Recent achievements on KMHD

and applications in the ICM

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Turbulence understanding have greatly improved in the past years;

Aims: understanding of energy transfer (scales) and diffusion of matter in the ISM

"direct" comparison of observables :

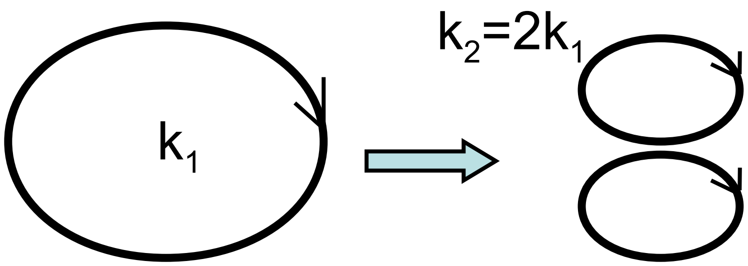
velocity (Esquivel et al. + Pogosian et al. + Falceta-Goncalves et al.)

density (Kowal et al. + Burkhart et al.)

magnetic fields (Falceta-Goncalves et al. + Falgarone et al. + Heitch et al.)

Turbulence: *Kolmogorov's theory*

incompressible fluids:
Homogeneity + Isotropy + Scale invariance + Locality



Energy "flows" from large to small scales: $\dot{\varepsilon} \approx \delta v_l^{\,2} / \tau_l$

being $\tau_l \approx l / \delta v_l$, ***therefore*** $\delta v_l \approx (\dot{\varepsilon} l)^{1/3}$ ***and, since***

$\delta v_l^{\,2} \approx \int_{k=1/l}^{\infty} E(k')dk'$, ***we get*** $E(k) \approx \dot{\varepsilon}^{\,2/3} k^{-5/3}$

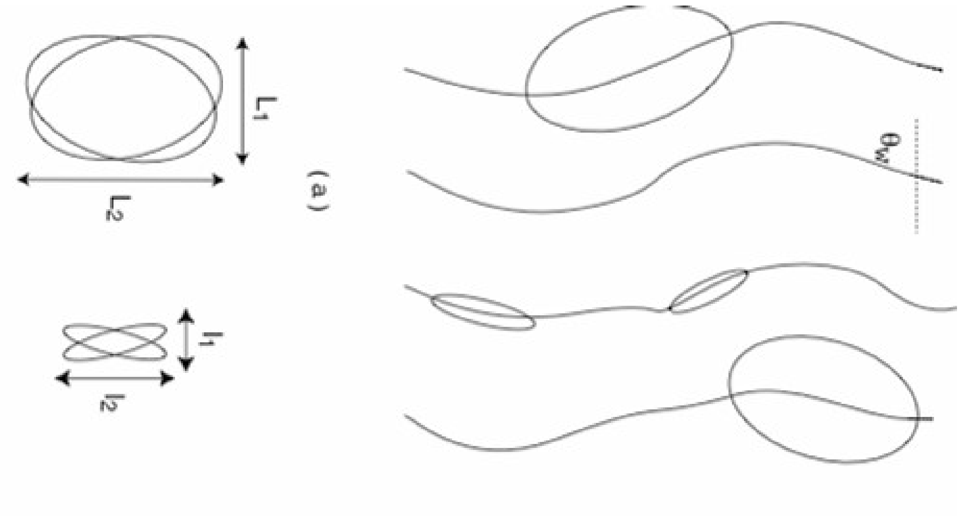
Magnetized Turbulence: *Goldreich-Sridhar theory*

strong wave-wave interactions

Anisotropy!

$$\tau_A \sim \tau_s \quad \Leftrightarrow \quad l_\parallel / l_\perp \sim v_A / \delta u_l \qquad l_\parallel \sim v_A \epsilon^{-1/3} l_\perp^{2/3} \sim k_{\parallel 0}^{-1} (l_\perp / l_*)^{2/3}$$

Kolmogorov spectrum for perpendicular direction



Anisotropy is: SCALE-DEPENDENT and LOCAL

	L	λ_{mfp}	ρ_{ion}
ISM	10^2 pc	10 AU	10^5 km
ICM	100 kpc	1kpc	10^6 km

← Fluid → Kinetic → E-MHD

Fluid **Kinetic** **E-MHD**

ISM	$\nu_{ii} >> \Omega$	**Maxwellian dist.**
ICM	$\nu_{ii} << \Omega$	**Anisotropic pressure**

Modeling collisionless plasma

... under fluid approximation

In the collisionless regime **moments of Vlasov equation**

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \boldsymbol{v}) = 0,$$

$$\frac{\partial \rho \boldsymbol{v}}{\partial t} + \nabla \cdot \left[\rho \boldsymbol{v}\boldsymbol{v} + \left(\mathsf{P} + \frac{B^2}{8\pi}\right) I - \frac{1}{4\pi}\boldsymbol{B}\boldsymbol{B}\right] = \boldsymbol{f},$$

$$\frac{\partial \boldsymbol{B}}{\partial t} - \nabla \times (\boldsymbol{v} \times \boldsymbol{B}) = 0,$$

$$\mathsf{P} = p_\perp \hat{I} + (p_\parallel - p_\perp)\hat{b}\hat{b}$$

Closure

$$\frac{\partial S_\perp}{\partial t} + \nabla \cdot (S_\perp \boldsymbol{v}) = 0, \qquad S_\perp = p_\perp B^{1-\gamma_\perp}$$

$$\frac{\partial S_\parallel}{\partial t} + \nabla \cdot \left(S_\parallel \boldsymbol{v}\right) = 0, \qquad S_\parallel = p_\parallel \left(B/\rho\right)^{\gamma_\parallel - 1}$$

