



MAX-PLANCK-GESELLSCHAFT



Self-modulation of relativistic cosmic rays penetrating dense molecular clouds

Alexei Ivlev

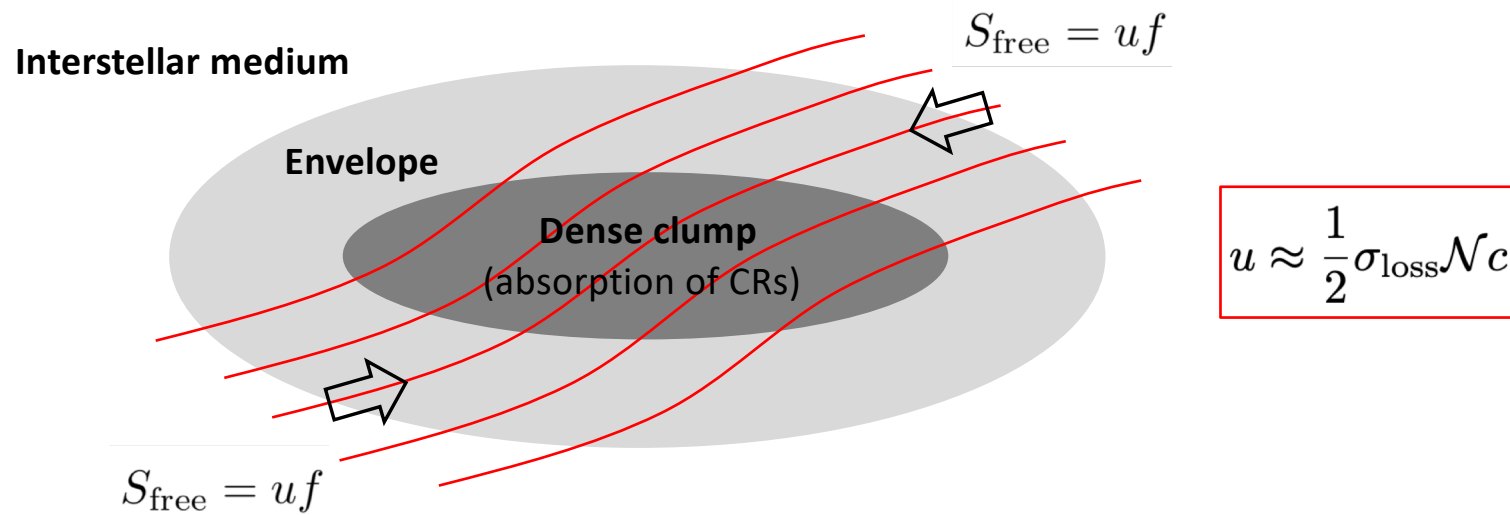
Max-Planck-Institut für extraterrestrische Physik, Garching, Germany

Dmitry Chernyshov, Alexander Kiselev

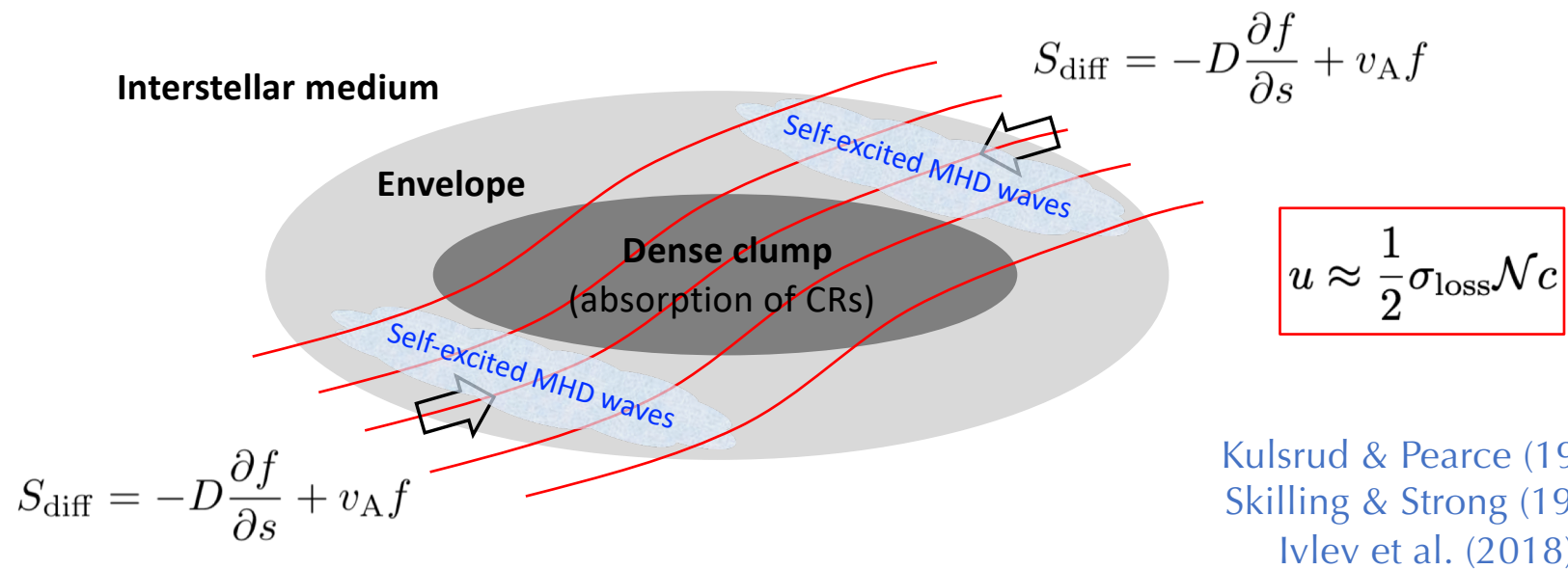
P. N. Lebedev Institute of Physics, Moscow, Russia

Chernyshov, Ivlev, & Kiselev (accepted to PRD)

