The Hebrew University of Jerusalem האוניברסיטה העברית בירושלים
מכון רקח לפיסיקה
The Racah Institute of Physics

Cosmic Ray propagation close to their acceleration site

Nava, Gabici, Marcowith,
Morlino, Ptuskin

Lara Nava
Marie Curie Fellow
The Hebrew University of Jerusalem

Since 1925

Outline

- Context: description of the problem
- Review of previous work
- Our model
- Some preliminary results
- Summary

The context

study the non-linear diffusion of a population of CRs after their escape from the acceleration site

We consider a situation where:

- **the transport of CRs is regulated by the scattering off Alfven waves**
- **a CR of energy *E* resonates with waves of wave number $k = 1/r_L(E)$**
- **quasi linear theory $\delta B/B_0 << 1$**

ambient magnetic field

Energy density *W(k)* of Alfven waves

$$\frac{\delta B^2}{8\pi} = \frac{B_0^2}{8\pi} \int W(k) \mathrm{d} \ln k$$

Bohm diffusion coefficient

Parallel diffusion coefficient:

$$D = \frac{4\, c\, r_L(E)}{3\pi\, W(k_r)} = \frac{D_B(E)}{W(k_r)}$$

- the problem is one dimensional:

  perpendicular diffusion coefficient is suppressed by a factor: $(\delta B_k / B_0)^4$

The context

$W(k,z,t)$

$P_{CR}(p,z,t)$

- the main source of Alfvenic turbulence is the streaming of CRs

Growth of turbulence by CR:
(resonant streaming instability)

$$\Gamma_{growth} = -V_A \frac{\partial P_{CR}}{\partial z}\frac{1}{W}$$

- turbulence damping mechanisms Γ_{damp}

Coupled equations to be solved

$$\frac{\partial P_{CR}}{\partial t} + V_A \frac{\partial P_{CR}}{\partial z} = \frac{\partial}{\partial z}\left(\frac{D_B}{W}\frac{\partial P_{CR}}{\partial z}\right)$$

$$\frac{\partial W}{\partial t} + V_A \frac{\partial W}{\partial z} = (\Gamma_{growth} - \Gamma_{damp})W + Q$$

Skilling 1970

$$\frac{\partial P_{CR}}{\partial t} + V_A \frac{\partial P_{CR}}{\partial z} = \frac{\partial}{\partial z}\left(\frac{D_B}{W}\frac{\partial P_{CR}}{\partial z}\right)$$

$$\frac{\partial W}{\partial t} + V_A \frac{\partial W}{\partial z} = (\Gamma_{growth} - \Gamma_{damp})W + Q$$

waves reach an equilibrium over a time scale much shorter than the CR transport time

slow crossing time: advection term can be neglected

constant in space and time

$$D = \frac{D_B \Gamma_{damp}}{Q - V_A \partial P_{CR}/\partial z}$$

$V_A \partial P_{CR}/\partial z \ll Q$

Level of turbulence determined by equilibrium between external injection and damping:

$W_0 = D_B/D = Q/\Gamma_{damp}$

$P_{CR} \propto t^{-1/2} \exp(-z^2/D_{ISM}\, t)$

Test-particle (TP) case

$V_A \partial P_{CR}/\partial z \gg Q$

Waves grow very quickly: large level of turbulence. CRs are locked to waves and only an unimportant amount of diffusion occurs.

CR-locked case

Ptuskin et al. 2008

$$\frac{\partial P_{CR}}{\partial t} + V_A \frac{\partial P_{CR}}{\partial z} = \frac{\partial}{\partial z}\left(\frac{D_B}{W}\frac{\partial P_{CR}}{\partial z}\right)$$

$$\frac{\partial W}{\partial t} + V_A \frac{\partial W}{\partial z} = (\Gamma_{growth} - \Gamma_{damp})W + Q$$

stationarity

slow crossing time

Kolmogorov damping

no source of turbulence

$$\Gamma_{growth} = \Gamma_{damp} = \Gamma_{Kol}$$

self-similar solution (with a variable $x=z/t^{3/2}$) which describes the non-stationary evolution of the cloud of relativistic particles confined in the magnetic field flux tube

Compared to the ordinary diffusion with constant *D*, the considered non-linear transport is characterized by a relatively slow expansion of the particle distribution around the source

Malkov et al., 2013

$$\frac{\partial P_{CR}}{\partial t} + V_A \frac{\partial P_{CR}}{\partial z} = \frac{\partial}{\partial z}\left(\frac{D_B}{W}\frac{\partial P_{CR}}{\partial z}\right)$$

$$\frac{\partial W}{\partial t} + V_A \frac{\partial W}{\partial z} = (\Gamma_{growth} - \Gamma_{damp})W + Q$$

no source of turbulence

slow crossing time

no wave damping

Method: they solve the two coupled equations and derive an analytic approximated solution

Conclusions: solution depends on two main parameters, W_0 and Π.

