INTERSTELLAR MEDIUM

- Stefano Bovino -

Cooling

ISM phases

Table 1 Phases of the ISM

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	∼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).

ISM phases

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

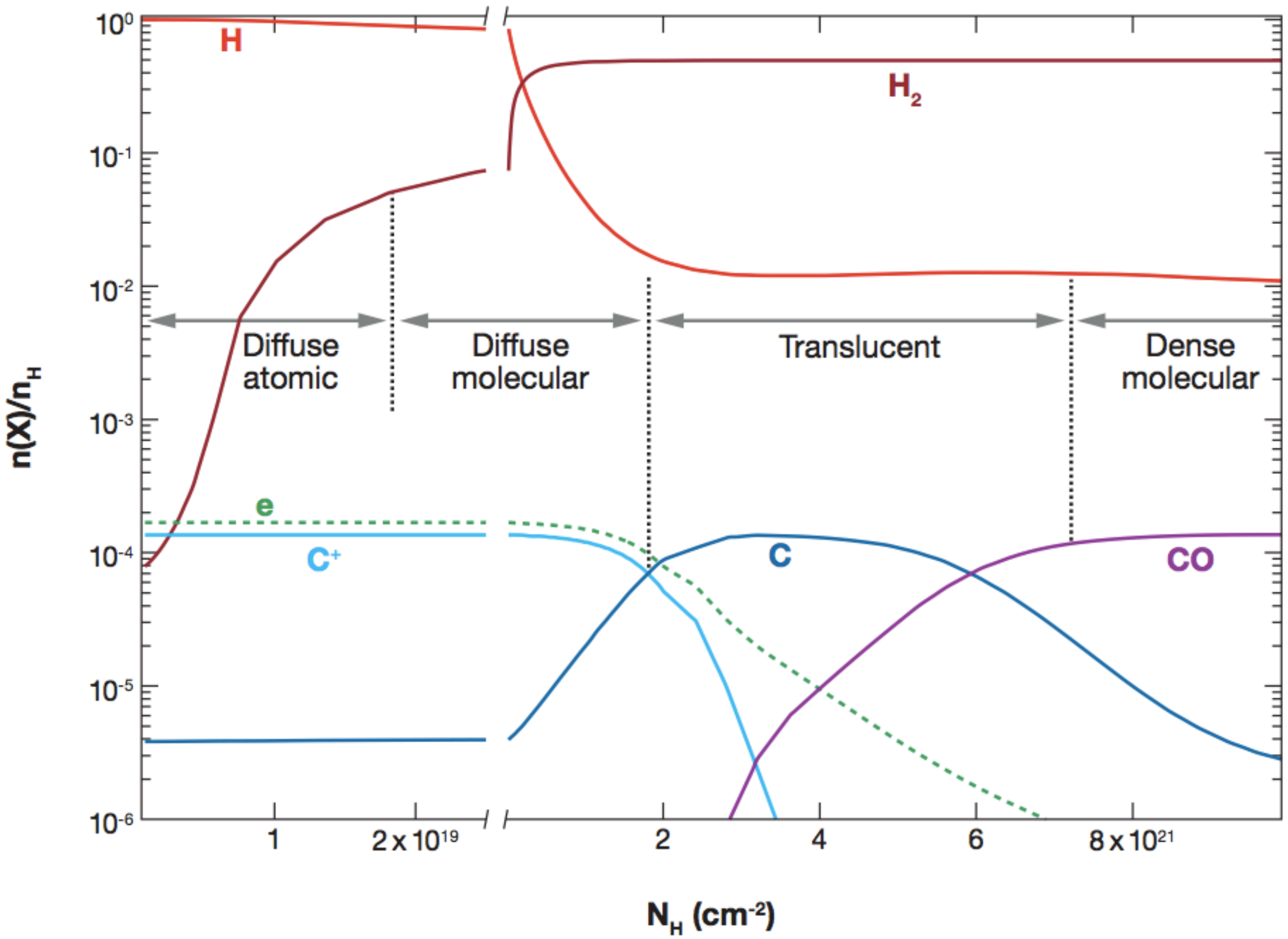
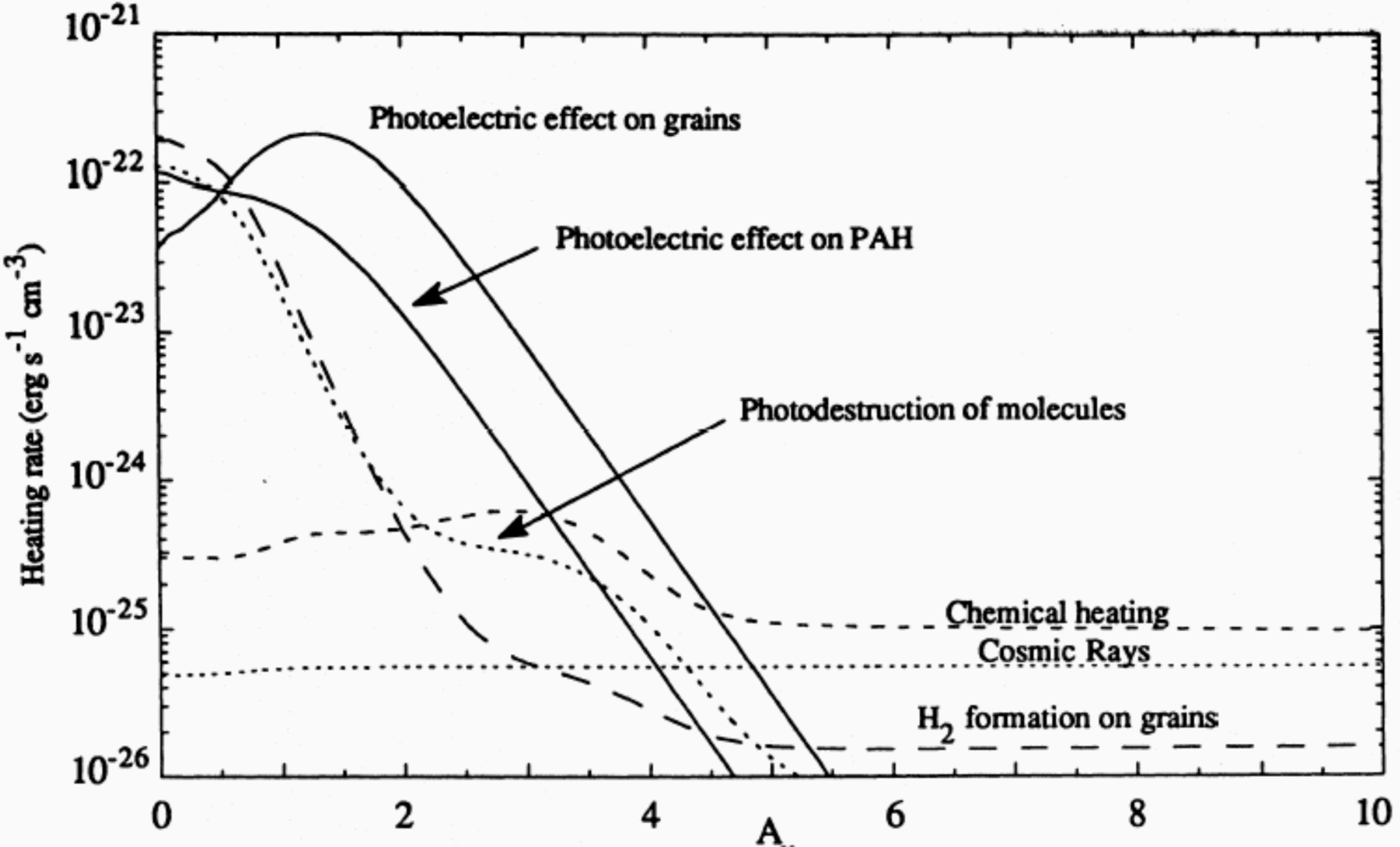


