Cosmic Rays and Cool Clouds

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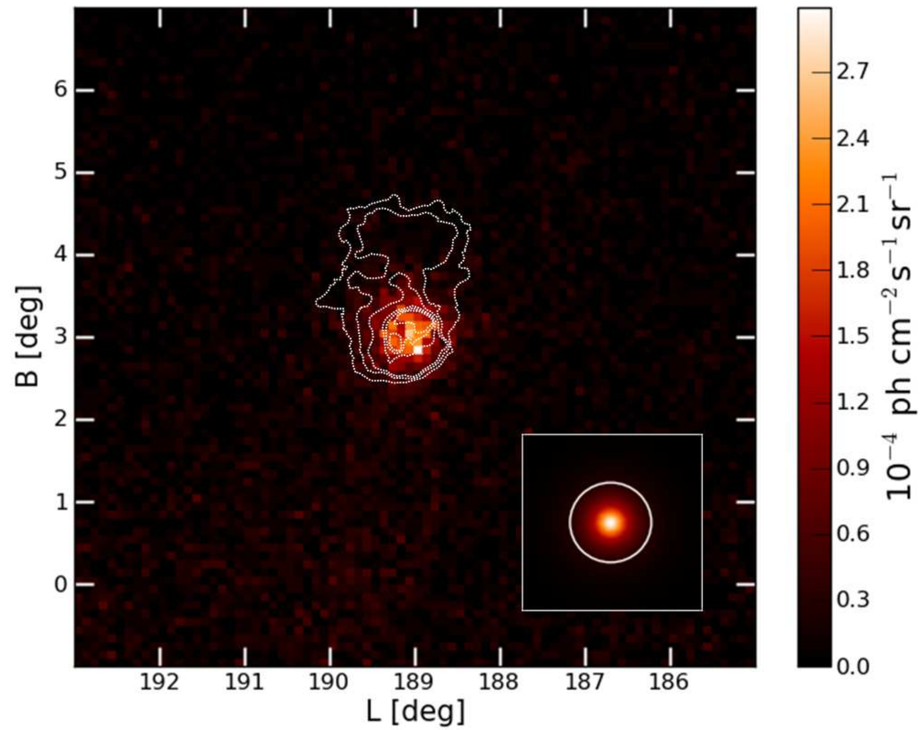
also, thanks to B. Benjamin, D. McCammon

Why consider Cosmic-Ray Diffusion in Cool Clouds?

$P_{\rm cr}$ or $n_{\rm cr}$ in clouds?

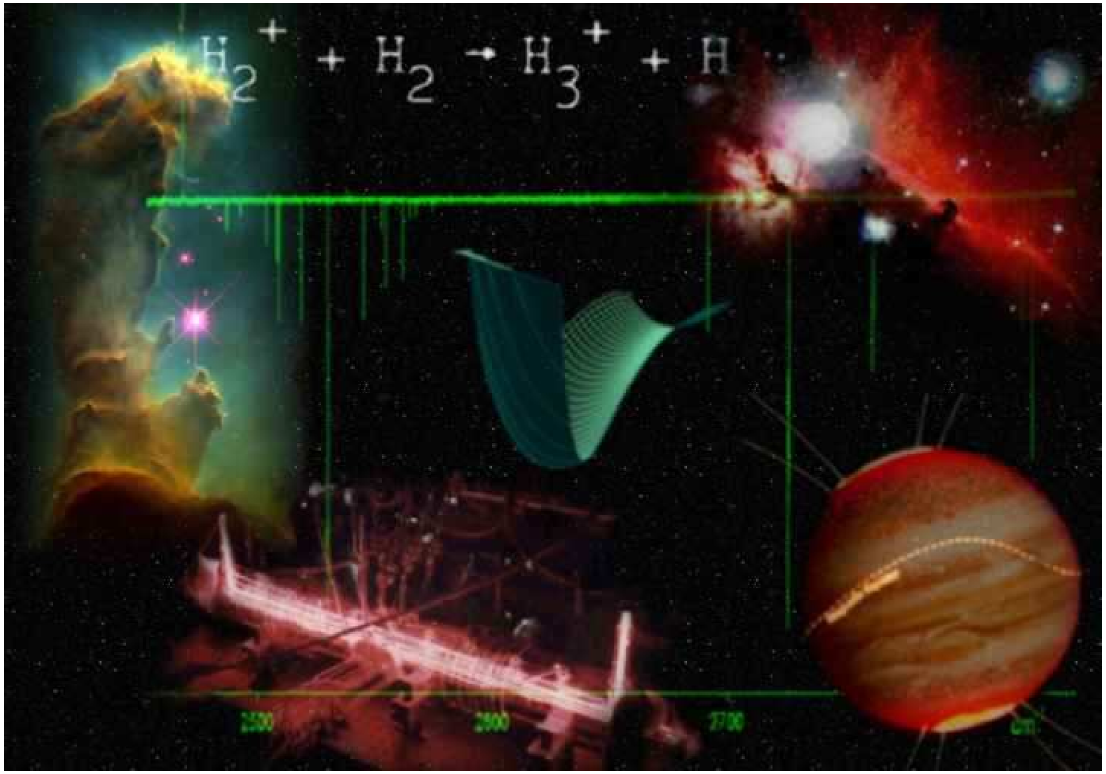
Fermi gamma-ray observations are weighted towards molecular clouds because of their higher density. Do such clouds have a "representative" $n_{\rm cr}$? Models (such as Torres et al., 2008) very often assume so.



