Ionization of the ISM by low-energy cosmic rays

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in collaboration with:

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Outline of talk

- Measured values of ζ_{CR} in diffuse and dense clouds.
- Possible explanation: extra flux of low-energy CRs.
- Effects of magnetic field (mirroring and focusing) on ζ_{CR} in cloud cores.

Motivations

Low-energy CRs are the primary source of ionization in shielded regions of molecular clouds ($A_v \geq$ 3-4 mag), the sites of star formation.

- <u>Dynamics</u>: ionization fraction determines coupling with the magnetic field: ambipolar diffusion

$$t_{AD} = x_e \langle \sigma v \rangle_{in} / (2\pi\, G\, \mu m_H) \approx 5 \times 10^{13}\, x_e \ \text{yr}$$

for $x_e \sim 10^{-7}$ → $t_{AD} \sim$ 3-10 Myr (Mestel & Spitzer 1958)

- <u>Chemistry</u>: ionization of molecular hydrogen drives the formation of polyatomic ions and molecules

Interstellar Cloud Classification

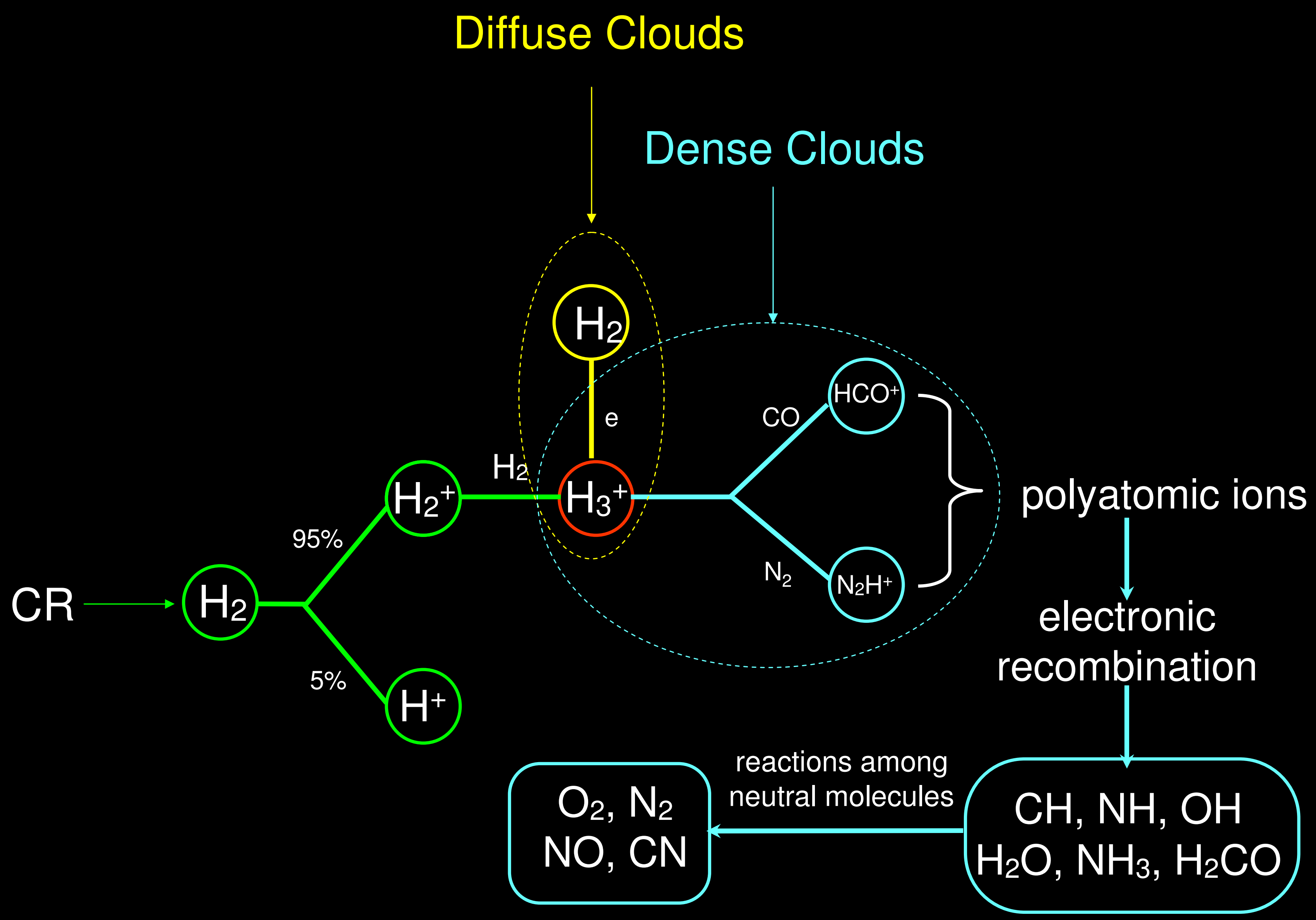
Dense molecular clouds:

- H_2
- $C \rightarrow CO$
- $n(H_2) \sim 10^4–10^6\ cm^{-3}$
- $x_e \sim 10^{-7}$
- $T \sim 10\ K$

Diffuse clouds:

- $H \approx H_2$
- $C \rightarrow C^+$
- $n(H_2) \sim 10^1–10^3\ cm^{-3}$
- $x_e \sim 10^{-4}$
- $T \sim 50\ K$

Snow & McCall (2006)



Diffuse Clouds

Dense Clouds

CR

H_2

95%

5%

H_2^+

H^+

H_2

H_3^+

e

H_2

CO

N_2

HCO^+

N_2H^+

polyatomic ions

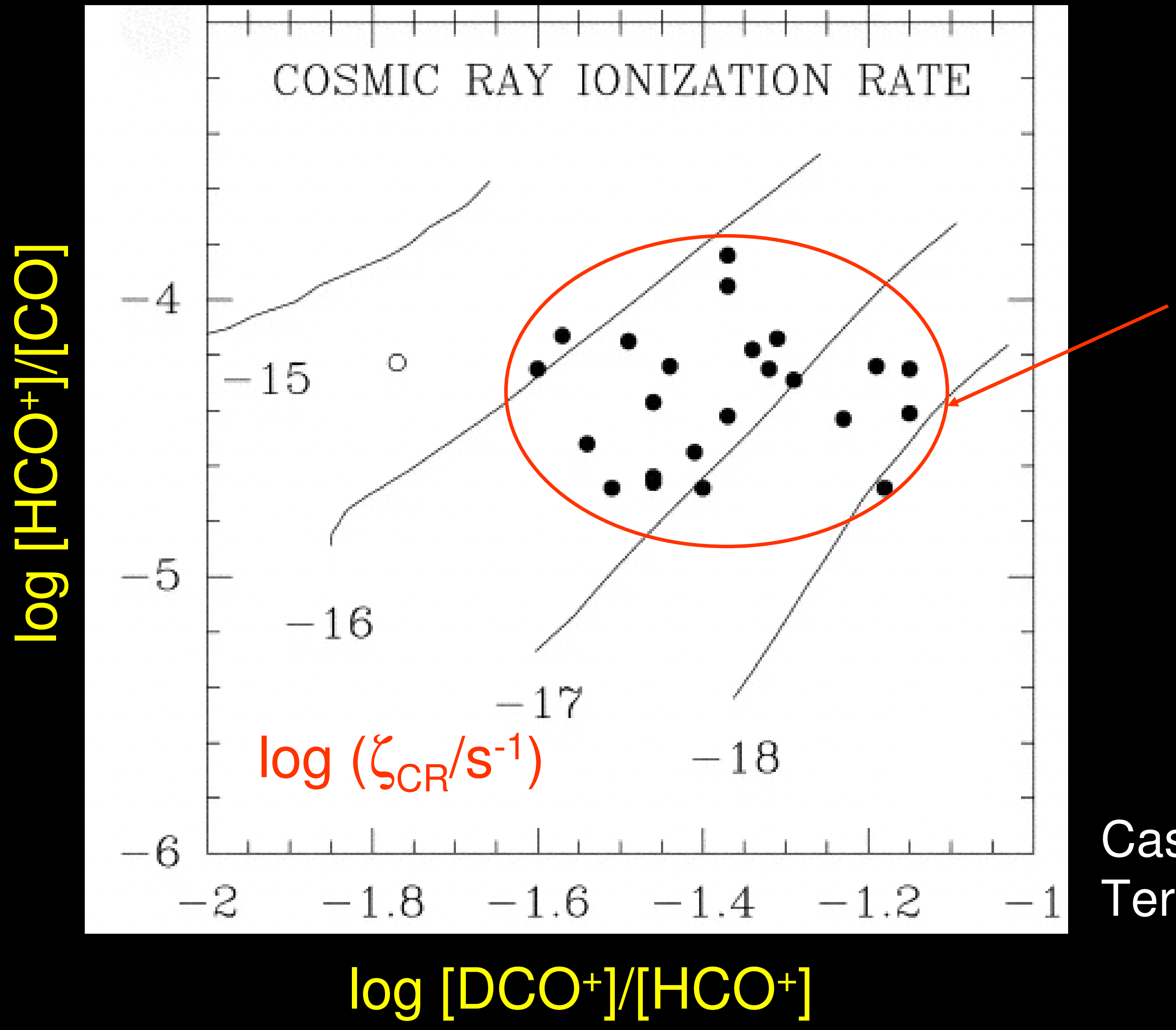
electronic recombination

CH, NH, OH
H_2O, NH_3, H_2CO

reactions among neutral molecules

O_2, N_2
NO, CN

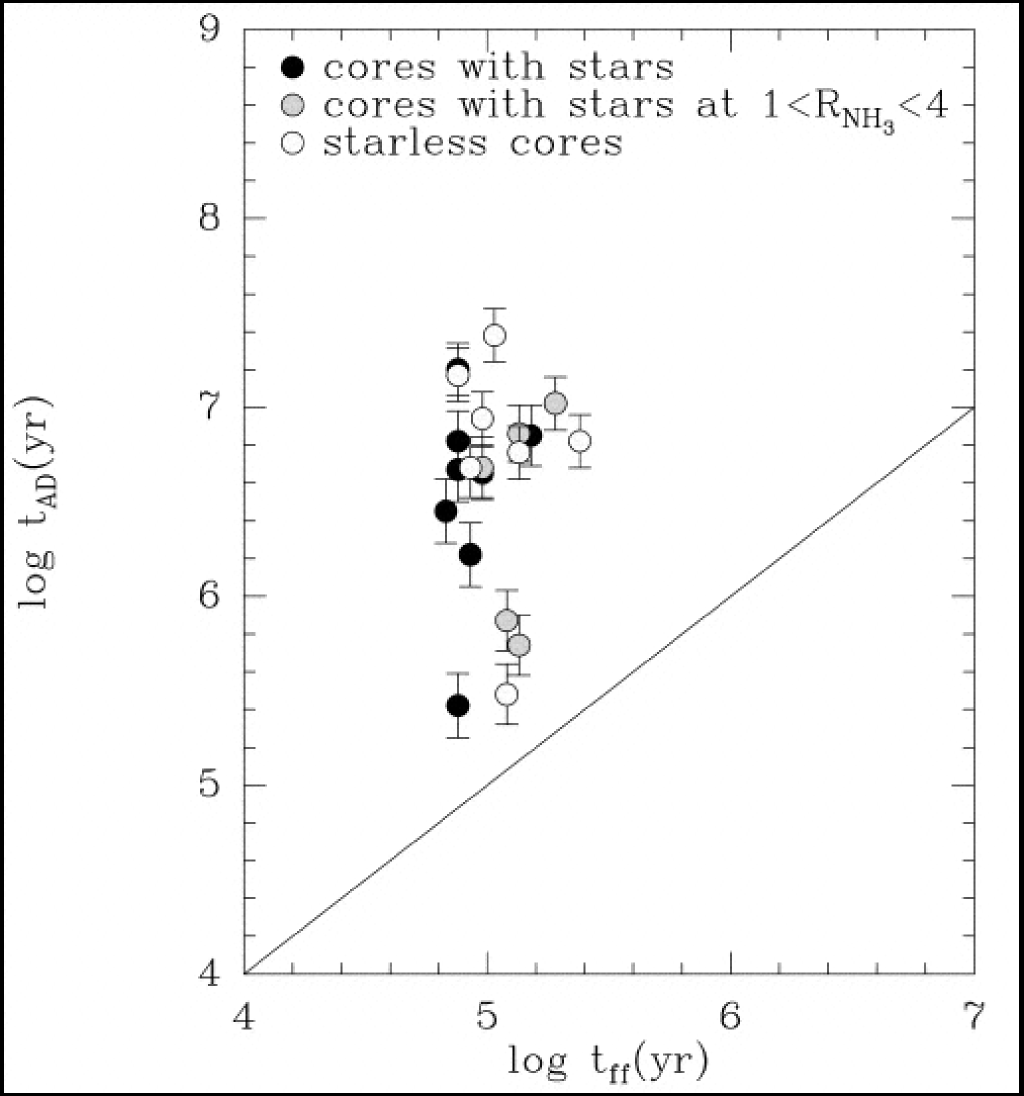
CR ionization rate in dense clouds



sample of 23
molecular
cloud cores

Caselli, Walmsley,
Terzieva & Herbst (1998)

t_{AD} and t_{ff} in dense clouds



Caselli, Walmsley, Terzieva & Herbst (1998)

CR ionization rate in diffuse clouds

At equilibrium, abundances OH, HD and NH given by

$$\zeta_{CR}\, n(H) \approx k_{UV}\, n(OH), \text{ etc.}$$

ζ_{CR} = CR ionization rate of H

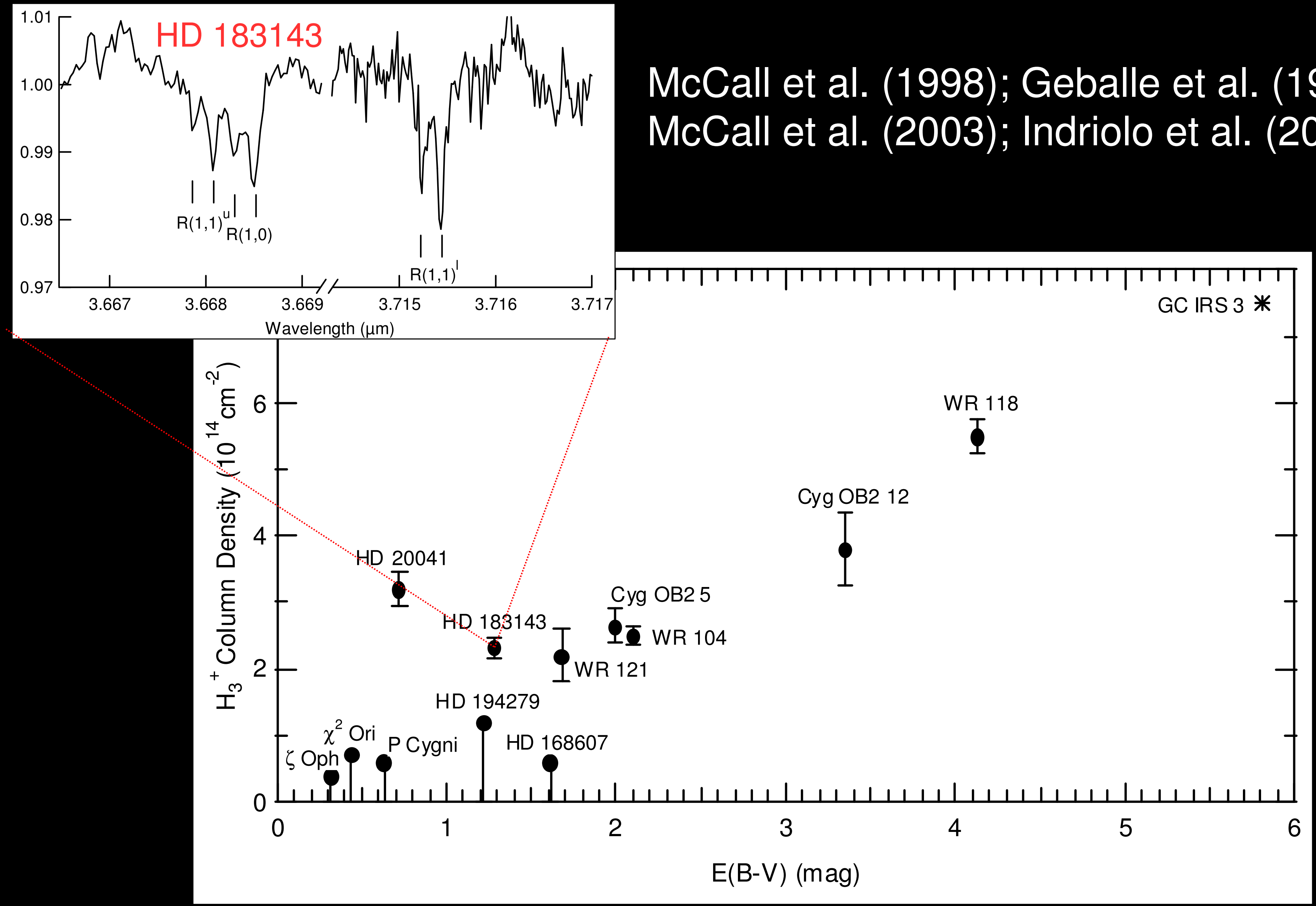
k_{UV} = photodissociation rate

→ $\zeta_{CR} \approx 10^{-17}$-$10^{-16}$ s^{-1} but sensitive to UV background and reaction rates

(Black & Dalgarno 1977; Hartquist et al. 1978; Black et al. 1978; van Dishoeck & Black 1986; Federman et al. 1996)

Discovery of H_3^+ in diffuse clouds

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



H_3^+ chemistry in diffuse clouds

Formation:

$CR + H_2 \rightarrow H_2^+ + e^-$ Rate = $\zeta_{CR}\, n(H_2)$

$H_2^+ + H_2 \rightarrow H_3^+ + H$ (fast)

Destruction:

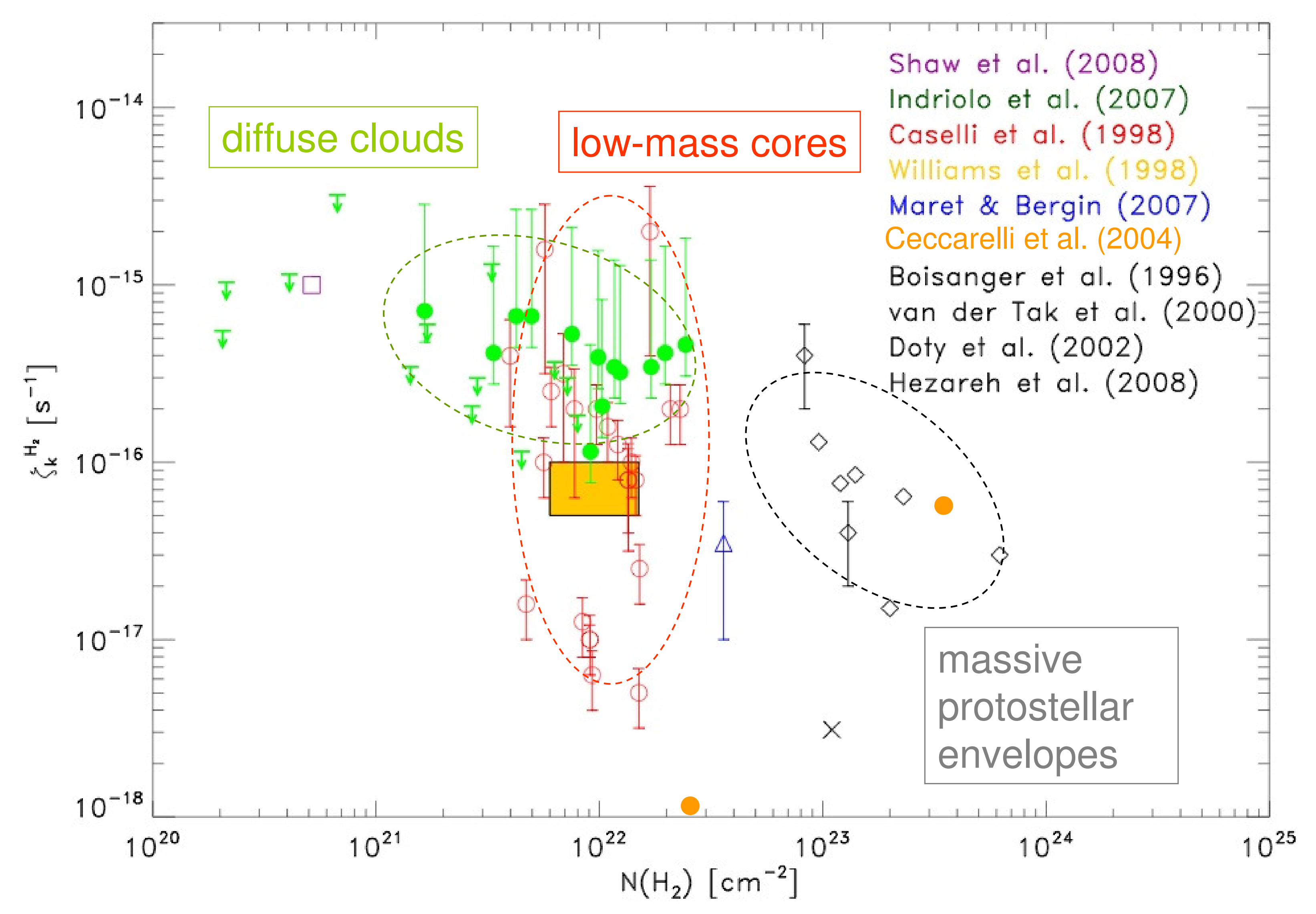
$H_3^+ + e^- \rightarrow H + H_2$ or 3H Rate = $k_e n(H_3^+) n(e^-)$

Steady State: $\zeta_{CR}\, n(H_2) = k_e\, n(H_3^+)\, n(e^-)$

$$\rightarrow \qquad \zeta_{CR} \approx k_e n(H) \frac{N(H_3^+)}{N(H)} \frac{x_e}{f_{H_2}} \approx 10^{-15} - 10^{-16} s^{-1}$$

~ one order of magnitude larger than in dense clouds

Summary of observations



Possible explanations

- High flux of low-energy CR (McCall et al. 2003)
- CR screening of dense clouds due to:
  - Self-generated Alfvèn waves in the plasma (Skilling & Strong 1976; Hartquist et al. 1978; Padoan & Scalo 2005)
  - Magnetic focusing/mirroring effects (Cesarsky & Volk 1978; Chandran 2000)

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

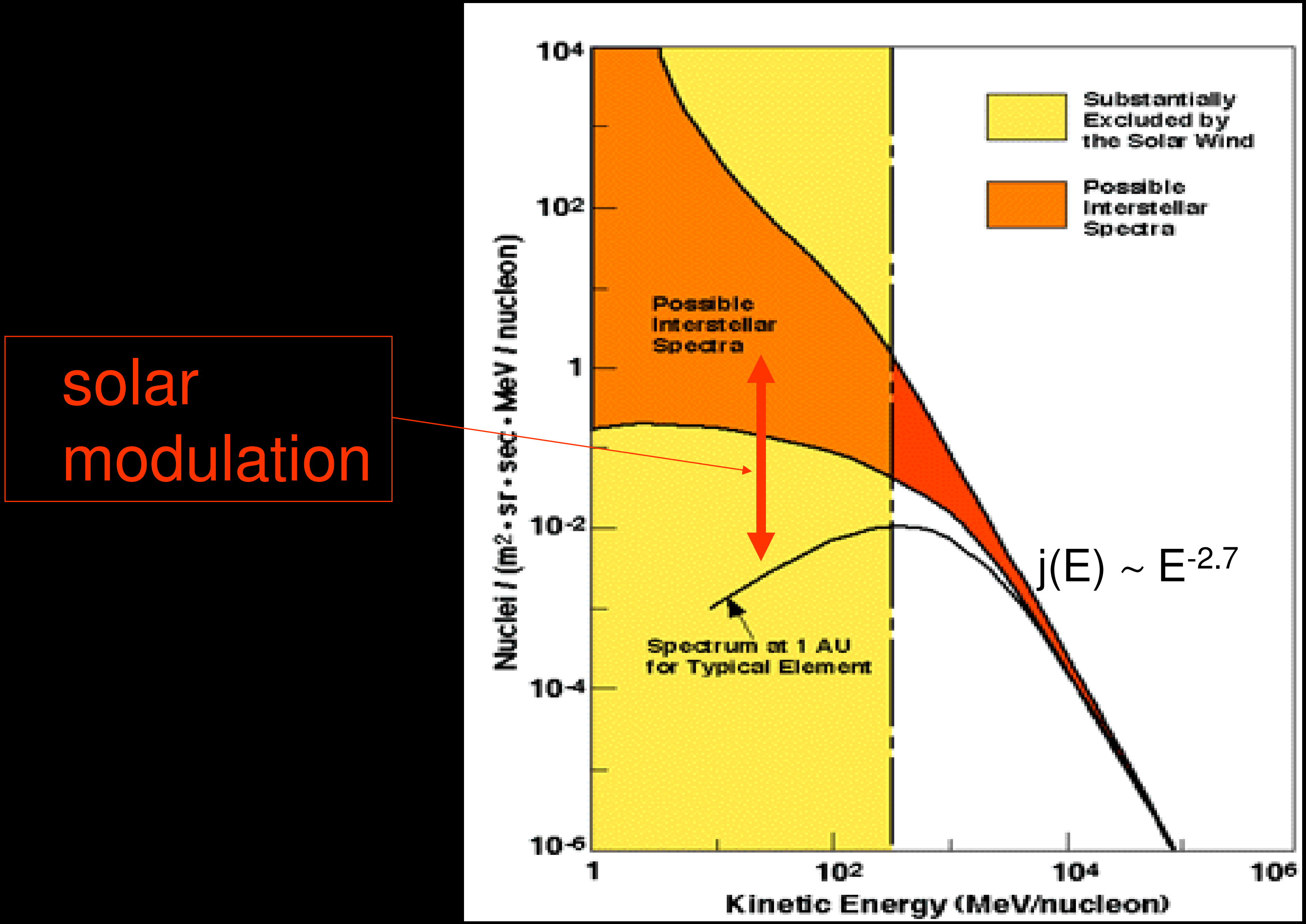
$$\zeta_{CR} = 4\pi \int_{E_{low}}^{E_{high}} j(E)\sigma(E)dE$$

Hayakawa et al. (1961); Spitzer & Tomasko (1968) for H

Glassgold & Langer (1974) for H_2

→ “standard” (Spitzer) value $\zeta_{CR} \approx 1\text{-}2 \times 10^{-17}\ s^{-1}$

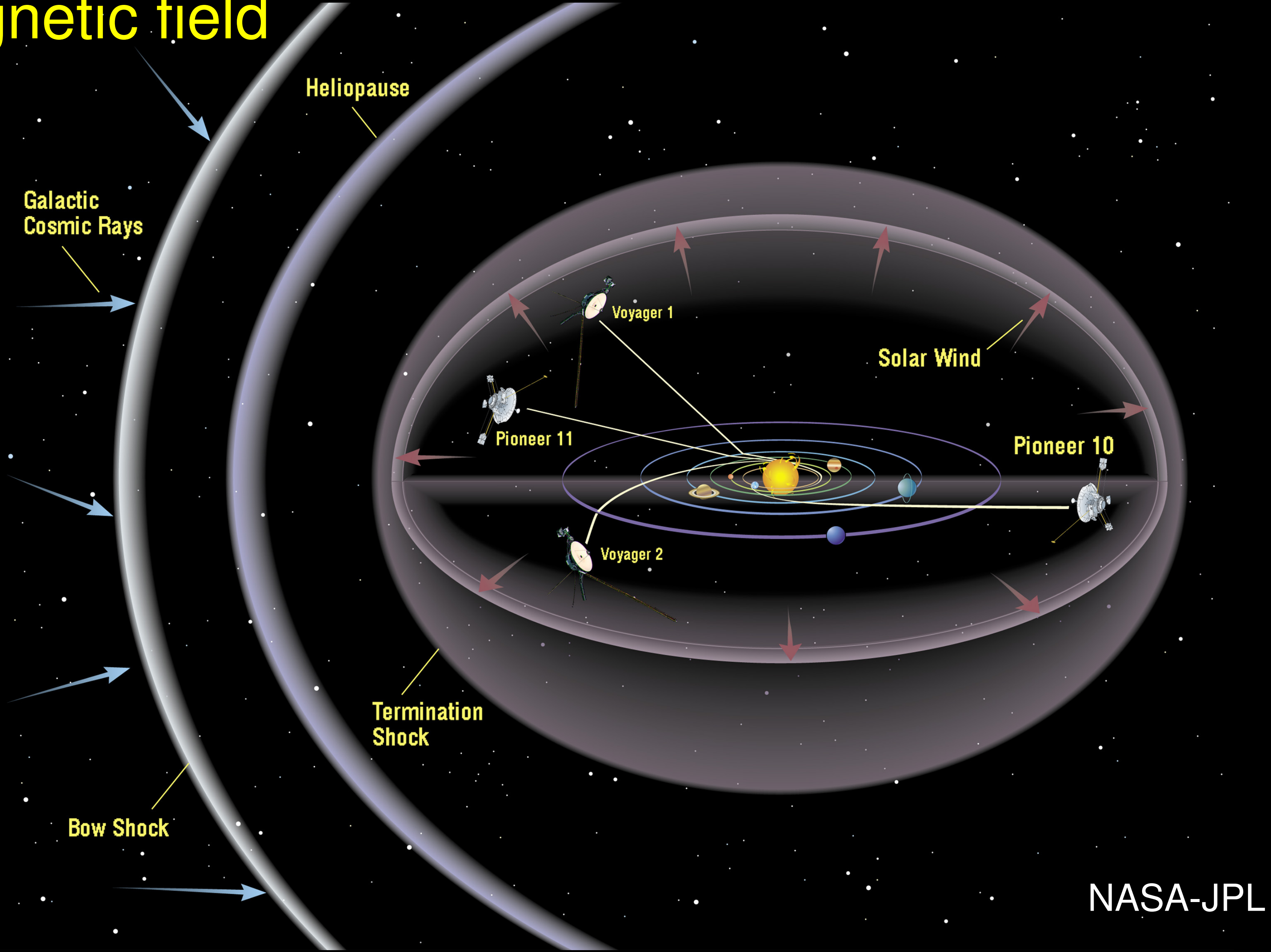
A high flux of low-energy CR?



solar modulation

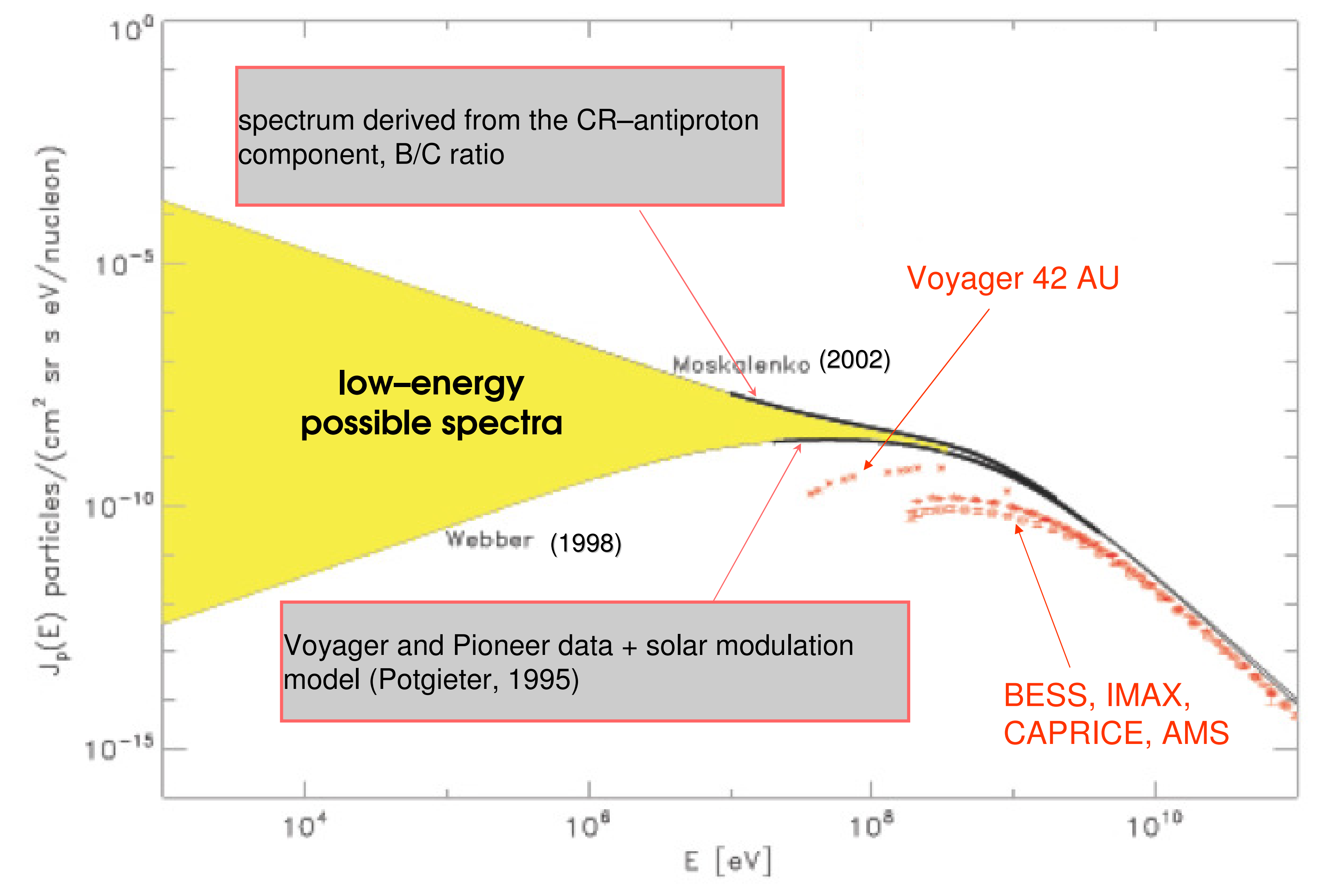
NASA-JPL

CRs below ~1 GeV are prevented from entering the heliosphere by the solar wind and the interplanetary magnetic field



NASA-JPL

Interstellar CR–proton spectrum

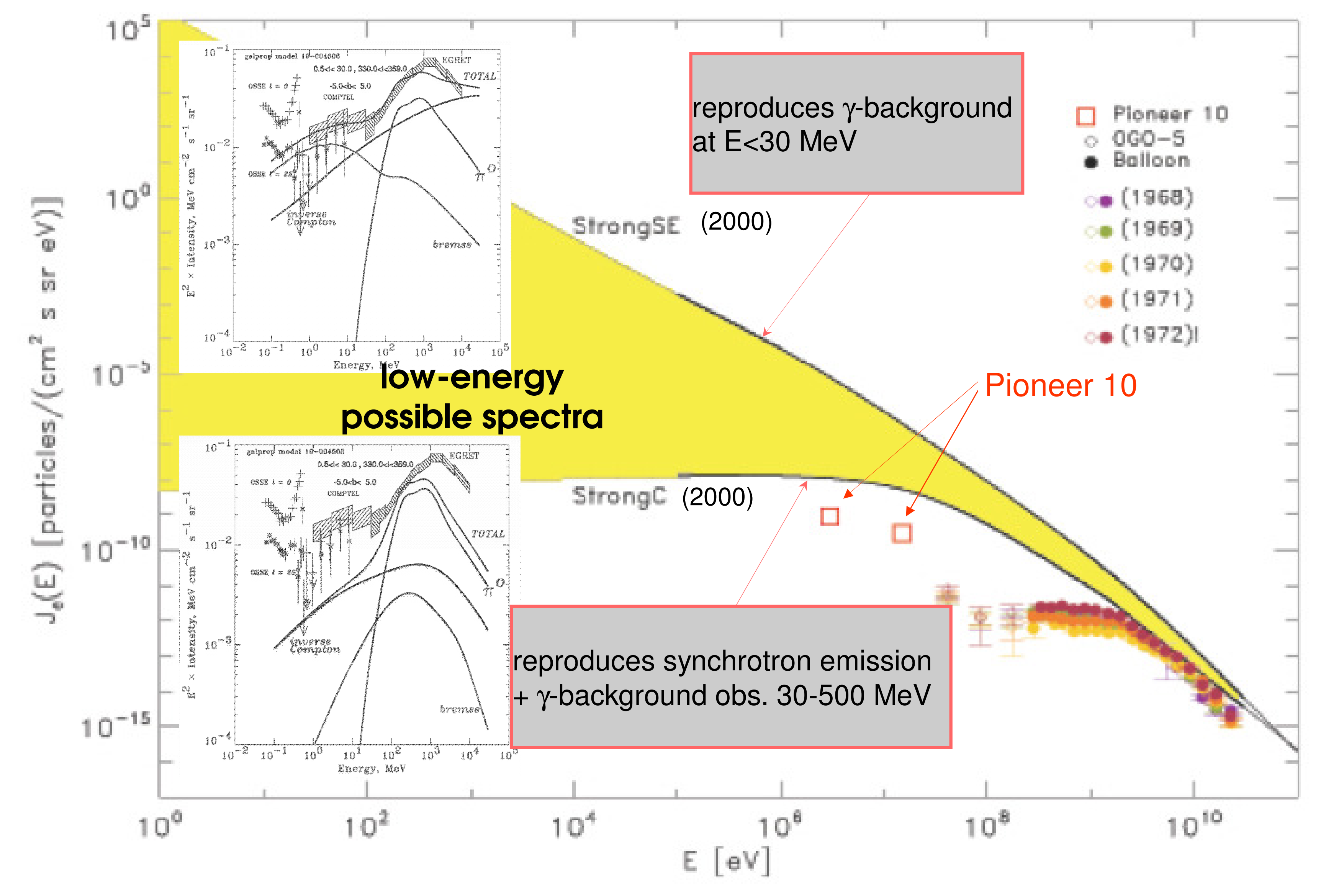


spectrum derived from the CR–antiproton component, B/C ratio

Voyager and Pioneer data + solar modulation model (Potgieter, 1995)

