Interaction of cosmic rays with molecular clouds

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Why molecular clouds?

- They are dense (x1000 ISM)
  - All processes proportinal to density are increased!
- They are cold (10 – 100 K)
  - All thermal processes are low-energetic
  - All high-energy processes are due to external sources
- Space calorimeters

Molecular clouds as tracers of CRp

- $L_\gamma = n_{gas} N_{CR}(14E_\gamma)\sigma_{pp} c V_{cl} \propto M_{cl} N_{CR}(14E_\gamma)$

If we assume $N_{CR} = N_0 E^{-\delta}$

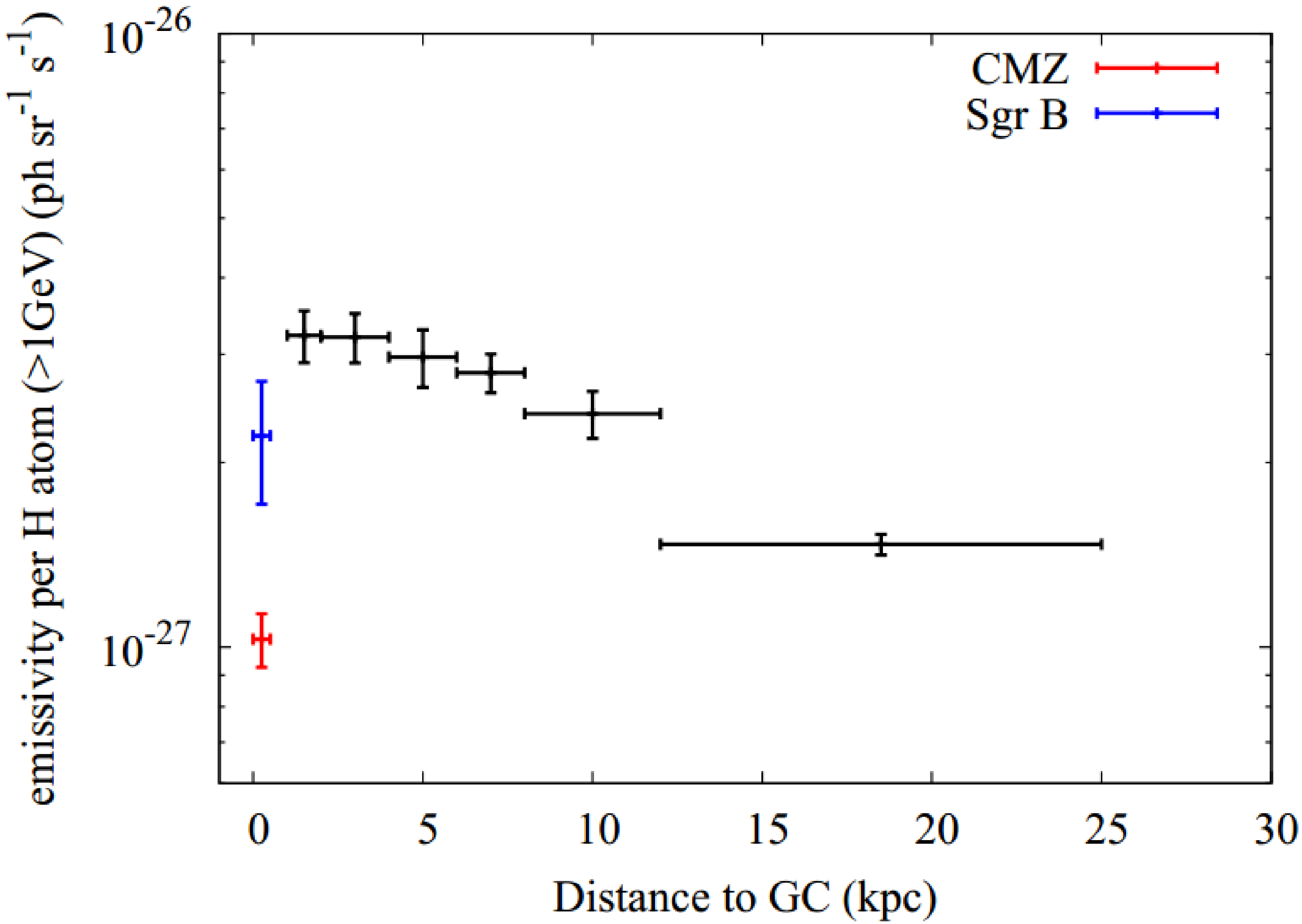
$$F_\gamma = f(\delta) N_0 E_\gamma^{-\delta} \left(\frac{M_{\text{cloud}}}{d^2}\right)$$

