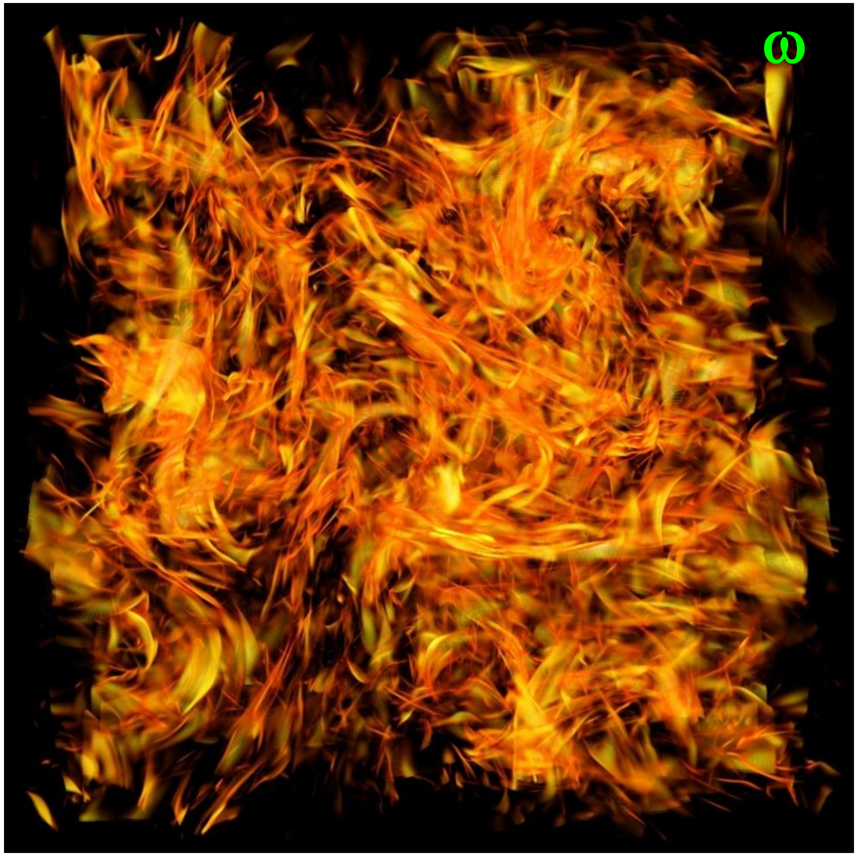
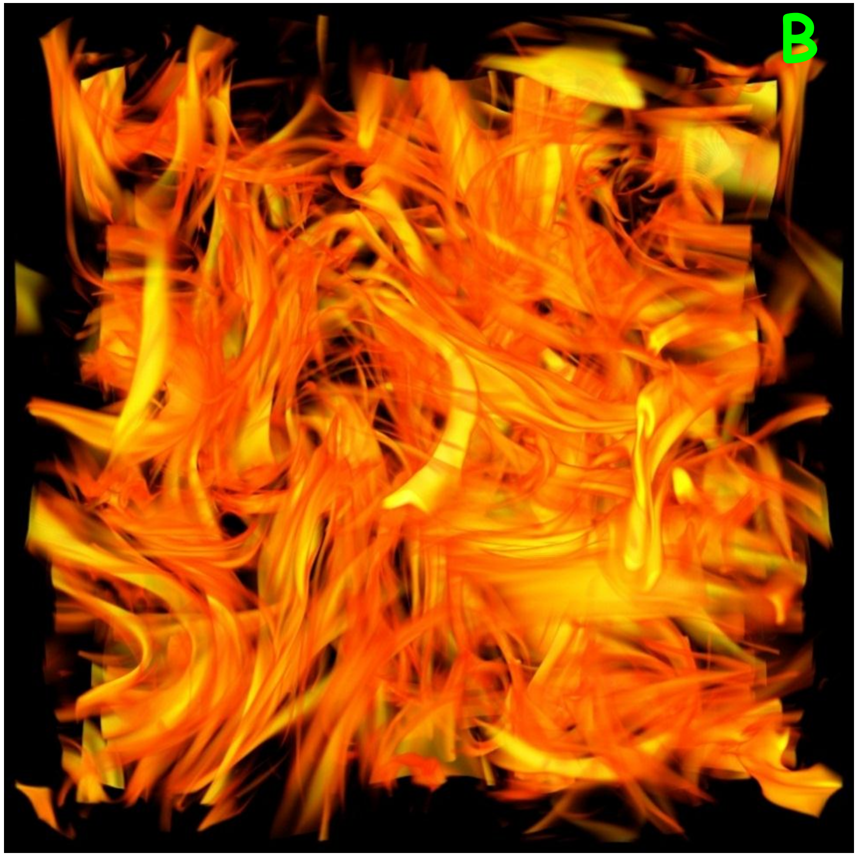
A Simulation Study of Intracluster Turbulence





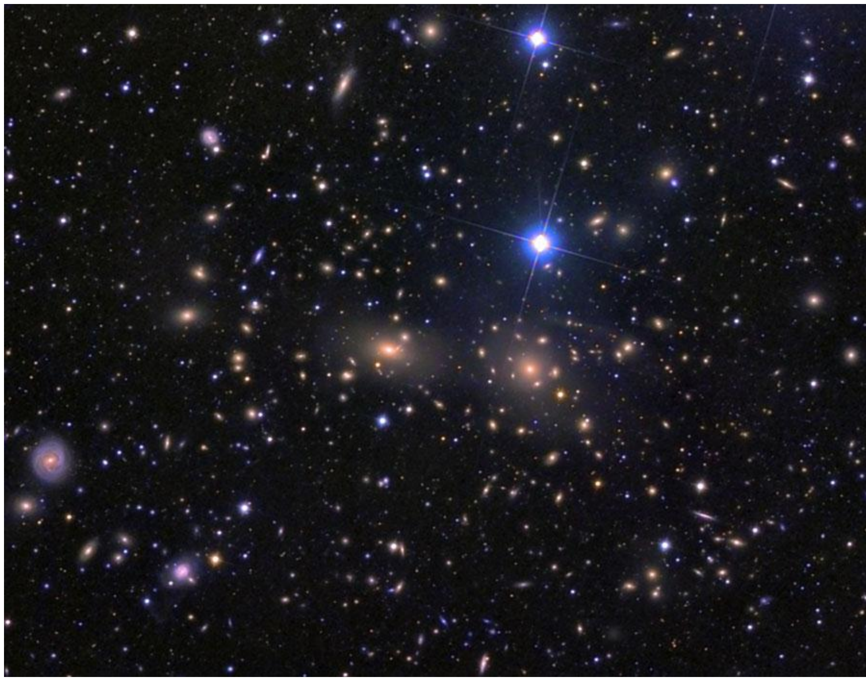
Dongsu Ryu (Chungnam National U, Korea)

Collaborators:

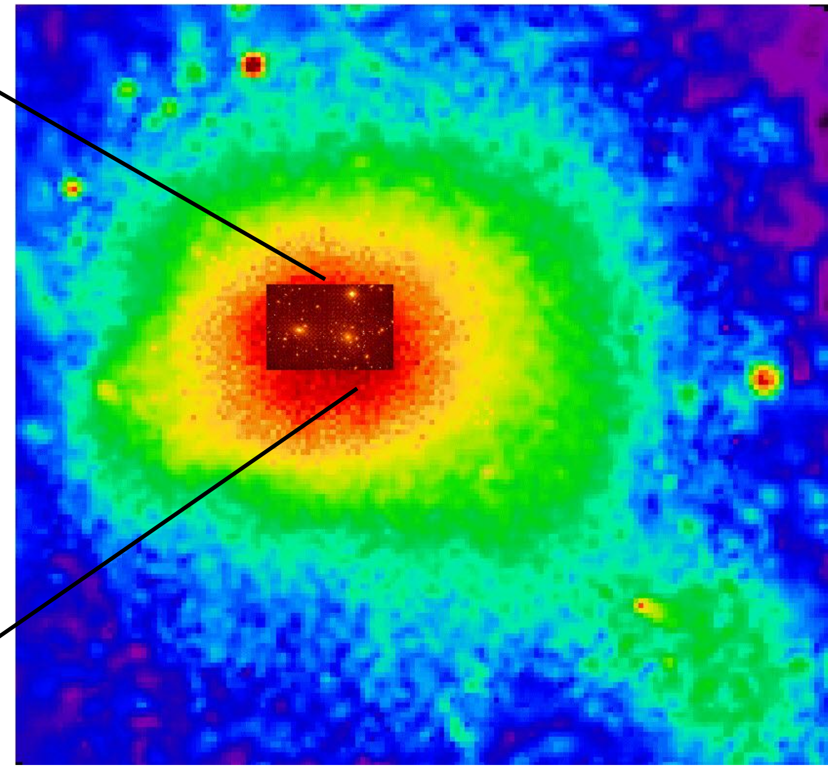
David Porter (Minnesota, USA), Tom W. Jones (Minnesota, USA), Jungyeon Cho (CNU, Korea)