Padovani et al. (2009)

Interstellar CR–electron spectrum



reproduces γ-background at E<30 MeV

(2000)

(2000)

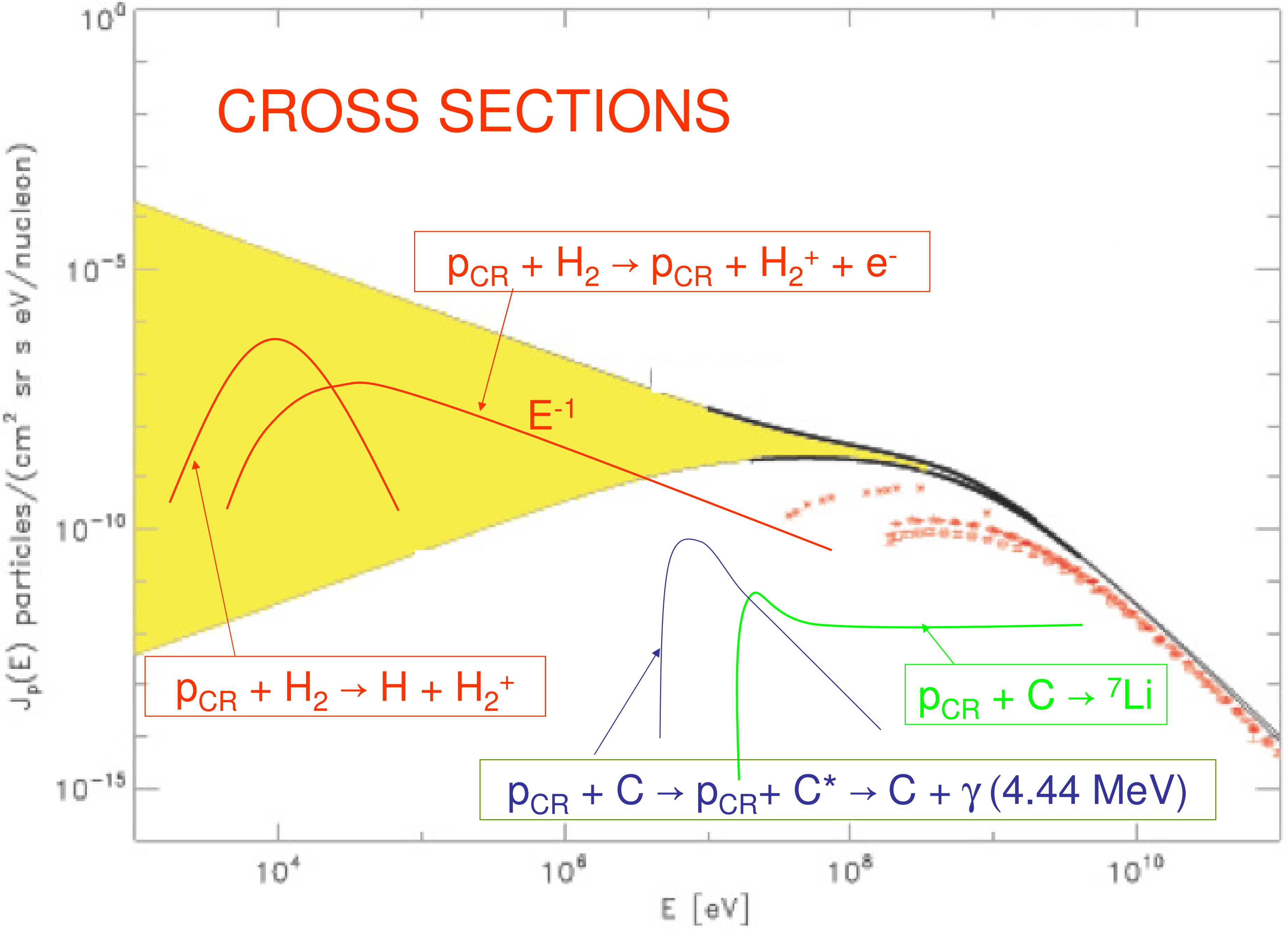
low-energy possible spectra

Pioneer 10

reproduces synchrotron emission + γ-background obs. 30-500 MeV

Padovani et al. (2009)

CROSS SECTIONS



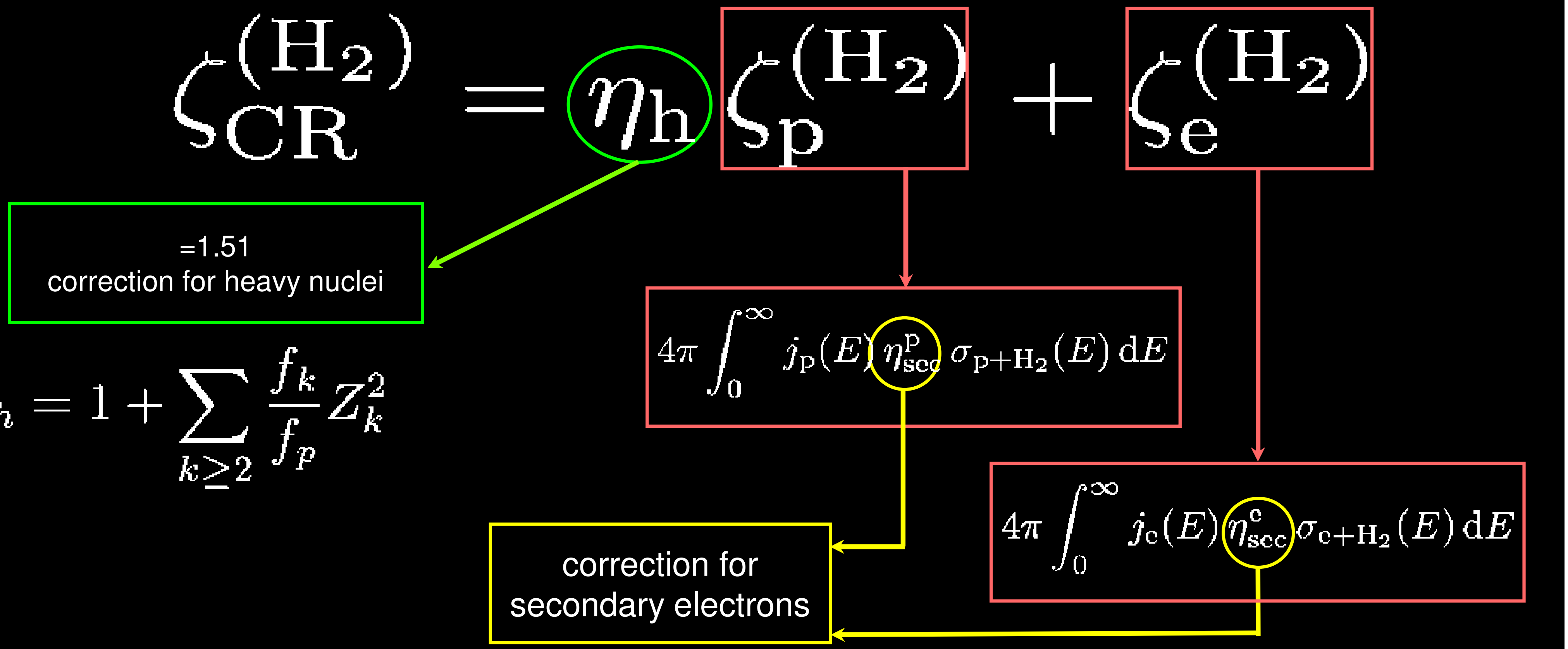
$p_{CR} + H_2 \rightarrow p_{CR} + H_2^+ + e^-$

E^{-1}

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

$p_{CR} + C \rightarrow {}^7Li$

$p_{CR} + C \rightarrow p_{CR} + C^* \rightarrow C + \gamma\,(4.44\ MeV)$



$$\zeta_{\mathrm{CR}}^{(\mathrm{H_2})} = \eta_{\mathrm{h}}\, \zeta_{\mathrm{p}}^{(\mathrm{H_2})} + \zeta_{\mathrm{e}}^{(\mathrm{H_2})}$$

=1.51
correction for heavy nuclei

$$\eta_h = 1 + \sum_{k \geq 2} \frac{f_k}{f_p} Z_k^2$$

$$4\pi \int_0^\infty j_{\mathrm{p}}(E)\, \eta_{\mathrm{scc}}^{\mathrm{p}}\, \sigma_{\mathrm{p+H_2}}(E)\, \mathrm{d}E$$

$$4\pi \int_0^\infty j_{\mathrm{c}}(E)\, \eta_{\mathrm{scc}}^{\mathrm{c}}\, \sigma_{\mathrm{c+H_2}}(E)\, \mathrm{d}E$$

correction for
secondary electrons

$$\eta_{\mathrm{scc}}^{k} = 1 + \phi_k(E_k)$$

$$\phi_k(E_k) = \frac{1}{\sigma_k^{\mathrm{ion}}(E_k)} \int_{E_{\mathrm{ion.}}}^{E'_e(E_k)_{\mathrm{max}}} P(E_k, E'_e)\, \sigma_e^{\mathrm{ion.}}(E'_e)\, \mathrm{d}E'_e$$

CR propagation inside a cloud

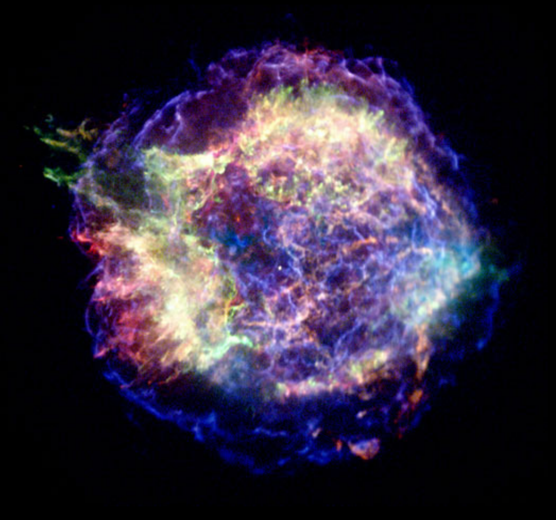
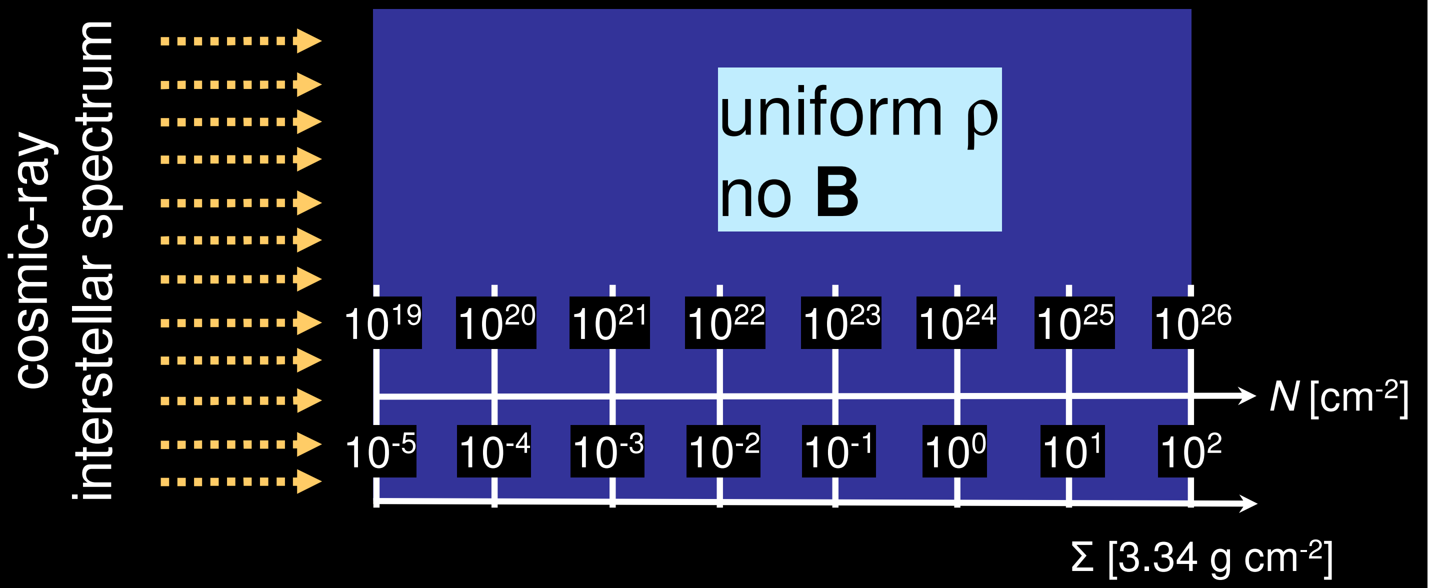


Image credit: NASA/CXC/UMass Amherst/M.D.Stage et al.



CR propagation inside a cloud

$$\zeta_{CR}^{(\mathrm{H}_2)}(N) = 4\pi \int_0^\infty \boxed{j(E,N)}\,\sigma(E)\,\mathrm{d}E$$

Assumptions:

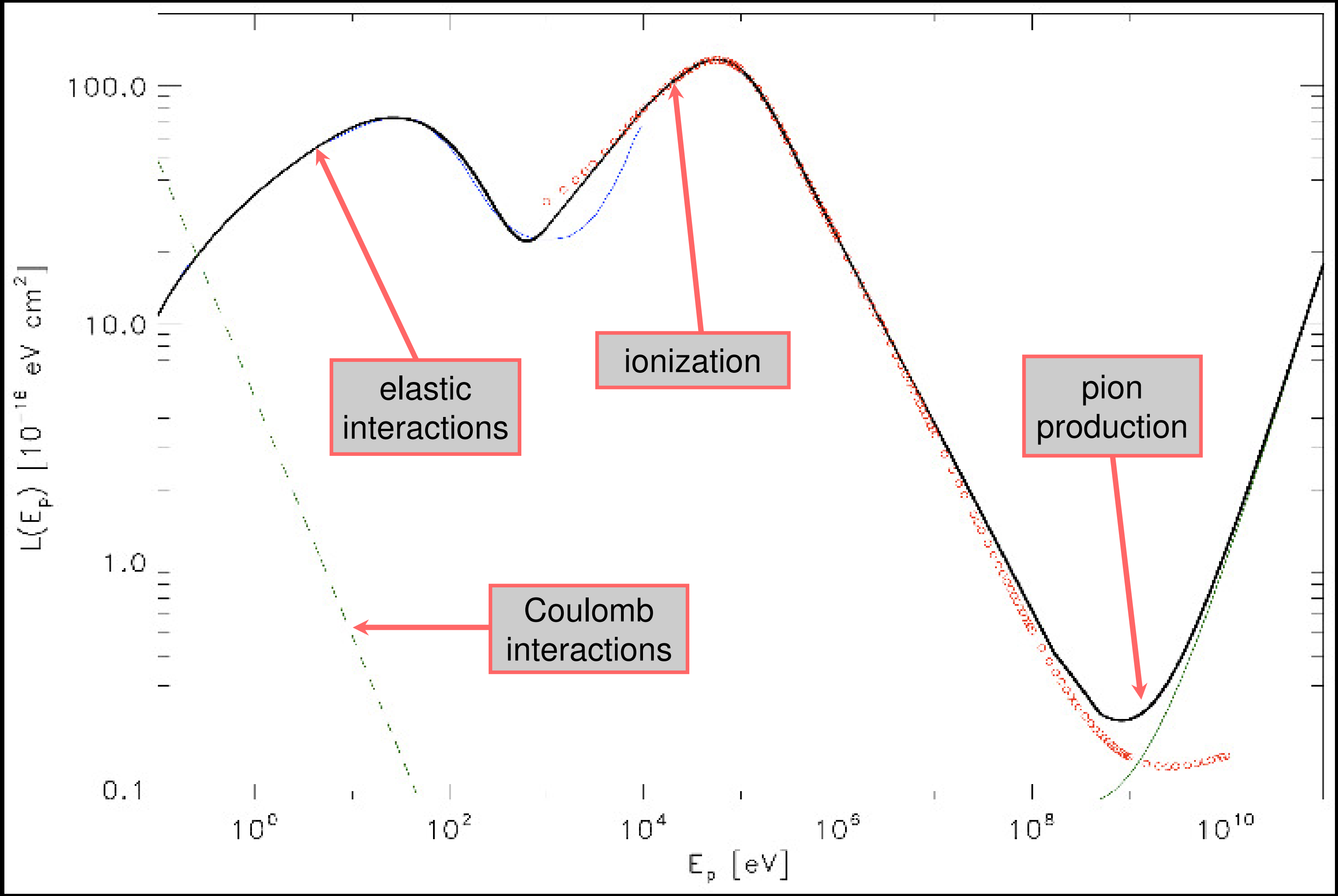
- slab geometry
- continuous slowing-down approximation (or thick target):
    - the energy loss of a particle depends on the thickness of the traversed matter and on its initial energy through L(E).

$$L(E) = -\frac{1}{n(\mathrm{H}_2)}\frac{\mathrm{d}E}{\mathrm{d}x} = -\frac{\mathrm{d}E}{\mathrm{d}N}$$

