MAX-PLANCK-GESELLSCHAFT

Self-modulation of relativistic cosmic rays penetrating dense molecular clouds

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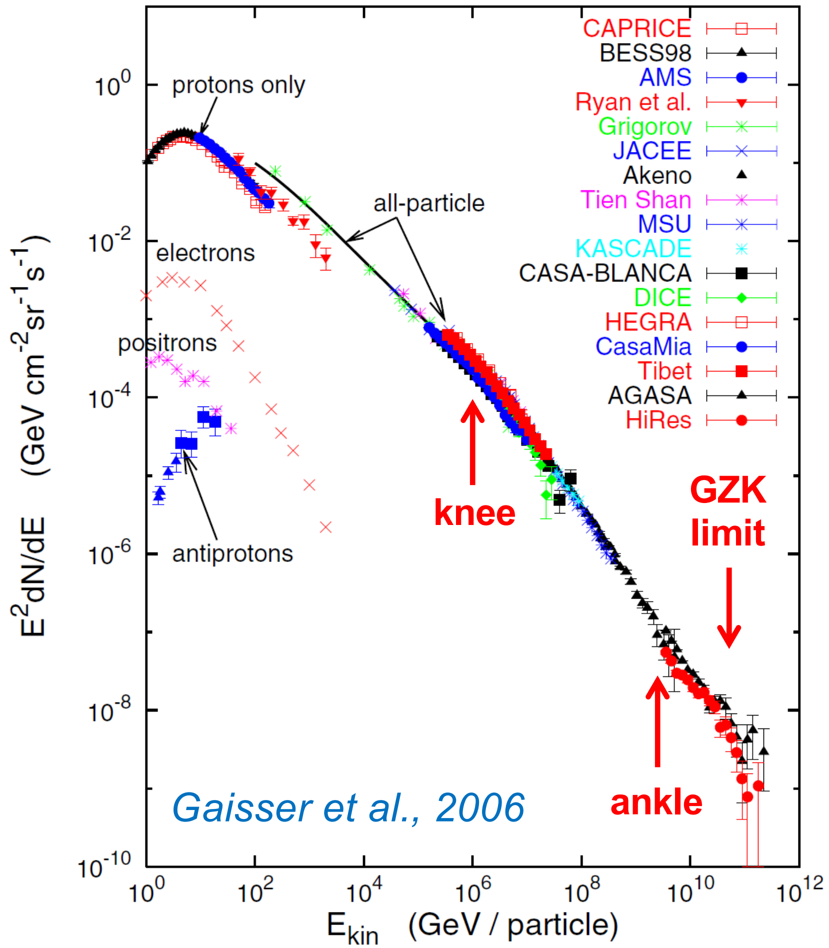
Chernyshov, Ivlev, & Kiselev, PRD **110**, 043012 (2024)

Galactic cosmic rays (CRs)



Energy density in the ISM:

$$W_{\mathrm{CR}} \approx 1.4\ \mathrm{eV/cm^3}$$

$$W_B \approx 0.9\ \mathrm{eV/cm^3}$$

$$W_T \approx 0.5\ \mathrm{eV/cm^3}$$

$$W_{\mathrm{turb}} \approx 0.2\ \mathrm{eV/cm^3}$$

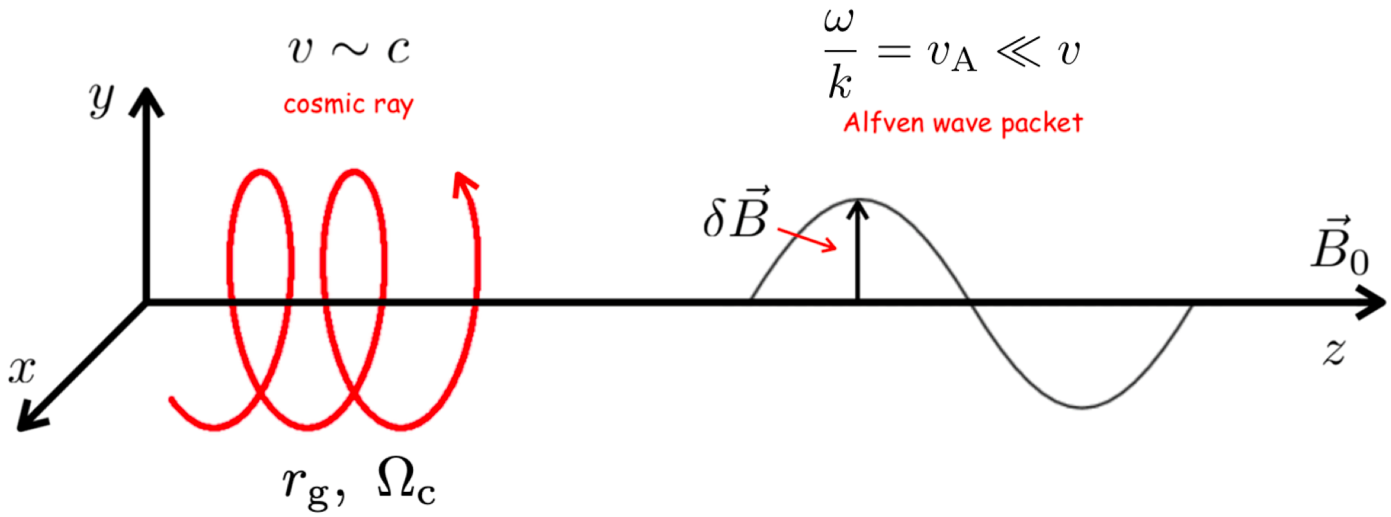
Cosmic Rays are:

dilute,
non-thermal,
high-pressure
relativistic gas

Variety of processes driven by CRs in MCs

- Gas ionization
  ⇒ coupling to magnetic field, properties of turbulence, …
- Gas heating
  ⇒ cloud dynamics, chemistry, …
- Dust evolution
  ⇒ dust coagulation, chemical processes on grain surface, …
- Processing of icy mantles
  ⇒ abundances of complex molecules, desorption of ices, …
- …

Pitch-angle resonant scattering



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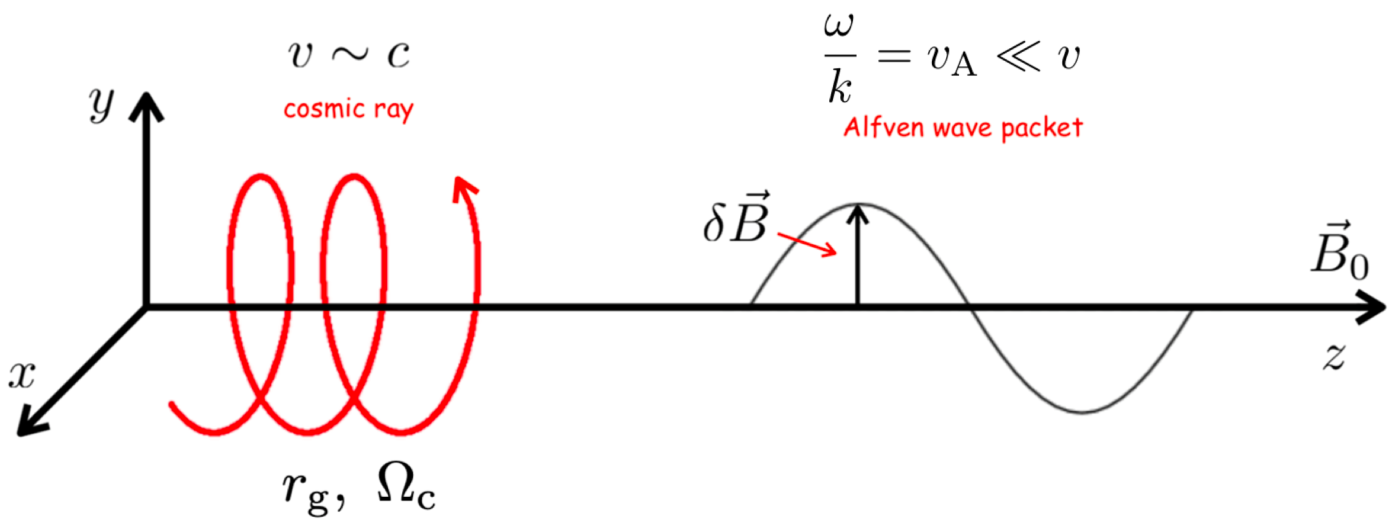