Resonant streaming instability



Resonant streaming instability



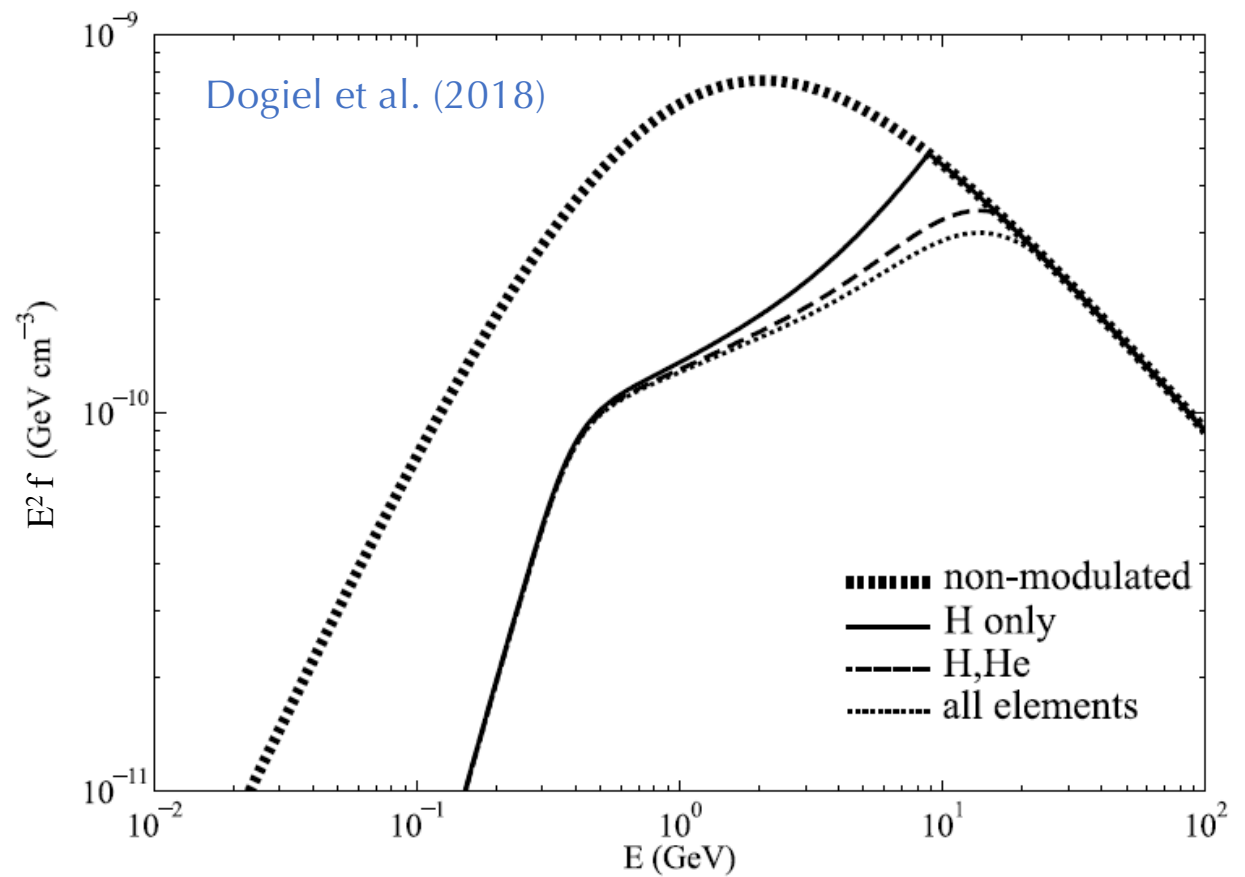
- Streaming CRs with $u > v_A$ resonantly excite MHD waves in the envelope, at $kr_g \sim 1$.
- The turbulence level is set by a balance of the wave excitation, $\gamma_{\text{CR}} \propto -D(\partial f / \partial z)$, and the ion-neutral damping, $\nu_{in} \propto n$.

Modulation of CR spectrum in the CMZ

$5 \times$ standard ISM spectrum

$$\mathcal{N} = 3 \times 10^{23} \text{ cm}^{-2}$$

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



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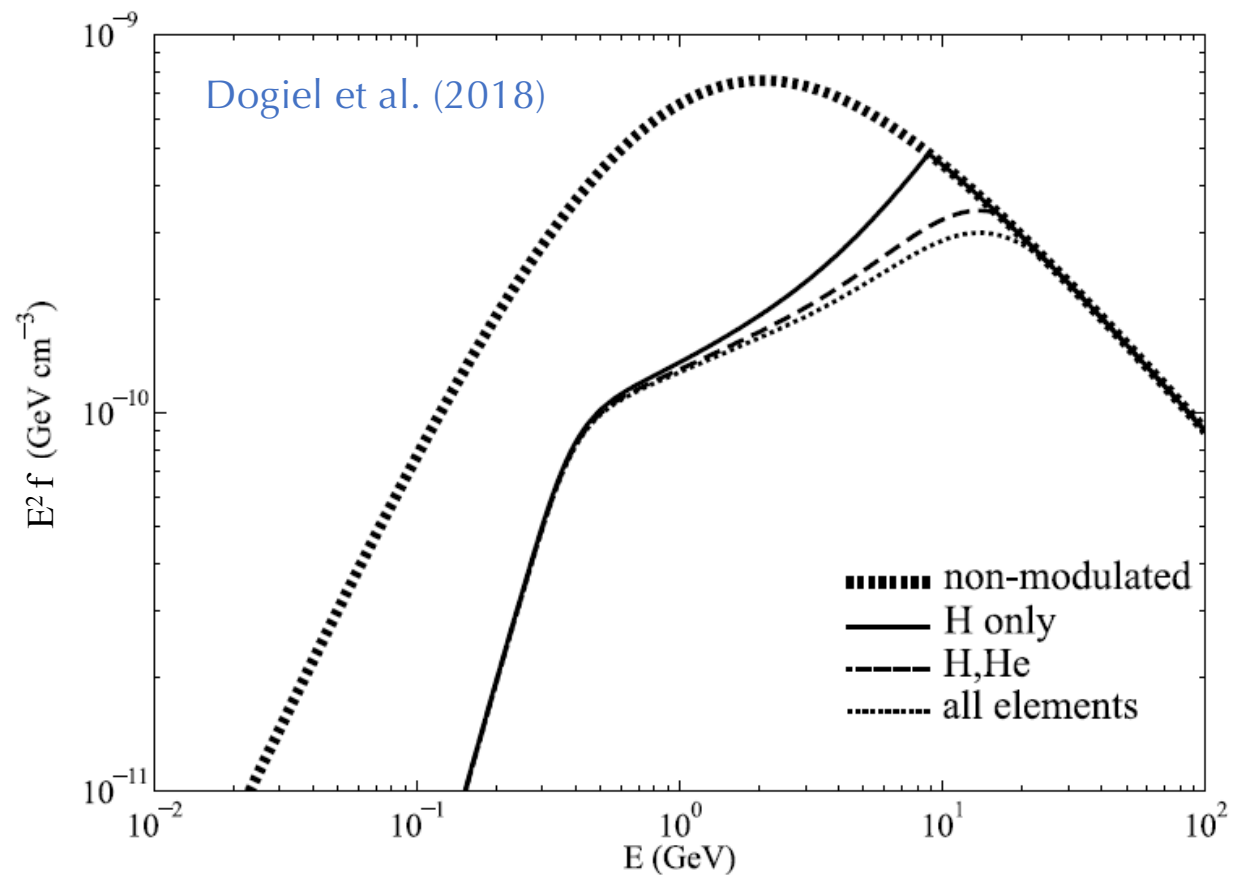
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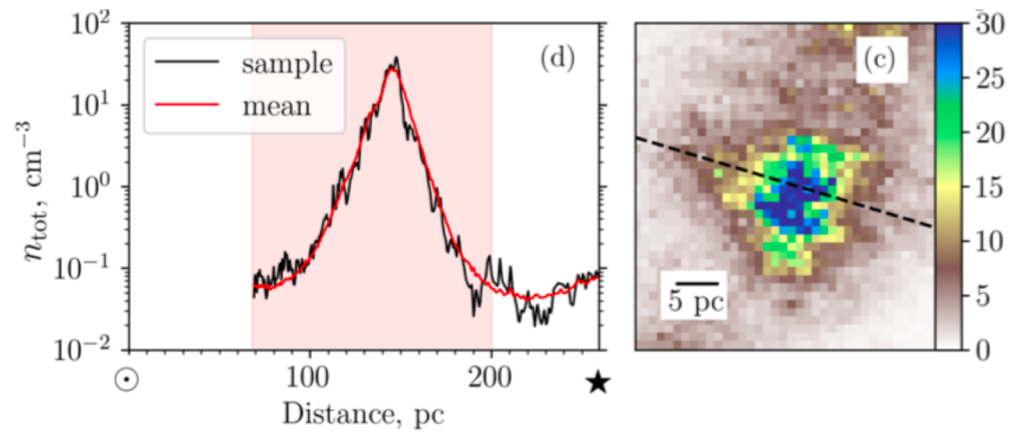
Model parameter
Assumed to be constant

