Cosmic-ray ionization and heating in molecular clouds

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Outline

- Importance of low-energy CRs:

1. Primary source of ionization in UV-shielded regions of MCs
2. Drive the formation of polyatomic ions and molecules
3. Important source of heating in MCs
4. Produce light elements (Li, Be, B) by spallation reaction

   $[p, \alpha]_{CR} + [C, N, O]_{ISM} \rightarrow [^{6}Li, ^{7}Li, ^{9}Be, ^{10}B, ^{11}B]$
5. Produce γ-ray diffuse emission by π_0 decay

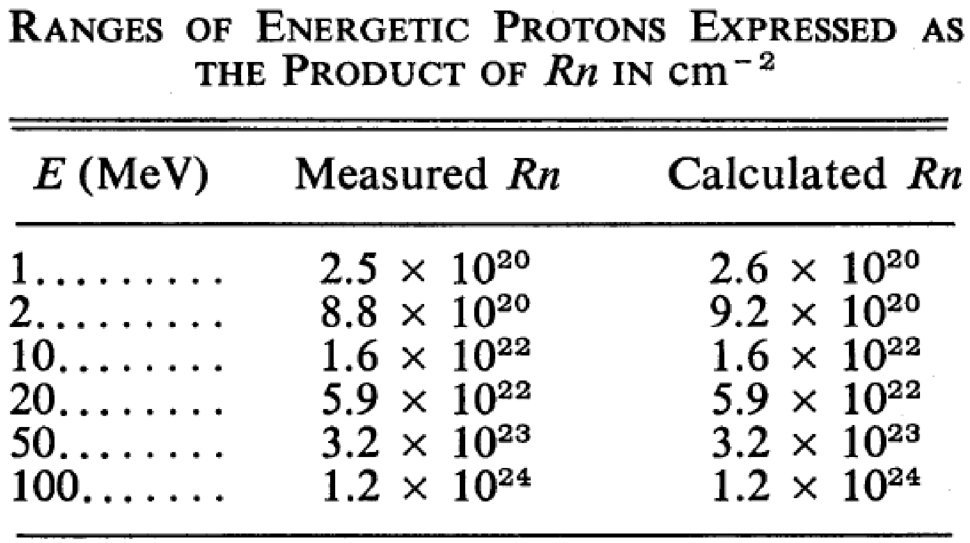
   $p_{CR} + p_{ISM} \rightarrow p + p + \pi^0 + \pi^+ + \pi^-$ $\quad \pi^0 \rightarrow 2\gamma$
6. Produce γ-ray lines by nuclear excitation

   $[p, \alpha] + [C, O] \rightarrow [C^*, O^*] \rightarrow \gamma$ (4.44, 6.13 MeV)

Consequence of 1:

- control the degree of coupling with B with gas (electrical resistivity)

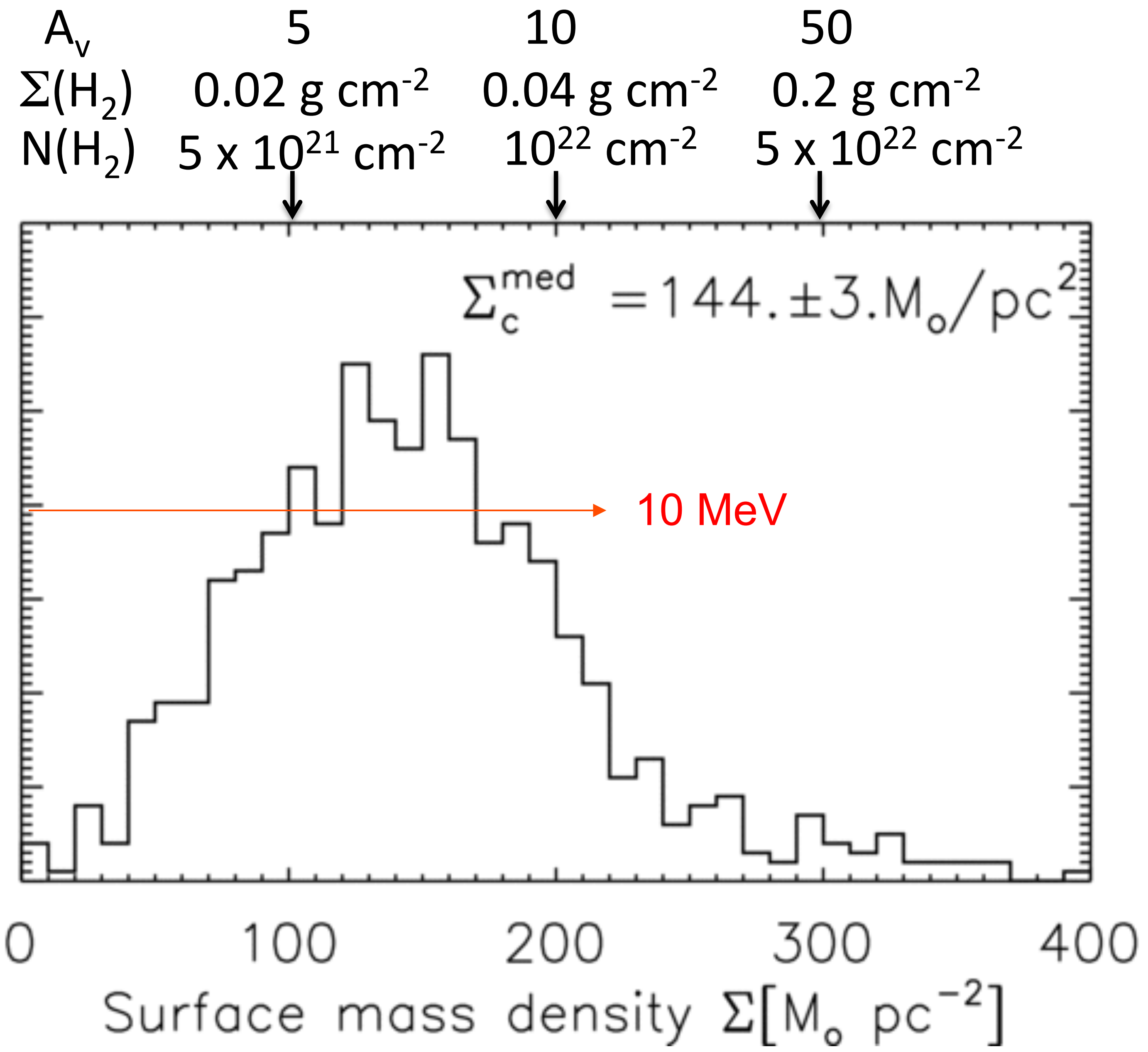
Molecular Clouds: “absorbers” of low-energy CRs



RANGES OF ENERGETIC PROTONS EXPRESSED AS THE PRODUCT OF *Rn* IN cm^{-2}

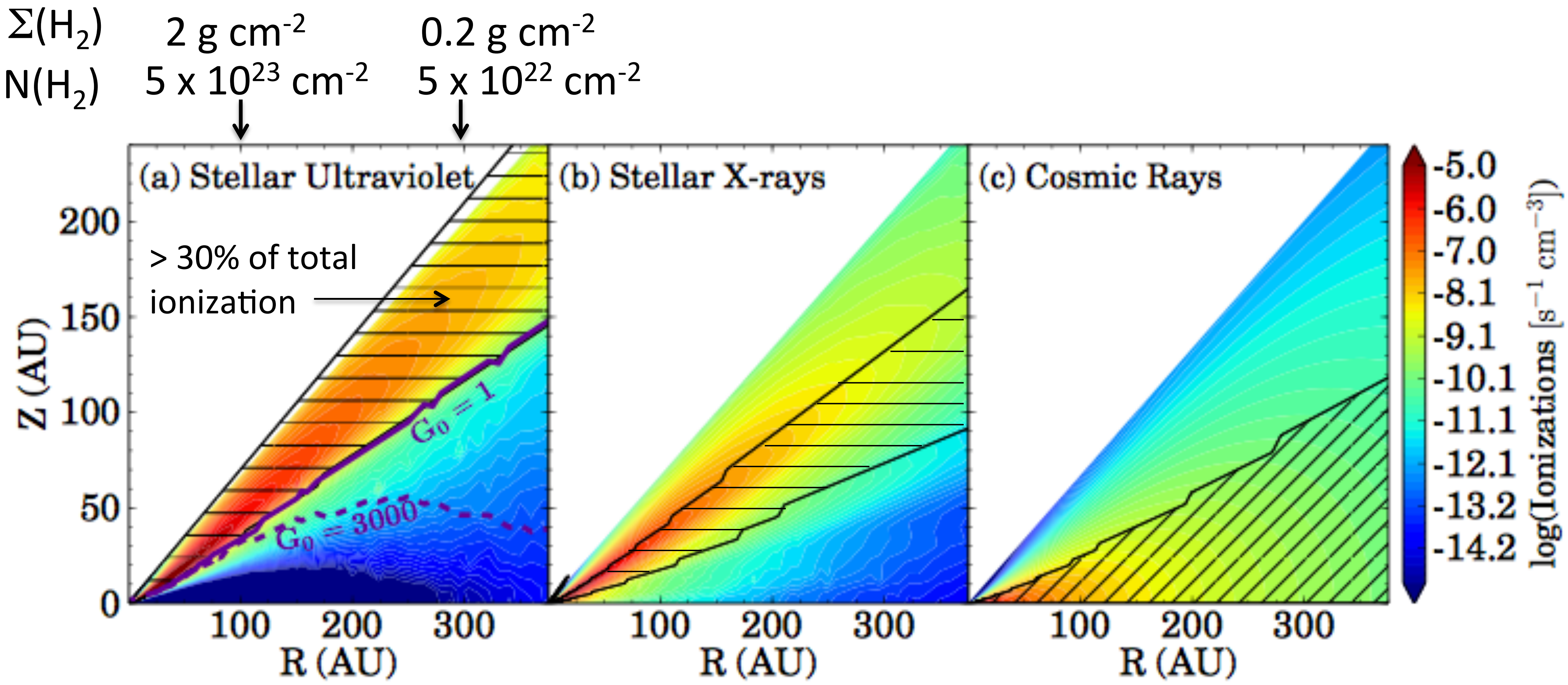
E (MeV)	Measured *Rn*	Calculated *Rn*
1.........	2.5×10^{20}	2.6×10^{20}
2.........	8.8×10^{20}	9.2×10^{20}
10........	1.6×10^{22}	1.6×10^{22}
20........	5.9×10^{22}	5.9×10^{22}
50........	3.2×10^{23}	3.2×10^{23}
100.......	1.2×10^{24}	1.2×10^{24}

Cravens & Dalgarno (1978)



Roman-Duval et al. (2010)

Cosmic ray penetration in protostellar disks



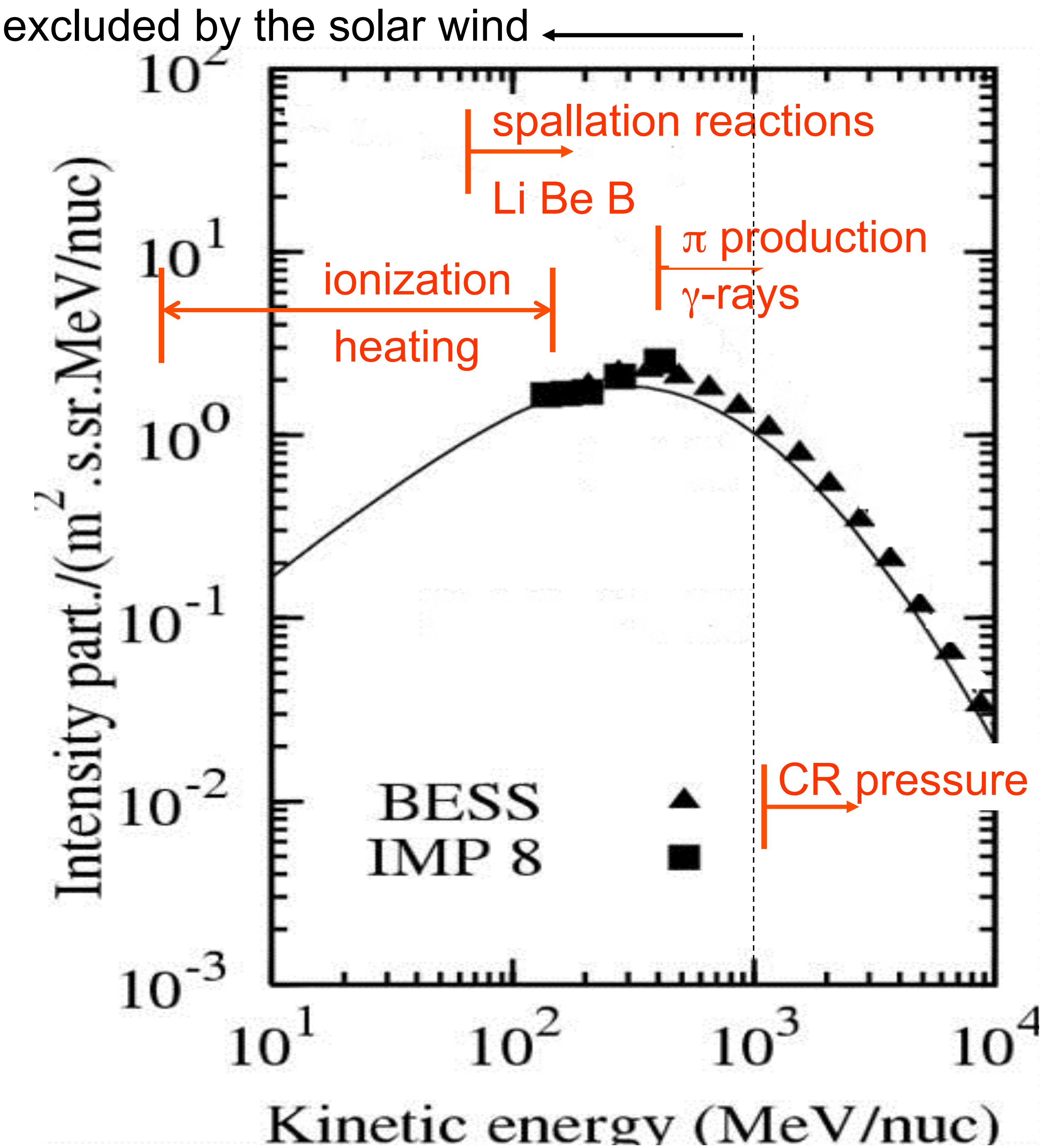
$\Sigma(H_2)$ 2 g cm^{-2} 0.2 g cm^{-2}

$N(H_2)$ 5 x 10^{23} cm^{-2} 5 x 10^{22} cm^{-2}

> 30% of total ionization

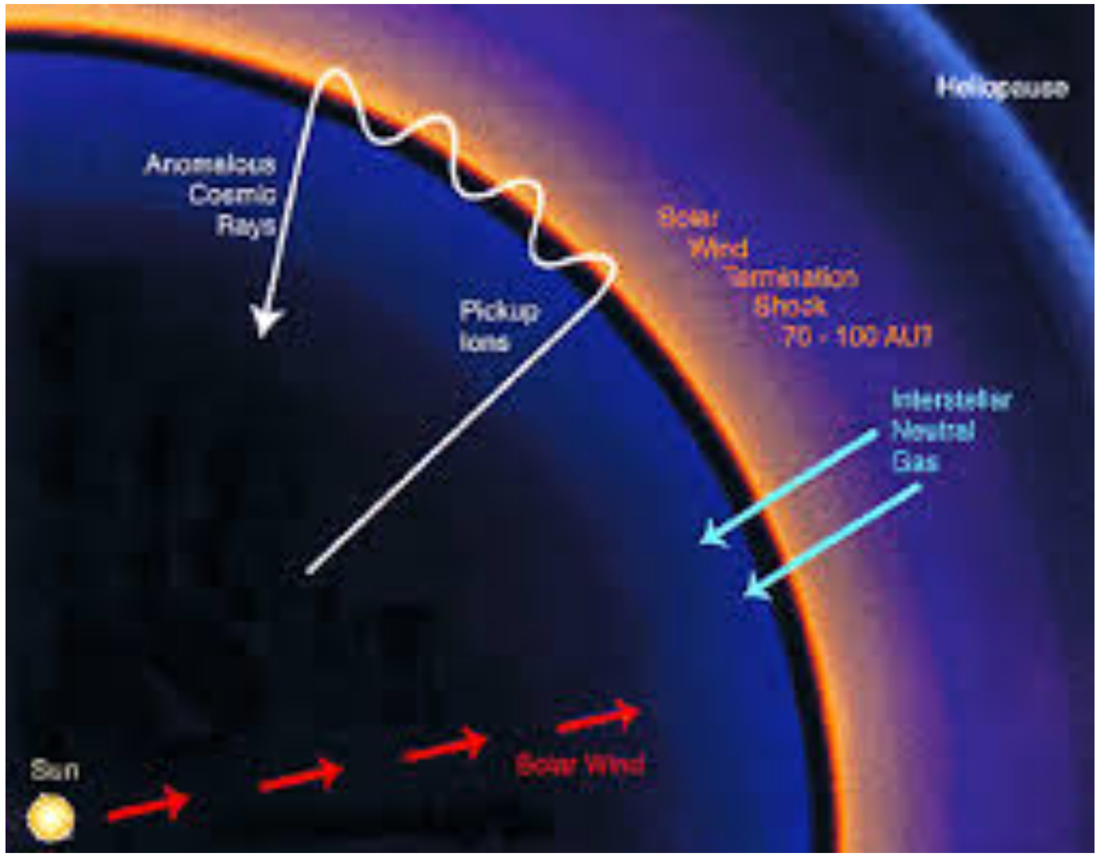
Cleeves, Adams & Bergin (2013)

