

Cosmic-ray ionization and heating in molecular clouds

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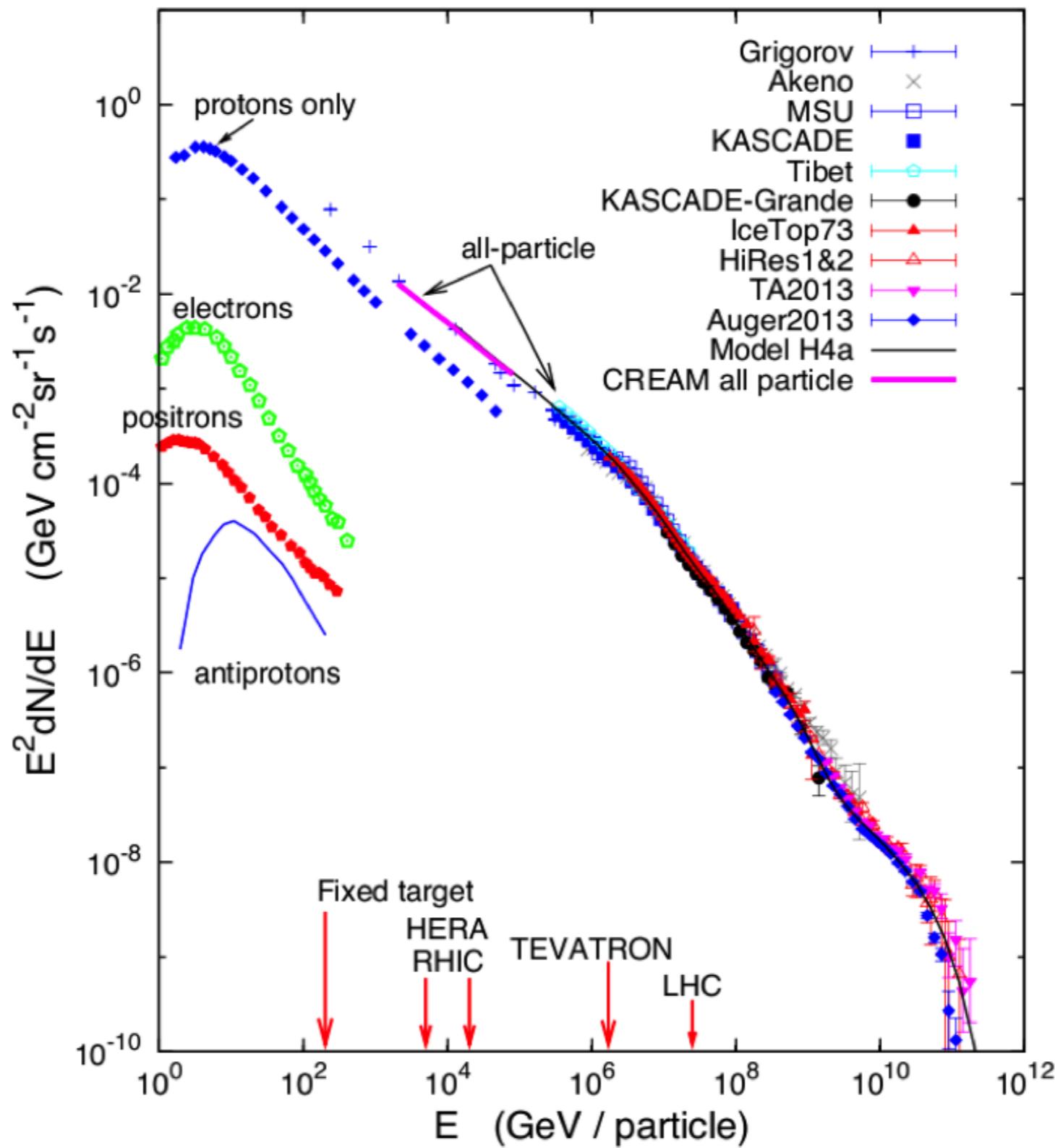
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Patrick Hennebelle (CEA Saclay)

Paola Caselli (MPE Munich)

Alexei Ivlev (MPE Munich)

Energies and rates of the cosmic-ray particles



Gaisser (2012)

- 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



5. Produce γ -ray diffuse emission by π_0 decay



6. Produce γ -ray lines by nuclear excitation



Consequence of 1:

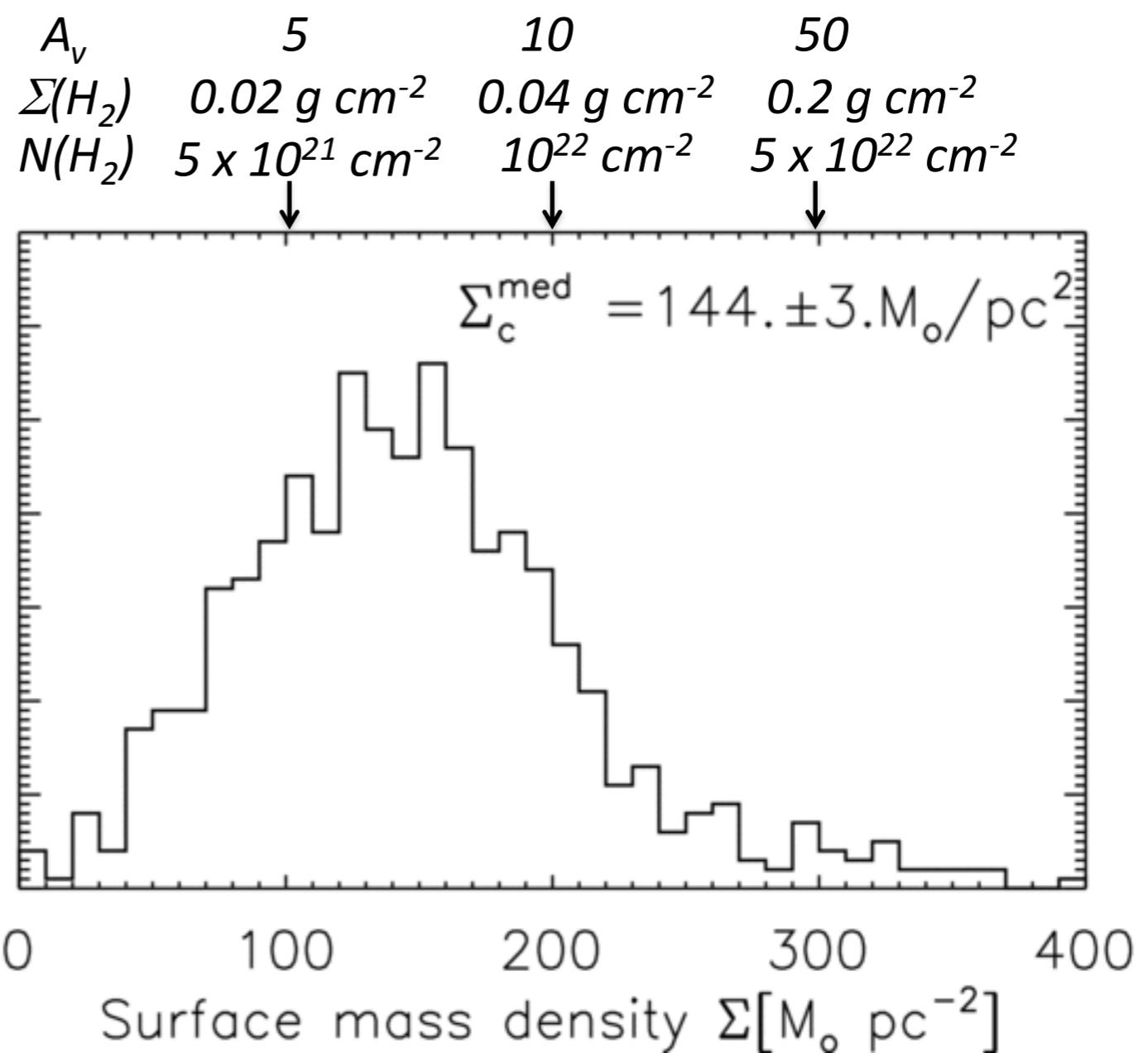
- control the degree of coupling with B with gas (electrical resistivity)

Molecular Clouds: “absorbers” of low-energy CRs

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

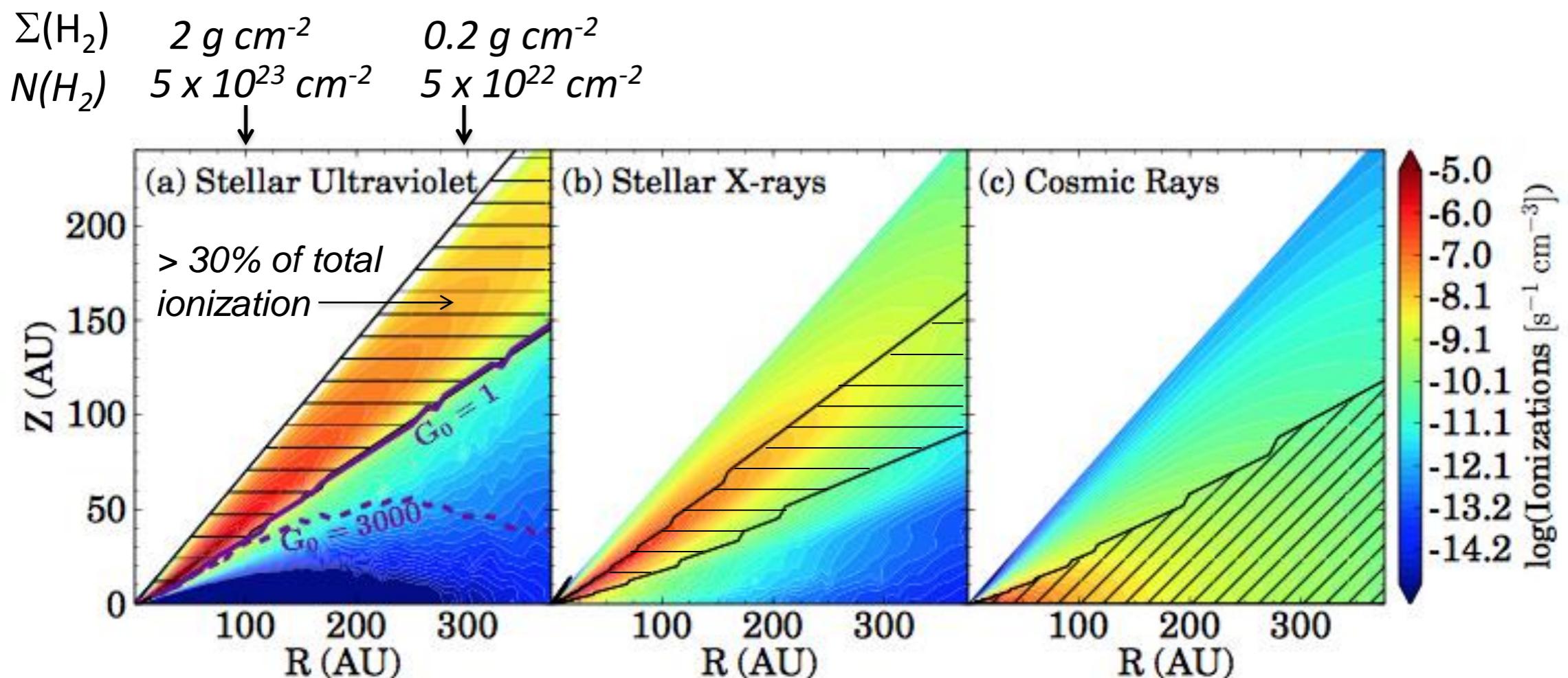
E (MeV)	Measured Rn	Calculated Rn
1.....	2.5×10^{20}	2.6×10^{20}
2.....	8.8×10^{20}	9.2×10^{20}
10.....	1.6×10^{22}	1.6×10^{22}
20.....	5.9×10^{22}	5.9×10^{22}
50.....	3.2×10^{23}	3.2×10^{23}
100.....	1.2×10^{24}	1.2×10^{24}

Cravens & Dalgarno (1978)

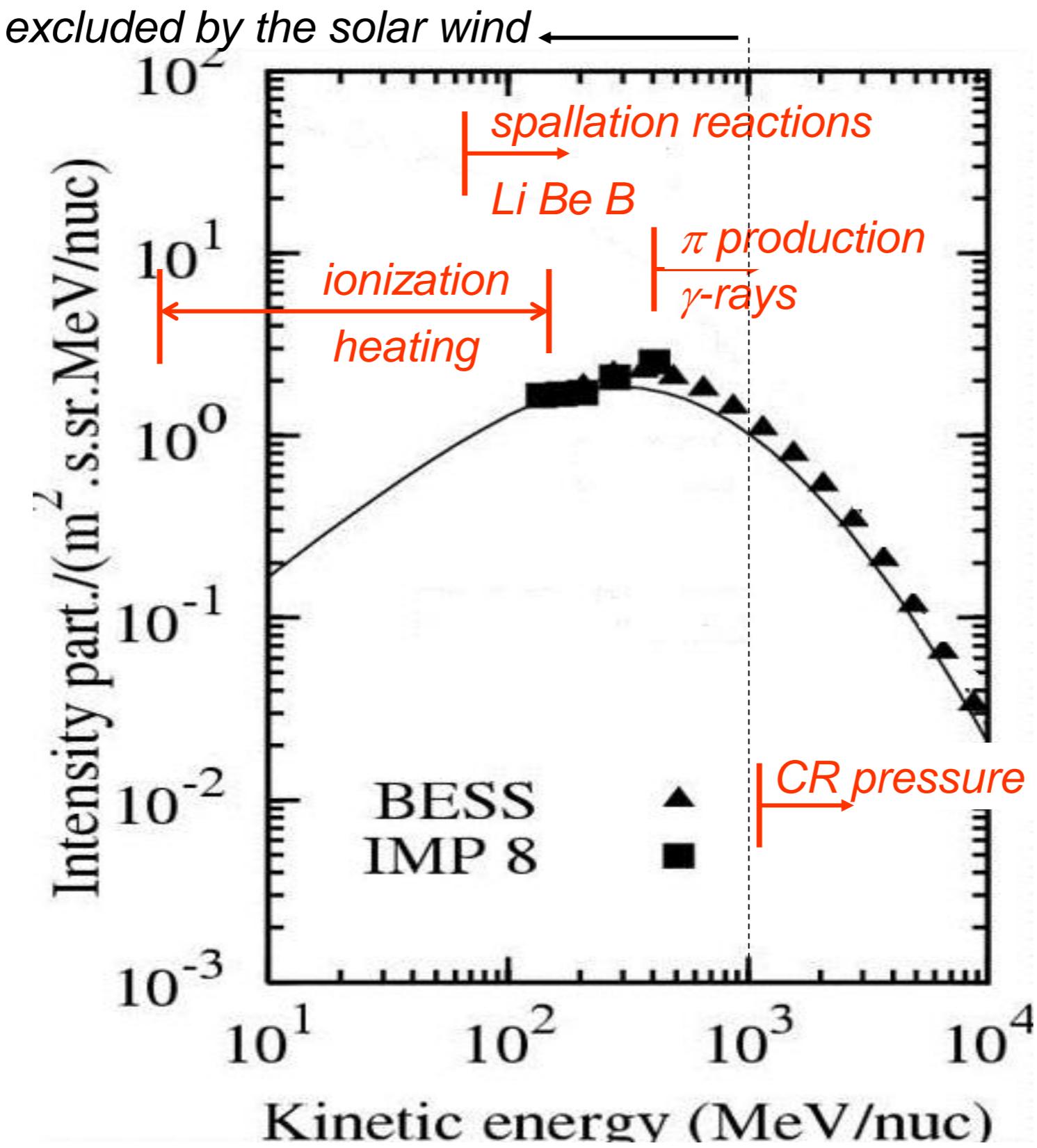


Roman-Duval et al. (2010)