SNR IC 443: Abdo et al. (2010)

ISM Cloud Ionization

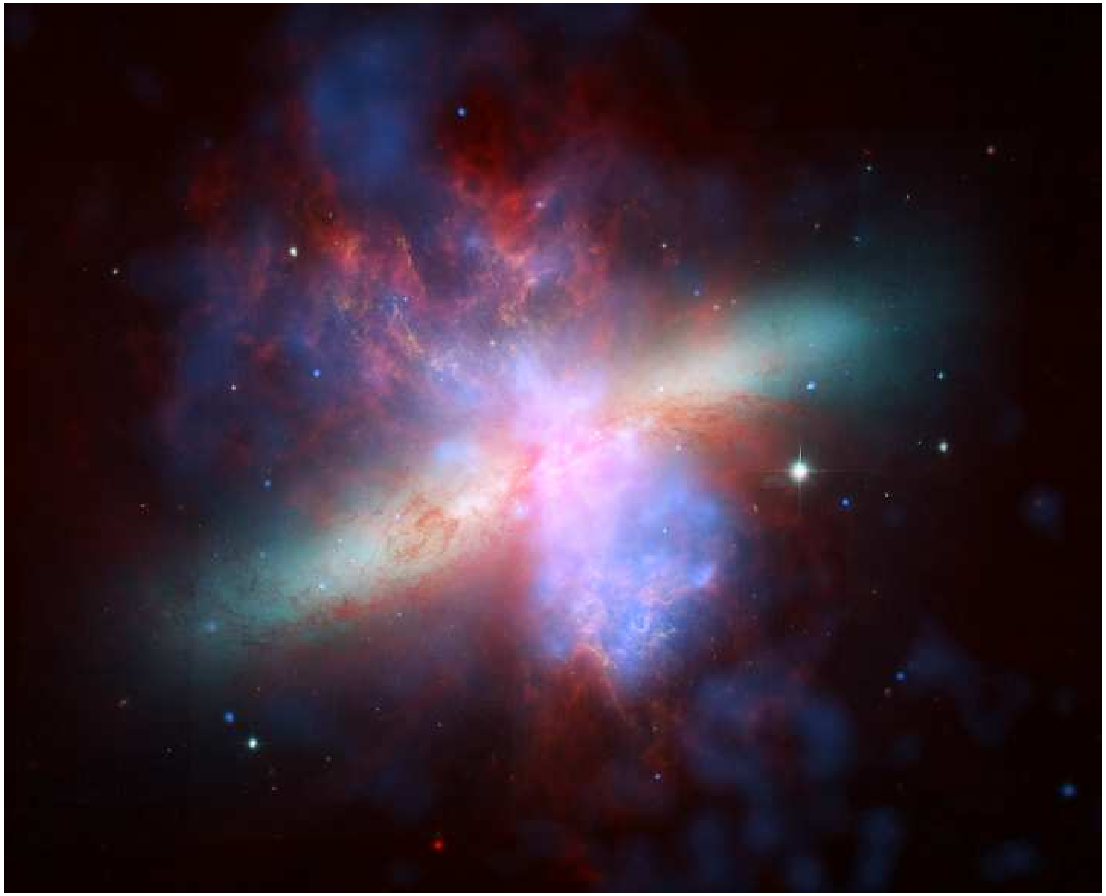
Cosmic rays are an important source of ionization in cool molecular clouds, helping to form new molecules, and helping to determine the role of magnetic fields in star formation.



(C.M. Lindsay, 2000; courtesy B. McCall)

Interaction of cool clouds in winds?

Cosmic rays help drive galactic outflows (JE et al. 2008); can those cosmic rays help drive embedded clouds?



(M82; Red: Infrared/*Spitzer*; Green: Optical/*HST*; Blue: X-ray/*Chandra*)
Strickland/Engelbracht/NASA (2006)

The Cosmic-Ray Streaming Instability in Cool Clouds

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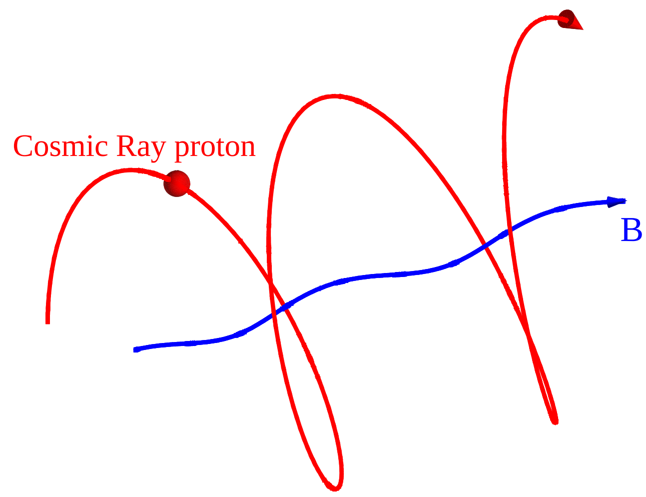
Cosmic-Ray Streaming Instability

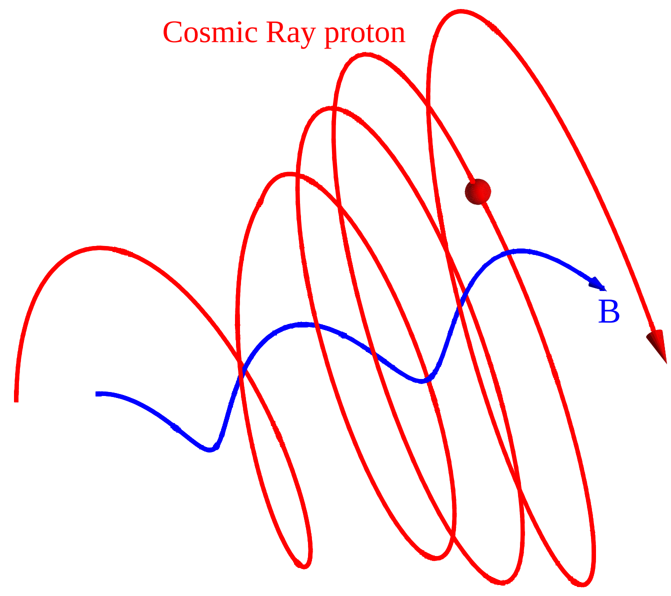
As cosmic rays stream down a pressure gradient, they interact with waves on the magnetic field (Kulsrud & Pearce 1969).

These interactions ‘scatter’ the cosmic rays to lower streaming velocities, and yield momentum to the waves.

Before:



After:



These waves are the ‘clutch’ which engages cosmic rays to the gas (Wentzel 1971; see also Skilling, 1971; Ipavich, 1975).

Overall approach

Our approach:

- Consider cosmic rays streaming from the hot ISM to a cool cloud with very low ionization ($x \equiv n_\mathrm{e}/n_\mathrm{H} \sim 10^{-3}$ to 10^{-4} in the cloud).
- We are interested in $E_\mathrm{cr} \lesssim 100$ GeV cosmic rays that are the source of ISM CR pressure & cloud ionization, and not much higher energy cosmic rays.
- Take account of “compound diffusion”: what are the variety of mechanisms that can scatter cosmic rays?
- Assume **B** constant for $n \lesssim 10^2$ cm^{-3} (approximately true; see Crutcher 2007).

