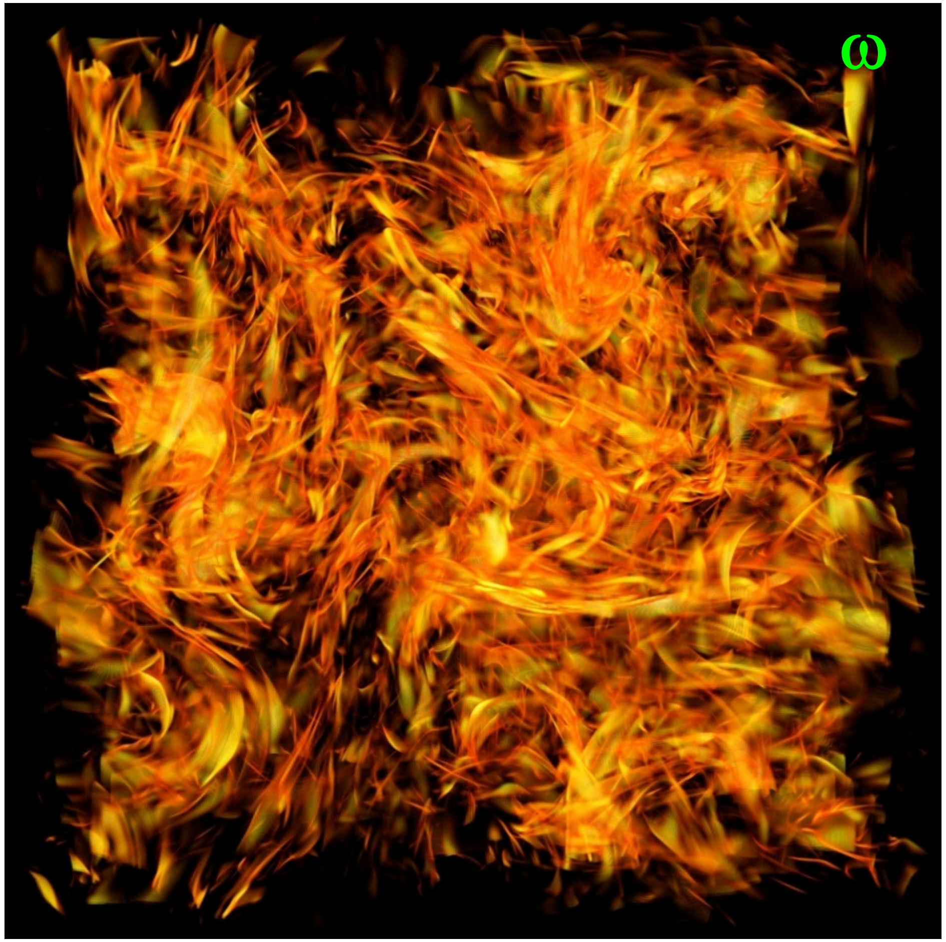
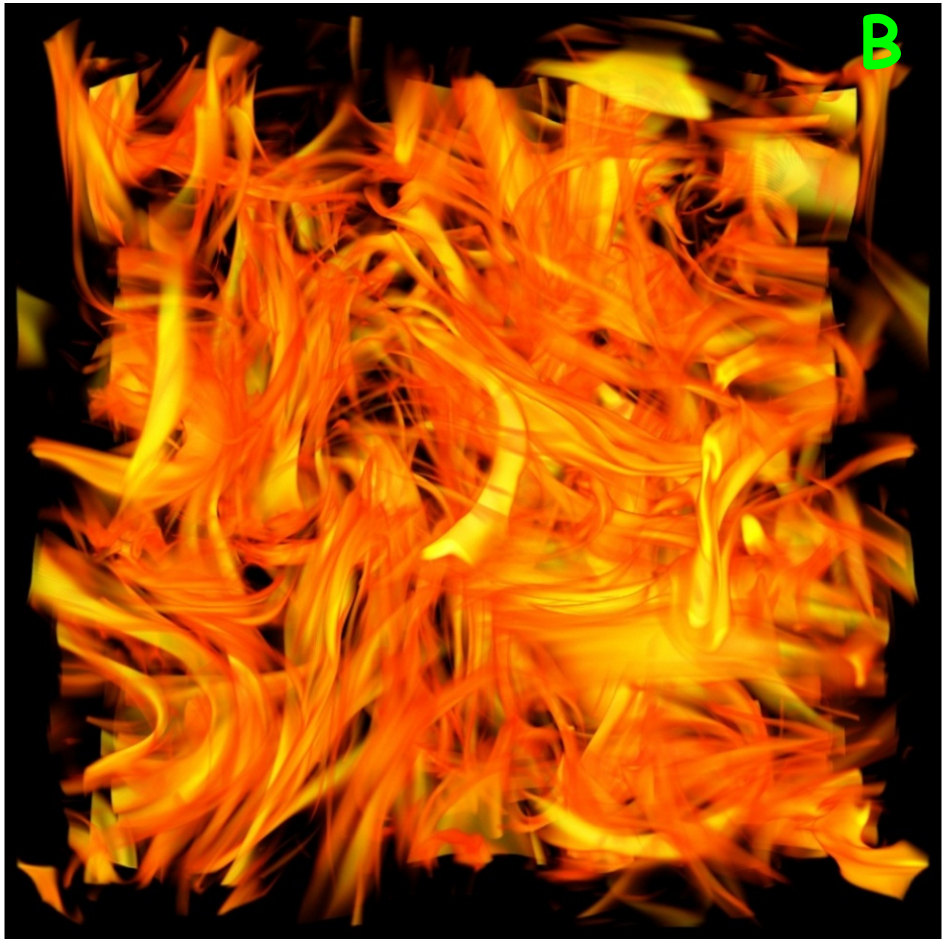
Turbulence in Clusters of Galaxies





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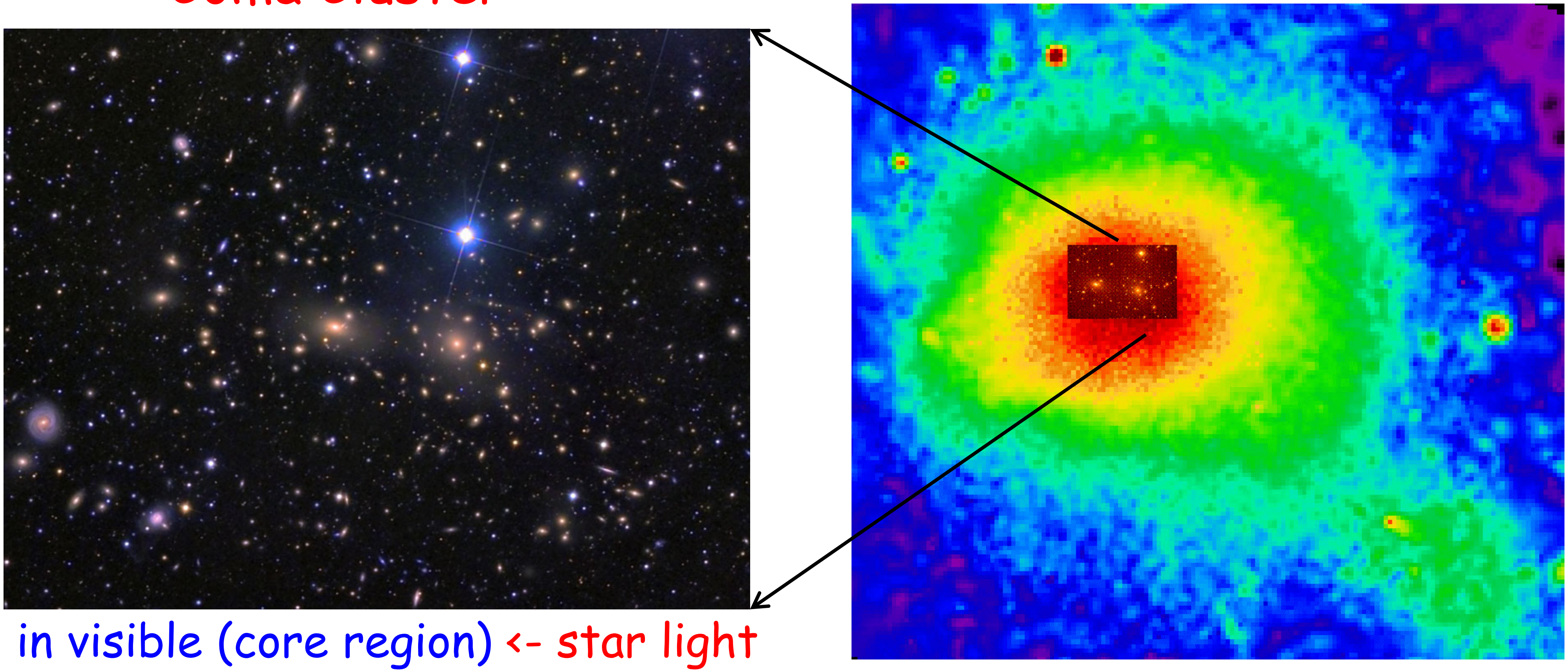
Zhibin Guo, Jahyung Jo, Jae-Min Kwon, Pat Diamond (NFRI, WCI)