Gamma-rays

Radio, IR

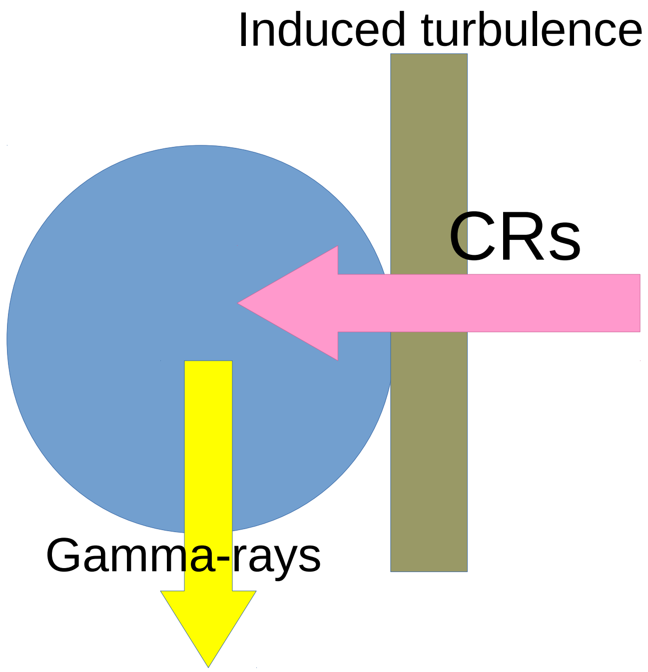
Black & Fazio 1973, Issa & Wolfendale 1981, Aharonian 1991, Casanova et al. 2010

CRs from diffuse molecular gas



Yang+ (2015)

Molecular clouds as CR "sinks"



