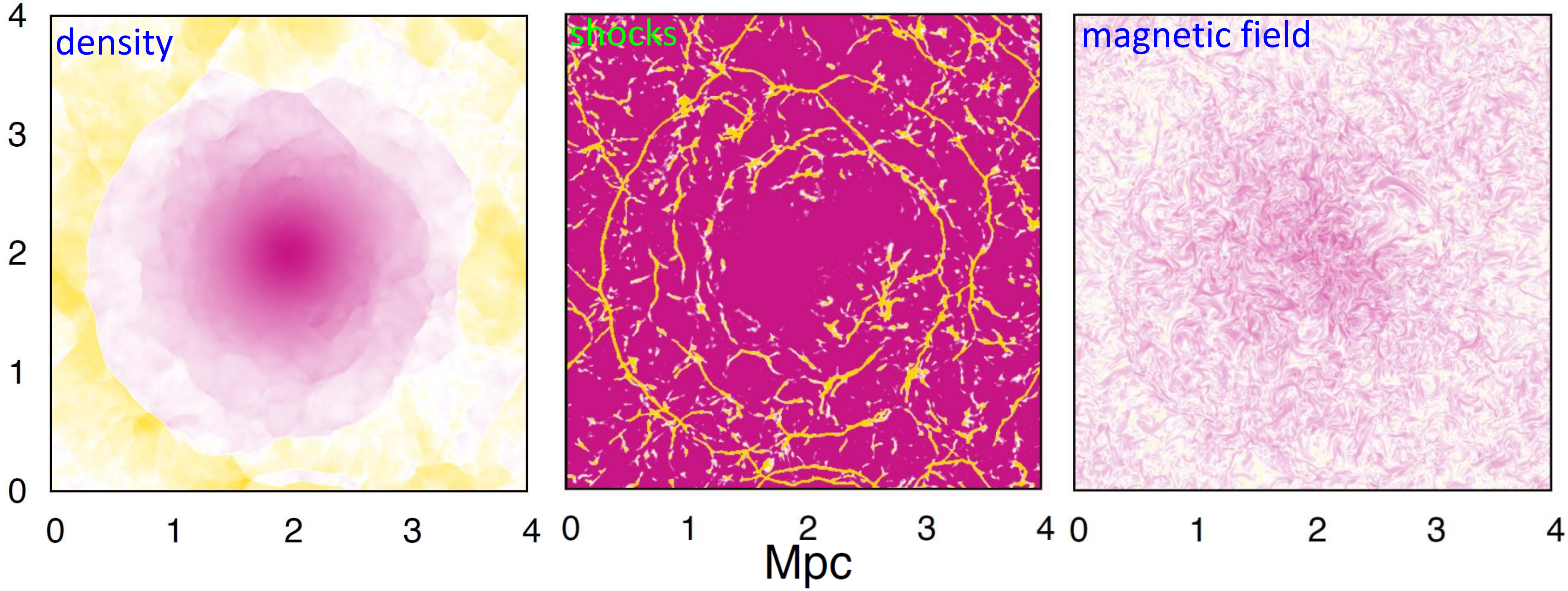
Turbulence and Magnetic Fields in the Outskirts of Galaxy Clusters

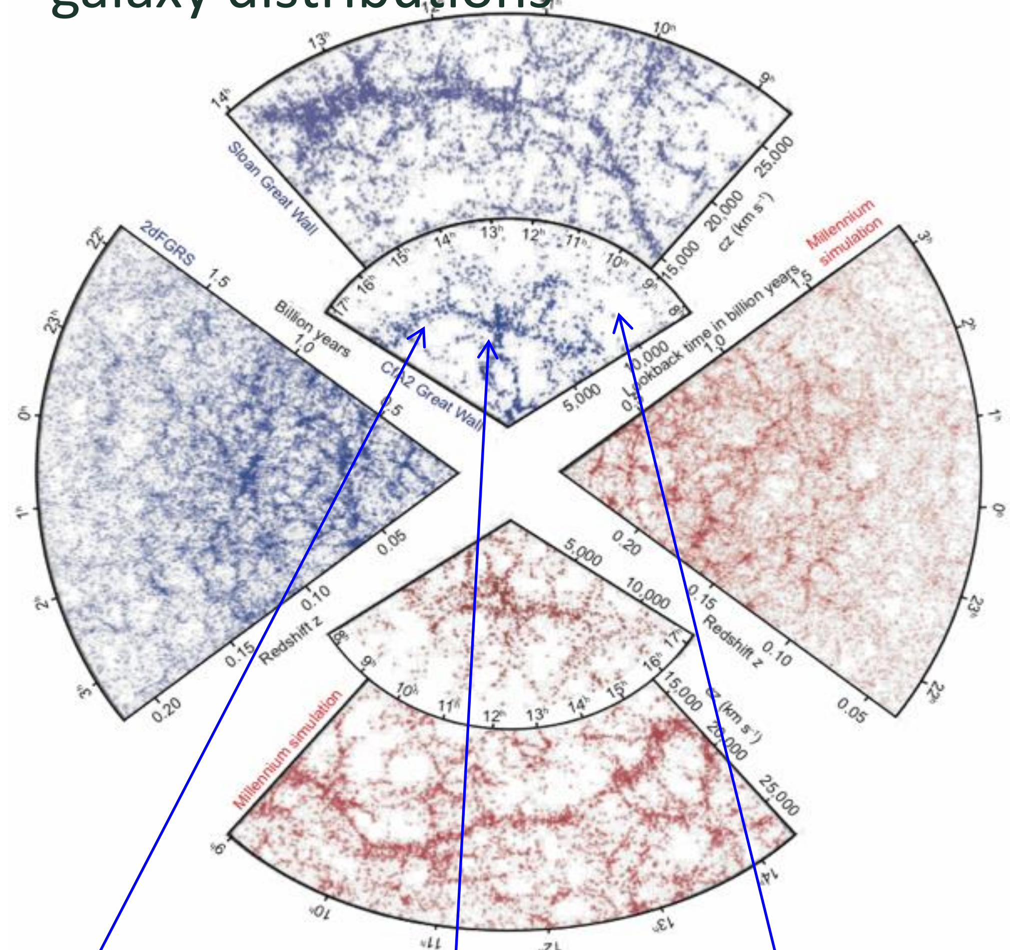


Dongsu Ryu (UNIST, Korea)

July 30 - August 3, 2018 8th East-Asia School and Workshop on Laboratory, Space, and Astrophysical Plasmas Daejeon, KOREA

