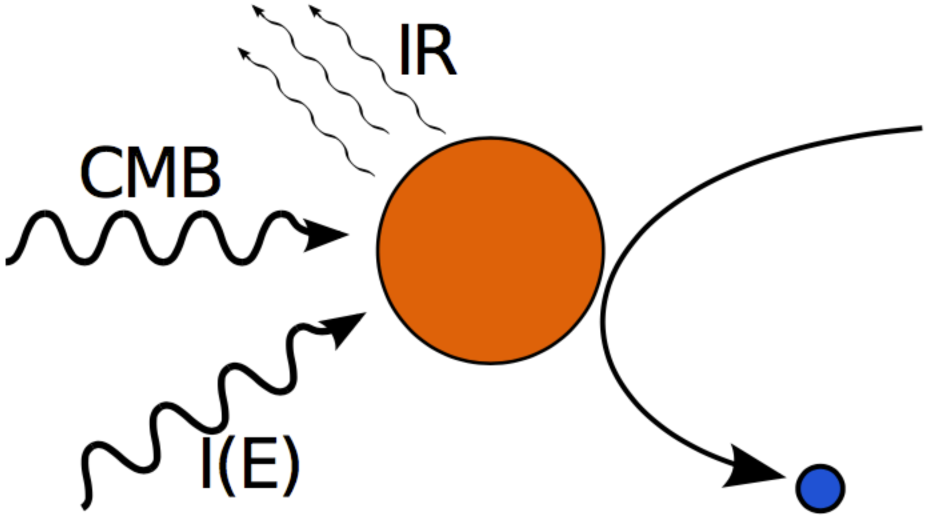
- In the ISM dust and gas are not in thermodynamical equilibrium
- Quite often different temperatures



$$\Gamma_{\rm em} = \Lambda_{\rm g\rightarrow d} + \Gamma_{\rm CMB} + \Gamma_{\rm abs}$$

Gas-grain

- the grain size ($\Gamma \propto \pi a^2$)
- dust and gas temperature
- gas velocity $v_g = \sqrt{\frac{8 k_b T_g}{\pi m_\mathrm{H}}}$