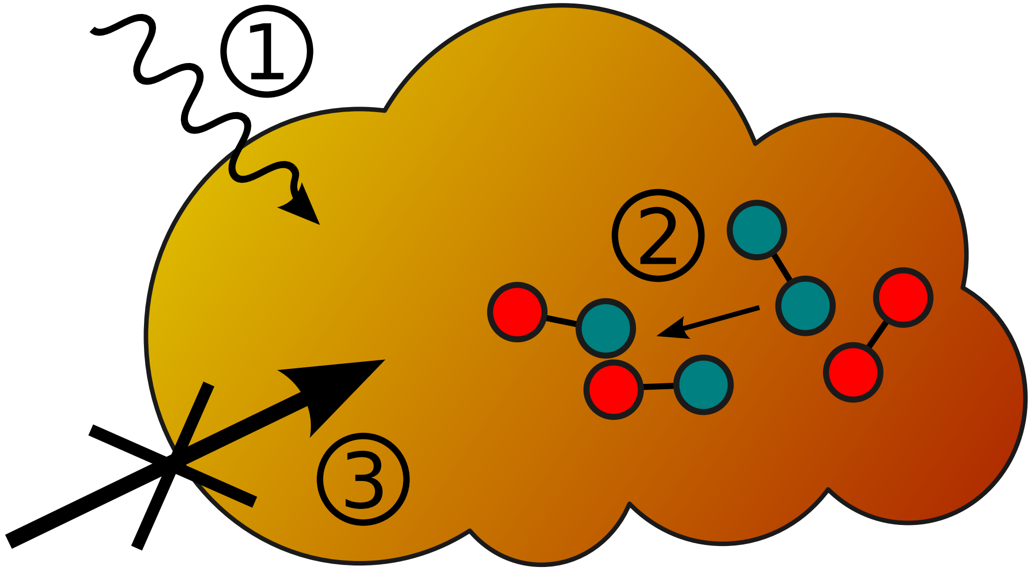
Table 1 Classification of Interstellar Cloud Types

	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

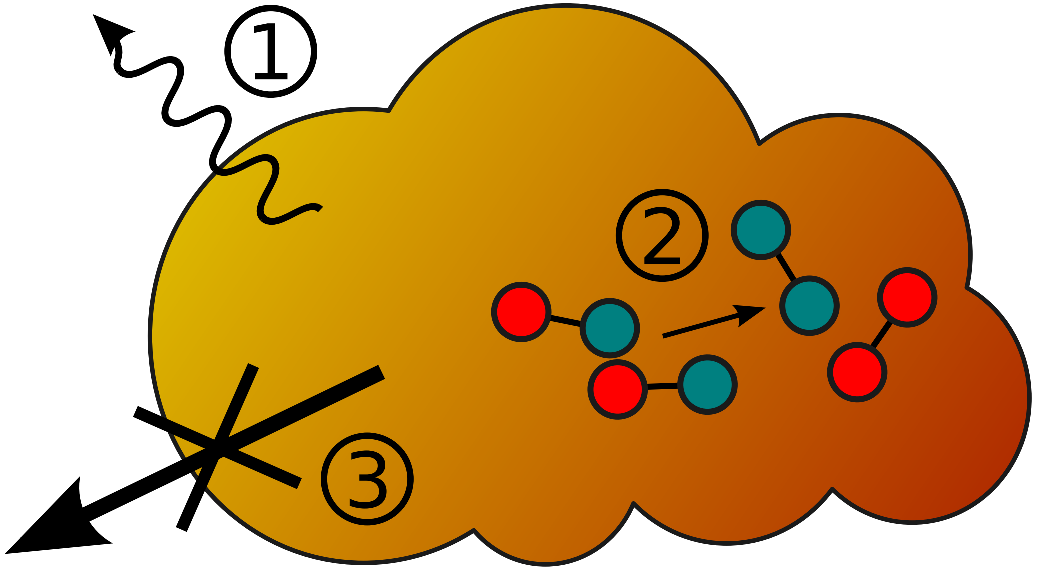


Photoelectric effect on grains
Photoelectric effect on PAH
Photodestruction of molecules
Chemical heating
Cosmic Rays
H2 formation on grains
Heating rate (erg s-1 cm-3)
10-21
10-22
10-23
10-24
10-25
10-26
0
2
4
6
8
10
Av

General concepts (1)