Cosmic-Ray Streaming + Damping

Using a hydrodynamical approach for the cosmic rays [modifying the equations of McKenzie & Völk (1982) and Breitschwerdt, McKenzie, & Völk (1991,1993), Everett et al. (2008)], we write:

$$\kappa_{\rm cr}\frac{d^2P_{\rm cr}}{dz^2} = \left(\frac{\kappa_{\rm cr}}{P_{\rm w}}\frac{dP_{\rm w}}{dz} - v_{\rm A}\right)\frac{dP_{\rm cr}}{dz} + \frac{\gamma_{\rm cr}P_{\rm cr}}{\rho}\left(\frac{v_{\rm A}}{2}\frac{d\rho}{dz}\right)$$

$$\frac{dP_{\rm w}}{dz} = \frac{1}{2}\frac{P_{\rm w}}{\rho}\frac{d\rho}{dz} - \frac{1}{2}\frac{dP_{\rm cr}}{dz} - \frac{L}{2v_{\rm A}}$$

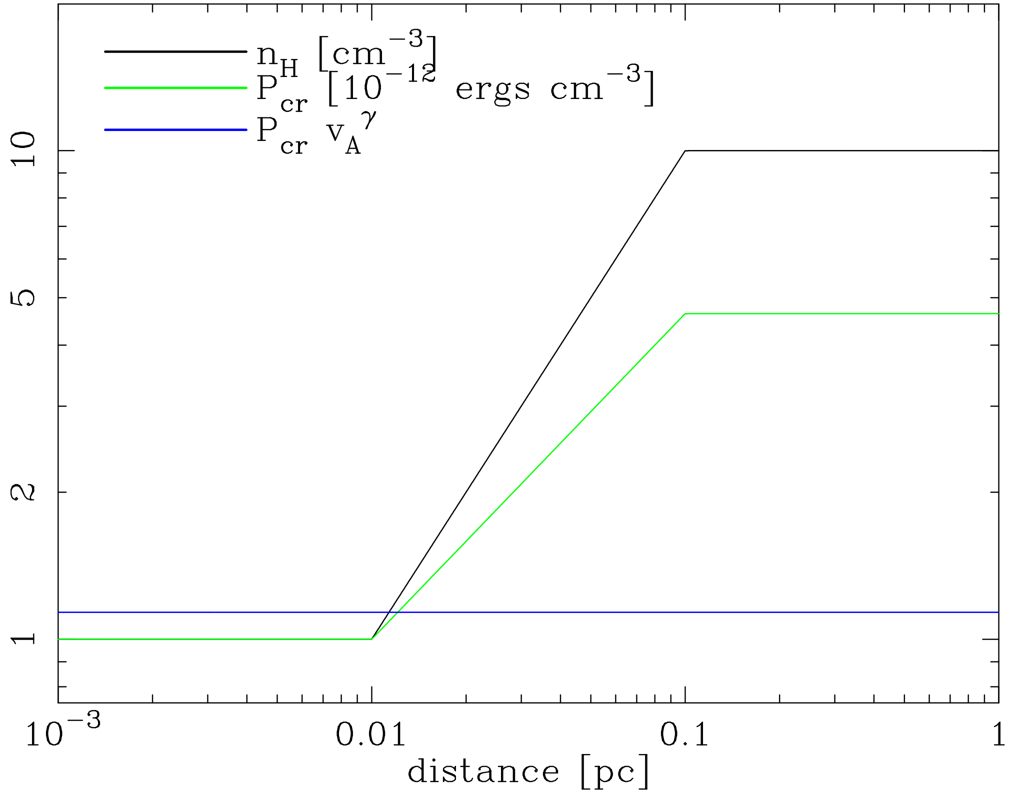
where the above symbols have the meanings:

$\kappa_{\rm cr}$	cosmic-ray diffusion coefficient = $\frac{4}{\pi}\frac{c}{3}\frac{r_{\rm gyro}}{(\delta B/B)^2}$
$P_{\rm cr}$	cosmic-ray pressure
$P_{\rm w}$	Alfven-wave pressure $\propto (\delta B)^2$
$v_{\rm A}$	Alfven speed
ρ	mass density
L	wave damping losses/gains

Code Testing

Assuming perfect locking of cosmic rays to the gas, we have calculated the variation of cosmic-ray pressure. As expected from analytical calculations, we find:

$$P_{\rm cr} v_{\rm A}^{\gamma_{\rm cr}} = \text{constant} \qquad (\kappa_{\rm cr} = 0)$$



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Wave Damping

We consider both non-linear Landau damping:

$$\Gamma_{\mathrm{non-linear\ Landau}} = \frac{1}{2}\sqrt{\frac{\pi}{2}}\frac{v_{\mathrm{ion,thermal}}}{c}\left(\frac{\delta B}{B}\right)^2$$