Ivlev et al. (2018)

Dogiel et al. (2018)

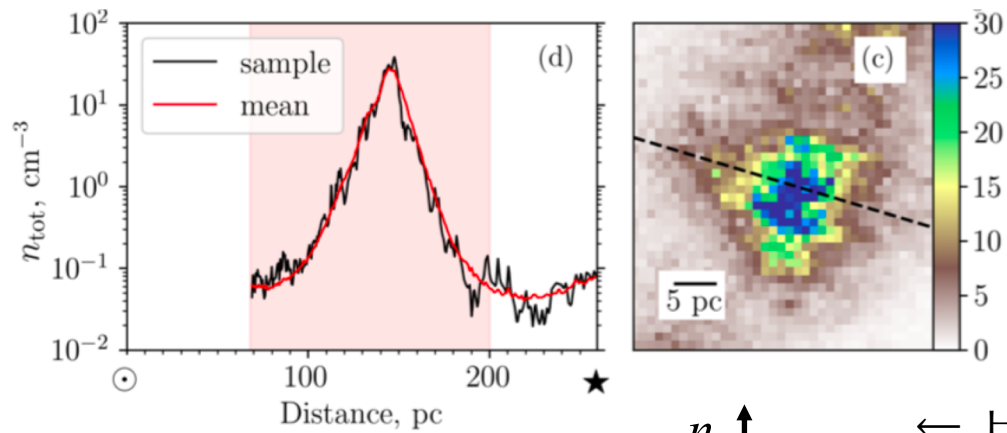


Gas distribution in envelopes



On average, gas density increases monotonically toward the dense clump.

