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Cosmic Rays propagation in the turbulent interstellar medium

Non-linear diffusion of Cosmic Rays escaping from Supernova Remnants in the atomic/molecular interstellar medium

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Outline

Why Cosmic Ray transport

Cosmic Rays (CRs) are a major component of the interstellar medium (ISM)

The effects of CRs over the ISM

→ Drive galactic winds [1]

→ Enrich the ISM through spallation

→ Strong ionization source in dense clouds [2]

The emission of CRs in the ISM

→ Accelerated by SNRs via diffusive shock acceleration (DSA)

→ Generate turbulence via streaming instability relaxation

[1] Recchia et al. 2017, Girichidis et al. 2016
[2] Padovani et al. 2009

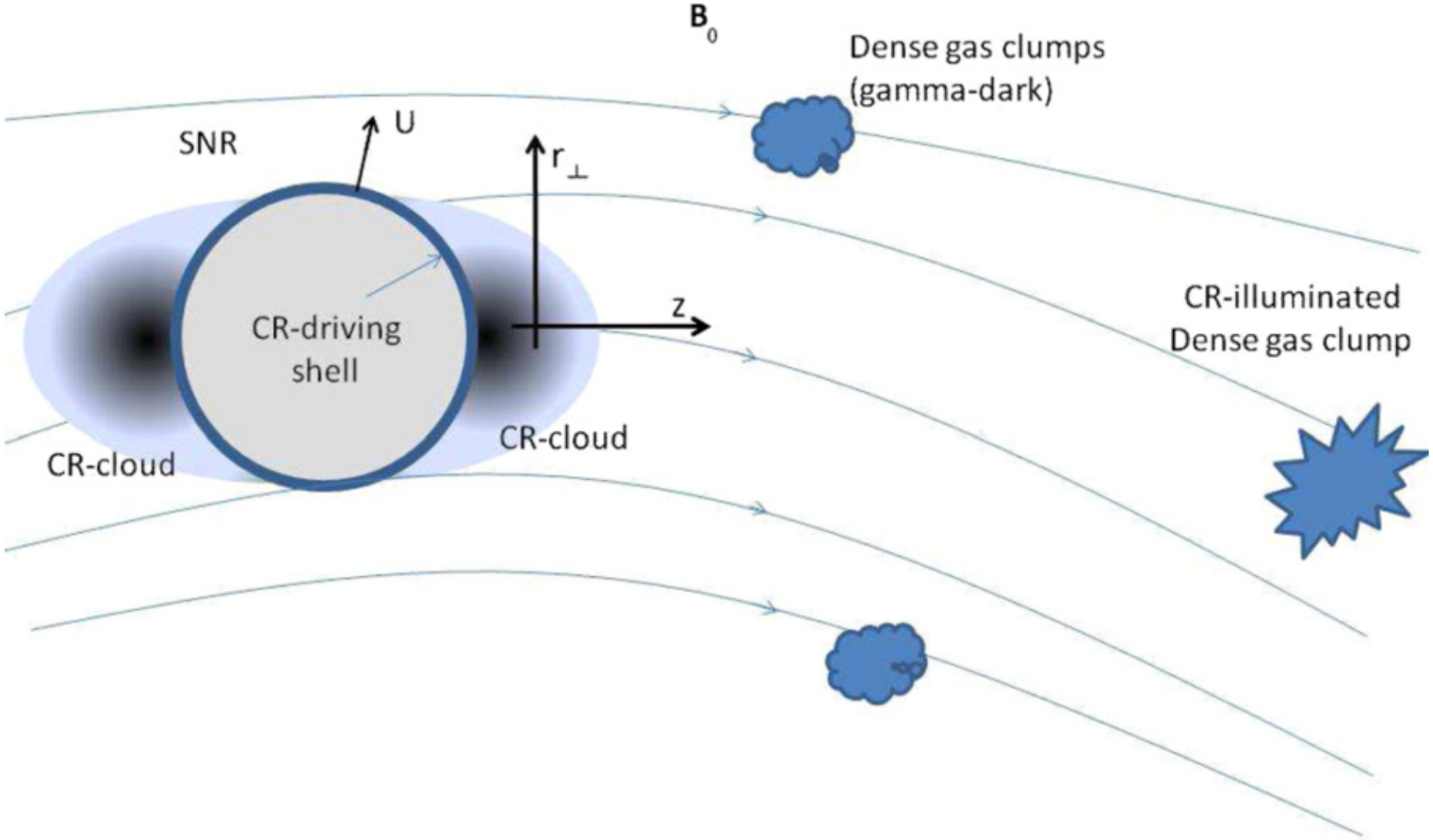
Why Cosmic Ray transport

There is no fully consistent theory explaining at the same time CR acceleration at SNR shocks and their escape in the ISM [3]