Resonance condition: $|\omega - kv_{||}| \sim \Omega_c \sim c/r_g \quad \Rightarrow \quad \boxed{kr_g \sim 1}$

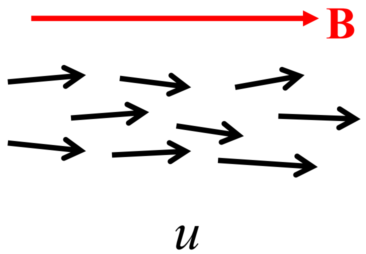
$$\langle F_z \rangle = \frac{e}{c}\langle v_\varphi B_y \rangle \neq 0$$

kinetic energy is conserved

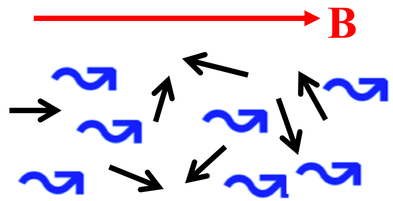
$\Rightarrow$ pitch-angle variation

Resonant wave excitation

Interstellar CRs stream freely
in quiescent ionized gas



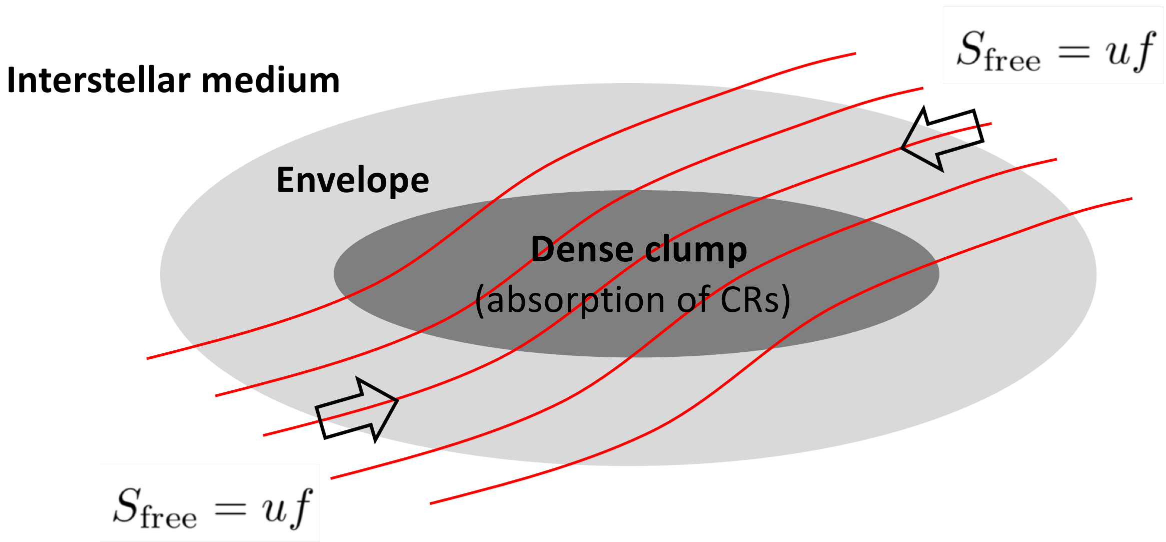
Excited MHD waves lead to CR isotropization
(in *co-moving* reference frame)



$$\gamma_{\rm CR}(p) \simeq -\pi^2 \frac{e^2 v_{\rm A}}{m_p c^2 \Omega_p} p f(p)(u - v_{\rm A})$$

Kulsrud & Pearce (1969); Skilling (1975)

Resonant streaming instability



$$u \approx \frac{1}{2}\sigma_{\rm loss}\mathcal{N}c$$

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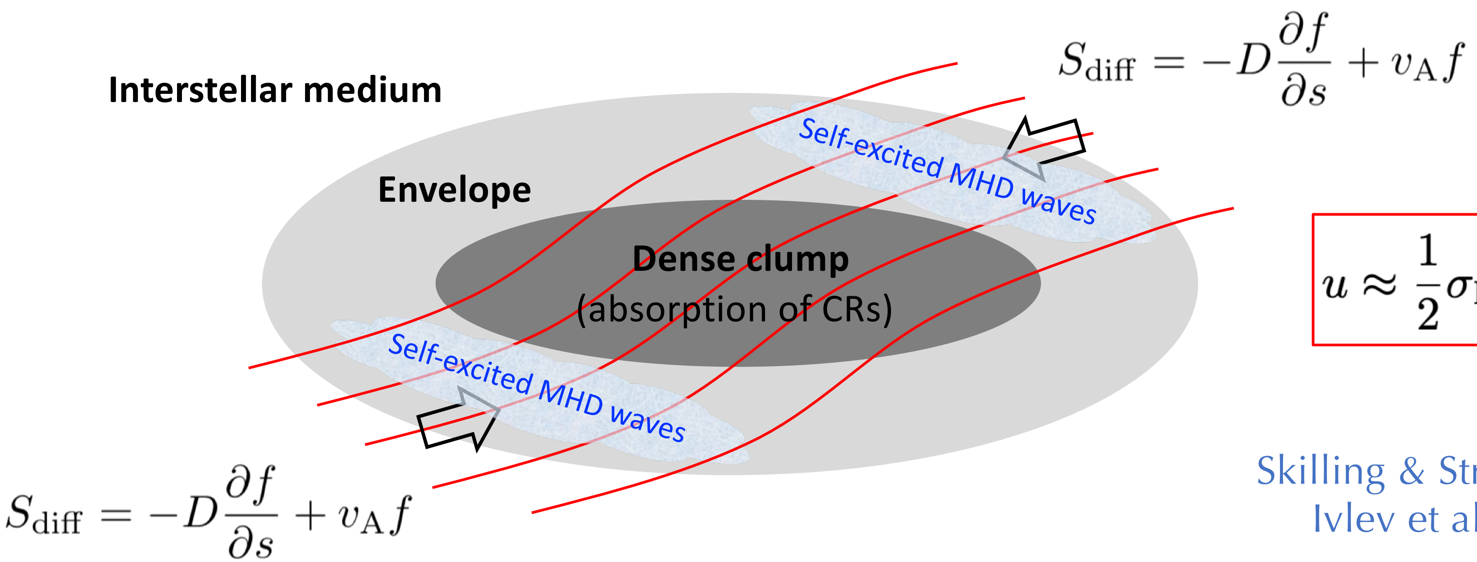

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Skilling & Strong (1976)
Ivlev et al. (2018)