Π: field-line-integrated CR pressure

$$\Pi = \frac{V_A}{D_B}\int_0^\infty P_{CR}\,dz$$

- The case Π < 1 is equivalent to the TP case.
- The case Π > 1…

The meaning of Π

$$\Pi = \frac{V_A}{D_B} \Phi_{CR}$$

$$\Phi_{CR} = \int_0^{\infty} \mathrm{d}z \, P_{CR}$$

Consider the initial setup of the problem: CRs are localized in a small region of size Δz. If the CR pressure within Δz is $P_{CR,0}$ then

$$\Phi_{CR} = P_{CR,0} \, \Delta z$$

growth time: $(V_A / W_0 \, \partial P_{CR} / \partial z)^{-1} \approx W_0 \Delta z / V_A P_{CR,0}$

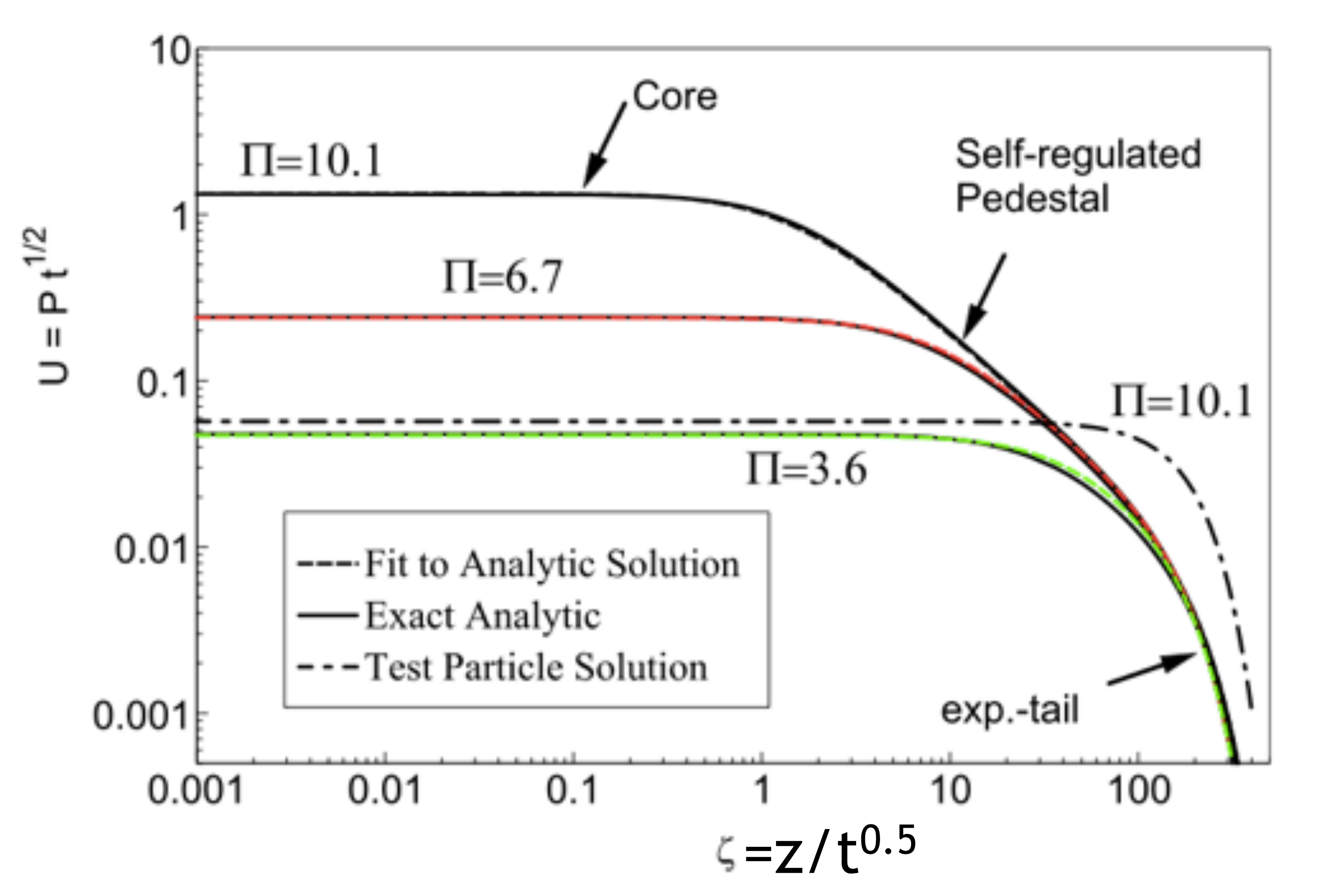
To have a significant growth of waves due to CR streaming, the growth time must be CR shorter than the time it takes the CR cloud to spread due to diffusion

$$\Delta z^2 / D \approx \Delta z^2 W_0 / D_B$$

The initial diffusion coefficient is equal to D_B / W_0.

