Cosmic Rays & Dissipation in the ICM

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Work in Progress

Plan of Talk

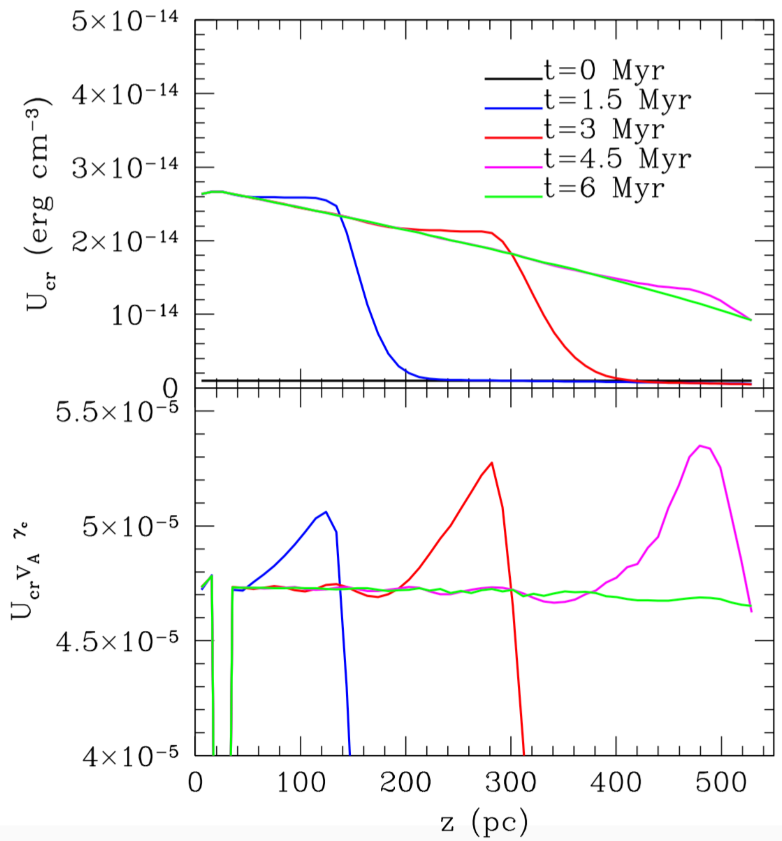
- Overarching questions & motivation
- Pressure anisotropy instability
- Origin of pressure anisotropy
- Scattering rate, heating rate, Fermi acceleration rate
- Conclusions

Cosmic Ray Confinement in a Nutshell

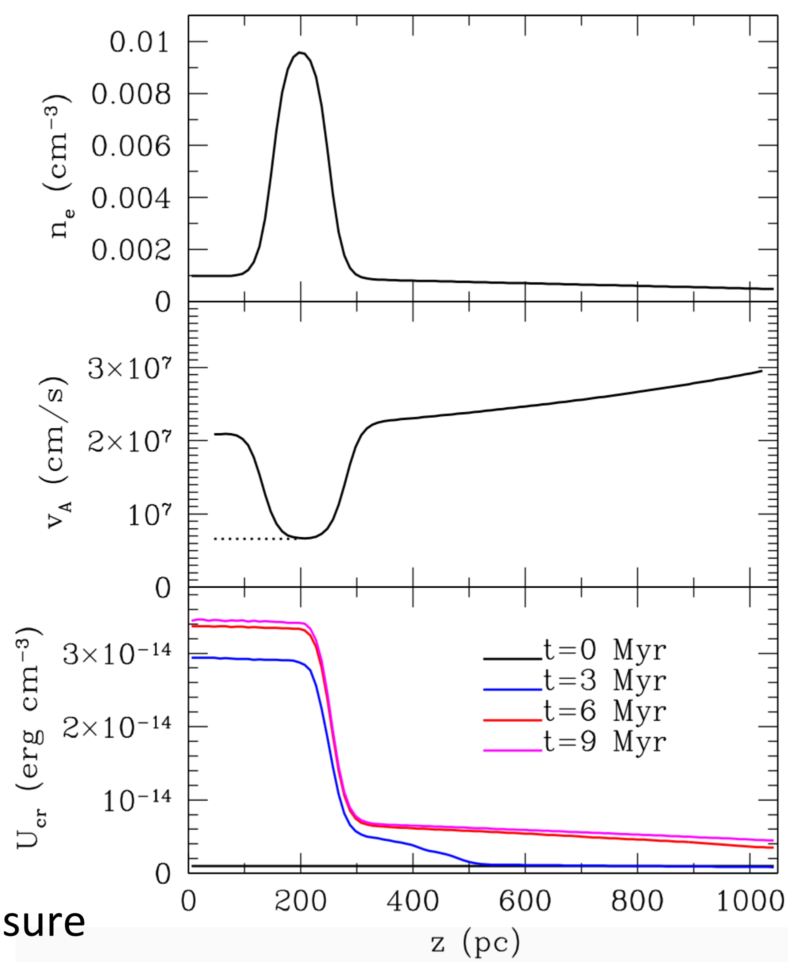
- Mediated by gyroscale (~AU) scale small amplitude waves.
- Wave are driven by a turbulent cascade (extrinsic turbulence) or generated by cosmic ray streaming anisotropy (self confinement)
- Cosmic rays exert a pressure gradient force in both cases and collisionlessly heat the gas by transferring energy to waves in the self confinement case ($H=|v_A \cdot \nabla P_c|$).