Gas distribution in envelopes

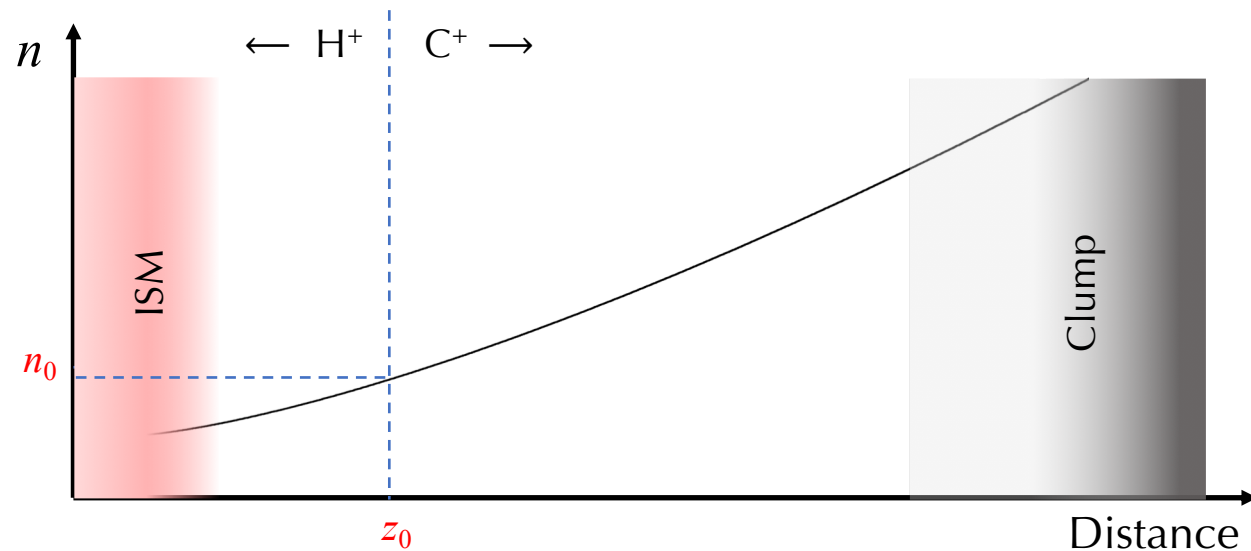


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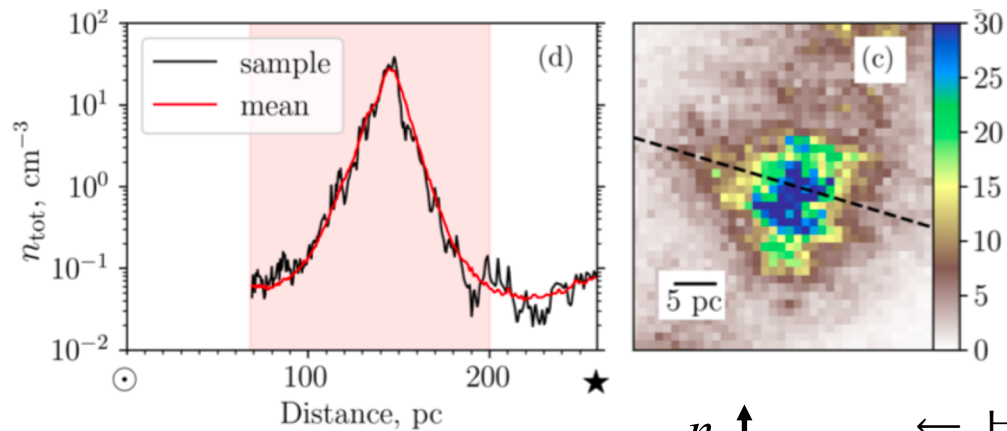
$$\nu_{in}(z) = \frac{1}{2} \frac{m_n n}{m_n + m_i} \langle \sigma_{in} v \rangle$$

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

$\Rightarrow$ no waves at $z < z_0$



Gas distribution in envelopes

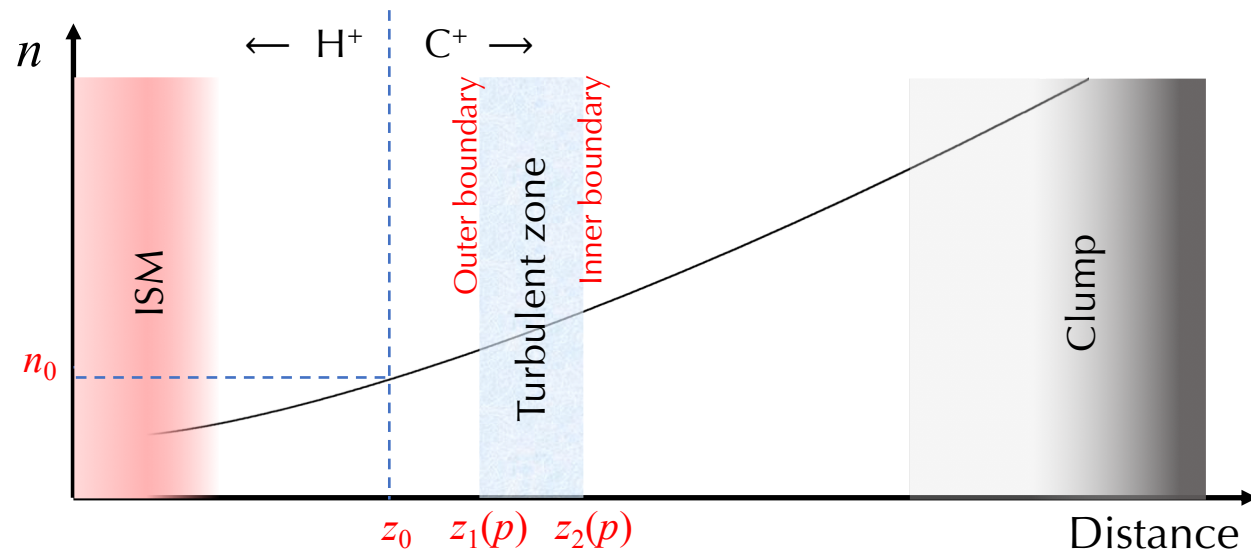


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Equations for the diffusion zone (CR protons)

Transport equation

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

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

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

Skilling (1975)
Skilling & Strong (1976)
Ivlev et al. (2018)

Excitation-damping balance

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

$$\gamma_{\text{CR}}(k, z) \simeq -\pi^2 \frac{e^2 v_A}{m_p c^2 \Omega_p} p \left(D \frac{\partial f}{\partial z} \right)$$

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$$S(p, z) = v_A f + S_D$$

total CR flux

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$$-D \frac{\partial f}{\partial z} = \frac{B c \nu_{in}}{\pi^2 e v_A p} \equiv S_D(p, z) \propto \frac{n^{3/2}}{p}$$

diffusion component of CR flux



Boundary conditions for relativistic protons

$$\frac{\partial}{\partial z} \left(v_A f - D \frac{\partial f}{\partial z} \right) + \frac{\partial}{\partial p} (\cancel{\dot{p}} f) = 0 \quad \Rightarrow \quad v_A f(p, z) + S_D = S_0(p)$$

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Outer boundary $z_1(p)$:

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

Inner boundary $z_2(p)$:

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

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$$\frac{df}{dz} = 0 \quad \Rightarrow \quad 3 S_D|_{z=z_{\text{cr}}} = v_A|_{z=z_{\text{cr}}} f_0$$

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

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

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Inner boundary $z_2(p)$:

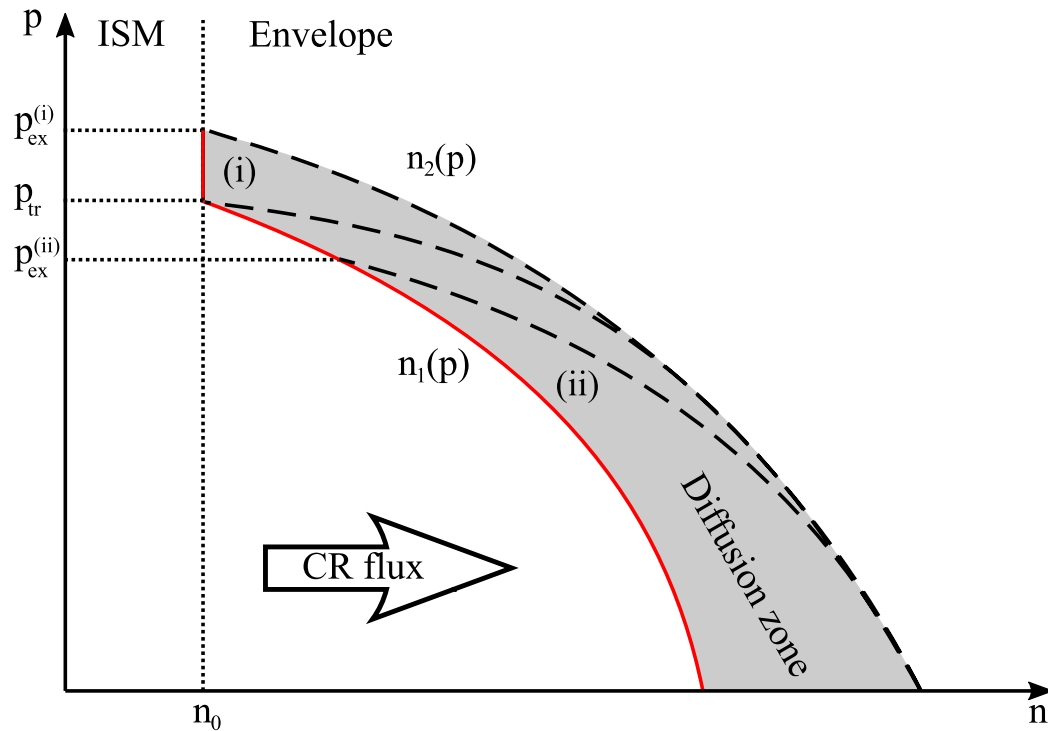
$$u f(p, z)|_{z=z_2} = S_0(p)$$



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

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

Diffusion zone



Excitation threshold p_{ex} :

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

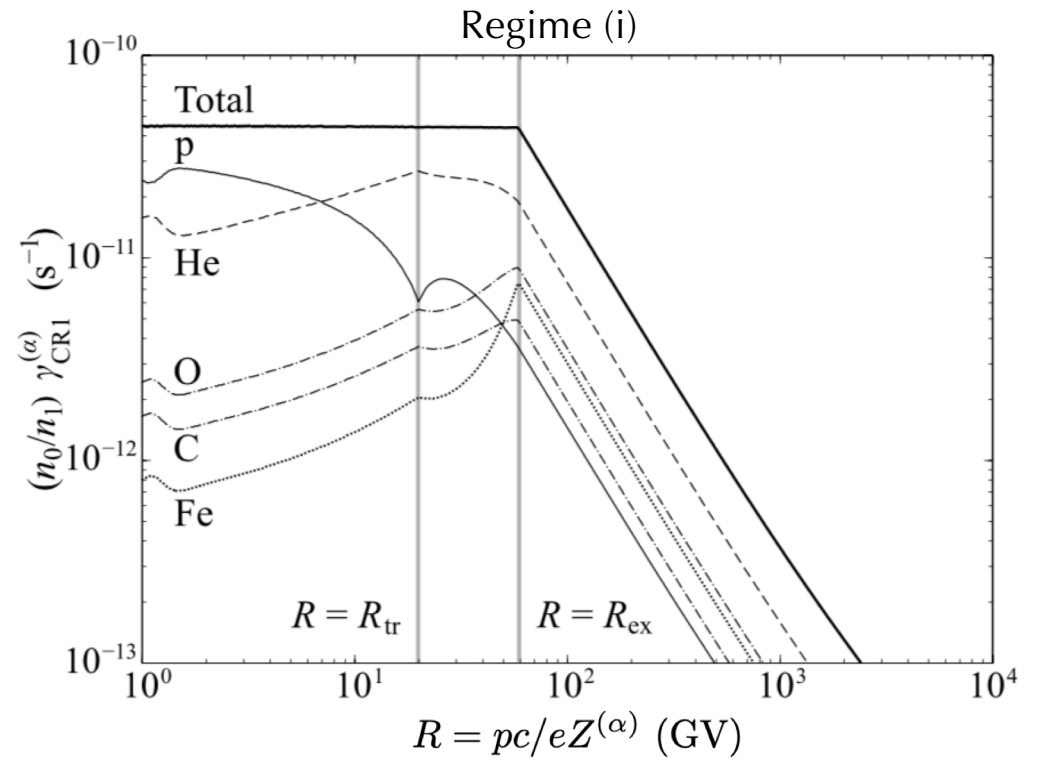
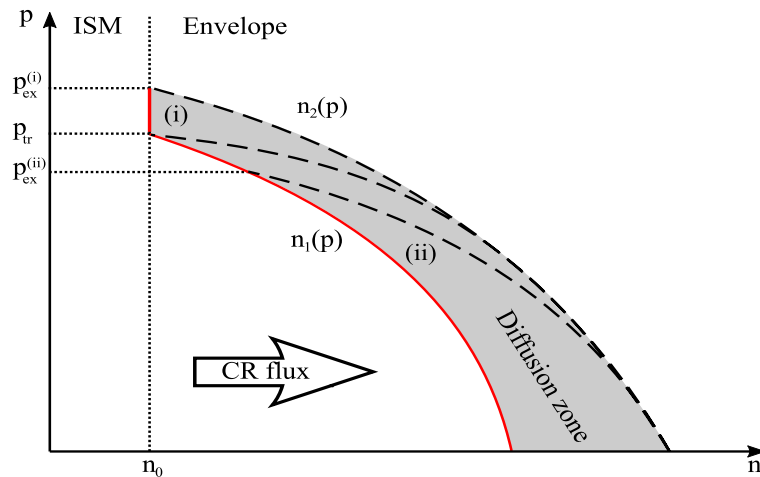
Regime (i): $v_{A0} < \frac{3}{4}u$

