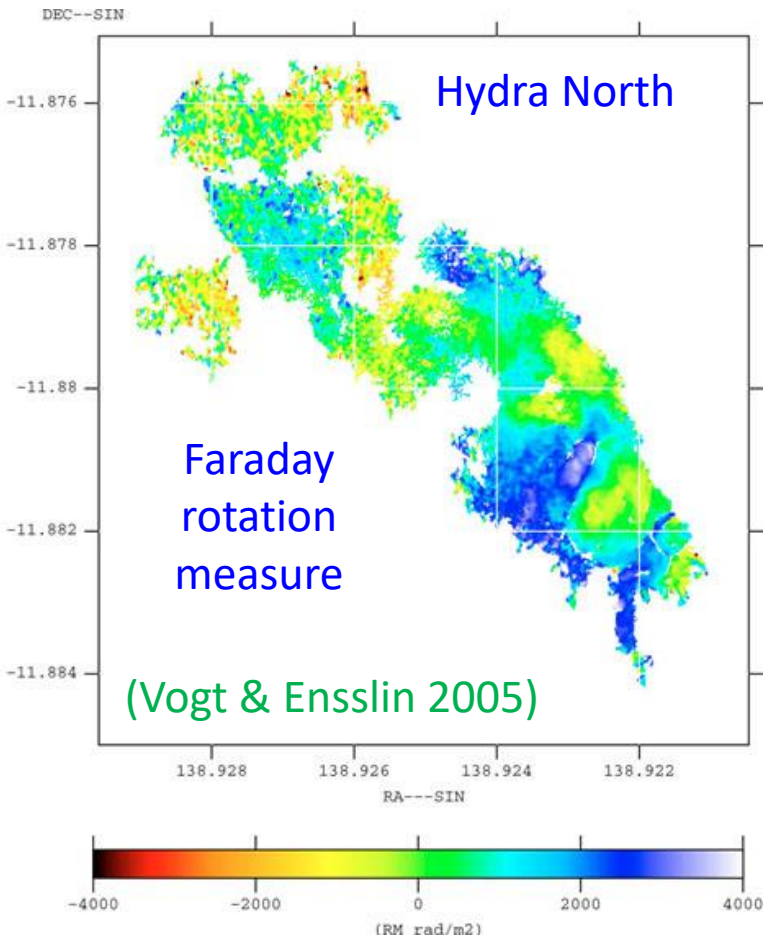
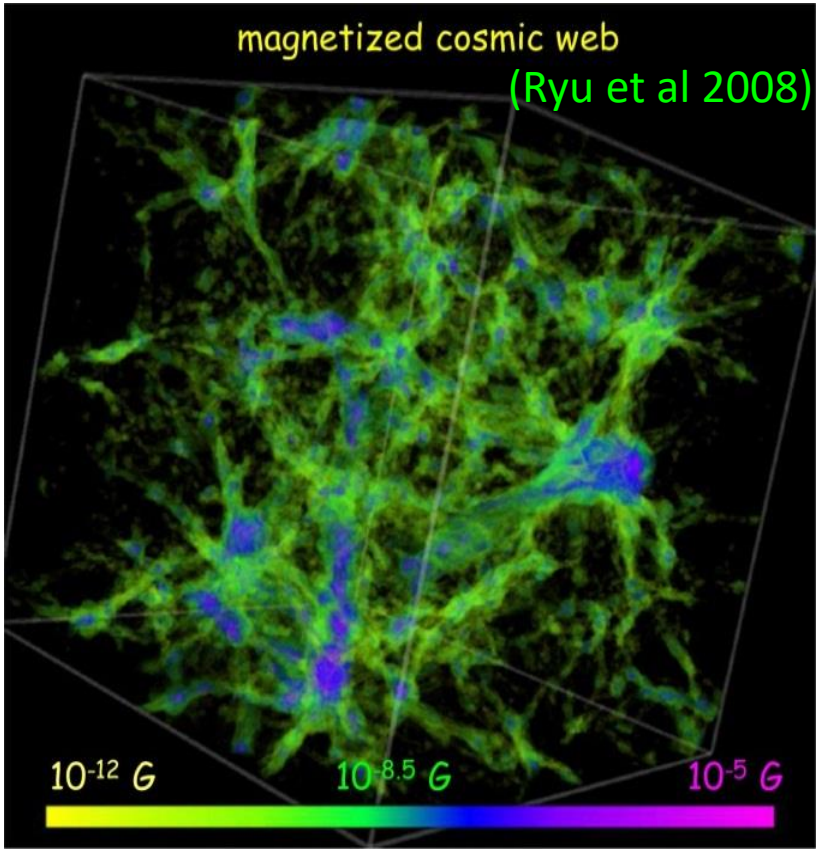
Magnetic Fields in Clusters of Galaxies

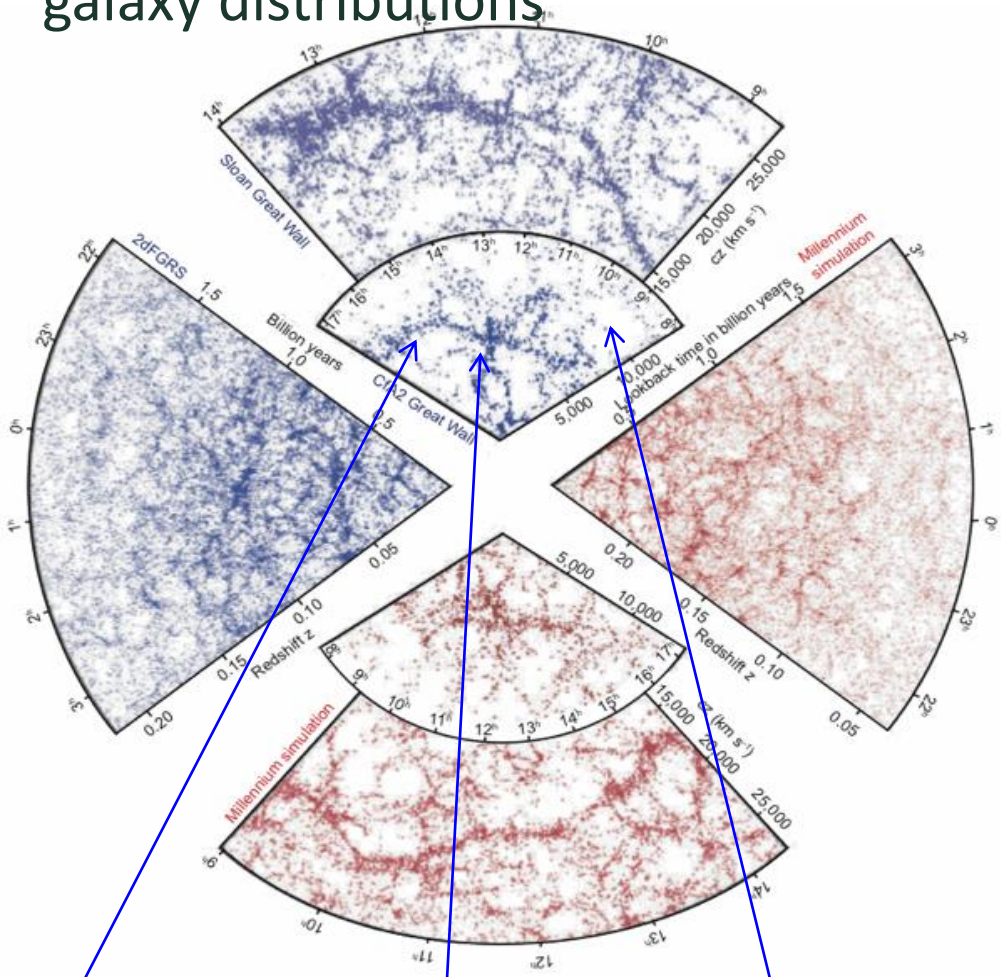


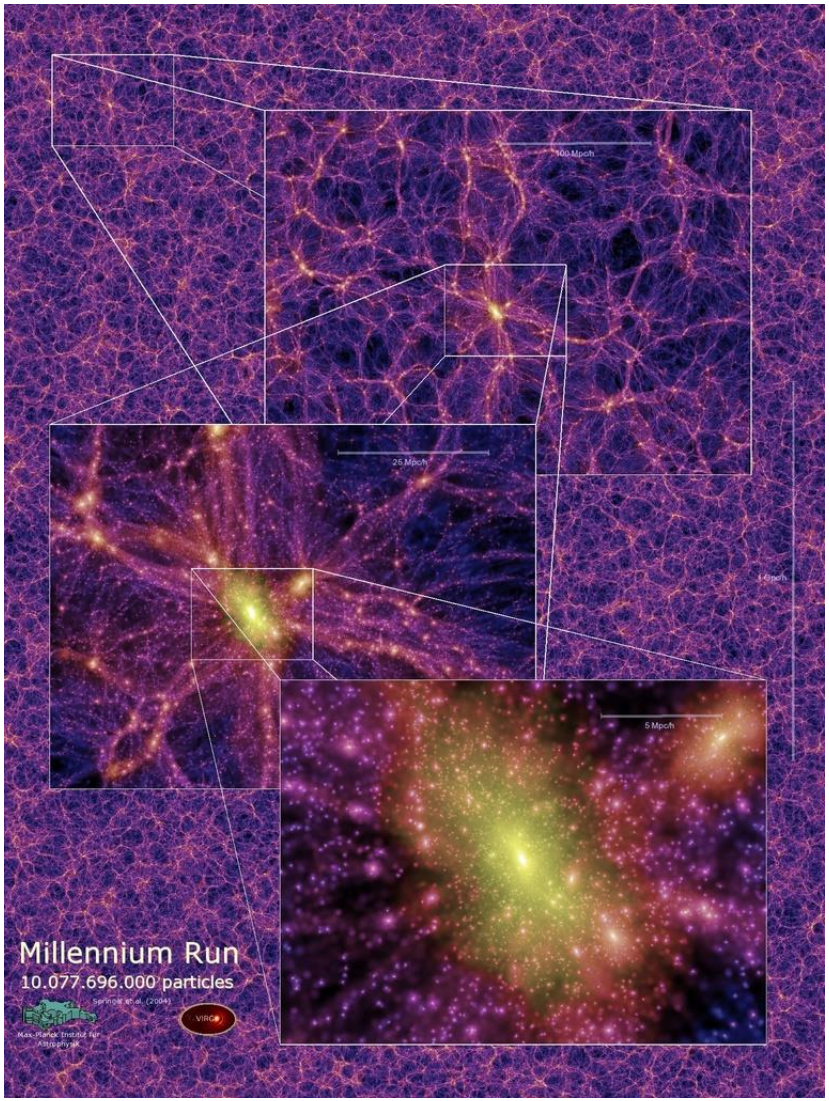


Dongsu Ryu (UNIST, Korea)

The large-scale structure of the universe
→ the cosmic web

observed and simulated galaxy distributions



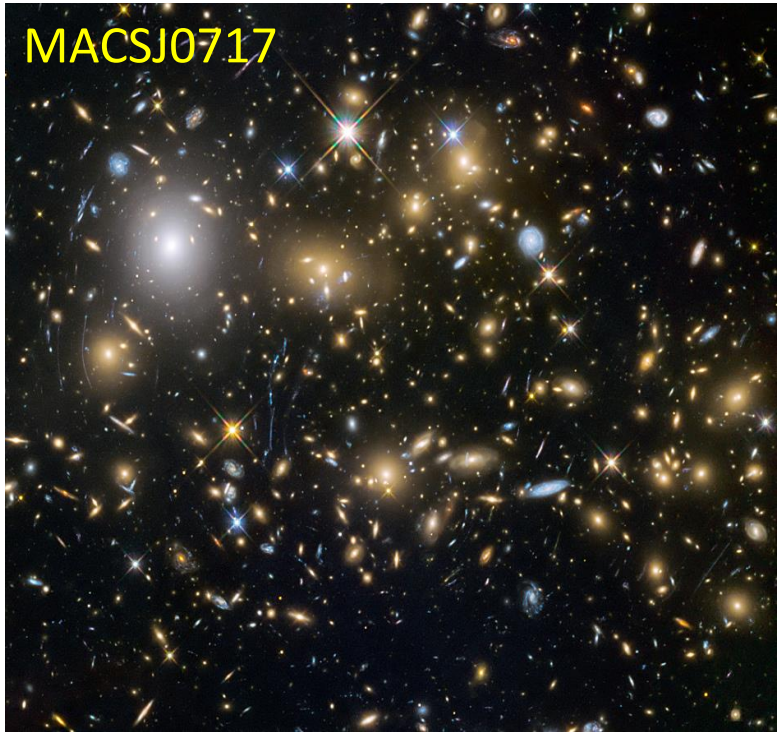


filaments **clusters** void regions

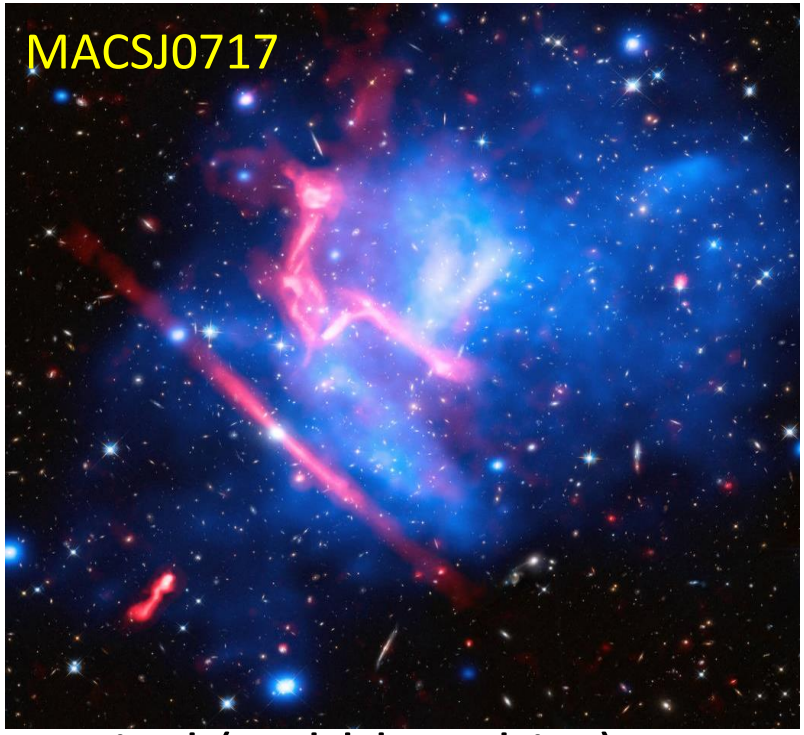
where most matters reside

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



Hubble space telescope image
← mostly star light

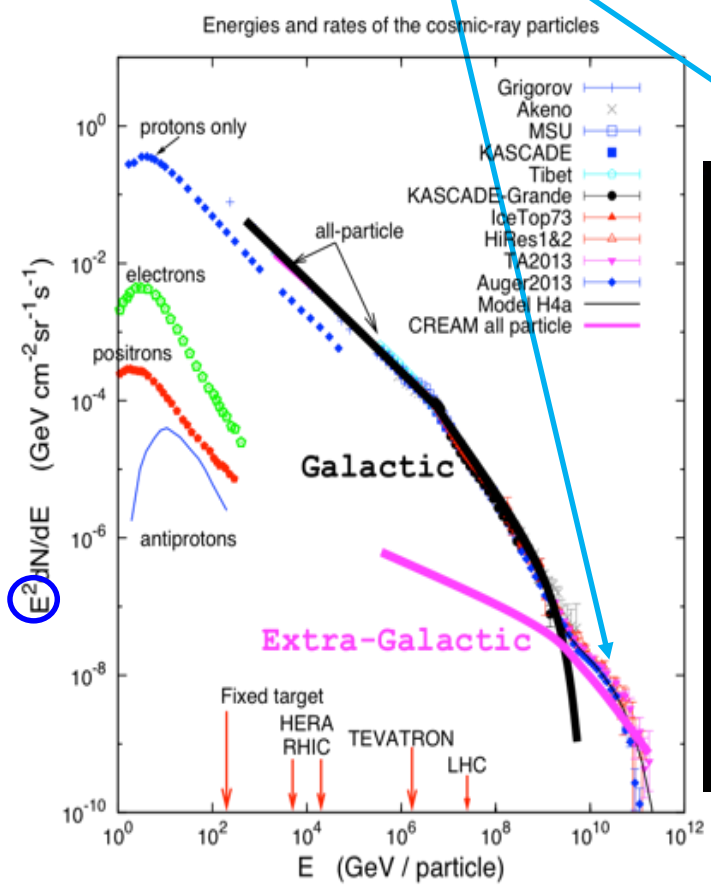


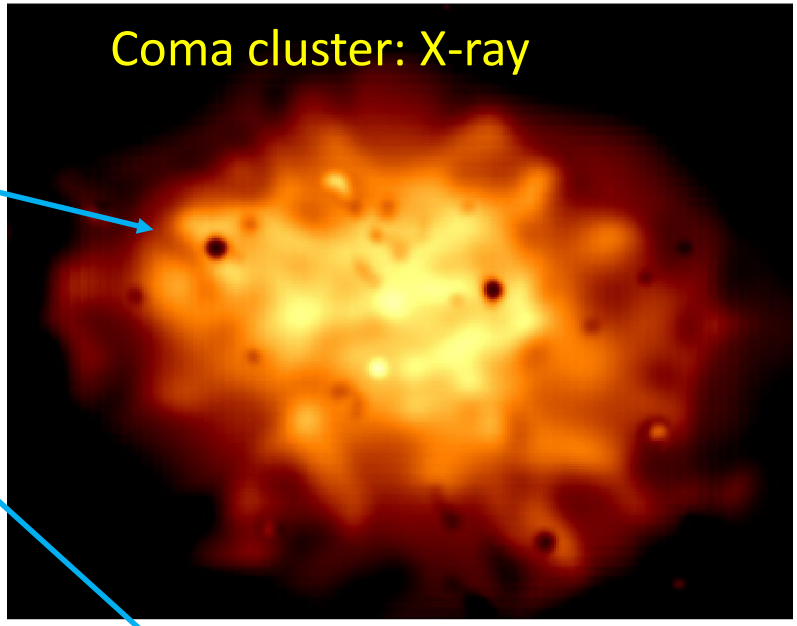
optical (Hubble, white)
X-ray (Chandra, blue) ← hot gas
radio (VLA, red) ← cosmic rays