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

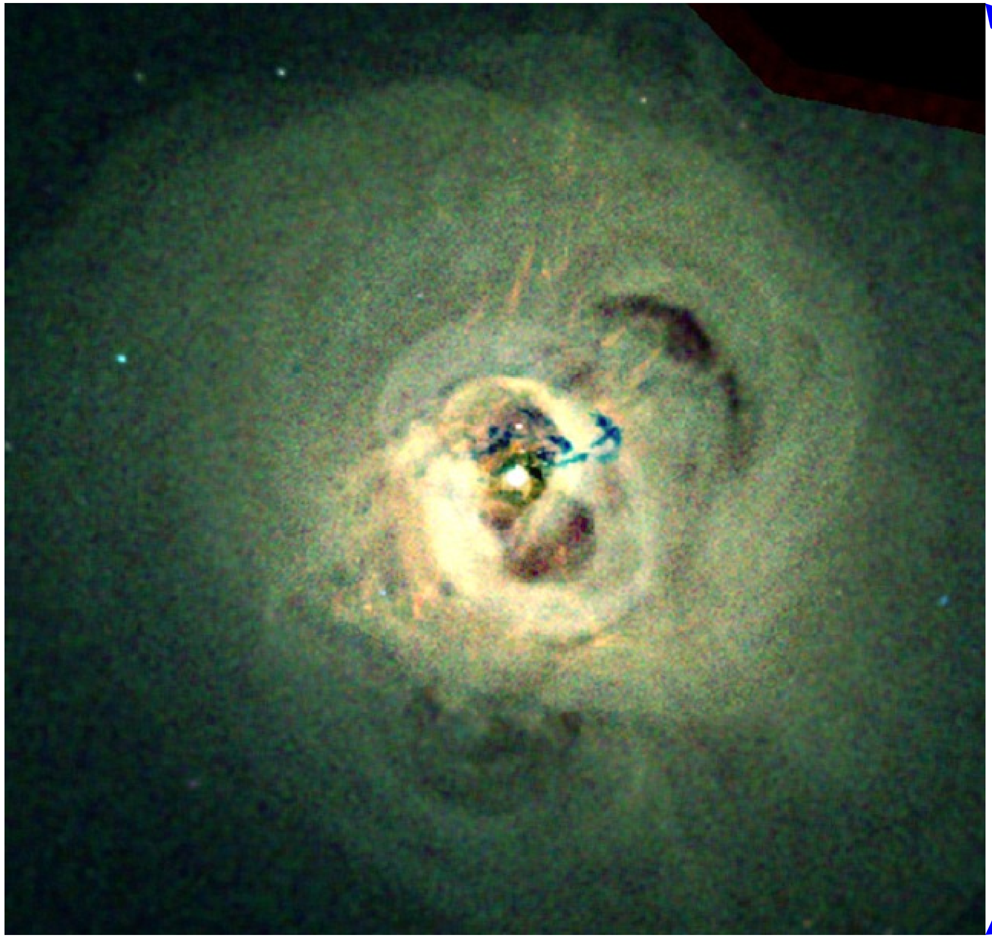


in visible (core region) <- star light

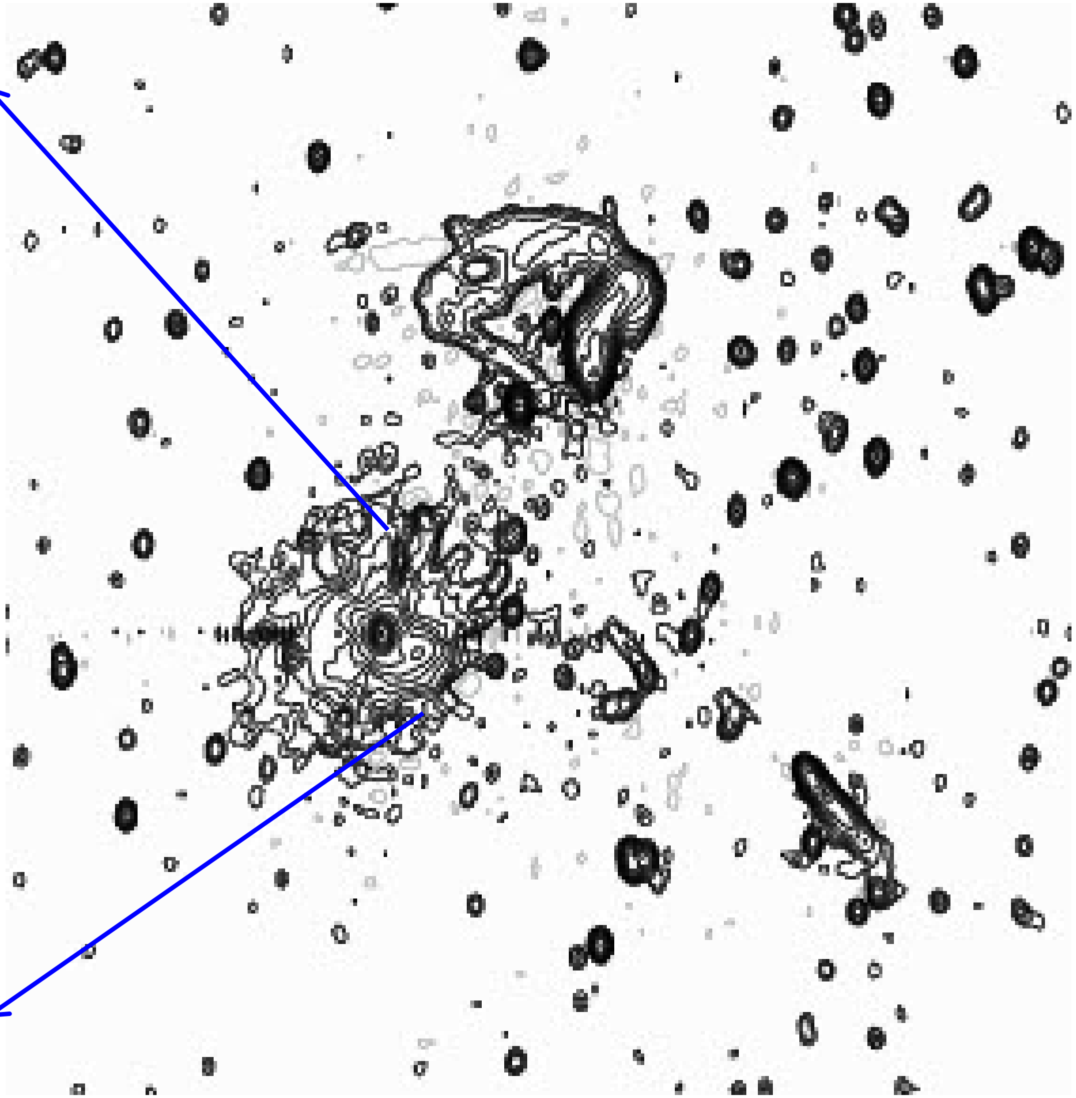
in X-ray <- hot gas of T ~ 8 keV

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

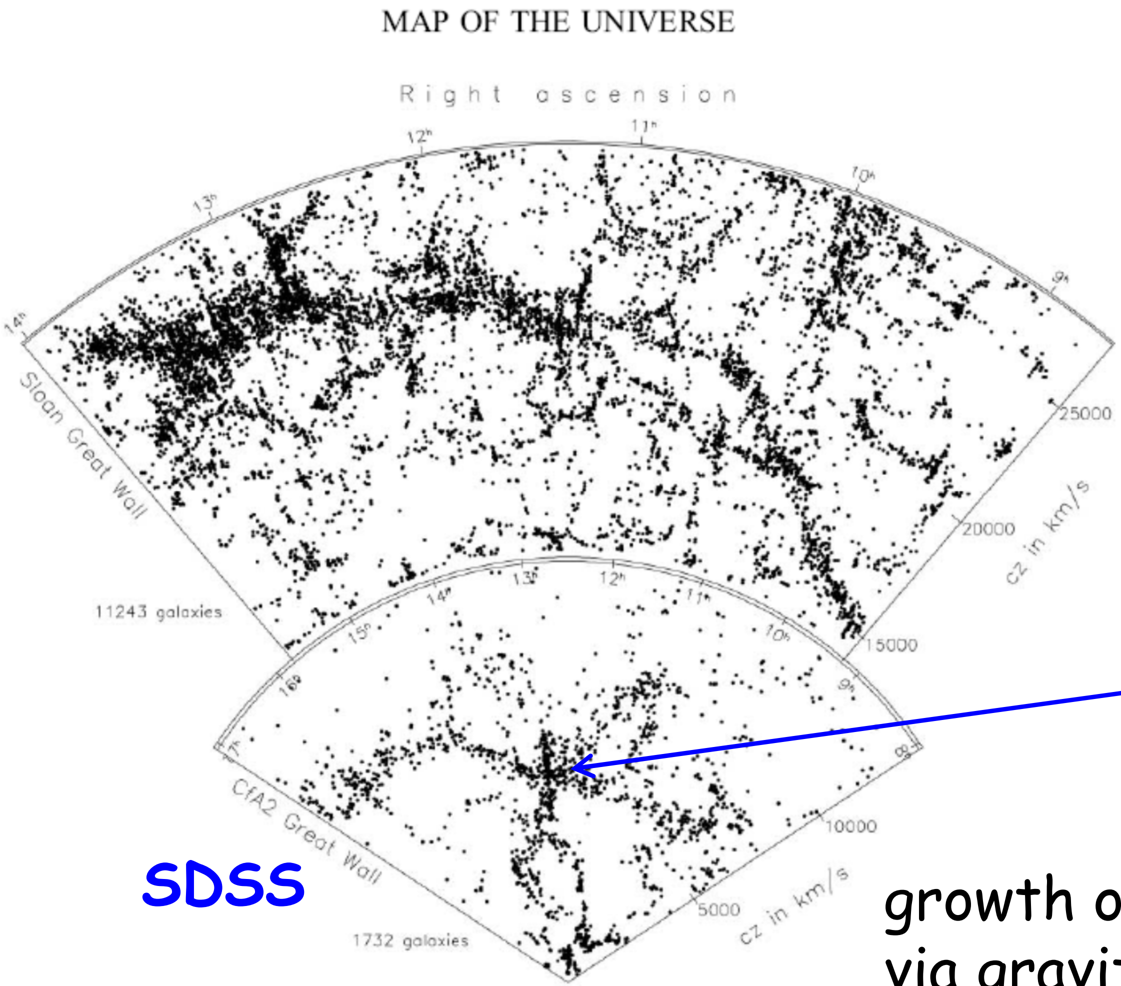
Perseus Cluster



X-ray from hot gas of T ~ 5 keV



radio due to non-thermal processes



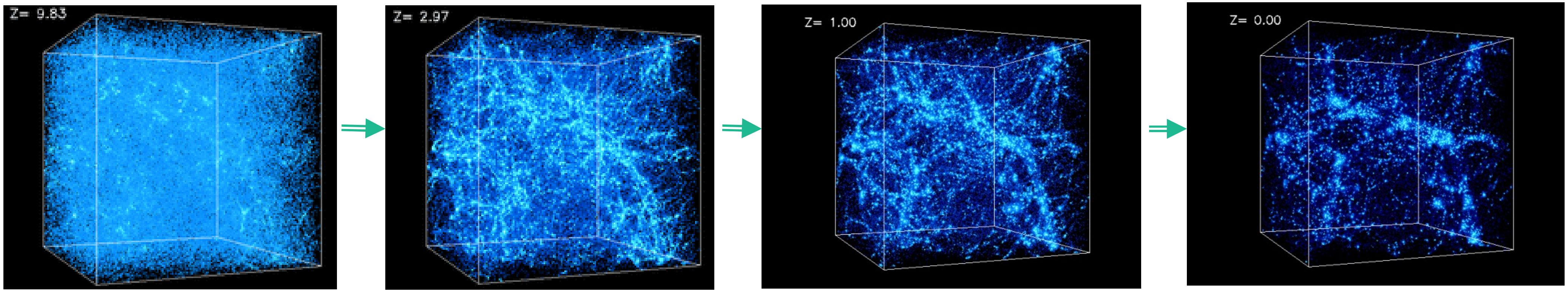
The large-scale structure of the universe seen in the galaxy distribution

"cosmic web of filaments"

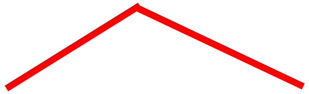
Coma cluster

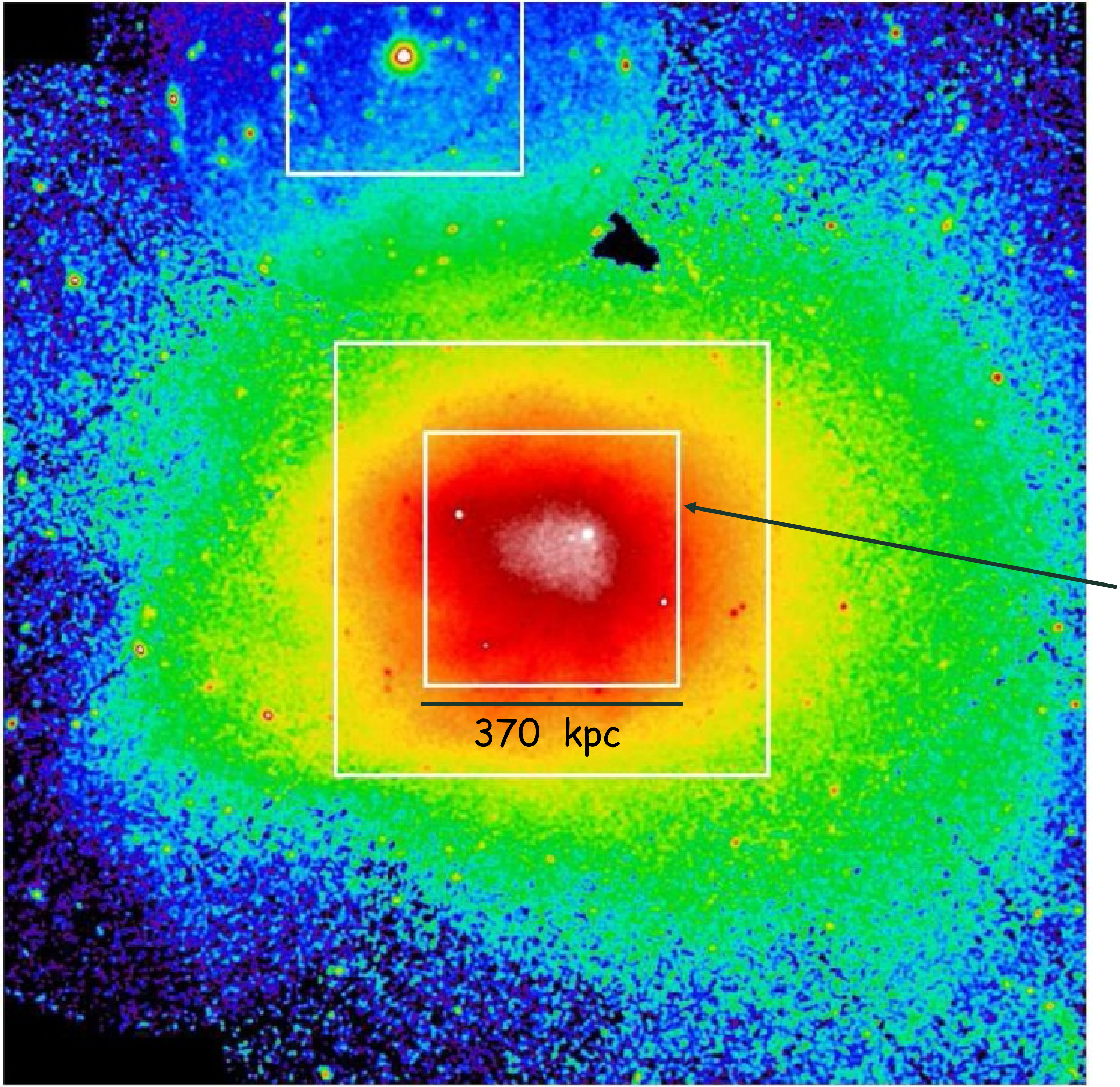
SDSS

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 Kolmogorov (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 …



XMM images of Coma

analyzed to get the power spectrum of gas density fluctuations

Churazov et al. (2011)

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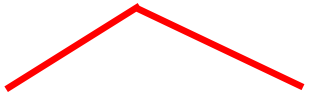
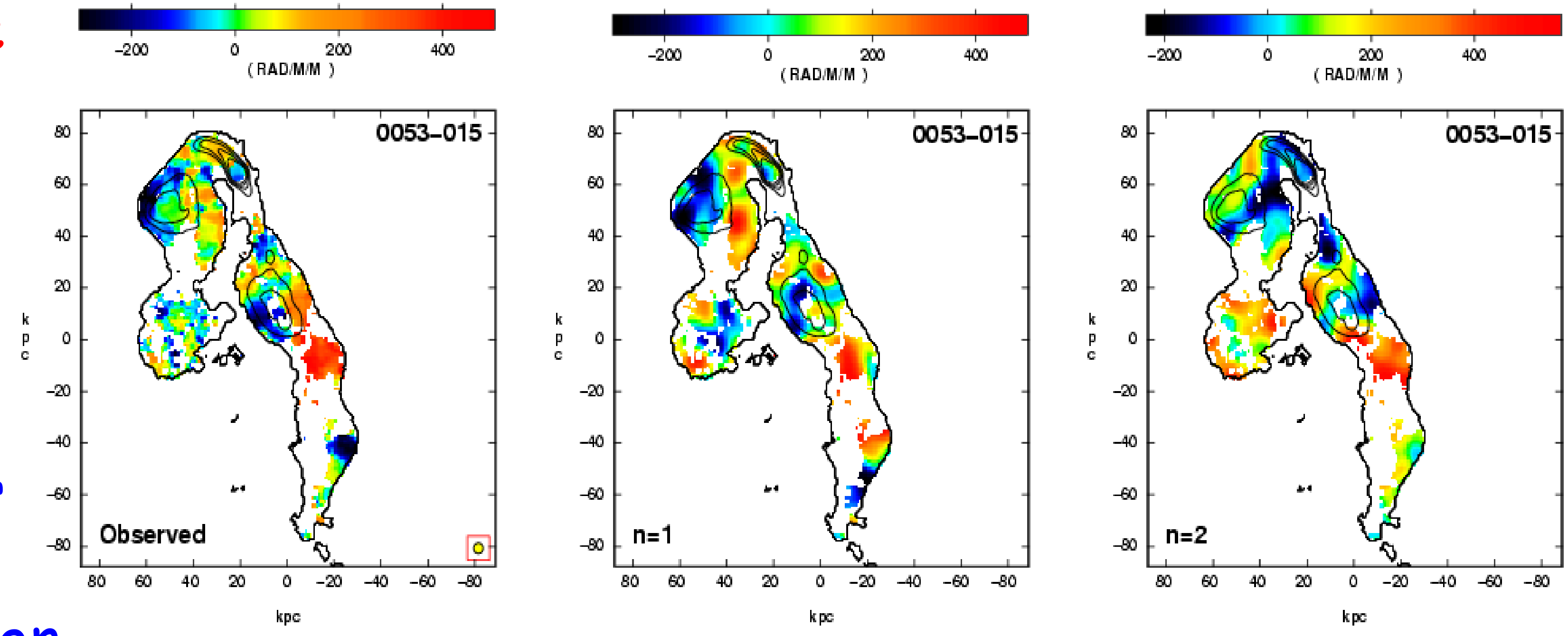
  $n \sim 0$ for B -> broken power-law? ( ?)