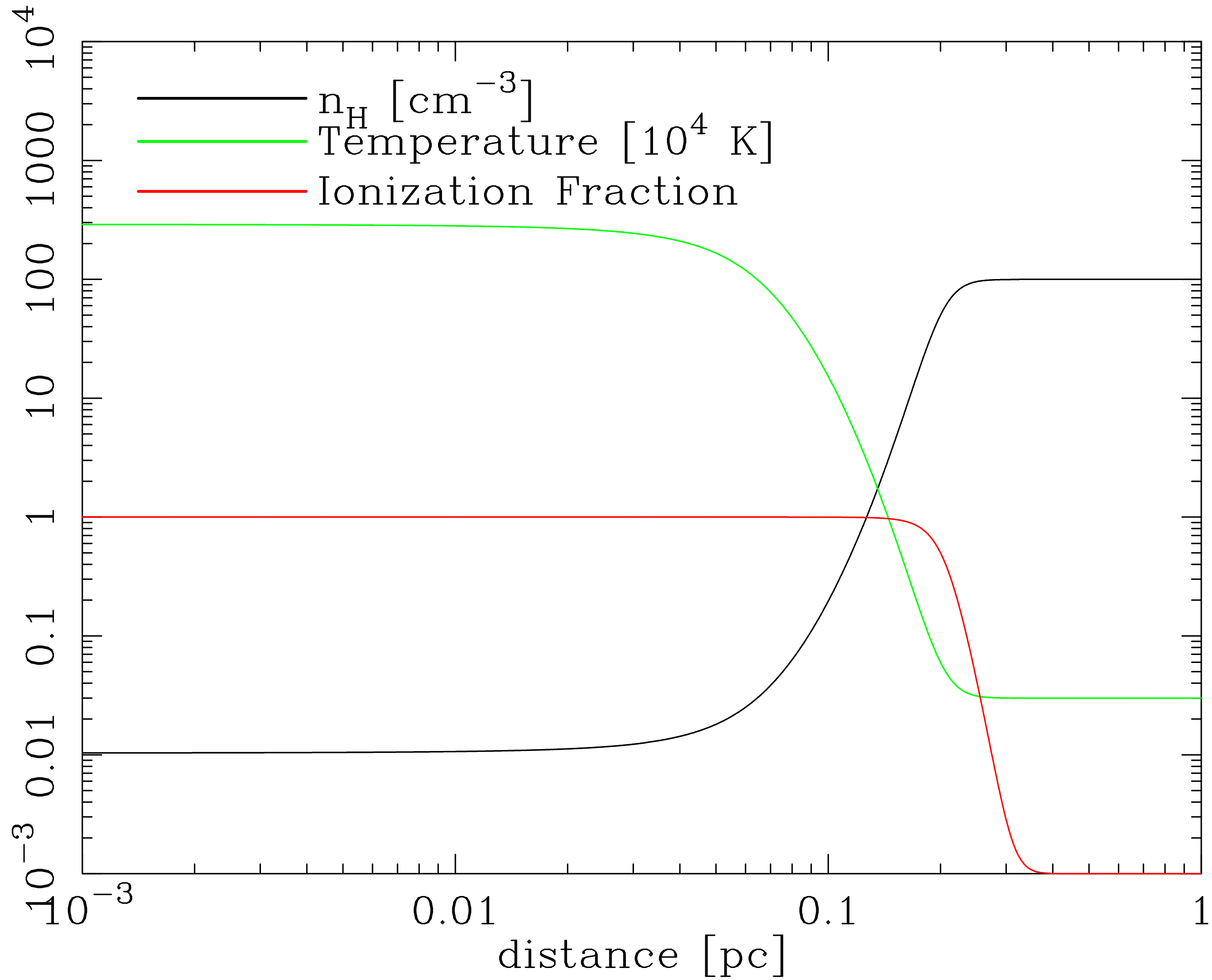
and ion-neutral friction:

$$\Gamma_{\mathrm{ion-neutral\ friction}} = \frac{1}{2}\nu_{\mathrm{in}}$$

(on the scale of the cosmic-ray gyroradius).

