PCMI INSU
PHYSIQUE et CHIMIE du MILIEU INTERSTELLAIRE
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# Cosmic-ray propagation in molecular clouds

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# The impact of cosmic rays on the ISM

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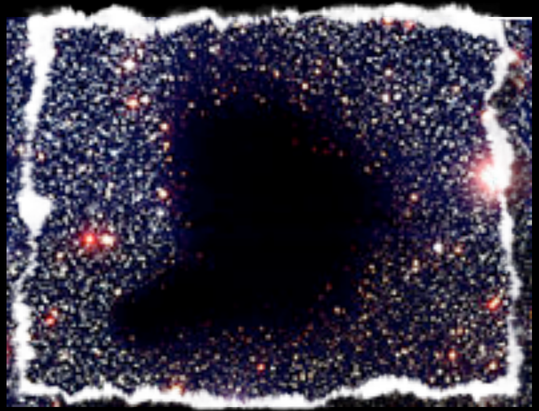
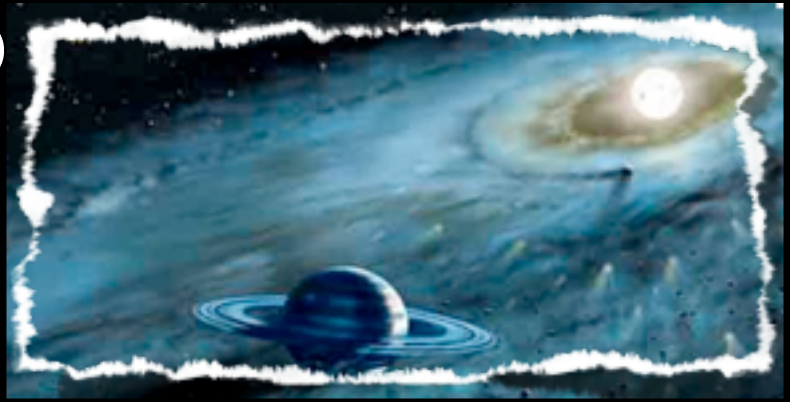
# Why CRs are so important?

**Cosmic rays are the dominant source of ionisation in dense, cold and UV-shielded gas.**

- In MCs, CRs originate the chemistry



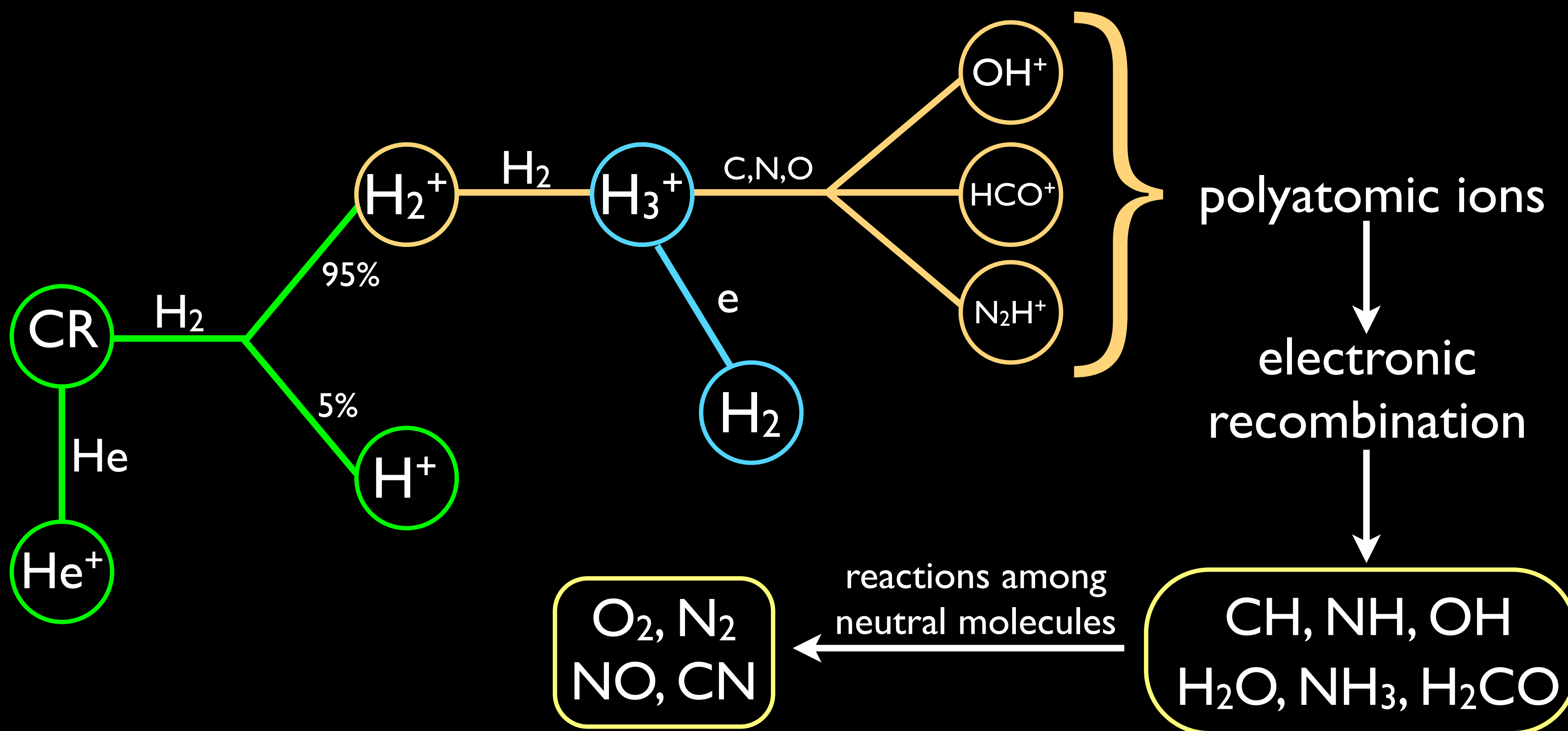
- CRs affect the planet formation process (e.g. via MRI)



- CRs affect the star formation process (e.g. via ambipolar diffusion)

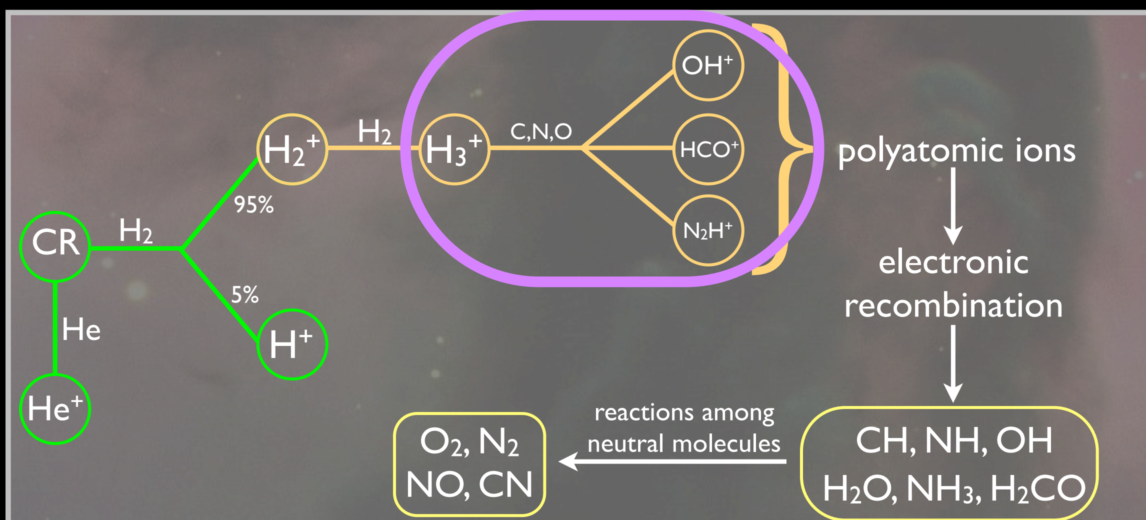
# CRs-ISM interaction

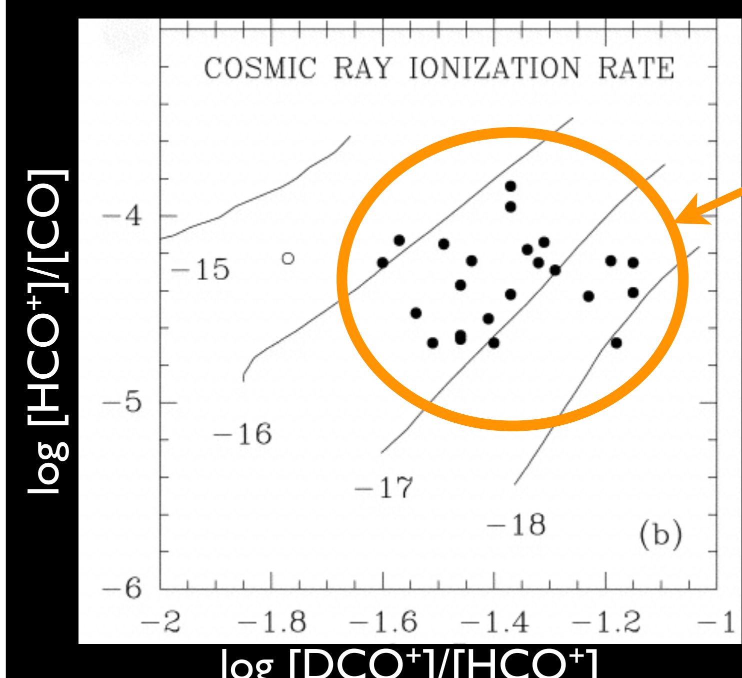
- Diffuse clouds ($A_v \sim 1$ mag) → the UV radiation field is the principal ionising agent (photodissociation regions);
- Dense clouds ($A_v \gtrsim 5$ mag) → the ionisation is due to low-energy CRs ($E < 100$ MeV) and, if close to young stars, to soft X–rays ($E < 10$ keV).



# Observational determination of the ionisation rate

## Dense clouds



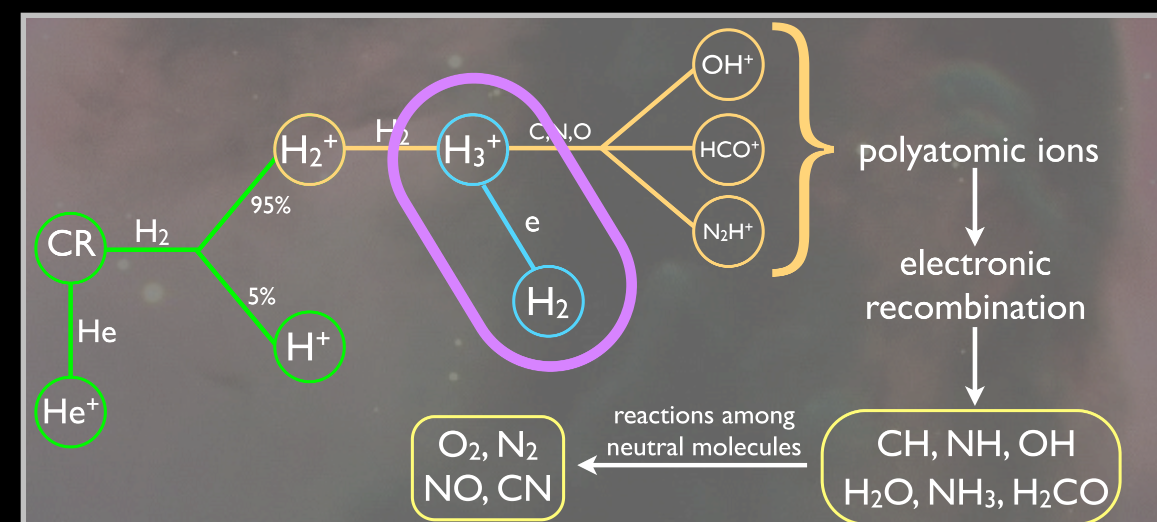




sample of 24 molecular cloud cores

Caselli+ 1998: analytical and chemical models. Results are dependent on the depletion of elemental carbon and oxygen.

## Diffuse clouds

- McCall+ 1998, 2002, 2003; Indriolo+ 2007, 2010, 2012; Crabtree+ 2011: **$H_3^+$ in diffuse clouds**.