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



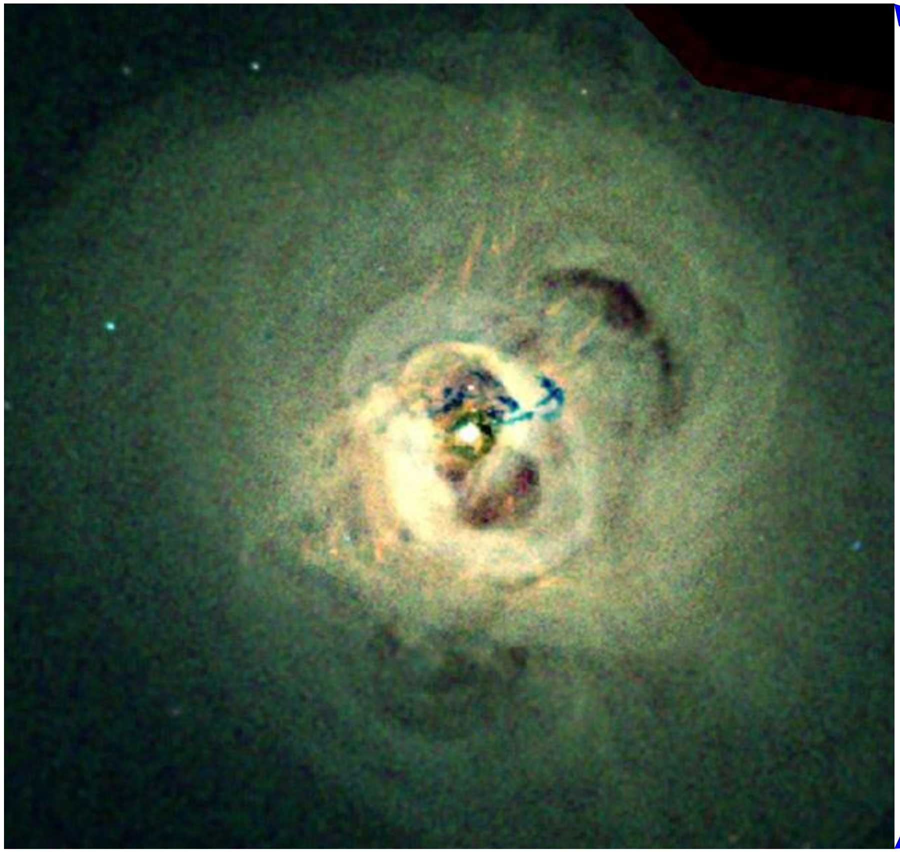
in visible (core region) <- star light



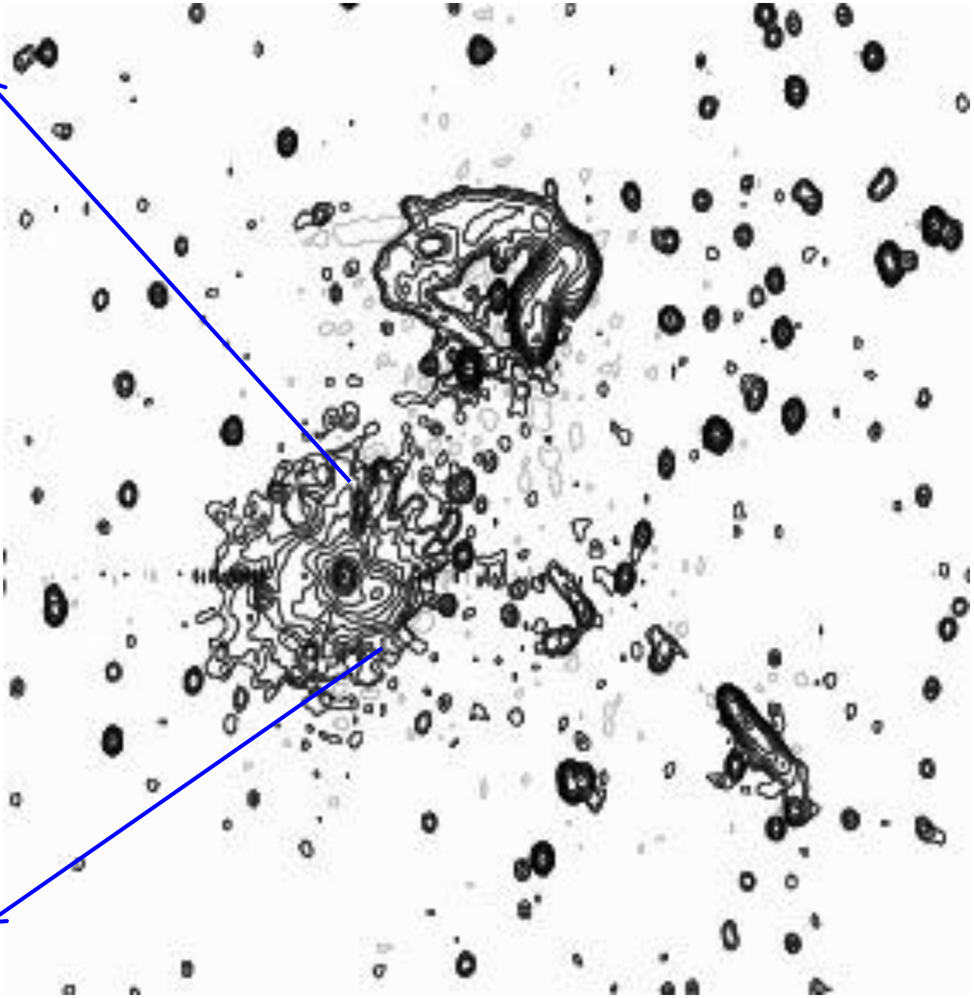
in X-ray <- hot gas of T ~ 8 keV

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

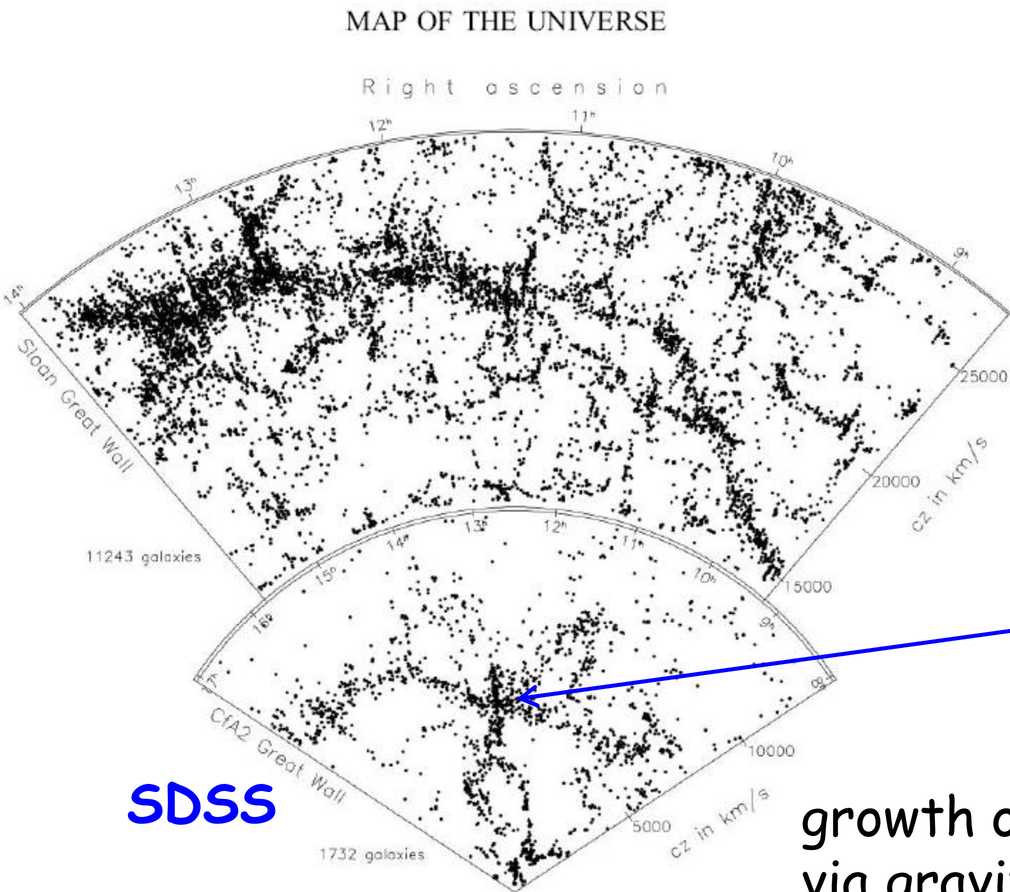
Perseus Cluster



X-ray from hot gas of T ~ 5 keV



radio due to non-thermal processes



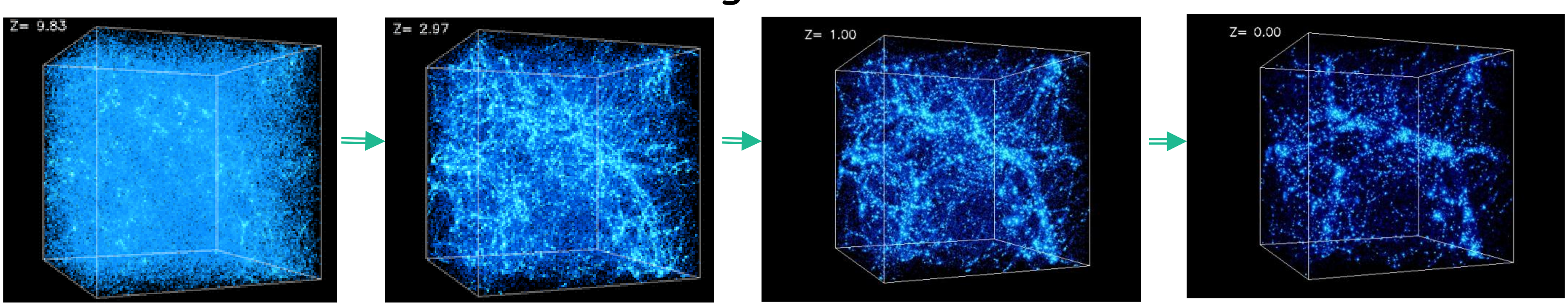
The large-scale structure of the universe seen in the galaxy distribution

"cosmic web of filaments"

Coma cluster

SDSS

growth of primordial density perturbations via gravitational instability to form the large scale structure of the universe



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 -> $E_{turb} / E_{tot} <\sim 0.1$

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

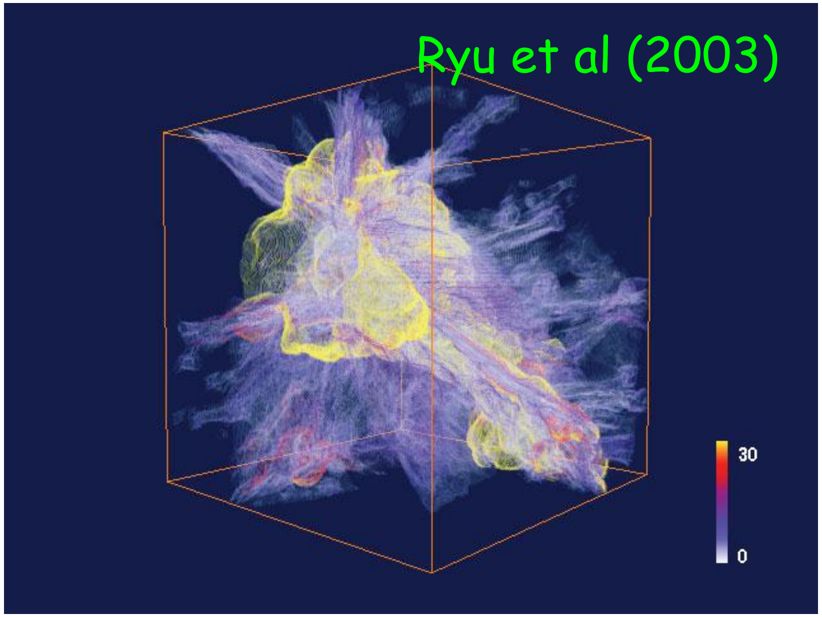
  $n \sim 0$ for B -> broken power-law? ( ?)

- and etc …

→ **<u>turbulence is subsonic!</u>**

Drivers of turbulence in clusters

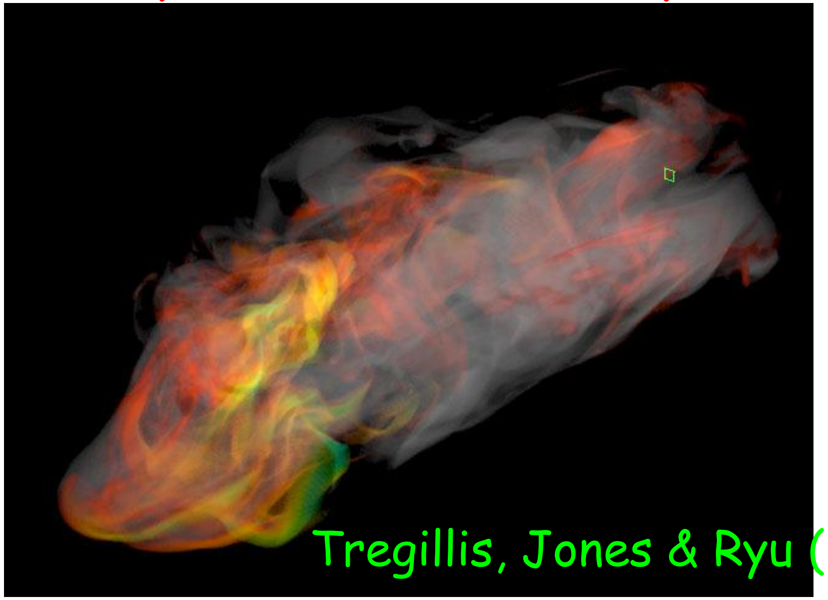
- **formation of large-scale structure: shocks from merger, accretion, …**
- AGN outflows, galactic winds, …
- MTI, buoyancy instabilities, …



Ryu et al (2003)

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

Mendygral et al



Tregillis, Jones & Ryu (2004)