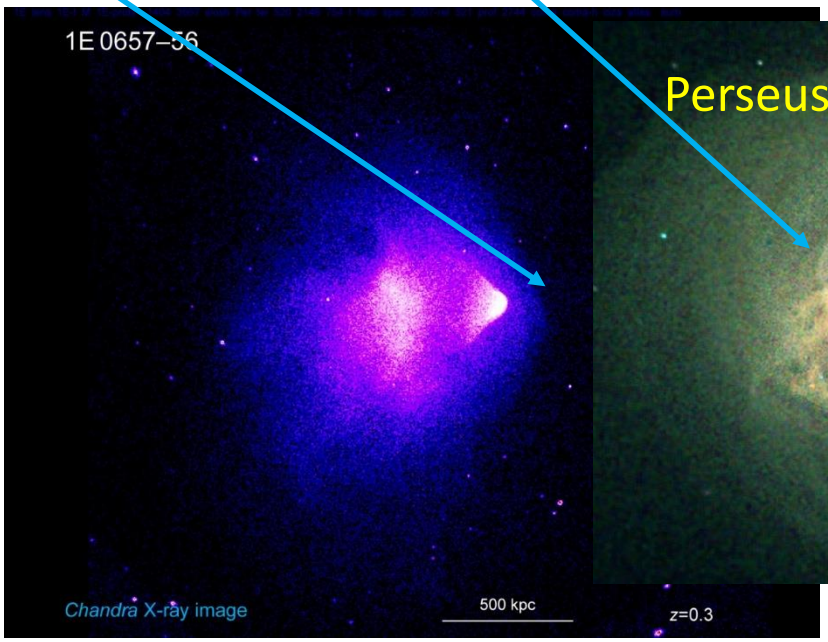
the intracluster medium (ICM) → the superheated **plasma with T ~ a few to several keV**, presented in clusters of galaxies

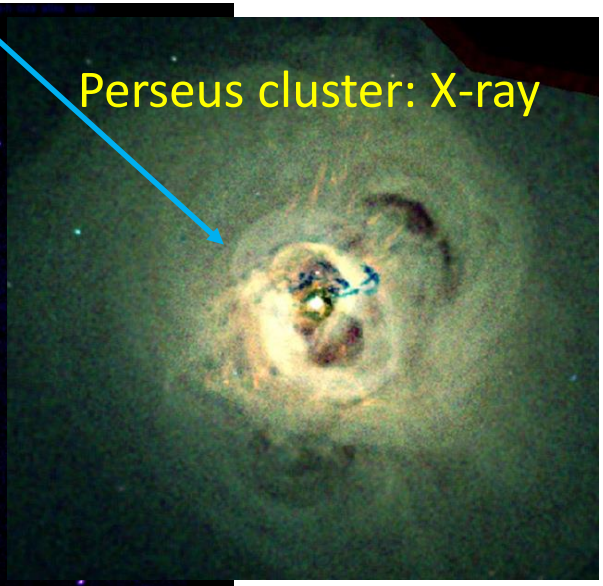
ICMs are dynamical:

- turbulent flow motions
- large-scale flow motions
- **magnetic fields**
- cosmic-rays
- shock waves

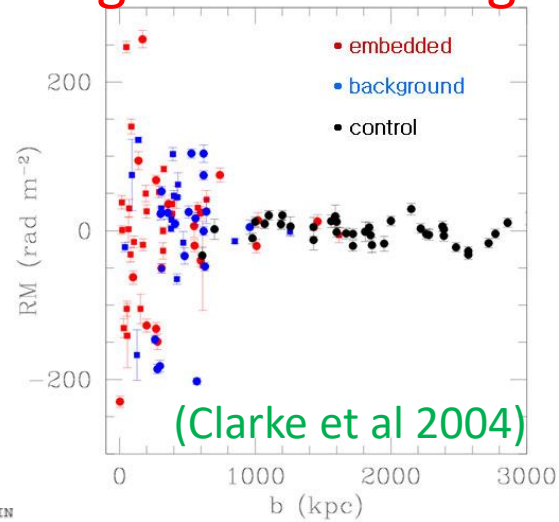


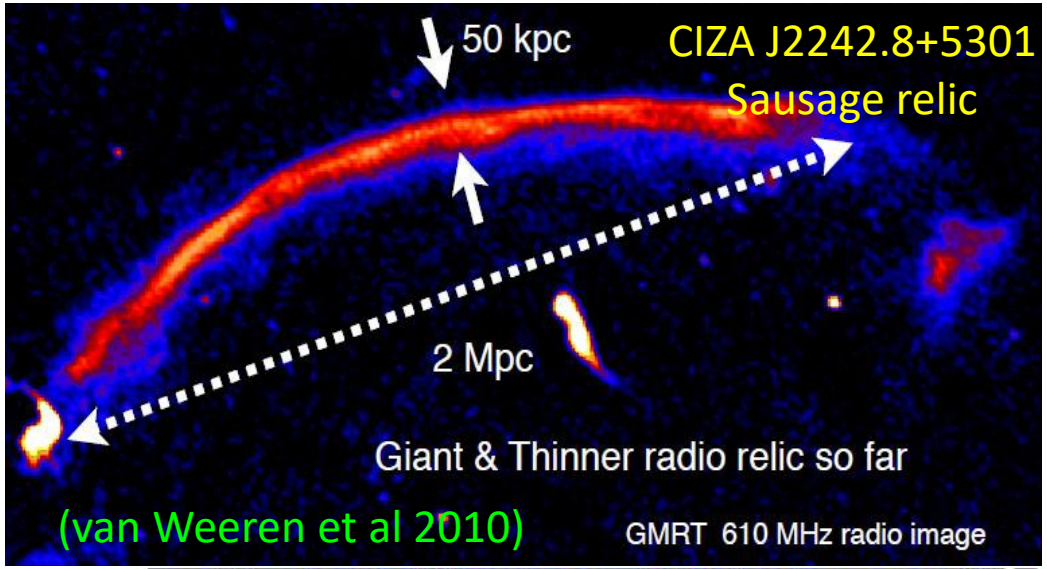


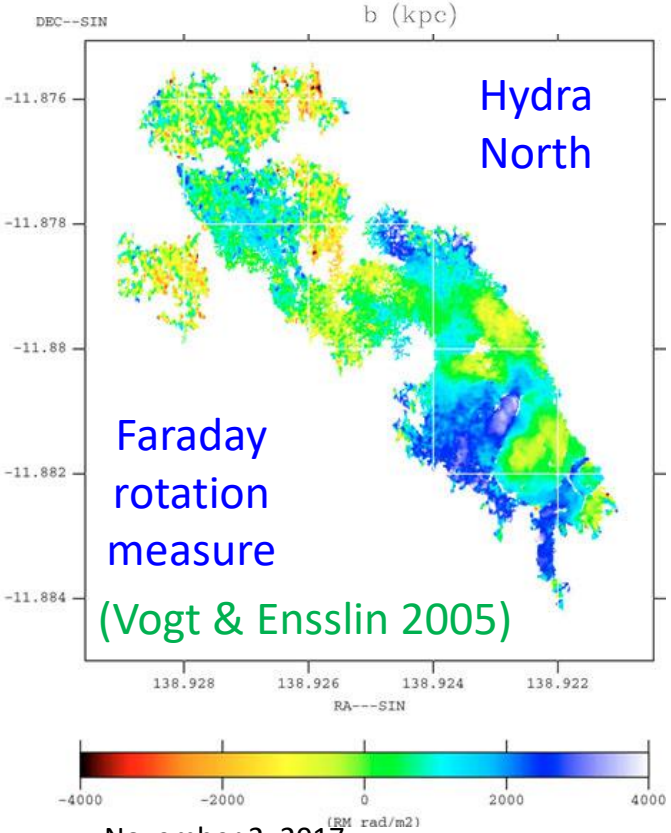


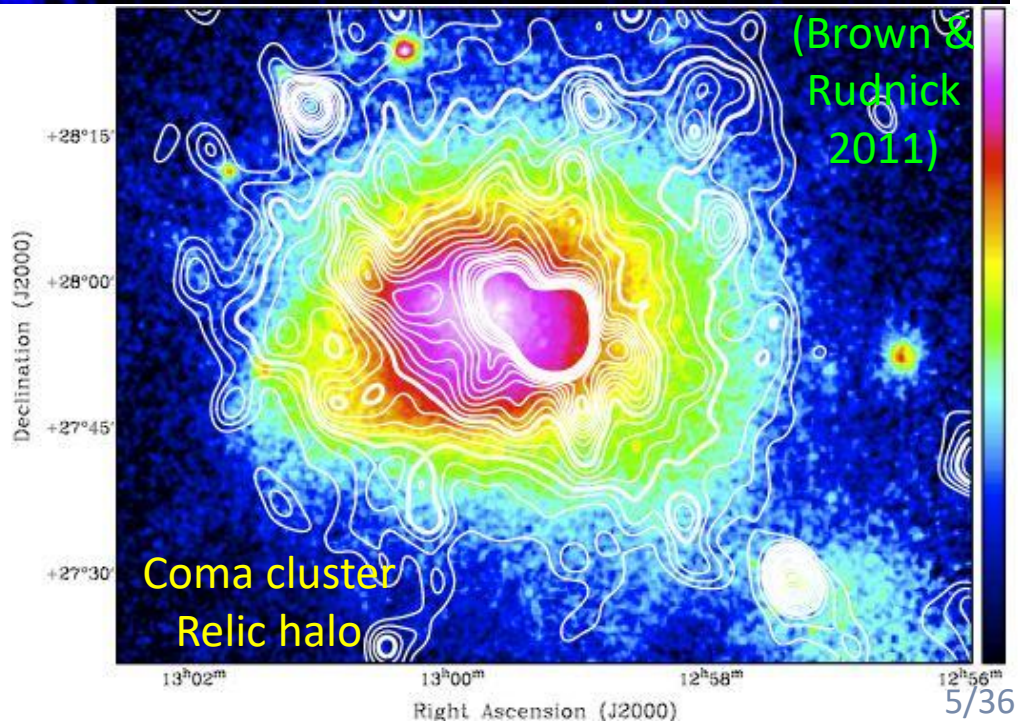


Magnetic fields in galaxy clusters appears in observations









(Govoni & Feretti 2004)

Table 3. Magnetic field estimates derived from various methods in the clusters Coma and A3667.

Name	Method	Field strength (μG)	Location	Reference
Coma	Equipartition	0.45	radio halo	34
	Equipartition	0.55	radio relic	77
	Faraday Rotation	7	cluster center	16
	Faraday Rotation	0.2	cluster center(large scale)	16
	Inverse Compton	0.2	cluster average	114
A3667	Equipartition	1.5–2.5	NW relic	86
	Inverse Compton	≥ 0.4	cluster average	120
	Faraday Rotation	1–2	cluster center	86
	Faraday Rotation	3–5	NW relic	86
	Cold front	10	along the cold fronts	153

Column 2 gives the method used to estimate the field strength, Column 3 the value of the magnetic field in μG, Column 4 describes the location in the cluster at which this estimation is made, Column 5 gives the reference.

modeling of synchrotron of the Sausage relic → B_1 ~ 2 – 2.5 G (Kang & Ryu 2015)

modeling of synchrotron of the Toothbrush relic → B_1 ~ 1 – 1.5 G

(Kang, Ryu, & Jones 2017)

Fluid quantities in ICM outskirts

size of clusters	$L_{cluster}$ ~ a few Mpc ~ 10^{25} cm
baryon number density	n ~ 10^{-3} cm
flow velocity	v ~ several x 100 km/s
gas temperature	T ~ 10^{8} K (8.6 keV) → c_s ~ 1,500 km/s
magnetic fields	B ~ a few x μG → c_A ~ 100 km/s

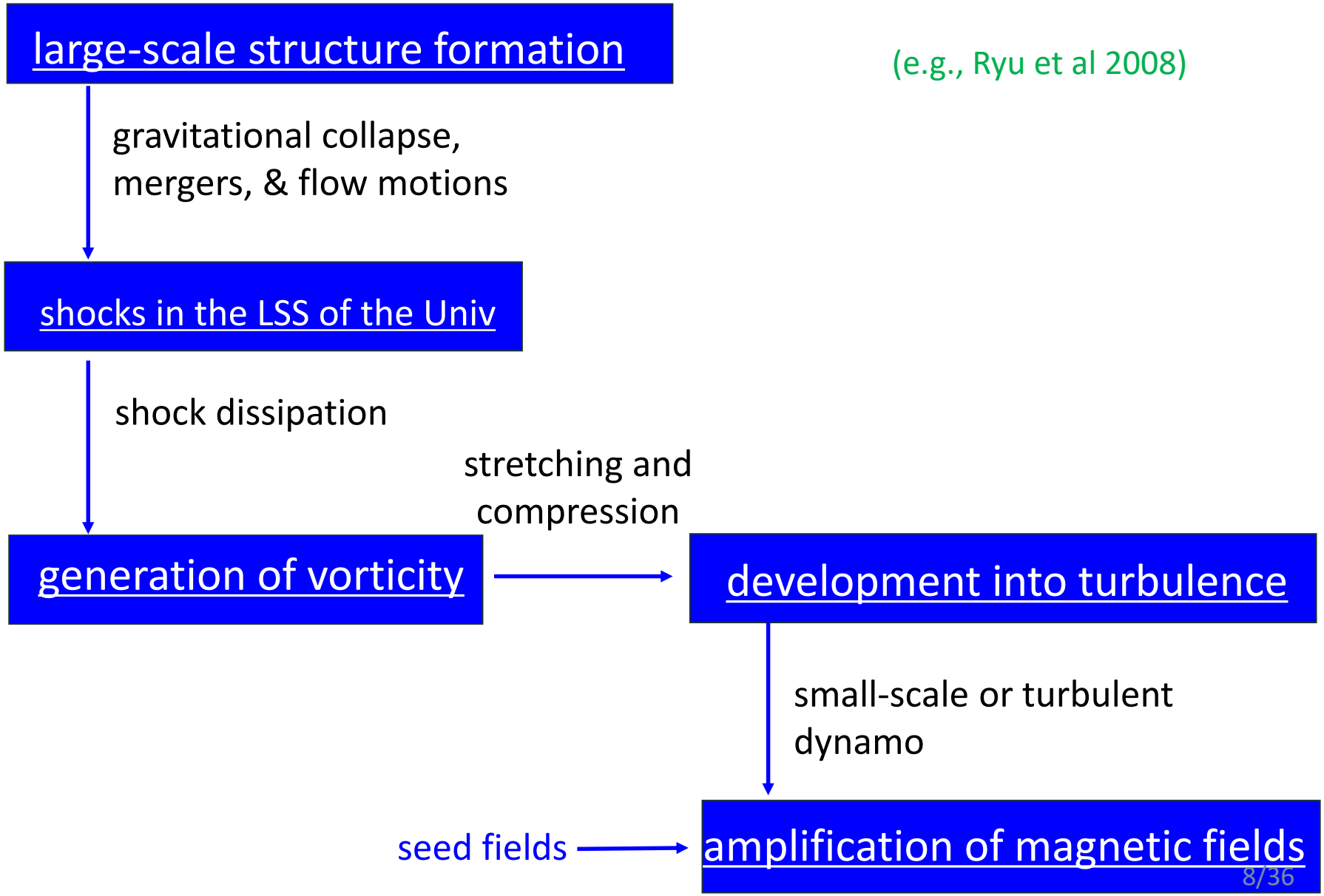
→ flows are subsonic (M_s ~ 0.5) but super-Alfvenic (M_A > 1)

gas thermal energy	$E_{thermal}$ ~ a few x 10^{-11} erg/cm^3
gas kinetic energy	$E_{kinetic}$ ~ a few x 10^{-12} erg/cm^3
magnetic energy	**$E_{magnetic}$ ~ a few x 10^{-13} erg/cm^3**
cosmic-ray energy	E_{CR} <~ a few x 10^{-13} erg/cm^3 ($E_{thermal}$ / 100)

