Turbulent Reacceleration of Streaming Cosmic Rays: Fluid Simulations

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Introduction

- Cosmic rays can gain energy from stochastic scatterings in a turbulent velocity field, i.e. **turbulent reacceleration** (a 2nd order Fermi mechanism). We consider two flavors of reacceleration:
    - Resonant — individual CRs resonantly scatter off magnetic perturbations with sizes ~ the CR gyroradius

$$D_{xx}D_{pp} = p^2V_A^2\left\langle\frac{1-\mu^2}{\nu_+ + \nu_-}\right\rangle\left\langle\frac{(1-\mu^2)\nu_+\nu_-}{\nu_+ + \nu_-}\right\rangle$$

    - Non-resonant — the bulk CR fluid undergoes large-scale compressions and rarefactions [1]
- Reacceleration can be important!
    - It appears to explain radio halos in merging galaxy clusters [2]
    - Proposed to simultaneously explain the bump in B/C ratio observed at ~ 1 GV, while maintaining a single power-law diffusion dependence [3]
- However, for GeV CRs, which are dominantly self-confined via the resonant streaming instability, the physical underpinnings of reacceleration are unclear.
    - Resonant reacceleration is not permitted. Only waves co-moving with the CR drift are excited: $\nu_- = 0 \rightarrow D_{pp} = 0$ [4,5]
    - Non-resonant reacceleration of self-confined or "streaming" cosmic rays is unexplored — **this is our focus**

Analytic Theory

Our *regime of interest:* **Self-confined CRs** ($E \lessapprox 300$ GeV [4]) in **subsonic** ($M_s = v/c_s < 1$), **compressive** turbulence

$$\frac{\partial E_{cr}}{\partial t} \sim -v \cdot \nabla P_{cr} + v_A \cdot \nabla P_{cr}$$

Energy loss (gain) from rarefaction (compression)

Energy transferred from CRs to Alfven waves: $t_{loss} \sim L/v_A$

- Fastest reacceleration occurs when CRs gain energy from compression but diffuse to a different turbulent eddy before rarefaction (energy loss) $\kappa_{crit} = Lv_{ph}$ (L = outer eddy scale, $v_{ph} = c_s$ = characteristic speed of compressible waves in the medium) [1]

$$t_{grow,crit} \sim \frac{v_{ph}L}{v^2}$$

$$\frac{t_{grow,crit}}{t_{loss}} \sim \frac{1}{\sqrt{\beta}M_s^2} \rightarrow$$

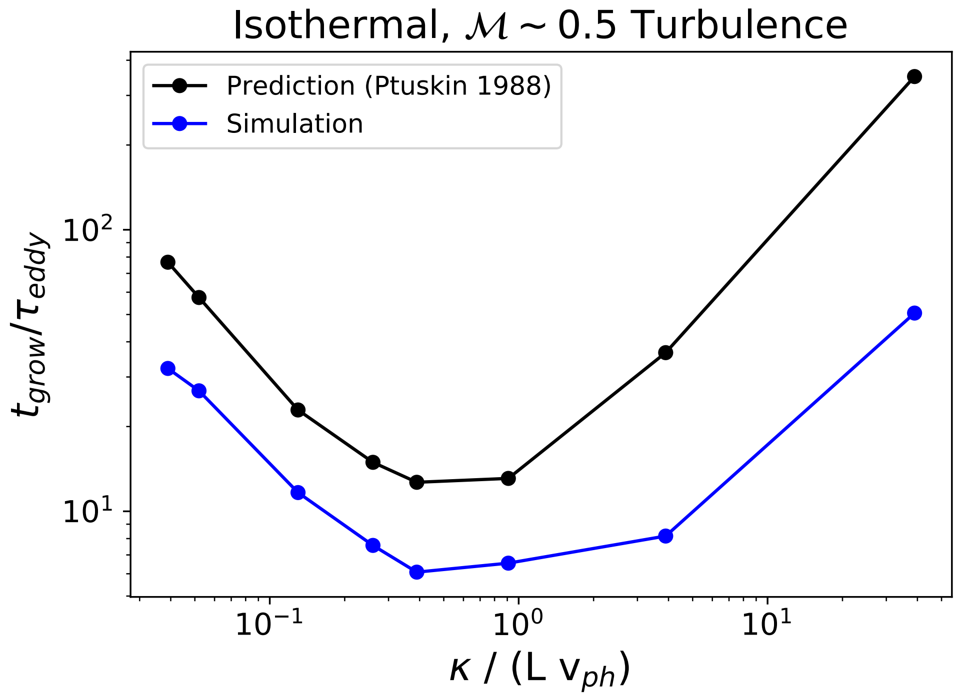
Unless $\beta \gg 1$, energy loss prevails over energy gain from subsonic turbulence

	WIM	CGM	ICM
v_{ph} (cm/s)	10^6	10^7	10^7
L	100 pc	1-10 kpc	100 kpc
$\kappa_{crit} = v_{ph}L$ (cm^2/s)	3×10^{26}	3×10^{27} - 3×10^{28}	3×10^{29}
β	1	10?	100
$t_{loss}/t_{grow,min}$	$\mathcal{M}_s^2$	$\sqrt{10}\mathrm{M}_s^2$	$10\ \mathcal{M}_s^2$