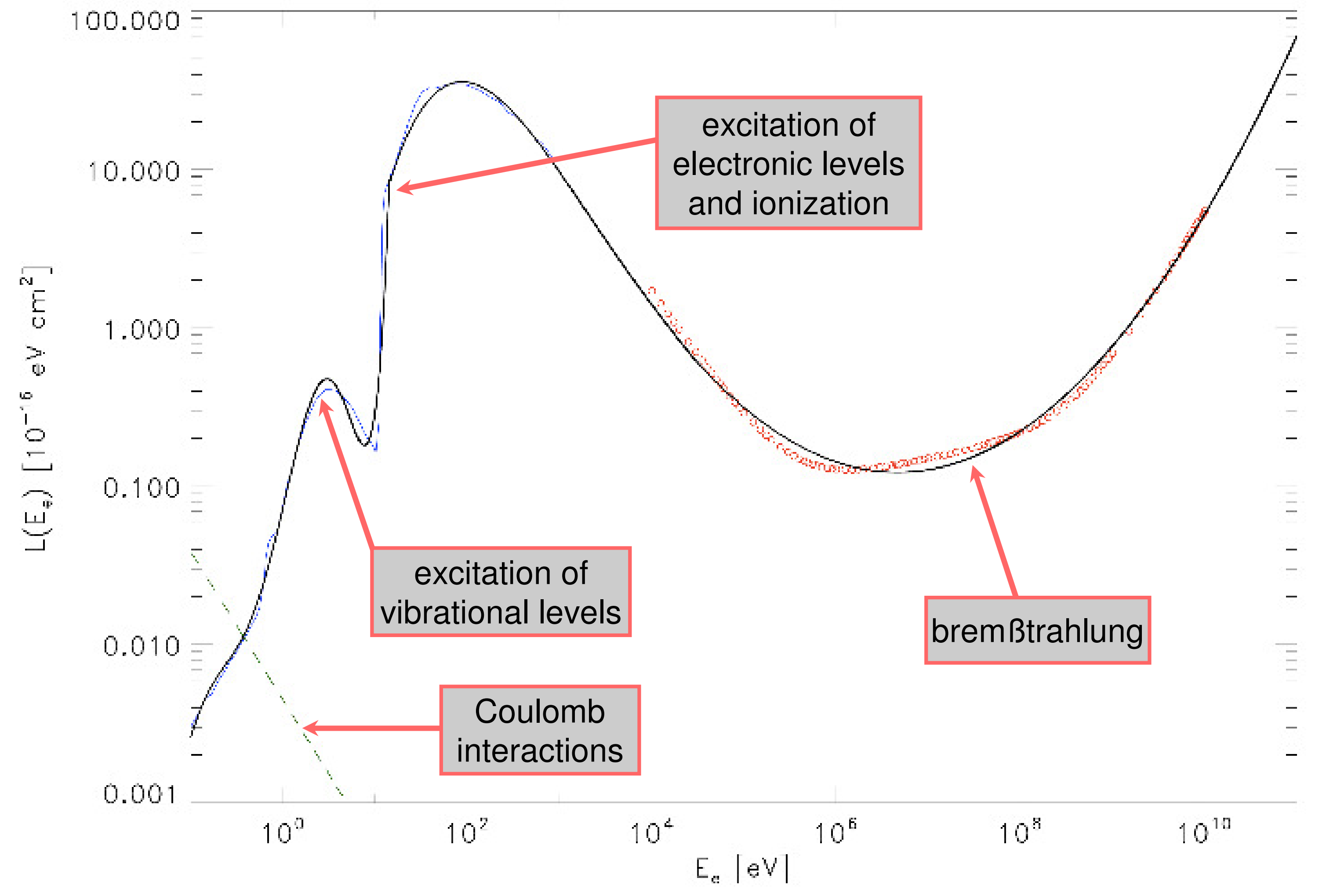
$$N(\mathrm{H}_2) = \int n(\mathrm{H}_2)\,\mathrm{d}x$$

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

Energy loss of CR–protons in H_2



Energy loss of CR-electrons in H_2

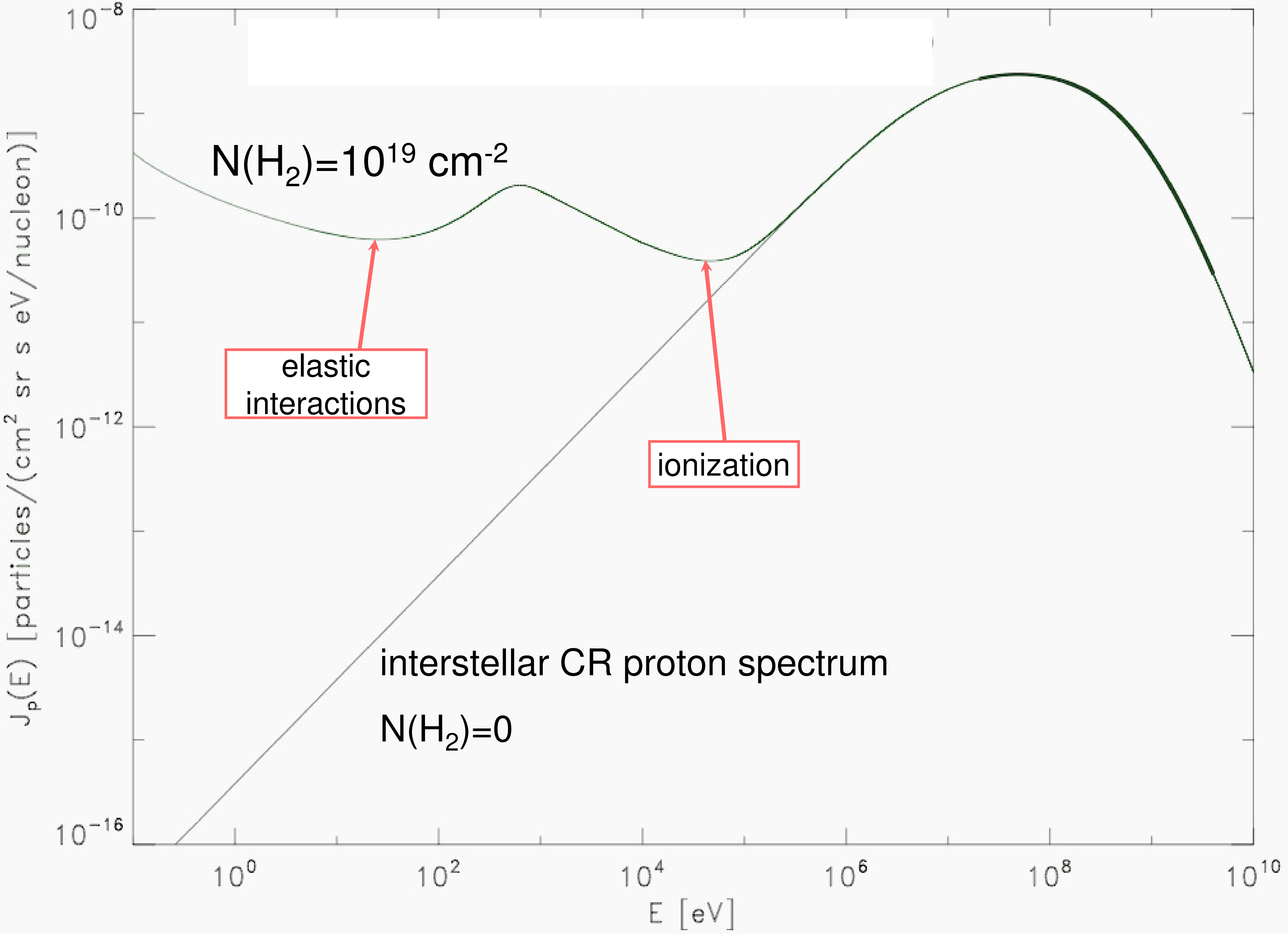


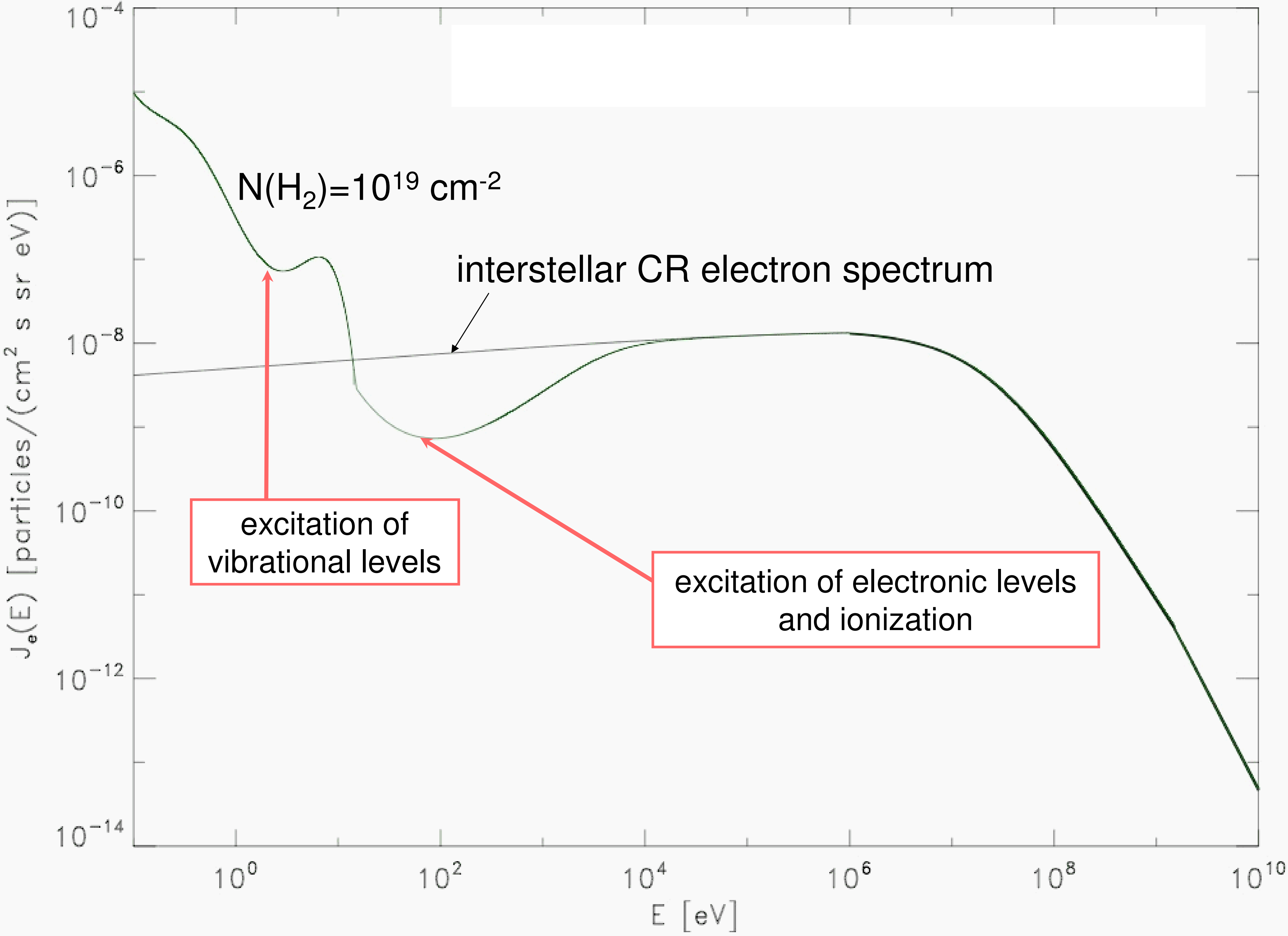
excitation of electronic levels and ionization

excitation of vibrational levels

Coulomb interactions

bremßtrahlung


$N(H_2)=10^{19}$ cm^{-2}
elastic interactions
ionization
interstellar CR proton spectrum
$N(H_2)=0$
$J_p(E)$ [particles/(cm^2 sr s eV/nucleon)]
10^{-8}
10^{-10}
10^{-12}
10^{-14}
10^{-16}
10^0
10^2
10^4
10^6
10^8
10^{10}
E [eV]



$N(H_2)=10^{19}$ cm^{-2}

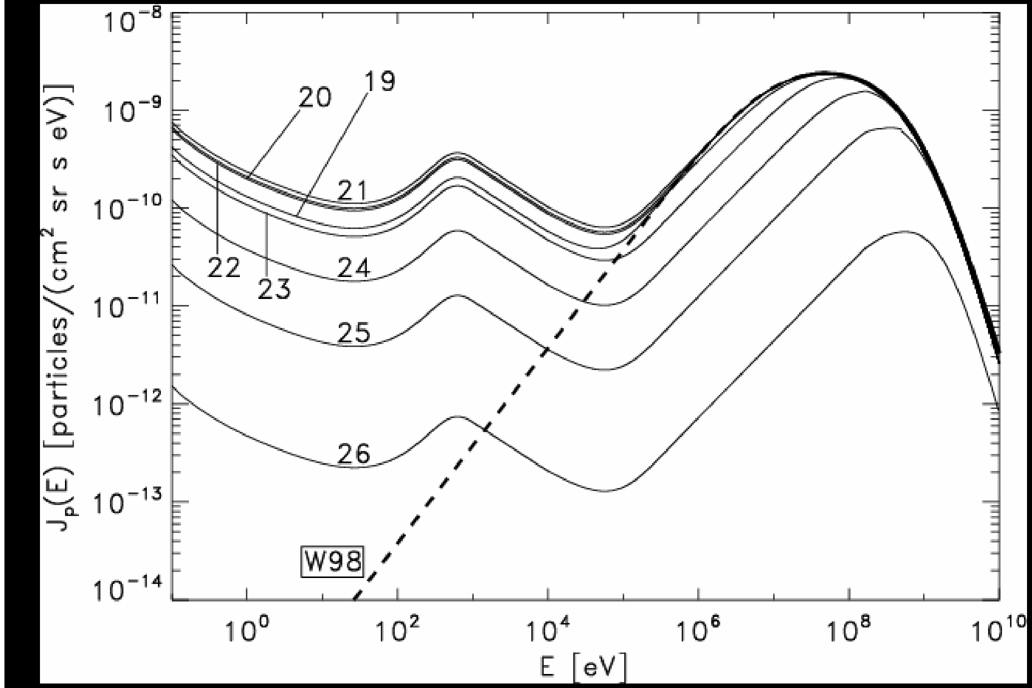
interstellar CR electron spectrum

excitation of vibrational levels

excitation of electronic levels and ionization

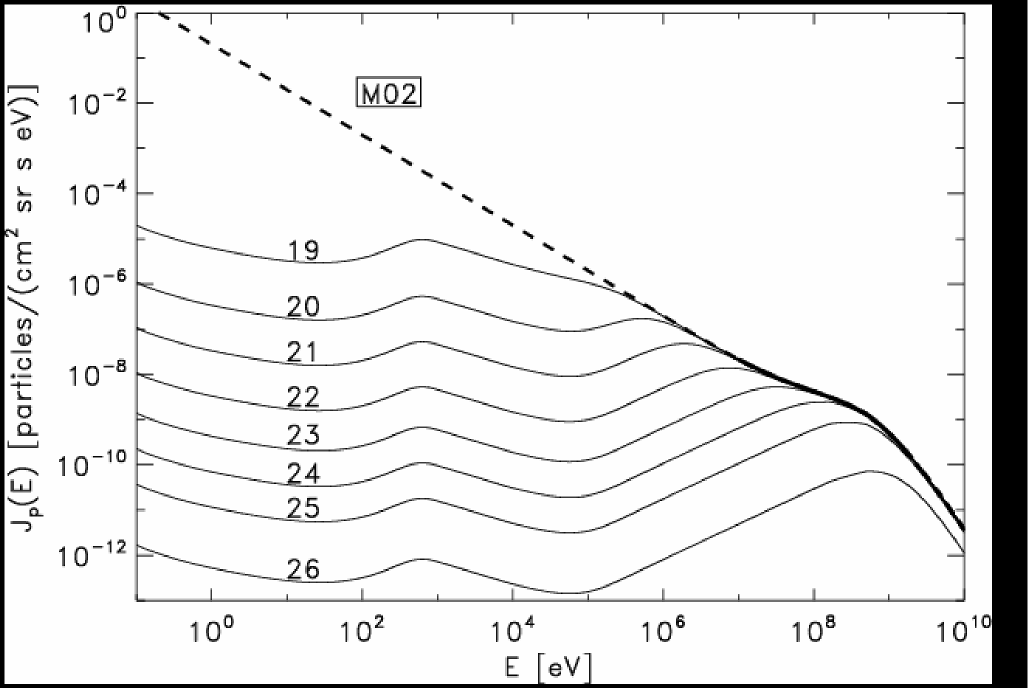
Animations

Evolution of CR proton spectrum



spectrum “low”

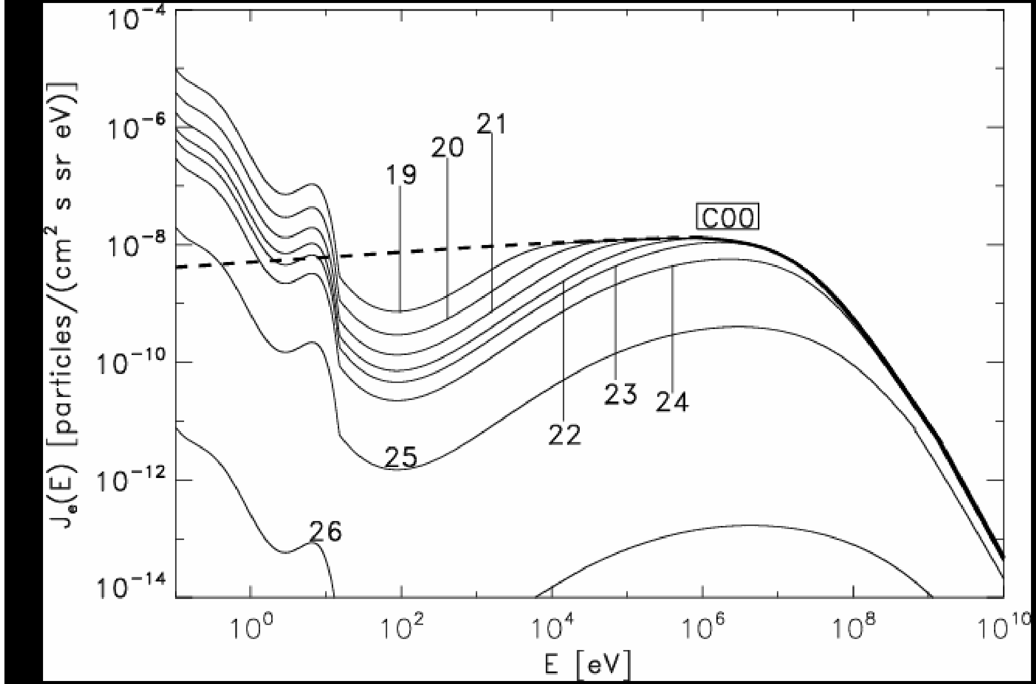
(Webber 1998)



spectrum “high”

