Cosmic-ray heating of molecular cloud cores

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Heating processes in the cold neutral medium

- Removal of an electron from an atom, molecule or dust grain by an energetic photon (UV or X-ray) or particle (CR).

- The suprathermal electron heats the gas by elastic collisions until it is thermalized:

$$t_{\rm therm} \sim \frac{1}{n\langle\sigma v\rangle}$$ ~ years for 1 eV electron in a molecular cloud

- The ionized atom or molecule reacts exothermally with other species by dissociative recombination or ionic reactions (*chemical heating*).

- *NB: different from the heating due to the dissipation of Alfvén waves created by CR streaming (see E. Zweibel's talk).*

Photon heating

- UV photons with $E_\gamma = h\nu$ < 13.6 eV can ionize low-I atoms, mostly C (I=11.3 eV)

→ important source of electrons in diffuse clouds, but heating inefficient:

  - narrow range of E_γ
  - maximum E_e=2.3 eV

- UV photons remove electrons from dust grains $E_e = h\nu - W$ where W is the grain work function (W=4.5 eV for graphite)

→ dominant heating process in diffuse clouds (*photoelectric heating*)

Cosmic-ray heating

- Dominant source of ionization and heating in the densest, UV-shielded molecular gas inside molecular clouds.

$$\Gamma_{\rm CR} = \zeta Q n$$

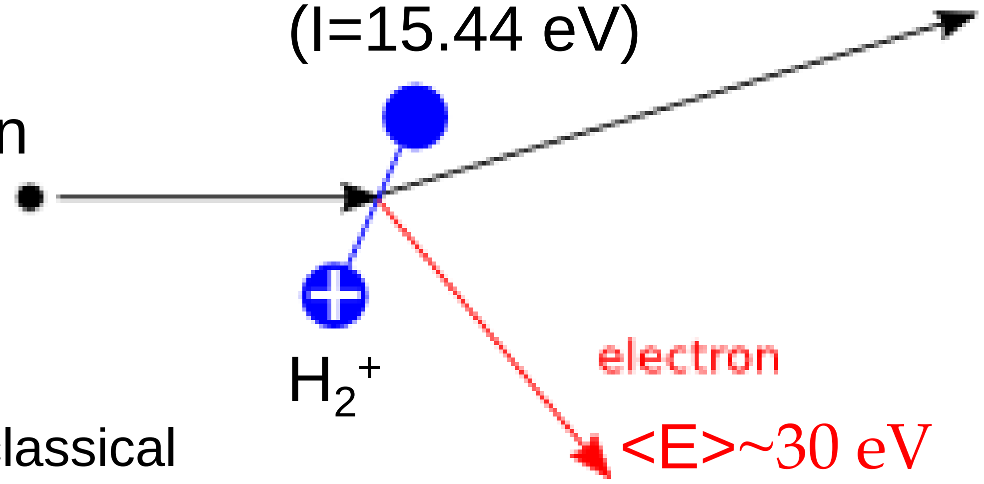
where n is the density and

$$\zeta = \int (1+\phi) j(E) \sigma_{\rm ion}\, dE$$ is the CR ionization rate (in s^{-1})

Q = average energy deposited as heat per ionization (in eV)

- $Q = 6$ eV (Glassgold & Langer 1973, Cravens & Dalgarno 1978)
- $Q = 7$ eV (Stahler & Palla 2004, Tielens 2005)
- $Q = 8$ eV (Tielens & Hollenbach 1985)
- $Q = 9$ eV (Maloney et al. 1996)
- $Q = 12$ eV (Yusef-Zadeh et al. 2007, Wolfire et al. 2010)
- $Q = 20$ eV (Goldsmith & Langer 1978, Goldsmith 2001)