Such condition can be rewritten as $\Pi > 1$

Malkov et al., 2013



Self-similar solution for the CR pressure for different values of the Π parameter.

Zone 1: Core	*Zone 2: intermediate*	*Zone 3: exponential cutoff*
$z < z$ D_{NL}	z_1	$z>z$
P_{CR} >>	P	P_{CR}

One major caveat with Malkov's approach:
Π can be in some cases too large and limit the applicability

OUR WORK

To quantify the range of applicability of Malkov+13 we explicitly estimate Π

$$\Pi(E; n, R_{esc}, \alpha) \propto E^{1-\alpha} n^{-1/2} R_{esc}^{-2}$$

assumptions →

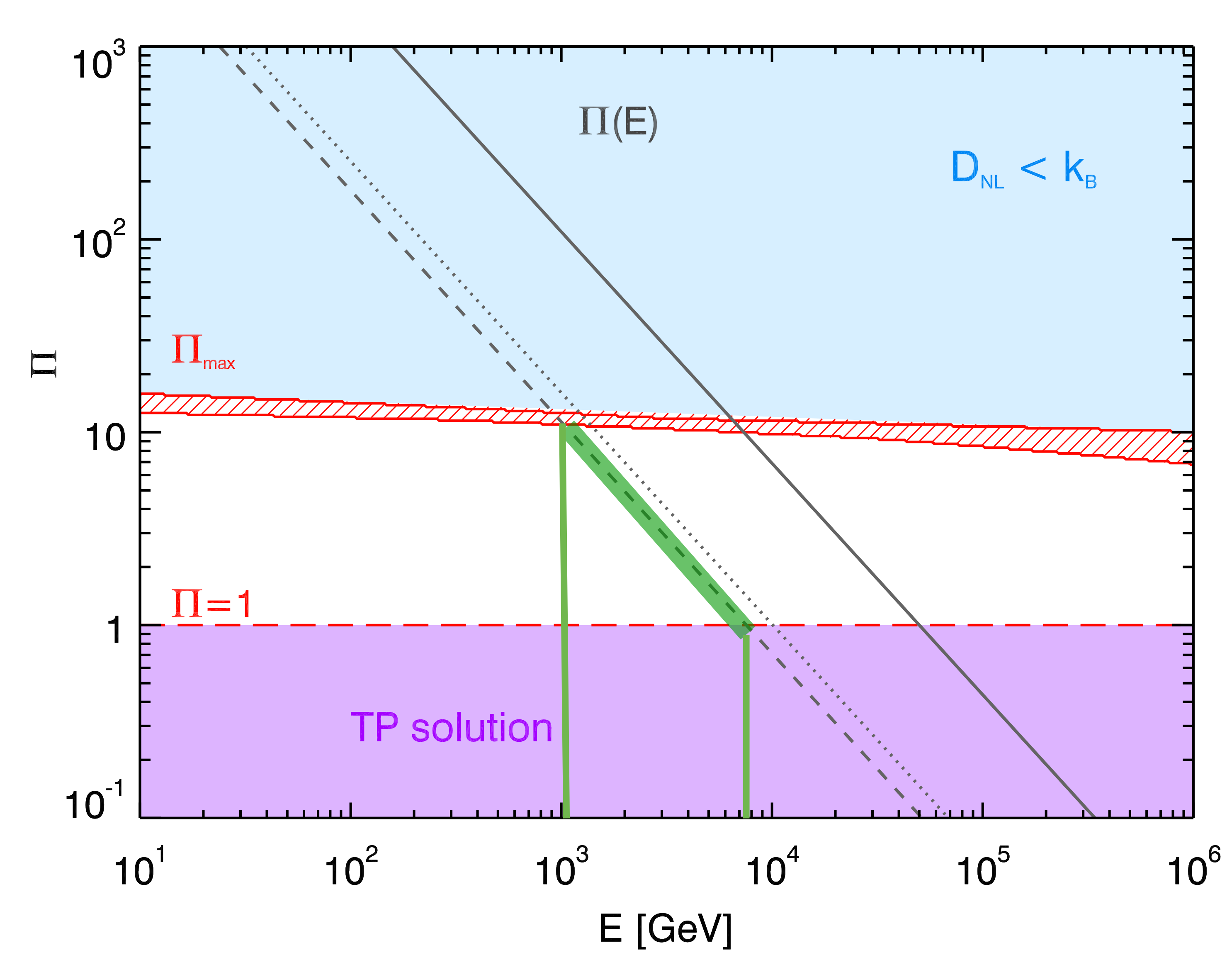
$$R_{esc} = 20\,\mathrm{pc}, \;\; \alpha = 2.2$$

There is an upper limit to Π: $D_{NL} < D_B$

$$\Pi_{max} = \Pi_{max}(E; D_{ISM}, B)$$

assumptions →

$$D_{ISM} = 10^{28} \left(\frac{E}{10\,GeV}\right)^{0.5} cm^2 s^{-1}$$



Shaded blue:
Not allowed region:
$\Pi > \Pi_{max}$

Hatched red: Maximum Π ($D_{NL}<D_B$) limit of the quasi-linear calculations of Malkov+13.