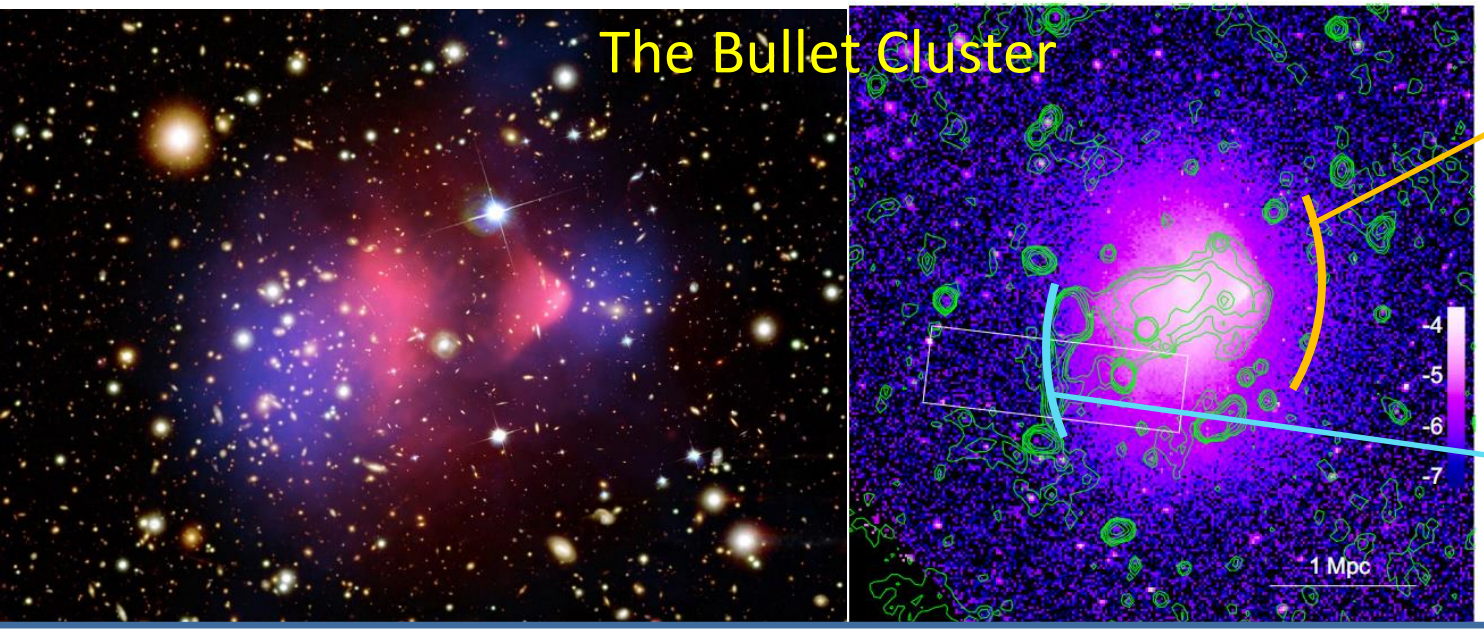
→ plasma beta is high with β ~ 50 - 100 $\left(\beta \equiv \frac{P_{thermal}}{P_{magnetic}} \equiv \frac{2E_{thermal}}{3E_{magnetic}}\right)$

Turbulence dynamo model for magnetic fields in clusters of galaxies

(e.g., Ryu et al 2008)

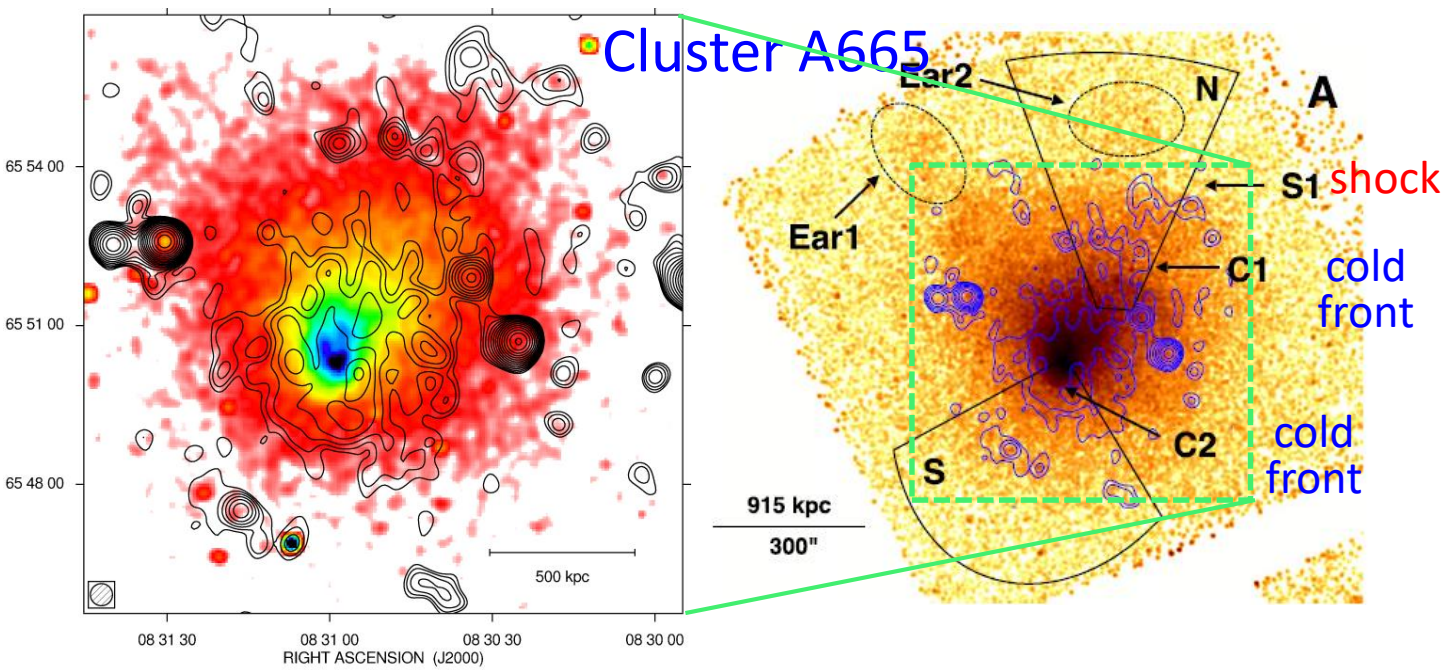


Observation of shocks in clusters: X-ray



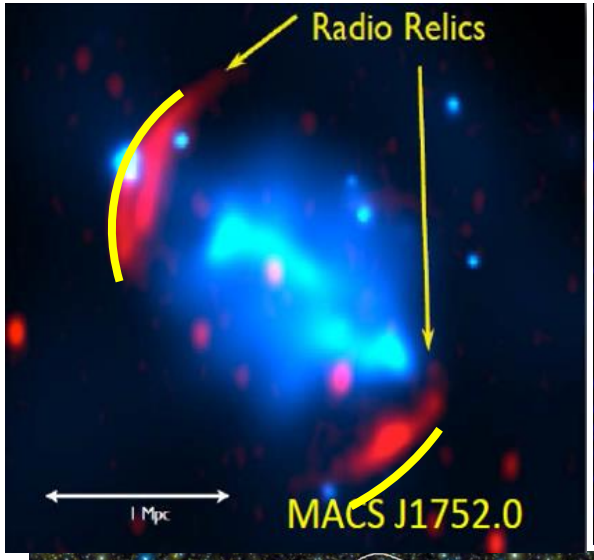
$M_X \approx 3.0$
(no associated radio relic)
(Markevitch 2006)

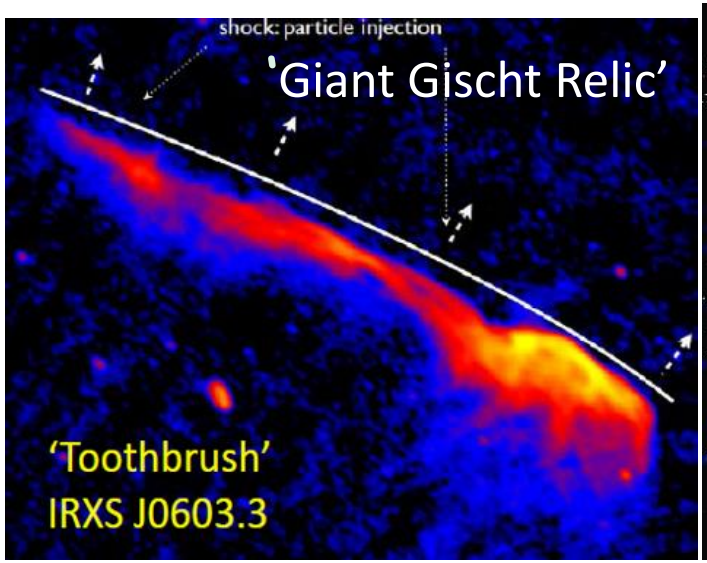
$M_X \approx 2.5$
(Shimwell et al. 2015)

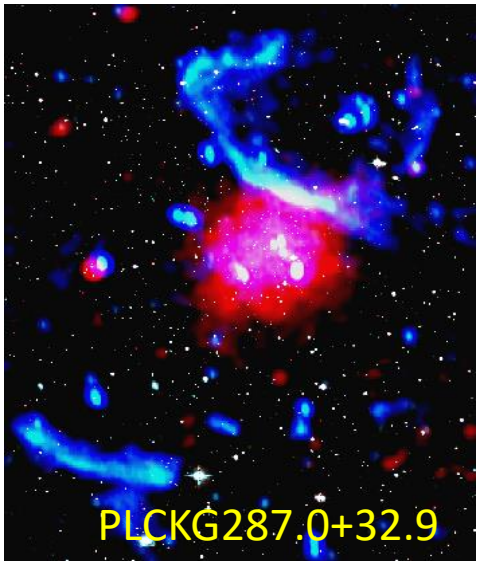


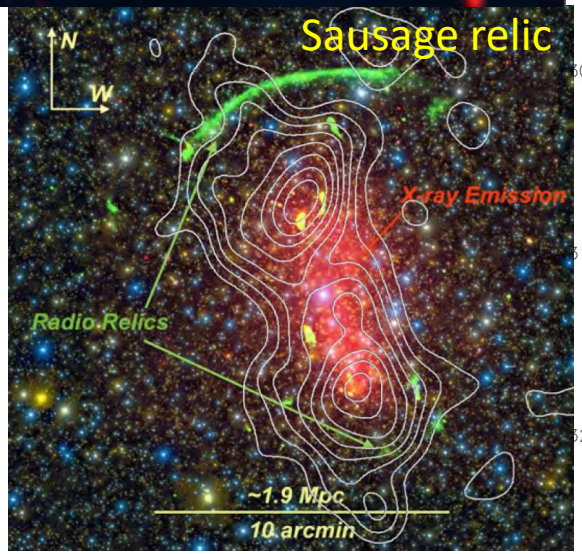
$M_X = 3 \pm 0.6$
(no associated radio relic)
(Dasadia et al. 2016)

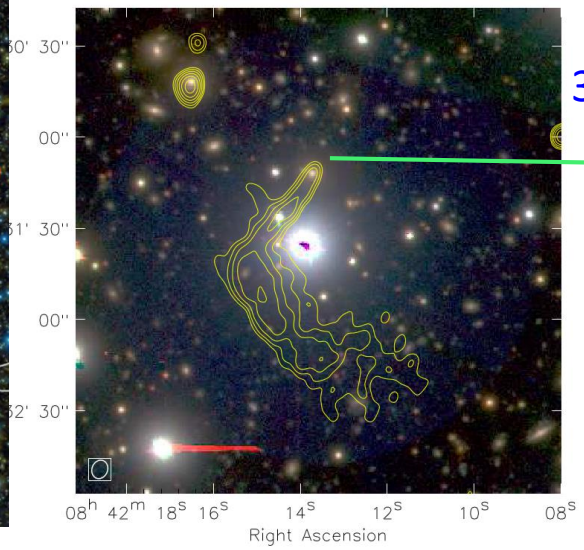
Observation of shocks in clusters: radio relics



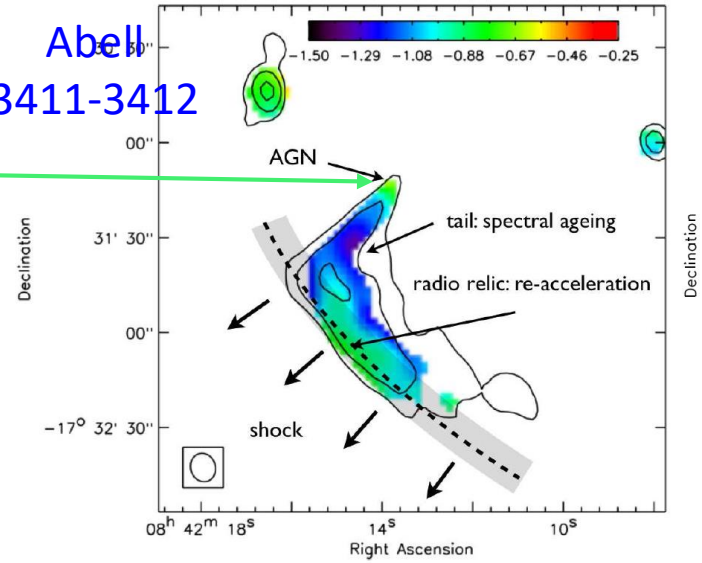








Abell 3411-3412



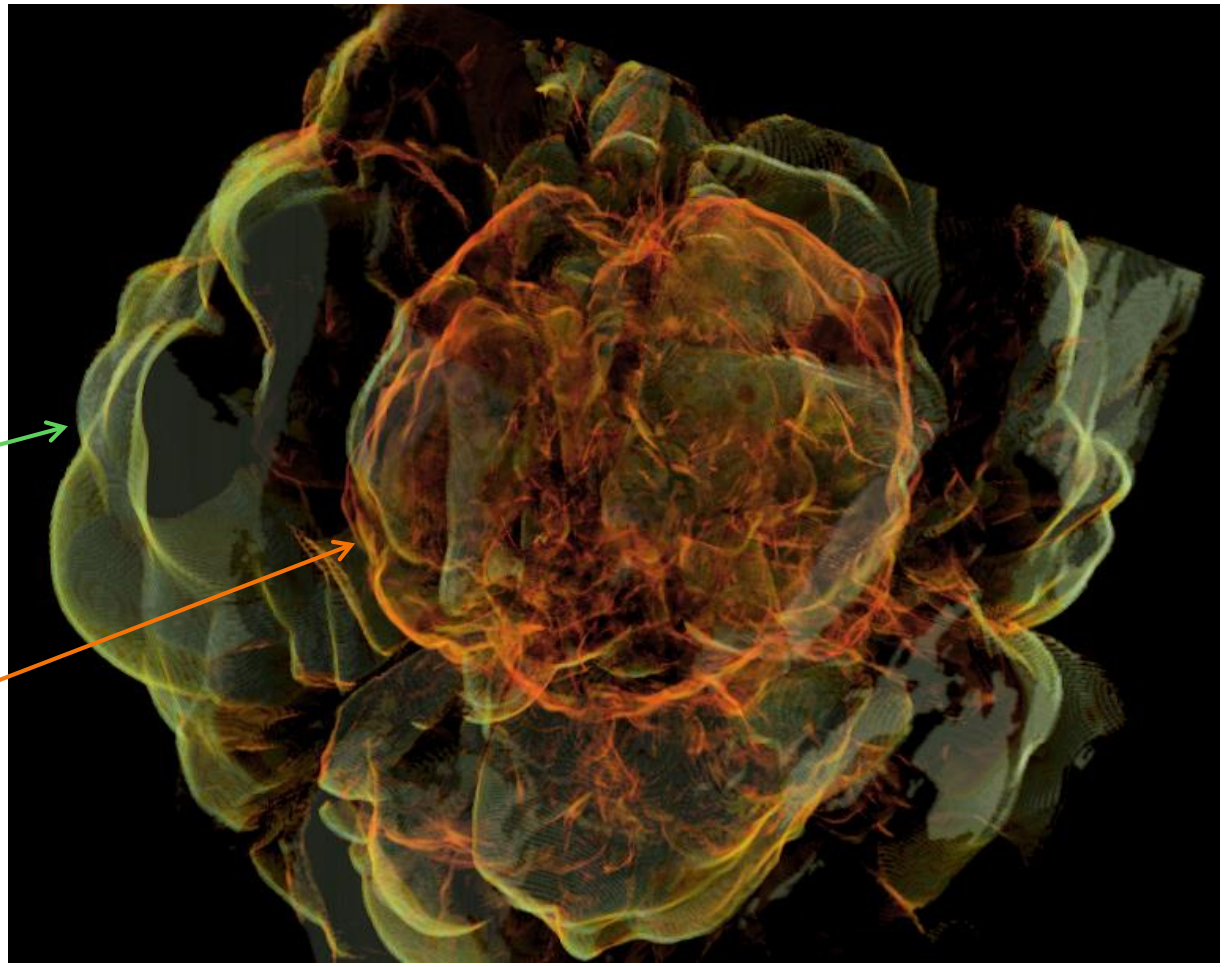
(van Weeren et al. + Ryu 2017)

Shock waves induced during the formation of the large-scale structure of the universe

Shock waves in a simulated clusters of galaxies

strong accretion shocks with M>10 (green)

weak inreacluster shocks with M<4 (orange)

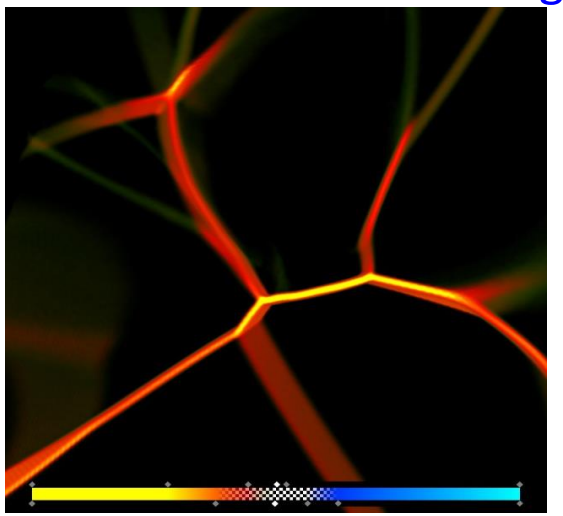


(Vazza et al + Ryu)

