

# *COSMIC RAY PENETRATION IN DIFFUSE CLOUDS*

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&

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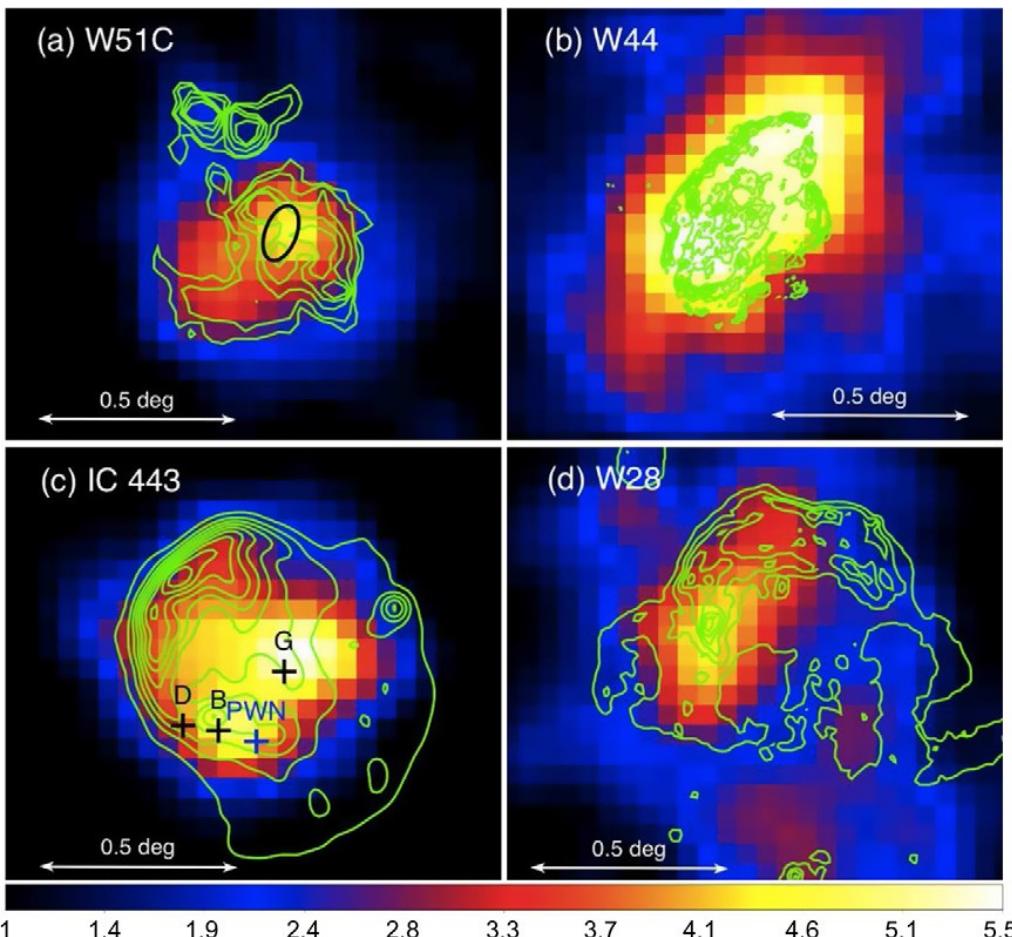
See *Morlino & Gabici, 2015, MNRAS 451, 100*

***International Cosmic Ray Conference***

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# Motivations I: MCs as CR barometers

Examples of  $\gamma$ -ray emission from clouds close or interacting with SNRs - [Fermi-LAT]



## OBSERVATIONS of MCs in $\gamma$ -RAYS:

- CRs interact inside MCs  
 $pp \rightarrow \pi^0 \rightarrow \gamma\gamma$
- strong emission in GeV range
- $\gamma$ -emission sensible to CR energy  $E > 280$  MeV
- MCs can be used to test different CR spectra:
  - 1) average Galactic spectrum (isolated clouds)
  - 2) injected spectrum (MC close to SNRs)

## DETECTION OF IONIZATION

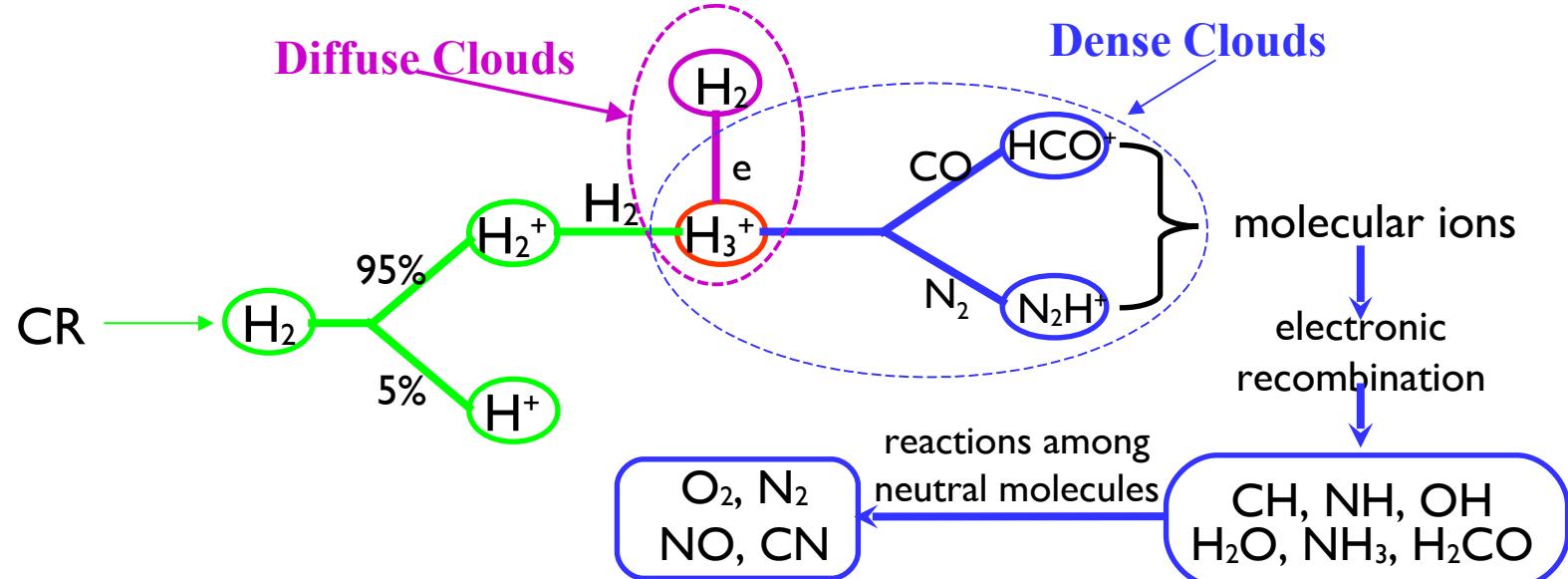
- The ionization rate of several molecules depends on the CR flux ( $H_2$ ,  $H_3^+$ ,  $CH$ ,  $OH$ ,  $C_2$ ,  $DCO^+$ ,  $HCO^+$ ,.....)
- Ionization sensible to CR energy  $E > 0.1$  MeV

Is it possible to use combined information from ionization and  $\gamma$ -ray emission to infer the CR spectrum from  $\sim$ MeV up to  $\sim$ TeV and beyond?