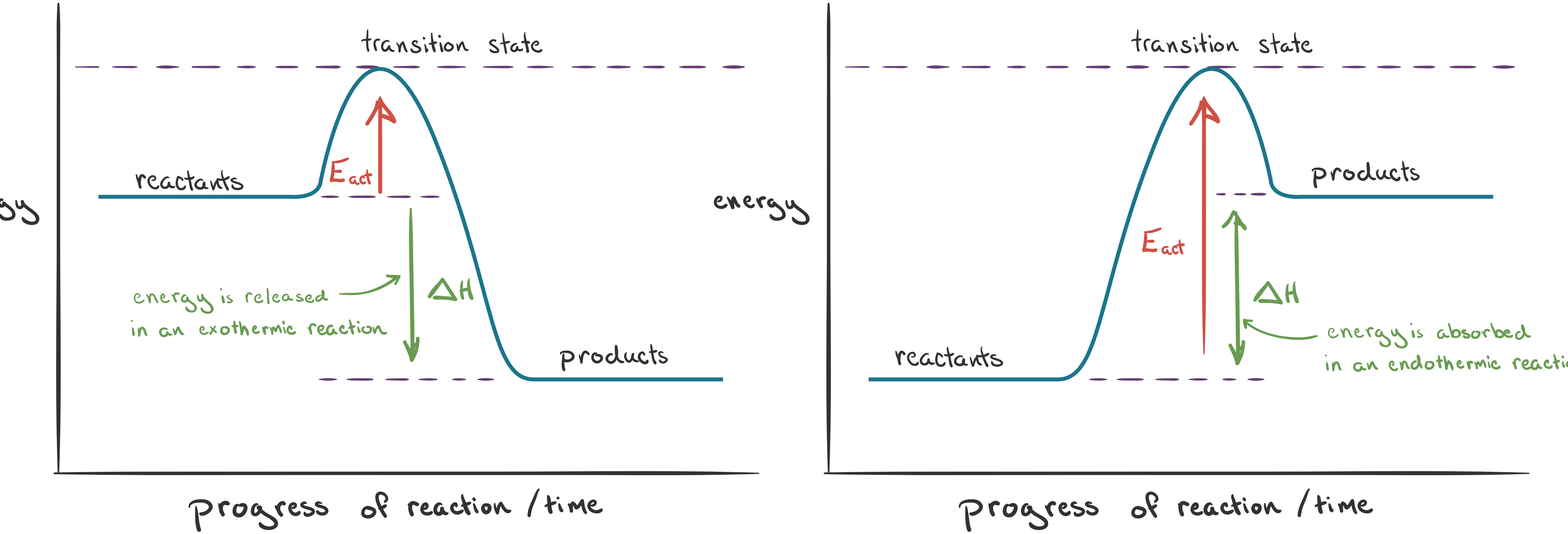


$$\Gamma_\mathrm{em} = \Lambda_\mathrm{g \to d} + \Gamma_\mathrm{CMB} + \Gamma_\mathrm{abs}$$

$$\boxed{\Lambda_{g \to d}(a, T_d) = 2\pi a^2 n_g n_d v_g k_b (T_g - T_d)\alpha} \quad T_g > T_d \to \text{cooling}$$

$$\boxed{\Gamma_{g \to d}(a, T_d) = 2\pi a^2 n_g n_d v_g k_b (T_d - T_g)\alpha} \quad T_d > T_g \to \text{heating}$$