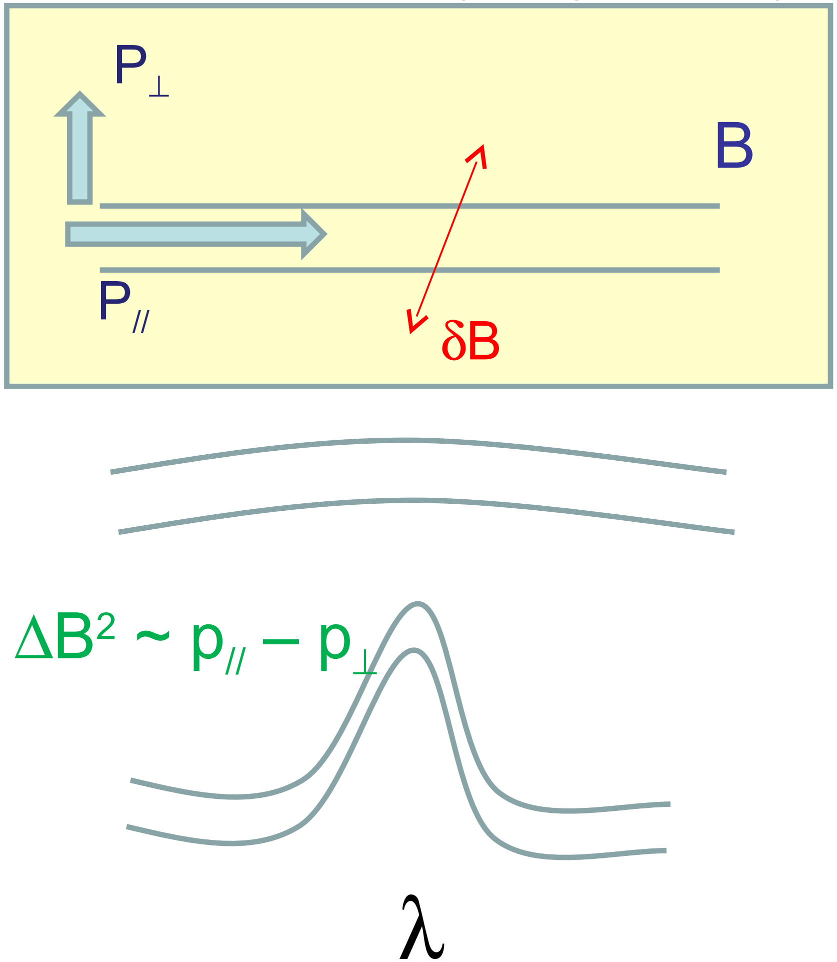
(Chew, Goldberger, Low 1956)

Instabilities: $\beta_{//} > 2\beta_\perp$ $\delta p_\perp \sim (1 - T_\perp / T_{//})\,\delta B$

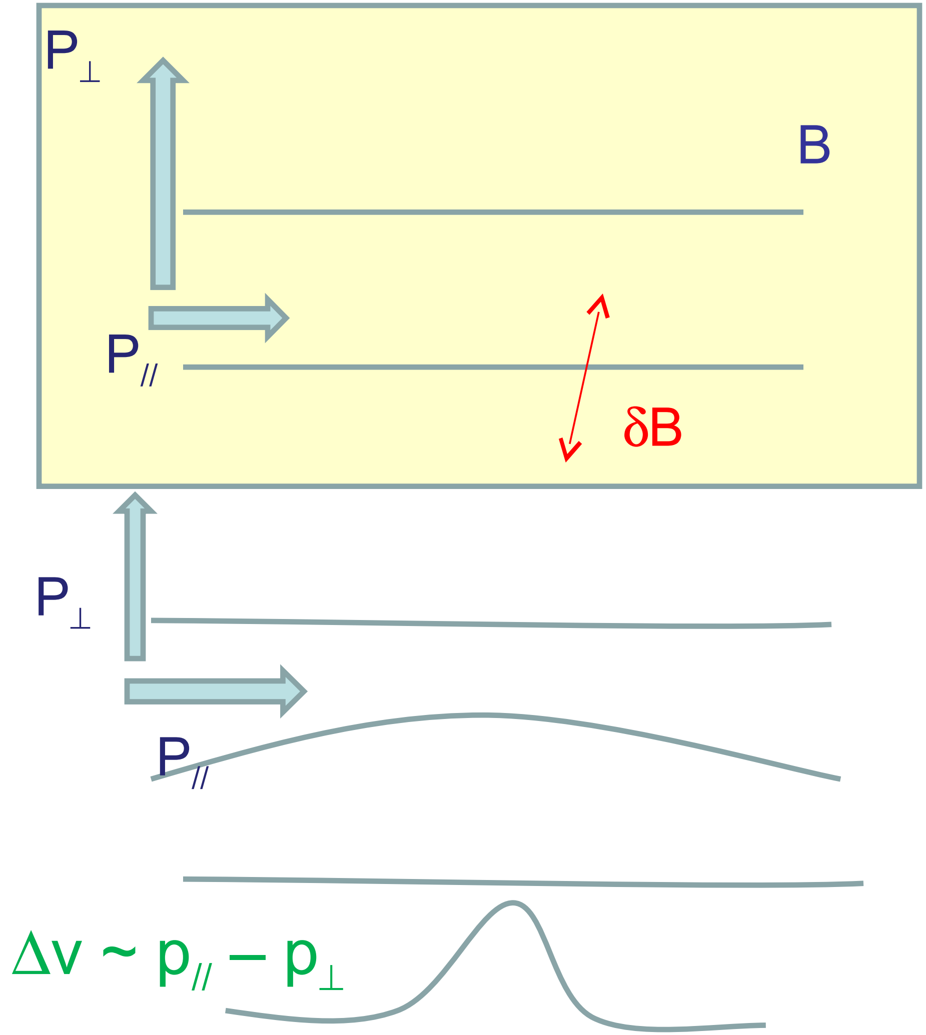
Double-isothermal case (the simplest case – not much):

$$p_\perp = a_\perp^2 \rho \text{ and } p_\parallel = a_\parallel^2 \rho$$

Instabilities (Hasegawa 1969):



