Collisionless MHD turbulence in the intracluster medium of galaxies

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Intracluster Medium is turbulent and magnetized

Major sources of turbulence:

- cosmological mergers of subclusters
- AGNs and galactic winds

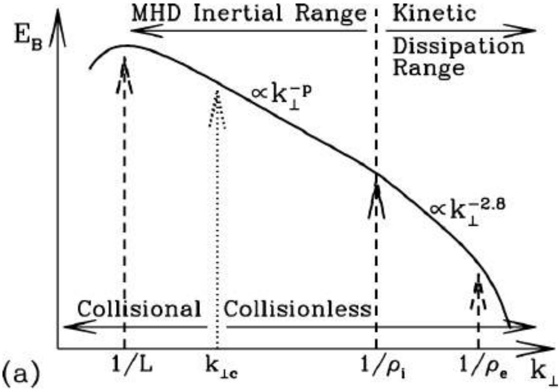
Origin of magnetic fields in the ICM: small-scale dynamo

MHD simulations of subclusters merger show the amplification of seed magnetic fields in the ICM until $\sim \mu$G (Kotarba et al. 2011).

(See K. Dolag's talk)

Seed fields: Biermann Battery, deposition by AGNs and galactic winds, primordial origin...

Turbulence cascade in the ICM



(from Howes 2012)

Scales

$L_{turb} \sim 500$ kpc

$\lambda_i \sim 30$ kpc

$\rho_i \sim 10^5$ km

$\rho_e \sim 10^3$ km

Collisionless plasma effects in the ICM

ICM collisionless scales:

- Large scale motions (turbulence) $+$ conservation of magnetic moment of charged particles $\rightarrow$ anisotropy in the thermal velocities distribution;
- Anisotropy in the thermal velocities distribution $\rightarrow$ instabilities;
- Instabilities important for ions: ion-cyclotron, mirror, firehose;
- Maximum linear growth rate for unstable modes at scales $\sim$ ion Larmor radius;

What is the role of the above collisionless effects in the ICM dynamics?

Collisionless MHD: two-temperature description

- Collisions frequency not high enough to relax the ions velocity distribution to a Maxwellian during dynamical time scales;
- Better approximation: bi-Maxwellian (two temperatures);
- Thermal pressure tensor: $P_{ij} = p_\perp \delta_{ij} + (p_\parallel - p_\perp)\mathbf{b}_i\mathbf{b}_j$;
- Mirror and firehose instabilities present in the **anisotropic** (two-temperature) MHD fluid description:

$$\frac{\partial}{\partial t}\begin{bmatrix}\rho \\ \rho\mathbf{u} \\ \mathbf{B}\end{bmatrix} + \nabla\cdot\begin{bmatrix}\rho\mathbf{u} \\ \rho\mathbf{uu} + \Pi_P + \Pi_B \\ \mathbf{Bu} - \mathbf{uB}\end{bmatrix} = \begin{bmatrix}0 \\ \mathbf{f} \\ 0\end{bmatrix}$$

$$\Pi_P = p_\perp \mathbf{I} + (p_\parallel - p_\perp)\mathbf{bb}, \quad \Pi_B = (B^2/8\pi)\mathbf{I} - \mathbf{BB}/4\pi$$

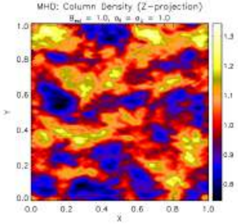
(G. Kowal's talk)

Collisionless MHD: double isothermal closure

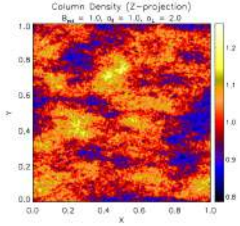
$$p_\perp = c_\perp^2 \rho \qquad p_\parallel = c_\parallel^2 \rho$$

Kowal, Falceta-Gonçalves & Lazarian (2011)

MHD

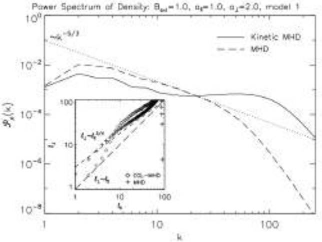


Mirror



$(c_\perp / c_\parallel = 2$, trans-S, sub-A)