$H_3^+$ chemistry in diffuse clouds is simpler

Formation: $CR + H_2 \rightarrow H_2^+ + e$

$H_2^+ + H_2 \rightarrow H_3^+ + H$

rate $= \zeta_{CR}\, n(H_2)$

Destruction: $H_3^+ + e \rightarrow H + H_2$ or $3H$

rate $= k_e\, n(H_3^+)\, n(e)$

**steady state** : $\zeta_{CR}\, n(H_2) = k_e\, n(H_3^+)\, n(e)$

$\zeta_{CR} \sim 10^{-16} - 10^{-15}\ s^{-1}$ ⟶ **ONE order of magnitude** larger than in dense clouds.

# Observational determination of the ionisation rate

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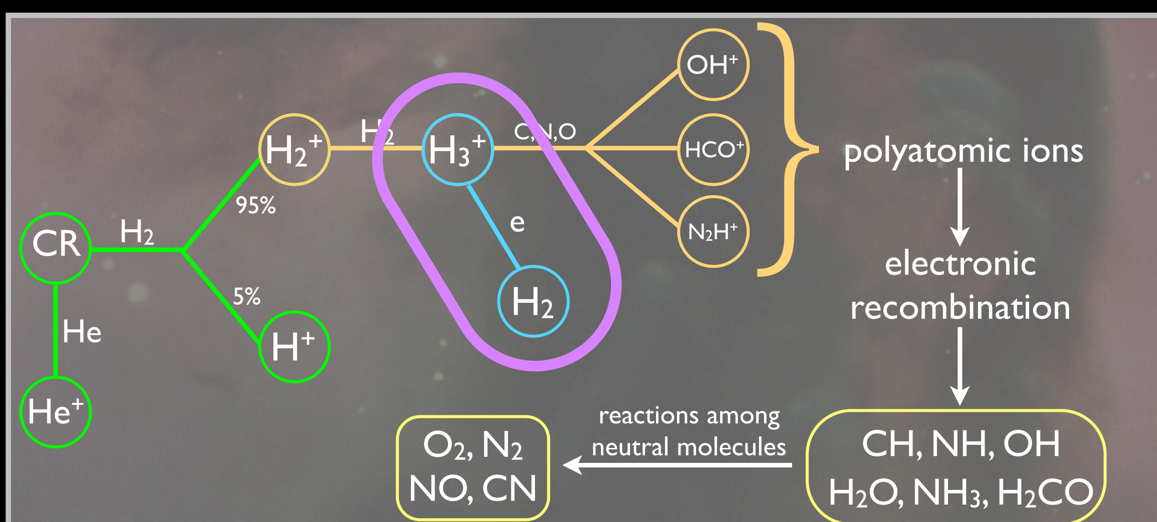


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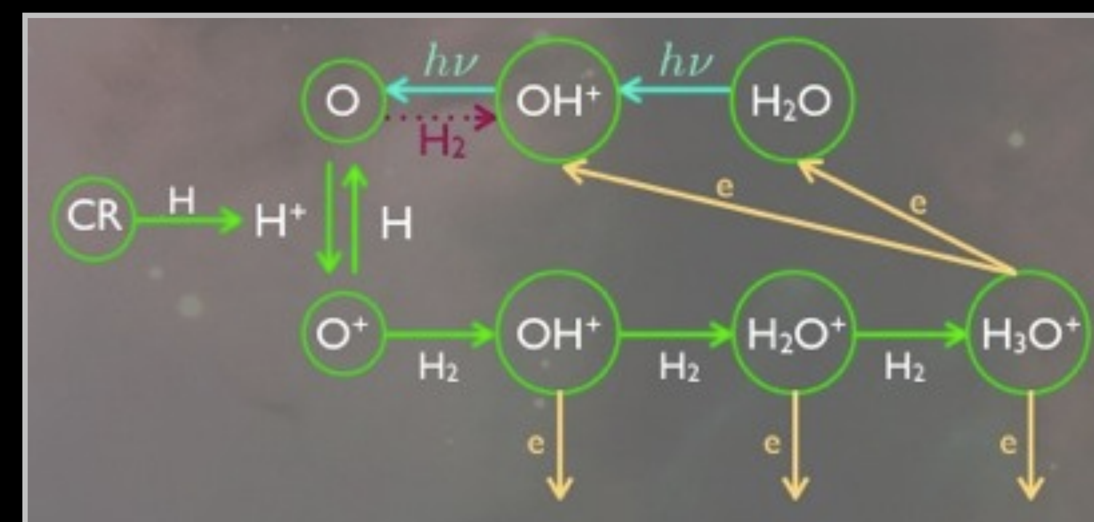
## Diffuse clouds

- Gerin+ 2010; Neufeld+ 2010: **probing the CR ionisation rate in clouds of low $H_2$ fraction**.




| Number | Reaction | Rate ($cm^{-3}s^{-1}$) |
|---|---|---|
| 1 | $OH^+ + H_2 \rightarrow H_2O^+ + H$ | $k_1 = 1.01 \times 10^{-9}$ |
| 2 | $H_2O^+ + H_2 \rightarrow H_3O^+ + H$ | $k_2 = 6.4 \times 10^{-10}$ |
| 3 | $H_2O^+ + e^- \rightarrow$ products | $k_3 = 4.3 \times 10^{-7}(T/300\,K)^{-0.5}$ |
| 4 | $H_3O^+ + e^- \rightarrow$ products | $k_4 = 4.3 \times 10^{-7}(T/300\,K)^{-0.5}$ |
| 5 | $OH^+ + e^- \rightarrow$ products | $k_5 = 3.75 \times 10^{-8}(T/300\,K)^{-0.5}$ |

$\zeta_{CR}(H) \sim 0.6 - 2.4 \times 10^{-16}\ s^{-1}$

Estimate in good agreement with Indriolo+ (2012) from the analysis of $H_3^+$ abundances.

# Hunting the CR production sites

**While the bulk of the ionisation is due to MeV CRs, GeV-TeV CRs interact with ISM atoms and molecules yielding $\pi^0 \rightarrow 2\gamma$**

interaction between CR-p and ISM-p,α

| | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| $p+p$ | $\rightarrow$ | $p$ | $+$ | $p$ | | | | | $+$ | $a(\pi^+ + \pi^-)$ | $+$ | $b\pi^0$ |
| $p+p$ | $\rightarrow$ | $p$ | $+$ | $n$ | $+$ | | | $\pi^+$ | $+$ | $a(\pi^+ + \pi^-)$ | $+$ | $b\pi^0$ |
| $p+p$ | $\rightarrow$ | $n$ | $+$ | $n$ | $+$ | | | $2\pi^+$ | $+$ | $a(\pi^+ + \pi^-)$ | $+$ | $b\pi^0$ |
| $p+\alpha$ | $\rightarrow$ | $p$ | $+$ | | | | | $\alpha$ | $+$ | $a(\pi^+ + \pi^-)$ | $+$ | $b\pi^0$ |
| $p+\alpha$ | $\rightarrow$ | $p$ | $+$ | $n$ | $+$ | | | $^3\mathrm{He}$ | $+$ | $a(\pi^+ + \pi^-)$ | $+$ | $b\pi^0$ |
| $p+\alpha$ | $\rightarrow$ | $p$ | $+$ | $p$ | $+$ | $n$ | $+$ | $^2\mathrm{H}$ | $+$ | $a(\pi^+ + \pi^-)$ | $+$ | $b\pi^0$ |
| $p+\alpha$ | $\rightarrow$ | $4p$ | $+$ | $n$ | $+$ | | | $\pi^-$ | $+$ | $a(\pi^+ + \pi^-)$ | $+$ | $b\pi^0$ |
| $p+\alpha$ | $\rightarrow$ | $3p$ | $+$ | $2n$ | | | | | $+$ | $a(\pi^+ + \pi^-)$ | $+$ | $b\pi^0$ |
| $p+\alpha$ | $\rightarrow$ | $2p$ | $+$ | $3n$ | | | | | $+$ | $a(\pi^+ + \pi^-)$ | $+$ | $b\pi^0$ |
| $p+\alpha$ | $\rightarrow$ | $p$ | $+$ | $4n$ | $+$ | | | $2\pi^+$ | $+$ | $a(\pi^+ + \pi^-)$ | $+$ | $b\pi^0$ |

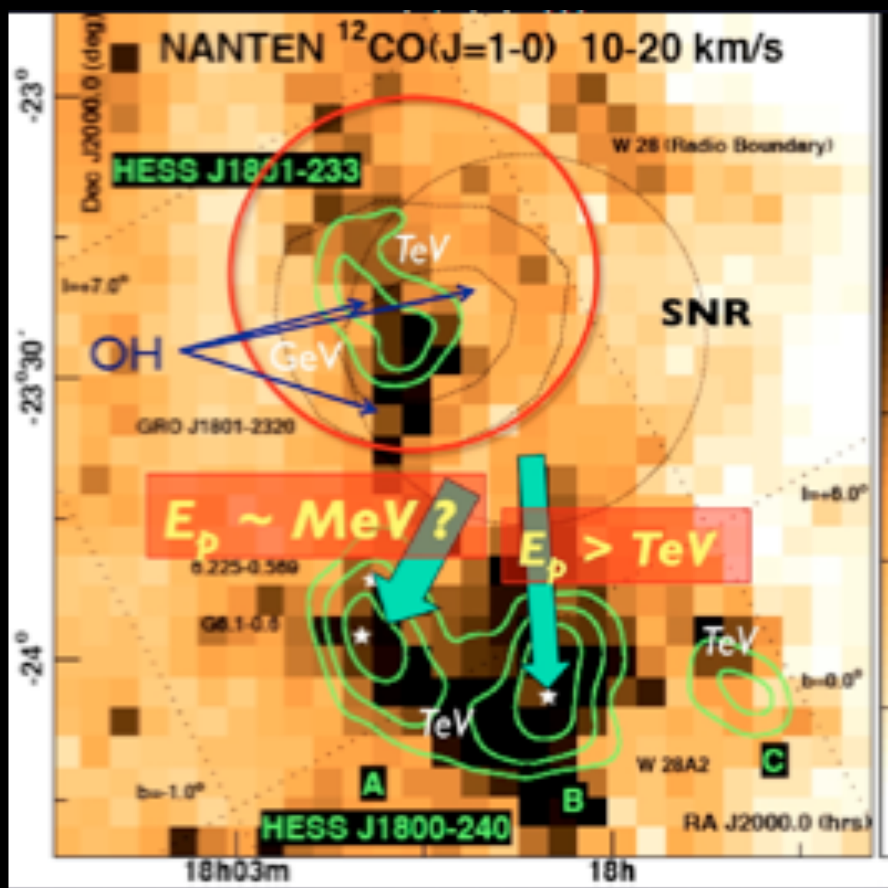
Criteria:

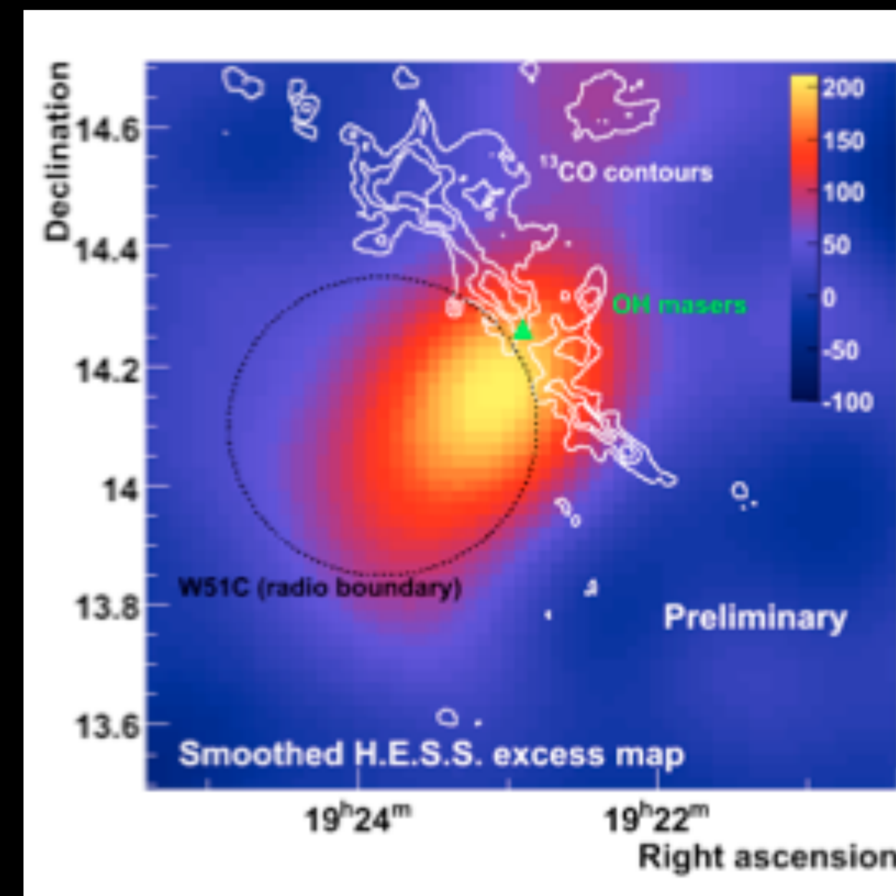
- The region must be close to a SNR
- The region has to be close to/associate with TeV emission
- The gas ionisation must be enhanced

$$F_\gamma = j_\gamma \frac{M_{\mathrm{cloud}}}{m_{\mathrm{p}} 4\pi d^2}$$

MCs associated with bright γ-ray sources likely probe enhanced >GeV CR densities.

