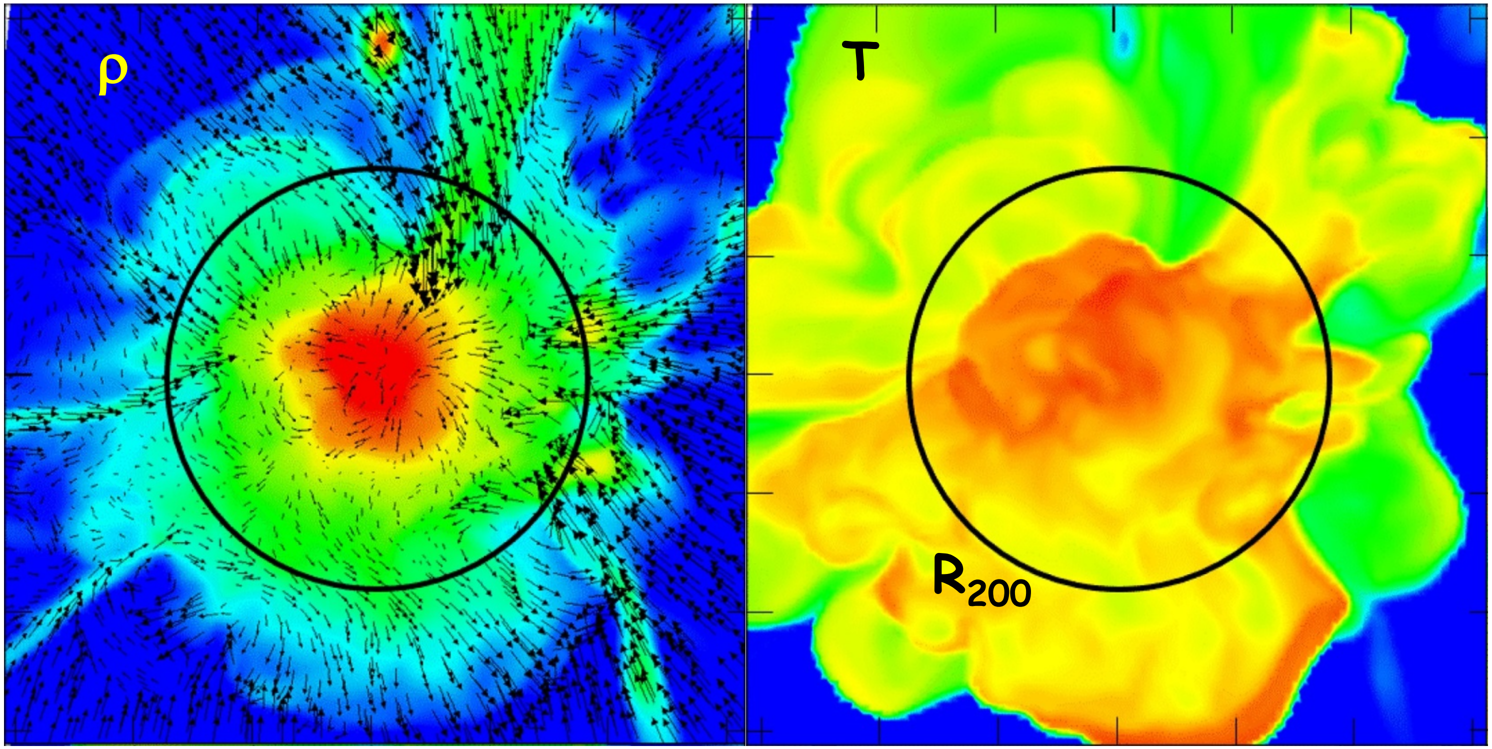
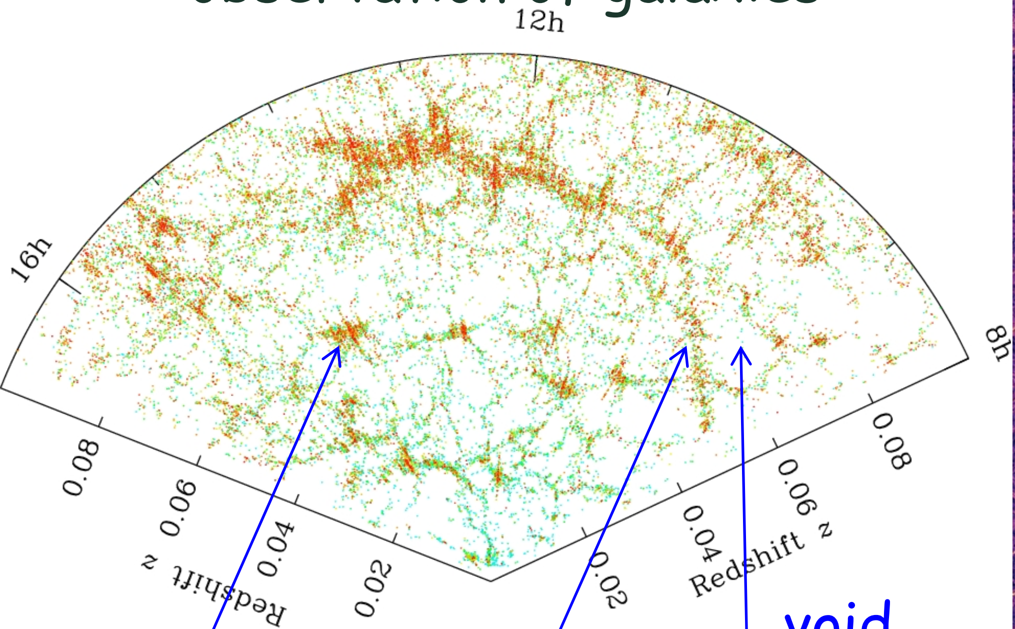
Turbulence (and Shock Waves) in Clusters of Galaxies



Dongsu Ryu (Ulsan National Institute of Science and Technology, Korea)
Hyesung Kang (Pusan National University, Korea),
Jungyeon Cho (Chunganam National University, Korea),
etc