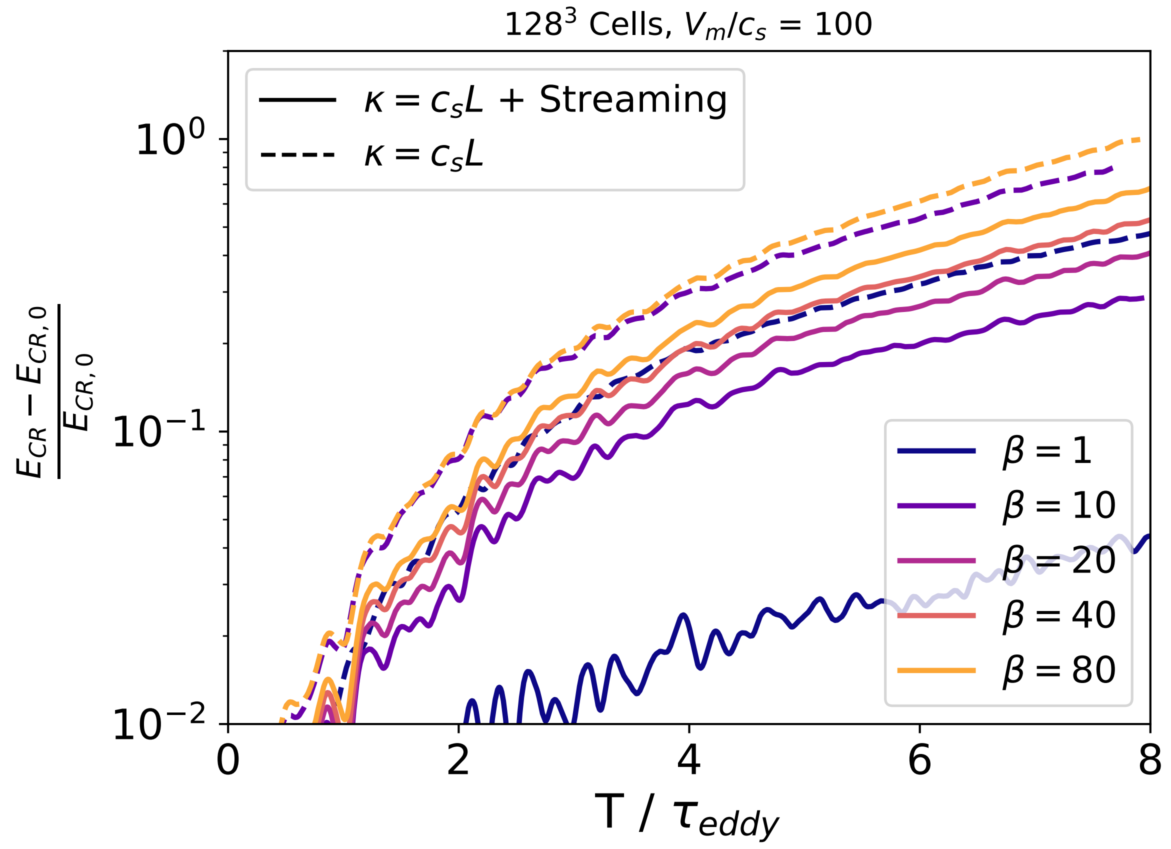
Non-resonant reacceleration is likely negligible in the warm ISM, but may still be efficient in the high-β ICM and possibly CGM

Simulations

- *Numerical tool:* Athena++ MHD code [6] with two-moment CR module [7]; solves the time-dependent CR energy and flux equations; streaming and field-aligned diffusion included
- *Setup and methods:* Cubical box with volume L^3, fiducially resolved by 128^3 cells; purely compressive, $M_s \sim 0.5$ turbulence driven parabolically at the outer scale (L) by an Ornstein-Uhlenbeck process; gas equation of state is isothermal; Initially $P_g/P_{cr} \sim 100$, $P_g/P_B = \beta$ is varied



→ **Simulations with pure diffusion (no streaming) recover analytic growth rates within a factor of 2, at least with $\kappa \lessapprox \kappa_{crit}$**



Pure diffusion with $\kappa = \kappa_{crit}$ results in fast growth over a few eddy turnover times. Adding in streaming, even with $\kappa = \kappa_{crit}$, gives slow growth unless β is large. t_{grow} monotonically decreases with increasing β

Conclusions

- Non-resonant reacceleration of self-confined CRs (E $\lessapprox 300$ GeV) is heavily stunted by energy losses in ISM-like ($\beta \sim 1$) environments
- As resonant reacceleration is similarly impermissible at GeV energies, canonical growth rates implemented in CR propagation models do not apply at GeV energies
    - Synchrotron constraints [8, 9, 10] and back-of-the-envelope calculations of reaccelerated CR power [11, 12] similarly disfavor this parameterization of reacceleration
    - Shock reacceleration [13] in supersonic turbulence is a separate and intriguing possibility
- Non-resonant reacceleration still operates efficiently in cluster environments and is less sensitive than resonant reacceleration to CR microphysics, turbulence properties, etc.

References: 1) Ptuskin 1988. 2) Brunetti and Lazarian 2011. 3) Heinbach and Simon 1995. 4) Zweibel 2017. 5) Amato and Blasi 2018. 6) Stone+ 2020. 7) Jiang and Oh 2018. 8) Trotta+ 2011. 9) Di Bernardo+ 2013. 10) Orlando and Strong 2013. 11) Thornbury and Drury 2014. 12) Drury and Strong 2017. 13) Bresci+ 2019