[3] Telezhinsky et al. 2012

A Cosmic Rays escaping and propagation model

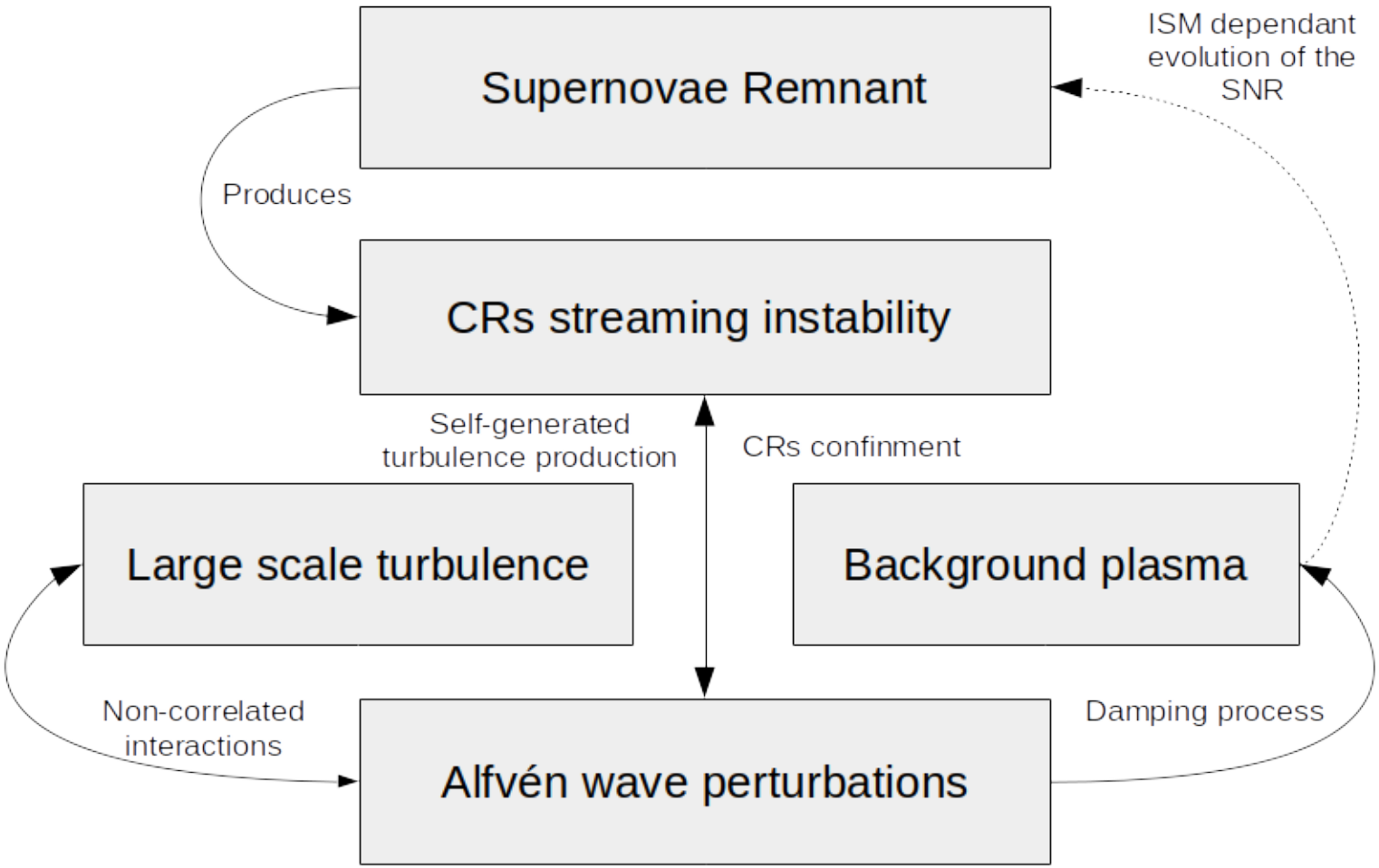
The Cosmic Ray Cloud (CRC) model - Malkov et al. (2013)