Firehose



Mirror

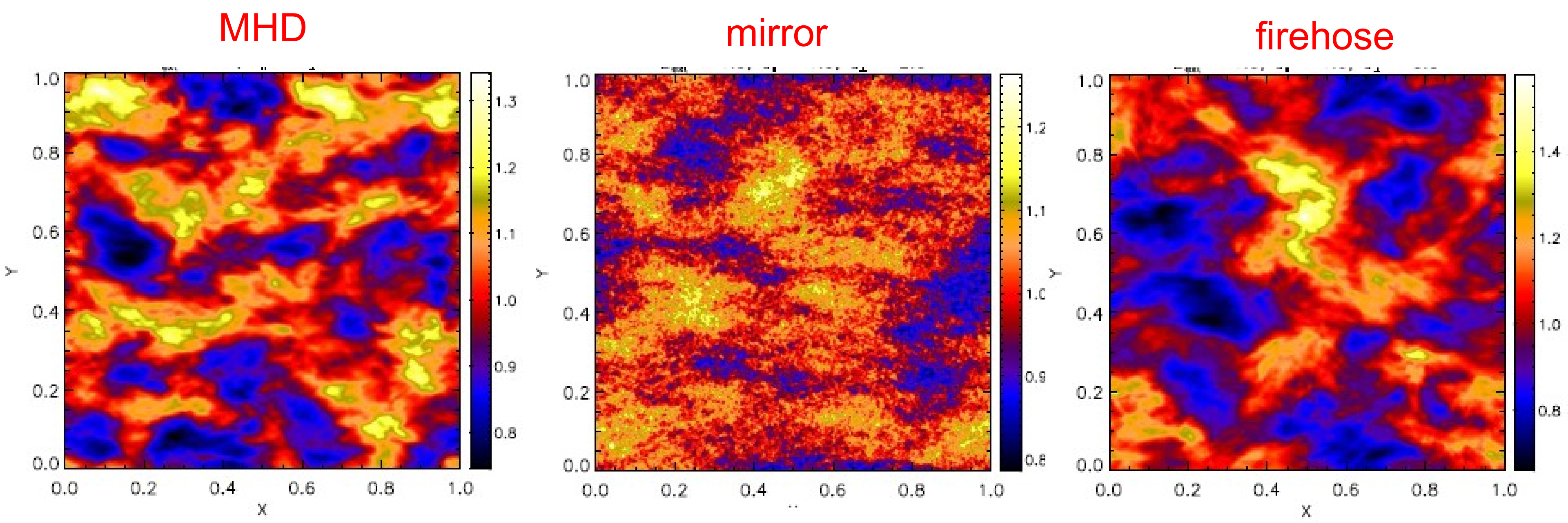
Kowal, Falceta-Goncalves & Lazarian 2011

Model	B_0	$a_{\|}$	$a_{\perp}$	$\xi \equiv a_{\|}^2/a_{\perp}^2$	$\mathcal{M}_s \equiv \langle \|v\|/a_{\perp} \rangle$	$\mathcal{M}_A \equiv \langle \|v\|/c_A \rangle$
1	1.0	1.0	2.0	0.25	0.7	0.7
2	1.0	1.0	0.5	4.00	0.7	0.7
3	0.1	0.1	0.2	0.25	7.0	2.0
4	0.1	0.1	0.05	4.00	7.0	2.0
5	0.1	1.0	0.5	4.00	0.7	2.0
6	1.0	0.1	0.2	0.25	7.0	0.7

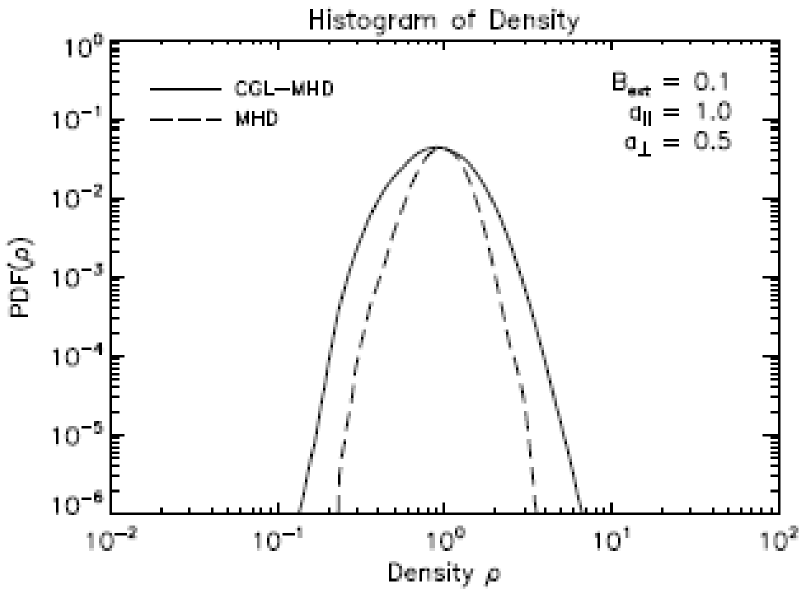
Res = 256^3 512^3 1024^3

- **Subsonic (supersonic) sub-alfvenic (super-alfvenic)**
- **Firehose / mirror-unstable**

Sub-alfvenic (super-alfvenic are quite similar)