Velocity power spectrum



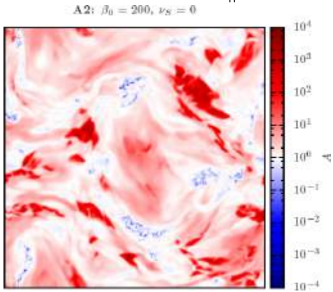
Collisionless MHD: CGL closure

Conservation of particles magnetic momentum and entropy

$$\frac{d}{dt}\left(\frac{p_\perp}{\rho B}\right) = 0 \qquad \frac{d}{dt}\left(\frac{p_\parallel B^2}{\rho^3}\right) = 0$$

(Chew, Goldberger & Low 1956)

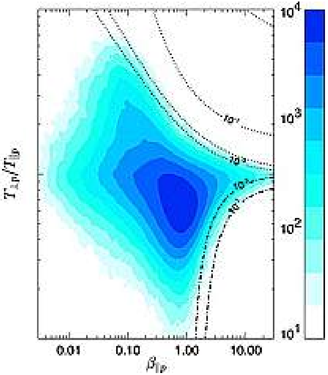
$$A = T_\perp / T_\parallel$$



(Santos-Lima et al. 2014)

Instabilities feedback

- Anisotropy in pressure/temperature observed to saturate in solar wind, plasma experiments and PIC simulatons (Marsh 2006, Keiter 1999, Riquelme et al. 2012)



(from Hellinger et al. 2006)

Collisionless MHD: CGL + scattering

- Electromagnetic fluctuations from the instabilities scatter particles, reducing anisotropy.

Bounded Anisotropy model (Denton et al. 1994)

$$\frac{dT_\perp}{dt} = \left(\frac{dT_\perp}{dt}\right)_{CGL} + \nu_S \left(T_\parallel - T_\perp\right)$$

$$\frac{dT_\parallel}{dt} = \left(\frac{dT_\parallel}{dt}\right)_{CGL} + 2\nu_S \left(T_\perp - T_\parallel\right)$$

- $\nu_S \left(B, T_\perp, T_\parallel\right)$ has to be determined by theory or kinetic calculations for each instability;

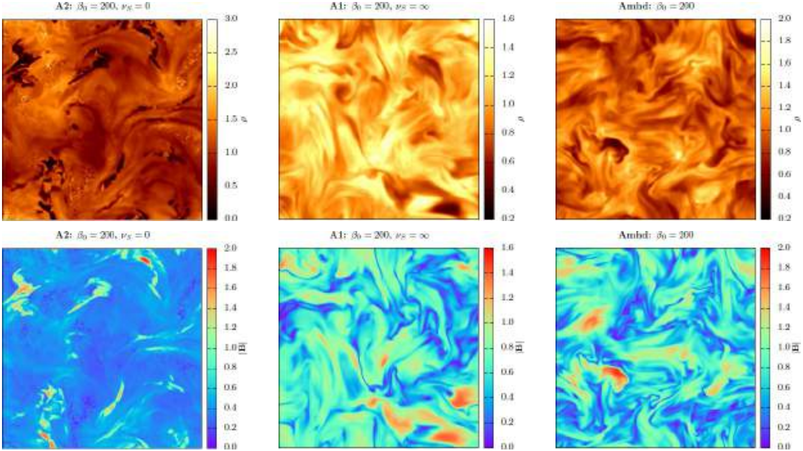
Collisionless MHD turbulence: numerical simulations

Santos-Lima, de Gouveia Dal Pino, Kowal, Falceta-Gonçalves, Lazarian, Nakwacki (2014)

Turbulence and small-scale dynamo in the intra-cluster medium:

- Modified Godunov code (Kowal et al. 2011);
- Forced turbulence (trans-sonic, super-Alfvenic) in a periodic box;
- $\beta_0 = 200$;
- Parameter study of the ions scattering: from $\nu_S = 0$ (CGL-MHD) to $\nu_S = \infty$