Shaded purple:
Test Particle solution, no need to apply Malkov+13

OUR WORK

$$\frac{\partial P_{CR}}{\partial t} + V_A \frac{\partial P_{CR}}{\partial z} = \frac{\partial}{\partial z}\left(\frac{D_B}{W}\frac{\partial P_{CR}}{\partial z}\right)$$

$$\frac{\partial W}{\partial t} + V_A \frac{\partial W}{\partial z} = (\Gamma_{growth} - \Gamma_{damp})W + Q$$

— Numerical procedure —

***Initial conditions*:**

- $P_{CR}(t=0,z>0)=P_{CR,back}$ and $P_{CR}(t=0,z=0)$ prescribed imposing that 10% of SN energy into CRs
- $D(t=0,z)=D_{ISM}=10^{28}cm^2/s\ [E/10GeV]^{0.5}$

***Boundary conditions*:**

- CR and wave fluxes vanish at $z=0$

***Solving scheme*:**

- Explicit finite differences (conditions for accuracy and stability required)

***Computing performances*:**

- Computation time on a standard workstation few minutes/hours dependent on the particle energy and spatial resolution

Some preliminary results

Nava, Gabici, Marcowith, Morlino & Ptuskin 14, in preparation

- 2 ISM phases: *WIM* and *WNM*
- 3 Energies: *20 GeV*, *1 TeV*, *20 TeV*
- 3 times: *2 kyr*, *10 kyr*, *50 kyr*

ISM phases

We consider 2 different ideal phases:

Warm neutral and ***Warm ionized*** medium

[Jean+09]

phase properties	Warm neutral WNM	Warm ionized WIM
Hydrogen density	0.2-0.5	0.2-0.5
temperature (K)	6000-10000	8000
ionization fraction	0.007-0.05	0.6-0.9
magnetic field (μG)	5	5

OUR WORK

Turbulence damping processes considered

Non-linear Landau damping (Γ_{NLL}): occurs due to the energy exchange between waves and particles. High-frequency waves are damped by the presence of low-frequency waves and the presence of thermal particles.

$$\Gamma_{NLL} = -\frac{1}{2}\sqrt{\frac{\pi}{2}\frac{k_{bolz}T}{m_p}}\frac{W}{r_L}$$

[Kulsrud 1978; Volk & Cesarsky 1982; Felice & Kulsrud 2001]

Farmer & Goldreich (Γ_{FG}): wave damping by background MHD turbulence. MHD turbulence act as a damping mechanism for CR-generated waves

$$\Gamma_{FG} = \frac{V_A}{\sqrt{L_{MHD} r_L}}$$

[Yan & Lazarian 2002; Farmer & Goldreich 2004]

Kolmogorov (Γ_{Kol}): Non-linear Kolmogorov-type wave interaction. Energy cascade of Alfvenic waves to large wave numbers is anisotropic: the main part of energy density in this turbulence is concentrated perpendicular to the local B.