Overall picture for the cosmological shock origin

large-scale structure formation

gravitational collapse & flow motions

cosmological shocks

shock dissipation

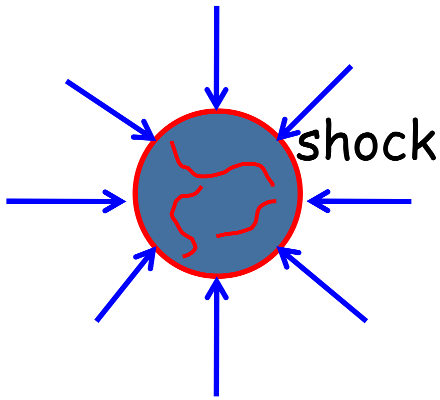
the main channel to flow the gravitational energy to the intergalactic medium

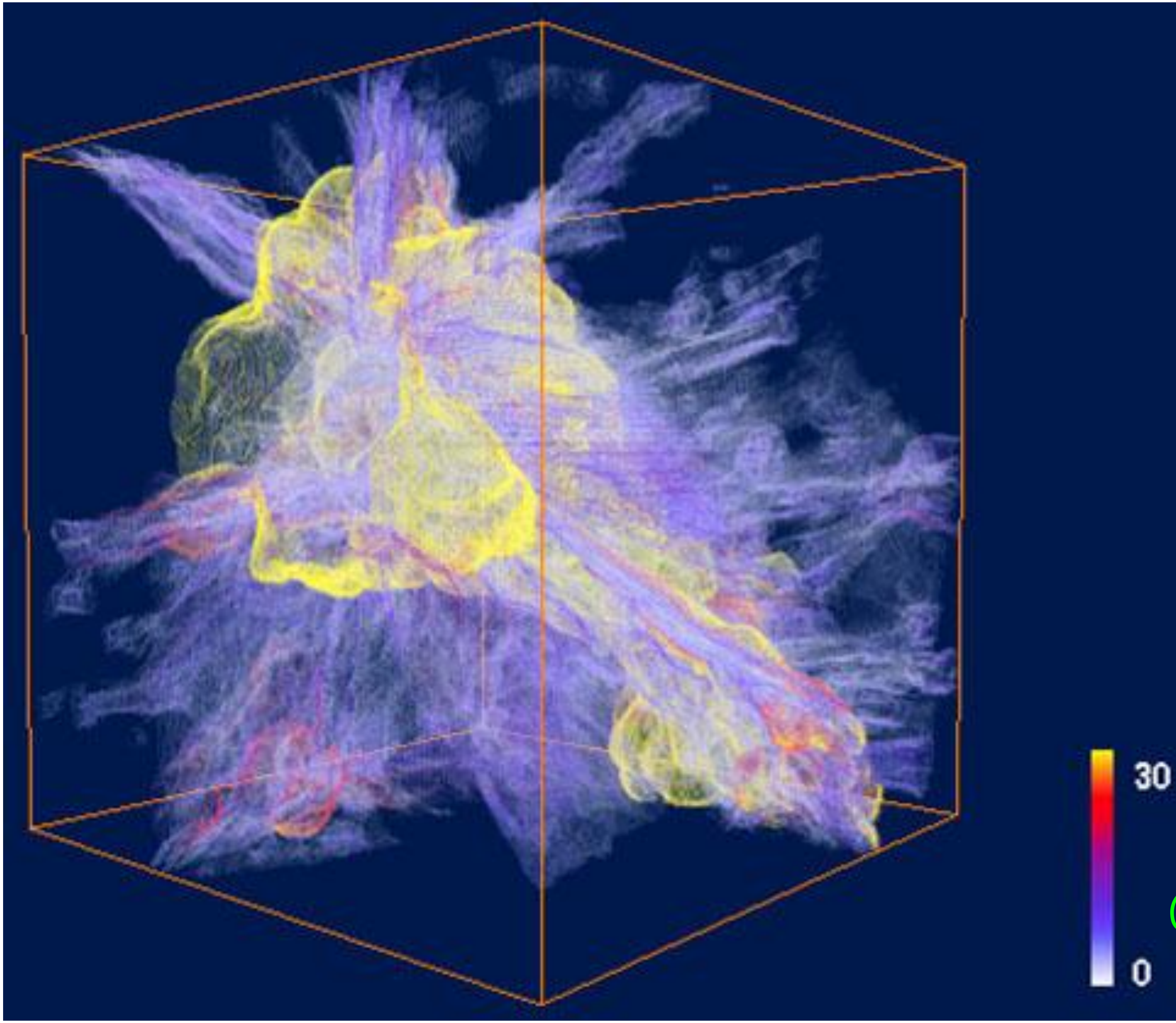
generation of heat
fresh acc. & re-acc. of CRs
genera. of magnetic fields
generation of vorticity

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

cascade into turbulence

turbulent amp. of mag. fields
turbulent acceleration of CRs

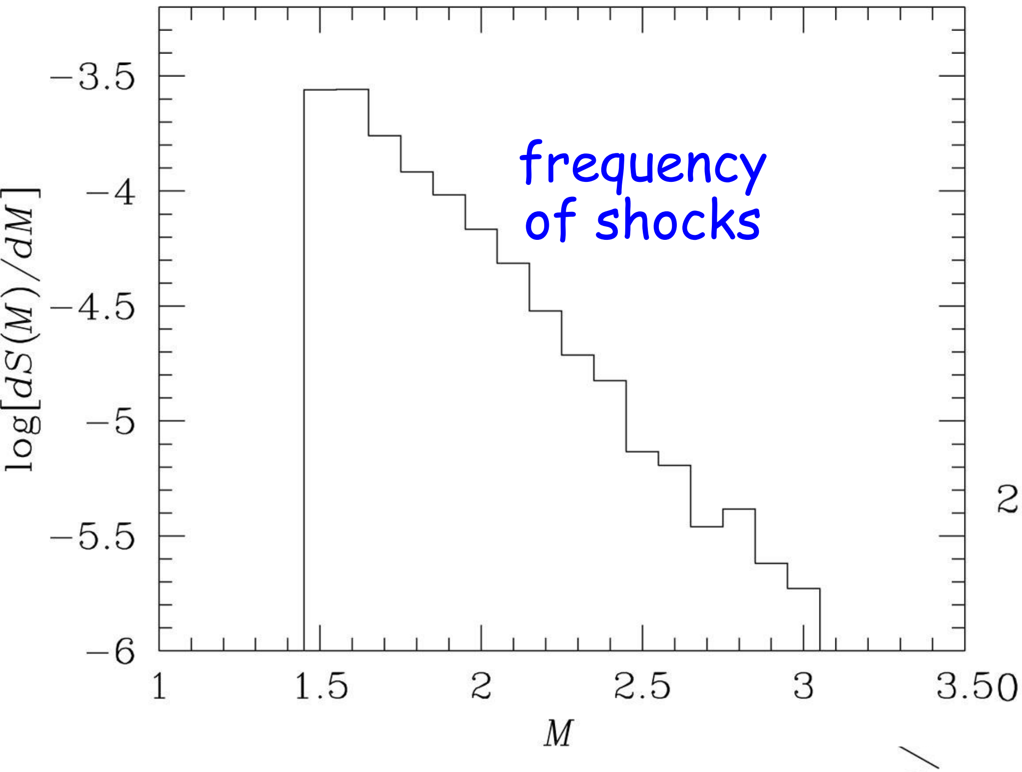




Mach number distribution of shocks around the cluster complex

(Ryu et al 2003)

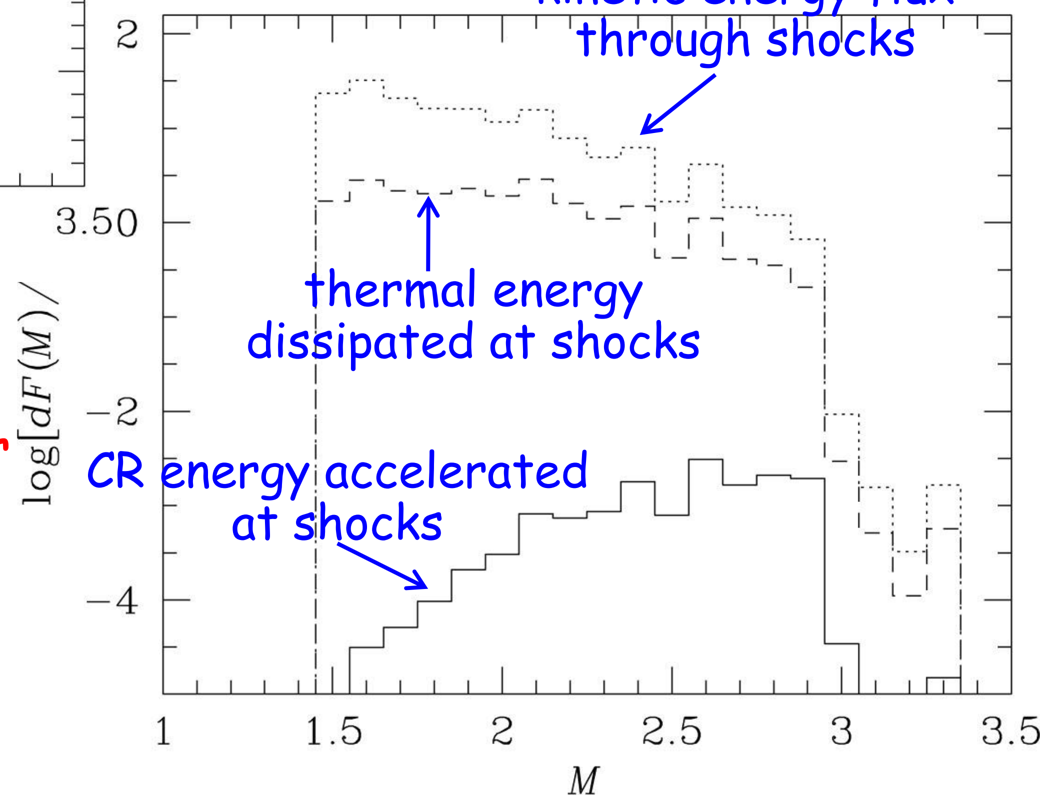
Shocks statistics



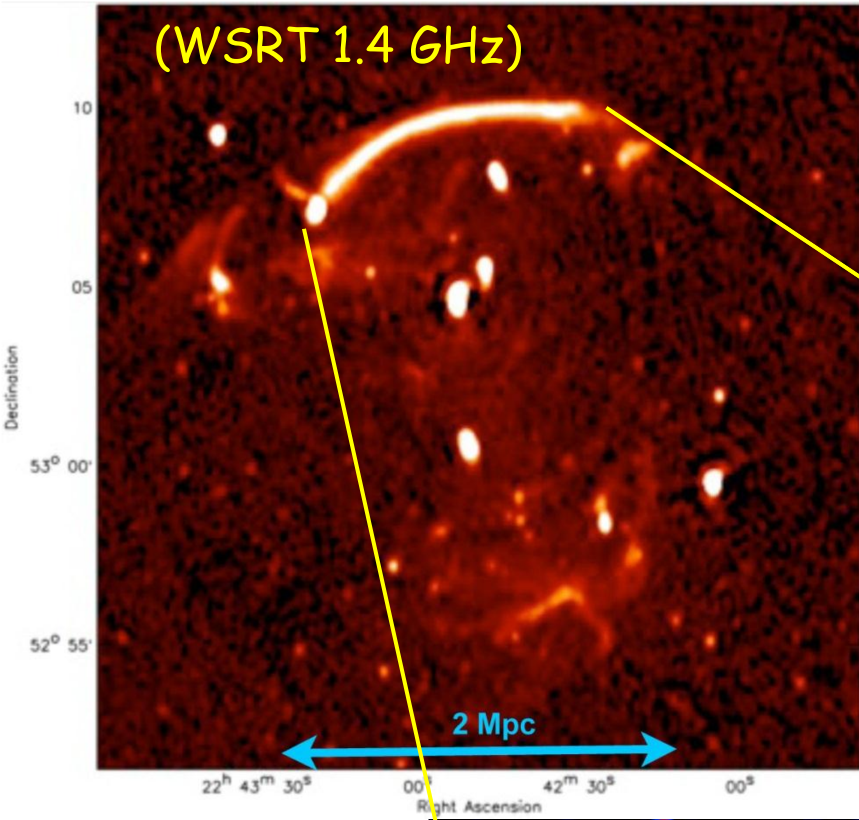
Kang & Ryu (2011)