# Motivations II: understanding the cloud chemistry and dynamics

1) CR are a primary source of ionization inside a cloud

- For column densities  $N_H > 10^{20} \text{ cm}^2$  CRs are the only agent able to penetrate the cloud
- The ionization fraction drives the chemistry of molecular clouds



2) CR affect the cloud temperature

3) Ionization controls the coupling between the gas and magnetic field  
(the gravitational collapse occurs in the very deep core when gas and  $\mathbf{B}$  decouple)

# Can low-energy CRs be excluded from clouds?

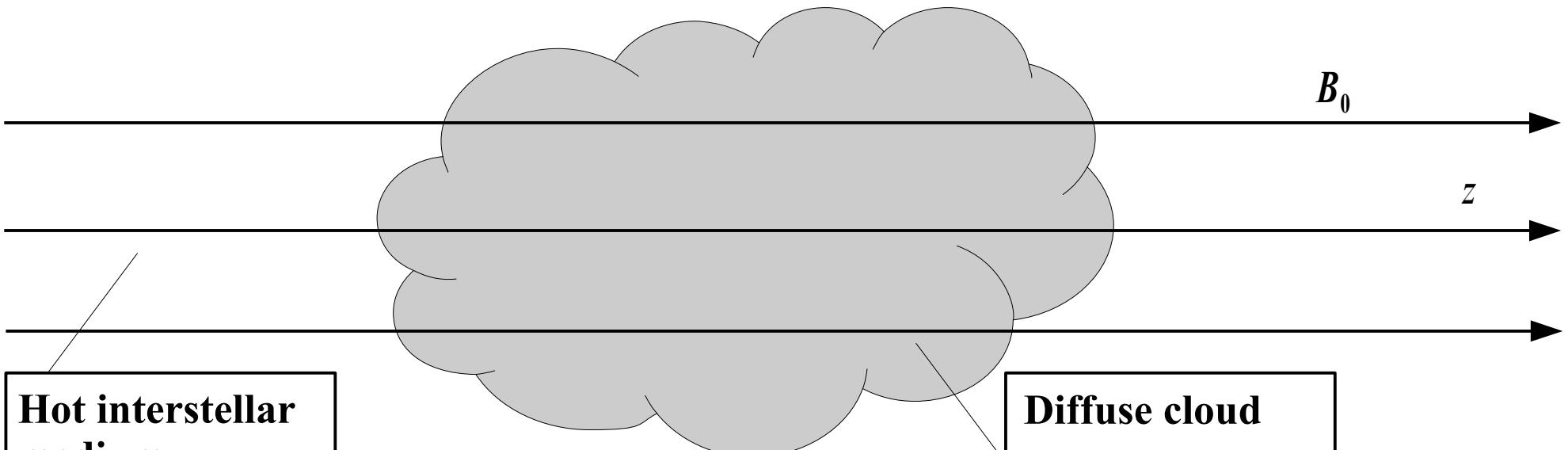
## Previous works give conflicting results

- ◆ Skilling & Strong (1976); Cesarsky & Völk (1977) (kinetic approaches)  
→ CR flux inside the MC decreases below  $\sim 50$  MeV
- ◆ Everett & Zweibel (2011) (fluid approach) → no significant variation of CR flux
- ◆ Padoan & Scalo (2005); → enhancement of CR density inside the cloud

$$n_{CR} \propto n_i^{1/2} \quad \text{for } E \sim 100 \text{ MeV}$$

- *We implemented a kinetic model for the full distribution function  $f_{CR}(x,p)$*   
→ *Inclusion of CR-amplification of Alfvén waves*

# Set up of the model



## Hot interstellar medium

$$\begin{aligned}n &\sim 0.01-0.1 \text{ cm}^{-3} \\T &\sim 10^4-10^5 \text{ K} \\x_{ion} &= 1\end{aligned}$$

## Diffuse cloud

$$\begin{aligned}n &\sim 10-100 \text{ cm}^{-3} \\T &\sim 10^2 \text{ K} \\x_{ion} &\approx 10^{-4}\end{aligned}$$

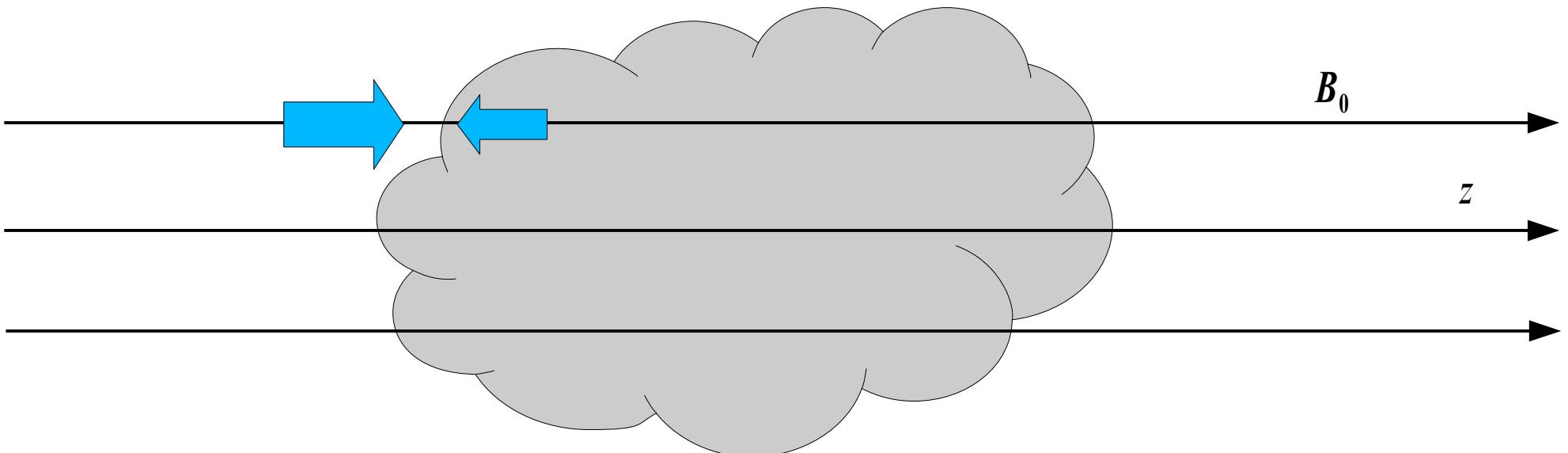
$B_0$  coherence length  $\sim 50-100$  pc  
Cloud size  $\sim 10$  pc



1-D approximation along the magnetic field lines

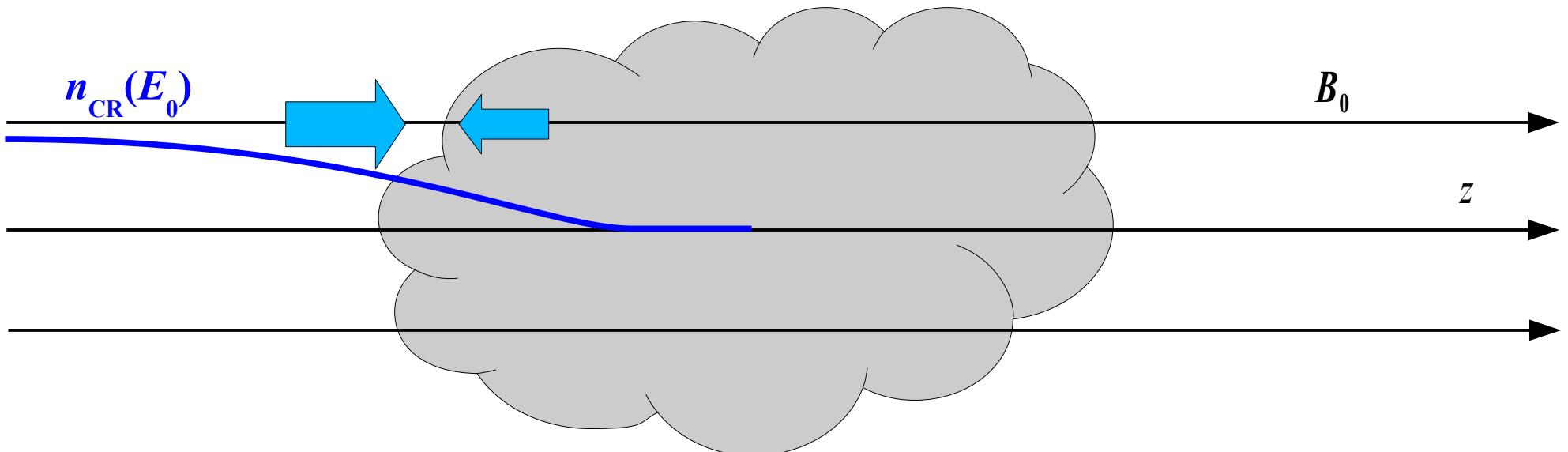
$B_0 = \text{const} = 3 \mu\text{G}$  observations show that for low density ISM ( $n < 300 \text{ cm}^{-3}$ ), the magnetic field strength is independent of the ISM density (Crutcher, 2010)