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

observed and simulated galaxy distributions

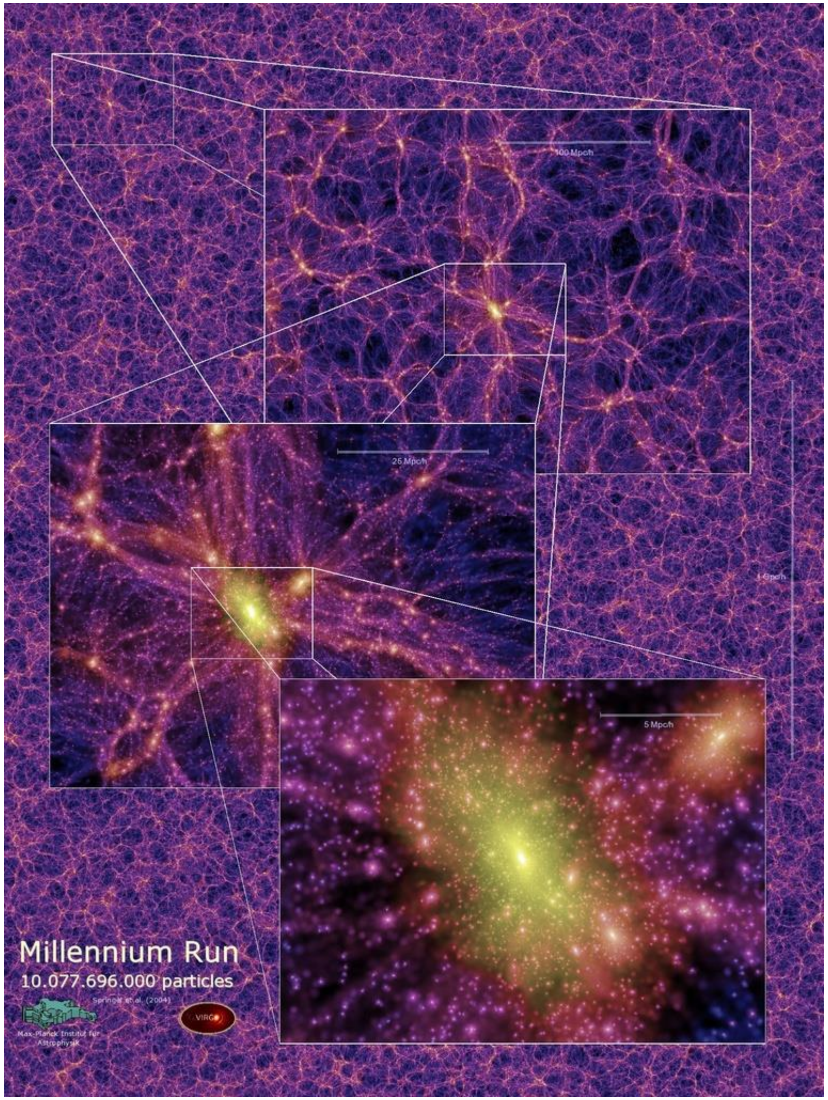


filaments

clusters

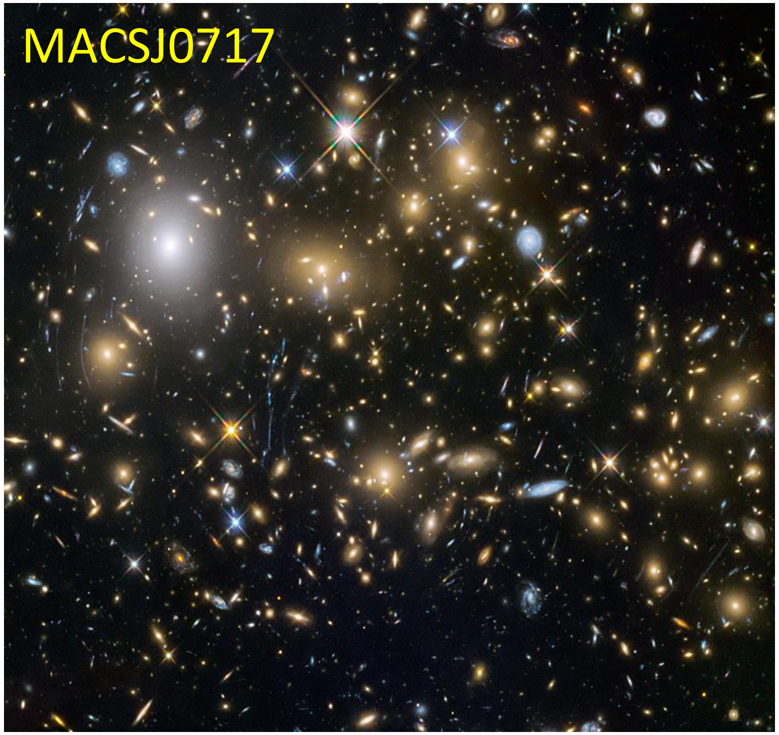
where most matters reside

void regions

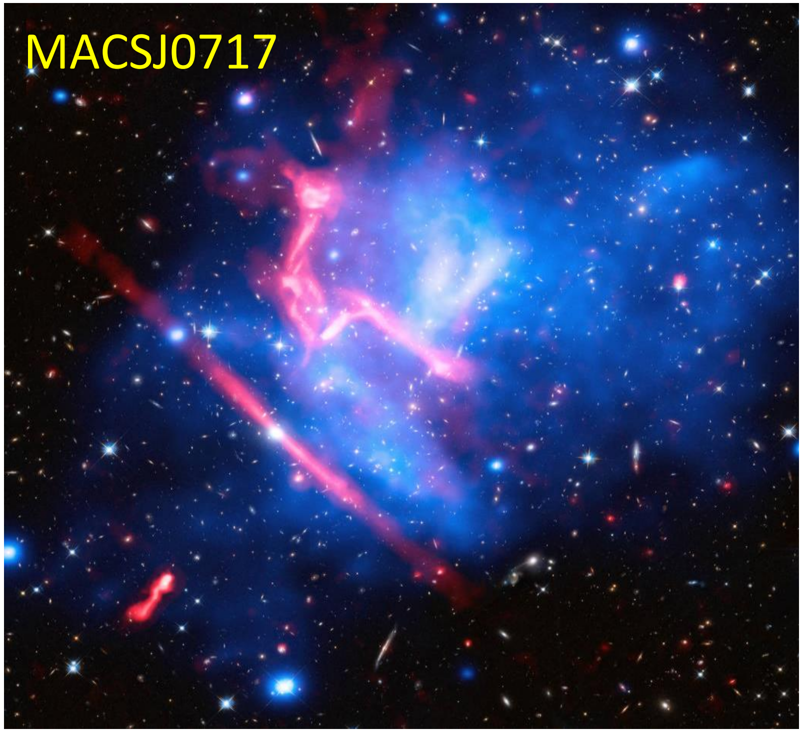


simulated matter distribution

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

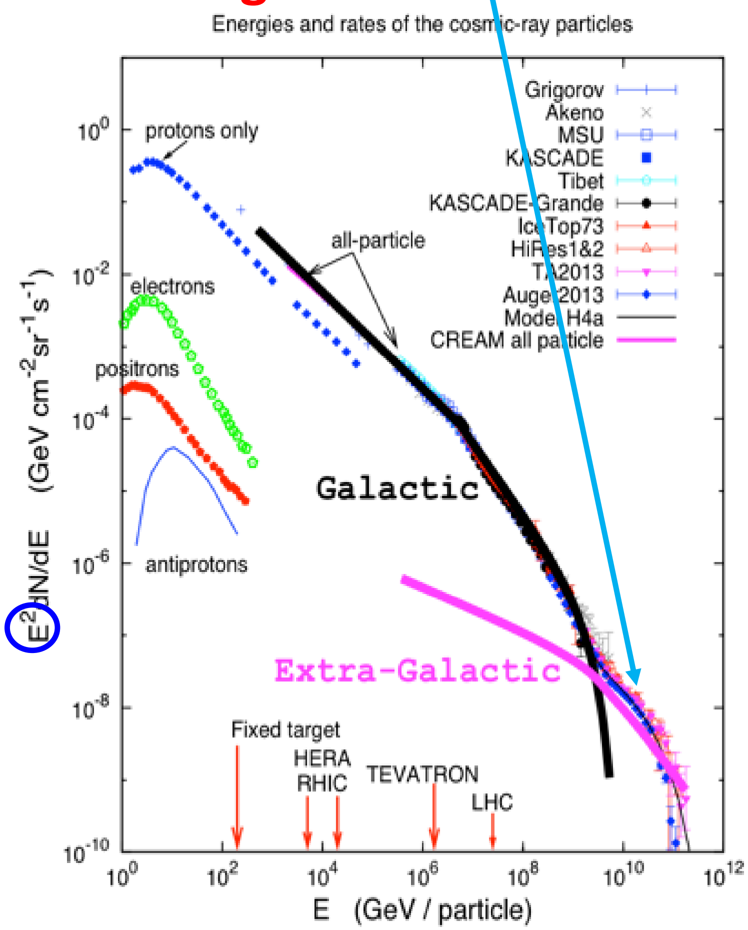


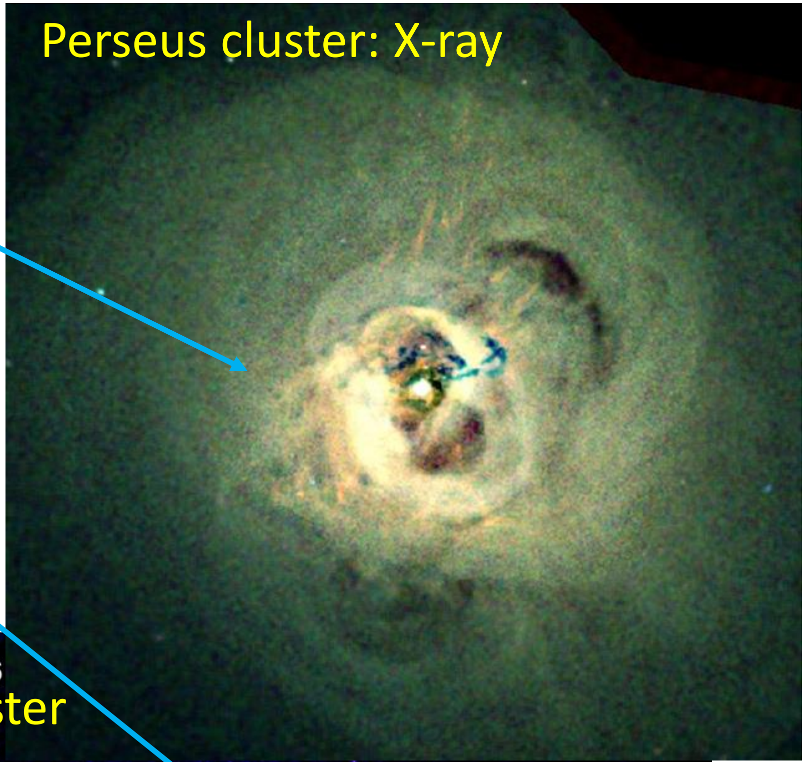
optical (Hubble, white)
X-ray (Chandra, blue) ← hot gas
radio (VLA, red) ← cosmic rays

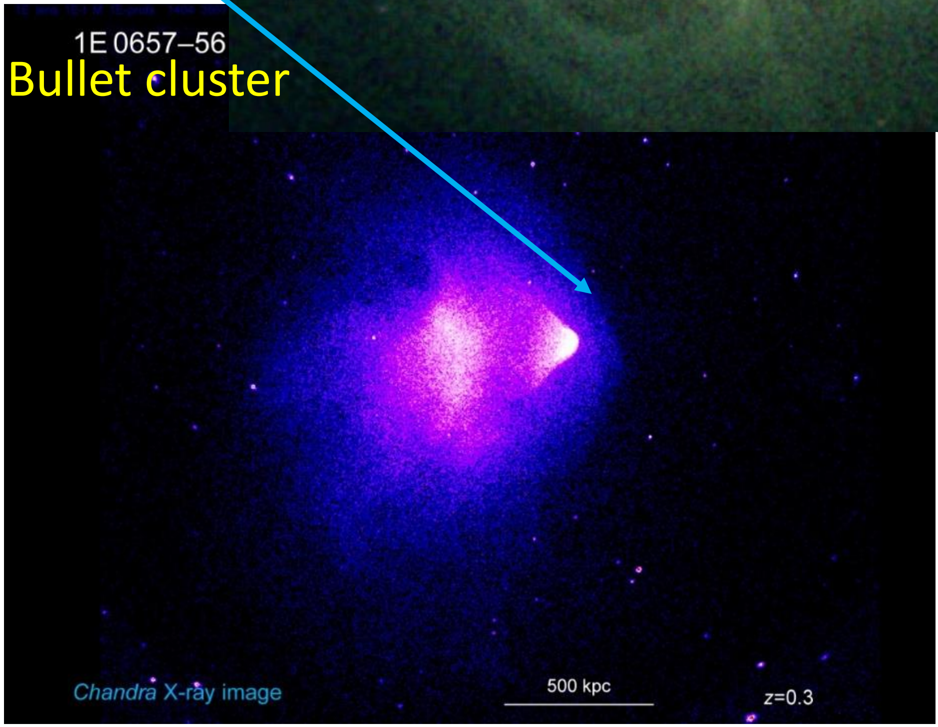
the intracluster medium (ICM) → the superheated **plasma with T ~ a few to several keV**, presented in clusters of galaxies

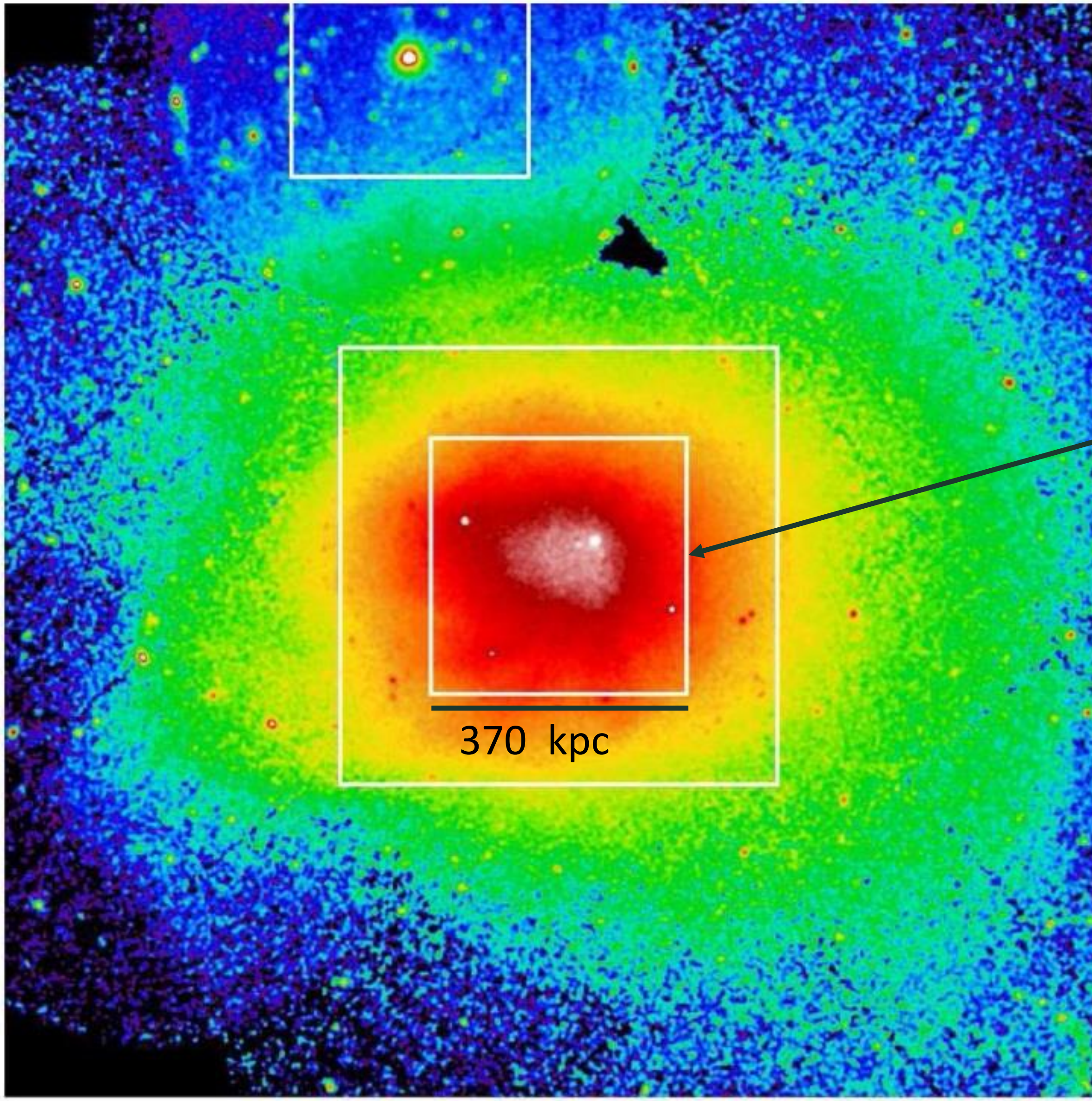
ICMs are dynamical:

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









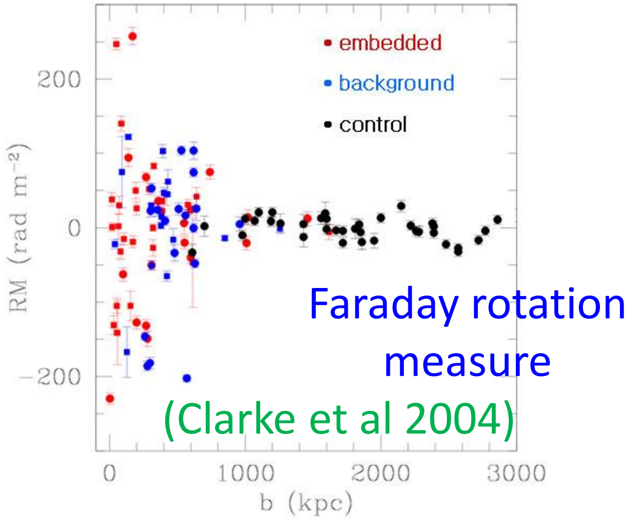
(Churazov et al. 2011)

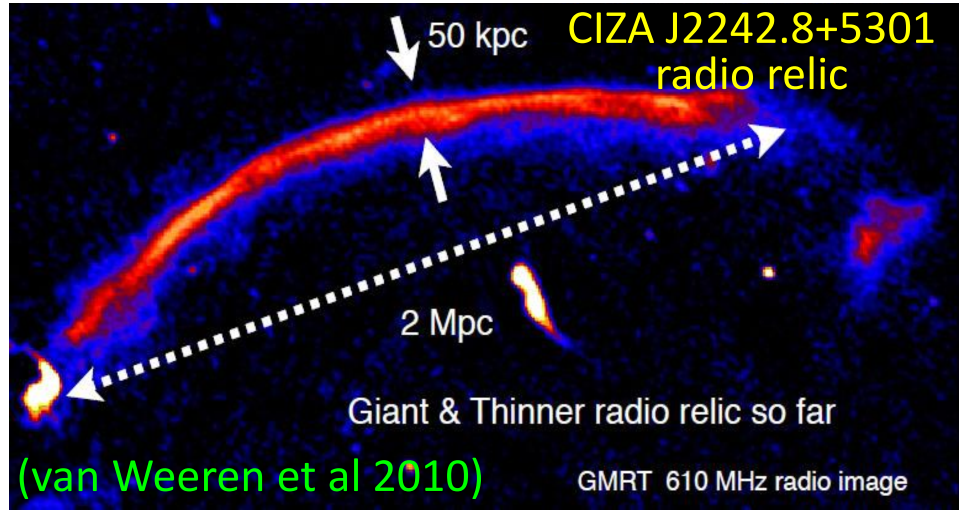
- XMM images of X-ray surface brightness fluctuations in Coma
- analyzed to get the power spectrum of gas density fluctuations

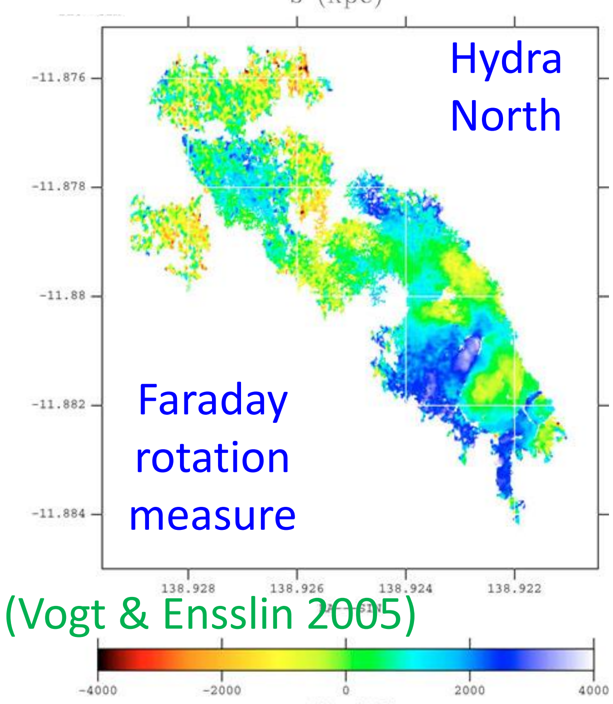
- $\Delta\rho/\rho \sim 0.1$
- $M_{turb} = v_{turb}/c_{sound} < 1\ (\sim 1/2)$

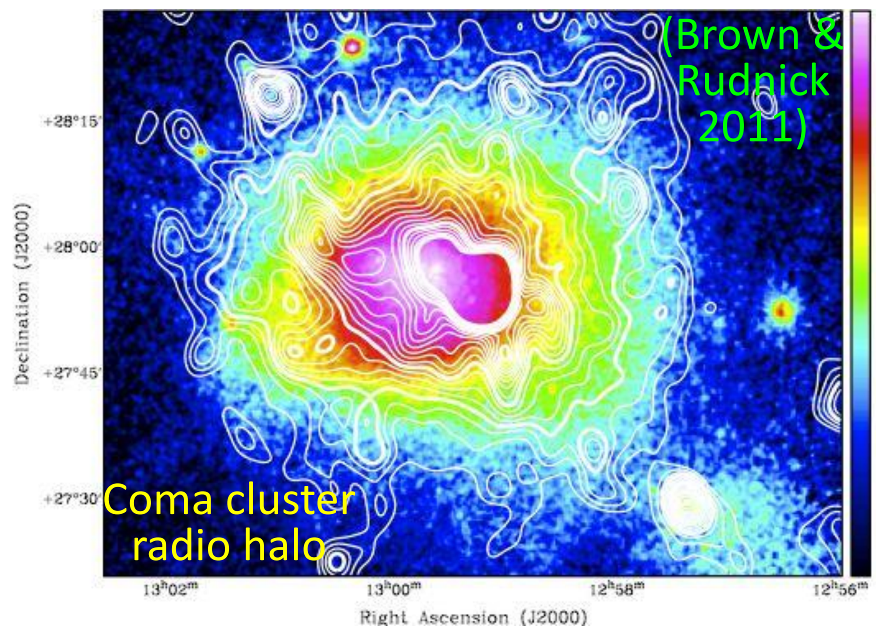
→ subsonic turbulence

Magnetic fields in galaxy clusters appeared in observations









➔ magnetic fields of order of ~μG in cluster outskirts

Fluid quantities in ICM outskirts

size of clusters	$L_{cluster}$ ~ a few Mpc ~ 10^{25} cm
baryon number density	n ~ 10^{-3} cm
gas temperature	T ~ 10^8 K (8.6 keV) → c_s ~ 1,500 km/s
flow velocity	**v ~ several x 100 km/s → M_s ~ ½ < 1**
magnetic fields	**B ~ a few x μG → c_A ~ 100 km/s, M_A > 1**

→ 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 $\left(\beta \equiv \frac{P_{thermal}}{P_{magnetic}} \equiv \frac{2E_{thermal}}{3E_{magnetic}}\right)$

A turbulence dynamo model for the origin of magnetic fields in clusters

(e.g., Ryu, Kang, Cho, & Das 2008)

large-scale structure formation

gravitational collapse, mergers, & accretion flow motions

turbulence

small-scale or turbulent dynamo

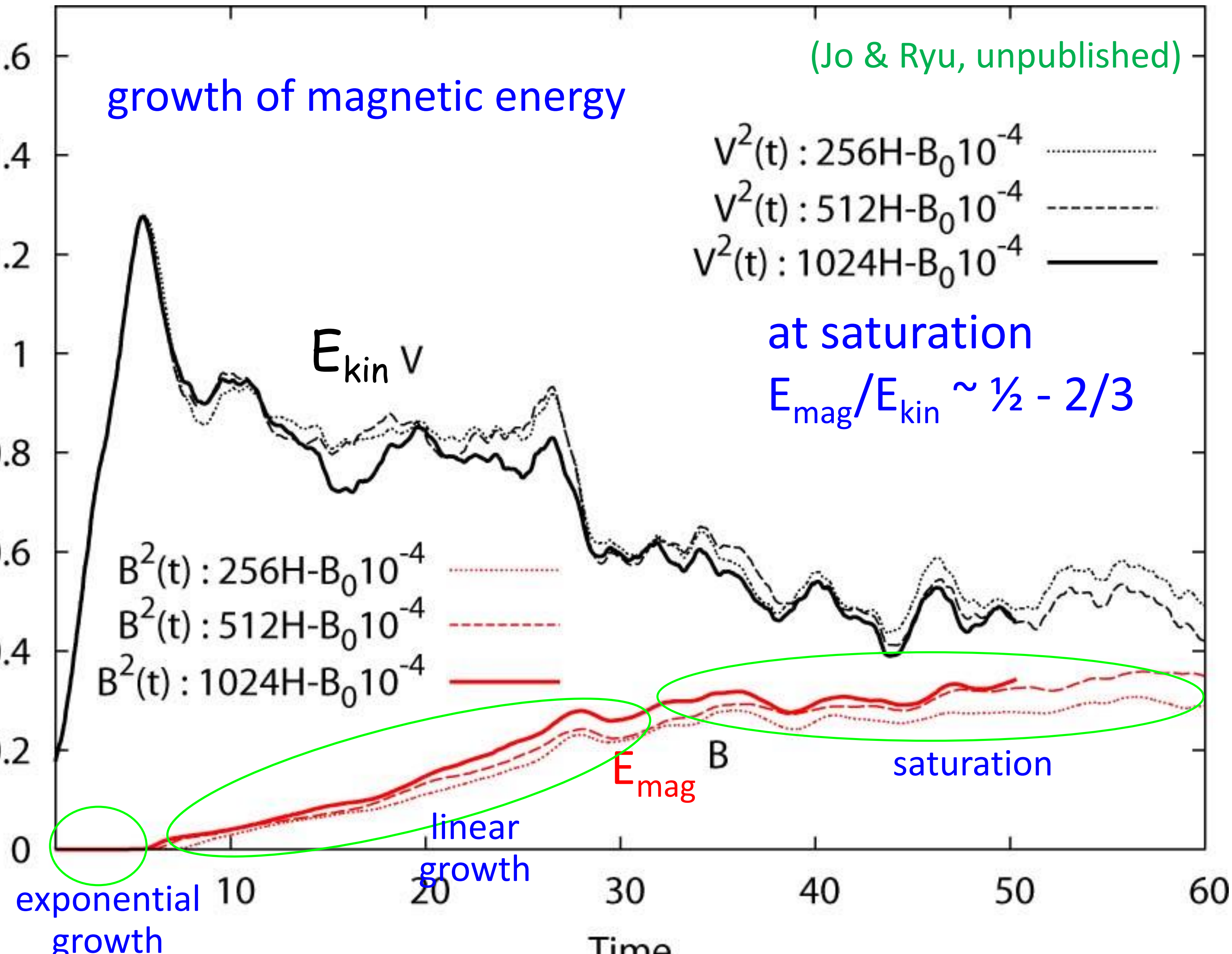
magnetic fields in clusters

other sources of turbulence and magnetic fields, such as AGN feedbacks

more important in cluster cores

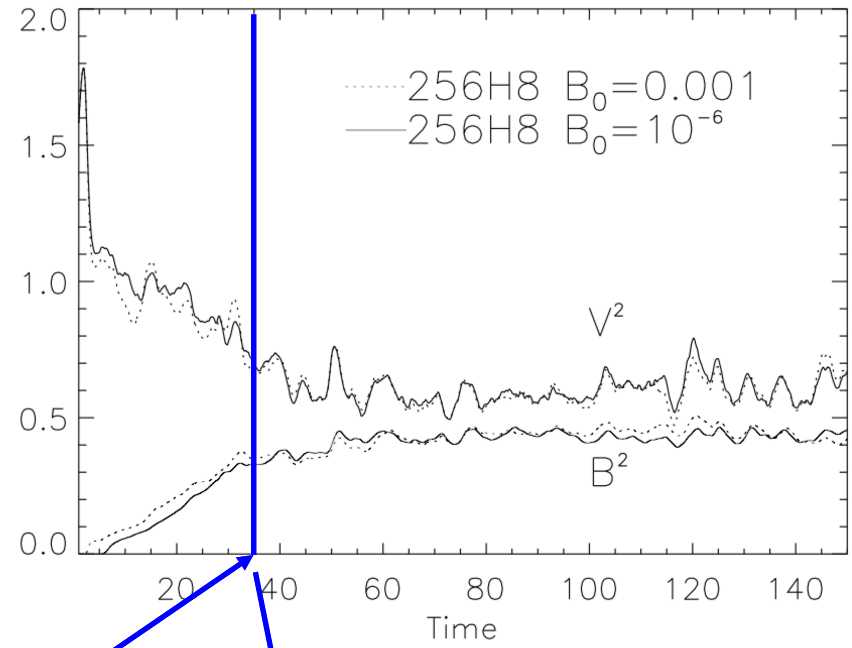
- **Issues regarding turbulence dynamo in galaxy clusters**
- **New simulations to study turbulence dynamo in galaxy clusters**