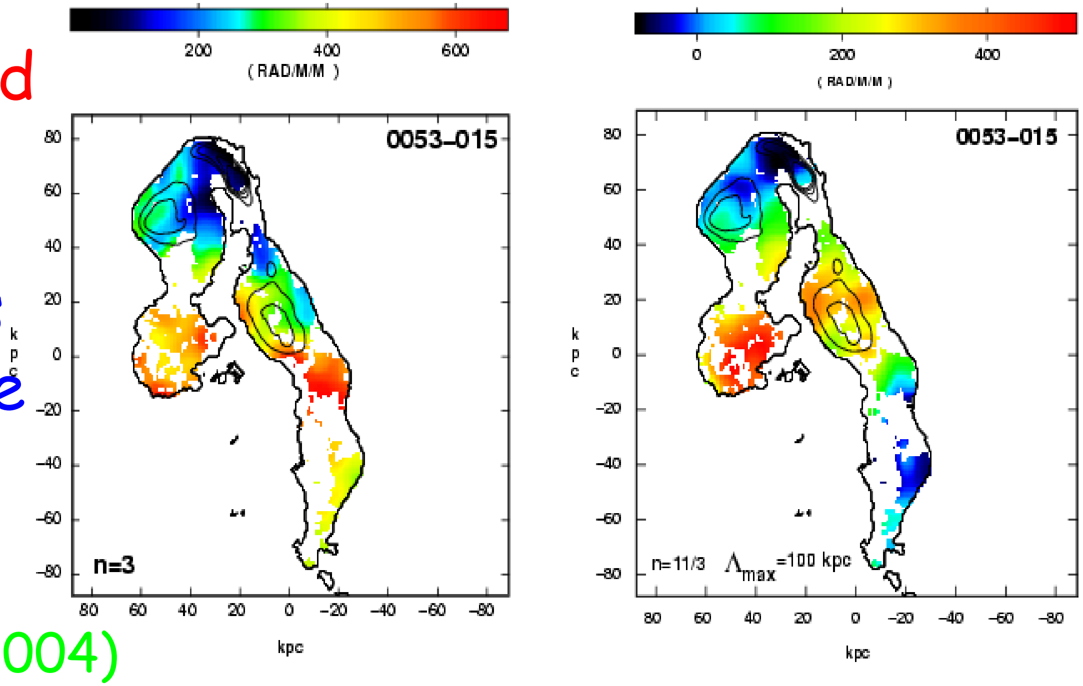
- and etc …

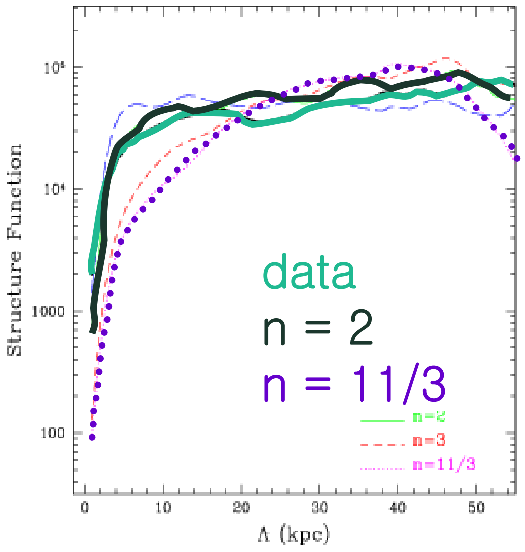
Turbulence in clusters: Faraday rotation

- used RM in Abell 119 for comparison with simulation

- n=2 is a good fit and Kolmogorov (n=11/3) does not reproduce the data







Murgia et al. (2004)

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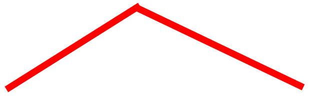
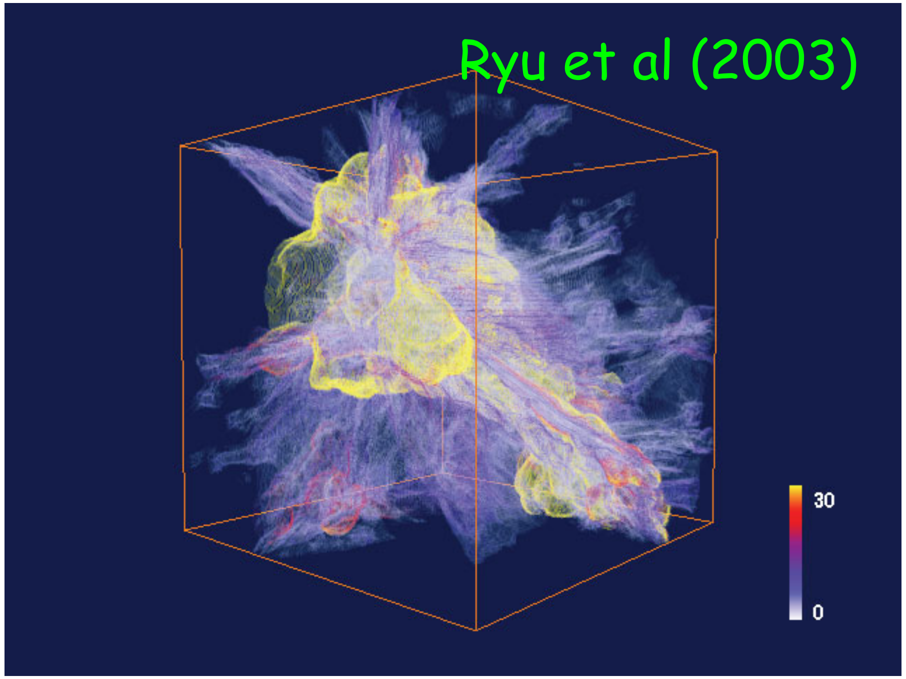
  $n \sim 0$ for B -> broken power-law? ( ?)
- and etc …

→ **turbulence is subsonic!**

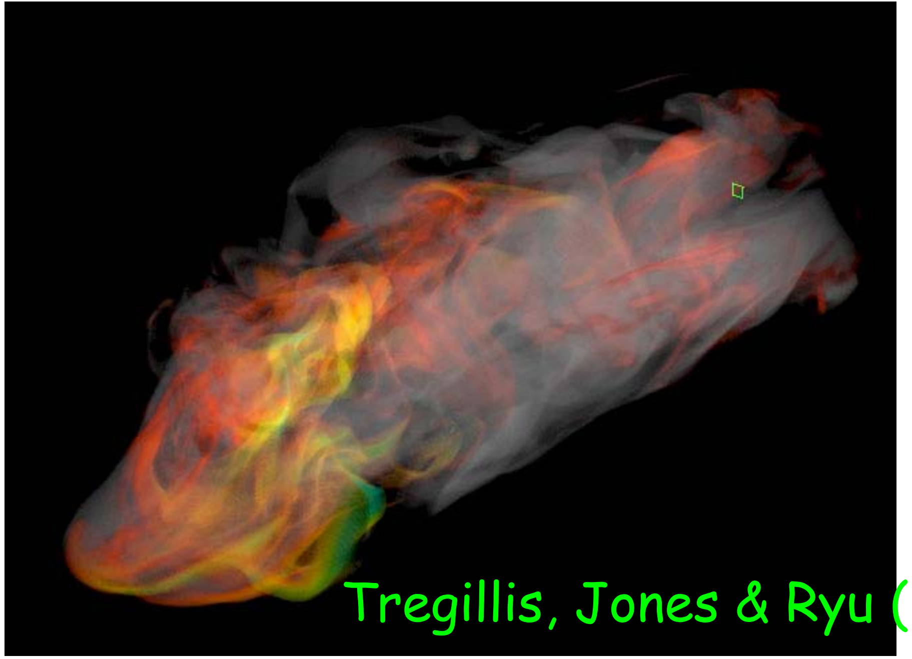
Drivers of turbulence in clusters

- **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 cosmological shocks

large-scale structure formation

gravitational collapse
& flow motions

cosmological shocks

shock dissipation

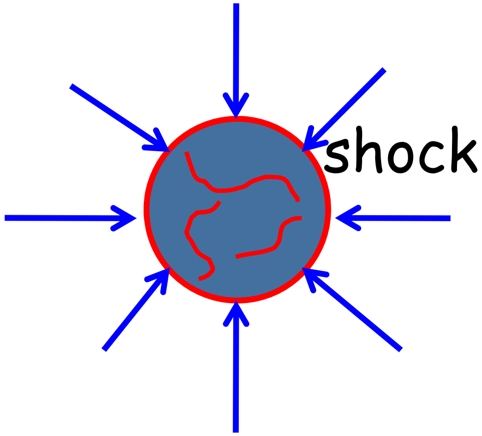
the main channel to flow the gravitational energy to the intergalactic medium

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

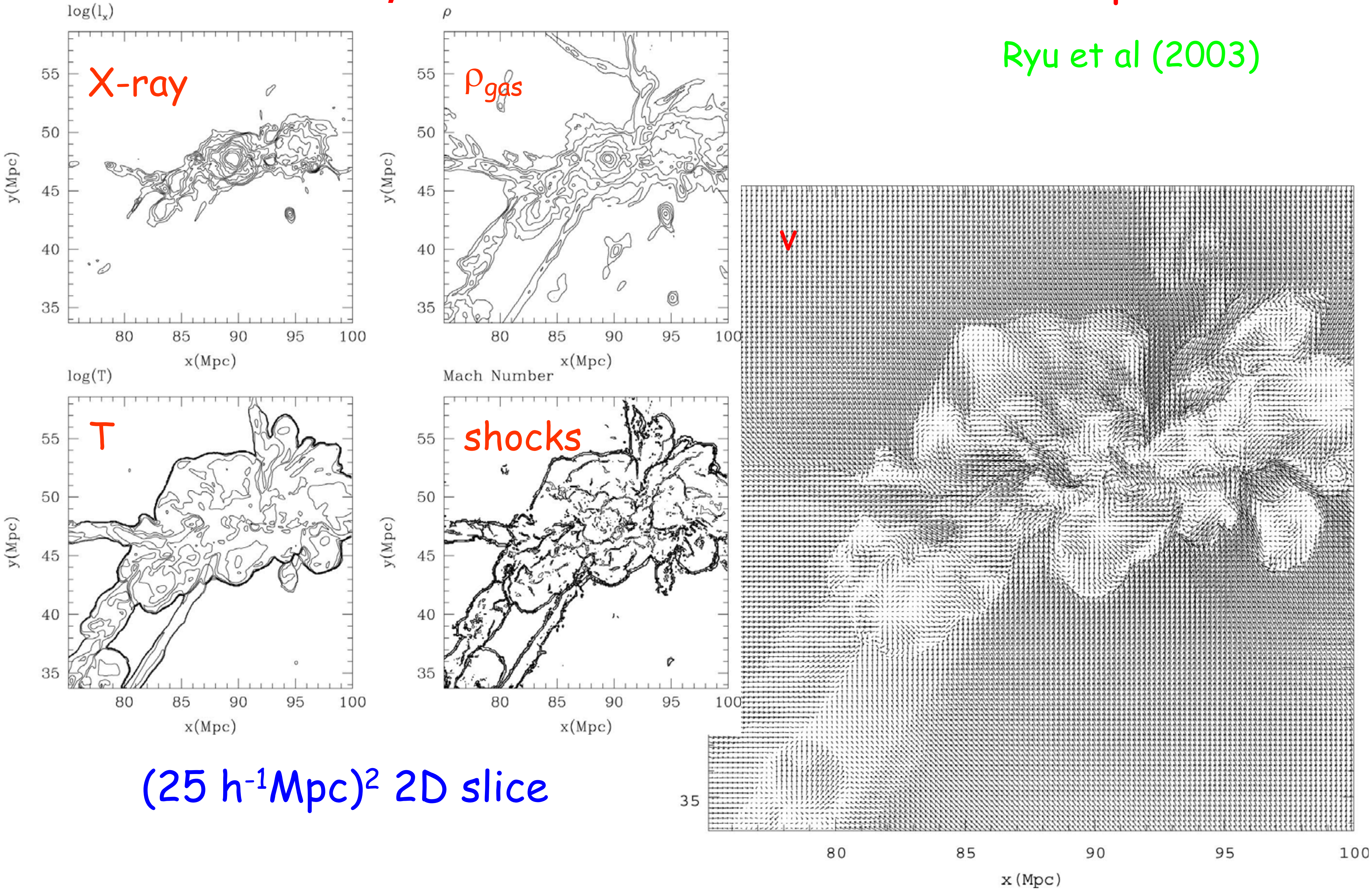
cascade into turbulence

turbulent amp. of mag. fields
turbulent acceleration of CRs



Velocity field and shocks in a cluster complex

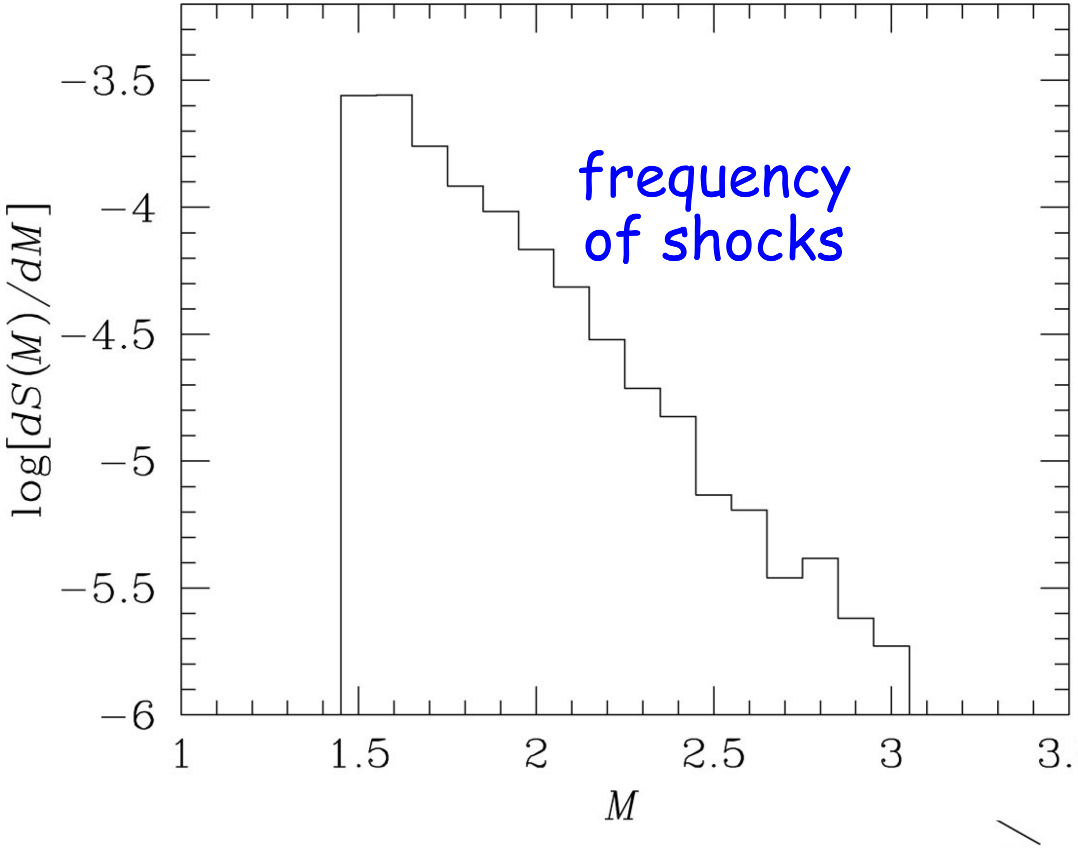
Ryu et al (2003)



