Cosmic-ray ionization in clouds and disks

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Cosmic-ray physics at Arcetri in the 1920's

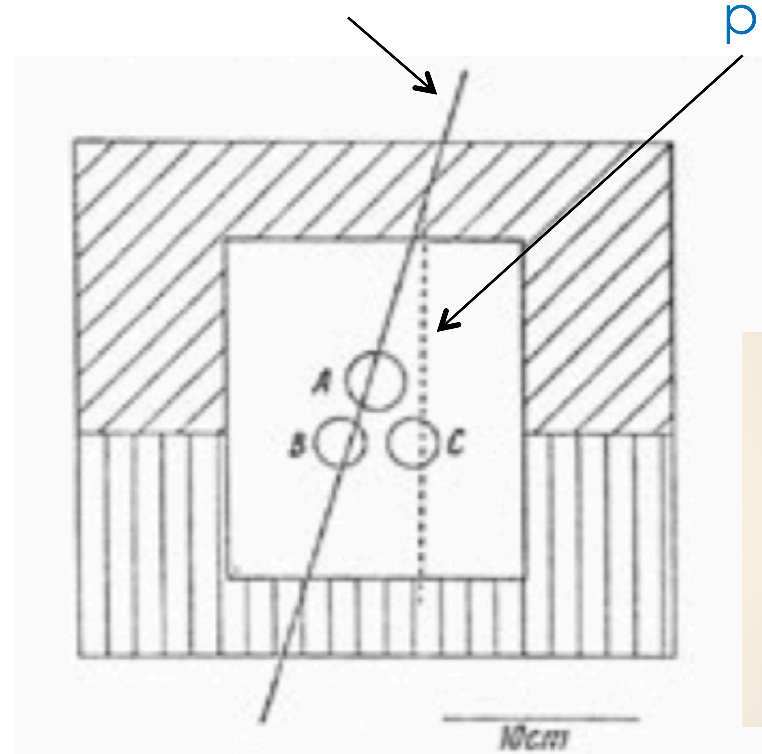
Bruno Rossi (Venice 1905- Cambridge1993)

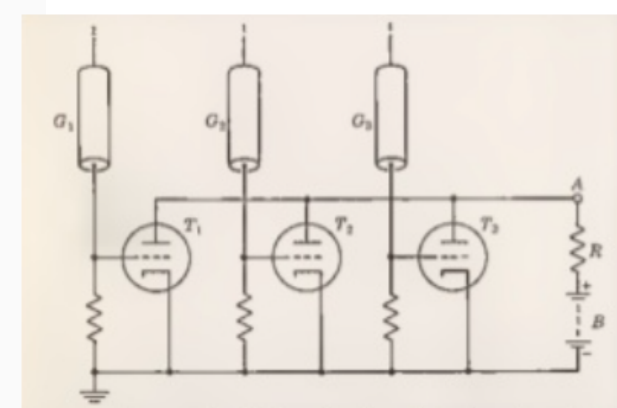
Enrico Fermi (Rome 1901- Chicago1954)

Bruno Rossi in Arcetri (1927- 1932)

- At the time, CRs were believed to be energetic e. m. radiation (Millikan)
- Rossi firmly established the curpuscular nature of CRs by experiments with the triple-coincidence circuit ("Rossi circuit", today called "AND gate")
- Found that primary particles interacting with matter produced groups of secondary particles ("showers")

Rossi in his Arcetri laboratory (ca. 1930)





Rossi's triple coincidence circuit

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COPIA

R. UNIVERSITA' DEGLI STUDI DI PADOVA

Prot. N. 7275 Addì 10 OTTOBRE 1938 XVI
Pos. N. 48

Al Ch.mo Prof. BRUNO ROSSI

PADOVA

OGGETTO: Difesa della razza nella Scuola fascista.

Compio il dovere di avvertirVI che, in applicazione dell'art. 3 del Regio Decreto Legge 5 settembre 1938 XVI, n. 1390, recante provvedimenti per la difesa della razza nella scuola fascista, a datare dal 16 ottobre corrente siete sospeso dal servizio.

IL RETTORE

F.to Anti

Padua, October 10, 1938

Object: *defense of the race in the fascist school*

I have the duty to inform you that … starting from October 16 you are suspended from service.

The University President

"I left Arcetri with a heavy heart. I was still young, and I knew that there would be, in my life, other periods of interesting and rewarding work. I also knew, however, that none would have the special flavor of my years on the Florentine hills."

B. Rossi "Moments in the life of a scientist" (1990)

Rossi's grave in the graveyard of the church of S. Miniato al Monte, Arcetri

- Importance of low-energy CRs in the ISM

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

$$[p, \alpha]_{CR} + [C, N, O]_{ISM} \rightarrow [^6Li, ^7Li, ^9Be, ^{10}B, ^{11}B]$$

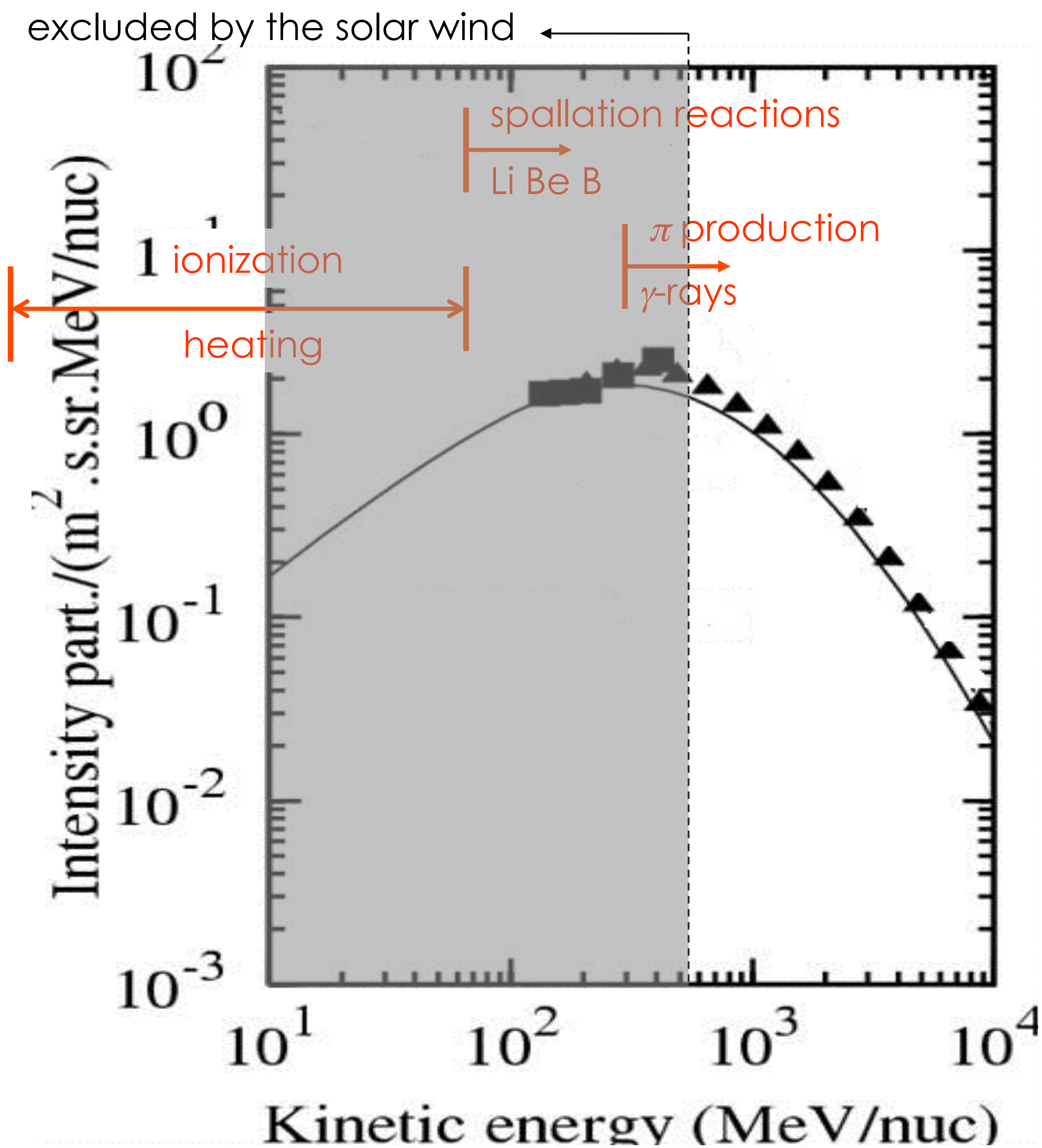
5. Produce γ-ray diffuse emission by π_0 decay

$$p_{CR} + p_{ISM} \rightarrow \pi + \pi + \pi^0 \qquad \pi^0 \rightarrow 2\gamma$$

Consequence of 1:

- CR control the degree of coupling with B with gas (electrical resistivity)
  → efficiency of magnetic braking during protostellar collapse
  → efficiency of MRI instability in circumstellar disks

Spectrum of low-energy CR protons



Valdès-Galicia et al. (2006)

- Given a CR spectrum *j(E)* and ionization cross section $\sigma(E)$, the CR *total* ionization rate ζ_{CR} is

$$\zeta_{\rm CR} = 4\pi \Sigma_k \int j_k(E)[1 + \phi_k(E)]\sigma_k^{\rm ion}(E)\, dE$$

where $\phi(E)$ = secondary ionizations and k=e,p,He,...

- The CR heating is $\Gamma_{\rm CR} = \zeta_{\rm CR} Q n$

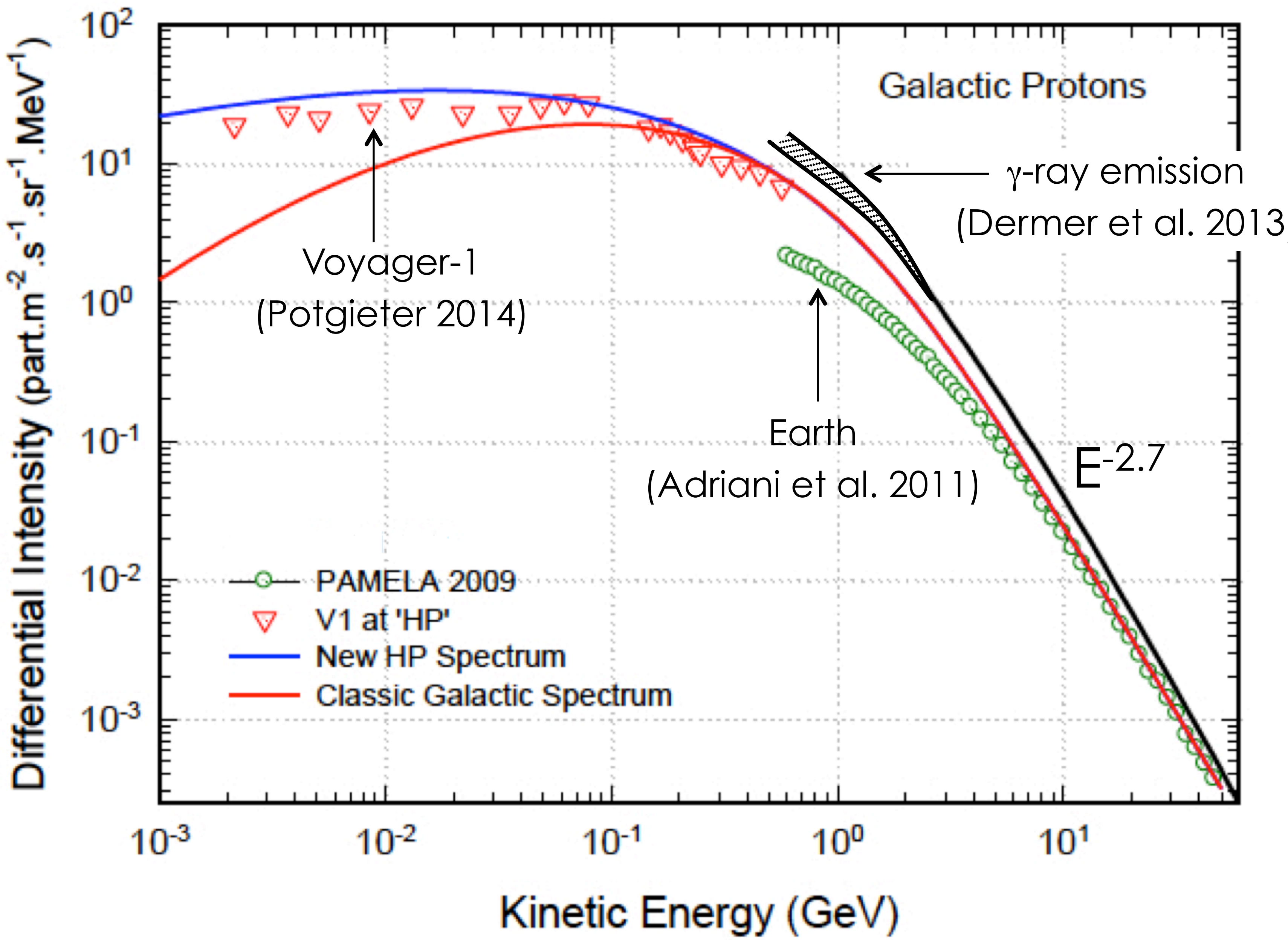
where Q is the heat deposited in the gas per ionization.