Heating



Cooling

Main cooling terms

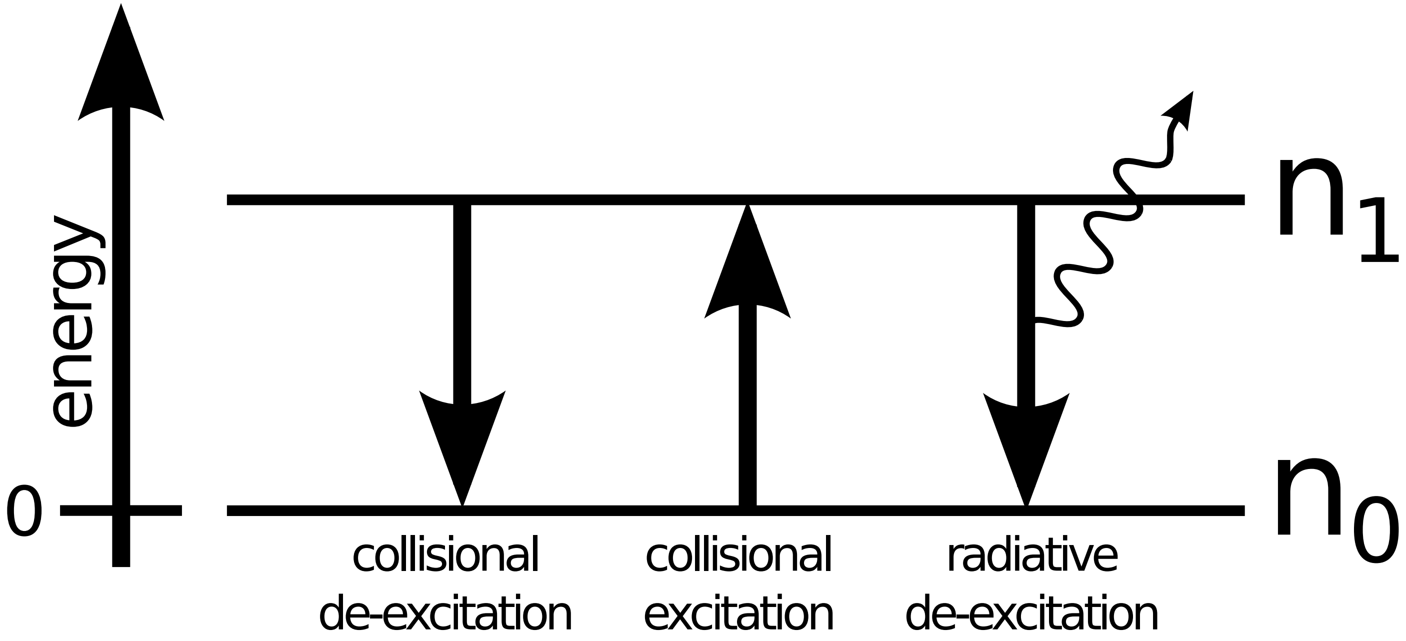
- The radiation observed from the ISM gas traces the primary cooling processes in the ISM
- We have two categories:
    - Radiative processes
    - Some of the inverse heating processes

