MAX-PLANCK-GESELLSCHAFT

Penetration of cosmic rays into dense molecular clouds

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Star-forming regions

Eagle Nebula

Image credit: NASA

Processes driven by *low-energy* CRs in clouds and disks

- **Ionization in UV- and X-ray-shielded regions:**

  coupling of gas to magnetic field

  ⇒ magnetic braking, onset of rotational instabilities, …

  gas heating

  ⇒ cloud dynamics, chemistry, …

  desorption of ice

  ⇒ gas density, abundances of complex molecules, …

  dust charging

  ⇒ dust coagulation, chemical processes on grains, …

- **Formation of polyatomic molecules:**

  $p_{CR} + H_2 \rightarrow H_2^+$ ⇒ $H_2^+ + H_2 \rightarrow H_3^+$ ⇒

  $H_3^+ + [O, CO, N] \rightarrow [OH^+, HCO^+, N_2H^+]$ ⇒ …

- …

Transport of CRs in clouds

CR protons up to $\sim 10^{15}$ eV are well magnetized at the scale of a problem, so their propagation is along the local magnetic field (coordinate s).

The CR distribution function $f(E,\, s,\, \mu)$ is governed by the transport equation:

$$\frac{\partial S}{\partial s} + \frac{\partial}{\partial E}\left(\dot{E} f\right) + \nu_{\mathrm{cat}} f = 0$$

Weak scattering: $S \approx \mu v f$ (e.g., Coulomb collisions)

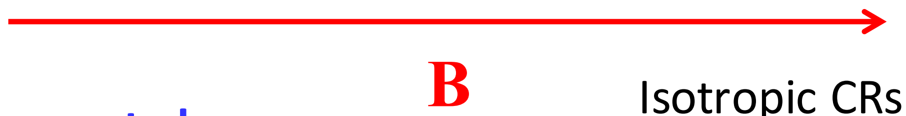
Strong scattering: $S \approx -D \dfrac{\partial f}{\partial s} + u f$ (e.g., MHD turbulence)

The solution critically depends on the scattering regime

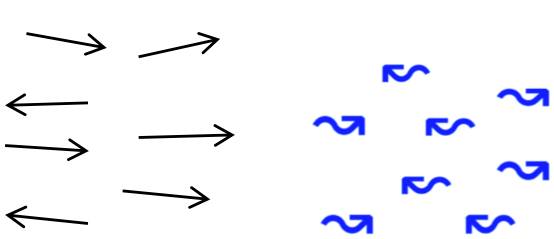
(*Silsbee & Ivlev 2019*)

Streaming instability

(Kulsrud & Pearce 1969; Skilling & Strong 1976)

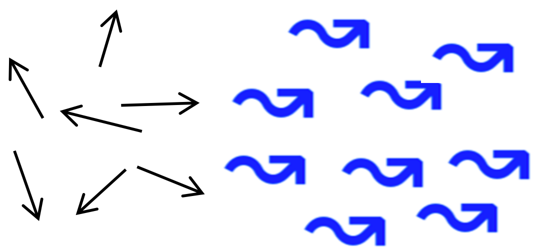


CR stream enters **quiescent plasma**



$$S_{\rm free} = uf$$

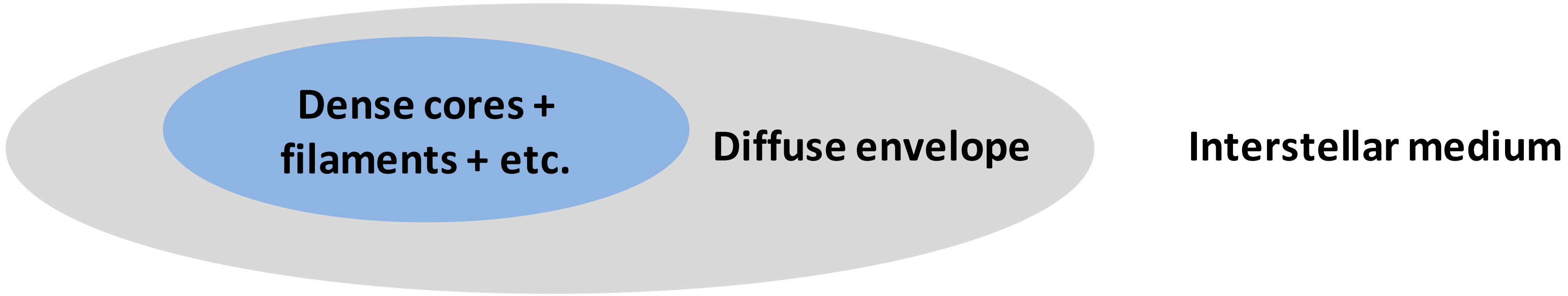
Isotropic CRs *diffuse* and *drift* with the **excited MHD waves**