- Early studies by Spitzer & Tomasko (1968) for H and Glassgold & Langer (1973) for H_2

Advances in the last 4 decades:

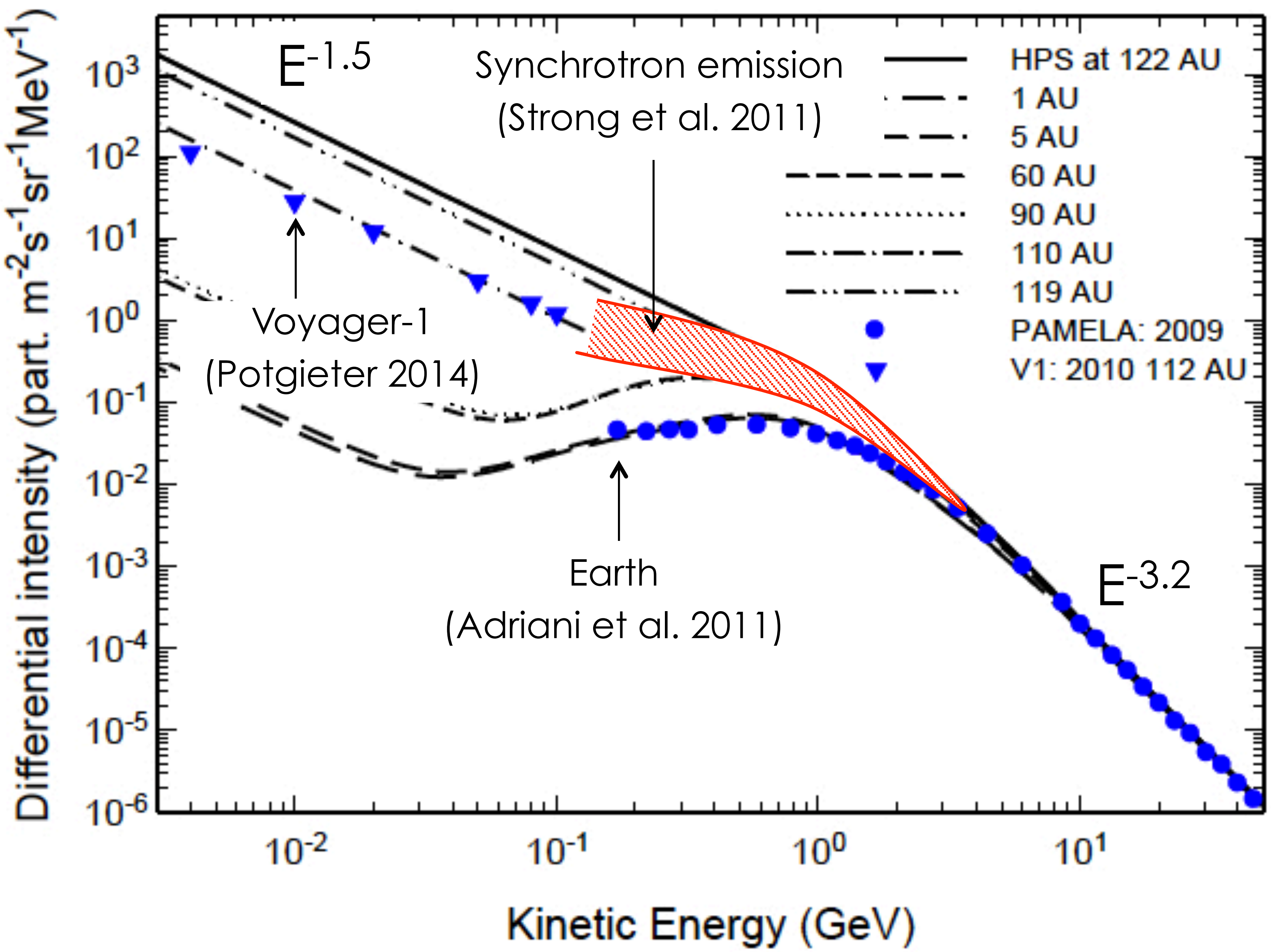
1. Constraints on *j(E)* at low-E from Voyager 1 (Stone et al. 2012, etc.)
2. New observational data on ζ_{CR} in the ISM (McCall et al. 1998, etc.)

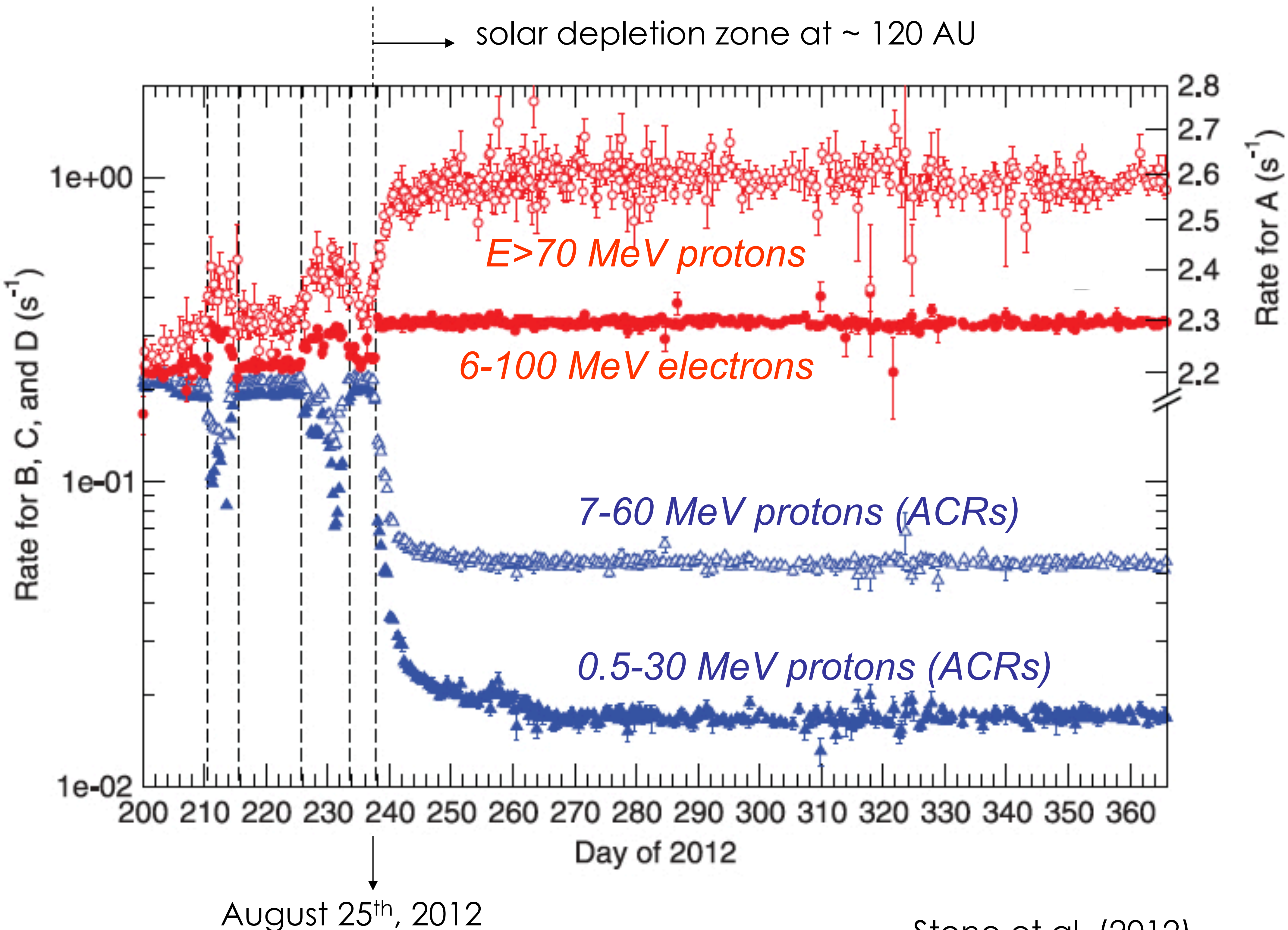
Voyager 1 proton spectrum



- Latest release: Cummings et al. (2016)
- V1 crossed termination shock in 2004 followed by V2 in 2007
- V1 crossed heliopause on August 25, 2012