CRC model - Figure from Malkov et al. 2013

A Cosmic Rays escaping and propagation model

From the energetic point of view



A Cosmic Rays escaping and propagation model

System of equations

$$\boxed{\frac{\partial P_{\mathrm{CR}}}{\partial t} + V_{\mathrm{A}} \frac{\partial P_{\mathrm{CR}}}{\partial z}} = \boxed{\frac{\partial}{\partial z}\left(D \frac{\partial P_{\mathrm{CR}}}{\partial z}\right)}$$

$$\boxed{\frac{\partial I}{\partial t} + V_{\mathrm{A}} \frac{\partial I}{\partial z}} = \boxed{2\left(\Gamma_{\mathrm{growth}} - \Gamma_{\mathrm{d}}\right) I} + \boxed{Q}$$

For CRs pressure $P_{\mathrm{CR}}(E_{\mathrm{CR}})$

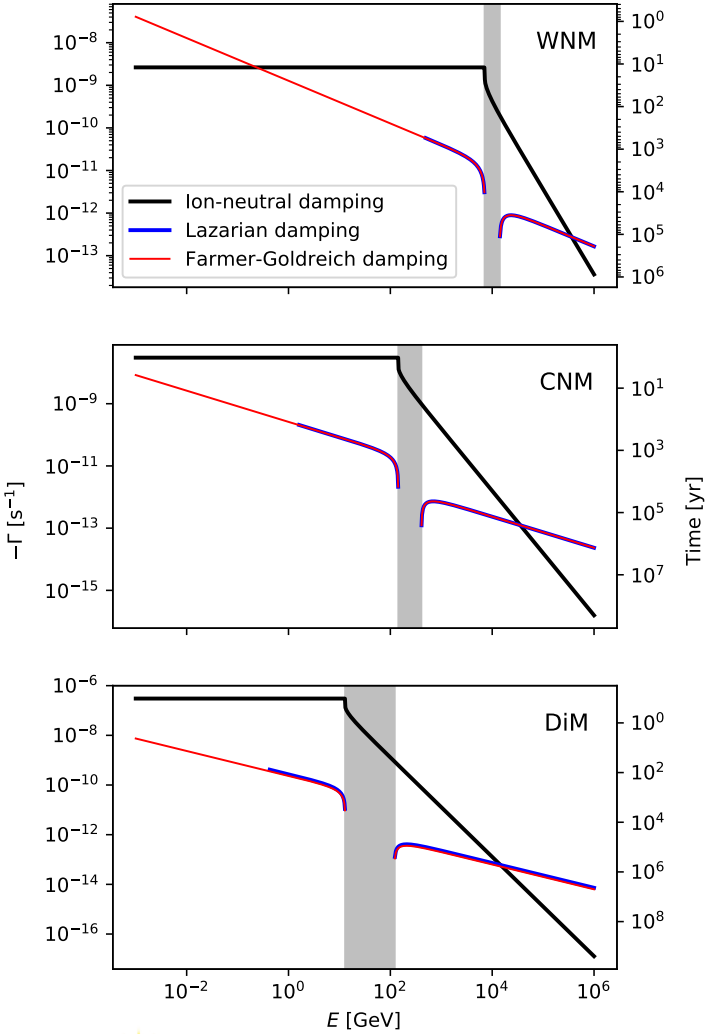
- $V_{\mathrm{A}} \frac{\partial P_{\mathrm{CR}}}{\partial z}$: CRs advection term
- $D = D_{\mathrm{B}}/I$: Non-linear diffusion coefficient of CRs

For waves energy density $I(k)$

- $V_{\mathrm{A}} \frac{\partial I}{\partial z}$: Waves advection term
- $\Gamma_{\mathrm{g}} = -\frac{1}{2} V_{\mathrm{A}} \frac{\partial P_{\mathrm{CR}}}{\partial z}$: CRs streaming instability
- Γ_{d} : Waves damping term
- Q : Background turbulence