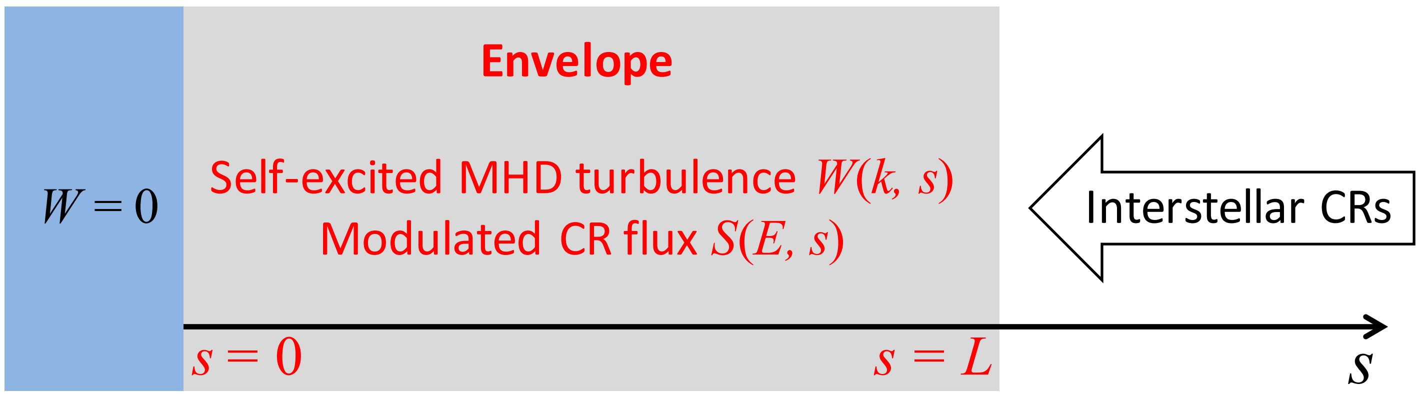
$$S_{\rm diff} = -D\frac{\partial f}{\partial s} + v_{\rm A} f$$

- Streaming CRs resonantly excite MHD waves (when $u >> v_{\rm A}$).
- The wave excitation rate $\gamma_{\rm CR} \propto pv(S - v_{\rm A} f)$.

Model setup: geometry



- We identify 3 characteristic regions, and focus on processes in the diffuse envelope.
- Absorption of CRs in the core generates their inward flux.



Universal flux of self-modulated CRs

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

- The excitation rate of MHD waves is $\gamma_{\rm CR} \propto pv(S - v_{\rm A} f)$.
- In a free streaming, assume $S(E) \sim j_{\rm IS}(E) = vf_{\rm IS}$. Then the balance of excitation and damping yields the threshold energy $E_{\rm ex}$:

$$pv\, j_{\rm IS}\big|_{E_{\rm ex}} = const$$

below which the turbulence is excited.