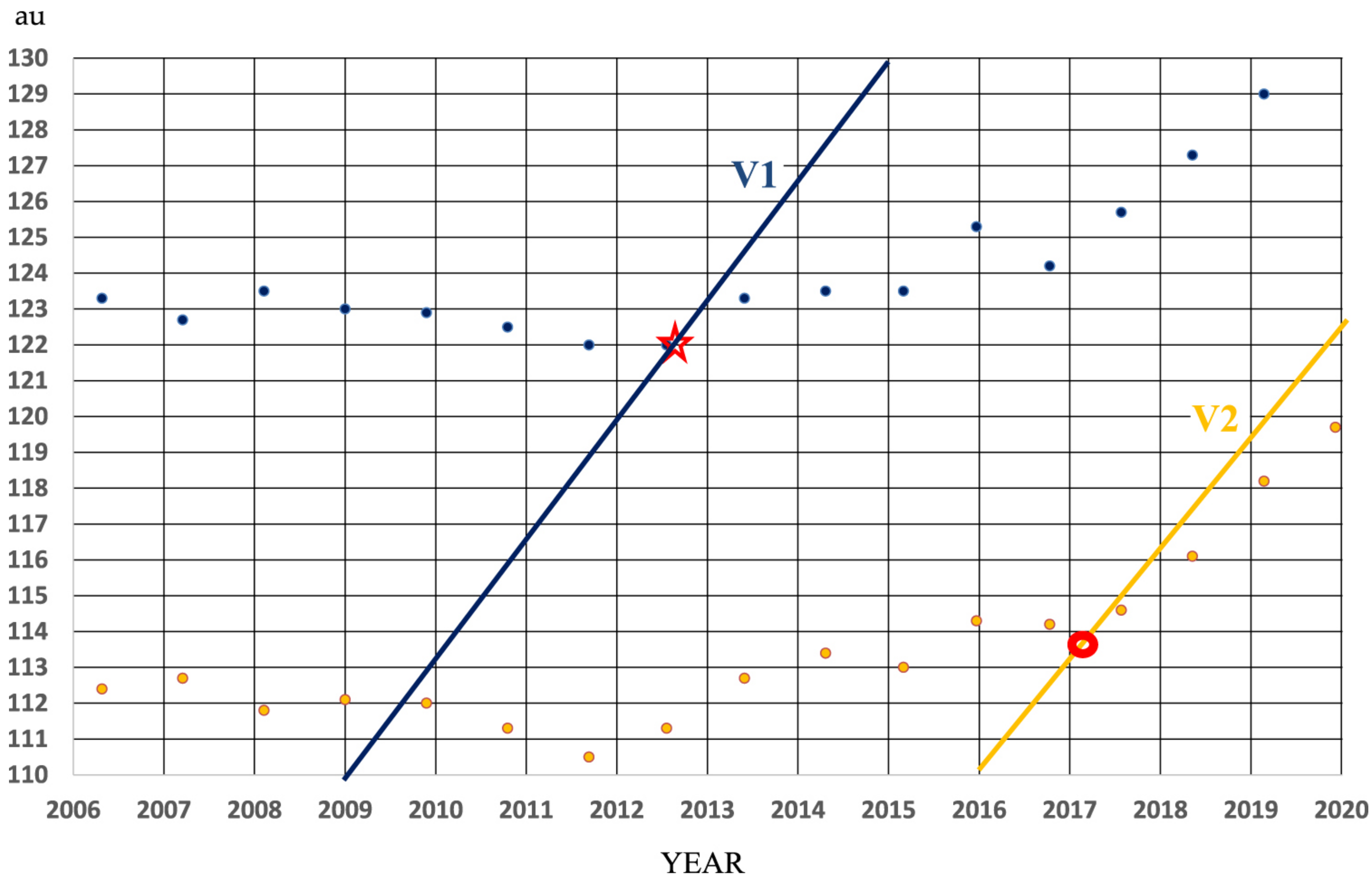
Voyager 1 electron spectrum





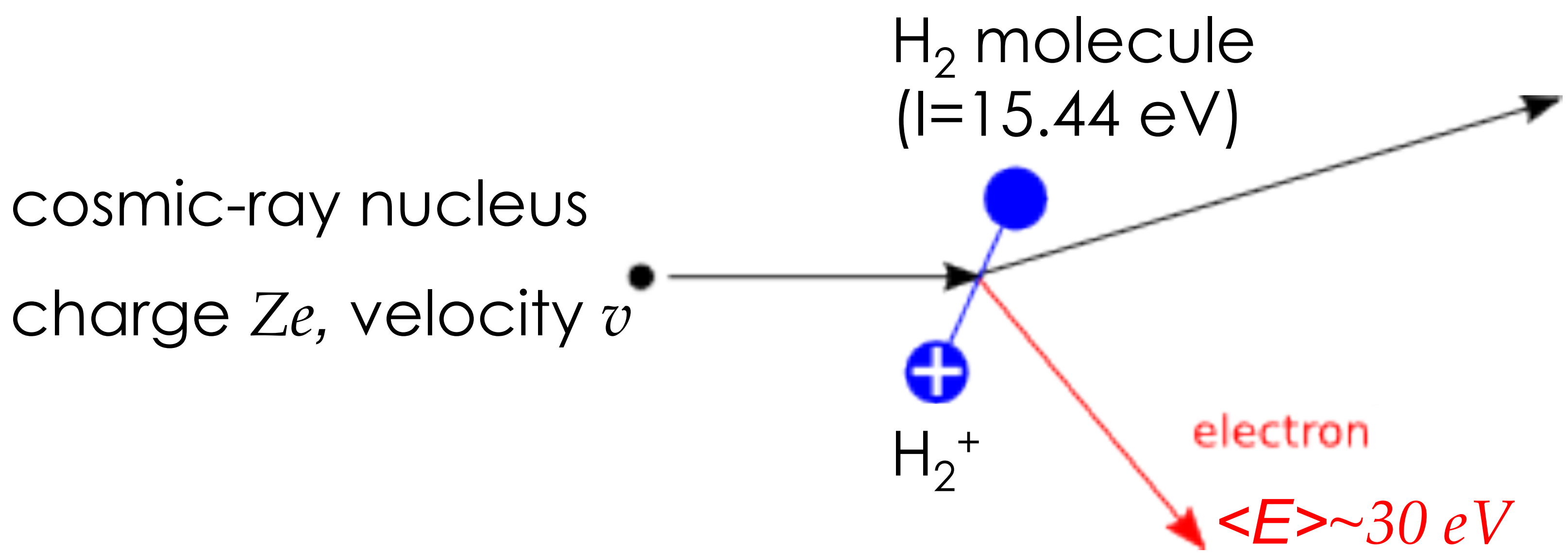
Stone et al. (2012)

Distance to the Heliopause along the V1 and V2 trajectories



Washimi et al. (2017)

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)

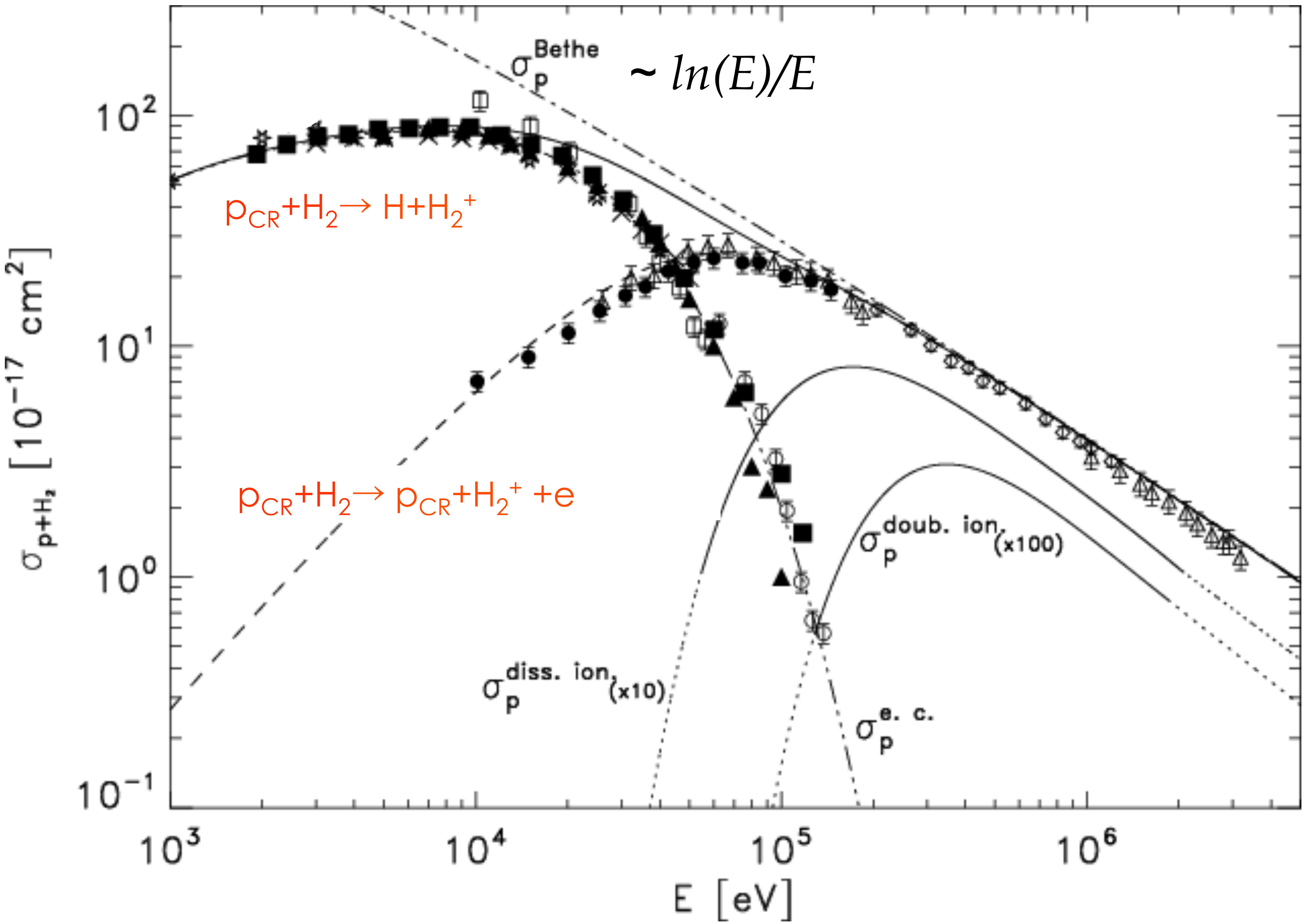
- Thomson (1912) and Bohr (1913) classical

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

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

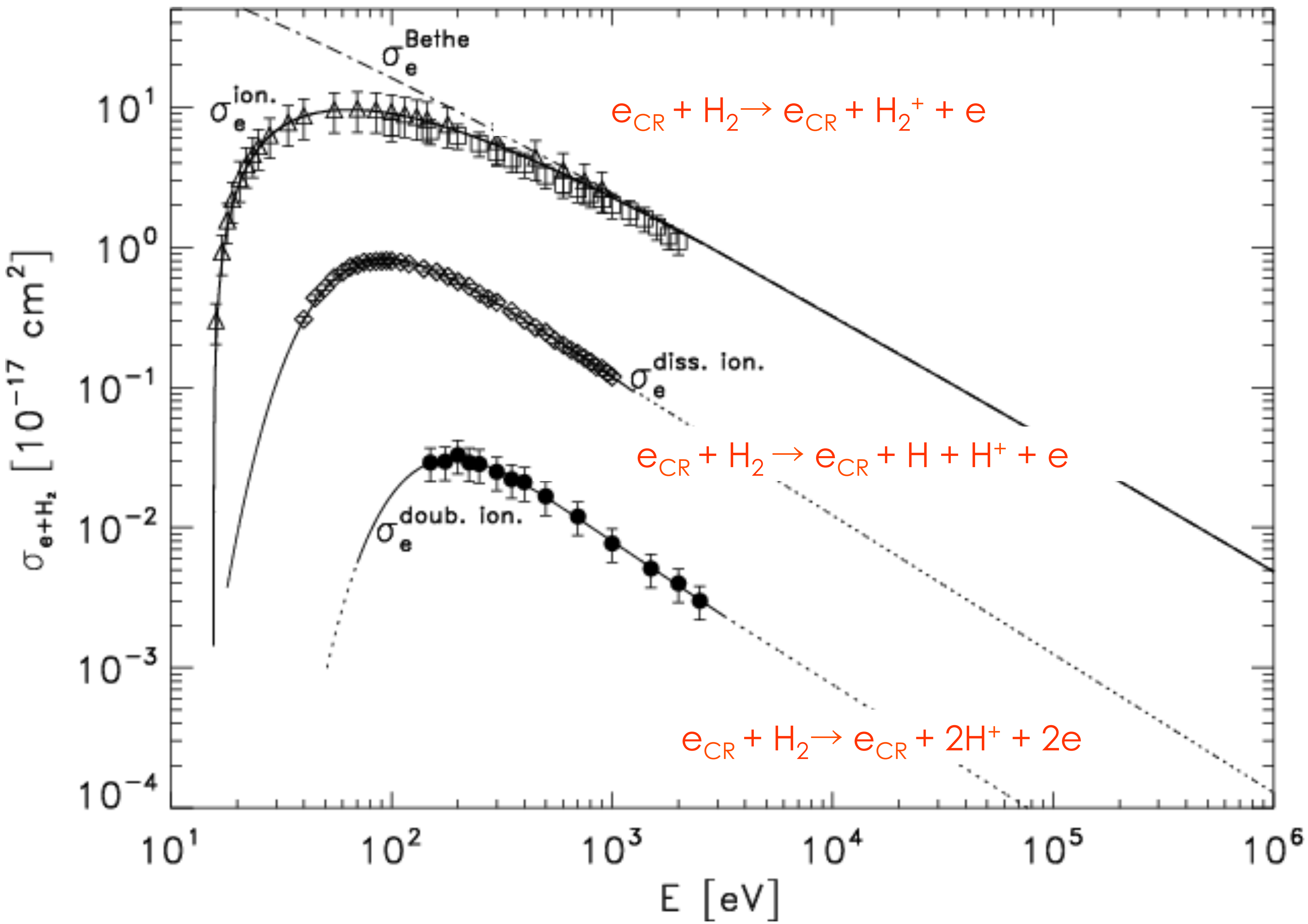
$$\sigma_B^{\rm ion} = \frac{4\pi Z^2 e^4}{m_e c^2 \beta^2}\left[\ln \frac{2 m_e c^2 \beta^2}{I(1-\beta^2)} - \beta^2\right]$$