A Cosmic Rays escaping and propagation model

The interstellar medium model



The ISM model

	WNM	CNM	DiM
T [K]	8000	50	50
n_{T} [cm^{-3}]	0.35	30	300
n_i/n_{T}	0.02	8×10^{-4}	10^{-4}

Ion-neutral damping [4]

→ Energy is transfered from ions to neutrals

→ Two regimes of wave propagation

→ Strongly dependant on the ionization rate

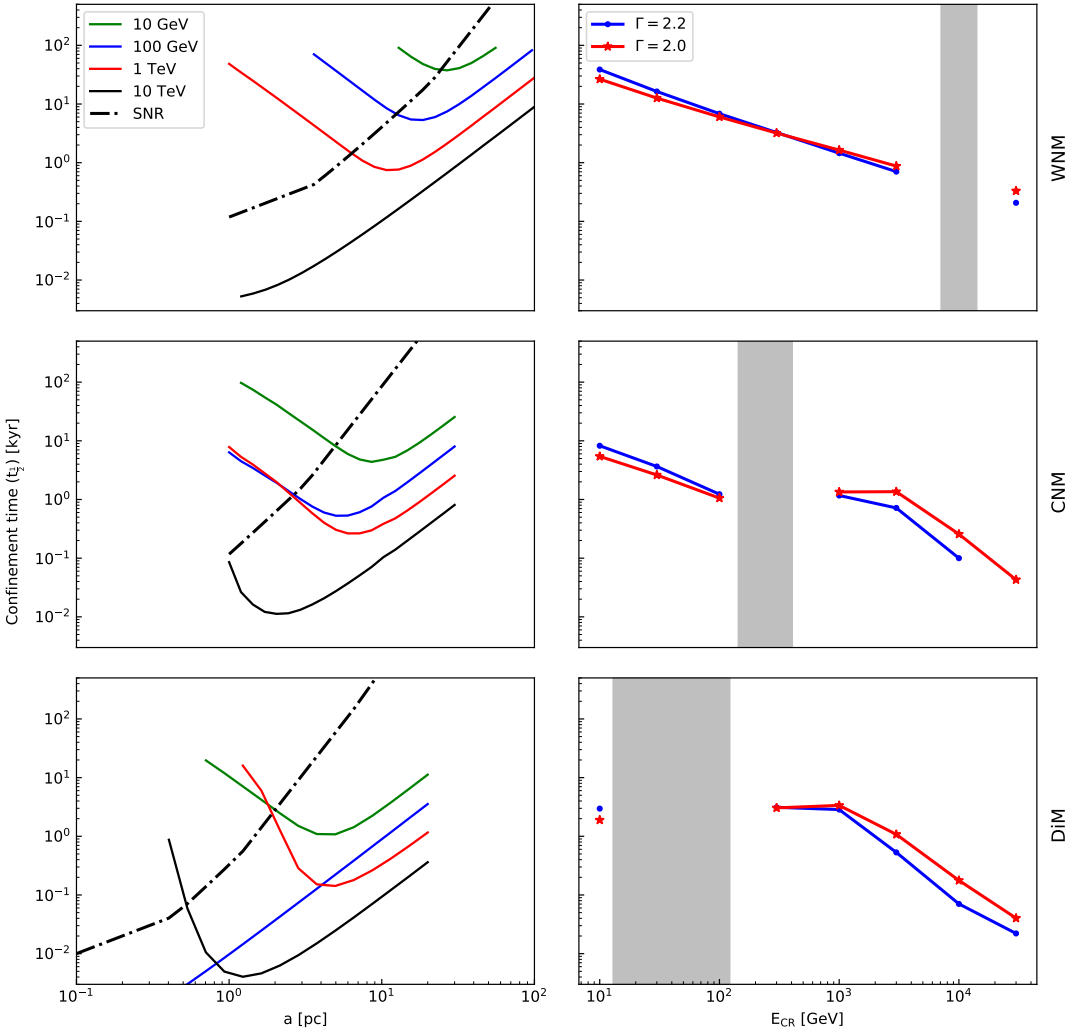
Turbulent damping [5]

→ Decorrelated interactions with large scale turbulence waves

[d] Xu et al. 2015
[e] Lazarian 2016

A Cosmic Rays escaping and propagation model

The CRs cloud model (CRC)