(25 h^{-1}Mpc)^2 2D slice

Shocks statistics

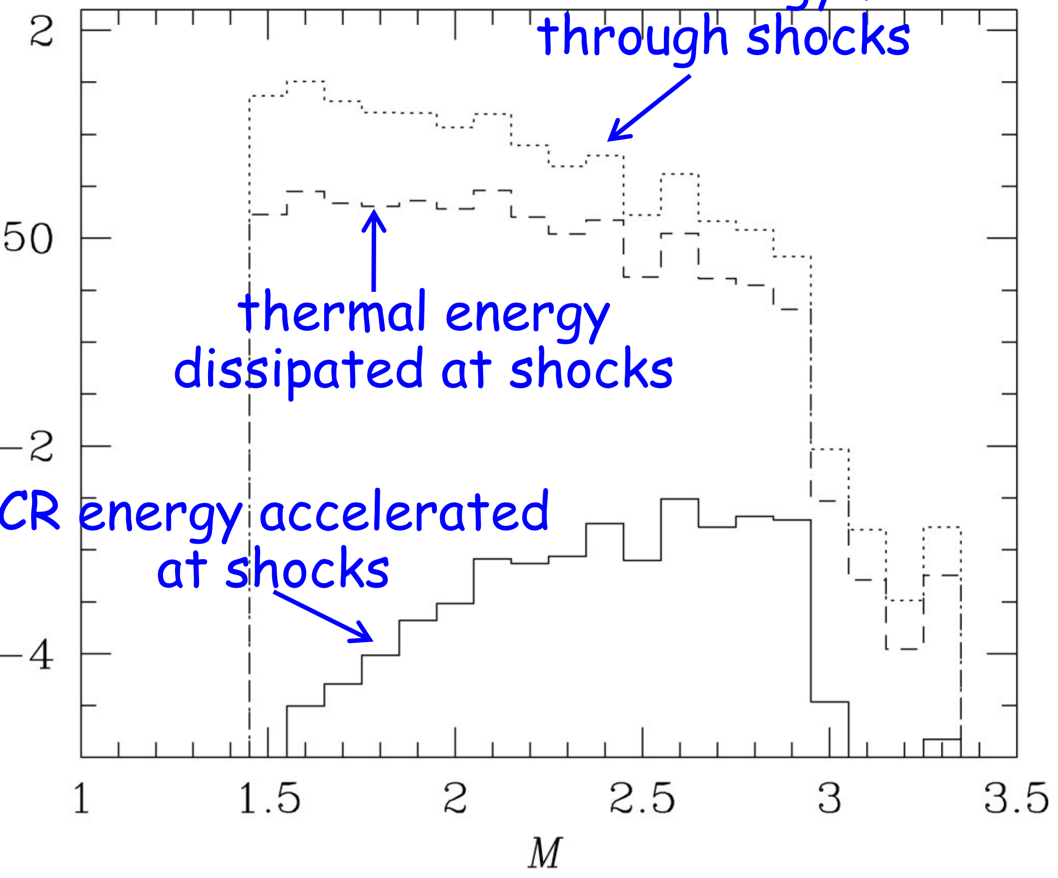
Kang & Ryu (2011)



frequency of shocks

in hot gas with T > 10^7

(inside and outside outskirts of clusters)



kinetic energy flux through shocks

thermal energy dissipated at shocks

CR energy accelerated at shocks

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

Radio relic in CIZA J2242.8+5301

shock Mach number

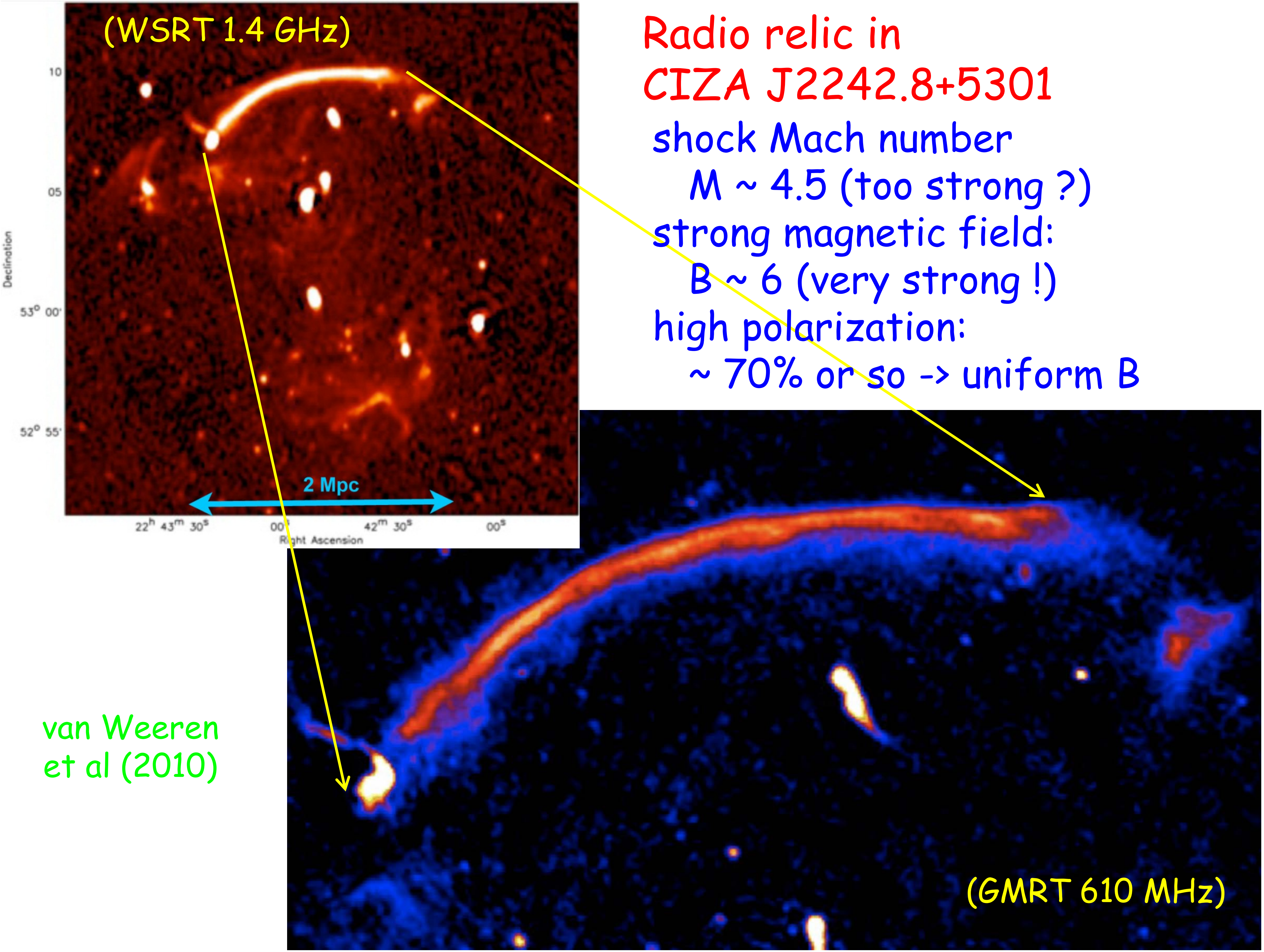
M ~ 4.5 (too strong ?)

strong magnetic field:

B ~ 6 (very strong !)

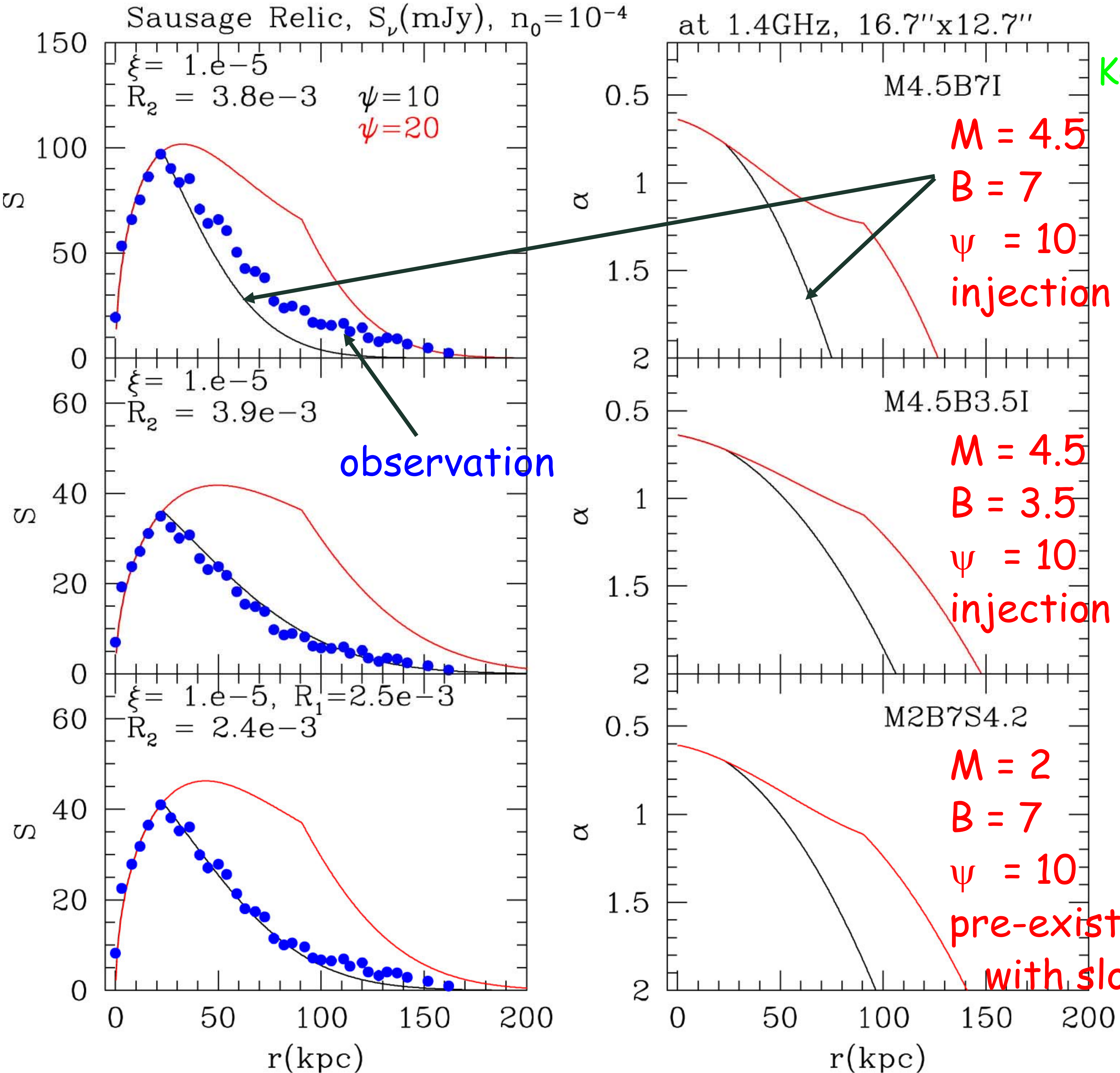
high polarization:

~ 70% or so -> uniform B



van Weeren et al (2010)

Kang, Ryu, & Jones (in preparation)

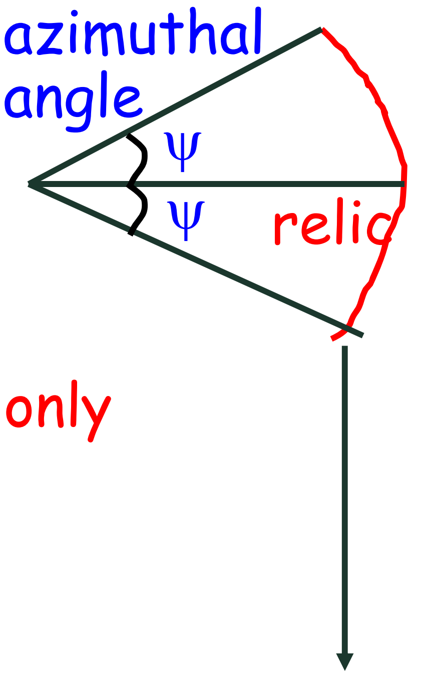


observation

M = 4.5
B = 7
ψ = 10
injection only

M = 4.5
B = 3.5
ψ = 10
injection only

M = 2
B = 7
ψ = 10
pre-existing CRs
with slope 4.2


azimuthal angle

ψ

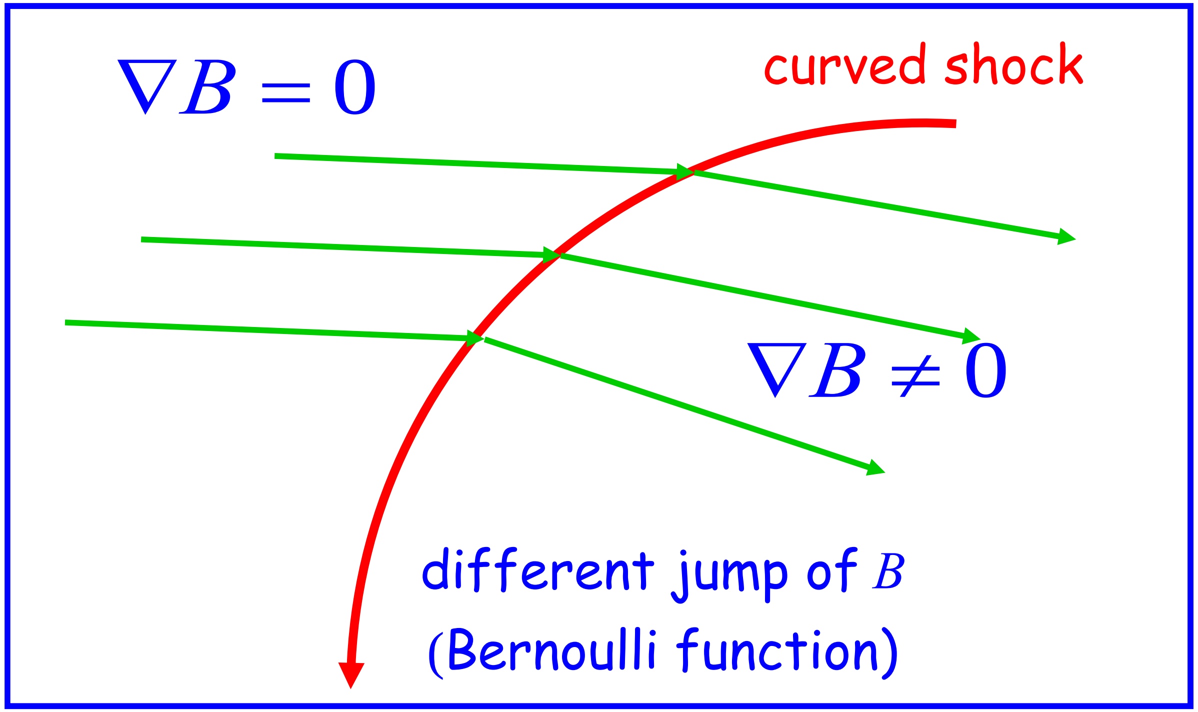
ψ

relic

observer

Vorticity generated at cosmological shocks

directly at curved shocks



⟹ at postshock

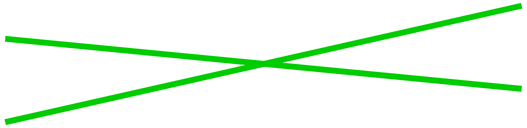
$$\varpi_{\mathrm{cs}} \sim \frac{(\rho_2-\rho_1)^2}{\rho_2\rho_1}\,\frac{\vec{U}\times\vec{n}}{R}$$