Cross section p_{CR}-H_2



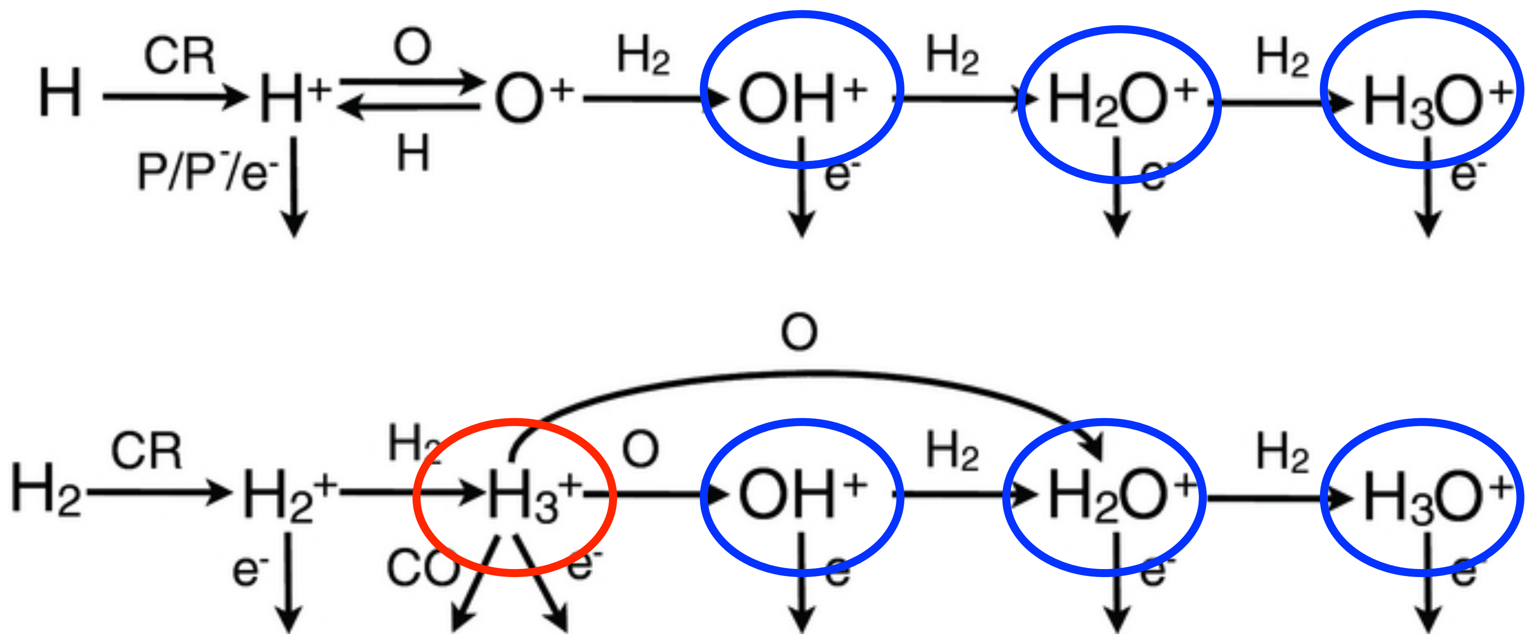
Padovani, Galli & Glassgold (2009)

Cross section e_{CR}-H_2



Padovani, Galli & Glassgold (2009)

CR-induced chemistry



Hollenbach et al. (2012)

- [H_3^+] in 21 *diffuse molecular* clouds (f_{H2} > 0.1, Indriolo & McCall 2012)
  $<\zeta_{CR}(H_2)> = 3.5_{-3.0}^{+5.3} \times 10^{-16}\ s^{-1}$

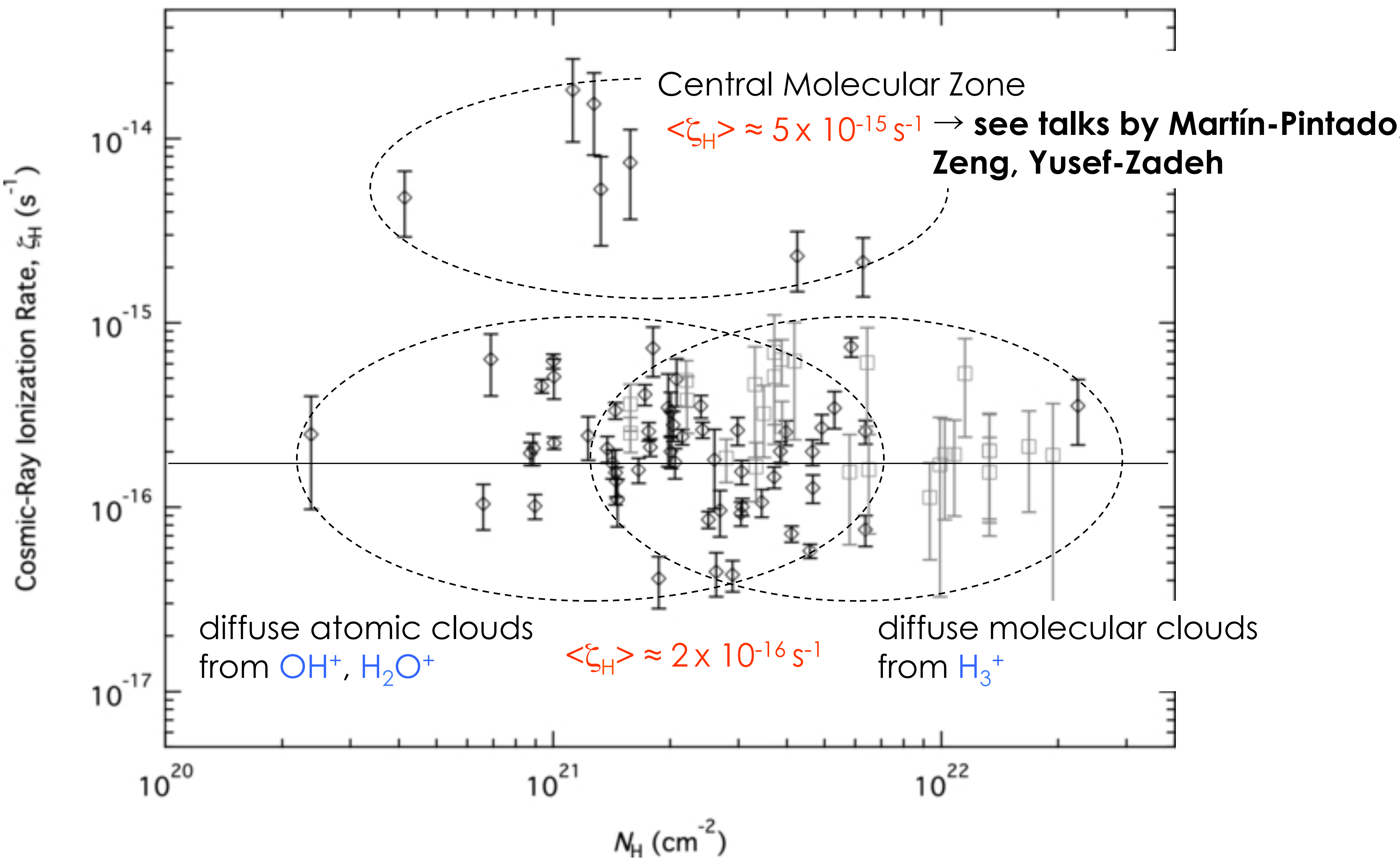
- [OH^+], [H_2O^+], [H_3O^+], in 20 *diffuse atomic* clouds (f_{H2} < 0.1, Indriolo et al. 2015)
  $<\zeta_{CR}(H)> = 1.8_{-0.9}^{+1.7} \times 10^{-16}\ s^{-1}$

Chemical model analysis (Neufeld & Wolfire 2017)

$<\zeta_{CR}(H)> = (2.2 \pm 0.3) \times 10^{-16}\ s^{-1}$ from ArH^+ OH^+ H_2O^+ in *diffuse atomic clouds* ($f(H_2)<0.1$)
$<\zeta_{CR}(H)> = (2.3 \pm 0.6) \times 10^{-16}\ s^{-1}$ from H_3^+ in *diffuse molecular clouds* ($f(H_2)>0.1$)

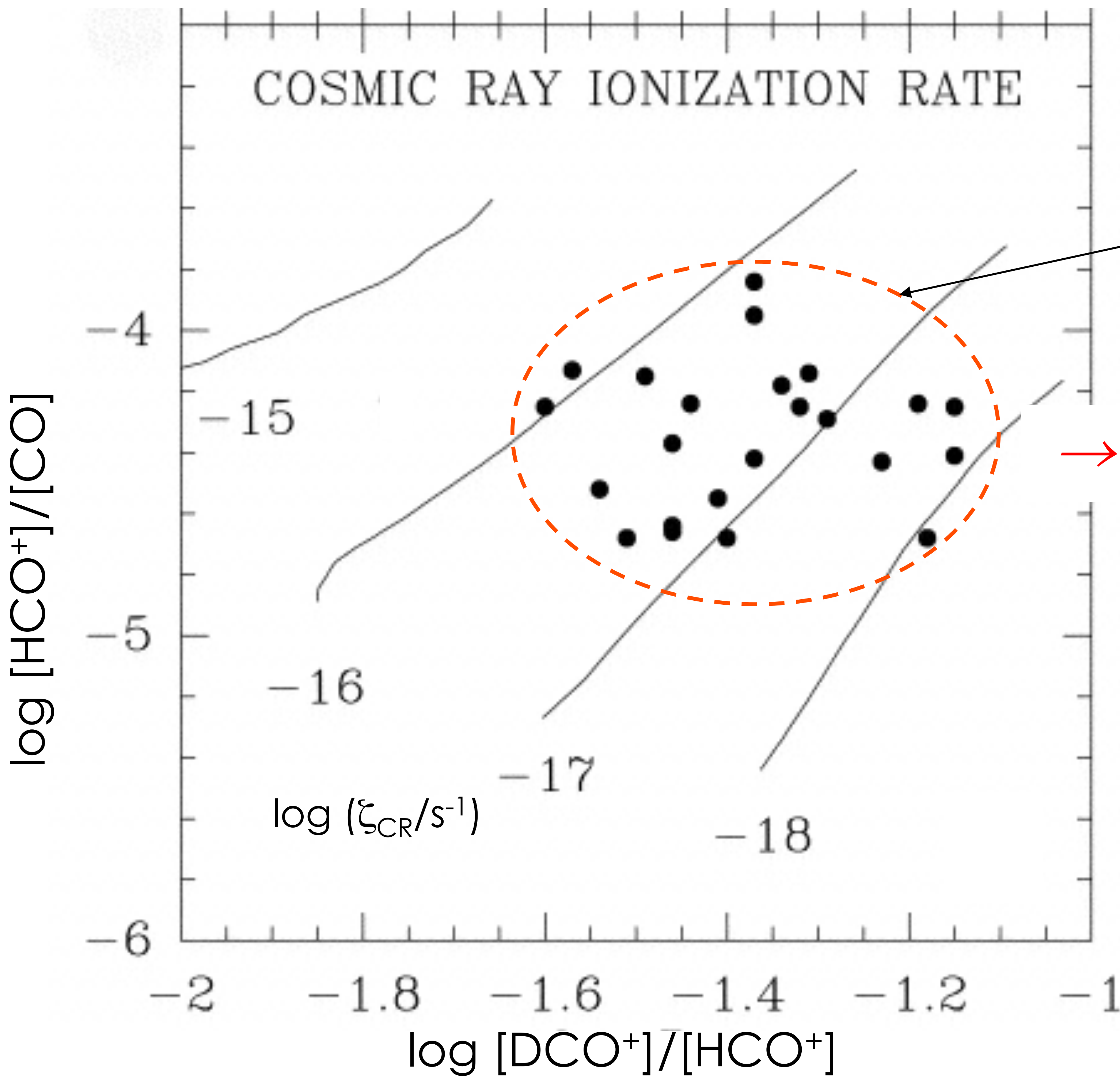
- In dense molecular cloud cores [DCO^+]/[HCO^+] (Guélin et al. 1977) or [DCO^+]/[HCO^+] plus [HCO^+]/[CO] (Caselli et al. 1998)

→ **see talks by Neufeld, Caselli, Oka, etc.**



Indriolo et al. (2015)