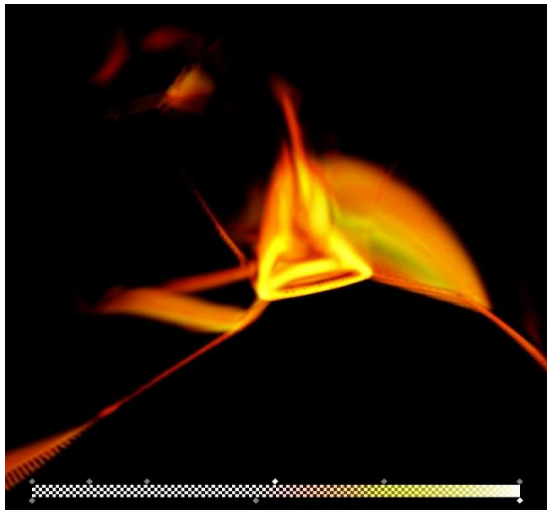
Vorticity generated at cosmological shocks

- directly at interacting and curved shocks

interacting shocks



div(v)



ω

at shocks

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

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

constant ρ

constant p

due to entropy variation induced at shocks

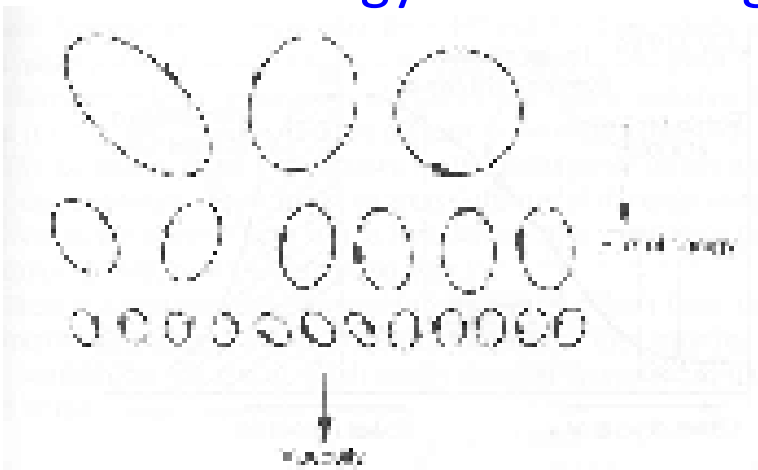
Magnitude of vorticity or enstropy (e) enhanced by stretching and compression increases during the development of turbulence

(Porter, Jones, Ryu 2015)

$$\frac{\partial\epsilon}{\partial t} = F_{adv} + F_{stretch} + F_{comp} + F_{baroc} + F_{mag} + F_{diss}$$

Theory of turbulence

Kolmogorov's theory for incompressible hydrodynamic turbulence: it is based on the notion that that large eddies can feed energy to the smaller eddies and these in turn feed still smaller eddies, resulting in a cascade of energy from the largest eddies to the smallest ones.



a schematic representation of the turbulent energy cascade from large to small scales

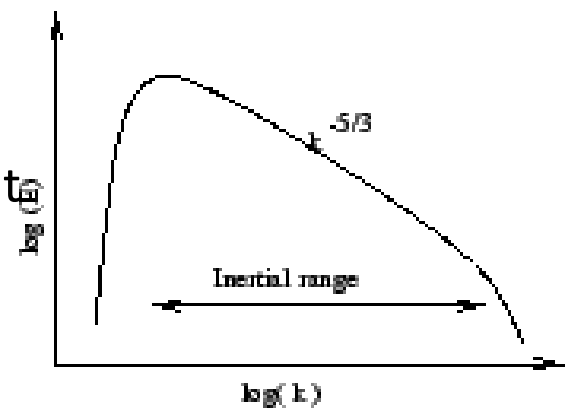
on dimensional grounds, the only way of writing ε (energy transfer rate) in terms of V (velocity) and l (scale) is

$$\varepsilon \sim \frac{V^2}{t} \sim \frac{V^3}{l} \sim \text{constant}$$

$$V \sim l^{1/3}$$

$$P_k \sim k^{-5/3}$$

power spectrum of velocity!

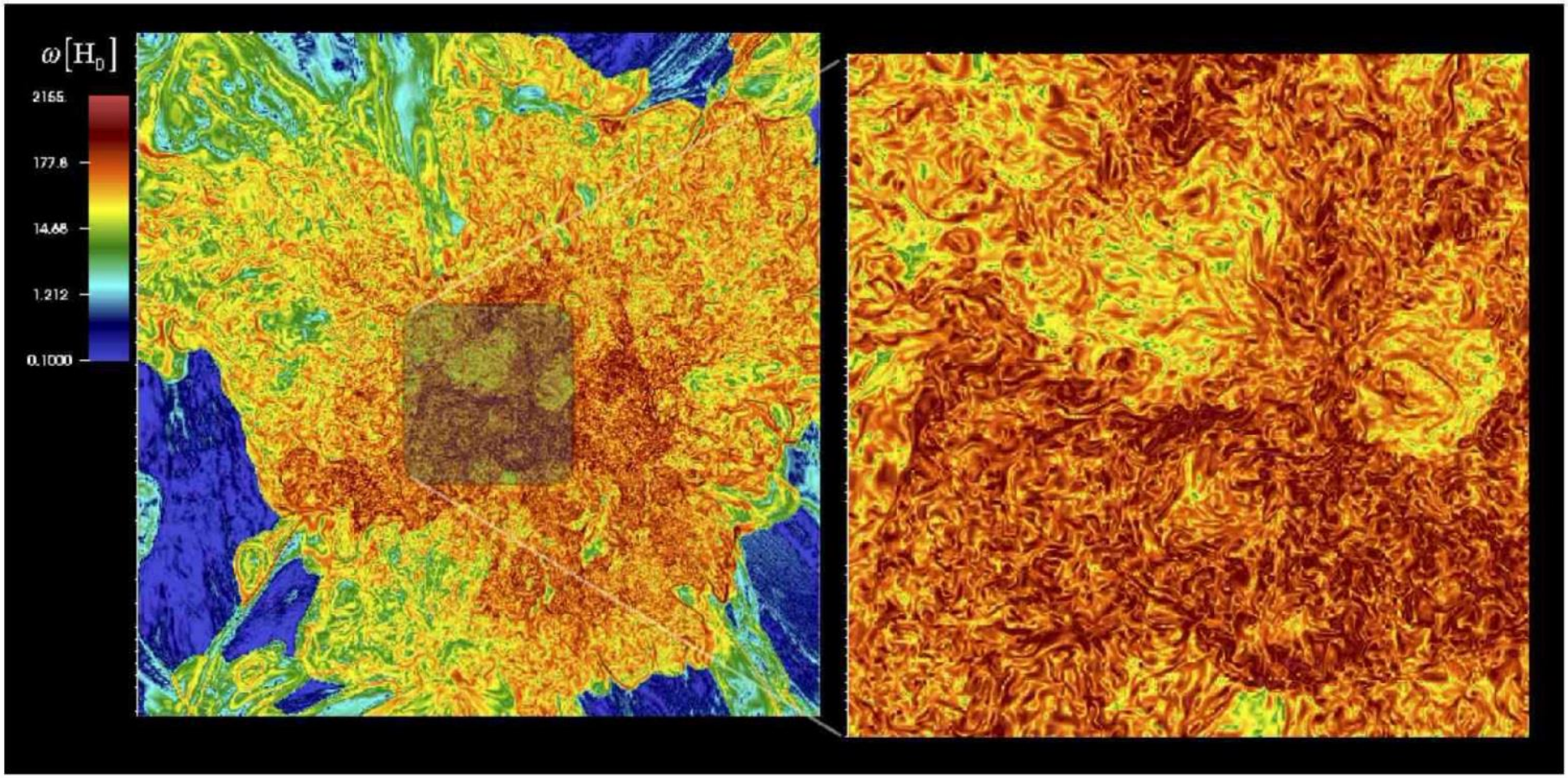


the spectrum of Kolmogorov turbulence

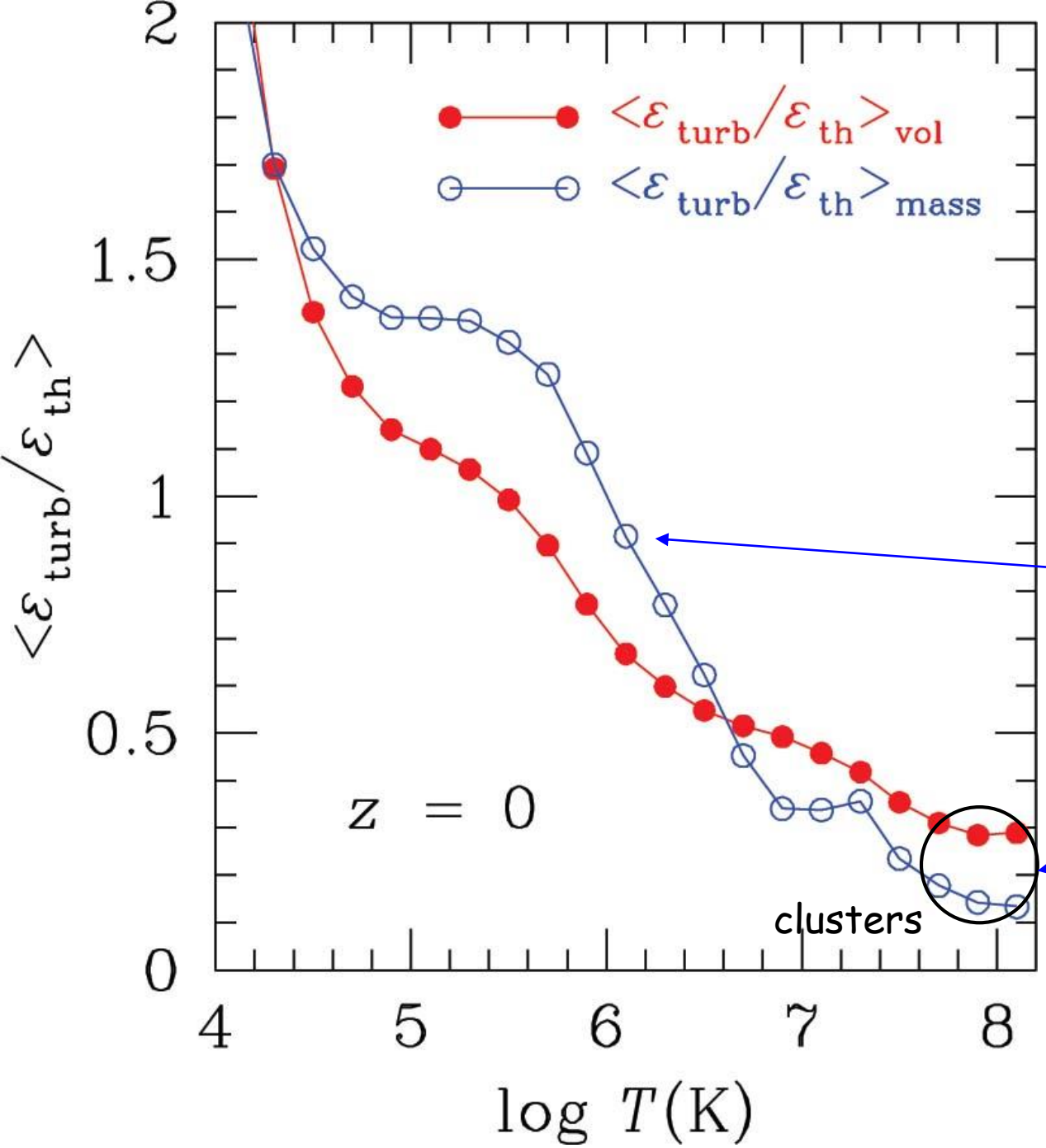
Turbulence in high resolution simulations of galaxy clusters

(Miniati 2013)

curl(v) in the plane through the cluster center



in simulations, turbulence exists in all over the clusters!



Turbulence energy of in the ICM

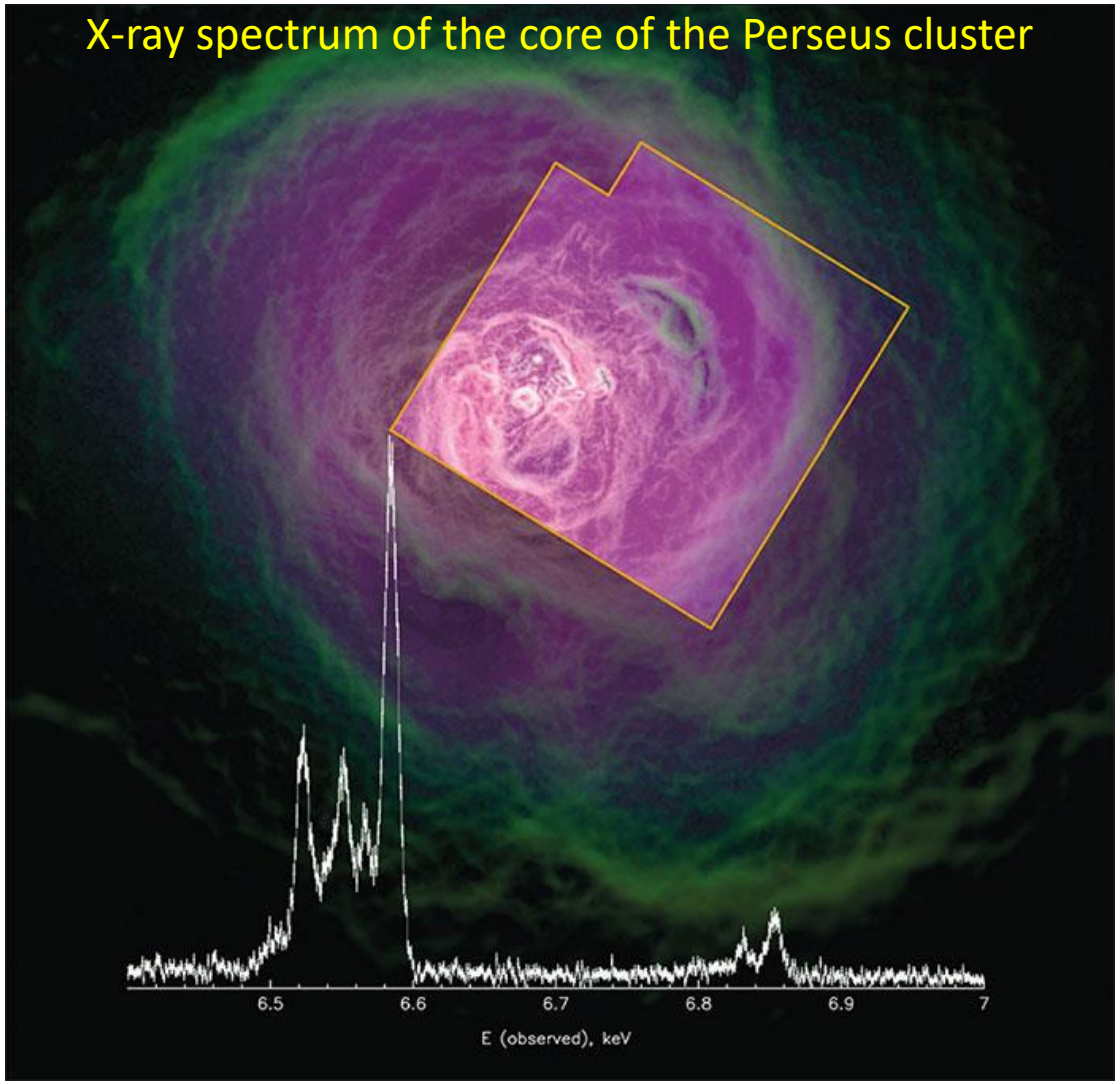
assuming that turbulence is contained in vortical motions

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

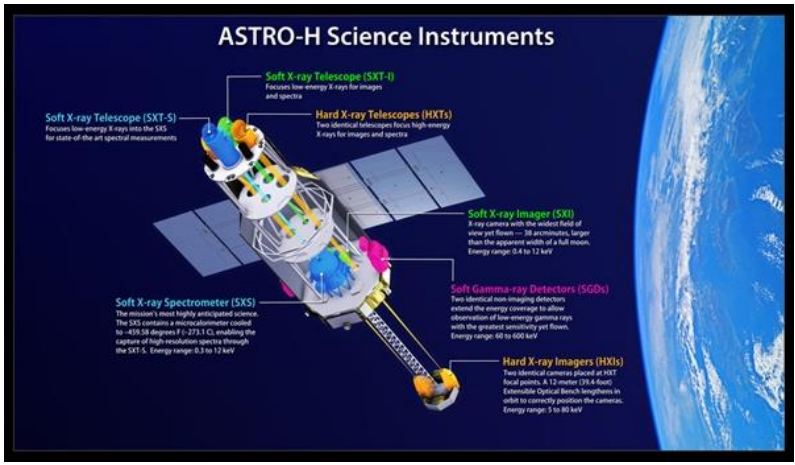
$M_{turb} < \sim 1$
(subsonic turbulence)
$E_{turb}/E_{therm} \sim 0.1 - 0.3$
inside and outskirts of clusters

(Ryu et al 2008)

Evidences for turbulence in clusters



(Hitomi Collaboration 2016)