$$\Gamma_{Kol} = 0.05\frac{V_A}{r_L}\sqrt{W}$$

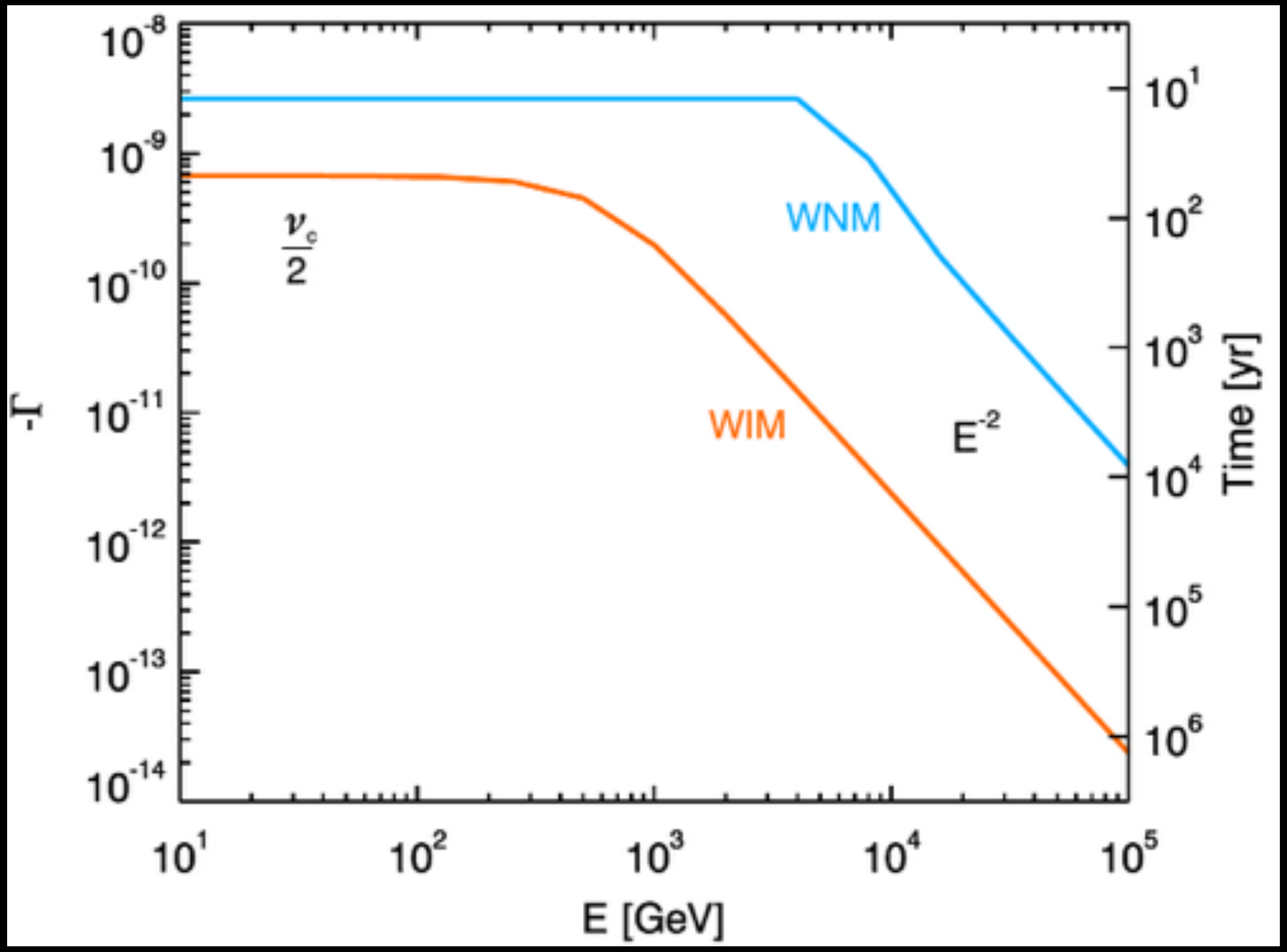
[Ptuskin & Zirakashvili 2003, 2005]

Ion-neutral collisions (Γ_{IN}): momentum-exchanging collisions between ions and neutral particles

[Kulsrud & Pierce'69; Zweibel & Shull'82]

Ion-neutral damping

OUR WORK



collision frequency

$$\nu_c = 1.68 \times 10^{-8} \left(\frac{T}{10^4\,K}\right)^{0.4} n_n\, s^{-1}$$

wave frequency

$$\omega \propto 1/r_L \propto E_{CR}^{-1}$$

$$\Gamma_{IN} = -\frac{\omega^2}{2\nu_c} \quad \text{for} \quad \omega \ll \nu_c$$