ζ_{CR} in dense clouds



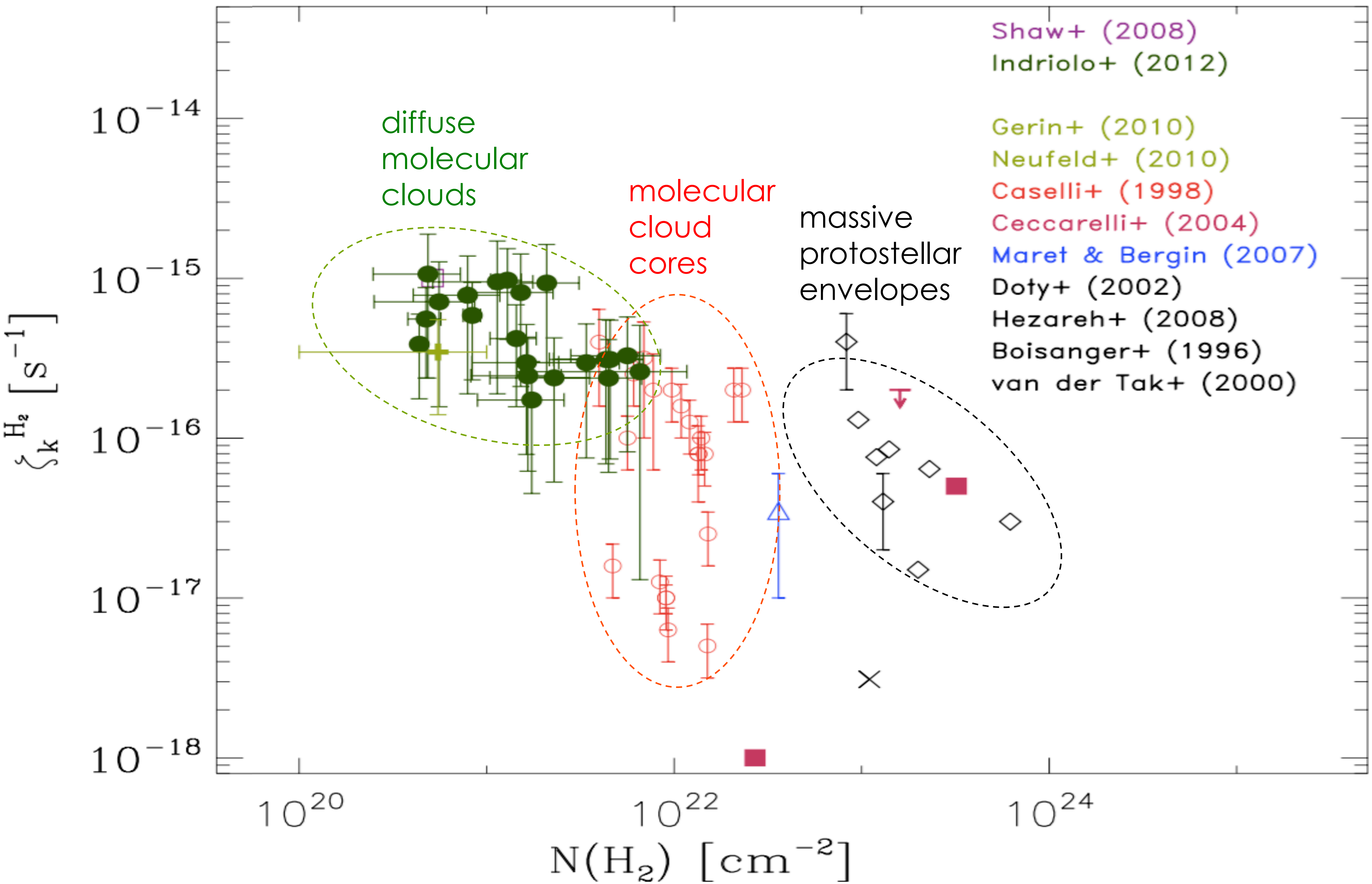
sample of 23 molecular cloud cores

→ $\zeta_{CR} \approx 10^{-18} - 10^{-16}\ s^{-1}$

Large scatter of ζ_{CR} in dense clouds: real or not?

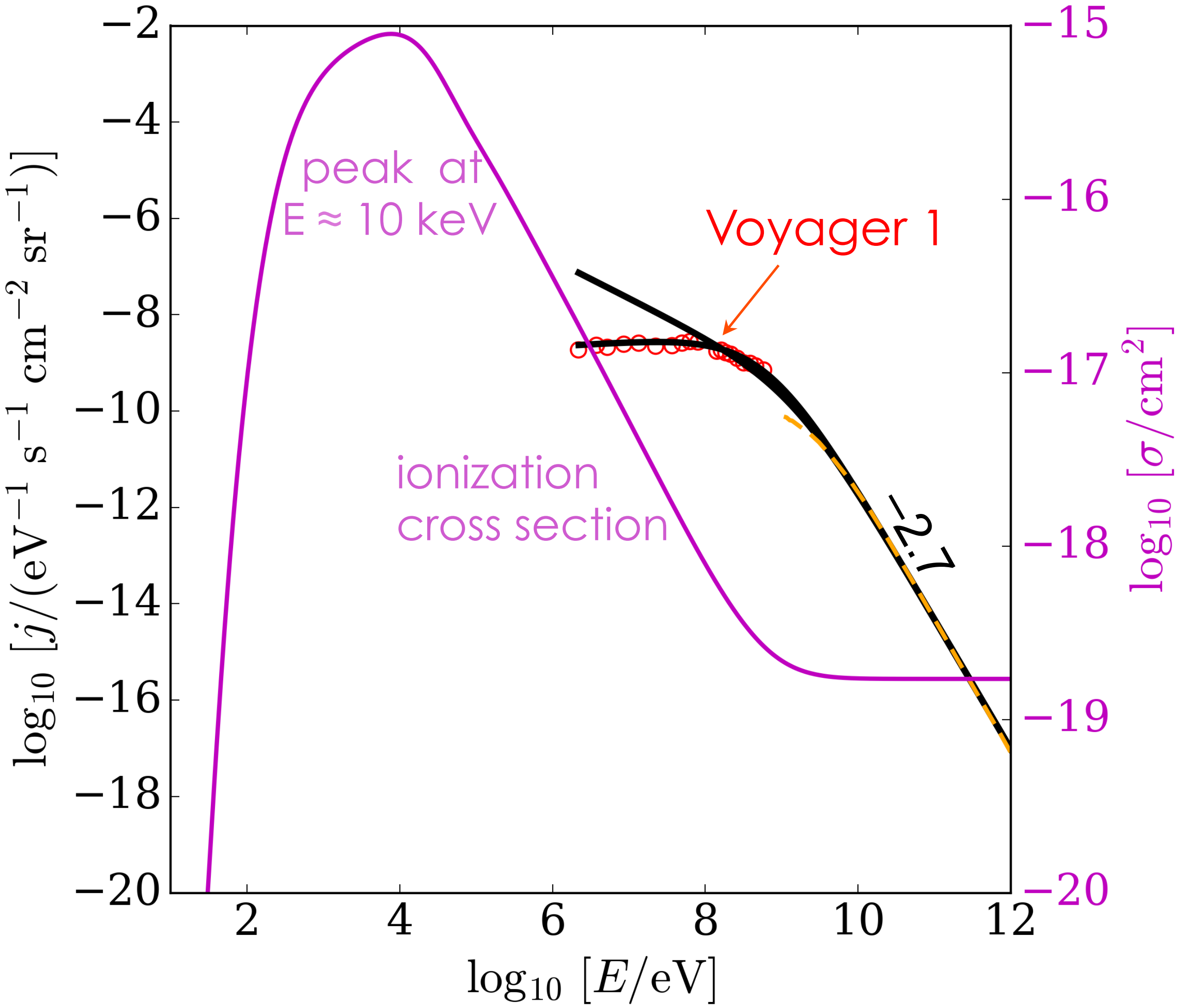
Caselli et al. (1998)