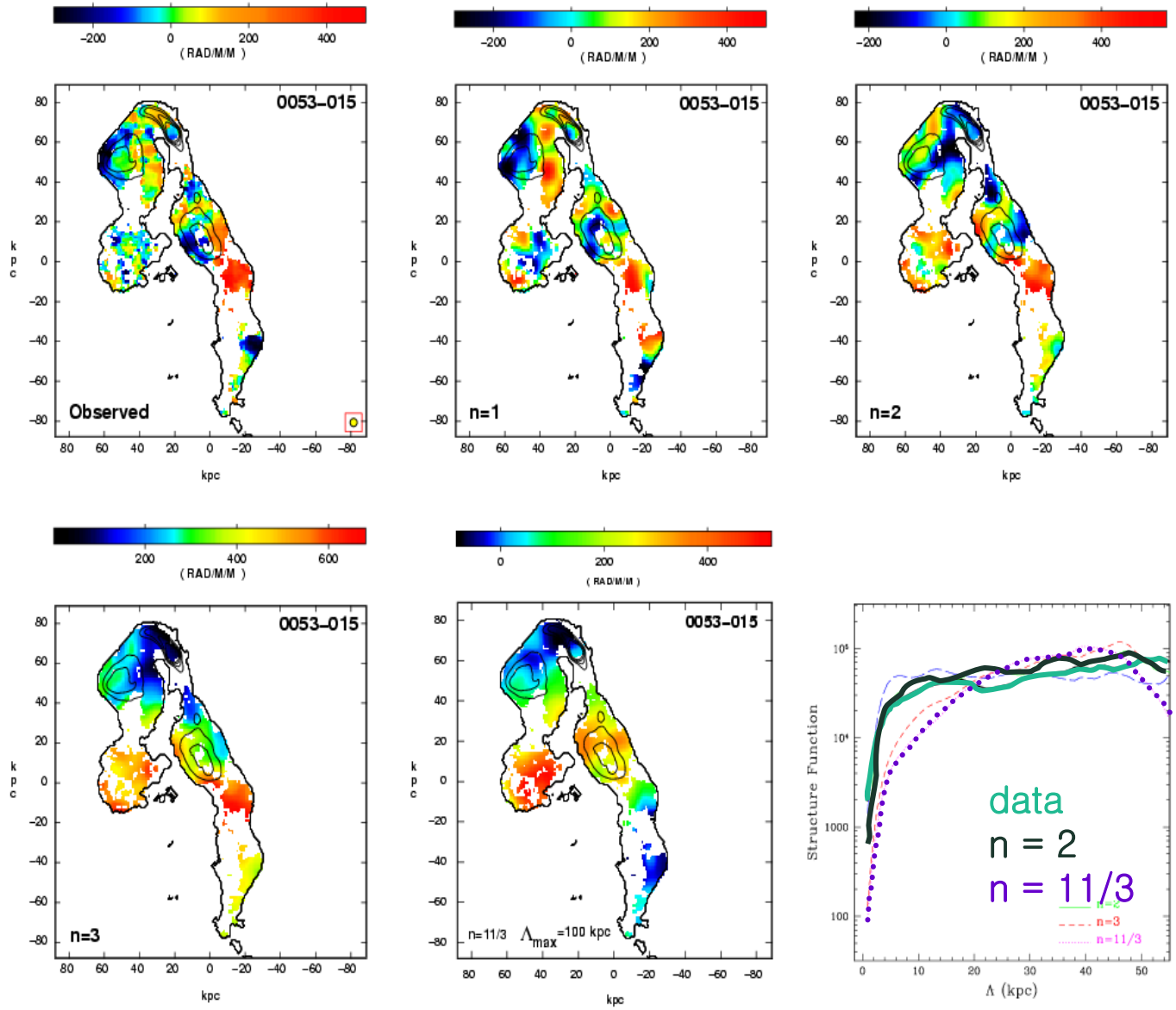
at the core of the Perseus cluster, the estimated turbulence velocity ~ 165 km/s, (while the expected value ~ 500 km/s)

observations of turbulence in clusters are mostly around core regions!

patchy Faraday rotation measure (RM) in clusters observed with radio galaxies

Murgia et al. (2004)

- RM in Abell 119 for comparison with simulation
- turbulent cluster magnetic fields with power-low slope n=2 give a good fit (Kolmogorov n=11/3)



an evidence for turbulence in cluster outskirts?

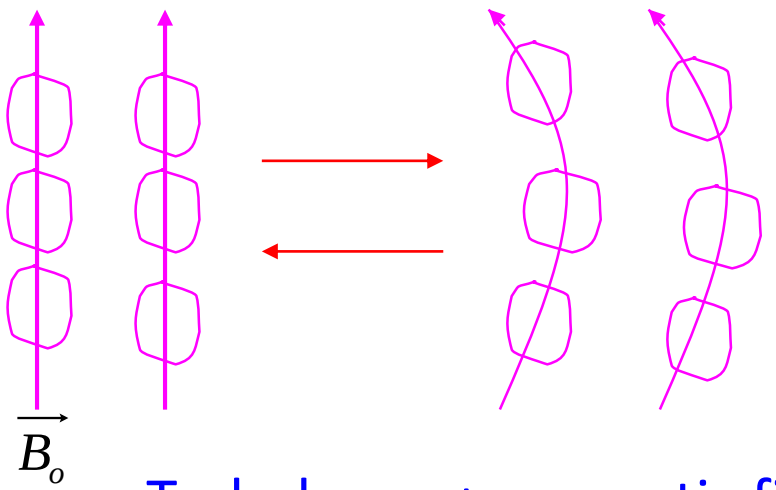
Turbulence in astrophysical environments with magnetic fields

Fluid and magnetic fields interact with each other

fluid → drags magnetic field

magnetic field → exerts tension and pressure

➔ fluid and magnetic field moves together ("frozen") with large magnetic Reynolds number



$$\frac{\partial \vec{\upsilon}}{\partial t} + \left(\vec{\upsilon} \bullet \vec{\nabla}\right)\vec{\upsilon} + \frac{1}{\rho}\vec{\nabla} p = \frac{1}{4\pi\rho}\left(\vec{\nabla} \times \vec{B}\right) \times \vec{B}$$

$$\frac{\partial \vec{B}}{\partial t} = -\vec{\nabla} \times \left(\vec{B} \times \vec{\upsilon}\right)$$

Turbulence + magnetic field

→ Magnetohydrodynamic turbulence

Origin of magnetic fields in clusters

- generation of seed fields

- amplification of seed fields by turbulent flow motions

Seed magnetic fields in the large-scale structure (LSS) of the universe

Suggestions include:

- generation in the early universe (e.g., see Widrow, Ryu et al 2012 for review)

  e.g.) during the electroweak phase transition ($t \sim 10^{-12}$sec)

  during the quark-hadron transition ($t \sim 10^{-5}$sec)

  → uncertain but maybe challenging (?)

- generation before the formation of the LSS of the universe through plasma physical processes (e.g., see Ryu et al 2012 for review)

  e.g.) Biermann battery or Weibel Instability at shocks

  (Kulsrud, Cen, Ostriker, & Ryu 1997) (Medvedev & Loeb 1999)

  instabilities, thermal fluctuations, photo-ionization and etc …

  → weak (~ 10^{-20} G) and some at small scales, yet most promising(?)

- astrophysical processes

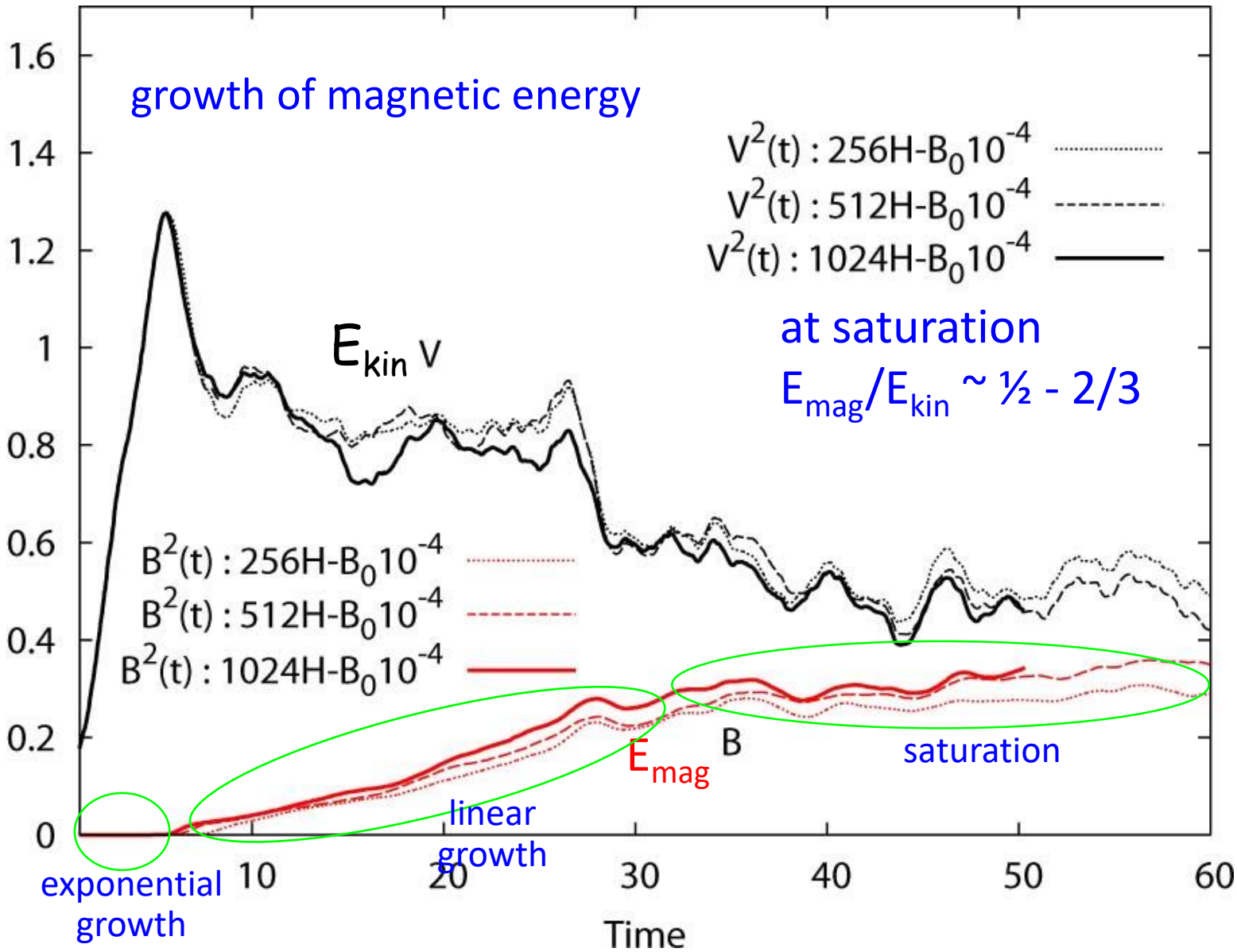
  e.g.) magnetic fields from the first stars

  → maybe not the first magnetic field

Origin of seeds for comic magnetic fields is uncertain!

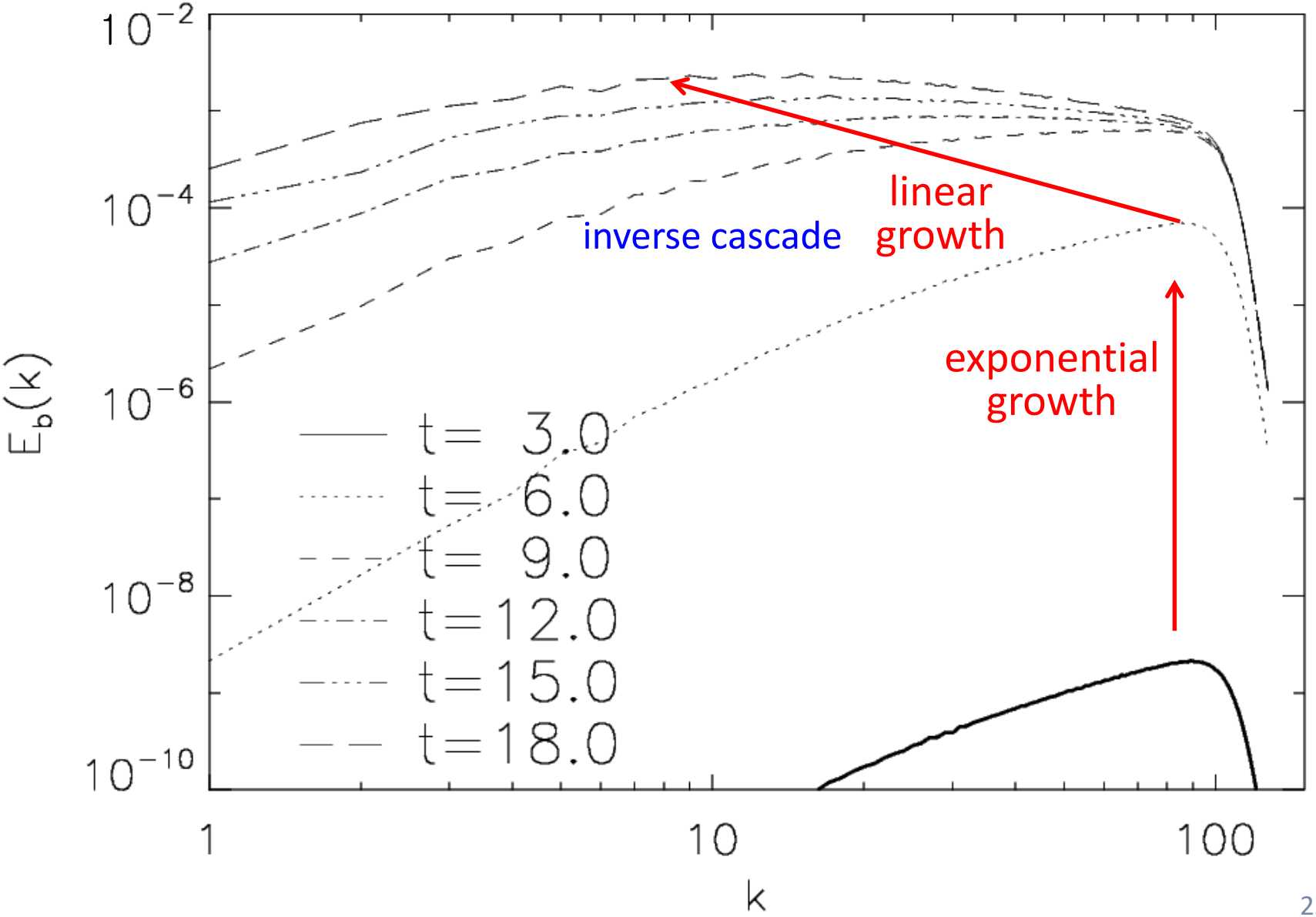
Small-scale dynamo of MHD turbulence with weak initial field

(Jo & Ryu, unpublished)



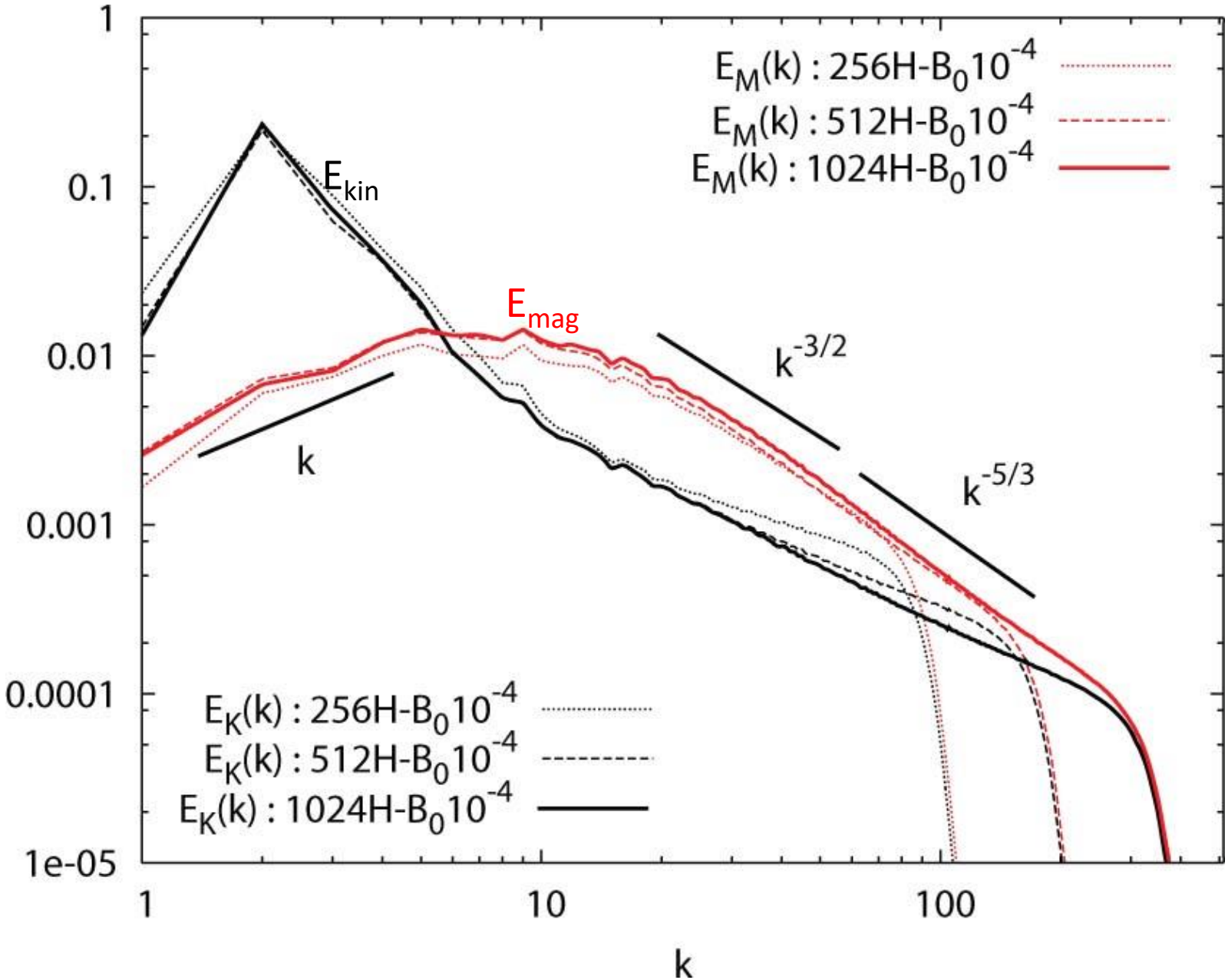
Evolution of magnetic field power spectrum at early stages