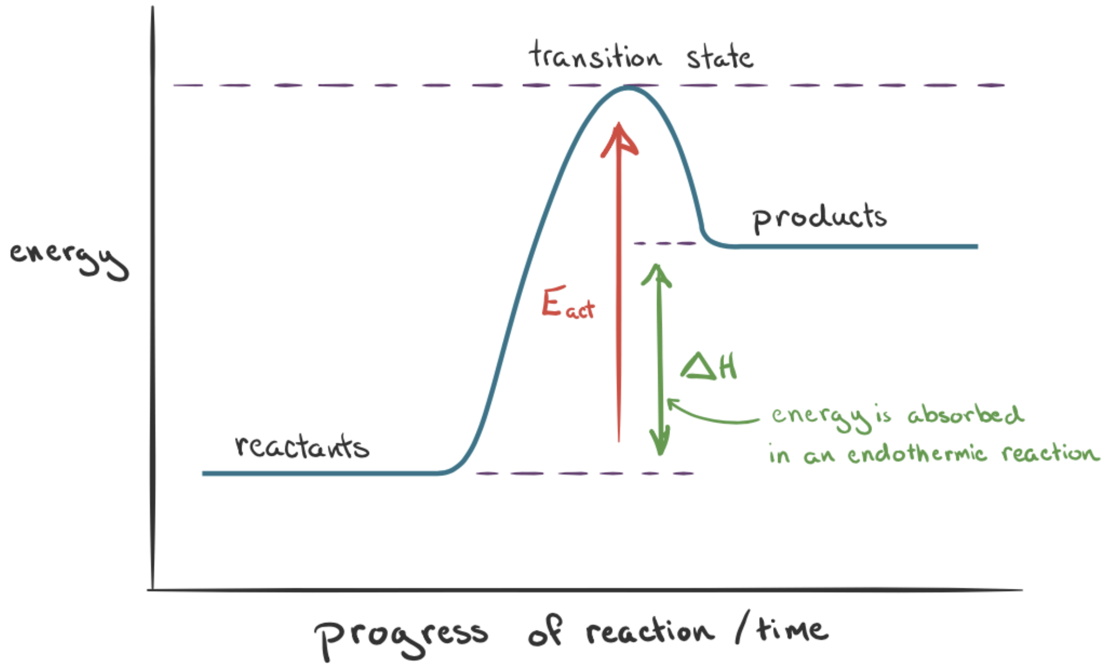
Chemical cooling



$$A + B \leftrightarrow C + D + \Delta E$$

Chemical cooling

needs energy from the medium, $\Lambda \propto nk(T)\Delta H$



- Collisional dissociation: $\mathrm{H_2} + \mathrm{H} \xrightarrow{\Delta H} \mathrm{H} + \mathrm{H} + \mathrm{H}$
- $\Delta H = 4.48$ eV

Cooling summary

Ionized regions

- H excitation requires 10.2 eV ($\sim 10^5$ K)
- recombination cooling ($e^- +$ proton)
- $T < 10^4$ K electronic transitions of metals (O^{++}, N^+)
- main collision partner: electrons

Atomic neutral regions

- metals with electronic energies below 1000 K
- C^+ or [CII], 158 μm

Molecular clouds

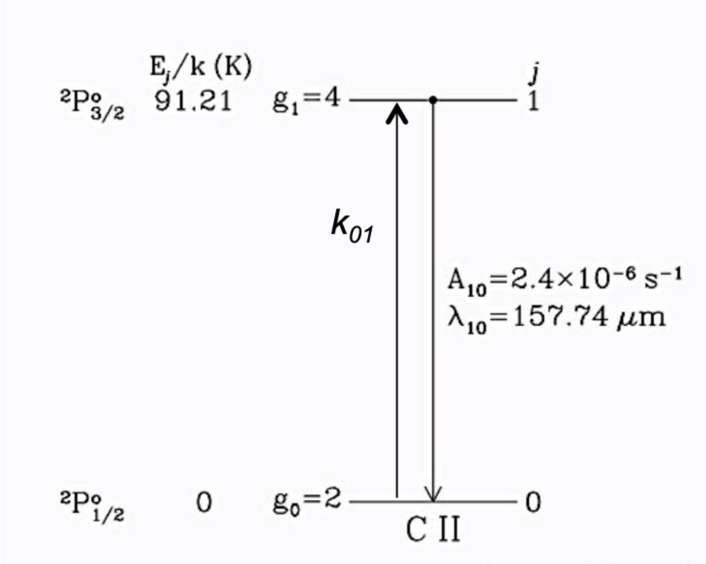
- CO, H_2O
- dust grains

Exercise (from Krome School)

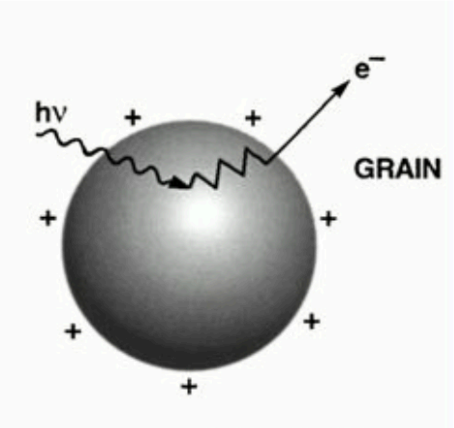
The typical hydrogen number density in the diffuse ISM is $n_H = 1\ cm^{-3}$, the radiation field is $G_0 = 1$, and the density of C^+ is $n(C^+) = 5\ 10^{-4}\ cm^{-3}$, $n(e^-) = 10^{-2}\ cm^{-3}$.

Assume that photoelectric heating is the main heating process and fine structure emission by the [CII] 158 μm is the dominant cooling process.

Derive an estimate for the gas temperature using the two-level approximation for [CII].



$$k_{01}(e^-) \approx 1.5\cdot10^{-6}(T)^{-0.5}\,cm^3 s^{-1}$$



Photoelectric heating rate per hydrogen atom

$$\Gamma_{PE}/n_H = 1.4\cdot10^{-26} G_0 erg/s$$