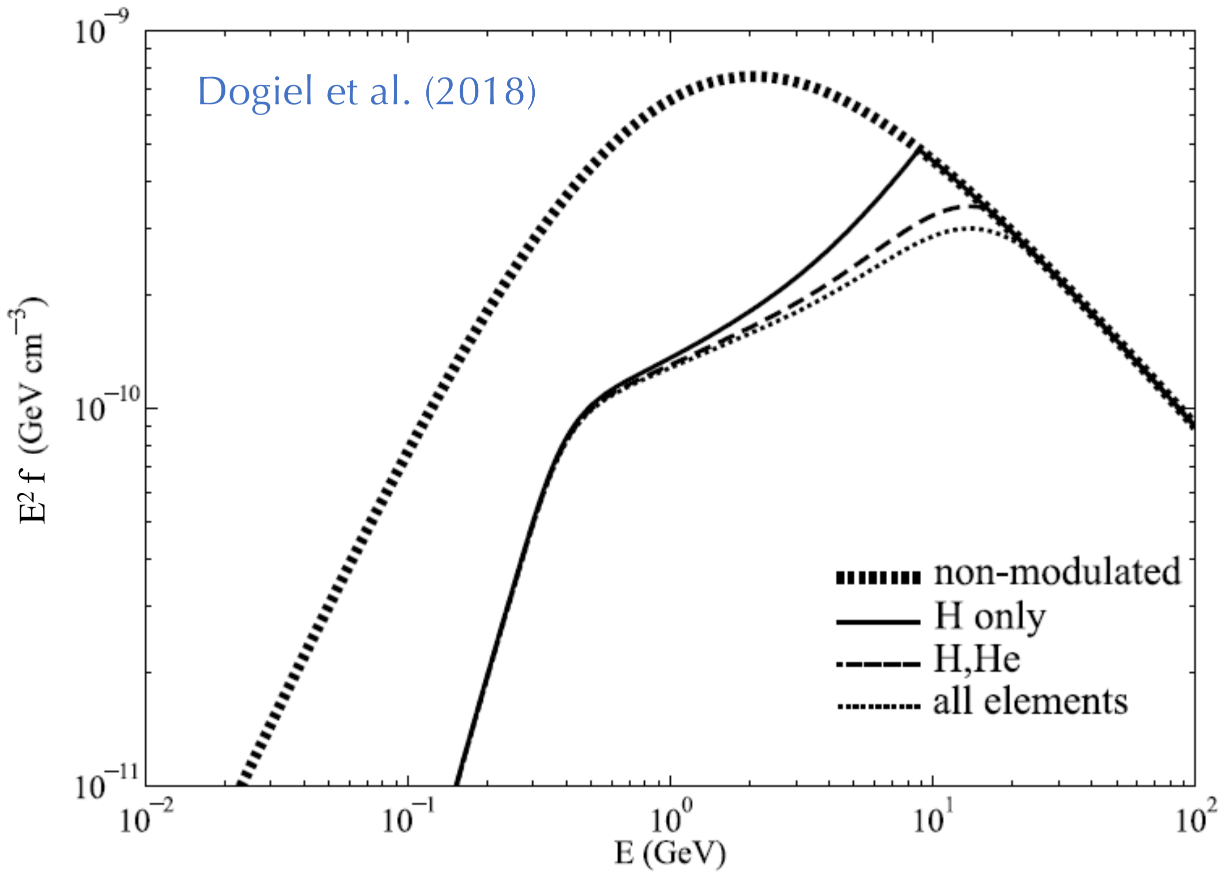
- Streaming CRs with $u > v_{\rm A}$ resonantly excite MHD waves in the envelope, at $kr_{\rm g} \sim 1$.
- The turbulence level is set by a balance of the wave excitation, $\gamma_{\rm CR} \propto -D(\partial f/\partial z)$, and the ion-neutral damping, $\nu_{in} \propto n$.

Modulation of CR spectrum in the CMZ

5 × standard ISM spectrum

$\mathcal{N} = 3\times10^{23}\ \mathrm{cm}^{-2}$

n (envelope) = 10 cm^{-3}



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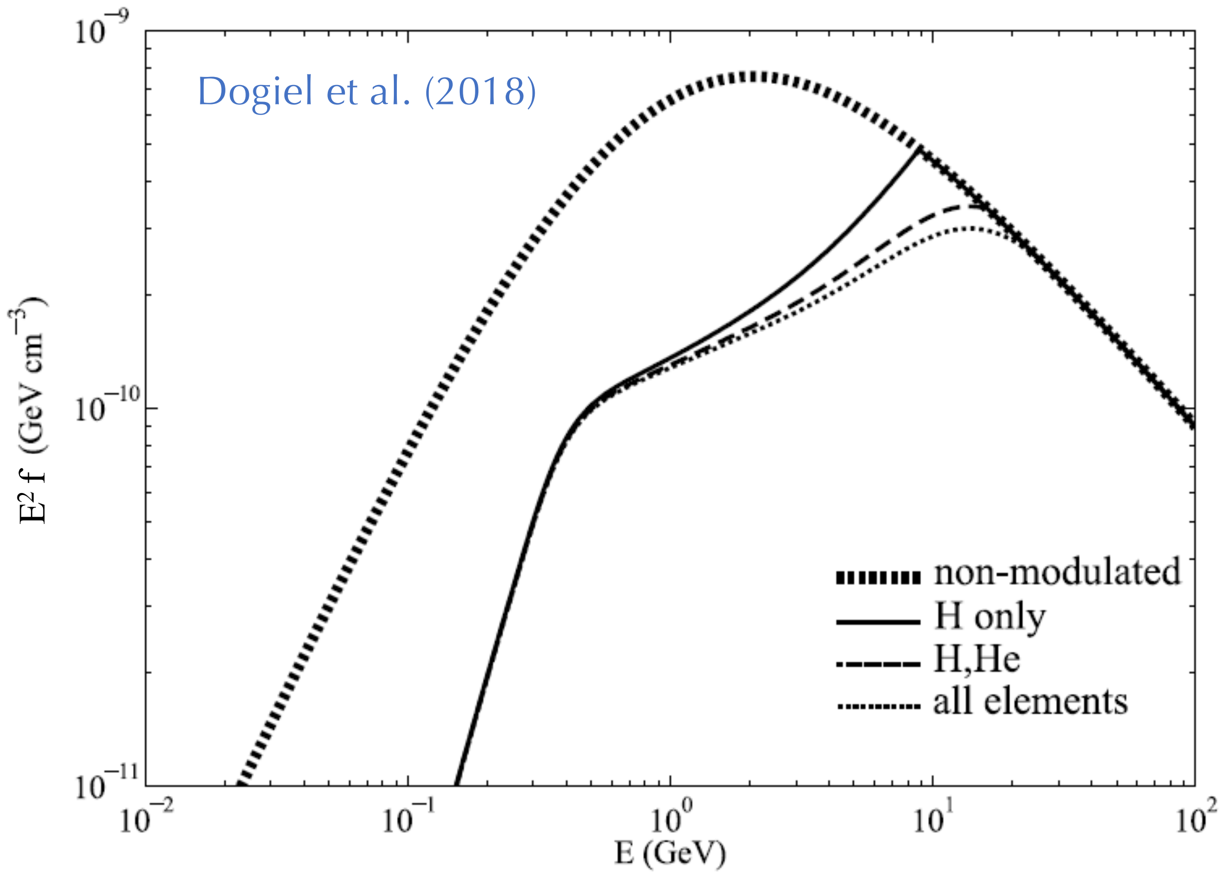
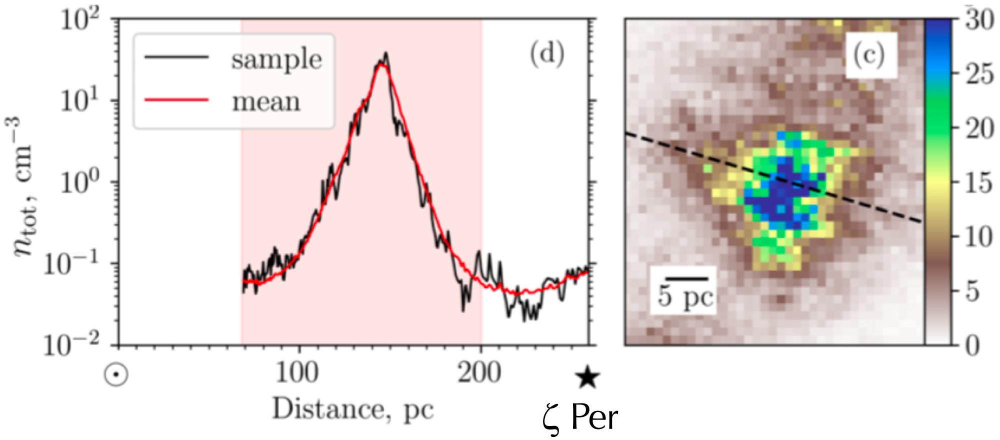
Model parameter
Assumed to be constant

Ivlev et al. (2018)
Dogiel et al. (2018)



Gas distribution in envelopes



According to 3D dust extinction maps (Leike et al. 2020; Edenhofer et al. 2024), gas density increases monotonically toward the dense clump.