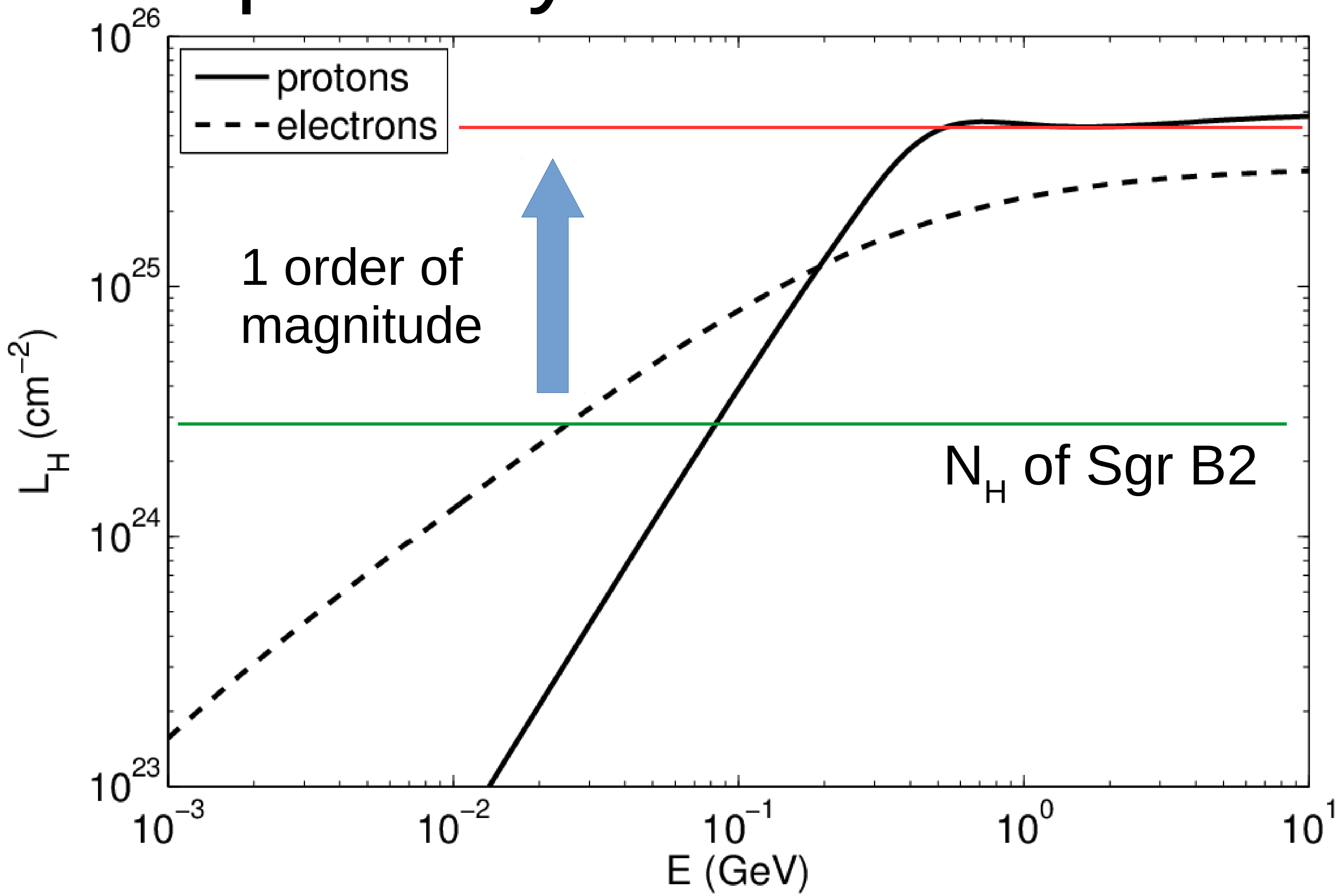
For Sgr B2 we know:

- Luminosity is 7×10^{35} erg/s
- Size is 12 pc
- CR density is 1 eV/cm^3
- Ionization rate 10^{-15} s^{-1}
- Ambient density is 100 cm^{-3}
- B = 10 uG
- $V_A = 10^8$ cm/s

For gamma-rays $v_s = \frac{L}{\epsilon S} = 2.8 \times 10^7 \, cm/s$

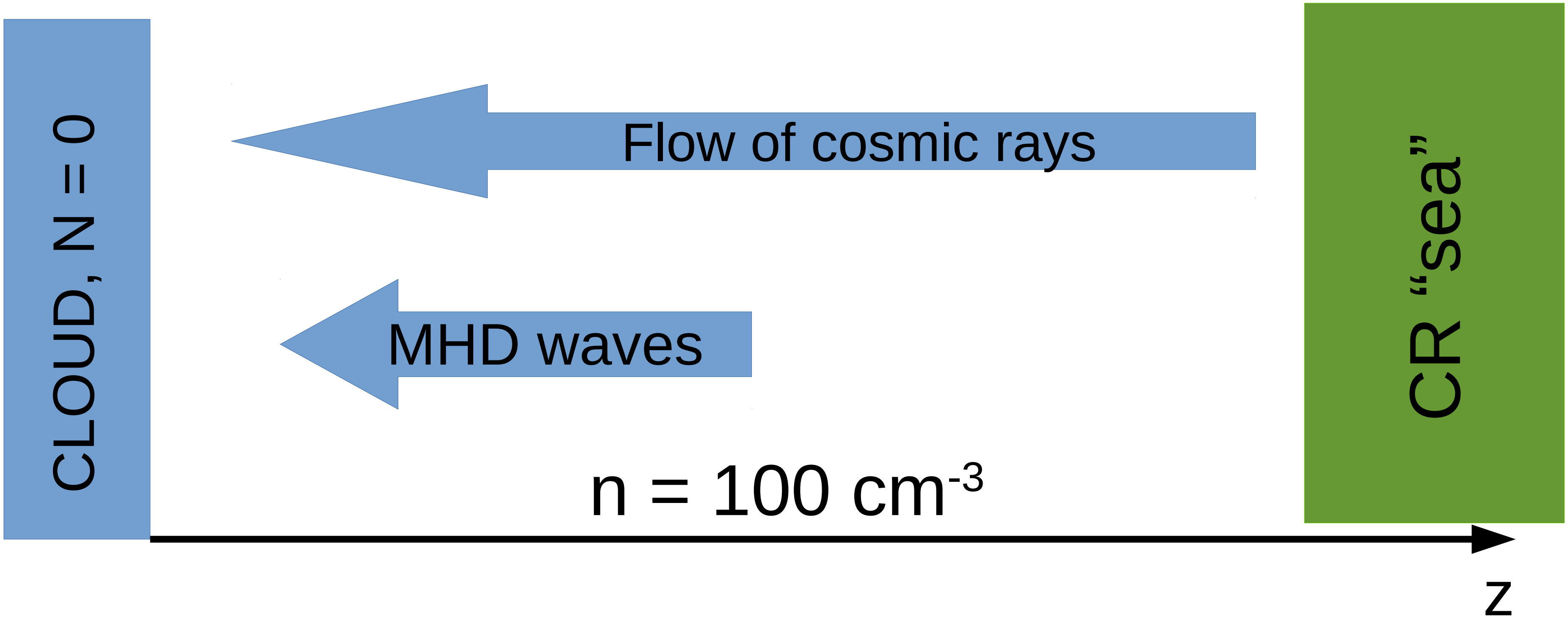
Given 30% initial proton energy goes into gamma-rays streaming velocity of protons is close to v_a (c.f. Morlino&Gabici 2015)