in hot gas with T > 10^7

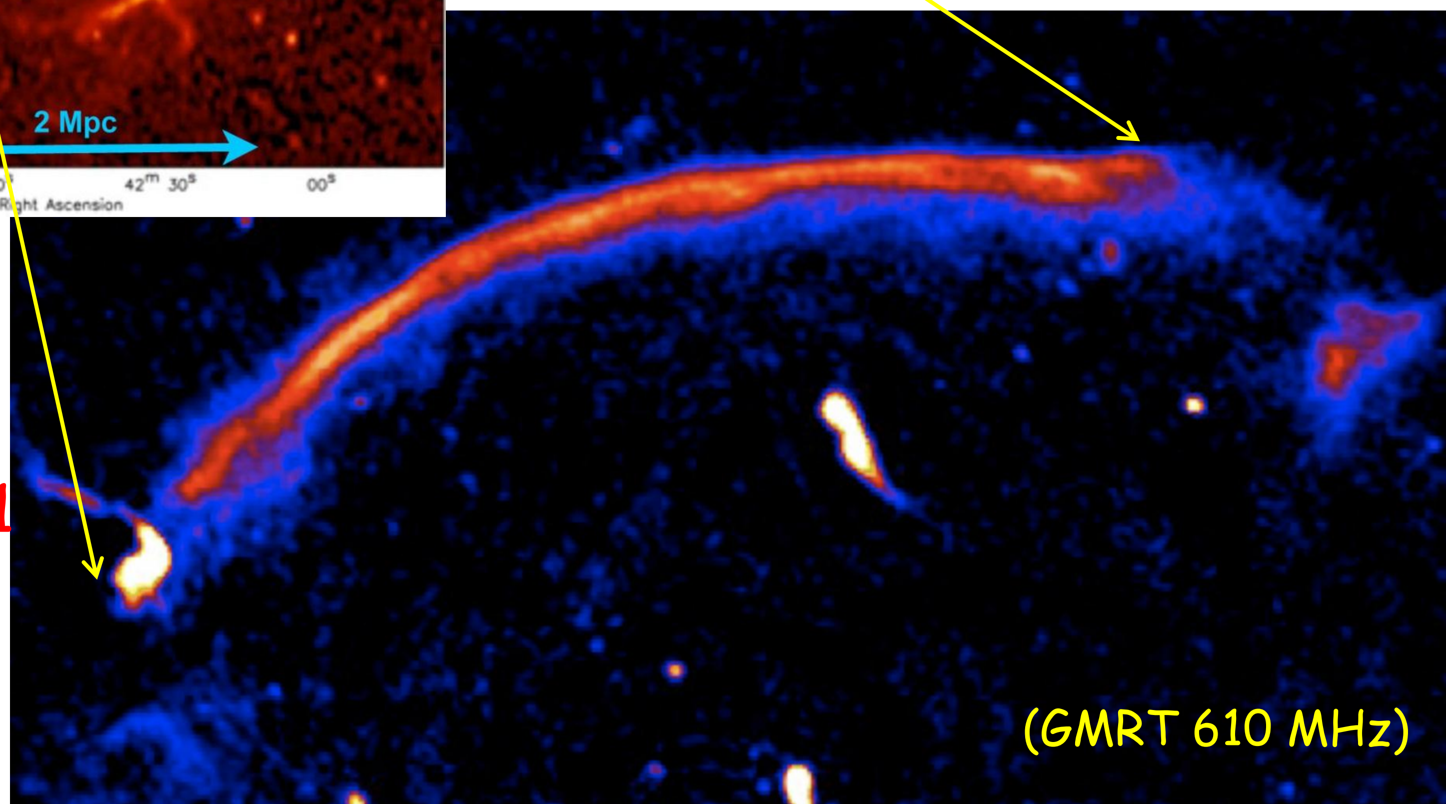
(inside and outskirts of clusters)



shocks with small Mach number are common and energetically important inside and outskirts of clusters



evidence for
electron acceleration &
magnetic field generation
at weak shocks ?



Radio relic in
CIZA
J2242.8+5301

van Weeren
et al (2010)

Various length scales in the intracluster medium

mean free-path for electron-electron & proton-proton collisions

$$l_{p-p} \sim l_{e-e} \sim \frac{10^5}{\ln \Lambda} \frac{T^2(\mathrm{K})}{n_e(\mathrm{cm}^{-3})} \mathrm{cm} \sim \text{a few kpc}$$

mean free-path for electron-proton relaxation

$$l_{e-p} \sim l_{p-p} \times \left(\frac{m_p}{m_e} \right)^{\frac{1}{2}} \sim 100\ \mathrm{kpc}$$

gyro-radius of protons

$$r_{\mathrm{gyro,p}} \sim \frac{\sqrt{T(\mathrm{K})}}{B(\mathrm{G})} \mathrm{cm} \sim 10^4\ \mathrm{km}$$

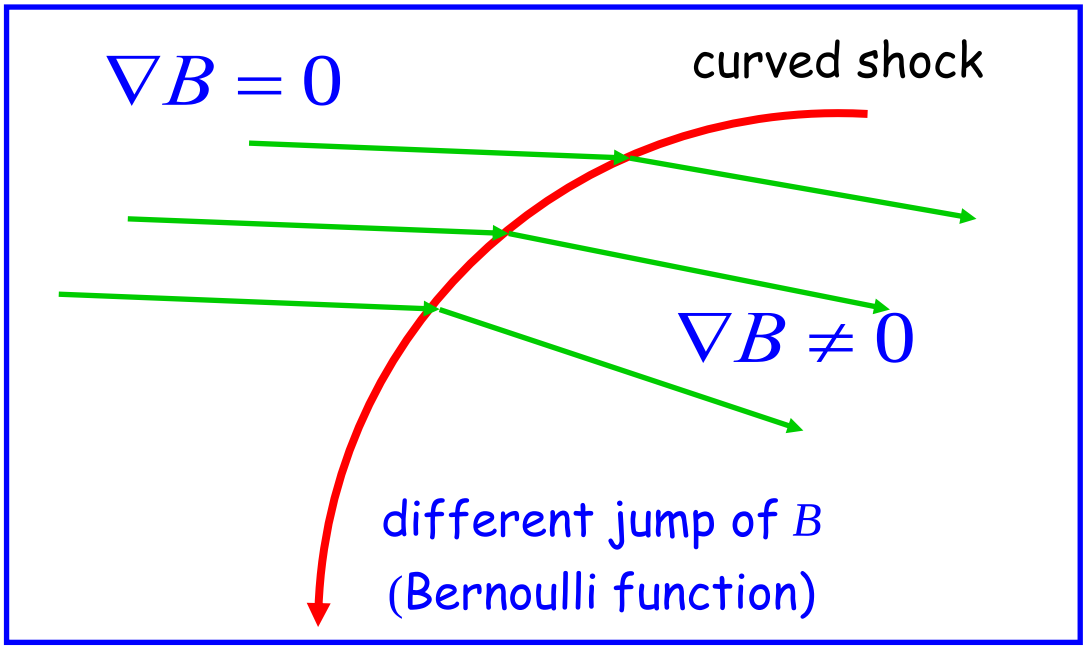
gyro-radius of elections

$$r_{\mathrm{gyro,e}} = r_{\mathrm{gyro,p}} \times \frac{m_e}{m_p} \sim 10\ \mathrm{km}$$

→ **collisionless shock waves of Much number ~ a few**

Vorticity generated at cosmological shocks

directly at curved shocks



⟹ at postshock

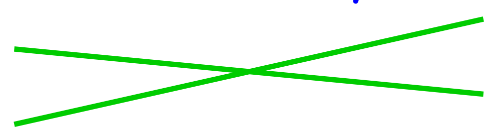
$$\varpi_{cs} \sim \frac{(\rho_2 - \rho_1)^2}{\rho_2 \rho_1} \frac{\vec{U} \times \vec{n}}{R}$$

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

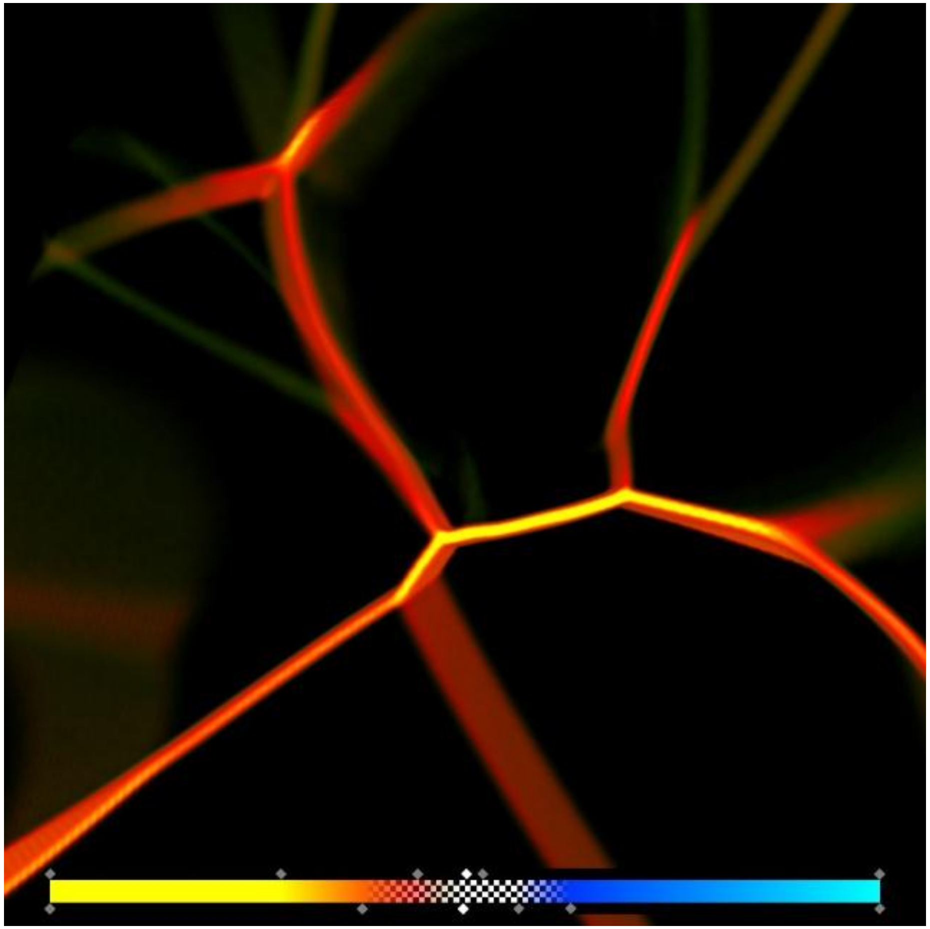
$$\dot{\varpi}_{bc} = \frac{1}{\rho^2} \vec{\nabla}\rho \times \vec{\nabla} p$$