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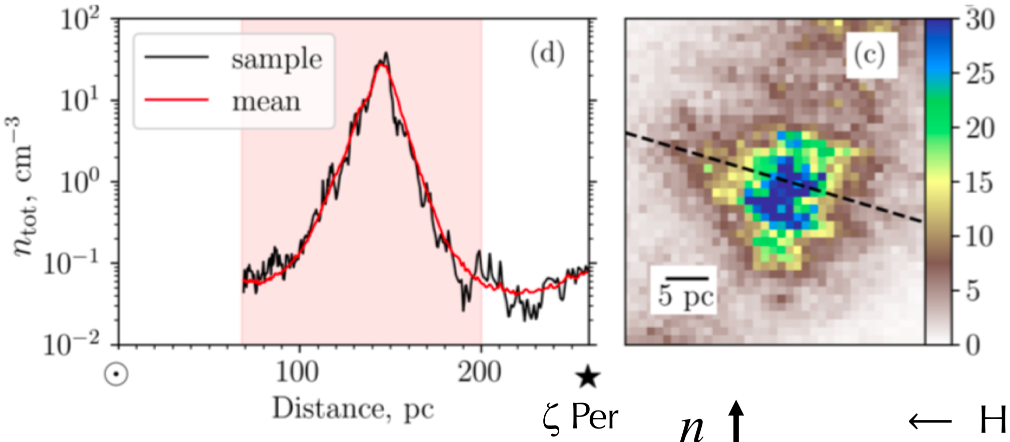

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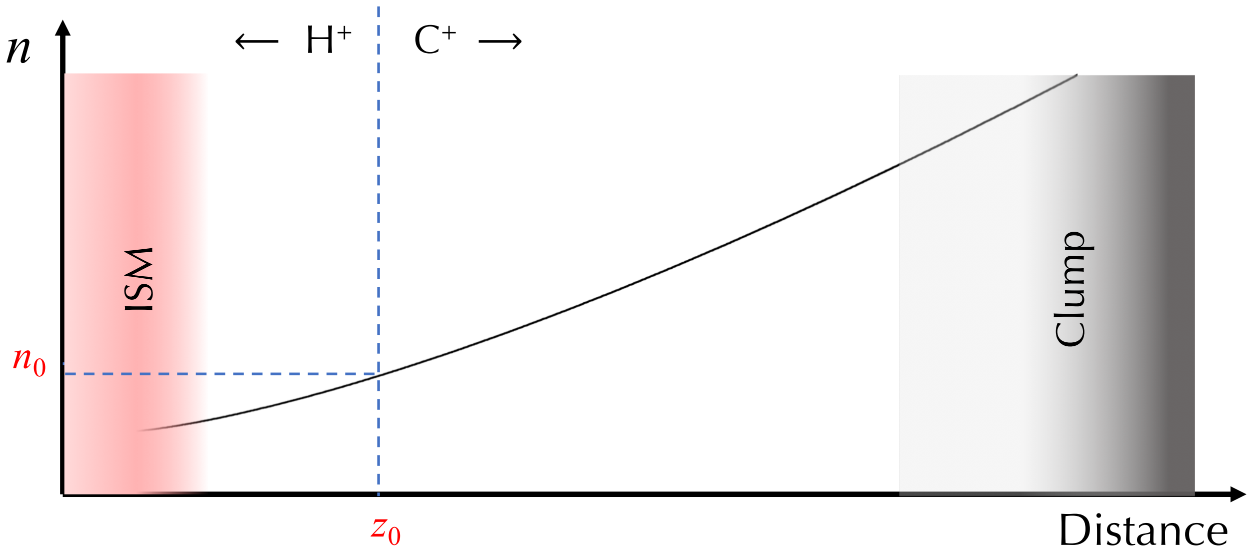
$$\nu_{in}(z) = \frac{1}{2}\frac{m_n n}{m_n + m_i}\langle\sigma_{in} v\rangle$$

$$\nu_{in}(z_0) \to \min$$

⇒ no waves at $z < z_0$



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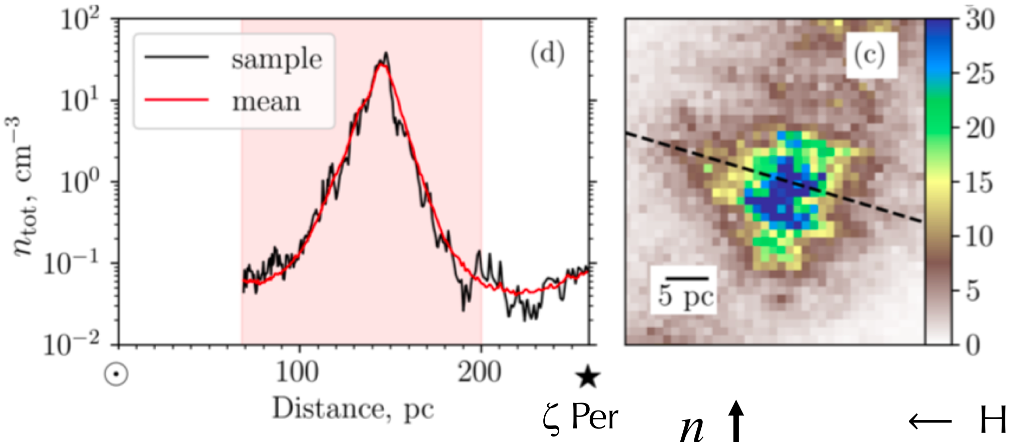

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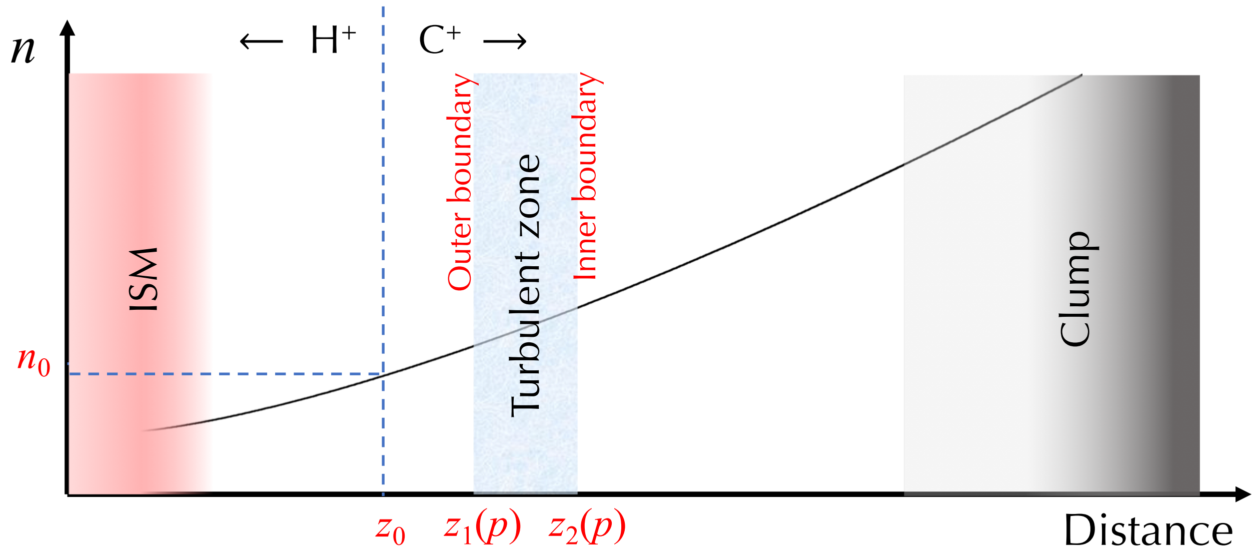

Equations for the diffusion zone (CR protons)