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

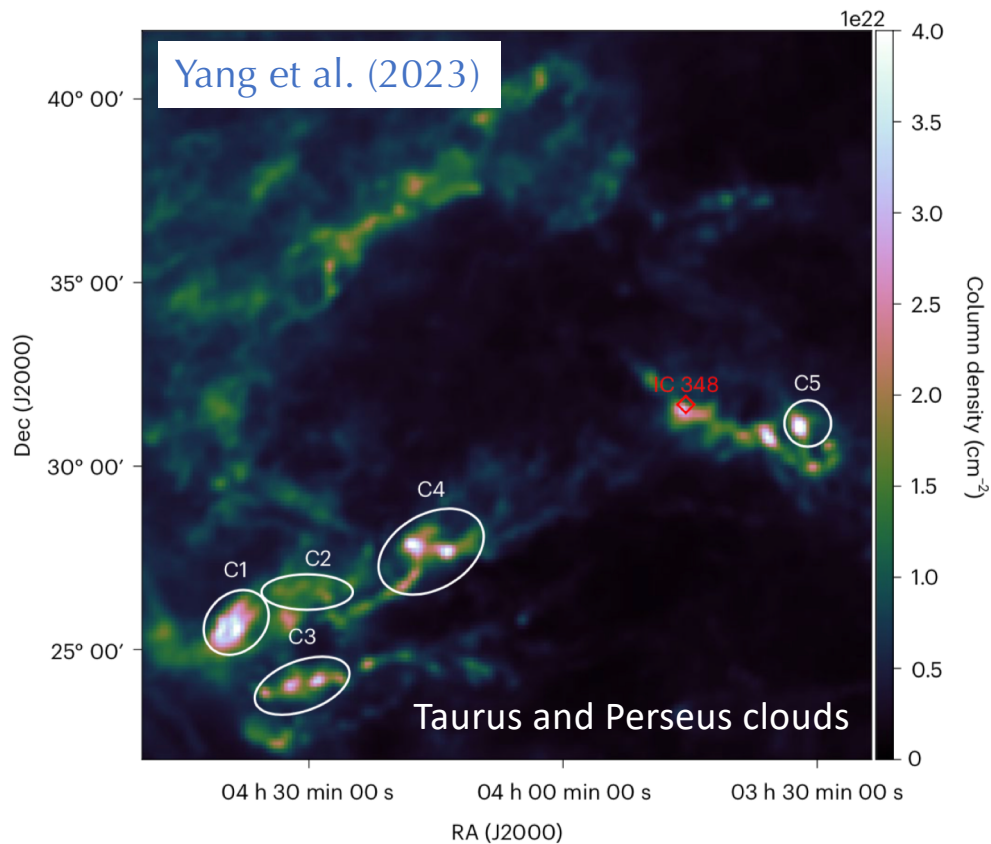
$$\frac{v_A}{D} = \frac{1}{2n} \left[4 - \mathcal{K} \left(\frac{n}{n_1} \right)^{-3/2} \right] \frac{dn}{dz}$$

Contribution of heavier CR nuclei

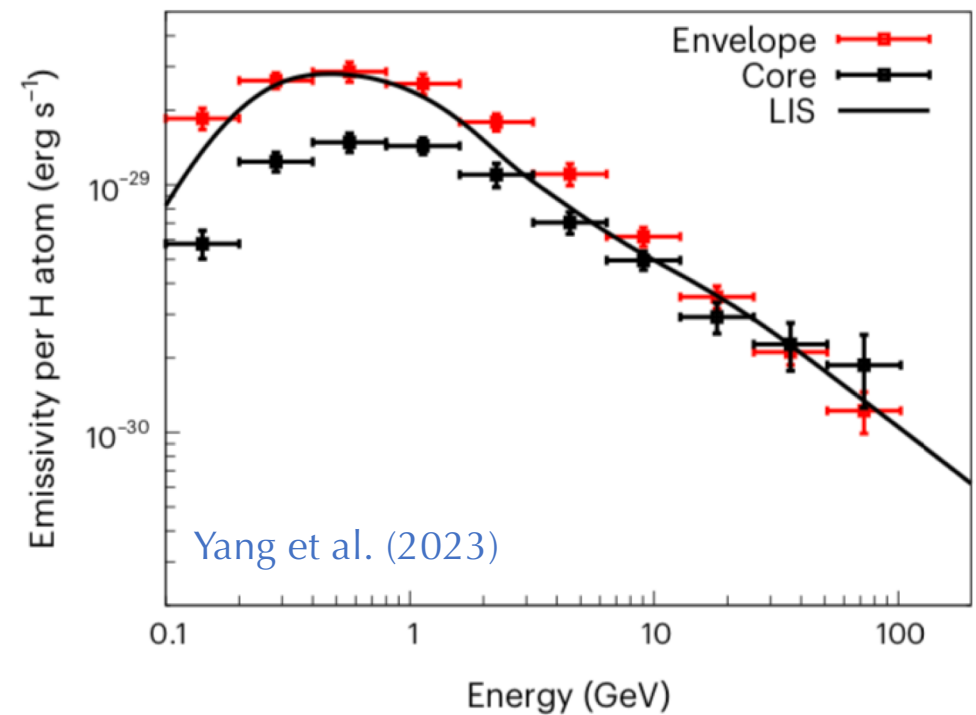
Wave excitation rate at the outer boundary $n_1(p)$