→ CRC half-life time [6]:

$$\int_{-R_{\rm esc}}^{+R_{\rm esc}} P_{\rm CR}(z, t_{\frac{1}{2}})\,{\rm d}z = 2R_{\rm esc}P^0_{\rm CR}/2$$

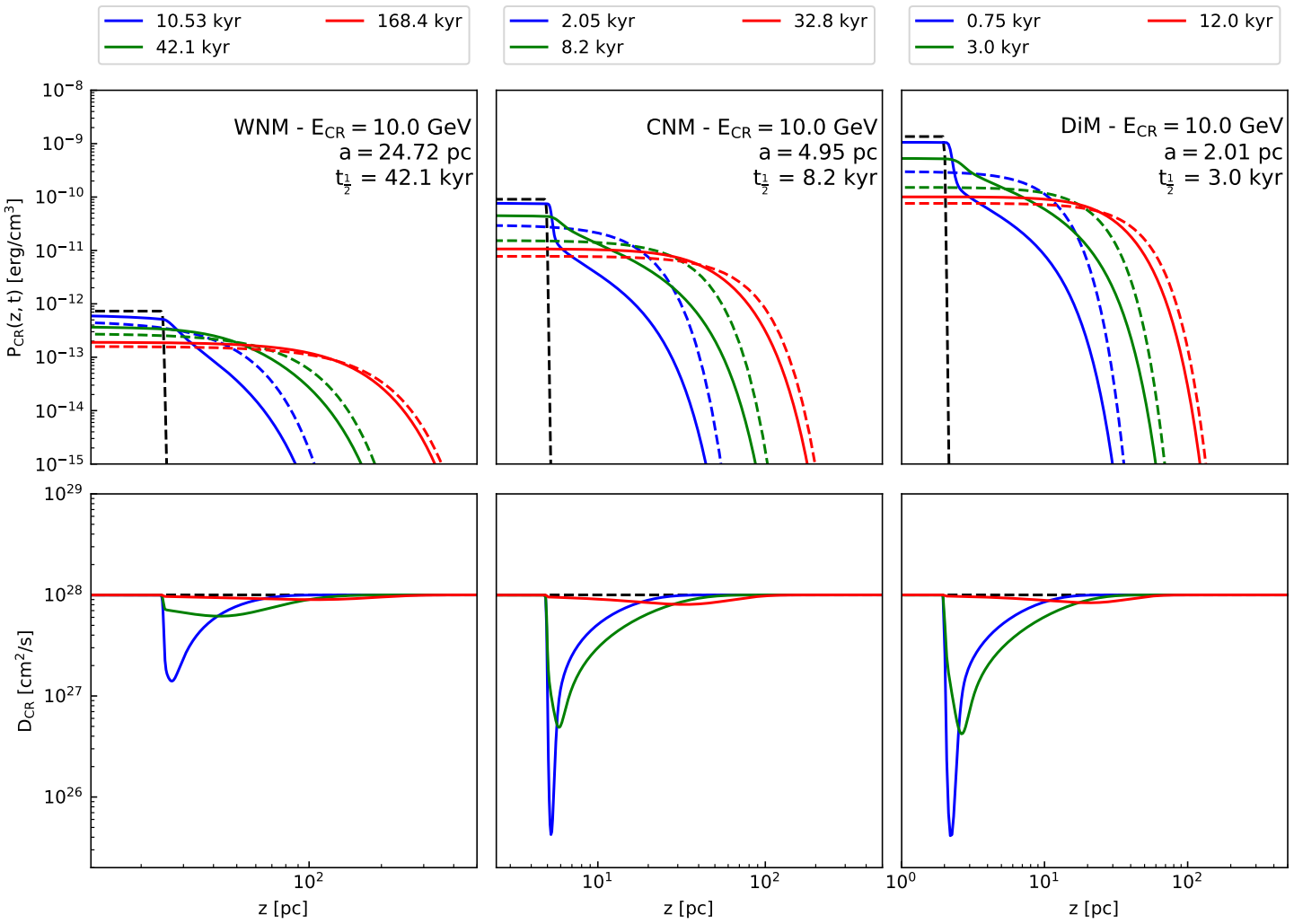
→ SNR shock radius evolution model [7]: $R_{\rm SNR}(t, {\rm ISM})$