# Hunting the CR production sites



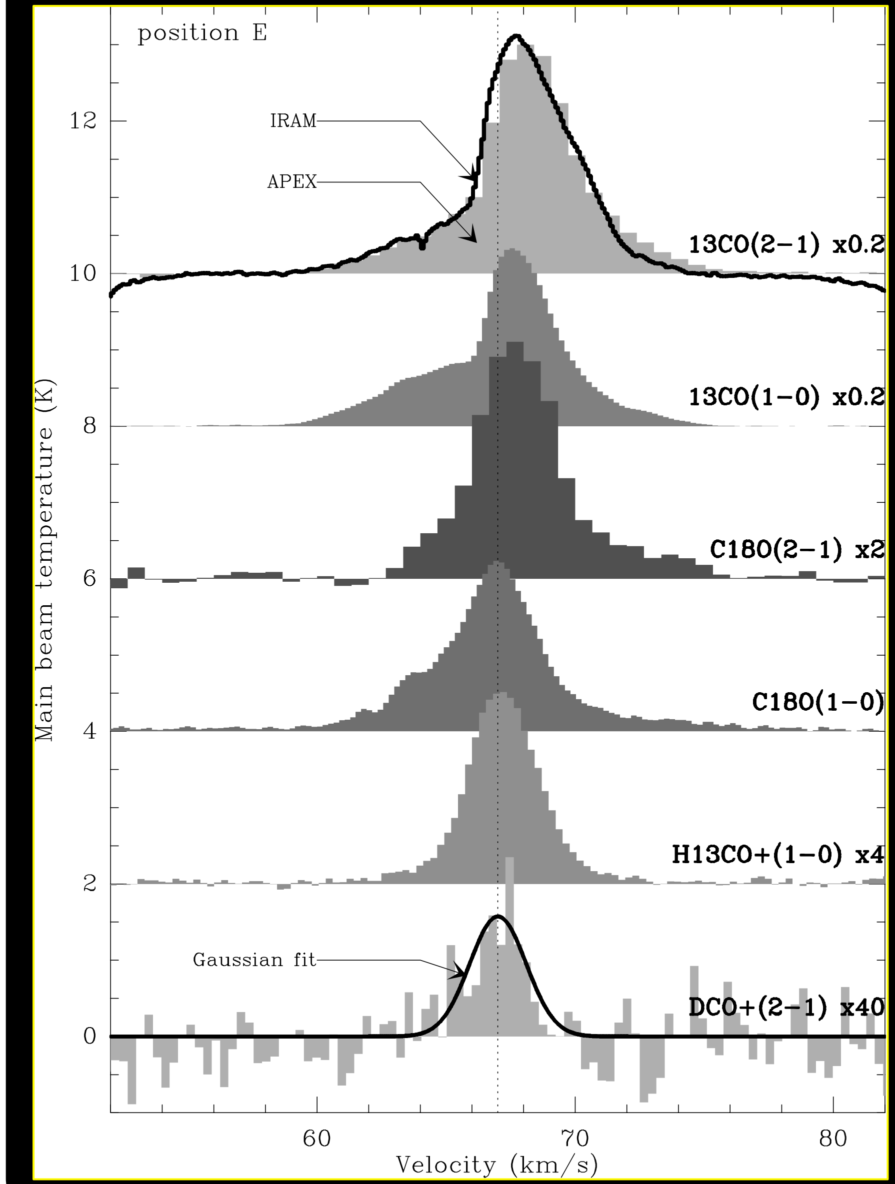




**The new HESS, MAGIC, FERMI-LAT observations provide high spatial resolution images of γ-ray emission and several images of TeV sources in proximity of MCs.**

# The region close to the SNR W51C

## Ceccarelli, Hily-Blant, Montmerle, Dubus, Gallant & Fiasson (ApJL 2011)

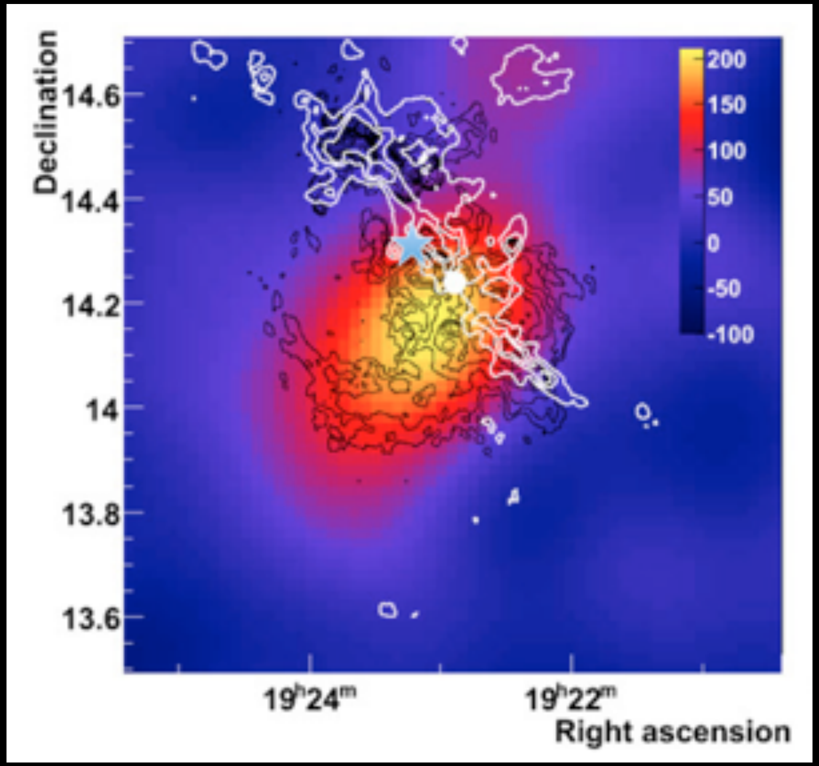
W51C is a SNR at ~ 6 kpc distance, associated with a bright TeV source, HESS J1923+141. A molecular cloud overlaps partially with the observed TeV emission.




6 lines observed

$C^{18}O$(1-0, 2-1), $^{13}CO$ (1-0, 2-1), $H^{13}CO^+$(1-0), $DCO^+$(2-1) towards 5 positions

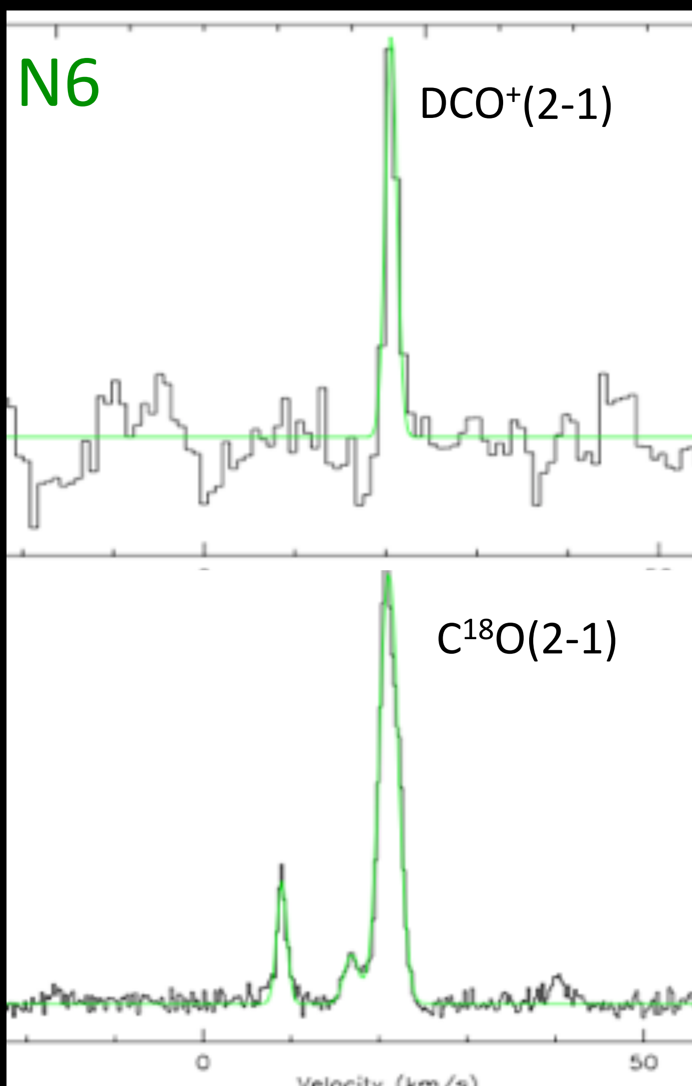
$DCO^+$ has been detected towards one position allowing to estimate the CR ionisation rate (stringent upper limits on the other four points).



# The region close to the SNR W28

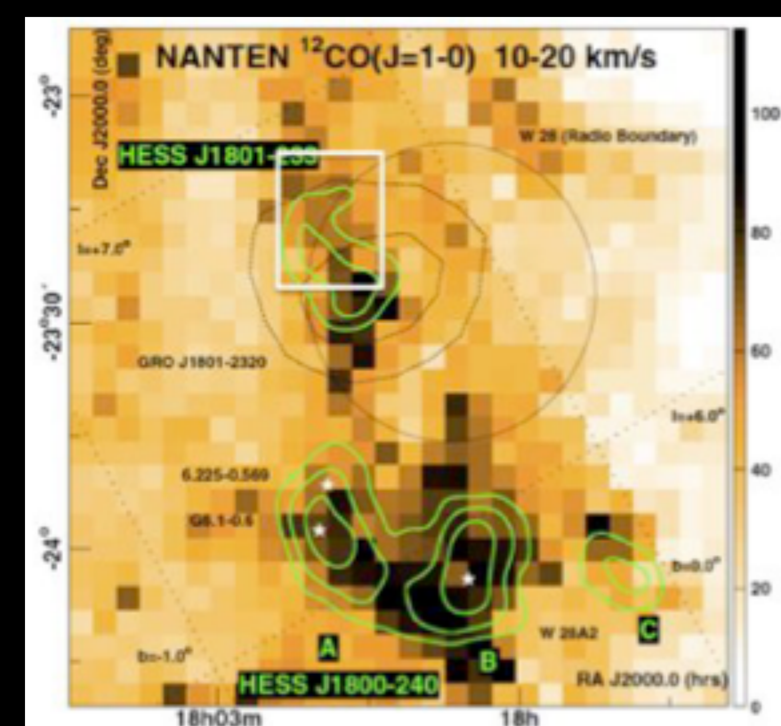
## Vaupre, Ceccarelli, Hily-Blant, Dubus, Lefloch & Montmerle (in prep.)

W28 is a SNR at ~ 2 kpc distance, associated with bright TeV emission broken into three peaks (see map). Several MCs are spatially overlapped with the observed TeV emission.




6 lines observed
$C^{18}O$(1-0, 2-1), $^{13}CO$ (1-0, 2-1), $H^{13}CO^+$(1-0), $DCO^+$(2-1)
towards a dozen positions, roughly mapping the three peaks.

$DCO^+$ has been detected towards two positions in the north cloud allowing to estimate the CR ionisation rate (stringent upper limits on the other points).