The large-scale structure of the universe

observation of galaxies

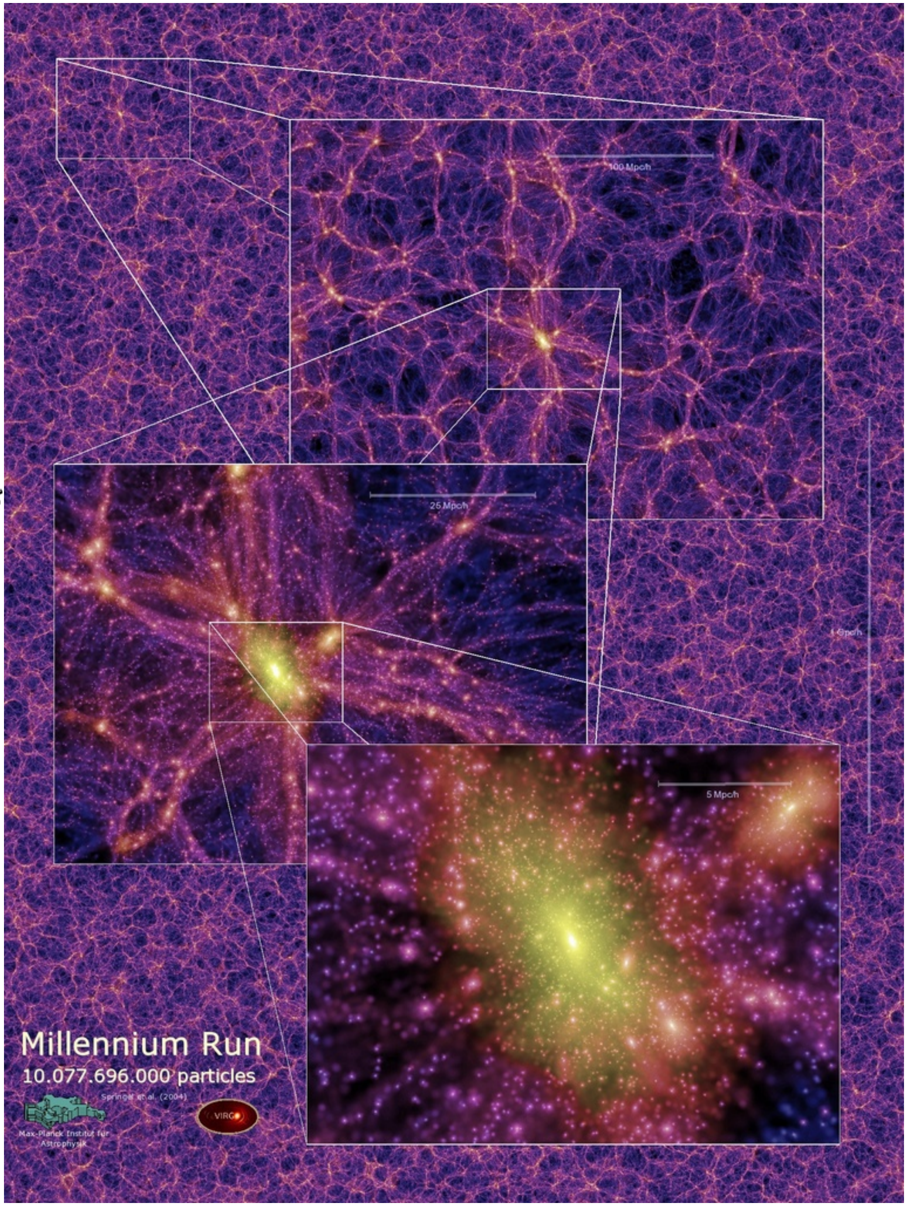


clusters of galaxies

filaments

void regions

→ the cosmic web

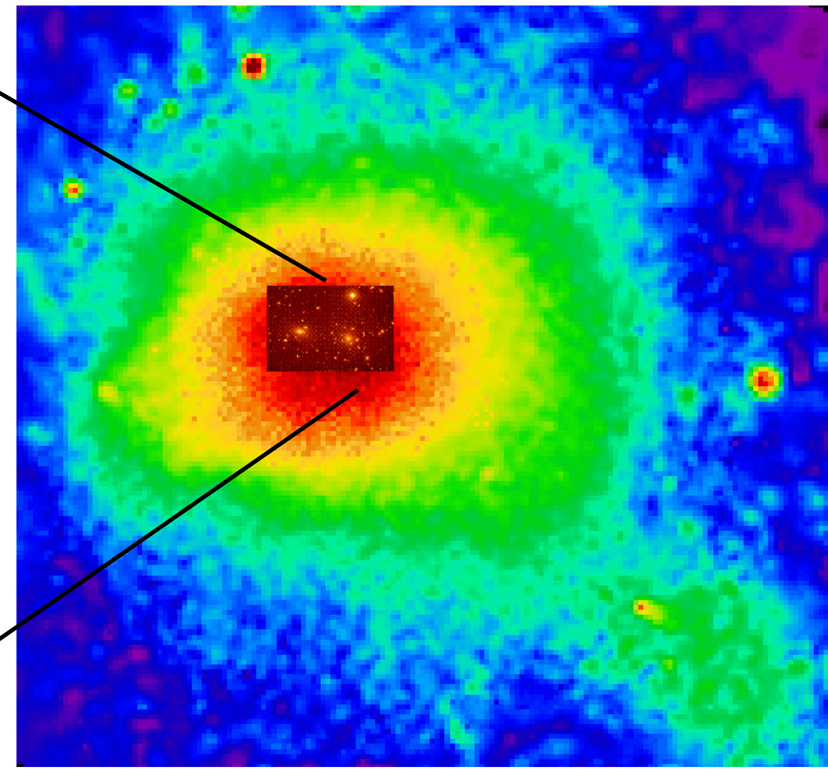


simulated matter distribution

Clusters of galaxies → aggregates of galaxies, which are the largest known gravitationally bound objects to have arisen thus far in the process of cosmic structure formation

Coma Cluster

in visible (core region) <- star light



in X-ray <- hot gas of T ~ 8 keV

The intracluster medium (ICM) → the superheated plasma with T ~ a few to several keV, presented in clusters of galaxies

Physical quantities in clusters of galaxies

size of clusters	$L \sim \text{a few Mpc} \sim 10^{7}\ \text{lyrs}$
density of baryonic matter	$n \sim 10^{-2}\,\text{cm}^{-3}$
flow velocity	$\upsilon \sim \text{several} \times 10^{2}\ \text{km/s}$
gas temperature	$T \sim 10^{8}\,\text{K}$
magnetic fields	$B \sim \text{a few}\ \mu\text{G}$

Energetics

gas thermal energy	$E_{\text{thermal}} \sim 10^{-10}\,\text{erg/cm}^{3}$
gas kinetic energy	$E_{\text{kinetic}} \sim 10^{-11}\,\text{erg/cm}^{3}$
cosmic-ray energy	$E_{\text{cosmic-ray}} \sim \text{a few} \times 10^{-12}\,\text{erg/cm}^{3}$
magnetic energy	$E_{\text{magnetic}} \sim \text{a few} \times 10^{-12}\,\text{erg/cm}^{3}$

intracluster media contain plasmas with $\beta \sim 100$ $\left(\beta \equiv \dfrac{P_{\text{gas}}}{P_{\text{magnetic}}} \right)$

Some Evidence for turbulence in clusters

- pressure fluctuations in Coma (Schuecker et al 2004)

  $\Delta P/P \sim 0.1$

  $n \sim 1/3 - 7/3$ ($P_k \sim k^{-n}$) -> consistent to Kolmogorov

- **X-ray surface brightness fluctuations in Coma** (Churazov et al 2011)

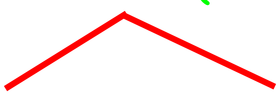
  $\Delta\rho/\rho \sim 0.1$

  $n \sim 2$ -> steeper than Kolmorogov (shock-dominated ?)