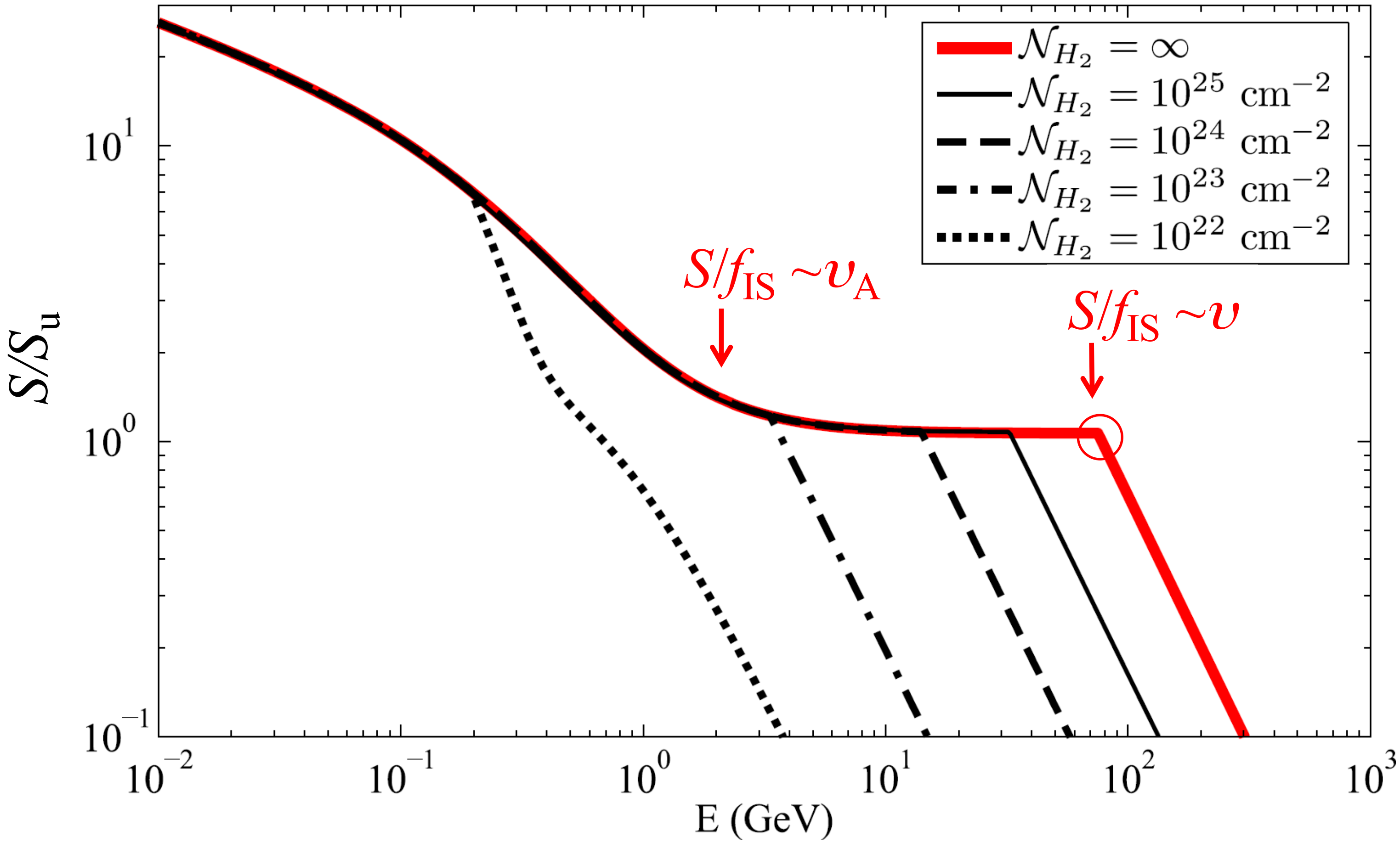
- For $E < E_{\rm ex}$, we obtain a universal flux:

$$\boxed{S(E) \approx const/(pv) \equiv S_{\rm u}(E)}$$

which does not depend on $f_{\rm IS}$ as long as $S/f_{\rm IS} >> v_{\rm A}$.