Summary of observations of ζ_{CR} vs. $N(H_2)$

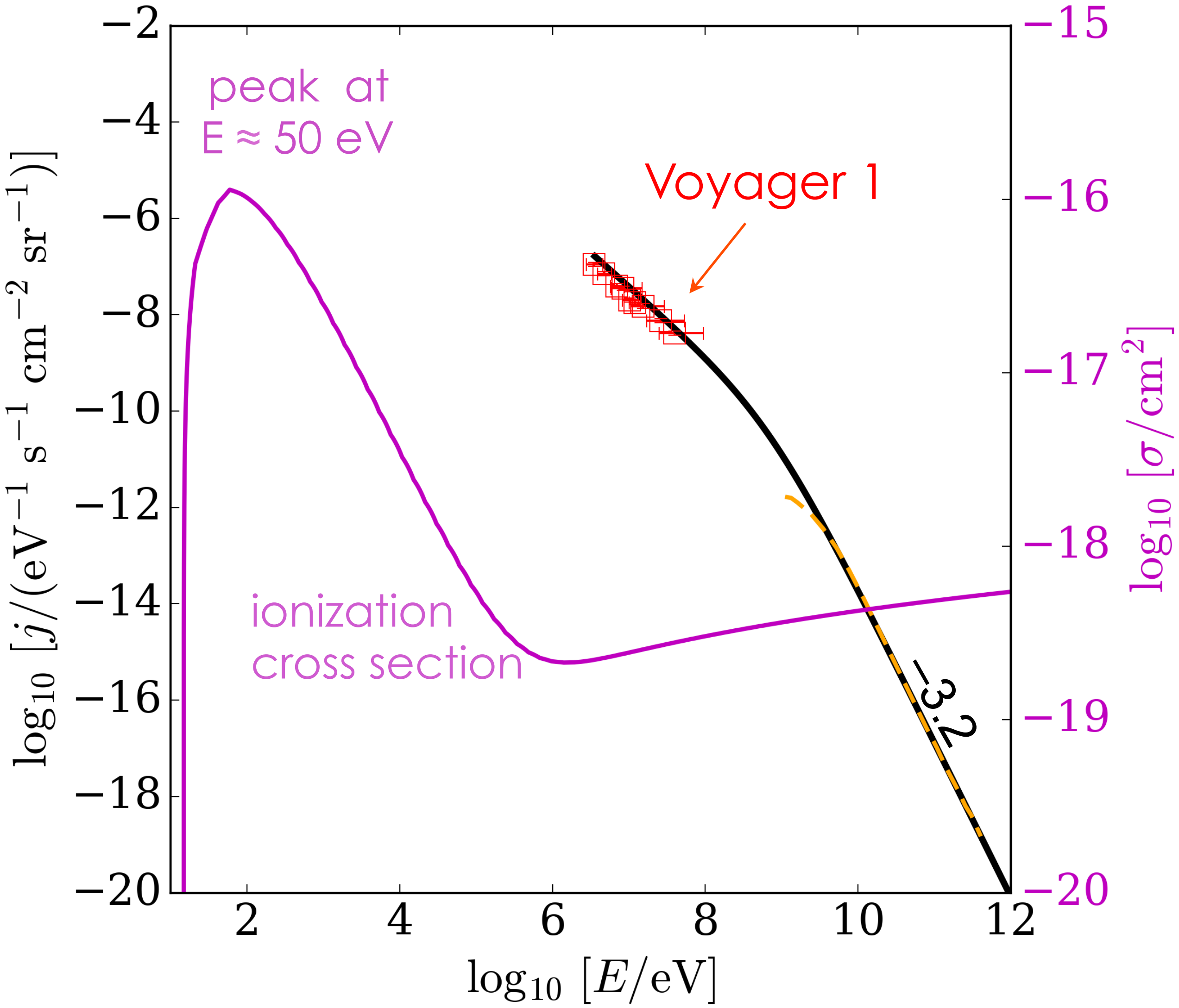


CR spectrum in the solar neighbourhood

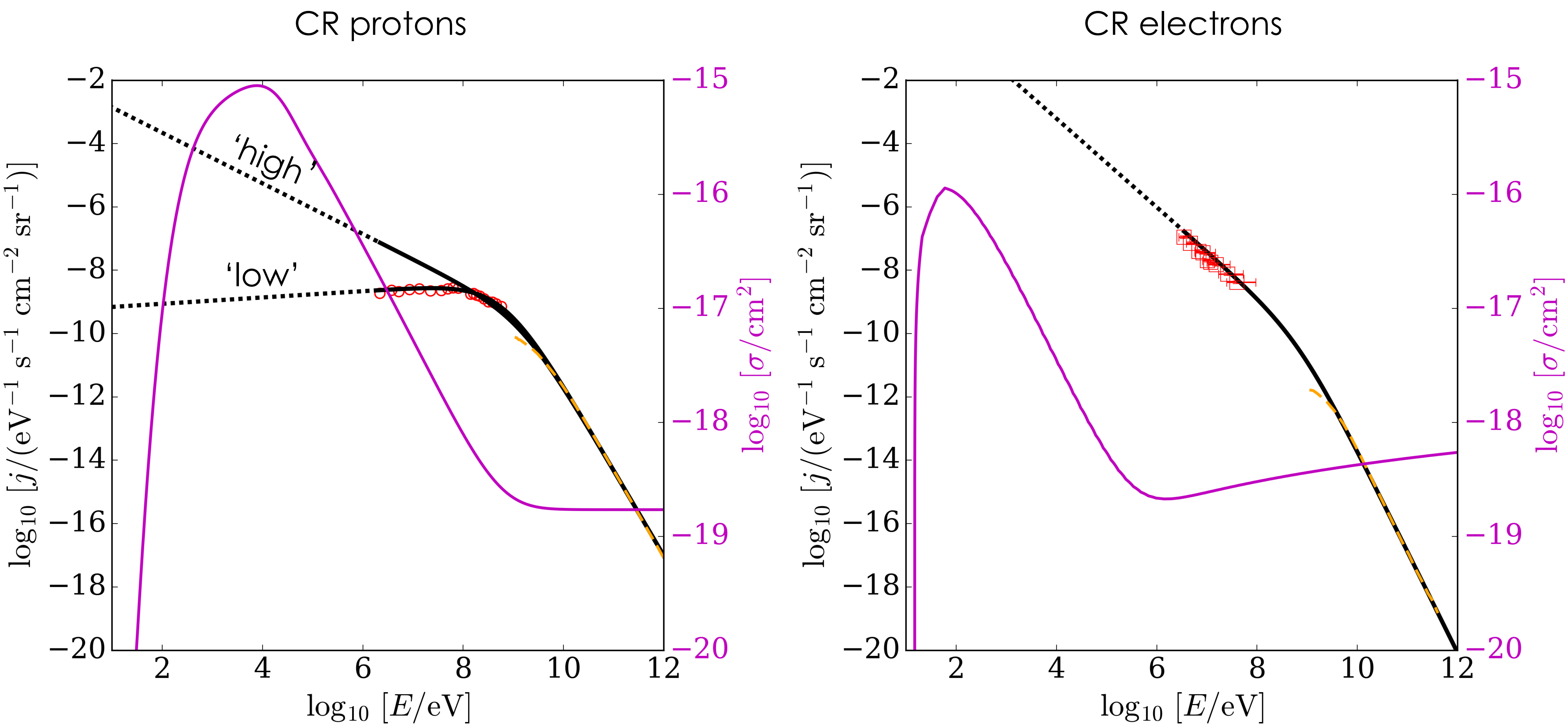
CR protons



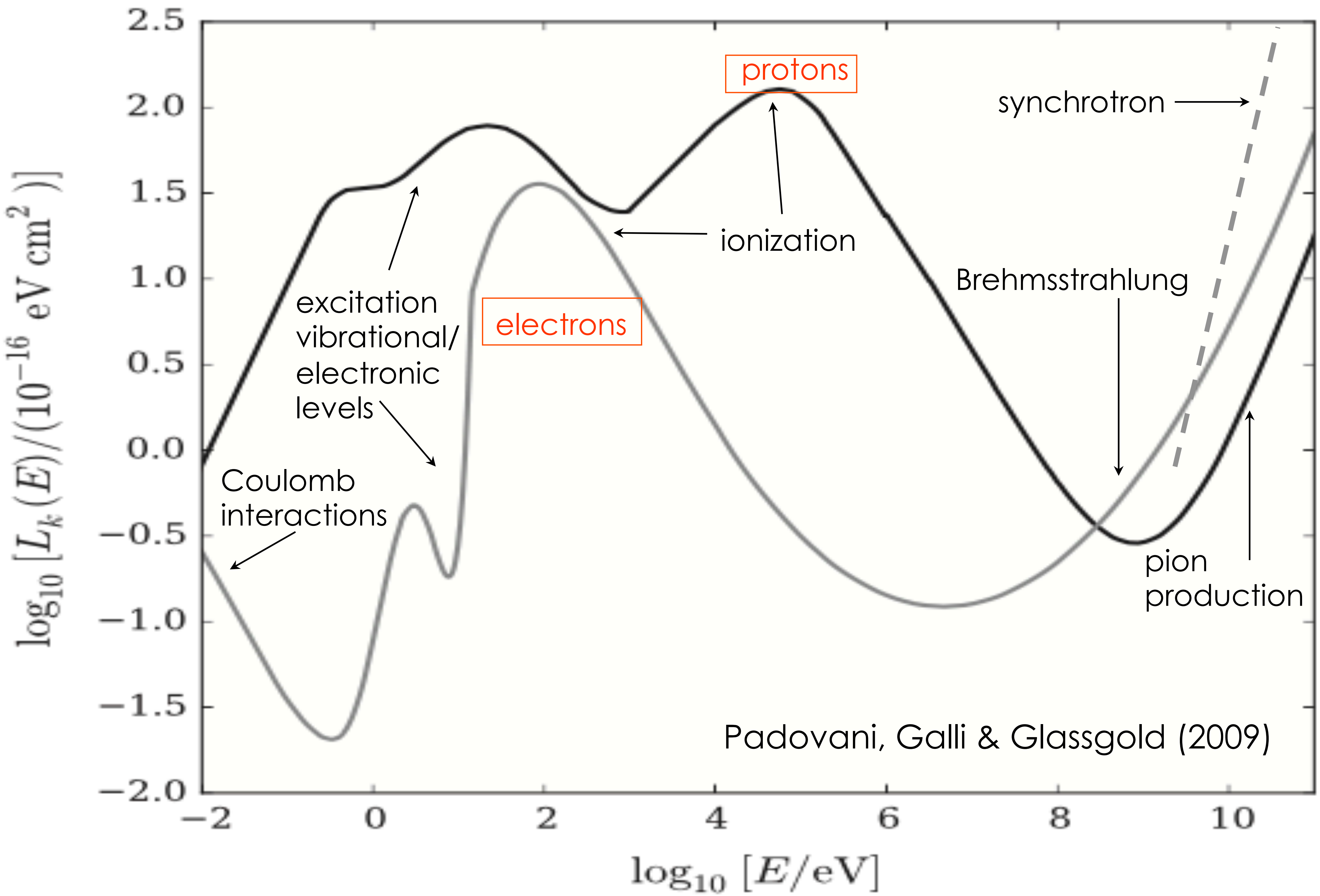
CR electrons



CR spectrum in the solar neighbourhood



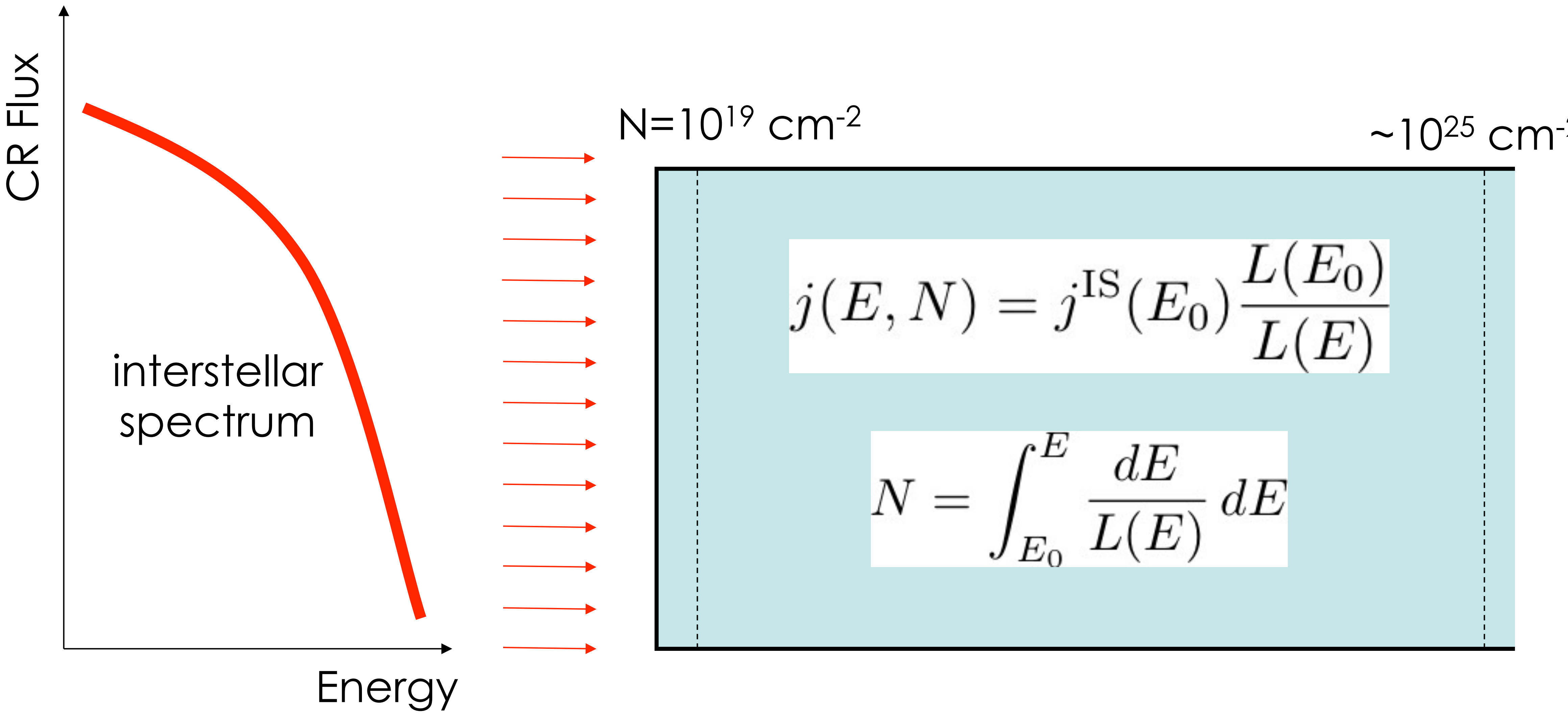
Energy losses of CR–protons and electrons in H_2