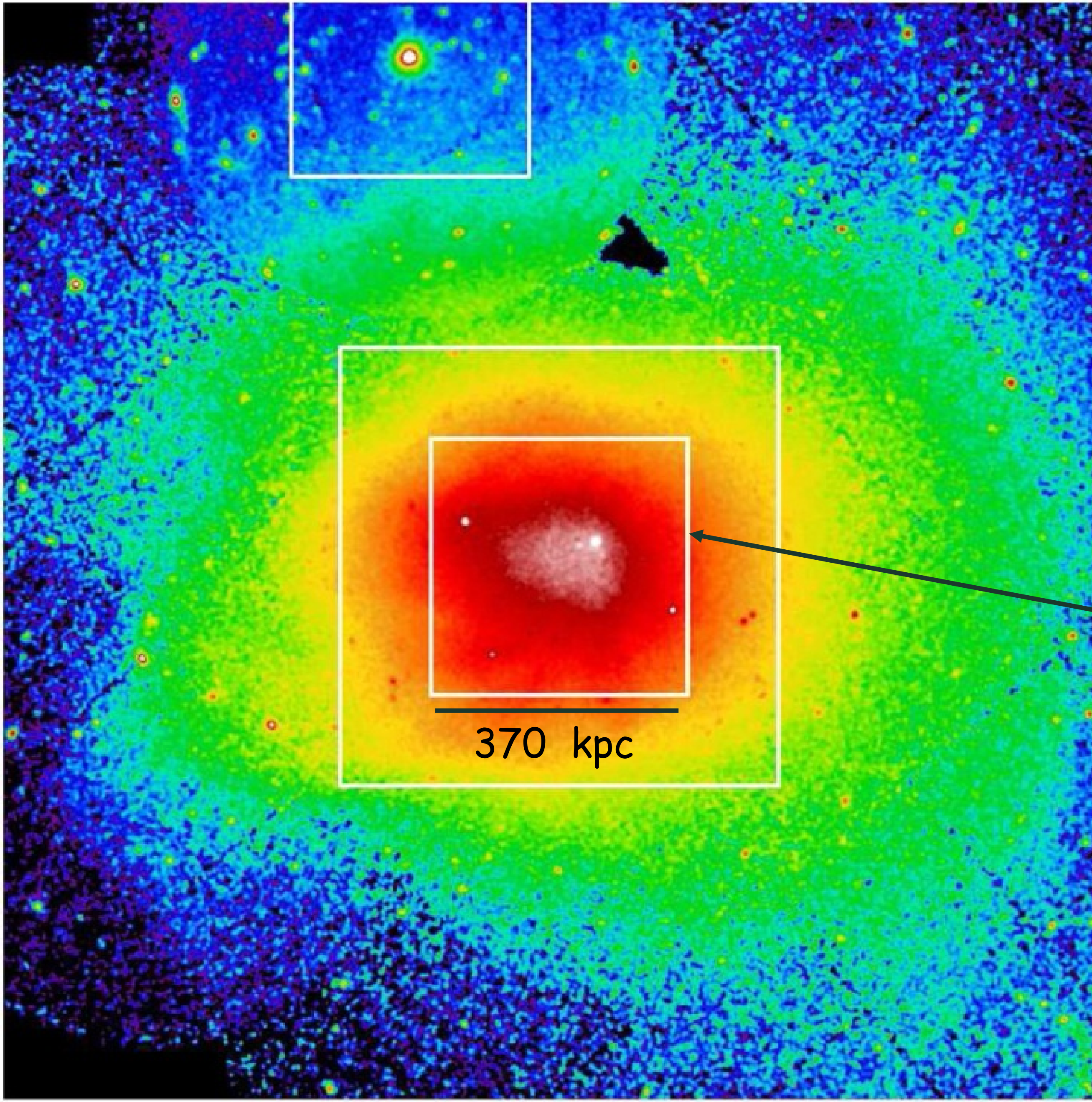
- line broadening limit in A1835 (Sanders et al 2010)

  $\Delta v < 274$ km/sec -> $E_{turb} / E_{tot} \lesssim 0.1$

- patchy Faraday rotation distributions in clusters (Murgia et al 2004)

  $n \sim 0$ for B -> broken power-law? ( ?)

- and etc …



XMM images of Coma

analyzed to get the power spectrum of gas density fluctuations

(Churazov et al. 2011)

Some Evidence for turbulence in clusters

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  $\Delta P/P \sim 0.1$

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- **X-ray surface brightness fluctuations in Coma** (Churazov et al 2011)

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- line broadening limit in A1835 (Sanders et al 2010)

  $\Delta v < 274$ km/sec -> $E_{turb} / E_{tot} <\sim 0.1$

- patchy Faraday rotation distributions in clusters (Murgia et al 2004)

  $n \sim 0$ for B -> broken power-law? (?)

- and etc …

→ Turbulence in ICMs is subsonic! Kolmogorov ?

Turbulence in astrophysical environments II

1. Turbulence in the interstellar medium (ISM) with $\beta \sim 1$

(strong guiding field $\left(B_0 >\sim \delta B\right)$)

2. Turbulence in the intracluster medium (ICM) with $\beta >> 1$

(negligible guidin g field $\left(B_0 << \delta B\right)$)

$$\left(\beta \equiv \frac{P_{\text{gas}}}{P_{\text{magnetic}}}\right)$$

Two turbulences should have different properties!

Goldreich & Sridhar model for turbulence

for strong regular field $\left(B_0 >> \delta B\right)$

in the incompressible limit $\left(\delta\rho << \rho_0\right)$

→ applicable, e.g., to the turbulence in the ISM with $\beta \sim 1$

Goldreich & Sridhar (1995) considered the dynamics of Alfvenic wave packets in the strong turbulence limit.

1. critical balance

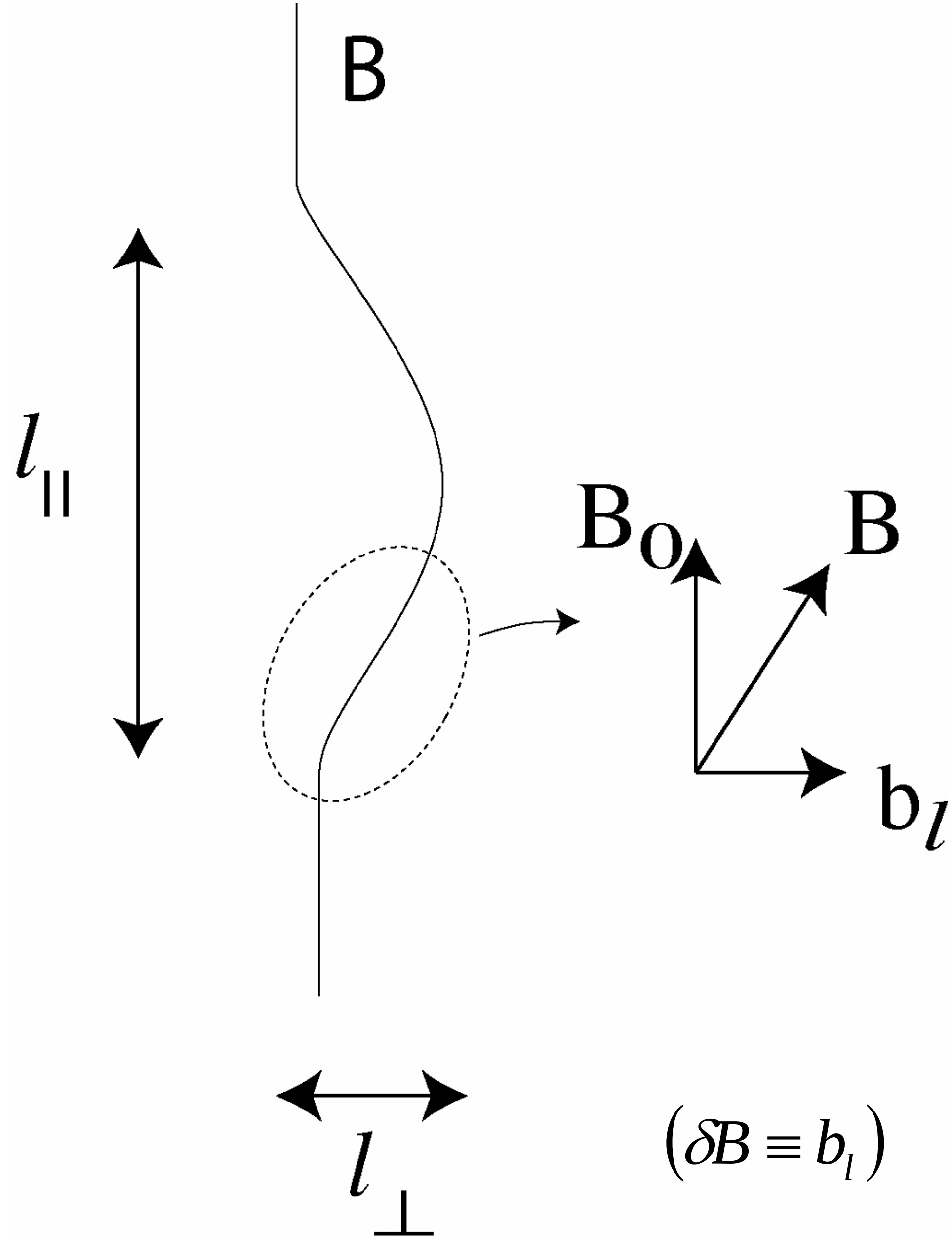
anisotropic eddy shape

$$\frac{l_\perp}{l_\parallel} \sim \frac{b_l}{B_o} \quad \text{or} \quad \frac{l_\parallel b_l}{l_\perp B_o} \sim 1$$