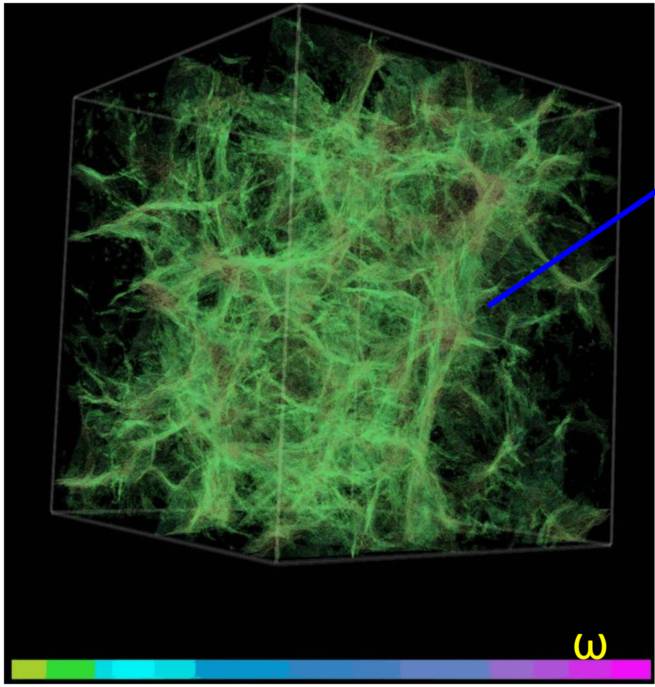
Growth of magnetic fields by turbulent flow motions: small-scale dynamo

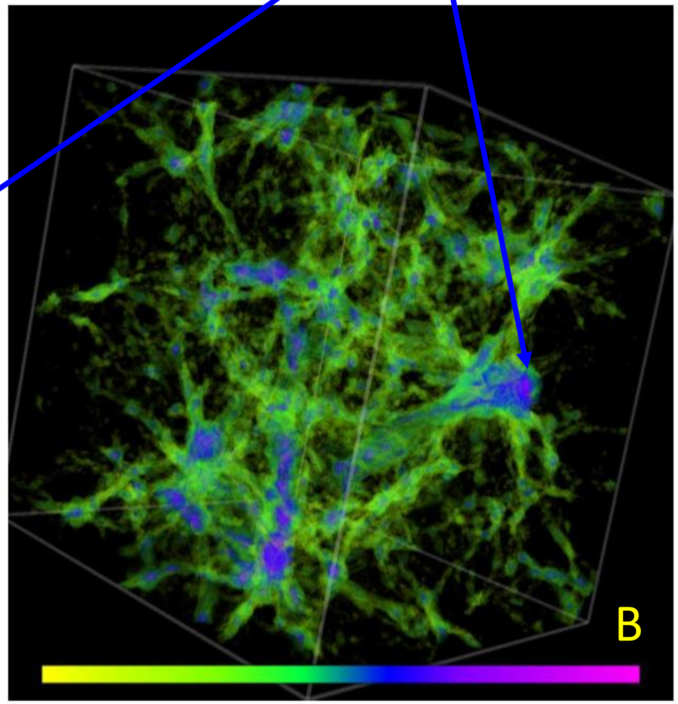


A model for the origin magnetic fields in galaxy clusters (Ryu, Kang, Cho, & Das 2008)

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





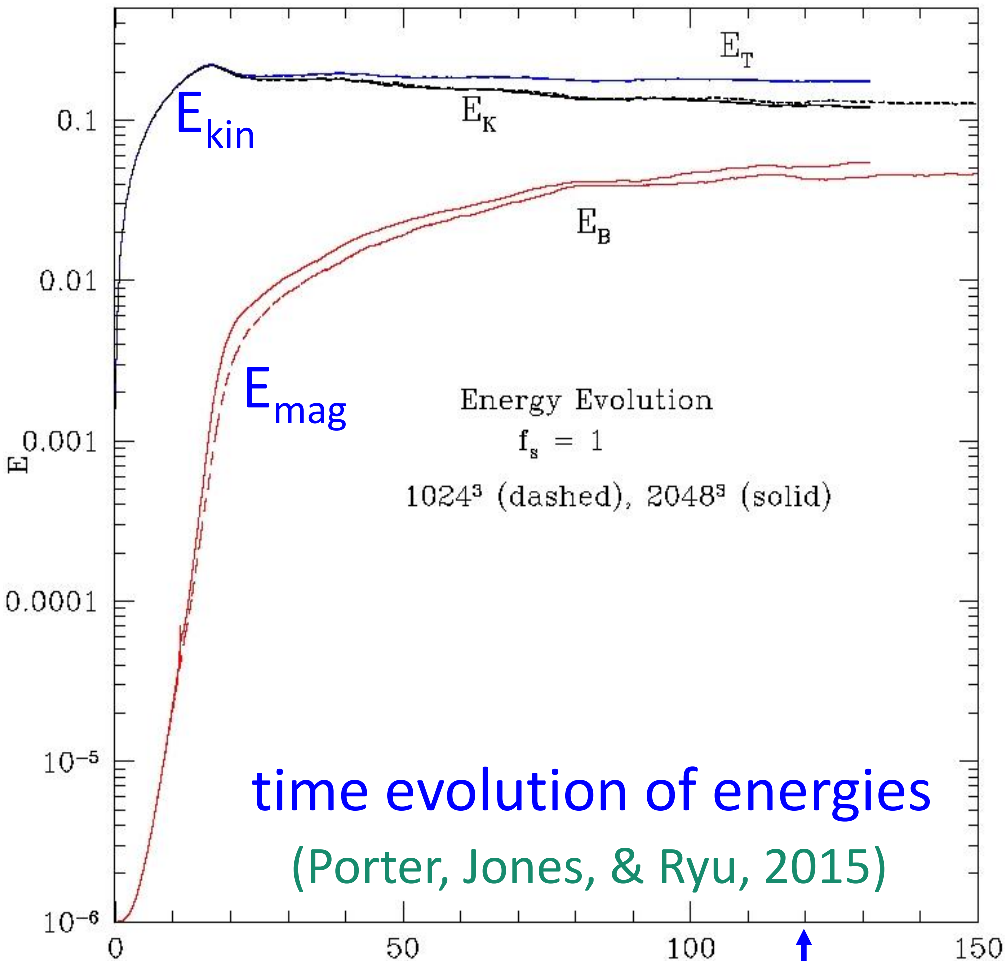


Does this model reproduce the observed magnetic fields!

There are issues in turbulence dynamo model for the origin of magnetic fields in galaxy clusters regarding

1. strength of magnetic fields
2. scale of magnetic fields

The growth of magnetic field strength in turbulence dynamo



$10\ t\ /\ t_{eddy}$ t_{age}

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

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

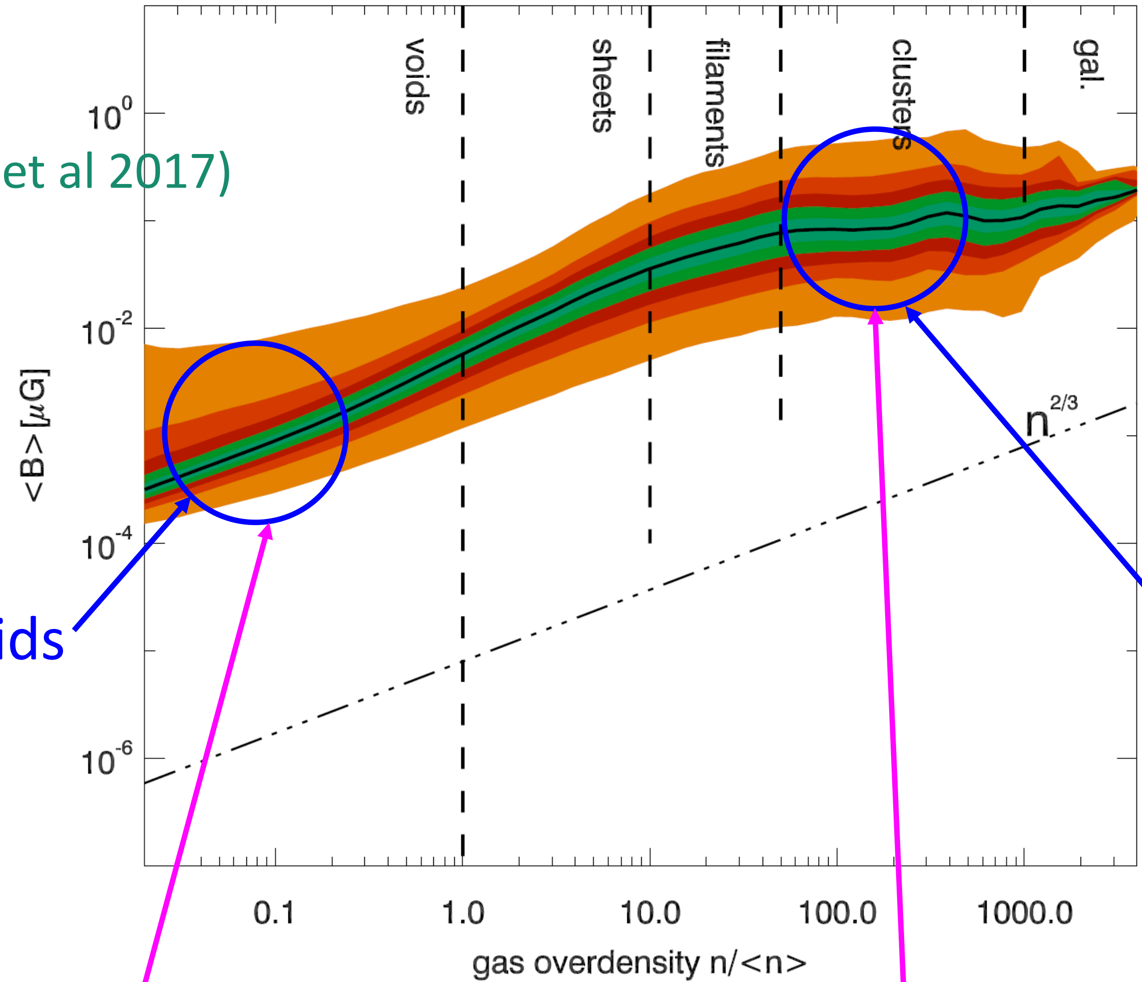
or $t_{age} \sim 1/10\ t_{eddy}$

(t_{age} the age of the universe)