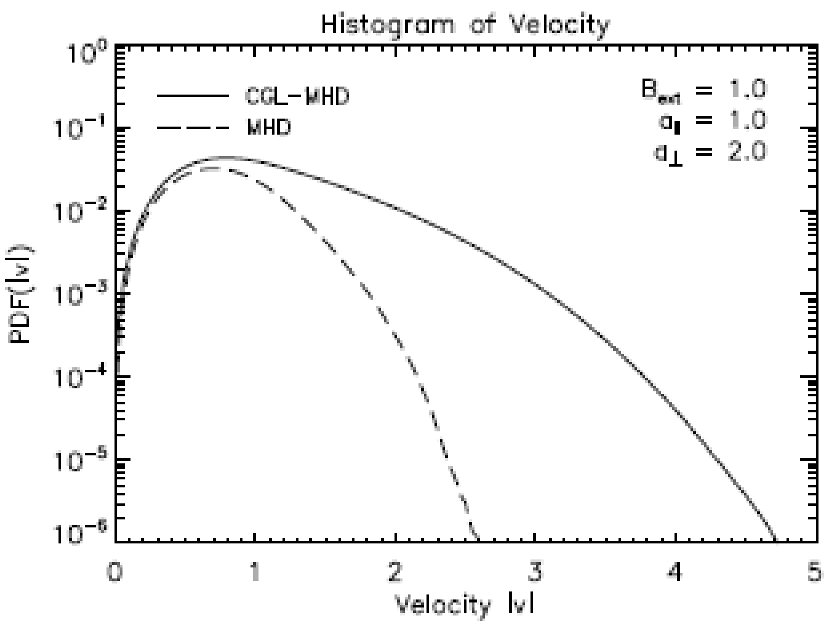


Density and Velocity PDFs

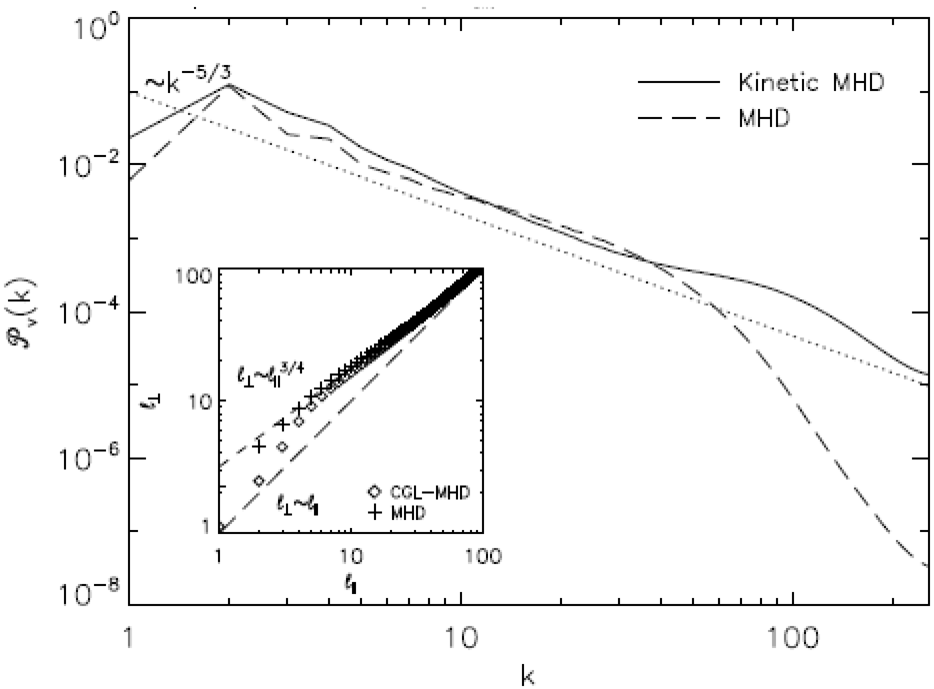


firehose

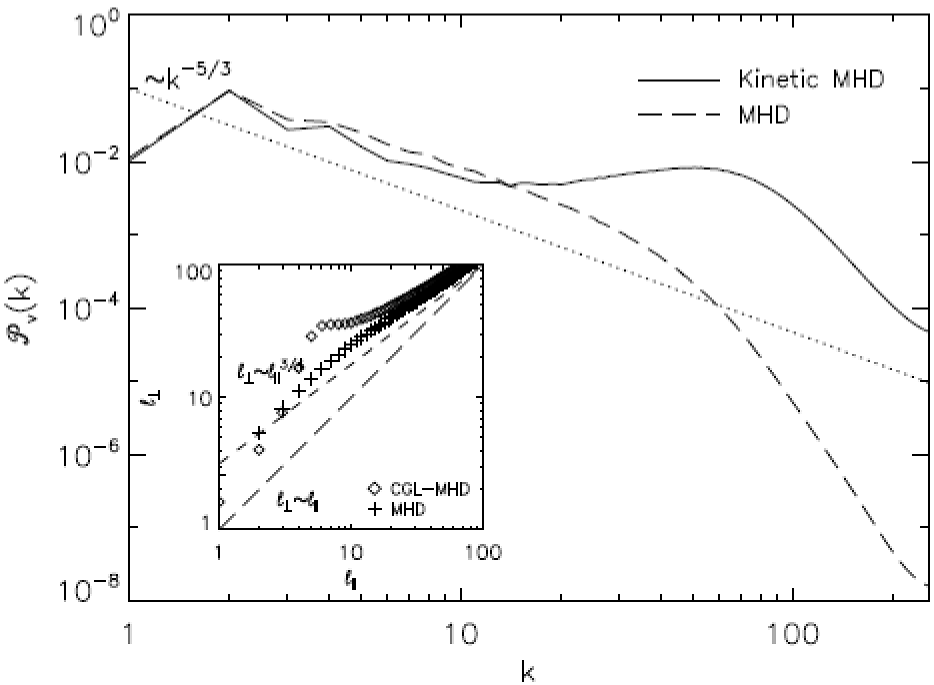
mirror



Spectra of velocity

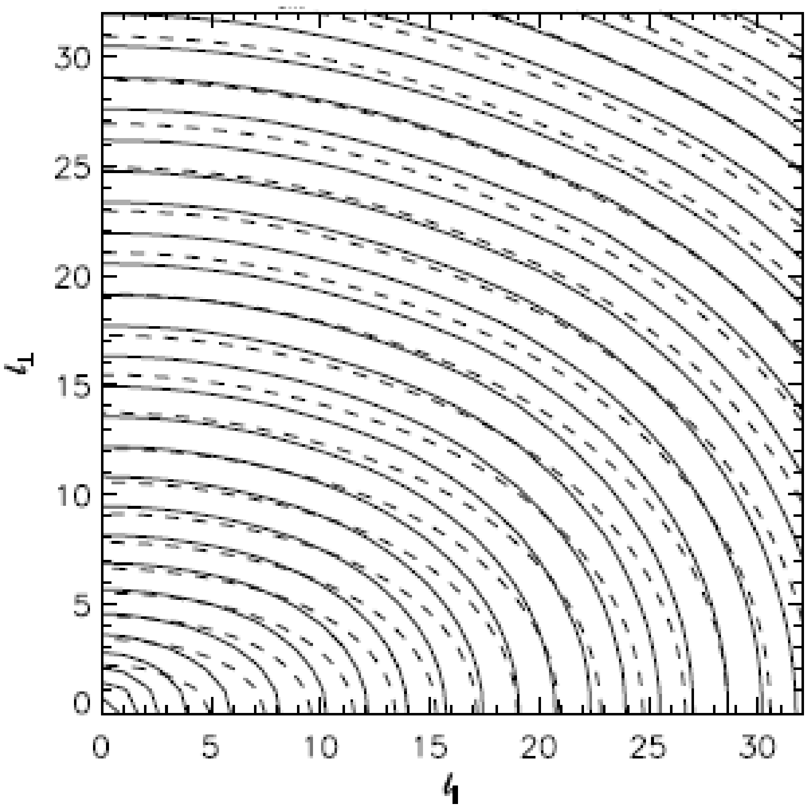


firehose

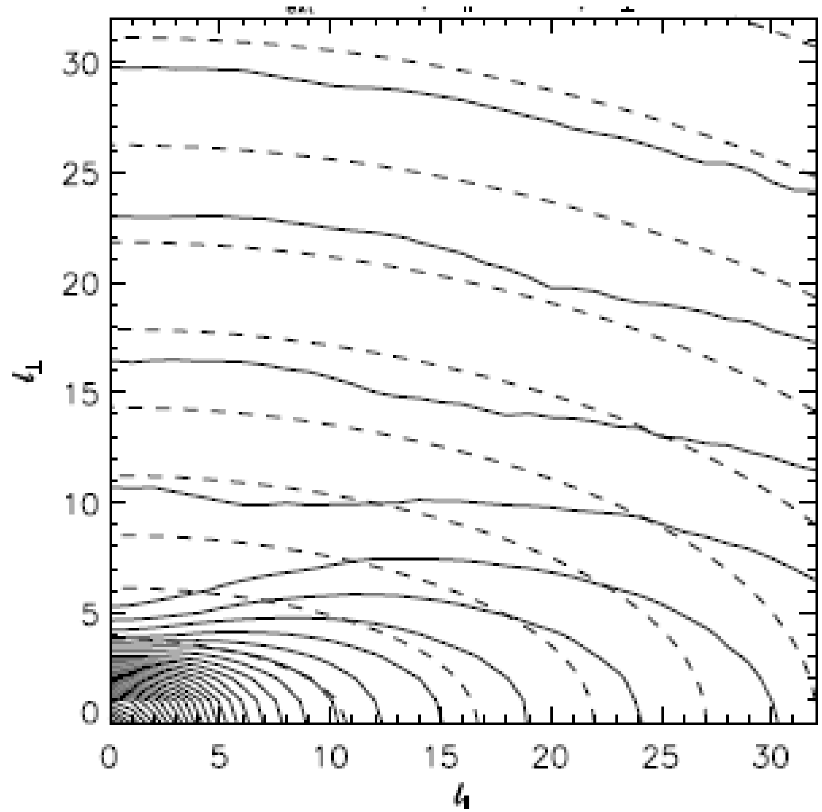


mirror

2nd order structure function



firehose



mirror

Saturation of instability is fast!

$$\tau_{sat} \sim 0.1\ \tau_{dyn}\ (<< \tau_{alf})$$

CGL-MHD turbulent dynamo (can be) is faster than MHD turbulent dynamo (do not miss Santos-Lima's talk)

Caveat: double-isothermal closure

External/internal processes could sustain pressure anisotropy (cosmic rays, anisotropic heat conduction, etc.)

The Intracluster medium

... best application