# Set up of the model



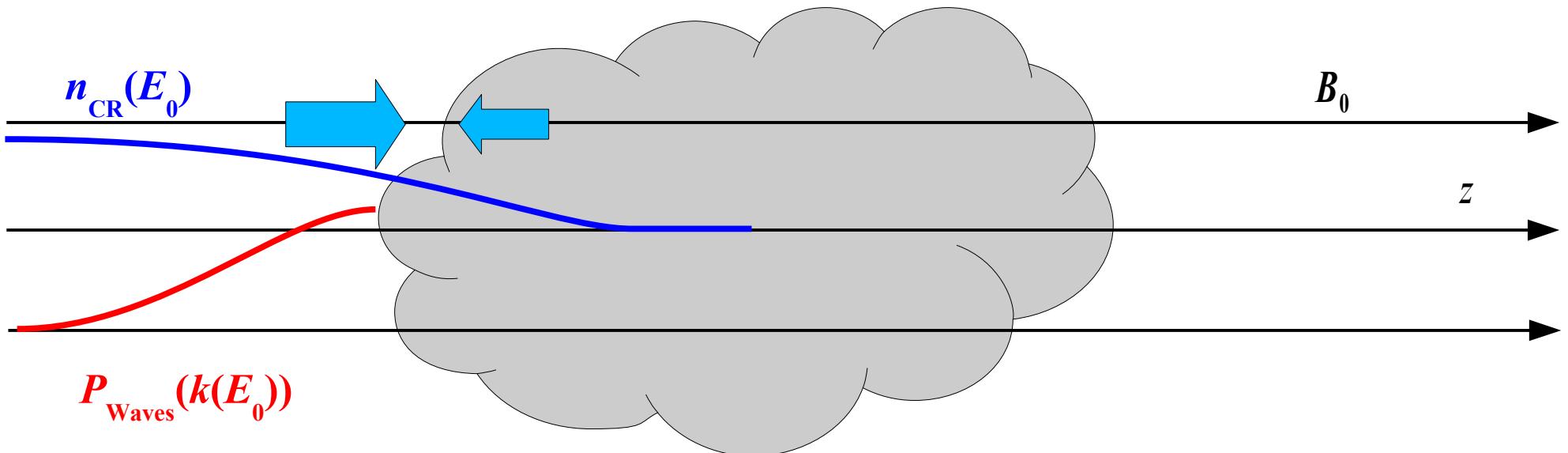
- Particles lose energy inside the cloud:  
→ The flux entering the cloud is larger than the flux escaping the cloud

# Set up of the model



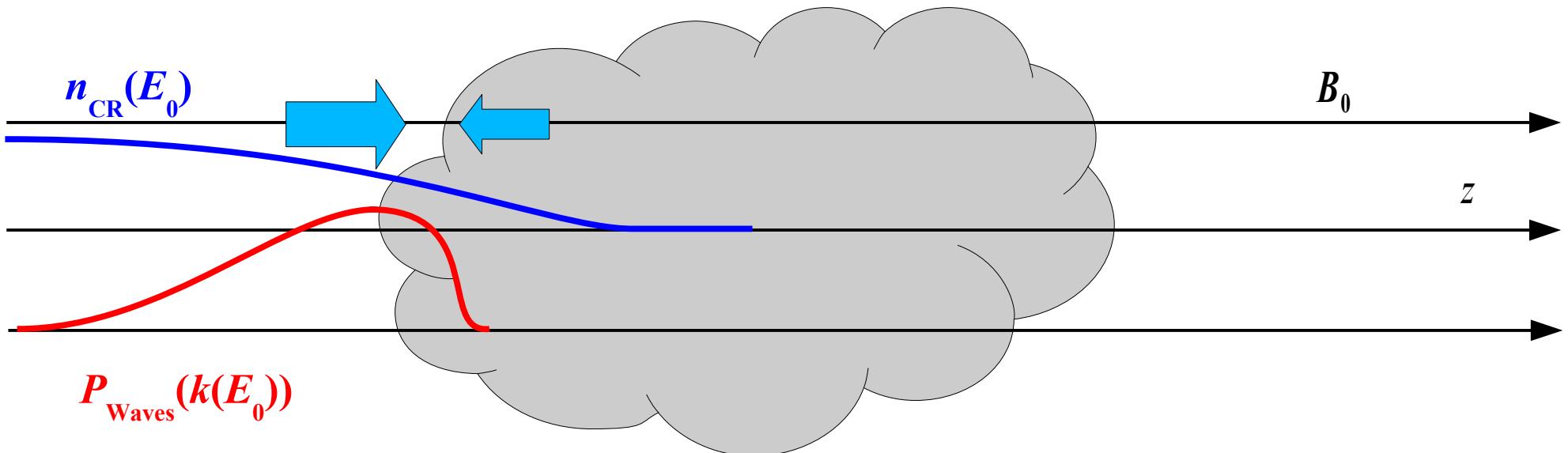
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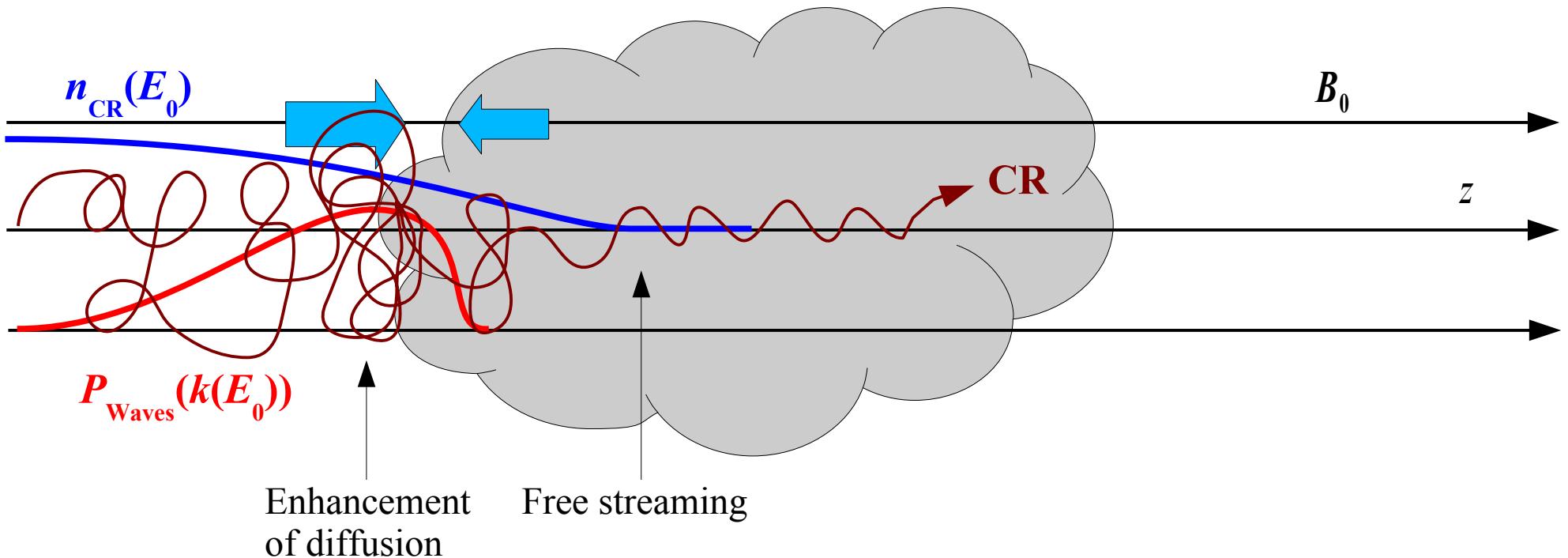
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  - Alfvén waves are excited by two stream instability