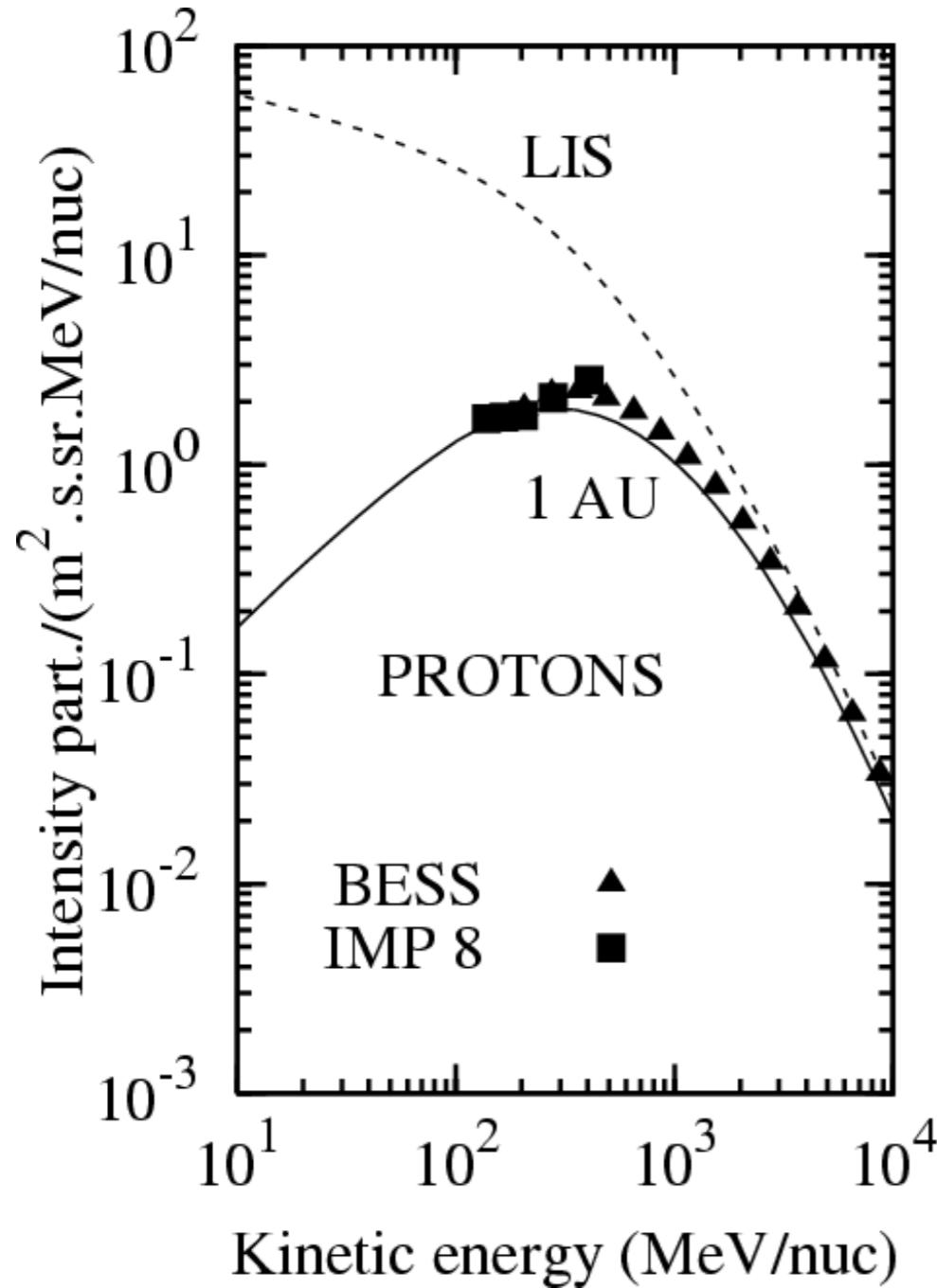
Cosmic ray penetration in protostellar disks



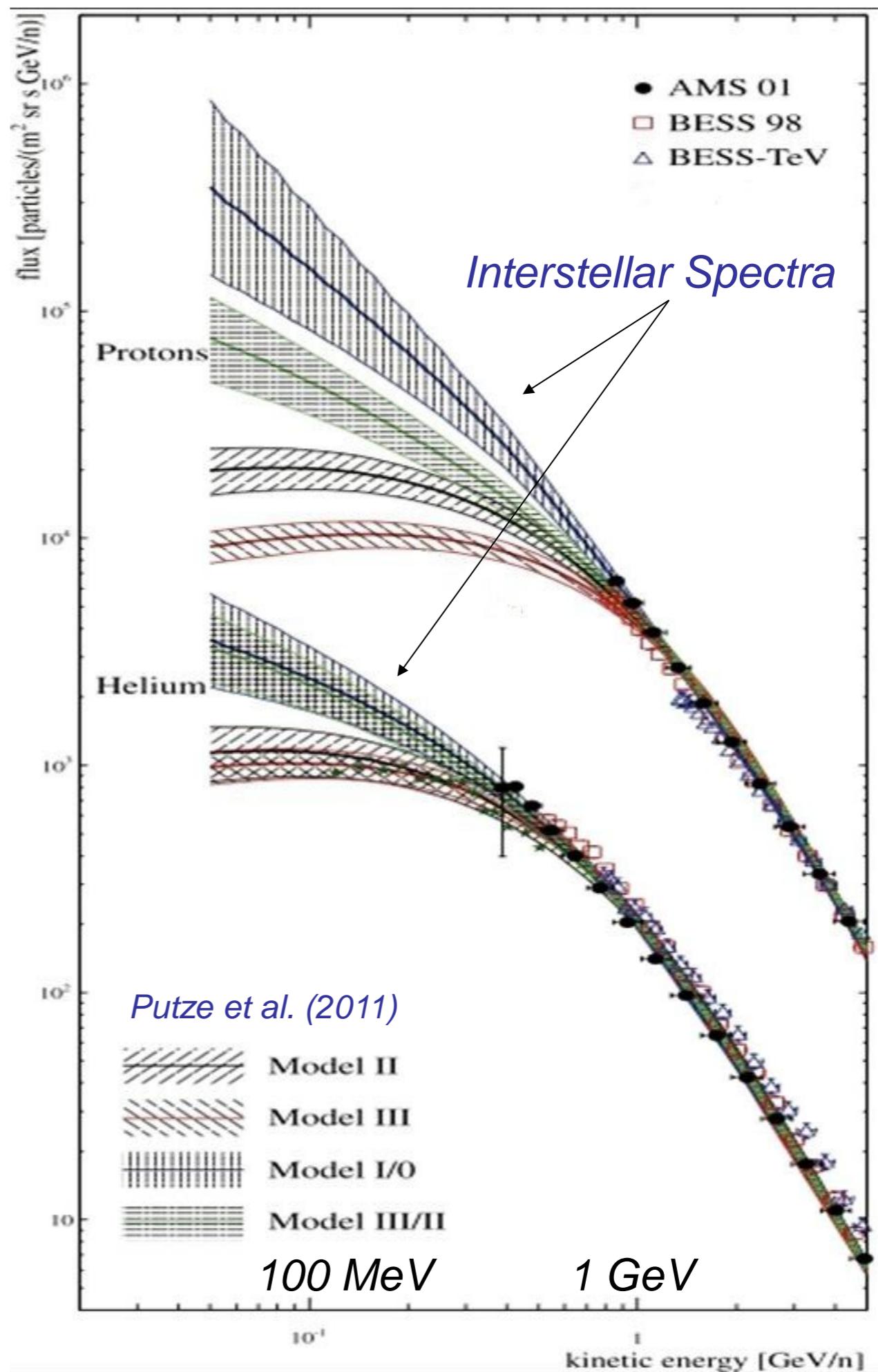
Spectrum of low-energy CR protons



The problem of demodulation



Valdès-Galicia et al. (2006)



Putze et al. (2011)

Model II

Model III

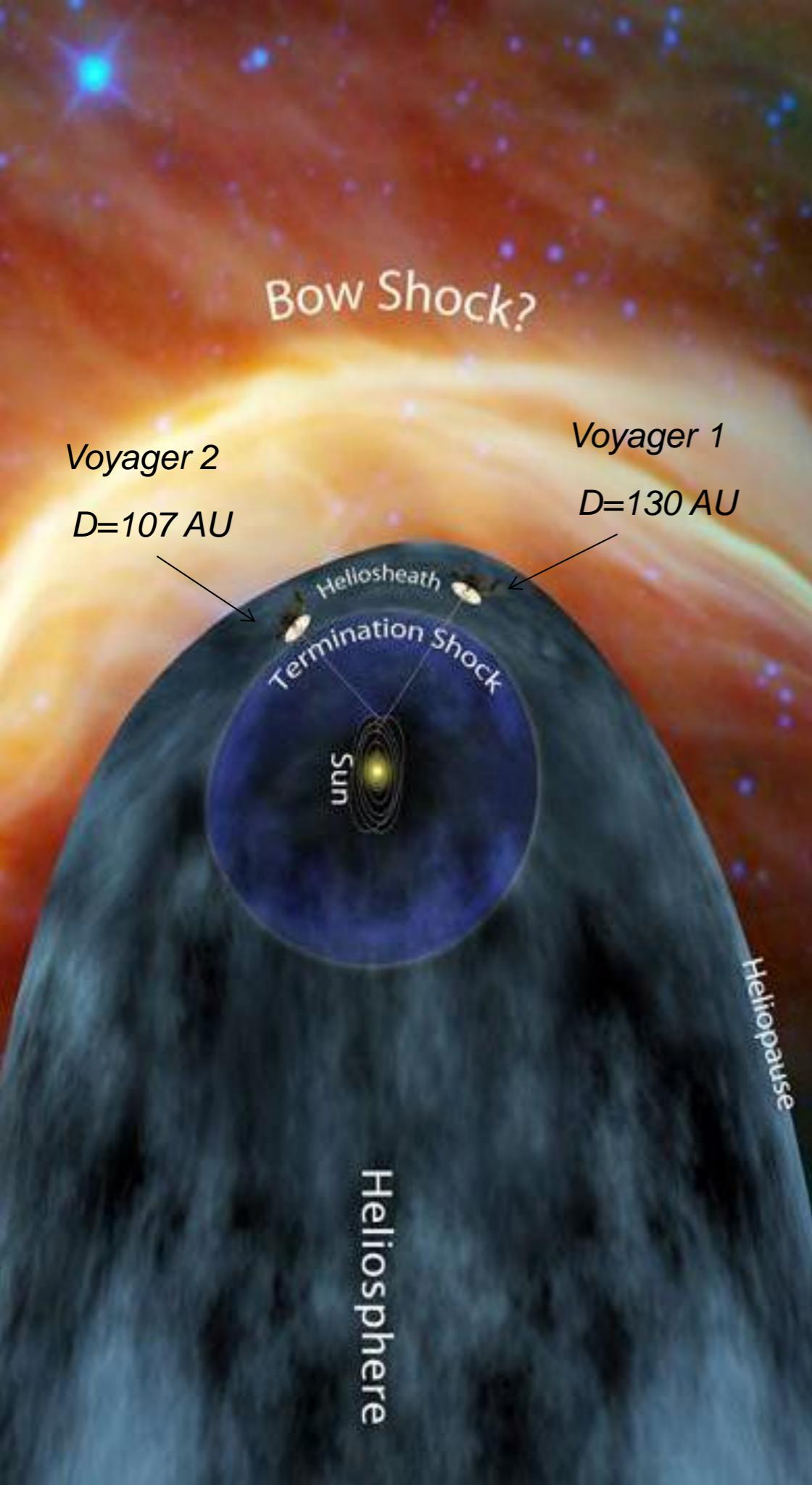
Model I/O

Model III/II

100 MeV

1 GeV

kinetic energy [GeV/nuc]



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News & Comment > News > 2013 > November > Article