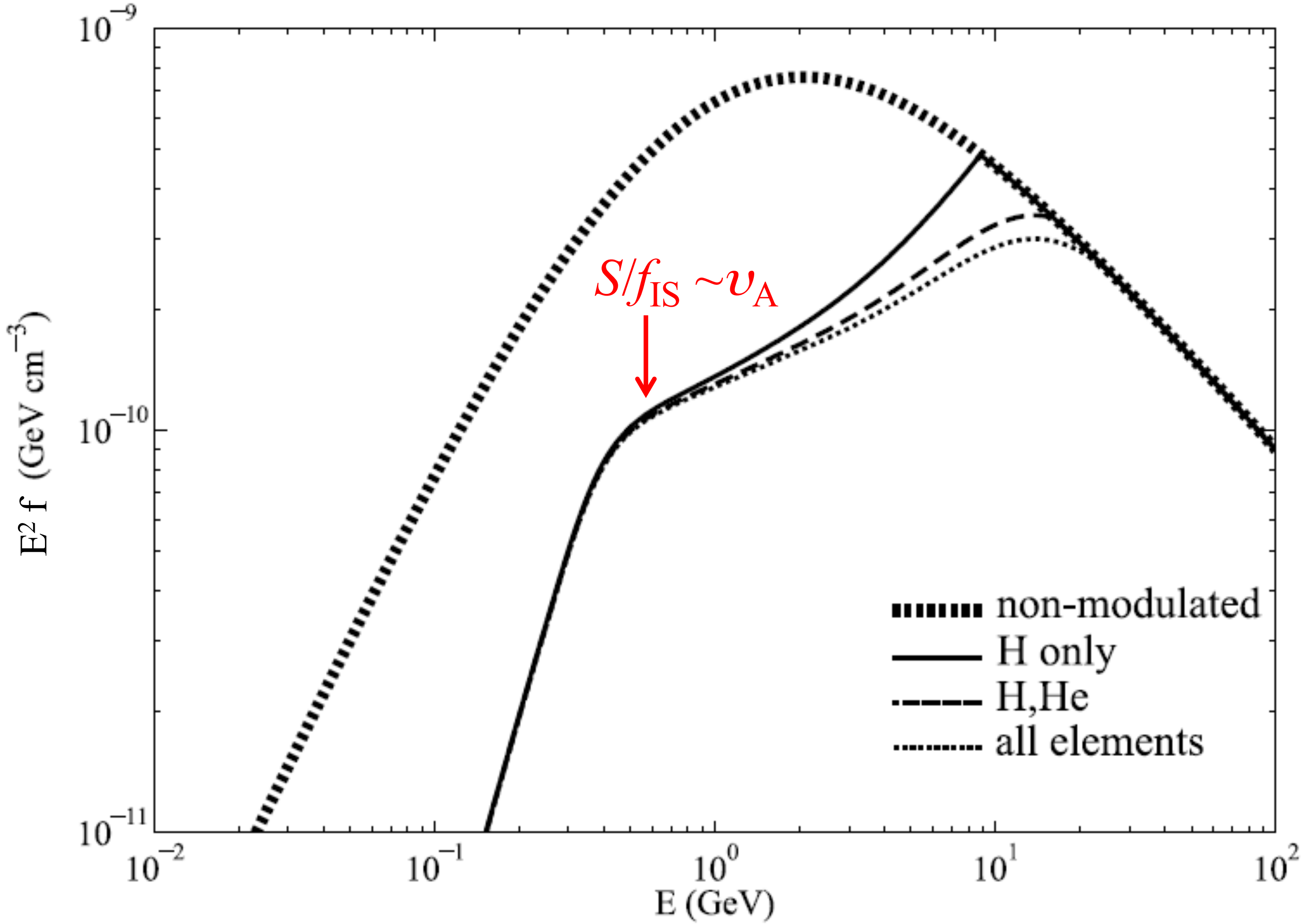
$S(E)$ curve for different $\mathcal{N}_{\mathrm{H2}}$