baroclinity

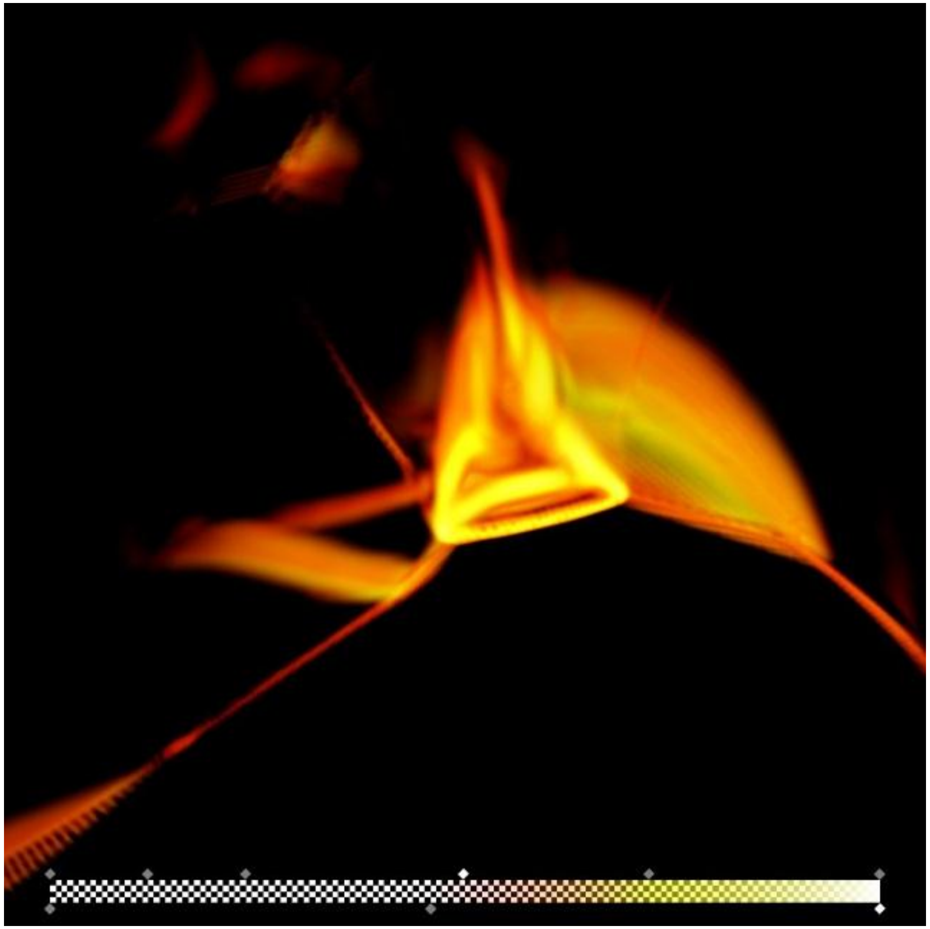


⟸ due to entropy variation induced at shocks

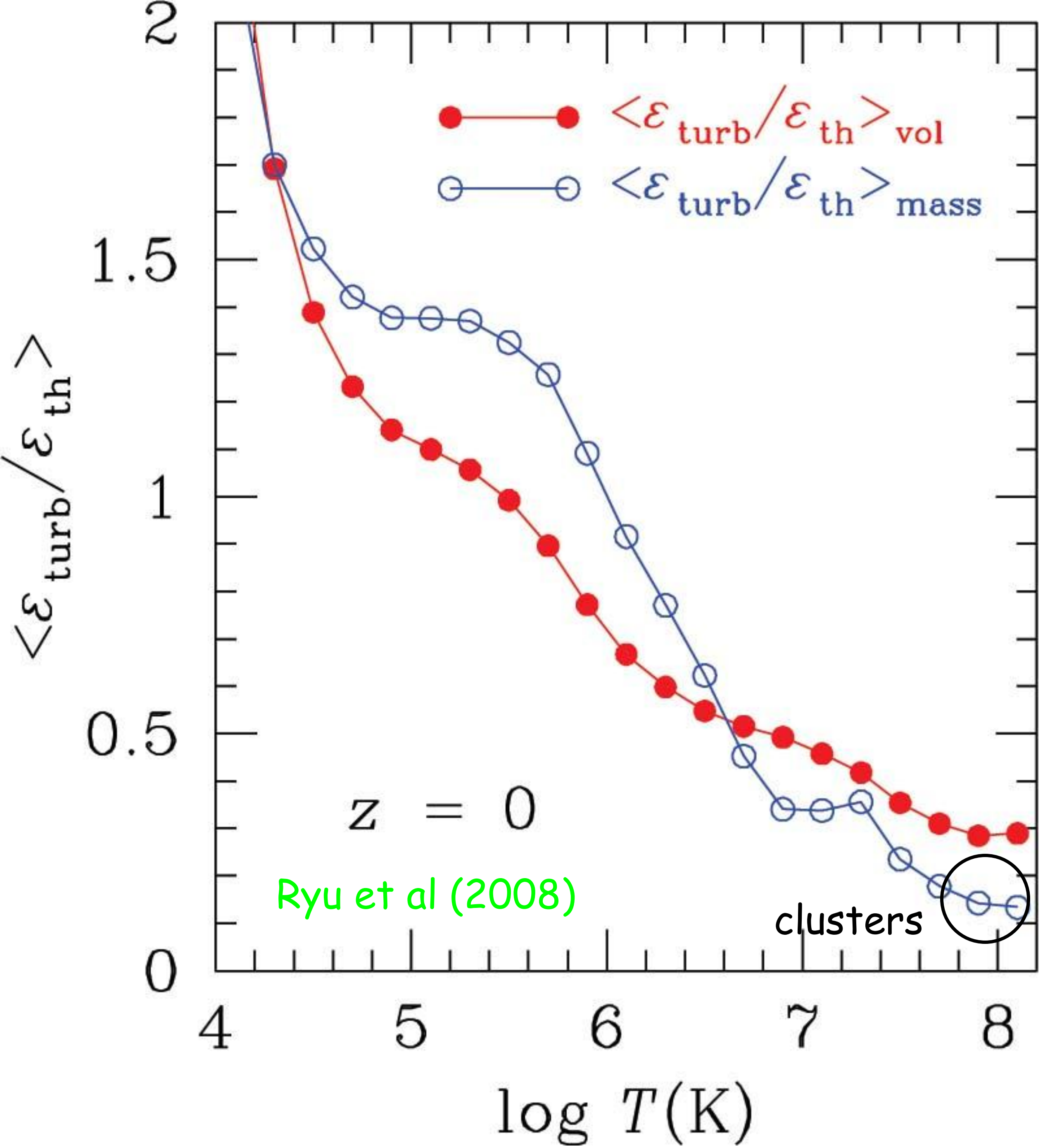
generation of vorticity at interacting shocks



div(v)



ω



Turbulence energy of in the ICM

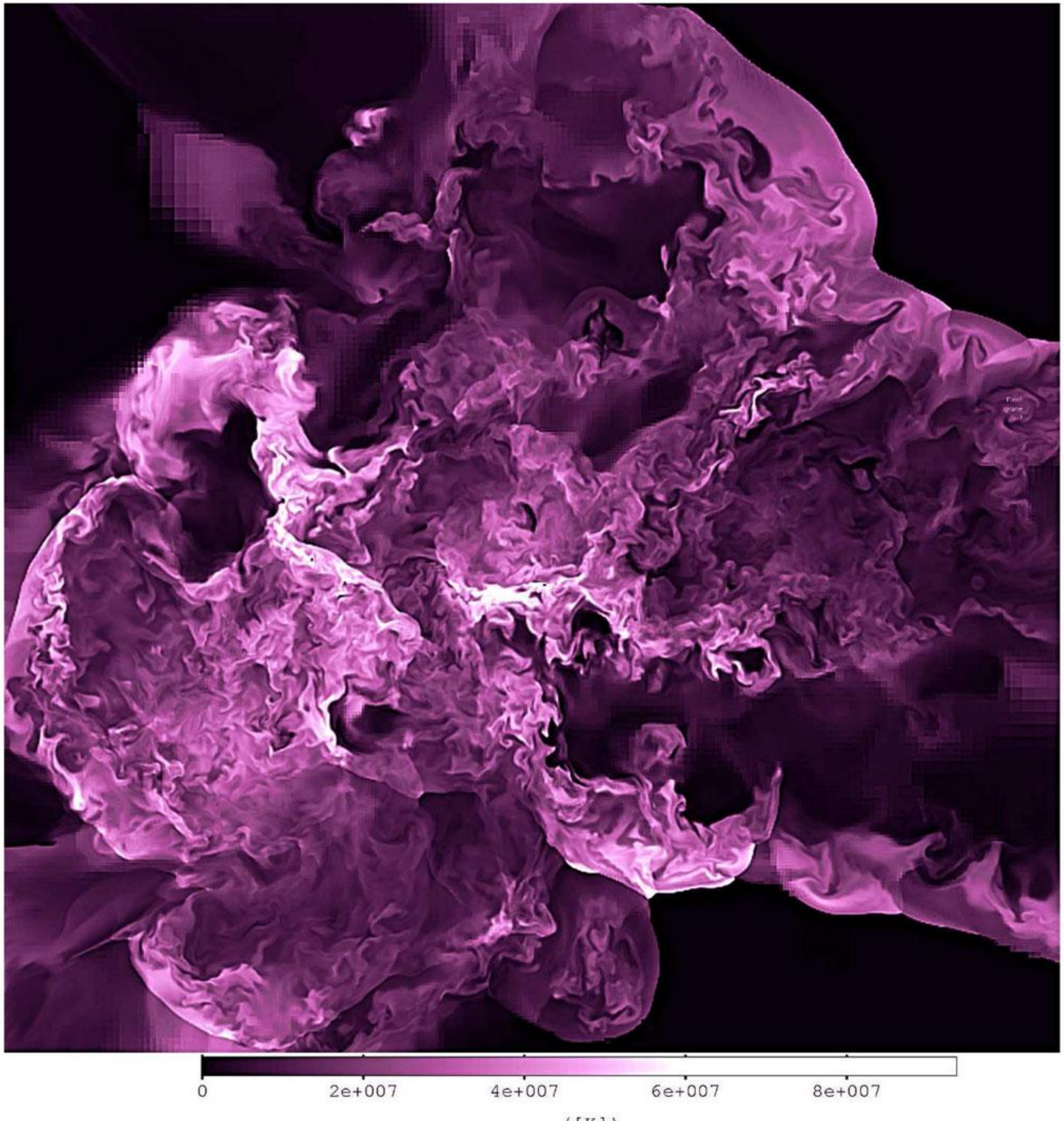
assuming that vorticity cascades down to induce turbulence

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

$E_{turb}/E_{therm} \sim 0.1 - 0.2$
inside and outskirts of clusters
-> agrees with obs.