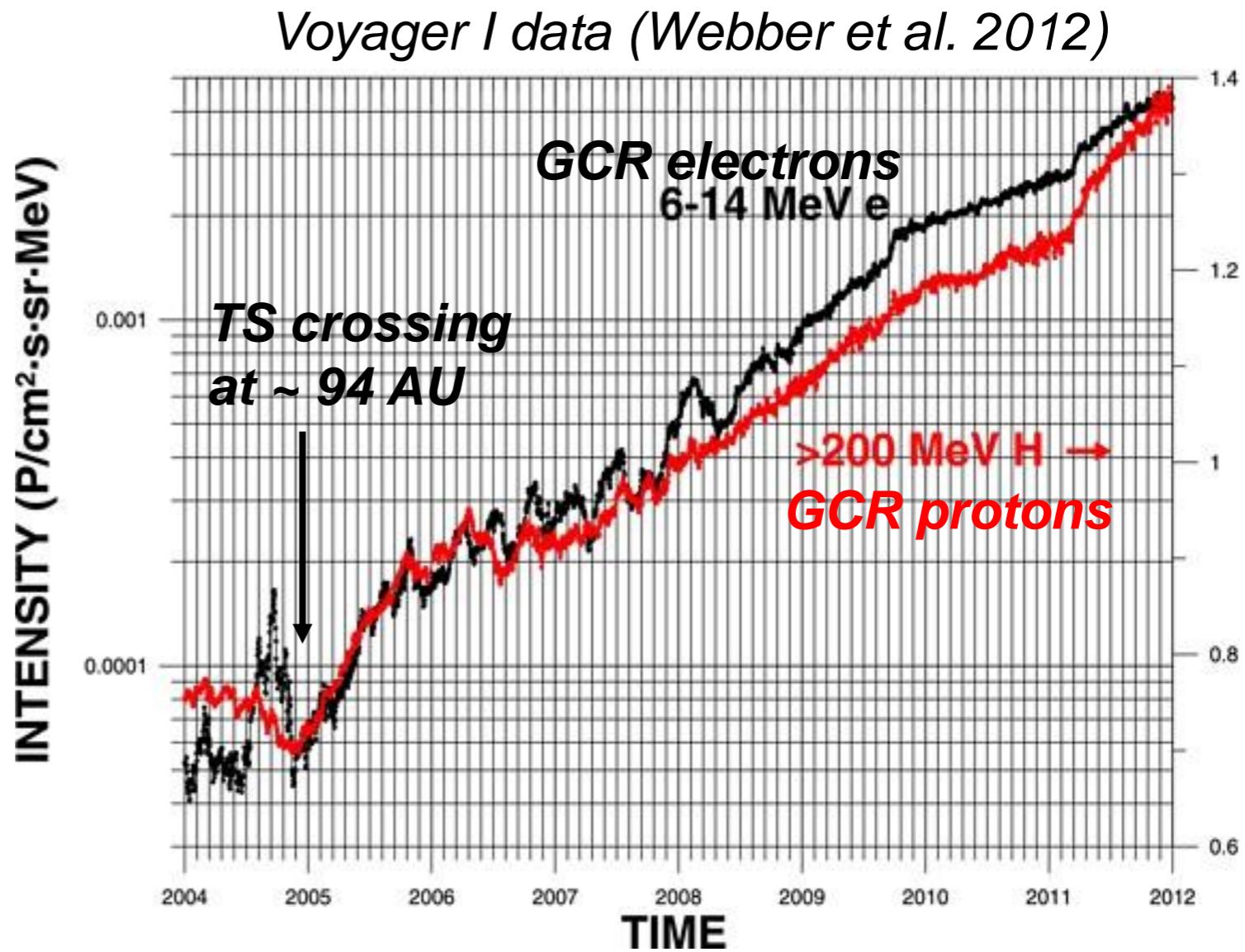
NATURE | NEWS

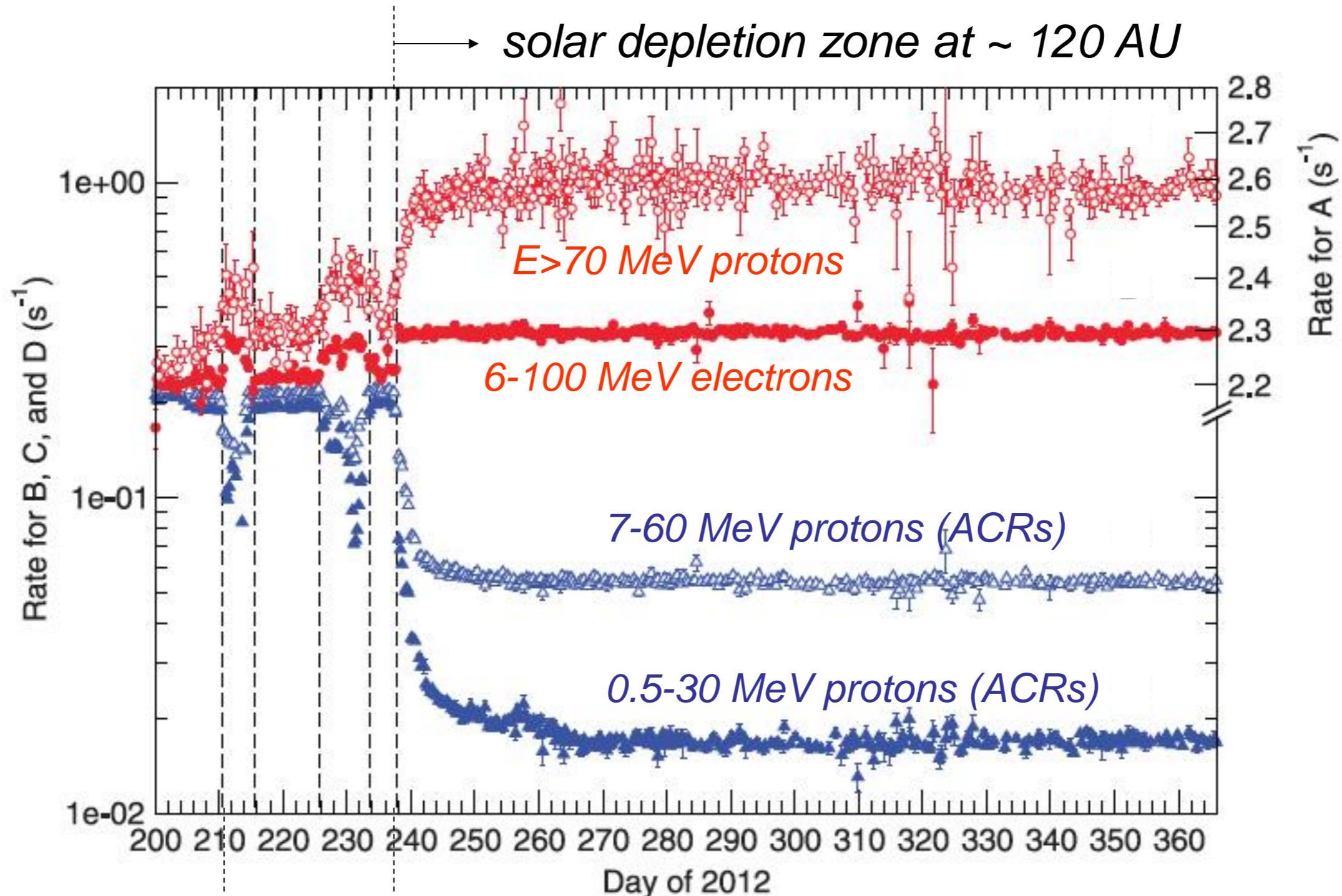
Voyager 1 has reached interstellar space

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

Ron Cowen

12 September 2013

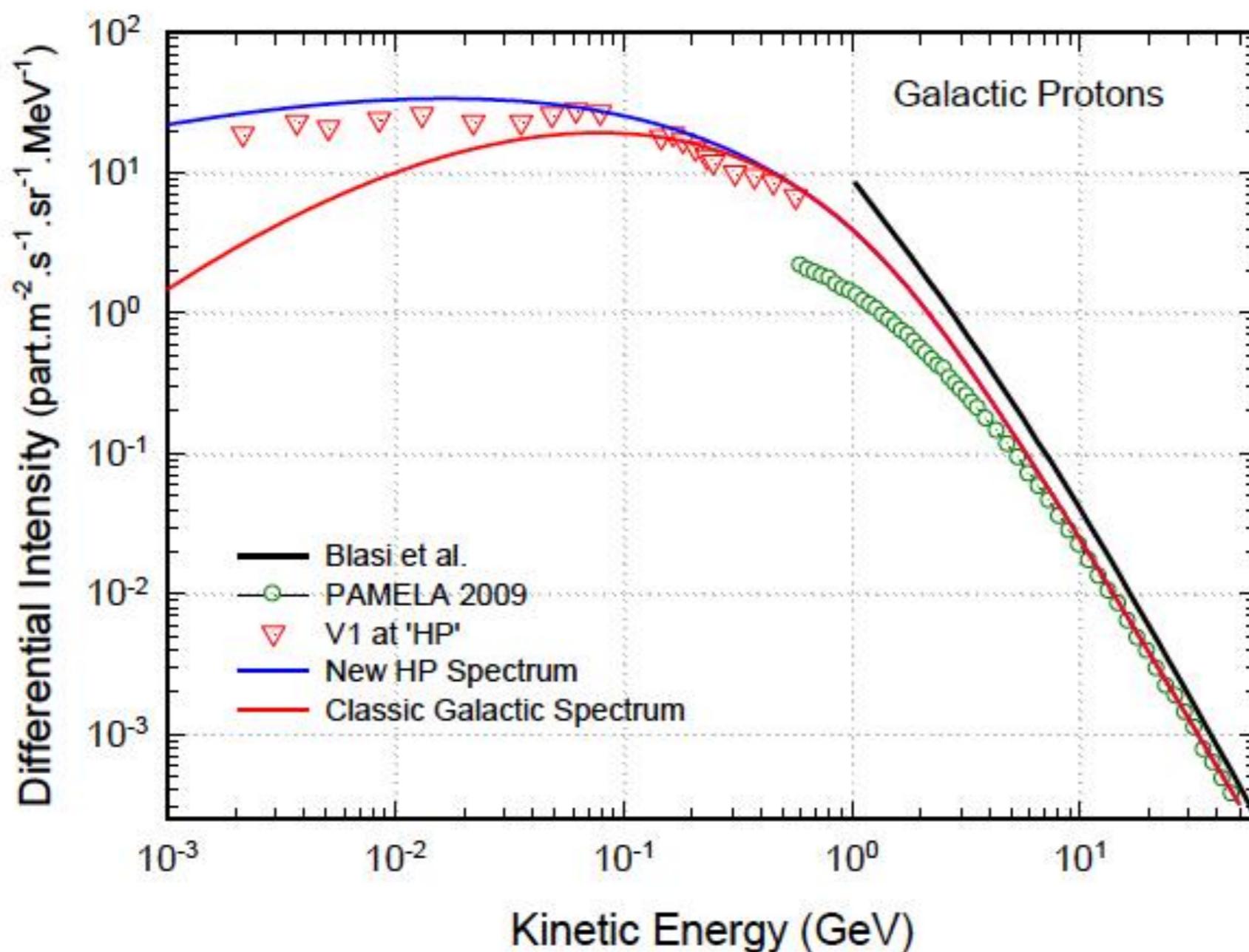




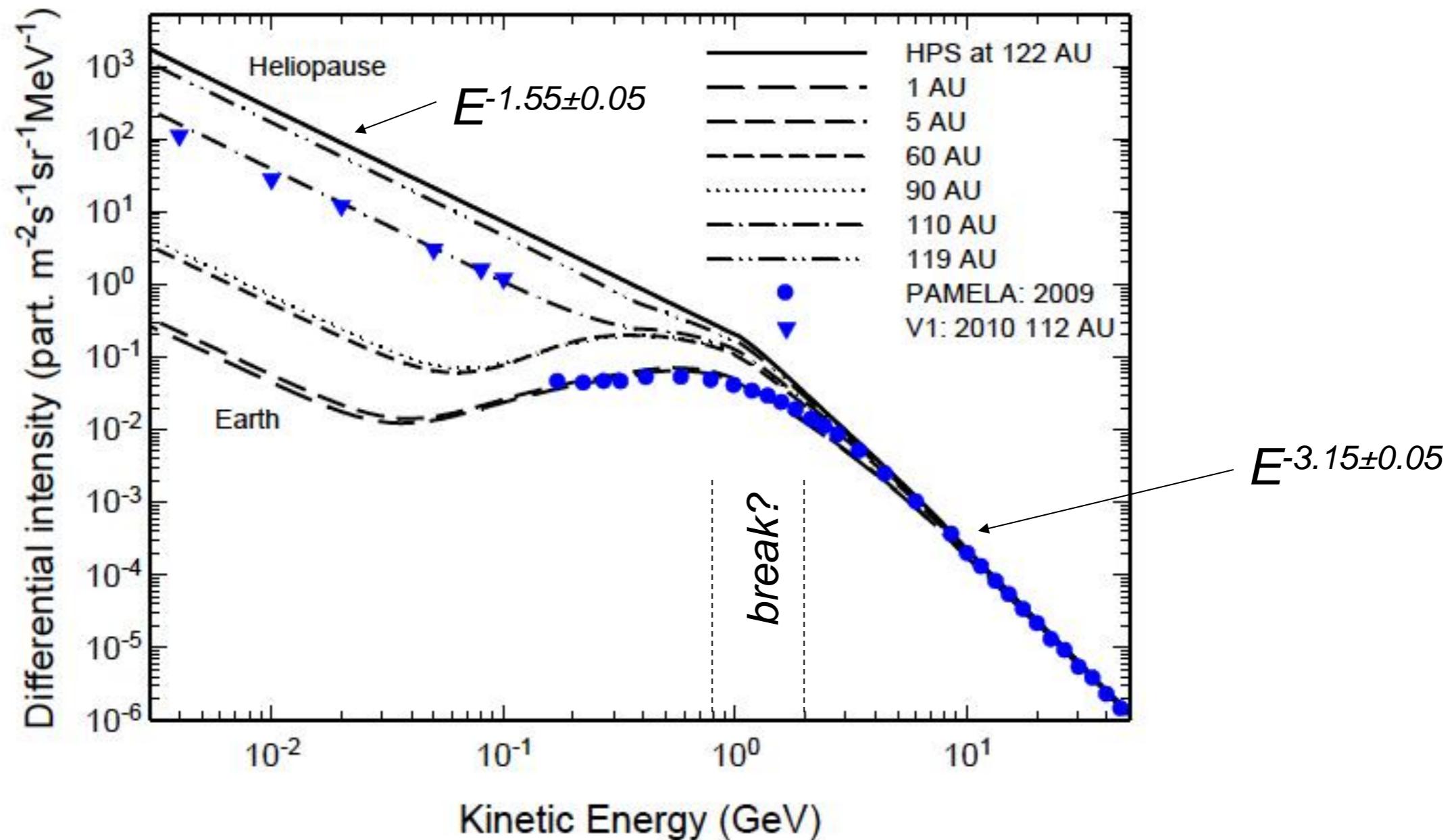
July-August 2012

Stone et al. (2012)

Voyager-1 proton spectrum



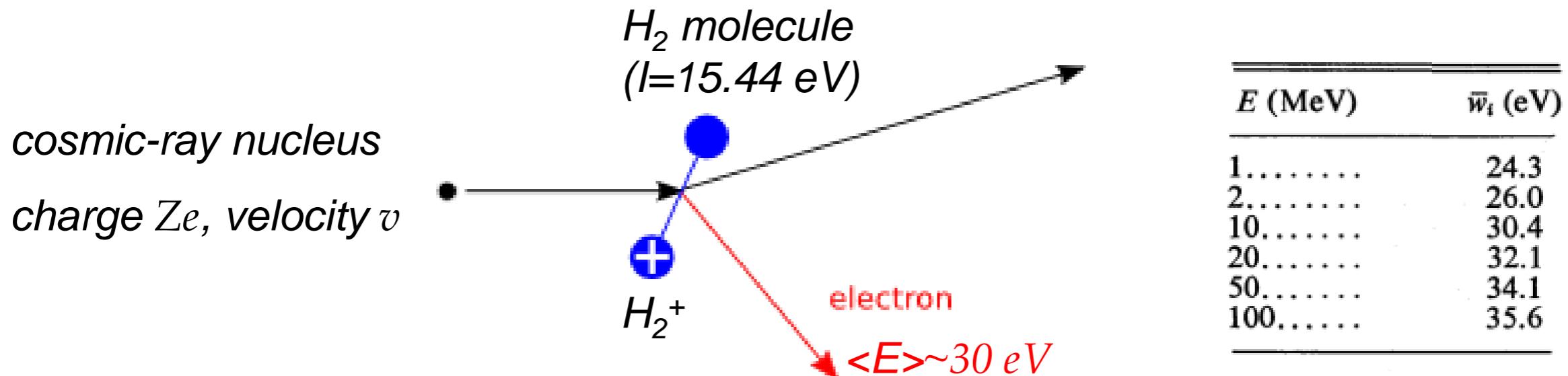
Voyager 1 electron spectrum



Warning: Voyager-1 spectra are heliopause spectra,
not Galactic spectra.

Potgieter (2013)

CR-ionization of H₂



Cravens & Dalgarno (1978)

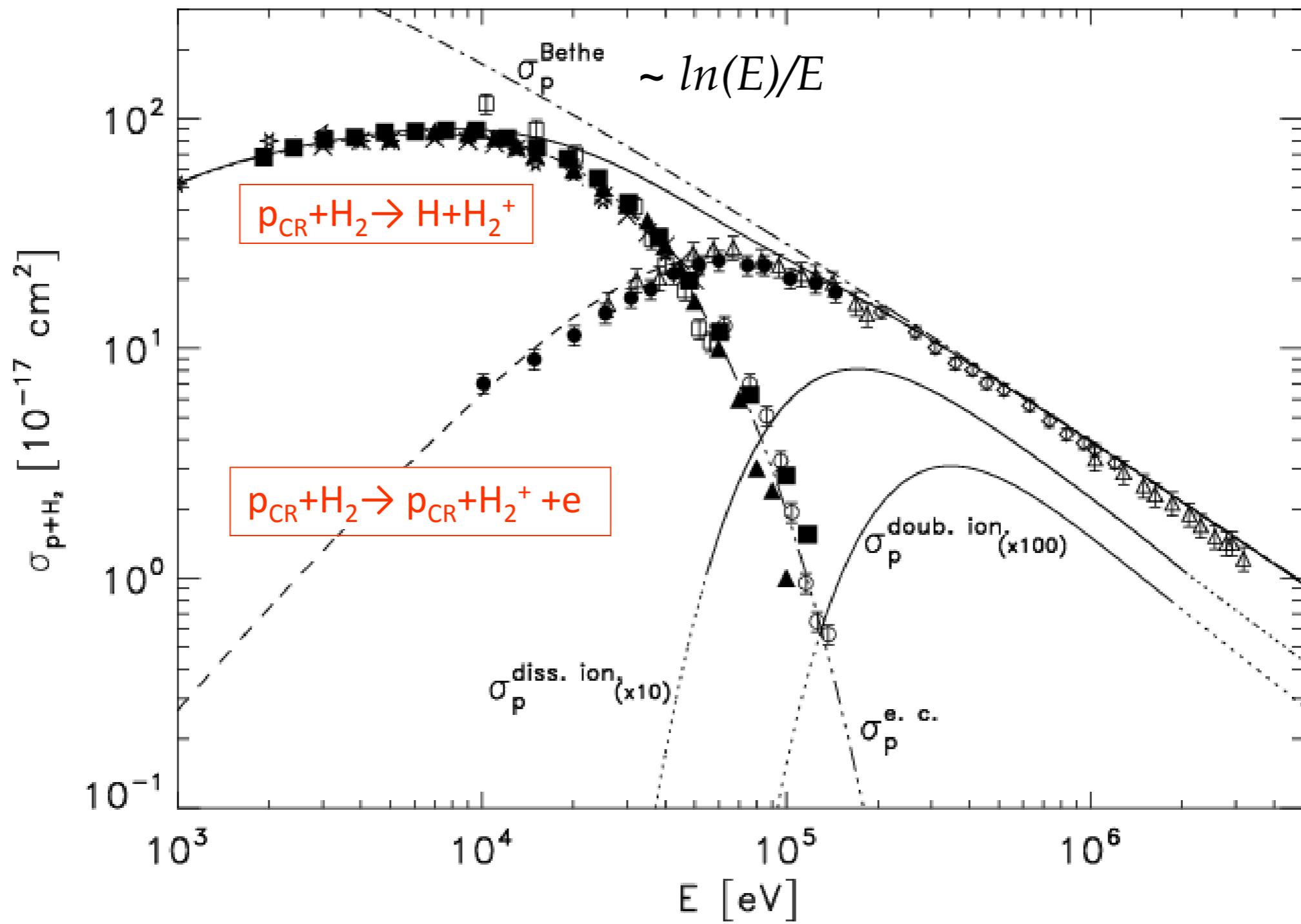
- Thomson (1912) and Bohr (1913) classical