$S_u = const/(p\upsilon)$



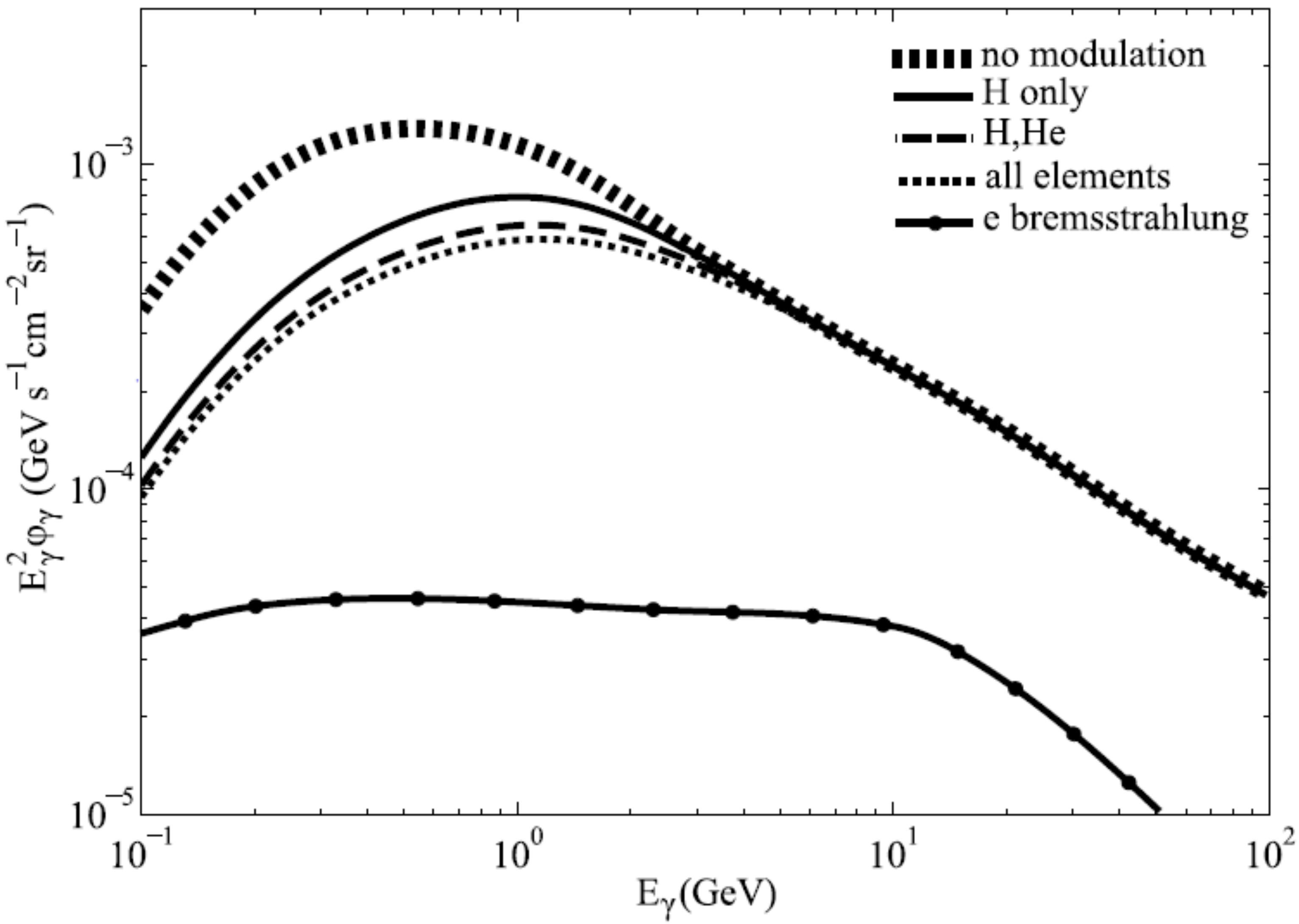
Decreasing $\mathcal{N}_{\mathrm{H2}}$ leads to lower E_{ex},
but the modulated flux at $E < E_{ex}$ remains unchanged.