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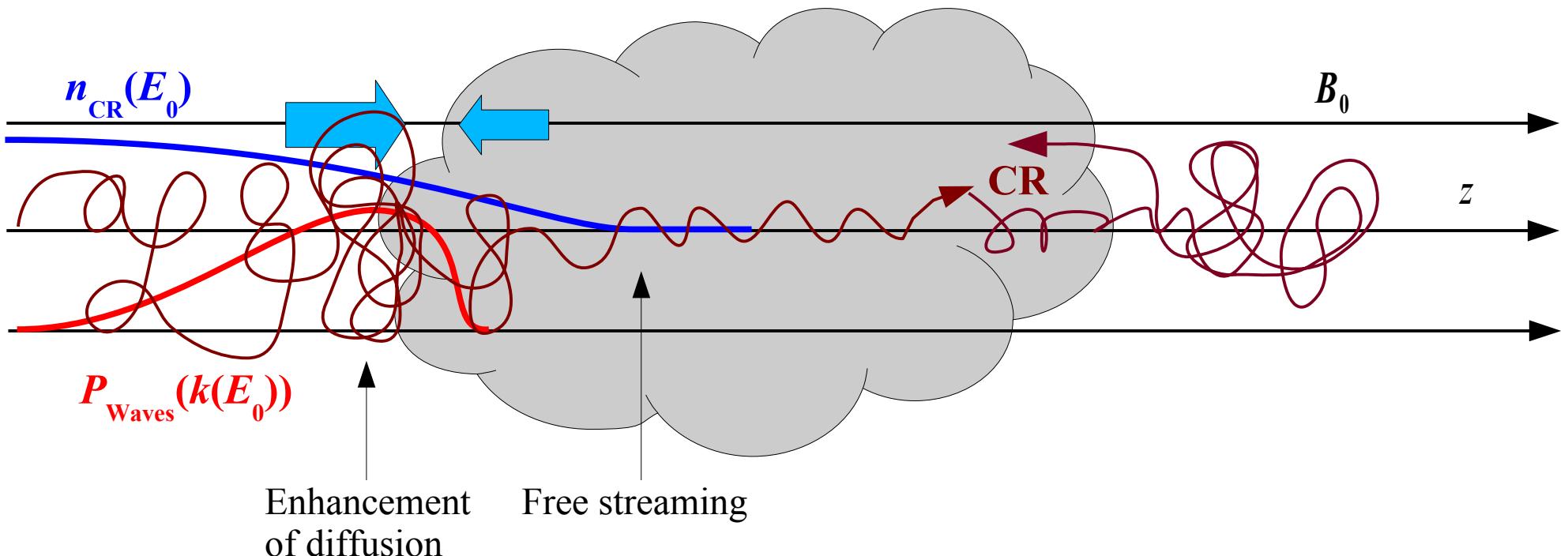
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- Magnetic turbulence is damped inside the cloud by ion-neutral damping

# Set up of the model



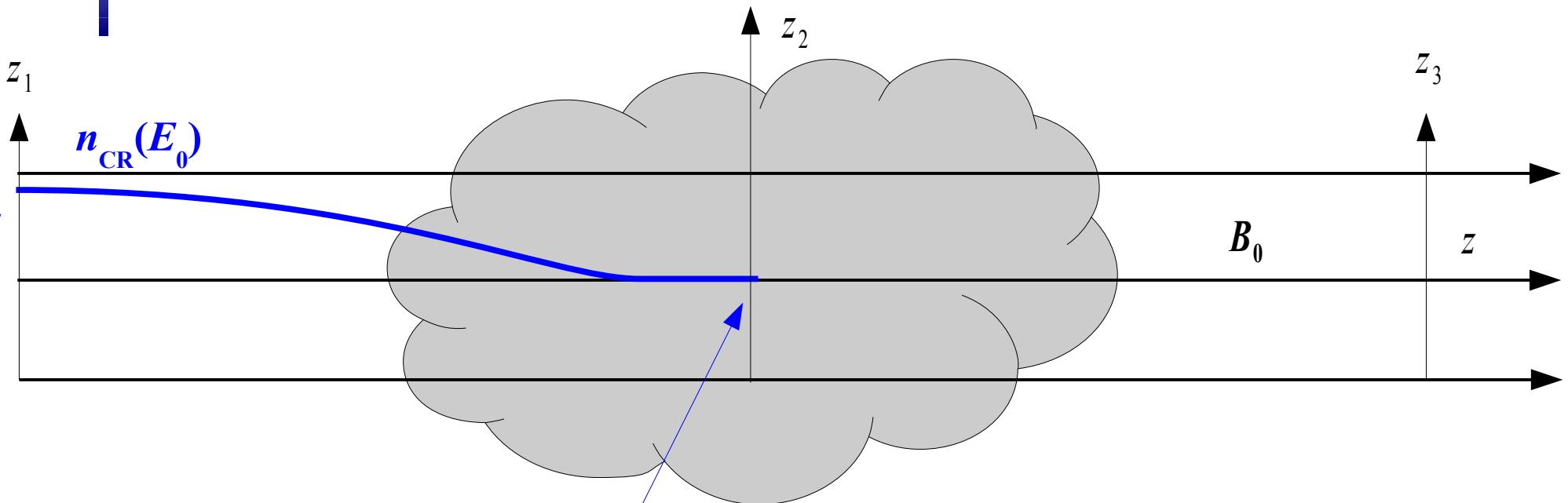
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# Set up of the model



- Particles lose energy inside the cloud:
  - The flux entering the cloud is larger than the flux escaping the cloud
  - a CR gradient develops outside the cloud
  - Alfvén waves are excited by two stream instability
- Magnetic turbulence is damped inside the cloud by ion-neutral damping
- Particles can escape from the cloud and return back because of diffusion
  - **multiple cloud crossing**

# Set up of the model



**Boundary conditions for CRs:**

$$f_{CR}(z_1) = f_{CR}(z_3) \rightarrow \left[ \frac{\partial f_{CR}}{\partial z} \right]_{z=z_2} = 0$$

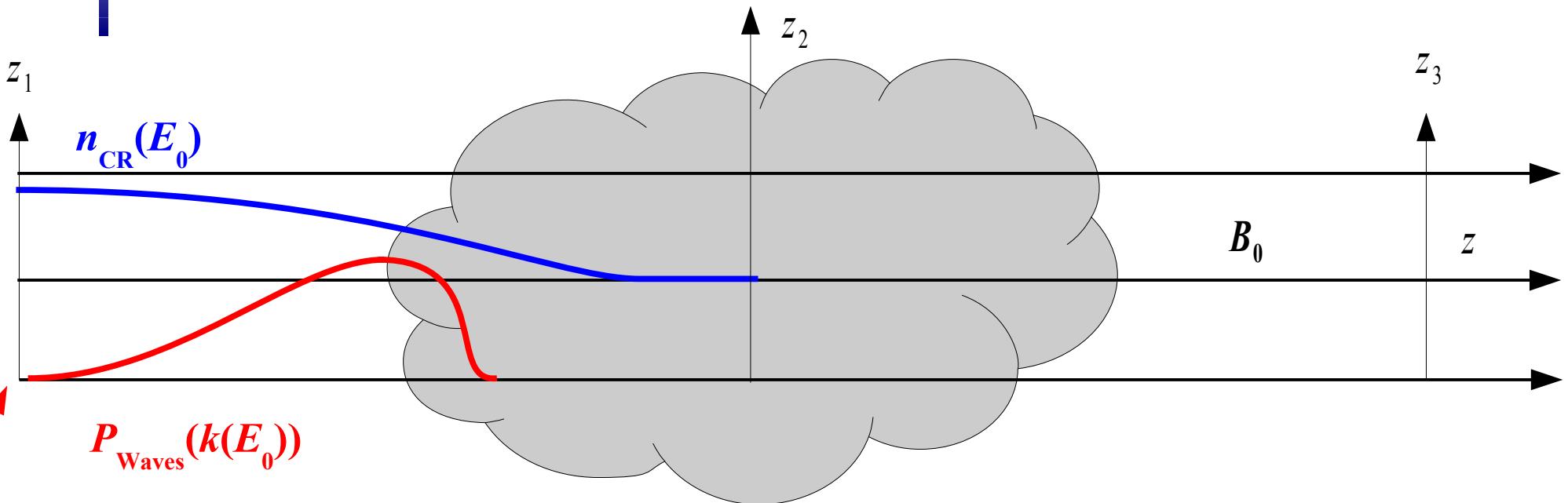
$$f_{CR}(z_1, p) = f_{Gal}(p)$$

Symmetric condition.