Transparency of molecular clouds



- For λ = 1 pc D = 10^{28} cm^2/s. Not that small !

Structure



- For simplicity assume that only self-generated turbulence exists
- Let's assume thick-target model i.e. N(0) = 0
- It should be correct if cloud is dense and $D_{cloud} >> D_{inter}$

Equations for wave+particles

$$\frac{\partial N}{dt} - \frac{\partial}{\partial z}\left(D(z,E)\frac{\partial N}{\partial z} - v_A N\right) + \left[\frac{\partial}{dE}\left(\frac{dE}{dt}N\right)\right] = 0$$

$$\frac{\partial W}{\partial t} + v_A \frac{\partial W}{\partial z} + \frac{\partial}{\partial k}\left(\frac{k\ W(k)}{T_{nl}}\right) = 2(\Gamma_{CR} - \nu_{in})W\ ,$$

$$\Gamma_{cr} \simeq \frac{\gamma - 1}{\gamma}\frac{\pi}{4}\Omega_{Hi}\frac{N(>p_{res})}{n_i}\left(\frac{u_0}{v_A} - 1\right)$$

- Important value – advection vs diffusion regime

$$\zeta = \int_0^z \frac{v_A dx}{D(x)}$$

Analytic approximation

No losses or damping. Non-relativistic regime

$$\frac{\partial}{\partial z}\left(\frac{\partial \zeta}{\partial \bar{\bar{k}}} - \frac{3}{2}\frac{\zeta}{\bar{\bar{k}}}\right) = B\left(\frac{\exp(-\zeta)}{1-\exp(-\zeta)}\right)\int\limits_{k_{min}}^{k} y^{-0.4}\left[1-\exp(-\zeta(y))\right]dy$$

In the "convection" region $\zeta > 1$ that gives $\frac{\zeta}{\bar{\bar{k}}^{3/2}} = const$

Fully-trapped particles (c.f. Morlino&Gabici 2015)

Should exist far away from boundaries i.e.

$$\zeta = \int\limits_0^z \frac{v_A dx}{D(x)} = \int\limits_0^{z_0} \frac{v_A dx}{D(x)} + \int\limits_{z_0}^{z} \frac{v_A dx}{D(x)} = const$$