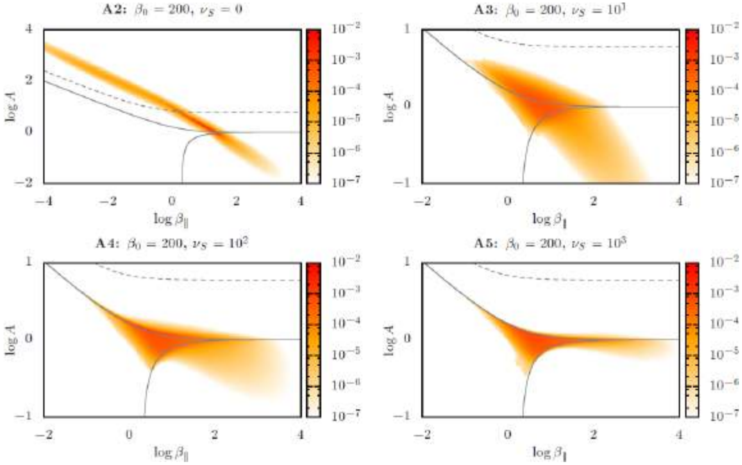
Collisionless MHD turbulence: numerical simulations



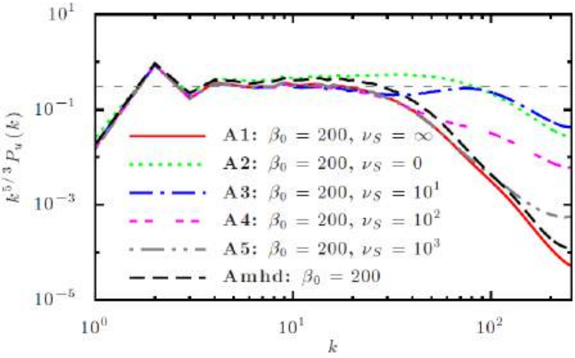
collisionless MHD no relaxation (CGL) | **collisionless MHD instant. relaxation** | **MHD**

Collisionless MHD turbulence: numerical simulations

$$\text{Log } p_{\|}/(B^2/8\pi) \quad \text{X} \quad \text{Log } T_{\perp}/T_{\|}$$



Velocity power spectrum ($\times k^{5/3}$)



MHD

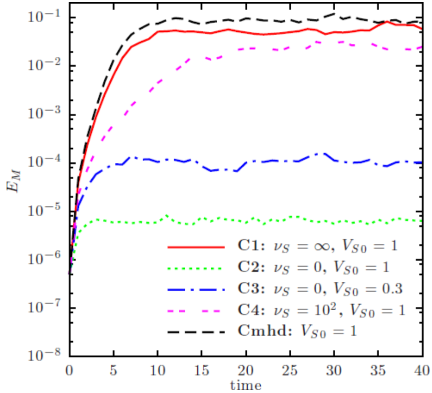
no relaxation (CGL)
$\nu_S = 0$

finite relaxation
$\nu_S \sim 10^1\ t_{turb}^{-1}$

finite relaxation
$\nu_S \sim 10^2\ t_{turb}^{-1}$

instant. relaxation
$\nu_S = \infty$

Time evolution of the magnetic energy



MHD

no relaxation (CGL)
$\nu_S = 0$

no relaxation (CGL)
$\nu_S = 0$, **supersonic**

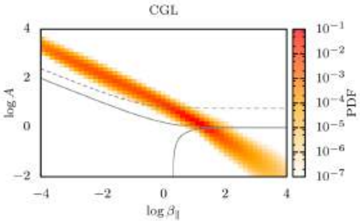
finite relaxation
$\nu_S \sim 10^2\ t_{turb}^{-1}$

instant. relaxation
$\nu_S = \infty$

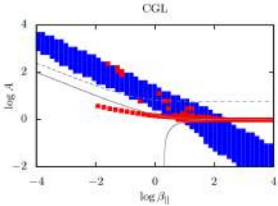
Ions scattering rate: quasi-linear calculations