We do not impose any condition on the CR gradient at  $z_1$  (different from Everett & Zweibel, 2011)

**The symmetric condition catches the physics of multiple cloud crossing.**

# Set up of the model



**Boundary conditions for magnetic turbulence:**

$$P_w(k, z_1) = \eta_w P_{B,0} \frac{2}{3} (k L_{\text{tur}})^{2/3} \quad \text{Kolmogorov spectrum with } L_{\text{tur}} = 50 \text{ pc} \rightarrow D(p) \propto p^{1/3}$$

$$\Gamma_{CR} = \frac{4\pi}{3} v_A \left[ p v \frac{\partial f}{\partial z} \right]_{\bar{p}(k)}$$

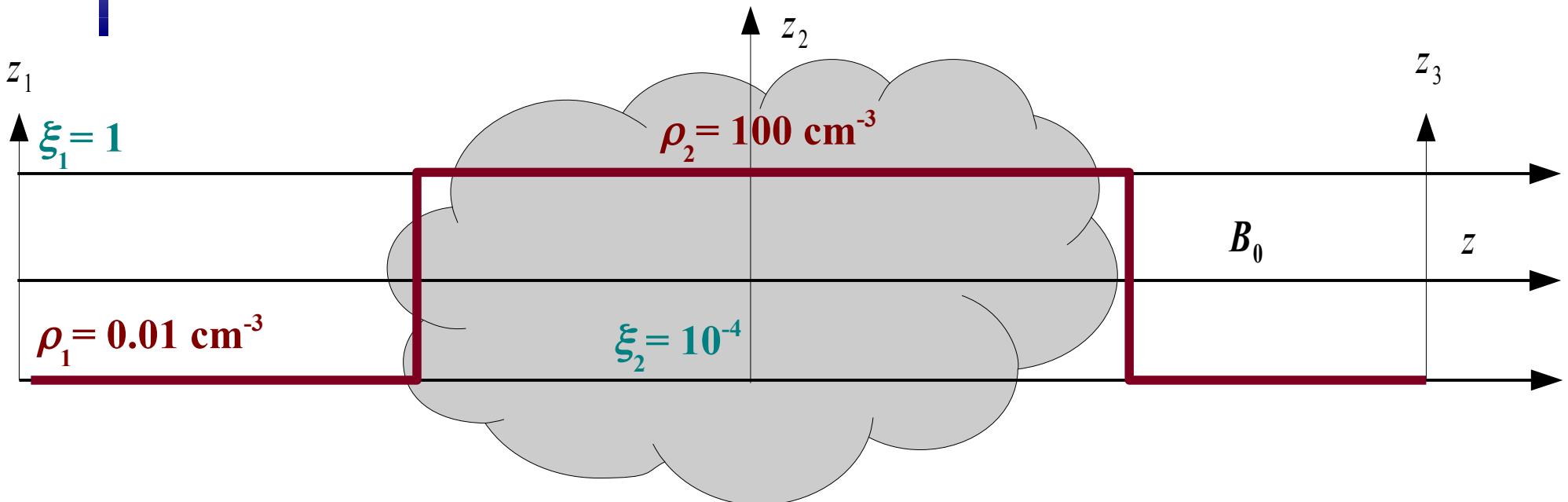
Amplification due to streaming instability

$$\Gamma_{ion-neutral} = -4.2 \times 10^{-9} \left( \frac{T}{10^4 K} \right)^{0.4} \left( \frac{n_H}{cm^{-3}} \right)^{0.4} s^{-1} \quad \text{Ion-neutral damping}$$

Amplification  
always in  
linear regime

$$\delta B \ll B_0$$

# Set up of the model



**Density profile of the cloud:**  
step function in density and ionization

$$v_A = \frac{B_0}{\sqrt{4\pi n \xi}} \rightarrow v_{A,c} = v_{A,Gal}$$

Alfvén speed depends only on the ion density:  
for ion and neutrals are decoupled  $\rightarrow E(k) < 10 \text{ GeV}$

$$k > \frac{v_{in}}{v_A} \frac{1 + n_i/n_H}{\sqrt{1 + \delta B^2/B_0^2}}$$

# Transport equation for CRs

Stationary transport equation for CRs in 1-D with losses:

$$\frac{\partial}{\partial z} \left[ D(z, p) \frac{\partial f_{CR}}{\partial z} \right] - v_A \frac{\partial f_{CR}}{\partial z} + \frac{1}{3} \frac{dv_A}{dz} p \frac{\partial f_{CR}}{\partial p} - \frac{1}{p^2} \frac{\partial}{\partial p} [\dot{p} p^2 f] = 0$$

Diffusion

Advection

Adiabatic  
compression

Energy  
losses

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Diffusion

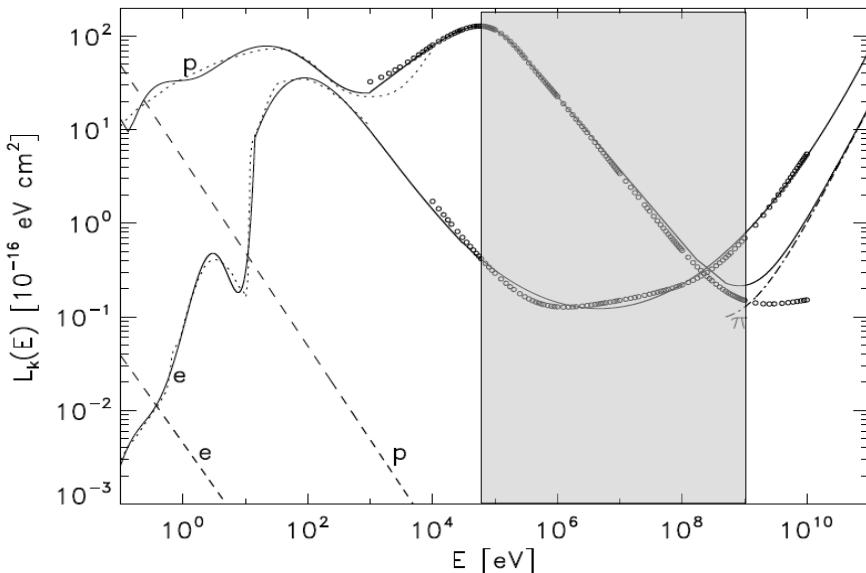
Advection

Adiabatic compression

Energy losses

$$\tau_{loss}(p) = \frac{p}{\dot{p}} = 1.46 \cdot 10^7 \left( \frac{p}{0.1 m_p c} \right)^\alpha \left( \frac{n_H}{cm^{-3}} \right)^{-1}$$

$\alpha = 2.58$ ; loss time for  $1 \text{ MeV} < E < 1 \text{ GeV}$



# Transport equation for CRs

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Diffusion coefficient outside the cloud determined by magnetic field amplification:

$$D(z, p) = \frac{4}{3\pi} \frac{v r_L}{(\delta B/B_0)^2} \rightarrow D(z \rightarrow \infty, p) = D_{Kol}(p) = 10^{28} \left( \frac{p}{m_p c} \right)^{1/3} \beta \text{ cm}^2/\text{s}$$