Analytic approximation

In the diffusion regime where ζ << 1 variables can be split and ζ(k,z) = ζ(k)z

It causes D(k,z) = D(k) and N(p,z) = N(p)z

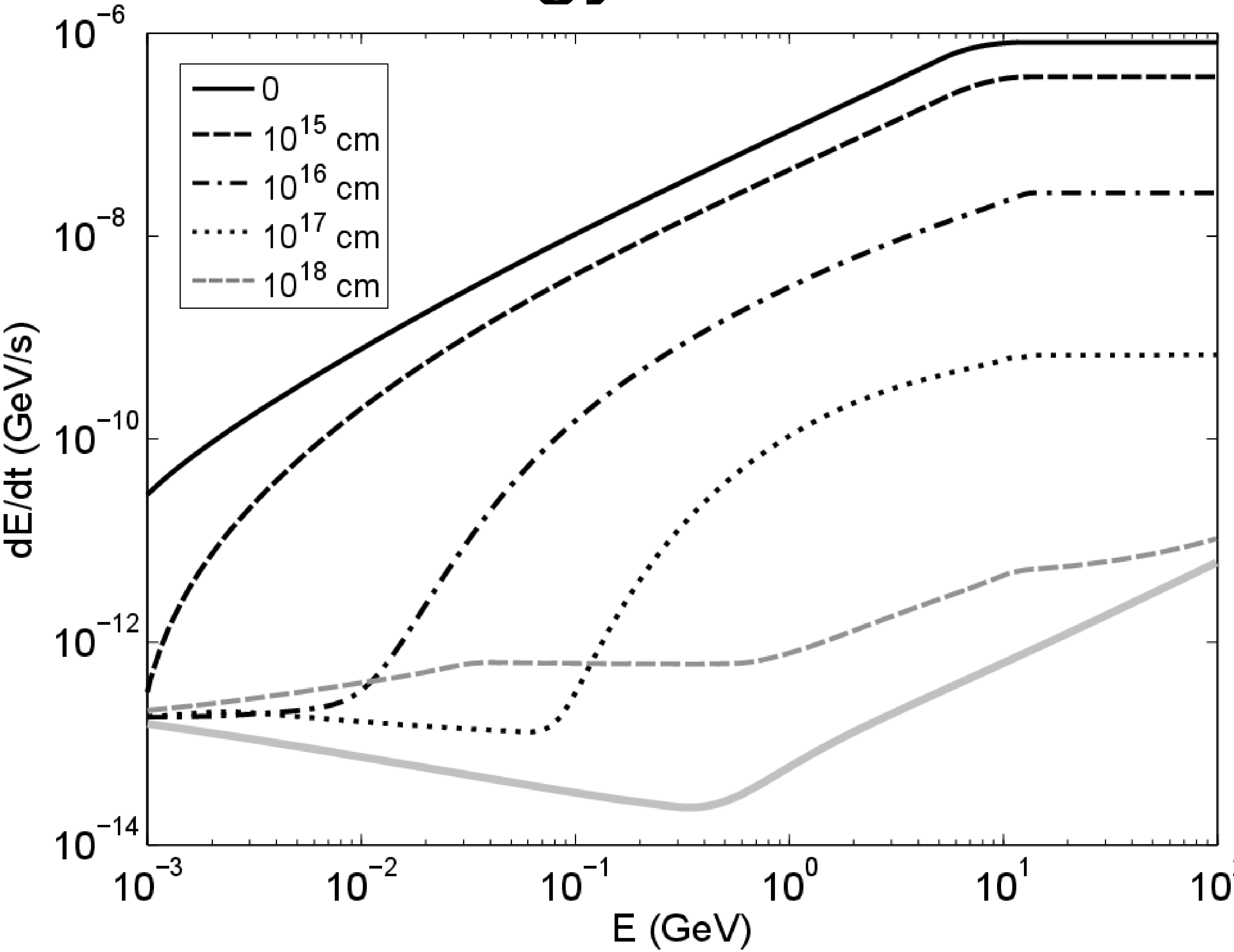
However in this case average streaming velocity is