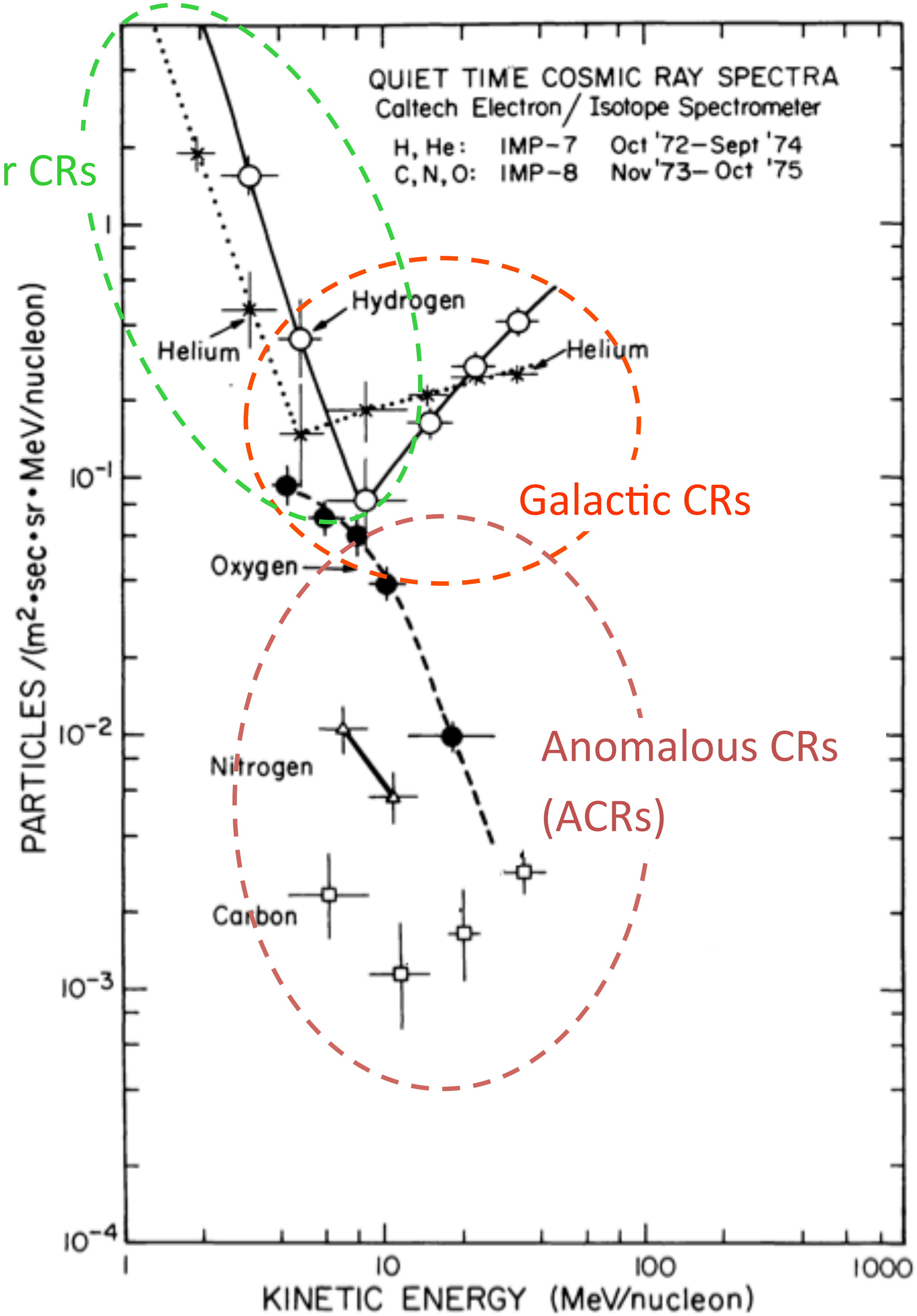
Spectrum of low-energy CR protons



Valdès-Galicia et al. (2006)

Components of low-energy CRs measured on Earth



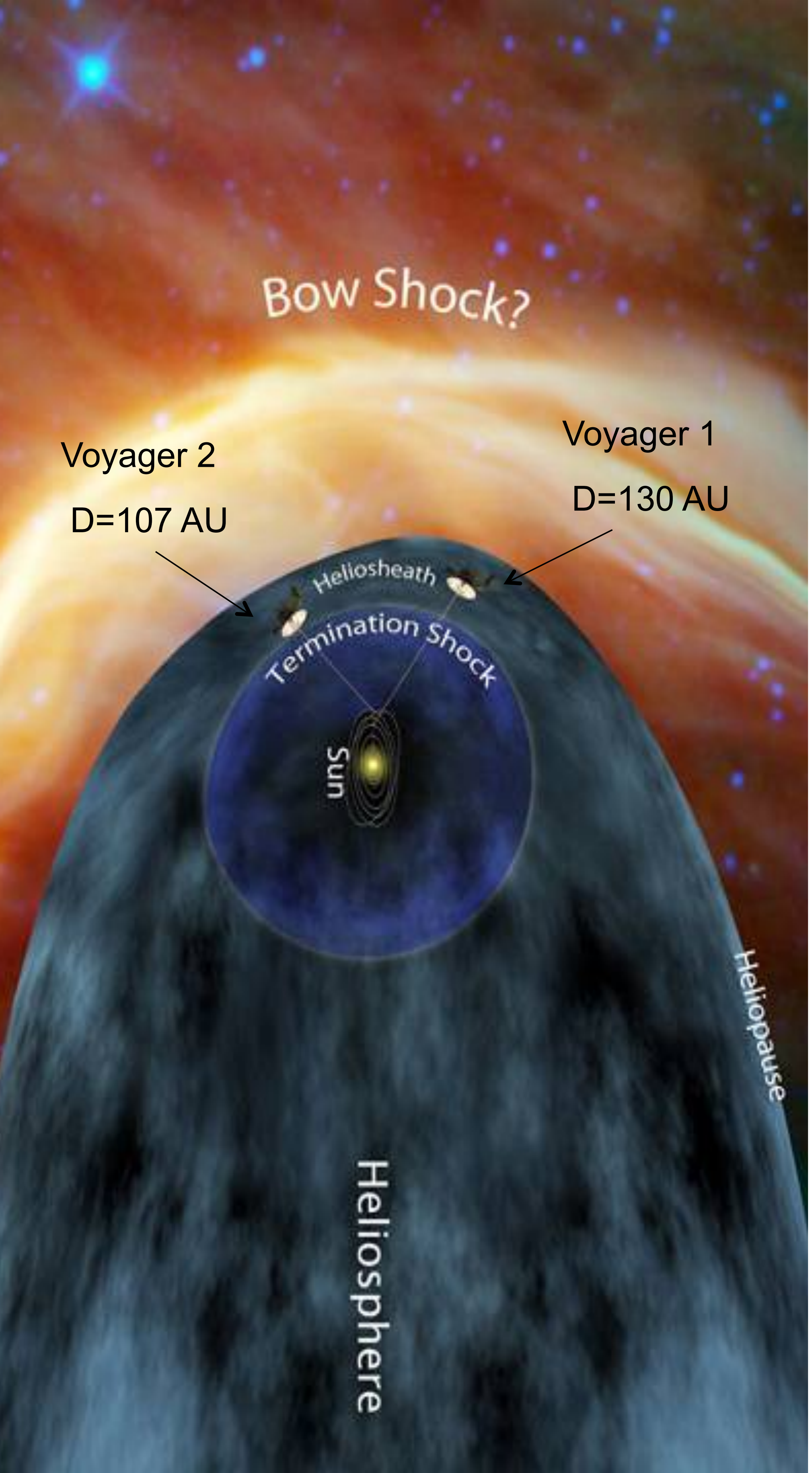


Solar CRs

Galactic CRs

Anomalous CRs (ACRs)

Stone (1977)



NATURE | NEWS

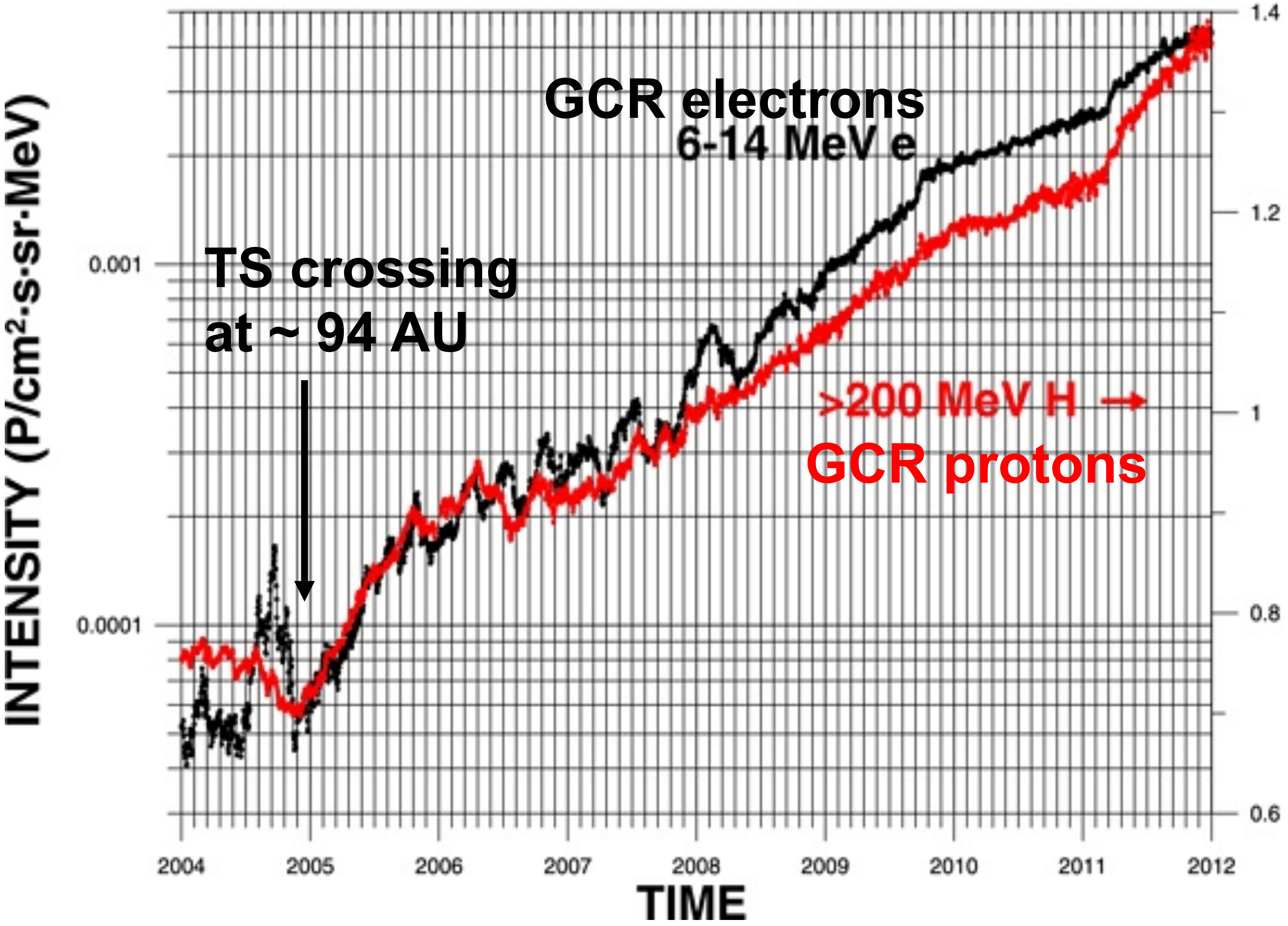
Voyager 1 has reached interstellar space

High electron densities show the craft left the Sun's bubble of influence in 2012.

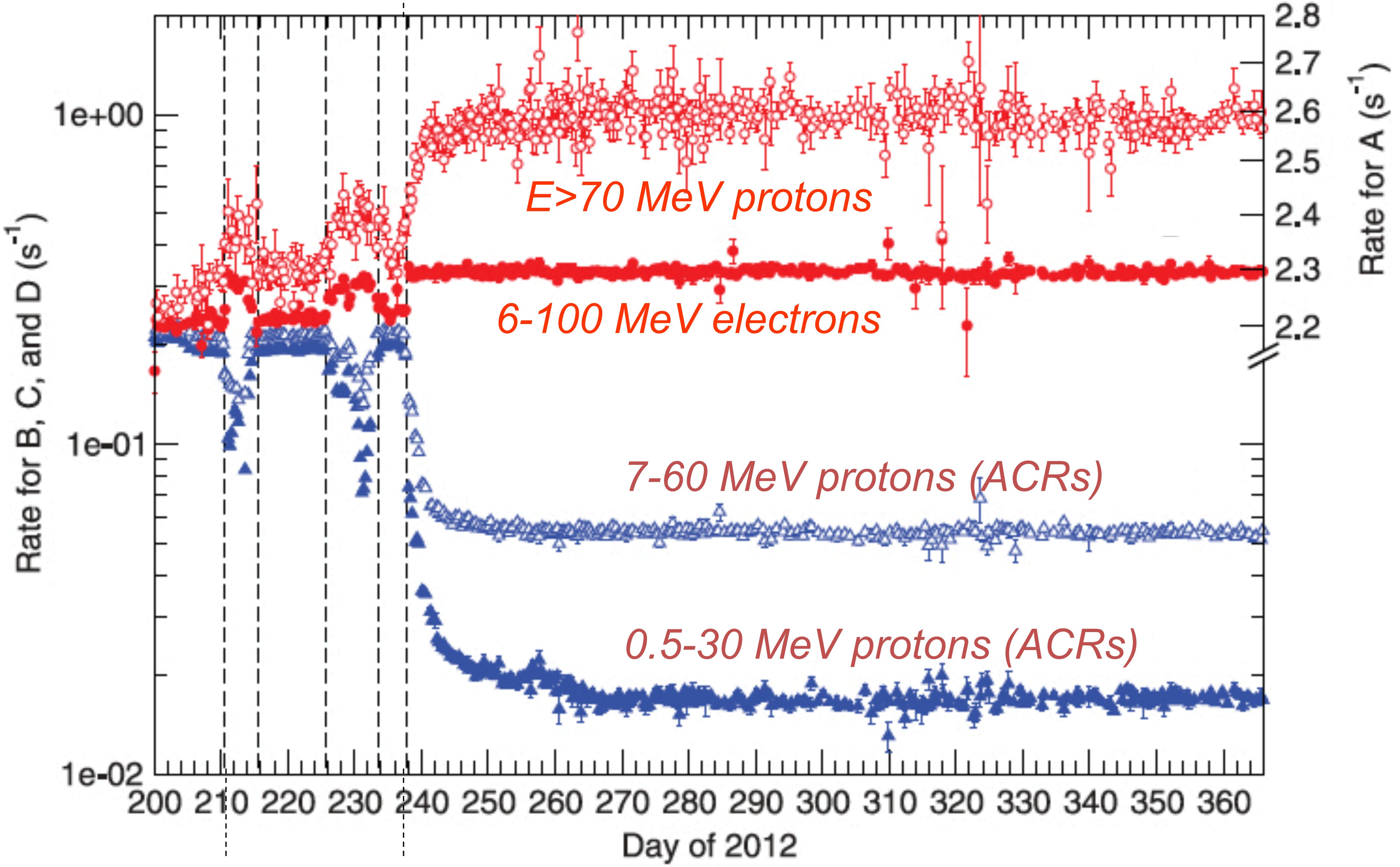
Ron Cowen

12 September 2013

Voyager I data (Webber et al. 2012)



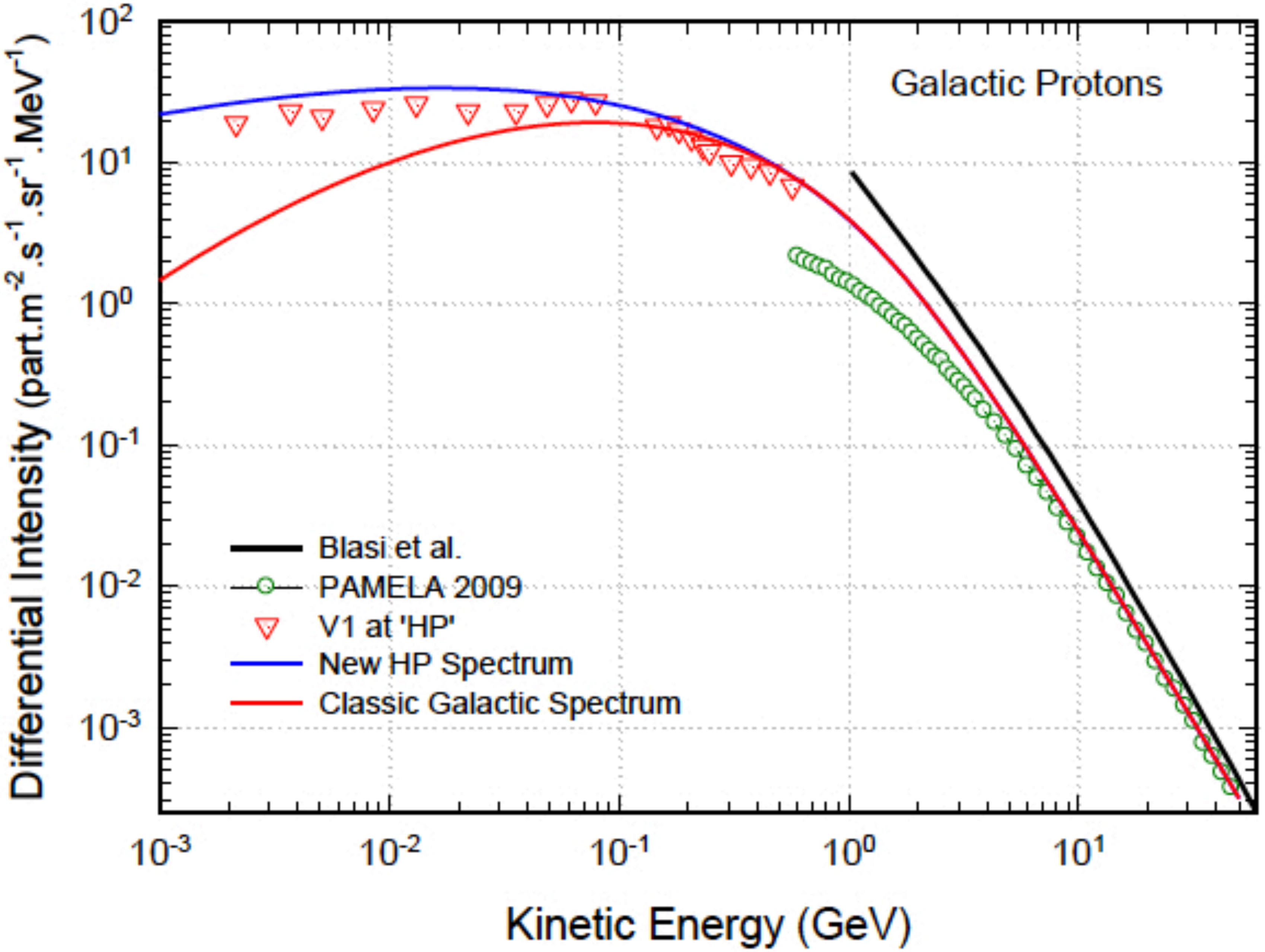
solar depletion zone at ~ 120 AU



July-August 2012

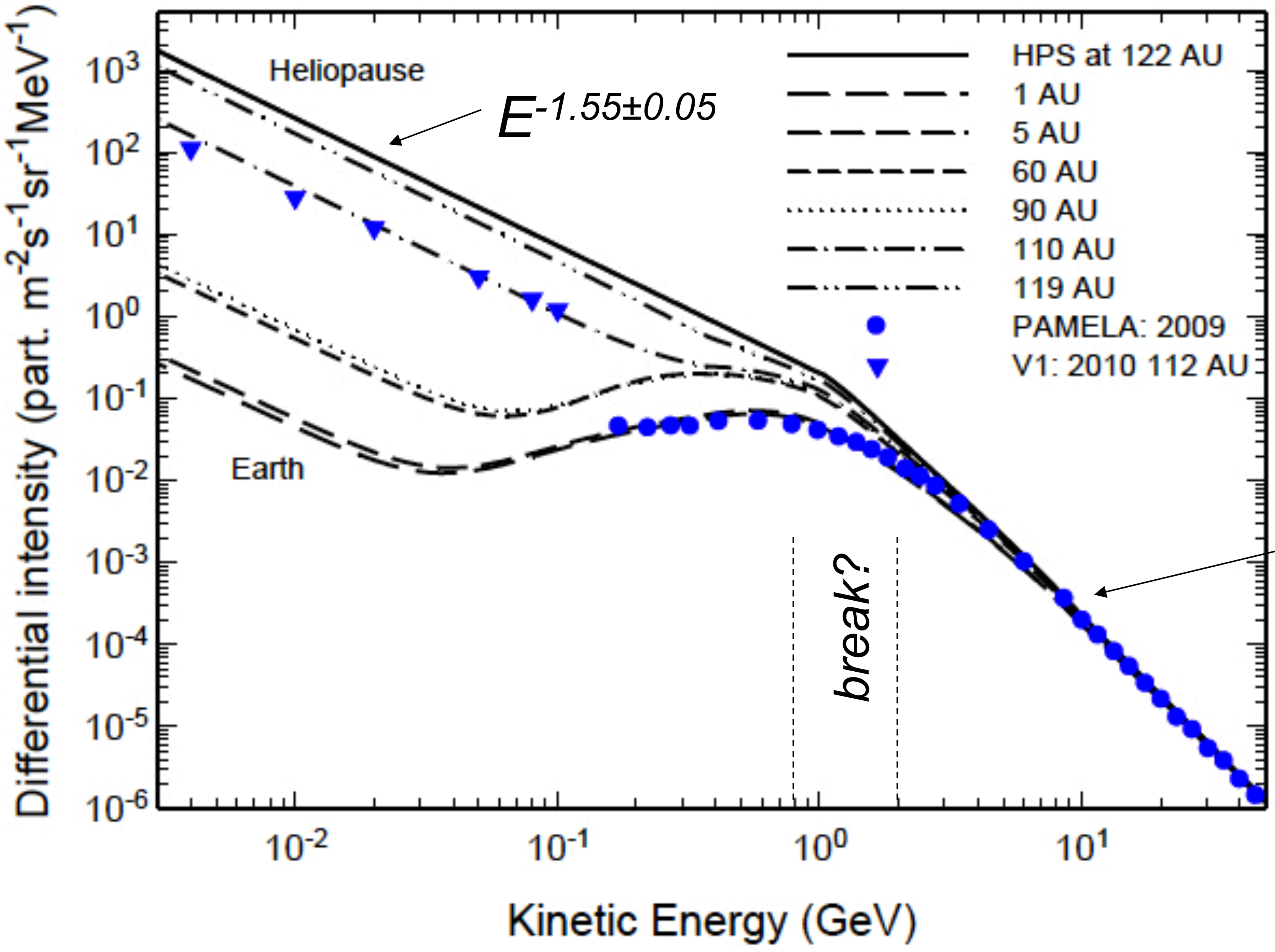
Stone et al. (2012)