The ICM and the cluster total mass

Usually, the ICM is believed to be in quasi-equilibrium :

$$\nabla P = -\rho \nabla \Phi$$

$$M(r) = -3.68 \times 10^{13} T(r) r \left(\frac{d \log \rho_{gas}}{d \log r} + \frac{d \log T}{d \log r} \right)$$

Sarazin (1988)

Density profile

For an isothermal plasma (isotropic), the emission is free-free:

Cavaliere & Fusco-Femiano (1978)

$$\Sigma(r) = \Sigma_0\left(1+\frac{r^2}{r_c^2}\right)^{-3\beta+1/2} \longrightarrow n_e(r) = n_0\left(1+\frac{r^2}{r_c^2}\right)^{-3\beta/2}$$

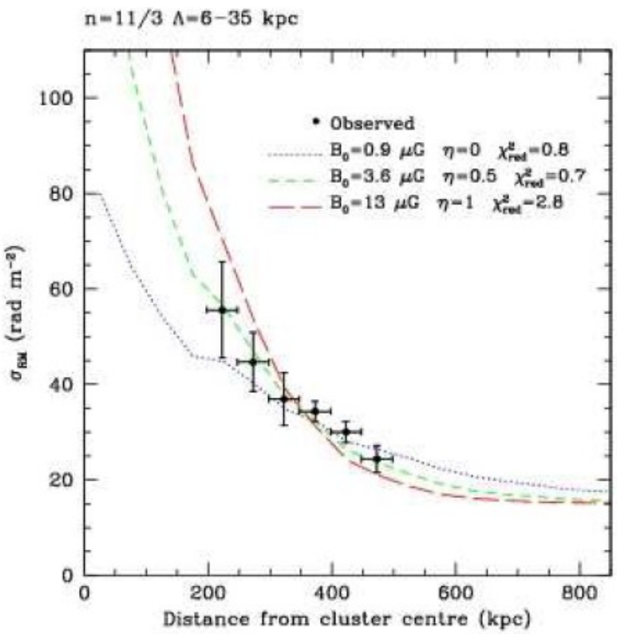
Vikhlinin et al. (2006)

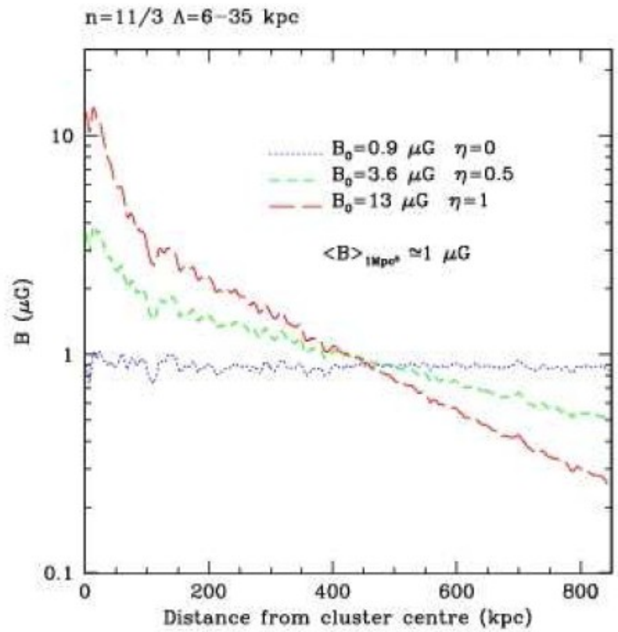
Relaxed clusters present cusps at central region, so the β model is not the best option