Marco Padovani

PCMI 2012

Paris *nov20th2012*

# Estimating the ionisation rate in W51C-E

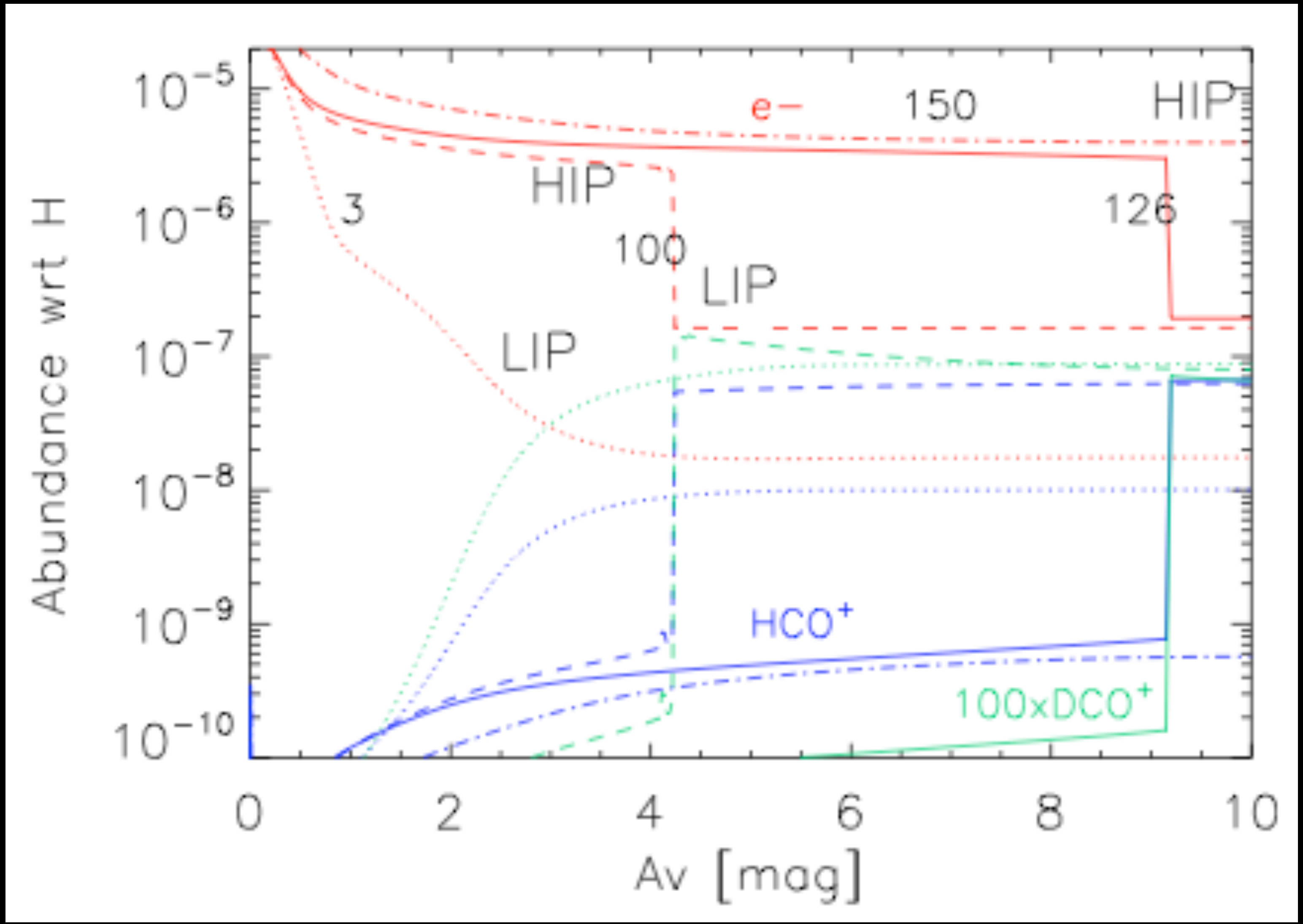
Physical parameters
*from $^{13}CO$ and $C^{18}O$ lines*

$T_{gas}$ = 21-24 K
n = 0.8-2×$10^4$ $cm^{-3}$
$N(C^{18}O)$ = 3.9-4.1×$10^{15}$ $cm^{-2}$
$A_V$ = 16-24 mag

Ionisation degree
*from $H^{13}CO^+$ and $DCO^+$ lines*

$DCO^+/HCO^+$ = 1.2-1.6×$10^{-3}$
x(e) > $10^{-5}$
analytical model

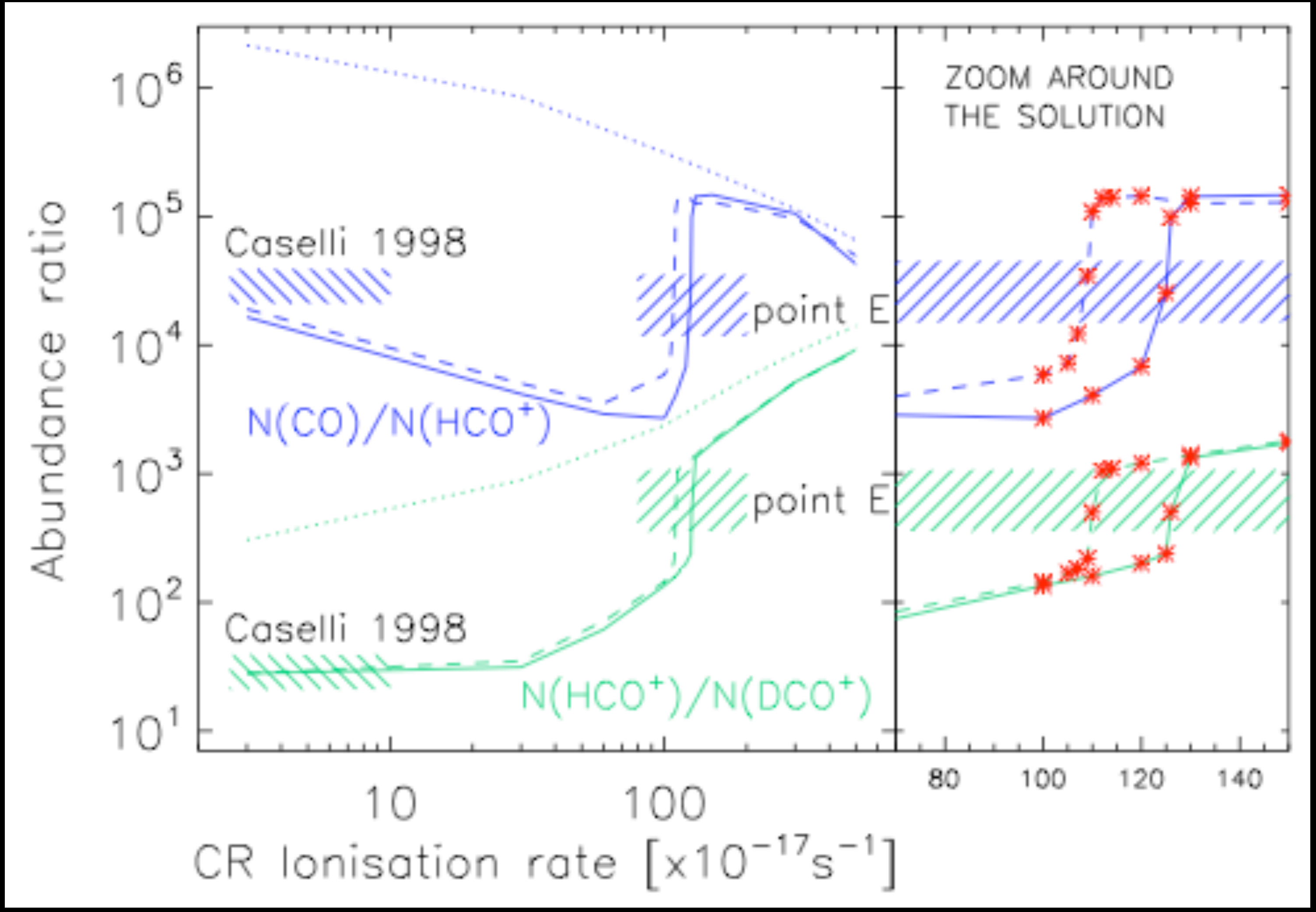
similar situation in W28




NOTE: LIP & HIP = LOW & HIGH IONISATION PHASE
(Pineau de Forêts et al. 1992)

In order to correctly evaluate the chemical structure of the cloud, including the penetration of the IS UV photons and a more complete chemical network, the PDR Meudon code (Le Petit+ 2006) has been used (thanks to J. Le Bourlot, F. Le Petit, and E. Roueff).

# Estimating the ionisation rate in W51C-E




A larger fraction of the cloud is in the HIP, while a small fraction (where $DCO^+$ is abundant) is in the LIP.

Similar situation in W28 (Vaupre+ in prep.)

Best solution achieved when $\zeta_{CR}$ is ~100 times the canonical value

## *The story so far...*

## Padovani, Galli & Glassgold (2009)

## Theoretical model

computing the variation of the ionisation rate due to cosmic rays, $\zeta_{CR}$ [$s^{-1}$], inside a molecular cloud, with the increasing of the column density, $N$ [$cm^{-2}$], of the traversed interstellar matter.

## Relevance of this work

- cosmic rays are the foremost ionising agents in dense molecular clouds;
- the chemistry of the interstellar medium originates from the hydrogen ionisation;
- partial coupling with magnetic field ***(Padovani & Galli 2011, A&A, 530, A109)***

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

correction due to the presence of heavy nuclei among CR

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

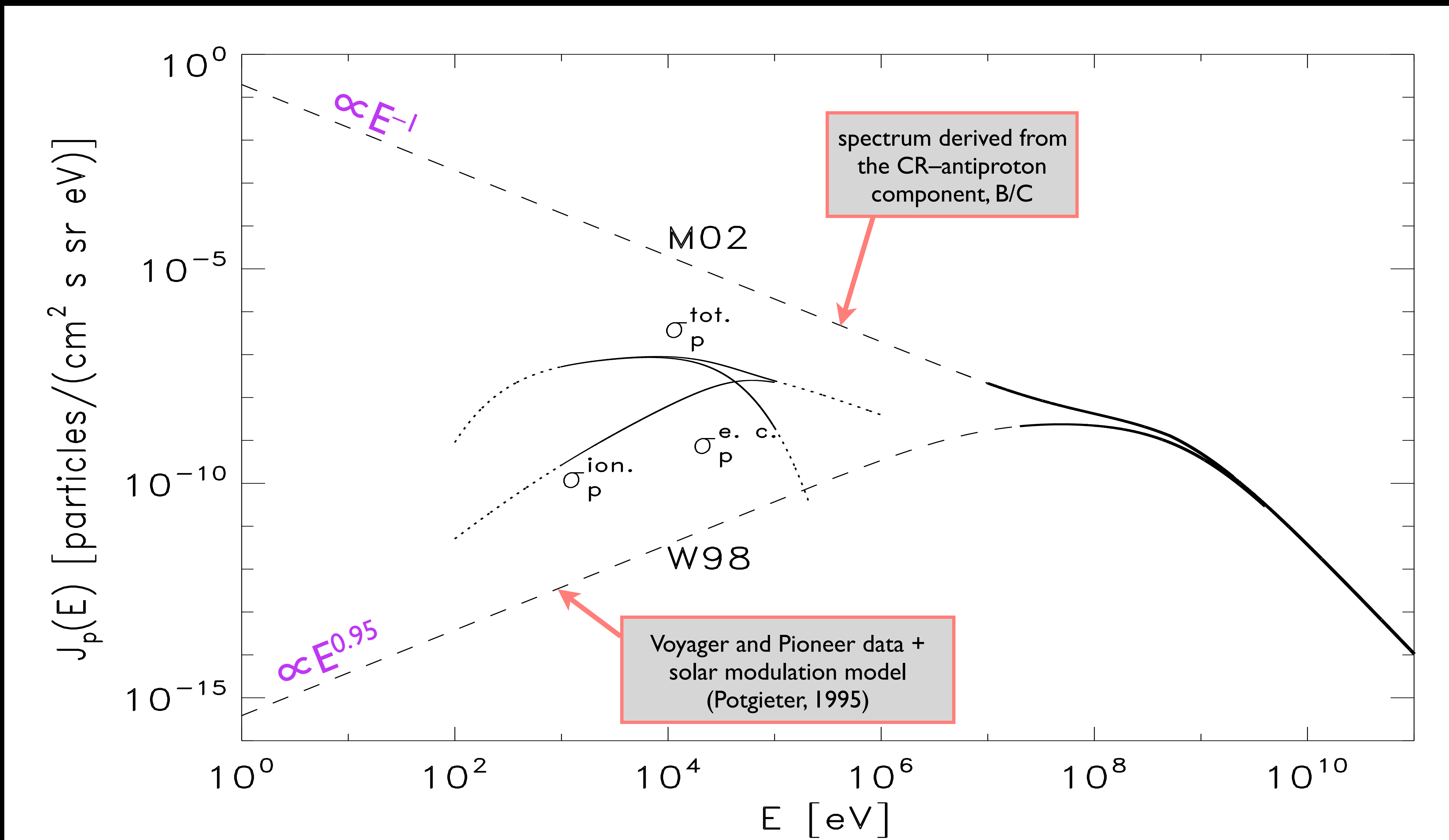
$$4\pi \int_0^\infty j_{\rm e}(E)\, \eta_{\rm sec}^{\rm e}\, \sigma_{\rm e+H_2}(E)\, {\rm d}E$$

correction due to the ionisation of secondary electrons

$$\begin{cases} \eta_{\rm sec}^{k} = 1 + \phi_k(E_k) \\ \phi_k(E_k) = \dfrac{1}{\sigma_k^{\rm ion.}(E_k)} \displaystyle\int_{E_{\rm ion.}}^{E_e'(E_k)_{\max}} P(E_k, E_e')\,\sigma_e^{\rm ion.}(E_e')\,{\rm d}E_e' \end{cases}$$