Voyager-1 proton spectrum



Potgieter (2013)

Voyager 1 electron spectrum



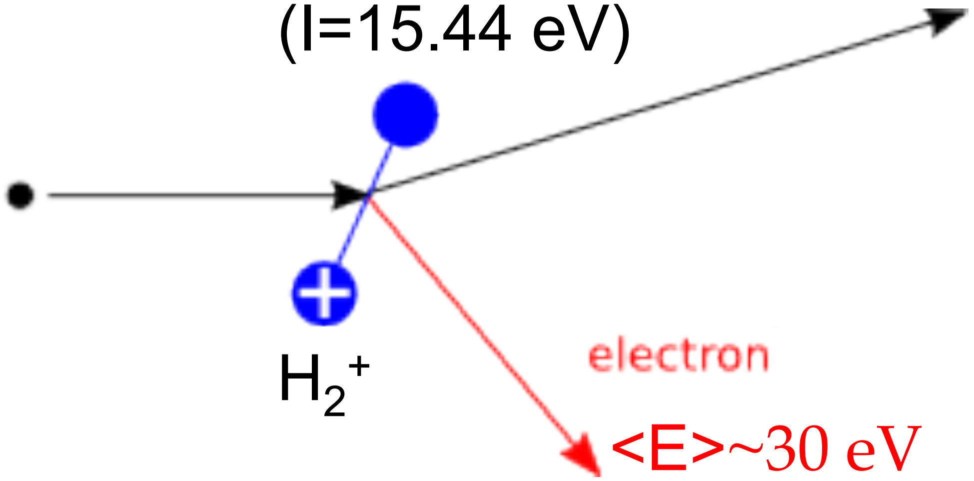
$E^{-1.55\pm0.05}$

$E^{-3.15\pm0.05}$

<u>Warning</u>: Voyager-1 spectra are heliopause spectra, not Galactic spectra.

Potgieter (2013)

CR-ionization of H_2



cosmic-ray nucleus

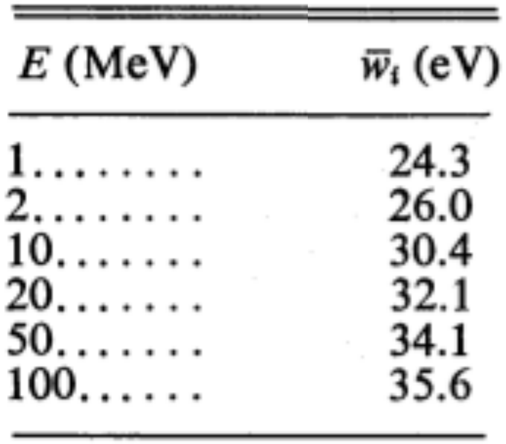
charge Ze, velocity v

H_2 molecule
(I=15.44 eV)

H_2^+

electron

$\langle E \rangle \sim 30$ eV



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

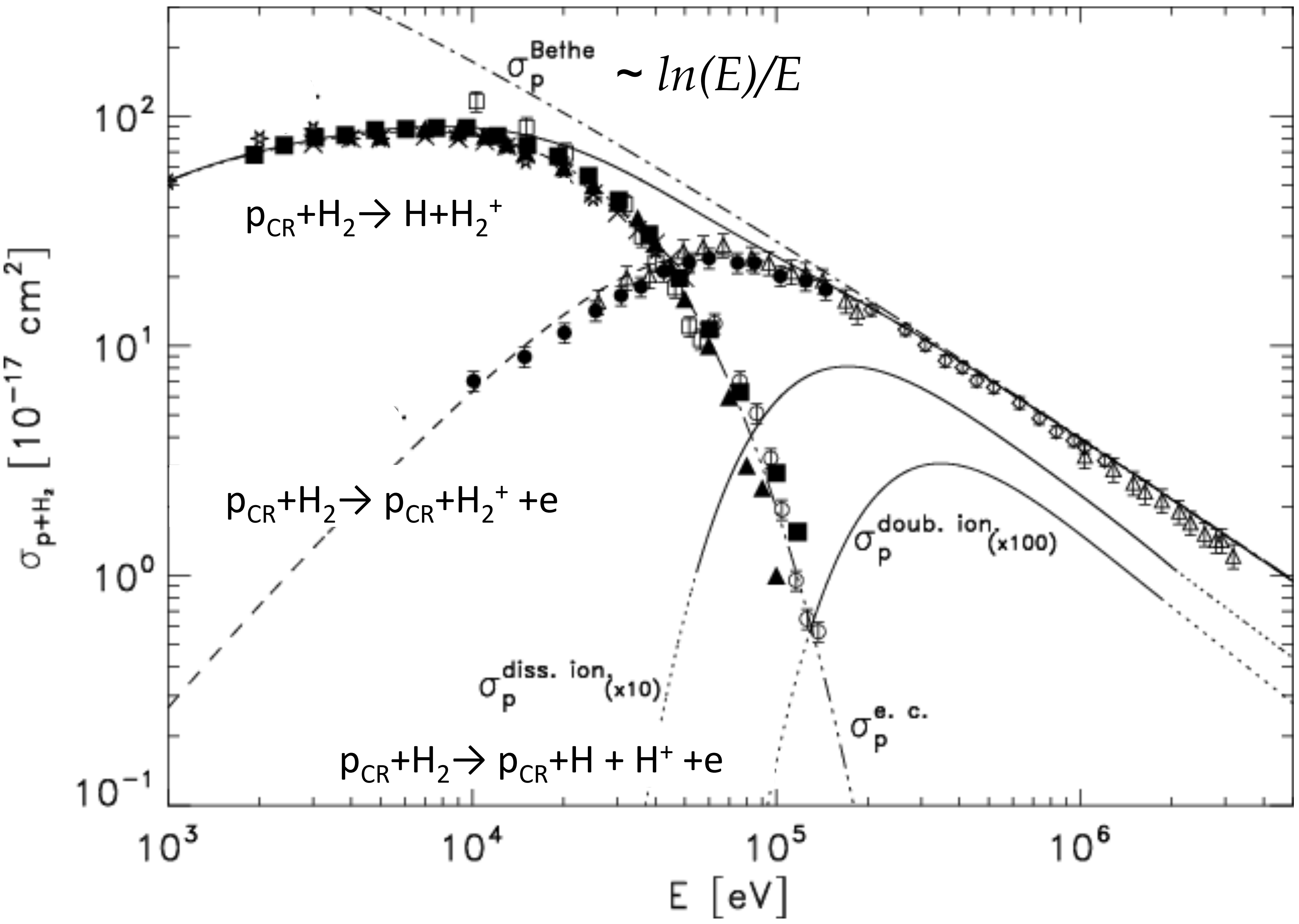
Cravens & Dalgarno (1978)

- Thomson (1912) and Bohr (1913) classical

$$\sigma_T^{\text{ion}}(v) = \frac{4\pi Z^2 e^4}{m_e v^2}\left(\frac{1}{I} - \frac{2}{m_e v^2}\right) \qquad \langle E_e \rangle \to I \ln(m_e v^2/2I) \quad \text{if } v^2 \gg 2I/m_e$$

- Bethe (1930, quantistic) and Bethe (1932, quantistic relativistic)

$$\sigma_B^{\text{ion}} = \frac{4\pi Z^2 e^4}{m_e c^2 \beta^2}\left[\ln \frac{2 m_e c^2 \beta^2}{I(1-\beta^2)} - \beta^2\right]$$



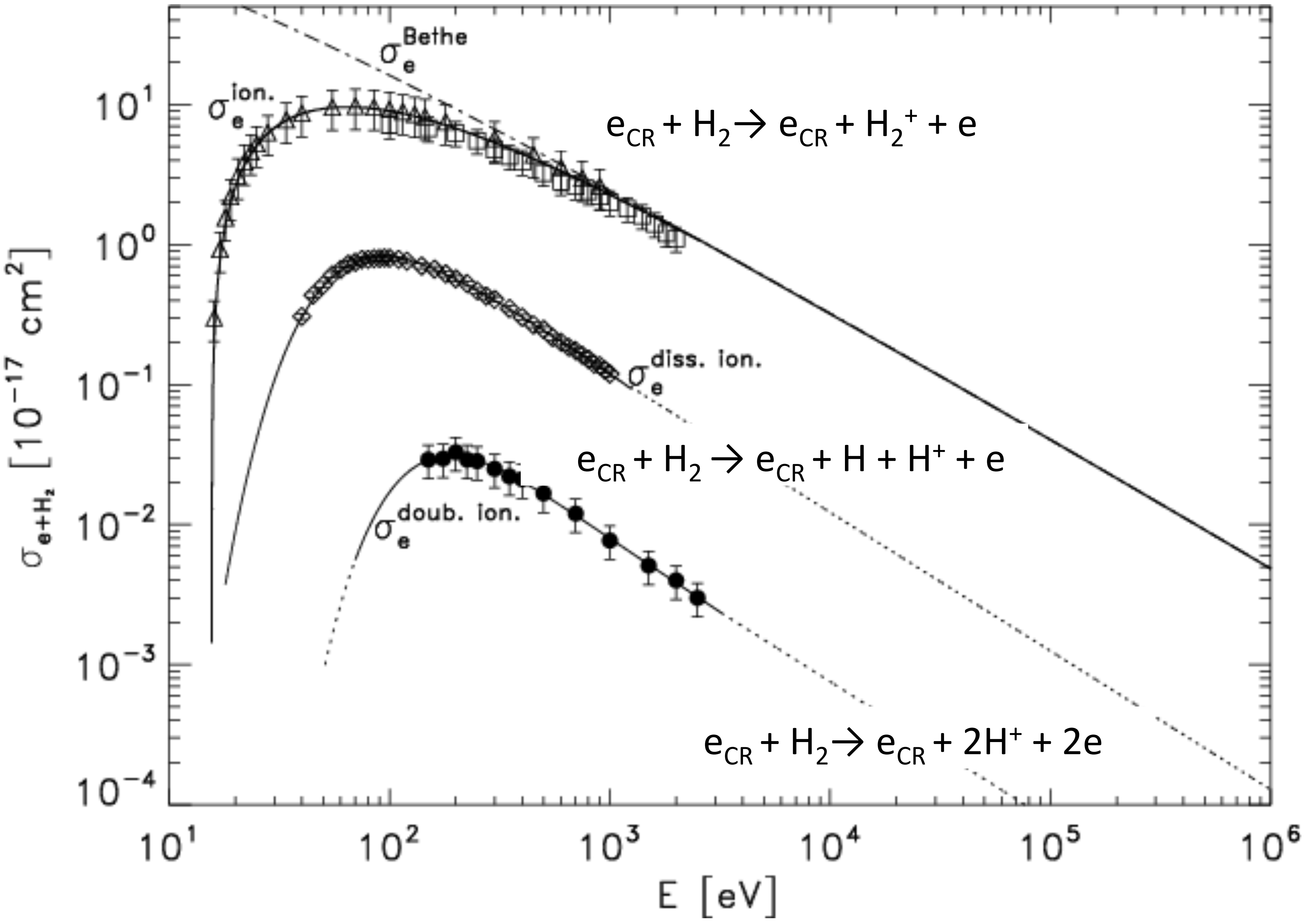
~ $ln(E)/E$

$p_{CR}+H_2 \rightarrow H+H_2^+$

$p_{CR}+H_2 \rightarrow p_{CR}+H_2^+ +e$

$p_{CR}+H_2 \rightarrow p_{CR}+H + H^+ +e$

Padovani et al. (2009)



$e_{CR} + H_2 \rightarrow e_{CR} + H_2^+ + e$

$e_{CR} + H_2 \rightarrow e_{CR} + H + H^+ + e$

$e_{CR} + H_2 \rightarrow e_{CR} + 2H^+ + 2e$

Padovani et al. (2009)

Given a cosmic ray spectrum j(E) and ionization cross section σ(E), the ionization rate ζ_{CR} can be calculated theoretically

$$\zeta_{CR} = 4\pi \int_{E_{low}}^{E_{high}} j(E)\sigma(E)dE$$

- Hayakawa et al. (1961), Spitzer & Tomasko (1968) for H
- Glassgold & Langer (1974) for H_2

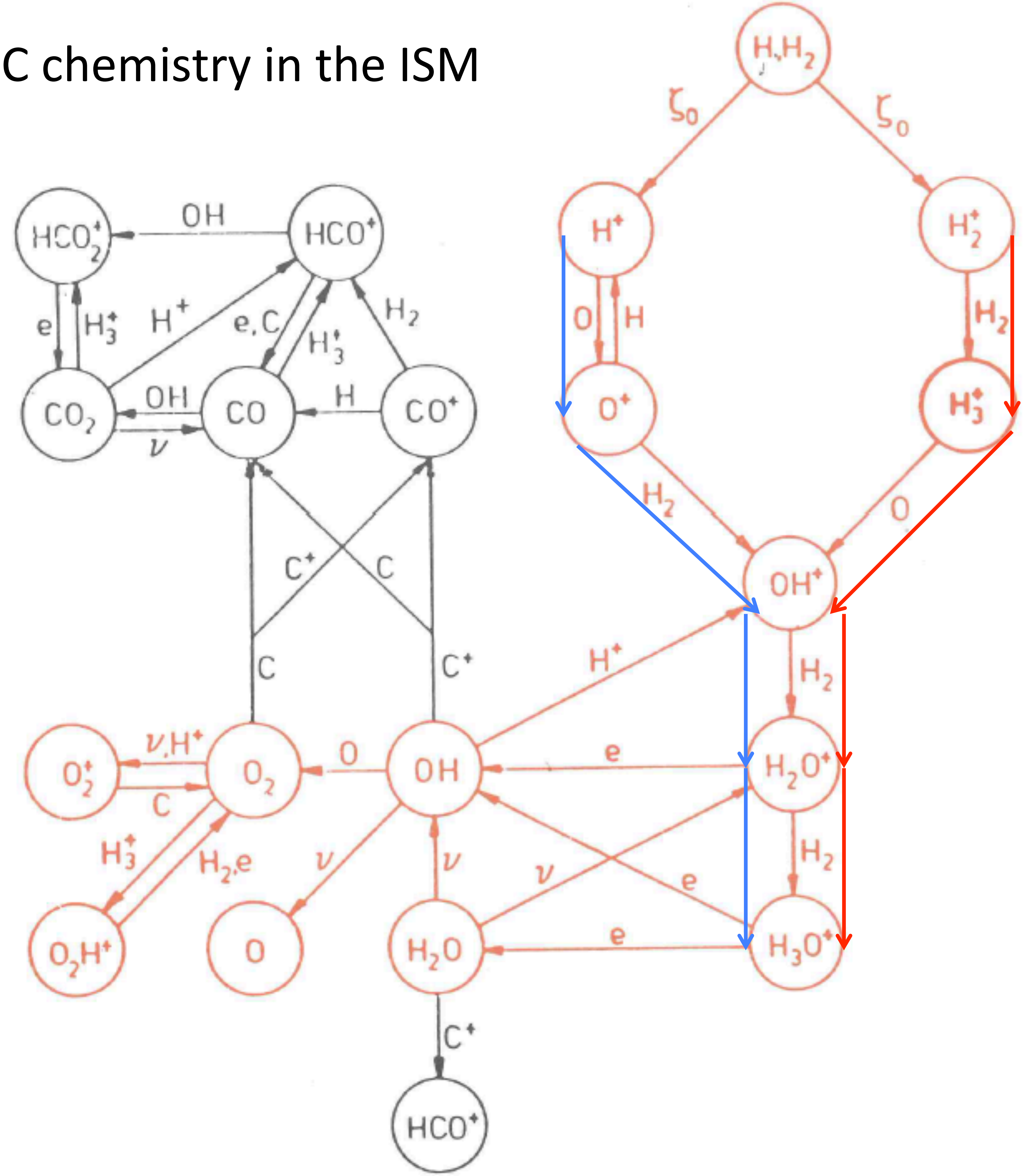
⟶ “Spitzer value” $\zeta_{CR} \approx 1\text{-}2 \times 10^{-17}\ \mathrm{s}^{-1}$

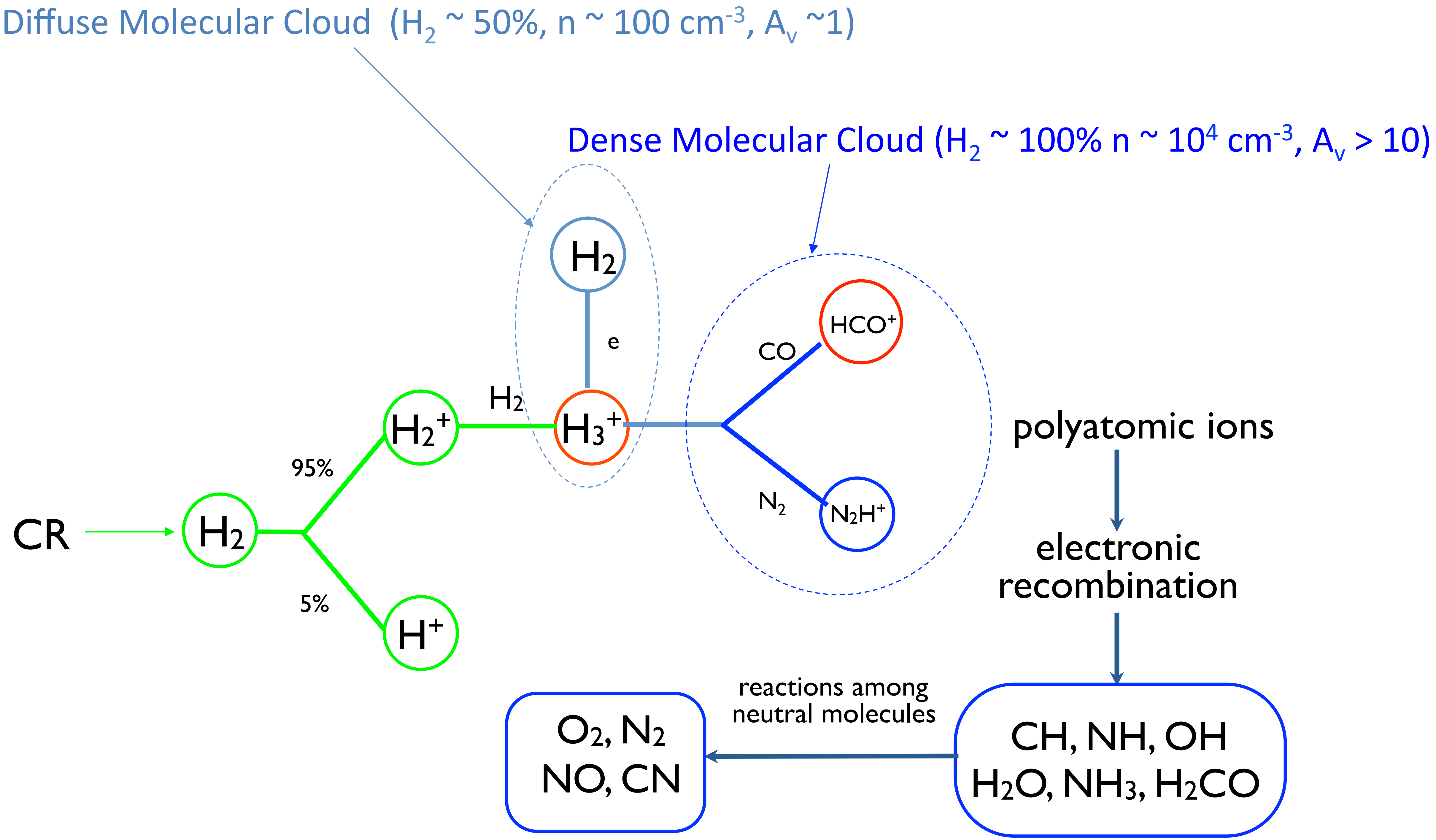
The cosmic ray heating rate is then

$$\Gamma_{CR} = \zeta_{CR}\, Q$$

Where Q is the heat deposited per ionization.