$$\Gamma_{IN} = -\frac{\nu_c}{2} \quad \text{for} \quad \omega \gg \nu_c$$

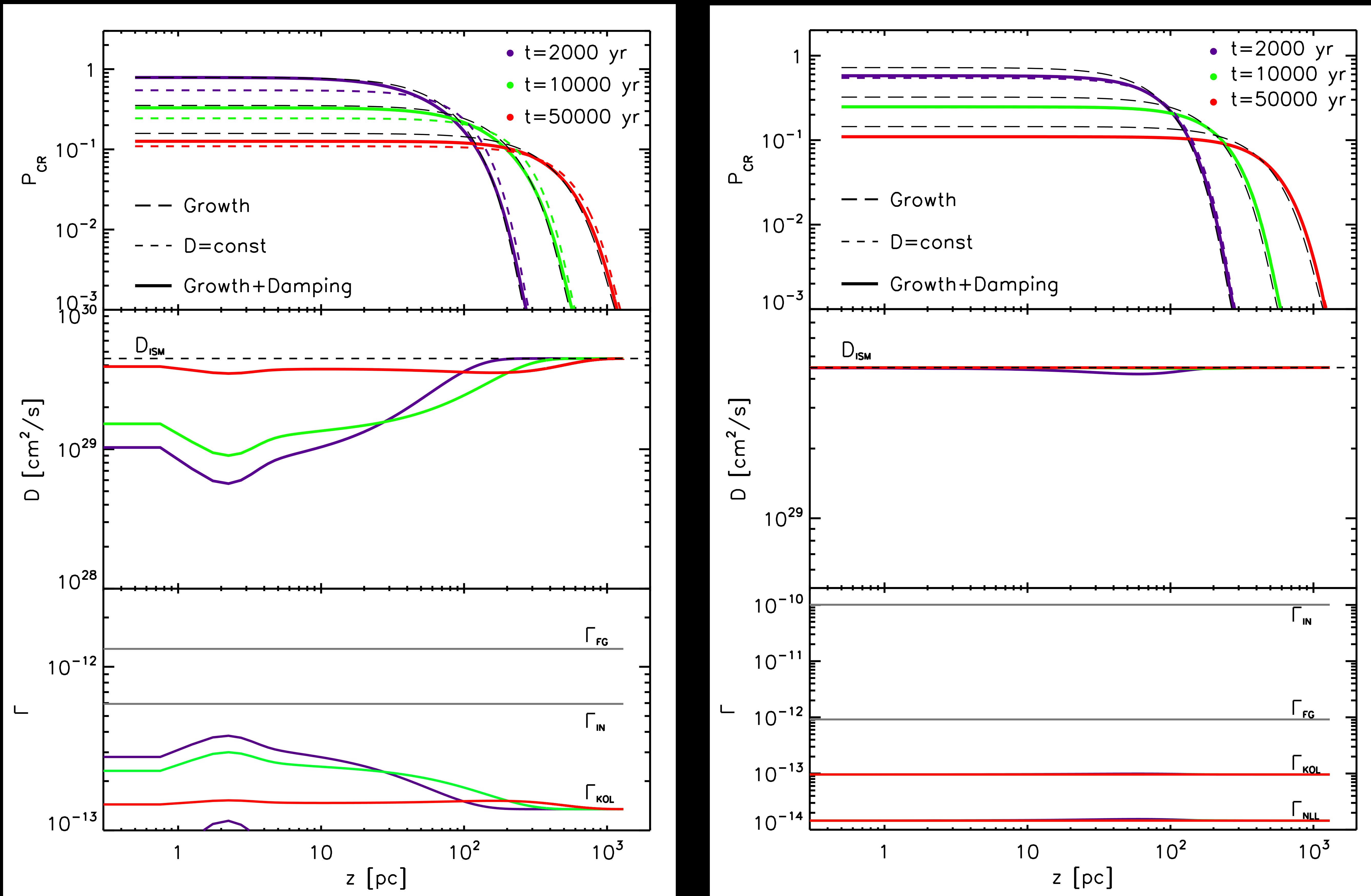
Frequent collisions reduce the Alfven speed to a value determined by the total mass density instead of the ionized mass density

$$V_A = \frac{B}{\sqrt{4\pi m_p n_i}} \longrightarrow V_A = \frac{B}{\sqrt{4\pi m_p n}}$$