We assume diffusive propagation also inside the cloud with  $D_c \gg D_{Kol}$

# Solution for the CR distribution

**Formal solution:**

$$f(z, p) = f_0(p) - \frac{1}{v_A} e^{v_A(z-z_c)/D_c} \int_{z_c}^{z_c+L_c/2} \frac{1}{p^2} \frac{\partial}{\partial p} \left[ \frac{p^3}{\tau_{loss}} f \right] e^{-v_A(z'-z_c)/D_c} dz'$$

# Solution for the CR distribution

**Formal solution:**

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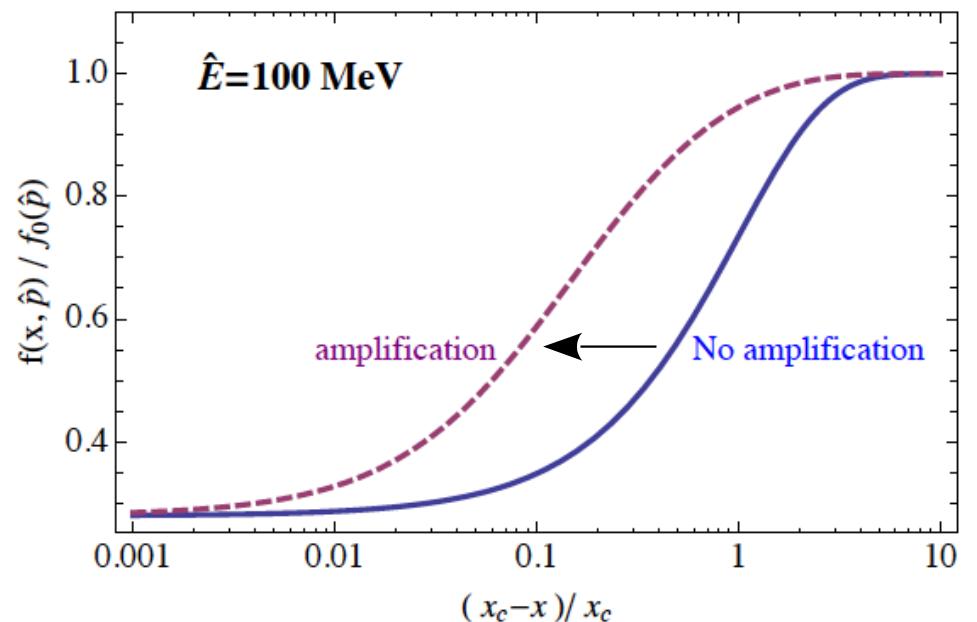
The spectrum is affected outside the cloud up to a distance  $z_c \sim D_{\text{Gal}}/v_A$

1) No magnetic amplification:

$$z_c = \frac{D_{Kol}}{v_A} \approx 300 \beta \left( \frac{B}{5 \mu G} \right)^{-1} \left( \frac{n_i}{0.01 \text{ cm}^{-3}} \right)^{1/2} \left( \frac{p}{m_p c} \right)^{1/3} \text{ pc}$$

2) Magnetic amplification (without damping):

$$z_c = \frac{D}{v_A} < \frac{D_{Kol}}{v_A}$$



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For  $D_c \gg L_c v_A \sim 10^{26} \left( \frac{L_c}{10 \text{ pc}} \right) \left( \frac{v_A}{30 \text{ km/s}} \right) \frac{\text{cm}^2}{\text{s}}$  

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 Distribution at the cloud border

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$\Rightarrow \frac{v_A \tau_{loss}}{L_c/2} \gg 1 \rightarrow f_c = f_0$

Distribution at the cloud border

$\Rightarrow \frac{v_A \tau_{loss}}{L_c/2} < 1 \rightarrow f_c = \begin{cases} f_c \propto p^{a-3} & s < 3 \\ f_c \propto p^{a-s} & s > 3 \end{cases}$

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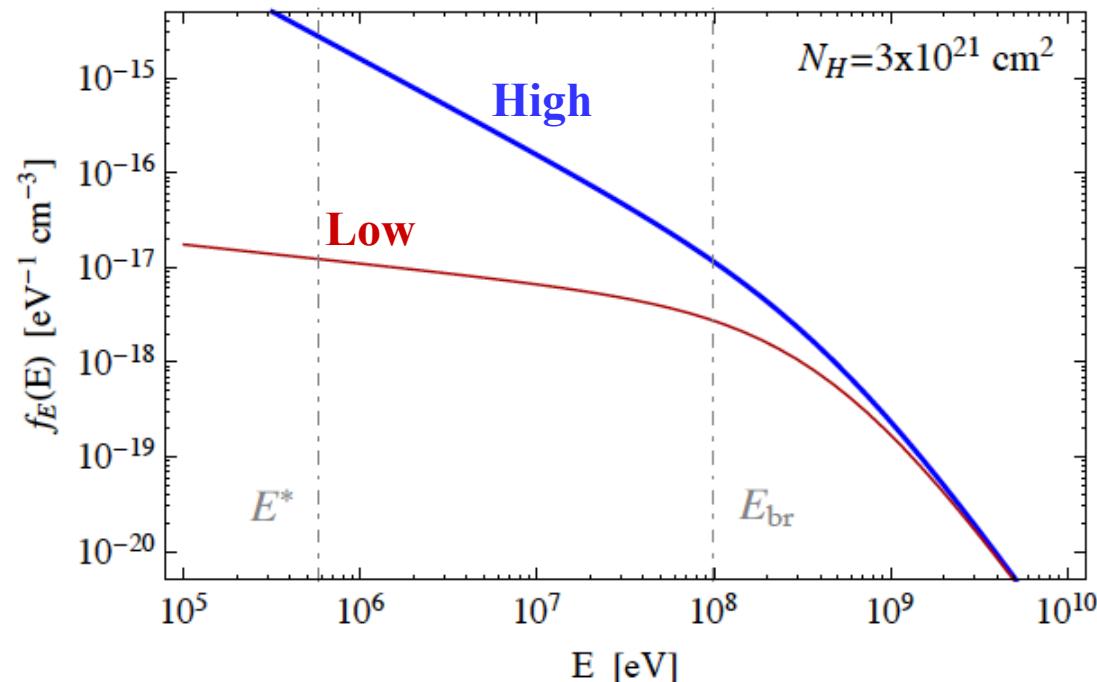
There is a breaking energy:

$$\frac{v_A \tau_{loss}}{L_c/2} = 1 \rightarrow \tau_{loss} = \frac{L_c/2}{v_{st}} \frac{v_{st}}{v_A} = \tau_{cross} \times \left( \frac{v_{st}}{v_A} \right)$$

$$E_{br} = 70 \left( \frac{v_A}{100 \text{ km/s}} \right)^{-2/\alpha} \left( \frac{N_H}{3 \cdot 10^{21} \text{ cm}^{-2}} \right)^{2/\alpha} \text{ MeV}$$