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

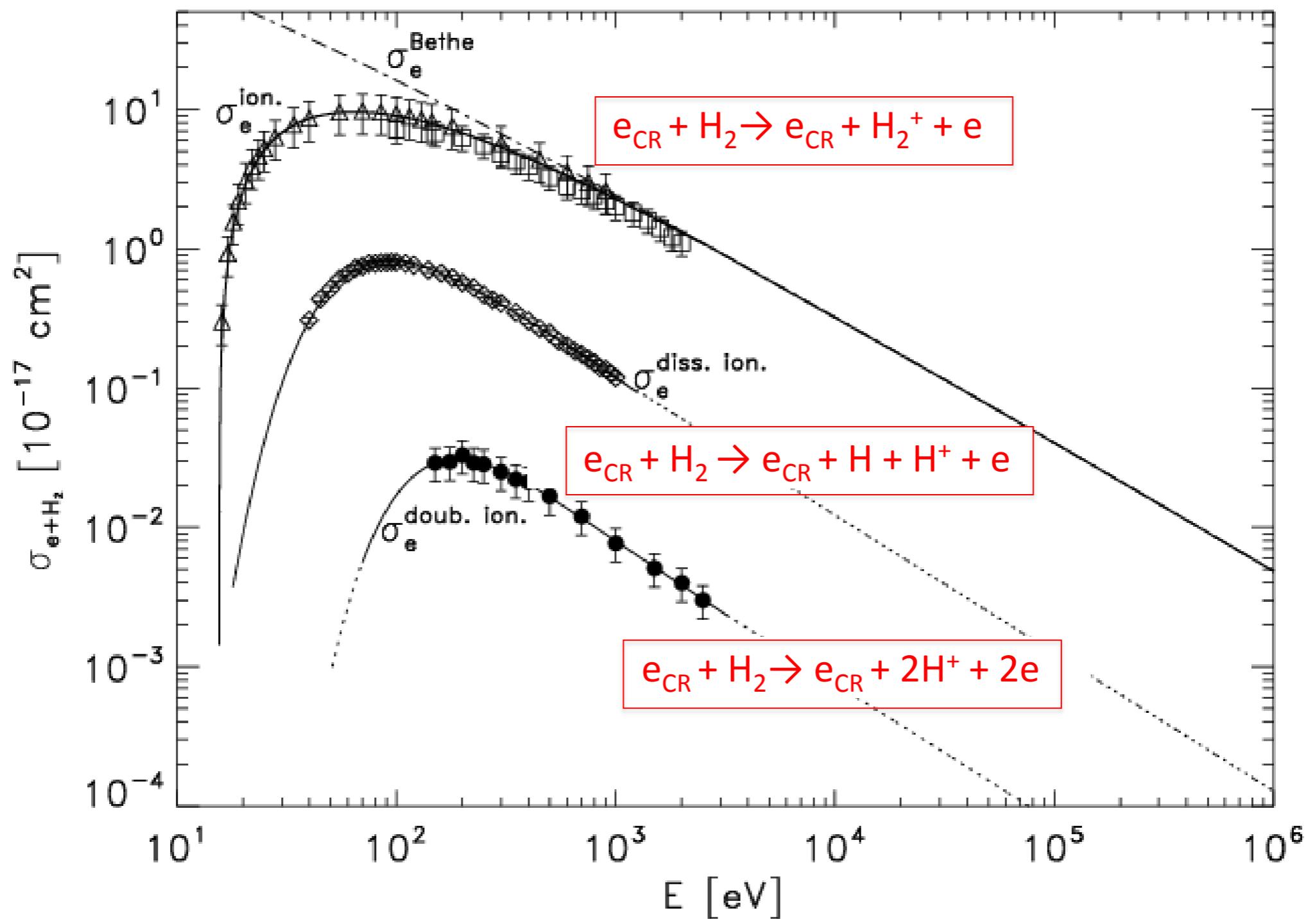
- Bethe (1930, quantistic) and Bethe (1932, quantistic relativistic)

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

Cross section $p_{\text{CR}}\text{-H}_2$

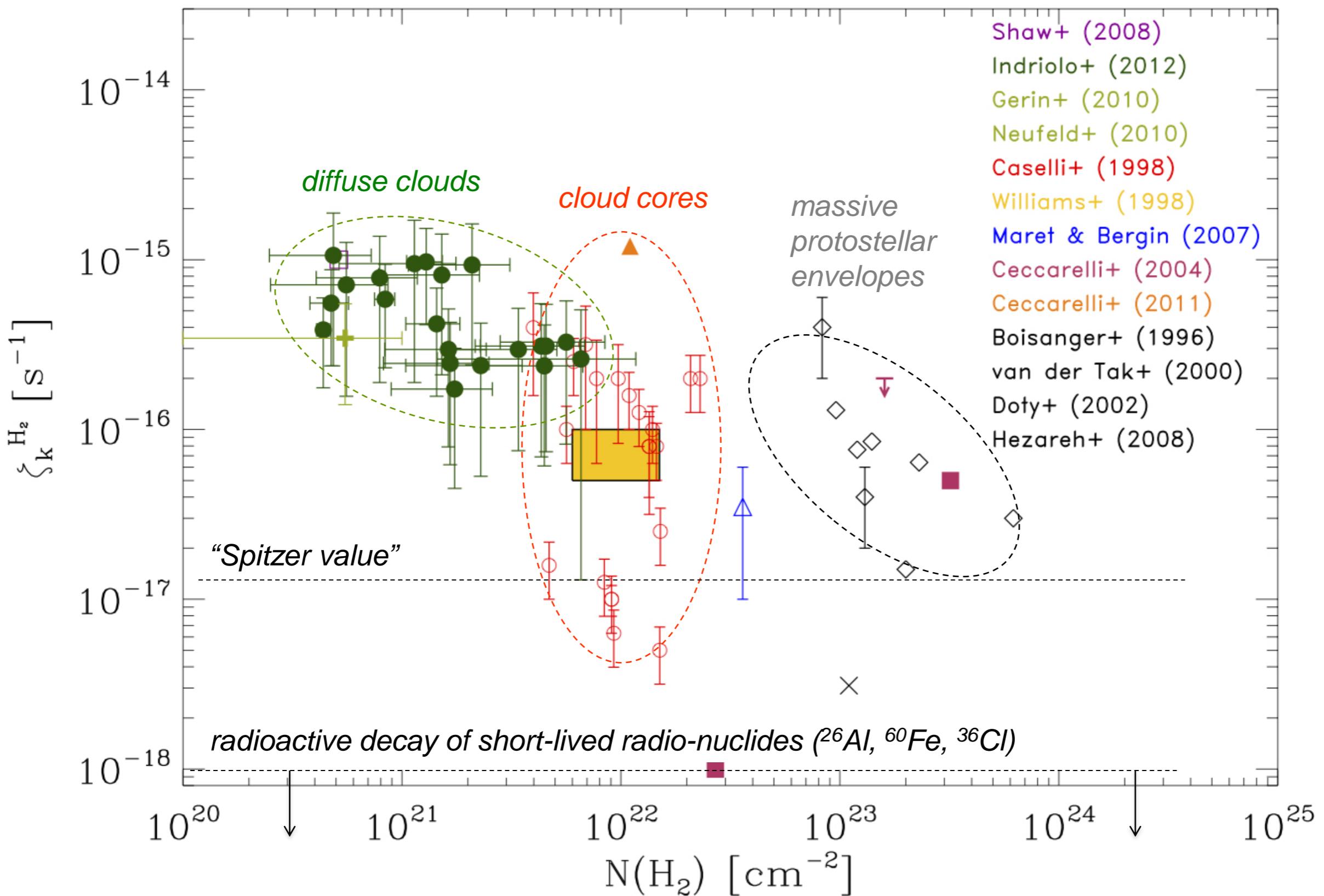


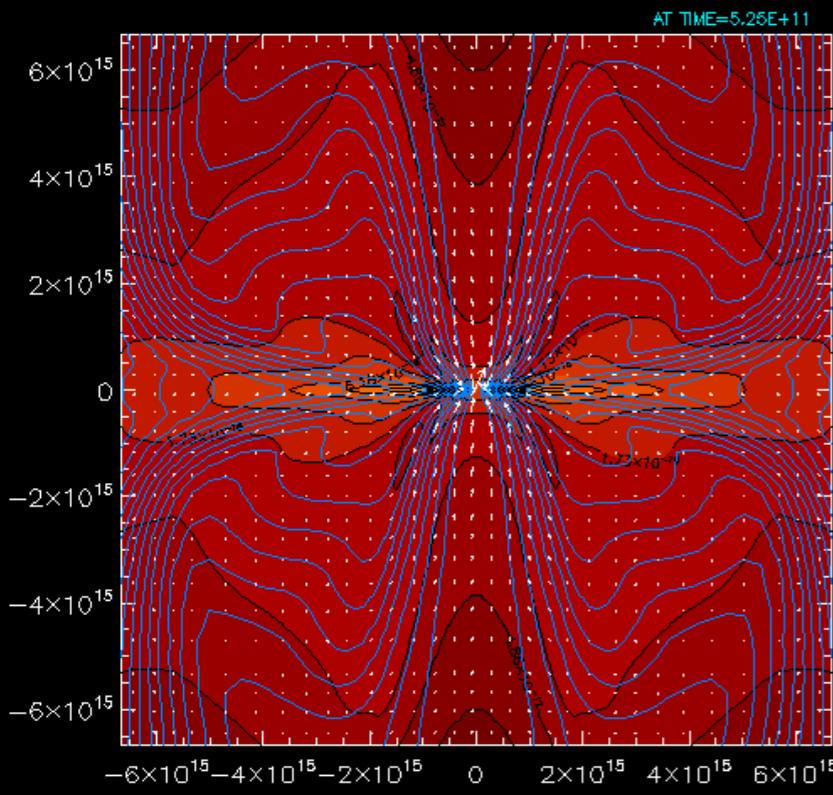
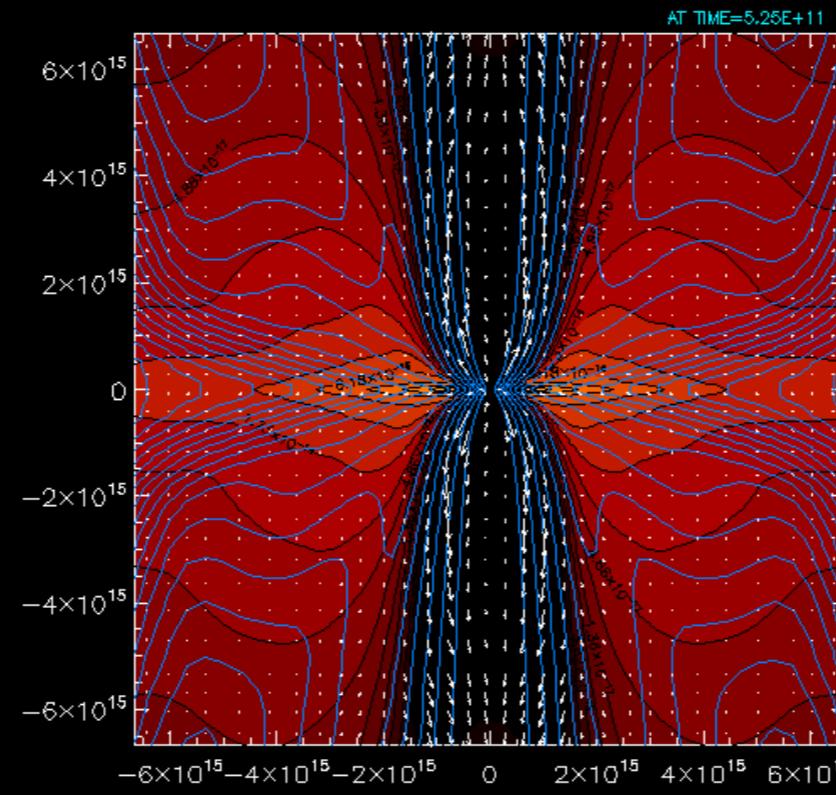
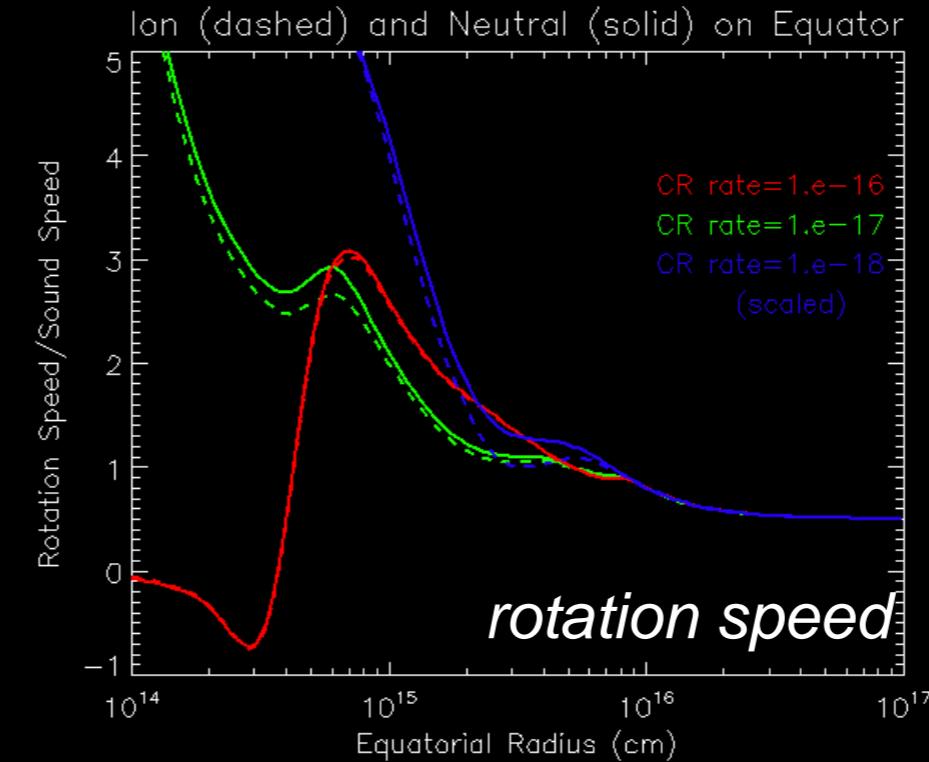
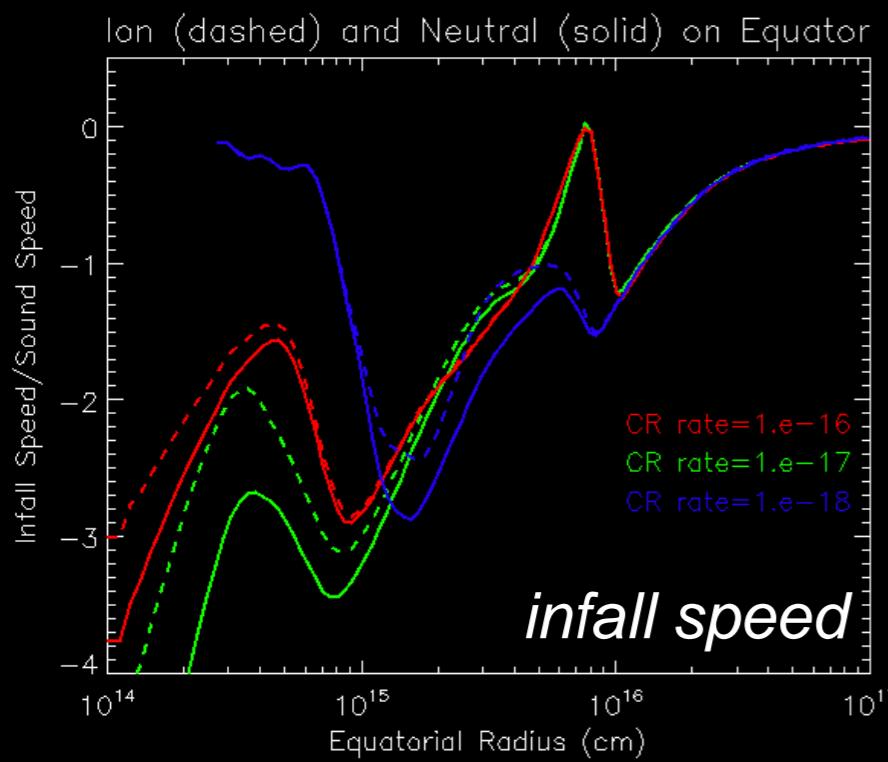
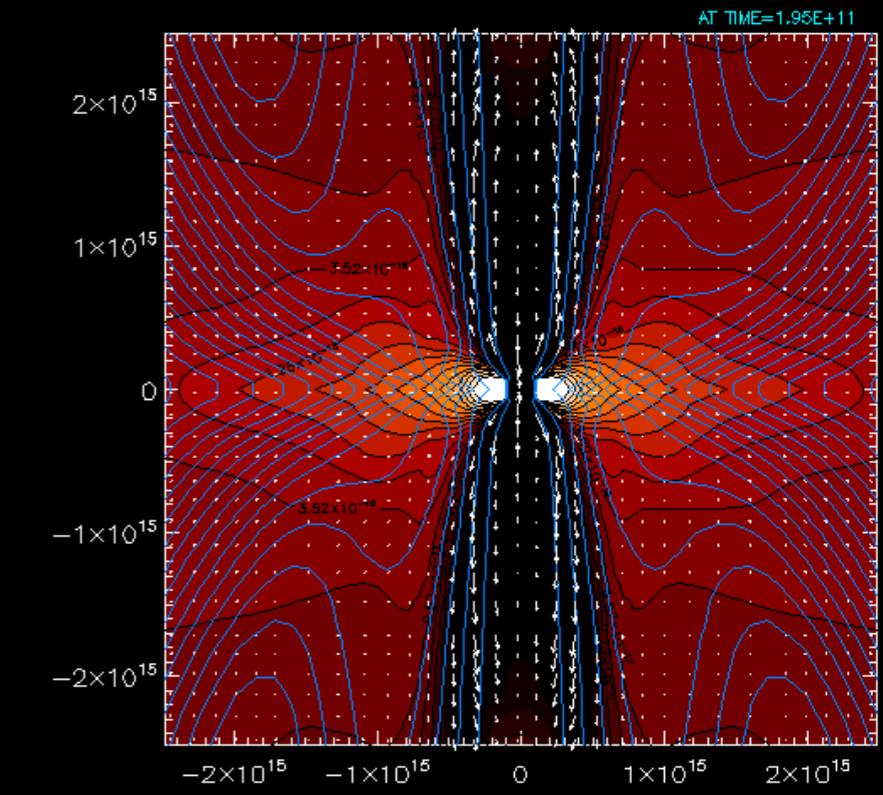
Padovani et al. (2009)