O and C chemistry in the ISM





Diffuse Molecular Cloud (H_2 ~ 50%, n ~ 100 cm^{-3}, A_v ~1)

Dense Molecular Cloud (H_2 ~ 100% n ~ 10^4 cm^{-3}, A_v > 10)

CR → H_2

95% H_2^+

5% H^+

H_2 H_3^+

e H_2

CO HCO^+

N_2 N_2H^+

polyatomic ions

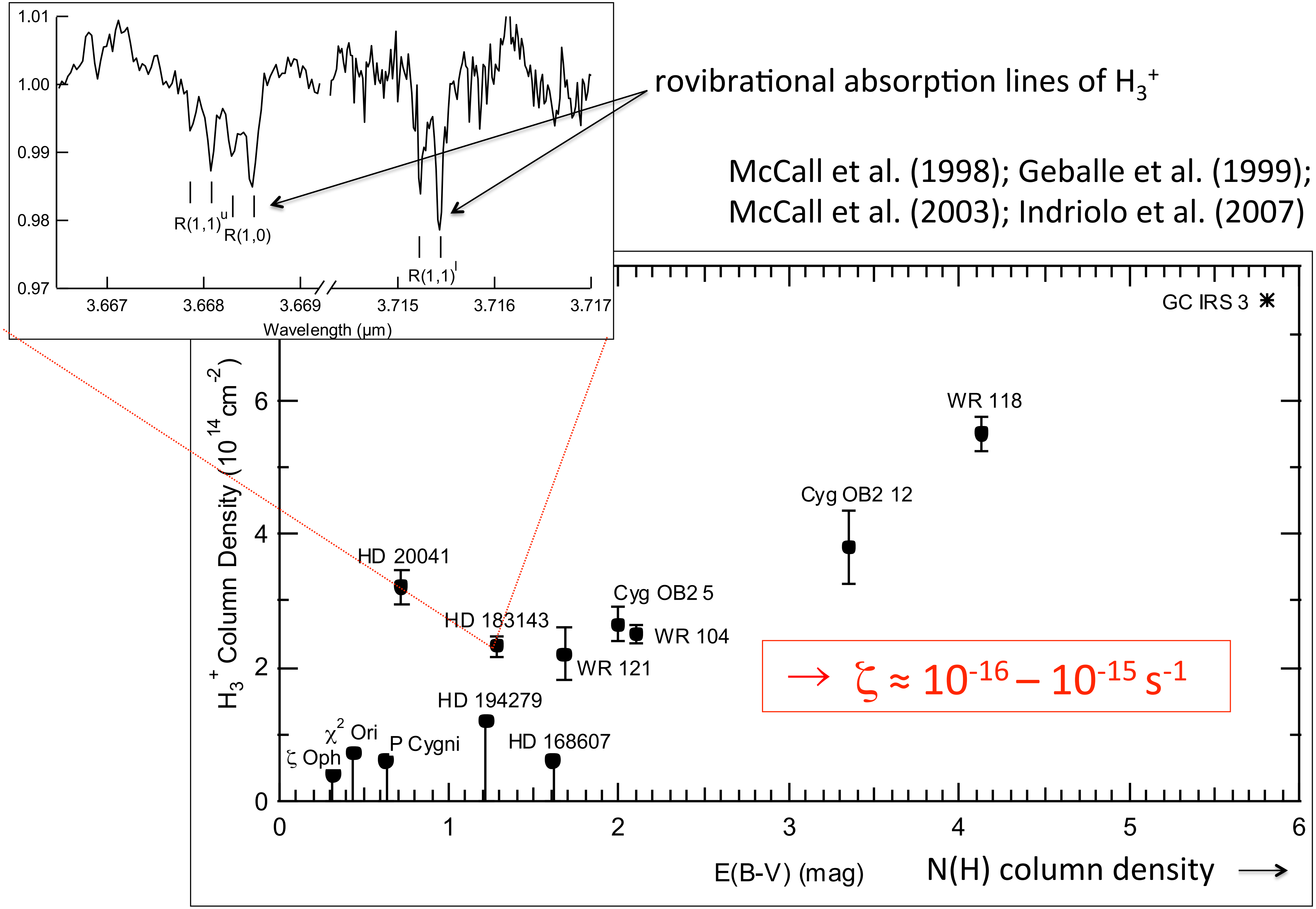
electronic recombination

CH, NH, OH
H_2O, NH_3, H_2CO

reactions among neutral molecules

O_2, N_2
NO, CN

CR ionization rate in diffuse clouds



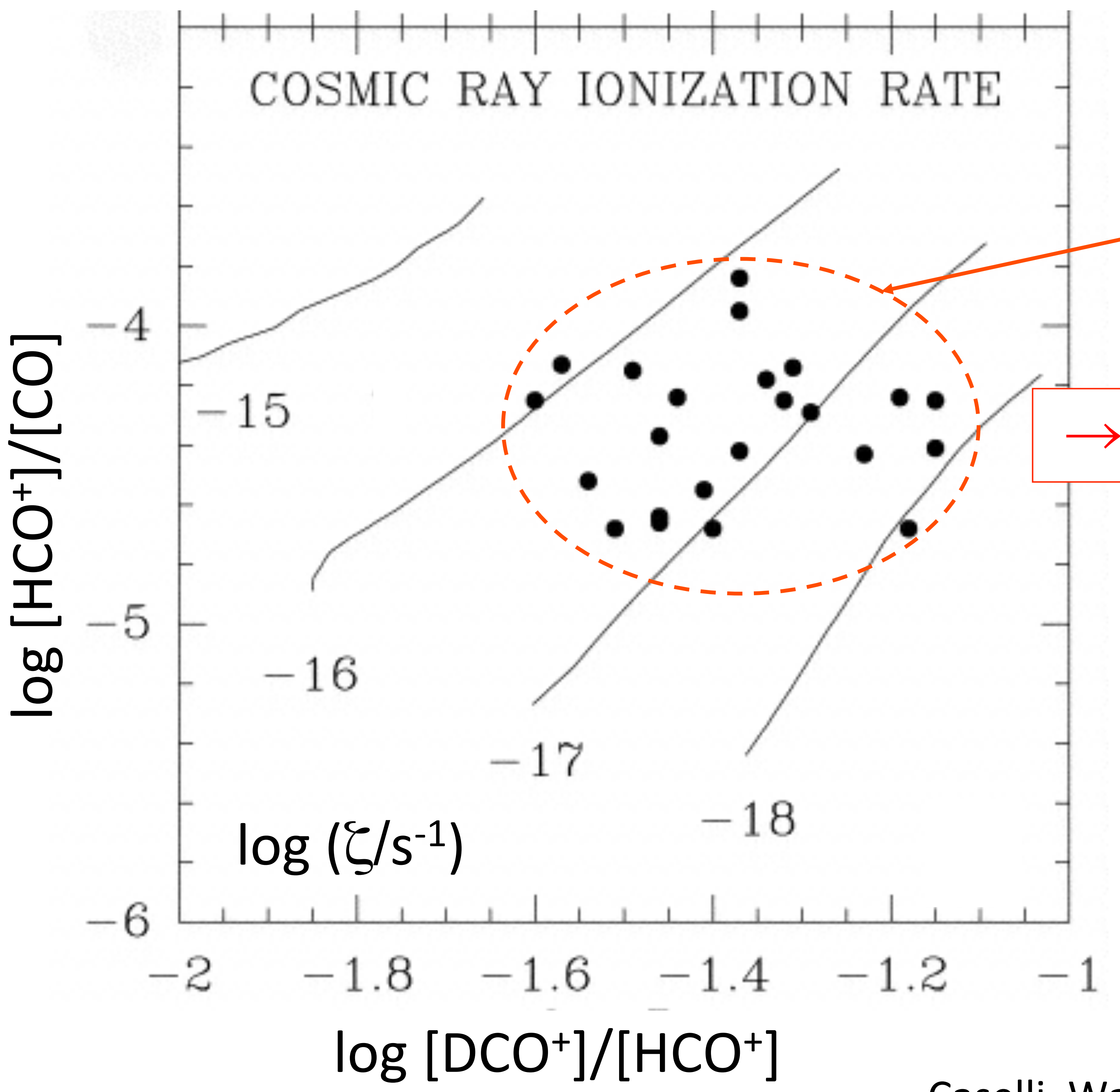
rovibrational absorption lines of H_3^+

McCall et al. (1998); Geballe et al. (1999); McCall et al. (2003); Indriolo et al. (2007)

→ $\zeta \approx 10^{-16} – 10^{-15}\ s^{-1}$

N(H) column density →

CR ionization rate in dense clouds



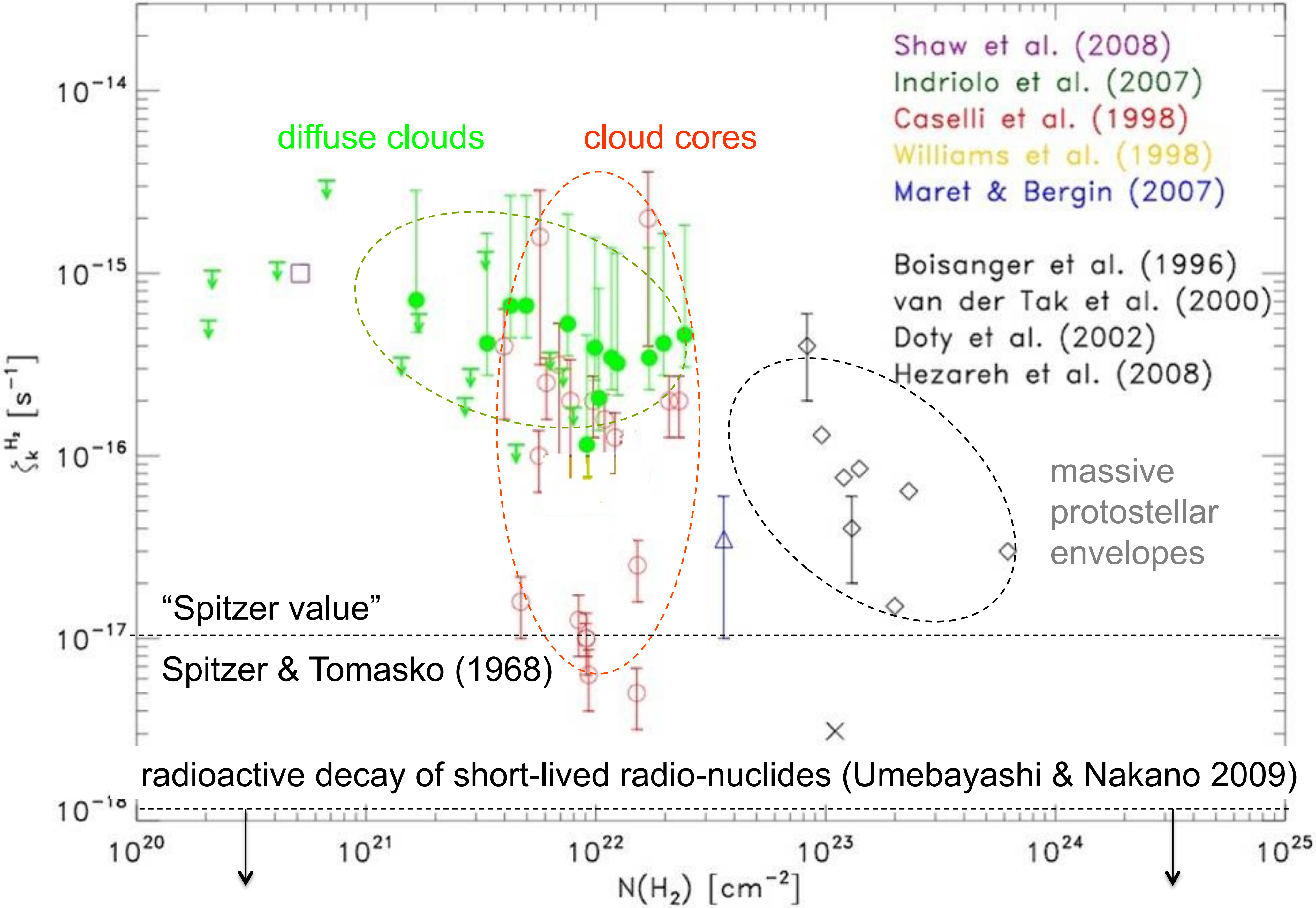
sample of 23 molecular cloud cores

→ $\zeta \approx 10^{-18} – 10^{-16}\ s^{-1}$

Large scatter of ζ in dense clouds: real or problems with chemical models?

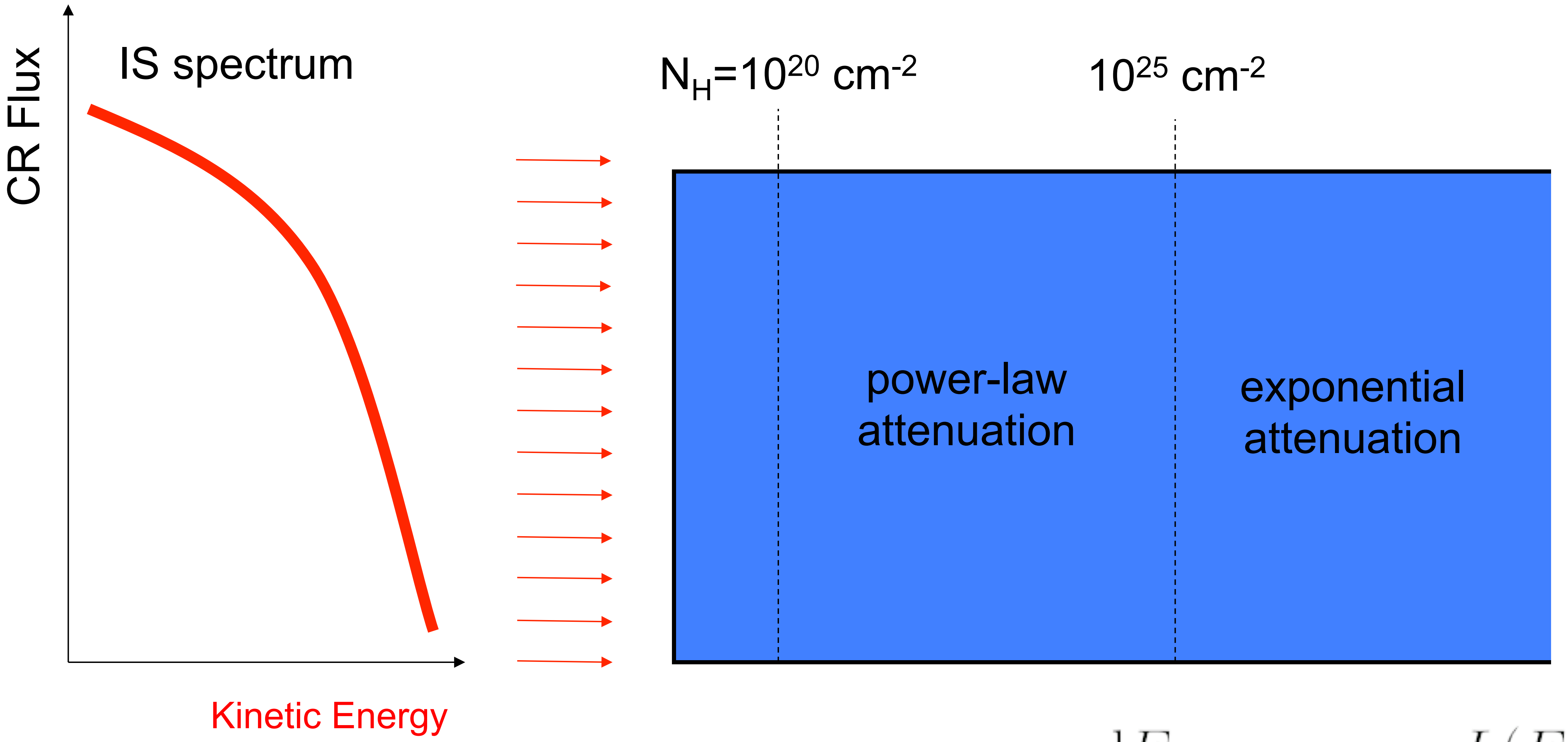
Caselli, Walmsley, Terzieva & Herbst (1998)