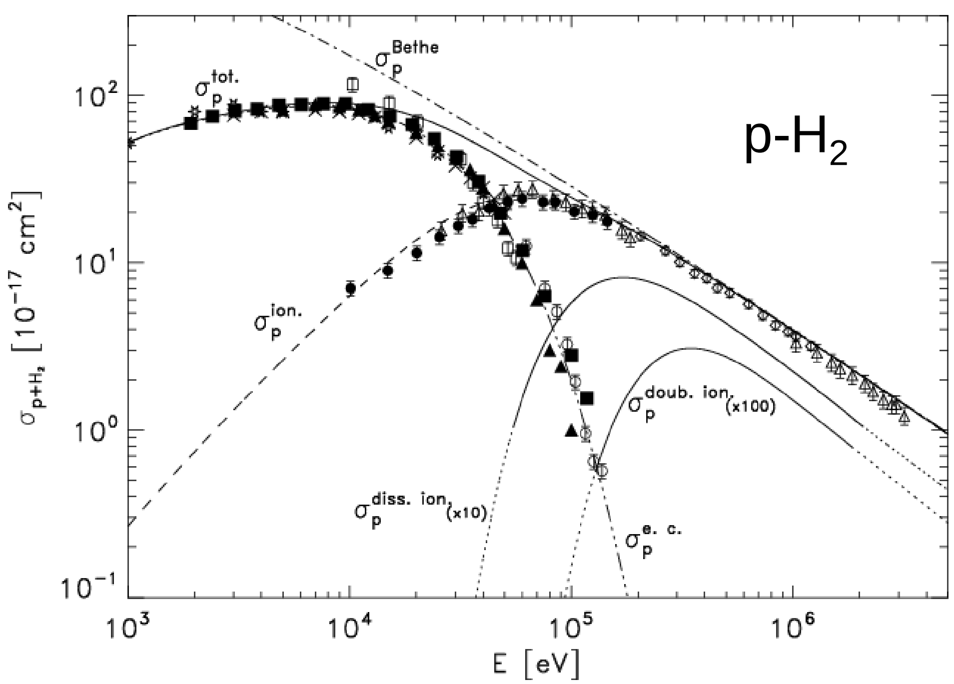
CR-ionization of H_2

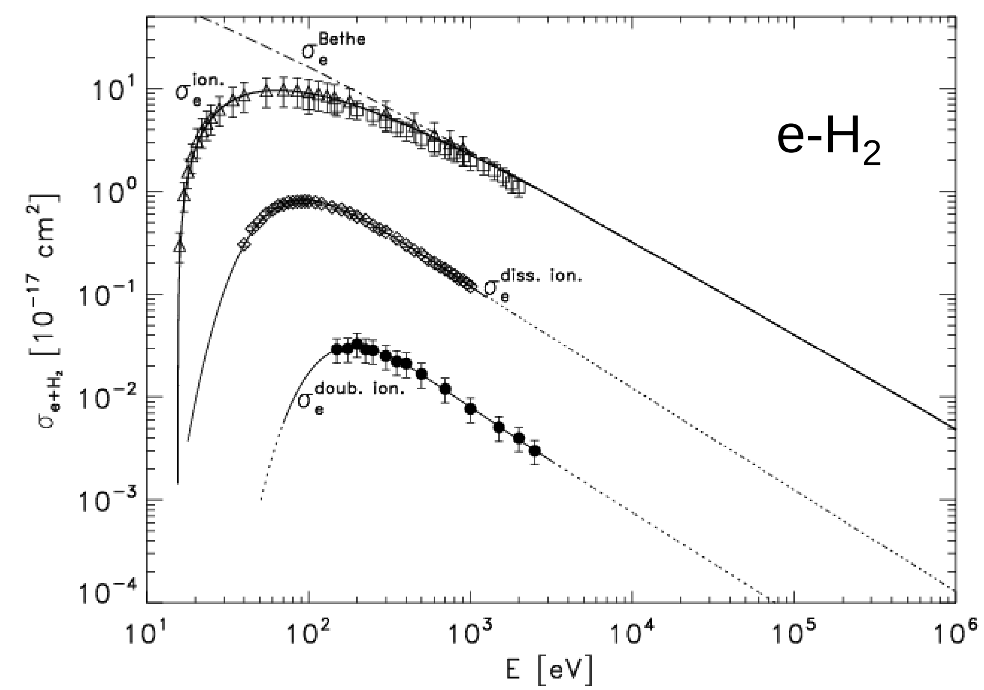


E (MeV)	$\bar{w}_i$ (eV)
1........	24.3
2........	26.0
10.......	30.4
20.......	32.1
50.......	34.1
100......	35.6

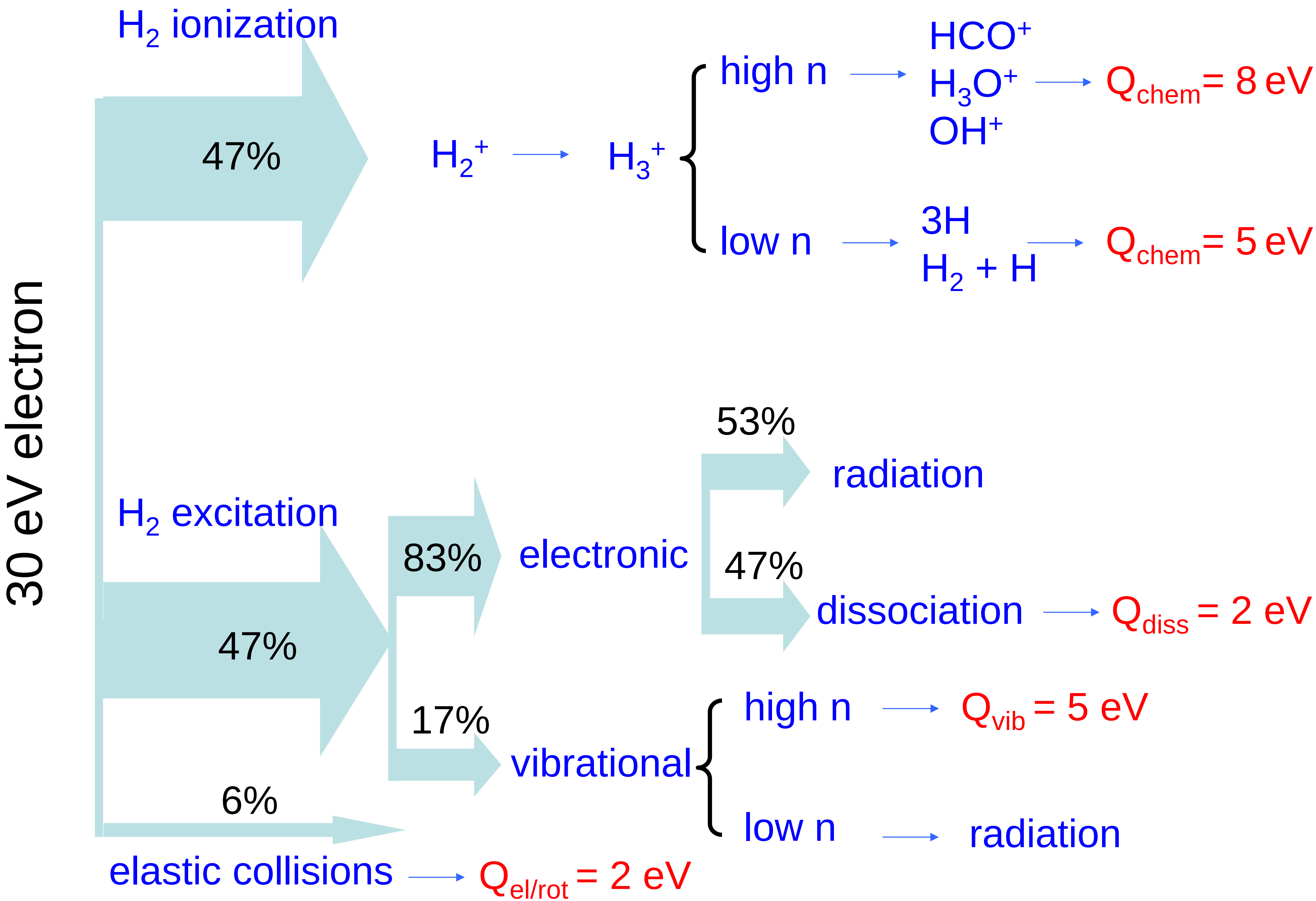
Cravens & Dalgarno (1978)

Thomson (1912) Bohr (1913) classical
Bethe (1930) quantistic
Bethe (1932) quantistic relativistic