[f] Nava et al. 2016, Malkov et al. 2013

[g] Cioffi et al. 1988, Truelove & McKee 1999

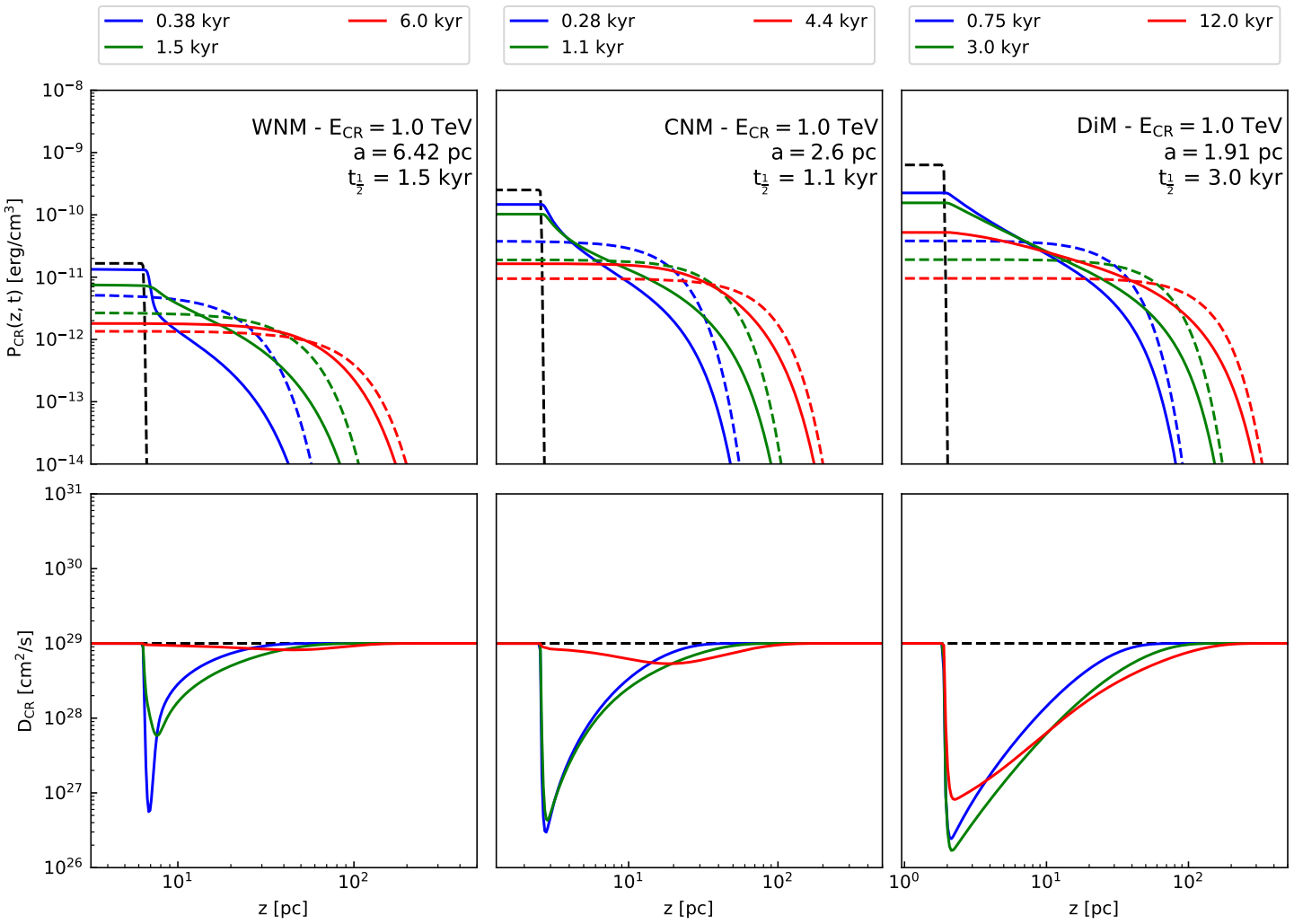
Numerical solutions

10 GeV CRs



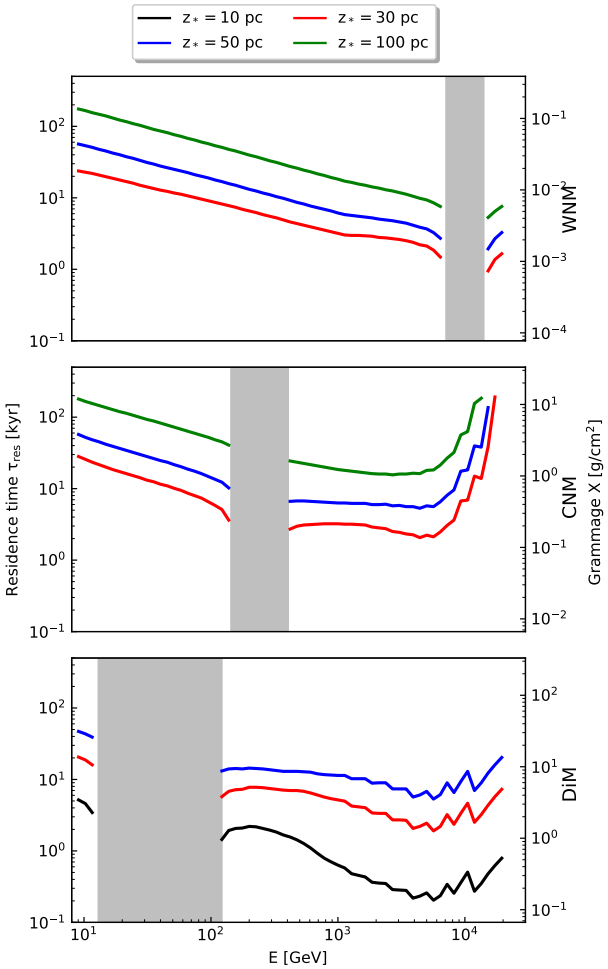
Numerical solutions

1 TeV CRs



Numerical solutions

Cosmic Ray grammage



→ The grammage is defined as [8]