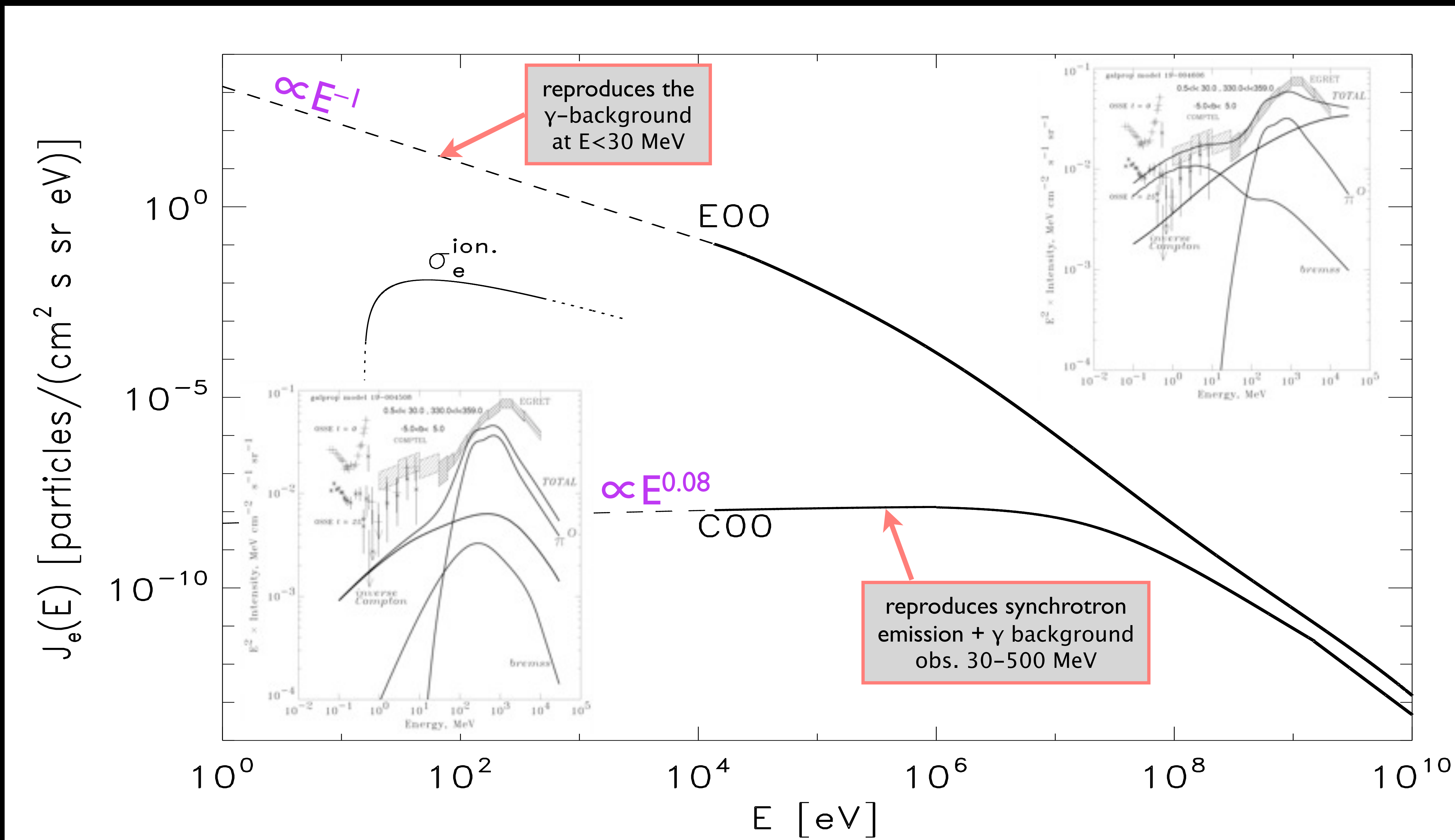
$$\left\{ \eta_h = 1 + \sum_{k\geq 2} \frac{f_k}{f_p} Z_k^2 \right.$$

# CR–proton spectrum in the solar neighbourhood




Padovani+ 2009

# CR–electron spectrum in the solar neighbourhood




Padovani+ 2009

# CR propagation inside a cloud

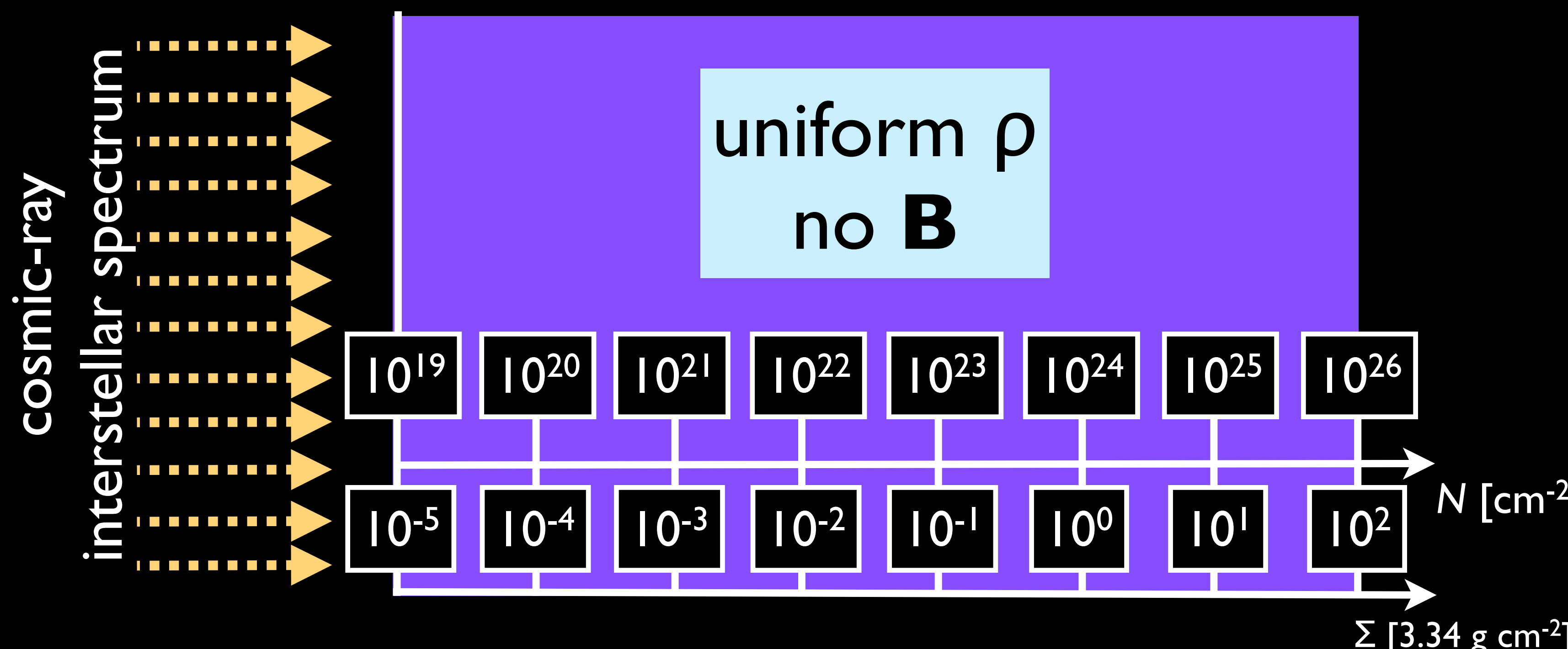
$$\zeta_{CR}^{(\mathrm{H}_2)}(N) = 4\pi \int_0^\infty j(E,N)\,\sigma(E)\,\mathrm{d}E$$

**Assumptions**:

*(i) slab geometry*
*(ii) continuous slowing-down approximation (or thick target)*

*(a)* particles propagate themselves along straight lines;
*(b)* the energy loss of a particle depends on the thickness of the traversed matter and on its initial energy through L(E).

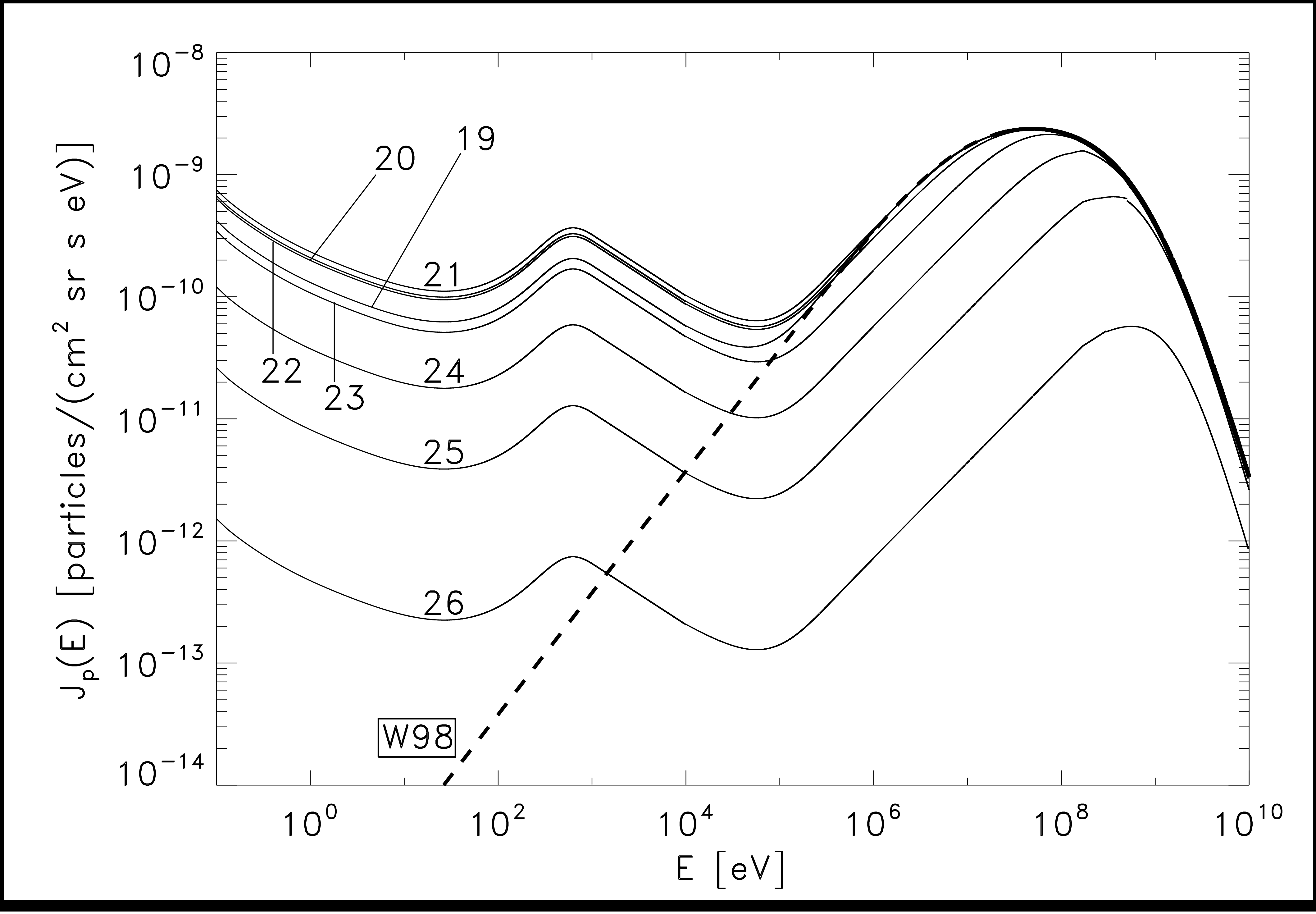
$$\begin{cases} L(E) = -\dfrac{1}{n(\mathrm{H}_2)}\dfrac{\mathrm{d}E}{\mathrm{d}x} = -\dfrac{\mathrm{d}E}{\mathrm{d}N} \\ N(\mathrm{H}_2) = \displaystyle\int n(\mathrm{H}_2)\,\mathrm{d}x \end{cases}$$