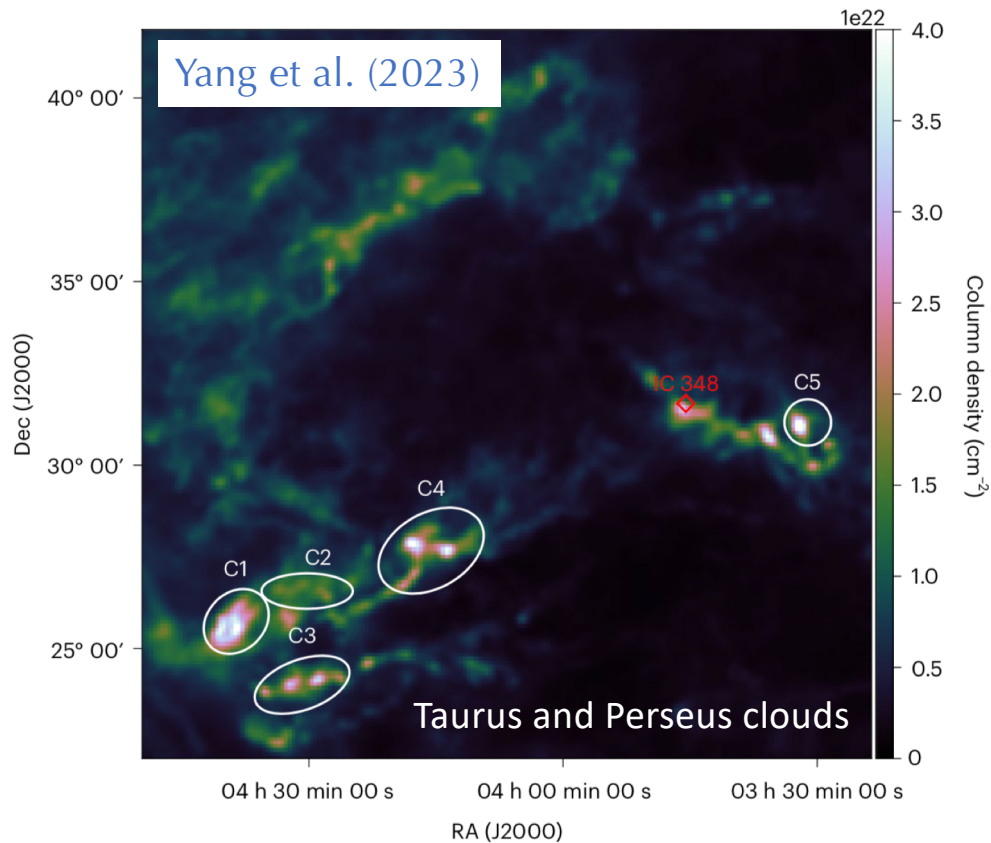
Gamma-ray emission from MCs



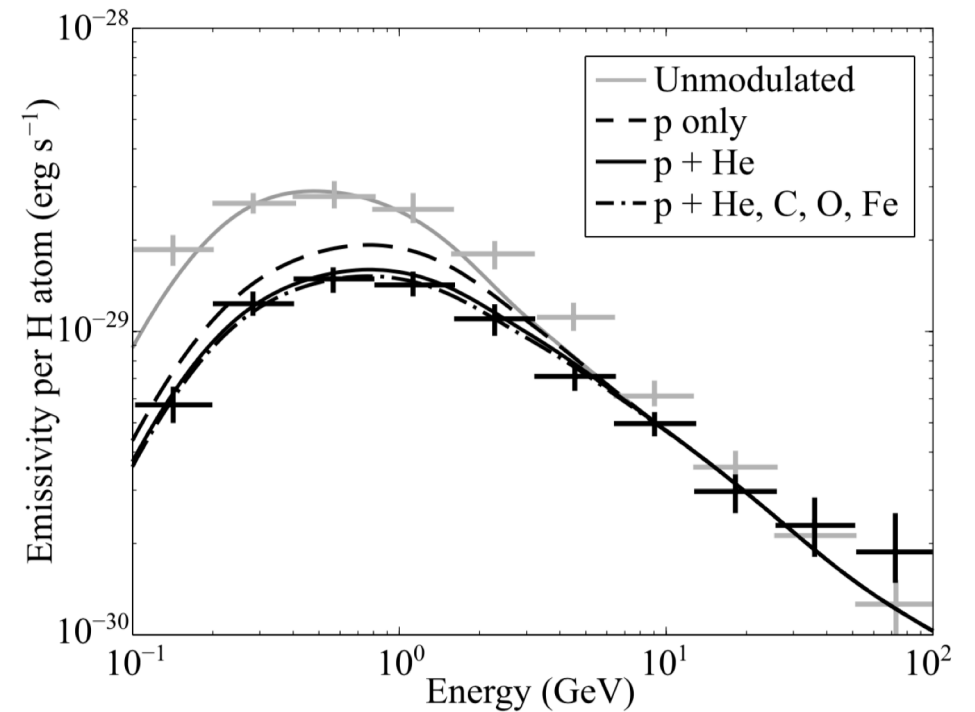
$\mathcal{N}$ varies between $\approx 5 \times 10^{22}$ and 10^{23} cm^{-2}



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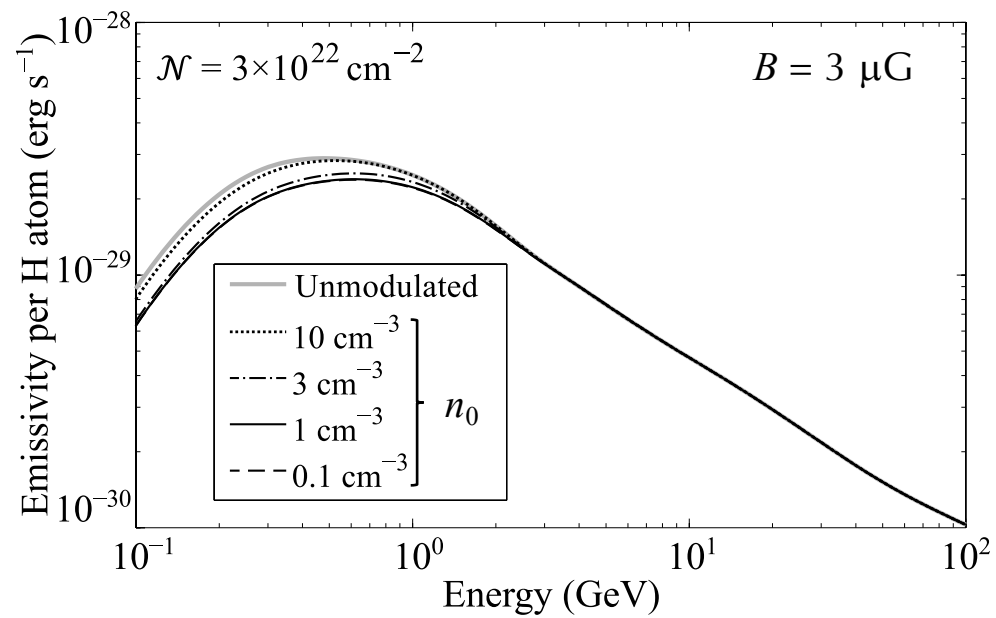