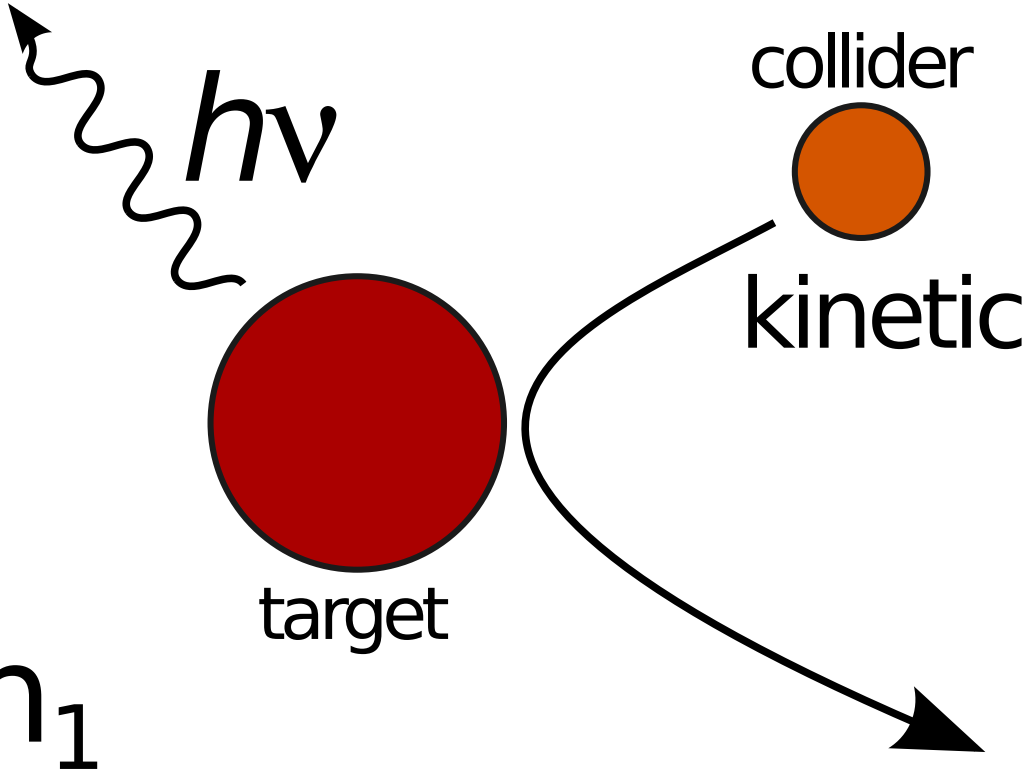
Main cooling terms

- 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

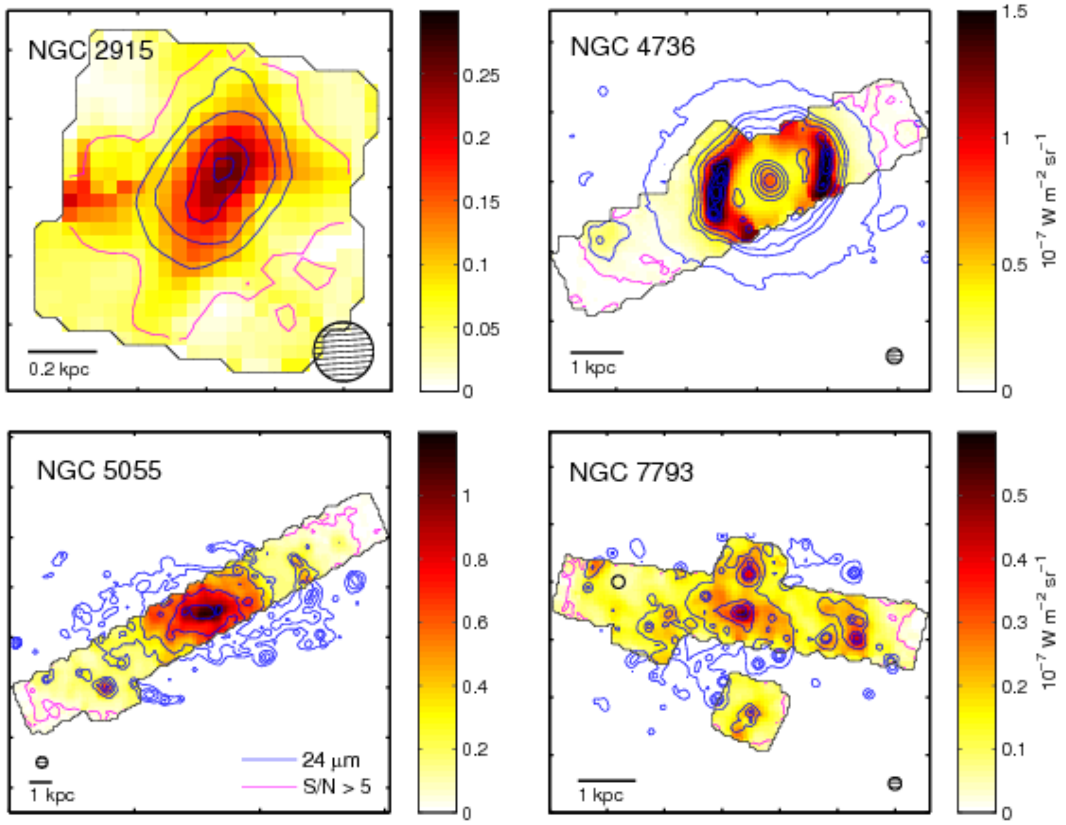
- Radiative processes:
  - Radiation by atoms/molecules/ions excited by collisions transfer part of the kinetic energy into radiation