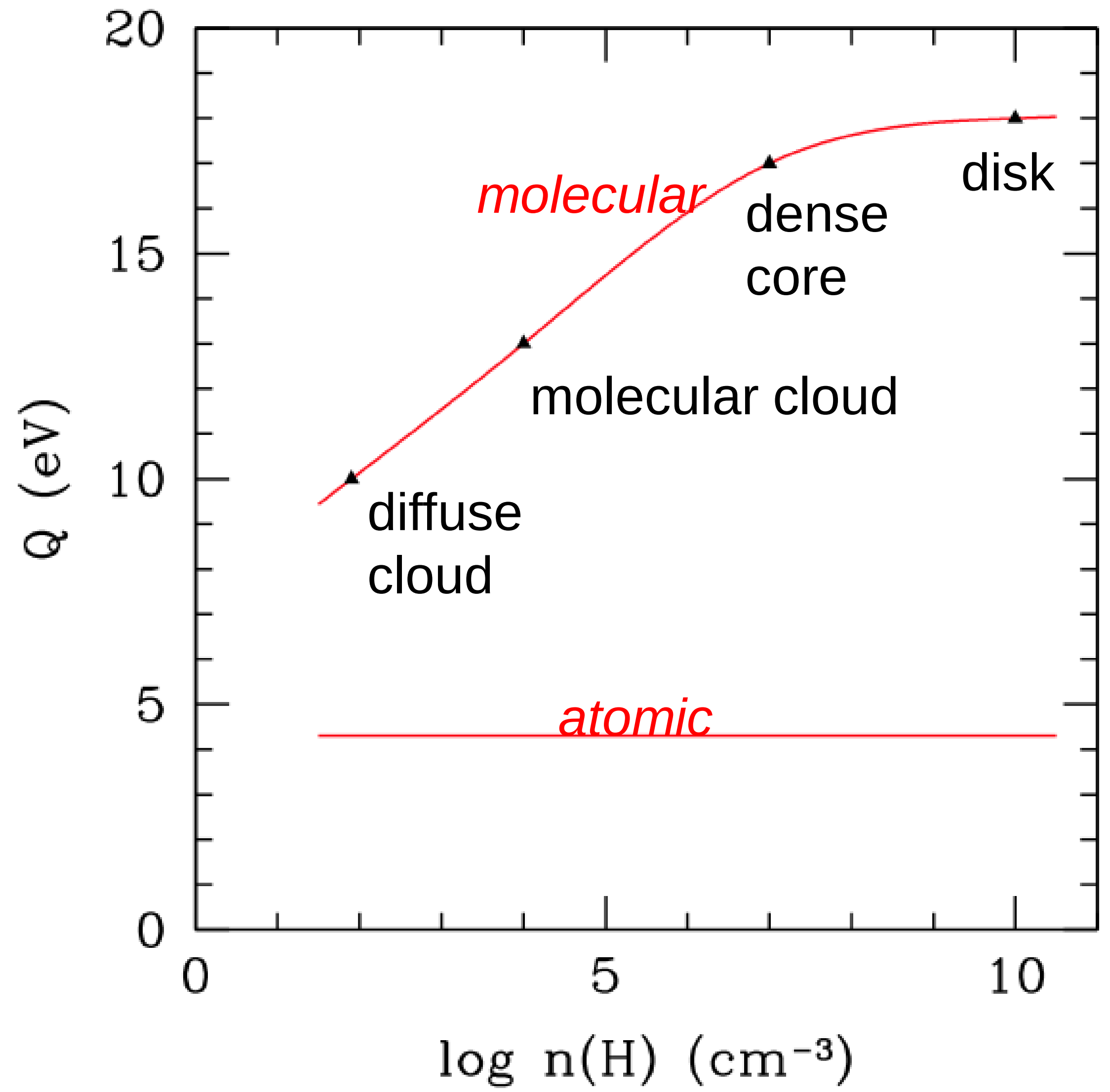
Padovani, Galli & Glassgold (2009)


30 eV electron
H2 ionization
47%
H2+
H3+
high n
HCO+
H3O+
OH+
Qchem= 8 eV
low n
3H
H2 + H
Qchem= 5 eV
H2 excitation
47%
83%
electronic
53%
radiation
47%
dissociation
Qdiss = 2 eV
17%
vibrational
high n
Qvib = 5 eV
low n
radiation
6%
elastic collisions
Qel/rot = 2 eV

X-Ray and Cosmic-ray Heating (in eV) in Molecular Regions

	ζ Per Diffuse Cloud	Molecular Cloud Clump	Prestellar Core Inner Region	Protoplanetary Disk Active Region at 1 AU
n_H (cm^{-3})	80	10^4	10^7	10^{10}
T (K)	≃60	10	6	1000
x_e	2×10^{-4}	10^{-7}	10^{-9}	10^{-6}
H_3^+ destruction	DR[a]	DR + I[a]	DR + I	DR + I
$Q_{el/rot}$ (eV)	4	2	2	2
Q_{vib} (eV)	0	0	5	5
Q_{diss} (eV)	1	2	2	2
Q_{chem} (eV)	5	9	8	9
Total heating Q (eV)	10	13	17	18

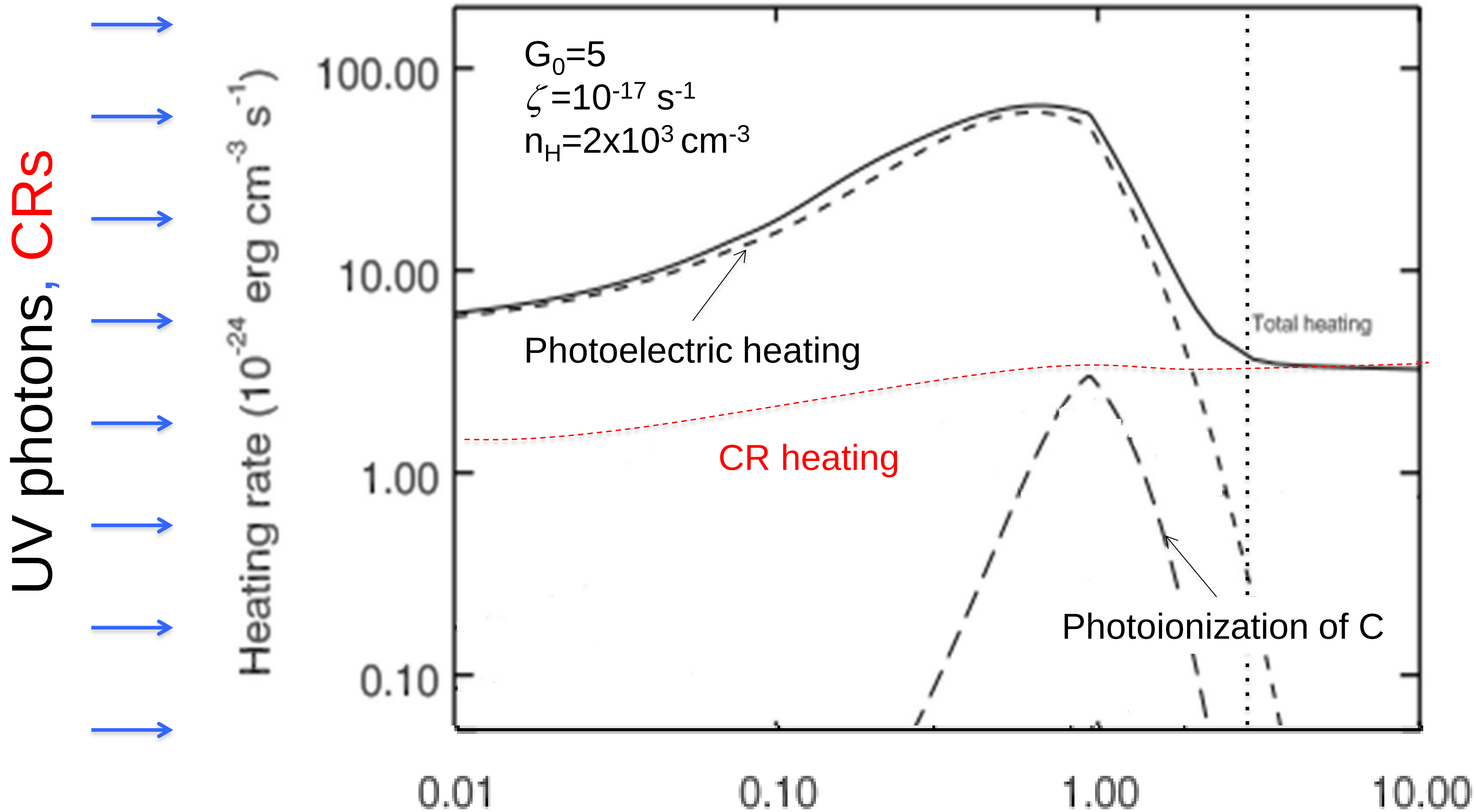
Note. [a] DR stands for dissociative recombination and I for ionic reactions.



