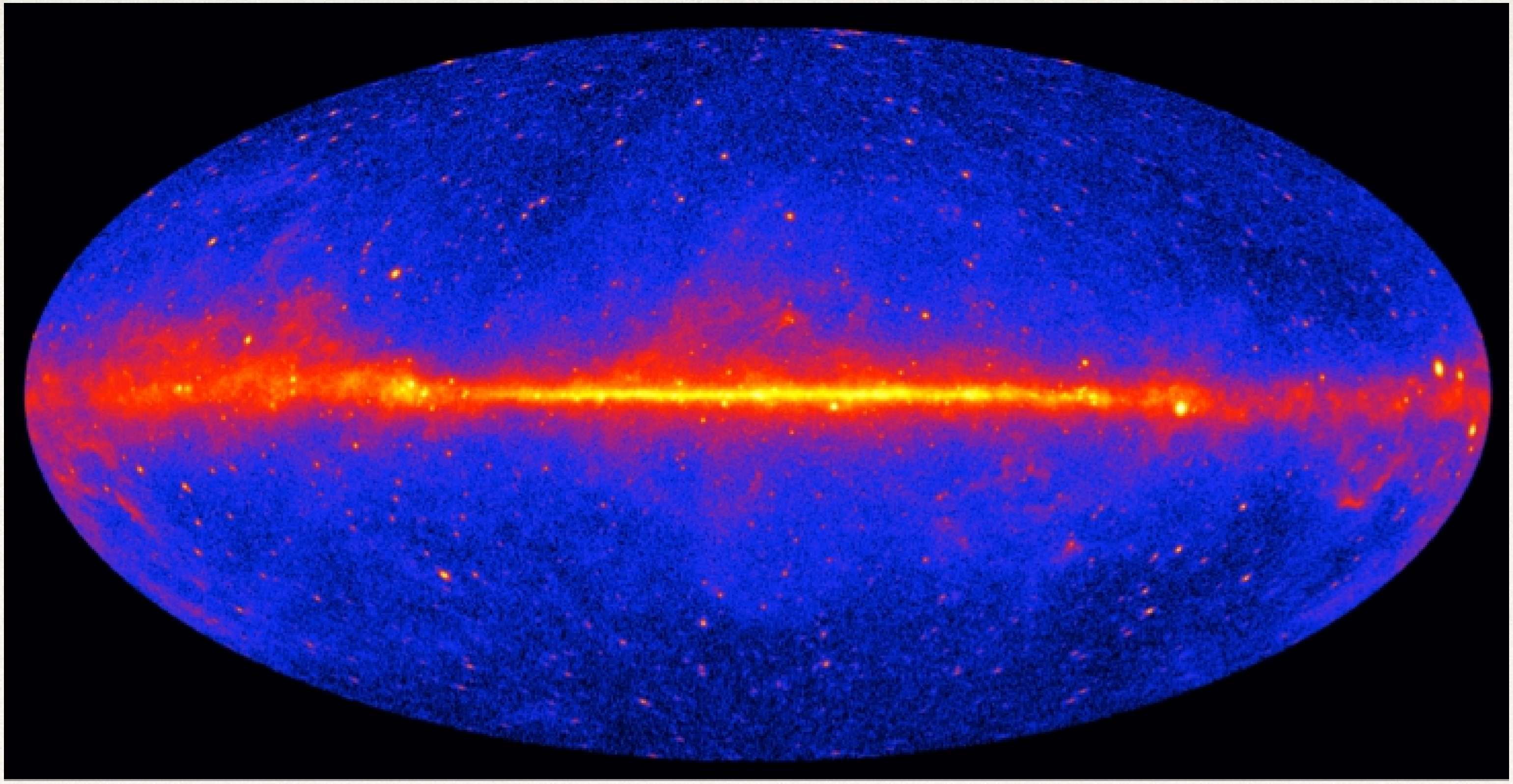


Effects of self generated turbulence on Galactic Cosmic Rays propagation

Giovanni Morlino, *Gran Sasso Science Institute*

In collaboration with S. Recchia, M. D'Angelo and P. Blasi

"Cosmic Ray beyond the standard model(s)" — September 22, 2016 — San Vito di Cadore

Diffusion in the Galactic Halo

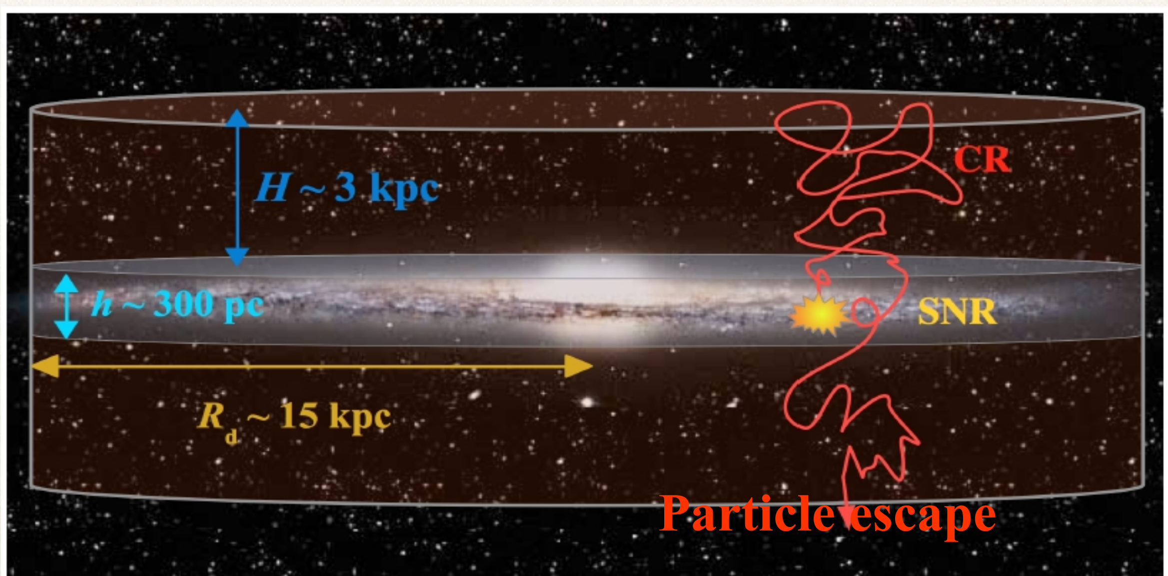
To infer the spectrum injected by sources we need to understand the CR diffusion in the Galactic halo.

The most widely used model is the leaky-box with the following properties

- The diffusion coefficient $D(E)$ is assumed constant everywhere in the halo
- The CR distribution vanish at $z = H$ (H~3-4 kpc inferred from diffuse synchrotron emission)

This picture is unsatisfactory for at least two reasons:

- Which is the physicalmeaning of H?
- What generates the diffusion?



Beyond the leaky-box model

A more realistic model should account for important physical ingredients:

- **Better description of the escaping process**
  - ^ **transition between the acceleration region and the Galactic diffusion**
- **Generation of turbulence by SN explotions**
  - ^ **dependence of $D(E)$ on galactocentric radius**
- **Cascade of the turbulence**
  - ^ **dependence of $D(E)$ on galactocentric radius and altitude**
- **Galactic wind (possibly driven by CRs)**
  - ^ **advection of particles**
  - ^ **energy dependent halo size $H(E)$**
- **Role of self-generated turbulence**

Role of self-generated turbulence

Whenever the CR gradient is different from zero, magnetic turbulence is produced.

Resonant streaming instability

$$\nabla P_{cr}\big|_{p=p_{res}}$$

Non-resonant Bell instability

$$F = -j_{cr} \times \delta \mathbf{B}$$

Self-generated turbulence plays a major role in determining the diffusion properties of CRs (see talk by P. Blasi)

- During the acceleration process ^ Both resonant and non-resonant
- **During the escaping from the sources**
- **During the propagation through the Galaxy**
- **Propagation close to molecular clouds**

$\left.\right\}$ Only resonant modes are important

Typically $\delta B < B_0$

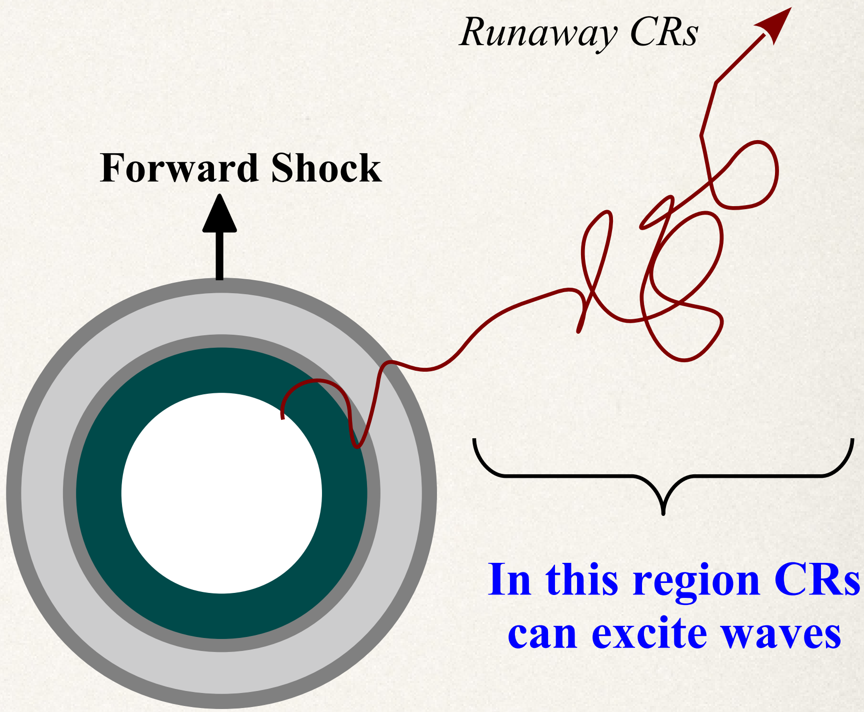
^ linear theory can be used

<u>But damping processes are important</u>

Effect of self-amplification near the CR sources

During the process of escaping, CR can excite magnetic turbulence (via streaming instability) that keep the CR close to the SNR for a long time, up to $\sim 10^5$ yr

[Malkom et al. (2013)
Nava et al. (2015)]



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(after this distance the diffusion becomes 3D and the CR dendity drops rapidly below the average Galactic value)

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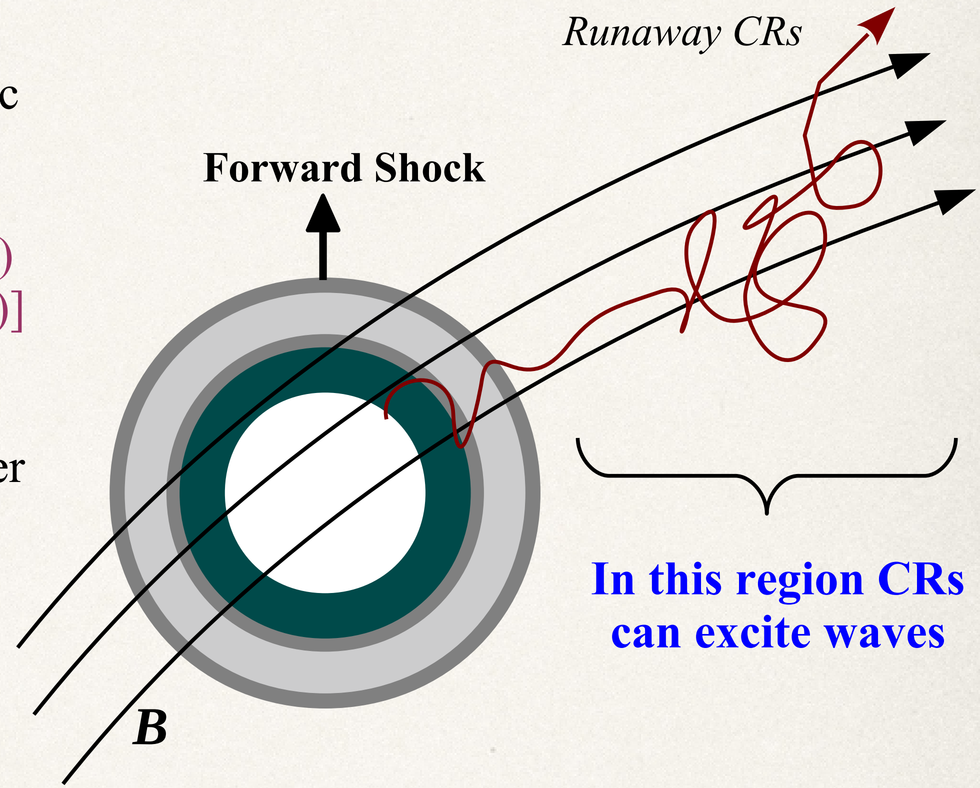

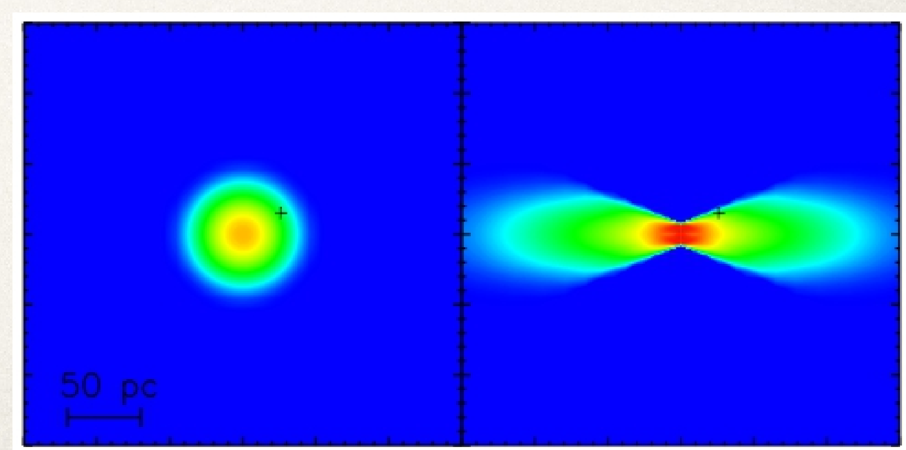

Simulation from Nava & Gabici (2012)

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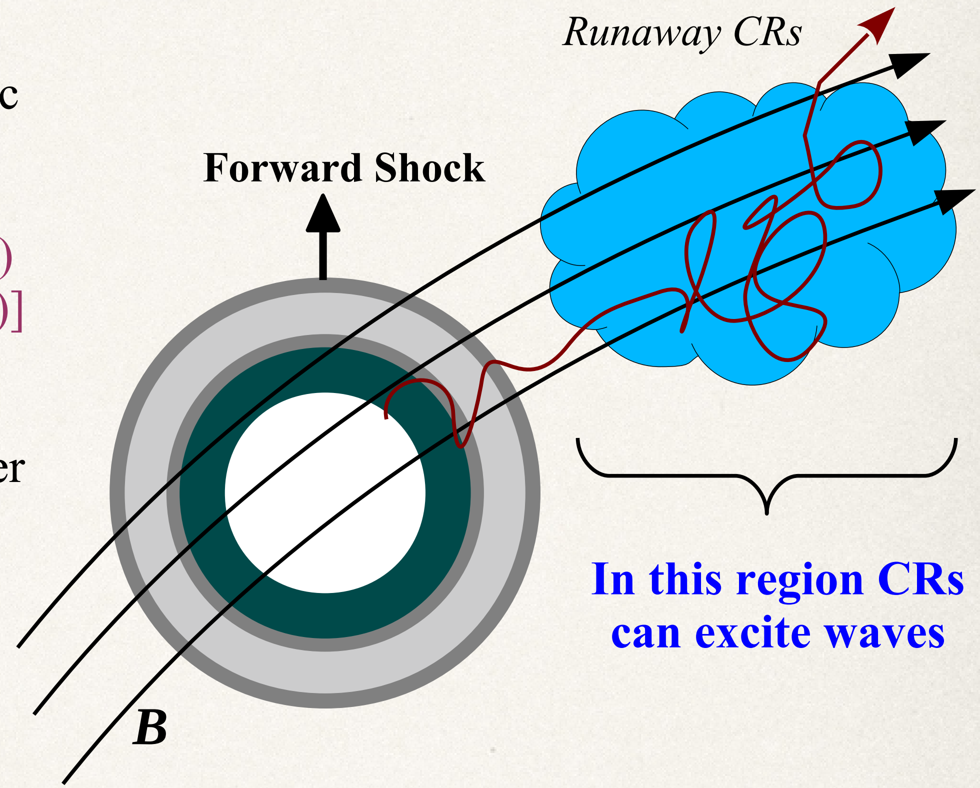
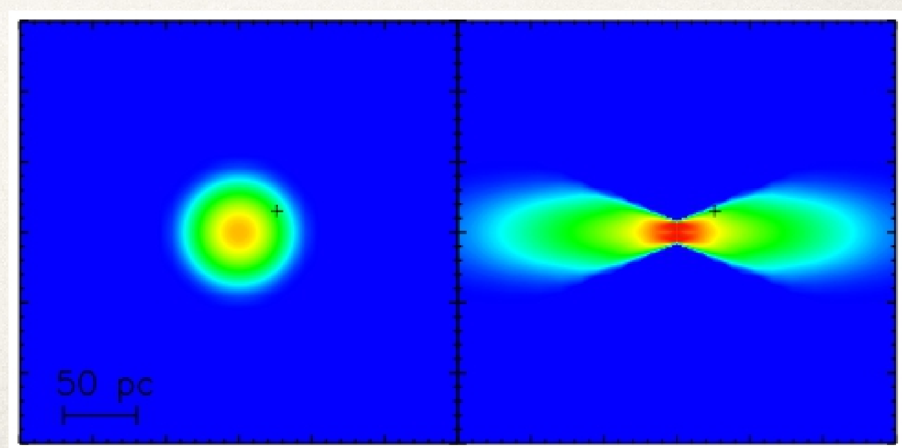
If a molecular cloud is close enough the enhanced γ-ray emission will be seen for long time

CTA will probably discover tens of SNR-MC associations



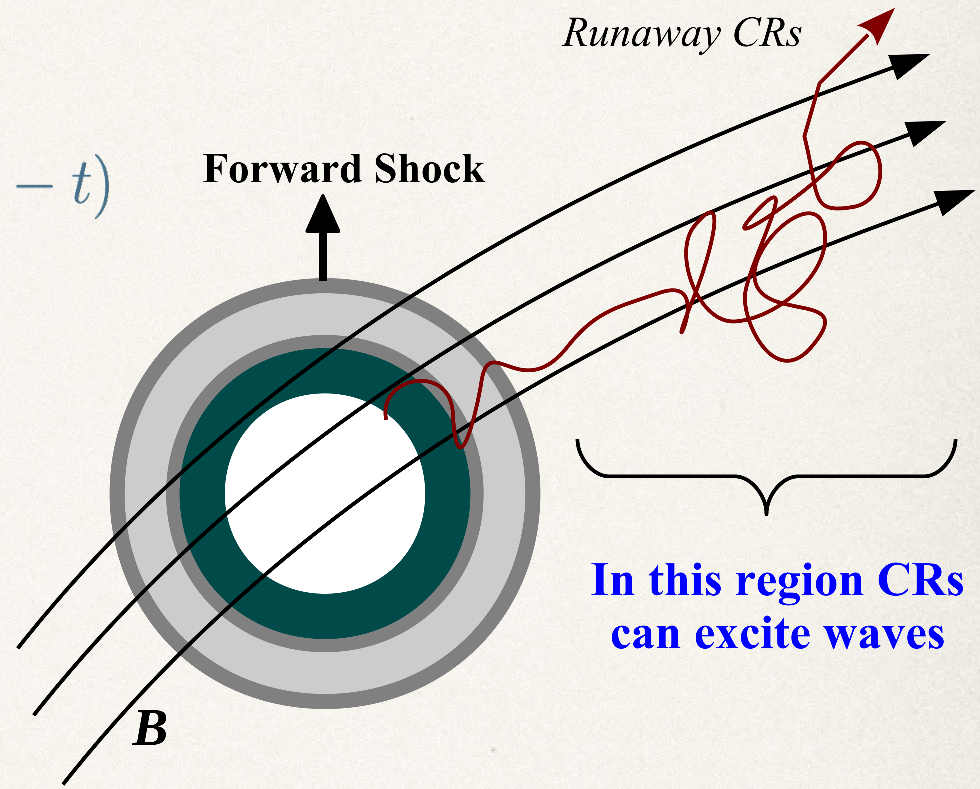


Simulation from Nava & Gabici (2012)

Effect of self-amplification near the CR sources: basic equations

CR transport equation in 1-D

$$\frac{\partial f}{\partial t} + v_A \frac{\partial f}{\partial z} = \frac{\partial}{\partial z}\left[D\frac{\partial f}{\partial z}\right] + q_0(p)\Theta\left(T_{SN} - t\right)$$