B_o regular background field

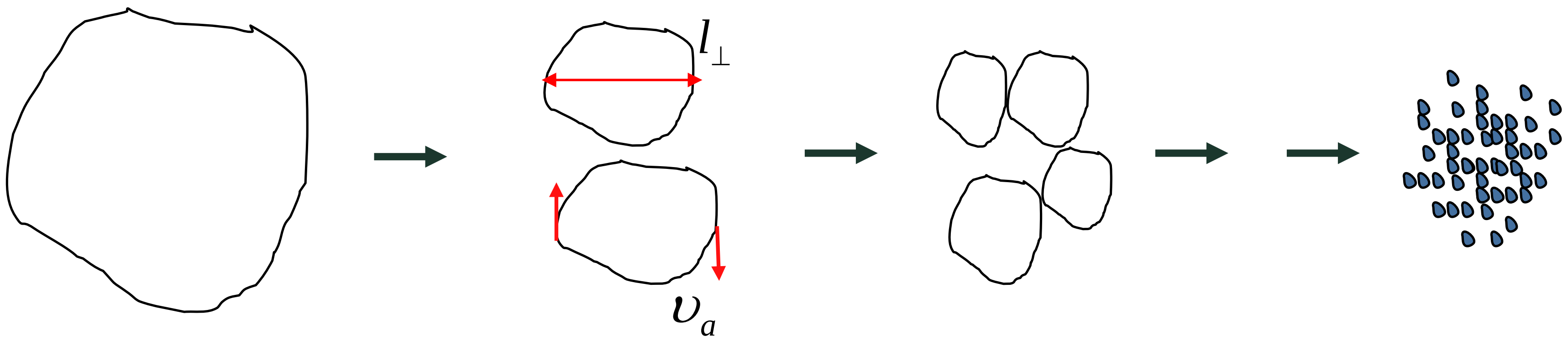
b_l perturbed field

(Kubo number $K = \frac{b_l}{B_0}\frac{l_\parallel}{l_\perp} \sim 1$)



$(\delta B \equiv b_l)$

2. energy cascade of Alfven waves



$$\varepsilon_{\text{cascade}} = \frac{b_l^2}{t_{\text{cascade}}} = \text{constant}$$

$$t_{\text{cascade}} \sim t_{\text{interaction}} = \frac{l_\parallel}{B_0} \sim \frac{l_\perp}{b_l} \longleftarrow \text{strong turbulence}$$

Goldreich & Sridhar model

critical balance

$$\frac{l_\perp}{l_{||}} \sim \frac{b_l}{B_o}$$

energy cascade

$$\varepsilon_{\text{cascade}} = \frac{b_l^2}{b_l / l_\perp} = \text{constant}$$

$$\longrightarrow$$

$b \sim l_\perp^{1/3}$ or $P_k \sim k^{-5/3}$

$$l_{||} \sim l_\perp^{2/3}$$

Turbulence in intracluster media

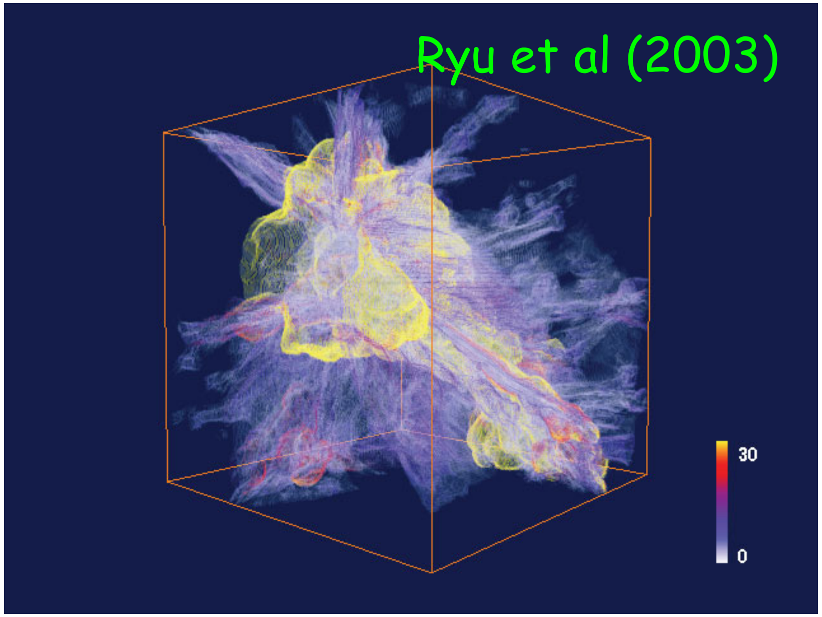
- It is difficult to produce strong coherent magnetic fields in the IGM before the formation of the large-scale structure of the universe, but rather it would be reasonable to assume that week, random seed fields were created.
- If seed fields exist, turbulence can amplify magnetic fields (the small-scale dynamo).
- Origin of seeds for comic magnetic fields is yet uncertain.

after turbulent amplification

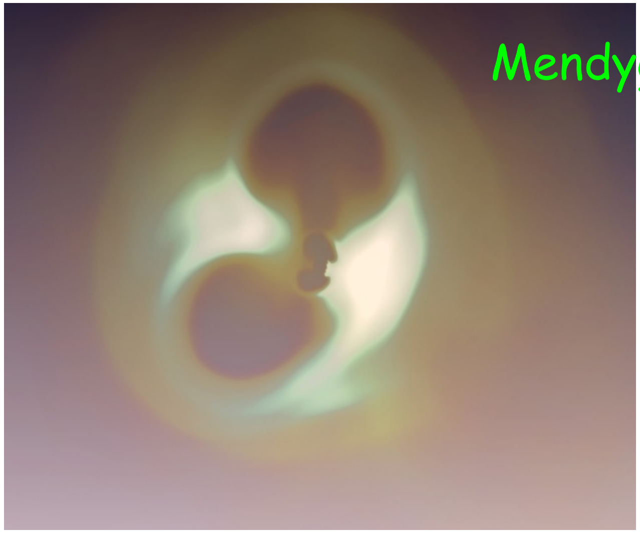
$$B_0 << \delta B$$

Drivers of turbulence in clusters

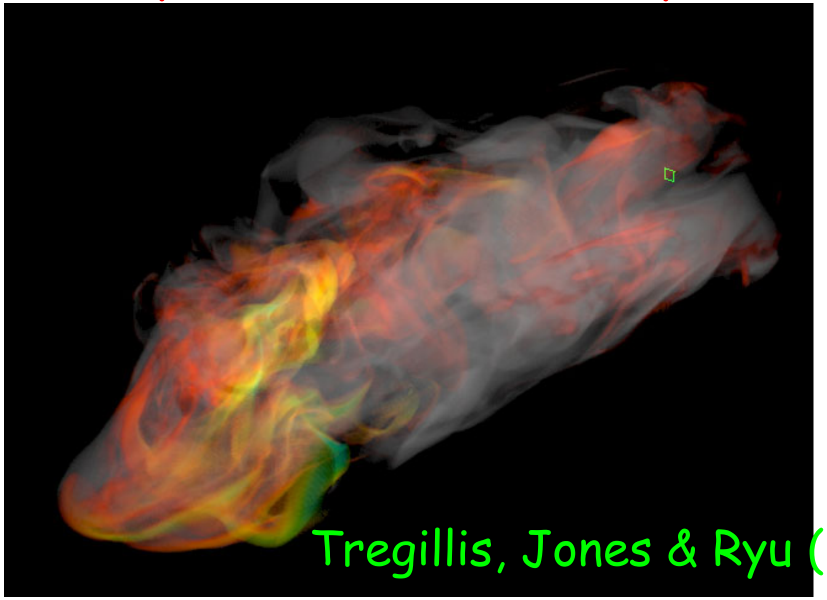
- **<u>formation of large-scale structure: shocks from merger, accretion, …</u>**
- AGN outflows, galactic winds, …
- MTI, buoyancy instabilities, …



wide range of injection scales: microscopic scales to ~ 1 Mpc



Mendygral et al



Tregillis, Jones & Ryu (2004)