CR propagation in 1D cloud

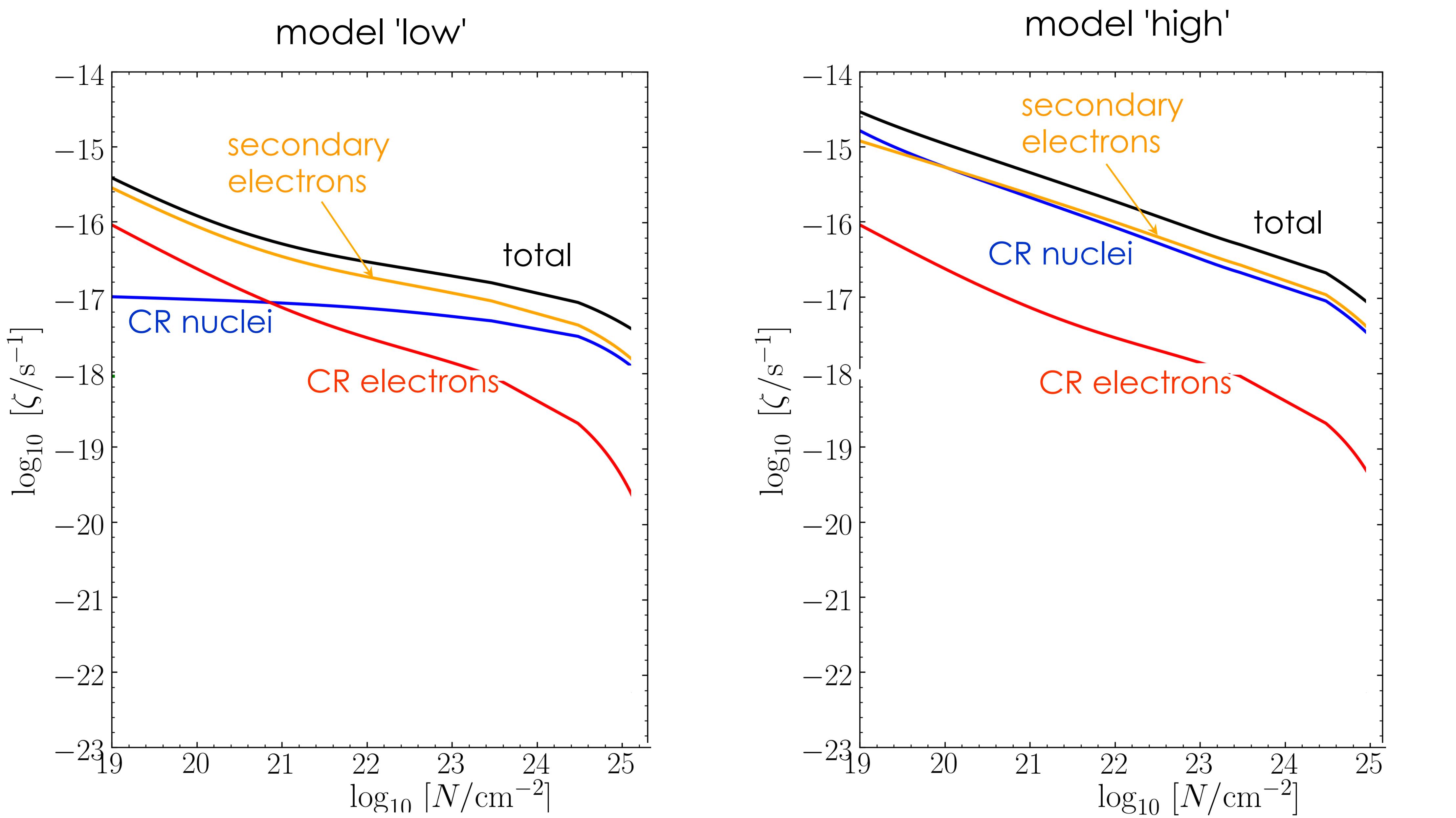
- Padovani et al. (2009) considered propagation of CRs and their secondaries dominated by continuous losses (continuous slowing down approximation)

$$\frac{\partial j}{\partial N} - \frac{\partial}{\partial E}[L(E)j] = 0 \qquad \text{where } L(E) \text{ is the loss function}$$



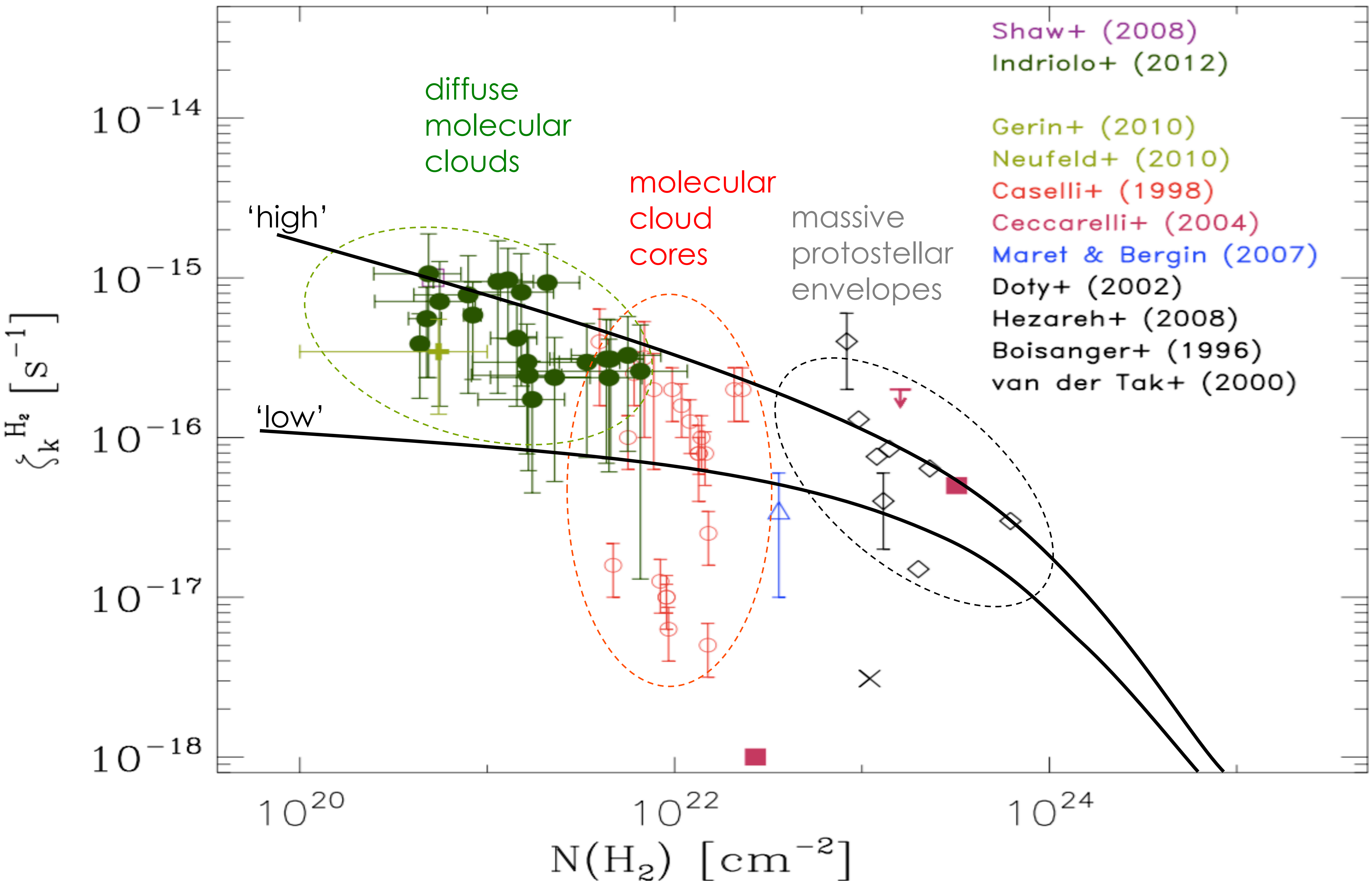
- Extended by Padovani et al. (2018) to higher N and E → **see talk by Ivlev**

CR ionization rate: results

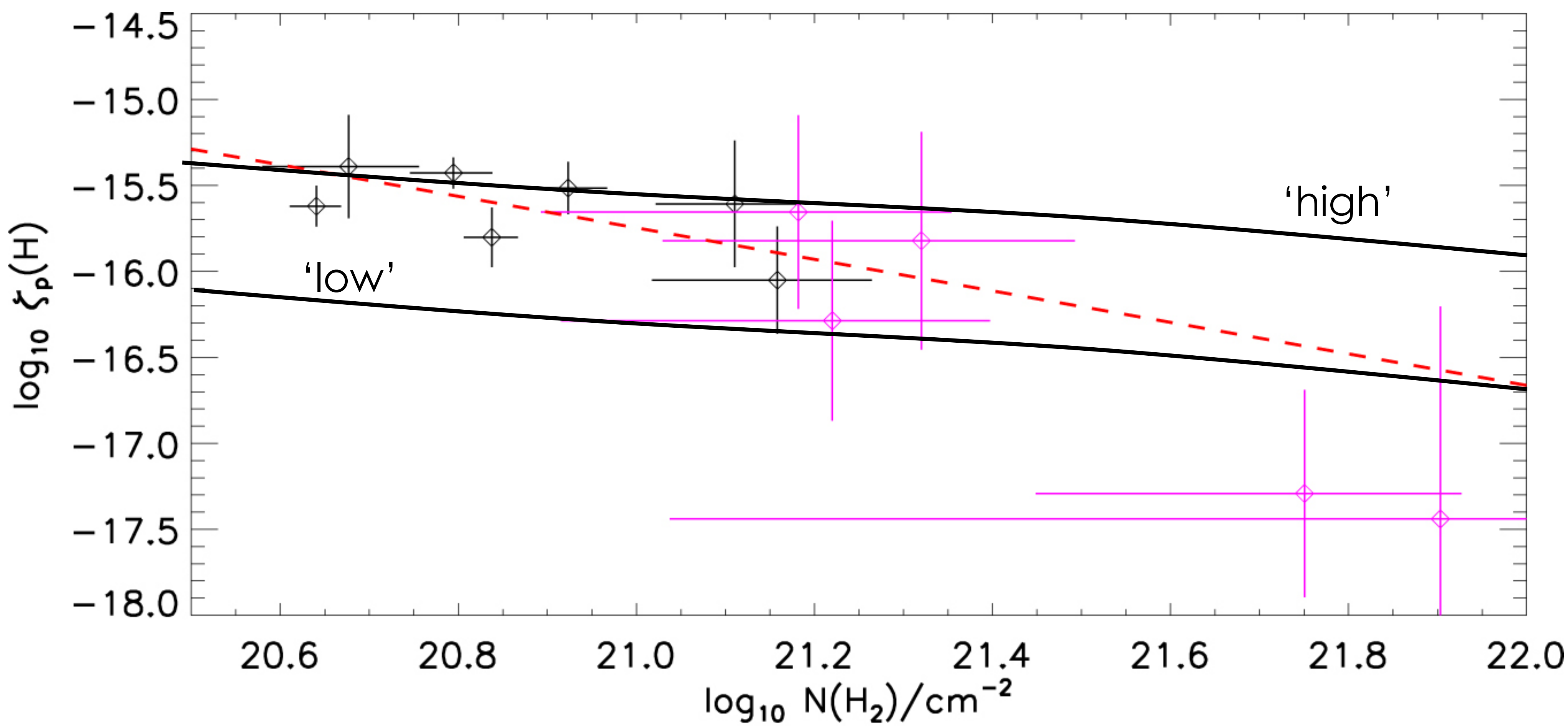


Padovani, Galli & Glassgold (2009)

Comparison with observations



Comparison with diffuse clouds



- Diffuse cloud data from Neufeld & Wolfire (2017)
- Models by Padovani et al (2009, 2018)
- Slope log ζ – log N: data -1, models -0.3