Faraday Rotation in the ICM

$$\psi_{obs} = \psi_{in} + \lambda^2 RM$$

$$RM \cong 812 \int_0^{L(kpc)} n_e(cm^{-3}) B_{//}(\mu G) dl \qquad (rad/m^2)$$





Guidetti et al. 2008

$$n(r) = n_0 \left(1 + \frac{r^2}{r_c^2}\right)^{-\frac{3}{2}\beta}$$

+

$$B(r) \propto n(r)^\eta$$

Turbulence in the ICM

$$K \approx \frac{U_g}{2} \qquad T \approx 10^{7-8} K$$

$$\sigma \approx 700 - 1000 \ \ km/s \qquad c_s \approx 300 - 1000 \ \ km/s$$

Subsonic (or mildly supersonic)

Injection scales ~ few hundreds of kiloparsecs

Total energy ~ 10^{63} ergs

Energy density ~ 10^{-11} erg/cm^3

KHMD models

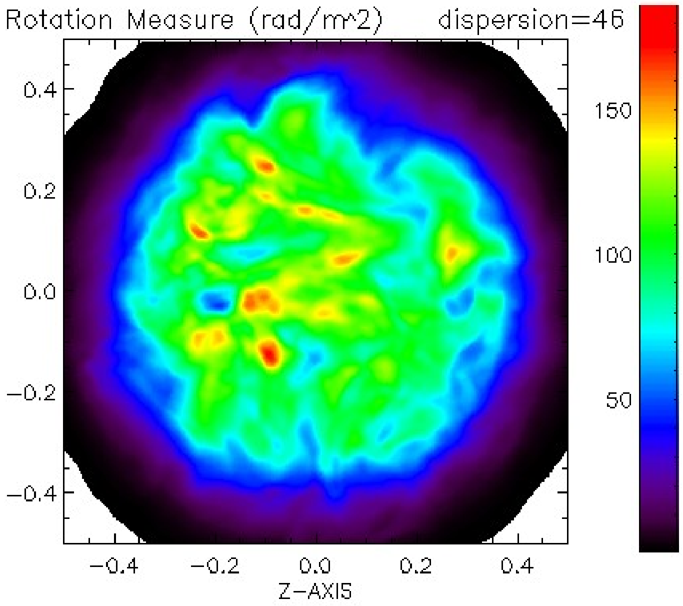
Probing magnetic fields

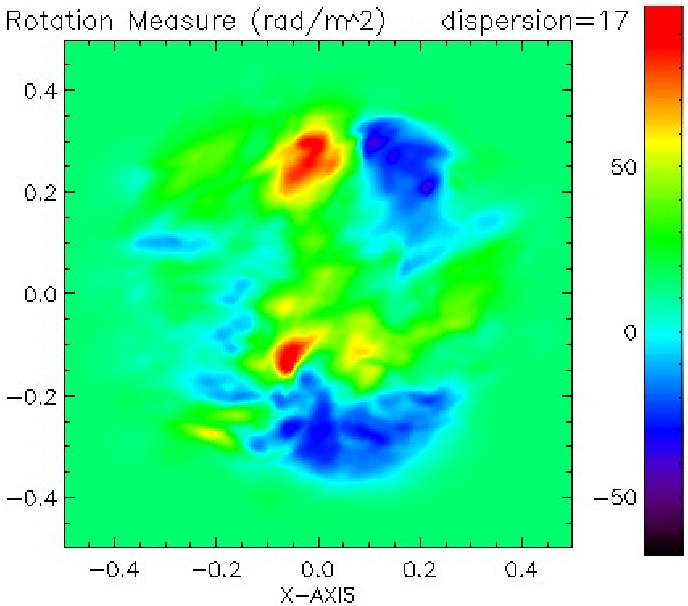
... or turbulent modes

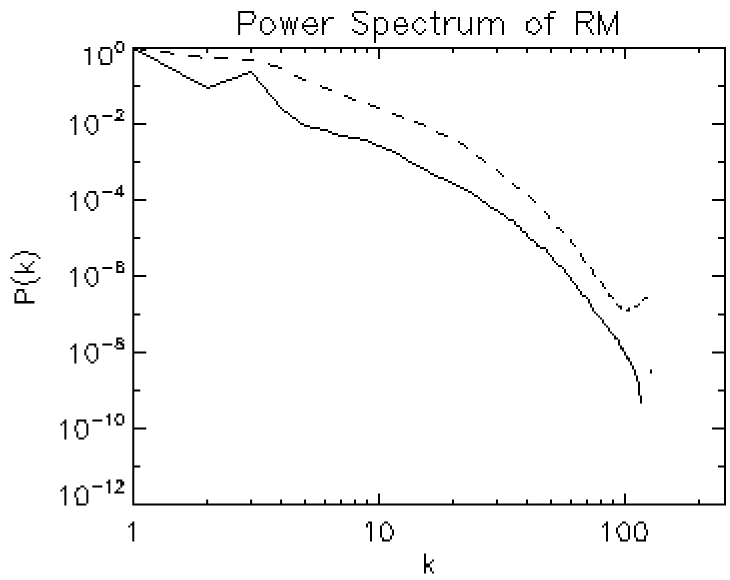
MHD

- B ~ 0.1μG
- L ~ 1Mpc
- n ~ 0.01cm^{-3}

- MHD is smooth

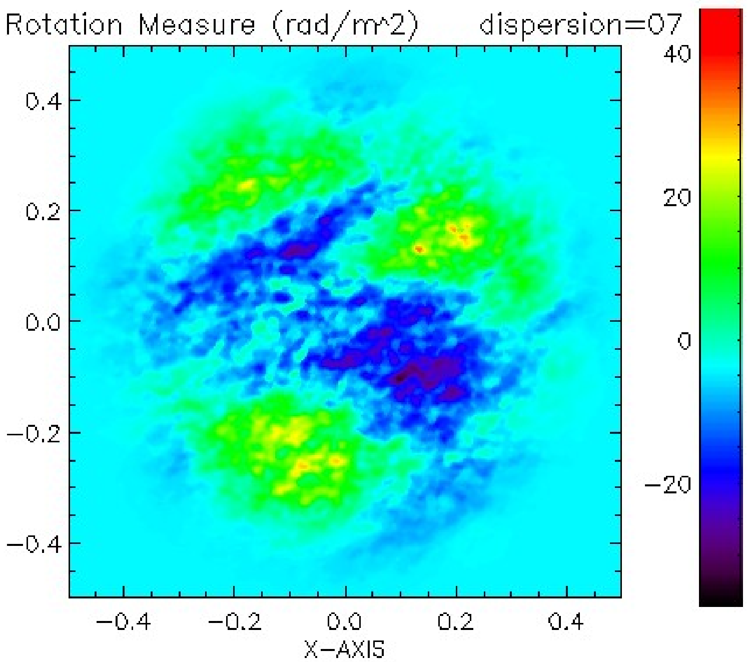


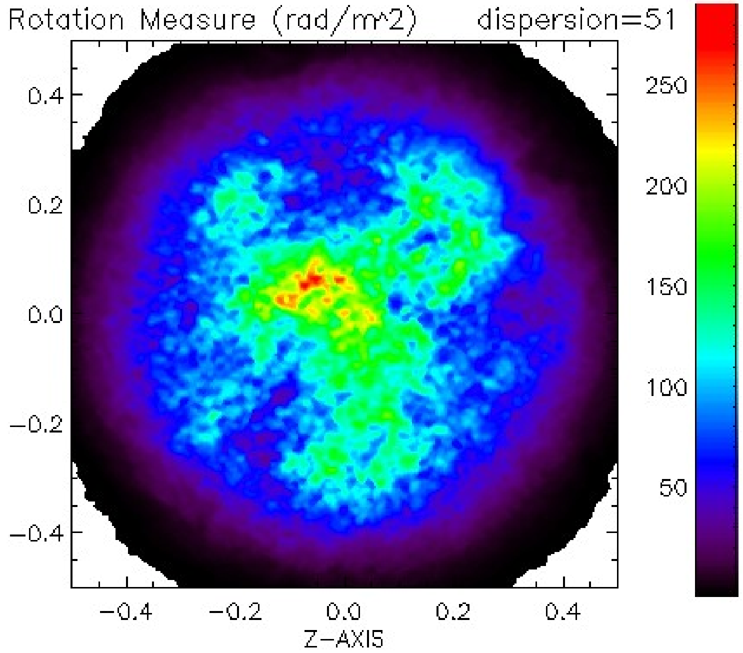


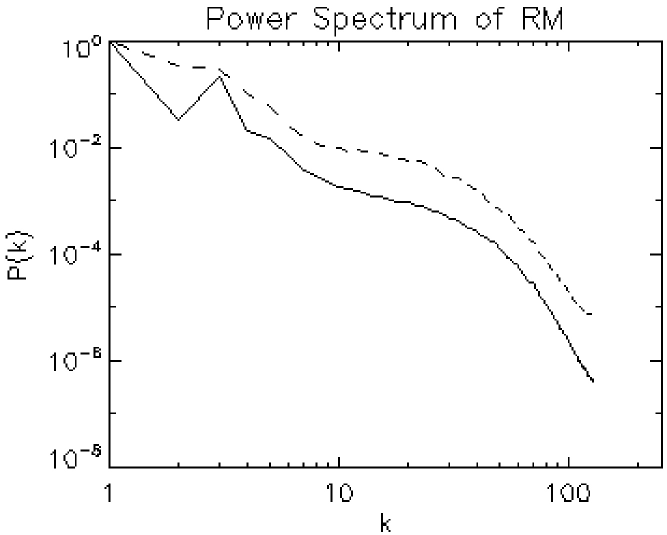


CGL-MHD

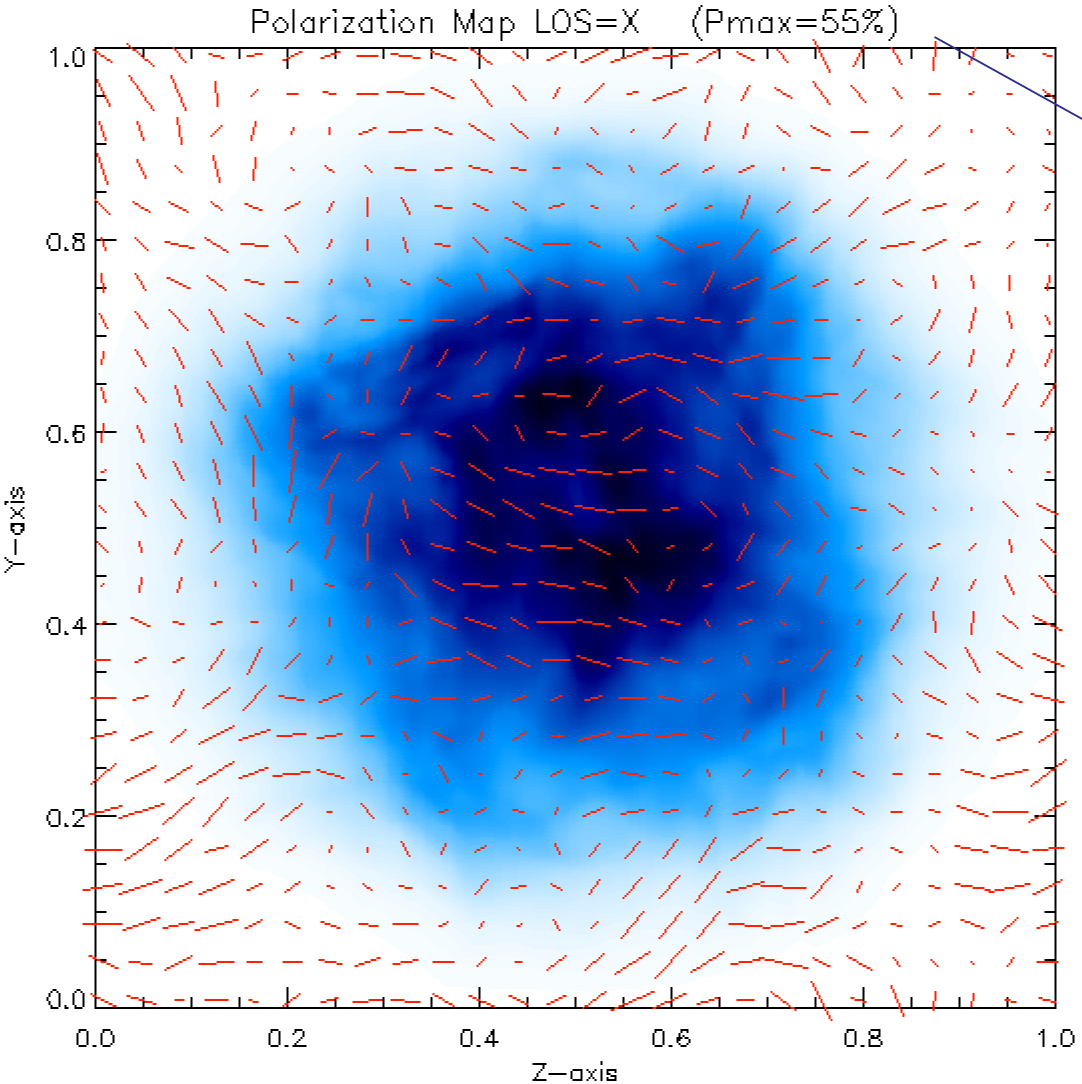
- Compared to the MHD case, power in small scale is increased;
- In the mirror case, RM intensity does not change much;
- In Firehose unstable scenario, RM decreases ~ 30 – 70 %