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

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

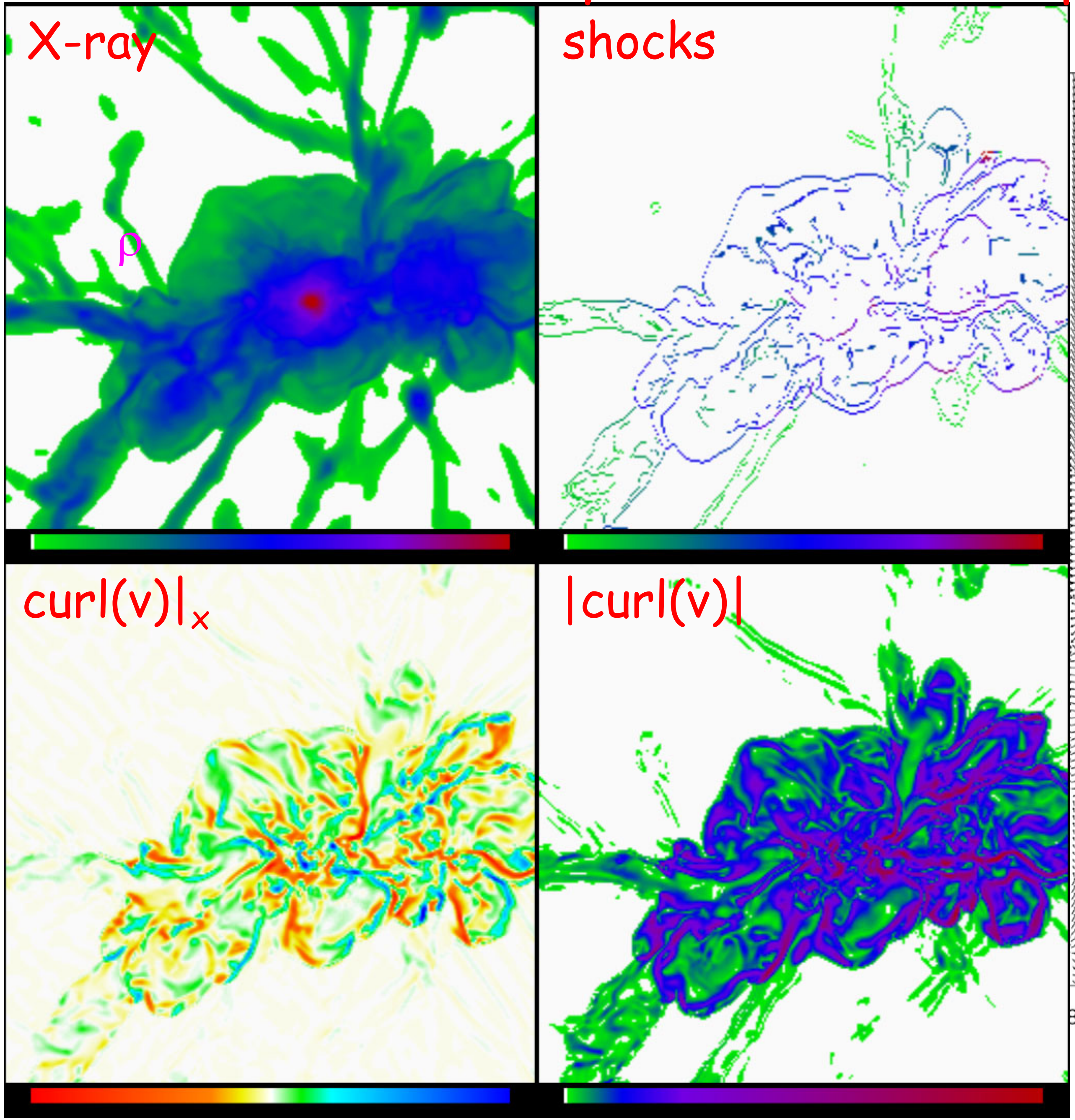
baroclinity



⟸ due to entropy variation induced at shocks

Vorticity in a cluster complex

Ryu et al (2008)



-1500 kms^{-1} / 300 kpc

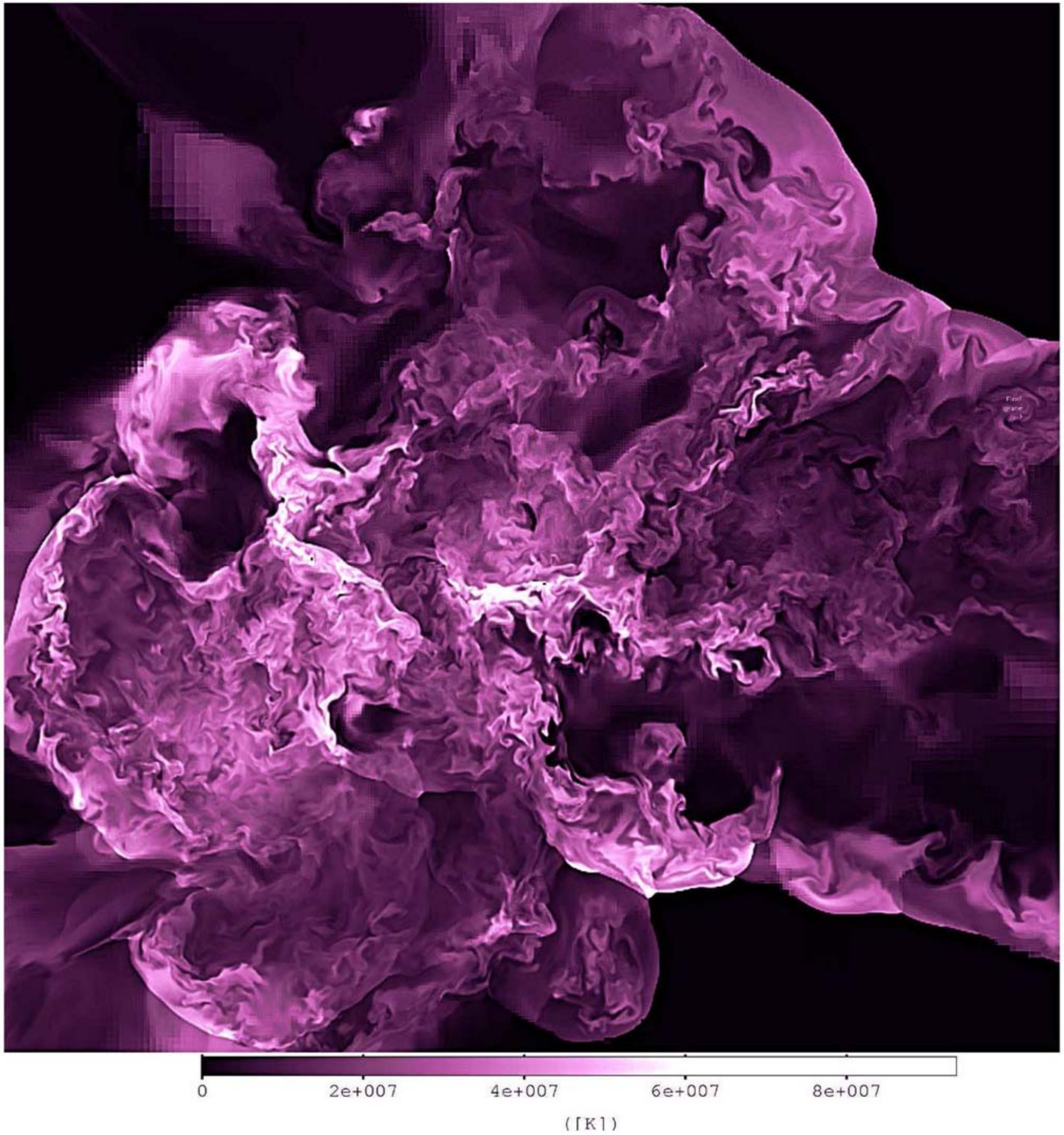
1500 kms^{-1} / 300 kpc

6 kms^{-1} / 300 kpc

2000 kms^{-1} / 300 kpc

(25 h^{-1}Mpc)^2 2D slice

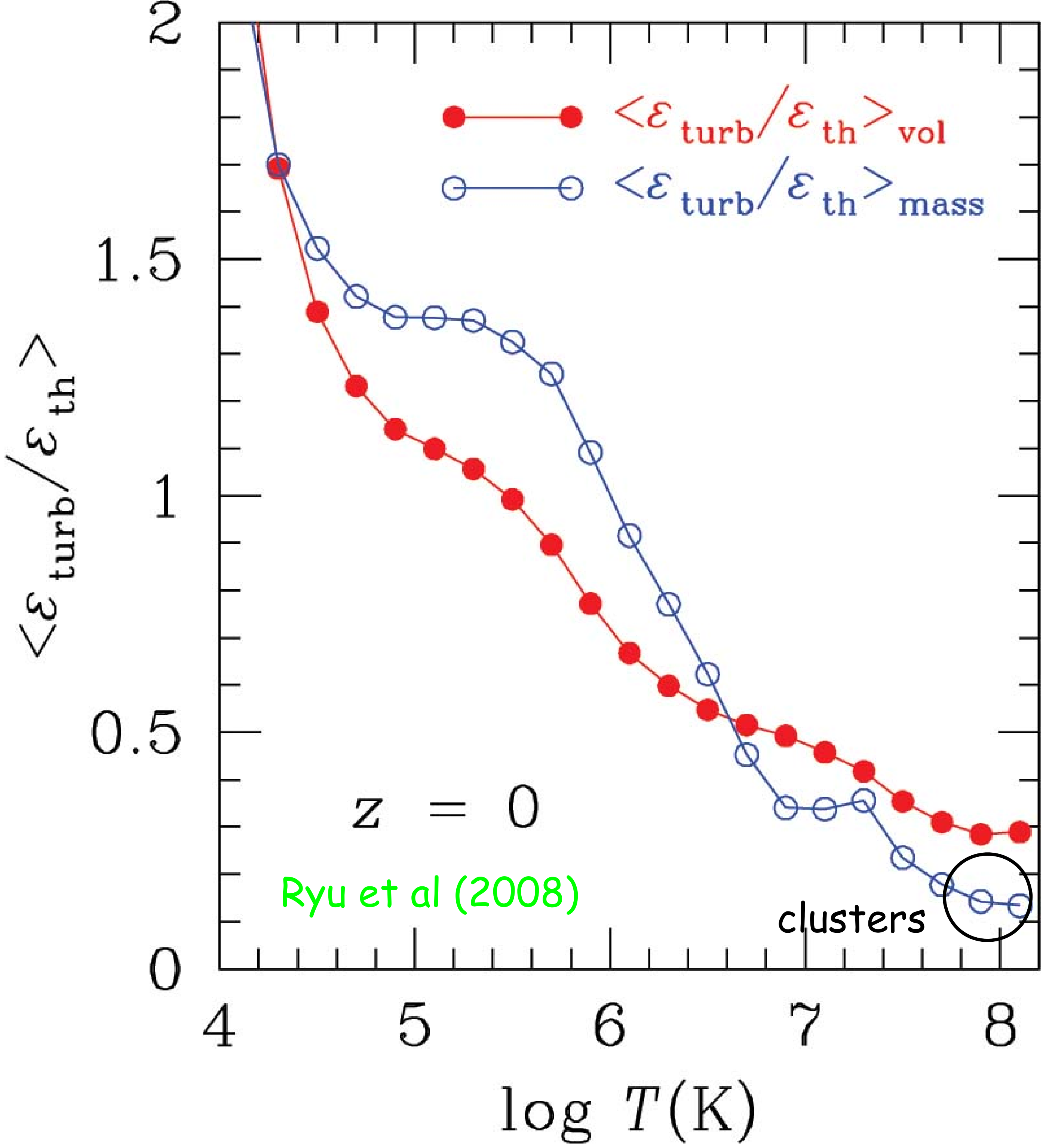
Turbulence in clusters: AMR simulations



temperature
distribution
in a merging
cluster

Vazza et al (2010)

Turbulence energy of in the ICM



Ryu et al (2008)

clusters

assuming that all the energy of vortical motions goes to turbulence

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

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

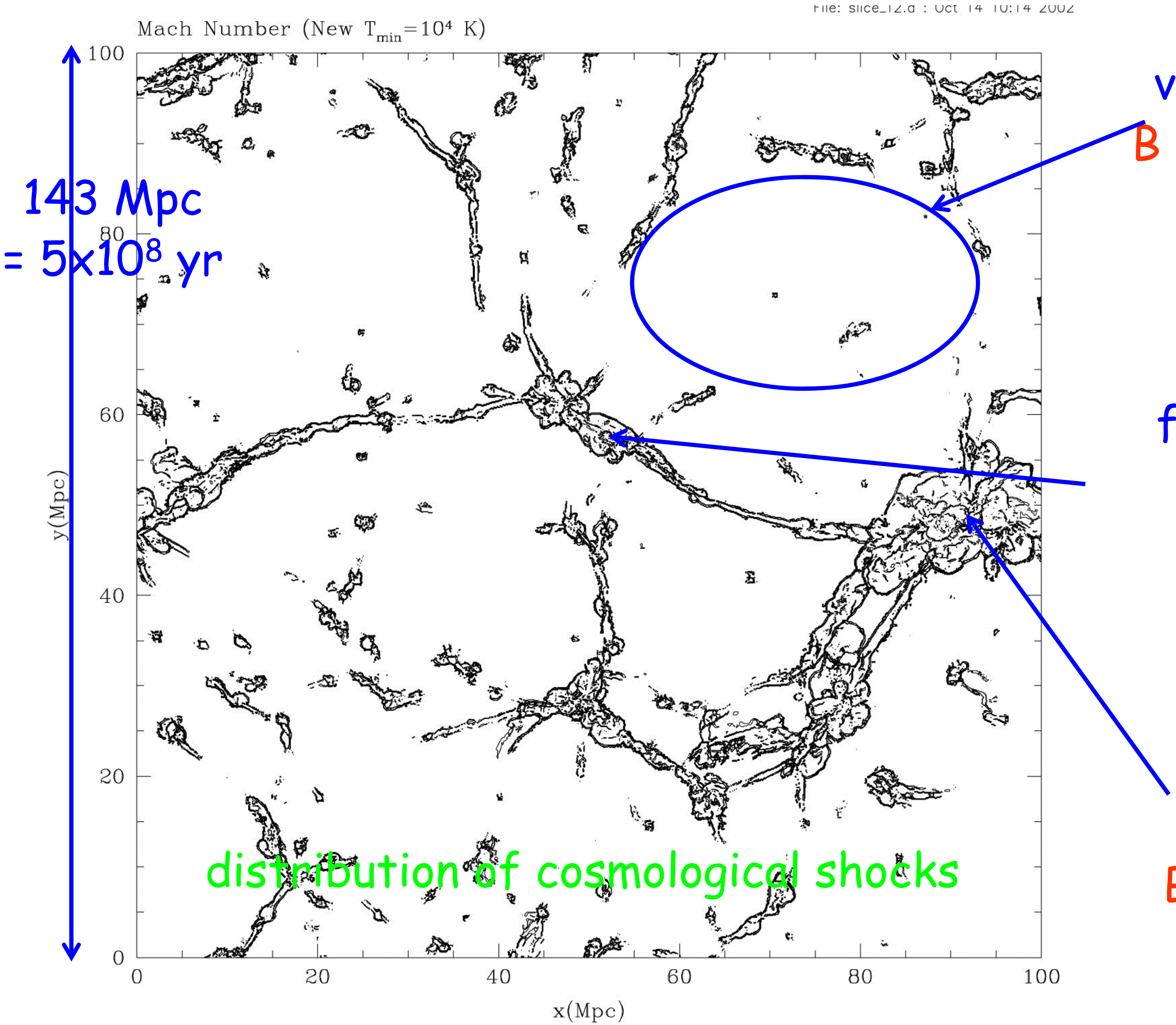
$M_{turb} \sim 1$
(transonic turbulence)
in filaments

Turbulence amplifies magnetic fields

-> **mangetohydrodynamic turbulence**

in astrophysical environments

Magnetic fields in the intergalactic space



143 Mpc
= 5×10^8 yr

distribution of cosmological shocks

void regions:
B >~ 10^{-16} G (?)