$$v_s = \frac{S}{N} \propto z^{-1}$$

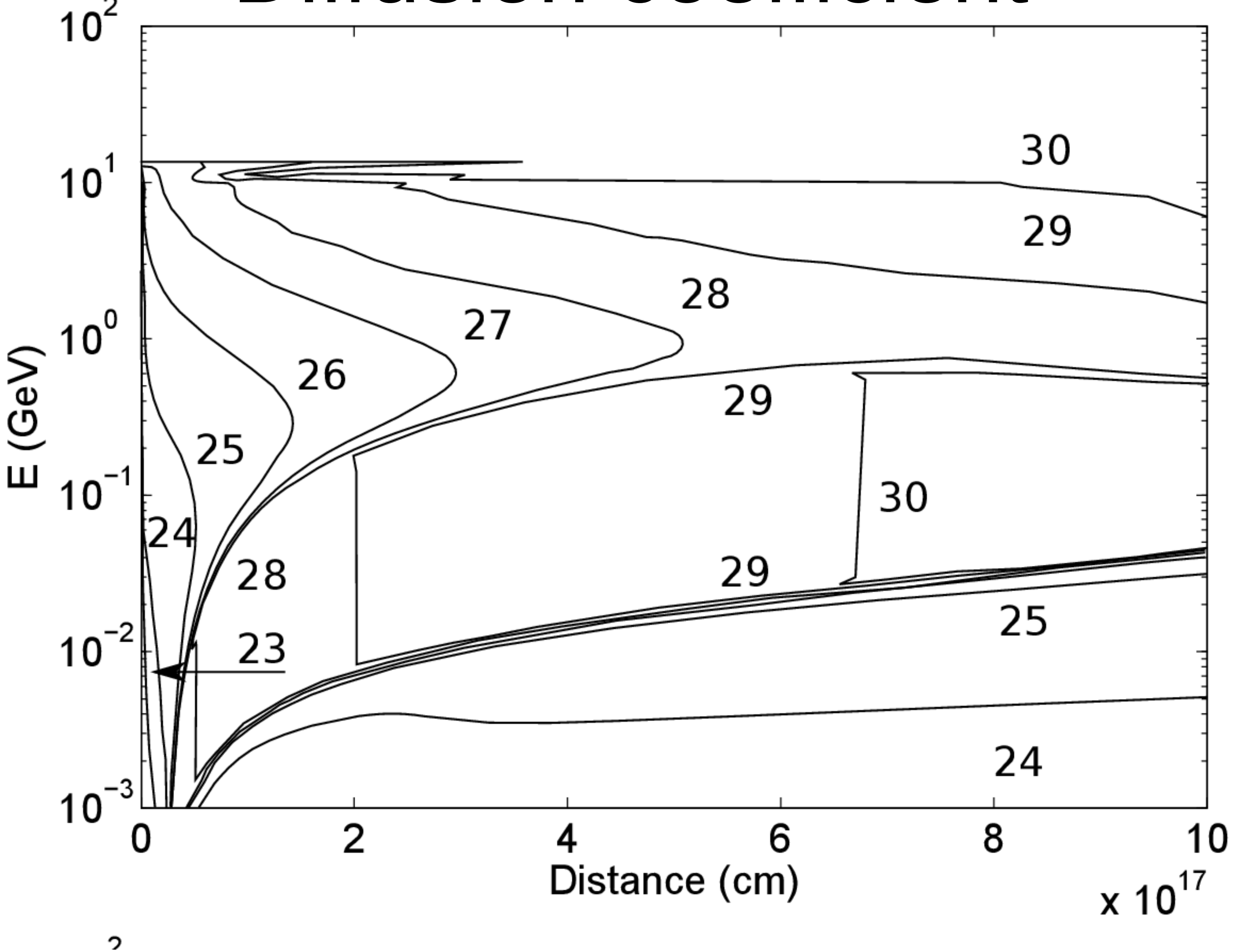
It may (and will!) exceed proper particle velocity

Different transport equation required!