Modulation of CR protons in CMZ

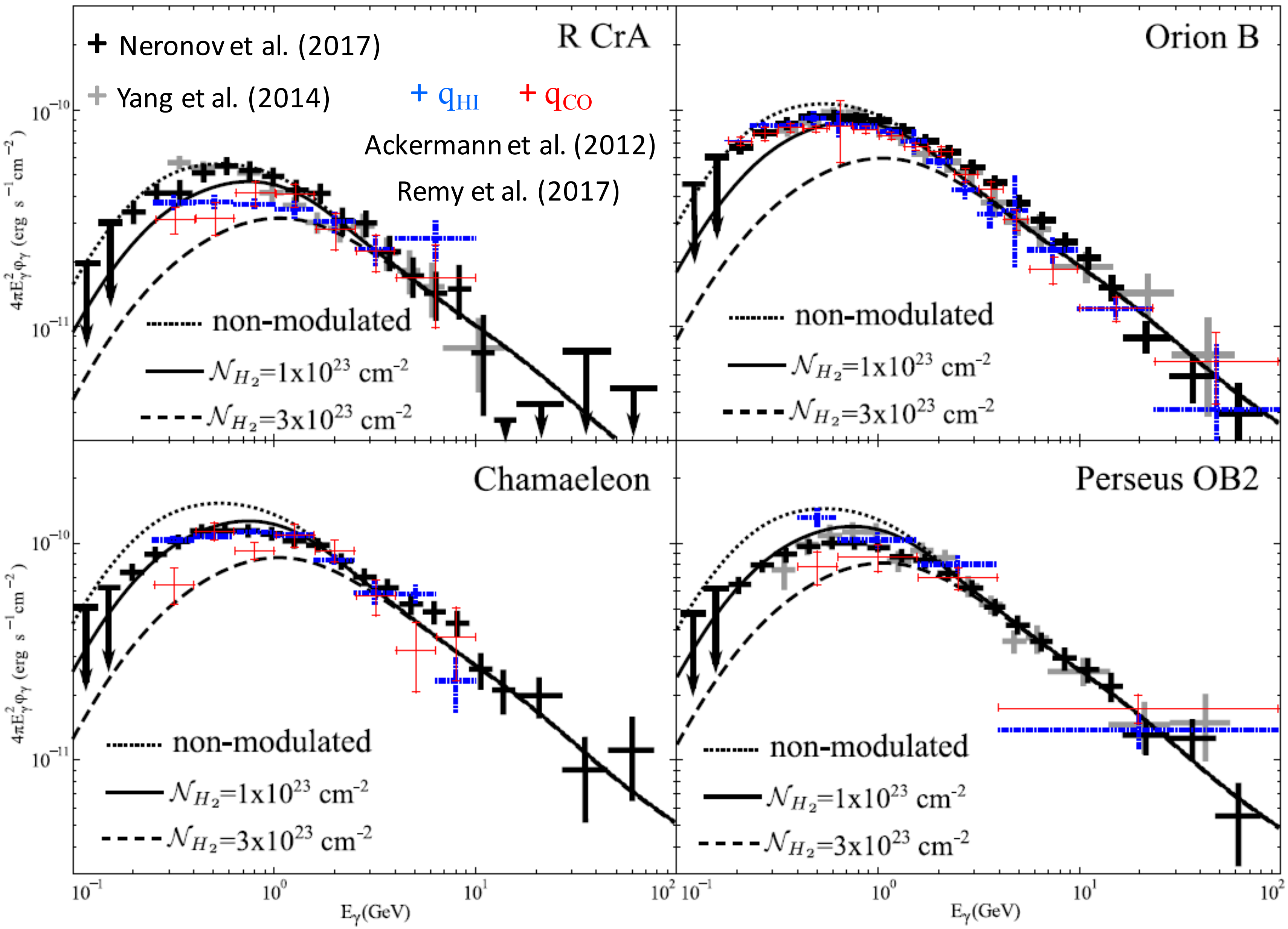


5 × standard IS spectrum; $\mathcal{N}_{H2} = 10^{23}$ cm^{-2}; n_{H2} (envelope) = 10 cm^{-3}

Gamma-ray flux from CMZ



Gamma-ray flux from local clouds



Conclusions

- Self-excited turbulence is crucial for penetration of (sub)GeV CRs into dense molecular clouds, leading to a strong flux modulation.
- The modulation occurs below the threshold energy $E_{\rm ex}$, which increases with $\mathcal{N}_{\rm H2}$.
- For CMZ parameters we get $E_{\rm ex} \sim 10$ GeV. This should lead to a depletion of gamma-ray emission (below $E_\gamma \sim 2$ GeV), a drastic reduction of ionization (by up to a factor of ~ 10), etc.
- The effect of CR self-modulation is missing in the standard models of CR propagation in the Galaxy (GALPROP, DRAGON, …).