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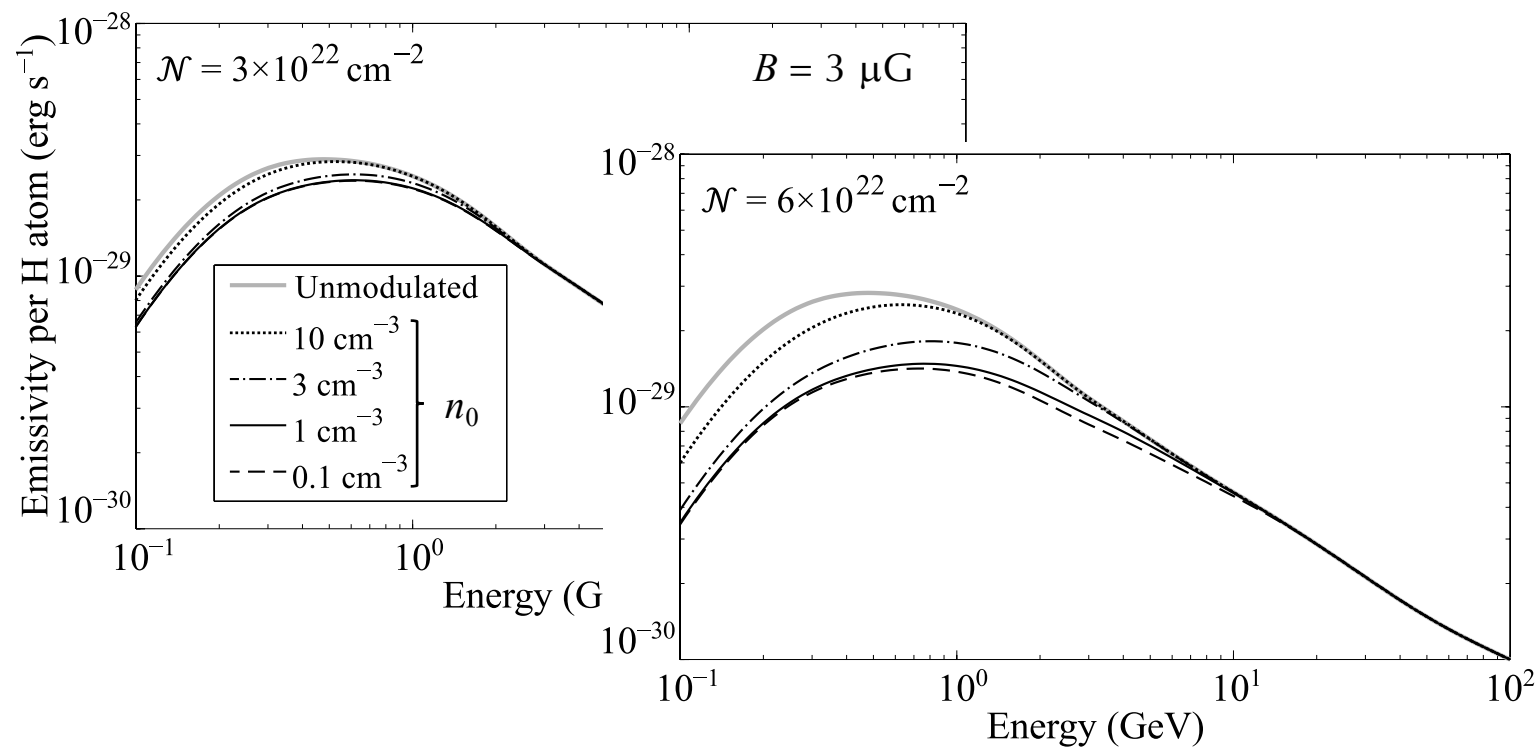


$$\mathcal{N} = 6 \times 10^{22} \text{ cm}^{-2}, n_0 = 1 \text{ cm}^{-3}, B = 3 \mu\text{G}$$

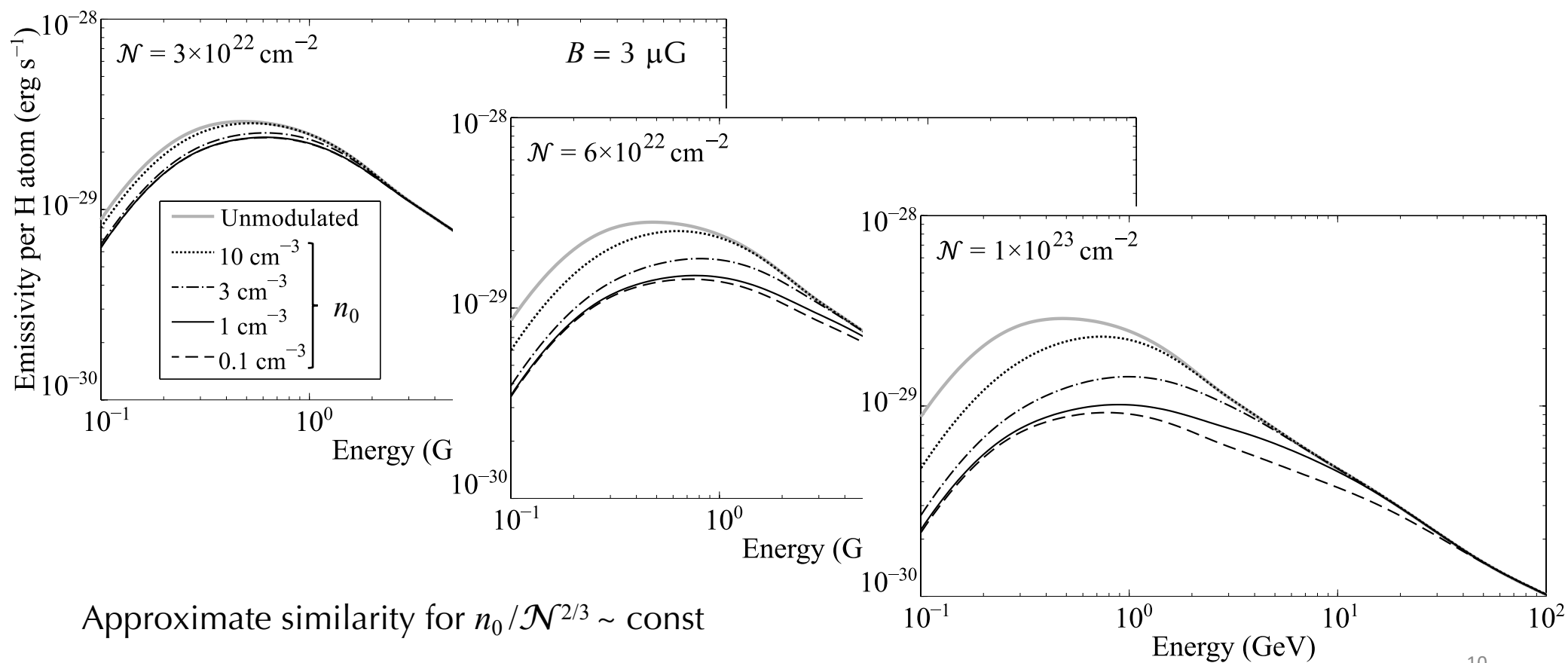
Dependence on $\mathcal{N}$, n_0 , and B



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Conclusions

- Gas density is the generalized coordinate $\Rightarrow$ **universal** analytical solution.
- Self-consistent boundary densities $n_1(p)$ and $n_2(p)$ are much **smaller** than the value assumed before $\Rightarrow$ a much **stronger** CR modulation.
- Solution depends only on $\mathcal{N}$, n_0 , and B (for a given ISM spectrum).
- **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** $\Rightarrow$ impact on ζ_{H_2} .