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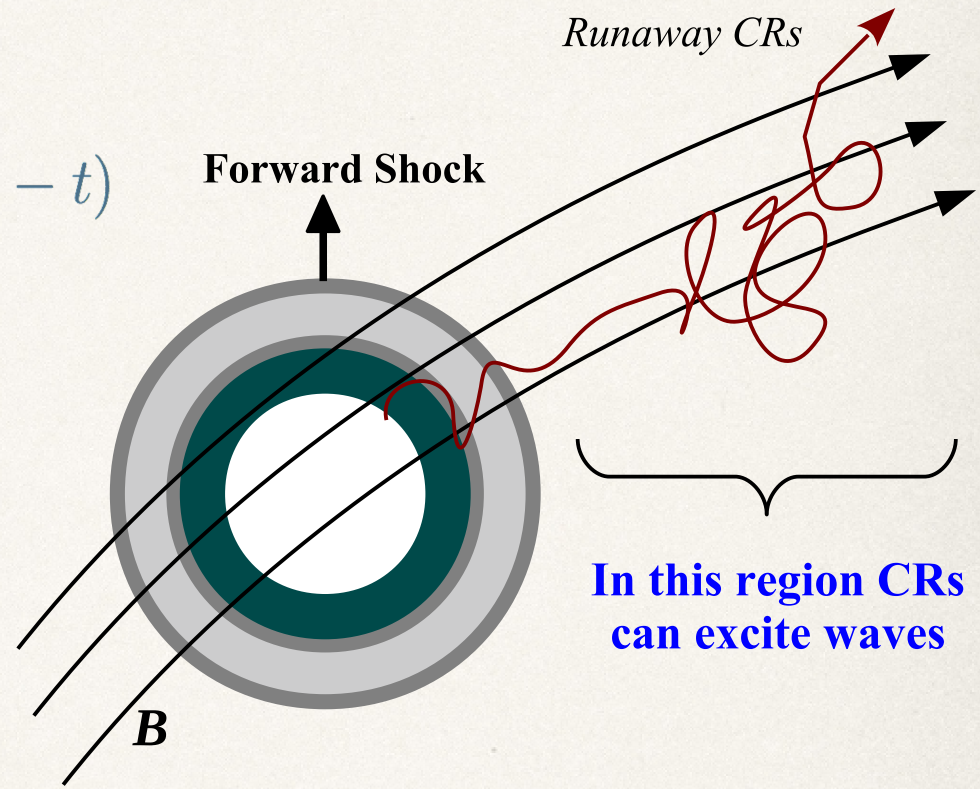
Self-generated diffusion coefficient

$$D(p, z, t) = \frac{r_L v}{3} \left.\frac{1}{\mathcal{F}(k, z, t)}\right|_{k=1/r_L(p)}$$

$$\frac{\delta B^2}{B_0^2} = \int \mathcal{F}(k) \frac{dk}{k}$$

Turbulence spectrum



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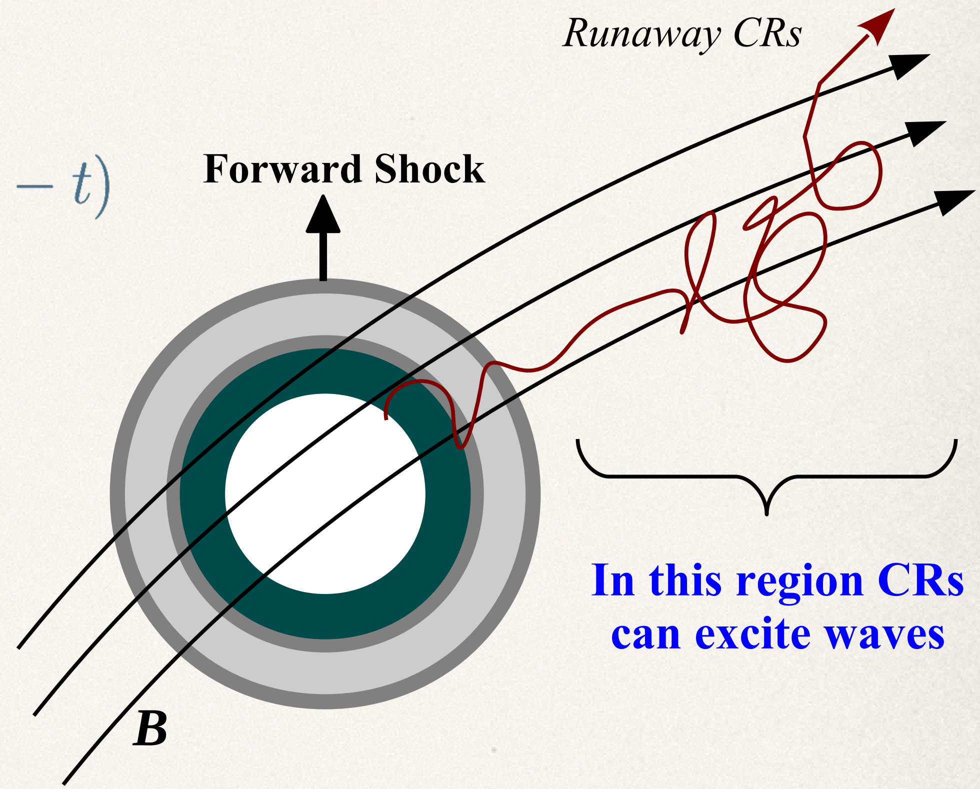

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Turbulence spectrum

Transport equation for magnetic turbulence

$$\frac{\partial \mathcal{F}}{\partial t} + v_A \frac{\partial \mathcal{F}}{\partial z} = \left(\Gamma_{CR} - \Gamma_D\right)\mathcal{F} + Q_w$$

Damping

Injection

Resonant amplification:

$$\Gamma_{CR} = \frac{16\pi}{3}\frac{v_A}{\mathcal{F}(k)B_0^2}\left[p^4 v \nabla f\right]_{p=p_{\rm res}}$$

Effect of self-amplification near the CR sources: damping mecanisms

Non-linear Landau damping
(Zhou & Matthaeus, 1990; Ptuskin Zirakashvili, 2004)

$$\Gamma_{NLD} = 0.05\, k\, v_A\, \mathcal{F}^{\frac{1}{2}} = 4.5 \times 10^{-9} \mathcal{F} \left(\frac{B_0}{3\mu G}\right)^2 \left(\frac{E}{10GeV}\right)^{-1} \left(\frac{n_i}{0.45}\right)^{-\frac{1}{2}} s^{-1}$$

Damping due to anisotropic cascade (wave-wave interaction)
(Farmer & Goldreich, 2004)

$$\Gamma_{FG} = \sqrt{\frac{k}{L_{MHD}}} v_A = 1.2 \times 10^{-11} \left(\frac{B_0}{3\mu G}\right)^{\frac{3}{2}} \left(\frac{E}{10GeV}\right)^{-1} \left(\frac{n_i}{0.45}\right)^{-\frac{1}{2}} s^{-1}$$

$$L_{MHD} = L_c$$

Damping due to ion-neutral friction
(Kulsrud & Pearce, 1969; Kulsrud & Cesarsky, 1971; Drury et al., 1996)

$$\Gamma_{IN} = \frac{\omega_i}{n_i/n_n} \frac{v_A^2 k^2}{v_A^2 k^2 + \omega_i^2} \quad \text{if} \quad \frac{n_i}{n_n} > 1$$

$$\text{with} \quad \omega_i = 4 \times 10^{-9} \left(\frac{n_i}{0.45}\right) \left(\frac{T}{10^4 K}\right)^{0.4} s^{-1}$$

Unless neutral hydrogen density is very low, the ion neutral damping dominates

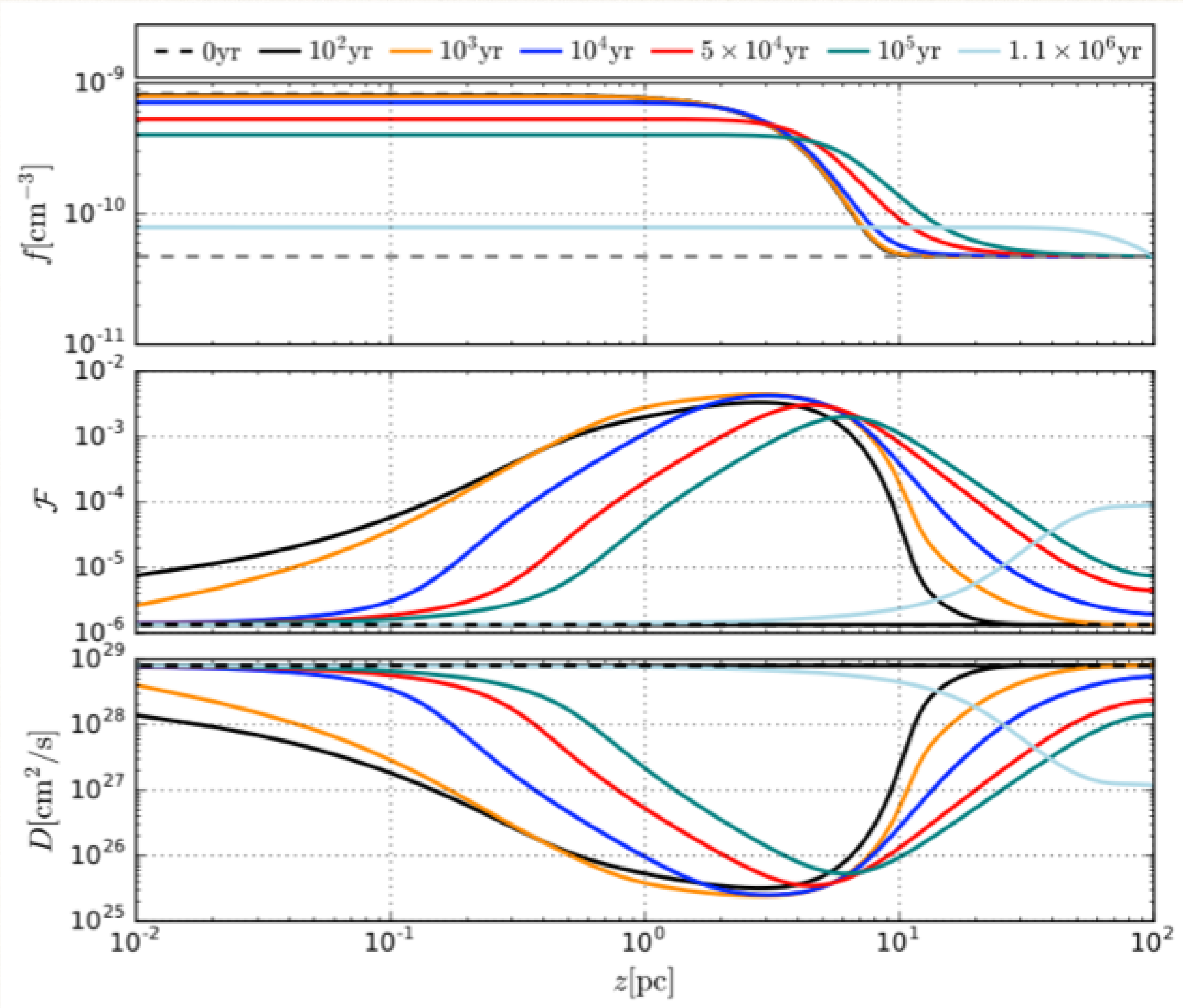
Evolution of CR density close to the source

(D'Angelo, GM, Amato, Blasi, in preparation)

CR distribution function @ 10 GeV For several ages

Distribution function of turbulence

Diffusion coefficient



Distance from the source in pc

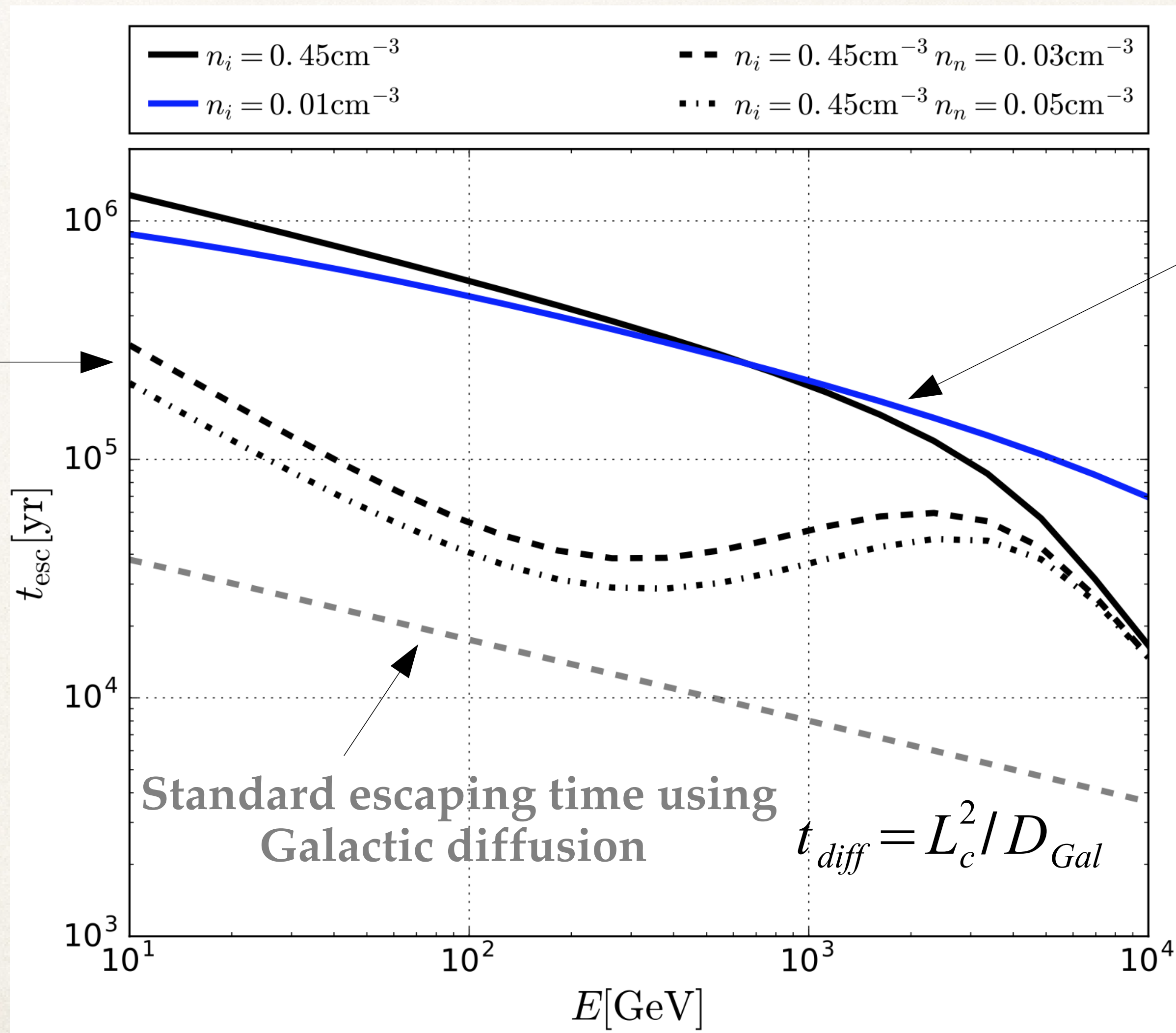
Evolution of CR density close to the source

(D'Angelo, GM, Amato, Blasi, in preparation)

Escape time as a function of particle's energy

With neutrals

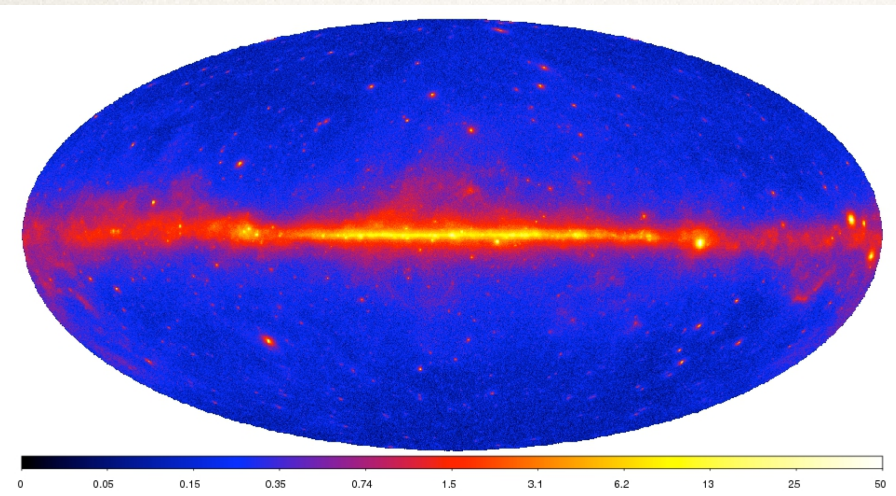
$n_H / n_i \sim 5\%\text{-}10\%$



No neutrals

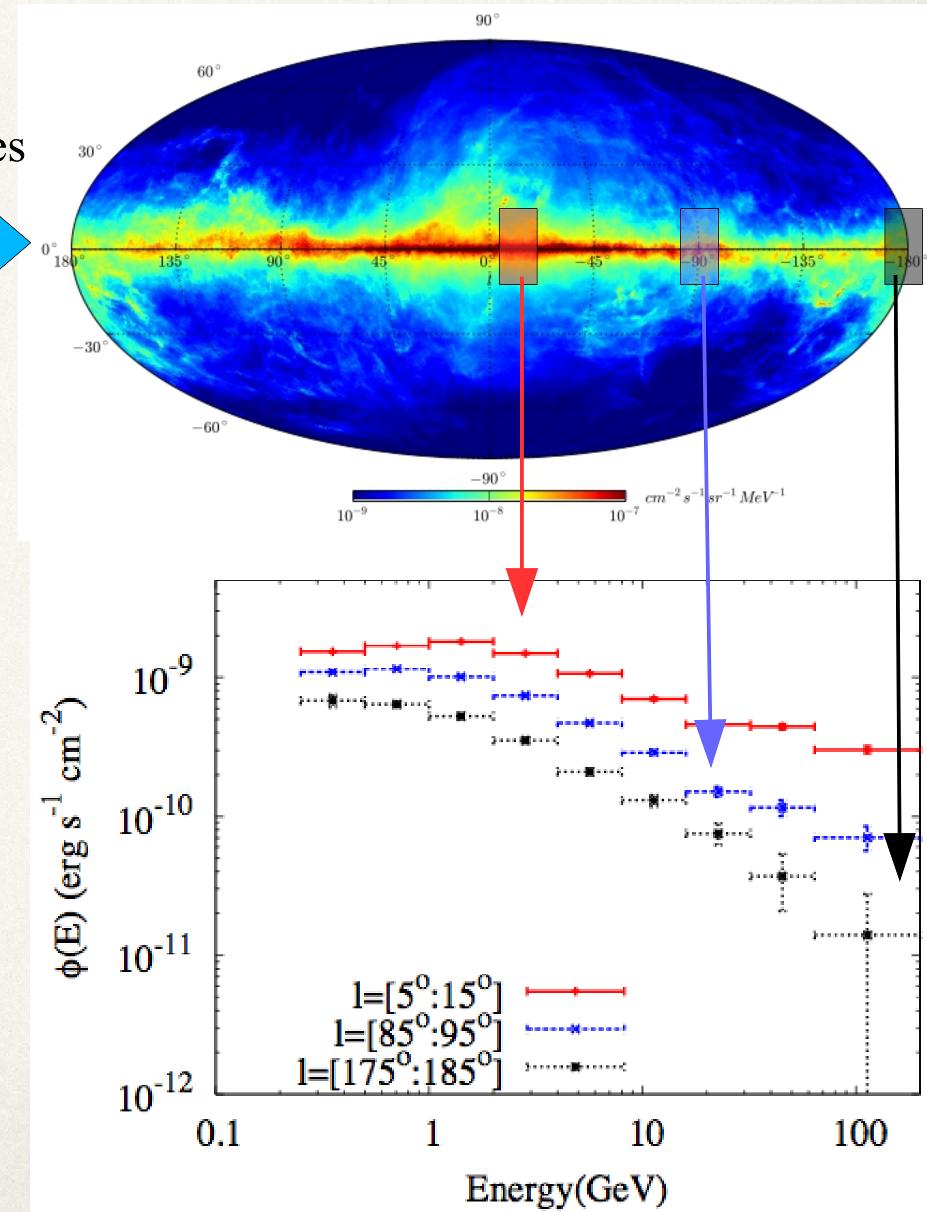
Diffuse Galactic emission

FermiLAT all sky map



Subtracting known sources

FermiLAT diffuse emission



Diffuse Galactic γ-ray flux for three different angular sectors extracted from the Fermi-LAT data
[Yang, Aharonian & Evoli, 2016]

Contribution of the escaping CRs to the diffuse Galactic emission

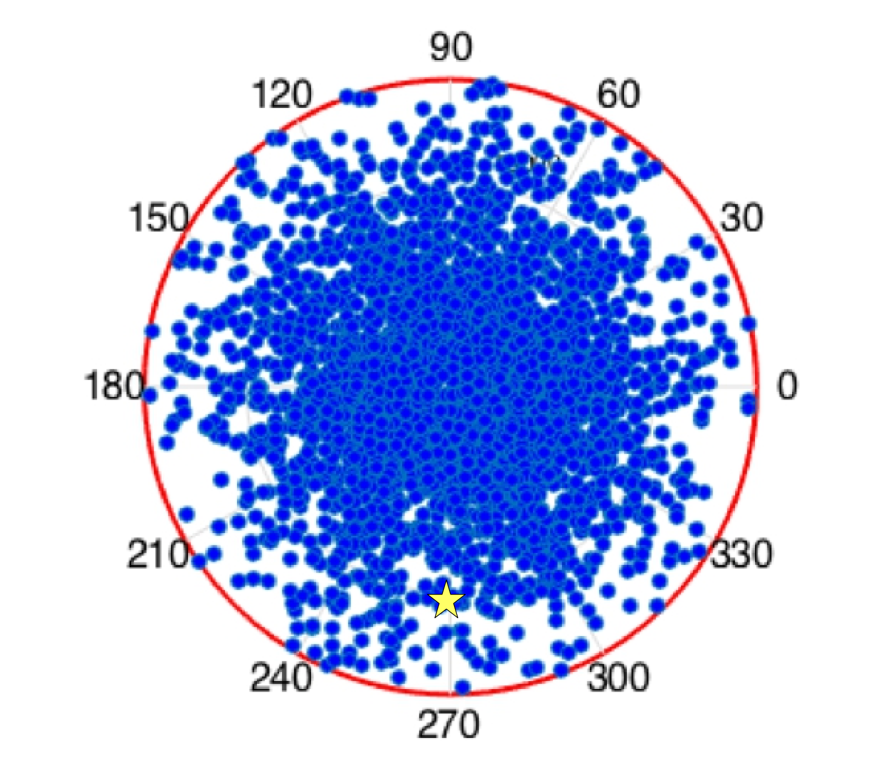
(D'Angelo, GM, Amato, Blasi, in preparation)