$X \approx 1.4 m_p n_{\mathrm{T}} c \tau_{\mathrm{res}}$

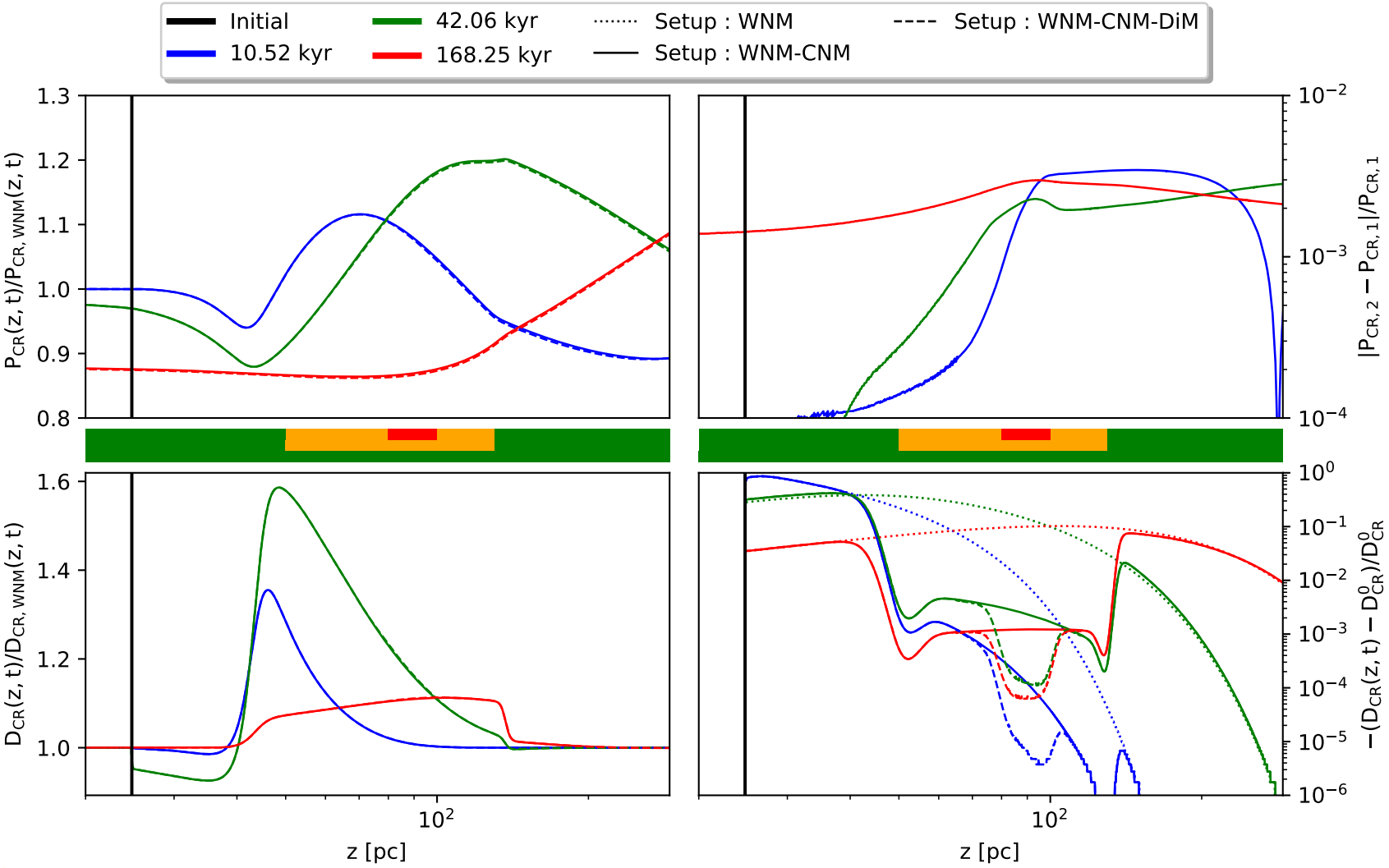
→ The CRs residence time is defined as [9]
$z_*^2 = \frac{\int_0^\infty z^2 P_{\mathrm{CR}}(E,z,\tau_{\mathrm{res}})\mathrm{d}z}{\int_0^\infty P_{\mathrm{CR}}(E,z,\tau_{\mathrm{res}})\mathrm{d}z}$