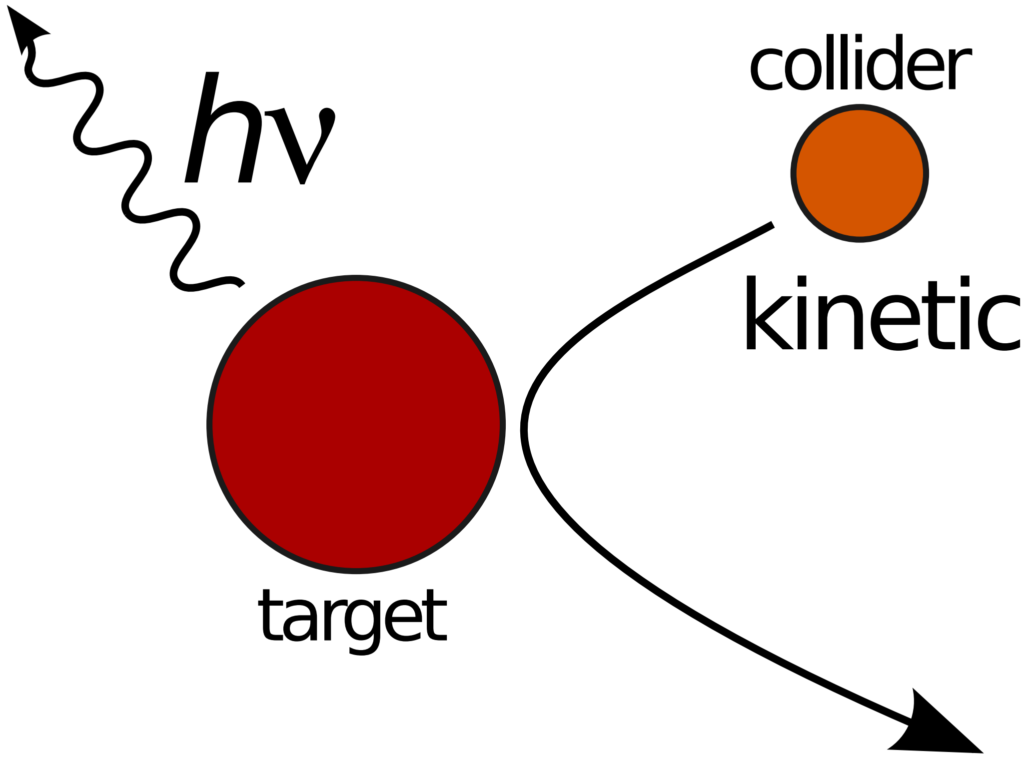




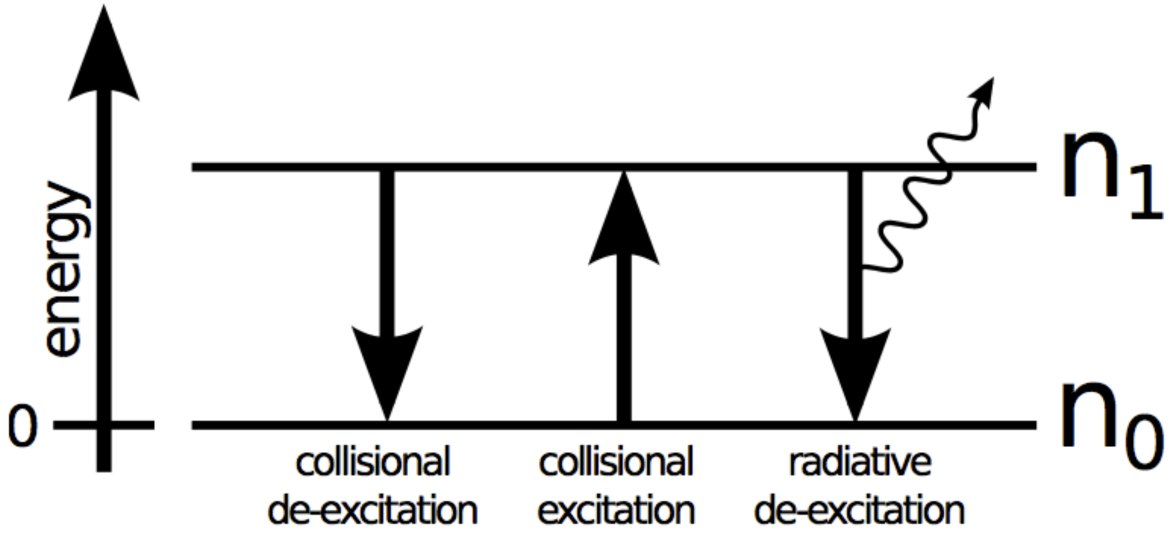
Radiative cooling

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





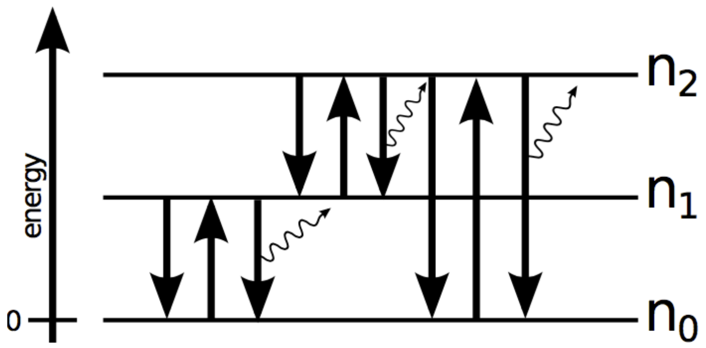
Total cooling function

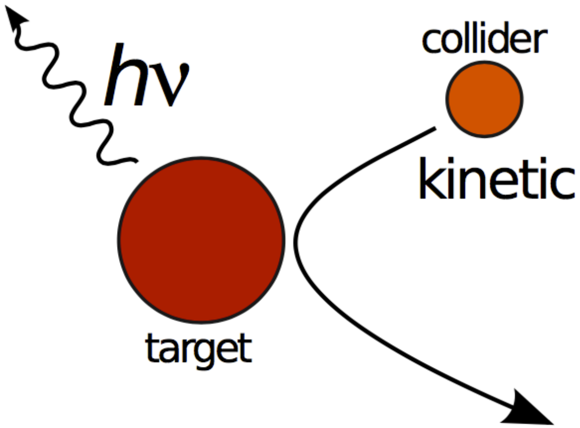


Total cooling

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

Multilevels cooling





general expression (N levels)

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

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

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