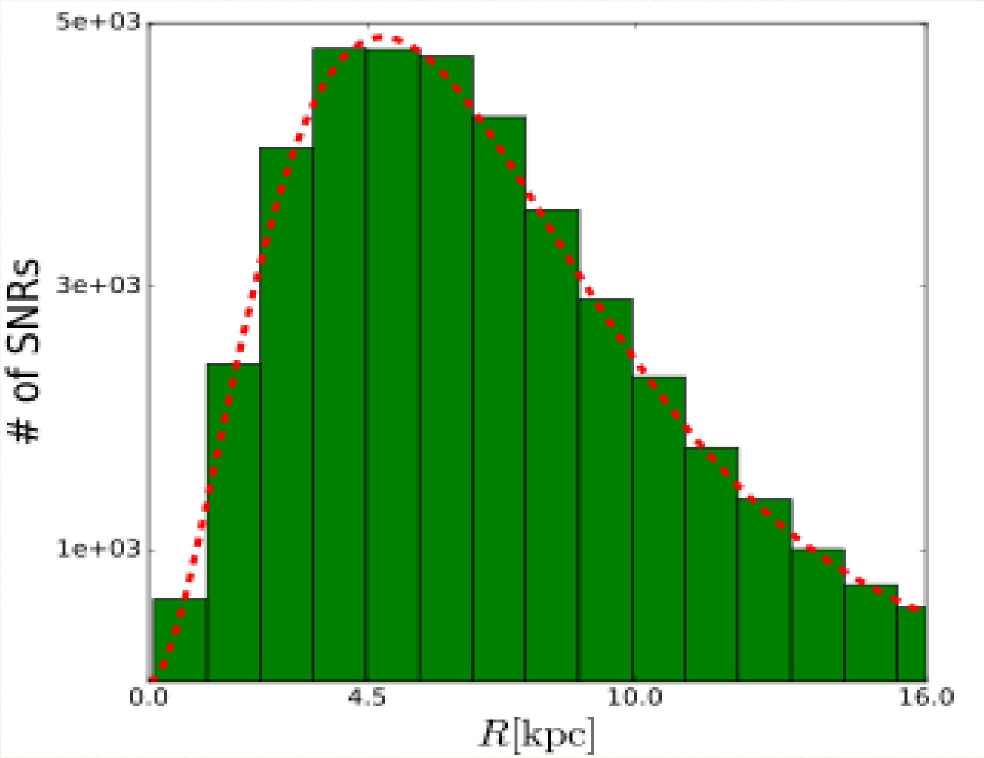
Distribution of SNR in the galactic plane during the last ~10^5 yrs using a rate of 1 SN/(30 yr)

We assume the SNR distribution according to the model by Green (2015)

$$f_{\rm SNR} \propto \left(\frac{R}{R_\odot}\right)^\alpha \exp\left(-\beta \frac{R - R_\odot}{R_\odot}\right)$$

$\alpha = 1.09$
$\beta = 2.87$





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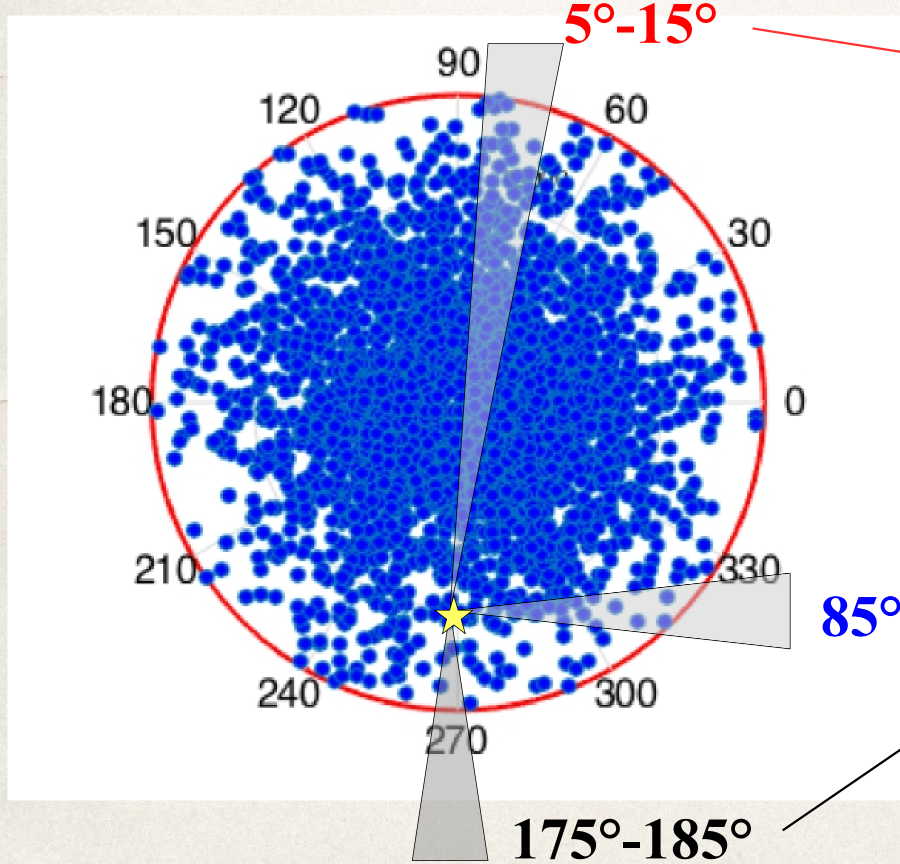
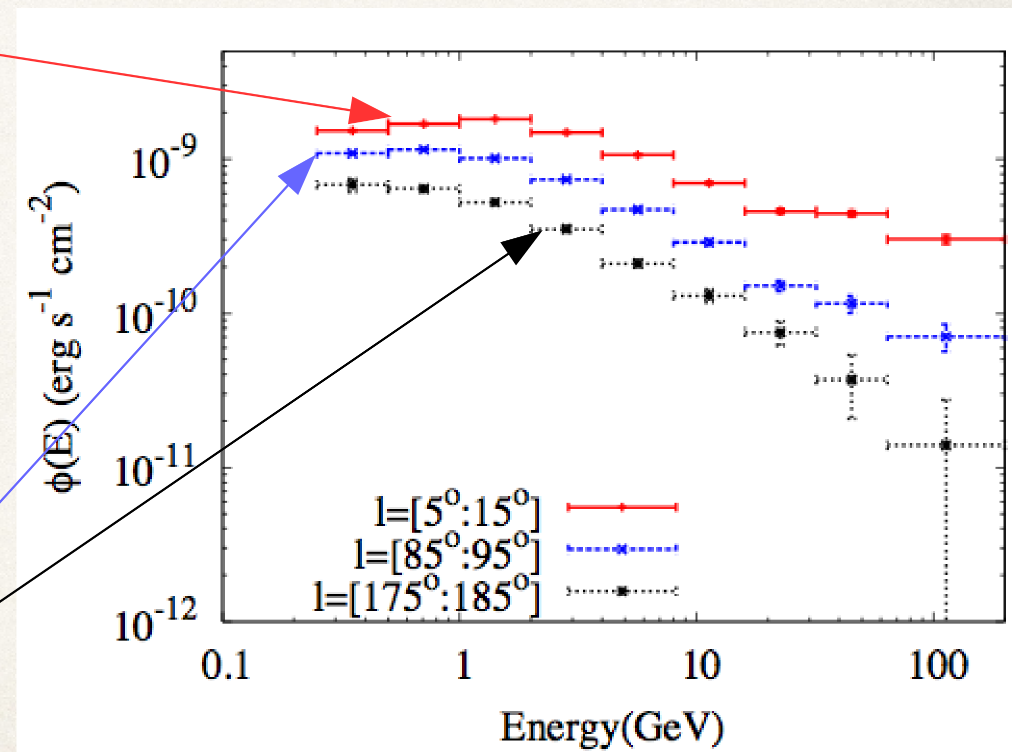
Fermi-LAT data analized by Yang et al. (2016)

5°-15°



85°-95°

175°-185°



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Number of sources contributing to the emission

Angular sector	Fully ionized	n_H=0.05
5°-15°	4500	740
85°-95°	350	57
175°-185°	77	13

$n_i = 0.45\,cm^{-3}$; $n_H = 0.0\,cm^{-3}$

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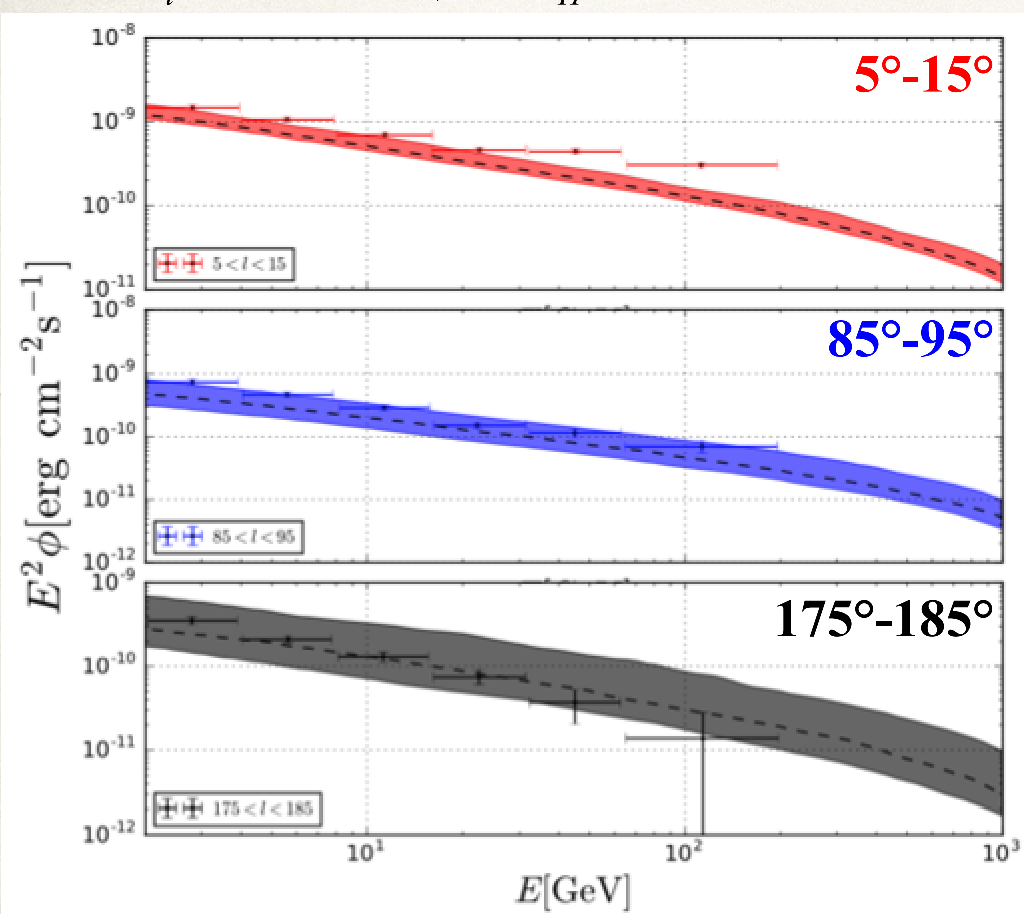

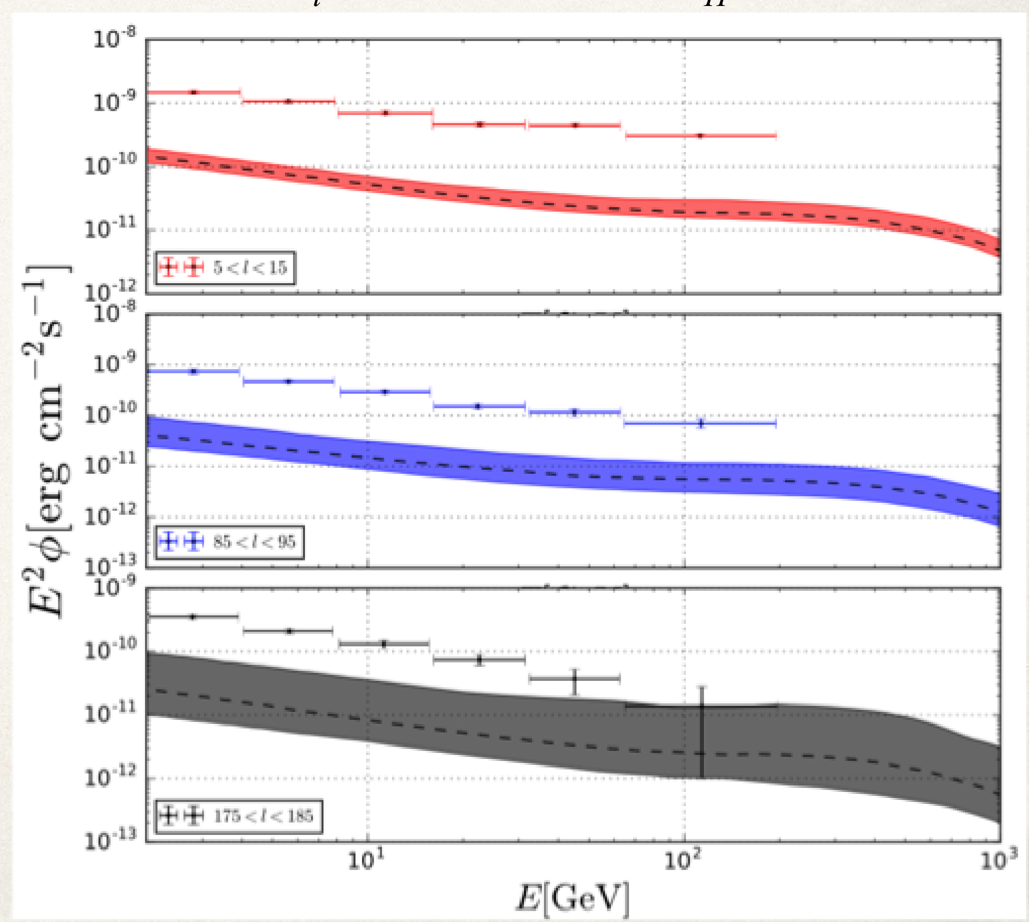

The *radial gradient* problem

The CR density inferred from the gamma-ray emission in the Galactic disk is much more weak dependent on the galactocentric distance than the CR sources

This result is well known since SAS-2 data (Stecker & Jones, 1997) COS-B (Bath et al. 1986, Bloemen et al. 1986)

Confirmed by EGRET (Strong & Mattox 1996; Hunter et al 1997) and more recently by Fermi-LAT (Ackermann et al 2011, 2012)

This analisys was done only for the external Galaxy

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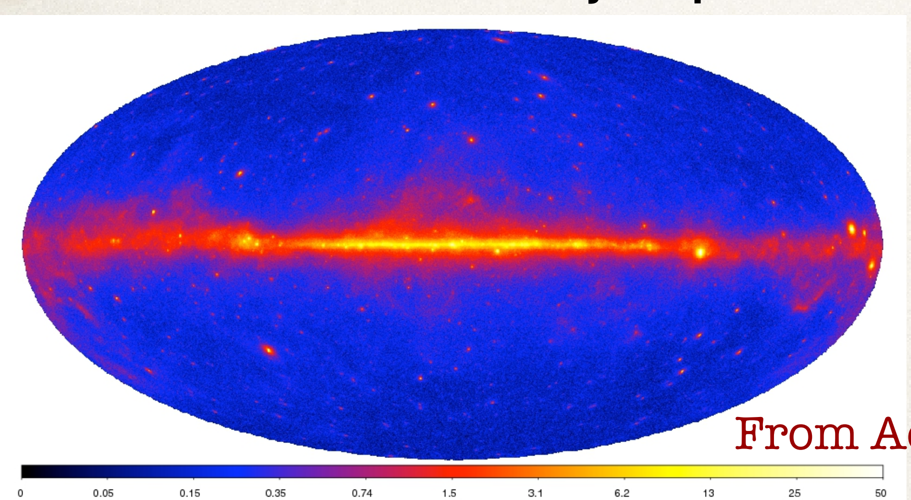

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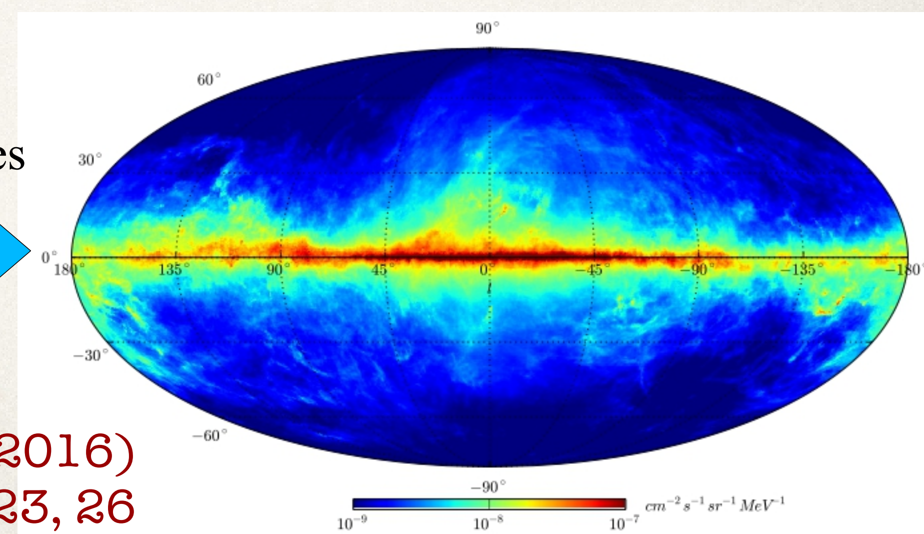
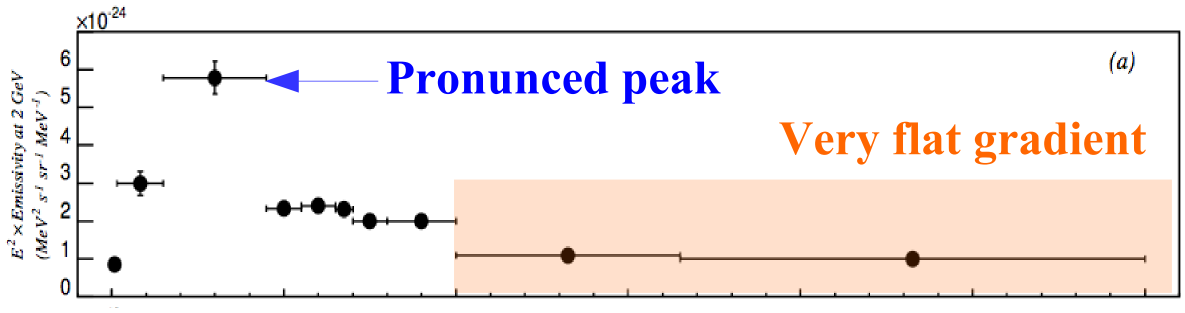


From Acero et al. (2016) ApJS, 223, 26

The problem of the cosmic ray gradient in the Galactic plane seen by Fermi-LAT



Recent results from FermiLAT collaboration on the CR distribution in the Galactic plane
[Acero et al. arXiv:1602.07246]

- In the outer region (R > 8kpc) the CR density at ~20 GeV is flat (i.e. decreases much slower than the source distribution)

- In the inner region the CR density has a peak at ~ 3 kpc

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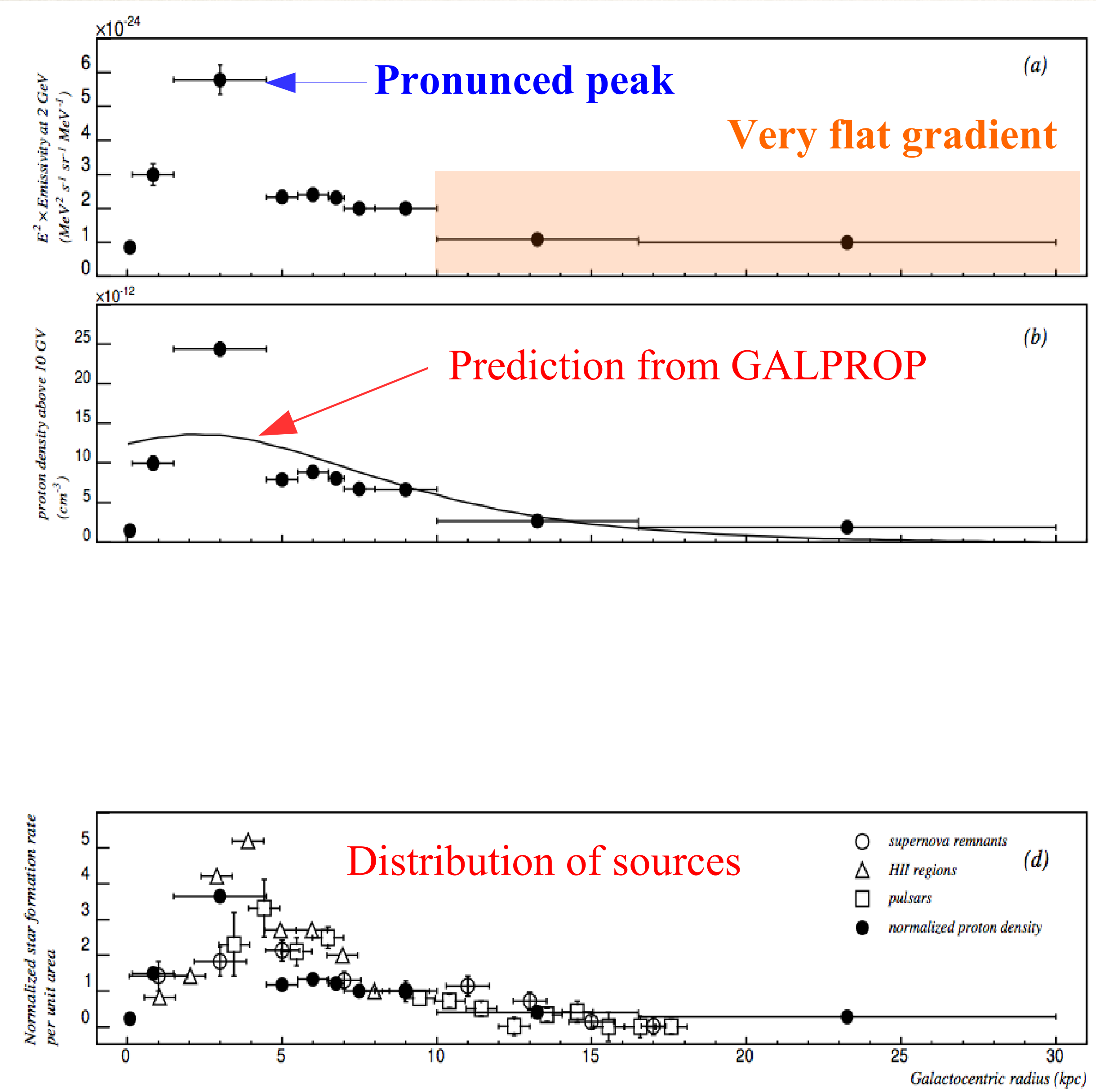