- Scattering of ions by the parallel ion-cyclotron + parallel firehose modes

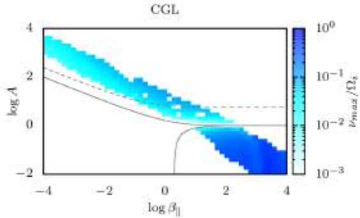
initial parameters



after 2000 Larmor periods



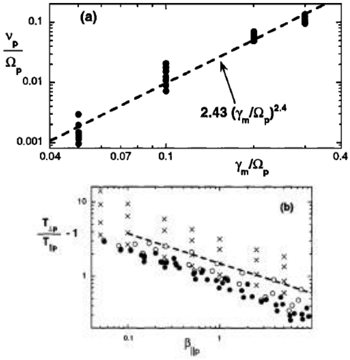
max. scattering rates



ICM:
$\Omega_i \sim 10^{-2}$ rad/sec
$\tau_{turb}^{-1} \sim 10^{-16}$ sec

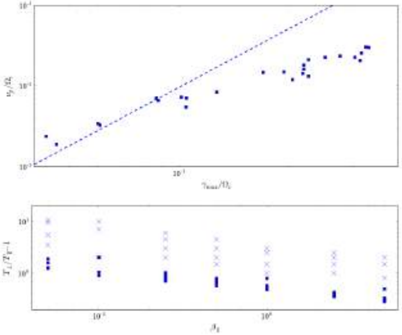
($B \sim 1\ \mu$G,
$L_{turb} \sim 500$ kpc,
$U_{turb} \sim 10^3$ km/s)

2D PIC



(from Gary et al. 2000)

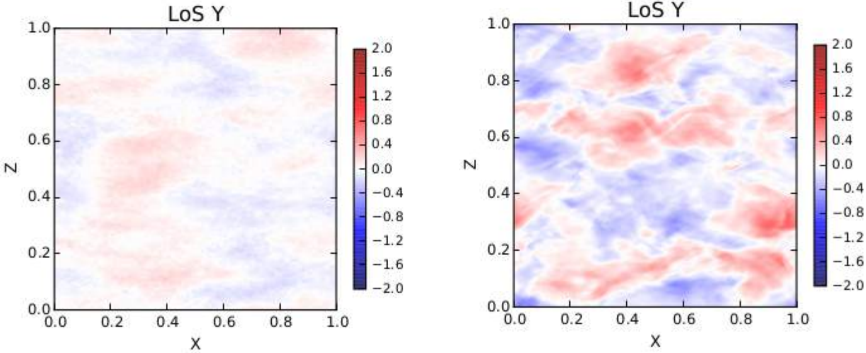
Quasi-linear (ion-cyclotron modes only)



Synthetic RM maps (1): constant temperatures models

- Faraday screen: periodic data cubes with double isothermal MHD turbulence models (Kowal et al. 2011);
- Effects of large (fluid) scales instabilities.

Mirror ($c_\perp / c_\parallel = 2$, trans-S, sub-A) **MHD**

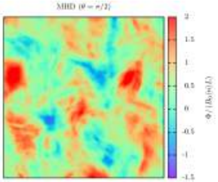


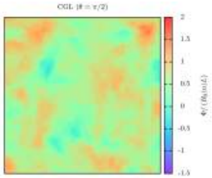
(Nakwacki, Kowal, Santos-Lima, de Gouveia Dal Pino, Falceta-Gonçalves, 2015)

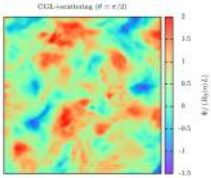
Synthetic RM maps (2): CGL + scattering models

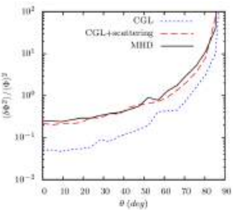
- Faraday screen: periodic data cubes with CGL-MHD (+ scattering) turbulence models (Santos-Lima et al. 2014);
- Effects of the particles scattering.

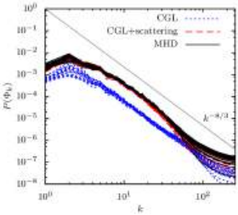
($\beta_0 = 200$, sub-S, super-A)











Summary

- Collisionless MHD models for the ICM: two temperatures $\rightarrow$ coupling between thermal and magnetic stresses $\rightarrow$ firehose and mirror instabilities;
- Development of temperature anisotropies due to local changes of $(\mathbf{B}, \rho)$ $+$ scattering of ions by the plasma instabilities at the kinetic scales;
- Limit of fast scattering of ions:
  - temperature anisotropy is pushed to marginal stability levels;
  - the turbulence statistics and magnetic field amplification $\approx$ one temperature MHD;
  - statistics of RM maps $\approx$ one temperature MHD;
- Limit of no scattering of ions:
  - most of plasma inside unstable regime, predominance of $T_\perp > T_\parallel$;
  - turbulence statistics $\rightarrow$ deviation from one temperature MHD;
  - **no** magnetic field amplification via small-scale dynamo;
  - statistics of the RM maps $\rightarrow$ smaller dispersion, changes in power spectrum;
- Quasi-linear plasma calculations point to **fast** scattering of ions.