Overall picture

Ryu et al (2008)

large-scale structure formation

gravitational collapse & flow motions

cosmological shocks

shock dissipation

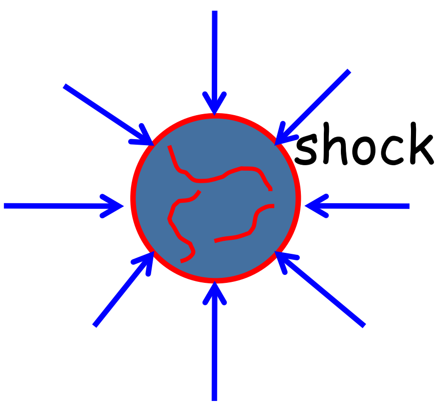
the main channel to flow the gravitational energy to the intergalactic medium

generation of heat
fresh acc. & re-acc. of CRs
genera. of magnetic fields
generation of vorticity

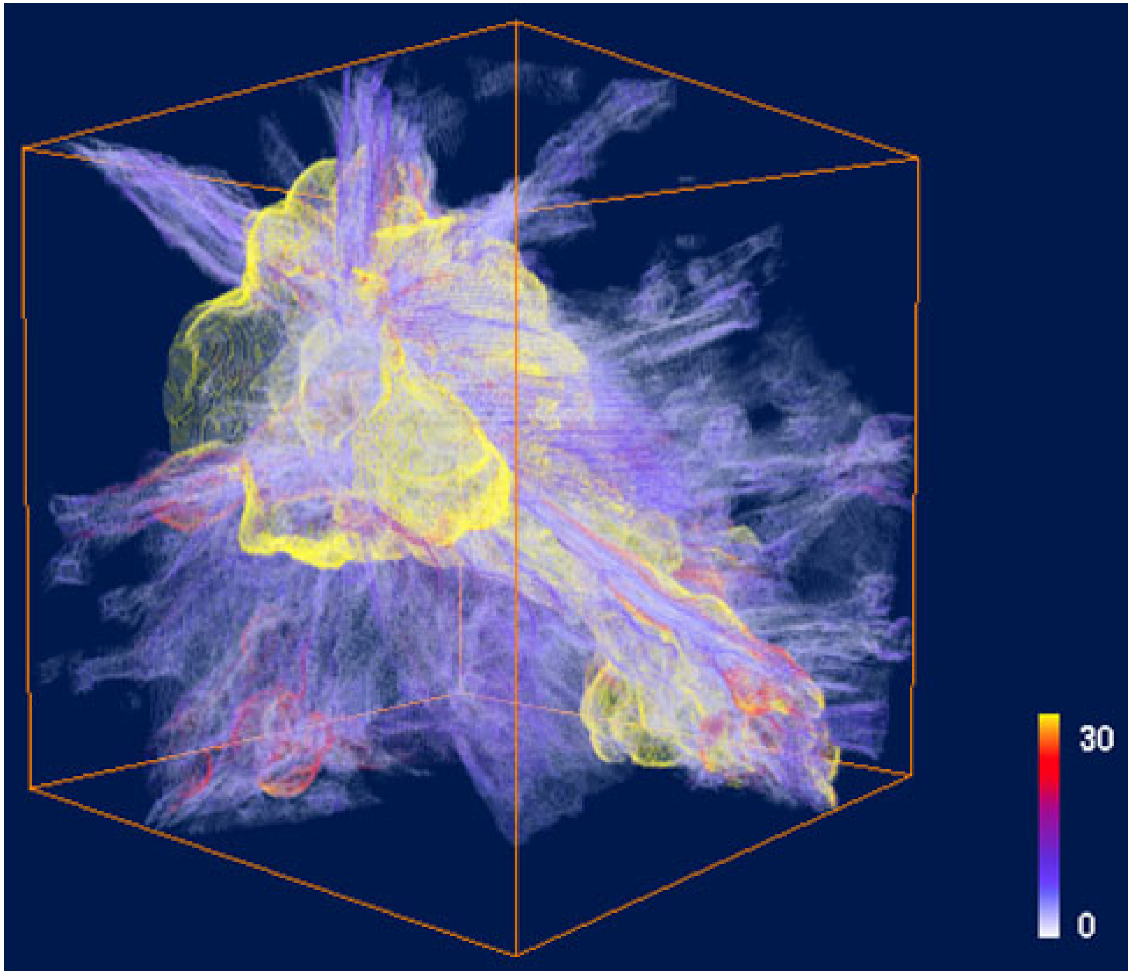
other sources, such as AGNs of heat, CRs, turbulence and magnetic fields

cascade into turbulence

turbulent amp. of mag. fields
turbulent acceleration of CRs



Mach number distribution of shocks around a cluster complex



(Ryu et al 2003)

external shocks surrounding the cluster complex:

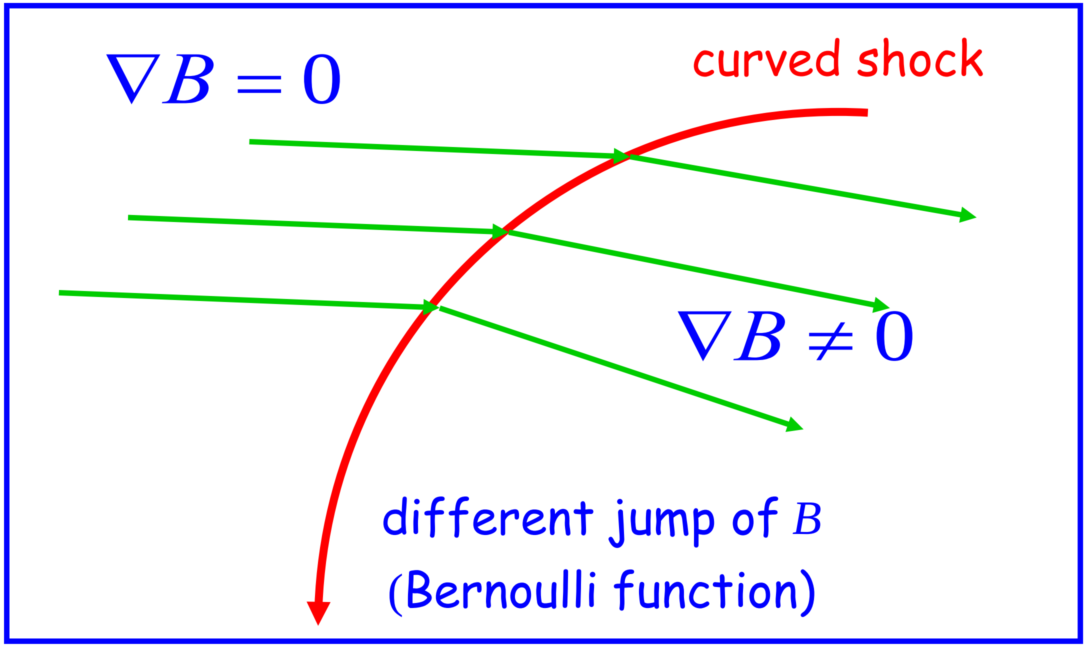
M_s > ~10

internal shocks inside the cluster complex

M_s < ~ several

Vorticity generated at cosmological shocks

directly at curved shocks



$\Longrightarrow$ at postshock

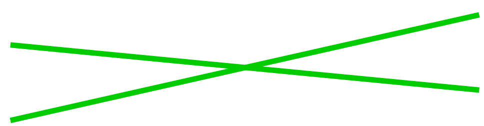
$$\varpi_{\rm cs} \sim \frac{(\rho_2 - \rho_1)^2}{\rho_2 \rho_1} \frac{\vec{U} \times \vec{n}}{R}$$