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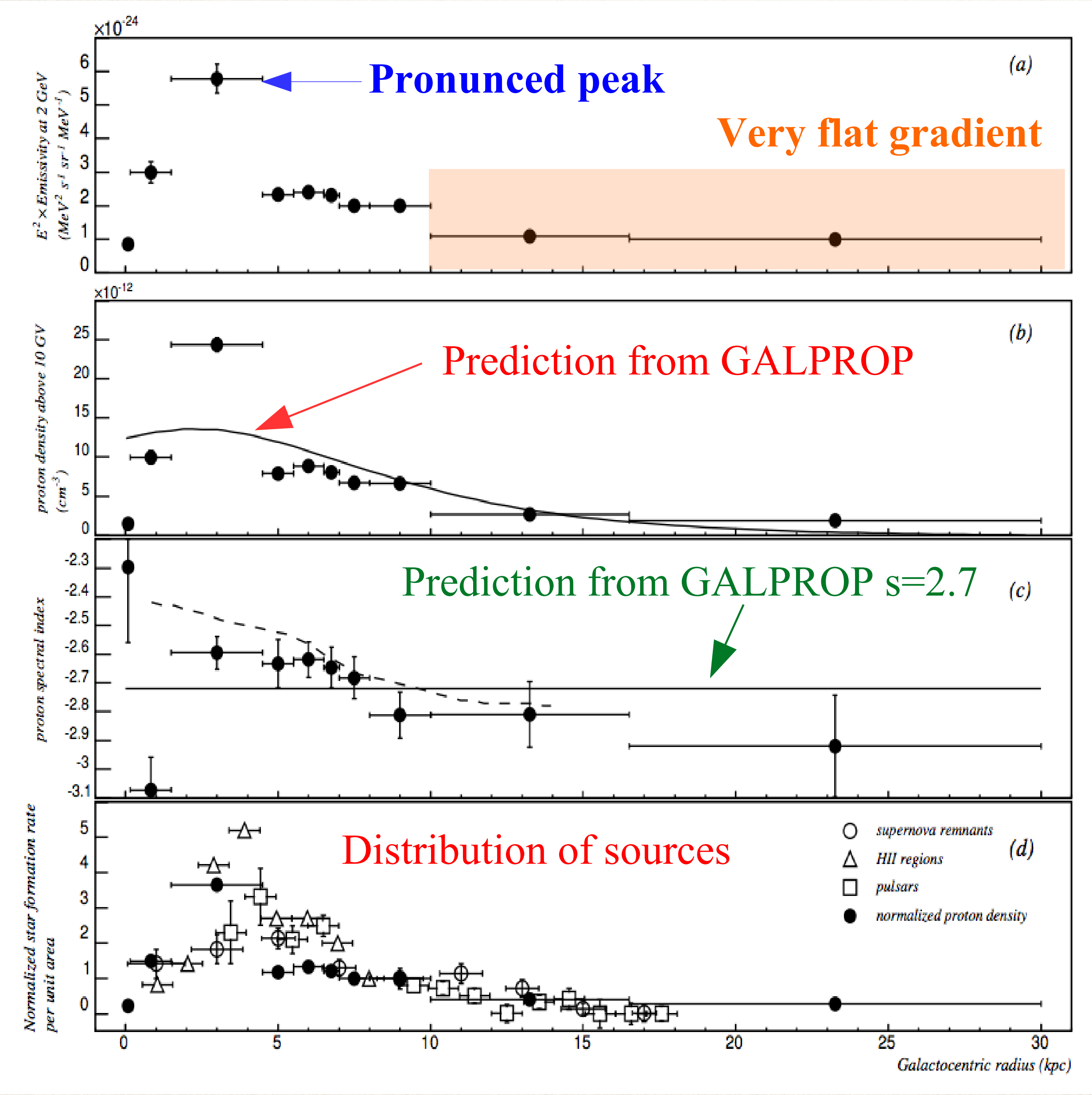

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(i.e. decreases much slower than the source distribution)

- In the inner region the CR density has a peak at ~ 3 kpc

- The slope @ 20 GeV is not constant

This scenario is difficult to accommodate in a standard leaky-box model

Possible solutions

In the context of leaky-box model several solution have been proposed:

- Extended halo, $H > 4$ kpc
  (Dogiel, Uryson, 1988; Strong et al.,1988; Bloemen, 1993, Ackerman et al., 2011)
  - ^ predices a flat spectrum (but not flat enough)
  - ^ cannot explain the denity bump in the inner Galaxy
- Flatter distribution of SNR in the outer Galaxy
  (Ackerman et al., 2011)
- Enhancement of CO/H_2 density ratio (X_{CO}) in the outer Galaxy (Strong et al., 2004)
- Injection dependence on the ISM temperature
  (Erlykin et al., 2015)

None of these ideas can simoultaneously account for all signatures

- flatness R > 8 kpc,
- peak at R~3-4 kpc,
- variation in the slope

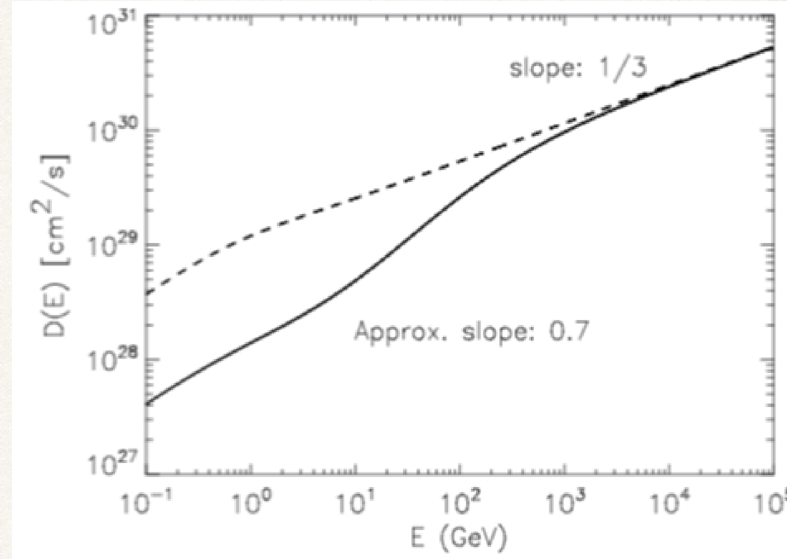
- Advection effects due to the Galactic wind
  (Bloemen, 1993; Breitschwerdt, Dogiel, Voelk, 2002)

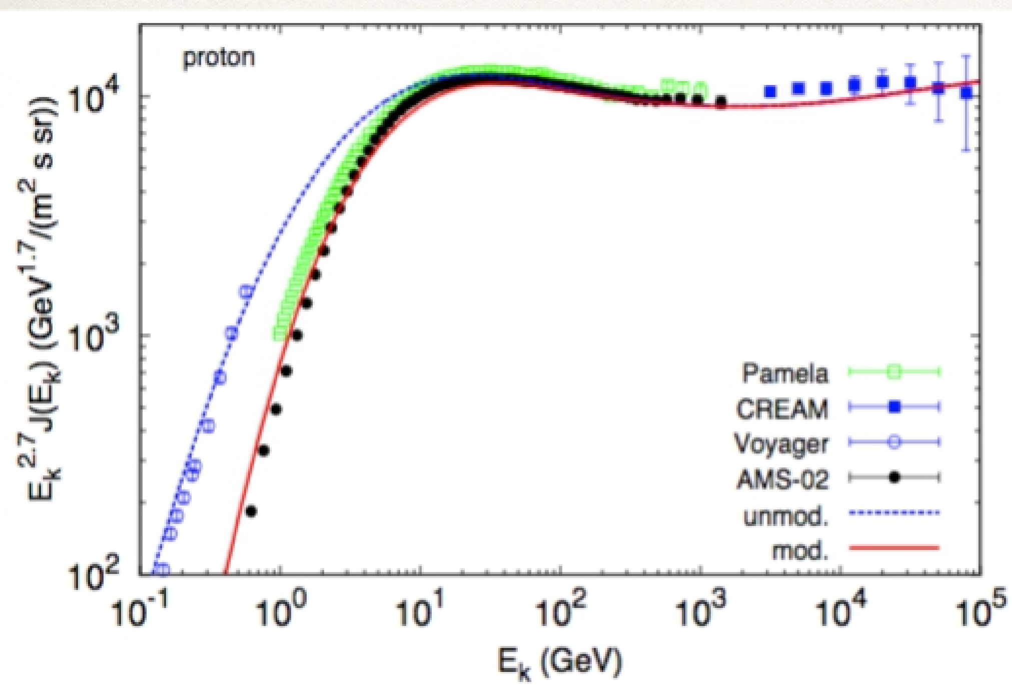
CAN SELF-GENERATED DIFFUSION EXPLAIN THE OBSERVATIONS?

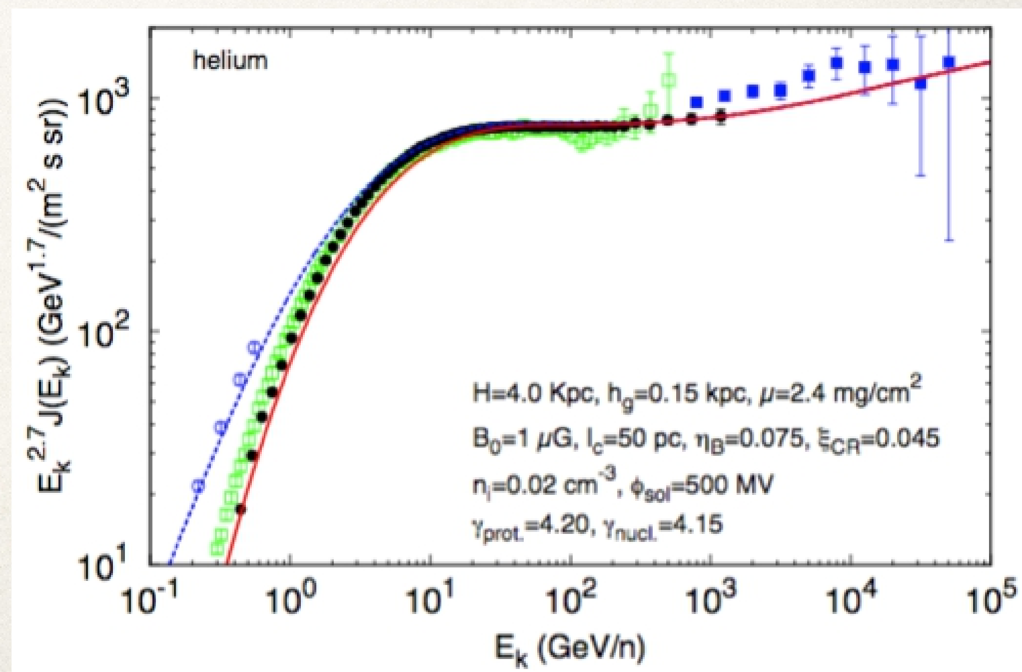
Spectral breaks as signatures of CR-induced turbulence

The presence of breaks in the PAMELA and AMS-02 data can be explained by a different diffusion regime
[Blasi, Amato Serpico (2012)
Aloisio, Blasi, Serpico (2015)]

- $E < 200$ GeV ^ self generated diffusion
- $E > 200$ GeV ^ external preexisting turbulence







1-D slab model with self-generated turbulence

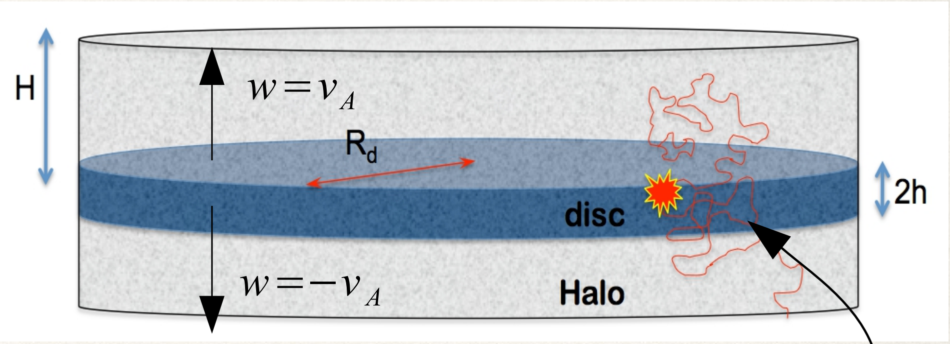
(Recchia, Blasi, GM, MNRAS 462, 2016)

CR transport equation with diffusion and advection due to Alfvén speed in the *z* direction only

$$-\frac{\partial}{\partial z}\left[D(z,p)\frac{\partial f}{\partial z}\right] + w\frac{\partial f}{\partial z} - \frac{p}{3}\frac{\partial w}{\partial z}\frac{\partial f}{\partial p} = Q_0(p)\delta(z),$$

Diffusion coefficient in the turbulence with power spectrum $W(k) = k\,\mathcal{F}(k)$

$$D(z,p) = \frac{r_L(p)v(p)}{3}\left[\frac{1}{\mathcal{F}(k)}\right]_{k=1/r_L}$$



Spectrum injected at the disk

$$Q_0(p) = \frac{\xi_{\rm inj}E_{\rm SN}\mathcal{R}_{\rm SN}(R)}{4\pi\Lambda c(m_pc)^4}\left(\frac{p}{m_pc}\right)^{-\gamma}$$

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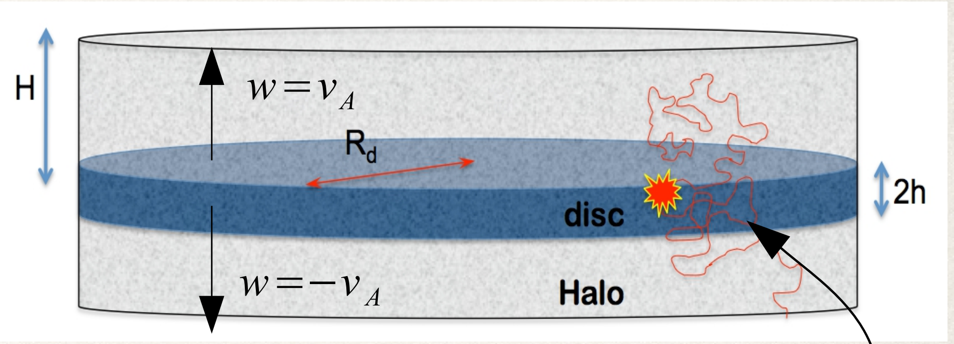

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CR amplification due to streaming instability

$$\Gamma_{\rm cr}=\frac{16\pi^2}{3}\frac{v_A}{\mathcal{F}(k)B_0^2}\left[p^4v(p)\frac{\partial f}{\partial z}\right]_{p=eB_0/kc}$$

Non-linear Landau damping

$$\Gamma_{\rm nlld}=(2c_k)^{-3/2}\,kv_A\,\mathcal{F}(k)^{1/2}$$

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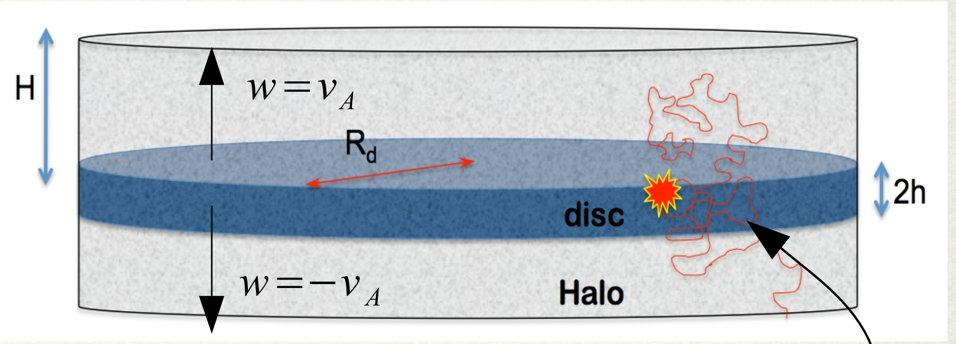

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Non-linear Landau damping

$$\Gamma_{\rm nlld}=(2c_k)^{-3/2}\,k v_A\,\mathcal{F}(k)^{1/2}$$

Assuming $\Gamma_{\rm cr} = \Gamma_{\rm nlld}$

In the diffusion dominated case ($D >> v_A H$) the solution is analytical:

$$f_0(p)=\frac{3c_k^3}{r_L v}\left(\frac{16\pi^2 p^4}{B_0^2}\right)^2 H Q_0(p)^3 \propto \frac{Q_0^3}{B_0^3}$$

1-D slab model with self-generated turbulence

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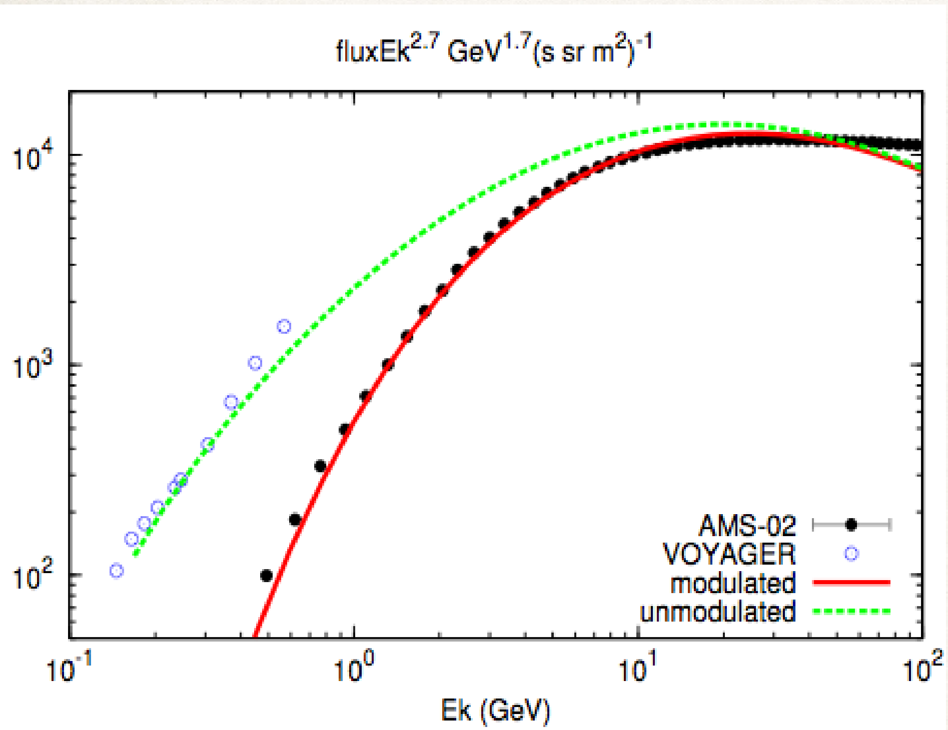
Local CR spectrum



Fitting the local CR spectrum provides

$$\frac{\xi_{inj}}{0.1} \times \frac{R_{SN}}{1/30\ yr} = 0.3$$

$$\gamma = 4.2$$

Injection efficiency and slope are assumed the same for the whole Galaxy

$B_{sun} = 1\,\mu G$ Poloidal magnetic field at the Sun position

We take the source distribution in the Galaxy from Green (2015)

$$f_{\mathrm{SNR}} \propto \left(\frac{R}{R_\odot}\right)^{\alpha} \exp\left(-\beta \frac{R - R_\odot}{R_\odot}\right)$$

$\alpha = 1.09$
$\beta = 2.87$

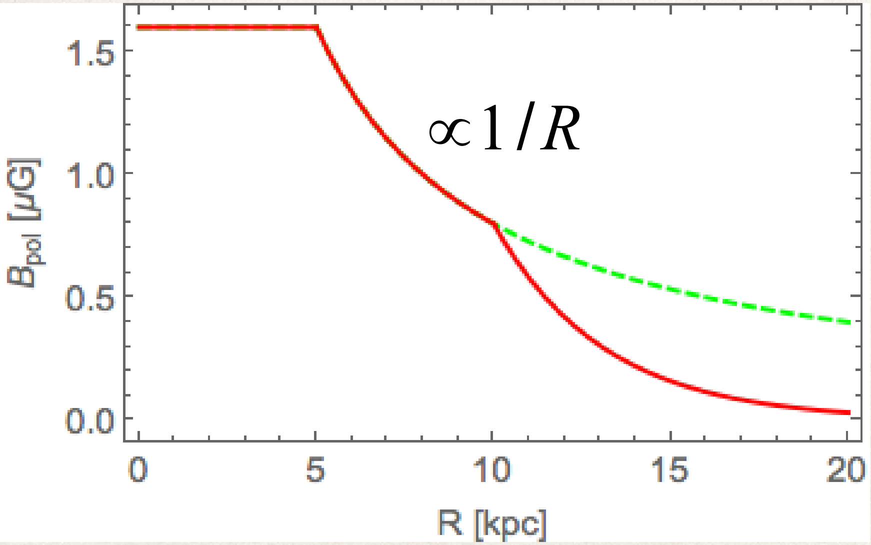
1-D slab model with self-generated turbulence

(Recchia, Blasi, GM, MNRAS 462, 2016)