$M_{turb} \sim 1$
(transonic turbulence)
in filaments

Turbulence in clusters: AMR simulations



temperature distribution in a merging cluster

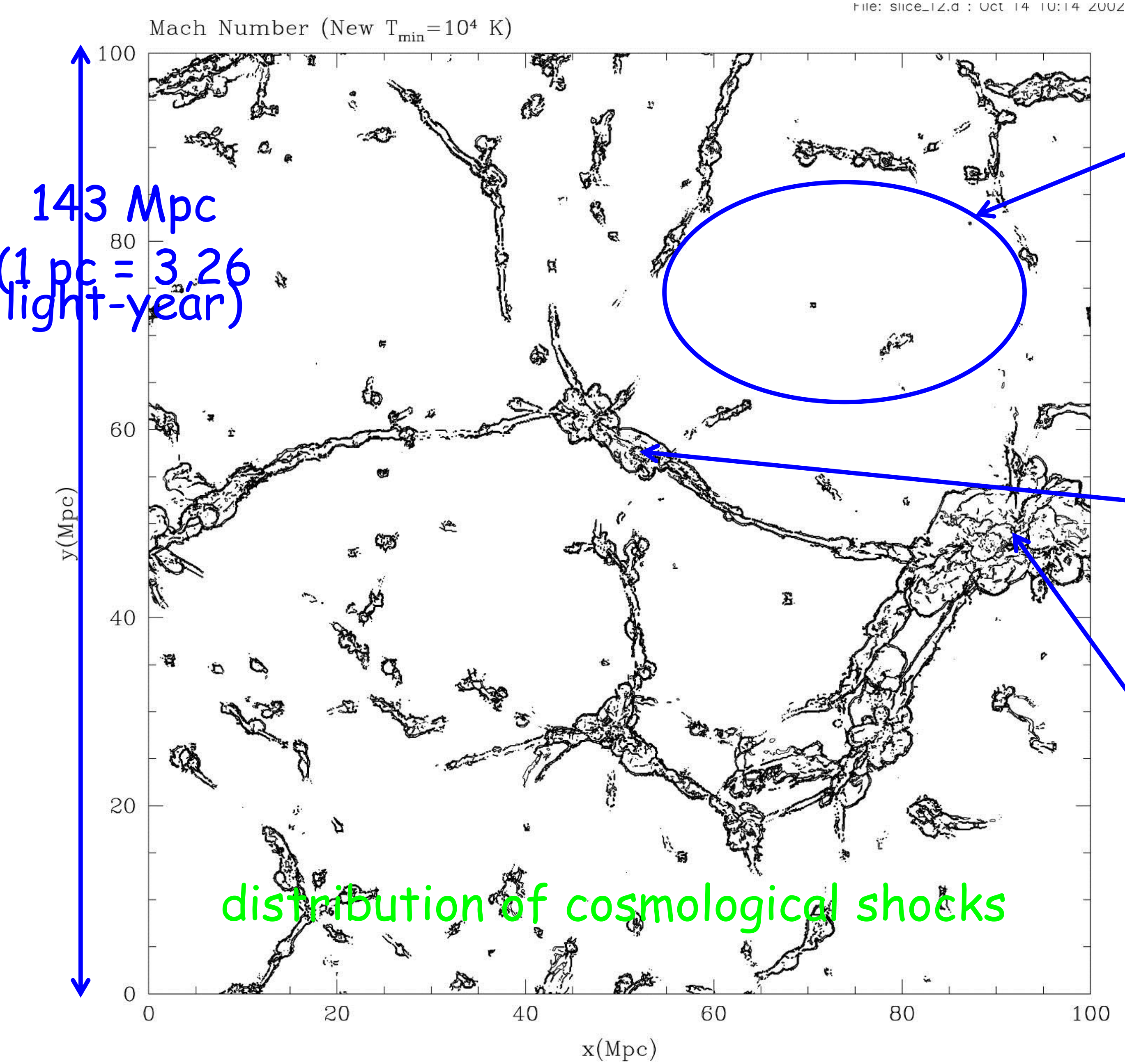
Vazza et al (2010)

Turbulence amplifies magnetic fields

-> **<u>mangetohydrodynamic turbulence</u>**

in astrophysical environments

Magnetic fields in the intergalactic space



void regions:
$B >\sim 10^{-16}$ G (?)

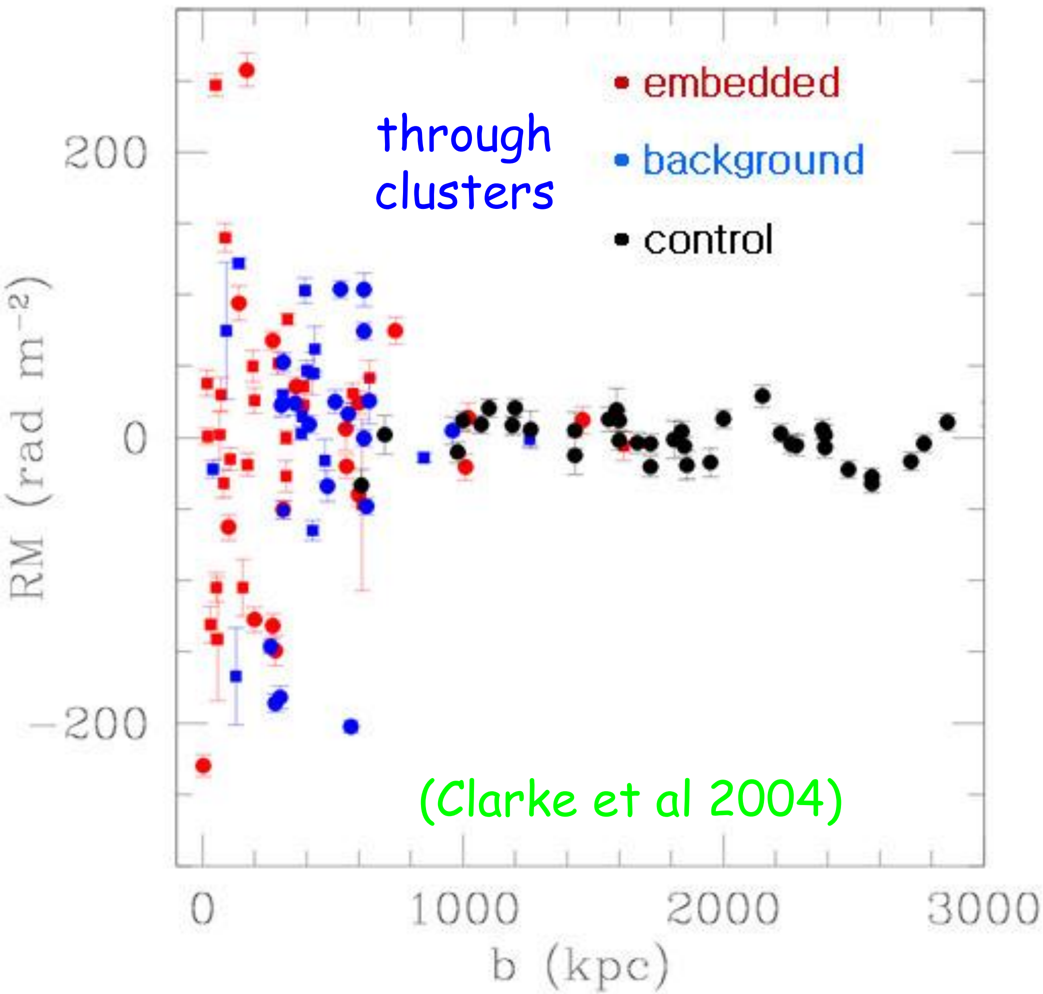
filaments of galaxies:
B ~ 10 nG

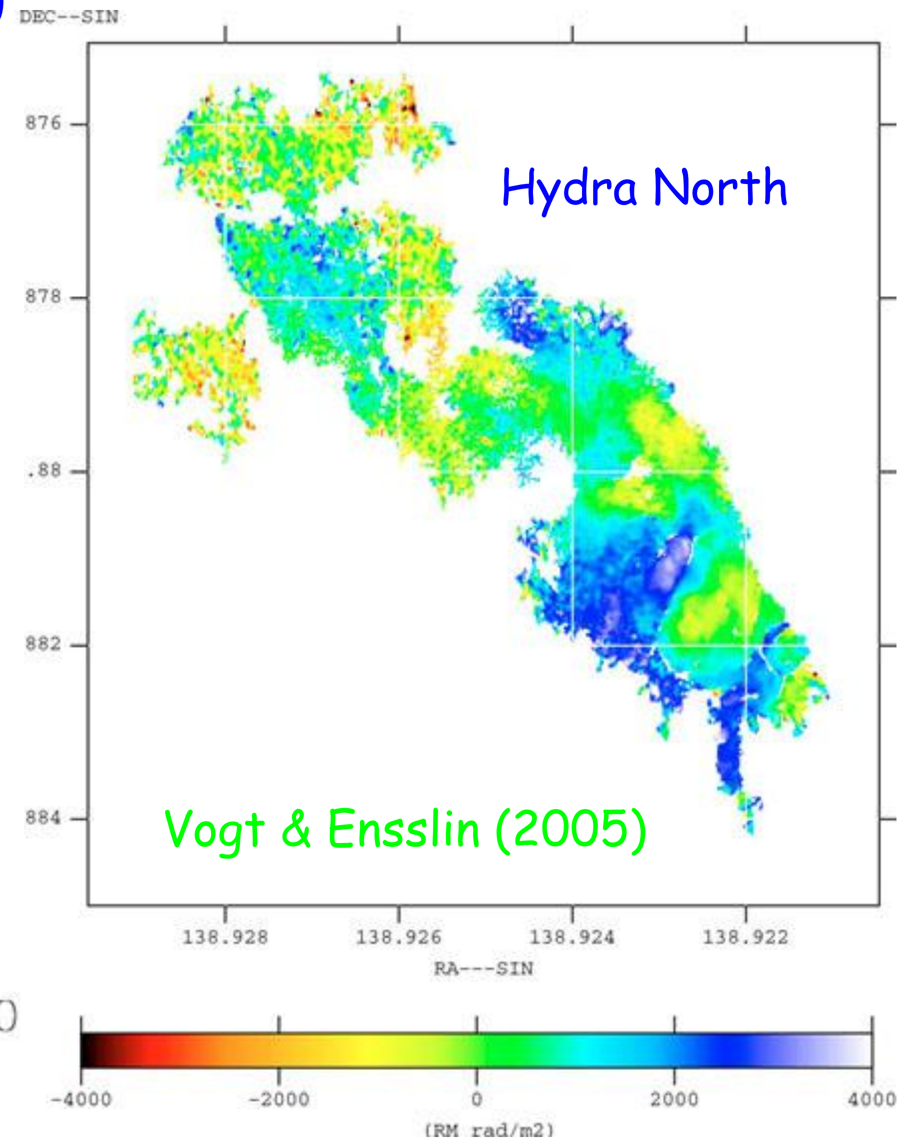
clusters of galaxies:
B ~ a few μG

Clusters of galaxies - magnetic fields

Faraday rotation measure of a few x 100 rad/m^2

-> B ~ a few μG (core region)





Origin of magnetic fields in clusters

- **turbulence dynamo** (or small-scale dynamo)

- AGN outflows, galactic winds, …

- microscopic instabilities, such as mirror, fire-hose …
  (contrinute only to very small-scale fields ?)