Glassgold, Galli & Padovani (2012)

UV photons vs. CRs

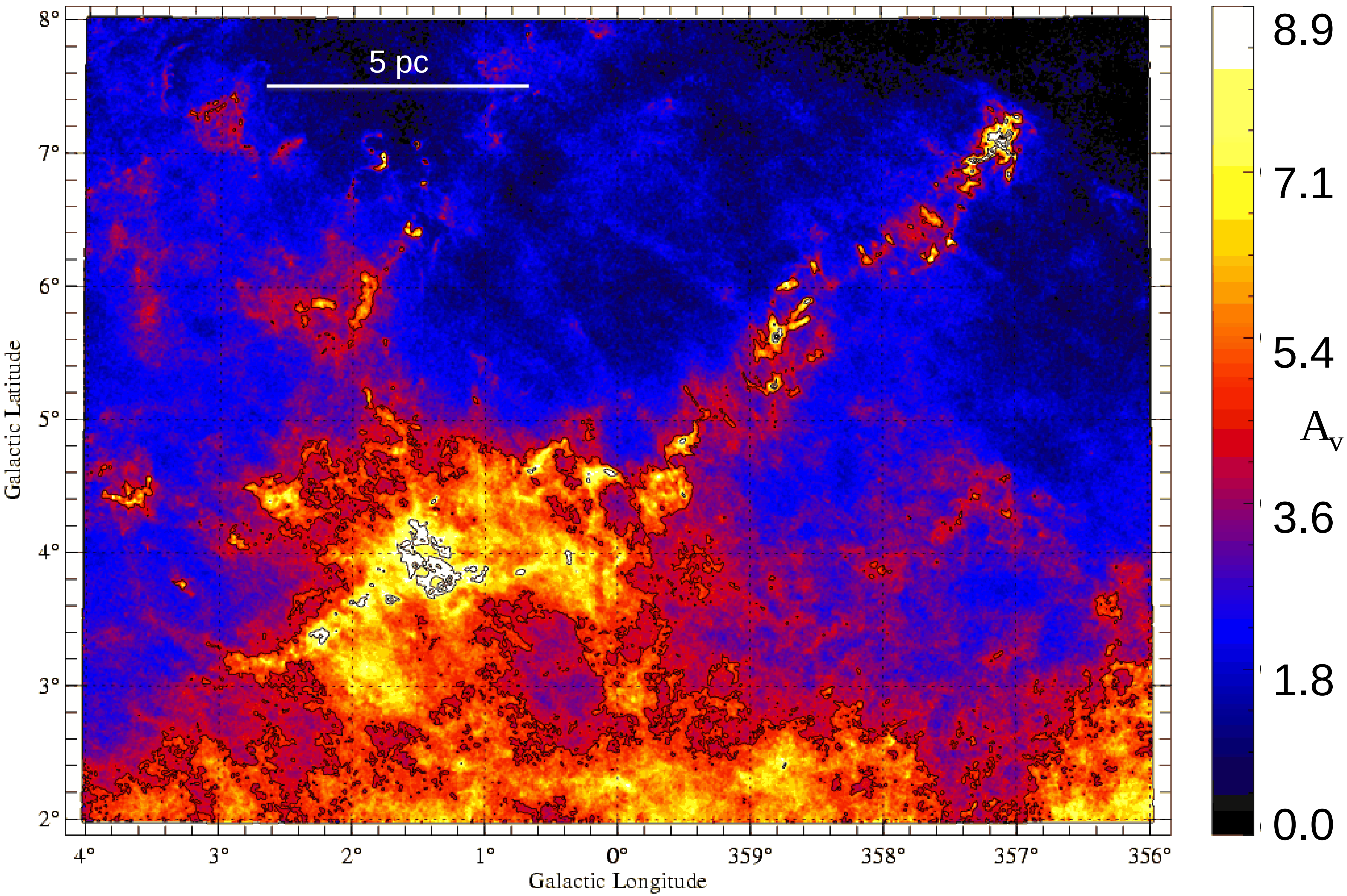
$$A_v^{\rm cr} \approx 4.0 + 0.6 \ln\left(\frac{G_0}{\zeta_{-17}}\right)$$



$$A_v = \left(\frac{N_{\rm H}}{2\times10^{21}\ {\rm cm}^{-2}}\right)$$

PDR model fom Habart et al. (2001)