Large scale magentic field in the Galaxy:

$$B_0(R < 5\,\mathrm{kpc}) = B_\odot R_\odot / 5\,\mathrm{kpc}$$
$$B_0(R > 5\,\mathrm{kpc}) = B_\odot R_\odot / R\,,$$

$$B_0(R > 10\,\mathrm{kpc}) = \frac{B_\odot R_\odot}{R} \exp\left[-\frac{R - 10\,\mathrm{kpc}}{d}\right]$$



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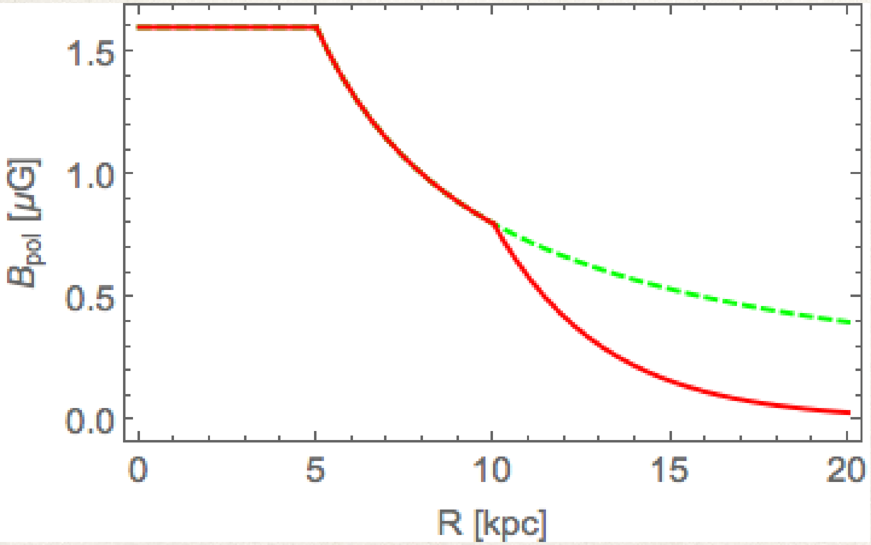
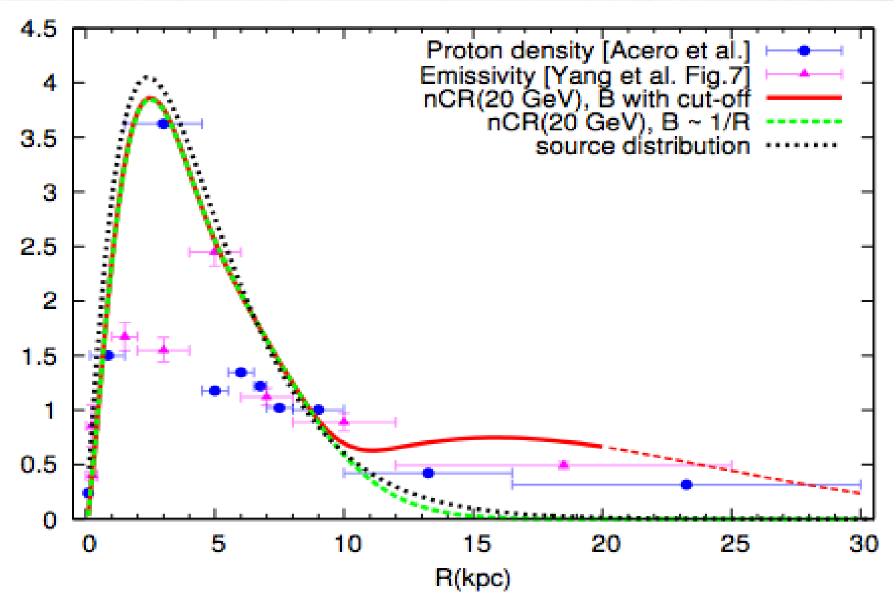


CR spectrum density @ 20 GeV



The flatning of CR spectrum occurs because:

$$f_{CR} \propto \left(\frac{Q_0(R)}{B_0(R)}\right)^s \quad with \quad s = 1-3$$

1-D slab model with self-generated turbulence

(Recchia, Blasi, GM, MNRAS 462, 2016)

Large scale magentic field in the Galaxy:

$$B_0(R < 5\,\mathrm{kpc}) = B_\odot R_\odot / 5\,\mathrm{kpc}$$
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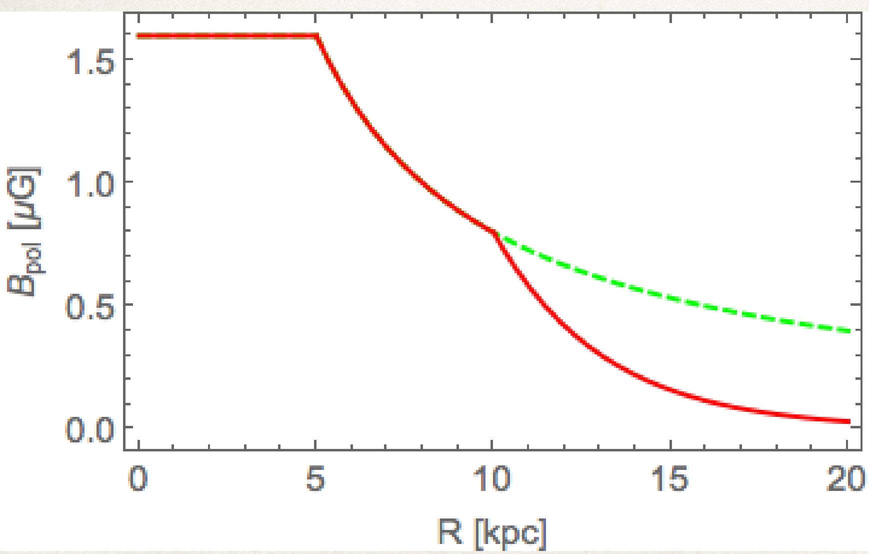
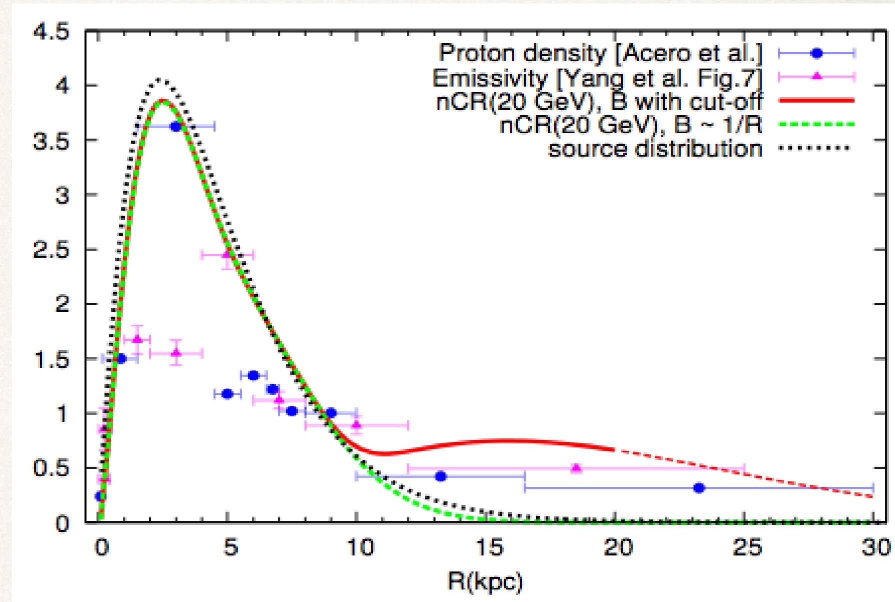
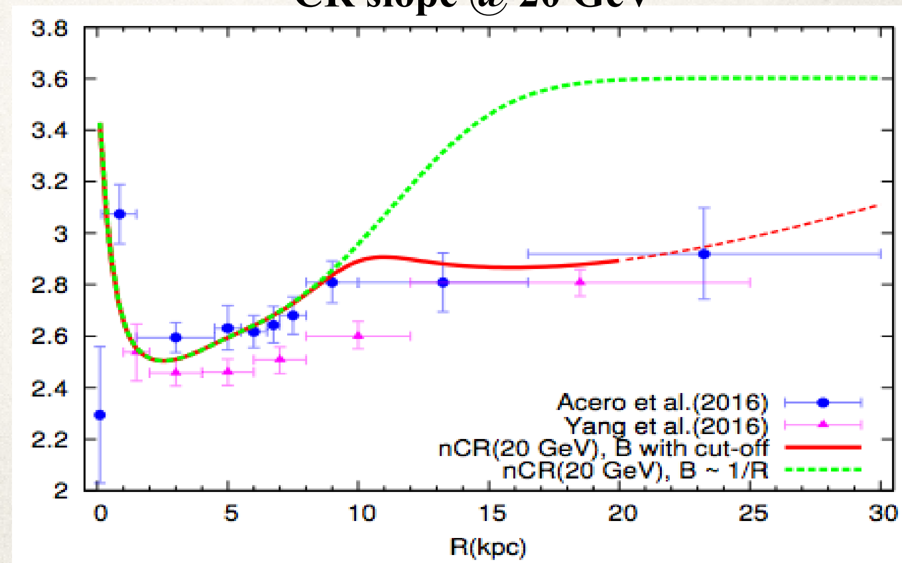
$$B_0(R > 10\,\mathrm{kpc}) = \frac{B_\odot R_\odot}{R} \exp\left[-\frac{R - 10\,\mathrm{kpc}}{d}\right]$$



CR spectrum density @ 20 GeV



CR slope @ 20 GeV



1-D slab model with self-generated turbulence

(Recchia, Blasi, GM, MNRAS 462, 2016)

- $D(p)$ is almost momentum independent for E <~ 10 GeV

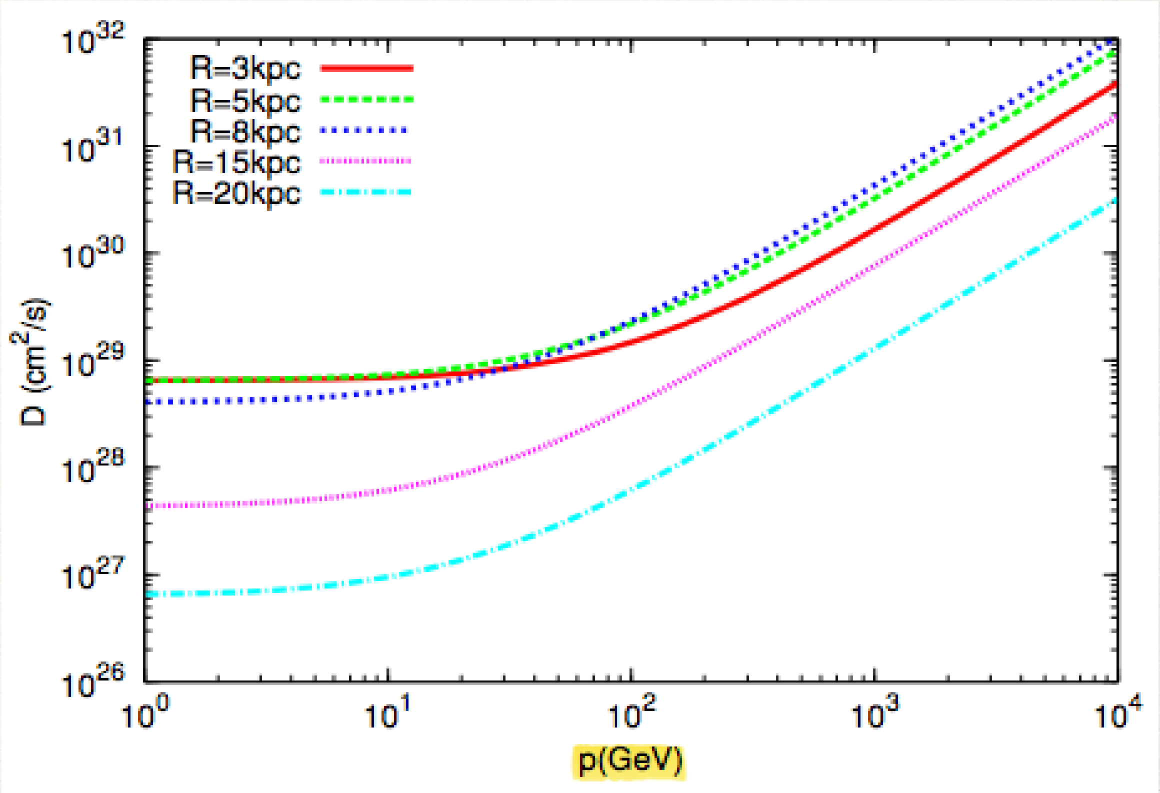
$$D(z,p) = D_H(p) + 2v_A(H-z)$$

This trend is often put by hand in numerical simulation to fit observations

- A simple prediction of our calculations is that the spectral hardening should disappear at higher energies, where transport is diffusion dominated at all galactocentric distances.

- For R >~ 20 kpc this approach lose validity because $\delta B \geqslant B_0$

Diffusion coefficient $D(p)$ at different position in the Galaxy



Conclusions – part I

- We still lack of a realstic description of the Galactic propagation

- Going beyond the simple view of the leaky-box model is required by data

- The effect of self-generated turblence produced via streaming instability could play a major role for the propagation of CRs with E <~ 100 GeV

  - Propagation close to sources ^ CRs spend more time close to the sources producing a non-negligible contribution to the diffuse γ-ray emission

  - Propagation in the Galactic halo ^ the balance between advection due to Alfvèn speed and diffusion determined by CR streaming produce a variation in both the spectrum slope and normalization that well account for the data.

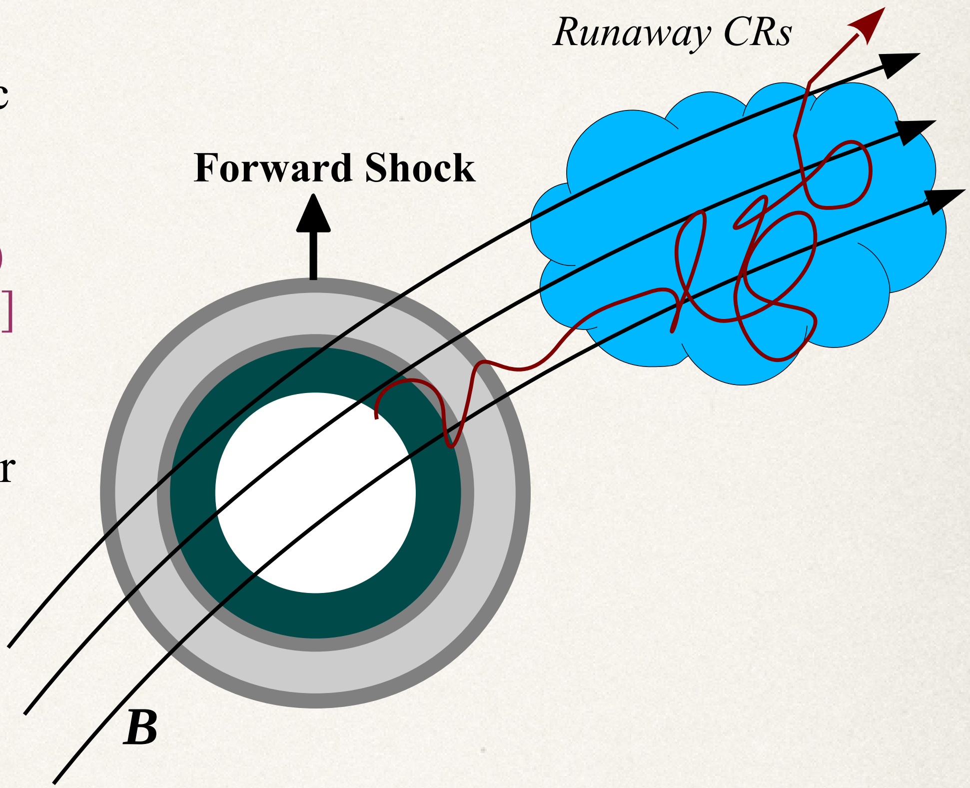
    * A clear test for this model is the CR spectrum slope at E >~ 100 GeV because the advection becomes negligible

- In a forthcoming work we will analize the effect of a CR-driven Galactic wind coupled to self-generated diffusion

SNR-MC associations

During the process of escaping, CR can excite magnetic turbulence (via streaming instability) that keep the CR close to the SNR for a long time, up to ~10^5 yr

[Malkom et al. (2013)
Nava et al. (2015)]



The region where this can happen is at most of the order of the coherence-length of the magnetic field (after this distance the diffusion becomes 3D and the CR dendity drops rapidly below the average Galactic value)

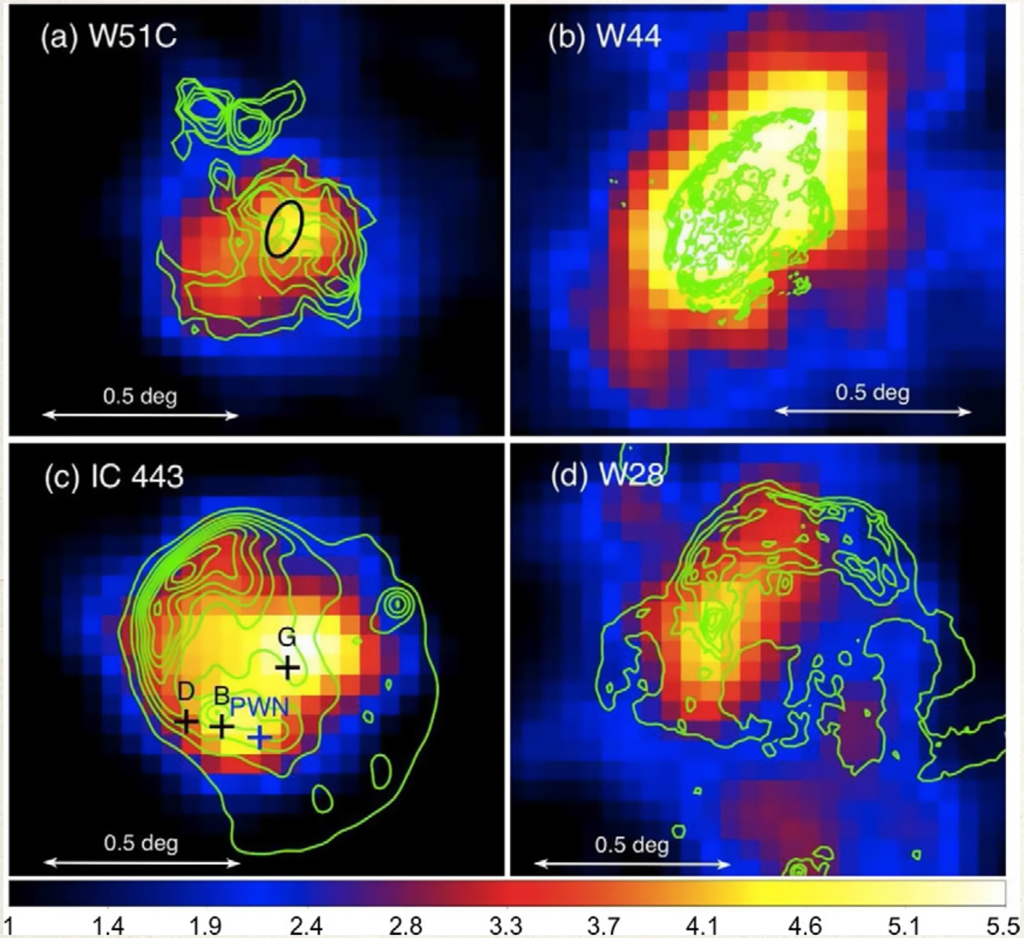
During the time CR spend in the vicinity of sources they can produce diffuse emission via $\pi^0 \rightarrow \gamma\ \gamma$

If a molecular cloud is close enough the enhanced γ-ray emission will be seen for long time

CTA will probably discover tens of SNR-MC associations

MCs as CR barometers

Examples of γ-ray emission from clouds close or interacting with SNRs - [*Fermi*-LAT]



<u>OBSERVATIONS of MCs in γ-RAYS:</u>

- CRs interact inside MCs
$$pp \rightarrow \pi^0 \rightarrow \gamma\gamma$$
- strong emission in GeV range
- γ-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)

<u>DETECTION OF IONIZATION</u>

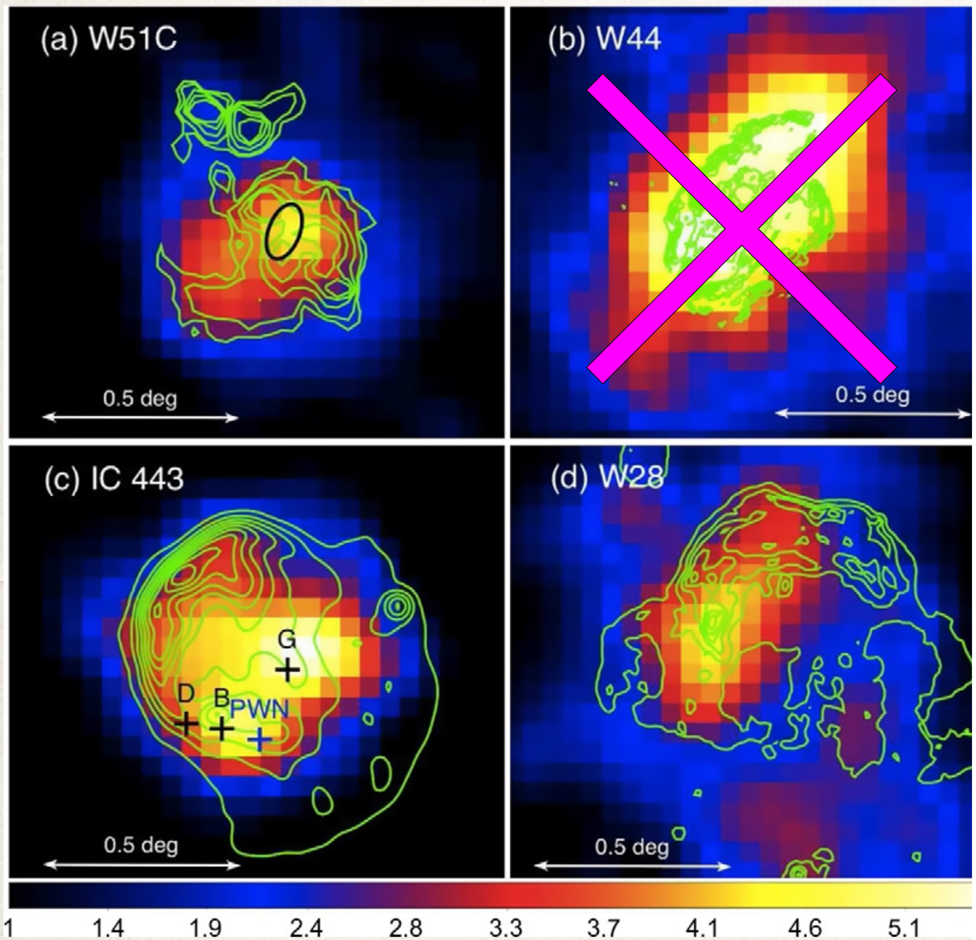
- The ionization rate of several molecules depends on the CR flux (H_2, H_3^+, CH, OH, C_2, DCO^+, HCO^+,......)