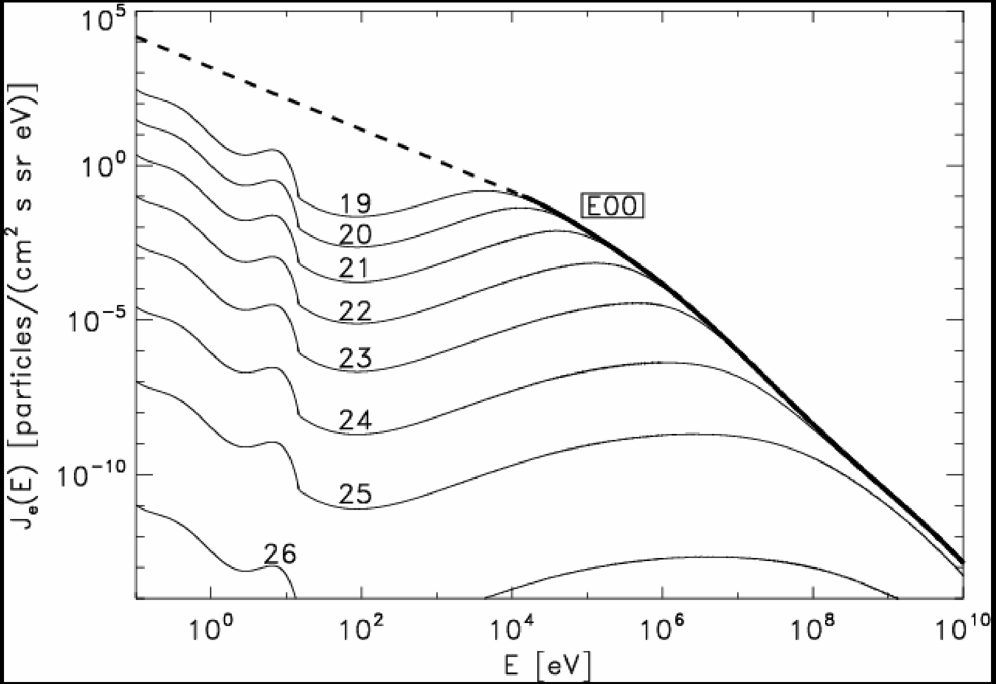
(Moskalenko et al. 2002)

Evolution of CR electron spectrum



spectrum “low”

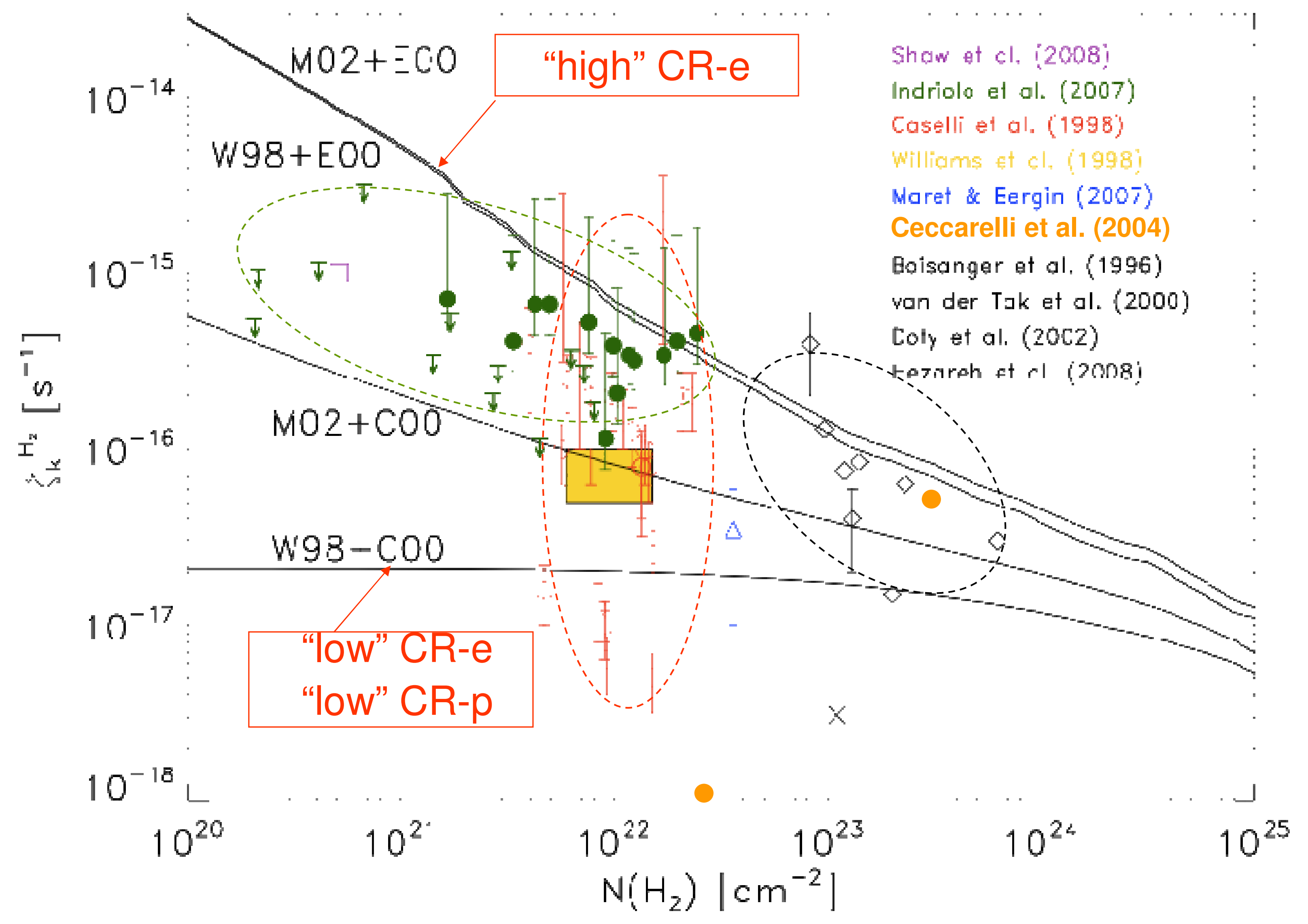
(Srong et al. 2000)



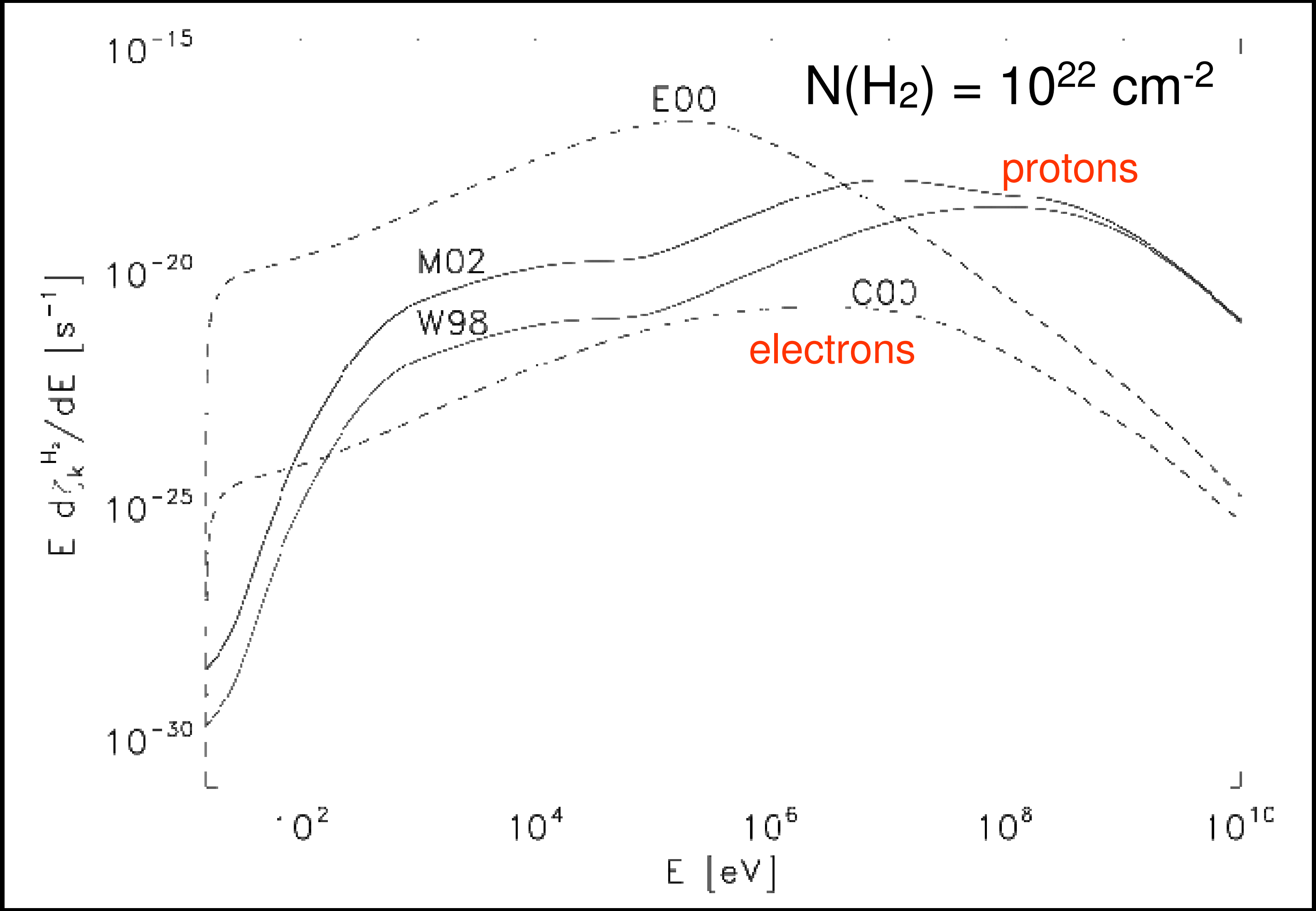
spectrum “high”

(Strong et al. 2000)

Comparison with observations



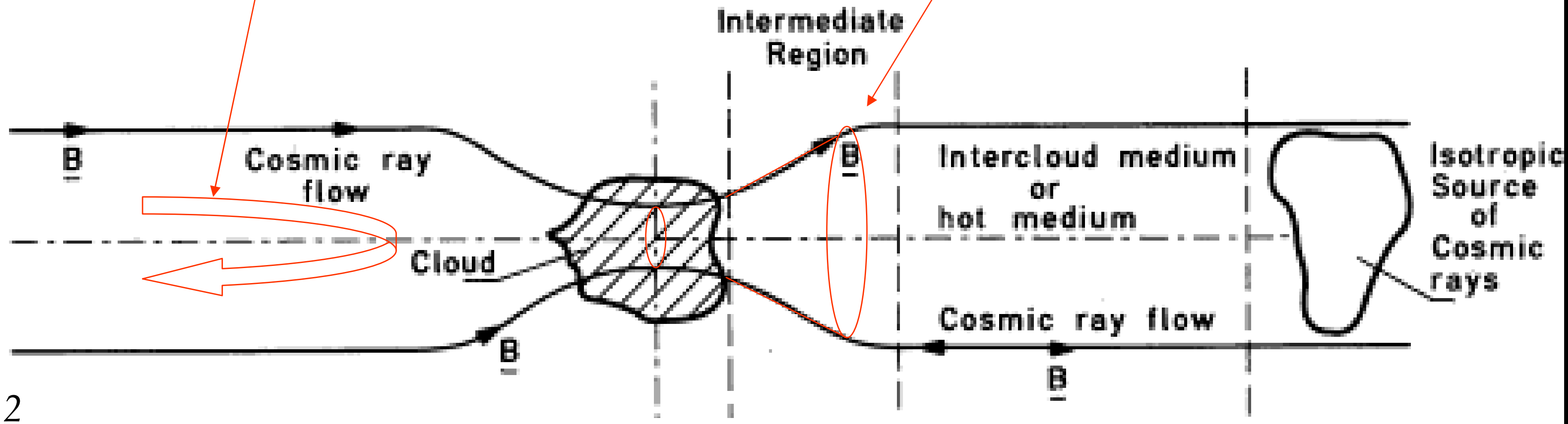
Differential contribution to CR-ionization rate



Padovani et al. (2009)

Magnetic mirroring bounces many CR out of the core

Magnetic focusing increases CR flux in the core



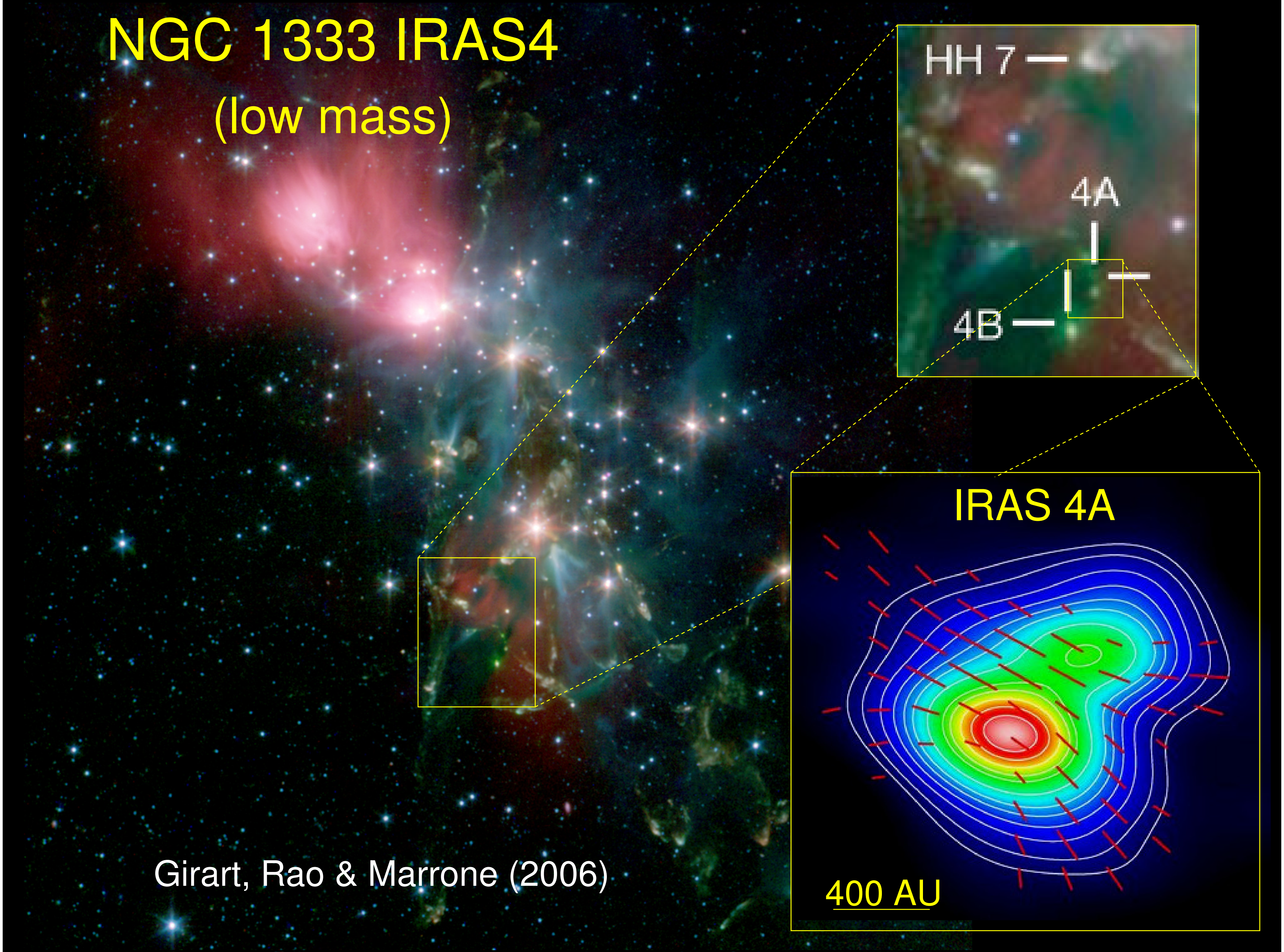
$$\frac{v_\perp^2}{B} = const.$$

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

Cesarsky & Volk (1978)

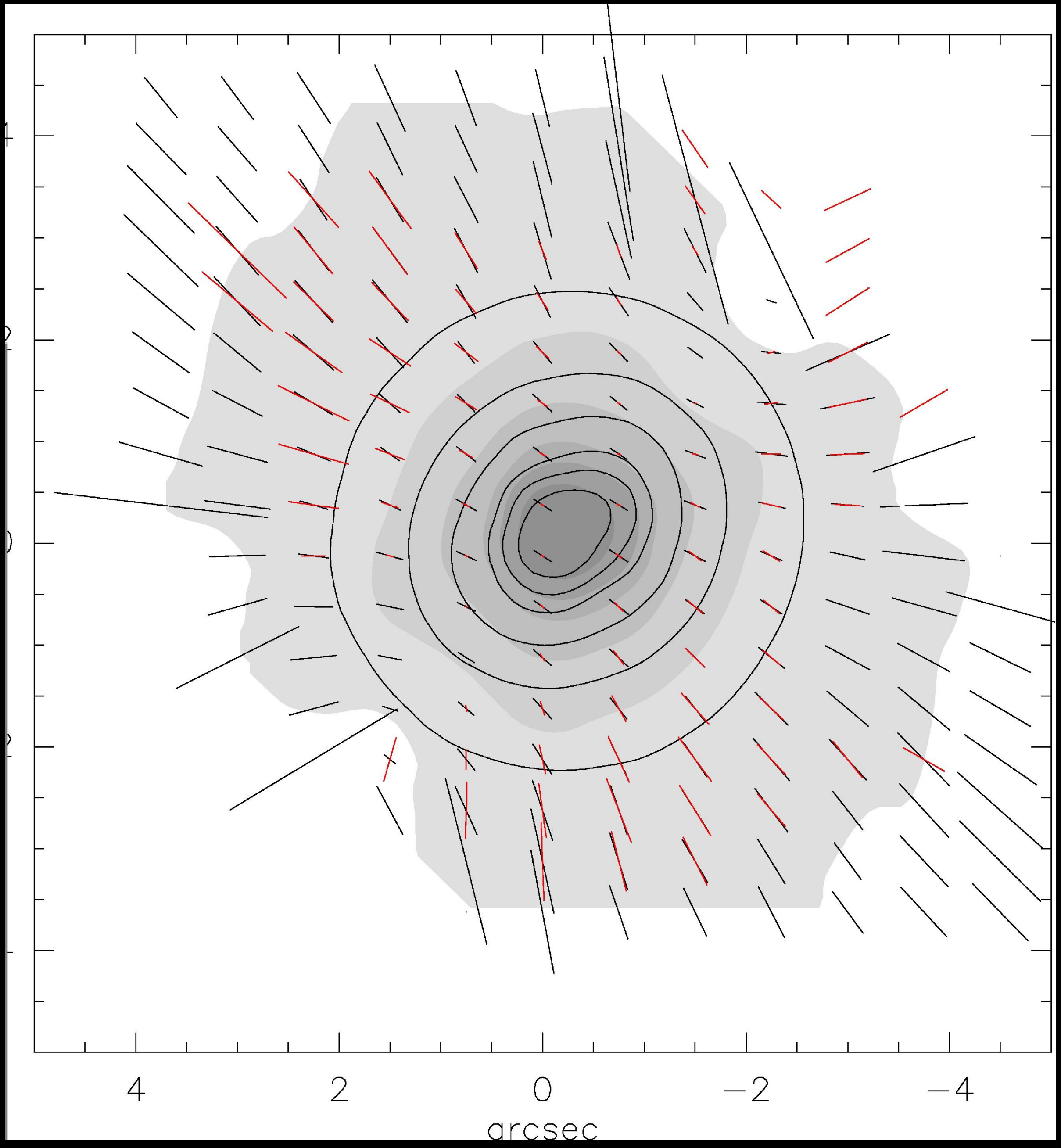
NGC 1333 IRAS4

(low mass)