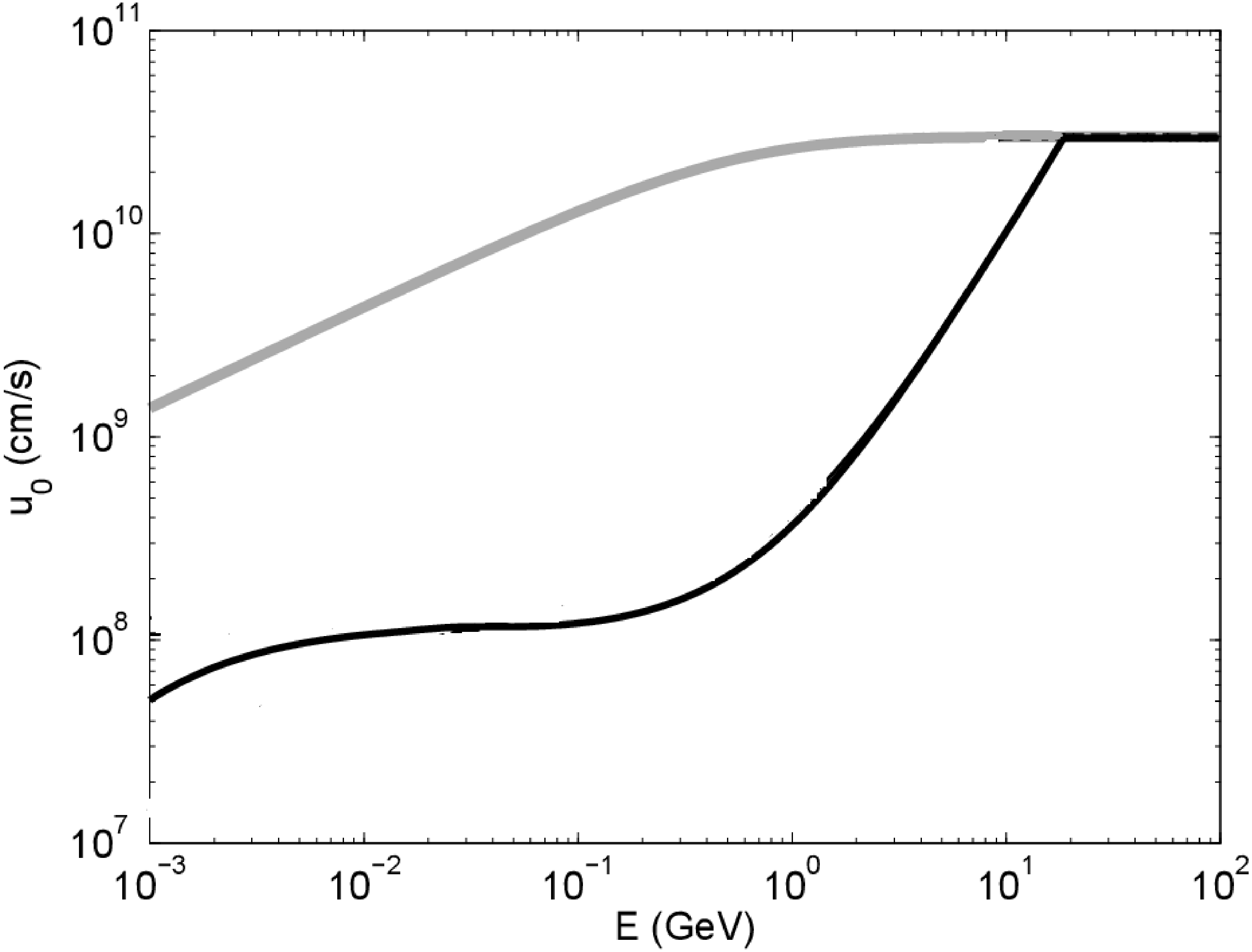
Energy losses



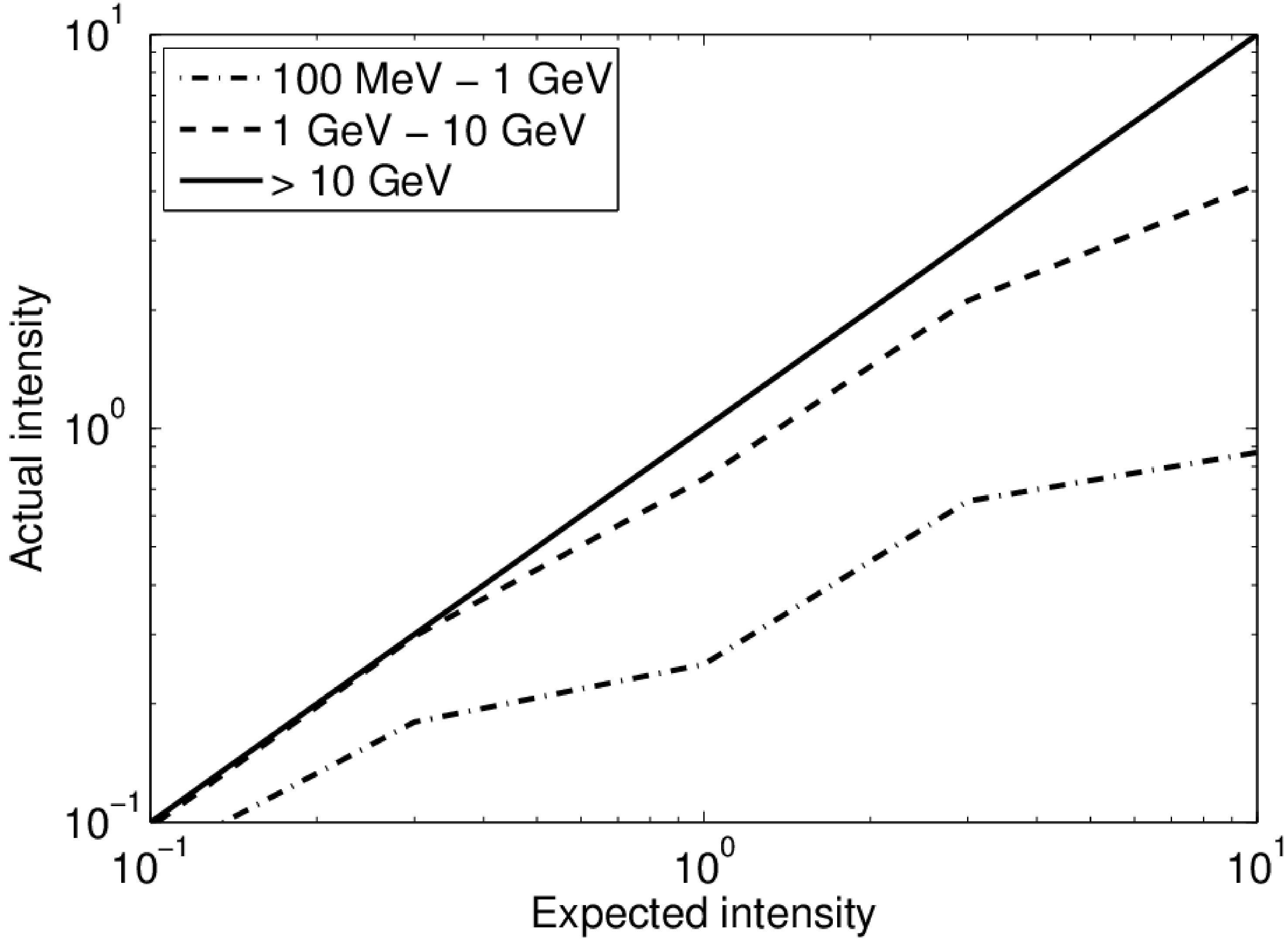
Diffusion coefficient



Average streaming velocity



Suppression of gamma-ray emission



Conclusions

- Self-generated turbulence is important for particle-cloud interactions
- Super-luminal velocities are expected in the case of diffusion equation
- Self-generated turbulence mainly affects sub-relativistic particles yet may also suppress gamma-ray emission

Additional slide 1

$$\frac{\partial f}{\partial t} + \text{div } S + \left(\frac{\partial}{\partial E}\frac{dE}{dt}f\right) = 0$$

$$S = \min\left\{-D\nabla f, v \cdot f\right\} \ ,$$

$$D(E) = \frac{vH^2}{12\pi k_{res}^2 W(k_{res})}$$

$$\frac{dE}{dt} = \frac{\gamma - 1}{\gamma}\frac{\pi}{4}\frac{\Omega_{Hi}}{n_i}\int\limits_{k_{res}}^{k_{max}} W\left(\frac{u_0}{v_a} - 1\right)dk$$