(From J. Cho)



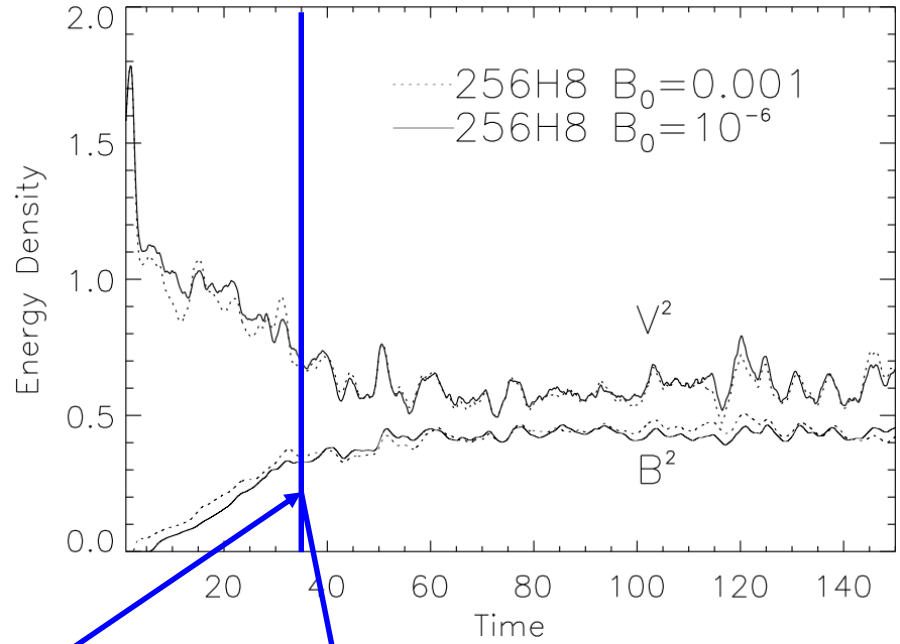
Power spectrum at saturation

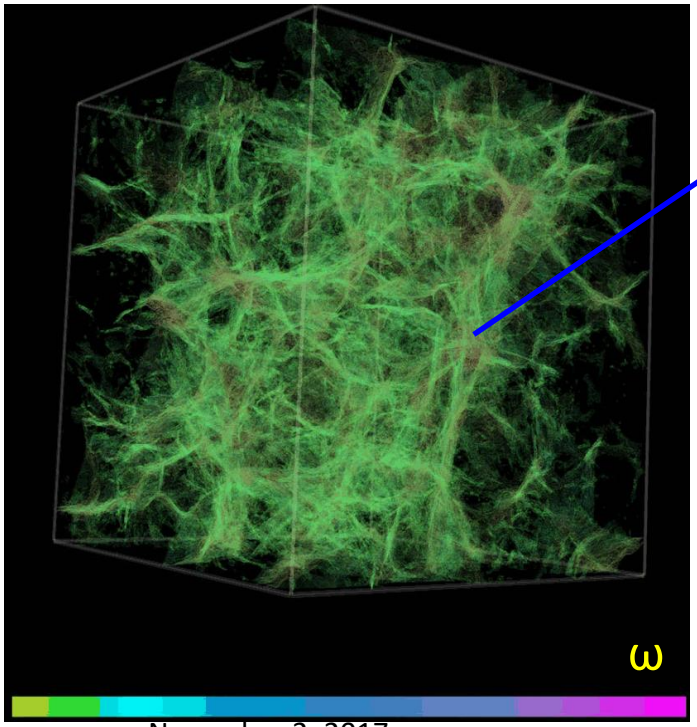
(Jo & Ryu, unpublished)

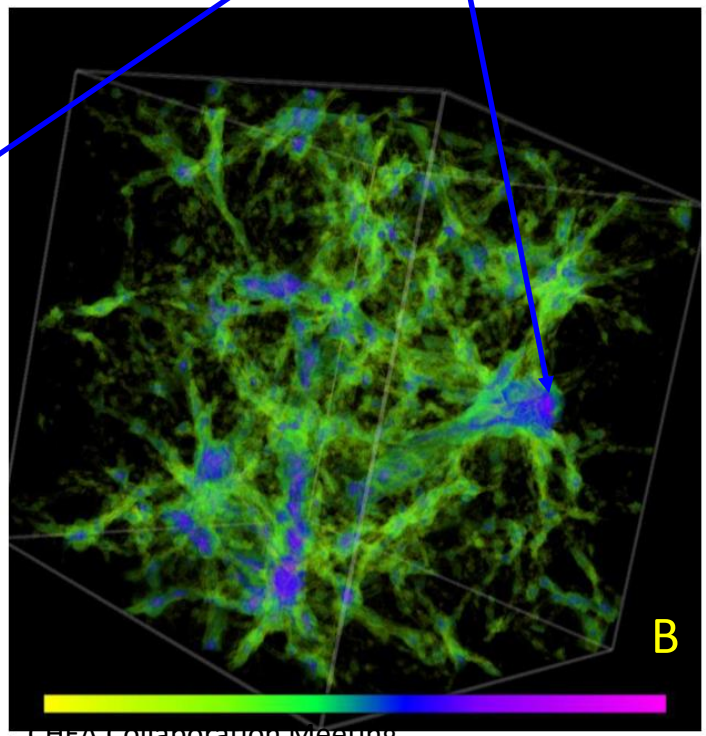


A model for magnetic fields in galaxy clusters

- vorticity generated at shocks and also due to baroclinity
- further enhanced by stretching and compression
- developed into turbulence
- magnetic field produced by turbulence dynamo





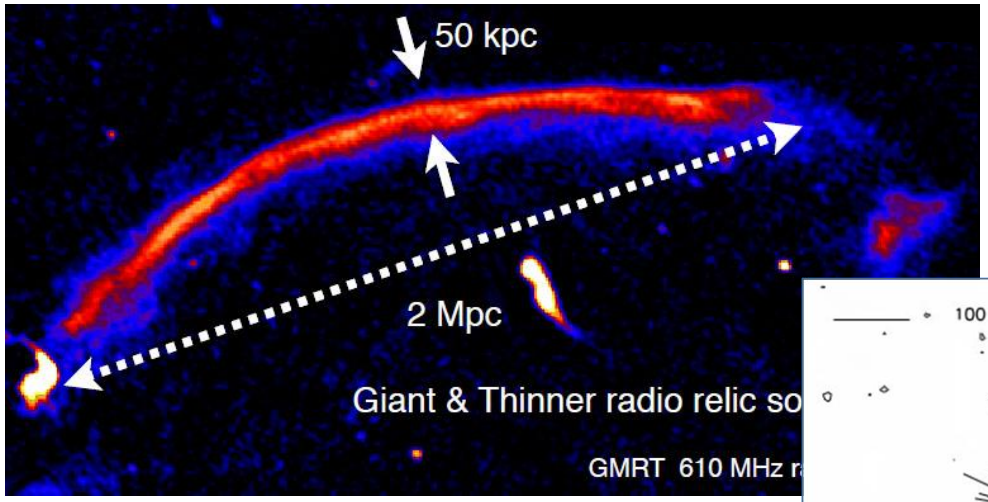


The model may reproduce the observed strength of magnetic field!

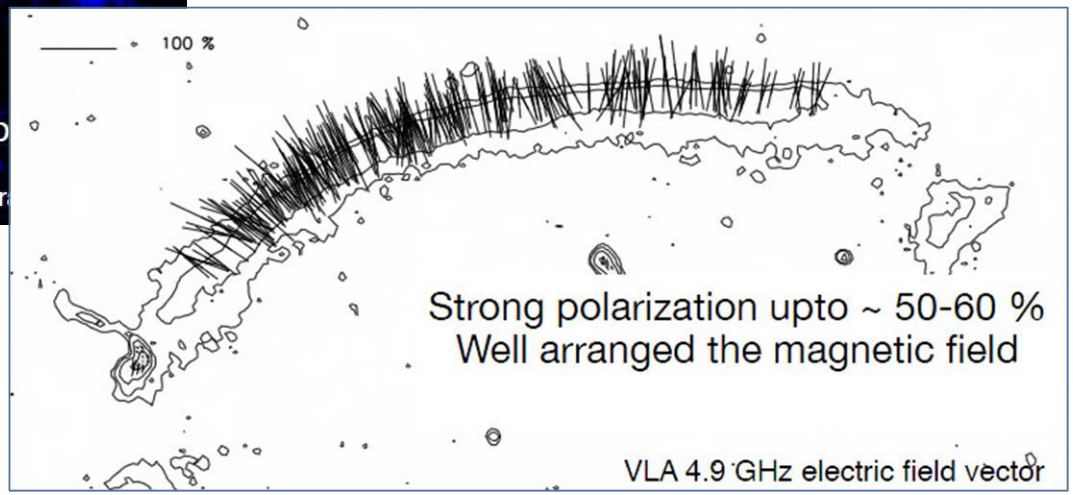
(Ryu et al 2008)

Large-scale magnetic fields in cluster outskirts ?

CIZA J2242.8+5301 (sausage radio relic)

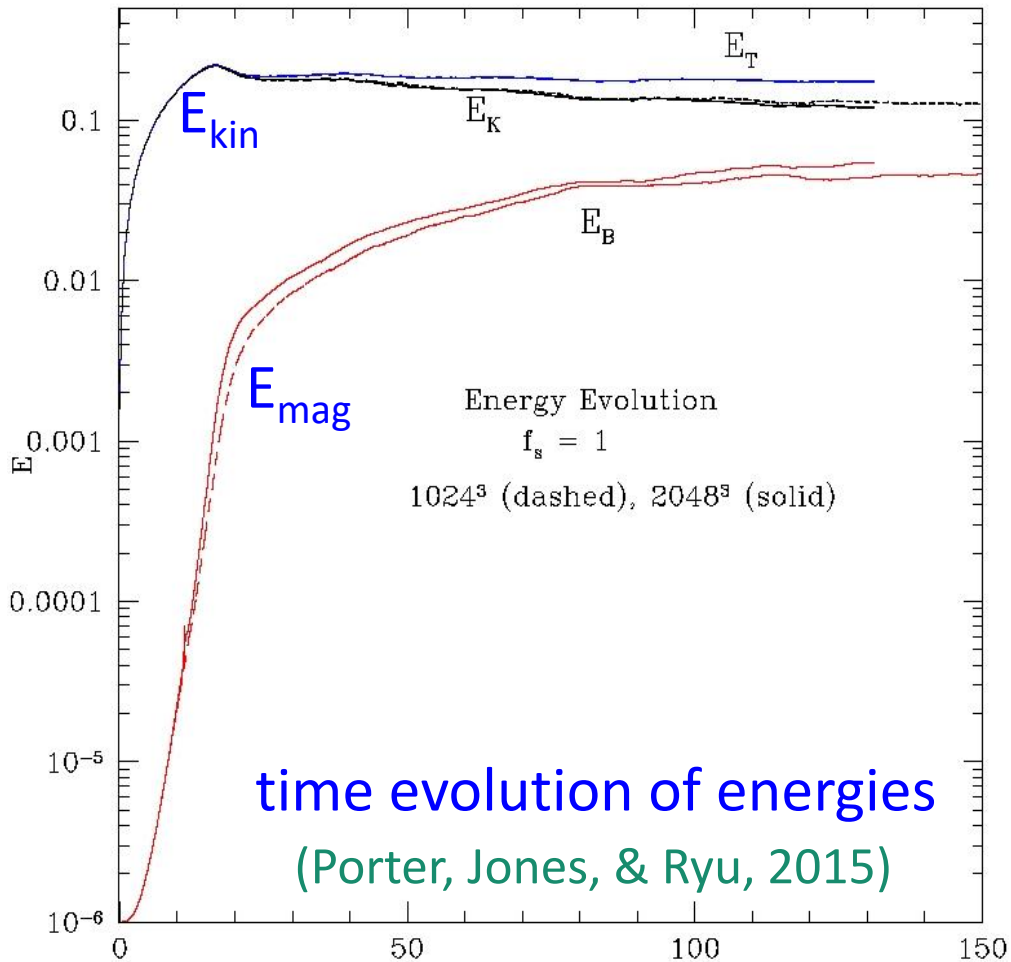


(van Weeren et al 2010)



Can Mpc-scale magnetic fields in outskirts , “if real”,
be explained by turbulence dynamo?

The growth time of magnetic fields in turbulence dynamo



time evolution of energies

(Porter, Jones, & Ryu, 2015)

$10\ t / t_{eddy}$

$t_{eddy} \equiv L_{injection} / v_{turb}$

It takes $t \sim$ several x t_{eddy} to reach

$E_{mag} \sim 1/10\ E_{kin}$

In clusters, if turbulence is driven mainly by major mergers,

$L_{injection} \sim 500$ kpc (clump size)

$v_{turb} \sim 500$ km/s

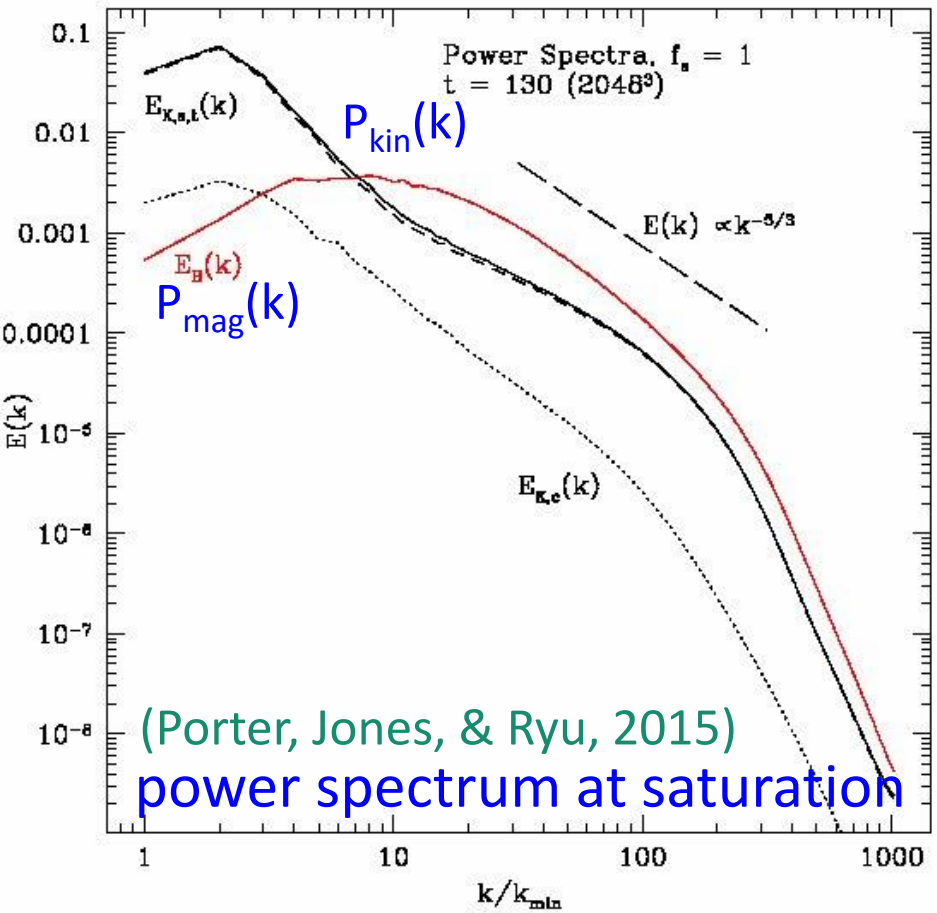
➔ $t_{eddy} \sim 1$ Gyrs $\sim 1/10\ t_{age}$

or $t_{age} \sim 1/10\ t_{eddy}$

(t_{age} the age of the universe)

There seems to be enough time for the growth of B!