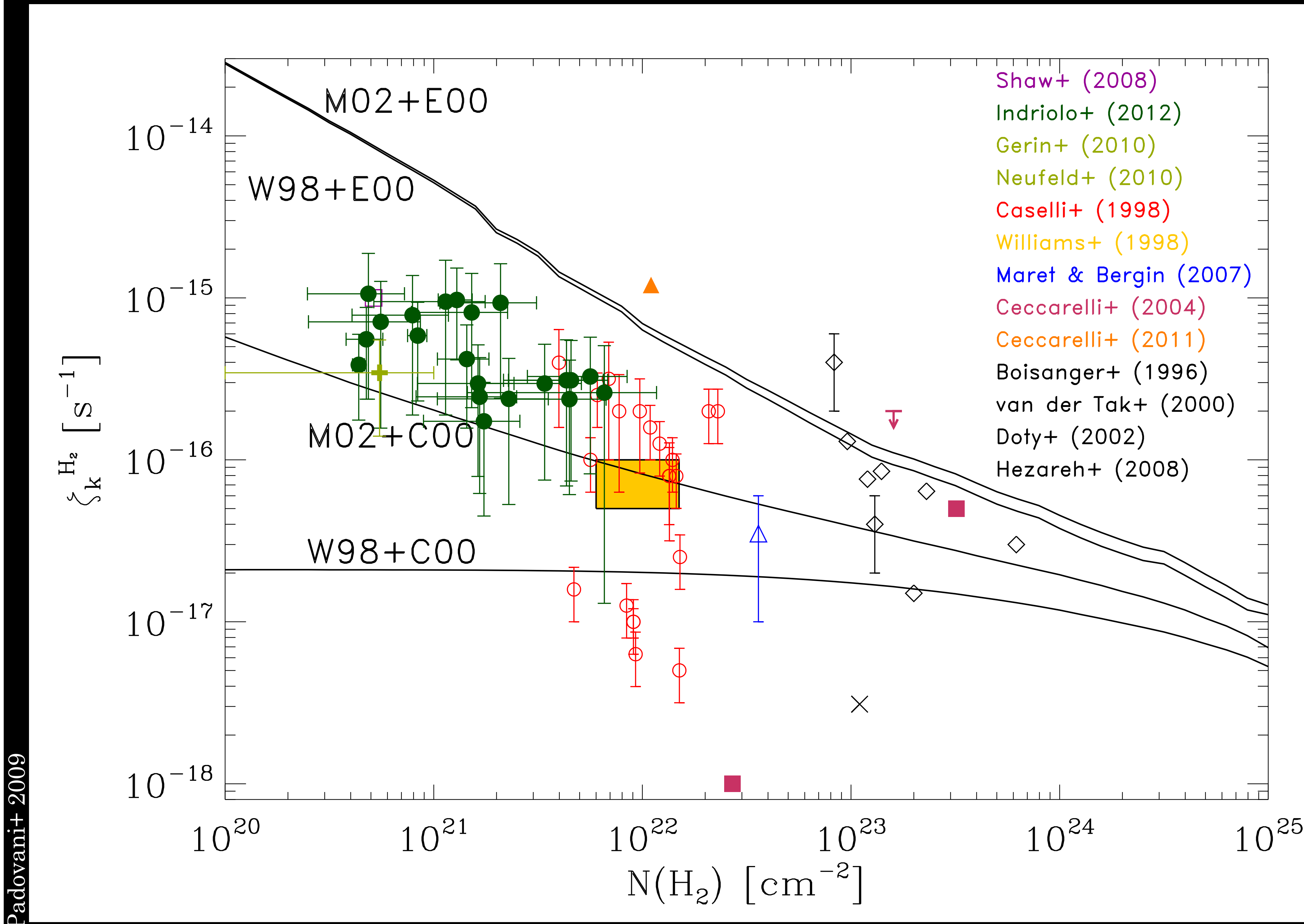

$$N = -\int_{E_0}^{E} \frac{\mathrm{d}E}{L(E)} = \int_{E}^{E_0} \frac{\mathrm{d}E}{L(E)}$$

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

**The low-energy tail in CR incident spectrum is produced during the propagation of CRs in the cloud EVEN when the incident spectrum is devoid of low-energy particles.**




Padovani+ 2009




**CR proton spectra**

W98
Webber+ (1998)

M02
Moskalenko+ (2002)

**CR electron spectra**

C00 "conventional"
Strong+ (2000)

E00 "enhanced"
Strong+ (2000)

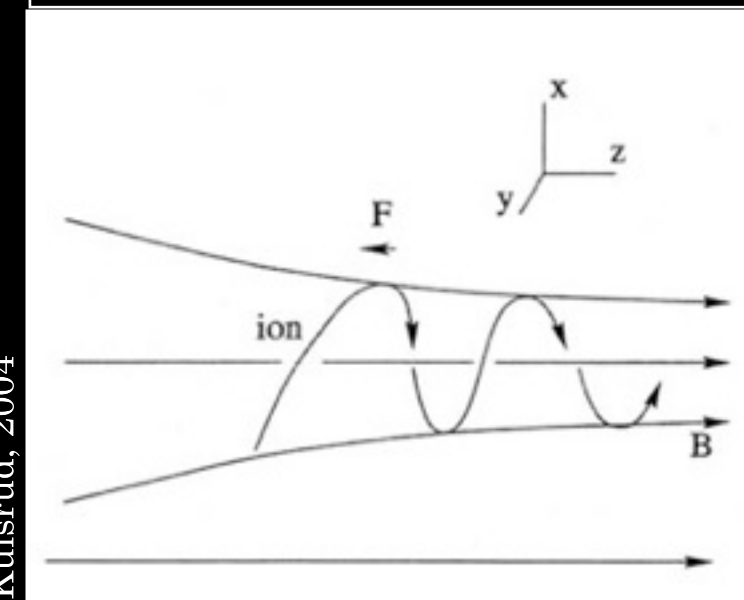
# Padovani & Galli (2011)

$\vec{B}$

**magnetic mirroring**
bounces many CRs
out of the core

**magnetic focusing**
increases CR flux
in the core

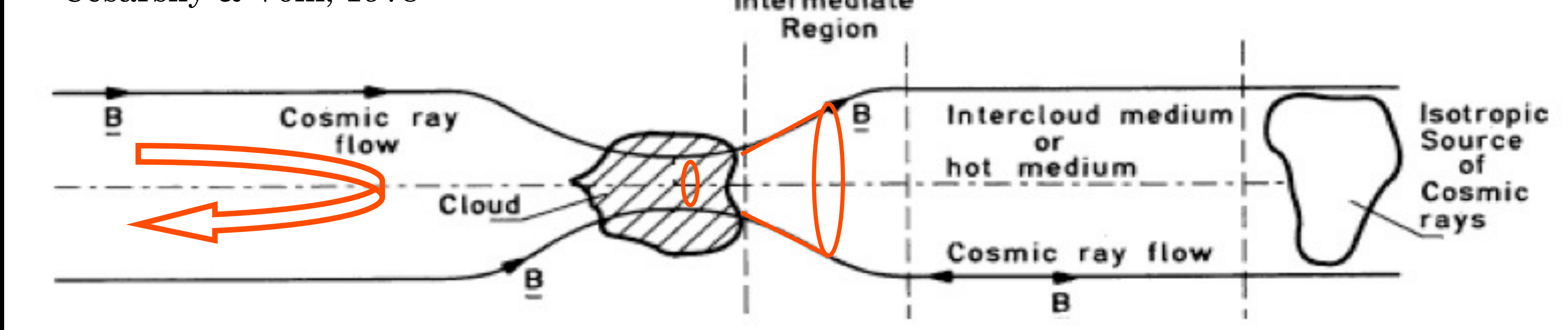
cosmic-ray helicoidal motion




Kulsrud, 2004

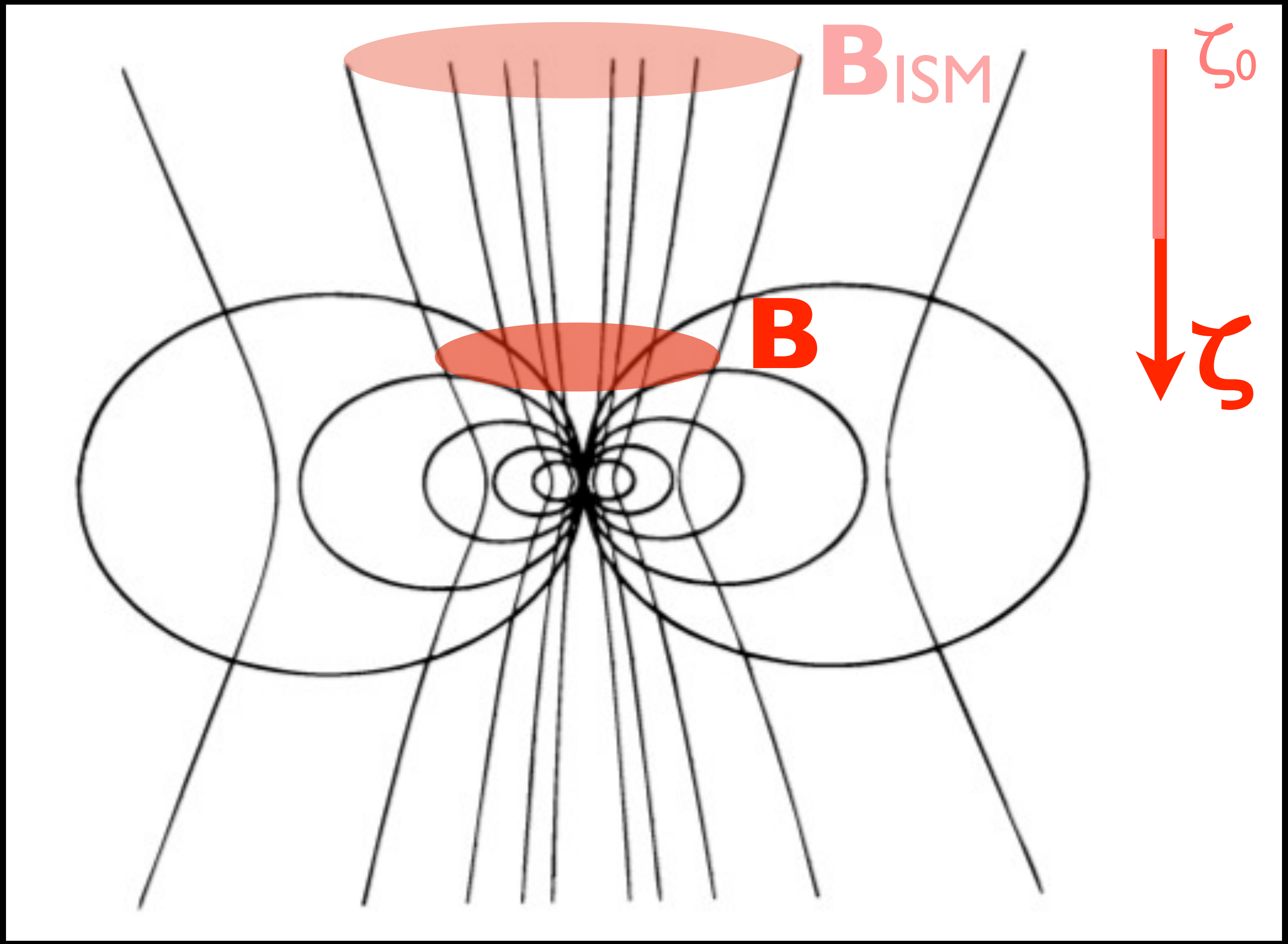
The Larmor radii of ionising CRs are smaller than typical sizes of Bok globules (~ 0.05 pc), dense cores (~ 1-5 pc), and GMC (~ 25 pc).

non-uniformity of the magnetic field




Césarsky & Völk, 1978

# Focusing




The ratio between the magnetic field in the cloud core, B, and the interstellar magnetic field, $B_{ISM}$, determines the degree of magnetic focusing.

$$\chi = B/B_{\rm ISM}$$

For the same number of CRs per length of field line, the flux of CRs must be proportional to the density of magnetic field lines per area unit.