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

Turbulence dynamo in cosmology simulations

(Vazza et al 2017)



from a cosmology simulation with 2400^3 grid zones in a box of 200 Mpc size

voids

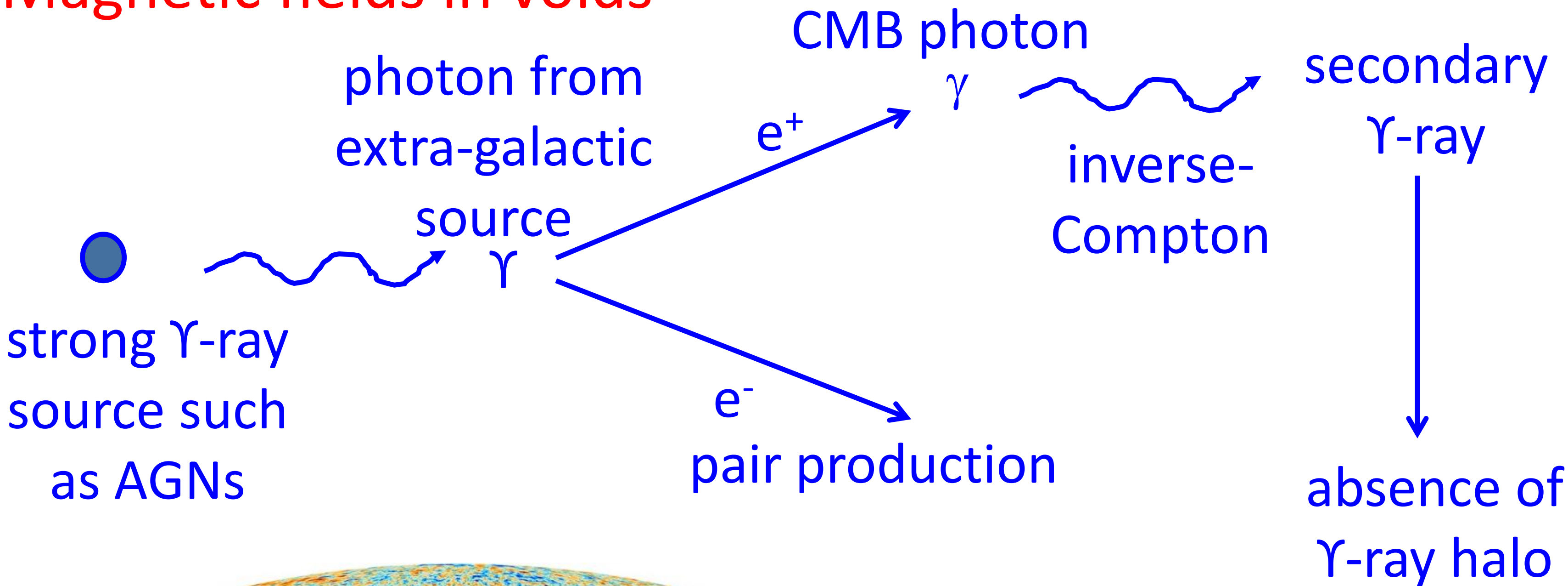
cluster outskirts

in simulations, so far, to reproduce $B_{cluster}$ ~μG at cluster outskirts

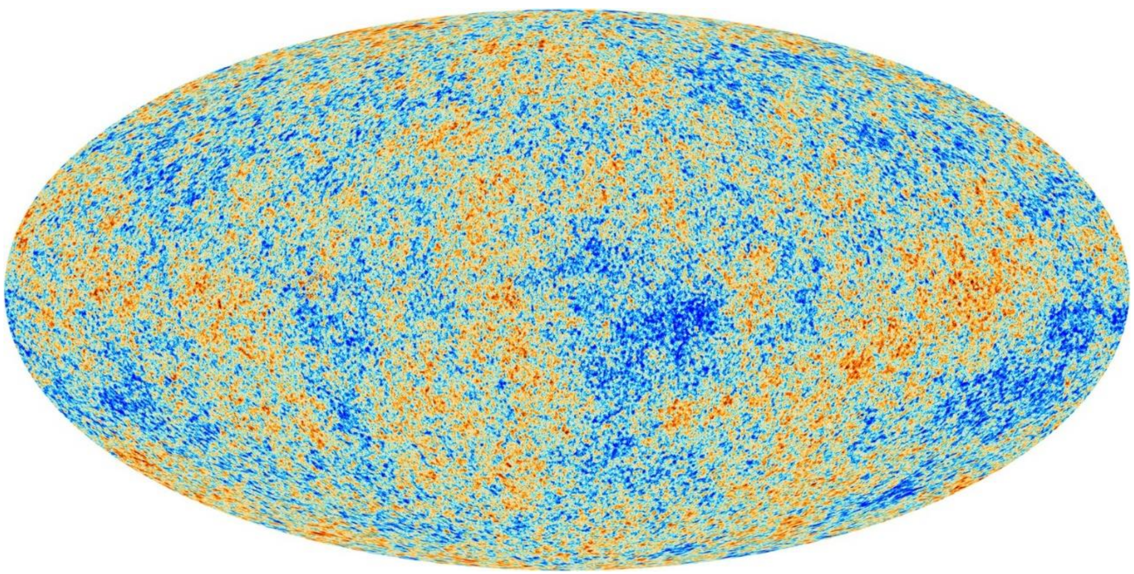
B_{seed} >~ 1 nG (comiving) fields at z ~ several x 10 are required !

→ B_{void} >~ 1 nG at voids at z = 0

Magnetic fields in voids



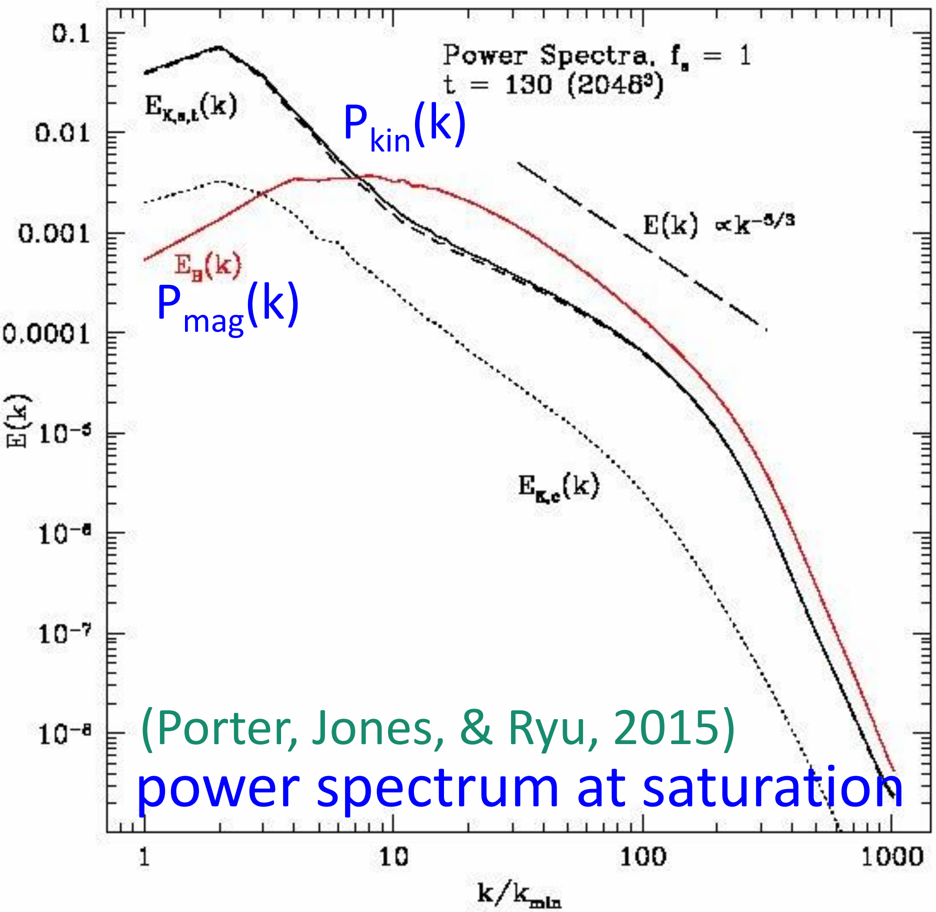
➔ B >~ 10^{-19} - 10^{-16} G



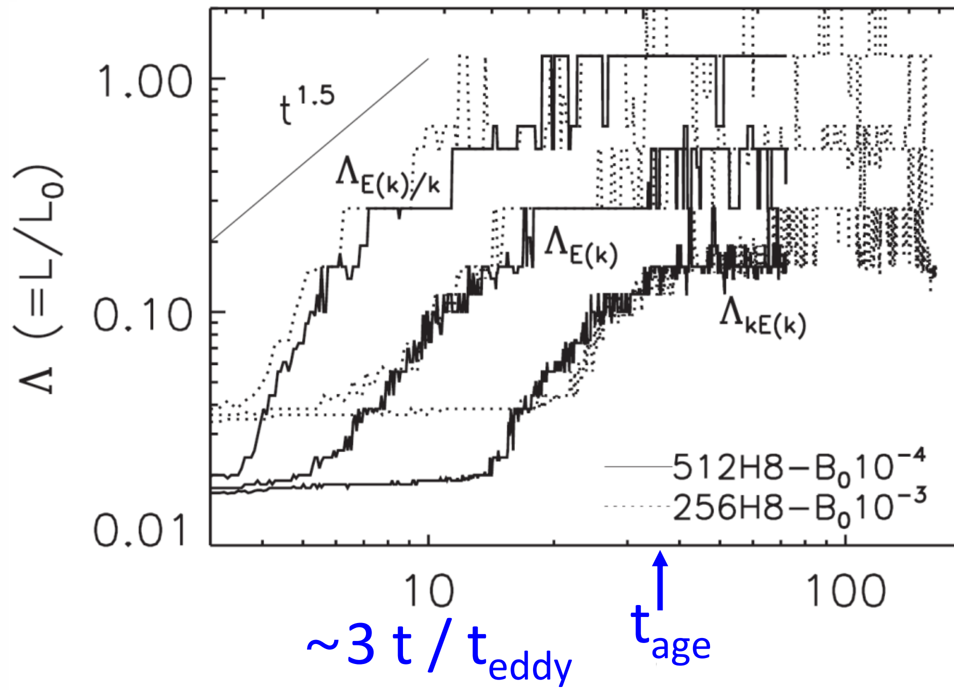
With seed field B$_{seed}$ ~ 10^{-19} - 10^{-16} G (comiving), can turbulence dynamo generate cluster magnetic fields of B$_{cluster}$ ~ μG ?