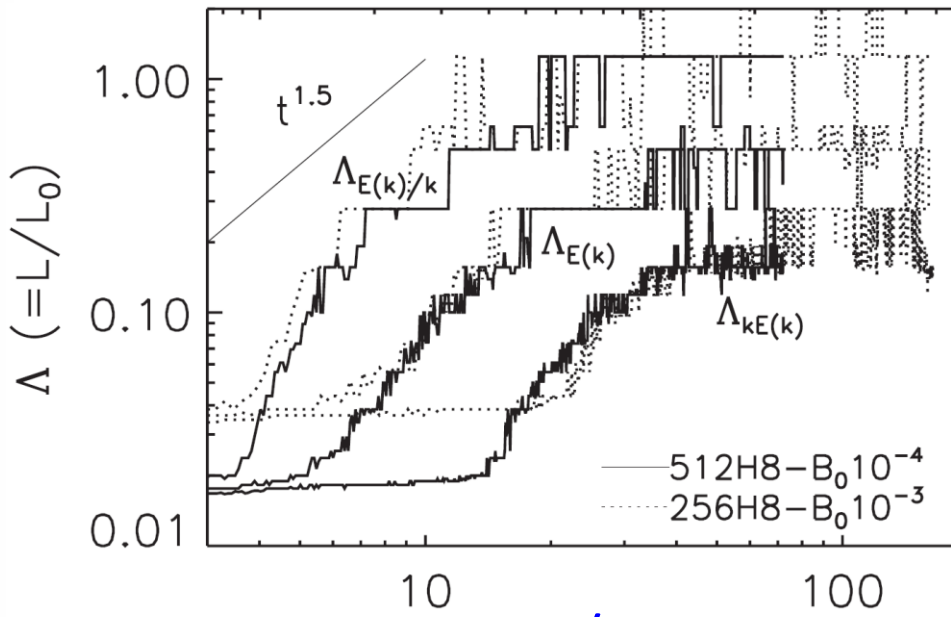
The scale of magnetic fields in turbulence dynamo



(Porter, Jones, & Ryu, 2015)

power spectrum at saturation

(Cho & Ryu 2009)



~3 t / t_{eddy}

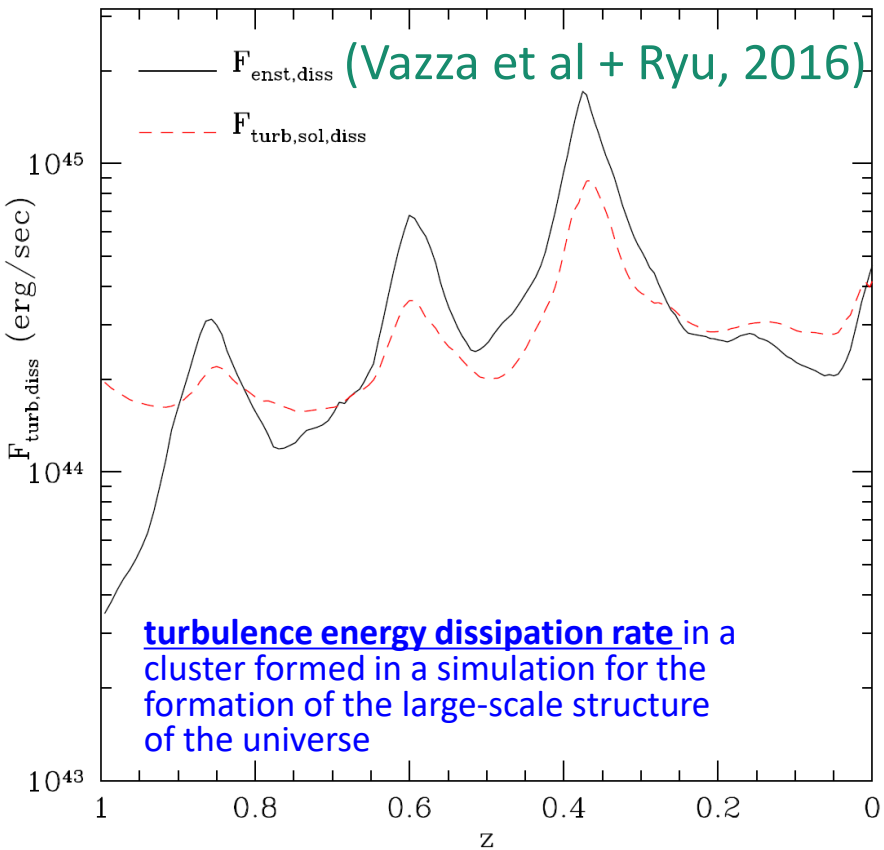
At t ~ 10 t_{eddy},
the peak of $P_{mag}(k)$ is ~ 1/3 $L_{injection}$
the peak of $kP_{mag}(k)$ is ~ 1/10 $L_{injection}$

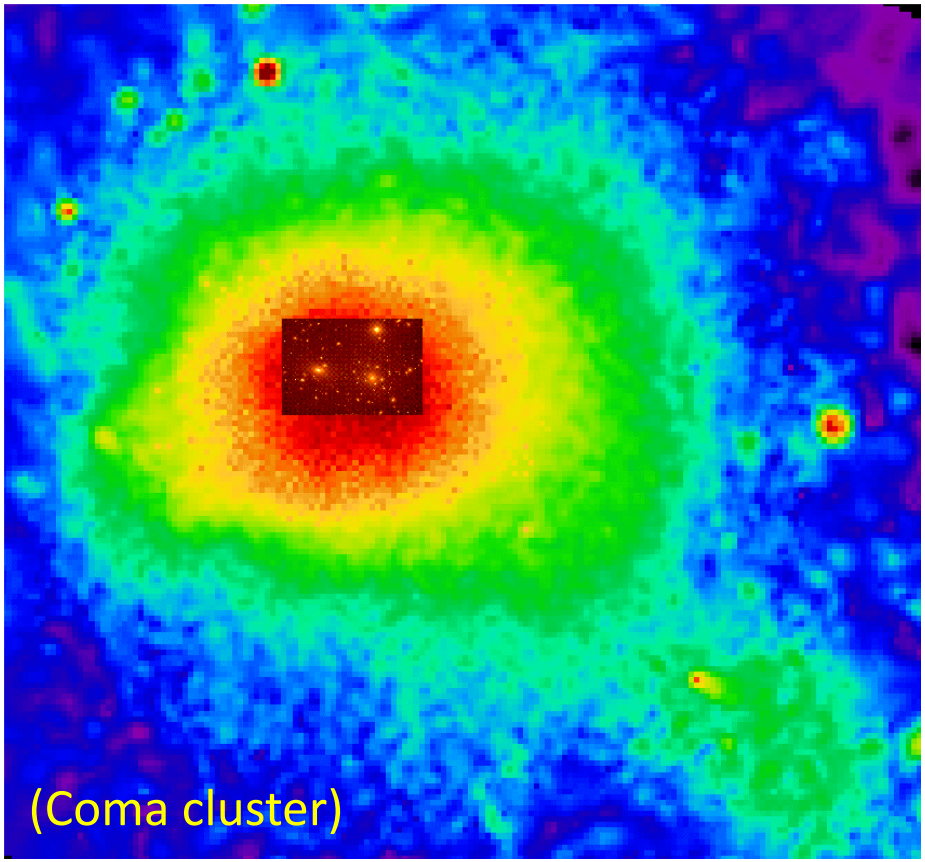
If $L_{injection}$ ~ 500 kpc,
the peak of "$kP_{mag}(k)$" (the peak scale of magnetic energy) ~ 50 kpc, too small?

in clusters

- turbulence is driven “sporadically”
- the medium is “stratified”

Turbulence dynamo in clusters

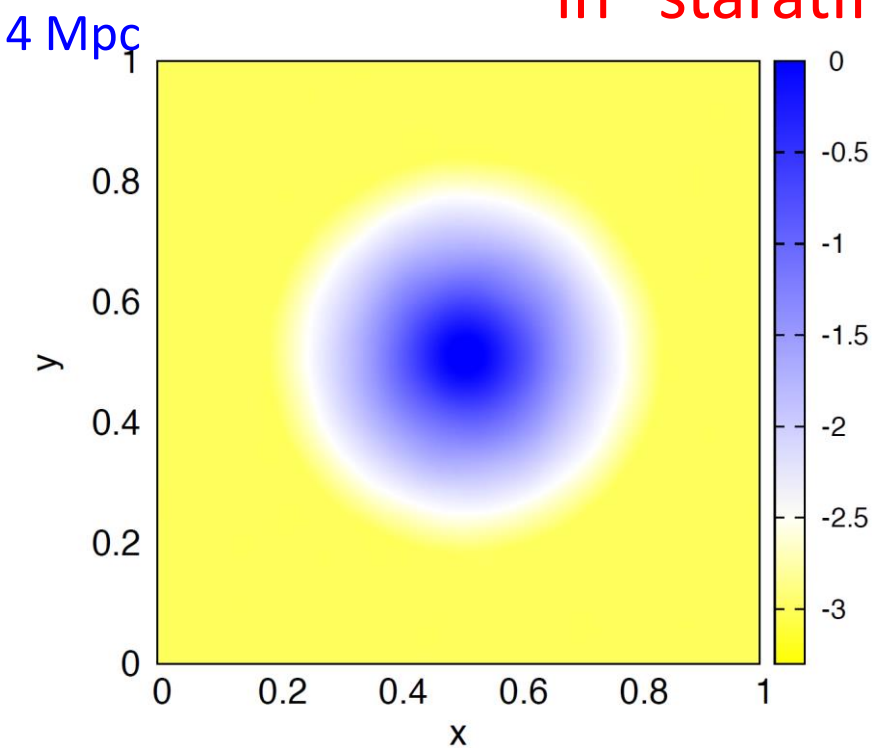


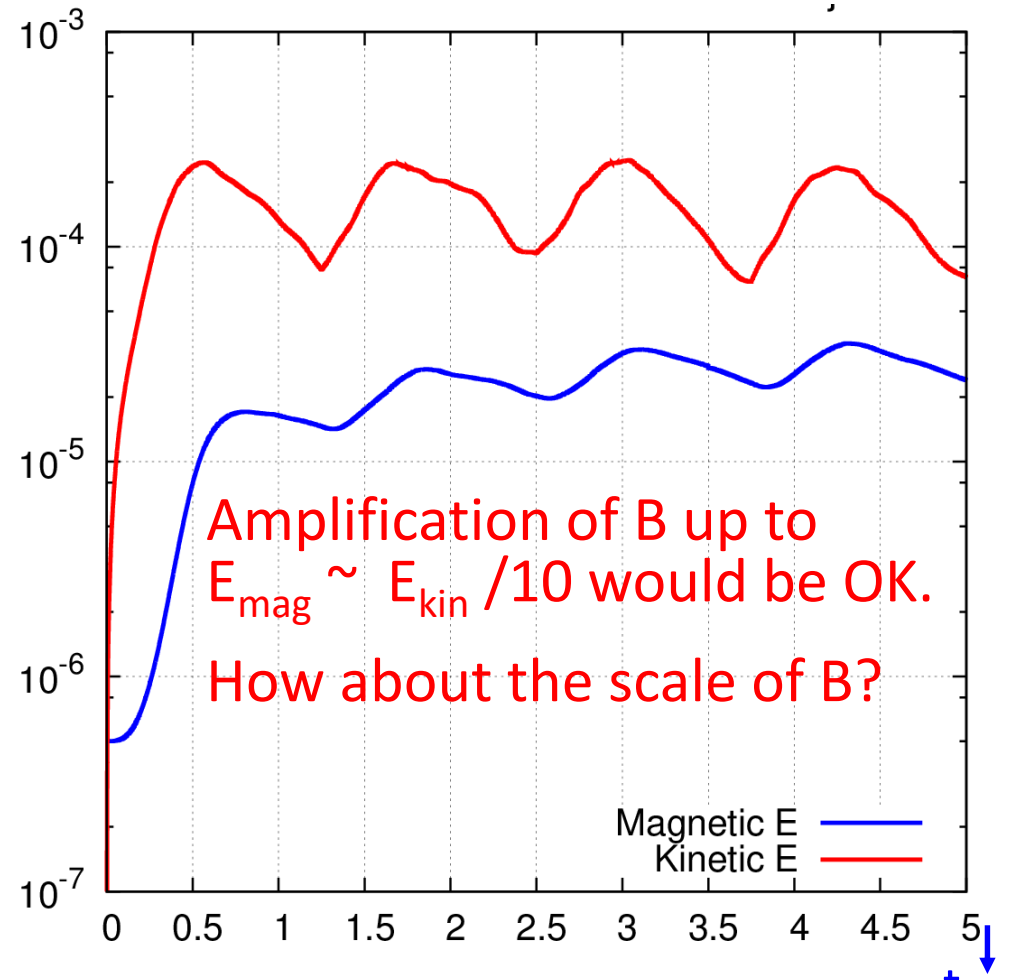


In clusters of galaxies, the turbulence is driven “sporadically”, mostly by “mergers”.

Intracluster media are highly “stratified”, i.e., high density at cores and low density at outskirts.

Simulations of turbulence "sporadically" driven in "staratified" clusters (Roh, Ha & Ryu, preliminary)





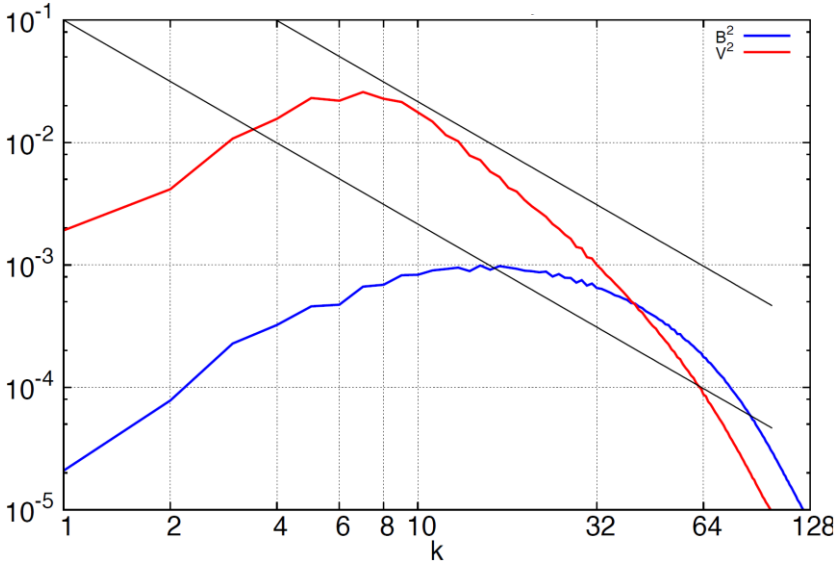
Amplification of B up to $E_{mag} \sim E_{kin}/10$ would be OK.

How about the scale of B?

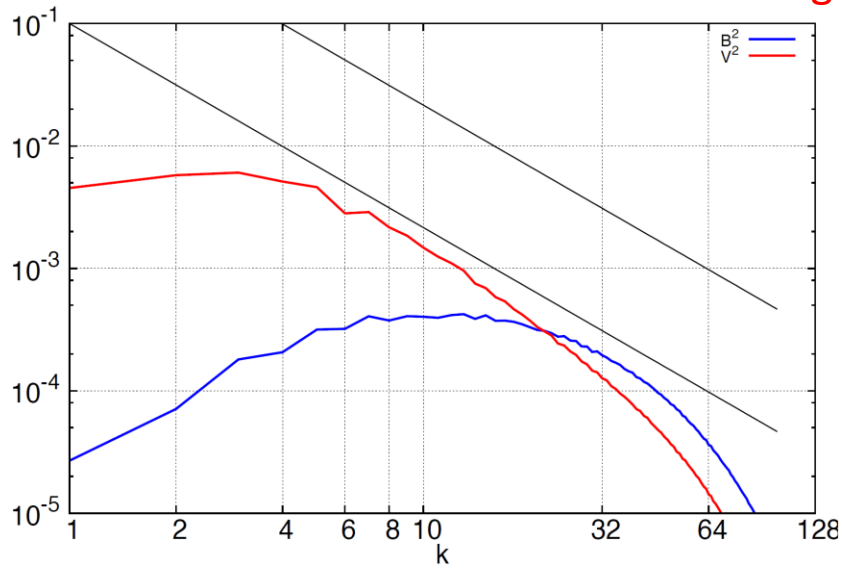
clusters of $T = 10^8$ K (c_s = 1,500 km/s) described the beta model with $\beta = 1$ and $r_c = 300$ kpc in a box of $L_{size} = 4$ Mpc

turbulence of $M_{turb} \sim ½$, driven for 4 times (that is, forcing on for $\Delta t = 0.1\ t_{age}$ and off for $\Delta t = 0.15\ t_{age}$) during the age of the universe, t_{age}, with the peak of forcing at $L_{injection} = 500$ kpc

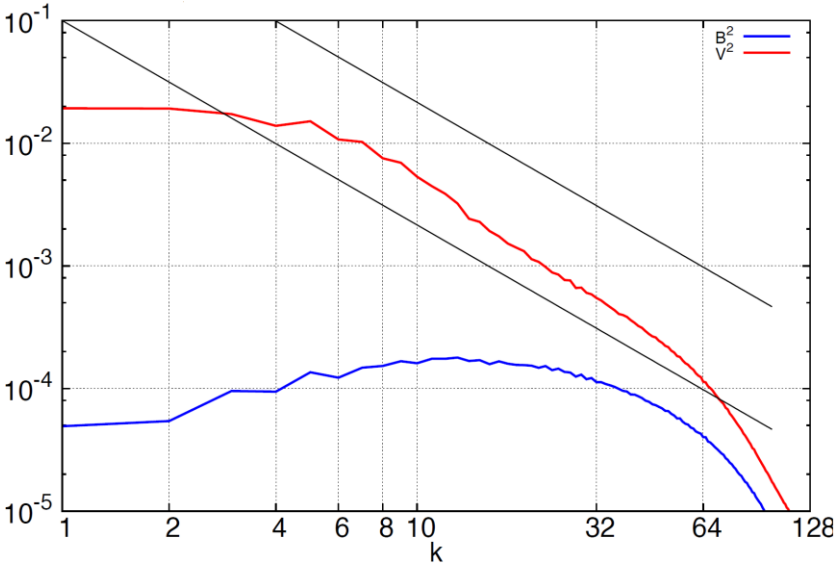
The power spectra of velocity and magnetic field at t = 5 (~ t_{age})