ρ_1 preshock density
ρ_2 postshock density
$\vec{U}$ preshock flow speed
$\vec{n}$ unit normal to shock surf.
R curvature radius of surf.

by the baroclinic term

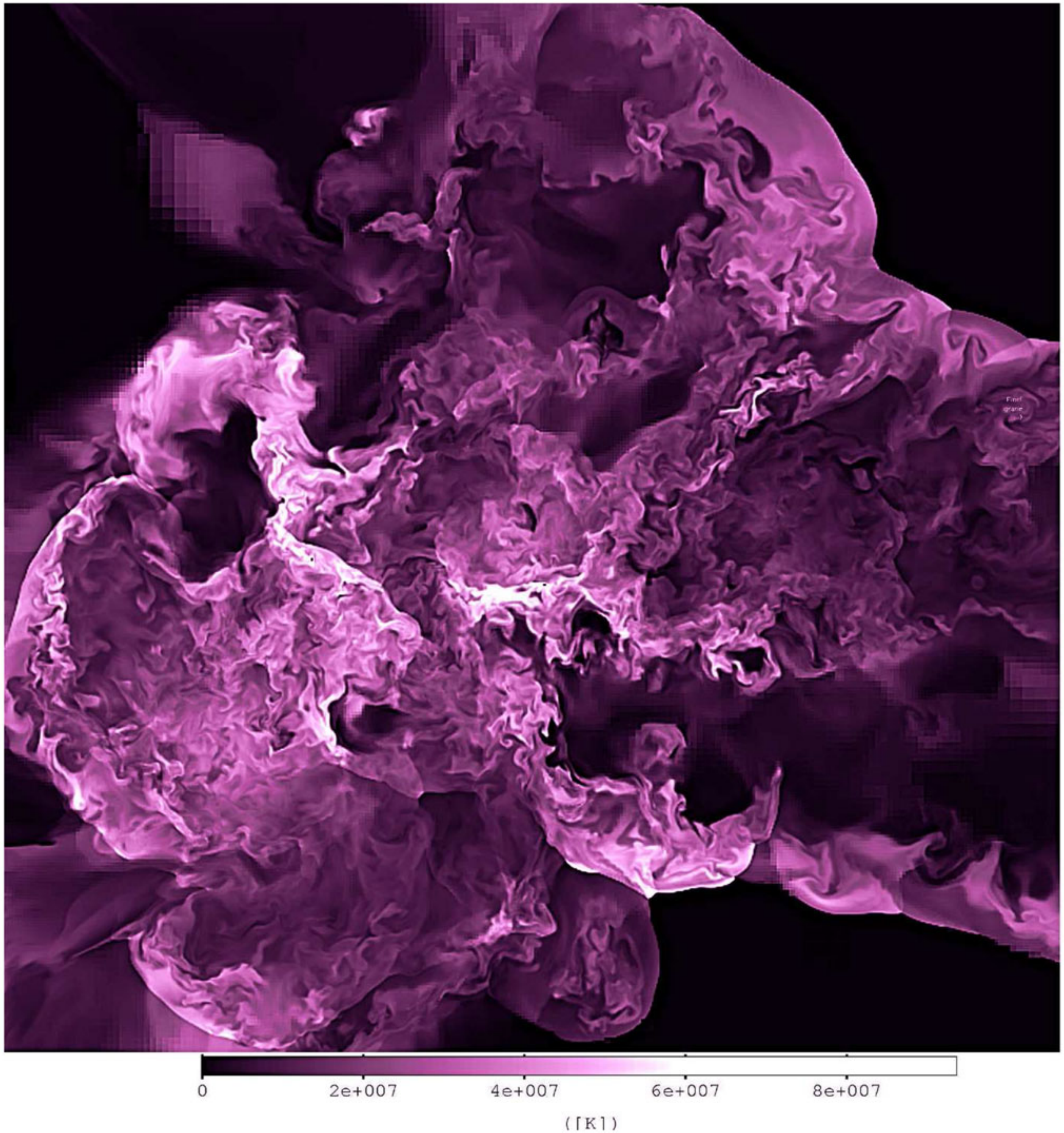
$$\dot{\varpi}_{\rm bc} = \frac{1}{\rho^2} \vec{\nabla} \rho \times \vec{\nabla} p$$

baroclinity



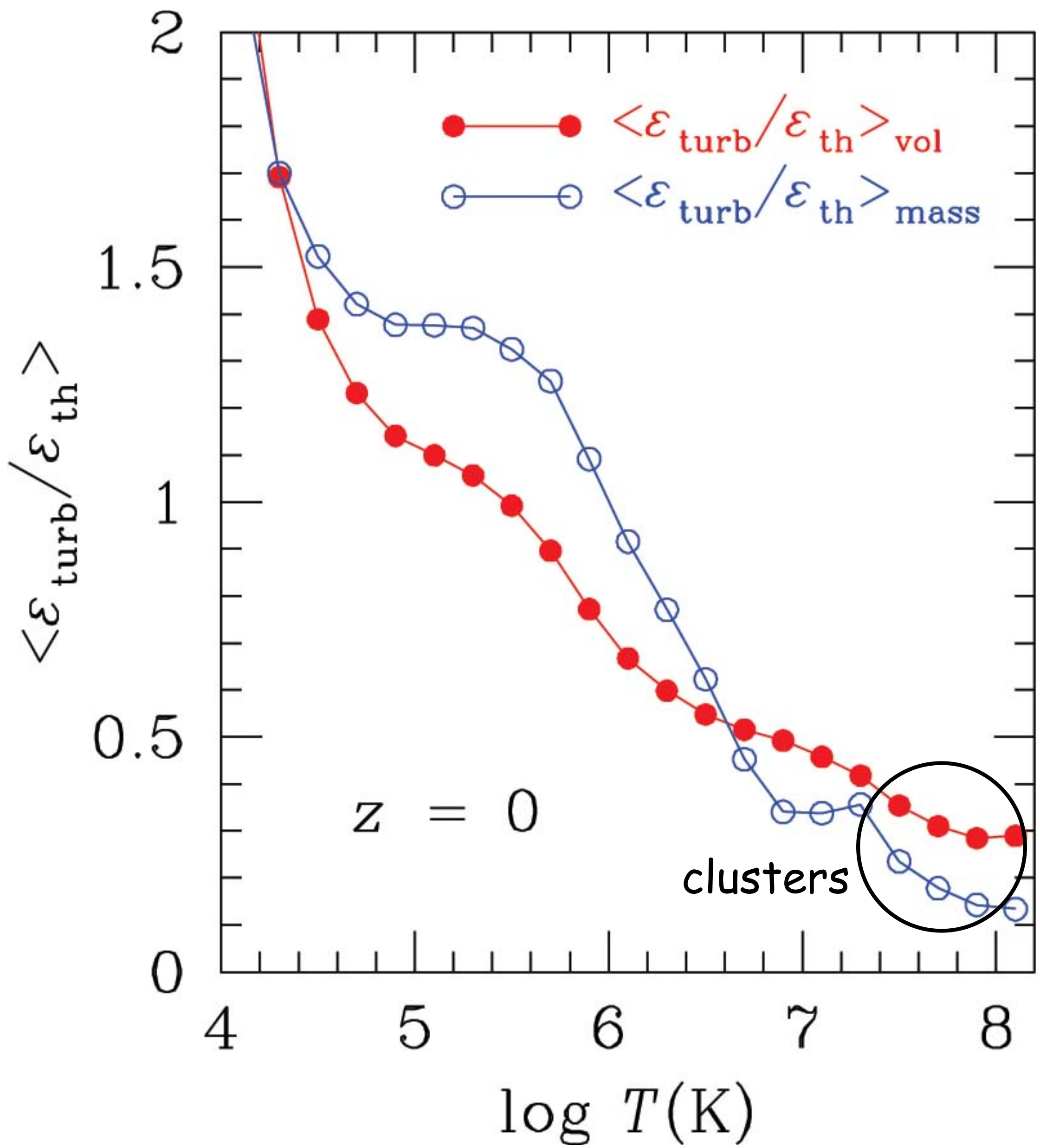
$\Longleftarrow$ due to entropy variation induced at shocks