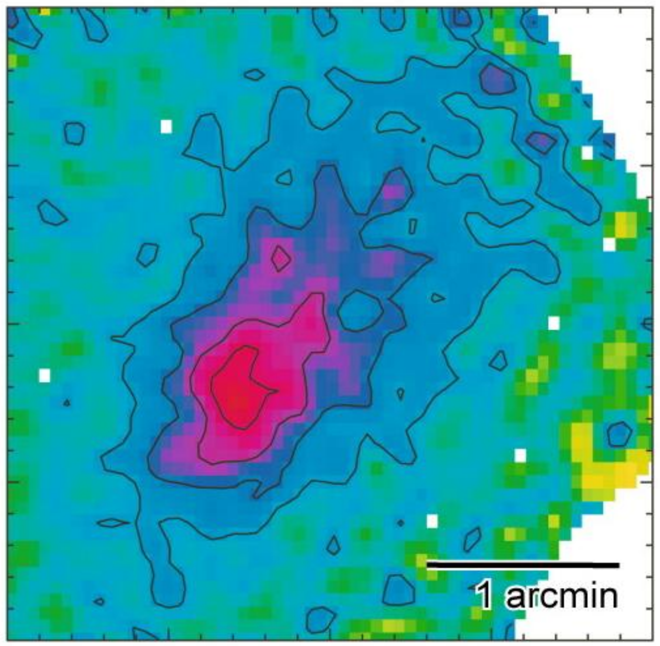
Extinction map of a molecular cloud

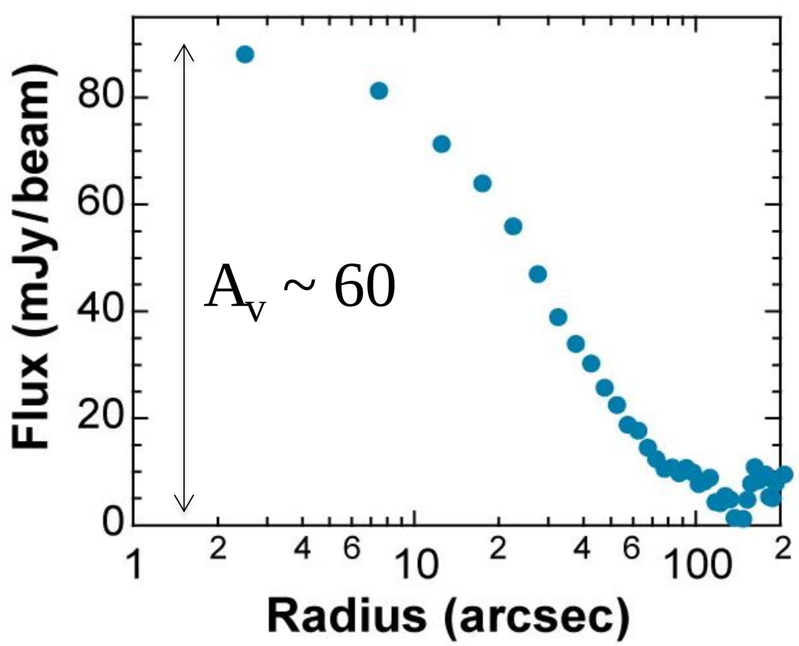


Lombardi, Alves & Lada et al. (2006)

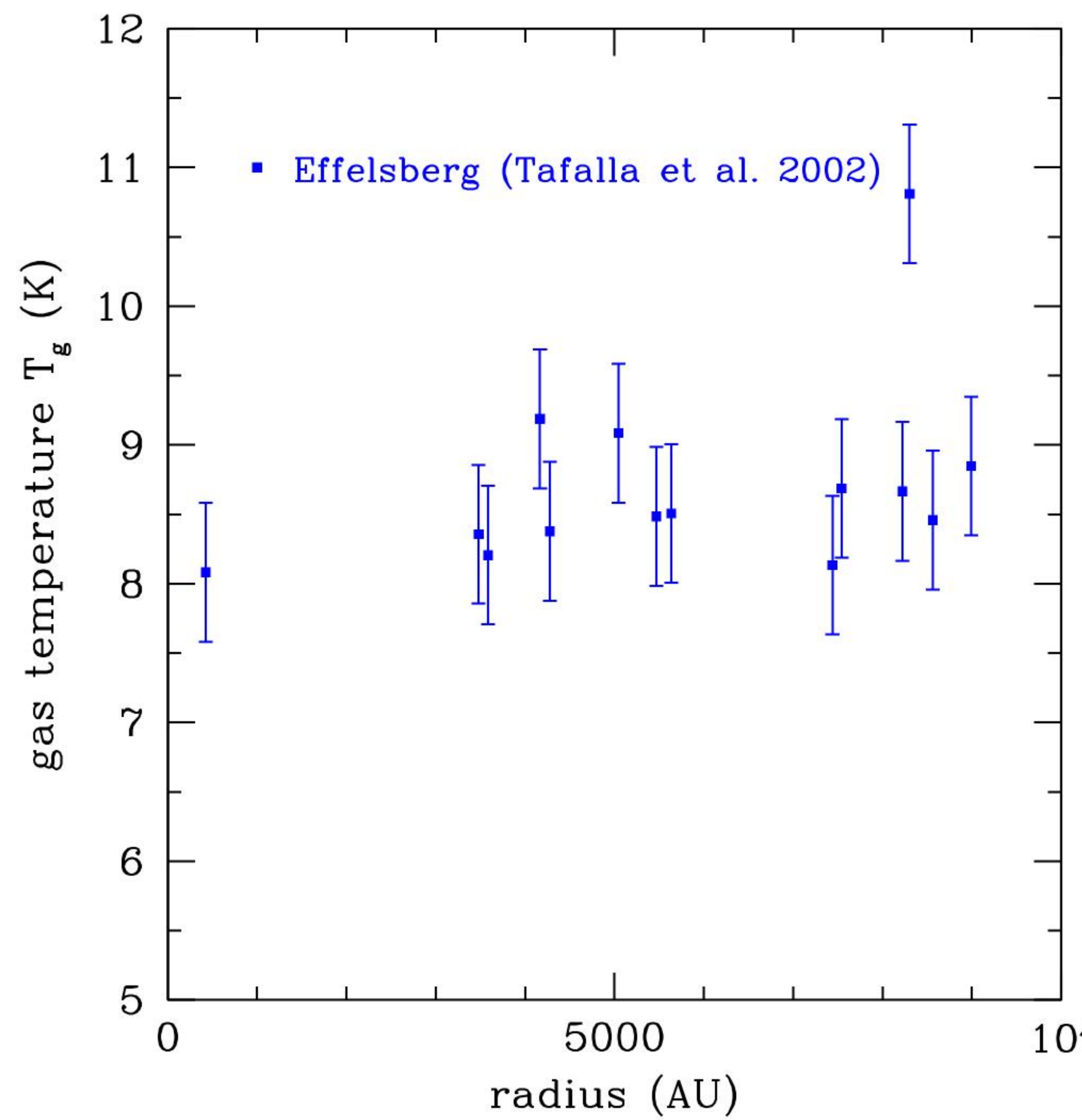
Gas temperature profile of a starless core from NH_3