Summary of observations of ζ_{CR}



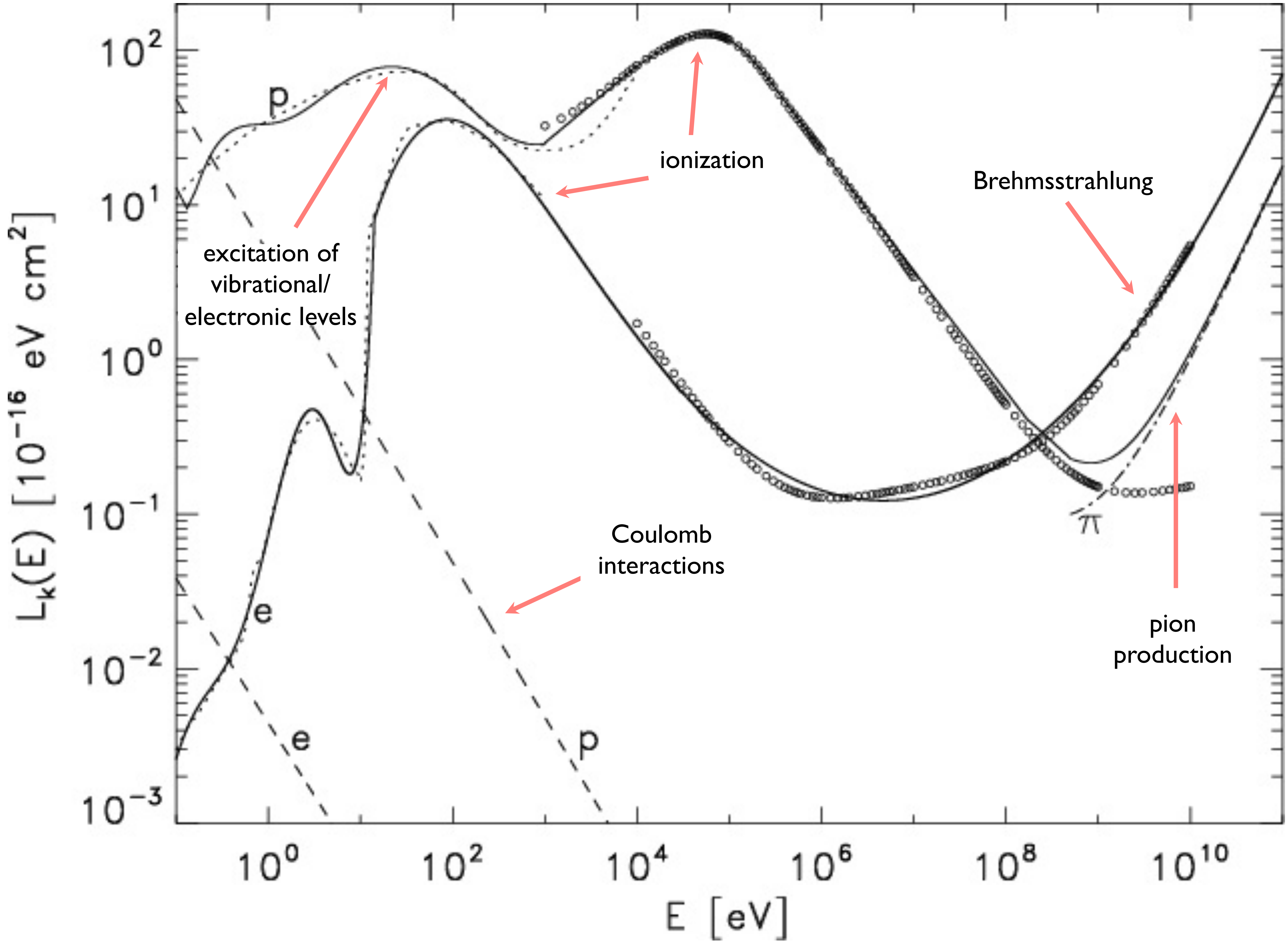
CR propagation in 1D cloud

- Uniform density
- No magnetic field
- Continuous slowing down (“thick target”) approximation



$$j(E,N) = j(E_0,0)\frac{\mathrm{d}E}{\mathrm{d}E_0} = j(E_0,0)\frac{L(E_0)}{L(E)}$$

Energy losses of CR–protons and electrons in H_2



excitation of vibrational/ electronic levels

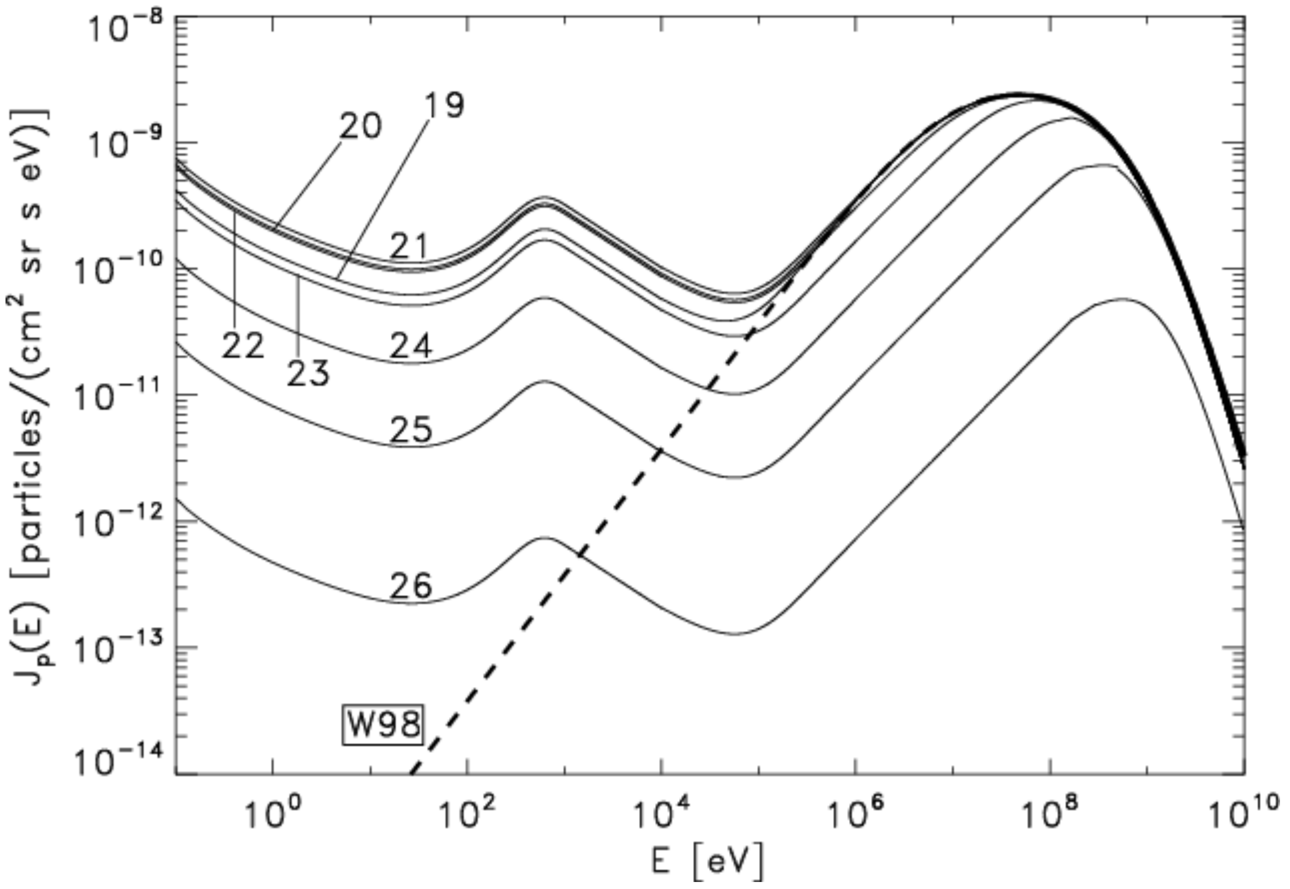
ionization

Brehmsstrahlung

Coulomb interactions

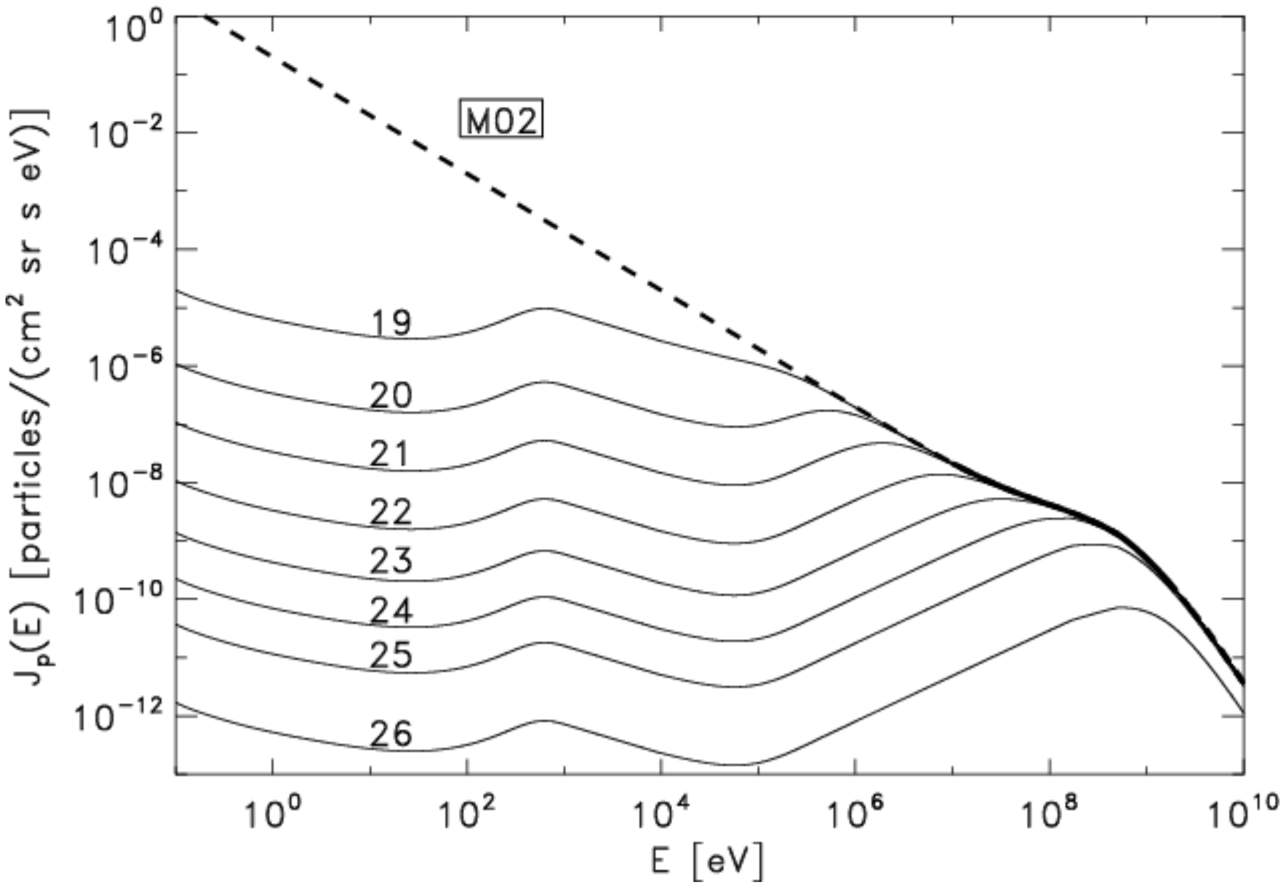
pion production

Evolution of CR-proton spectrum as function of log N(H_2)



“minimum” LIS spectrum

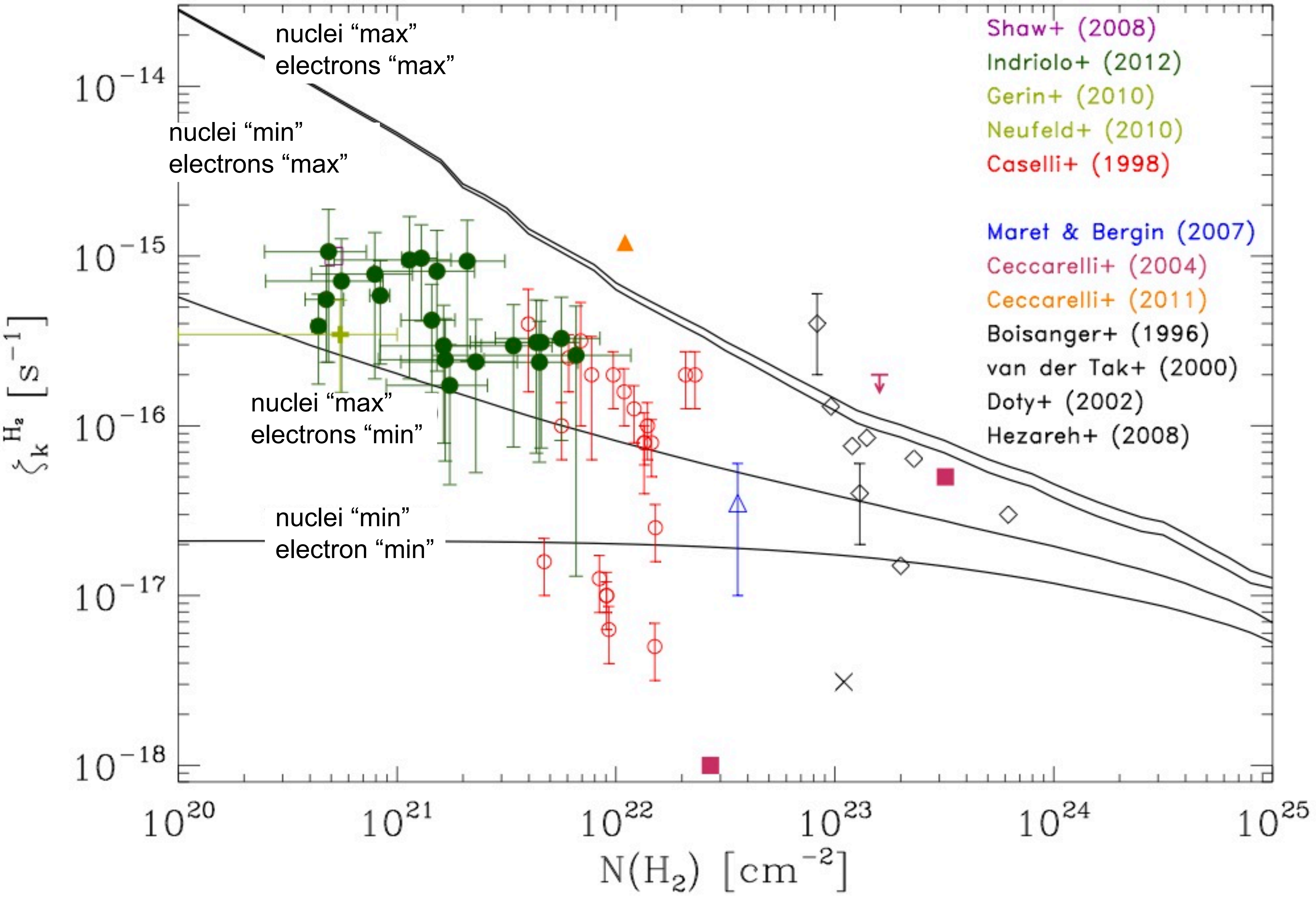
(Webber 1998)



“maximum” LIS spectrum

(Moskalenko et al. 2002)

Comparison with observations



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:

$t_{\rm therm} \sim \frac{1}{n\langle\sigma v\rangle}$ ~ few yr 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.*

Cosmic-ray heating

- Dominant source of ionization and heating in the densest,

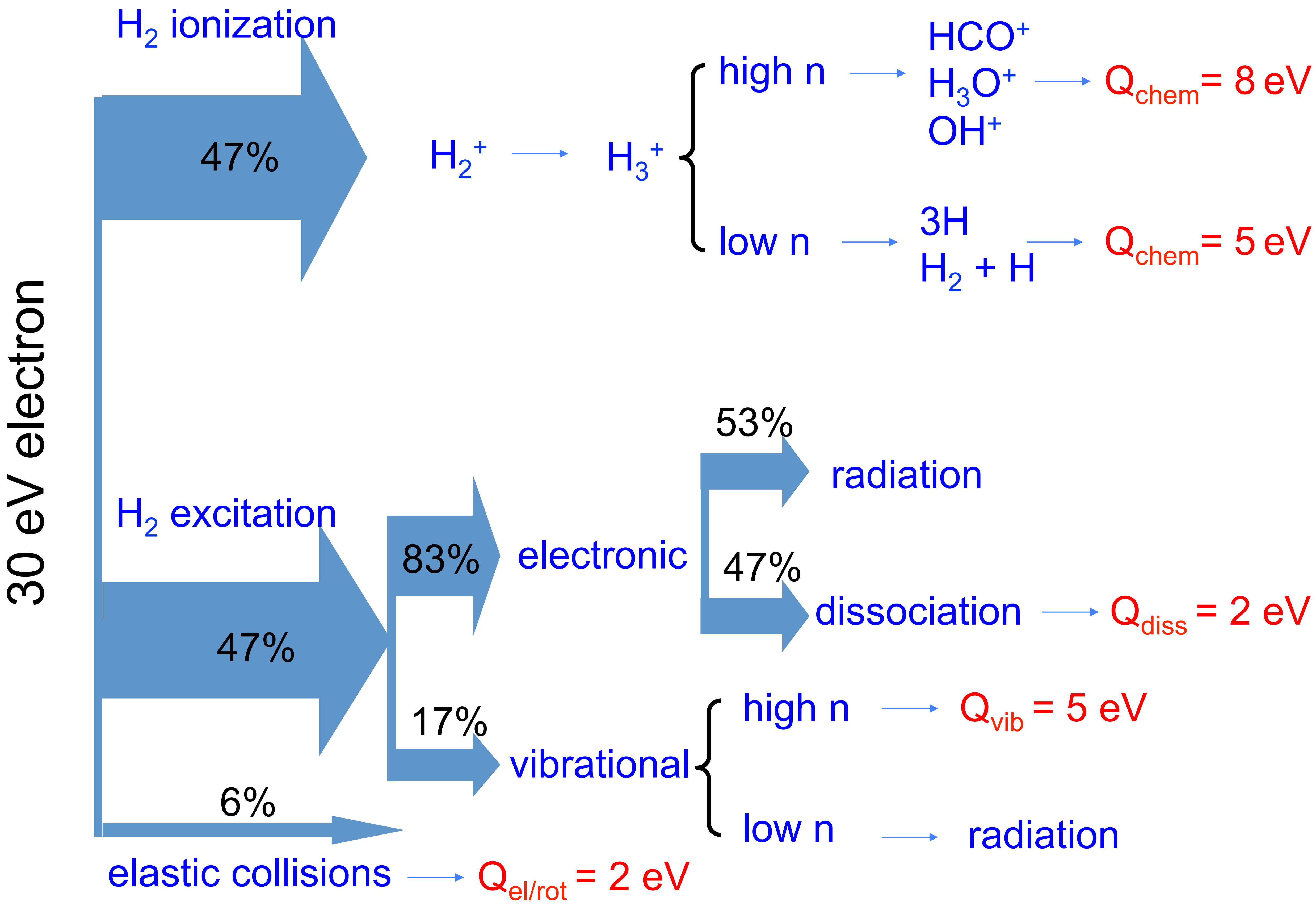
UV-shielded molecular gas inside molecular clouds.