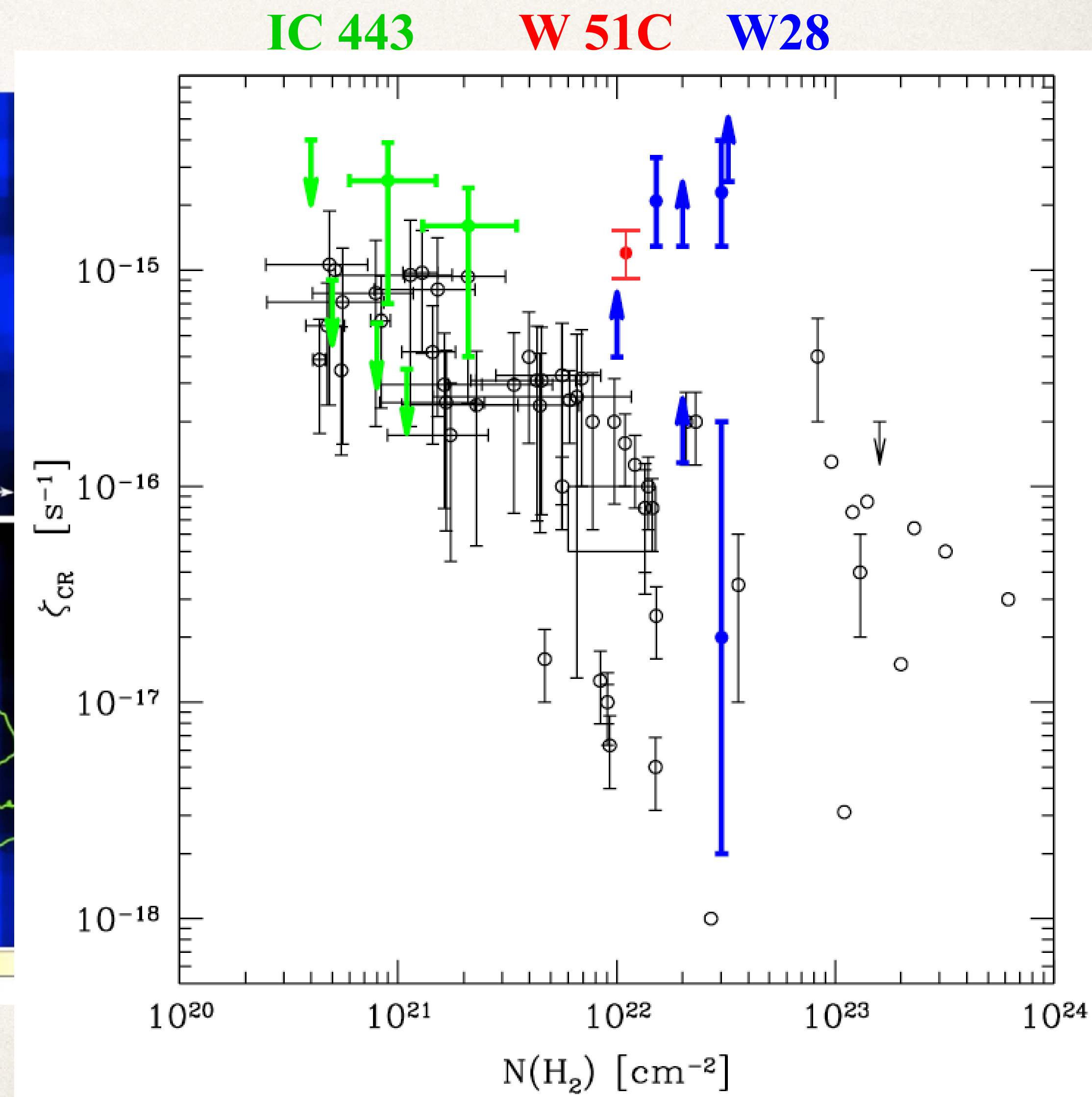
- Ionization sensible to CR energy $E > 0.1$ MeV

Is it possible to use combined information from ionization and γ-ray emission to infer the CR spectrum from ~MeV up to ~TeV and beyond?

Enhanced ionization rate in MC-SNR systems

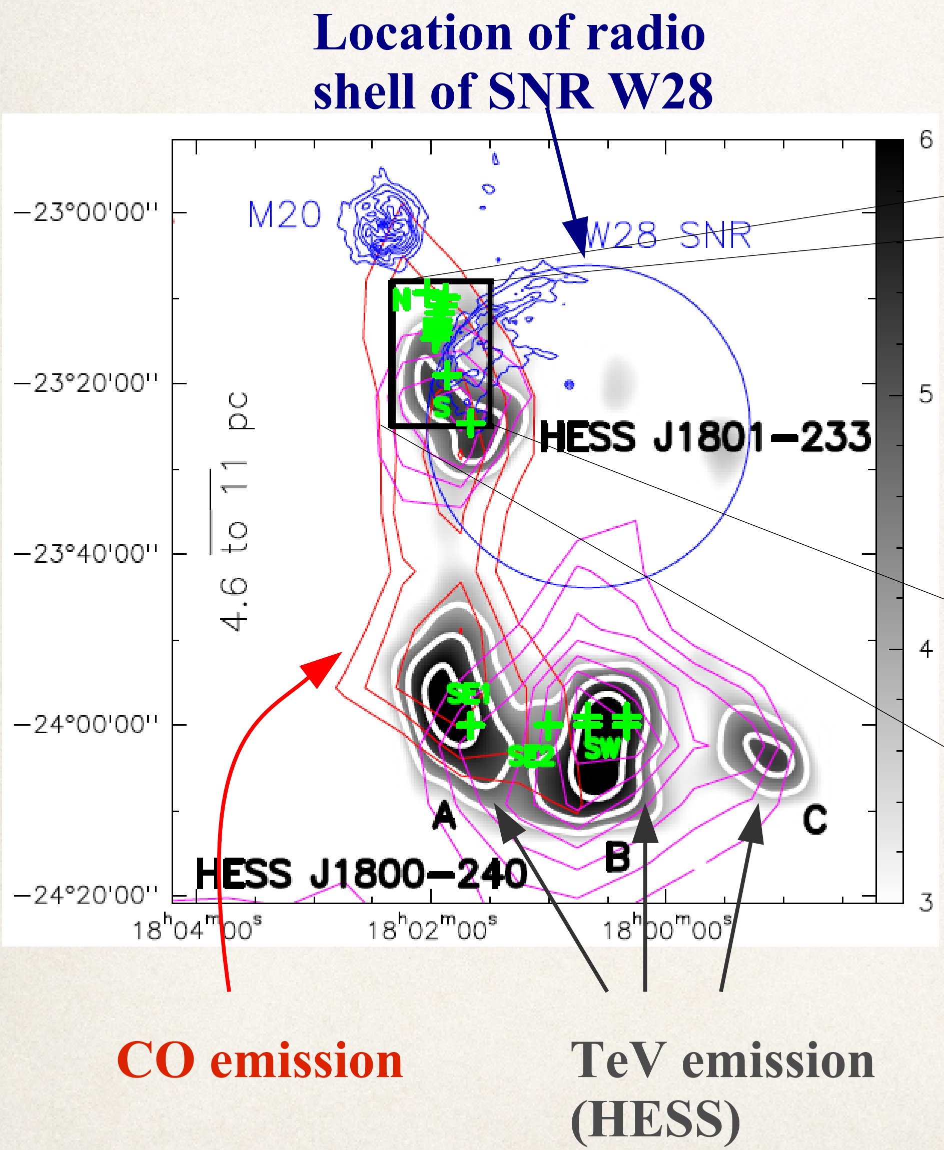
Examples of γ-ray emission from clouds close or interacting with SNRs - [*Fermi*-LAT]

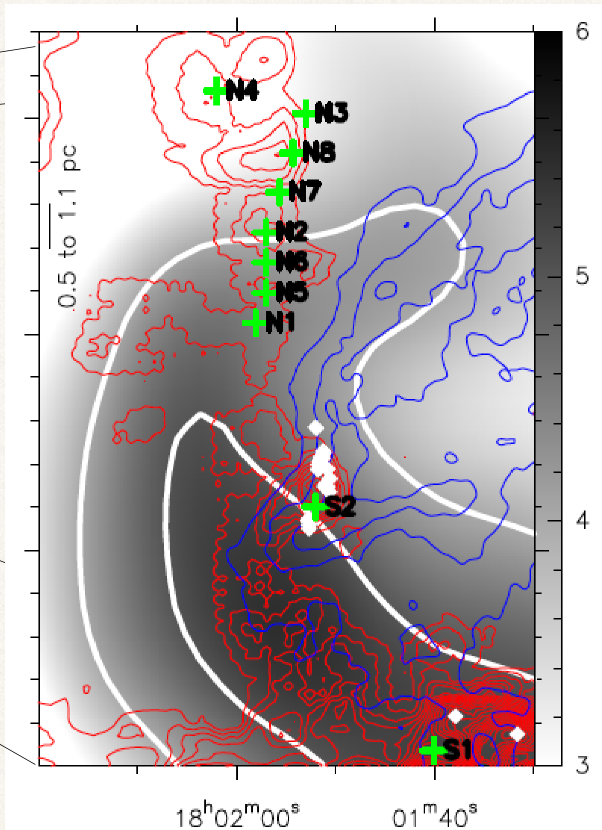




CR induced ionization of molecular clouds interacting with SNR W28

[Vaupr³, Hily–Blant, Ceccarelli, Dubus, Gabici &. Montmerle 2014, *A&A*]





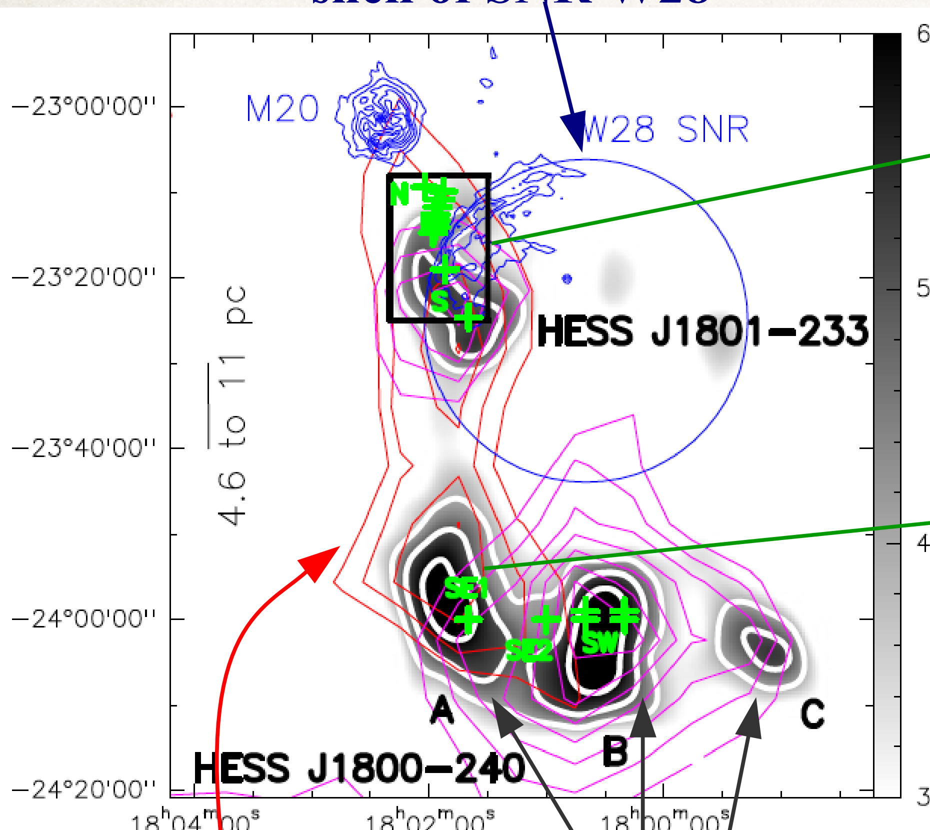
✚ HCO^+, DCO^+ , etc.

◆ HO maser

CR induced ionization of molecular clouds interacting with SNR W28

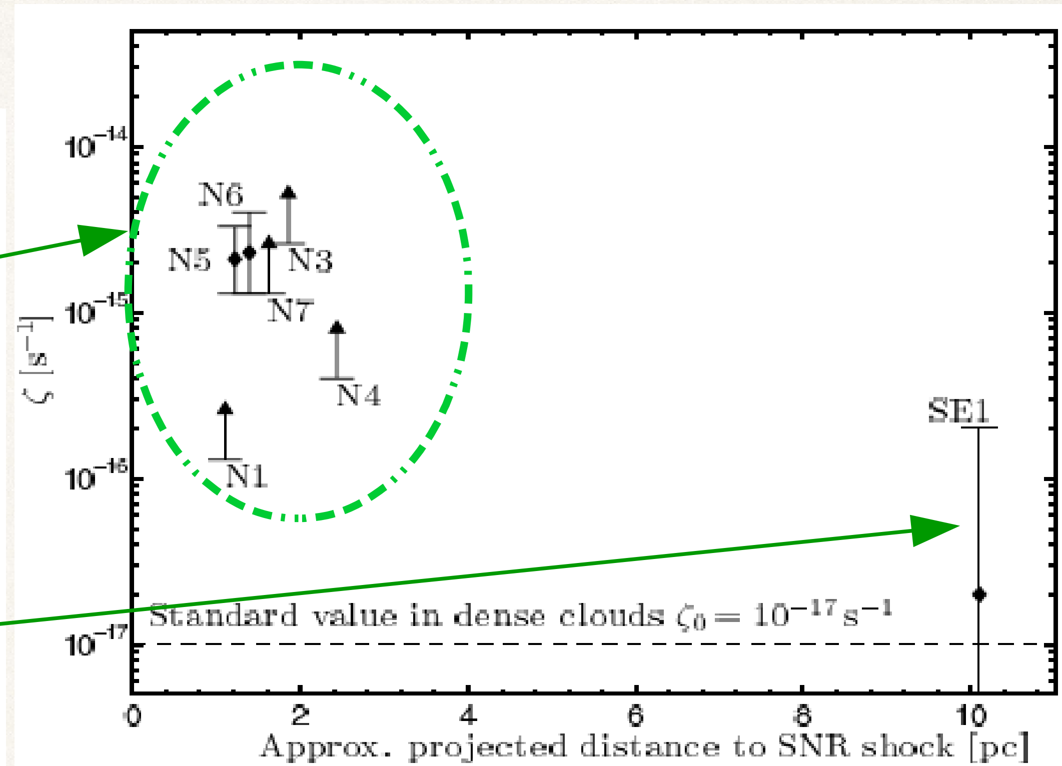
[Vaupr[3], Hily−Blant, Ceccarelli, Dubus, Gabici &. Montmerle 2014, *A&A*]

Location of radio shell of SNR W28



CO emission

TeV emission (HESS)

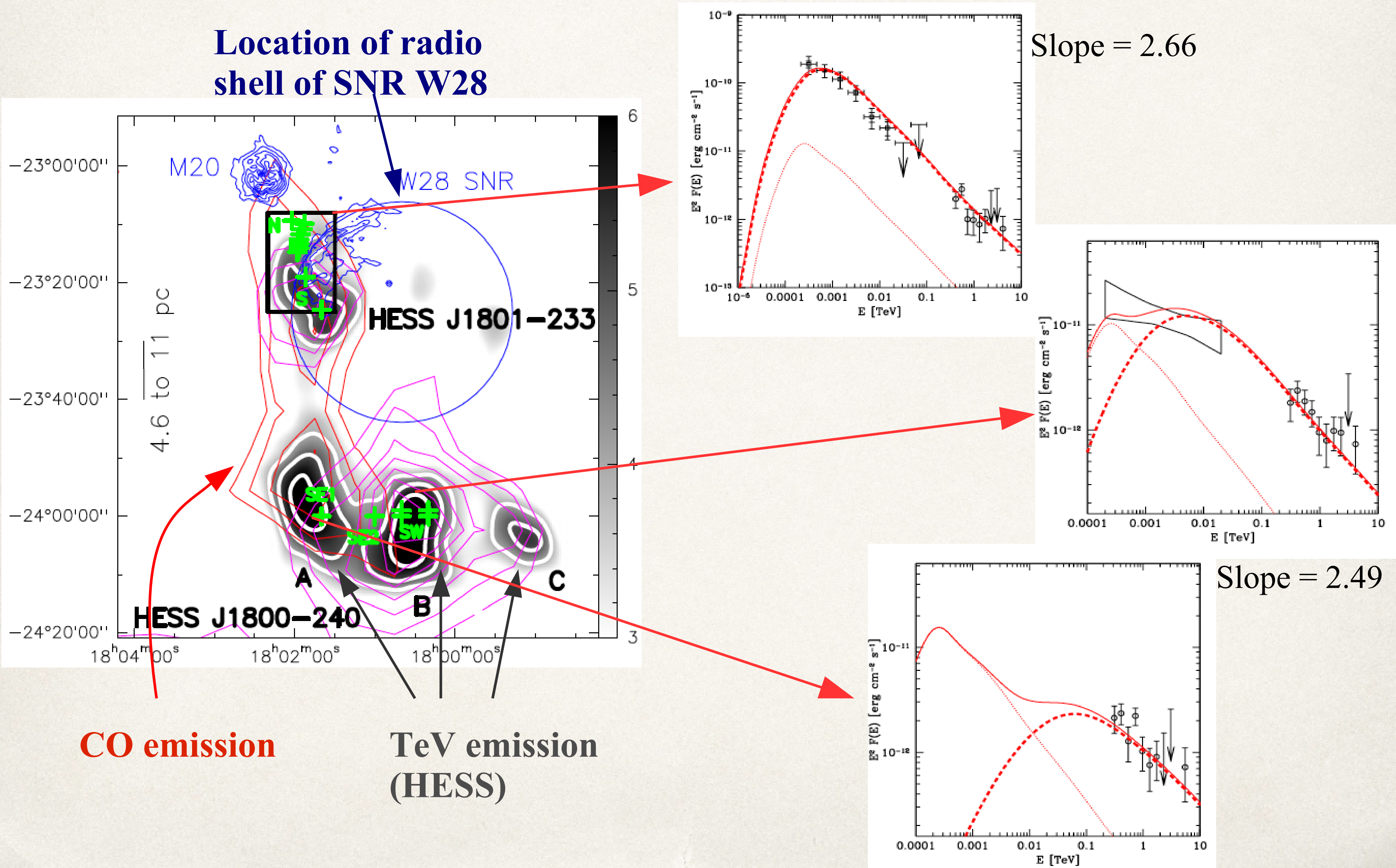


1) Towards positions located close to the supernova remnant, CR ionisation rates is much larger (> 100) than those in standard galactic clouds.

2) Towards one position situated at a larger distance, the CR ionisation rate is close to the standard value in Galactic dense clouds

CR induced ionization of molecular clouds interacting with SNR W28

[Gabici &. Montmerle, ICRC 2015]



Can low-energy CRs be excluded from clouds?