L1544 1.2 mm continuum





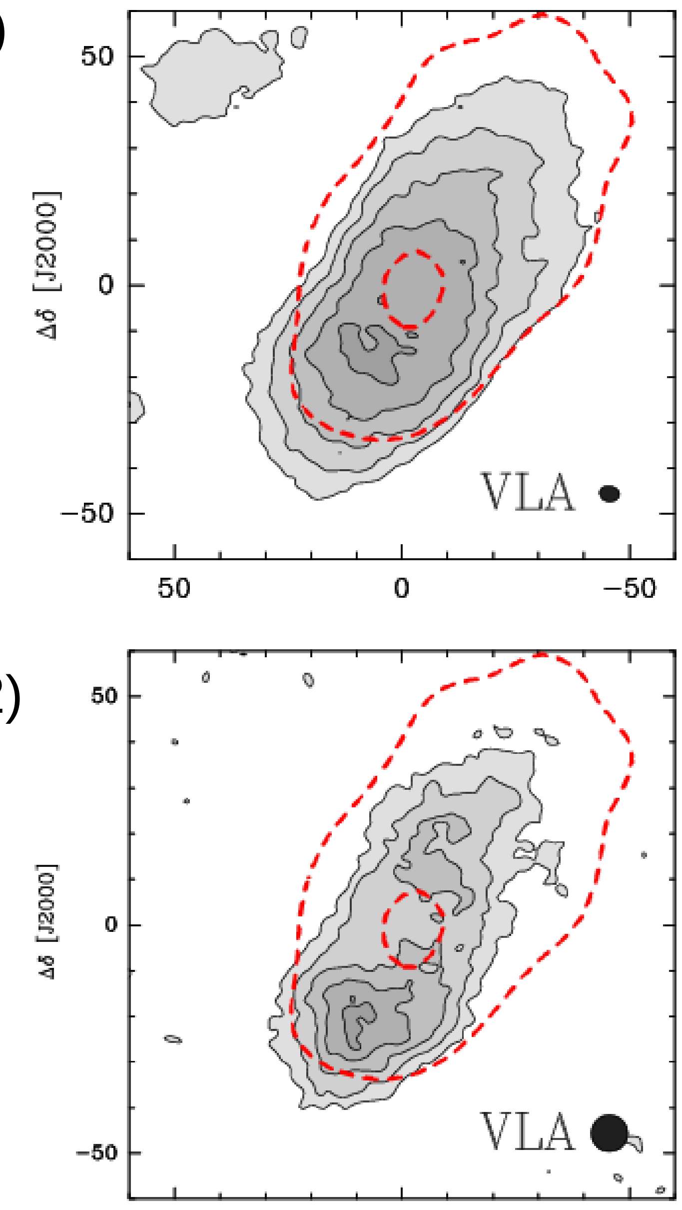
Ward-Thompson, Motte & André (1999)
Bacmann et al. (2000)
Tafalla at al. (2002)



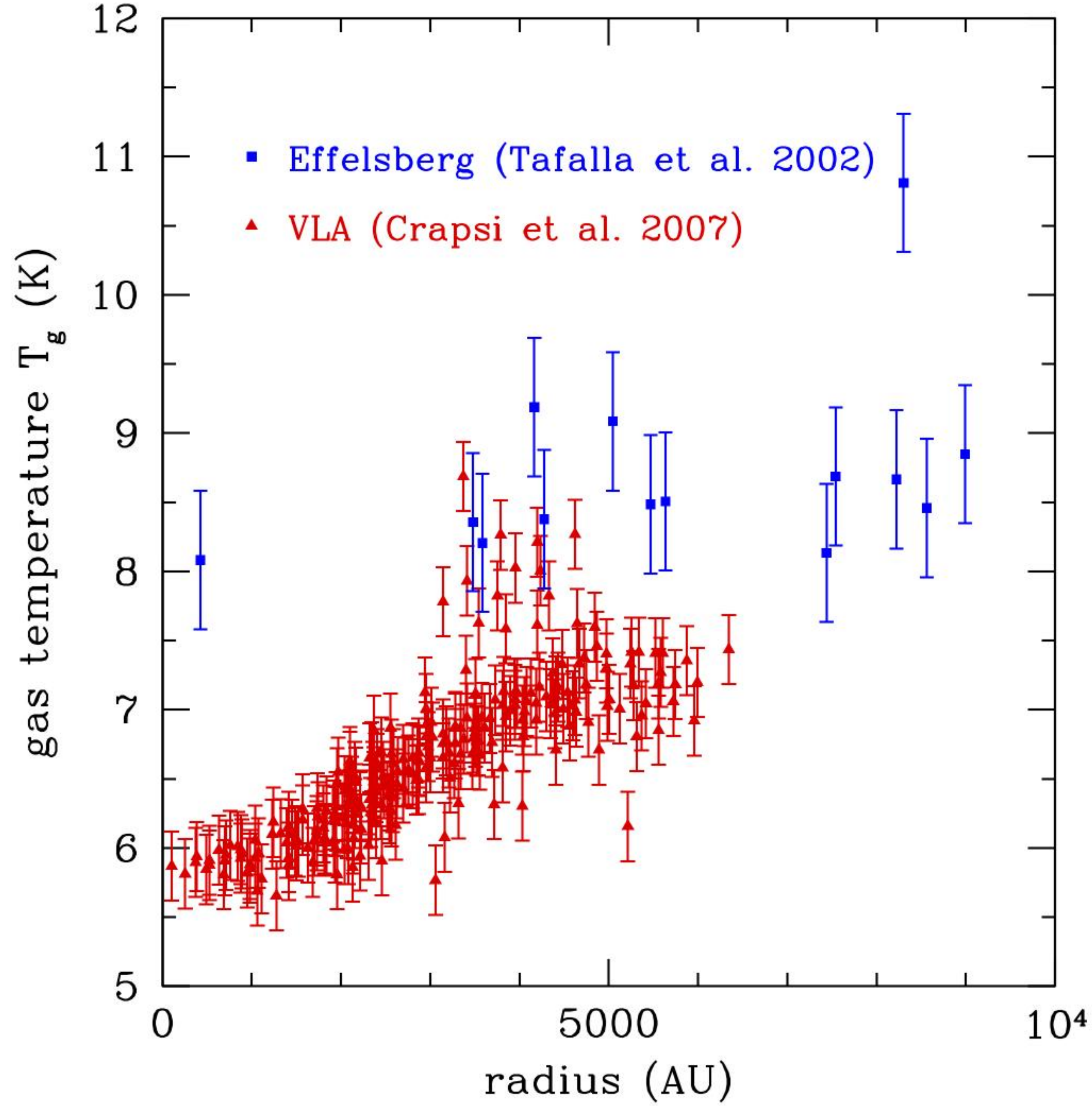
Gas temperature profile of a starless core from NH_3