Padovani et al. (2009)

Summary of observations of ζ_{CR}



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

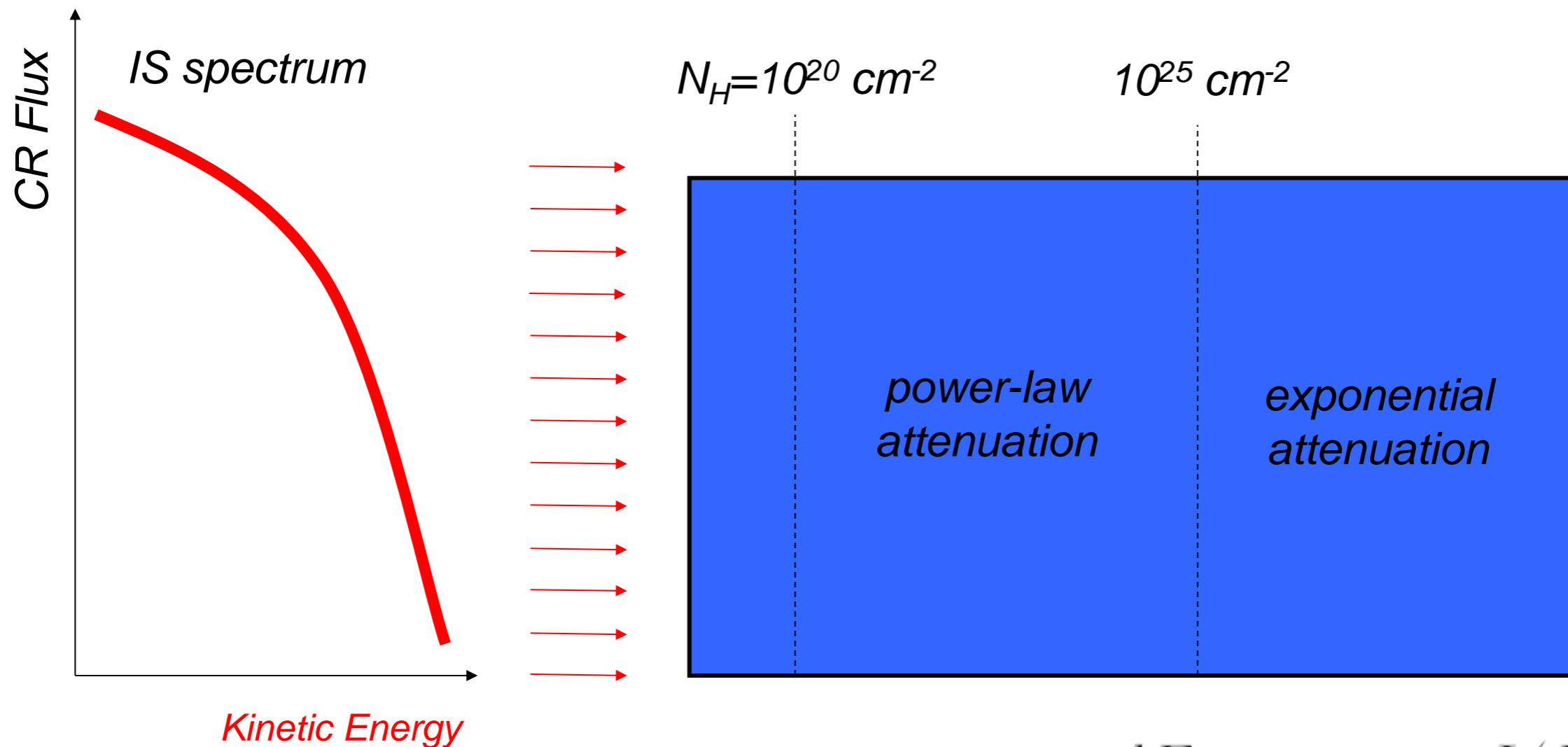
*Gravitational collapse
with ambipolar
diffusion
and variable ζ*

Mellon & Li (2009)

(see also Bo Zhao's shotgun presentation)

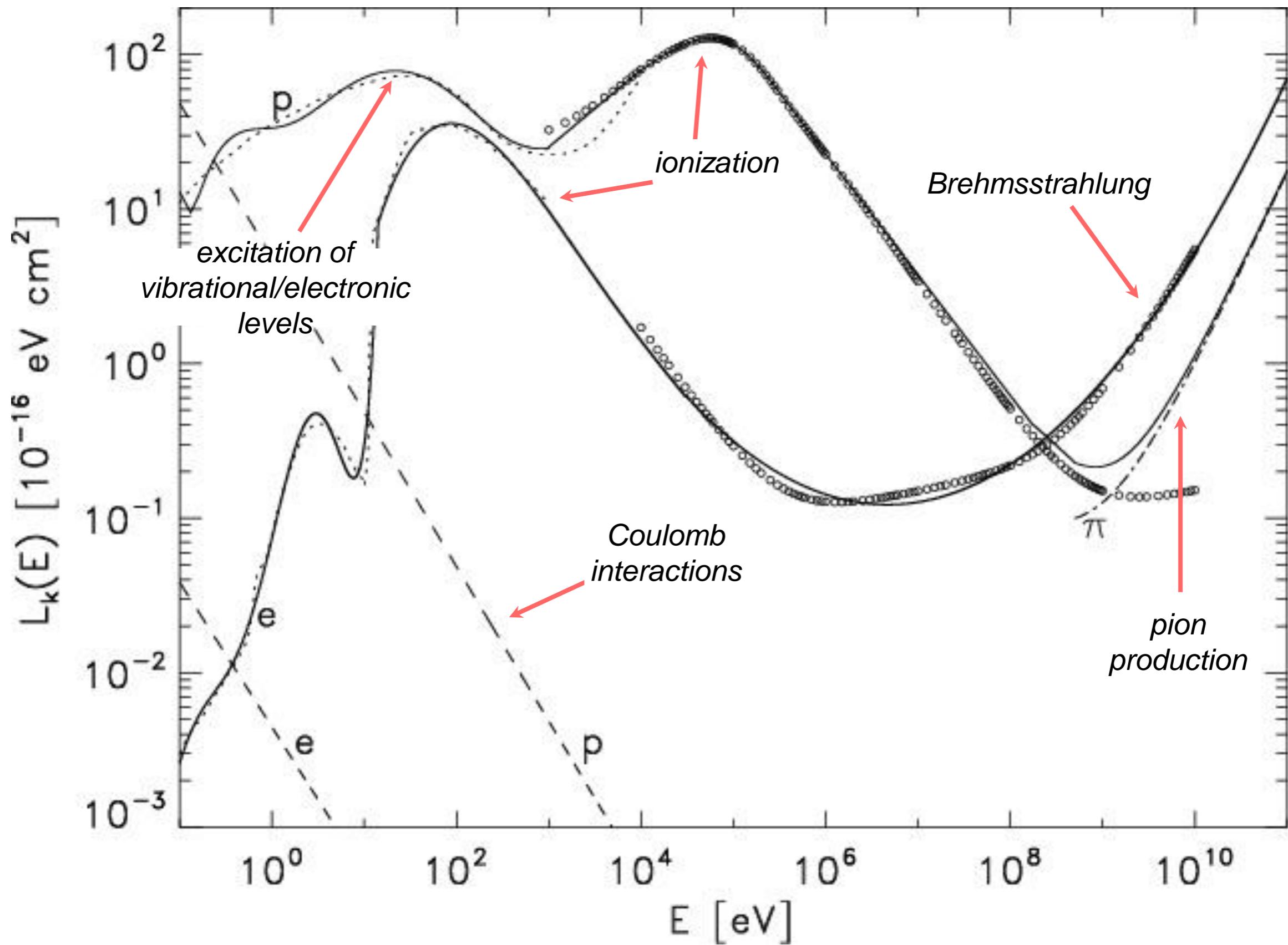
CR propagation in 1D cloud

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

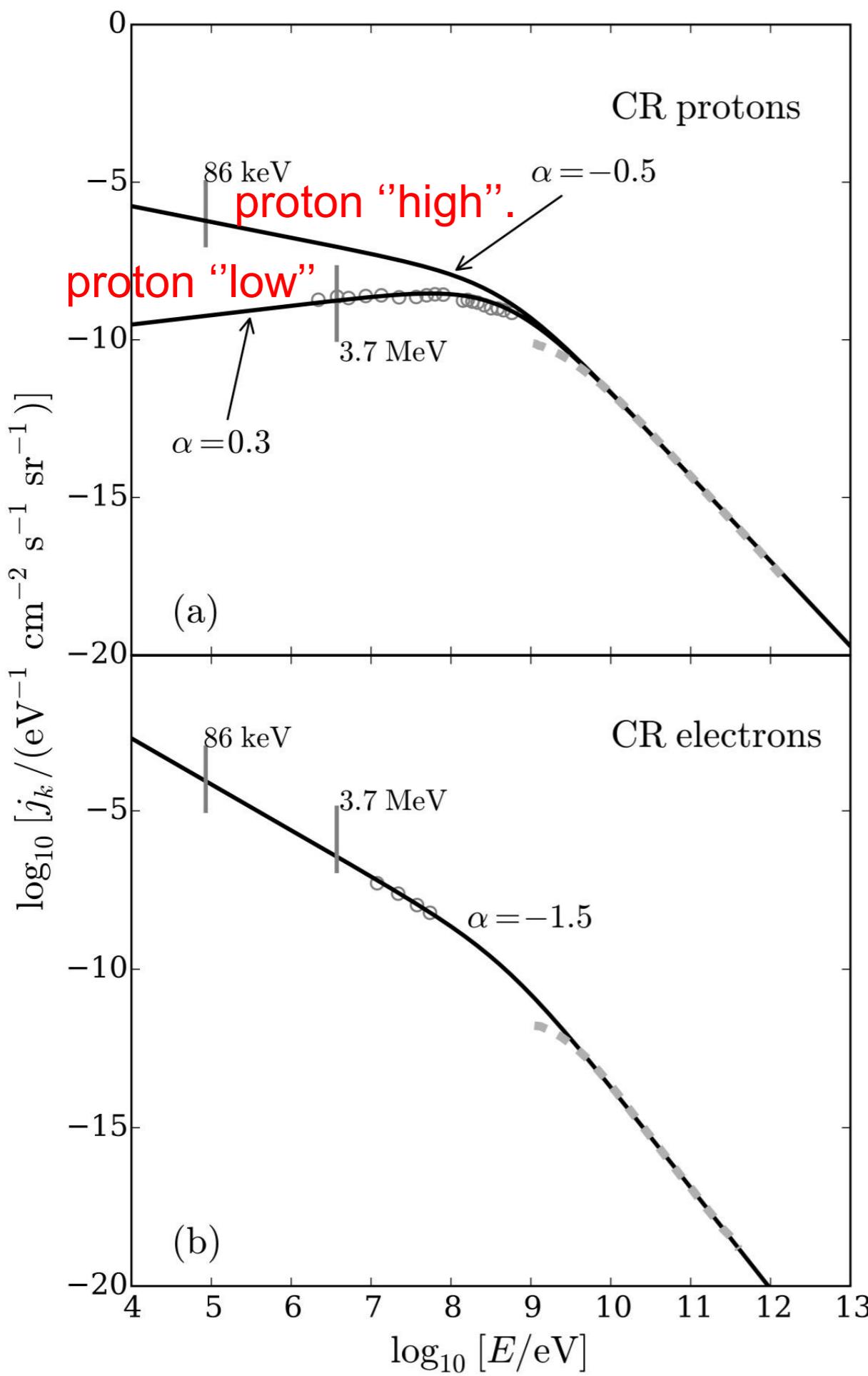


$$j(E, N) = j(E_0, 0) \frac{dE}{dE_0} = j(E_0, 0) \frac{L(E_0)}{L(E)}$$

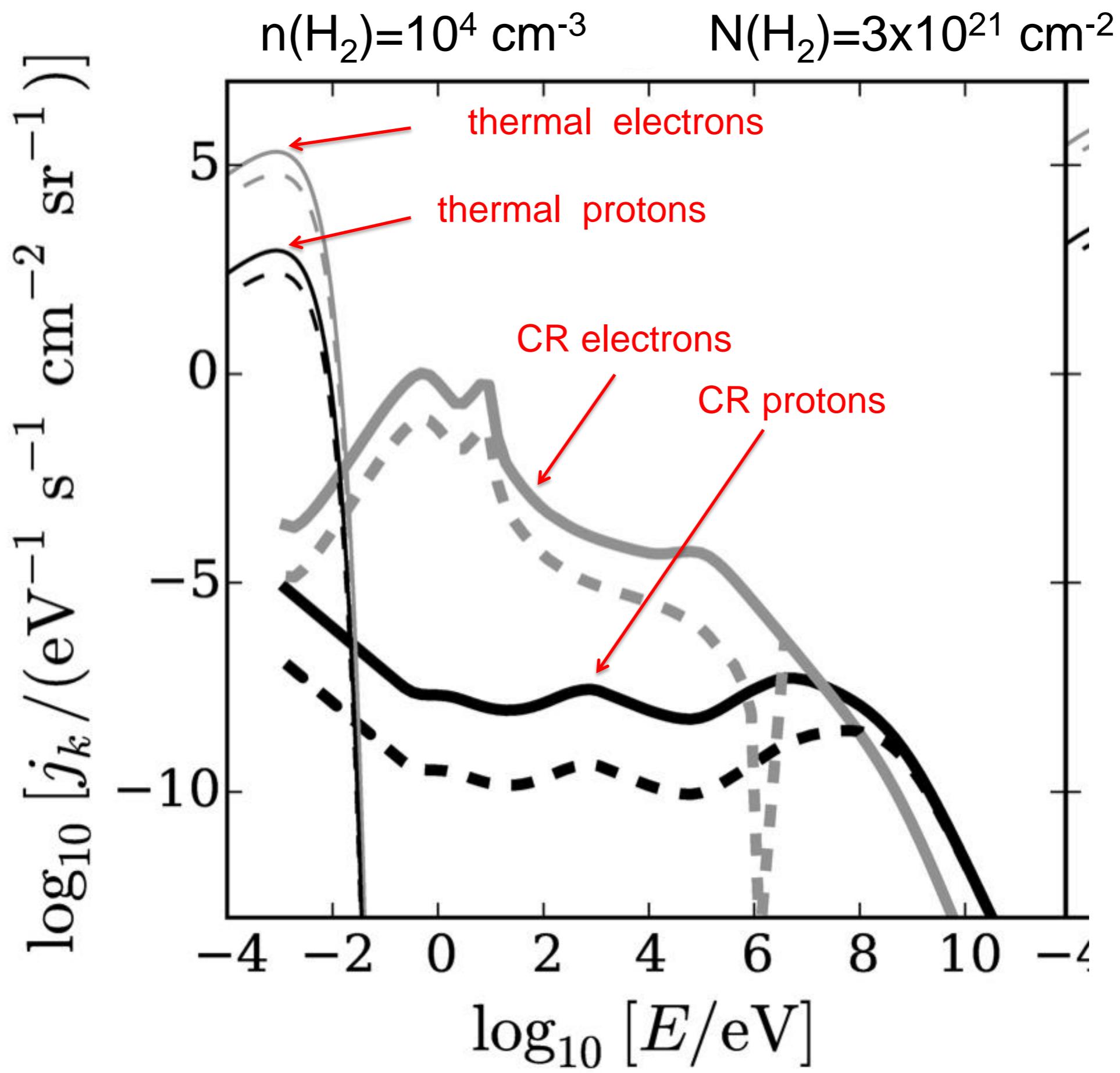
Energy losses of CR–protons and electrons in H₂