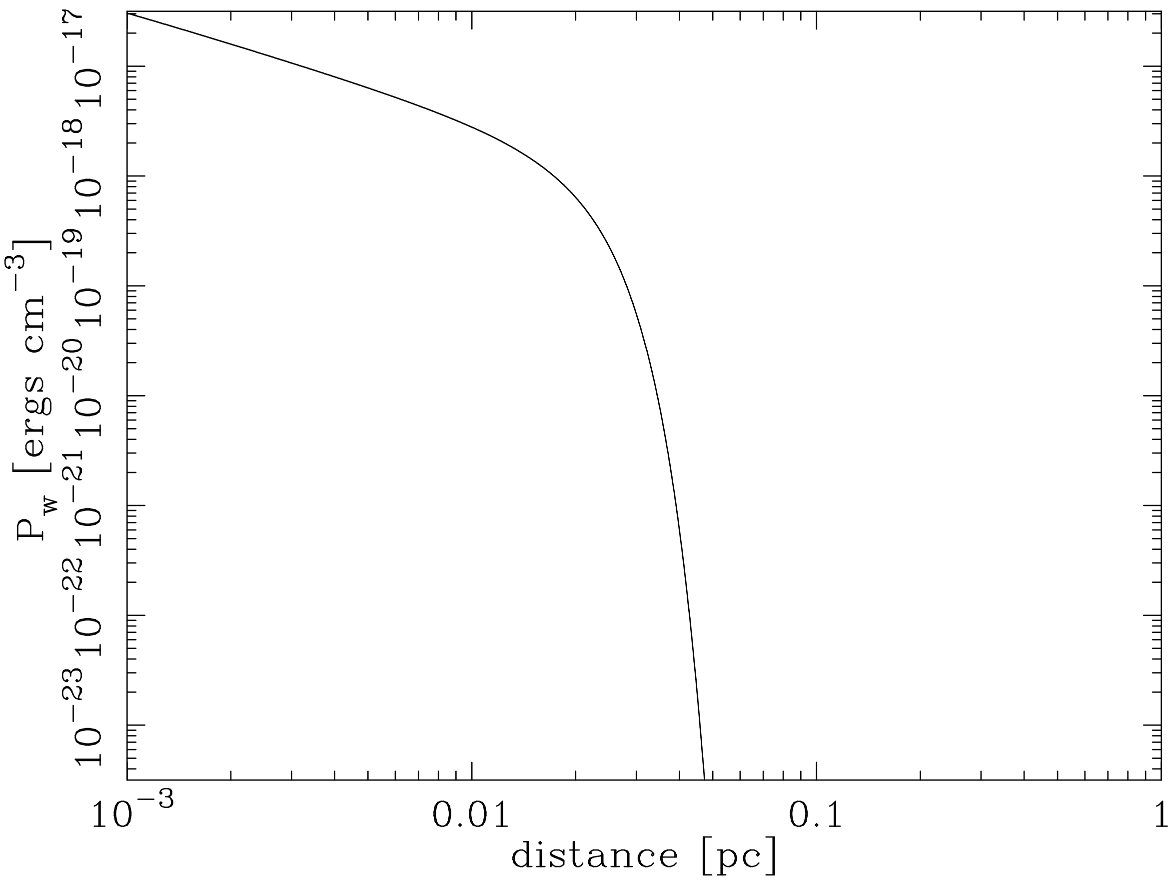
Setup & Results

Setup for the Cool Cloud

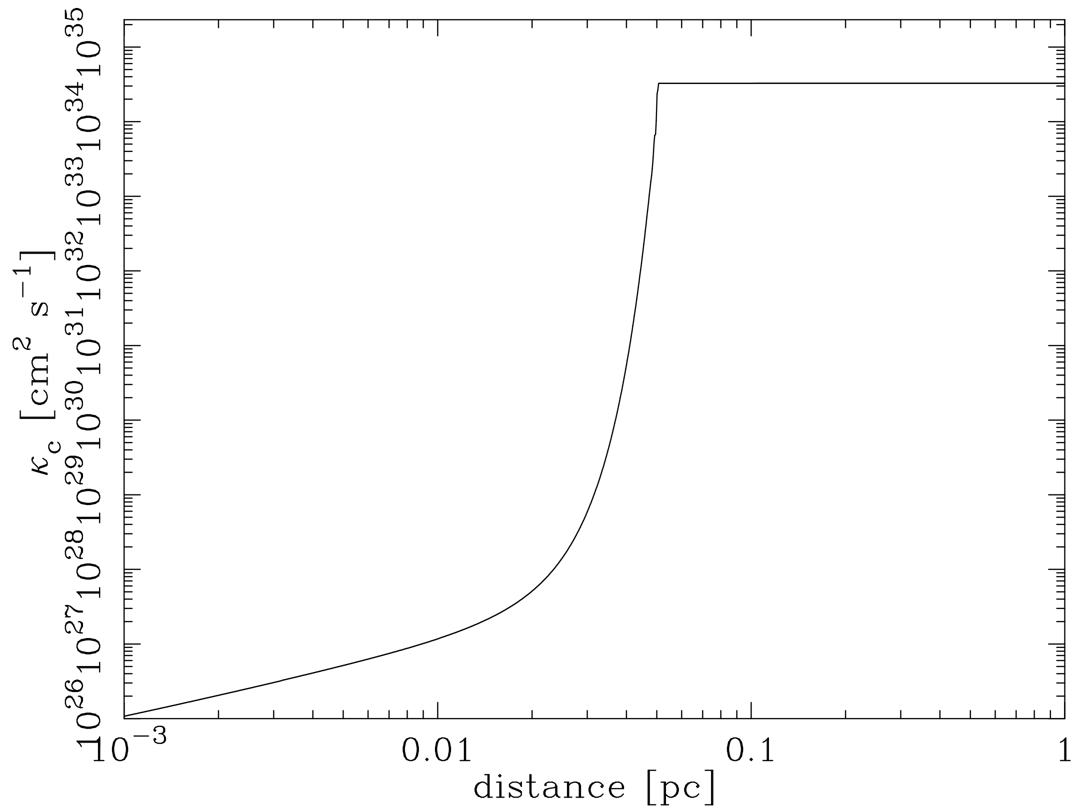


Cosmic-Ray Generated Turbulence Dies Out

$$\frac{dP_{\rm w}}{dz} \propto -\frac{1}{2}\frac{dP_{\rm cr}}{dz} - \frac{L}{2v_{\rm A}}$$

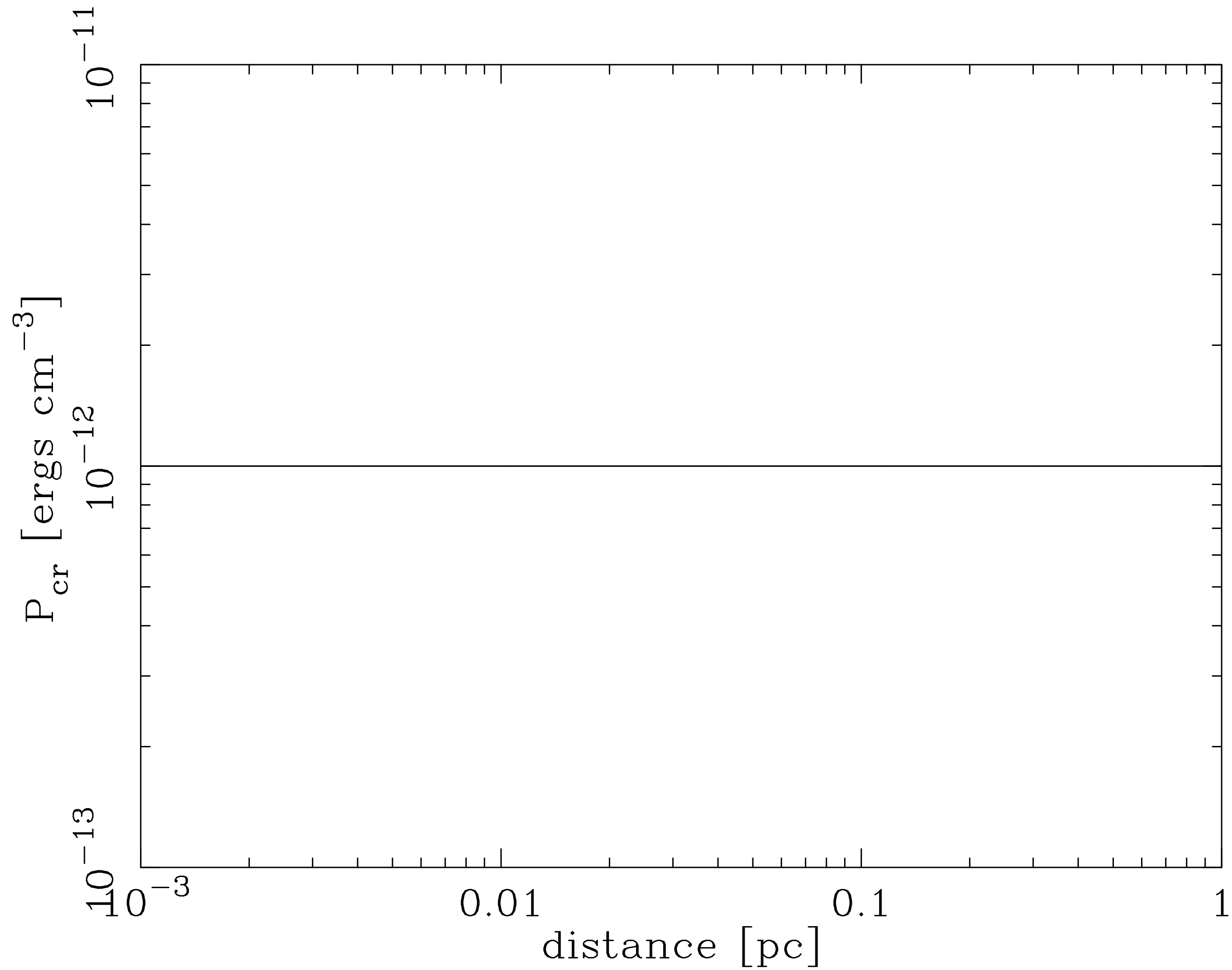


Cosmic-Ray Diffusivity Increases



The maximum cosmic-ray diffusivity ($\kappa \sim 10^{34}\ \mathrm{cm}^2\ \mathrm{s}^{-1}$) is limited by numerical precision. Beyond that level, the mean free path exceeds the size of the cloud, and the cosmic-rays are free-streaming through the cloud, and not diffusing.