Turbulence in clusters: AMR simulations



temperature distribution in a merging cluster

Vazza et al (2010)



Turbulence energy

assuming that all the energy of vortical motions goes to turbulence

M_{turb} < 1
(subsonic turbulence)
inside and outskirts of clusters

E_{turb}/E_{therm} ~ 0.1 – 0.3
inside and outskirts of clusters
-> agrees with obs.

M_{turb} ~ 1
(transonic turbulence)
in filaments

turbulence in clusters is subsonic!

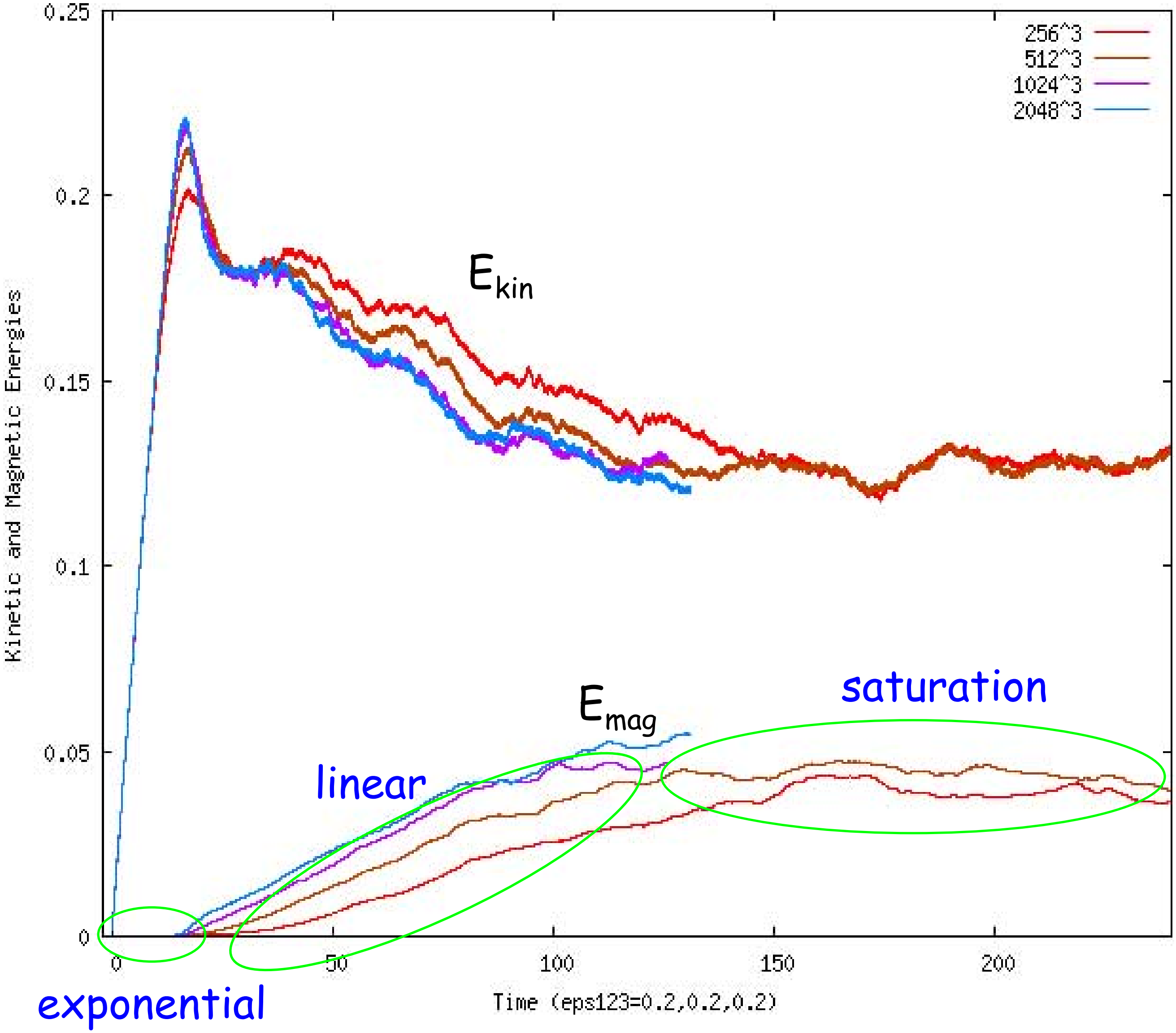
Turbulence + magnetic field

→ Magnetohydrodynamic turbulence

Magnetic fields can be amplified by turbulence from weak seed fields

→ Turbulence dynamo or small-scale dynamo

Time evolution of kinetic and magnetic energies



at saturation

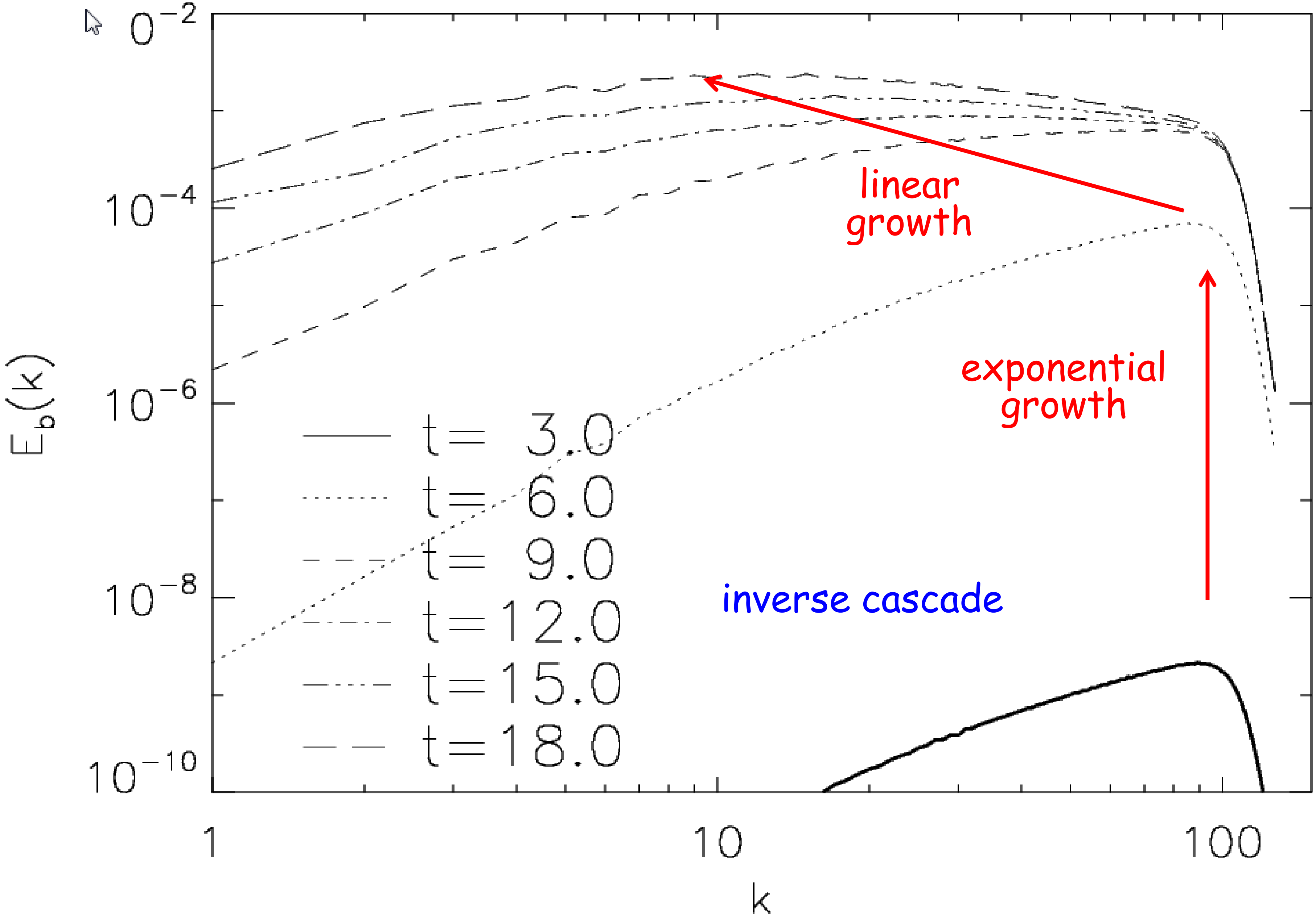
$E_{mag}/E_{kin} \sim 1/2$

in 2048^3 run,

while $E_{mag}/E_{kin} \sim 2/3$

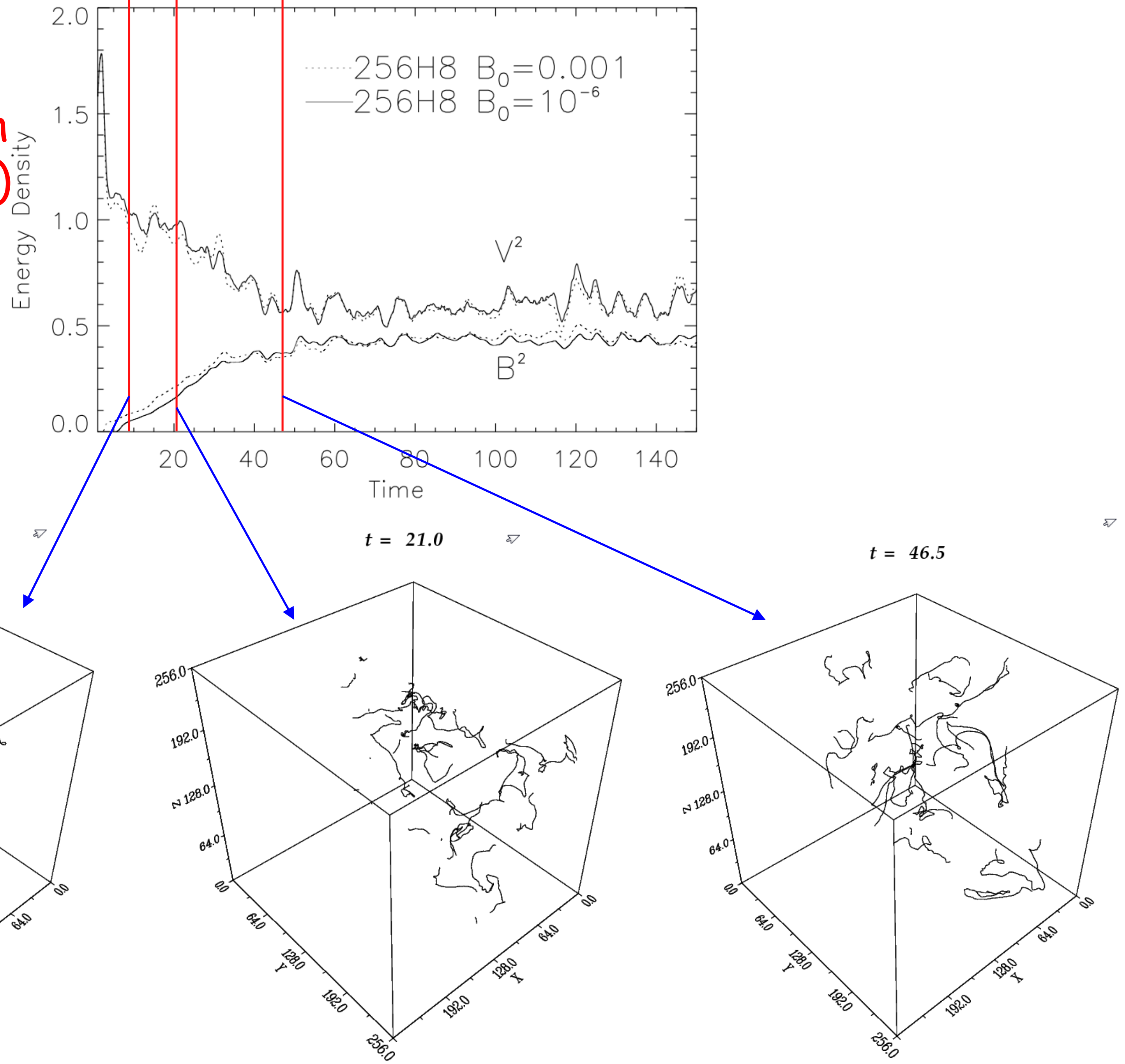
in incompressible run

(Porter, Jones, Ryu, Cho in preparation)



10^{-2}
10^{-4}
10^{-6}
10^{-8}
10^{-10}
$E_b(k)$
1
10
100
k
t= 3.0
t= 6.0
t= 9.0
t=12.0
t=15.0
t=18.0
linear growth
exponential growth
inverse cascade

Growth of coherence length (inverse cascade)