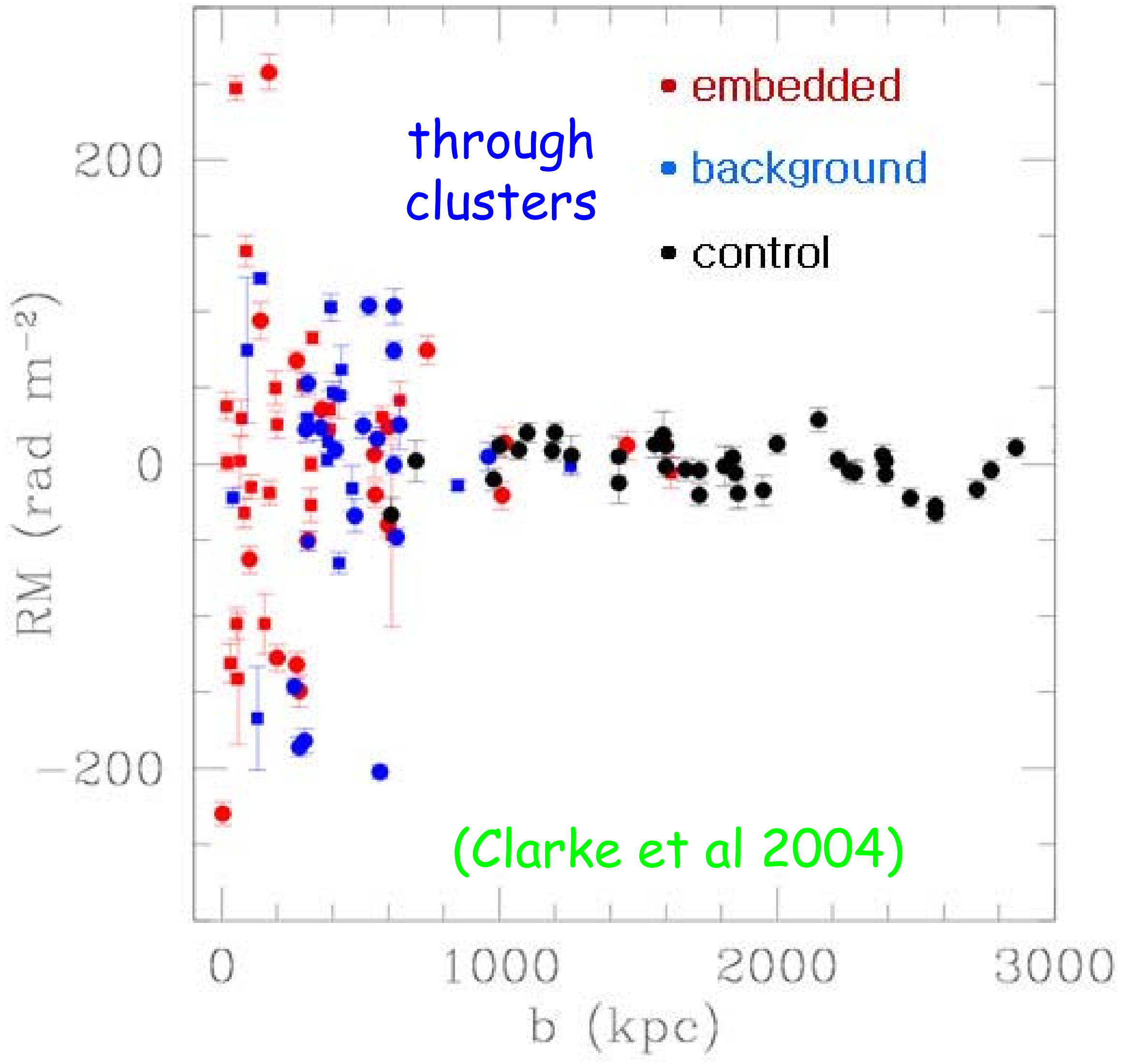
filaments of
galaxies:
B ~ 10 nG

clusters of
galaxies:
B ~ a few μG

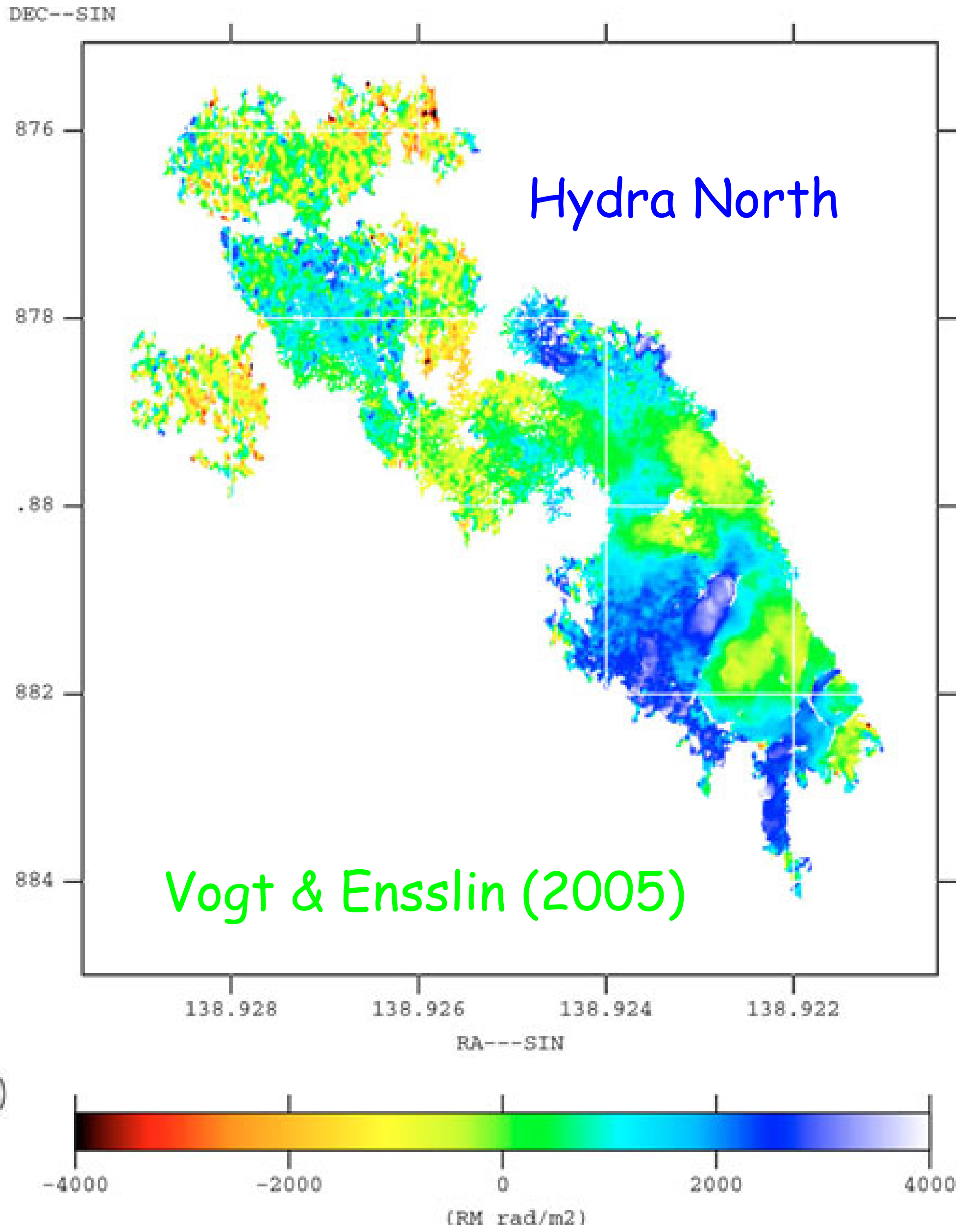
Clusters of galaxies - magnetic fields

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

-> B ~ a few μG (core region)



(Clarke et al 2004)



Vogt & Ensslin (2005)

Origin of magnetic fields in clusters

- **turbulence dynamo**

- AGN outflows, galactic winds, …

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

- and etc …

Seed magnetic fields in the LSS of the universe

Origin of seeds for comic magnetic fields is uncertain.
some suggestions:

1. generation in the early universe
   e.g.) during the electroweak phase transition ($t \sim 10^{-12}$sec)?
   during the quark-hadron transition ($t \sim 10^{-5}$sec)?
2. generation before cluster formation
   e.g.) plasma processes such as thermal fluctuations
   or at shocks
3. magnetic fields from the first stars and active galaxies

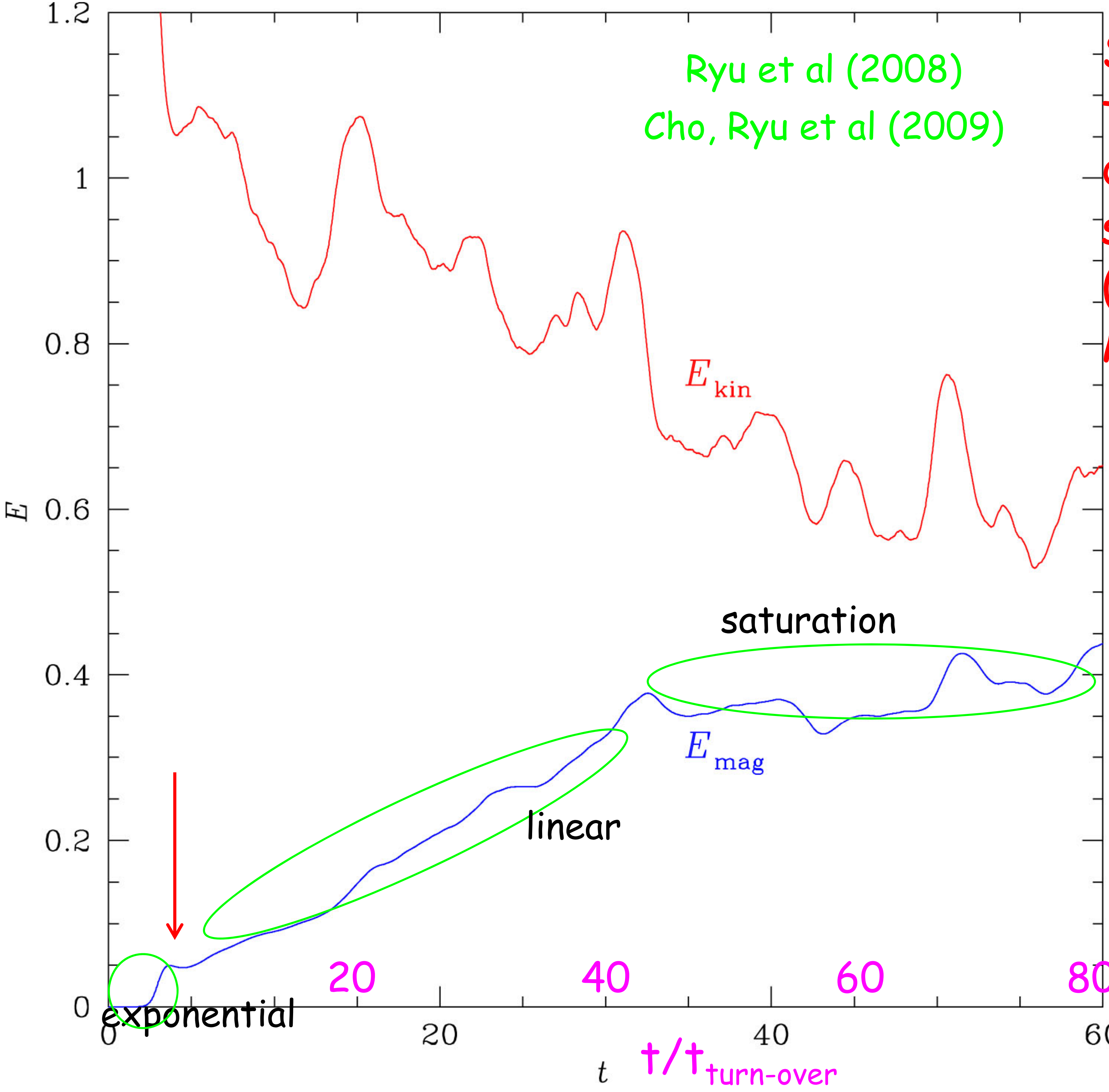
…

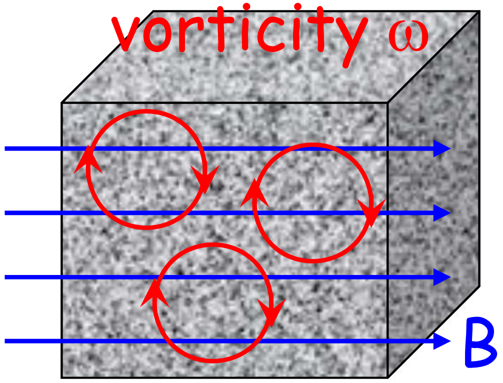
It is difficult to produce strong coherent magnetic fields in the IGM before the formation of the large-scale structure of the universe, but rather it would be reasonable to assume that week, random seed fields were created.

after turbulence amplifies magnetic fields

$B_0 << \delta B$ in the ICM (while $B_0 \sim \delta B$ in the ISM)

Simulation of turbulence dynamo or small scale dynamo (incompressible MHD)