Transport equation

$$\frac{\partial}{\partial z}\left(v_{\rm A} f - D\frac{\partial f}{\partial z}\right) + \frac{\partial}{\partial p}\left(\dot{p} f\right) = 0$$

total CR flux

$$v_{\rm A}(z) = \frac{B}{\sqrt{4\pi m_i \xi_i n}}$$

$$D(p,z) \simeq \frac{1}{6\pi^2}\frac{vB^2}{k^2 W}$$

Excitation-damping balance

$$\gamma_{\rm CR} = \nu_{in}$$

$$\gamma_{\rm CR}(k,z) \simeq -\pi^2 \frac{e^2 v_{\rm A}}{m_p c^2 \Omega_p} p D \frac{\partial f}{\partial z}$$

$$\nu_{in}(z) = \nu_0 \frac{n}{n_0}$$

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$$\Downarrow$$

$$-D\frac{\partial f}{\partial z} = \frac{Bc\nu_{in}}{\pi^2 e v_{\rm A} p} \equiv S_{\rm D}(p,z) \propto \frac{n^{3/2}}{p}$$

diffusion component of CR flux

$$S(p,z) = v_{\rm A} f + S_{\rm D} \quad \Leftarrow$$

total CR flux

Boundary conditions for relativistic protons

$$\frac{\partial}{\partial z}\left(v_{\mathrm{A}} f - D\frac{\partial f}{\partial z}\right) + \frac{\partial}{\partial p}(\dot{p} f) = 0 \quad \Rightarrow \quad \boxed{v_{\mathrm{A}} f(p,z) + S_{\mathrm{D}} = S_0(p)}$$

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<u>Outer boundary $z_1(p)$:</u>

$$f(p,z)|_{z=z_1} = f_0(p)$$

<u>Inner boundary $z_2(p)$:</u>

$$u\, f(p,z)|_{z=z_2} = S_0(p)$$

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$$u\, f(p,z)\big|_{z=z_2} = S_0(p)$$

$$\frac{df}{dz} = 0 \quad \Rightarrow \quad 3\, S_{\rm D}\big|_{z=z_{\rm cr}} = v_{\rm A}\big|_{z=z_{\rm cr}} f_0$$

$$\Rightarrow \quad \boxed{n_{\rm cr}(p) = \sqrt{\frac{\pi p f_0(p) n_0}{12\xi_i}\frac{\Omega_i}{\nu_0}}}$$

$$\boxed{n_1(p) = \max\{n_{\rm cr}(p),\, n_0\}}$$

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Inner boundary $z_2(p)$:

$$u\ f(p,z)\big|_{z=z_2} = S_0(p)$$

$$\Downarrow$$

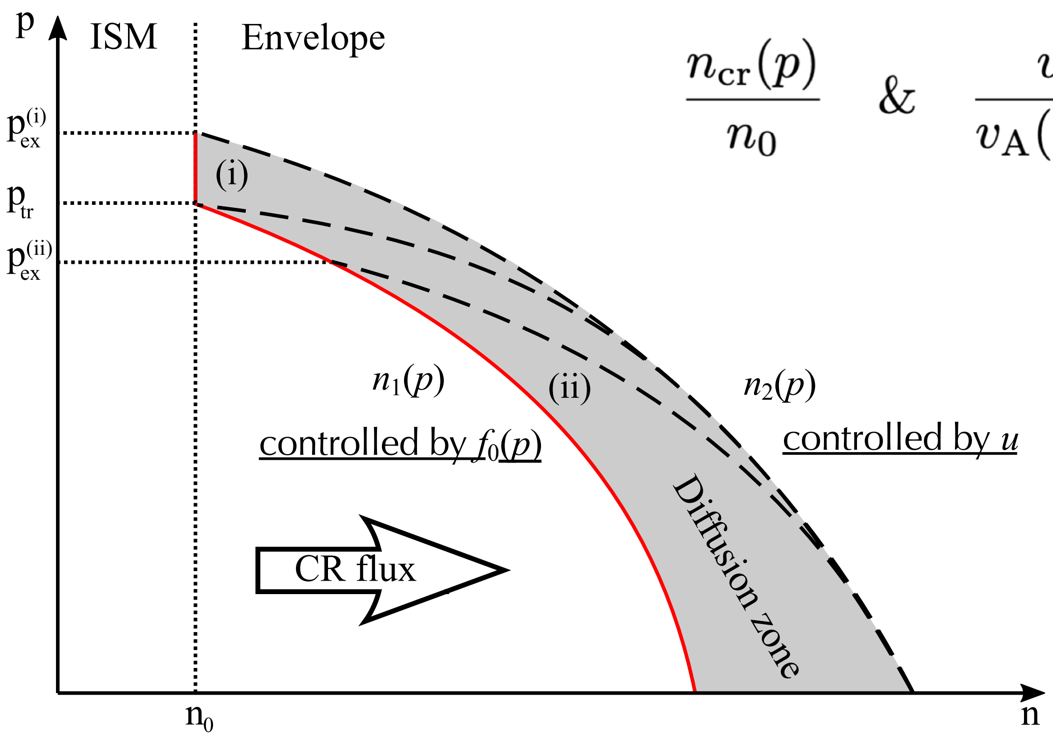
$$\boxed{\frac{n_2(p)}{n_1(p)} = \left[\mathcal{K}\left(1 - \frac{v_{\rm A}(n_2)}{u}\right)\right]^{2/3}}$$

$$\mathcal{K}(p) = 3\left(\frac{n_{\rm cr}(p)}{n_1(p)}\right)^2 + 1$$

Diffusion zone

Similarity parameters:

$$\frac{n_{\rm cr}(p)}{n_0} \quad \& \quad \frac{u}{v_{\rm A}(n_0)}$$



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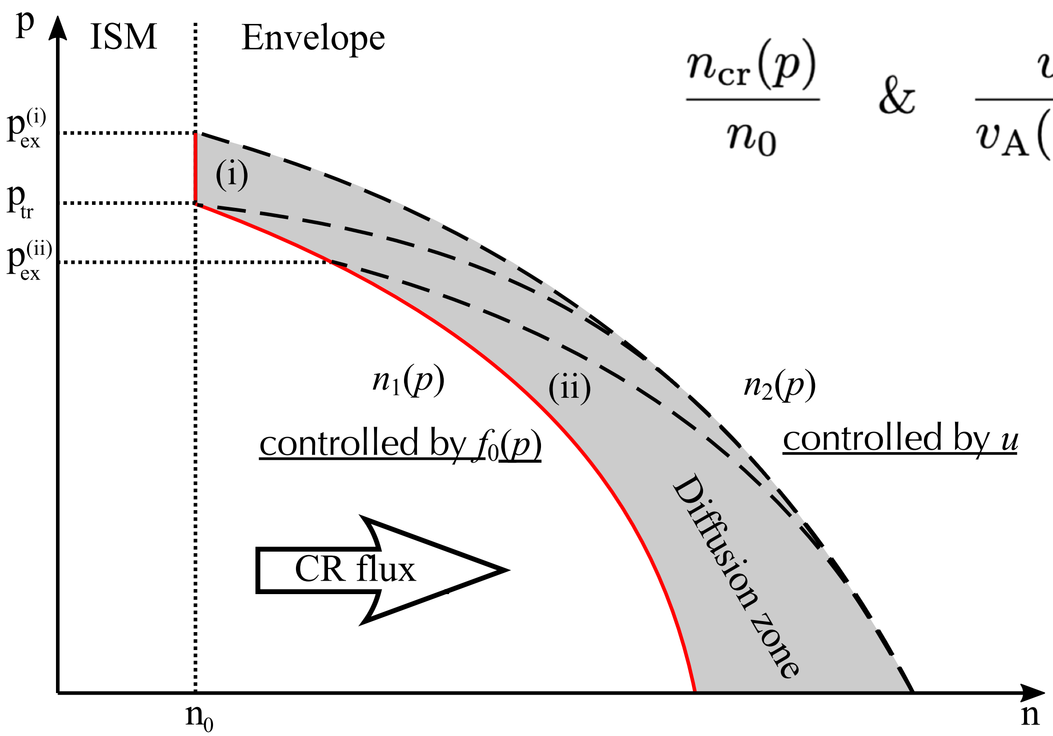