- and etc …

Simulations of isothermal compressible MHDs to study turbulence in clusters

- $c_s = 1$, $V_{rms} \sim 0.45$ (so $M_s \sim 0.45$) at saturation
  subsonic turbulence ($E_{kin}/E_{therm} \sim 0.1$)

- initially very weak field with $\beta = 10^6$

Porter, Jones, Ryu, Cho
(in preparation)

- purely solenoidal forcing
  (and purely compressive forcing)

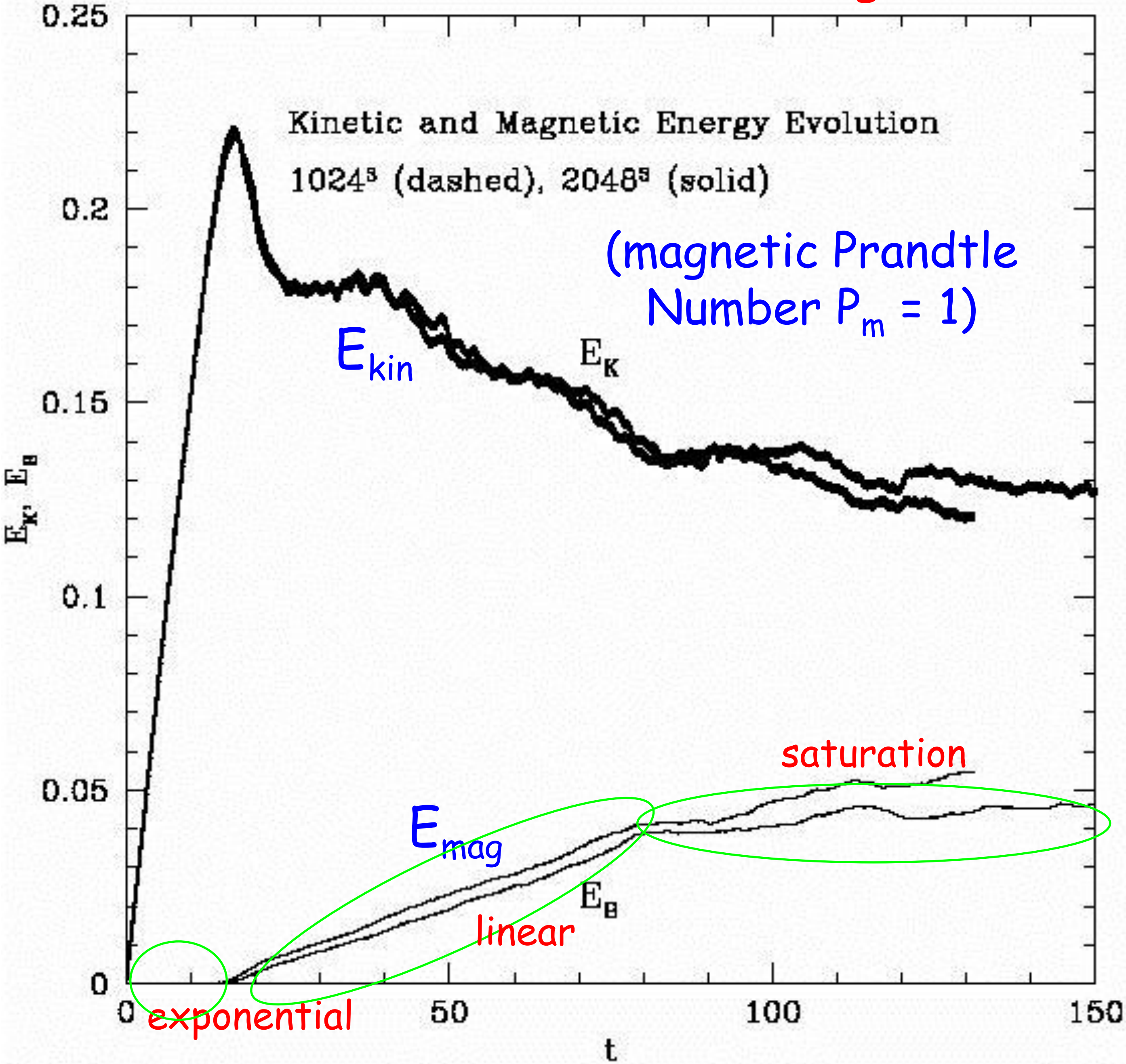
- ideal MHD, so Pr ~ 1
  (and Pr >> 1)

- injection at $L_{inj} \sim 1/2\ L_{box}$

- in a periodic box with $L_{box} = 10$
  sound crossing time ~ 10
  eddy turn-over time ~ 22

- up to 2048^3 grid zones

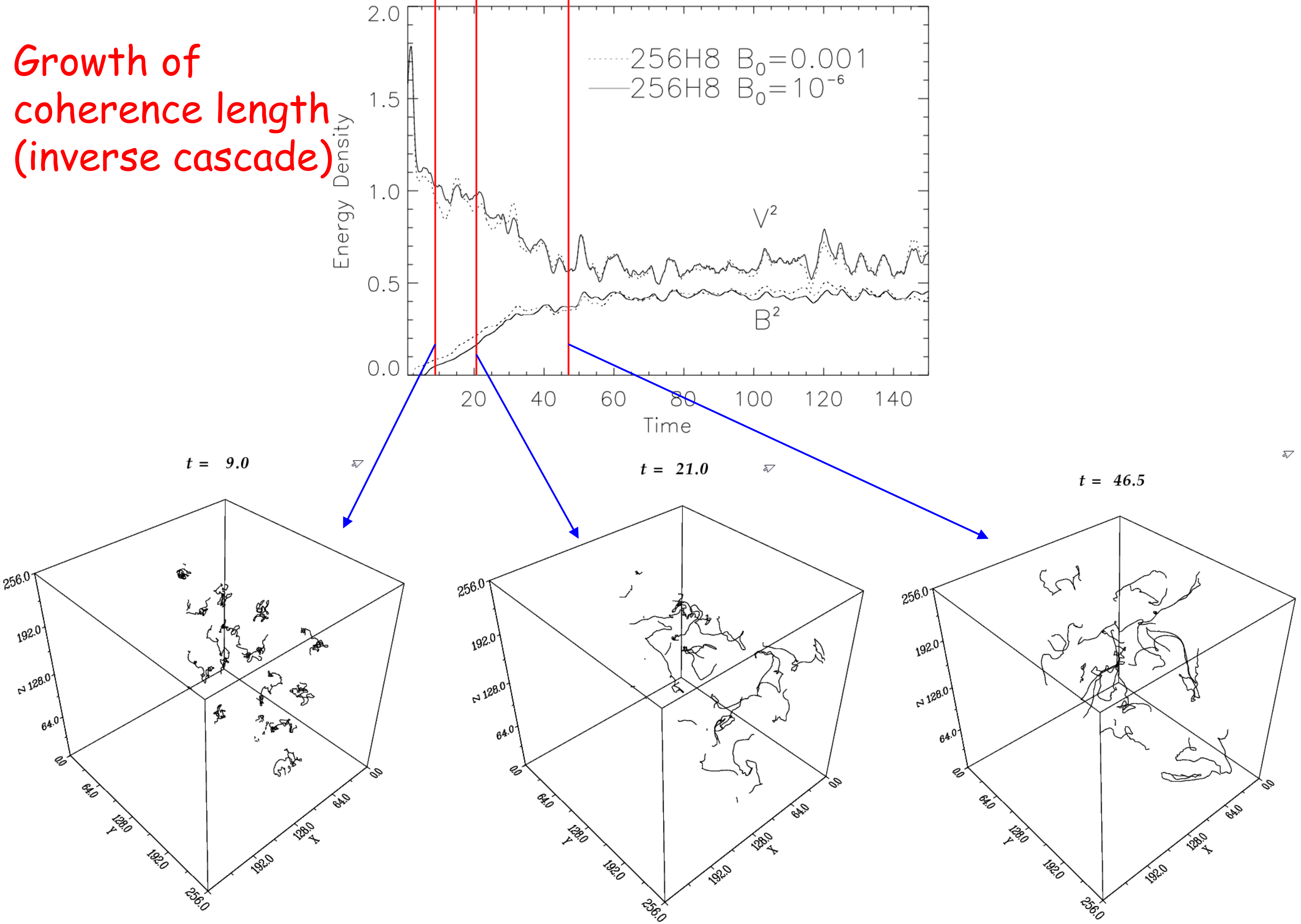
Evolution of kinetic and magnetic energies



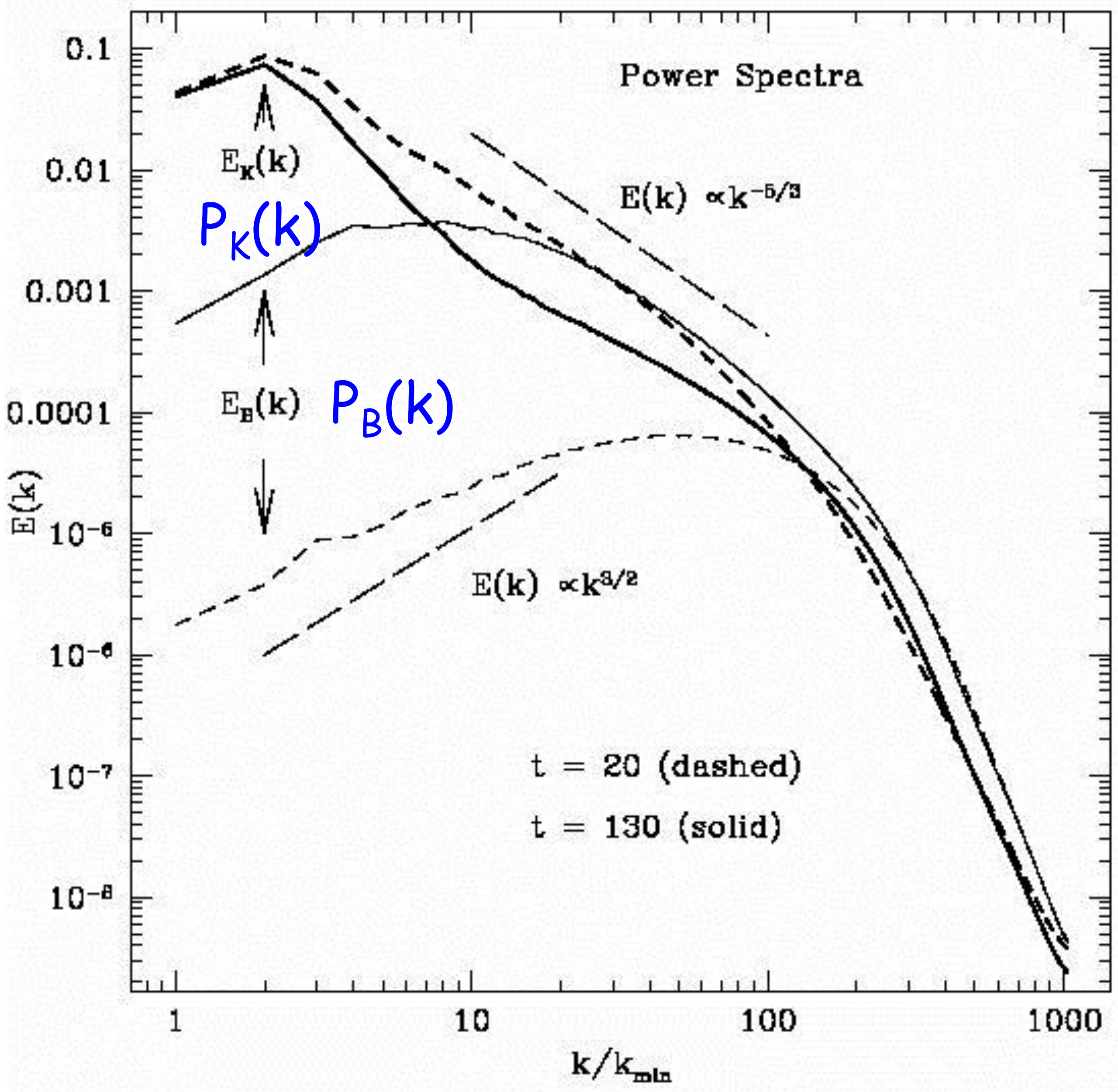
at saturation E_{mag}/E_{kin} ~ 1/2 in 2048^3 run, while E_{mag}/E_{kin} ~ 2/3 in incompressible run