→ see talk by Gabici

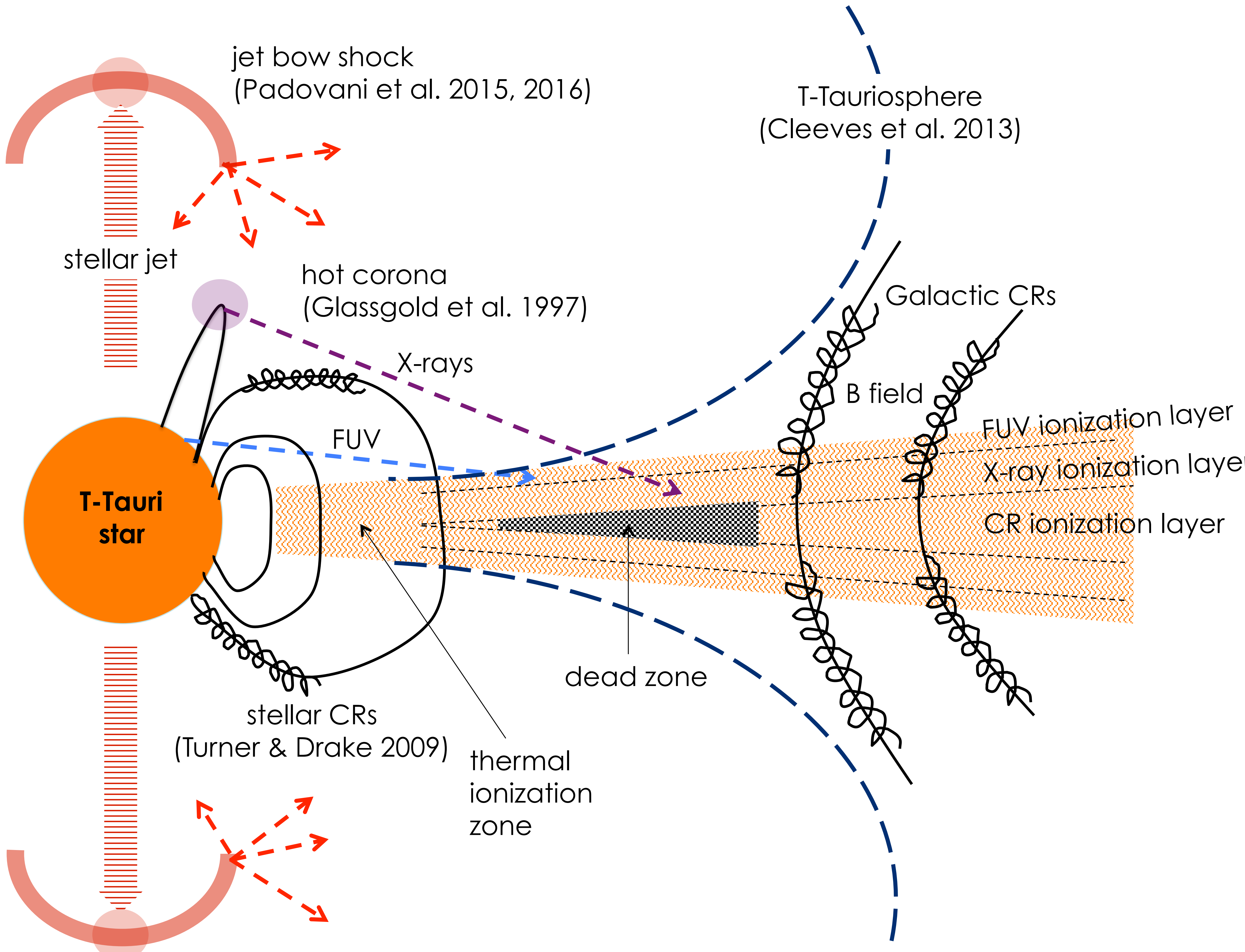
Ionization processes in a protostellar disk

- Inner disk: collisional ionization of alkali species (e.g. Na, K)
  $\rightarrow x_e \approx 10^{-3}$ at $T \approx 10^3$ K ($R \approx 0.1$-1 AU) $\rightarrow$ good coupling with B

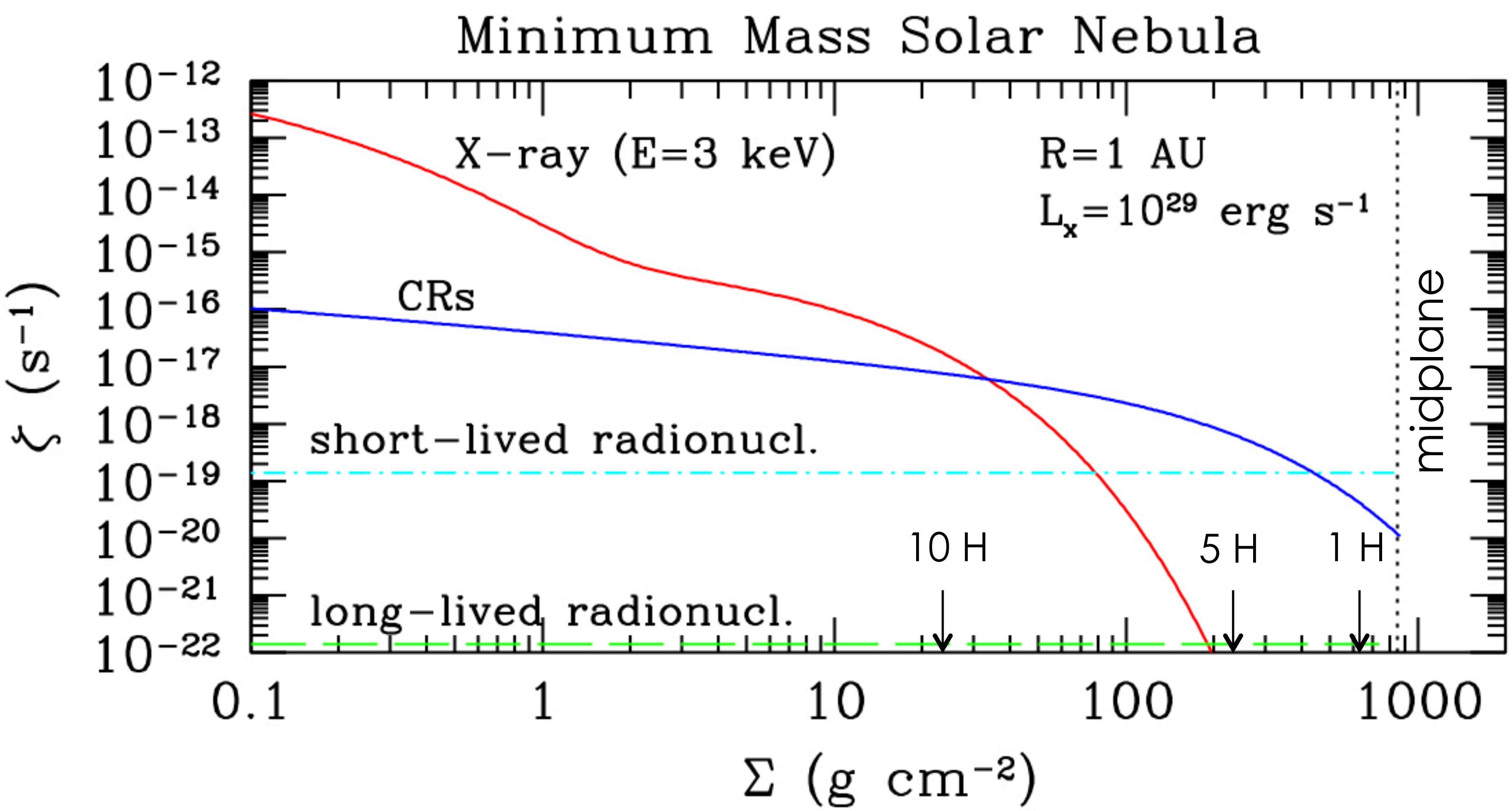
- Larger radii:
  - stellar FUV photons
  - stellar X-rays
  - stellar protons

  (stellar FUV photons, stellar X-rays, stellar protons): geometrically diluted as $1/r^2$
  - CRs
  - short- and long-lived radionuclides

- Typical attenuation columns:
  - UV photons: $\sim 10^{-3}$ g cm^{-2}
  - 1 keV X-rays: ~ 0.5 g cm^{-2}
  - CRs: ~ 100 g cm^{-2}

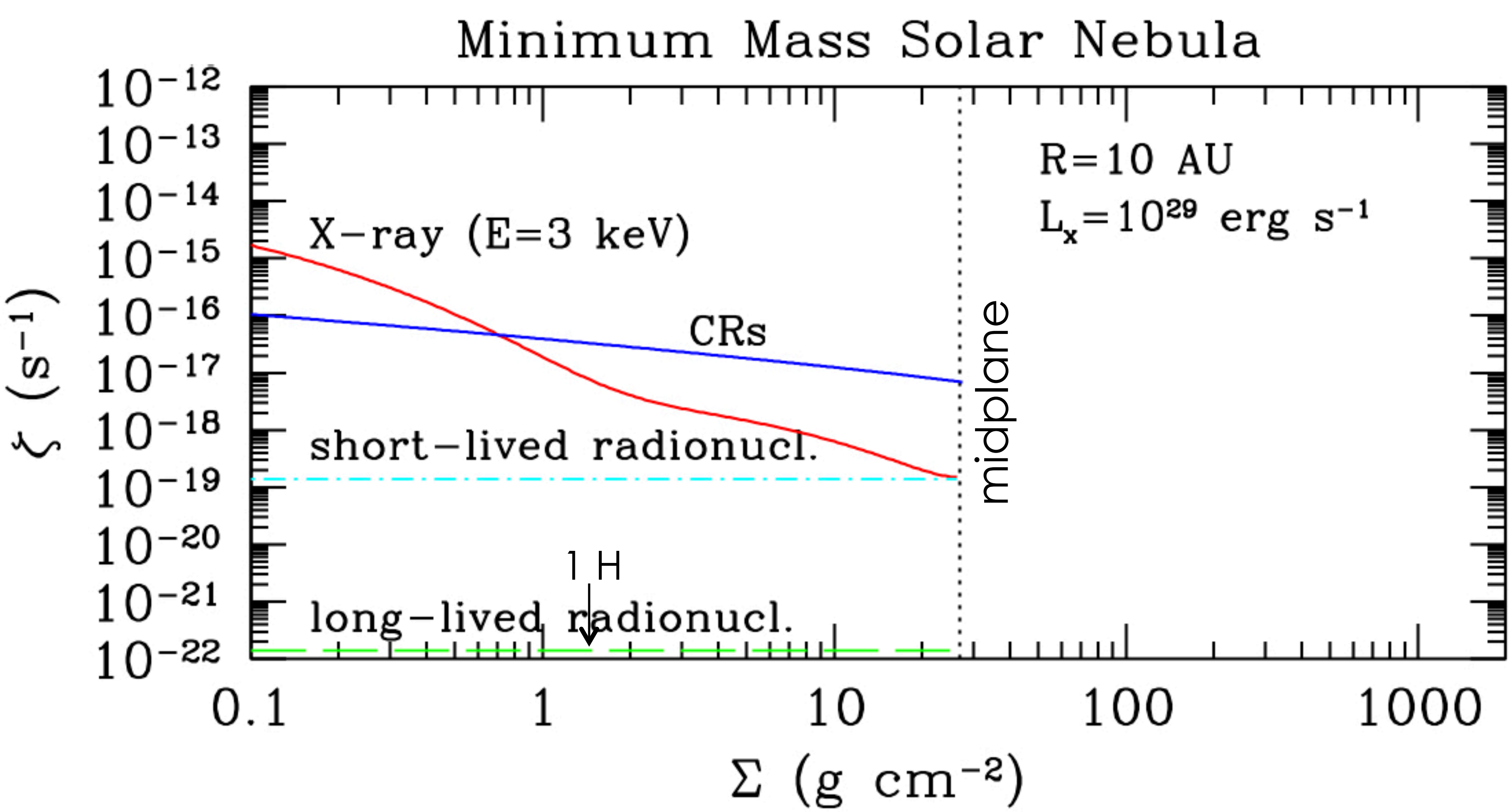

jet bow shock
(Padovani et al. 2015, 2016)
T-Tauriosphere
(Cleeves et al. 2013)
stellar jet
hot corona
(Glassgold et al. 1997)
Galactic CRs
X-rays
B field
FUV
FUV ionization layer
X-ray ionization layer
T-Tauri star
CR ionization layer
dead zone
stellar CRs
(Turner & Drake 2009)
thermal ionization zone

Vertical profile of disk ionization at 1 AU



- X-ray from Glassgold et al (1997), Ercolano et al. (2008)
- CRs from Padovani et al. (2009, 2018)
- SL and LL radionuclides from Umebayashi & Nakano (2009)

Vertical profile of disk ionization at 10 AU



Conclusions

- A high flux of low-energy CRs (below ~100 MeV) is needed to explain ionization in diffuse and dense clouds. Voyager spectra $\rightarrow$ too low ζ_{CR} .
- Ionization in diffuse clouds: reliable data/modeling $\rightarrow$ good constraints.
- Ionization in molecular cloud cores: more observations needed. Measurements of T_{gas} in UV-shielded dense cores can also constrain ζ_{CR}.
- Propagation dominated by losses $\rightarrow$ $\zeta_{CR} \sim N(H_2)^{-\alpha}$ depending on IS spectrum with $\alpha \approx 0.3$ up to $N_H \approx 10^{25}$ cm^{-2}.
- Ionization in disks: crucial for disk dynamics (magnetic braking, MRI). Dominated by galactic CRs in the disk's midplane. Modulation by the protostellar wind unclear.