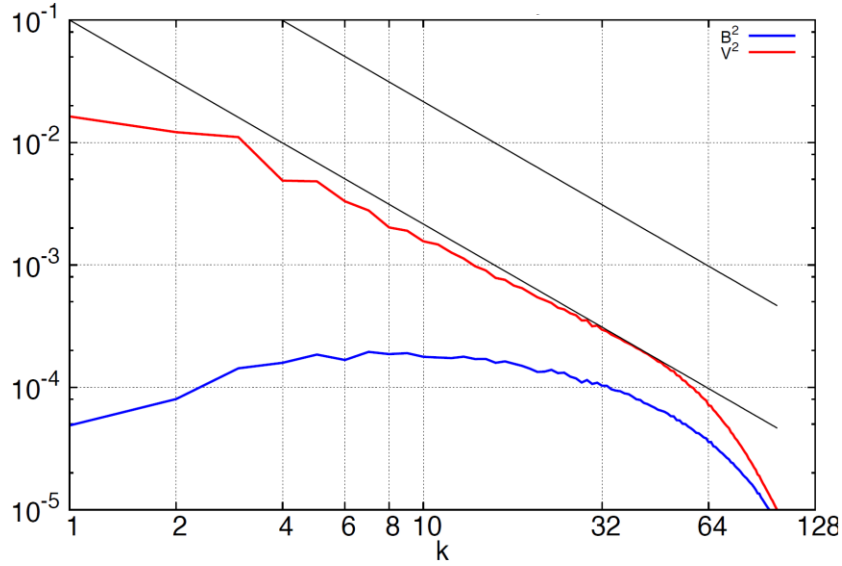
uniform medium, constant forcing



uniform medium, sporadic forcing

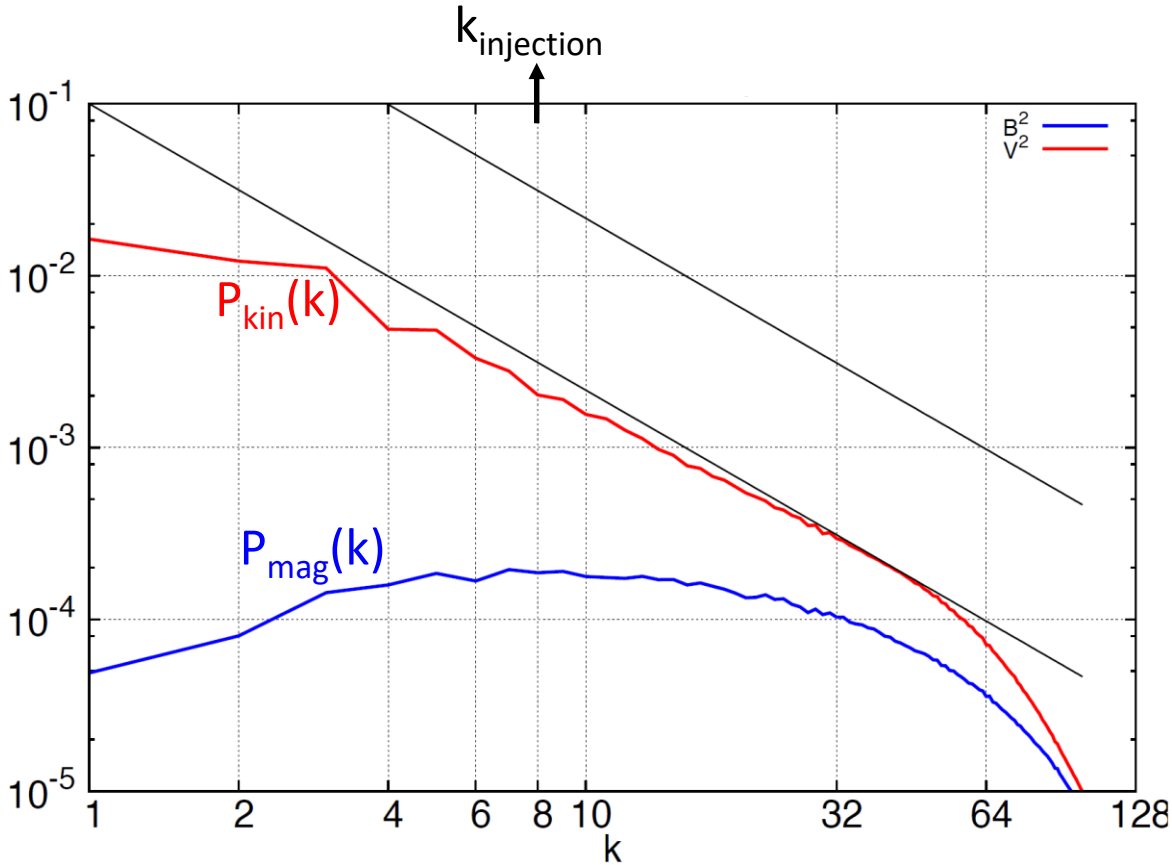


stratified medium, constant forcing



stratified medium, sporadic forcing

Power spectra of turbulence in stratified medium with sporadic forcing

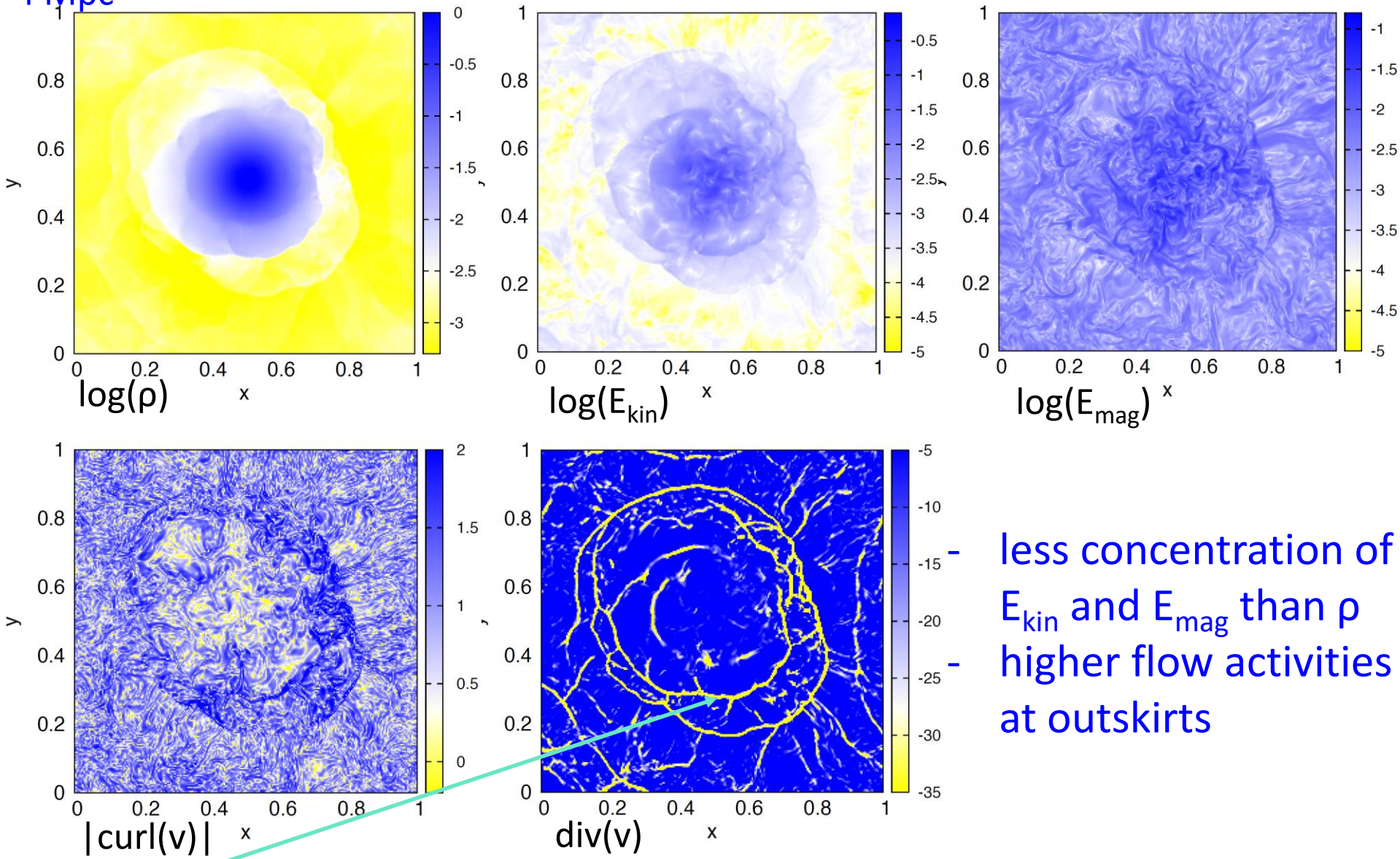


- $P_{kin}(k)$ shows large-scale (scales up to the box size) powers
- $P_{mag}(k)$ has a broad peak over ½ $k_{injection}$ – 2 $k_{injection}$
- $kP_{mag}(k)$ has a peak at ~ $2k_{injection}$

or if $L_{injection}$ = 500 kpc, the peak scale of magnetic energy ~200 - 300 kpc

Slice images through the cluster center at t = 4.5

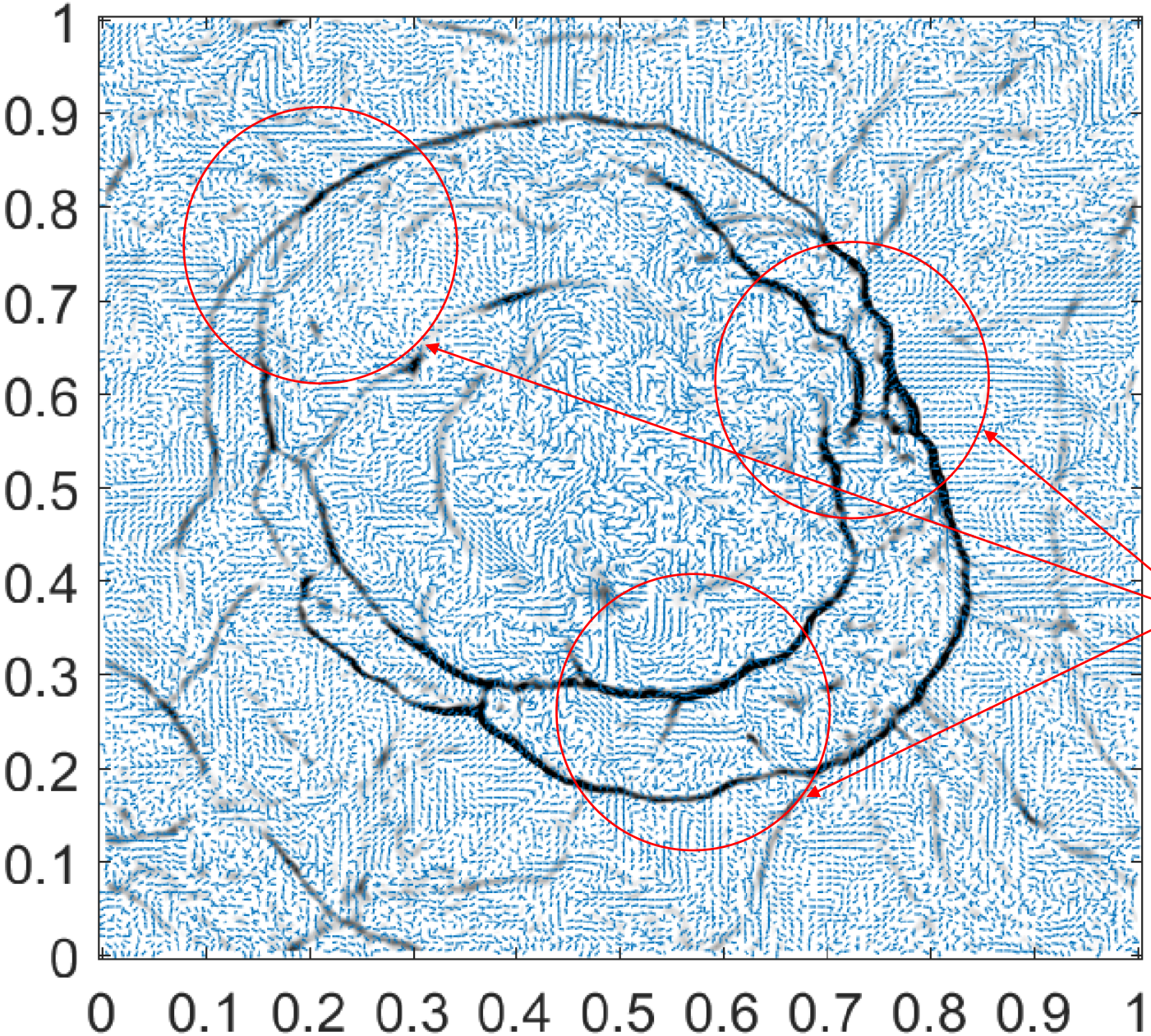
4 Mpc



- less concentration of E_{kin} and E_{mag} than ρ
- higher flow activities at outskirts

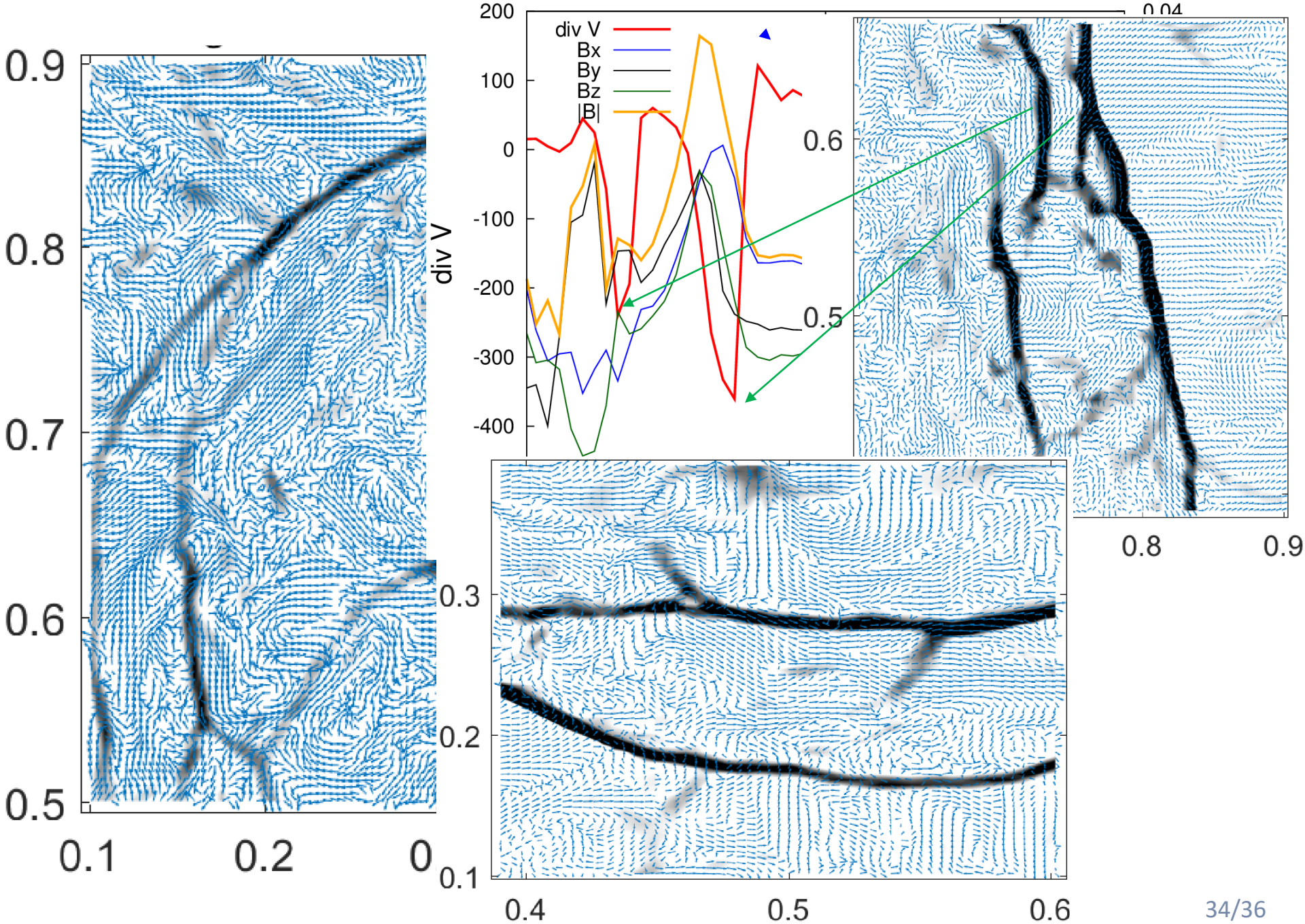
➔ can this reproduce the observed polarization properties of radio relics?

Shocks and magnetic fields



B on the top of div(v)
(|B| on the log scale)

zoomed regions showing perpendicular shocks (B and shock normal are perpendicular)


div V
Bx
By
Bz
|B|
200
100
0
-100
-200
-300
-400
0.9
0.8
0.7
0.6
0.5
0.1
0.2
0
0.3
0.2
0.1
0.4
0.5
0.6
0.8
0.9

Summary

- Magnetic field is ubiquitous in the large-scale structure of the universe including in clusters of galaxies.
- Magnetic fields of ~ a few μG in cluster outskirts could be explained by turbulence dynamo.
- The existence Mpc-scale magnetic fields in cluster outskirts need to be established in observation.
- Explaining large-scale magnetic fields of ~ Mpc scale, if they exist, would remain challenging in the picture of turbulence dynamo.

Thank you !