Viscosity and resistivity the ICM

kinetic viscosity $\nu \sim \upsilon_{p-p}^{\text{therm}} l_{p-p} \sim \dfrac{l_{p-p}^2}{t_{p-p}}$ (?)

or substantially smaller ?

resistivity $\eta \sim \dfrac{(c/\omega_p)^2}{t_{e-p}} \quad \left(\omega_p = \left(\dfrac{4\pi\, n_e e^2}{m_e} \right)^{1/2} \right)$ (?)

much smaller than viscosity?

⟹ high magnetic Prandtle number ?

$$P_m = \frac{\nu}{\eta} \sim 10^{20} \text{ or larger ?}$$

Conclusions: Why simulation of turbulence in clusters?

- Turbulence amplifies and transports magnetic fields.
- Turbulence transports entropy, metals, cosmic rays, etc.
- Turbulence is a key to shocks and turbulent acceleration of cosmic rays.
- Turbulent pressure contributes to the support of the ICM, so its presence influences HSE mass estimates.

in turn

- Turbulence is affected by shocks, magnetic fields, dissipations, and etc.

in the end

- Understanding turbulence is important in understanding physics in. intracluster media, and yet to be done.
- Numerical simulation is a key in understanding turbulence as well as other astrophysical phenomena in intracluster media.

Thank you !