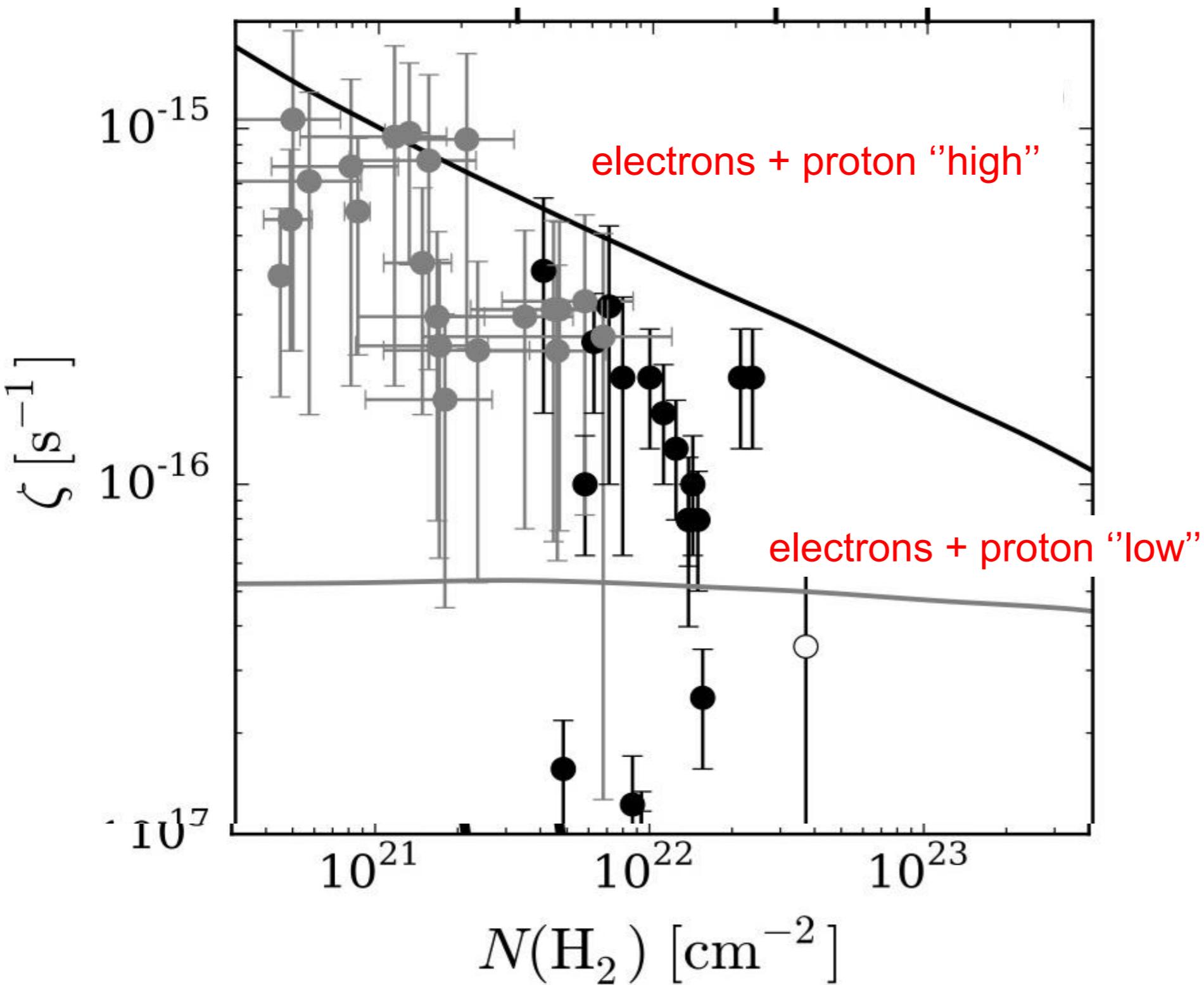
Cosmic –ray interstellar spectra



Ivlev, Padovani, Galli
& Caselli (2015)



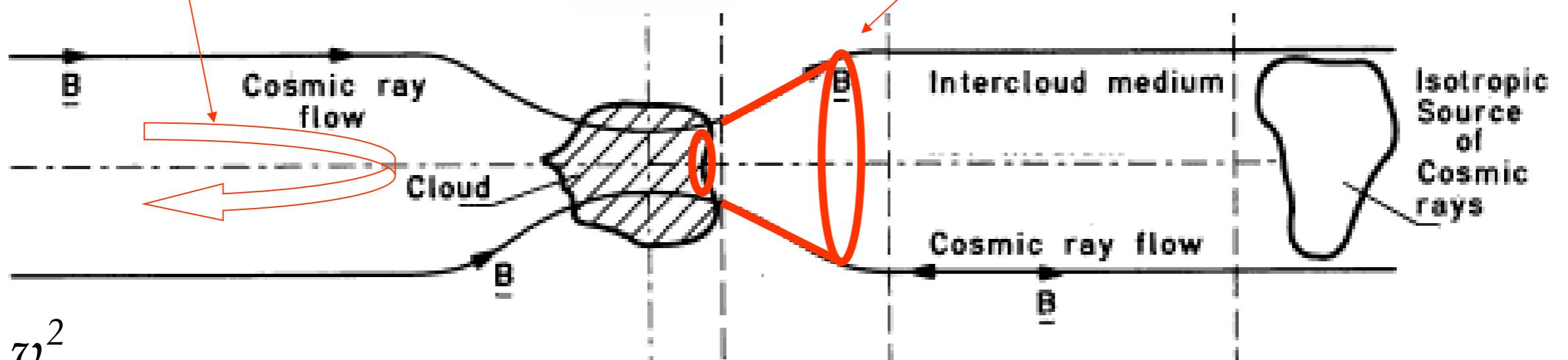
Cosmic-ray ionization rate ζ



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



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

$$v_{\perp}^2 + v_{\parallel}^2 = \text{const.}$$

Cesarsky & Volk (1978)

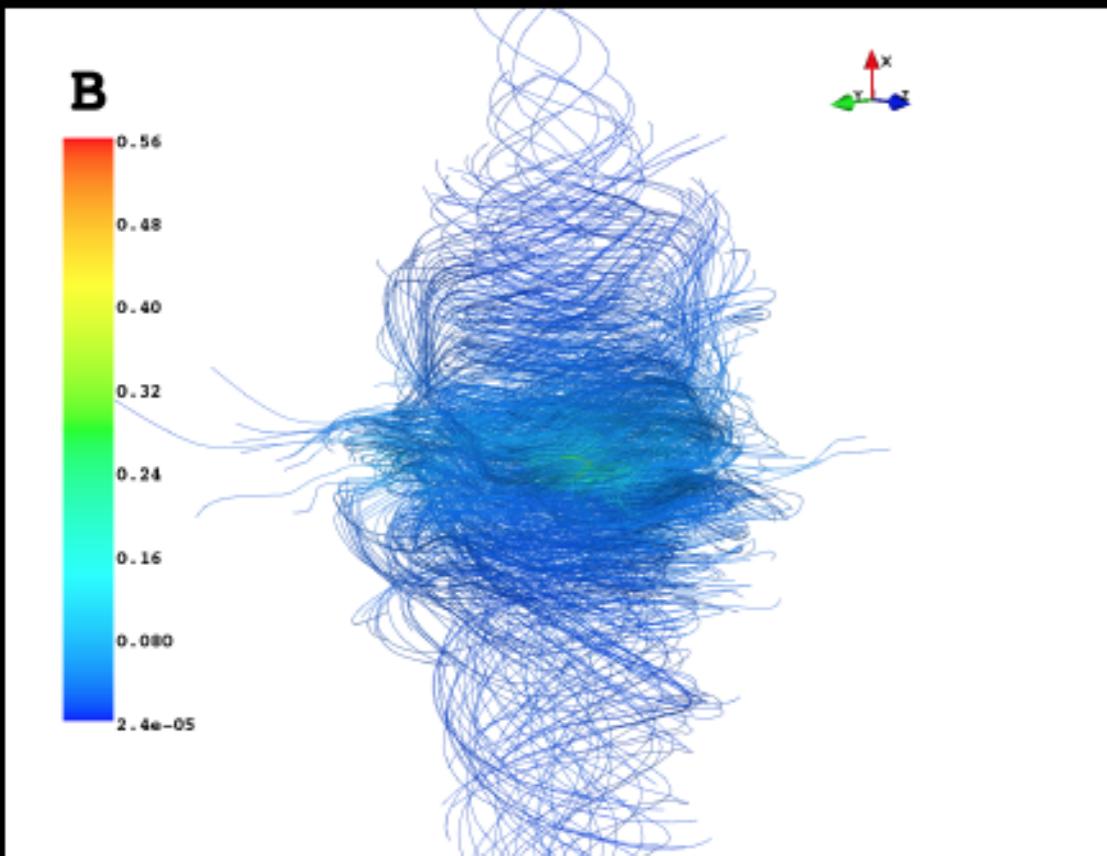
Numerical models : rotating collapsing core

Weak magnetisation $\lambda=17$

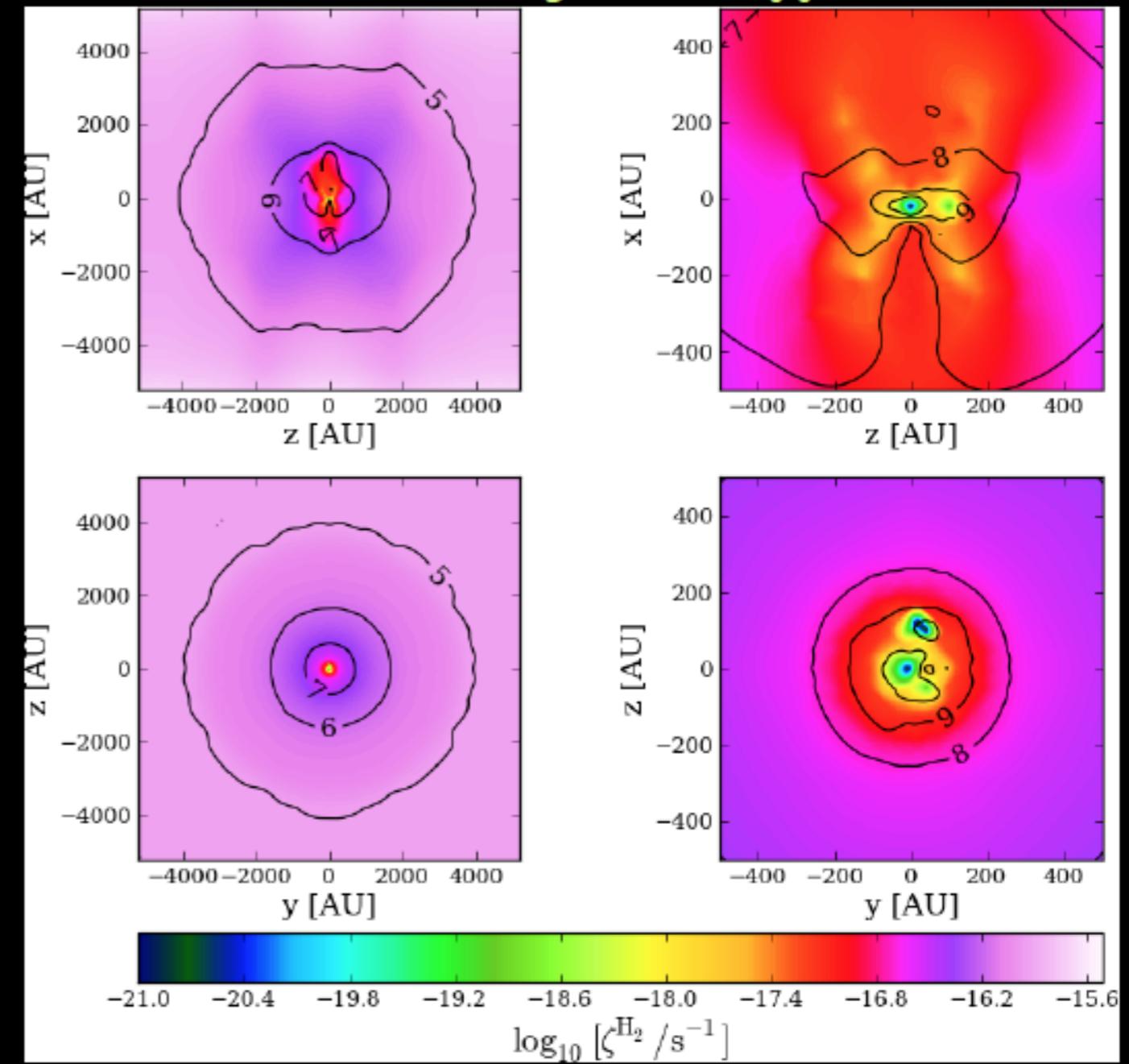
Aligned rotator (\mathbf{J}, \mathbf{B})=0

The magnetic braking is very faint and the rotation acts in wrapping powerfully the field lines. The region with $\zeta_{\text{CR}} < 10^{-18} \text{ s}^{-1}$ broadens out along the rotation axis where field line tangling up is very marked.