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

where n is the density and ζ 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)



30 eV electron

H_2 ionization

47%

H_2^+ → H_3^+

high n → HCO^+, H_3O^+, OH^+ → Q_{chem} = 8 eV

low n → 3H, H_2 + H → Q_{chem} = 5 eV

H_2 excitation

47%

83% electronic

53% radiation

47% dissociation → Q_{diss} = 2 eV

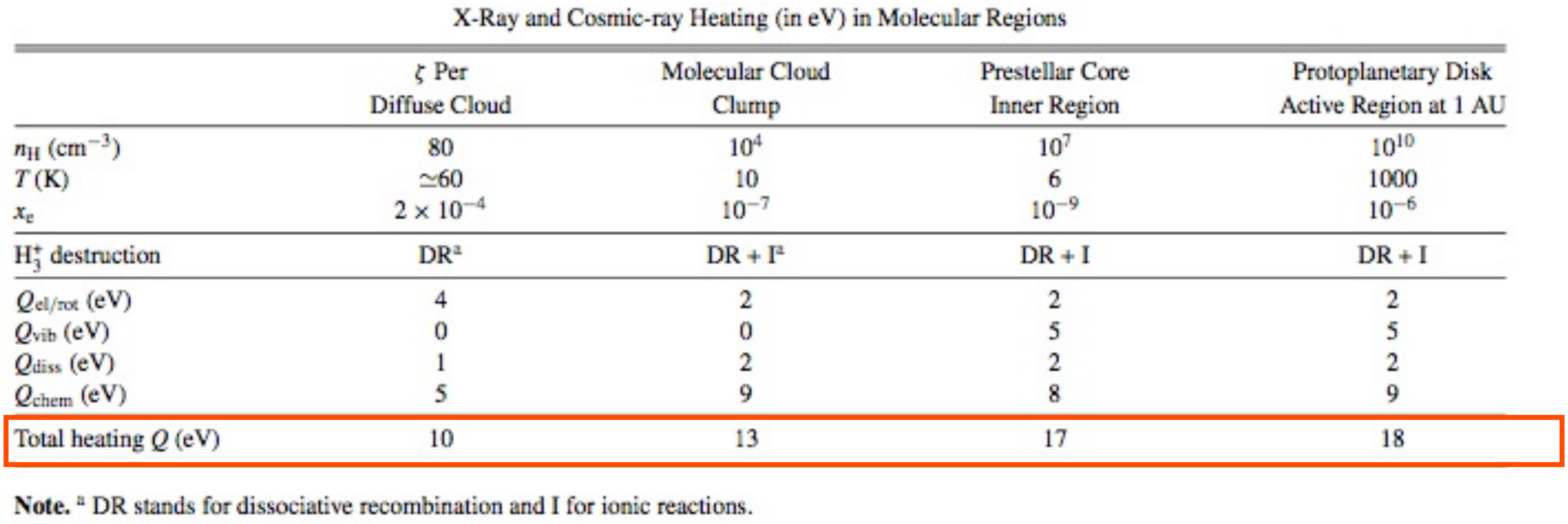
17% vibrational

high n → Q_{vib} = 5 eV

low n → radiation

6%

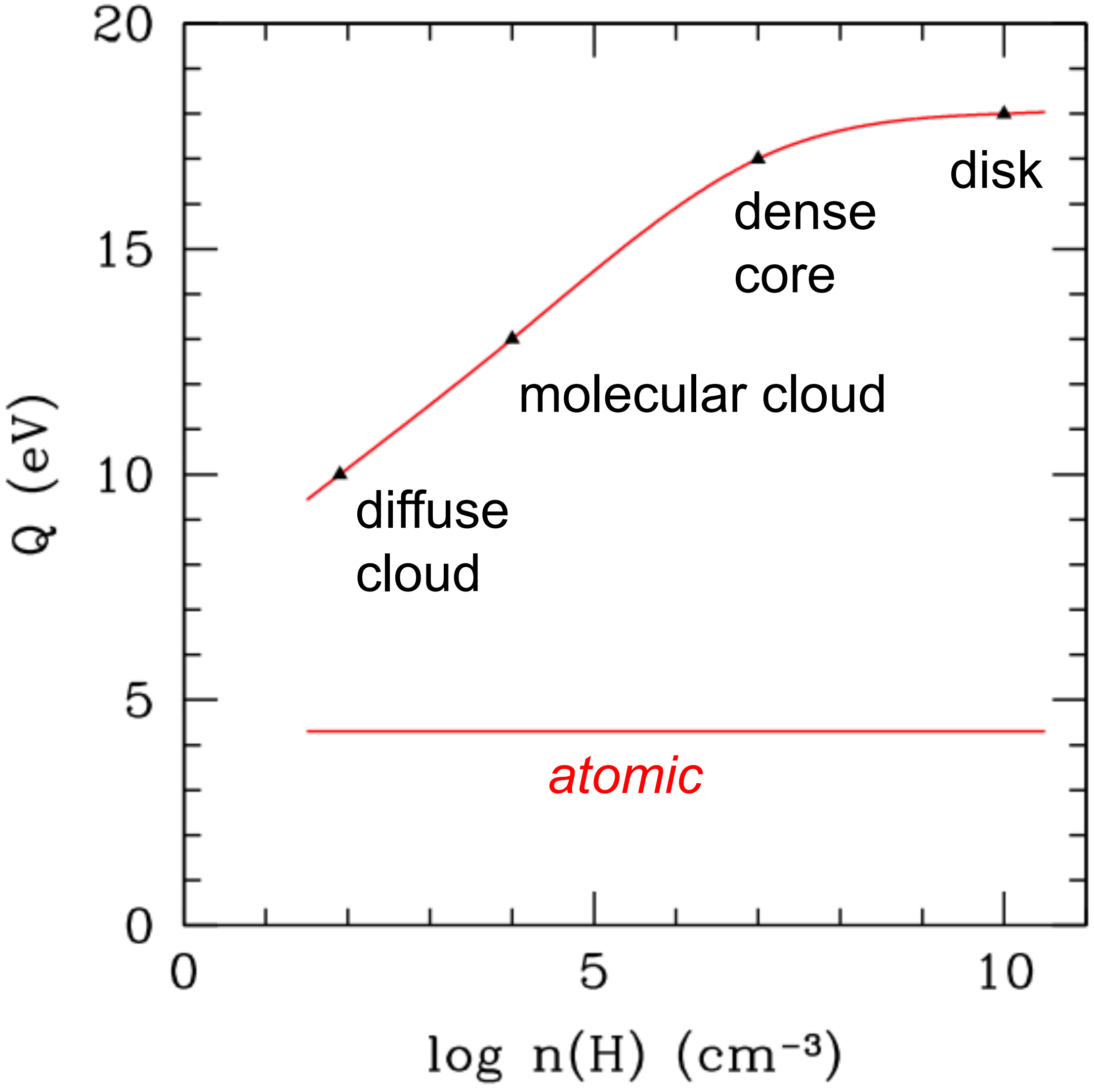
elastic collisions → $Q_{el/rot}$ = 2 eV



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

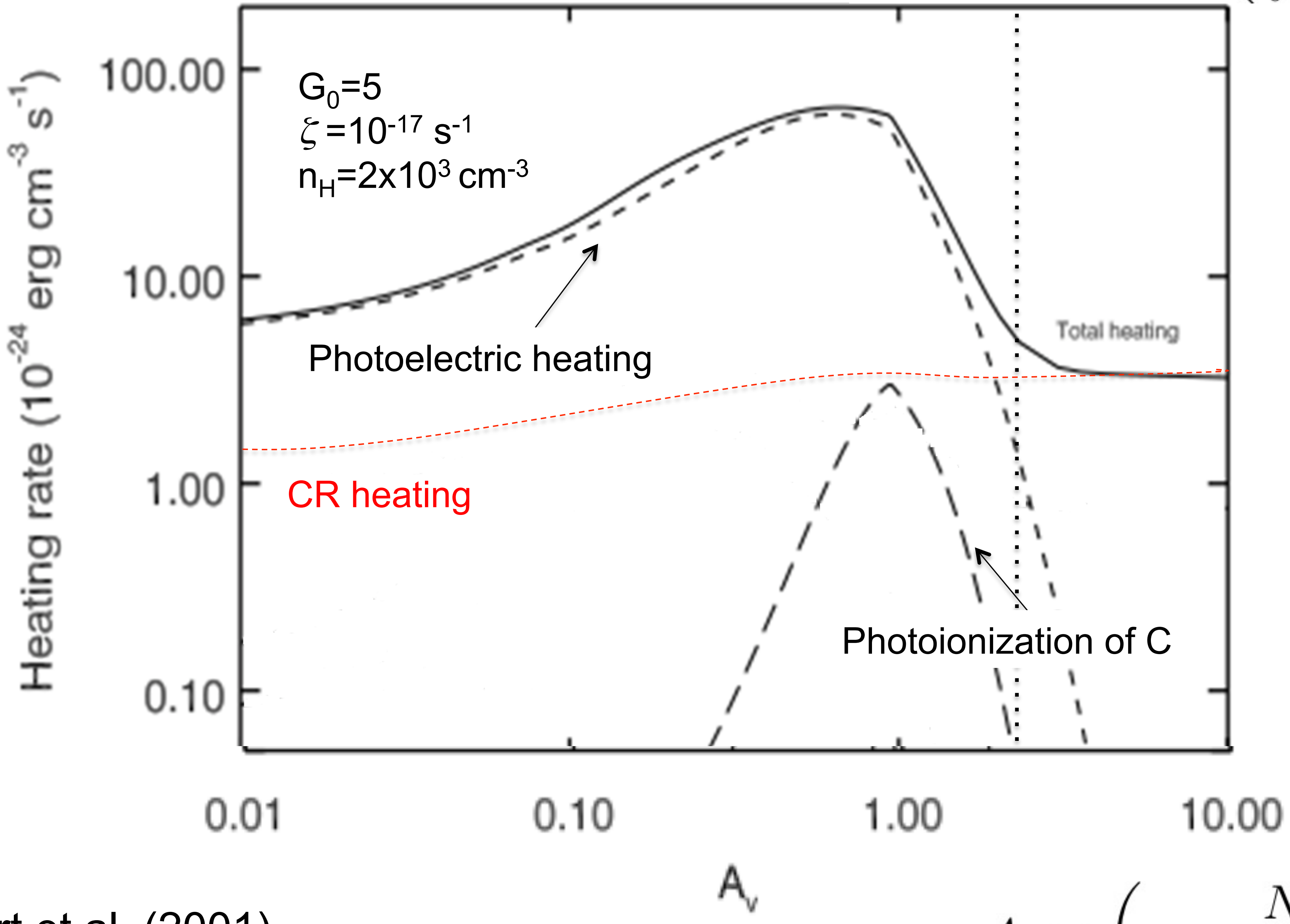
Note. [a] DR stands for dissociative recombination and I for ionic reactions.



Glassgold, Galli & Padovani (2012)

UV photons vs. CRs

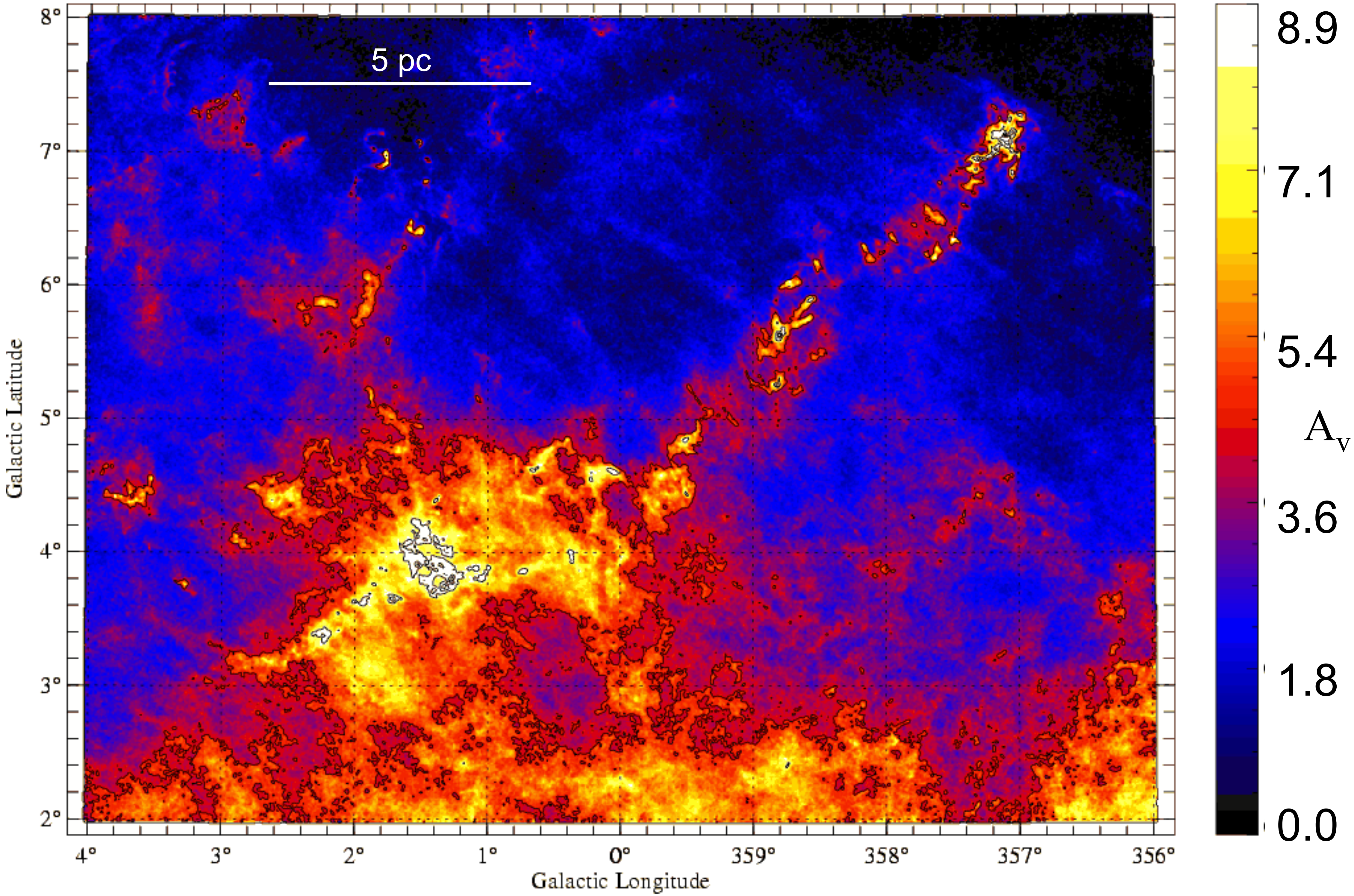
$$A_v^{\mathrm{cr}} \approx 4.0 + 0.6 \ln \left(\frac{G_0}{\zeta_{-17}} \right)$$



$$A_v = \left(\frac{N_{\mathrm{H}}}{2 \times 10^{21}\ \mathrm{cm}^{-2}} \right)$$

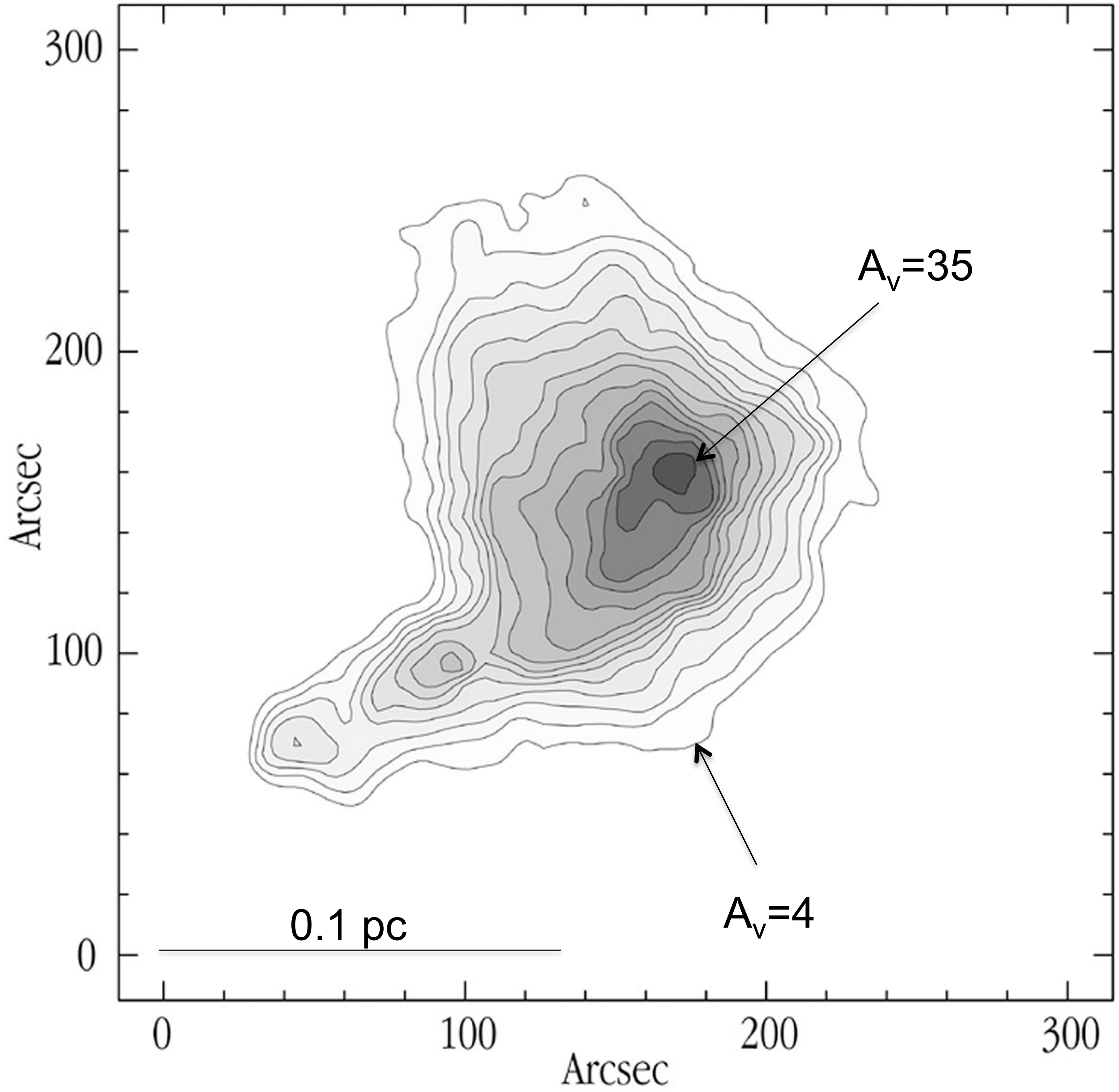
Habart et al. (2001)
PDR model: Le Bourlot et al. (1993)

Extinction map of a molecular cloud (Pipe nebula)



Lombardi, Alves & Lada et al. (2006)

Extinction map of a starless core (B68)



Alves, Lada & Lada (2001)

Thermal balance of gas and dust

- Thermal balance of dust (T_{dust})

$$\Gamma_{dust} - \Lambda_{dust} + \Lambda_{gd}=0$$

- Thermal balance of gas (T_{gas})

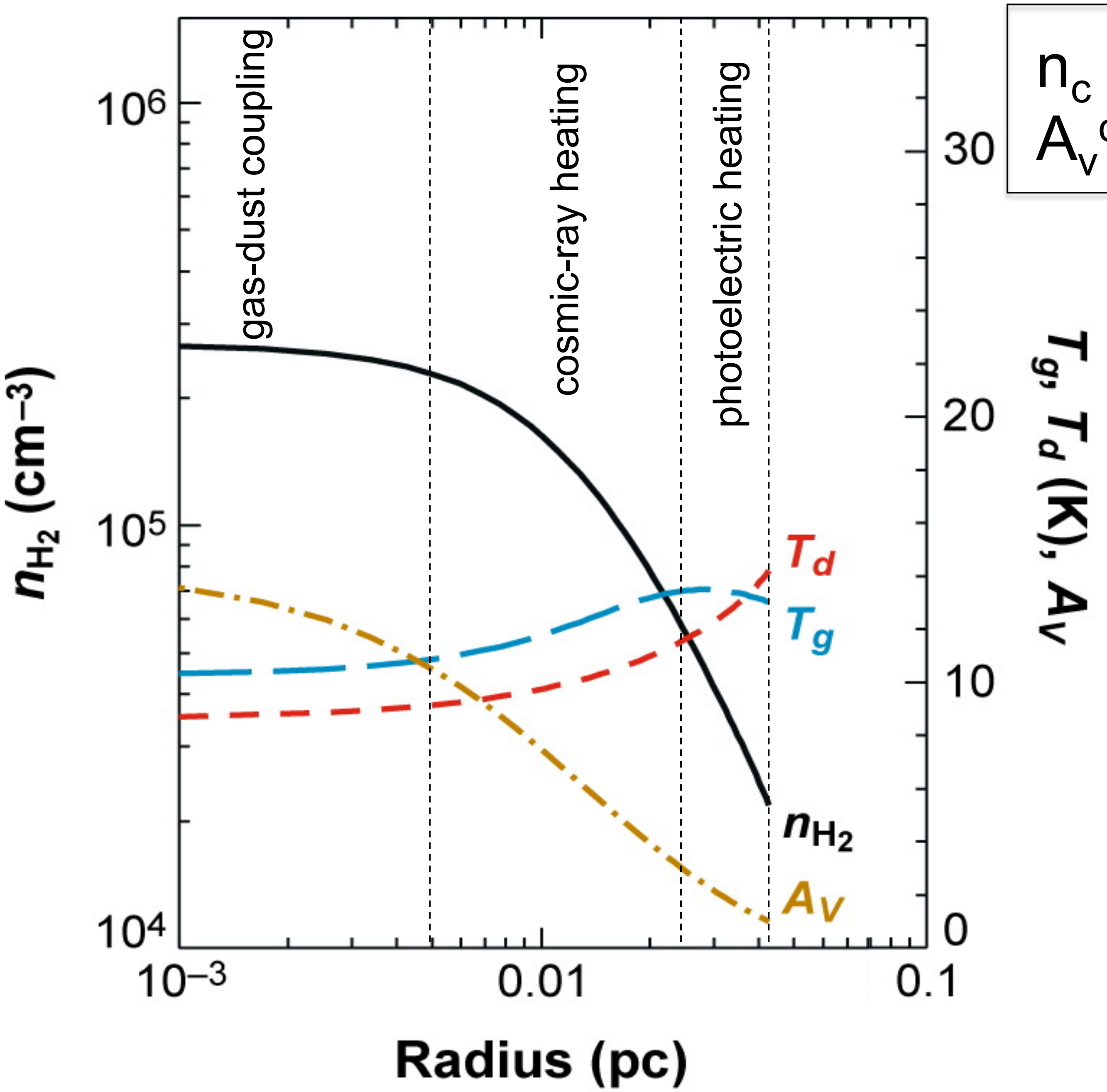
$$\Gamma_{CR} - \Lambda_{gas} - \Lambda_{gd}=0$$

$\Gamma_{cr} = \zeta_{CR}\, Q$

$\Lambda_g = \alpha T_{gas}^{\beta}$ with α, β function of $n(H_2)$, depletion, etc.