(Porter, Jones, Ryu, & Cho, in preparation)

Growth of coherence length (inverse cascade)



Power spectrum



- the scales of magnetic fields grow as turbulence develops
- the peak of $P_B(k)$ occurs at ~1/2 L_{inj} at saturation

Kubo number

$$K = \frac{\delta B}{B_0}\frac{l_{\parallel}}{l_{\perp}} >\sim 1$$

at cluster scales

Resulting magnetic fields and numbers in clusters of galaxies

magnetic fields	$B \sim \text{a few } \mu\text{G}$
density of baryonic matter	$n \sim 10^{-2}\,\text{cm}^{-3}$
turbulent flow speed	$\upsilon \sim \text{several} \times 10^{2}\ \text{km/s}$
gas temperature	$T \sim 10^{8}\,\text{K}$
gas thermal energy	$E_{\text{thermal}} \sim 10^{-10}\,\text{erg/cm}^{3}$
turbulent energy	$E_{\text{turb}} \sim 10^{-11}\,\text{erg/cm}^{3}$
magnetic energy	$E_{\text{magnetic}} \sim 10^{-12}\,\text{erg/cm}^{3}$

magnetic fields
<- could be produced and maintained mostly by turbulence dynamo
but also contributed by feedbacks from galaxies

Conclusions

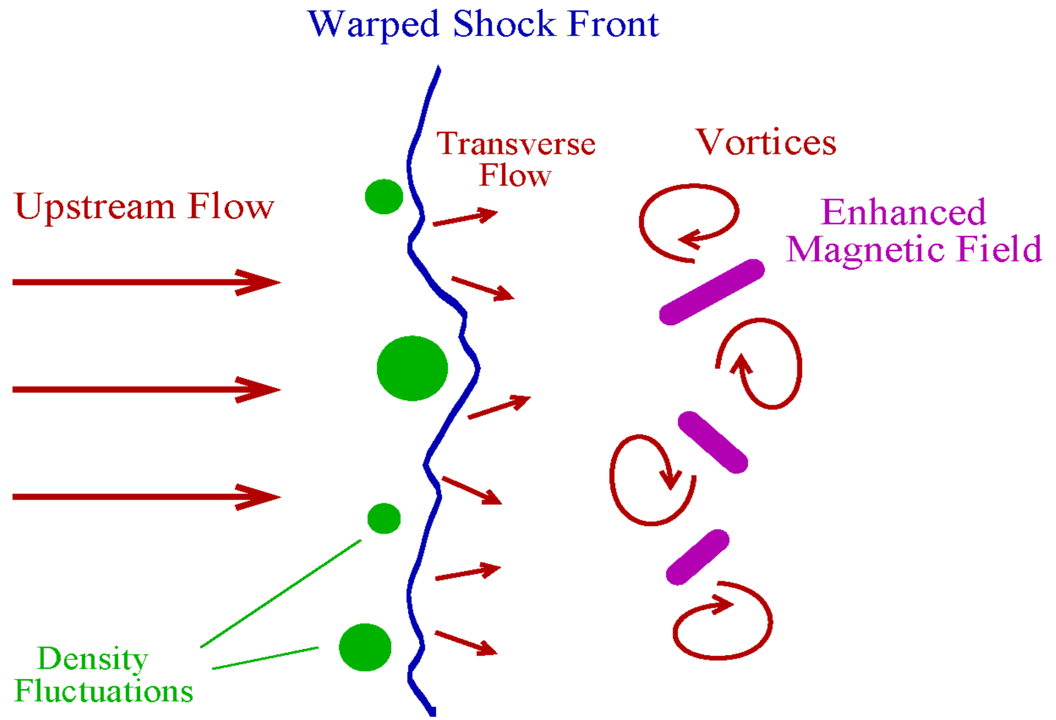
- Intracluster media provide a distinctive environment where diverse physical processes, such as shocks particle acceleration, turbulence, magnetic field generation and etc, play an important role.

- Understanding turbulence in intracluster medium is rather tricky, mostly **<u>because the physics there is not well understood</u>**.

- Laboratory experiments can help understand turbulence as well as other astrophysical phenomena in intracluster media

Once shocks are produced, turbulence can be induced !

Most, if not all, turbulence in astrophysics is induced by shocks or related processes.



Viscosity and resistivity the ICM

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

or substantially smaller ?

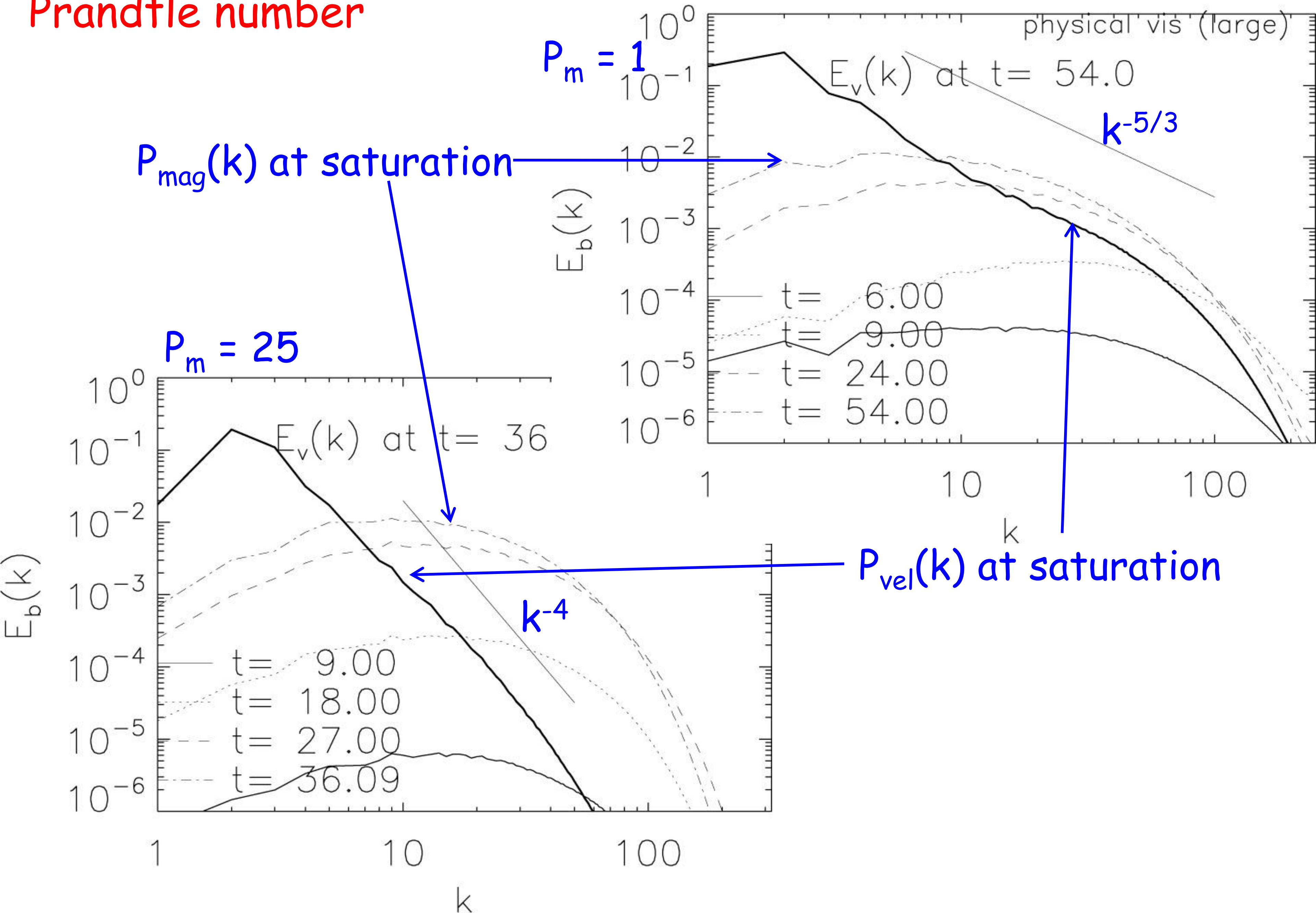
resistivity $\eta \sim \dfrac{(c/\omega_p)^2}{t_{e-p}}$ $\left(\omega_p = \left(\dfrac{4\pi\, n_e e^2}{m_e} \right)^{1/2} \right)$ (?)

much smaller than viscosity?

⟹ high magnetic Prandtle number ?

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

Incompressible MHD turbulence with different magnetic Prandtle number



Viscosity and resistivity the ICM

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

or substantially smaller ?

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

much smaller than viscosity?

transportation of particles is affected by magnetic fields

⟹ much smaller Prandtle number ?

Conclusions

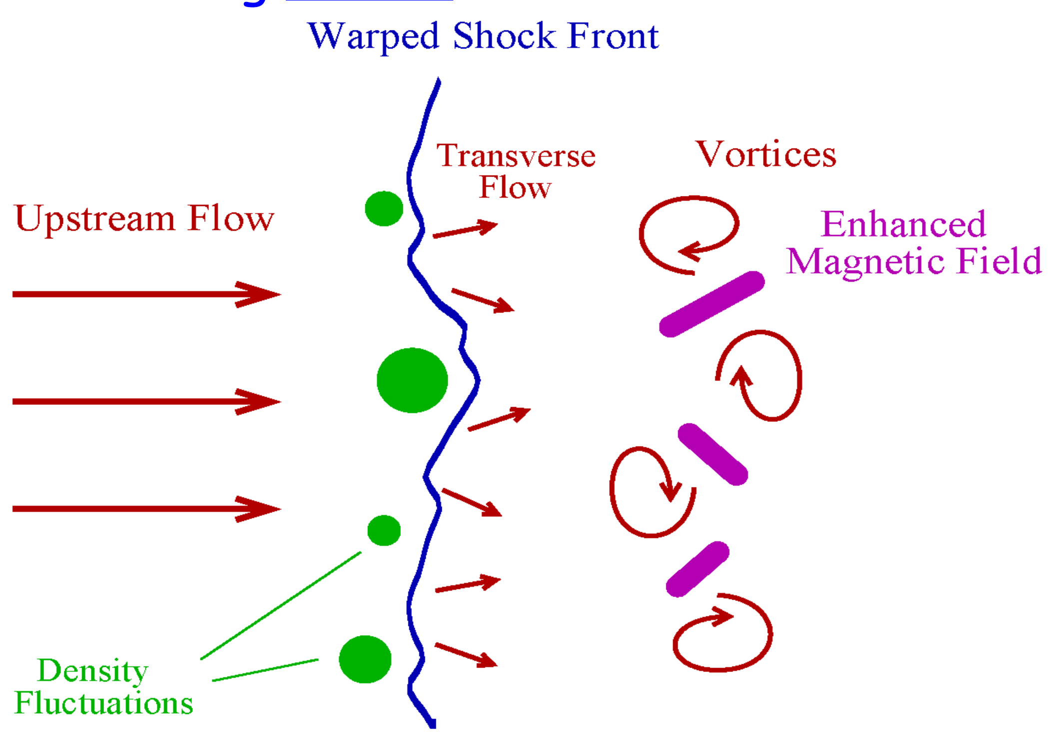
- Intracluster media provide a distinctive environment where diverse physical processes, such as shocks particle acceleration, turbulence, magnetic field generation and etc, play an important role.

- Understanding turbulence in intracluster medium is rather tricky, mostly because the physics there is not well understood.

- Laboratory experiments can help understand **turbulence** as well as other astrophysical phenomena including **shocks** in intracluster media

Once shocks are produced, turbulence can be induced !

Most, if not all, turbulence in astrophysics is induced by shocks or related processes.



Thank you !