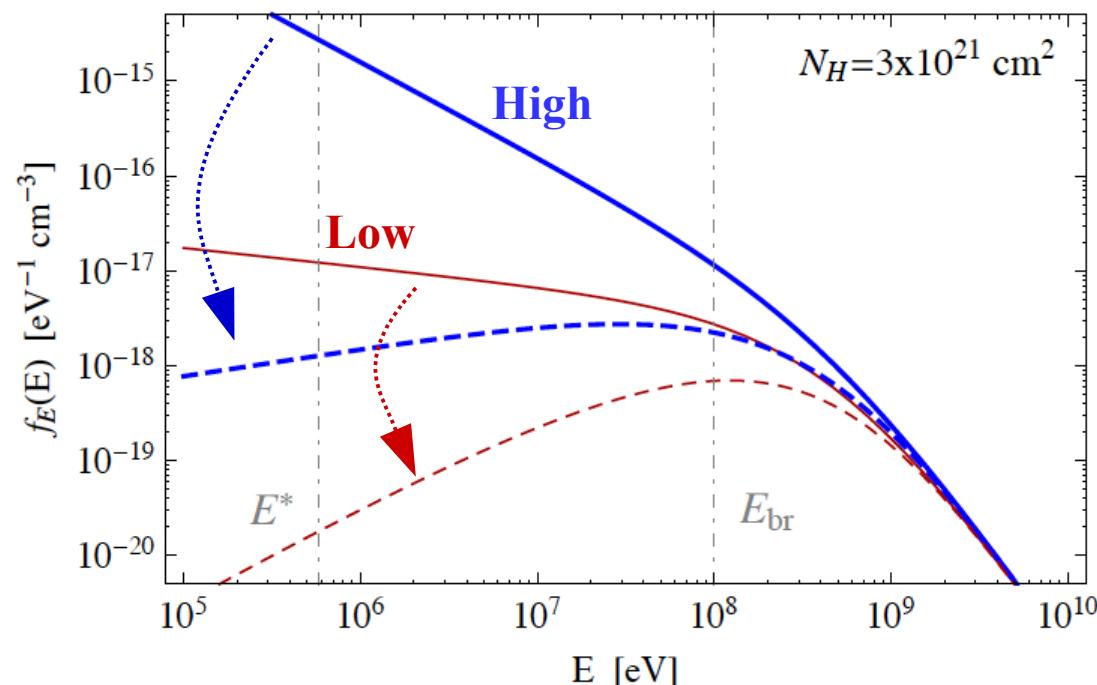
# Effect on ionization rate

Spectra from Ivlev et al.2015 [arXiv:1507.00692]



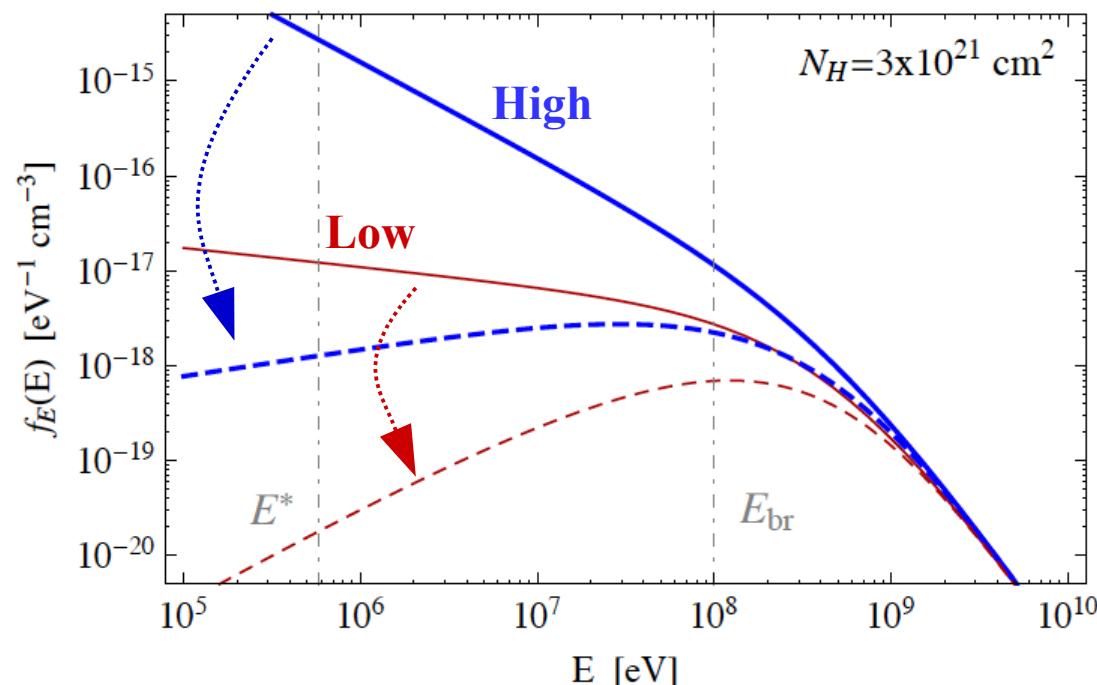
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## Ionization rate of $\text{H}_2$ due to protons

$$\zeta^{H_2} = 4\pi \sum_k \int_{I(H_2)} j_k(E) \sigma_k^{\text{ion}}(E) dE$$

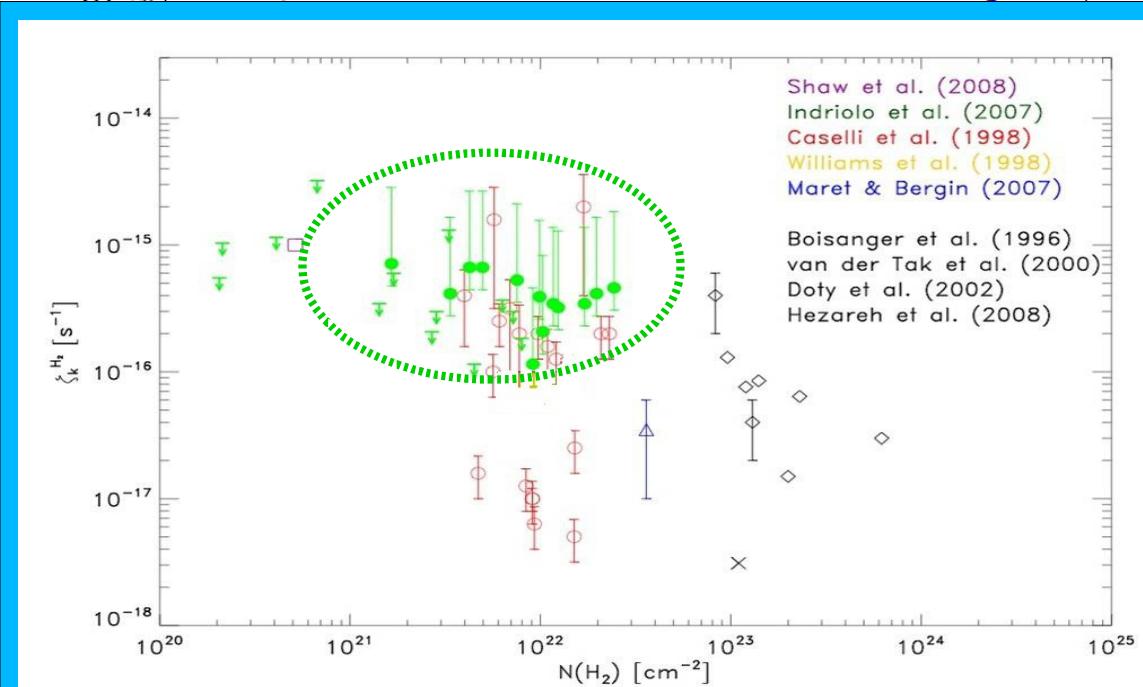
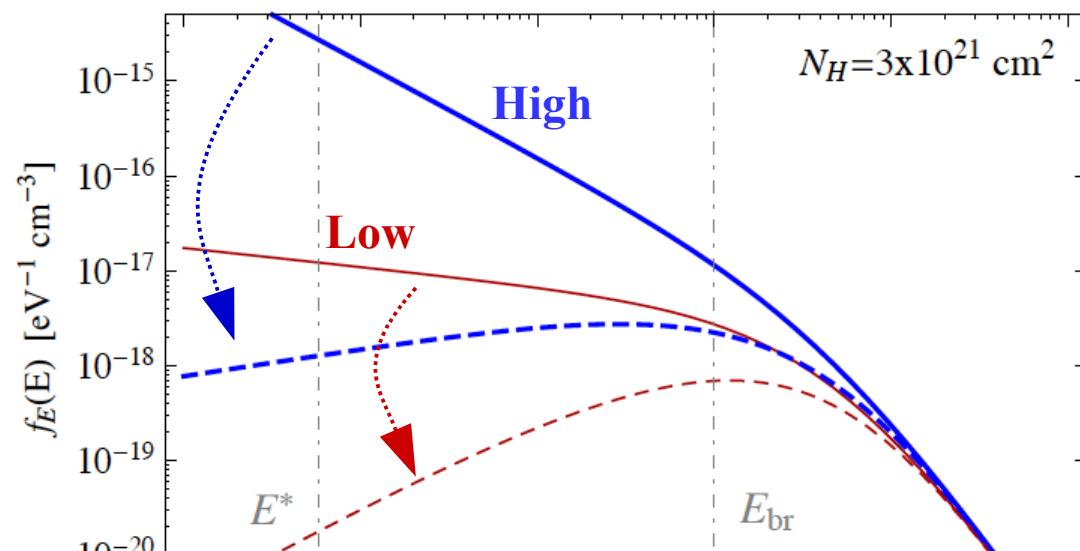
	Free-streaming propagation	Propagation including multiple crossing
High	$3.6 \times 10^{-16}$	$2.6 \times 10^{-17}$
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Ionization calculated using  
**CRIME** code.