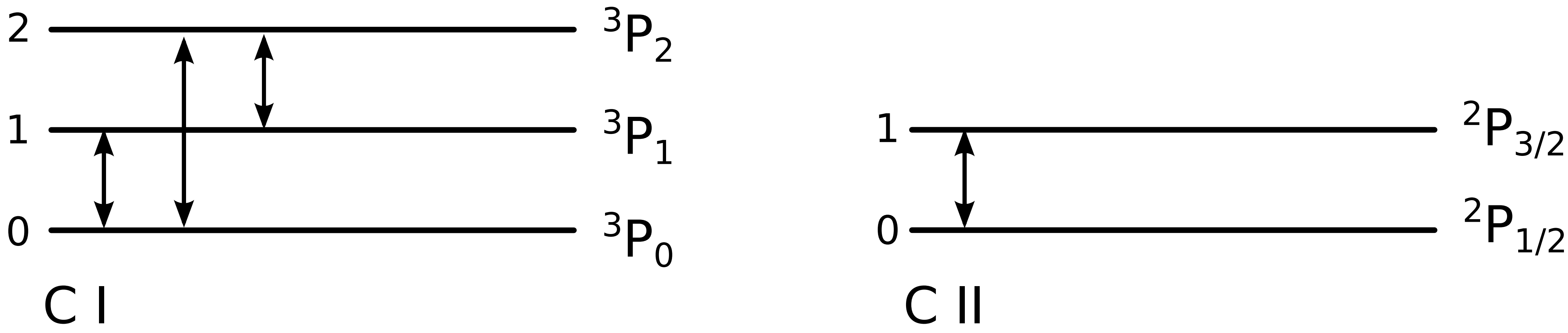
- In neutral regions CII and OI dominate
    - In the low temperature only upper fine structure of CII (91.2 K), line intensity @ 158 micron.
    - OI first fine-structure level is @ 228 K, WNM
- In ionized regions OII, OIII, NII, NIII, NeII and NeIII
    - Excitation by electron collisions with ions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

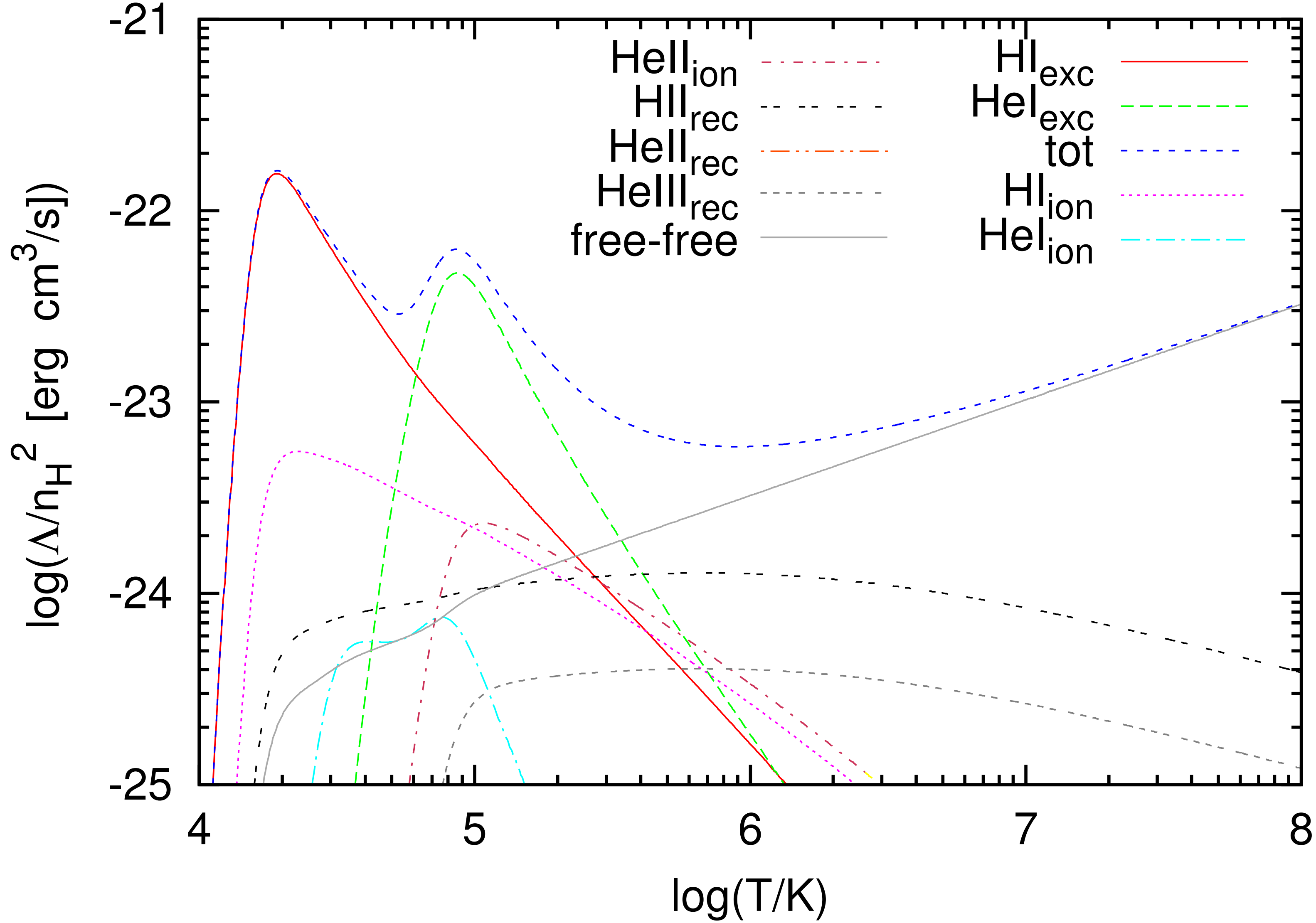
- The most important: rotational emission lines of CO
- Also the emission line of the CI fine-structure line 23.4 K