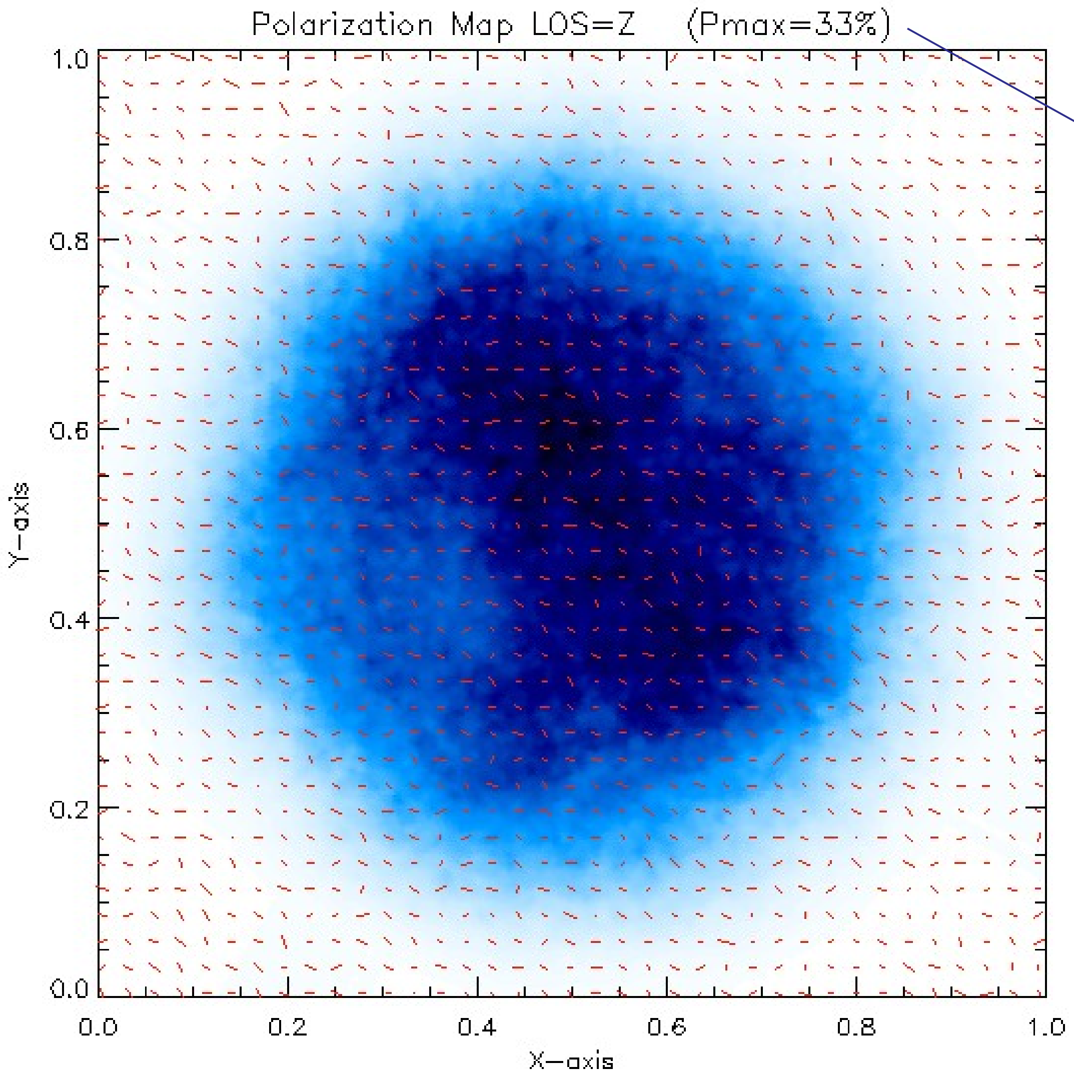
MHD



- Polarization degree is slightly reduced
- due to the turbulence mostly

(Falceta-Gonçalves et al. 2008)

CGL-MHD



- Polarization degree is reduced in the Firehose unstable regime
- Cause is the decrease of the decorrelation length due to the instabilities

Conclusions

Some kinetic effects taken into account may change the dynamics of the plasma;

Depending on the regime, fast increase of magnetic field may take place;

As well as acceleration (fluid motions);

These occur at smaller scales;

Result in modifications of statistics of RM and synchrotron polarization

May increase reconnection rate and particle acceleration (seed for 2nd order Fermi)