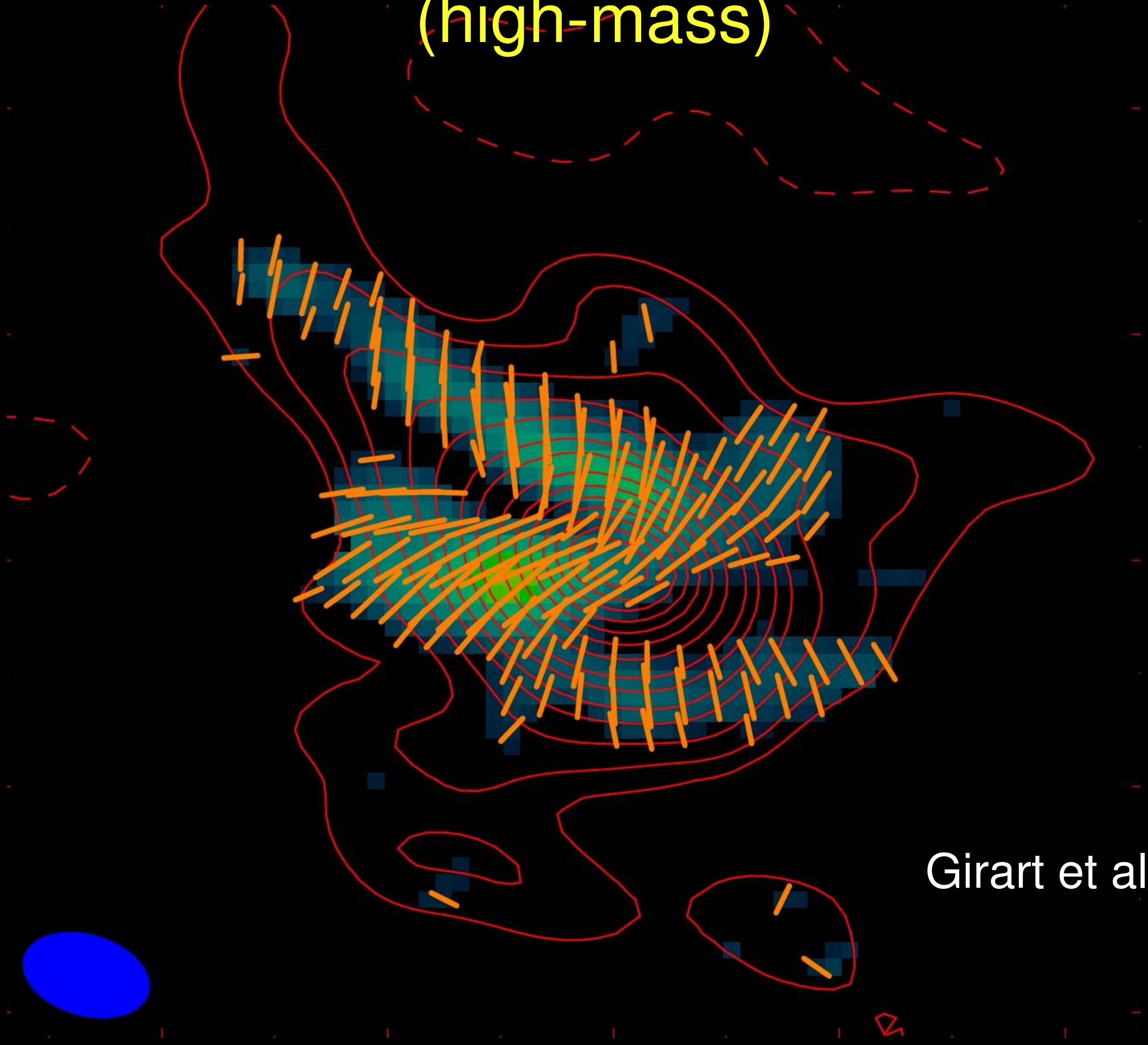
Girart, Rao & Marrone (2006)

NGC 1333 IRS 4A – polarization map

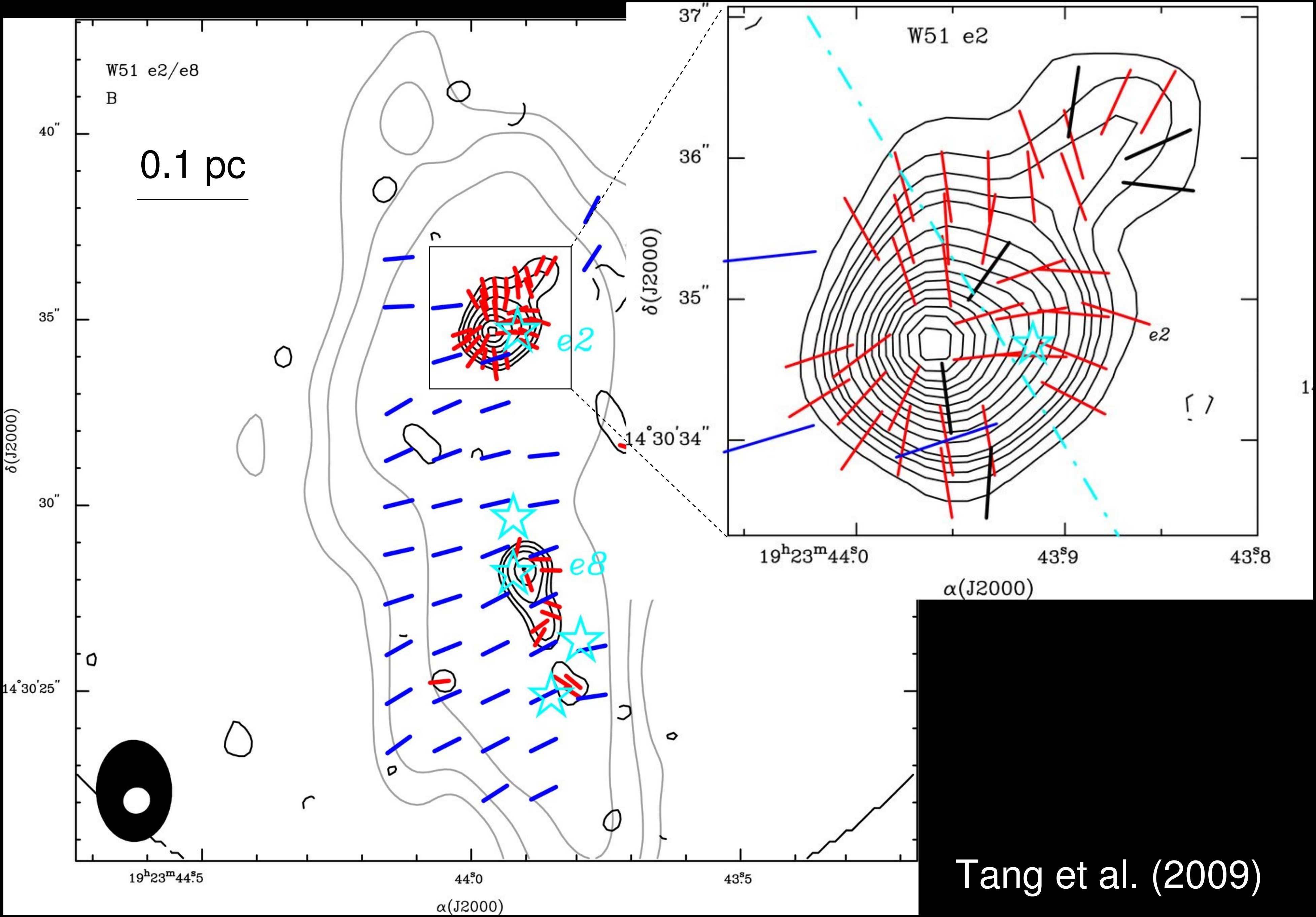


- red: data (Girart et al. 2006)
- black: model (Gonçalves, Galli & Girart 2007)

G31.41+0.31
(high-mass)

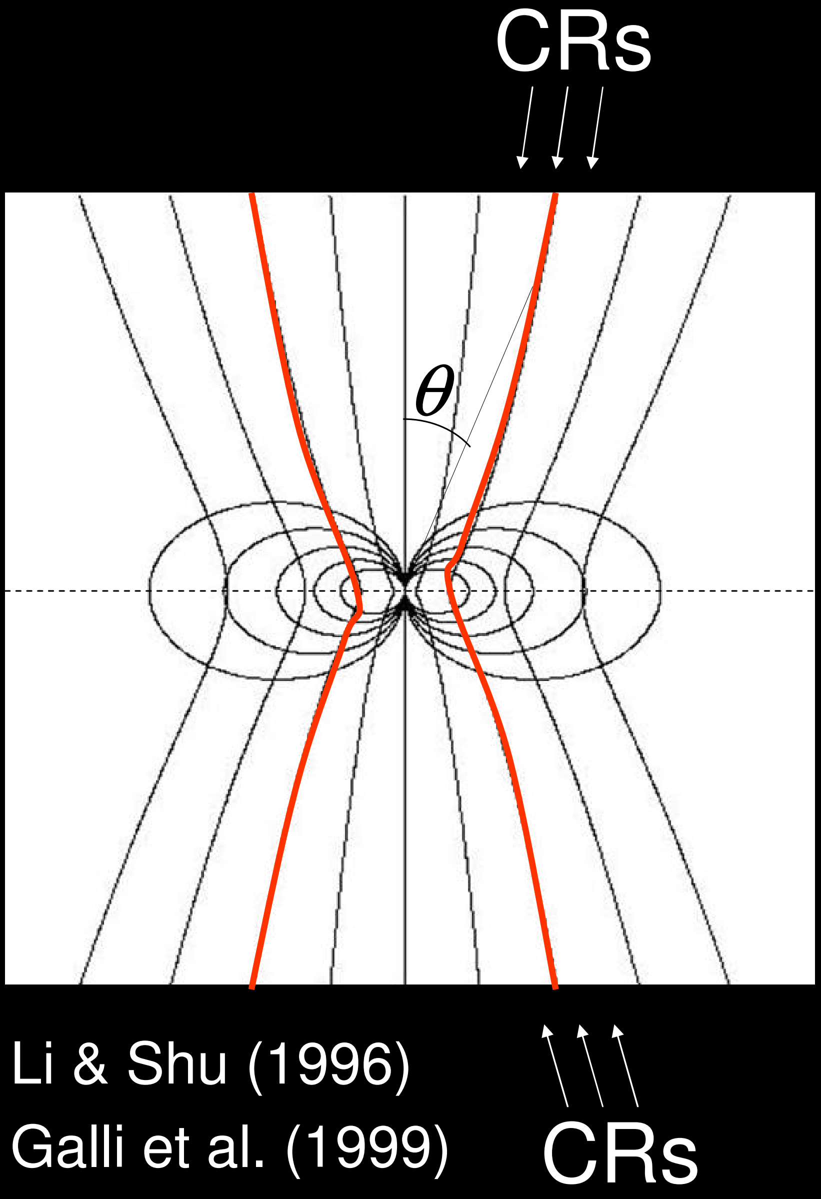


Girart et al. (2009)

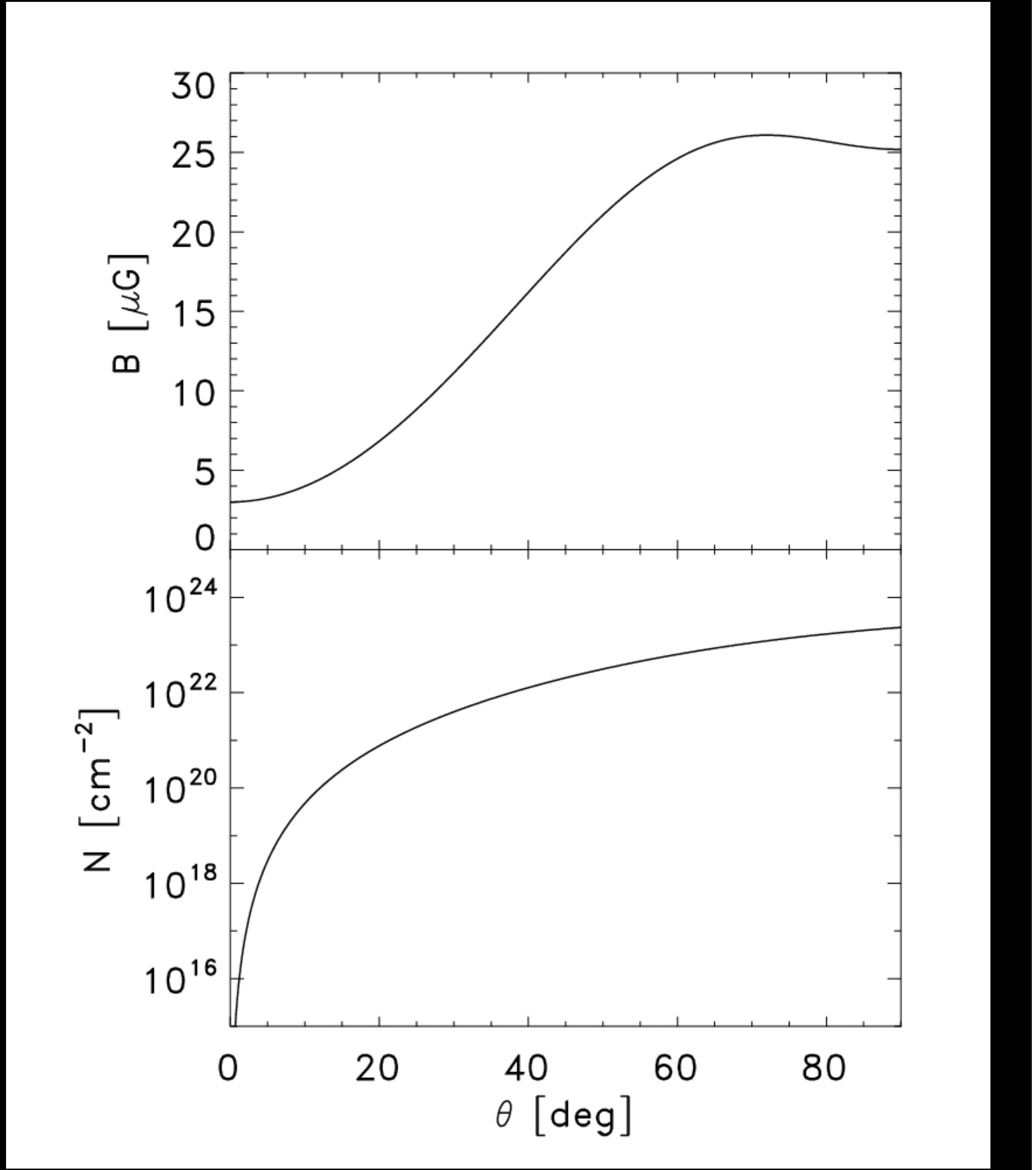


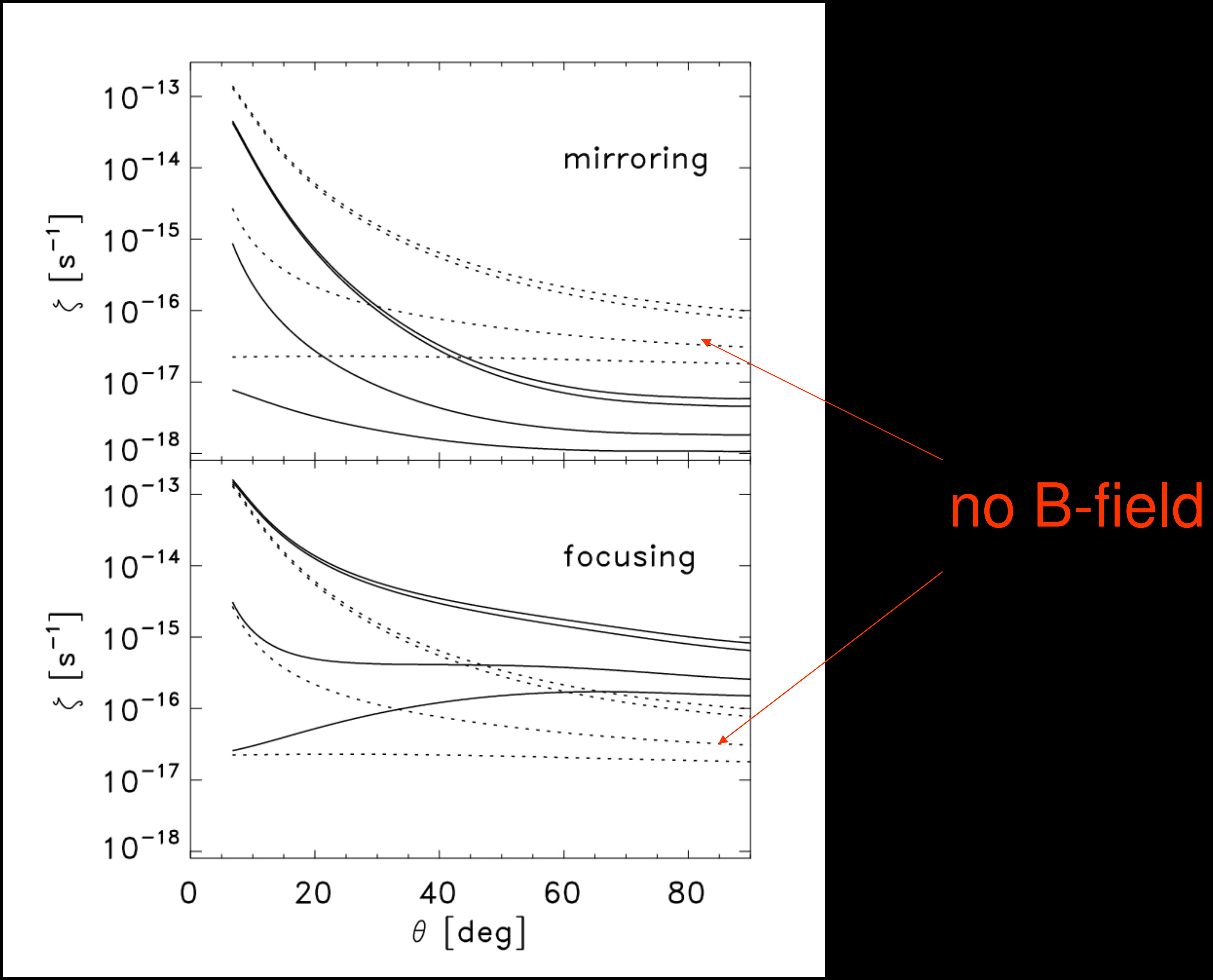
Tang et al. (2009)