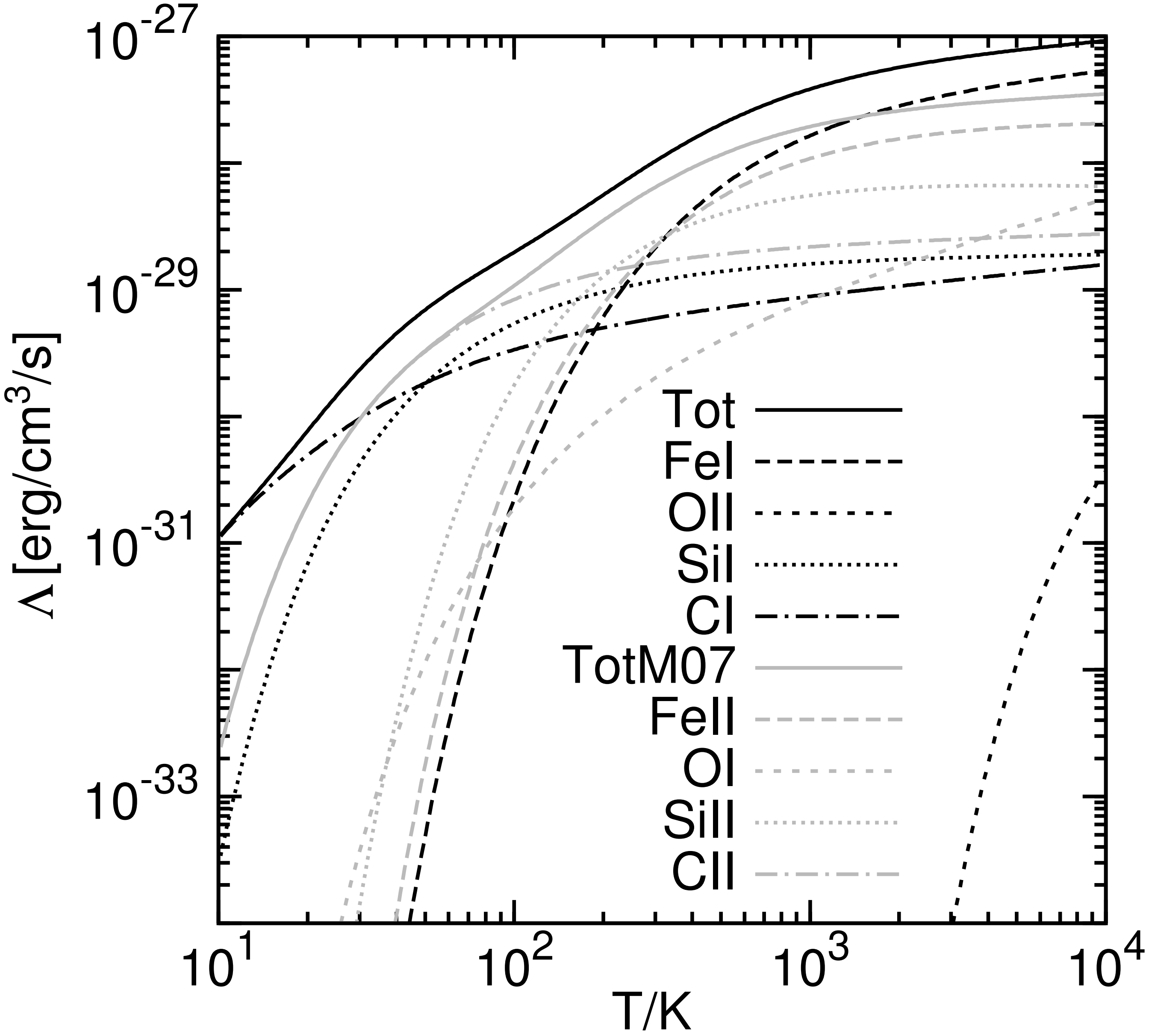
Requirements for cooling

- 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

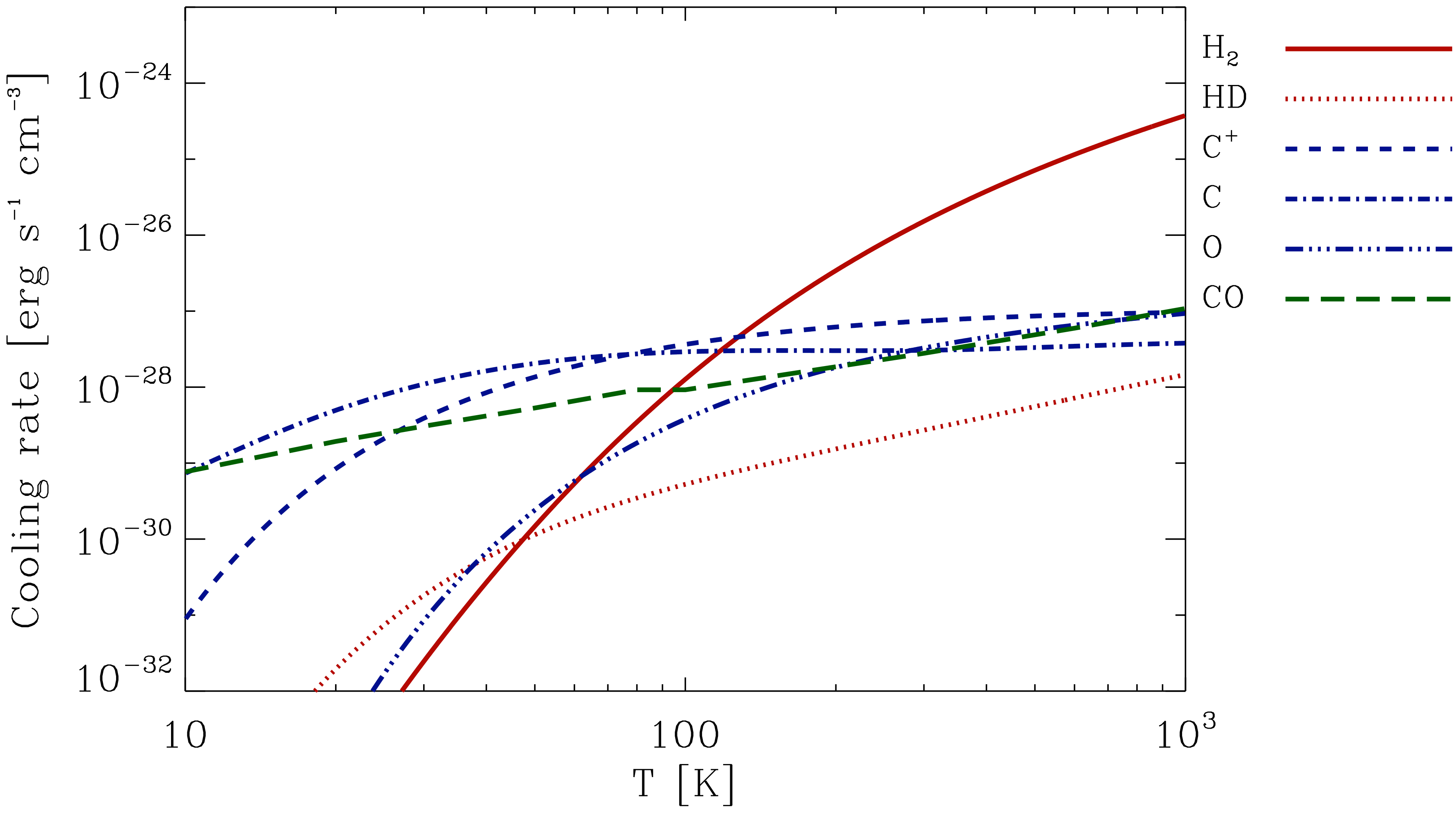
Cooling functions



Cooling functions

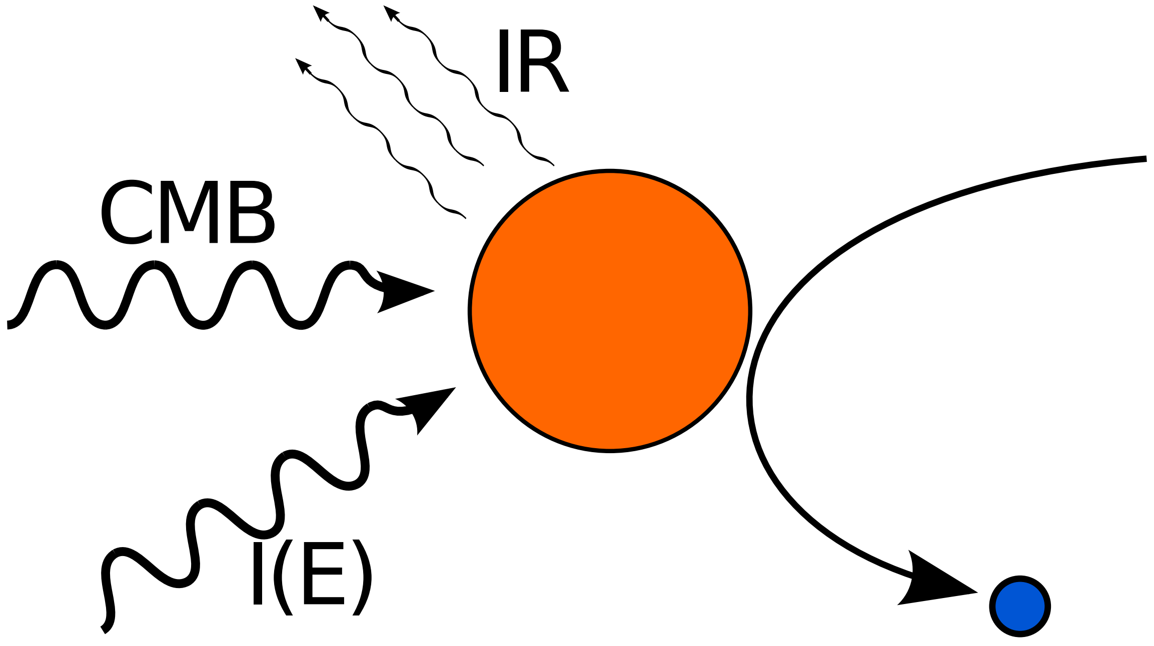


Cooling functions



Gas-grain

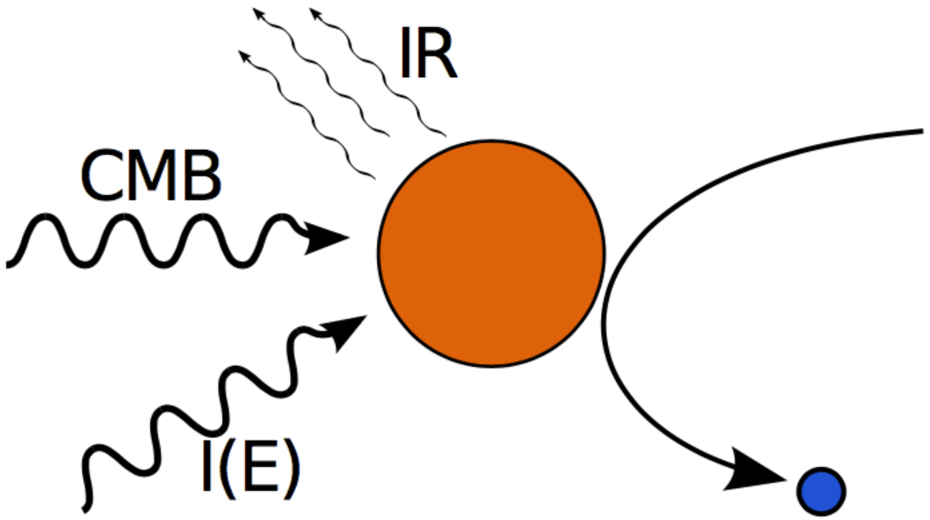
- In the ISM dust and gas are not in thermodynamical equilibrium
- Quite often different temperatures