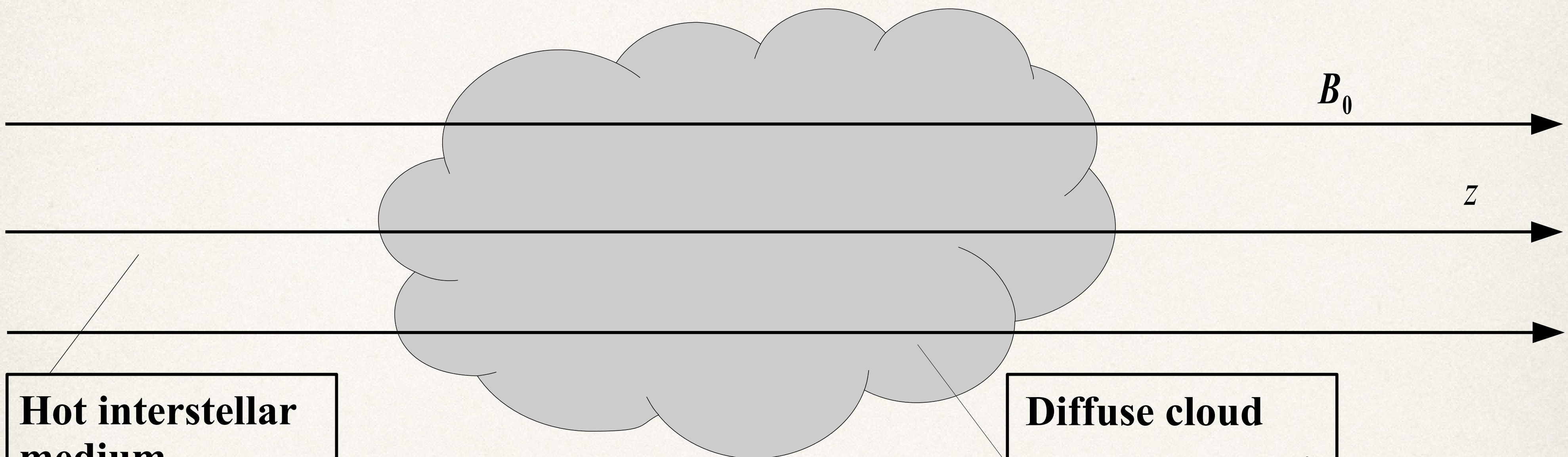
Previous works give conflicting results

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

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

→ 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

$n \sim 0.01 - 0.1\, cm^{-3}$

$T \sim 10^4 - 10^5\, K$

$x_{ion} = 1$

Diffuse cloud

$n \sim 10 - 100\ cm^{-3}$

$T \sim 10^2\ K$

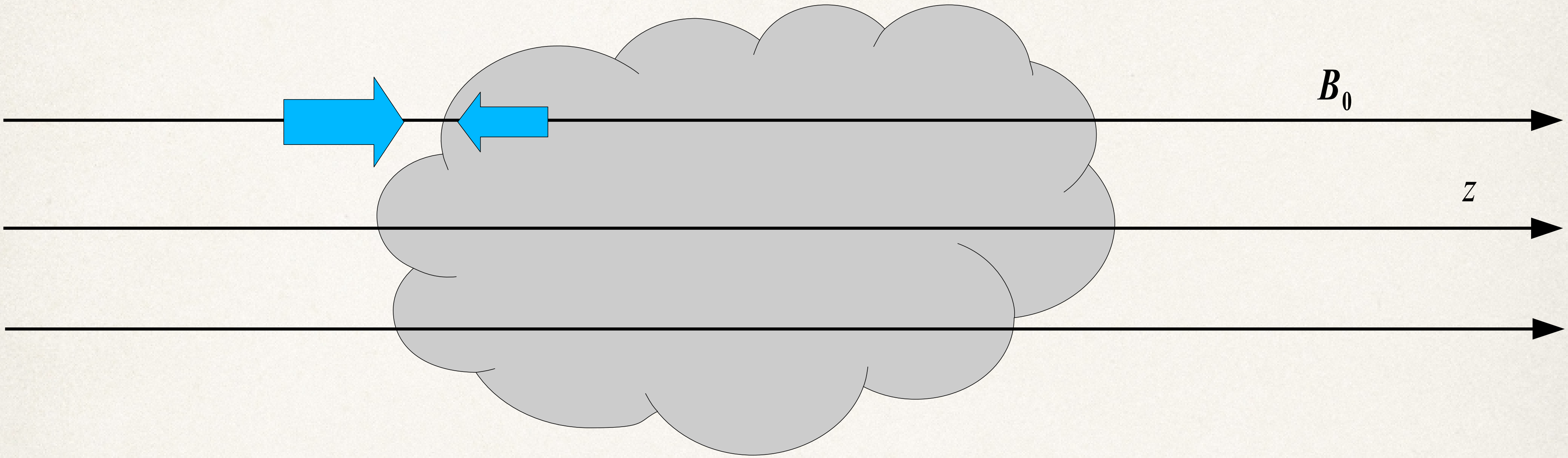
$x_{ion} \approx 10^{-4}$

$\boldsymbol{B_0}$ coherence length ~ 50-100 pc
Cloud size ~10 pc

→ 1-D approximation along the magnetic field lines

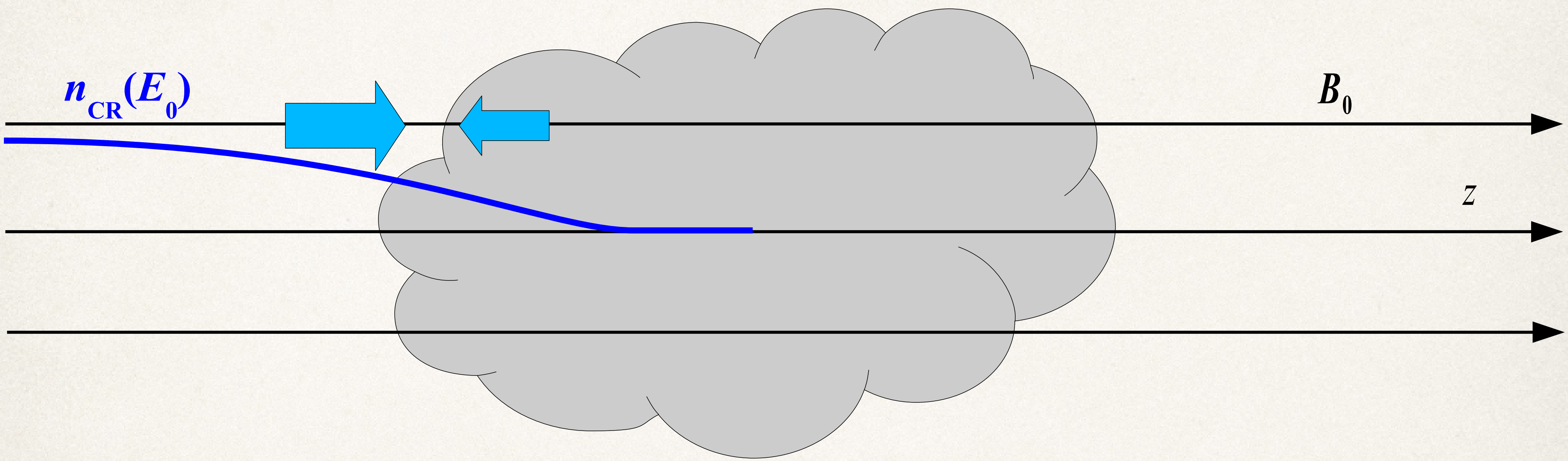
$\boldsymbol{B_0}$ = const = 3 μG observations show that for low density ISM (n < 300 cm^{-3}), the magnetic field strength is independent of the ISM density (Crutcher, 2010)

Set up of the model



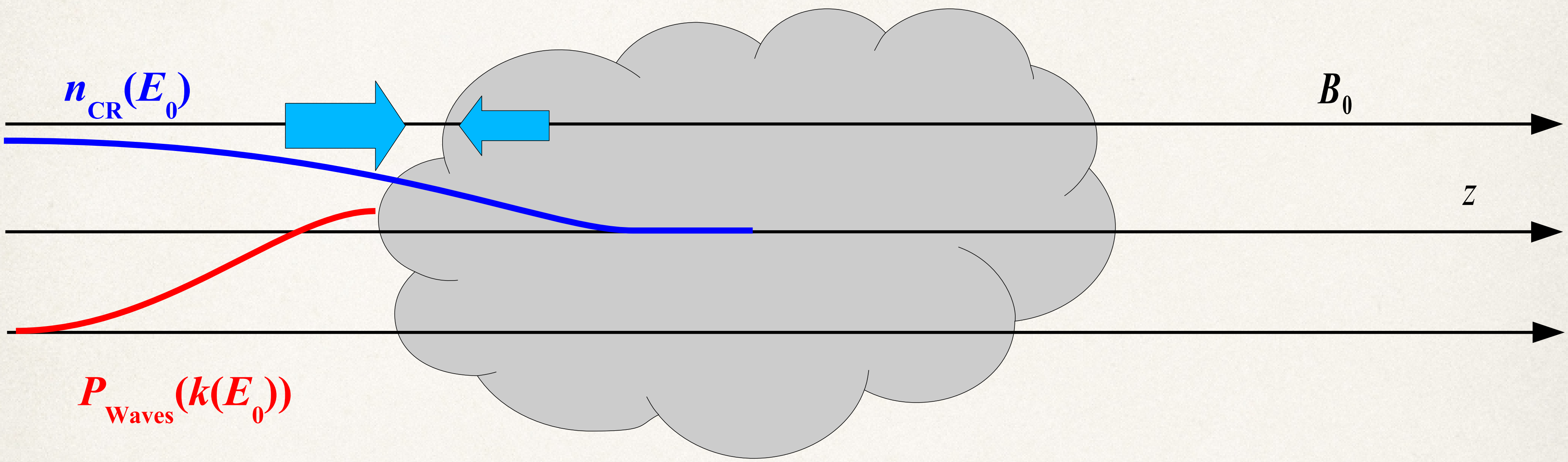
- Particles lose energy inside the cloud:
  → The flux entering the cloud is larger than the flux escaping the cloud

Set up of the model



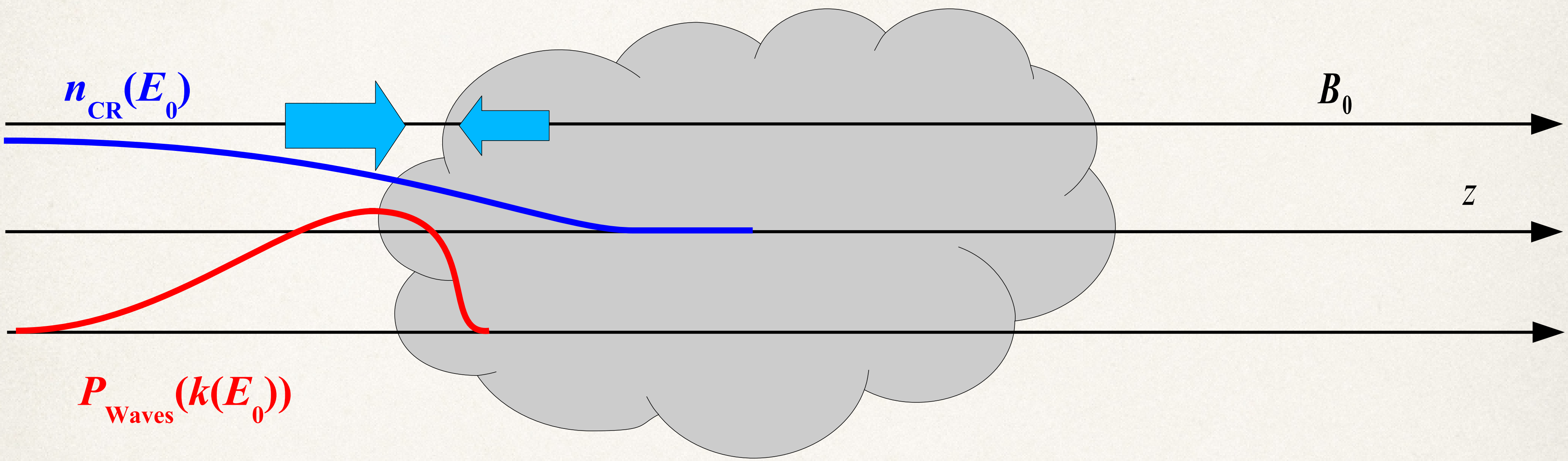
- Particles lose energy inside the cloud:
  → The flux entering the cloud is larger than the flux escaping the cloud
  → a CR gradient develops outside the cloud

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

Set up of the model



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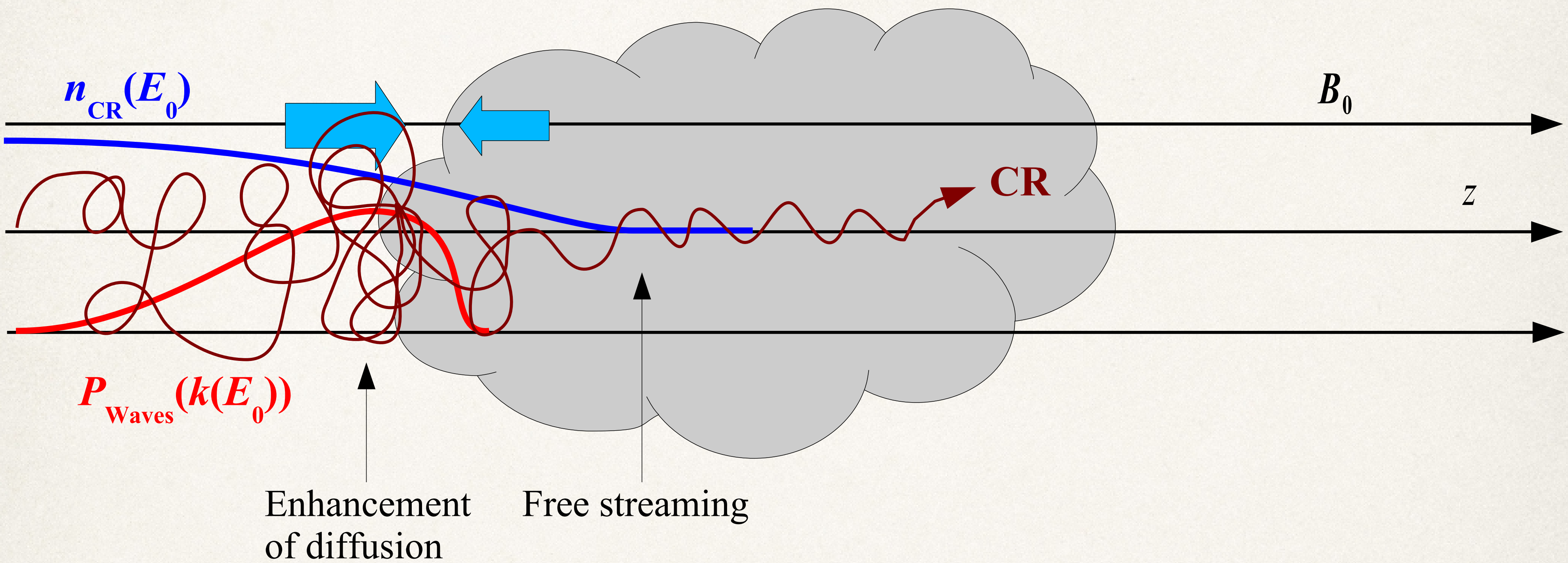
- Magnetic turbulence is damped inside the cloud by ion-neutral damping

Set up of the model



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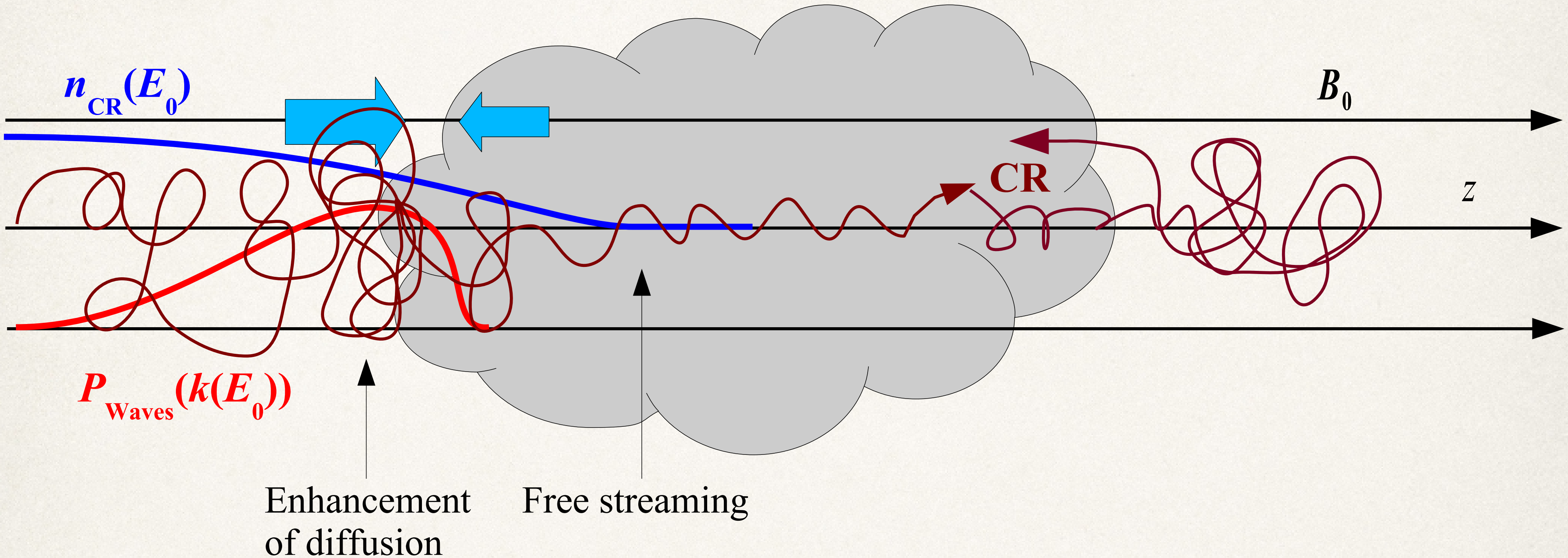
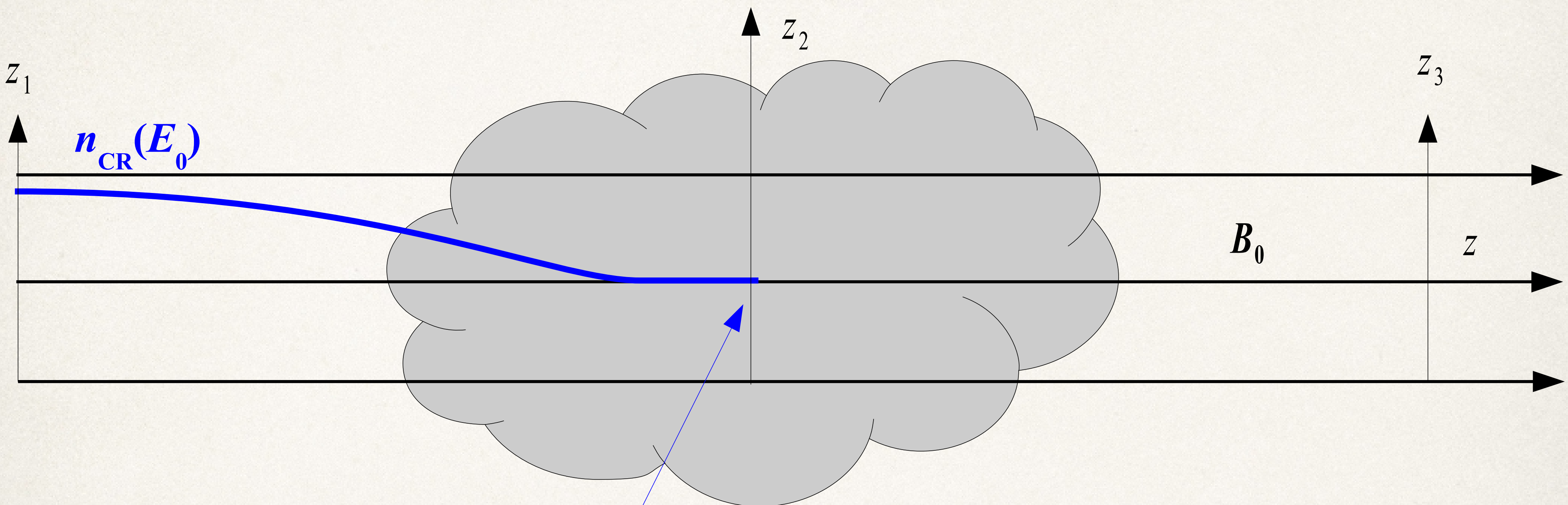


- Particles lose energy inside the cloud:
  - → The flux entering the cloud is larger than the flux escaping the cloud
  - → a CR gradient develops outside the cloud
  - → Alfvén waves are excited by two stream instability

- 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:

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

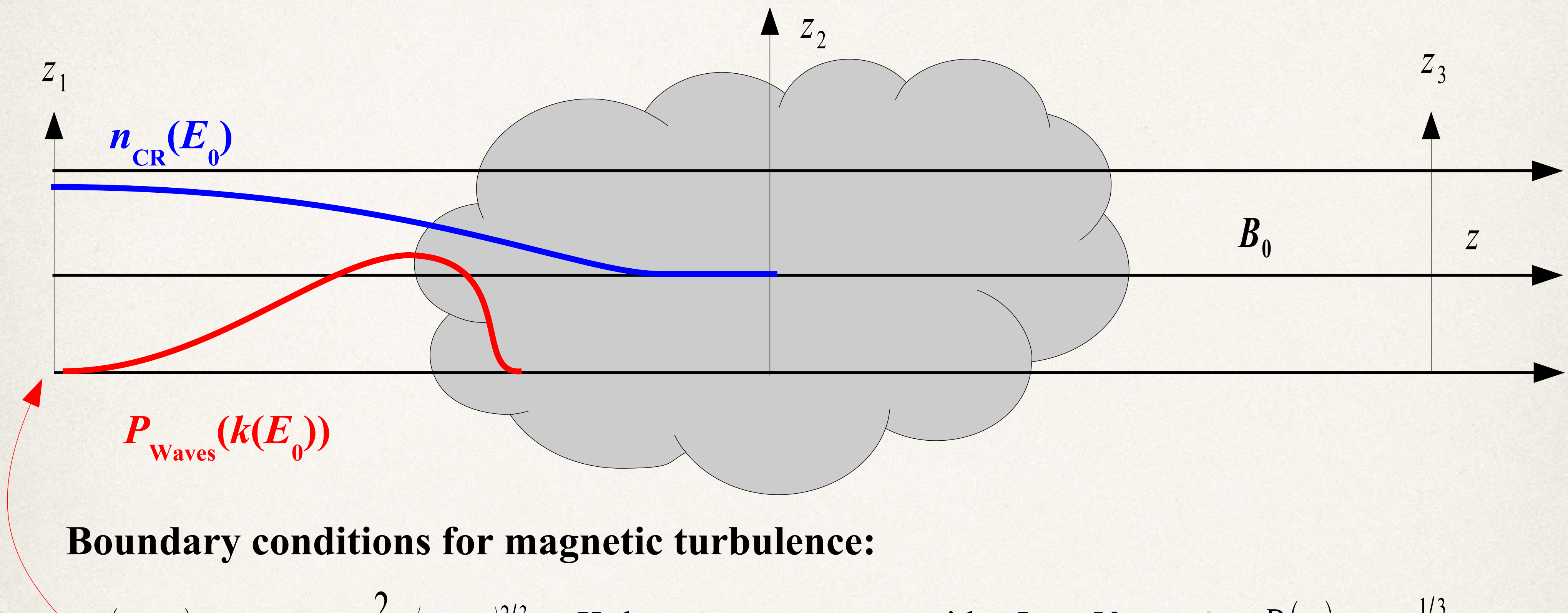
$$f_{CR}(z_{1,}p) = f_{Gal}(p)$$

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:

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

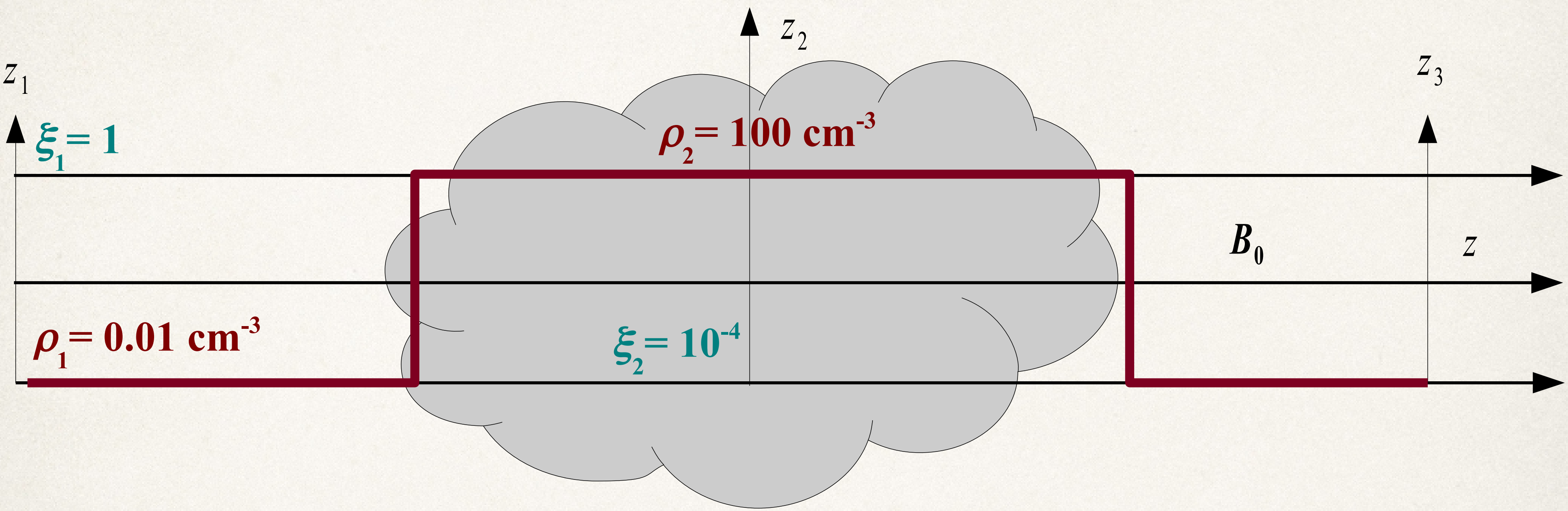
$$\Gamma_{CR} = \frac{4\pi}{3} v_A \left[p v \frac{\partial f}{\partial z} \right]_{\bar{p}(k)}$$ Amplification due to streaming instability

$$\Gamma_{ion-neutral} = \frac{1}{2} n_H \langle \sigma v \rangle = 8.4 \times 10^{-9} \left(\frac{T}{10^4 K} \right)^{0.4} \left(\frac{n_H}{cm^{-3}} \right)^{0.4} s^{-1}$$ 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 $\rightarrow E(k) < 10$ GeV

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

Transport equation for CRs

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

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

Diffusion	Advection	Adiabatic compression	Energy losses

Transport equation for CRs

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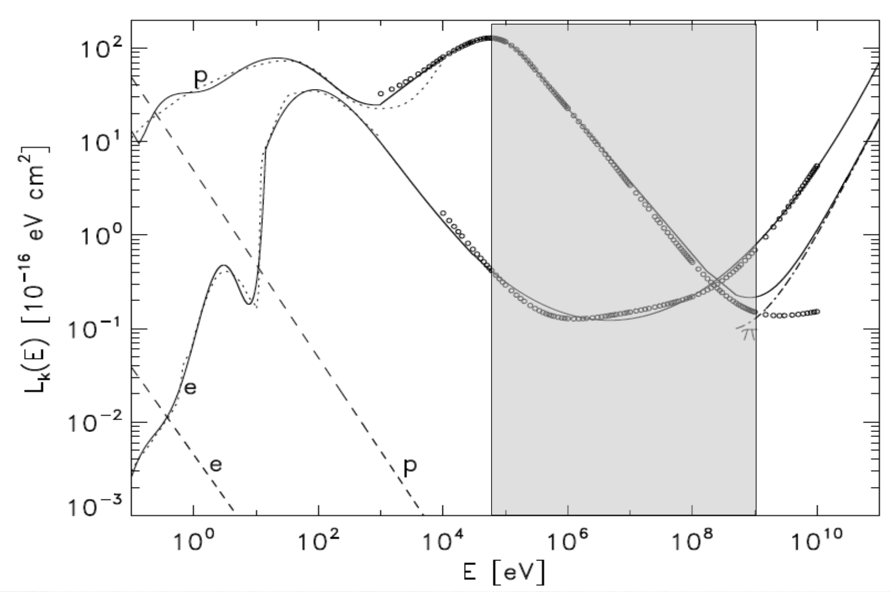
Diffusion | Advection | Adiabatic compression | Energy losses

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

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



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Diffusion　　Advection　　Adiabatic compression　　Energy losses

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Diffusion coefficient outside the cloud determined by magnetic field amplification:

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

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

Solution for the CR distribution

Formal solution:

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

Solution for the CR distribution

Formal solution:

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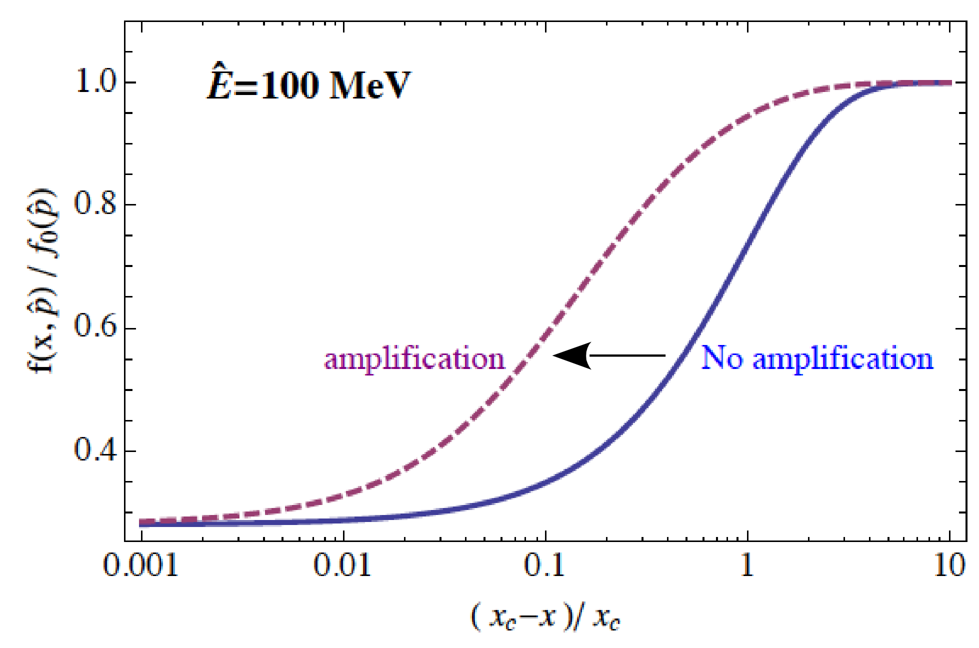
The spectrum is affected outside the cloud up to a distance $z_c \sim D_{Gal}/v_A$

1) No magnetic amplification:

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

2) Magnetic amplification (without damping):

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



Solution for the CR distribution

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For $D_c \gg L_c v_A \sim 10^{26}\left(\frac{L_c}{10\,pc}\right)\left(\frac{v_A}{30\,km/s}\right)\frac{cm^2}{s}$ $\Rightarrow$ $f(z,p) = f_0(p) - \frac{e^{v_A(z-z_c)/D}}{v_A}\frac{L_c}{2}\frac{1}{p^2}\frac{\partial}{\partial p}\left[\frac{p^3}{\tau_{loss}} f_c\right]$

Distribution at the cloud border

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

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

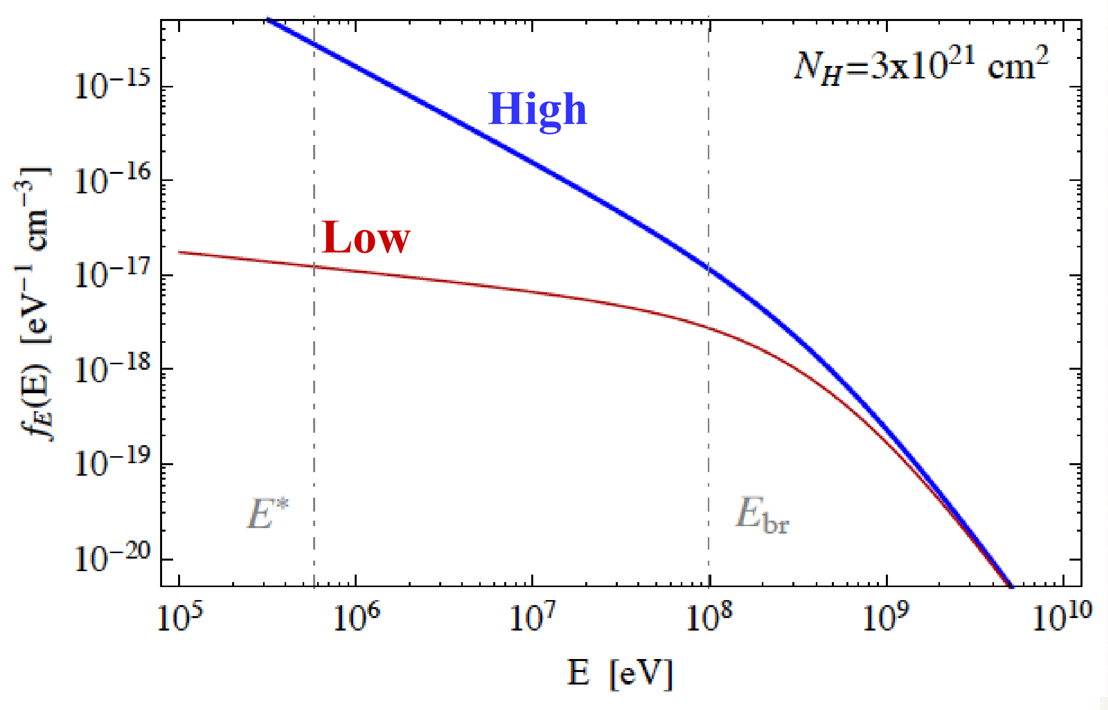
There is a breaking energy:

$\frac{v_A \tau_{loss}}{L_c/2} = 1 \rightarrow \tau_{loss} = \frac{L_c/2}{v_{st}}\frac{v_{st}}{v_A} = \tau_{cross} \times \left(\frac{v_{st}}{v_A}\right)$ $\Rightarrow$ $\boxed{E_{br} = 70\left(\frac{v_A}{100\,km/s}\right)^{-2/\alpha}\left(\frac{N_H}{3\cdot 10^{21}\,cm^{-2}}\right)^{2/\alpha} MeV}$

number of cloud crossing

Effect on ionization rate

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



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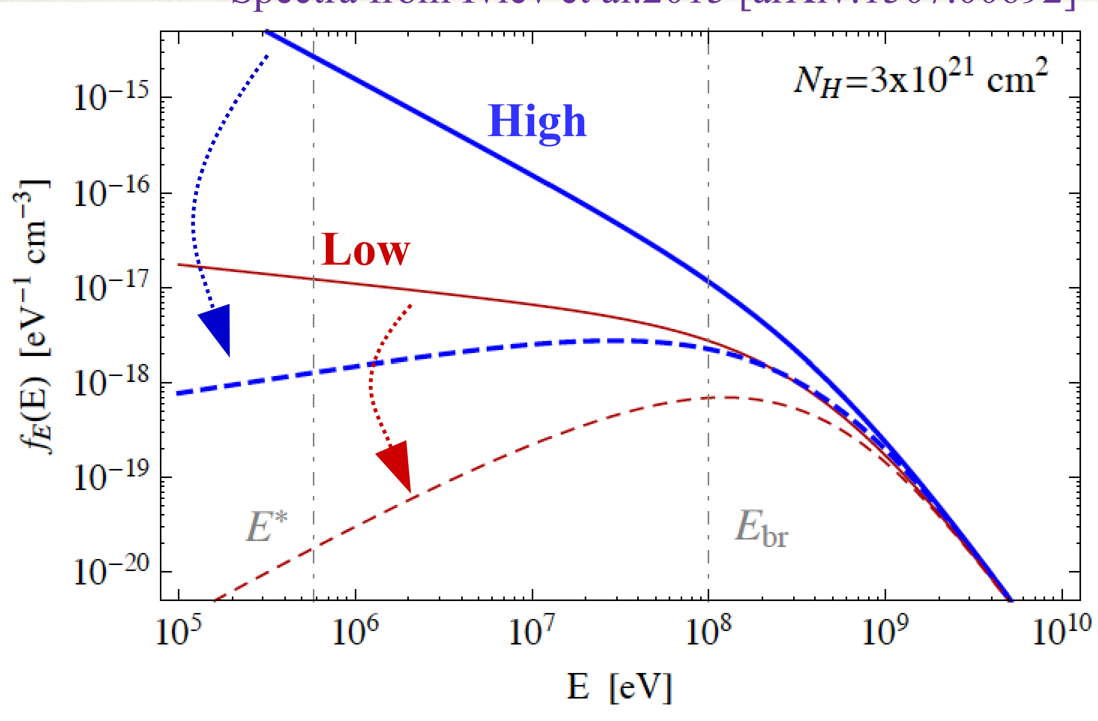

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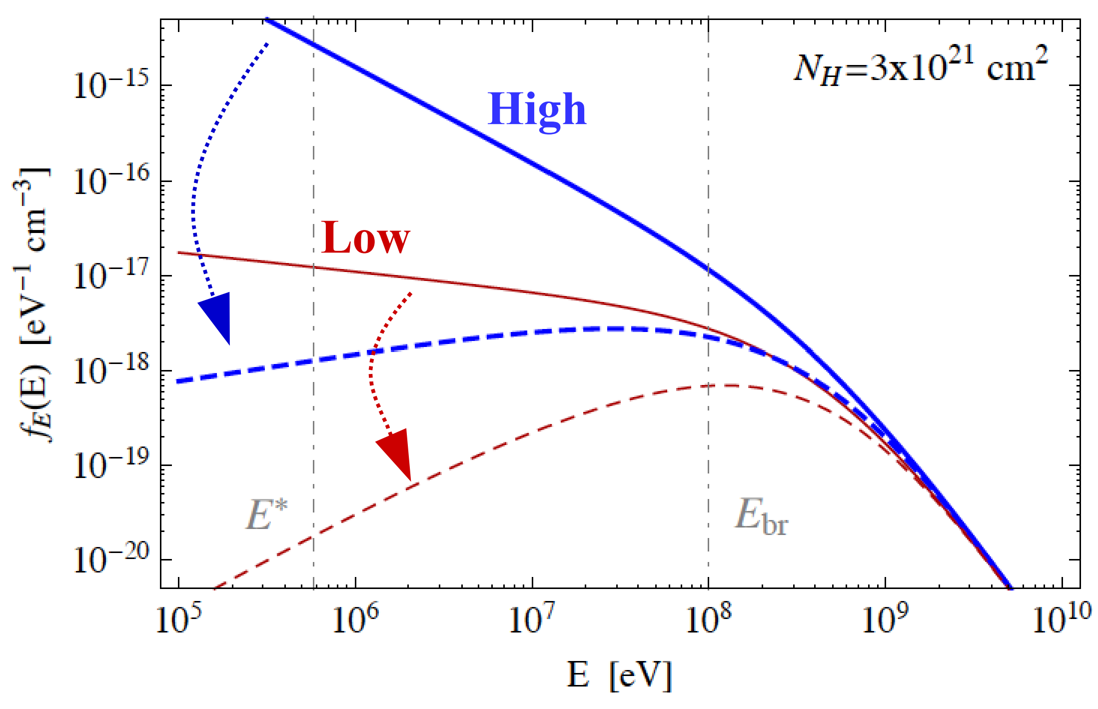


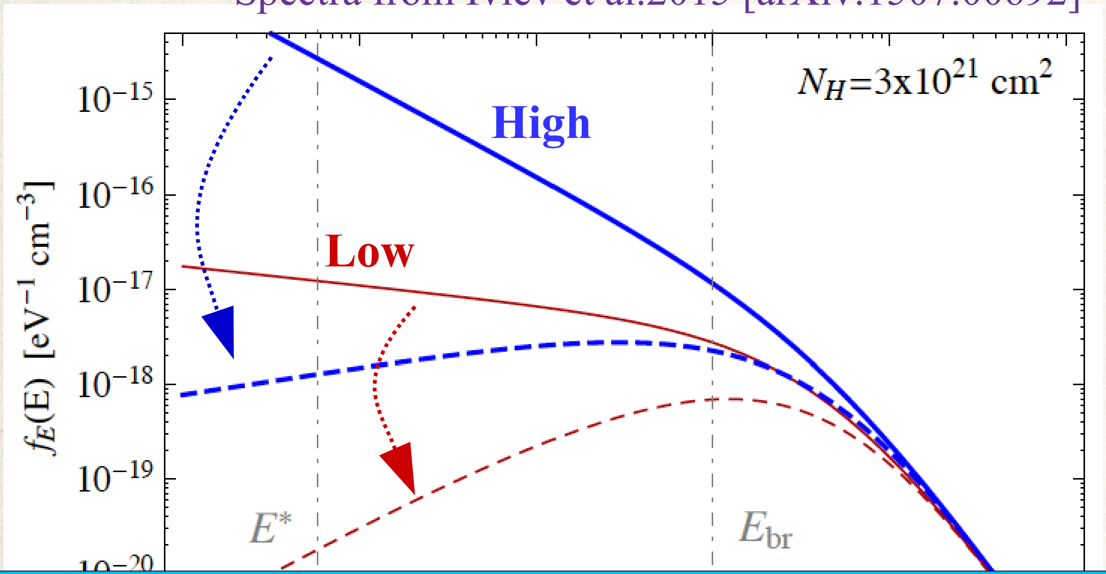
Ionization rate of H_2 due to protons

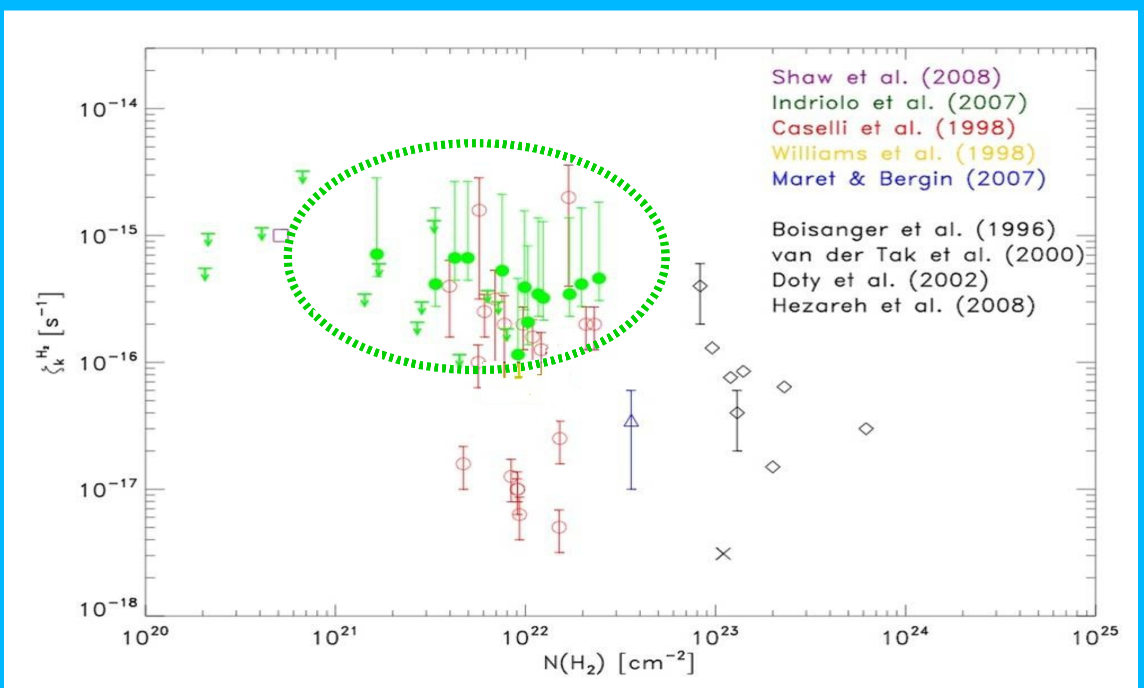
$$\zeta^{H_2} = 4\pi \sum_k \int_{I(H_2)} j_k(E)\, \sigma_k^{ion}(E)\, dE$$

	Free-streaming propagation	Propagation including multiple crossing
High	3.6 x 10^{-16}	2.6 x 10^{-17}
Low	3.5 x 10^{-17}	1.0 x 10^{-17}

Effect on ionization rate

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





Ionization rate of H_2 due to protons

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

	Free-streaming propagation	Propagation including multiple crossing
High	3.6 x 10^{-16}	2.6 x 10^{-17}
Low	3.5 x 10^{-17}	1.0 x 10^{-17}

Predicted ionization not enough to explain observation

Electrons could play a major role

Conclusions – part II

Take away points:

- The presence of MCs affect the CR spectrum *inside* and *outside* the MC
  → Up to a distance min[L_{cohe} , D_{Gal}/v_A] far away from the MC
  → For CR energies up to ~ **100 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~ MeV
  → Better description of particle transport inside the cloud
  → Description of electron spectrum