Cosmic-Ray Pressure is Constant

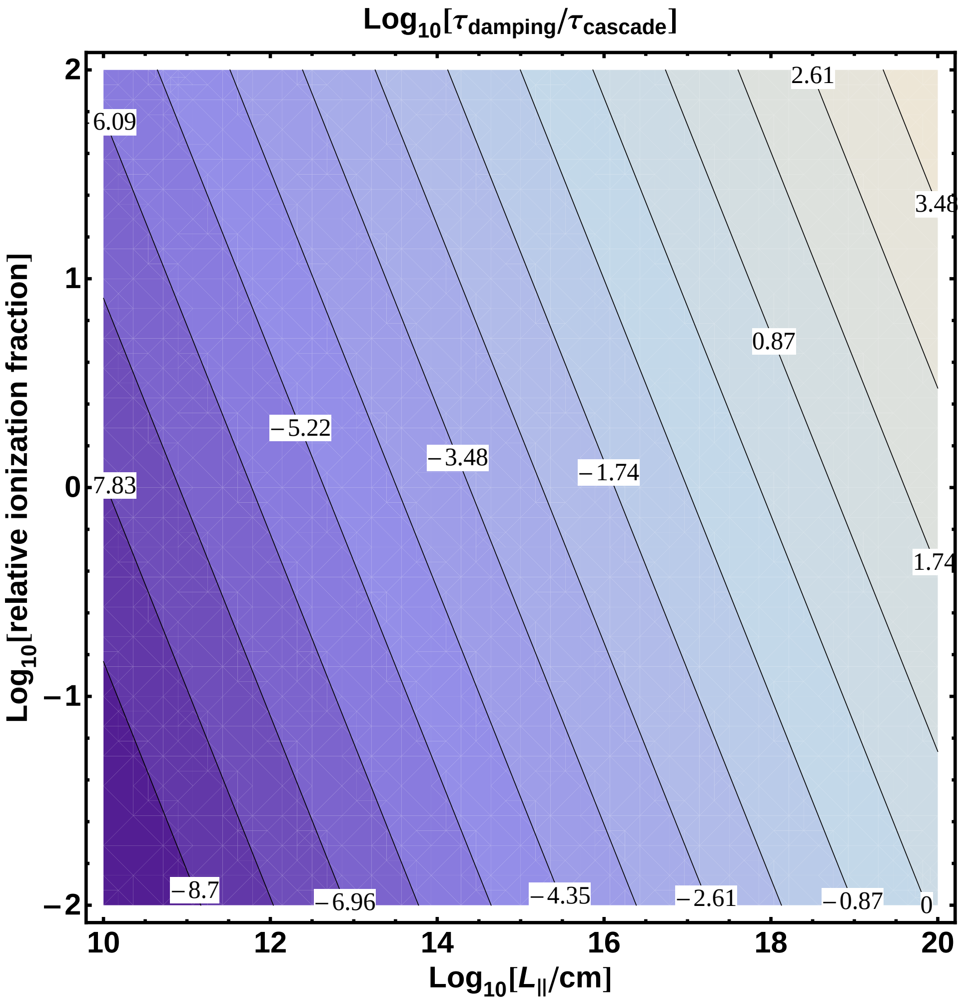


Can Turbulence Scatter CRs? (Pt I)

Within our 'fiducial' cool cloud, cosmic rays cannot generate their own turbulence. *Can normal turbulence decrease $\kappa_{\rm cr}$?*

- Cosmic rays are (gyro-resonantly) scattered by turbulence on the scales of $r_{\rm gyro} \sim 10^{12}$ cm (1 GeV cosmic rays, $B = 3\,\mu$G field).

  Can turbulent power cascade down to those scales in cool clouds?



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(Not a new result)

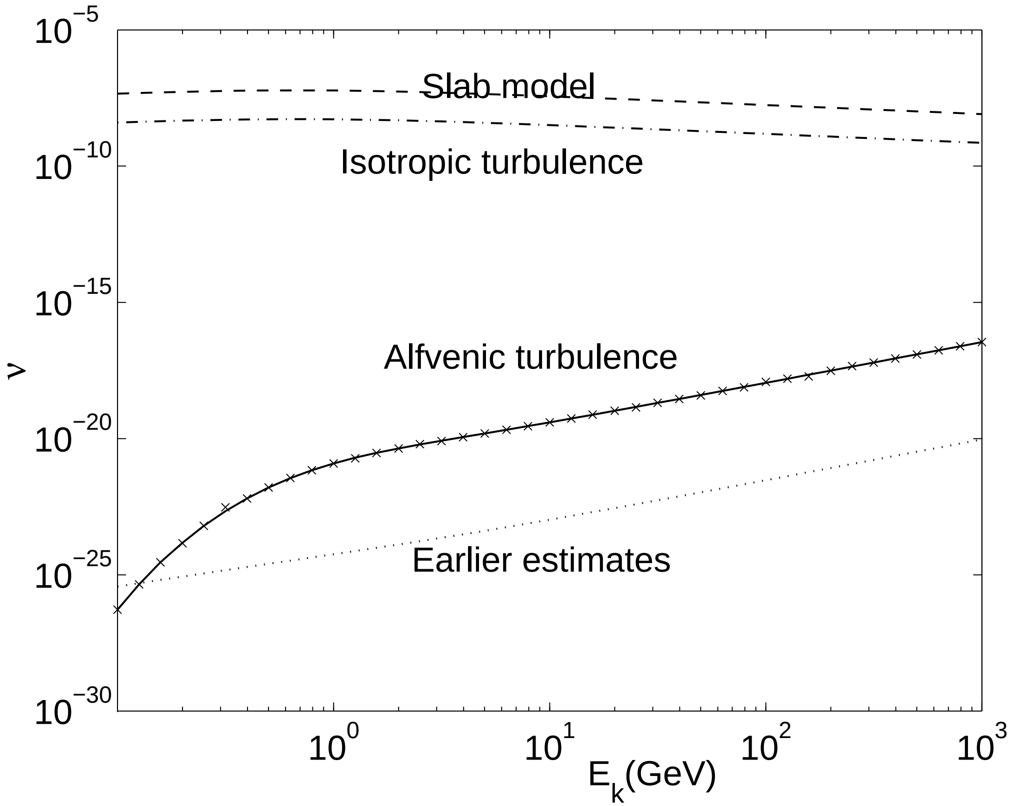
Other groups have shown how quickly ion-neutral damping damps the turbulent cascade:

- Zweibel & Josafatsson (1983)
- Elmegreen & Fiebig (1993)
- Lazarian, Vishniac, & Cho (2004); Lazarian & Beresnyak (2006)
- Spangler (2007)
- Jean et al. (2009)
- Basu & Dapp (2010)
- Tilley & Balsara (2010)
- observed by Pineda et al. (2010)?

Can Turbulence Scatter CRs? (Pt II)

Within our ’fiducial’ cool cloud, cosmic rays cannot generate their own turbulence. *Can normal turbulence decrease* $\kappa_{\rm cr}$*?*

- And even if it does cascade, the anisotropy of the Alfven turbulent cascade (Goldreich & Sridhar, 1995) yields $k_\perp \gg k_\parallel$. This turbulence is very inefficient for scattering cosmic rays (Chandran, 2000).



Yan & Lazarian (2002)

Conclusion

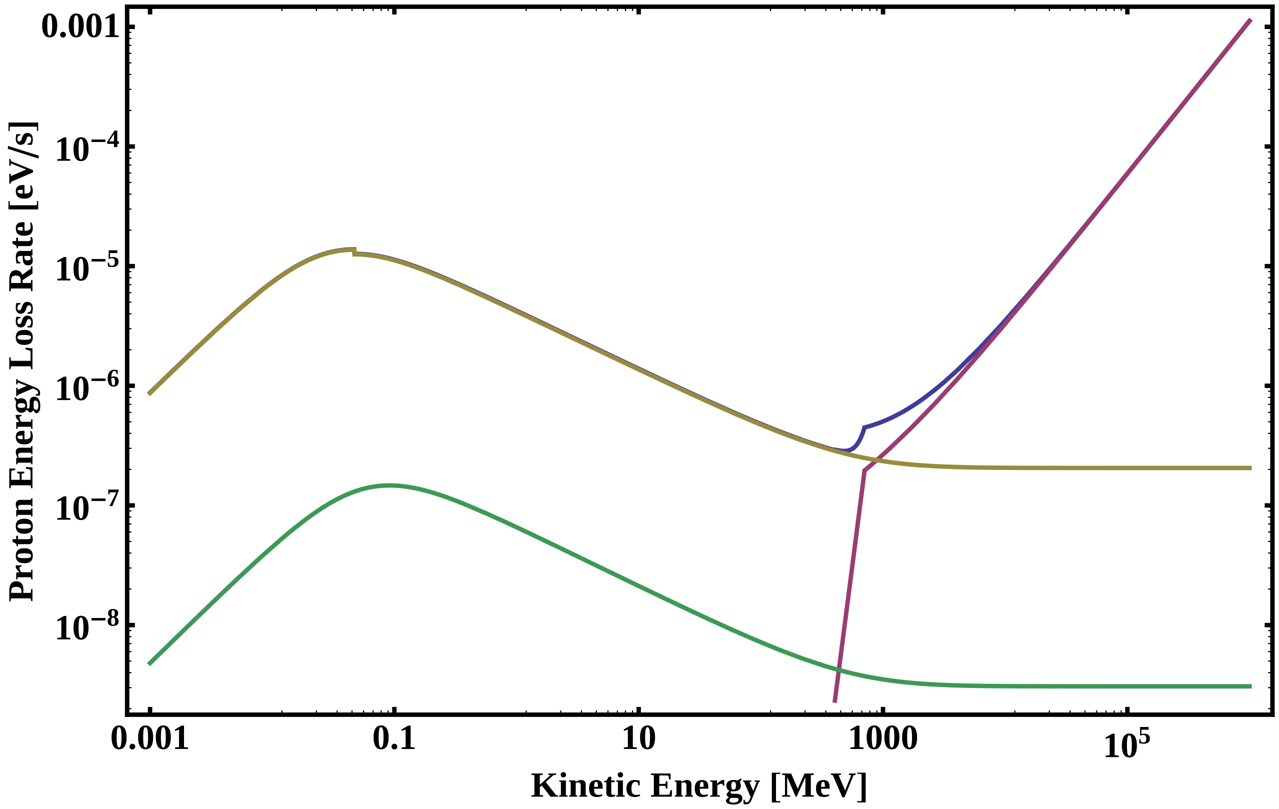
Conclusions

Conclusions

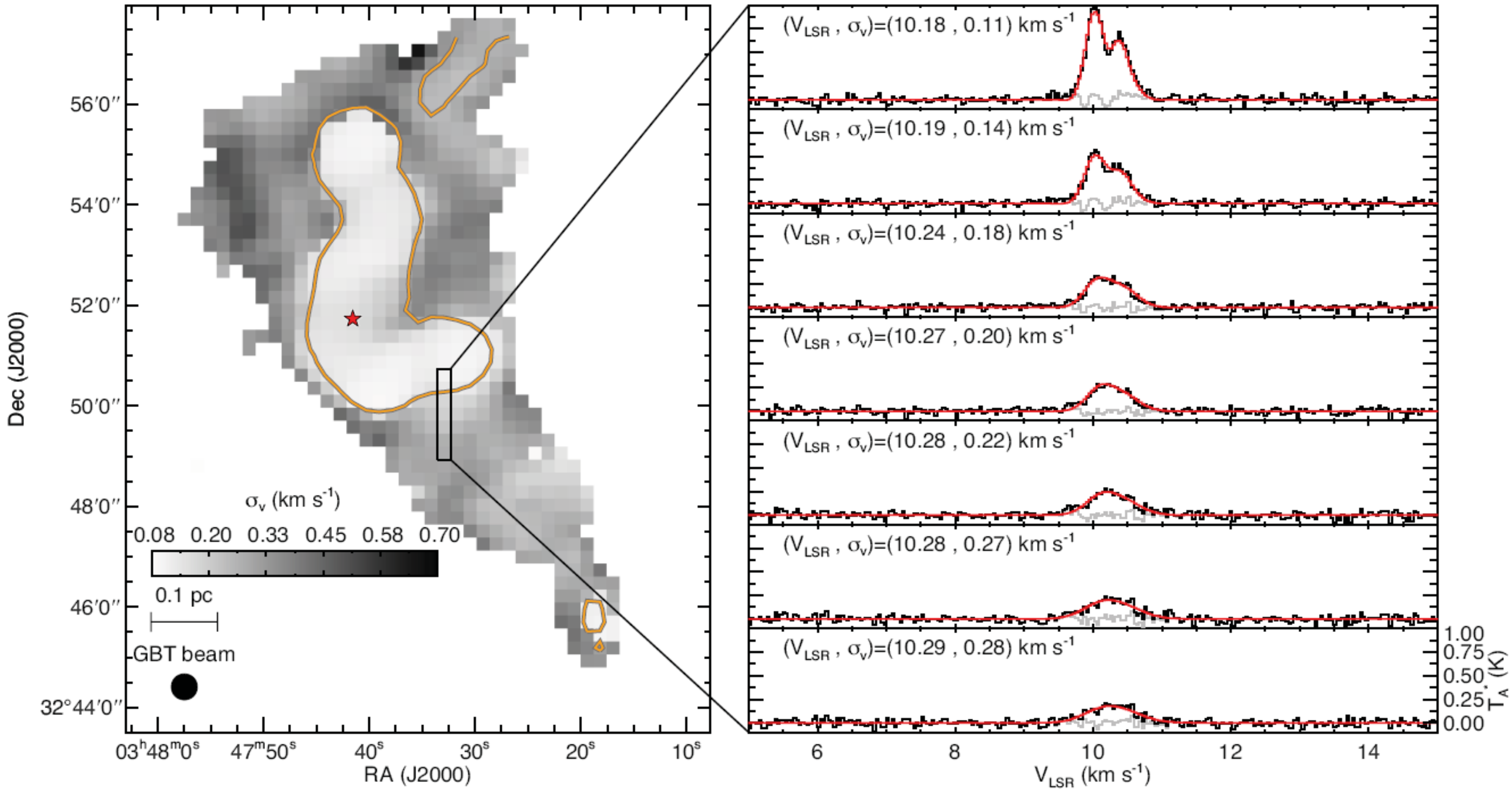