Similarity parameters:

$$\frac{n_{cr}(p)}{n_0} \quad \& \quad \frac{u}{v_A(n_0)}$$

Excitation threshold p_{ex}:

$$p_{ex}: \qquad n_2(p_{ex}) = n_1(p_{ex})$$

Regime (i): $v_{A0} < \frac{3}{4}u$

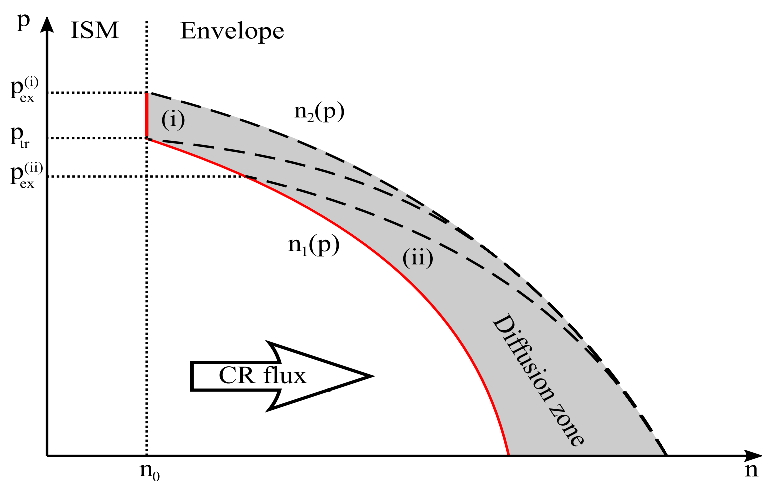
Regime (ii): $v_{A0} > \frac{3}{4}u$

Self-consistent diffusion coefficient

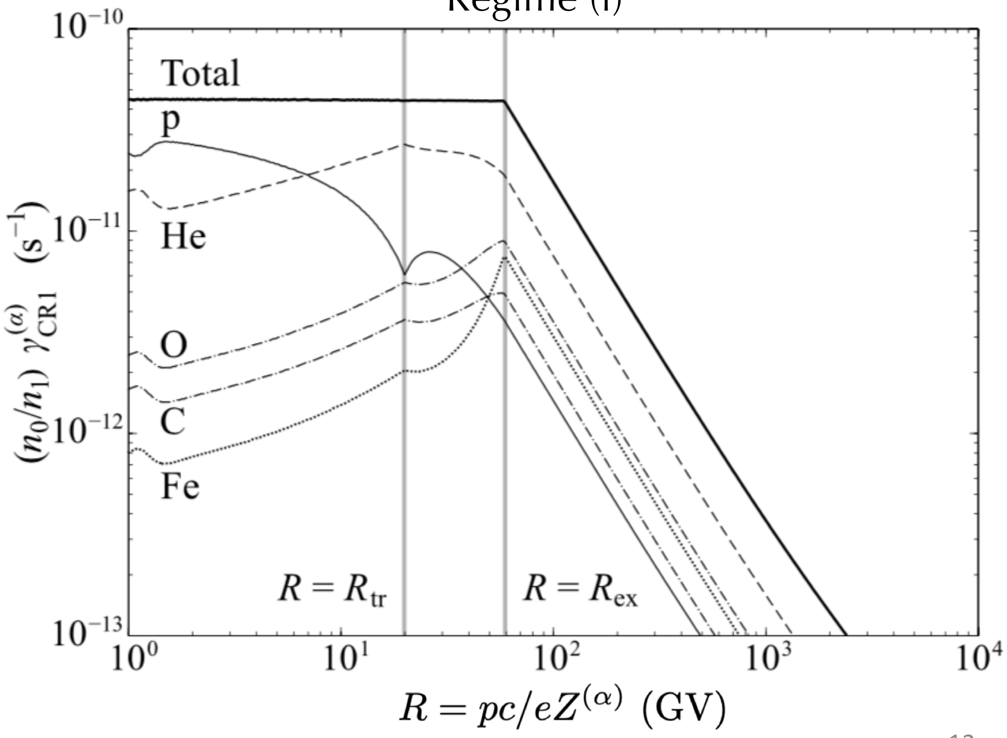
$$\frac{v_A}{D} = \frac{1}{2n}\left[4 - \mathcal{K}\left(\frac{n}{n_1}\right)^{-3/2}\right]\frac{dn}{dz}$$

Contribution of heavier CR nuclei

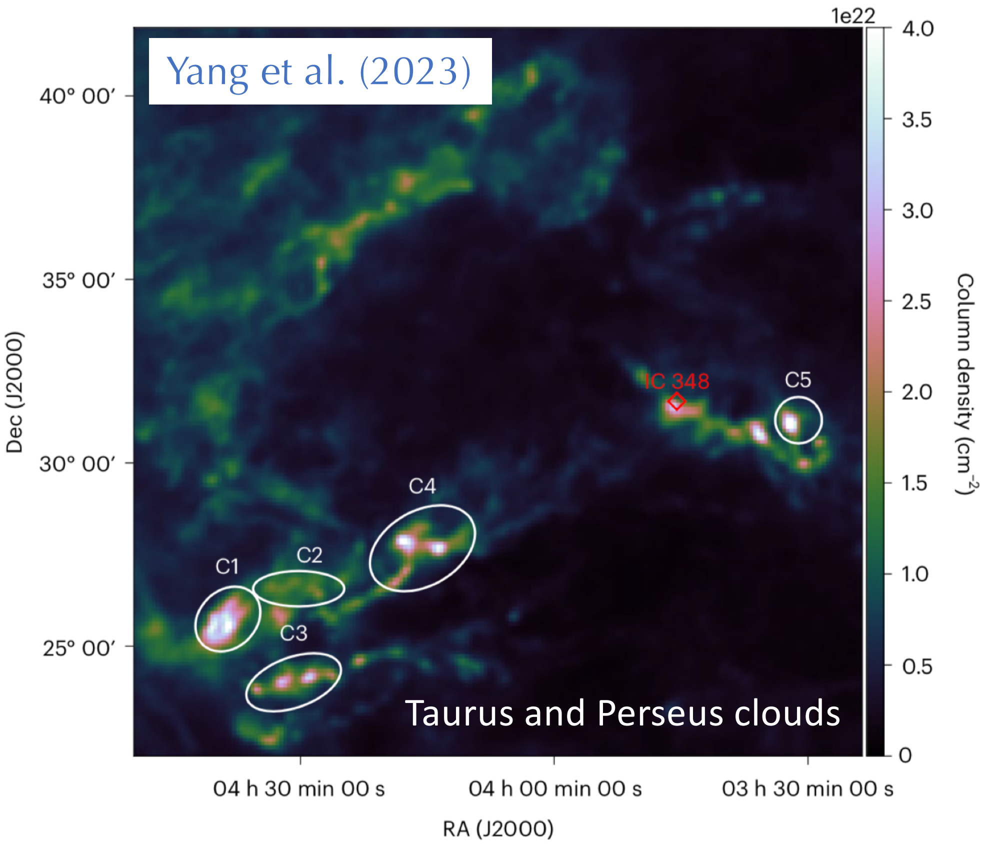
Wave excitation rate at the outer boundary $n_1(p)$:

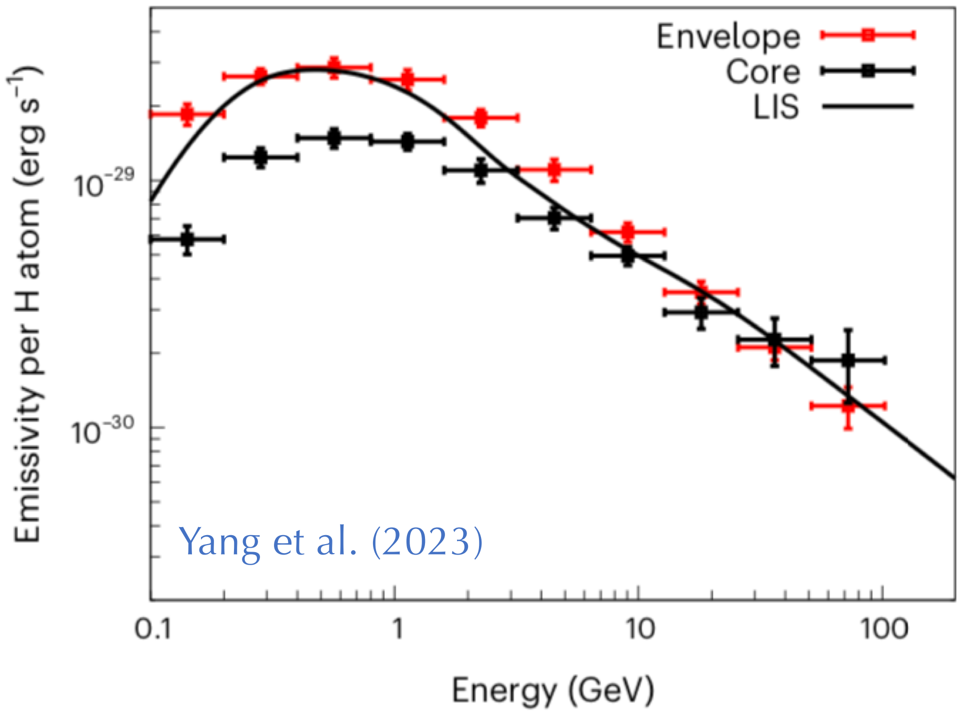


Regime (i)



Gamma-ray emission from MCs





$\mathcal{N}$ varies between ≈ 5×10^{22} and 10^{23} cm^{-2}

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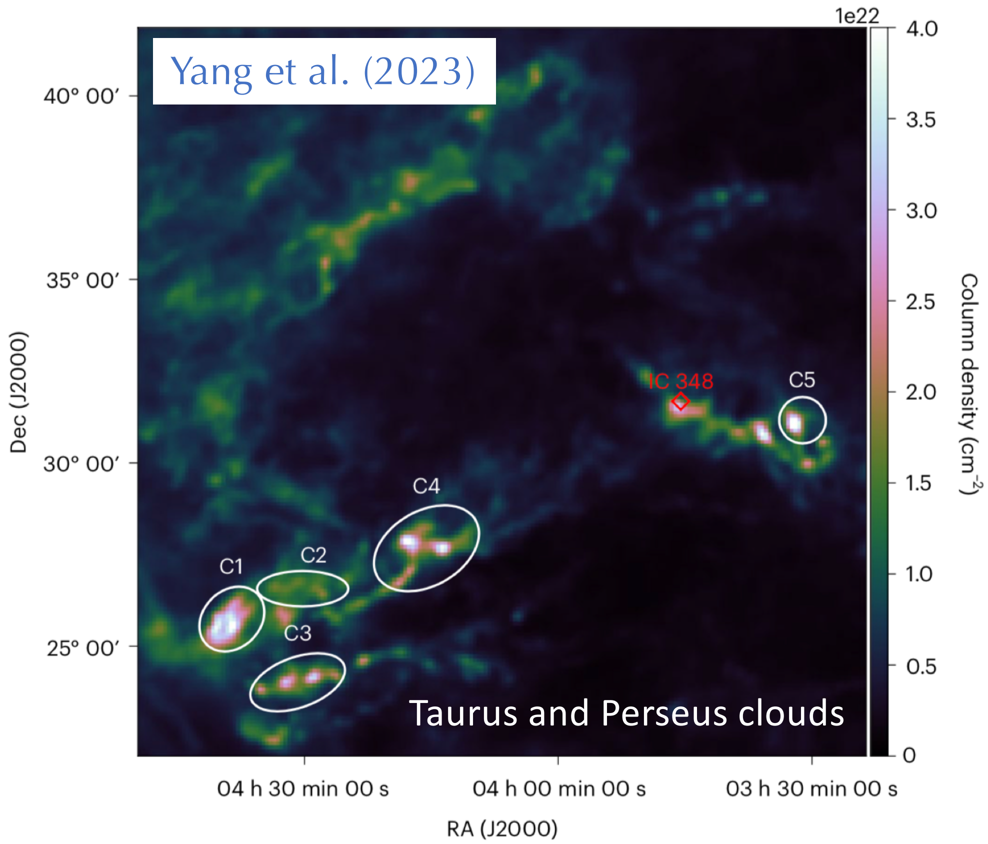

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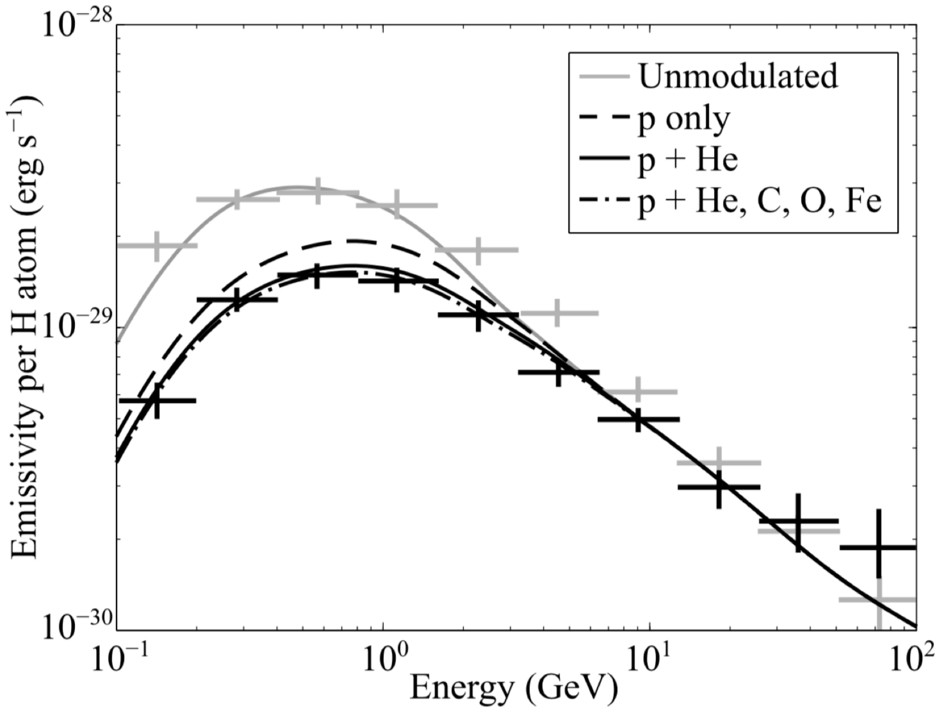
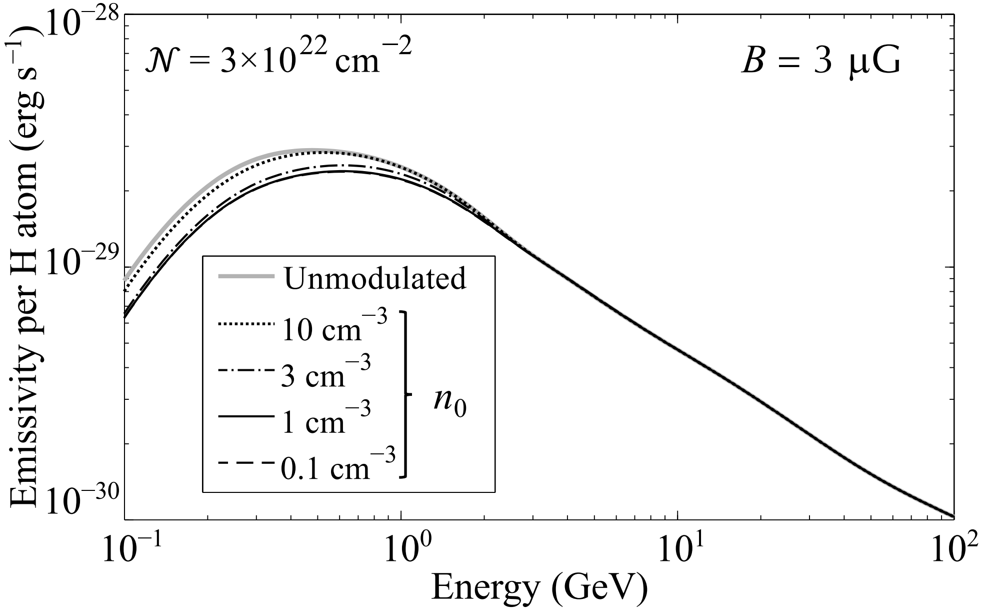