Bottleneck Effect

No Cloud



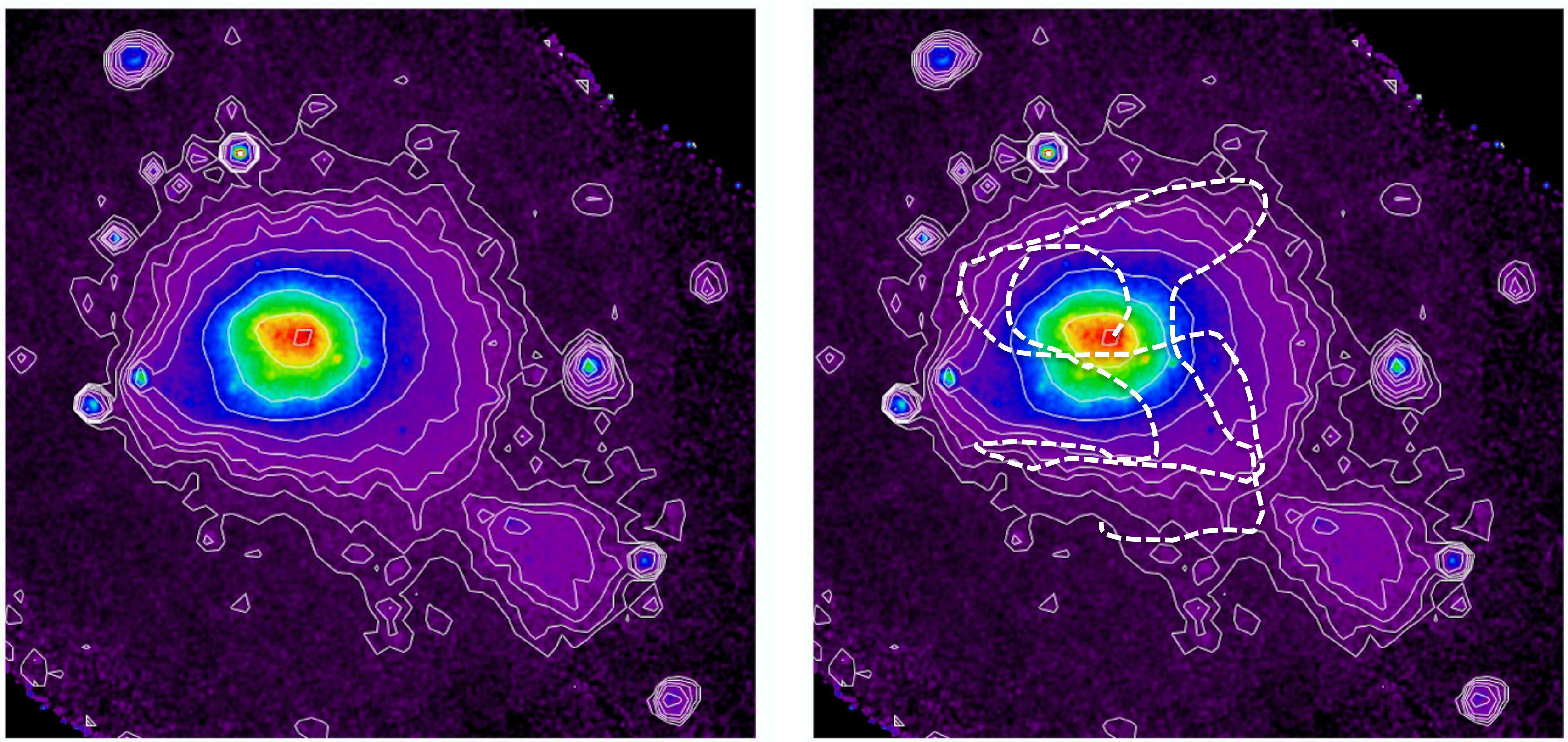
Cloud



Left: Cosmic rays streaming down their pressure gradient at v_A evolve to constant $P_c/\rho^{\gamma_c/2}$. If ρ has a maximum, P_c behind it must go flat (Right).

Wiener, Oh, EZ (2017), Wiener, EZ, Ruszkowski arXiv tomorrow

Propagation in a Tangled Magnetic Field



Rosat x-ray image of Coma Cluster. White dashed line shows how magnetic field might zigzag radially, creating nonlocal cosmic ray transport effects.