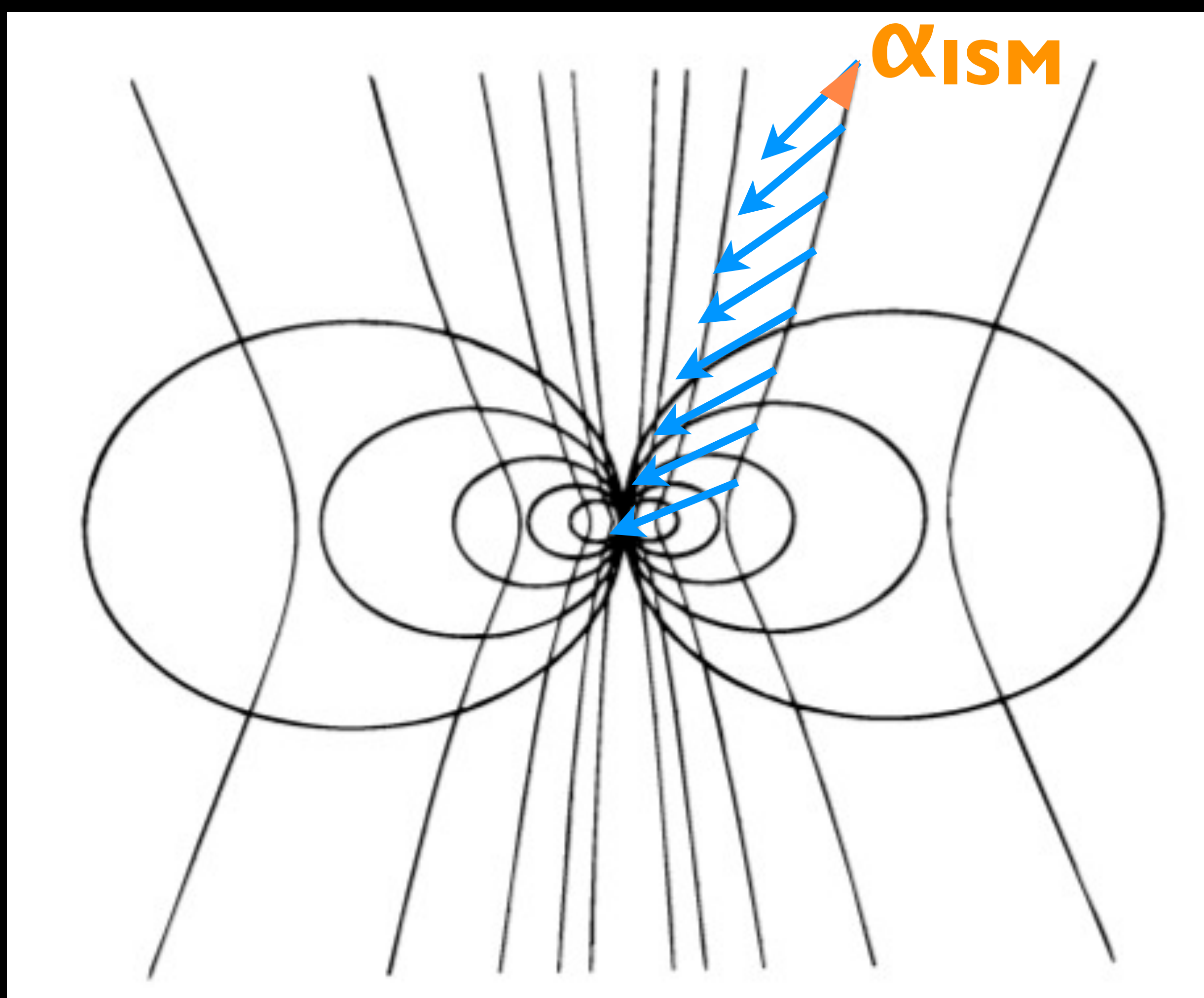
$\zeta > \zeta_0$ $\zeta$ increases!

$$j(E) = \chi\, j_{ISM}(E)$$

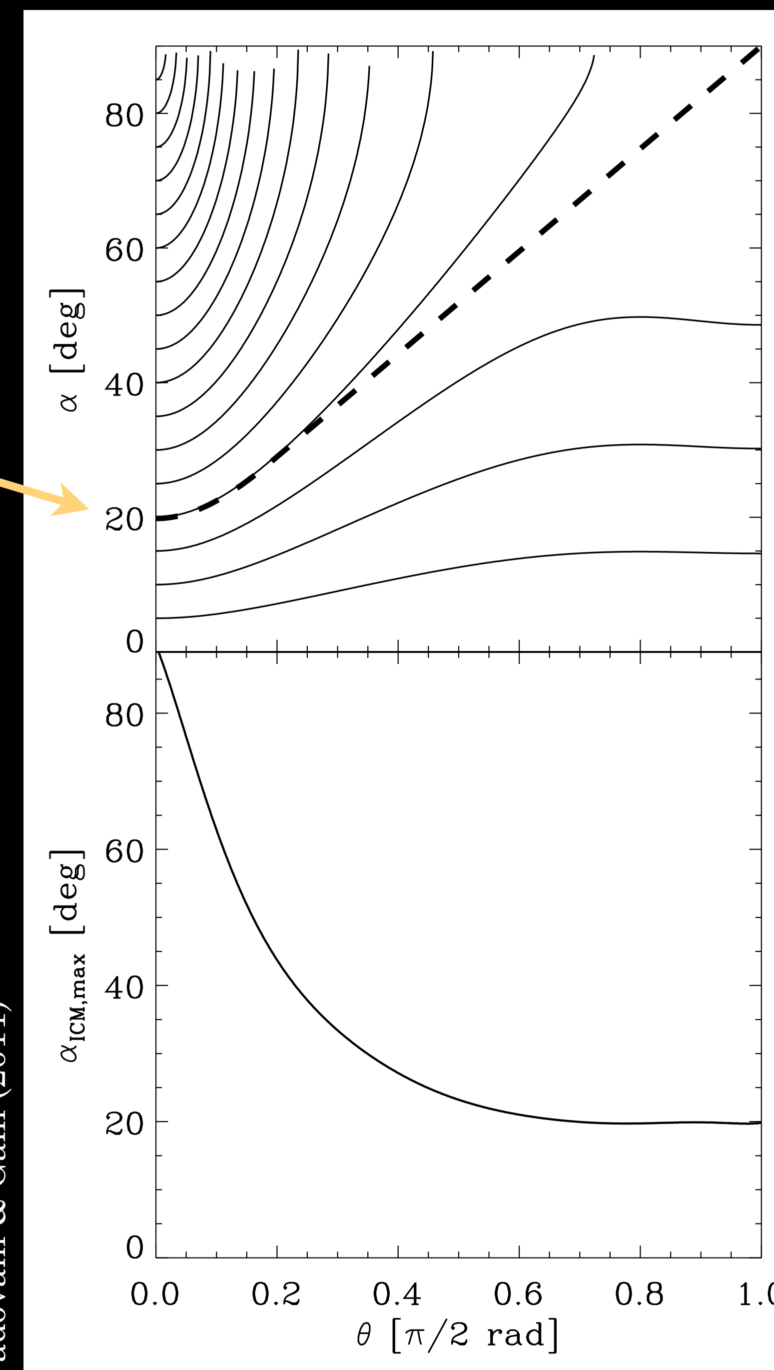
# Mirroring

$$\alpha = \arccos\sqrt{1-\chi+\chi\cos^2\alpha_{\rm ISM}}$$

$\alpha_{\rm ISM} < \alpha_{\rm cr}$




$\alpha_{\rm cr}$




Padovani & Galli (2011)