$\Lambda_{gd} = \alpha_{gd}\, n(H_2)^2\, T_{gas}^{1/2}\, (T_{gas}-T_{dust})$

Temperature profile of a prestellar core

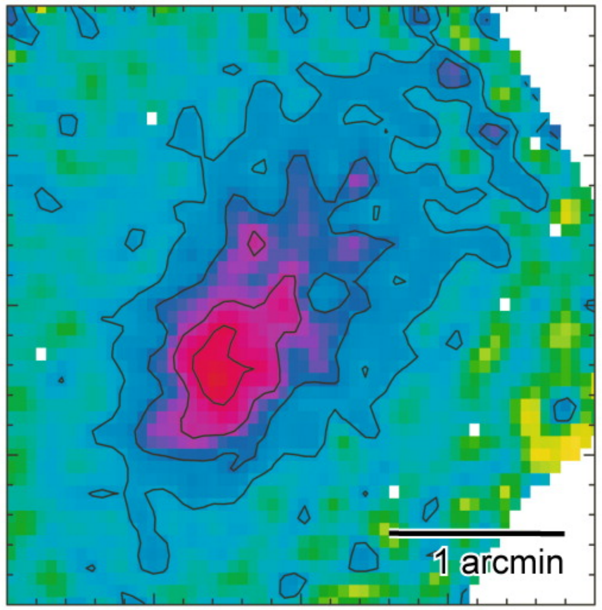


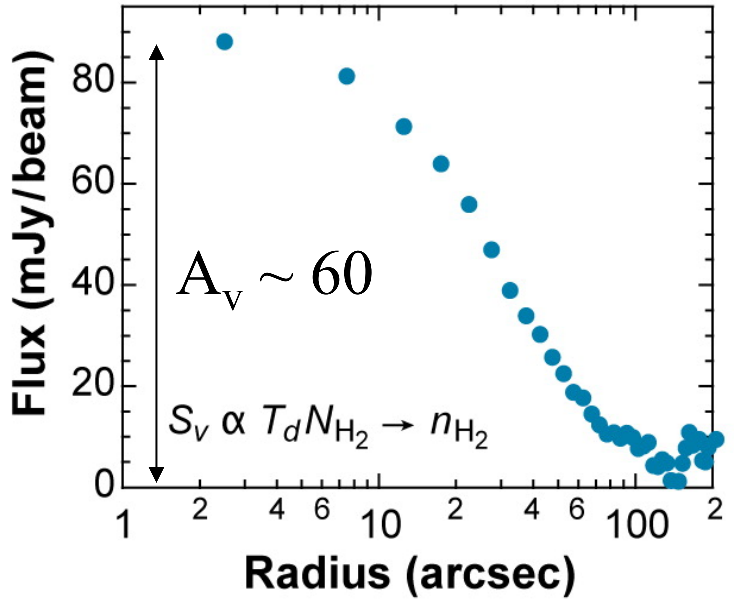
n_c = 2.5 x 10^5 cm^{-3}
A_v^c = 14

Galli, Walmsley & Gonçalves (2002)

Measurements of T_{gas} constrain ζ_{CR} in L1544

L1544 1.2 mm continuum

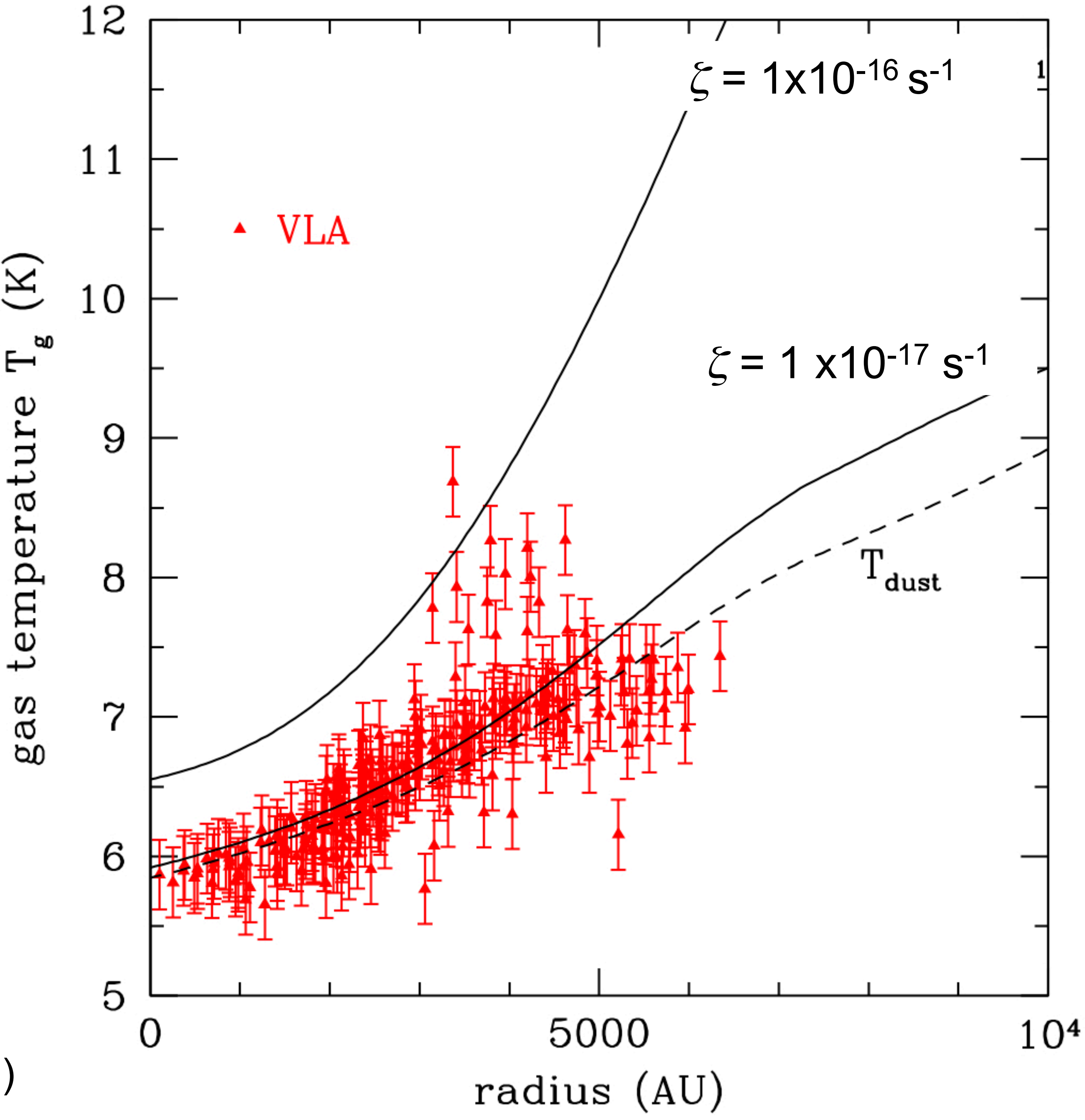




Ward-Thompson, Motte & André (1999)

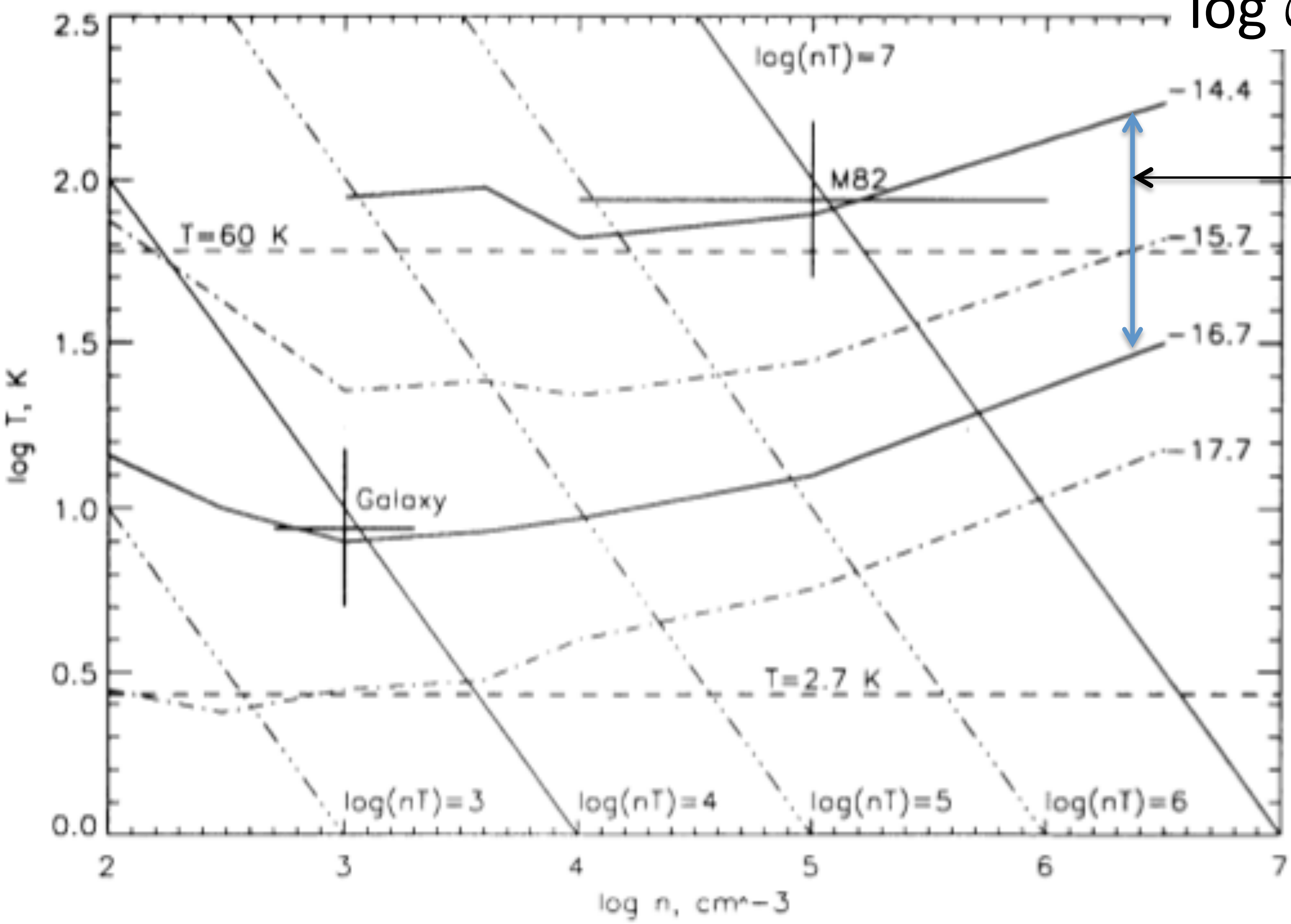
Bacmann et al. (2000)

Crapsi et al. (2007)



from chemical modeling $\zeta = 1.3 \times 10^{-17}\ s^{-1}$ (Vastel et al. 2006)

Temperature of molecular clouds in the MW and M82



log ζ_{CR}

factor of ~ 200

From synchrotron emission: j_{CR} (M82)/j_{CR}(MW) ~ 170

Suchkov, Allen & Heckman (1993)

Ionization fraction and magnetic field diffusion

- CR ionization of H_2 balanced by recombination:

$$\zeta_{CR}\, n(H_2) \approx \beta\, n(i)\, n(e)$$

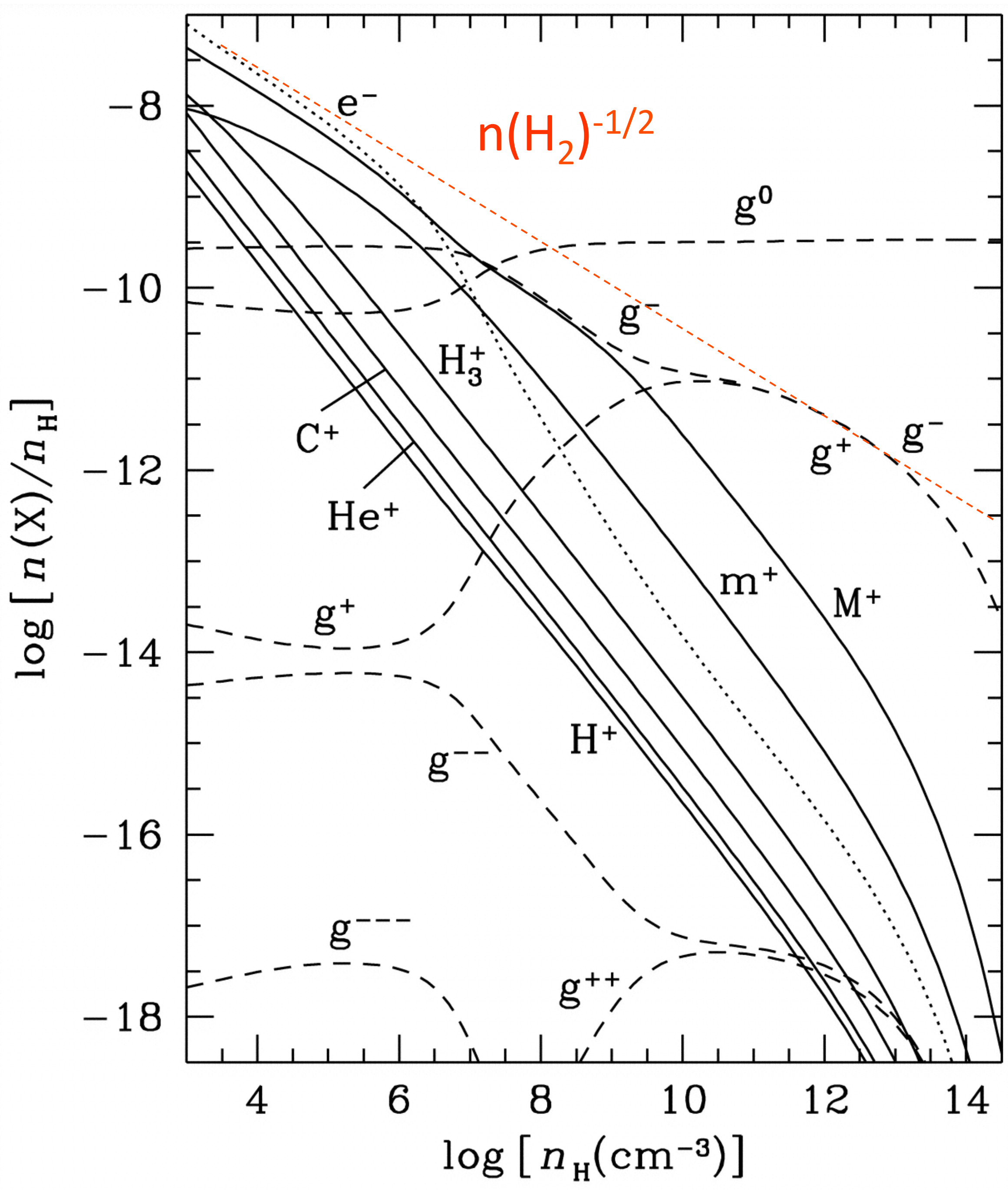
$$\rightarrow x_e \approx (\zeta/\beta)^{1/2}\, n(H_2)^{-1/2}$$

For $\zeta \approx 10^{-17}\ \mathrm{s}^{-1}$, $\beta \approx 10^{-9}\ \mathrm{cm}^3\ \mathrm{s}^{-1}$
$\rightarrow x_e \approx 10^{-7}$ for $n(H) \approx 10^6\ \mathrm{cm}^{-3}$