"upper" limits from CMB ➔ B <~ nG

The growth of magnetic field scales in turbulence dynamo



(Cho & Ryu 2009)

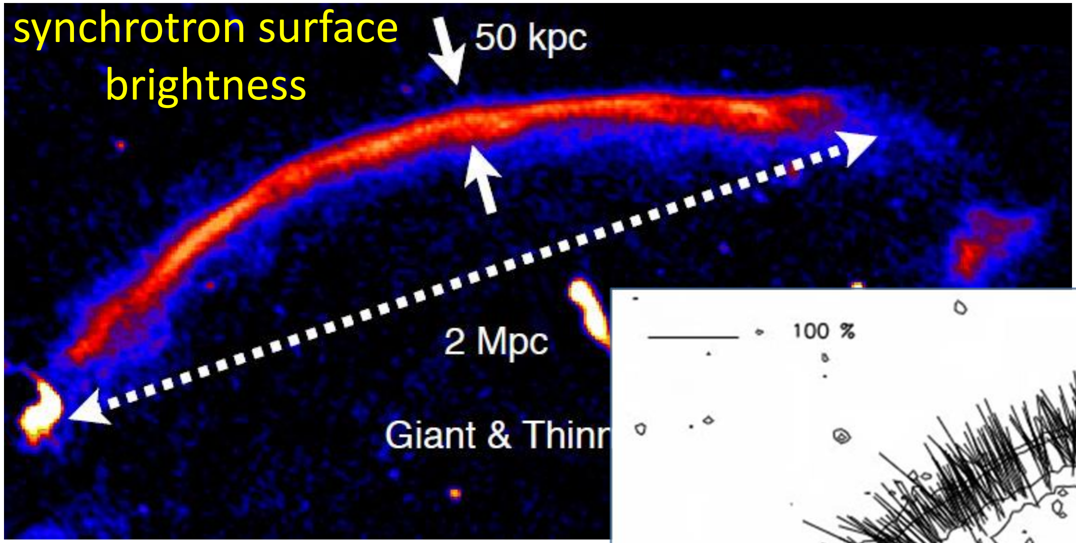


At t ~ 10 t_{eddy},
the peak of $P_{mag}(k)$ is ~ 1/3 $L_{injection}$
the peak of $kP_{mag}(k)$ is ~ 1/10 $L_{injection}$

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

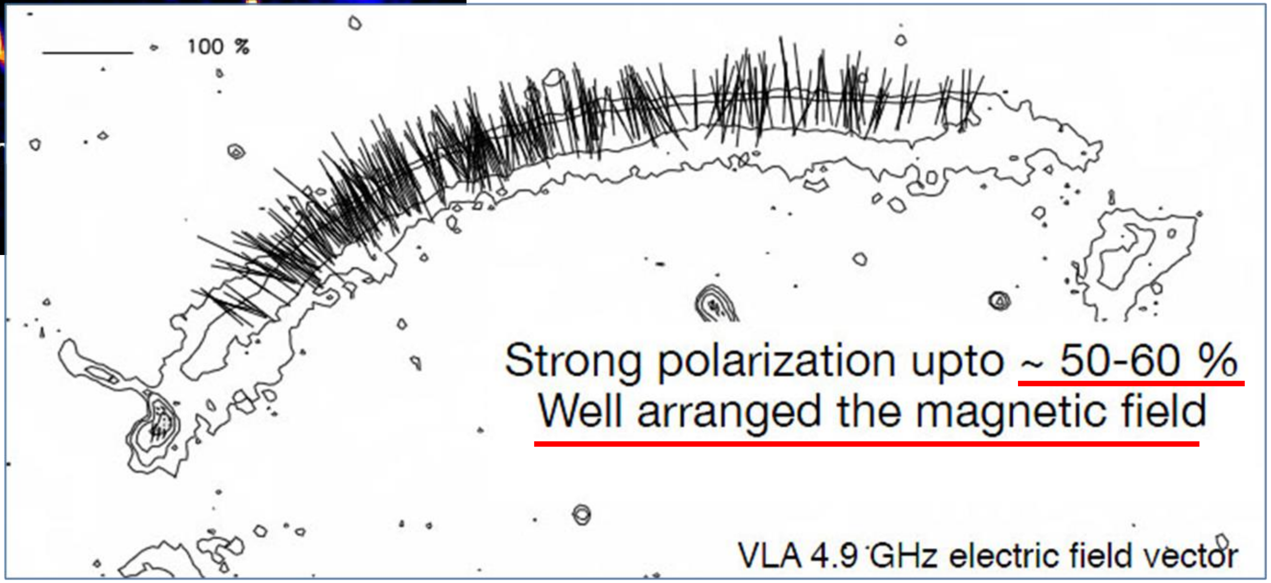
Evidence for large-scale magnetic fields in cluster outskirts ?

CIZA J2242.8+5301 (Sausage radio relic)



(van Weeren et al 2010)

synchrotron
polarization vectors

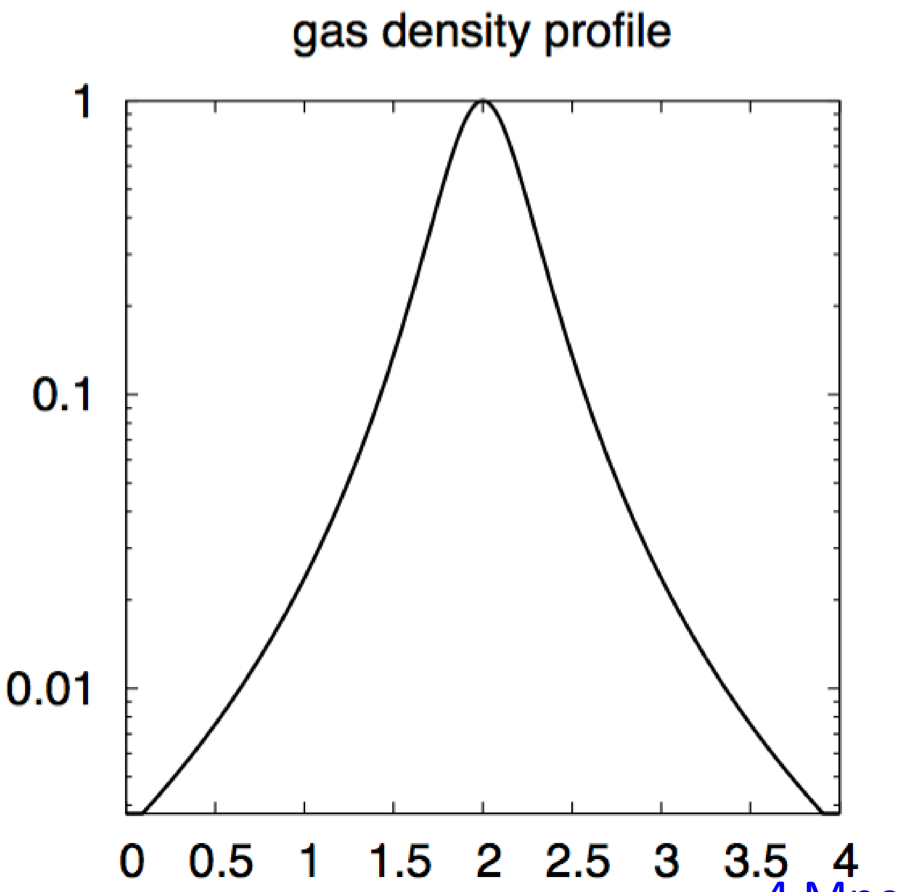


Is this an indication of "Mpc-scale" magnetic fields in outskirts?

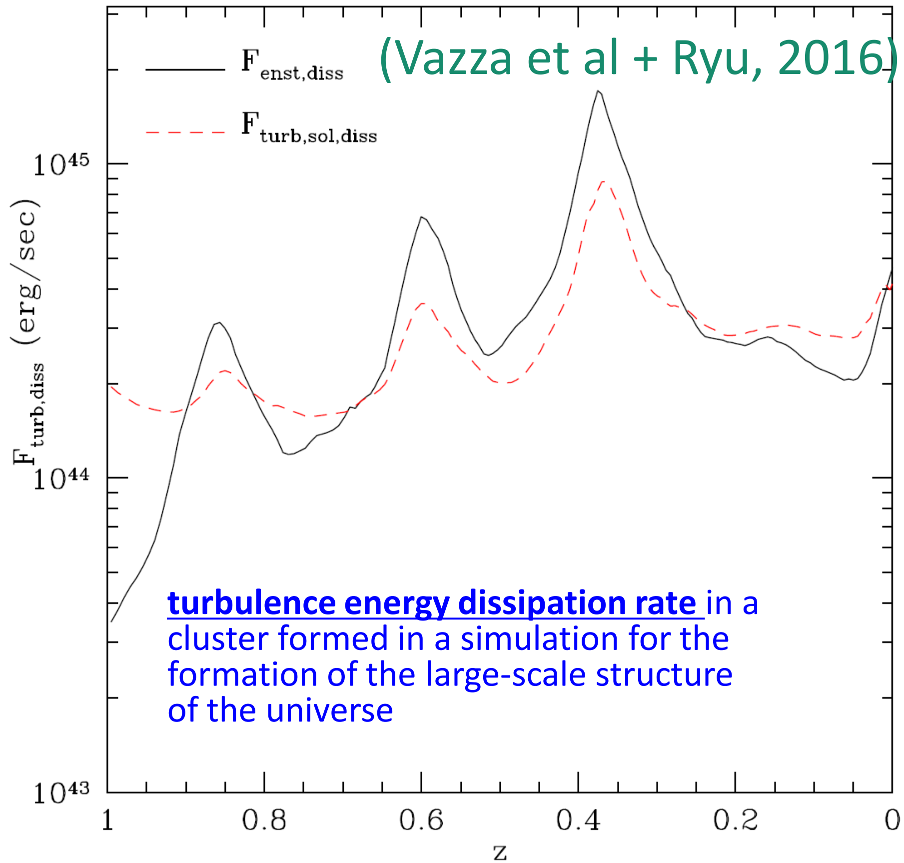
Can it be reproduced with turbulence dynamo?

Turbulence simulations in clusters need to consider

- the medium is "**stratified**"
- turbulence is driven "**sporadically**"



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

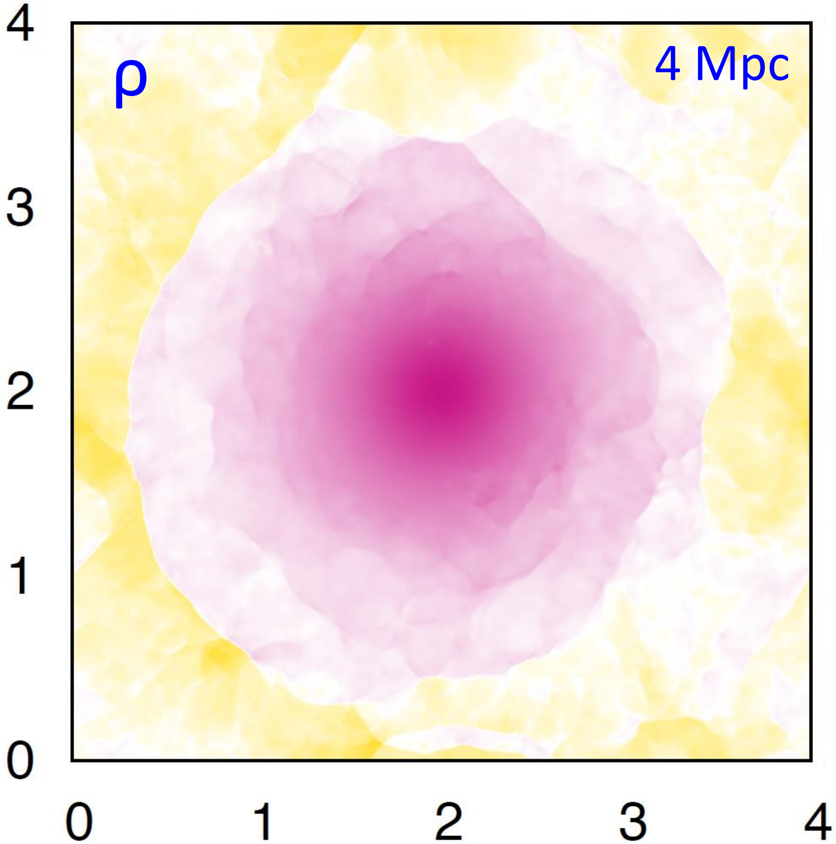


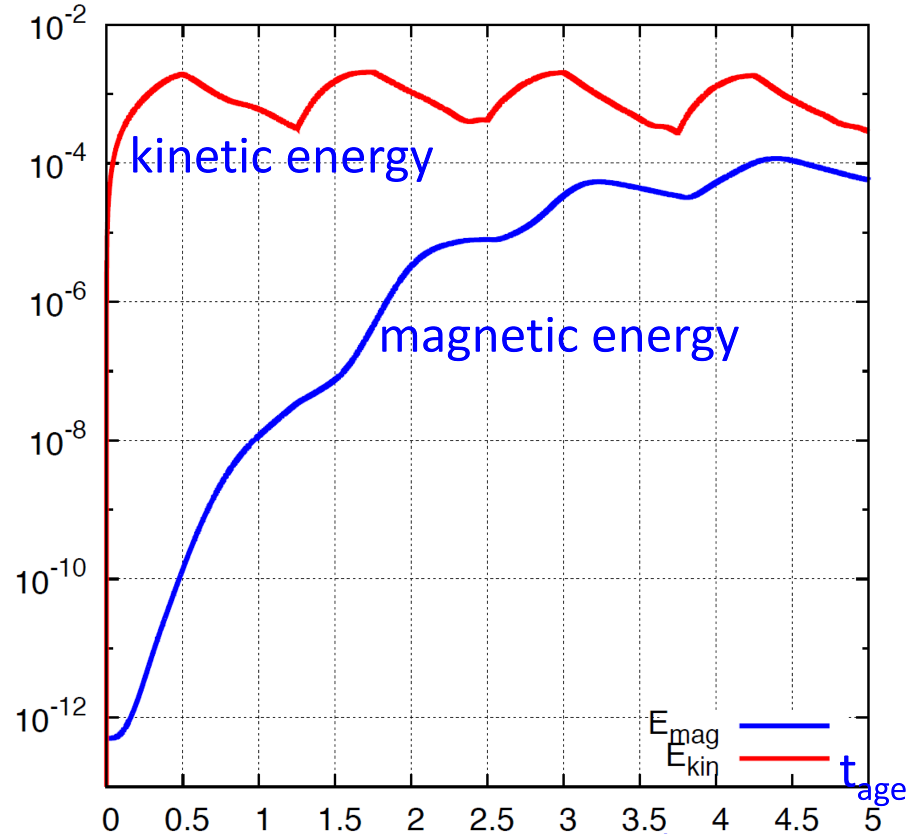
In clusters of galaxies, the turbulence is driven "sporadically", mostly by "mergers".