NH_3 (1,1)

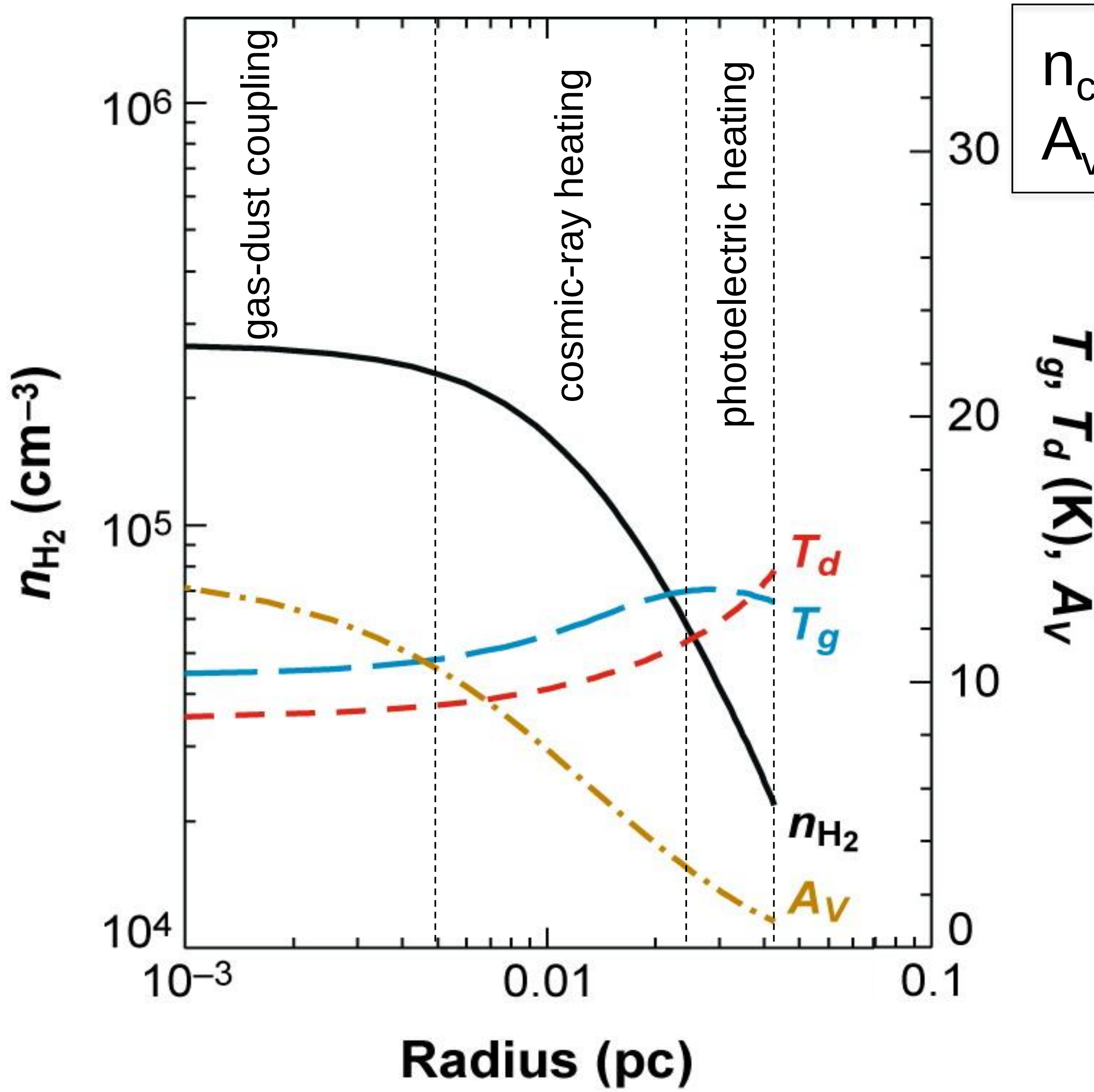
NH_3 (2,2)



Crapsi et al. (2007)



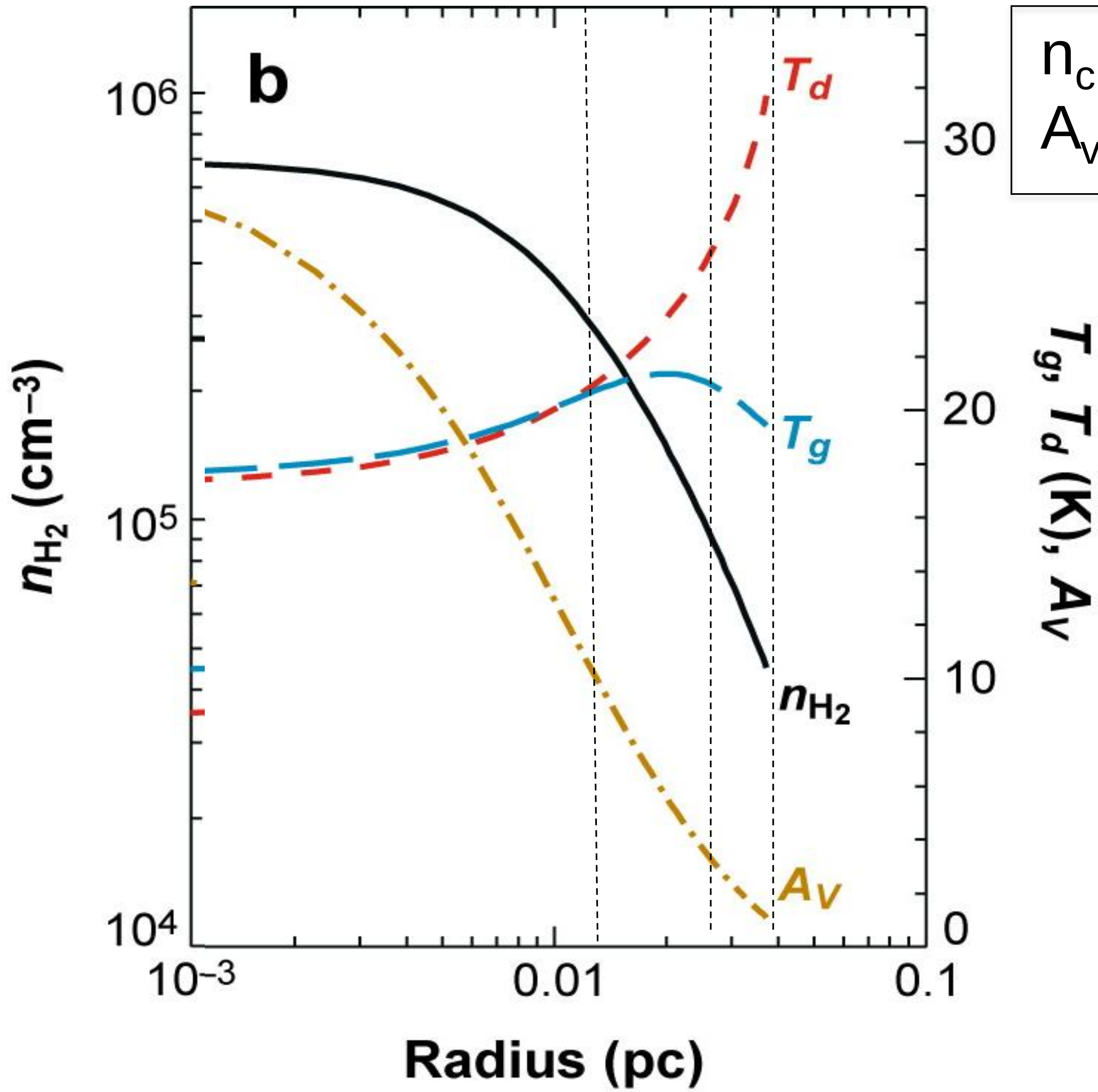
Temperature profile of a prestellar core