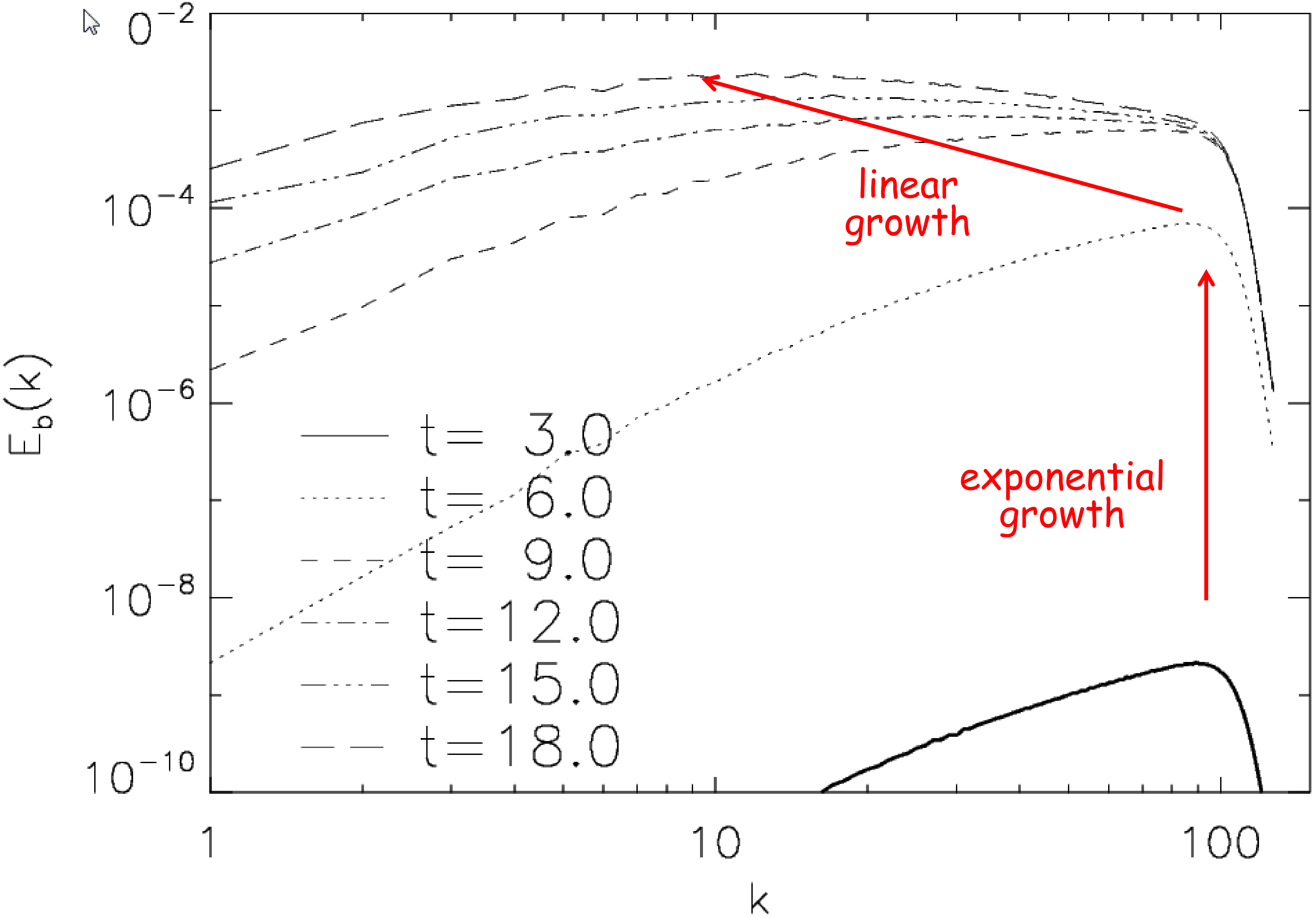




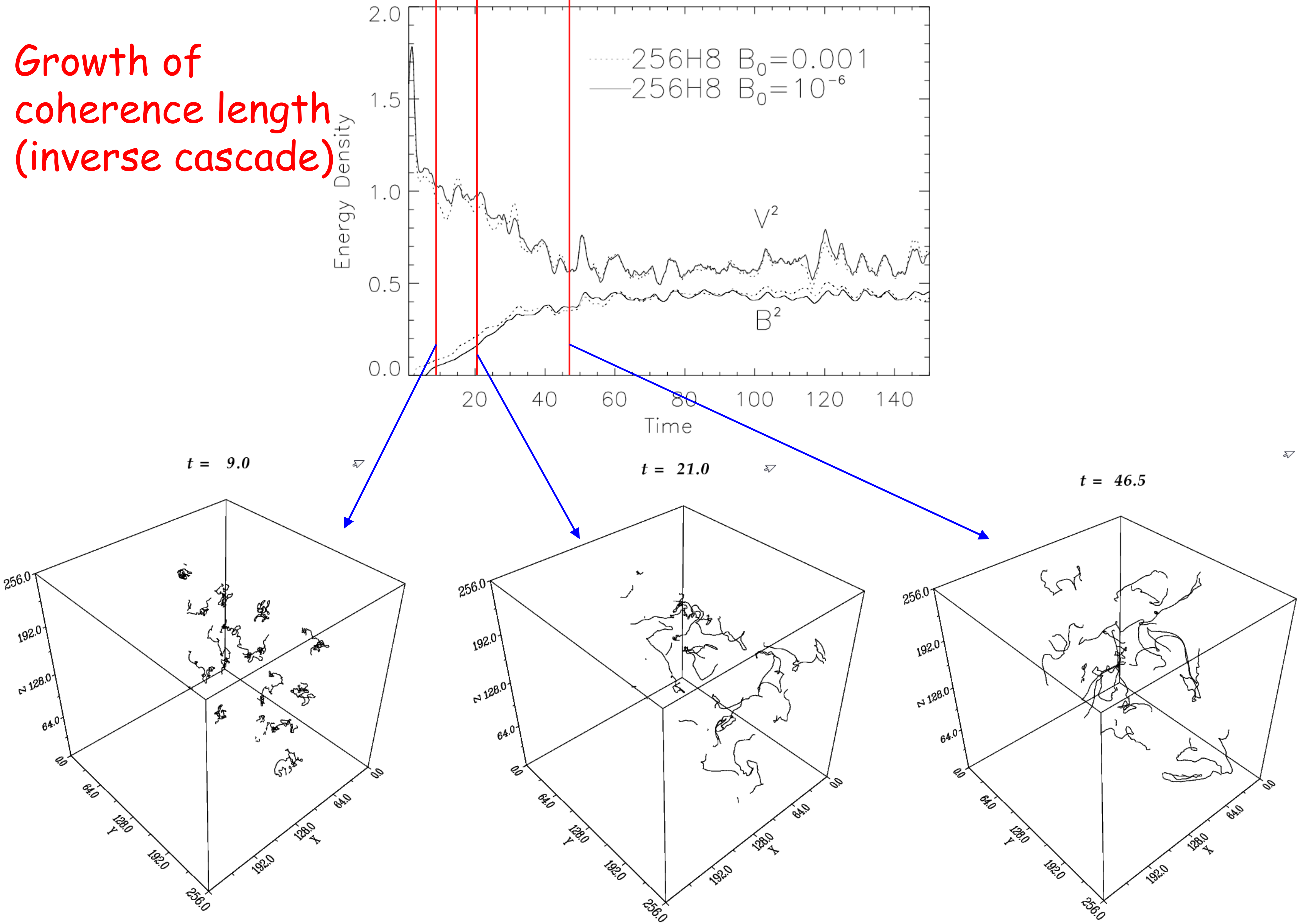
$E_{mag} \sim 2/3\ E_{kin}$

at saturation

$t_{\text{turn-over}} \sim 1/\omega$

$E_b(k)$
k
0^-2
10^-4
10^-6
10^-8
10^-10
1
10
100
t= 3.0
t= 6.0
t= 9.0
t=12.0
t=15.0
t=18.0
linear growth
exponential growth

Growth of coherence length (inverse cascade)



Resulting magnetic fields and numbers in clusters of galaxies

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

Why care about turbulence in clusters?

- turbulence transports heat and momentum
    - -> controls **heat conduction** and **viscosity**

- turbulence accelerates particles
    - -> turbulent acceleration of cosmic rays

← see talks on tomorrow!

- turbulence transports entropy, metals, etc

- turbulent pressure contributes to the support of the ICM
    - -> its presence influences HSE mass estimates

- and etc…

Diffusions in the ICM

heat conductivity $$\chi \sim \upsilon_e^{\text{therm}} l_{e-e} \sim \frac{l_{e-e}^2}{t_{e-e}}$$ (?)

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

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

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

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

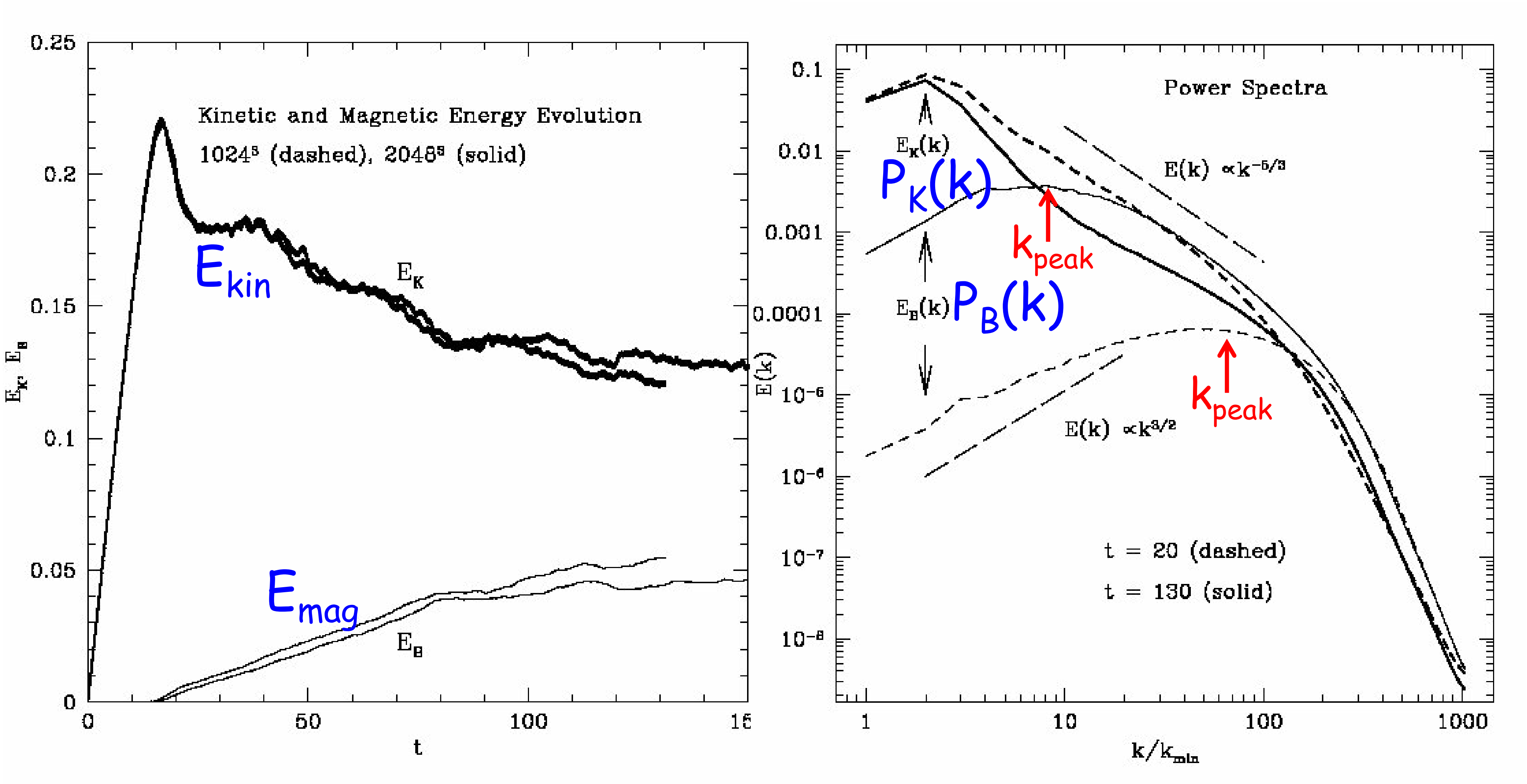
gyro-radius of elections

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

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

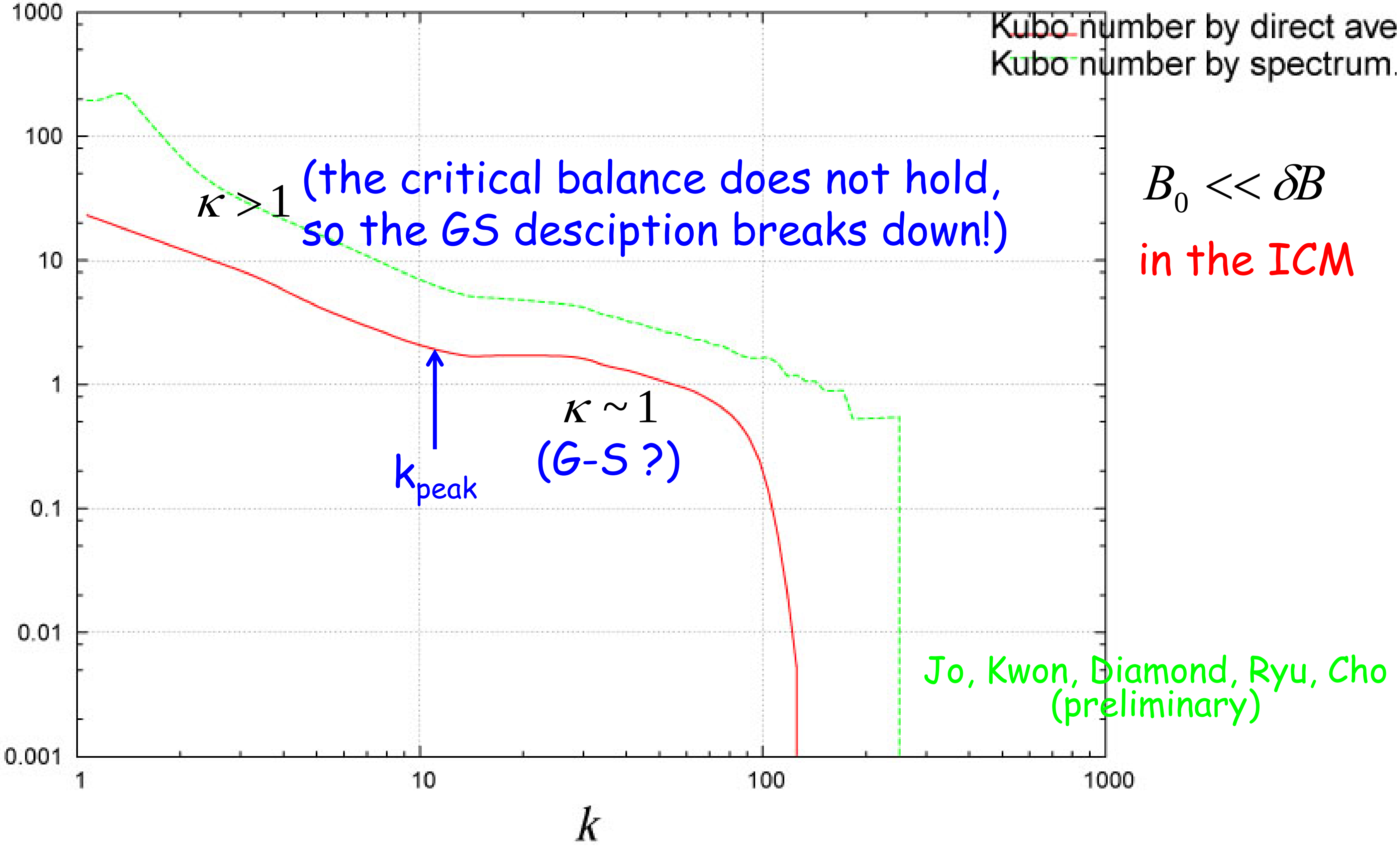
Simulations of MHD turbulence in clusters

Porter, Jones, Ryu, Cho (in preparation)



- the peak scale of magnetic fields, k_{peak}, grows as turbulence develop
- it occurs at L_{peak} ~1/2 L_{inj} at saturation

Kubo number $\kappa = \frac{\delta B}{B_0} \frac{l_\parallel}{l_\perp}$



$\kappa > 1$ (the critical balance does not hold, so the GS desciption breaks down!)