$\mathcal{N} = 6\times10^{22}$ cm^{-2}, $n_0 = 1$ cm^{-2}, $B = 3$ μG

Dependence on $\mathcal{N}$, n_0, and B



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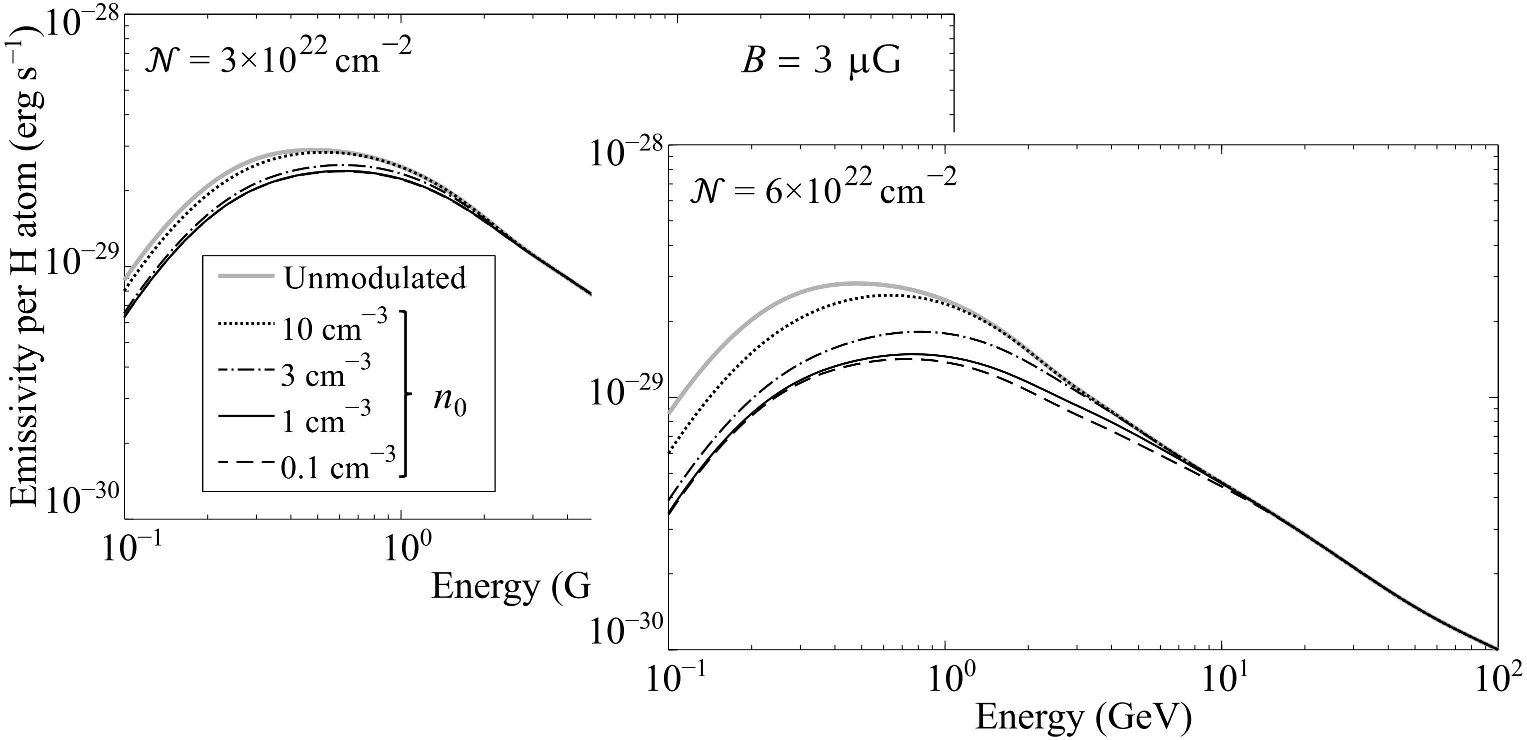

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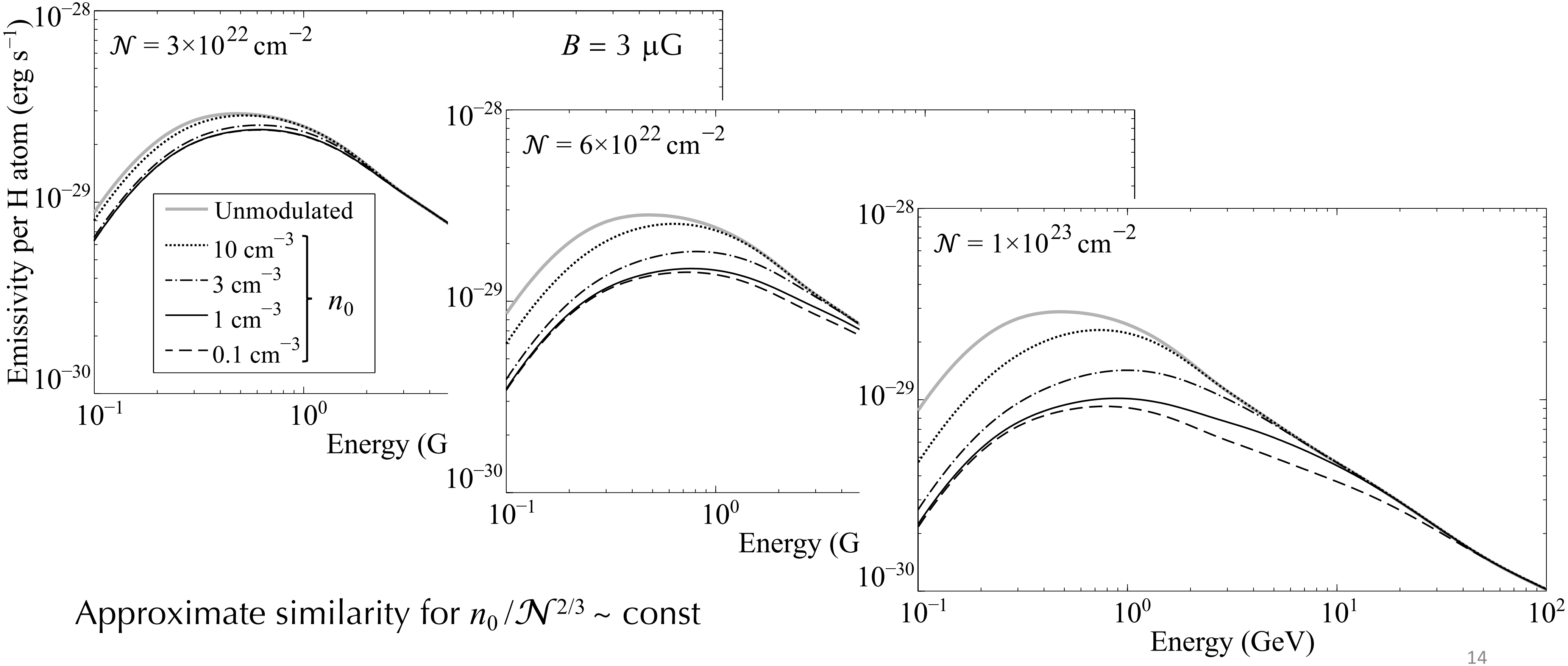

Approximate similarity for $n_0/\mathcal{N}^{2/3} \sim$ const

Conclusions

- Self-modulation of CRs penetrating dense molecular clouds has a universal analytical solution.
- A much stronger modulation effect than obtained earlier (Ivlev et al. 2018, Dogiel et al. 2018).
- Excellent agreement with recent gamma-ray observations of nearby GMCs (Yang et al. 2023) for a conservative set of the parameters.
- The theory can be extended to sub-relativistic CRs ⇒ impact on ζ_{H2} .