# Mirroring

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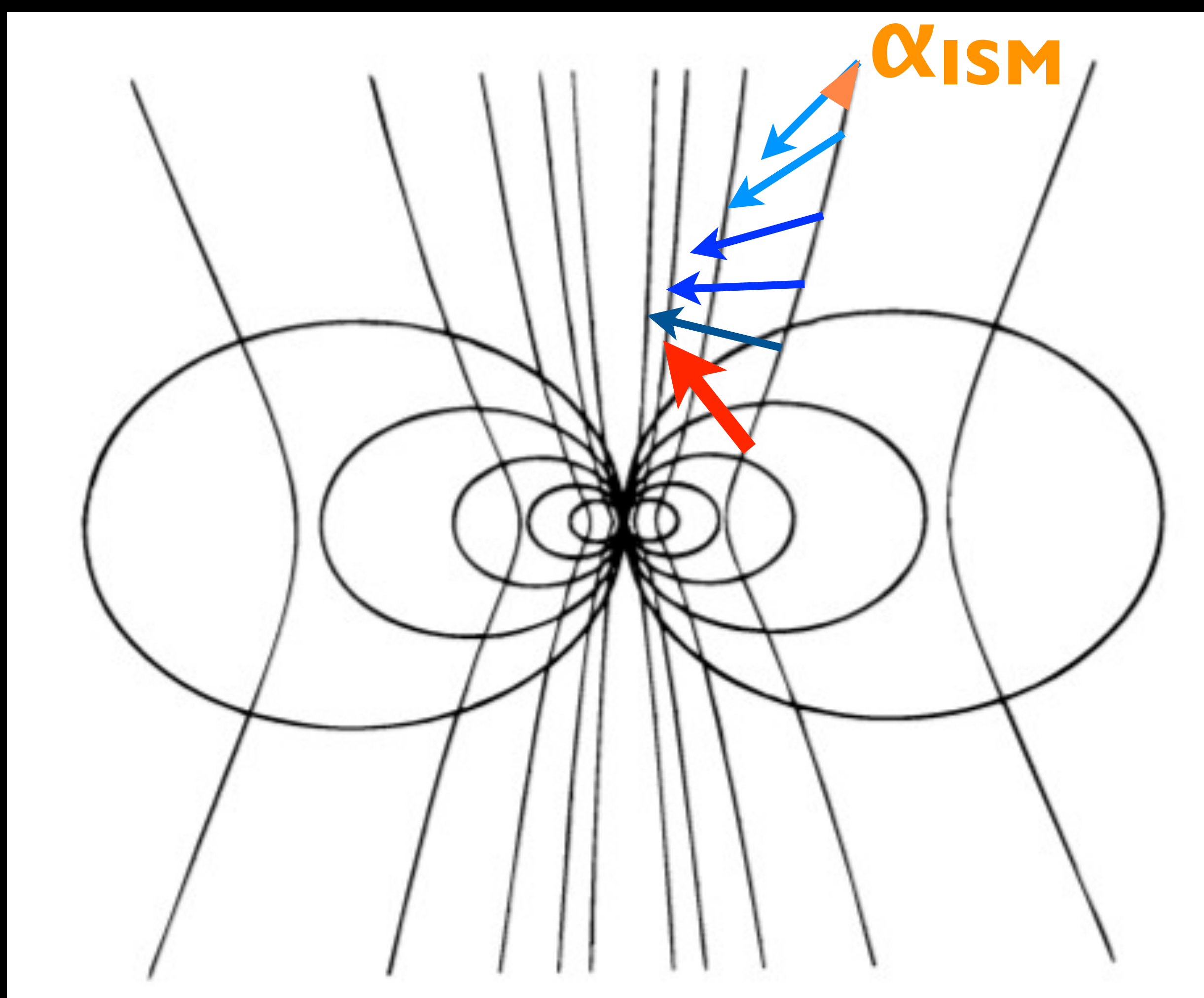
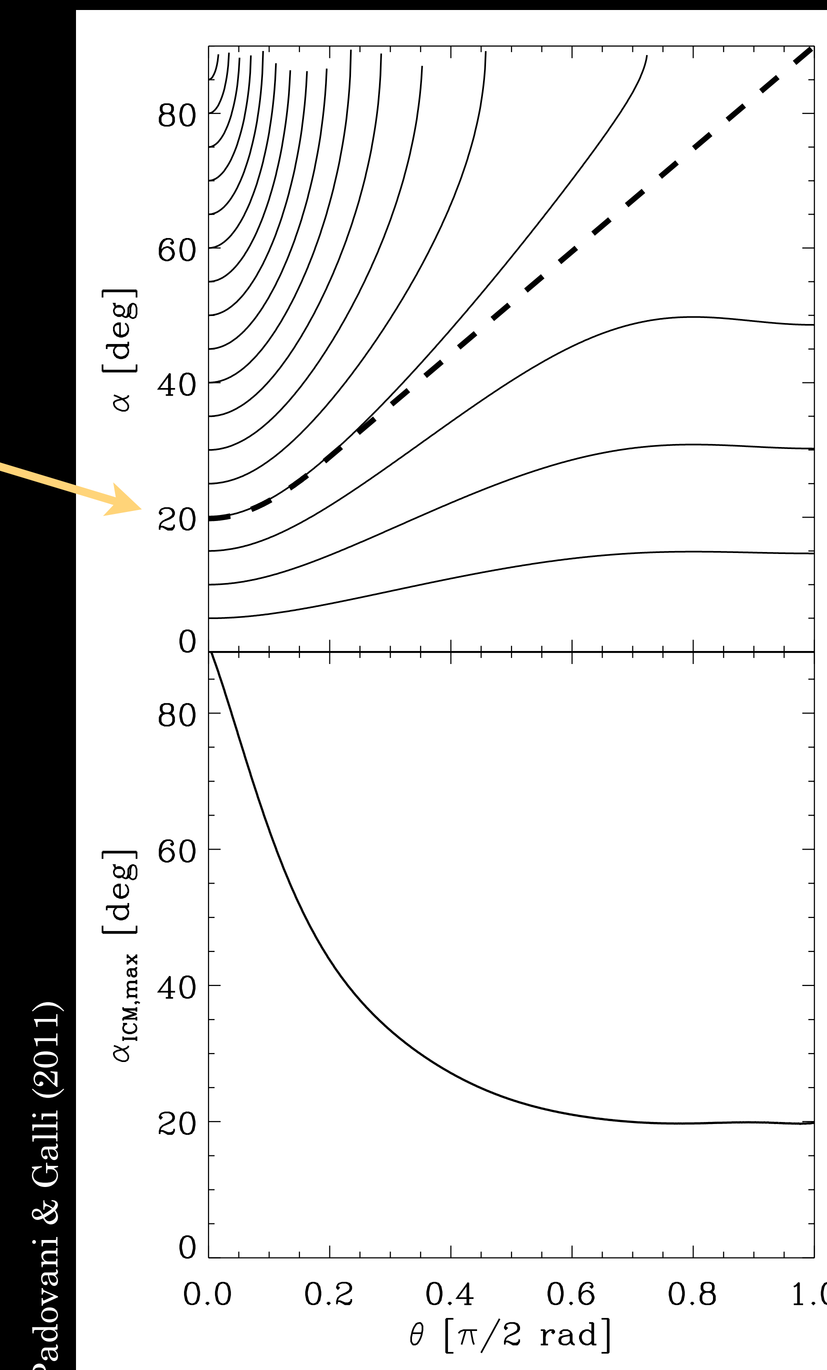



$\alpha_{\rm cr}$

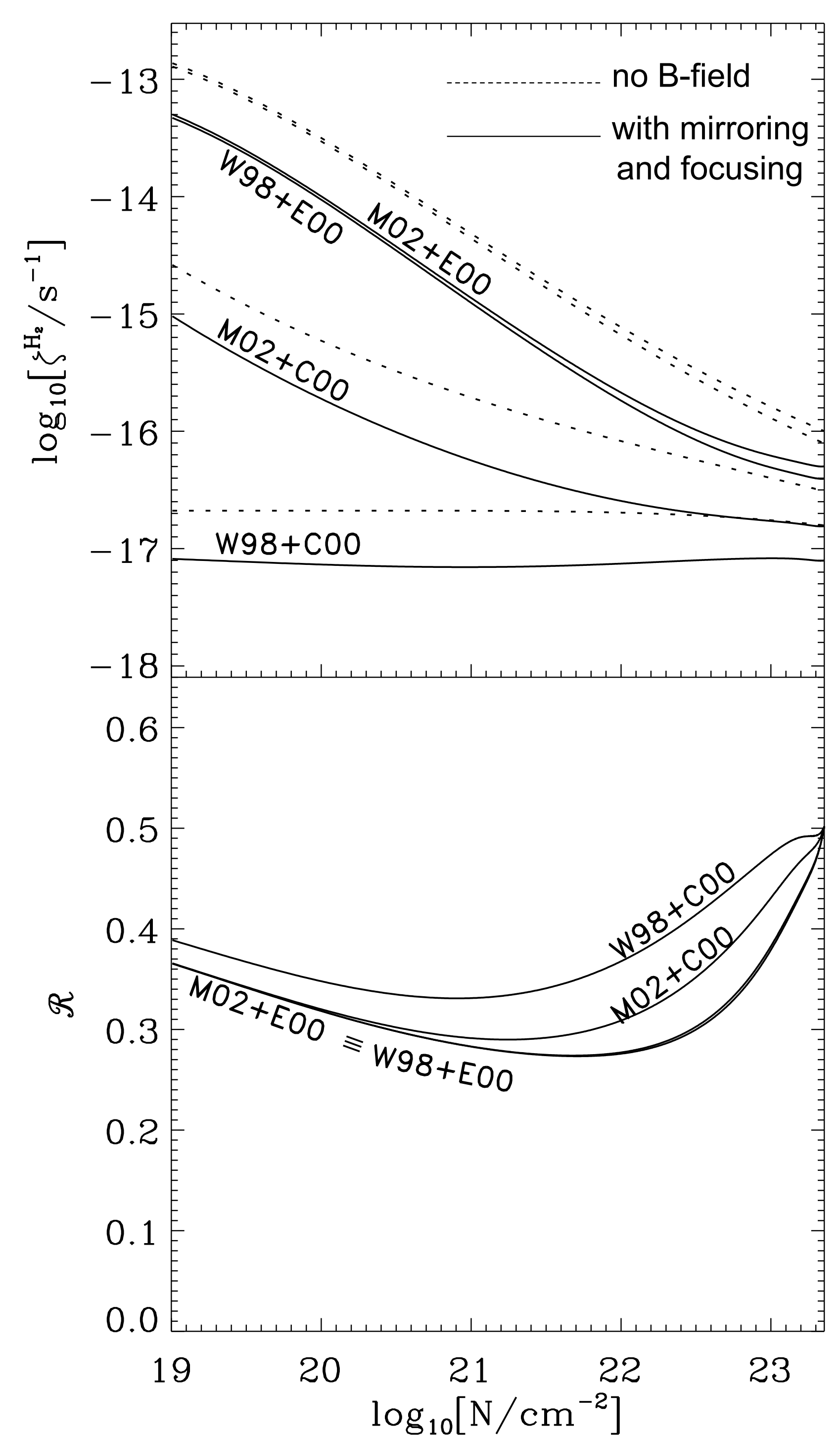



ζ decreases!

# Reduction of $\zeta(H_2)$ in a molecular cloud core by mirroring and focusing

Magnetic mirroring of cosmic rays reduces their flux in a molecular cloud core more than magnetic focusing increases it. The total effect is a reduction of the ionisation rate of a factor between 0.3 and 0.5.

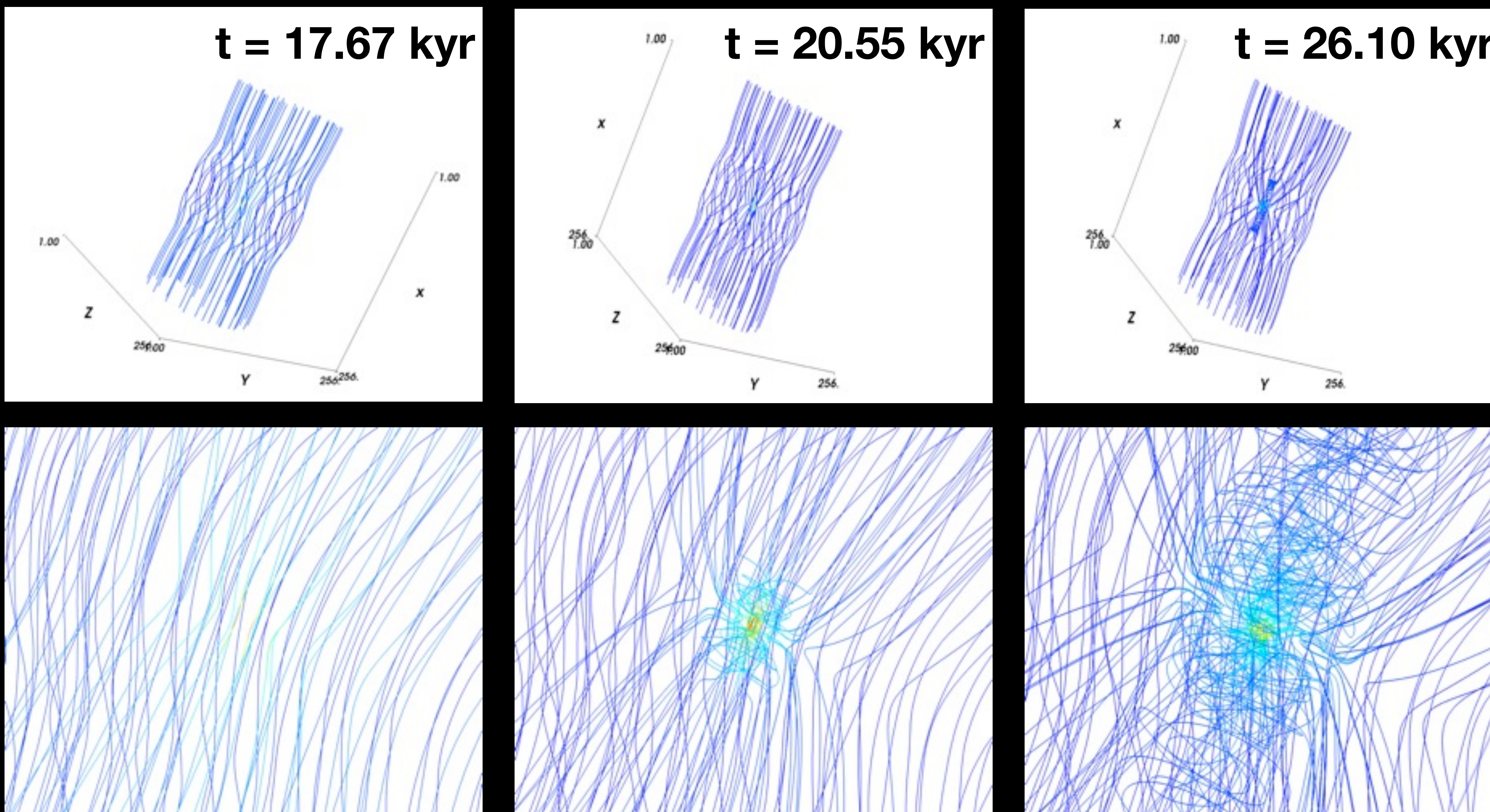
$$\mathcal{R} = \frac{\zeta^{H_2}}{\zeta_0^{H_2}}$$



Padovani & Galli (2011)

# Propagation of CRs in RAMSES simulations

RAMSES outputs of a collapsing rotating core with several mass-to-flux ratio



# Take-home message

$$\zeta_{\rm CR}(A_{\rm V}) \neq {\rm cost}$$