- We are interested in what happens to cosmic-ray pressure (and density) as cosmic rays move from the hot ISM to cool clouds.
- This has implications for models of gamma-ray emission, cool-cloud ionization, and interaction of cool clouds in galactic winds.
- From our *early* calculations, we find that the cosmic-ray pressure and density do not appear to change in clouds.

Ionization Losses

We use the formulation of Schlickeiser (2002) for various nucleon loss terms:



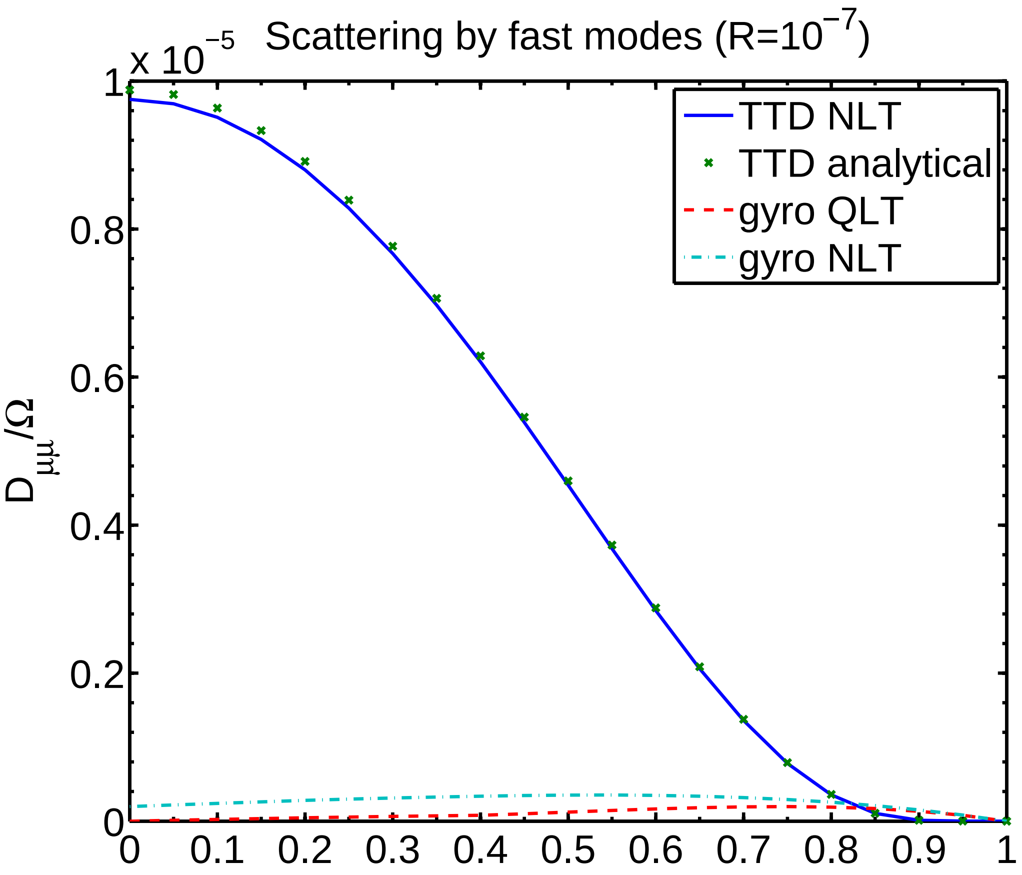
Pineda Et Al. (2010)



CR Scattering by fast modes?

Yan & Lazarian (2002, 2004, 2008), and Lerche & Schlickeiser (2001) have shown:

Fast modes are anisotropically damped, and so it appears that turbulence on the gyro-resonant scale is still required.



Yan & Lazarian (2008)