Alternative Scenario for Cosmic Ray Self-Confinement

Energy source drives large scale turbulence

Compression & shear drive cosmic ray pressure anisotropy due to adiabatic Invariance of magnetic moment & longitudinal action

Gyroresonant cosmic ray pressure anisotropy instability amplifies gyroscale waves, which provide scattering & confinement.

Also of interest for ISM

Cosmic rays are gyroviscously heated *a la* Kunz et al

Gyroscale wave energy transferred to thermal plasma & Fermi-accelerates cosmic rays

Questions

- What is the cosmic ray scattering mean free path λ in this scenario?
- Is significant energy removed from the turbulent cascade at large scales?
- How is the energy extracted from the turbulence apportioned between thermal gas and cosmic rays?

If Cosmic Rays are Confined by Extrinsic Turbulence

Energy source drives large scale turbulence

Compression & shear drive cosmic ray pressure anisotropy due to adiabatic Invariance of magnetic moment & longitudinal action

Cosmic rays absorb turbulent energy through gyroviscous heating.

Do cosmic rays absorb significant energy from the turbulent cascade?

Anisotropy Instability

Also see Lazarian & Beresnyak 2006

- Driven by cosmic rays which "see" a Doppler shifted wave frequency equal to their (relativistic) gyrofrequency.
  - Waves are circularly polarized & travel in either direction; direction of travel & sense of polarization depend on sign of anisotropy:

$$\Gamma_n = -\frac{\pi}{8}\Omega_0 \frac{a-3}{a-2}\frac{n_c(>p_1)}{n_g}\left[1+\frac{4}{5}n\hat{\mathbf{k}}\frac{c}{v_A}\frac{a-2}{a^2-1}\frac{P_{\parallel}-P_{\perp}}{P}\right]$$

$p_1 \equiv m\Omega_0/k$, a is spectral index, n_c, n_g are cosmic ray & plasma densities, Ω_0 is cyclotron frequency.

Origin of Pressure Anisotropy

- Low frequency turbulence change particle momentum p & cosine of pitch angle μ so as to conserve magnetic moment & longitudinal action:

$$\frac{dp}{dt} = \frac{1-3\mu^2}{2}\frac{p}{B}\frac{dB}{dt} + \mu^2\frac{p}{n}\frac{dn}{dt},$$

$$\frac{d\mu}{dt} = \mu\left(1-\mu^2\right)\left(\frac{1}{n}\frac{dn}{dt} - \frac{3}{2B}\frac{dB}{dt}\right)$$

- This is opposed by scattering from gyroresonant waves

This Plays Out as a Fokker-Planck Equation

$$\frac{\partial f}{\partial t} + R\left[P_2(\mu)p\frac{\partial f}{\partial p} + \frac{3}{2}\mu\left(1-\mu^2\right)\frac{\partial f}{\partial \mu}\right] + \frac{\dot{n}}{3n}p\frac{\partial f}{\partial p} = \frac{1}{p^2}\frac{\partial}{\partial p}\left(p^2 F_p\right) + \frac{\partial F_\mu}{\partial \mu},$$

where P_2 is the Legendre function of order 2 and

$$R \equiv \frac{2\dot{n}}{3n} - \frac{\dot{B}}{B}$$

The F represent diffusion in momentum space due to scattering.

Simplify & Take Fluid Approach

$$\frac{\partial\left(P_{\|}-P_{\perp}\right)}{\partial t}-\frac{8R}{5}U_c+3\nu\left(P_{\|}-P_{\perp}\right)=0,$$

ν is scattering frequency

$$\frac{\partial U_c}{\partial t}-\frac{\dot{n}}{n}(U_c+P_c)-R\left(P_{\|}-P_{\perp}\right)=2\int\Gamma(\omega,k)I(\omega,k)d\omega dk$$

Adiabatic response Gyroviscous heating **H** Energy transferred to waves

Cosmic Ray Energization

$$H = \frac{5}{48}\left(\frac{\delta P_c}{P_c}\right)^2 \nu U_c \equiv \frac{5}{48}\left(\frac{\zeta v_A}{c}\right)^2 \nu U_c$$

at marginal stability.

$$H_F = \frac{4}{3}\left(\frac{v_A}{c}\right)^2 \nu U_c$$

Gyroviscous heating H & Fermi acceleration due to gyroresonant scattering have same parametric dependences

Estimates

$$\frac{\delta P_c}{P_c} \rightarrow M_t k_{eff} \lambda$$

turbulent Mach number   spectrally weighted k

$$H \rightarrow \frac{5}{48} \zeta M_t k_{eff} v_A U_c$$

$$H_t \sim \rho k_0 M_t^3 c_s^3$$

Summary & Provisional Conclusions

- Turbulent compression and shearing can trigger cosmic ray pressure anisotropy instability of AU-scale Alfven waves.
- Scattering by the waves confines the cosmic rays, & drains a modest amount of energy from the turbulent cascade. Some of this heats the plasma and some is kept by the cosmic rays.