Magnetostatic self-gravitating cloud core



Li & Shu (1996)
Galli et al. (1999)

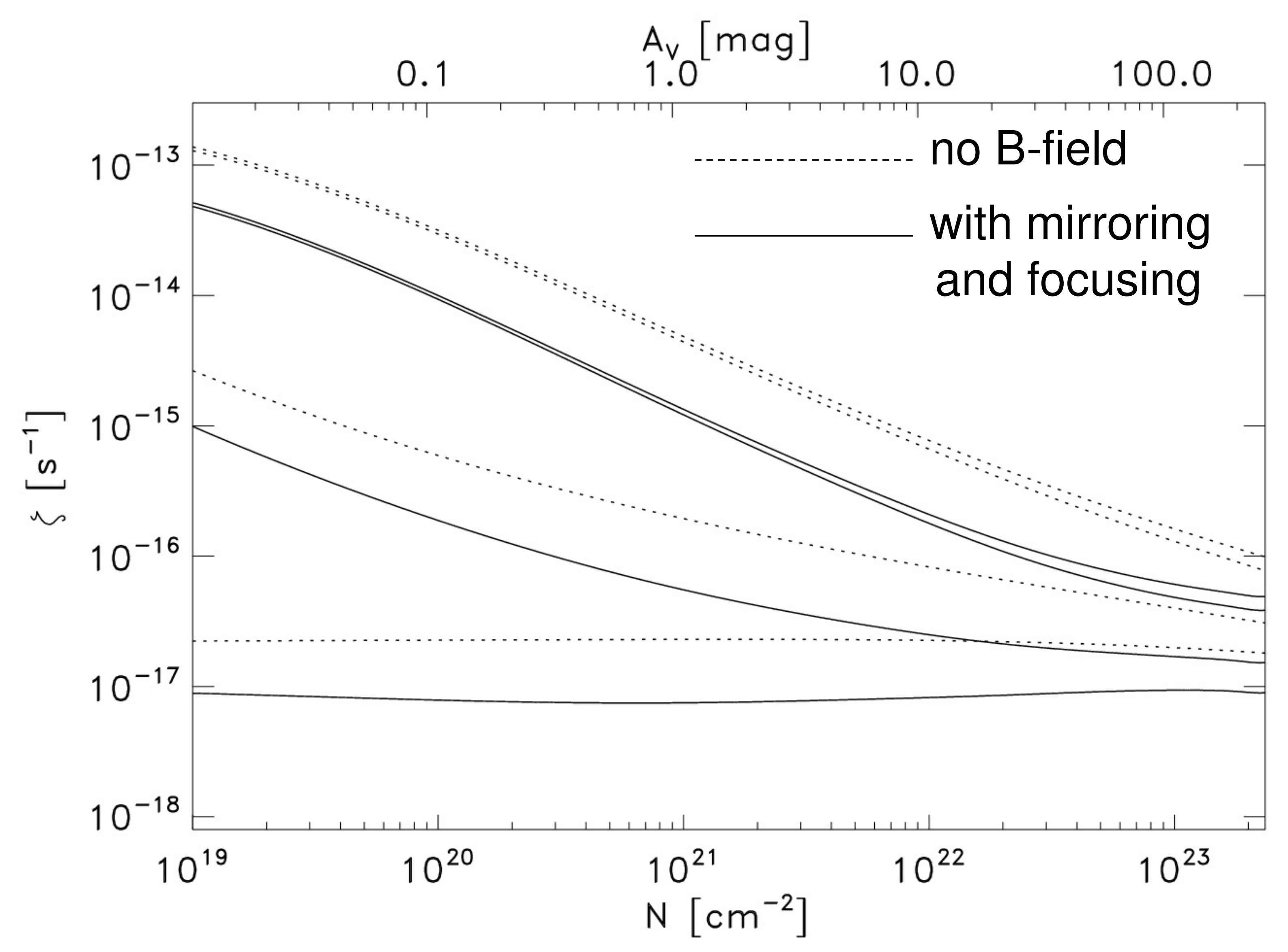




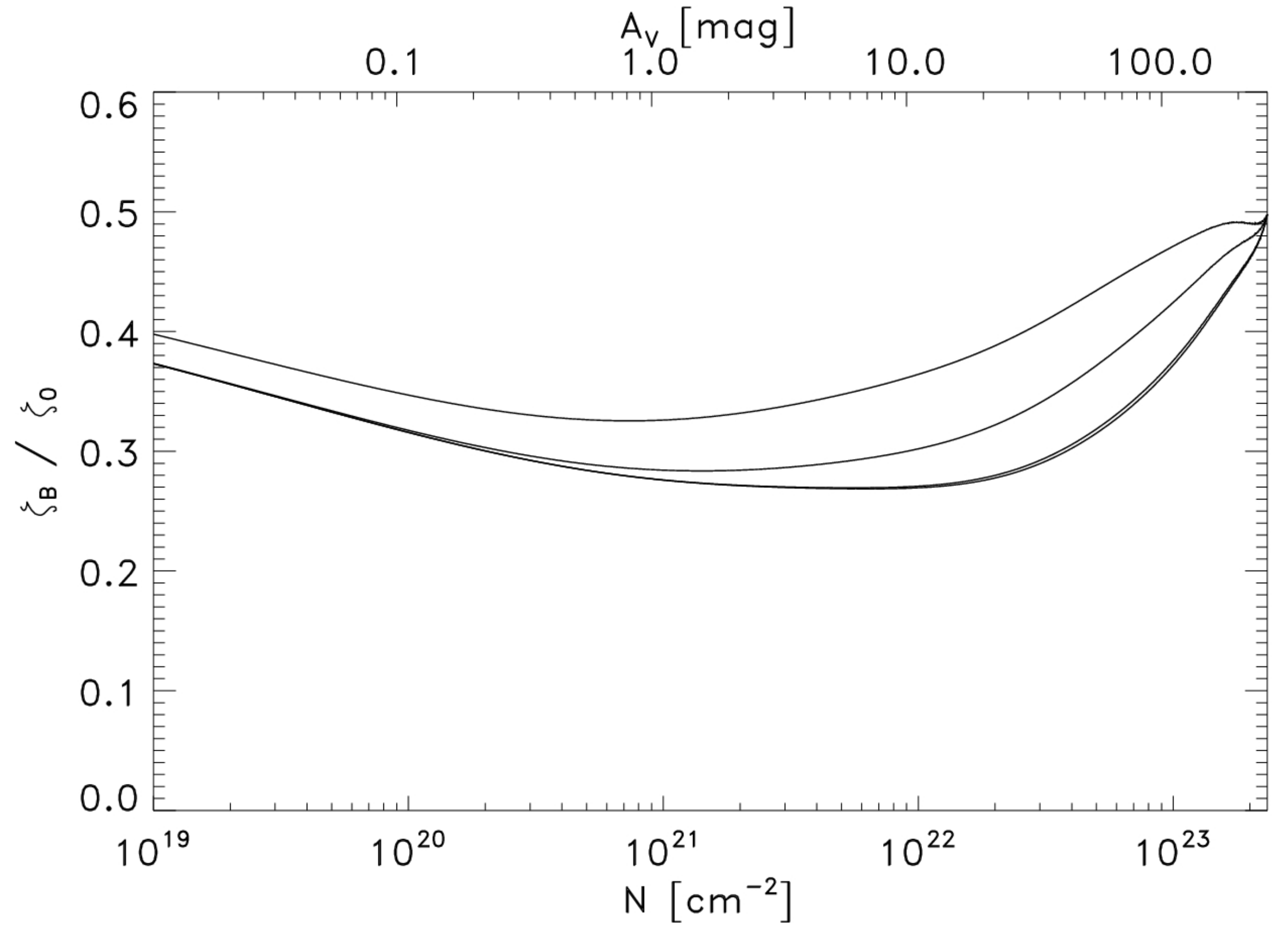
no B-field

Padovani et al., in prep

ζ_{CR} in a molecular cloud core



Reduction of ζ_{CR} in a molecular cloud core by mirroring and focusing



Conclusions

- Low-energy CR (below ~100 MeV) can explain higher ionization rates in diffuse clouds.

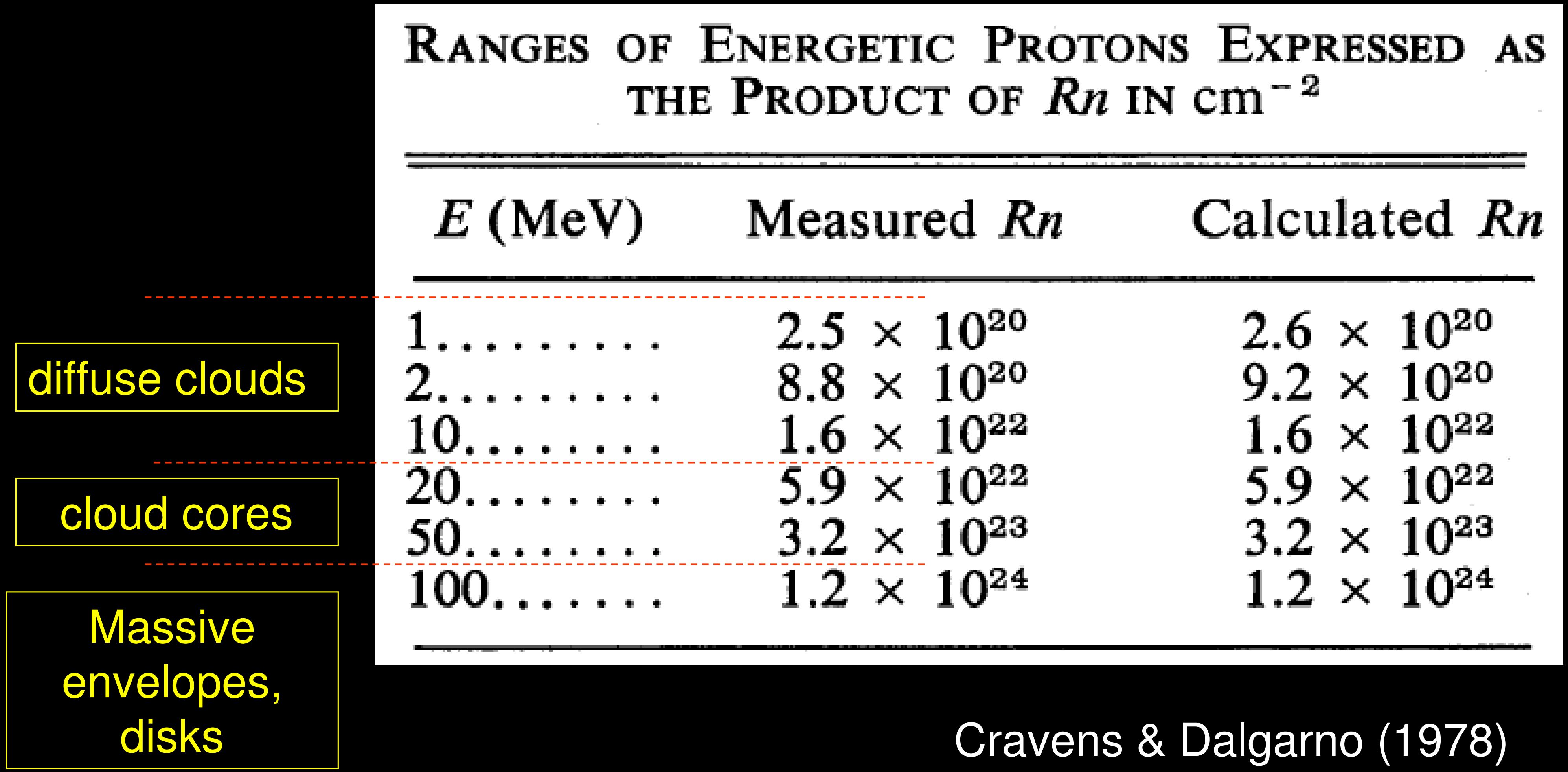
- Rising spectra of CR protons and/or electrons required to explain highest values of ζ_{CR} in diffuse clouds.

- The ionization rate at any depth in a cloud CANNOT be calculated by simply removing from the incident spectrum particles with energies corresponding to ranges below the assumed depth.

- Large spread of ζ_{CR} in dense clouds: problems with chemistry? Cloud's magnetic fields?

- Values of $\zeta_{CR} < 10^{-17}$ s^{-1} require suppression mechanism.

- In cores, mirroring > focusing: factor of ~2 reduction of ζ_{CR}.