→ Two confinement signatures in the CNM and DiM :
→ Weak confinement at low energy
→ Strong confinement at high energy

[h] D'Angelo et al. 2016
[i] Nava et al. 2018

Numerical solutions

Illustration of the multiphase case (cf. Brahimi et al. 2019 submitted)



Conclusion

High energy CRs grammage shows that the confinement effect can be enhanced compared to the linear case. This may impact γ-ray signatures as foreseen for CTA

Other conclusions

- $\rightarrow$ Self-regulated waves regulate CR propagation around sources especially at high energies (beyond TeV)
- $\rightarrow$ Enhanced grammage with respect to linear propagation in background turbulence
- $\rightarrow$ May impact γ-ray signatures of TeV γ-rays around CRs sources
- $\rightarrow$ TeV CRs can also modify the propagation of GeV particles (Inoue 2019)

Perspectives

More complete system of equations

$$\begin{aligned}
\frac{\partial P_{\mathrm{CR}}}{\partial t} + \mathbf{V_A}\nabla P_{\mathrm{CR}} &= \nabla D \nabla P_{\mathrm{CR}} + \frac{E}{3}(\nabla \cdot \mathbf{V_A}\ \partial P_{\mathrm{CR}}/\partial E\ -\ \partial \mathbf{V_A}/\partial E\ \nabla P_{\mathrm{CR}}) \\
&- \frac{4}{3}\nabla \cdot \mathbf{V_A} P_{\mathrm{CR}} \\
\frac{\partial I}{\partial t} + \mathbf{V_A}\nabla I &= -I\nabla \cdot \mathbf{V_A} + (\Gamma_g - \Gamma_d)I + Q
\end{aligned}$$

where $\Gamma_g = -\frac{12\pi}{B_0^2 I}\frac{\partial P_{\mathrm{CR}}}{\partial \mathbf{r}}\frac{\mathbf{B}}{B}$, $P_{\mathrm{CR}} = P_{\mathrm{CR}}(\mathbf{r}, T, t)$, $D = D(\mathbf{r}, E, t)$, $\mathbf{V_A} = \mathbf{V_A}(\mathbf{r}, p)$ and $I = I(\mathbf{r}, k)$.

Aims

- $\rightarrow$ Increase the dimensions of our problem (2D)
- $\rightarrow$ Take in account the CRs energy dependance, calculate the γ-ray equivalent spectra ($p + p \rightarrow 2\gamma$)
- $\rightarrow$ Take in account Coulomb losses of low energy CRs ($<$ MeV)