Field lines in the inner 600 AU



without magnetic effects



Padovani+ 2013

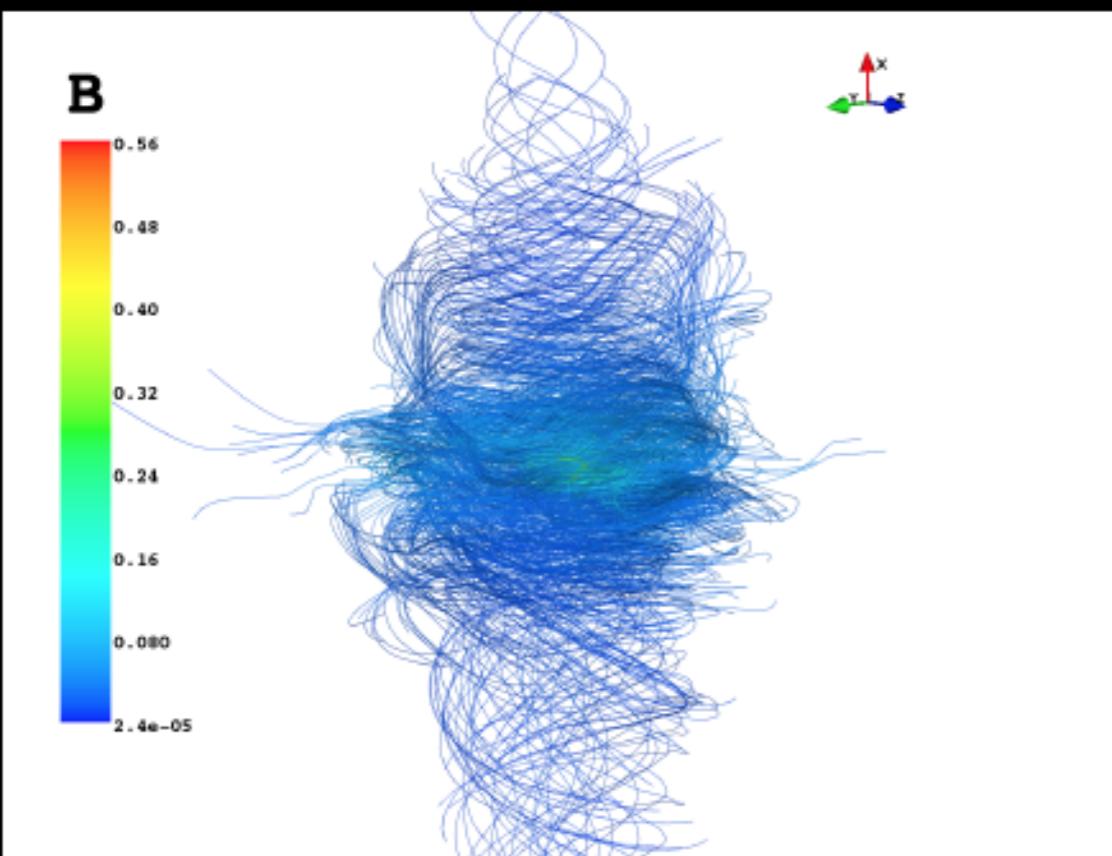
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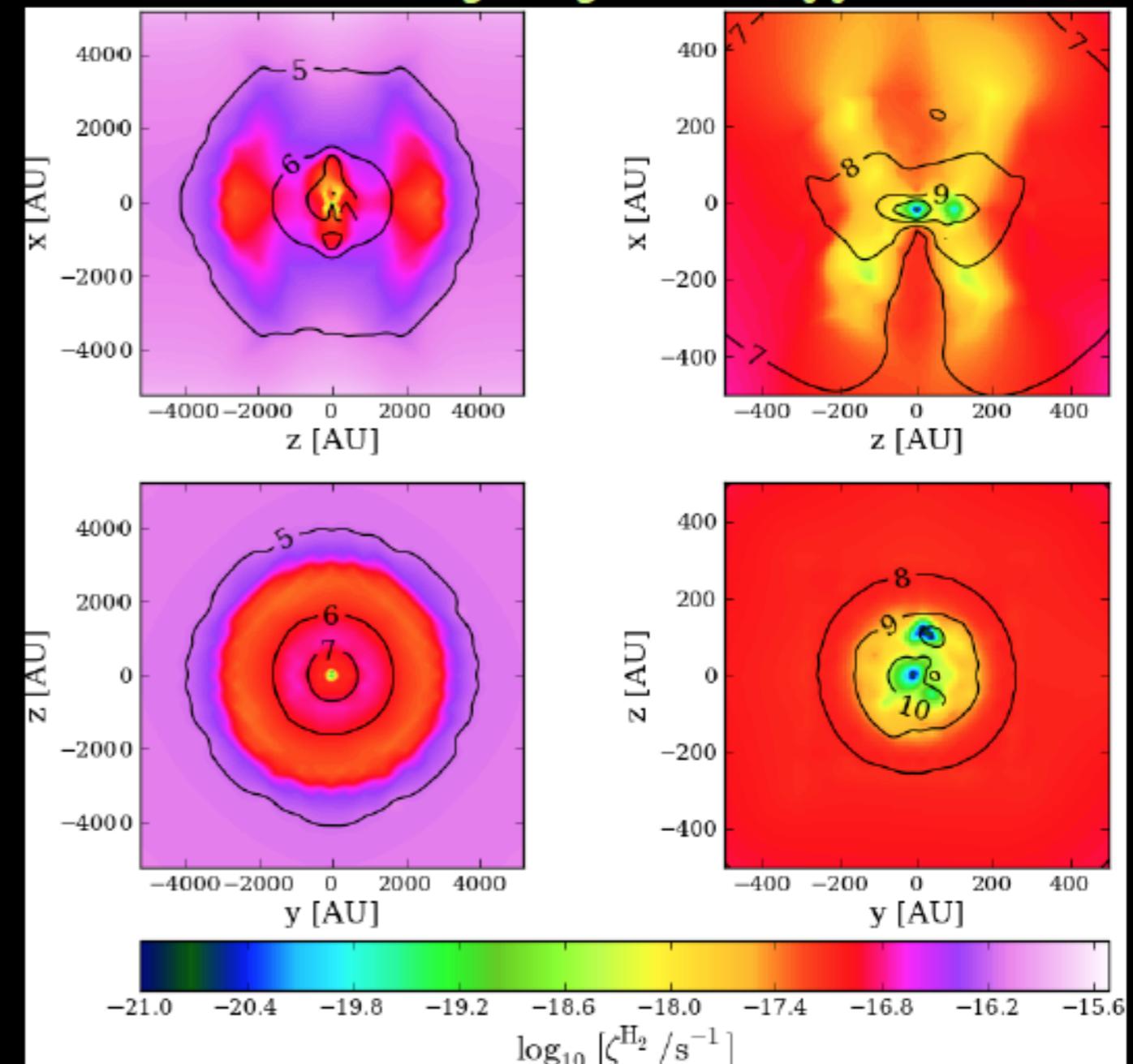
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Field lines in the inner 600 AU



including magnetic effects



Padovani+ 2013

Cosmic-ray heating

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

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

where n is the density and

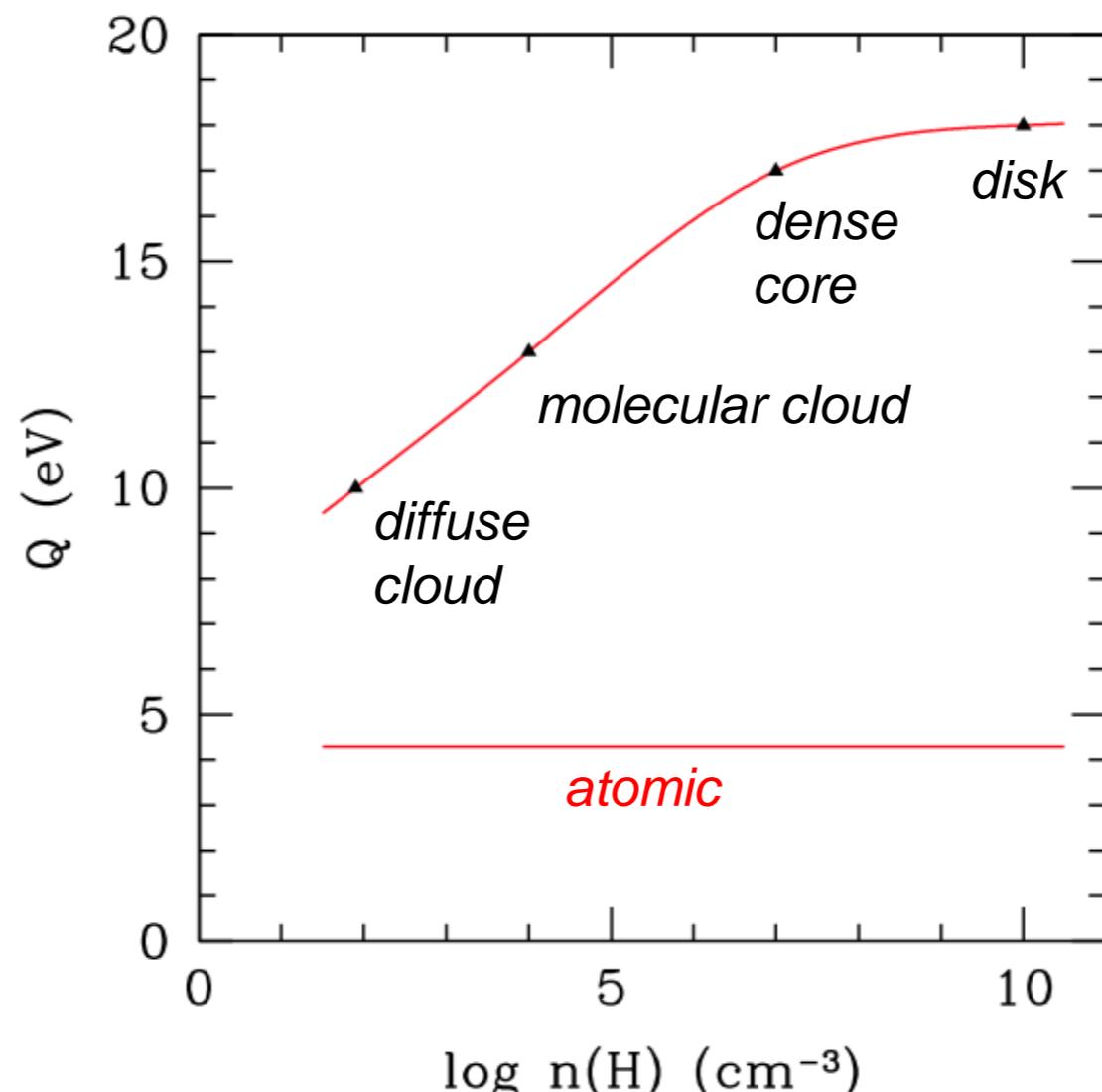
$$\zeta = \int (1 + \phi) j(E) \sigma_{\text{ion}} dE \text{ is the CR ionization rate (in s}^{-1}\text{)}$$

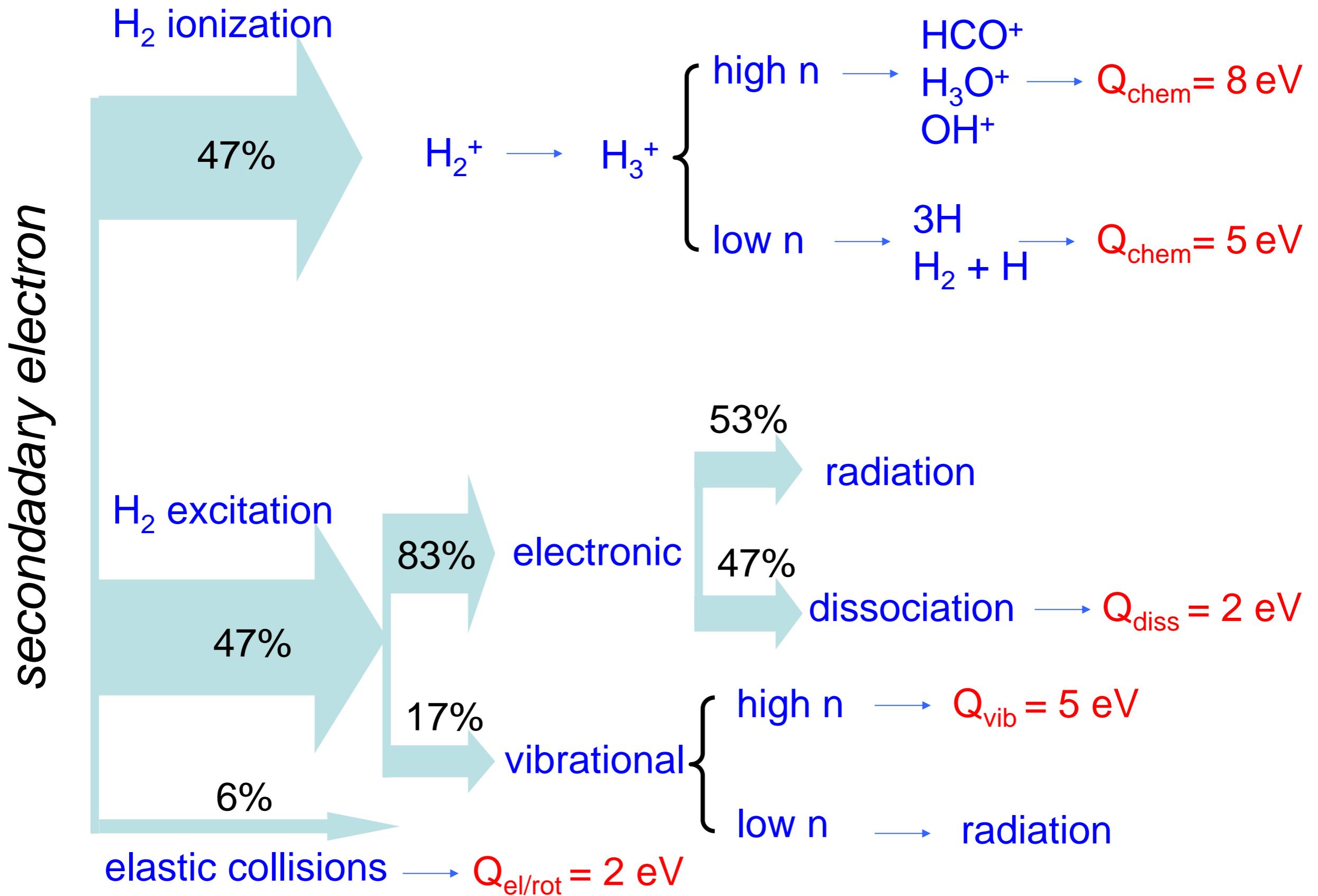
Q = average energy deposited as heat per ionization (in eV)

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)	$\simeq 60$	10	6	1000
x_e	2×10^{-4}	10^{-7}	10^{-9}	10^{-6}
H $_3^+$ destruction	DR ^a	DR + I ²	DR + I	DR + I
$Q_{\text{el/rot}}$ (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

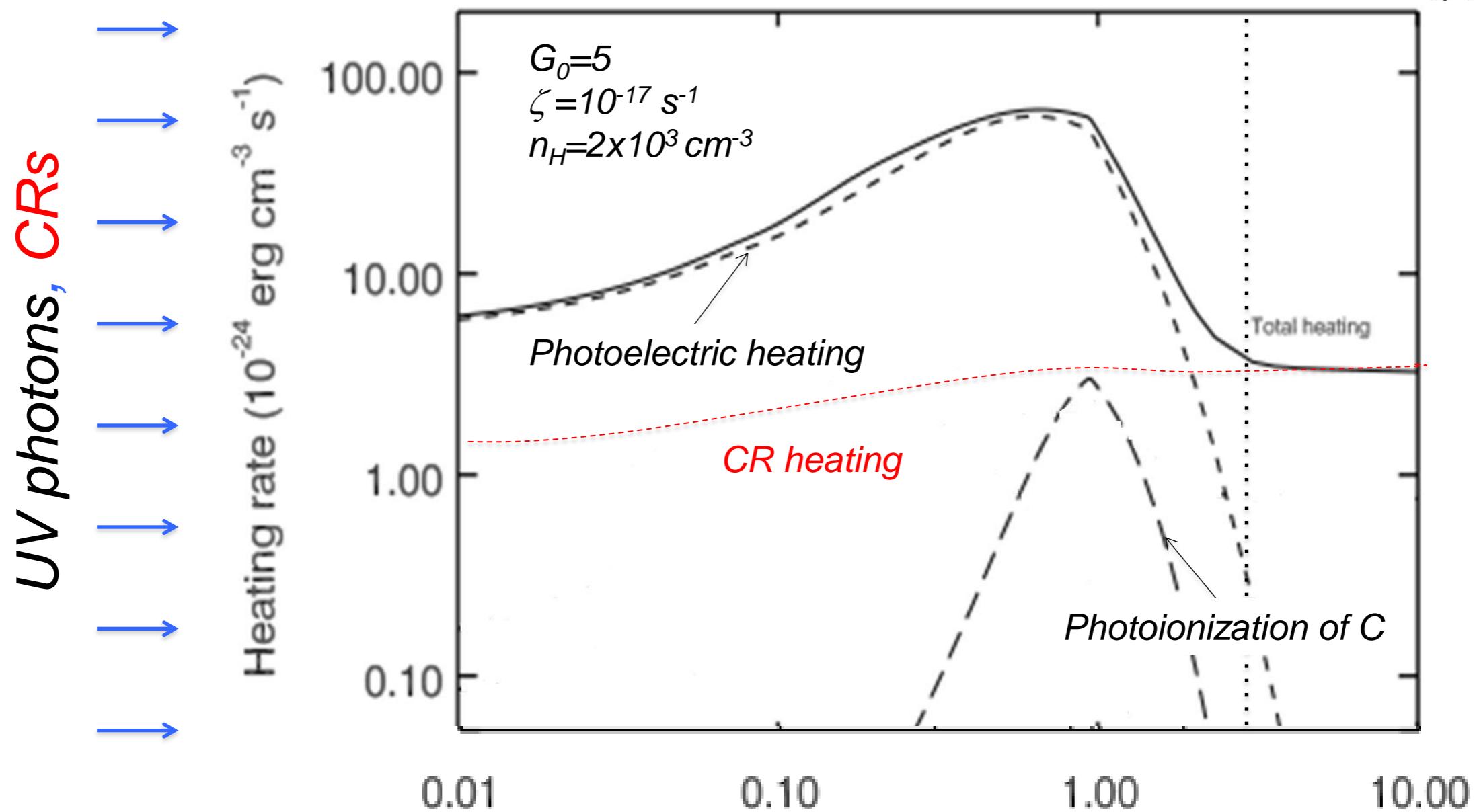
Note. ^a DR stands for dissociative recombination and I for ionic reactions.