- The field and the ions slip through the neutrals on a time scale

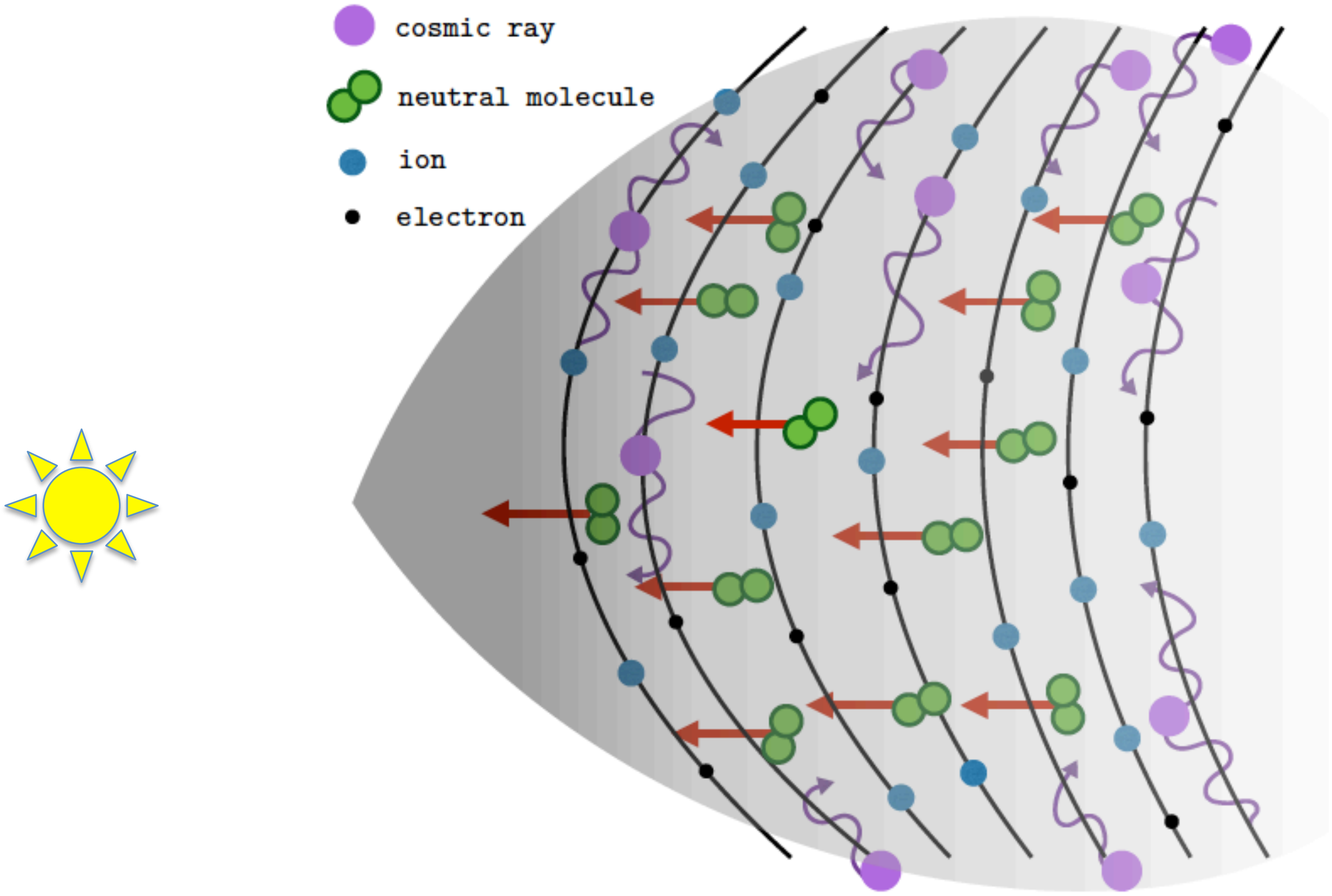
$$t_{AD}/\mathrm{yr} \approx 5 \times 10^{13}\, x_e$$

For $x_e \approx 10^{-7} \rightarrow t_{AD} \approx$ 3-10 Myr



Nakano et al. (2002)

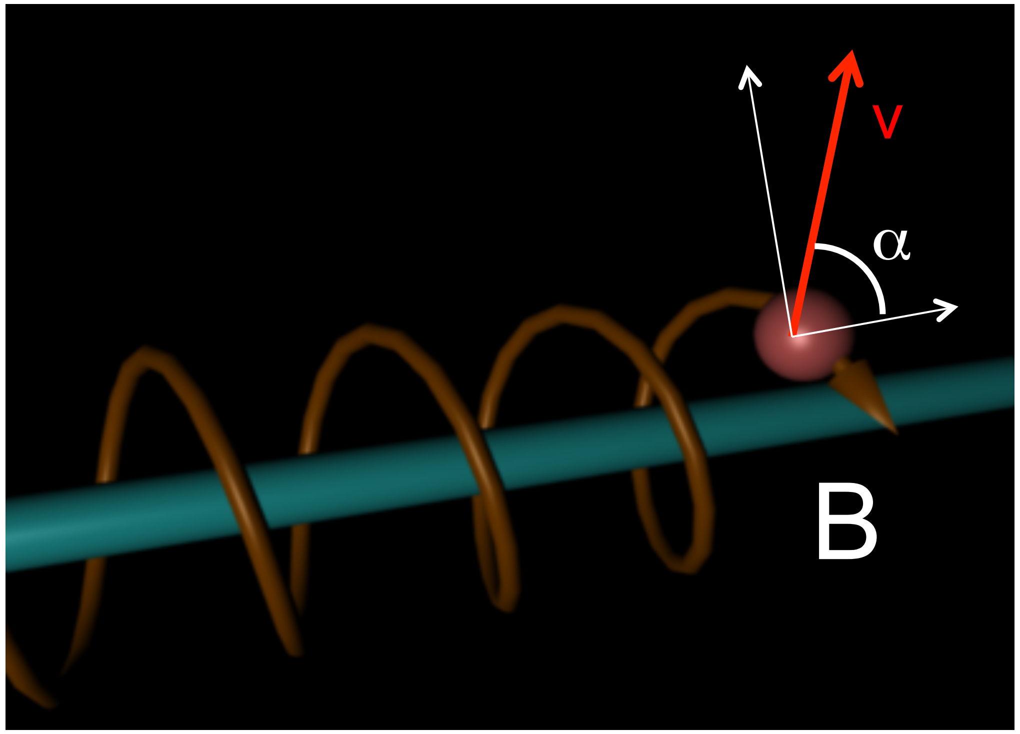
Ambipolar diffusion in a weakly ionized gas



——— field diffusion ———→

←—— drift of neutrals ———

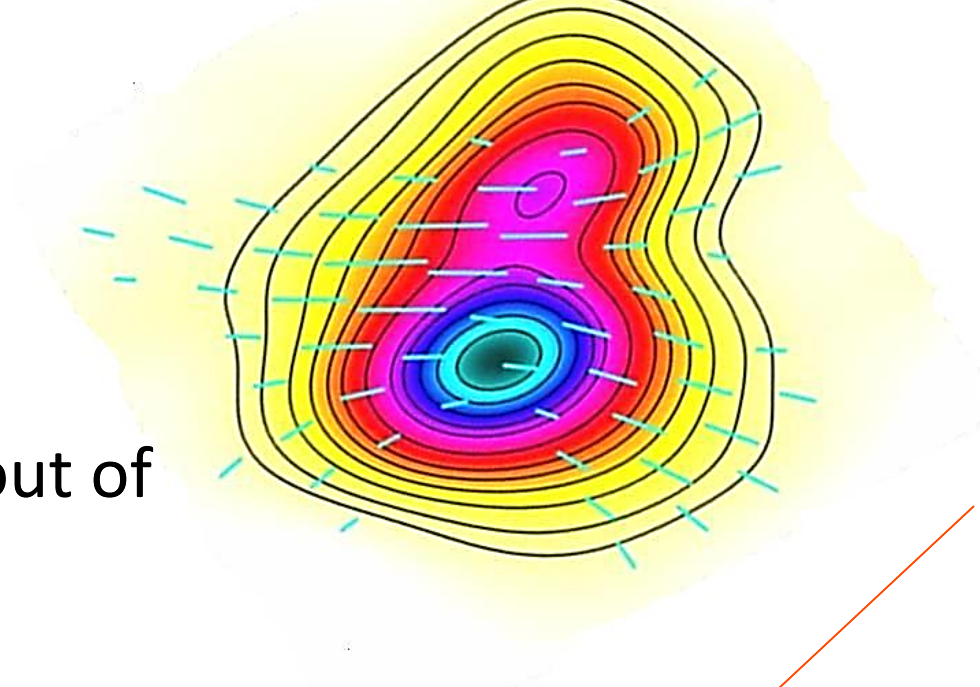
CRs in magnetic fields: $r_B >> r_L$



- Effective column density: N(H) /cos α
- Focusing: enhances CR flux (proportional to B)
- Mirroring: reduced CR flux (μ adiabatic invariant)

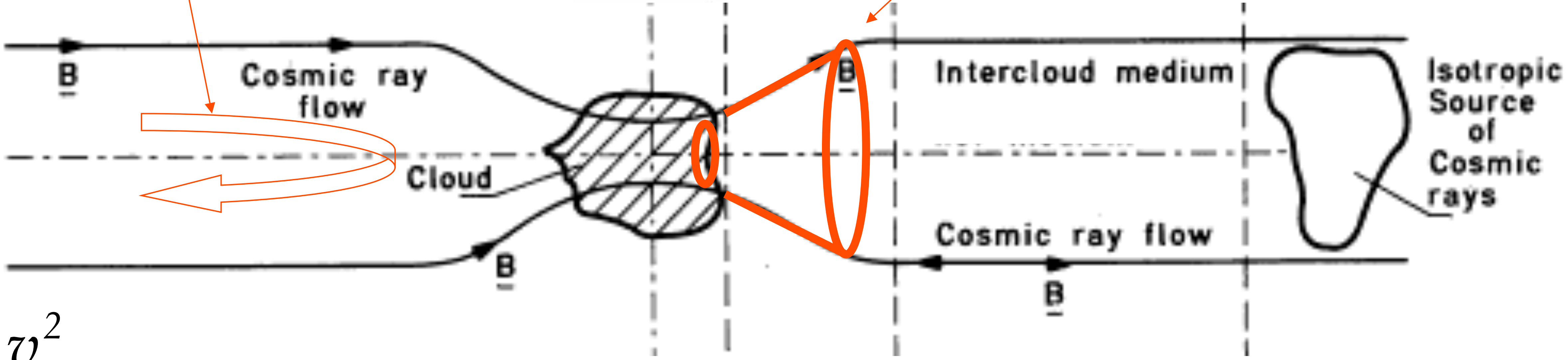
$r_L \approx 10^{-2}\ (E/\mathrm{GeV})^{1/2}\ (B/10\ \mu\mathrm{G})^{-1}\ \mathrm{AU} \quad (E < \mathrm{GeV})$

NGC1333 IRAS4A (Girart et al. 2006)
hourglass magnetic field



Magnetic mirroring bounces many CRs out of the core

Magnetic focusing increases CR flux in the core



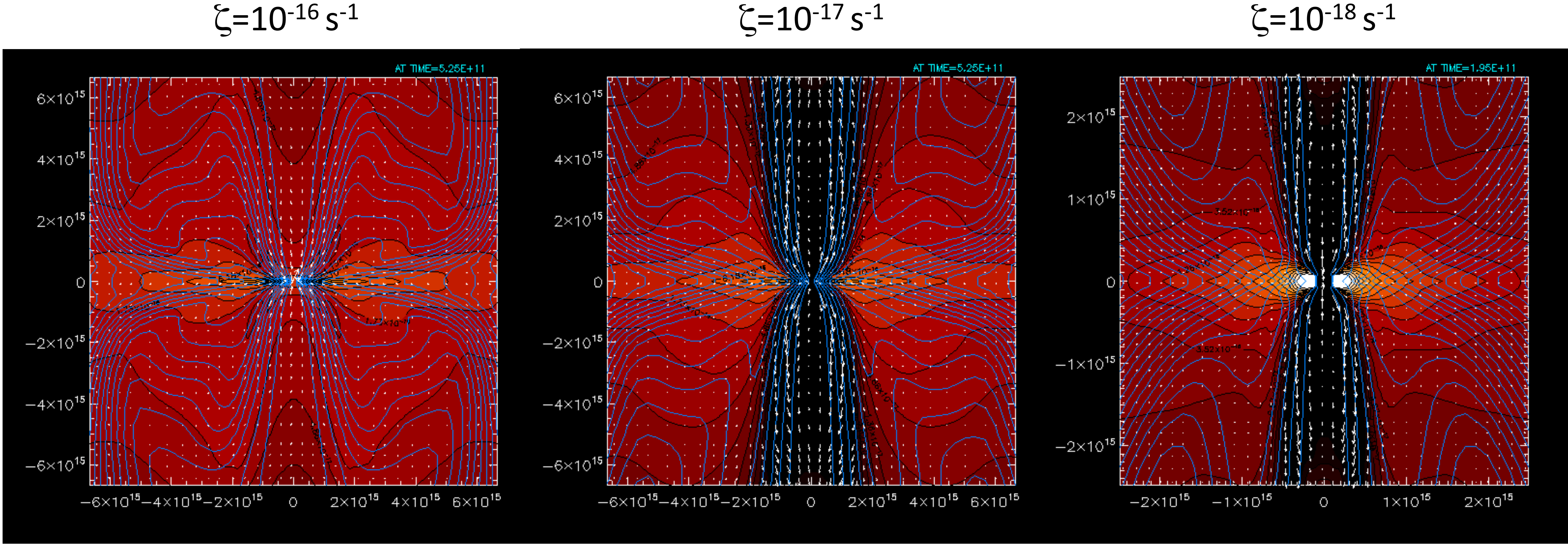
$$\frac{v_\perp^2}{B} = const.$$

$$v_\perp^2 + v_{/\!/}^2 = const.$$

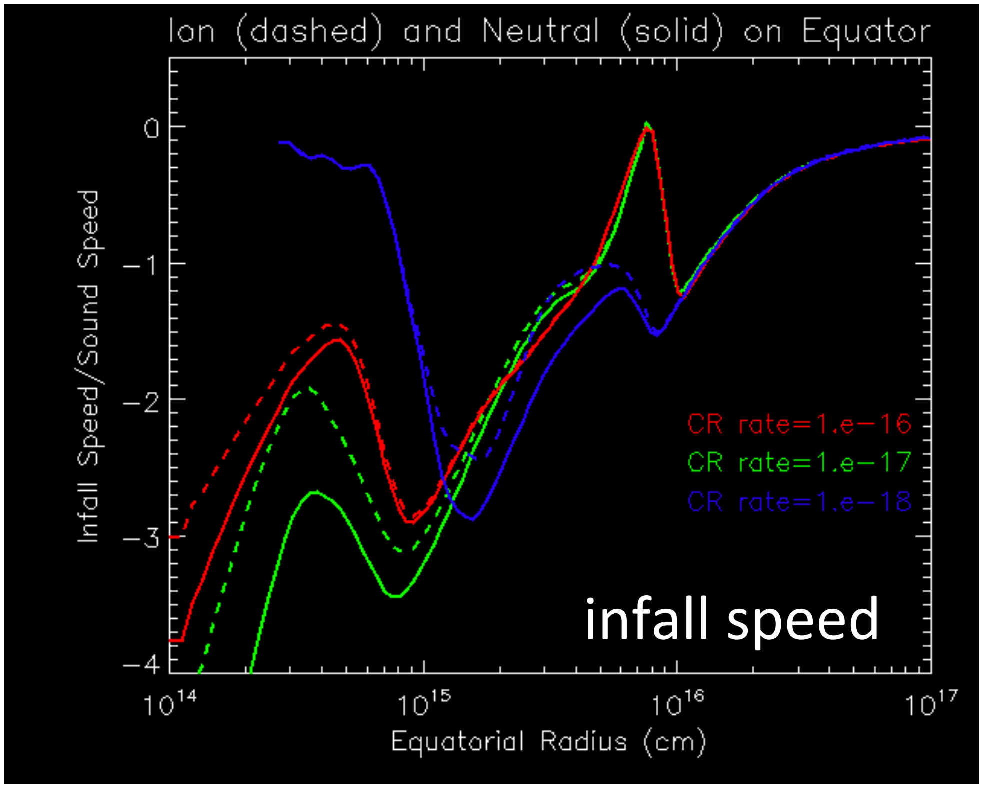
Cesarsky & Volk (1978)

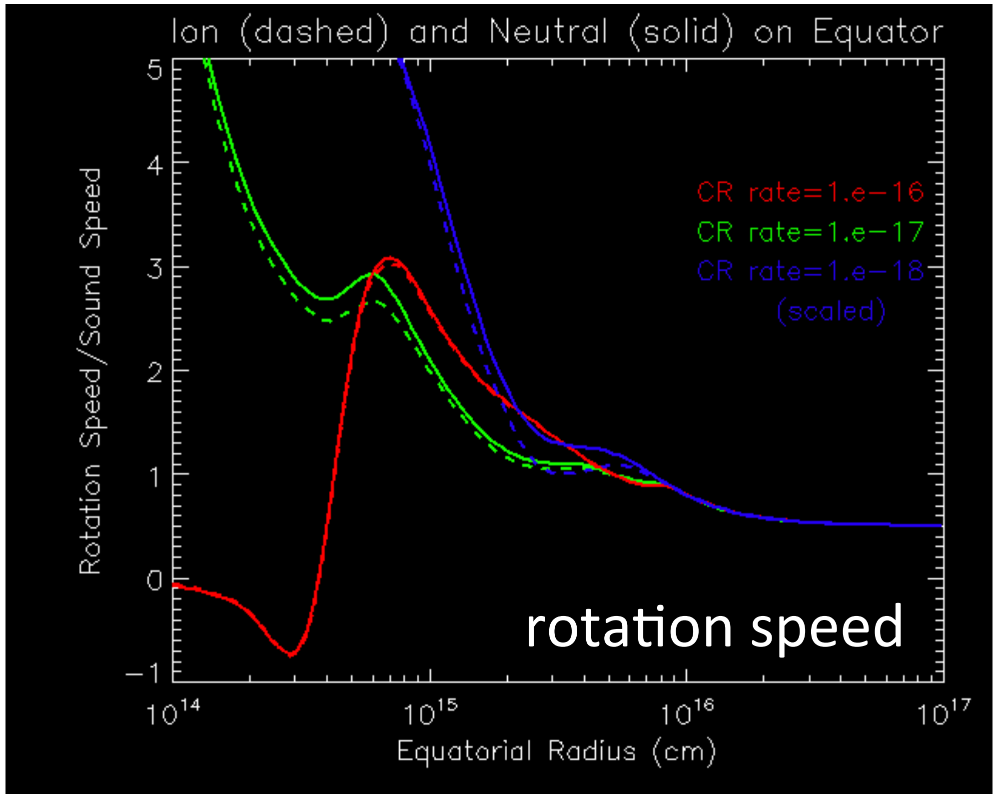
CRs in small-scale magnetic fields: $r_B \sim r_L$

- Small-scale magnetic fluctuations (``MHD waves'') scatter CRs
- MHD waves: part of the turbulent cascade or self-excited by CRs
- MHD waves in MCs damped by ion-neutral collisions
  $\Gamma_{in}=1/2\ \nu_{in}=1/2\ n_n <\sigma\ v>\ m_n/m_i$
- If waves efficiently damped: MCs are "free zones" where CRs stream freely (Kulsrud & Pierce 1969; Skilling 1971).
- Can low-energy CRs be "excluded" from clouds?
  (Skilling & Strong 1976; Cesarsky & Volk 1978; Everett & Zweibel 2012; Morlino 2014)



$\zeta=10^{-16}\,s^{-1}$ $\zeta=10^{-17}\,s^{-1}$ $\zeta=10^{-18}\,s^{-1}$





Gravitational collapse with ambipolar diffusion and variable ζ

Mellon & Li (2009)

Conclusions

- An increasing flux of low-energy CR (below ~100 MeV, either nuclei or electrons) is needed to explain ionization rates in diffuse and dense clouds. Origin?
- ζ_{CR} in clouds ~ $N(H_2)^{-\alpha}$ with $0 < \alpha < 1$ up to $N(H_2) \approx 10^{25}$ cm^{-2}. Then exponential decrease ~ exp $(-\Sigma_0)$ with $50 < \Sigma_0 < 100$ g cm^{-2} .
- Temperature measurements in UV-shielded dense gas (cores) can constrain ζ_{CR} as much (or better) than chemistry.
- Variations of ζ_{CR} in the range 10^{-16} s^{-1} – 10^{-18} s^{-1} affect the dynamics of cloud collapse and star formation.
- Simple "hourglass" B-field: mirroring > focusing but ζ_{CR} reduced only by factor 2-3. More complex B? (see Marco's talk).