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}

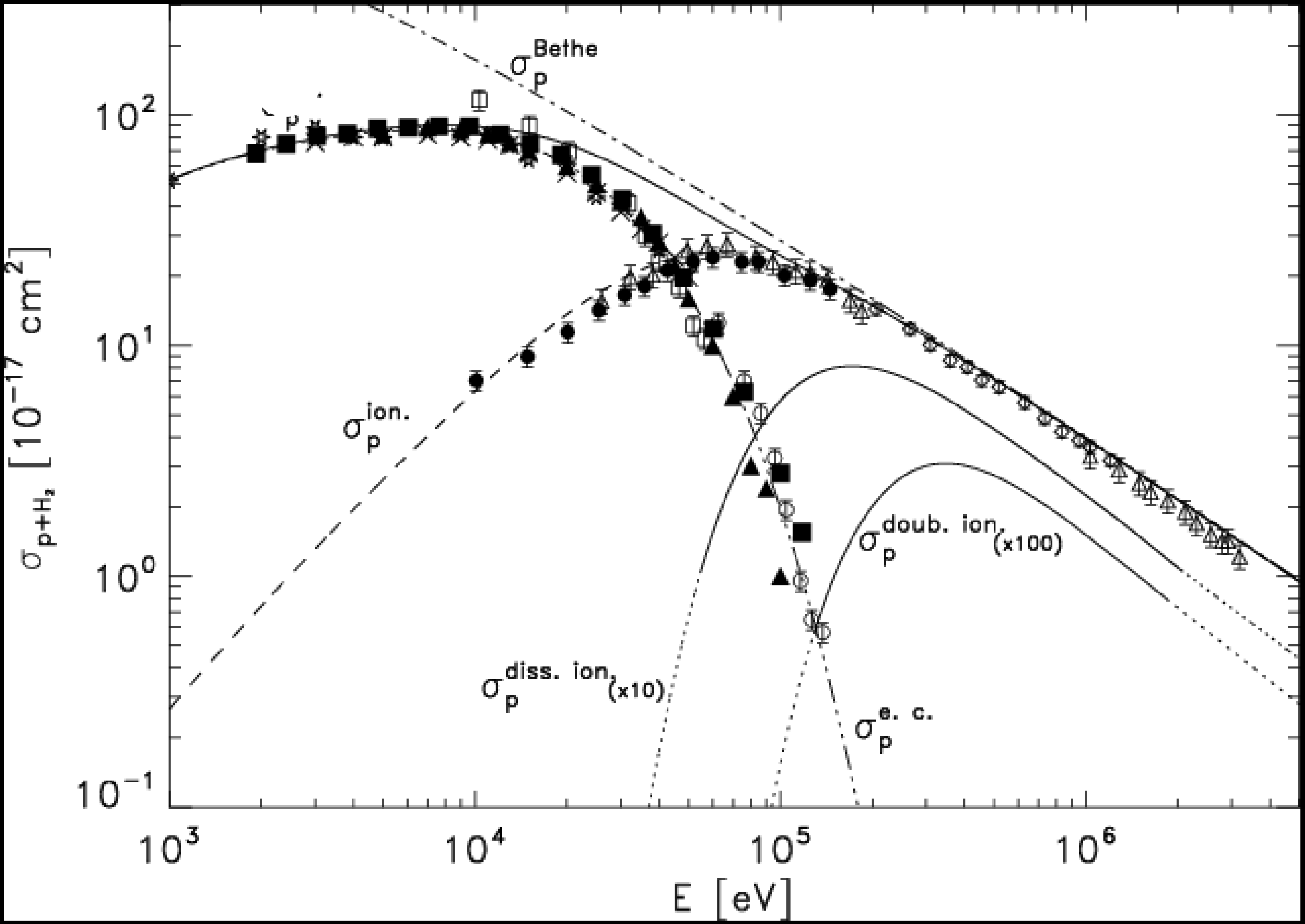
diffuse clouds

cloud cores

Massive envelopes, disks

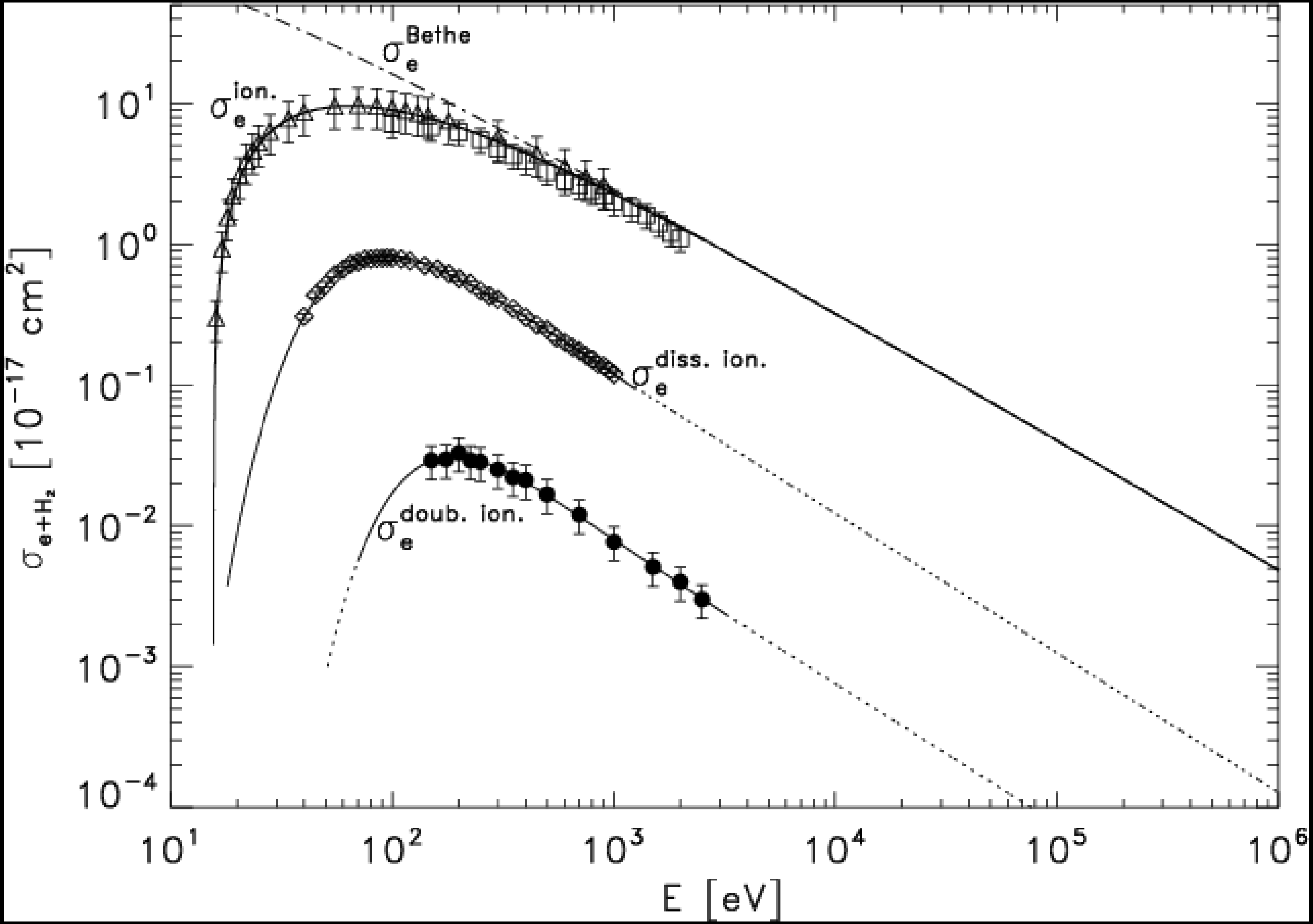
Cravens & Dalgarno (1978)

proton impact on H_2



Padovani et al. (2009)

electron impact on H_2



Padovani et al. (2009)

Energy Constraints

- CR protons
  - 0.95 eV cm^{-3} (“low” spectrum)
  - 1.2 eV cm^{-3} (“high” spectrum)
- CR electrons
  - 0.017 eV cm^{-3} (“low” spectrum)
  - 0.57 eV cm^{-3} (“high” spectrum)

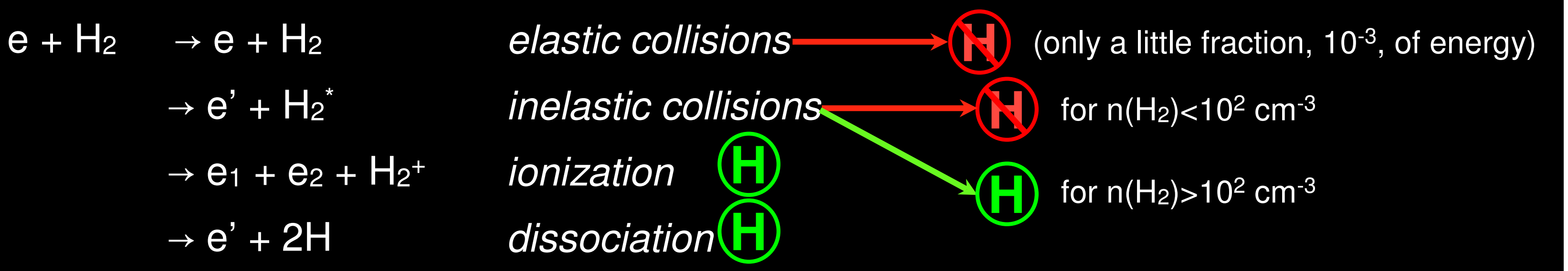
→ Total energy density = 0.97-1.8 eV cm^{-3}

corresponding to $B_{eq} \approx$ 6-8 μG

B = (6 ± 2) μG in the CNM (Heiles & Troland (2005)

H_2 regions : the excitation of the ro-vibrational levels leads to energy losses (**heating**) through inelastic collisions down to 0.044 eV, the threshold of the excitation of the level j = 0→2 for para–hydrogen.

electrons



$e + H_2 \rightarrow e + H_2$ *elastic collisions* (only a little fraction, 10^{-3}, of energy)

$\rightarrow e' + H_2^*$ *inelastic collisions* for $n(H_2)<10^2\ cm^{-3}$ / for $n(H_2)>10^2\ cm^{-3}$

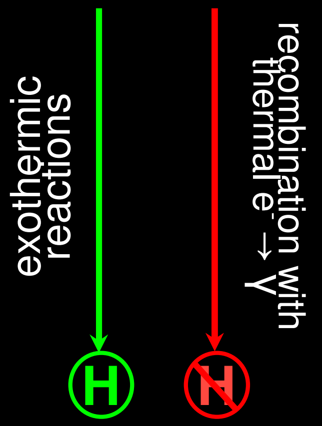
$\rightarrow e_1 + e_2 + H_2^+$ *ionization*

$\rightarrow e' + 2H$ *dissociation*

$$Q(E) = Q_{\rm ion} + Q_{\rm slow}(E) + Q_{\rm fast}(E)$$

protons

$p + H_2 \rightarrow H_2^+ + p_1 + e$



Glassgold & Langer (1973) : σ_{ion} only depends on the velocity and the charge of the incident particle, thus the ionization of a proton with energy E_p is equivalent to the one of an electron with energy $E_e = E_p\,(m_e/m_p)$.

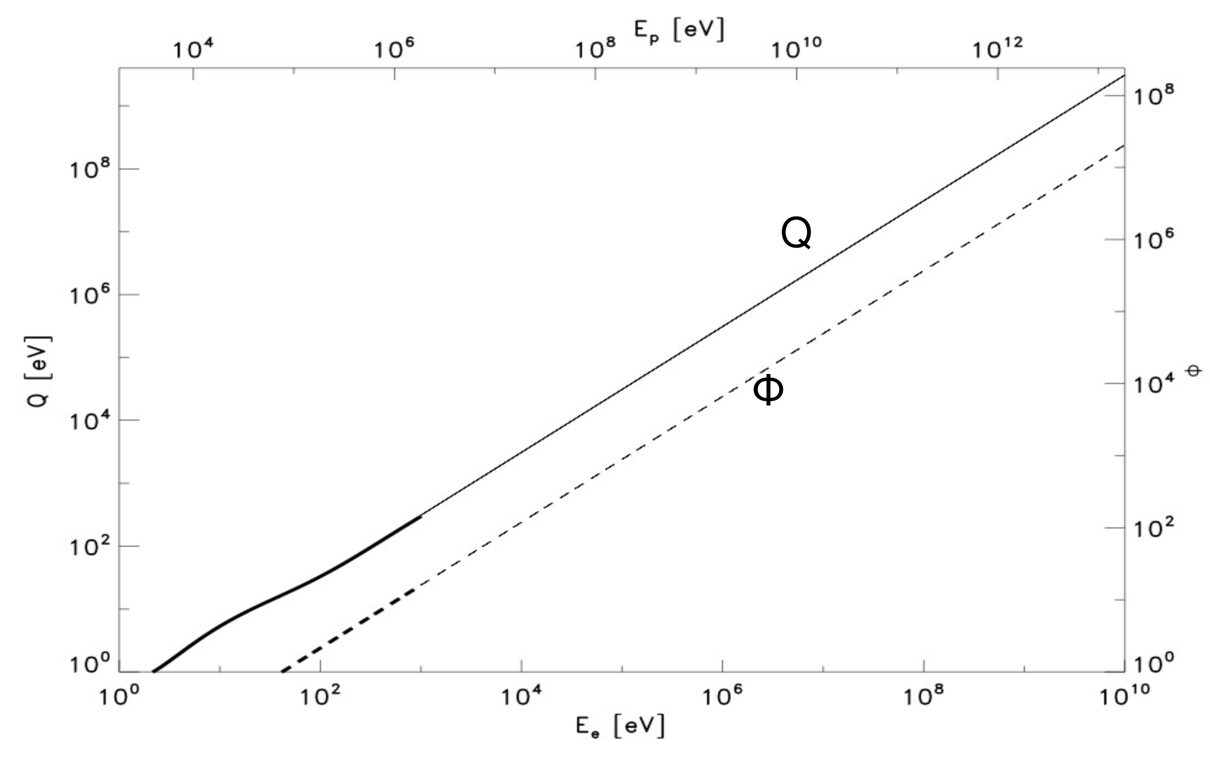
$$\langle E_{\rm h}\rangle = \frac{\int_0^\infty Q(E)\, j(E)\, \sigma(E)\, {\rm d}E}{\int_0^\infty [1+\phi(E)]\, j(E)\, \sigma(E)\, {\rm d}E}$$

~ 8.4 eV for protons
~ 12.9 eV for electrons

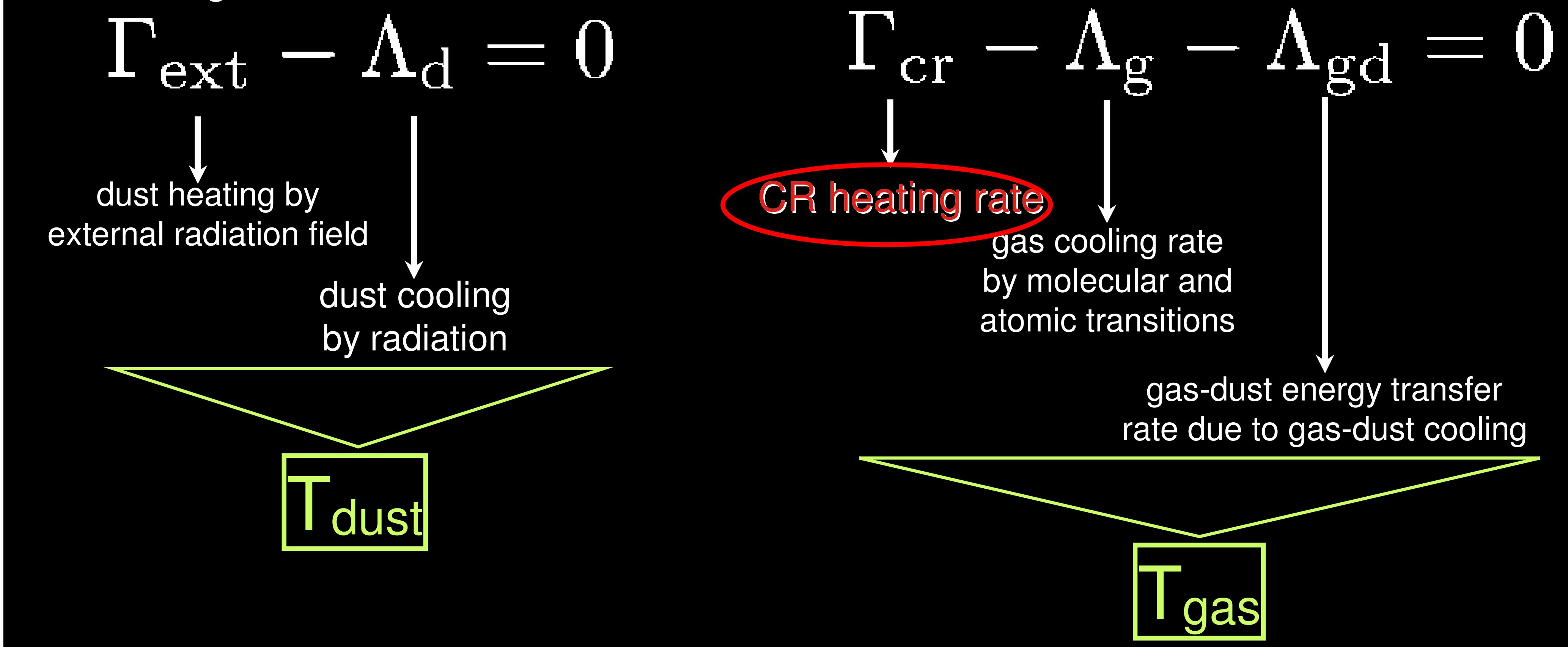
CR heating rate

$$\Gamma_{\rm CR} = \zeta_{\rm CR} \langle E_{\rm h} \rangle$$

Glassgold & Langer (1973) where Φ(E)
represents the number of secondary ionizations.



Study of the thermal equilibrium in prestellar cores in the approximation where the dust temperature is independent of interactions with the gas and where the gas is heated by cosmic rays and cooled by molecular and atomic transitions and collisions with dust grains.



$$\Gamma_{\mathrm{ext}} - \Lambda_{\mathrm{d}} = 0$$

dust heating by external radiation field

dust cooling by radiation

T_{dust}

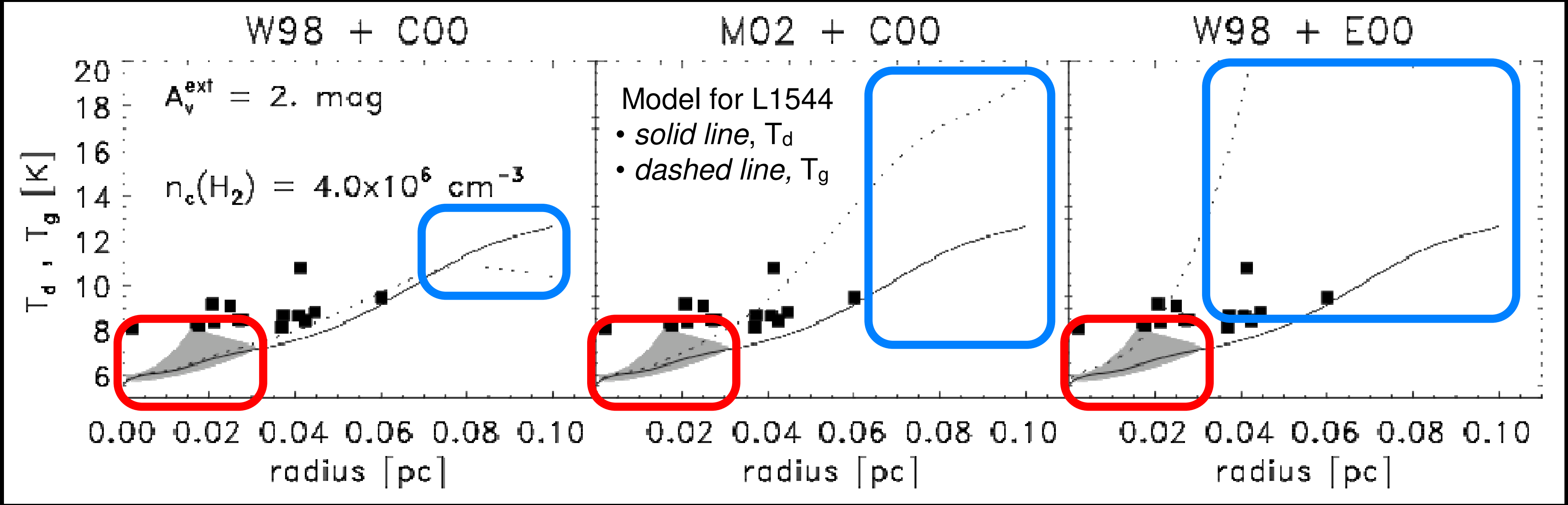
$$\Gamma_{\mathrm{cr}} - \Lambda_{\mathrm{g}} - \Lambda_{\mathrm{gd}} = 0$$

CR heating rate

gas cooling rate by molecular and atomic transitions

gas-dust energy transfer rate due to gas-dust cooling

T_{gas}



NEW CHALLENGES with NH_3 observations at Green Bank Telescope *(submitted proposal)*

(i) extending the NH_3 observations to larger radii is crucial. This is a challenge, because the emission drops fast with radius;

(ii) it is useful to redo the Effelsberg observations with the GBT telescope because of the much better beam efficiency of the latter;

(iii) as regard L1544, a GBT map is a follow-up of the observations done with the VLA (see Crapsi et al. 2007): given the expected size of emission, a single-dish observation is an important complementary aid, avoiding the problem of missing flux;

(iv) GBT observations are useful, in preparation for future observations at the VLA using the new correlator.

CR propagation inside a cloud

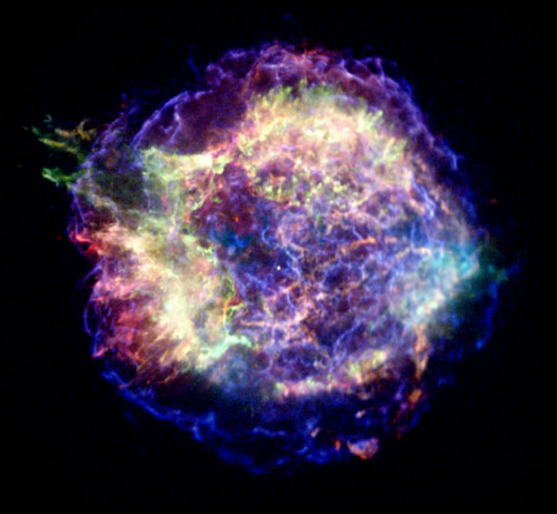


Image credit: NASA/CXC/UMass Amherst/M.D.Stage et al.