20 TeV

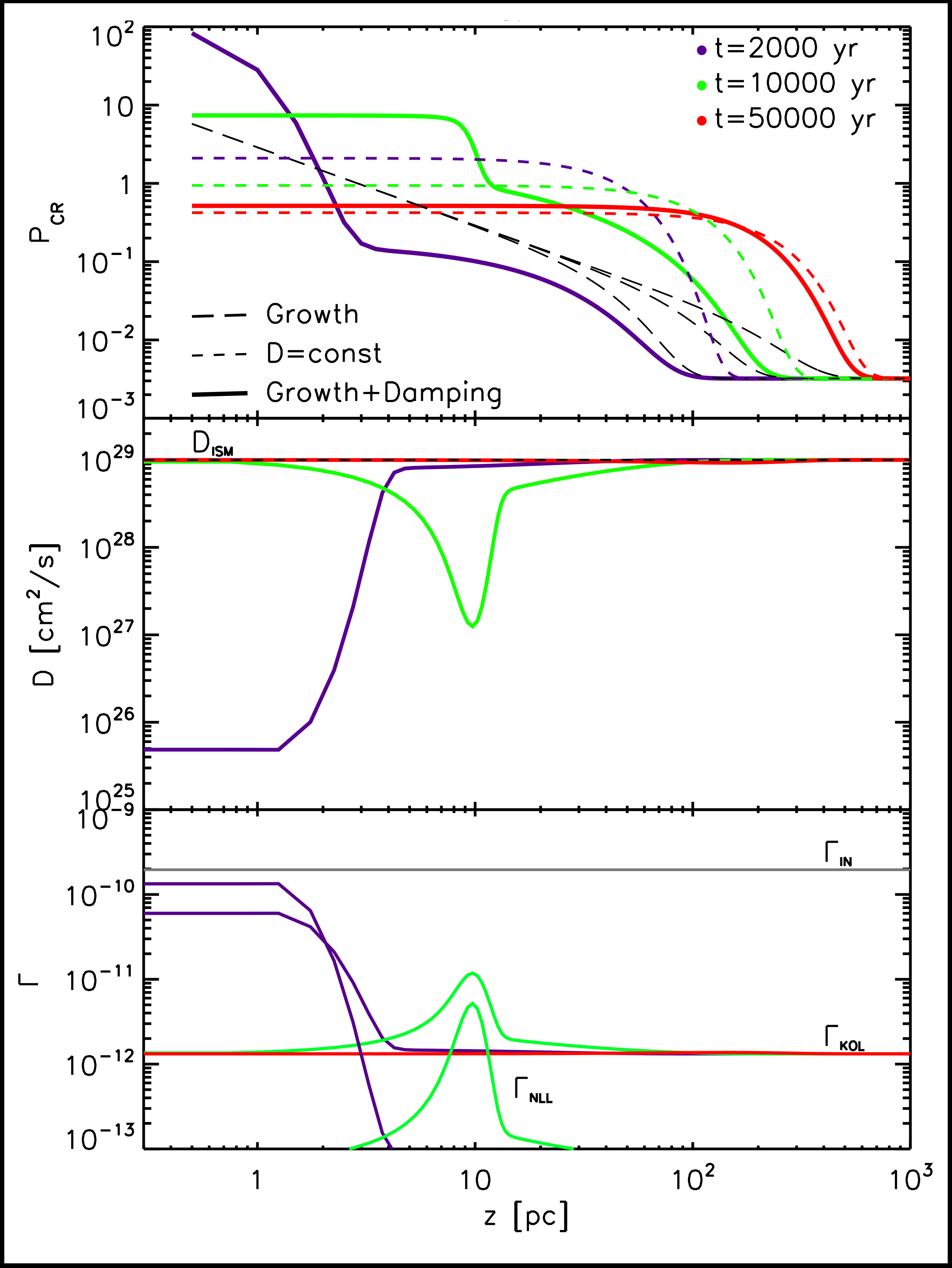
WIM

WNM



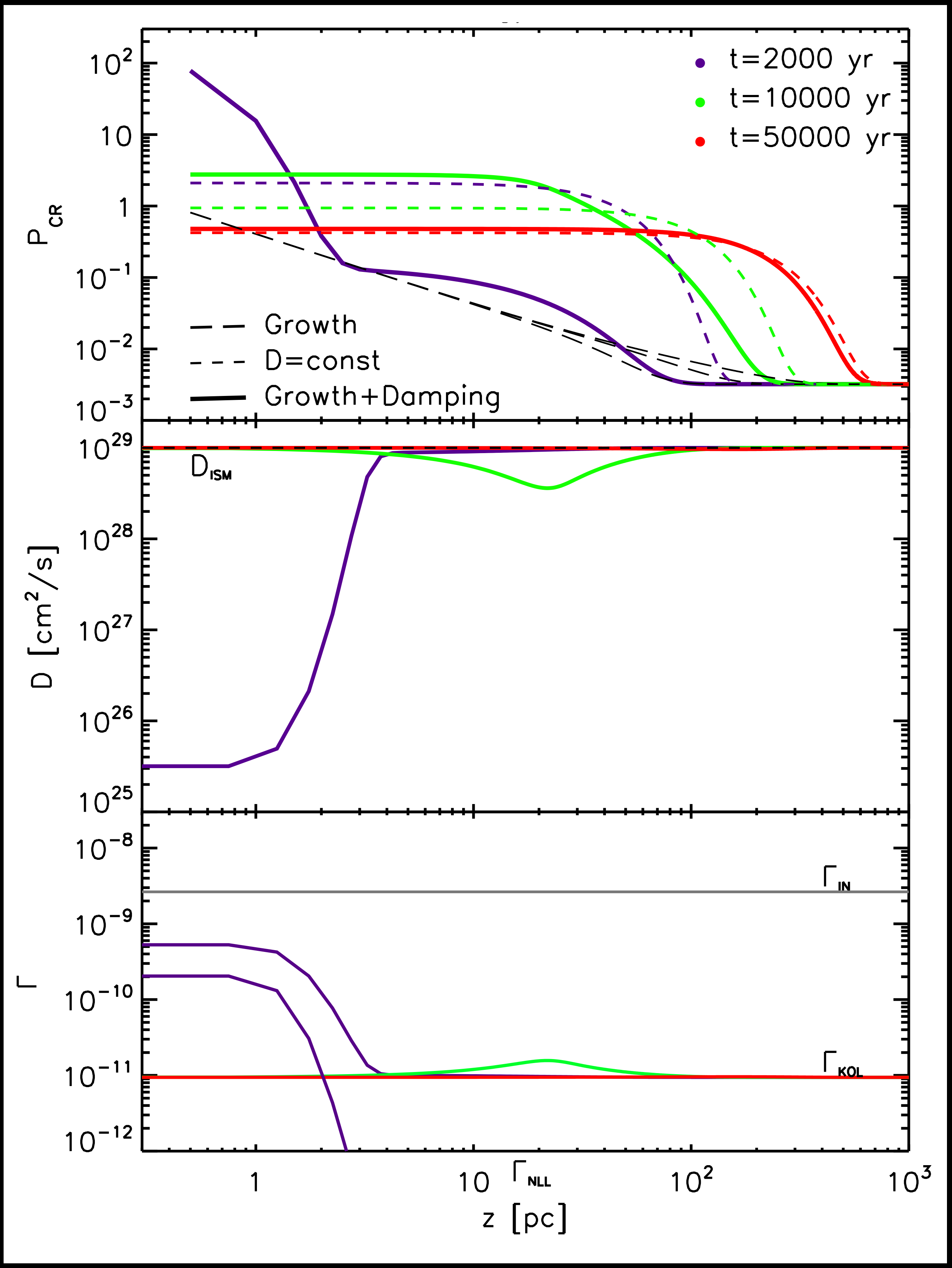
1 TeV

WIM



t=2000 yr
t=10000 yr
t=50000 yr
Growth
D=const
Growth+Damping
P_CR
D_ISM
D [cm²/s]
Γ_IN
Γ_KOL
Γ_NLL
Γ
z [pc]