Simulations of turbulence "sporadically" driven in "staratified" clusters using a new high-resolution code (5^{th}-order WENO)

(Roh, Ryu et al, in preparation)

(code written by Hanbyul Jang)

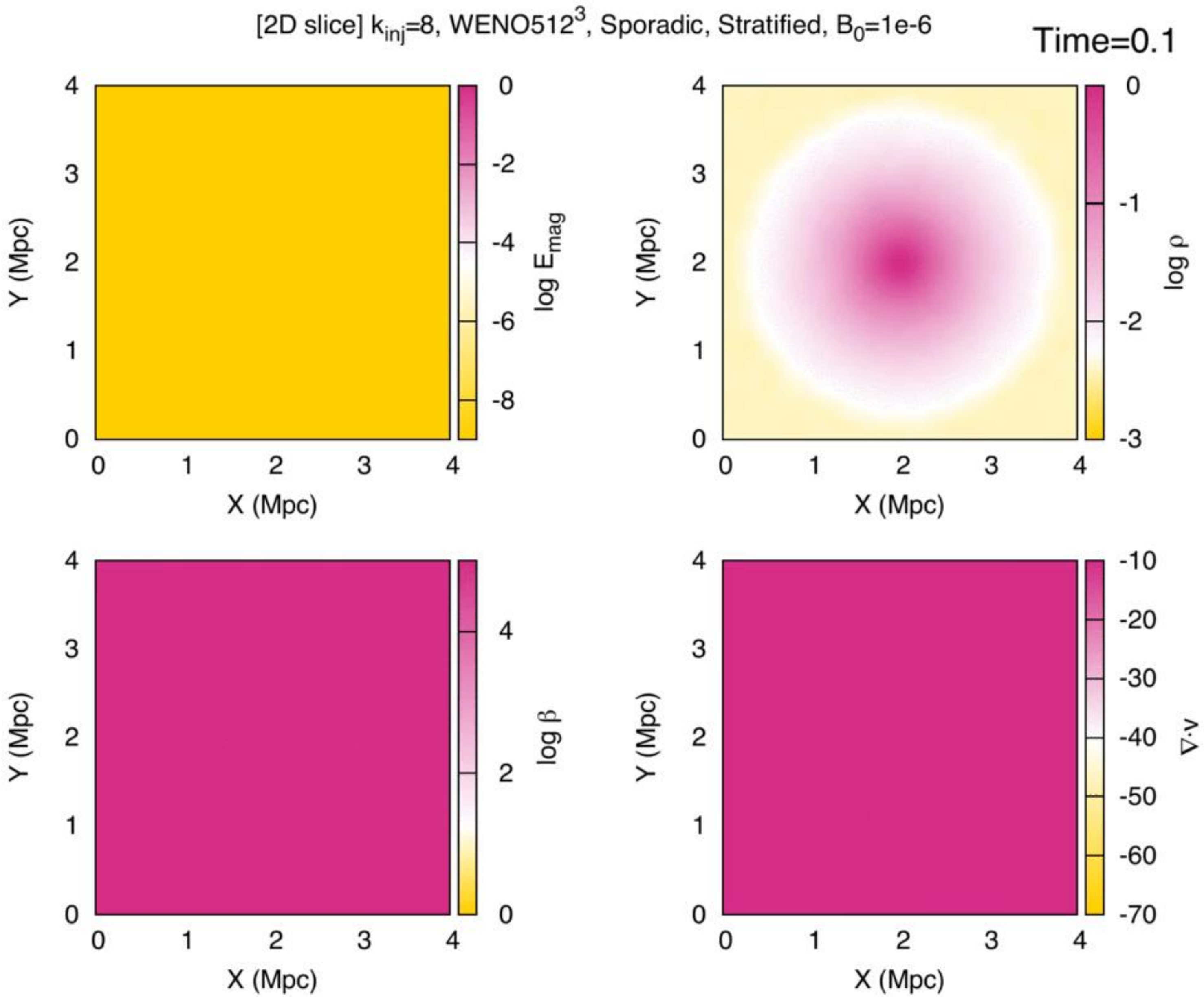




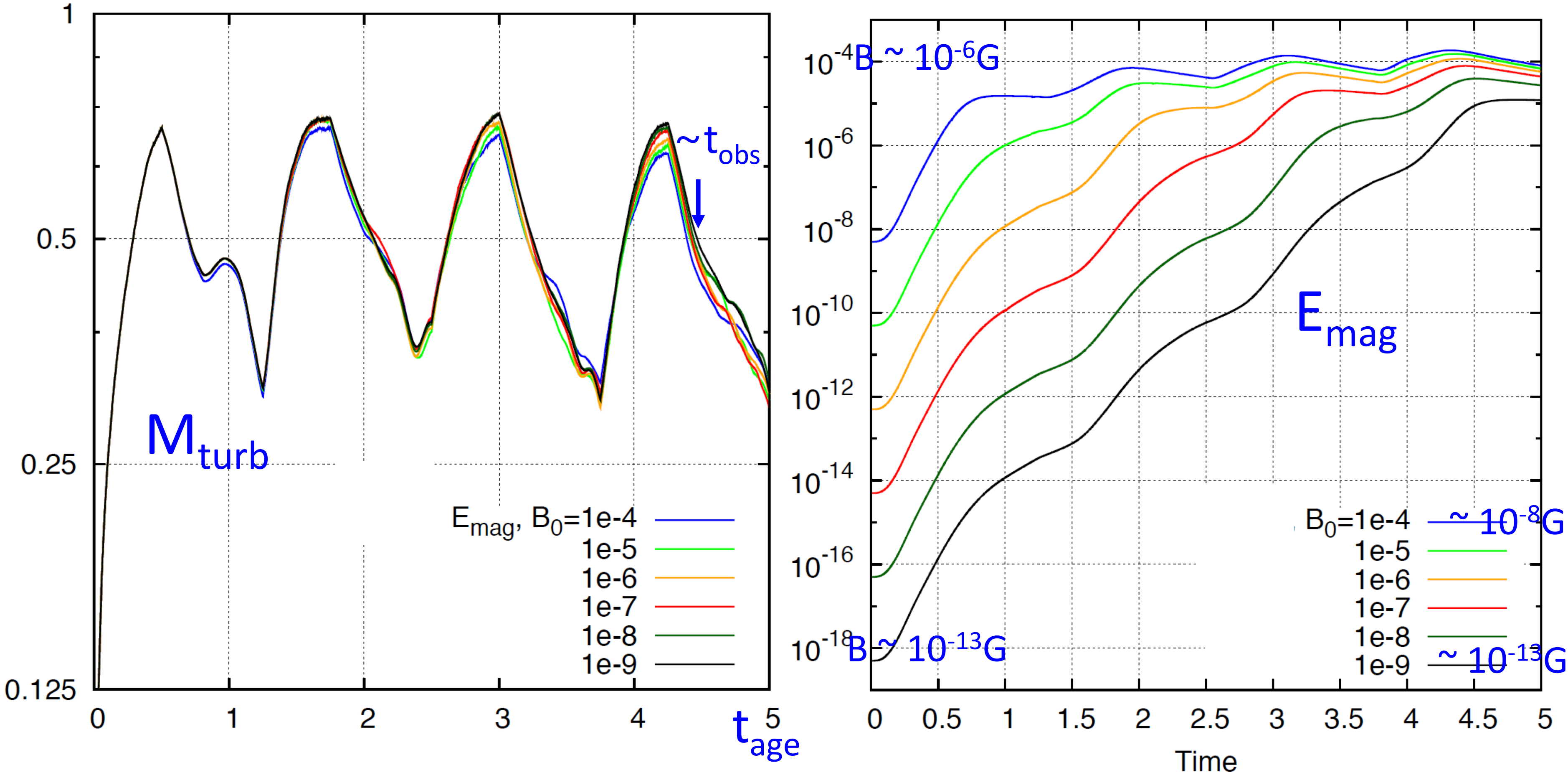
clusters of $T = 10^8$ K (c_s = 1,500 km/s) described the beta model with $\beta = 1$ and r_c = 300 kpc in a box of L_{size} = 4 Mpc

turbulence 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

Time evolution of turbulence and magnetic field

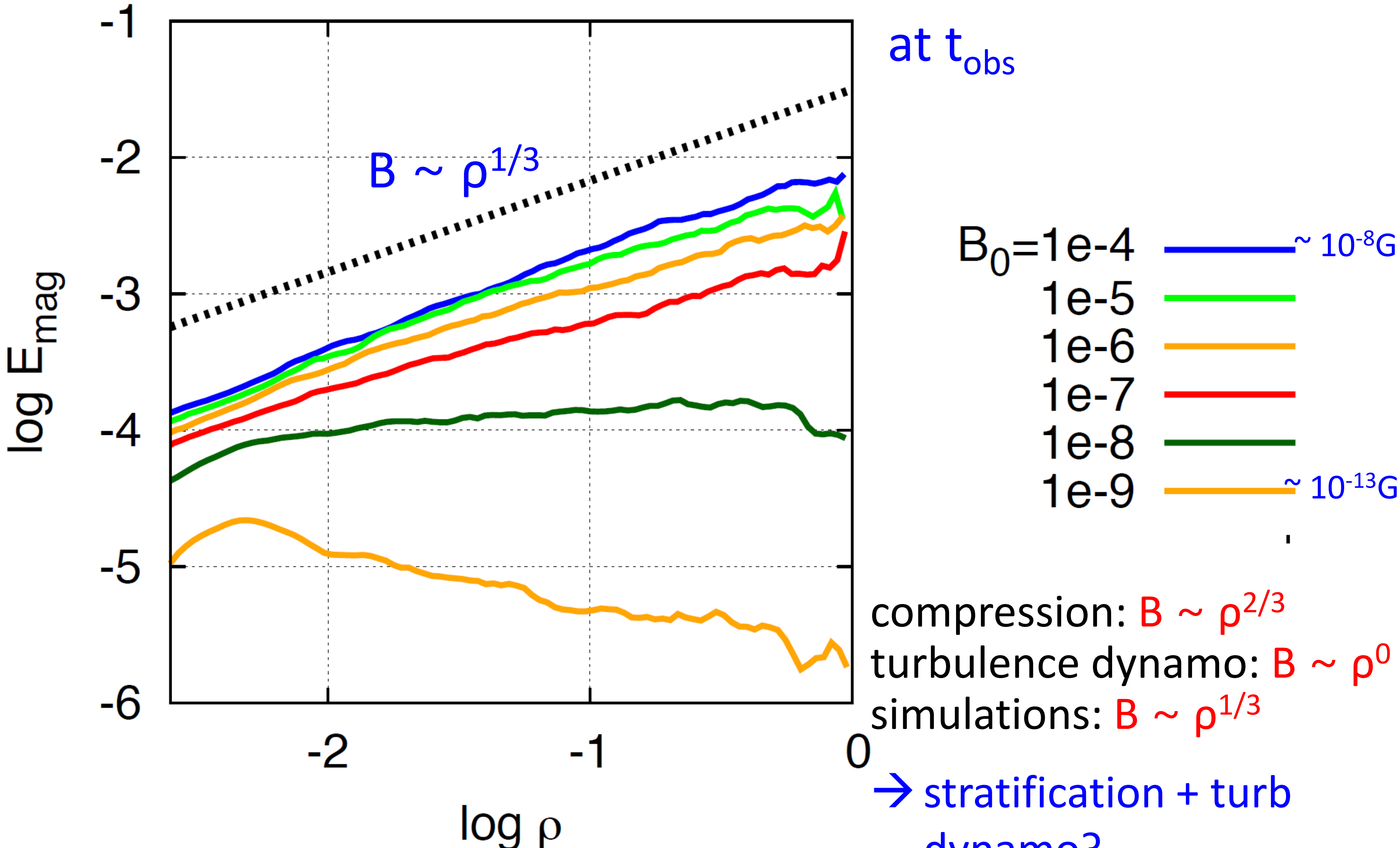


Growth of magnetic field strength



simulations with 512^3 zones (Δx ~8 kpc): when turbulence has $<M_s>$ ~ ½, if B_{seed} >~ 10^{-11} G, the magnetic field is amplified up to $B_{cluster}$ ~ 1 μG within the age of the universe.