$n_c = 2.5 \times 10^5$ cm^{-3}
$A_V^c = 14$

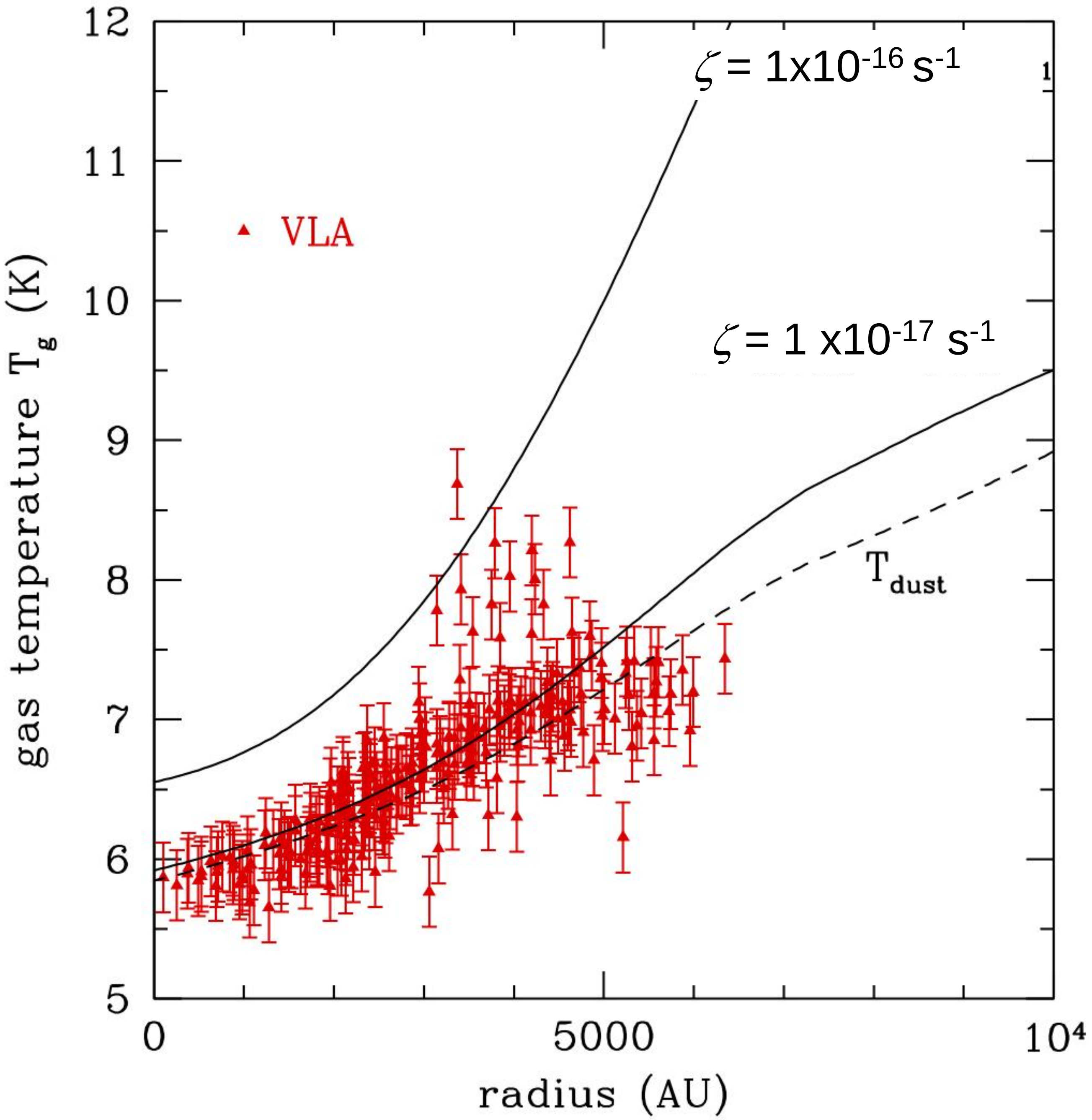
Galli, Walmsley & Gonçalves (2002)

Temperature profile of a prestellar core



n_c = 7 x 10^5 cm^{-3}
A_v^c = 27

Galli, Walmsley & Gonçalves (2002)



Best-fit from chemical modeling of molecular ion abundances gives ζ=1.3 x 10^{-17} s^{-1} (Vastel et al. 2006)

Conclusions

- Cosmic rays ionize and heat the dense cores of molecular clouds
- The heat deposited in the gas per ionization is

  Q=5 eV in HI clouds

  Q=10 eV in diffuse molecular clouds

  Q=17 eV in dense cores
- T_{gas} → additional constraint on ζ
- in the dense core L1544, both T_{gas} and chemistry give $\zeta \sim 1 \times 10^{-17}\ s^{-1}$