WNM



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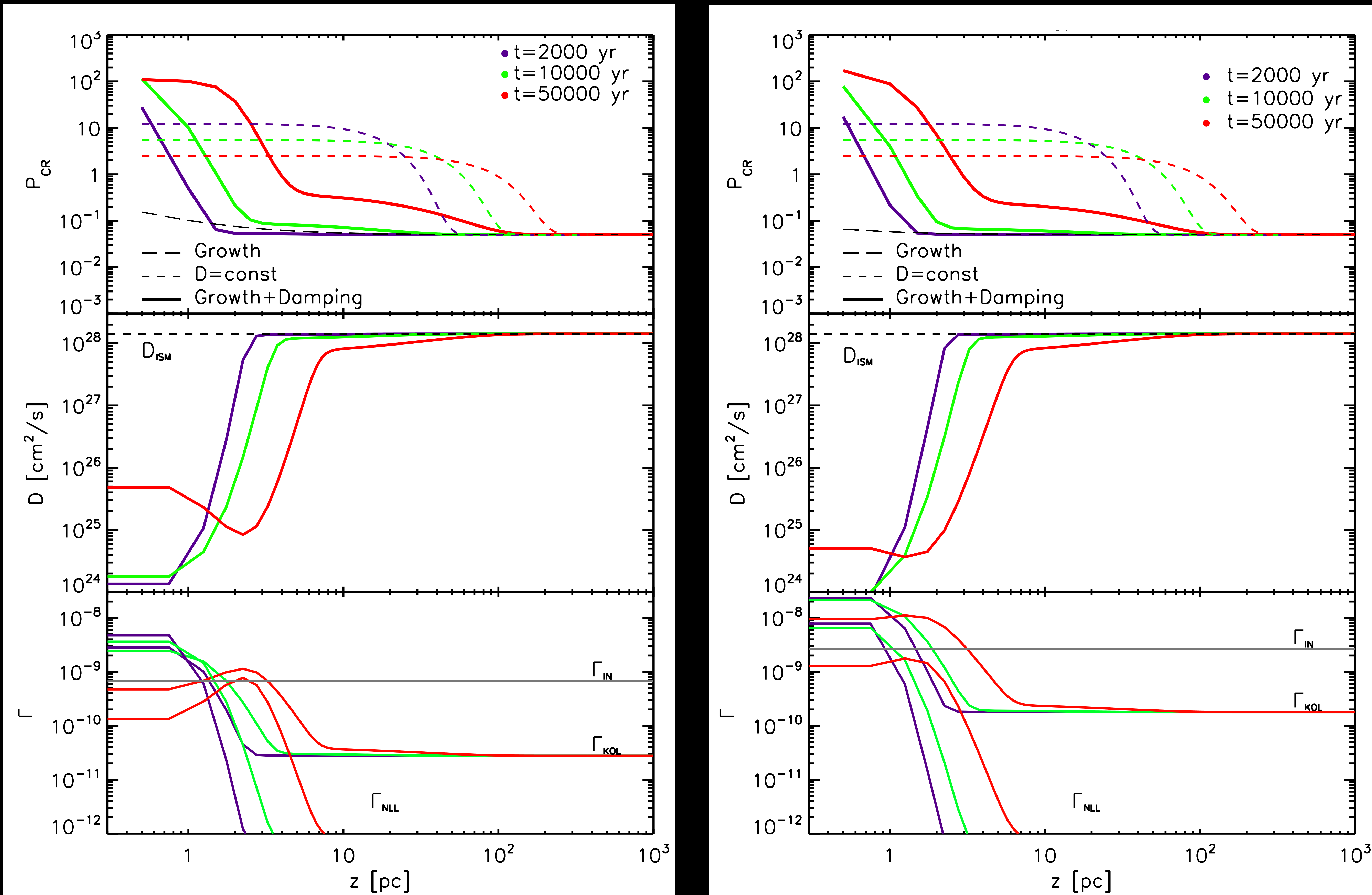
20 GeV

WIM   WNM



Summary

- Self-consistent solutions of D and P_{CR} in the quasi-linear limit
- Streaming instability as source of turbulence
- Different collisional and collisionless damping
- Two ISM phases: WNM & WIM
- Deviation from the test particle solution at E_{CR}<1 TeV
- Strong self-confinement of CRs of GeV CRs, even at late times

Further developments:

- CR spectra and gamma-ray spectra: constraints from gamma-ray observations, gamma-ray production from clouds => introduce inhomogeneous models of ISM