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

Gas-grain

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

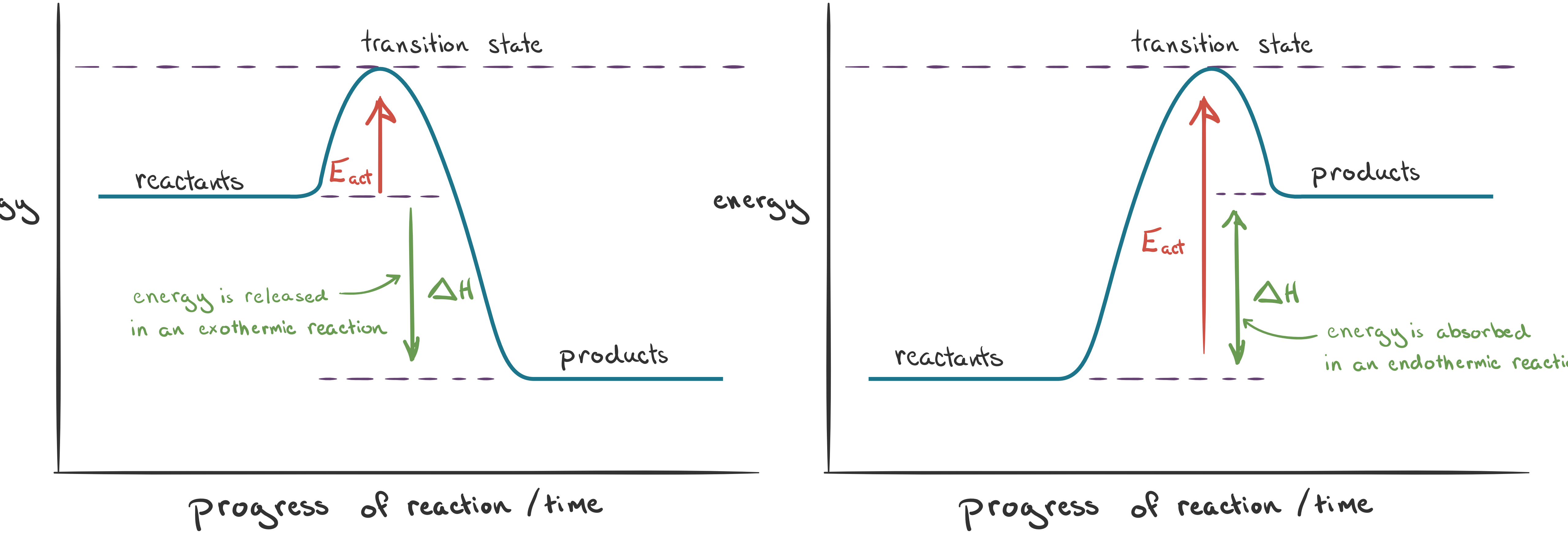


$$\Gamma_{\mathrm{em}} = \Lambda_{\mathrm{g}\rightarrow\mathrm{d}} + \Gamma_{\mathrm{CMB}} + \Gamma_{\mathrm{abs}}$$

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

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

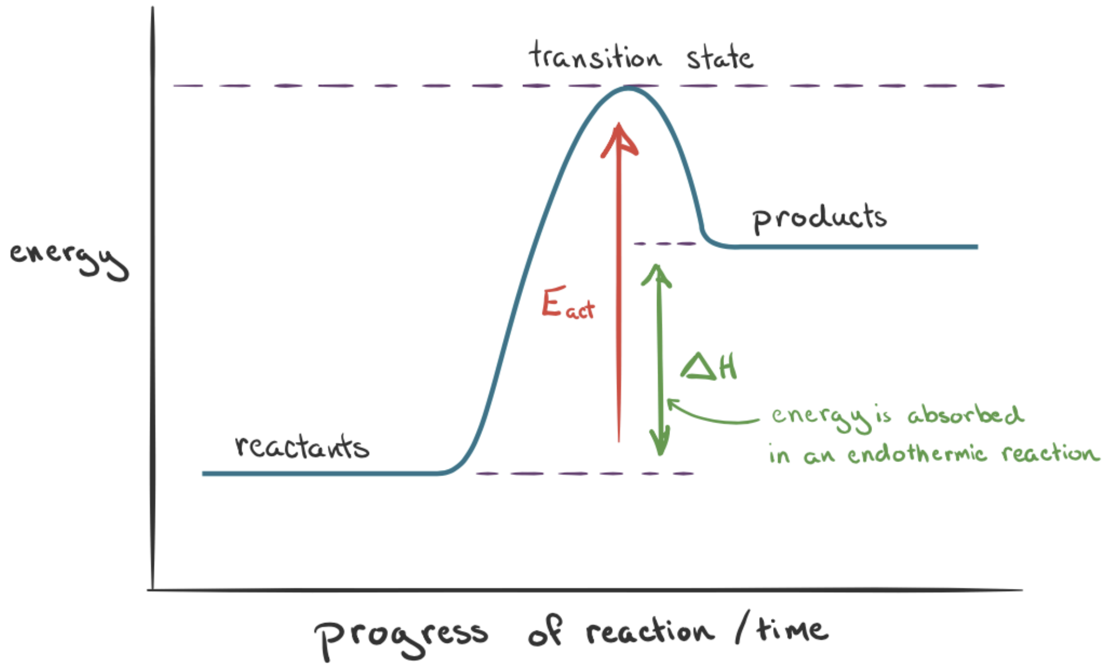
Chemical cooling



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

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