See J. Krause's talk in this section.

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Predicted ionization not enough to  
explain observation

Electrons could play a major role

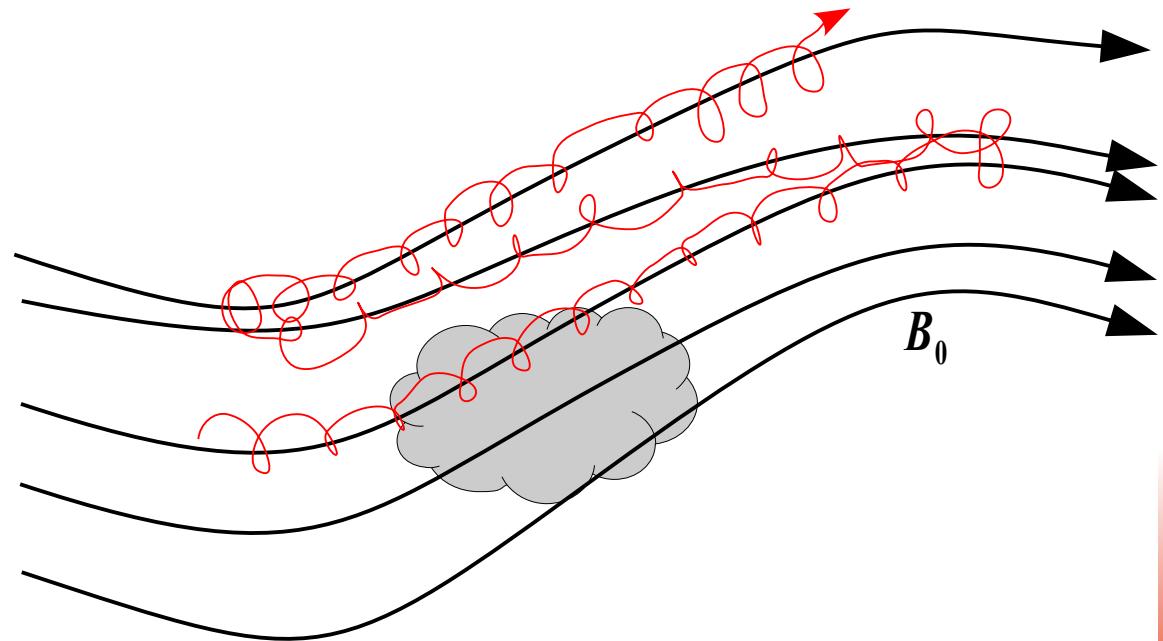
# Caveat: diffusion outside the cloud

- 1) We use  $D_{\text{kol}}$  with normalization derived from B/C,  
this gives  $D$  on scales  $> L_{\text{cohe}}$ . What is  $D$  on smaller scale?

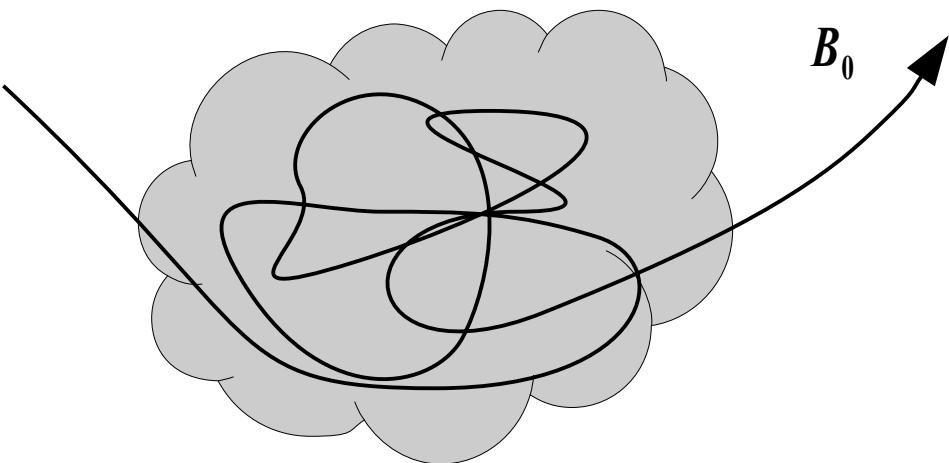
$$z_c = \frac{D_{\text{kol}}}{v_A}$$

- 2) if CR propagates beyond  $L_{\text{cohe}}$ , the geometry can transit to a 3-D

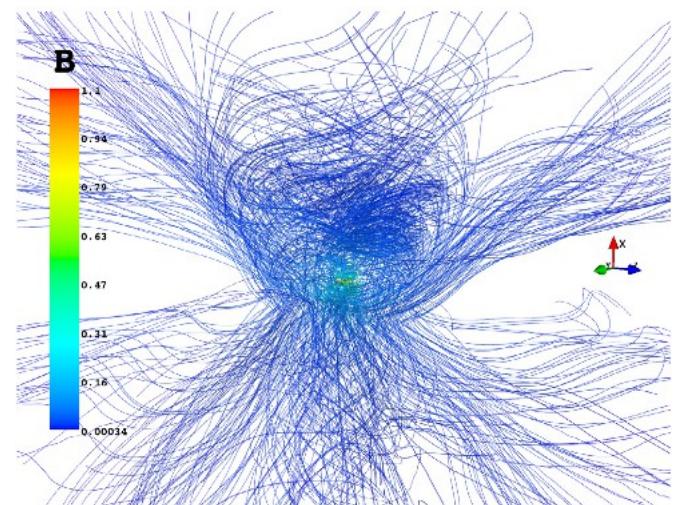
$\rightarrow E_{\text{br}}$  decreases



# Caveat: transport inside the cloud



[Padovani, Hennebelle & Galli, 2013]



We assumed free streaming inside the cloud (or  $D_c \gg v_A L_c$ ).

BUT:

Magnetic field can be tangled inside the cloud as a consequence of hydrodynamical turbulence and gravitational collapse

- The effective column density experienced by a particle increases
- $E_{\text{cr}}$  increases

# Conclusions

## Take away points:

- The presence of MCs affect the CR spectrum inside and outside the MC
  - Up to a distance  $\min[L_{\text{cohe}}, D_{\text{Gal}}/\nu_A]$  far away from the MC
  - For CR energies up to  $\sim 100 \text{ MeV}$
- The shielding effect can have important consequence on the CR ionization of clouds

## Challenges:

- Use combination of ionization in MCs plus gamma-ray data to reconstruct the CR spectrum down to  $E \sim \text{MeV}$ 
  - Better description of particle transport inside the cloud
  - Description of electron spectrum

# Caveat: stationarity

We assumed stationarity.

Typical timescales of the problem:

- Diffusion time:  $\tau_{diff} = L_c^2 / D_{kol}$

- Advection time:  $\tau_{adv} = L_c / v_A$

- Loss time (single crossing):  $\tau_{loss}$

- Loss time (multiple crossing):

$$\tau_d = \frac{D}{v_A^2} = 10^6 \left( \frac{D}{D_{kol}} \right) \left( \frac{v_A}{100 \text{ km/s}} \right)^{-2} \text{ yr}$$

- Dynamical (free-fall) time of a cloud:

$$\tau_{dyn} = (G \rho)^{-1/2} \approx 10^7 \left( n_H / 100 \text{ cm}^{-3} \right) \text{ yr}$$