Correlation between B vs ρ



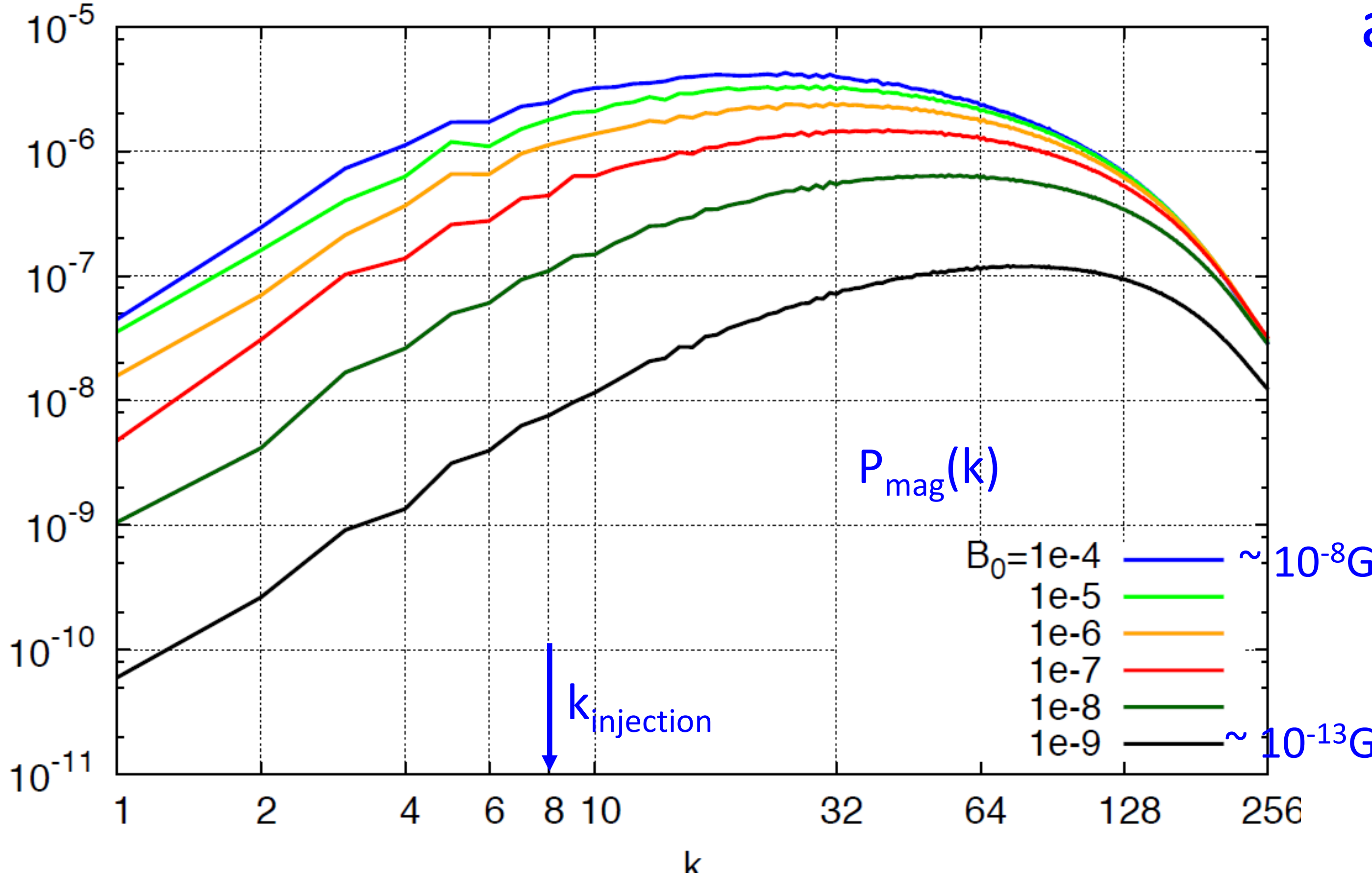
at t_{obs}

compression: B ~ $\rho^{2/3}$
turbulence dynamo: B ~ ρ^0
simulations: B ~ $\rho^{1/3}$

→ stratification + turb dynamo?

Power spectra of turbulence in stratified medium with sporadic forcing

at t_{obs}



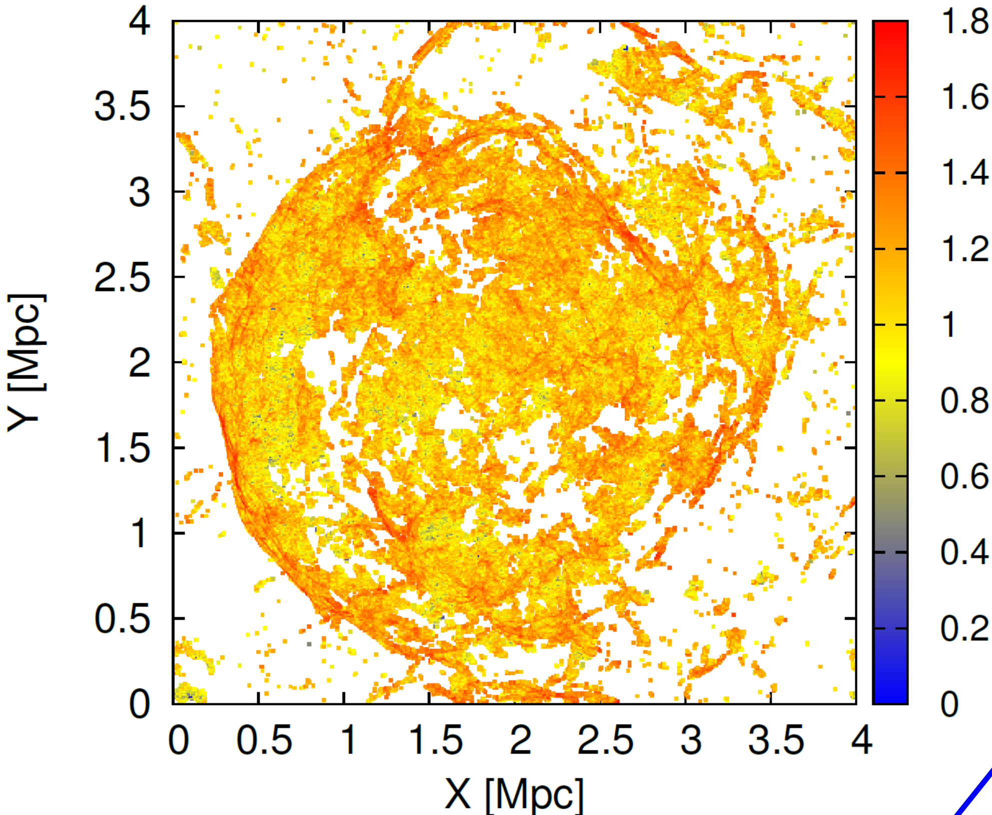
- $P_{kin}(k)$ shows large-scale (larger than the injection scale) powers
- $P_{mag}(k)$ has a broad peak over $k_{injection}$ – 10 $k_{injection}$
- $kP_{mag}(k)$ has a peak at ~ $5k_{injection}$

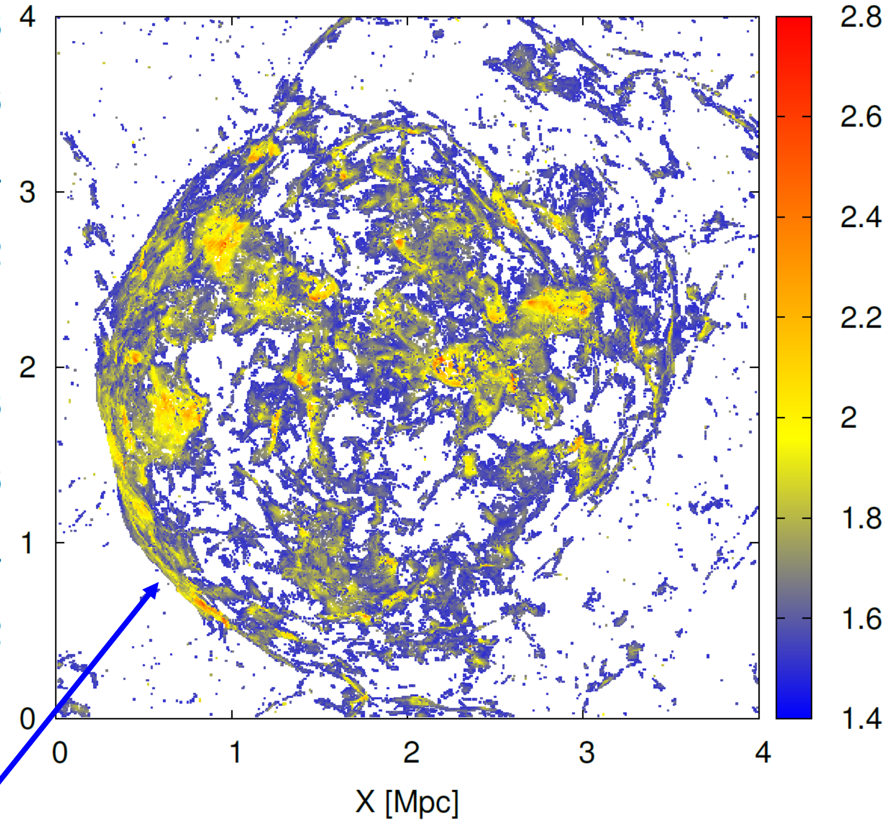
or if $L_{injection}$ = 500 kpc, the peak scale of magnetic energy ~100 kpc

← too small to explain Mpc-scale magnetic fields?

Appearance of turbulence in "real" space

at t_{obs}





$\log_{10}$(numbers of shock zones along lines of sight)

average shock Mach number along LOS weighted with synchrotron emissivity

Can these reproduce the observed polarization properties of "radio relics"?

Summary

- Magnetic field → ubiquitous in the large-scale structure (LSS) of the universe including in clusters of galaxies.
- Turbulence dynamo → suggested as a viable mechanism for the origin of the magnetic fields in the LSS of the universe
- Magnetic fields of ~ a few μG in cluster outskirts → could be explained by turbulence dynamo, but needs to be confirmed through high-resolution simulations
- Magnetic fields of ~ Mpc scale in cluster outskirts → are "not" yet clear to be explained by turbulence dynamo. They may need something else, such as fast large-scale dynamo (talk by E. T. Vishniac)?

Thank you !