$\kappa \sim 1$ (G-S ?)

k_{peak}

$B_0 << \delta B$

in the ICM

Jo, Kwon, Diamond, Ryu, Cho
(preliminary)

Various length scales in the intracluster medium

peak scale of magnetic field power spectrum

$$L_{peak} \sim \text{a few - 100 kpc}$$

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

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

gyro-radius of protons

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

gyro-radius of elections

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

We need to consider diffusion in different regimes:

$\kappa > 1$ & collisional for $L >\sim 100 \text{ kpc}$

$\kappa \sim 1$ & collisionless for $L >\sim \text{a few kpc}$

and also

$\kappa > 1$ & collisionless

$\kappa \sim 1$ & collisional

Guo, Diamond, Ryu (preliminary)

Conclusions

- Turbulence in clusters is important and yet to be understood.

- Simulating turbulence in clusters is rather tricky business, both because the physics is not well understood and because the computational requirements are very demanding.

- Good progress has been made, however, in attacking this and improving our understanding of the properties and roles of turbulence in this environment.

- Most importantly, there are a wealth of physics issues, waiting for us to solve them!

Thank you !

Simulations of isothermal compressible MHDs to study turbulence in clusters

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

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

Porter, Jones, Ryu, Cho
(in preparation)

- purely solenoidal forcing
  (and **purely compressive forcing**)

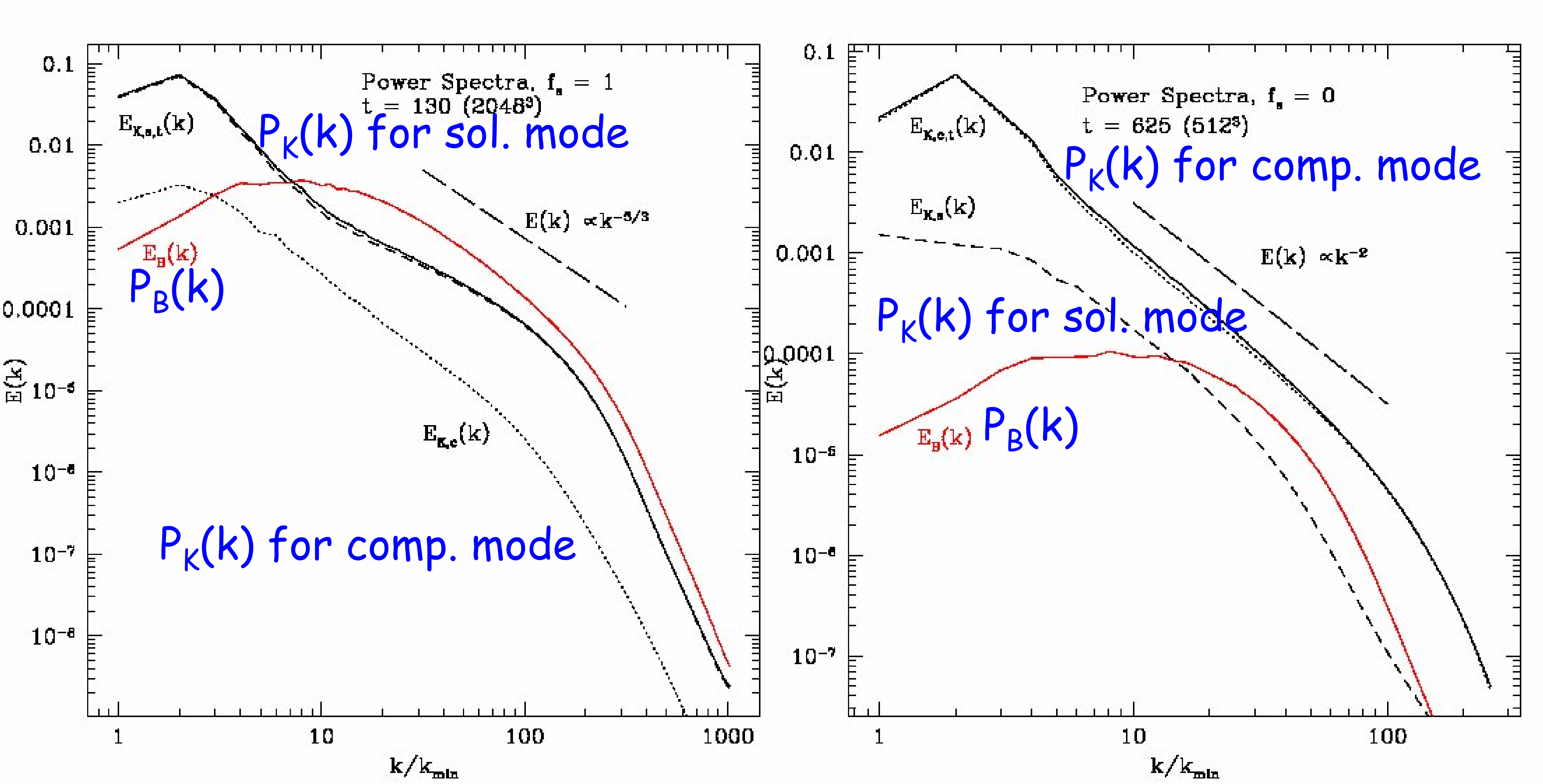
- ideal MHD, so Pr ~ 1
  (and Pr >> 1)

- injection at L_{inj} ~ 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

Power spectrum



purely solenoidal forcing

purely compressible forcing

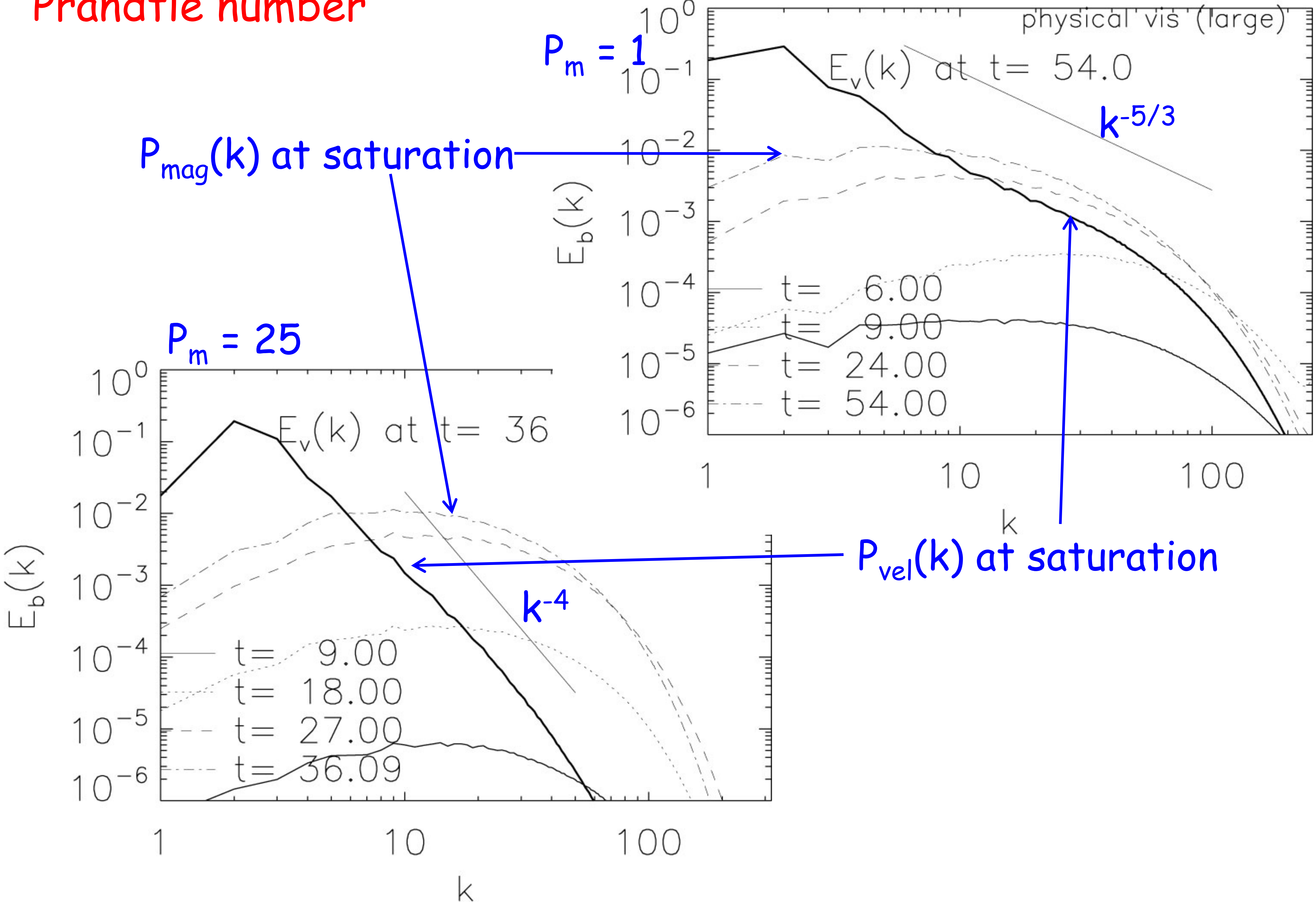
for subsonic (M_s ~ 0.45) and high beta ($\beta = 10^6$) turbulence

Simulations of isothermal compressible MHDs to study turbulence in clusters

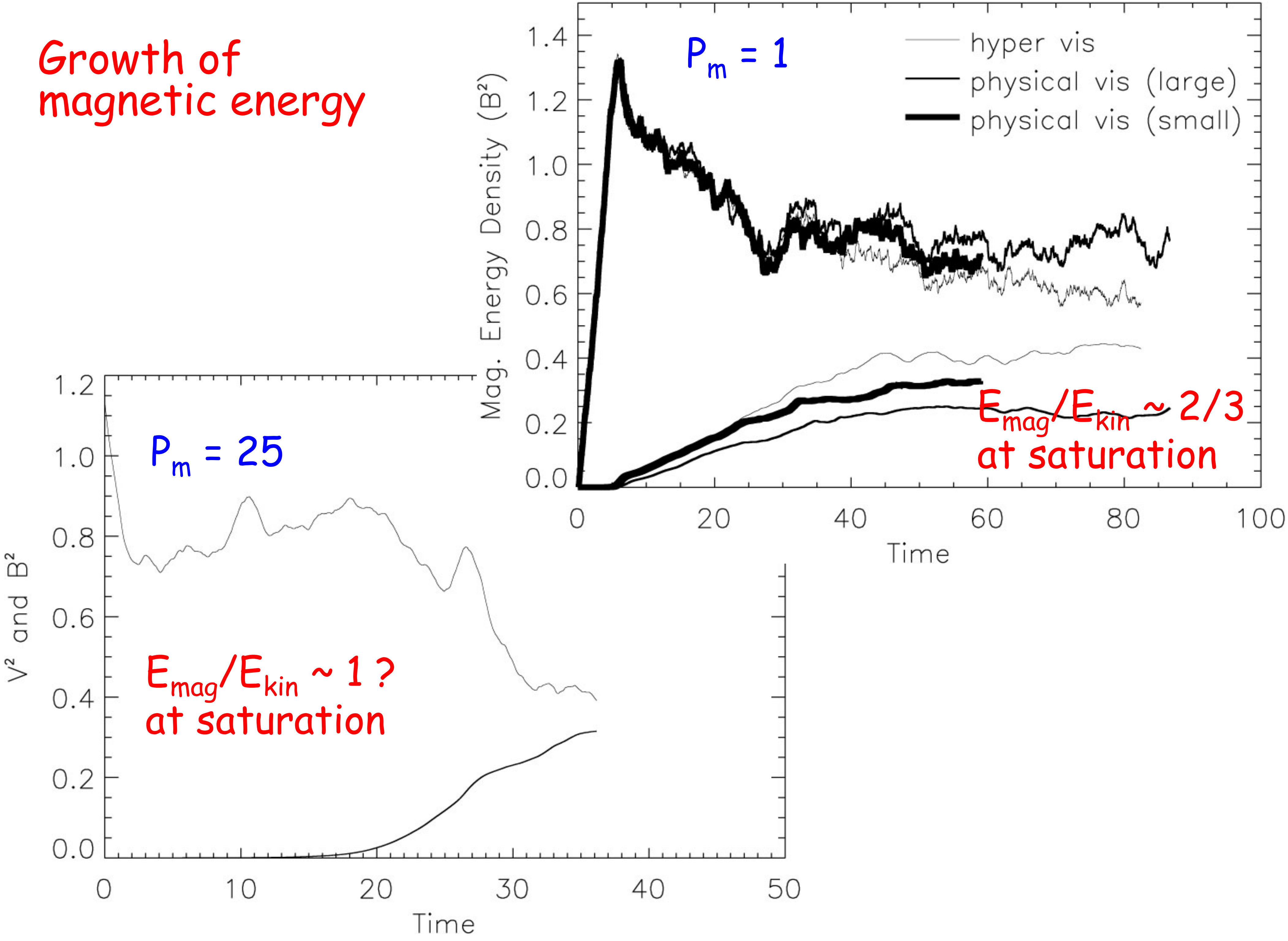
Porter, Jones, Ryu, Cho
(in preparation)

- $c_s = 1$, $V_{rms} \sim 0.45$ (so $M_s \sim 0.45$) at saturation
  subsonic turbulence ($E_{kin}/E_{therm} \sim 0.1$)
- initially very weak field with $\beta = 10^6$
- purely solenoidal forcing
  (and purely compressive forcing)
- ideal MHD, so Pr ~ 1
  (and <u>**Pr >> 1**</u>)
- 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

Incompressible MHD turbulence with different magnetic Prandtle number



Growth of magnetic energy



$P_m = 1$

$E_{mag}/E_{kin} \sim 2/3$
at saturation

$P_m = 25$

$E_{mag}/E_{kin} \sim 1$?
at saturation