UV photons vs. CRs

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



PDR model from Habart et al. (2001)

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

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})

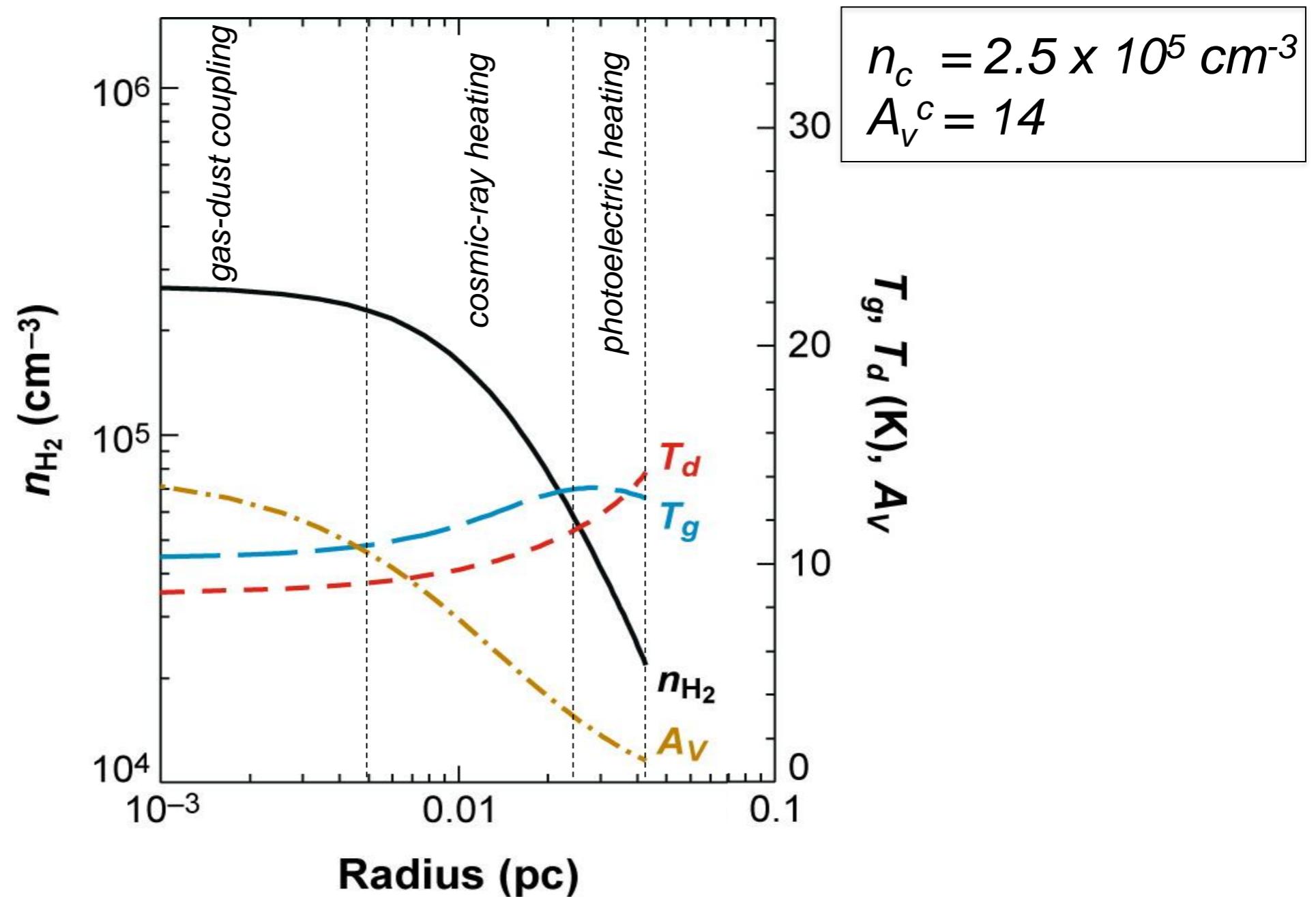
$$\Gamma_{CR} - \Lambda_{gas} - \Lambda_{gd} = 0$$

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

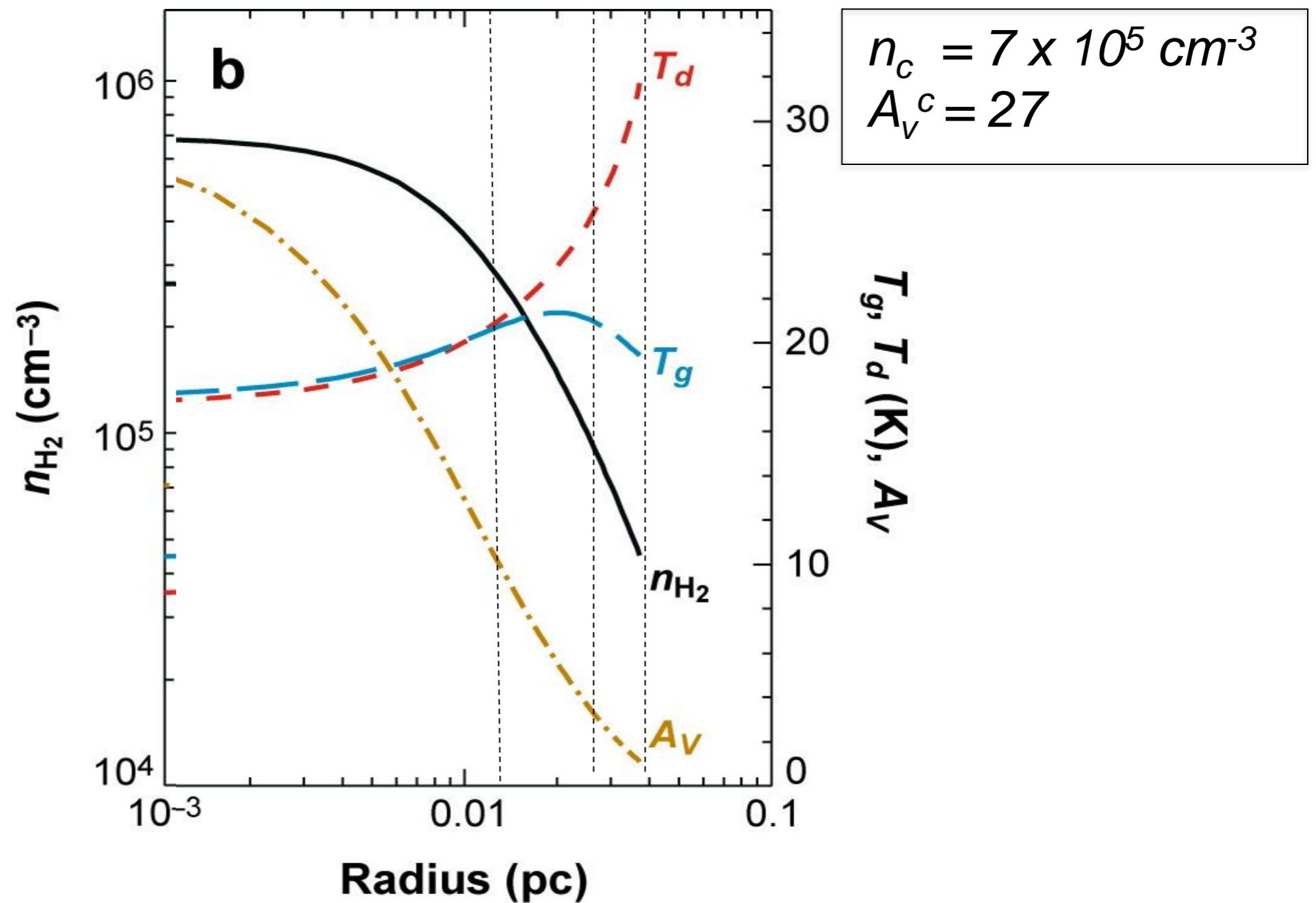
$\Lambda_g = \alpha T_{gas}^\beta$ with α, β function of $n(H_2)$, depletion, etc.

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

Temperature profile of a prestellar core

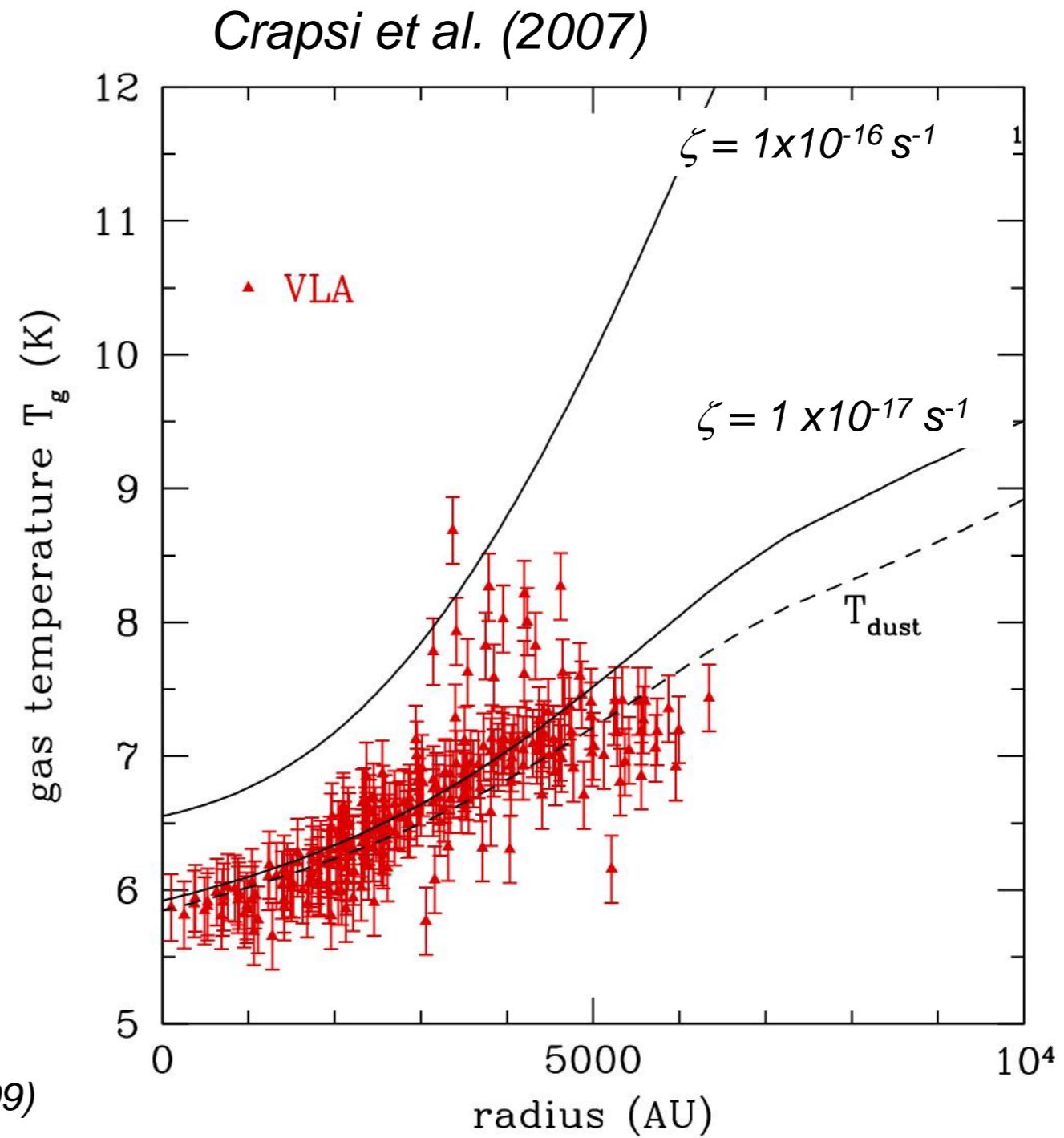
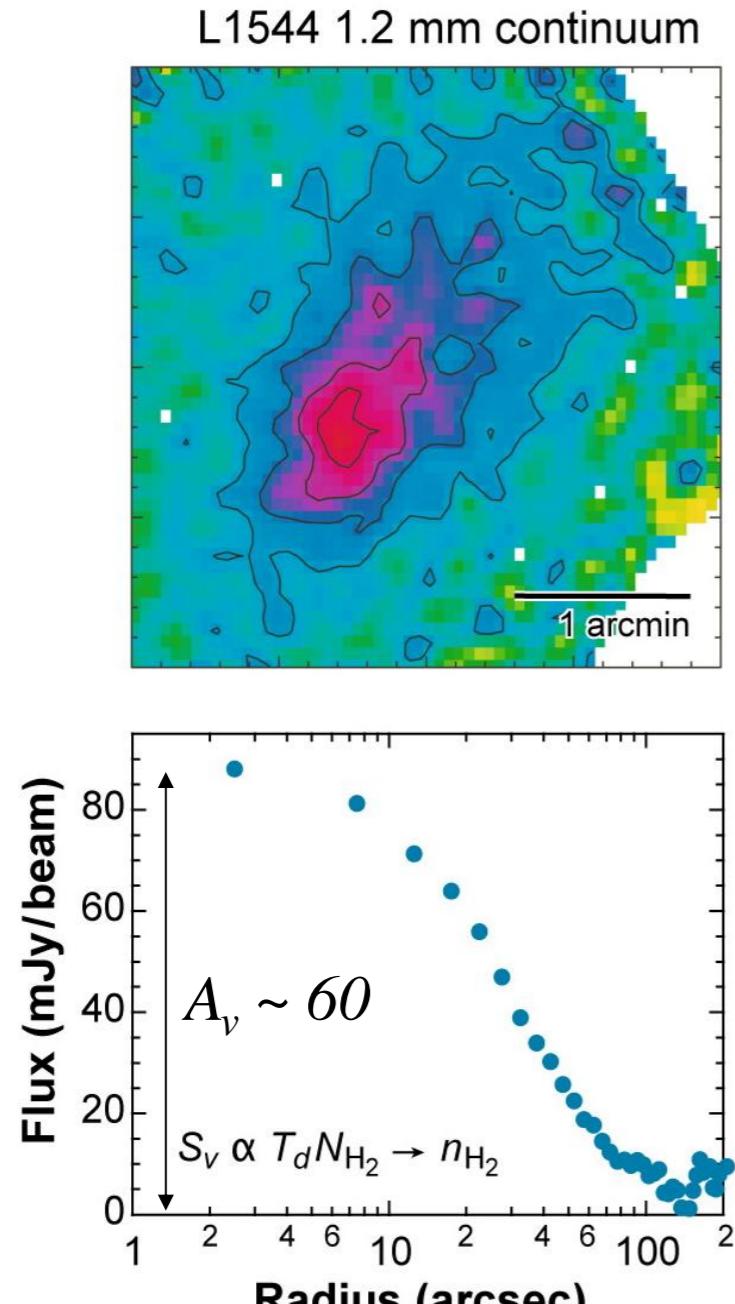


Temperature profile of a prestellar core



Galli, Walmsley & Gonçalves (2002)

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



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

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 $\sim N(\text{H}_2)^{-\alpha}$ with $0 < \alpha < 1$ up to $N(\text{H}_2) \approx 10^{25} \text{ cm}^{-2}$. Then exponential decrease $\sim \exp(-\Sigma_0)$ with $50 < \Sigma_0 < 100 \text{ g cm}^{-2}$.
- Variations of ζ_{CR} in the range $10^{-16} \text{ s}^{-1} - 10^{-18} \text{ s}^{-1}$ affect the dynamics of cloud collapse and star formation.
- Temperature measurements in UV-shielded dense gas (cores) can constrain ζ_{CR} as much (or better) than chemistry.
- “Hourglass” B-field: mirroring \sim focusing, ζ_{CR} reduced only by factor 2-3. Strong reduction of ζ_{CR} in complex B-fields.