The Role of Turbulence in Galaxy Clusters

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1. How and where is turbulence produced?

merger shocks, motions of galaxies, AGN

2. What does turbulence do for clusters?

i) Provide pressure?	**Yes, in outskirts.**
ii) Mess with instabilities?	**Yes.**
iii) Heat cluster?	**Yes,** but does not solve cooling flows.
iv) Accelerate particles?	**Probably.**
v) Generate B fields?	**Maybe.**
vi) Mix metals and entropy?	**Yes.**

Evidence for turbulence in clusters

• metal profiles in clusters (e.g. *Simionescu et al. 2008, Rebusco et al. 2006*)

• lack of resonant scattering in 6.7 keV Fe line in Perseus (*Churazov et al. 2004, Werner et al. 2010*)

• thermal pressure studies (*Churazov et al. 2010)*

• turbulent broadening of emission lines (*Sanders et al. 2009)*

Churazov et al. (2010)

Werner et al. (2010)

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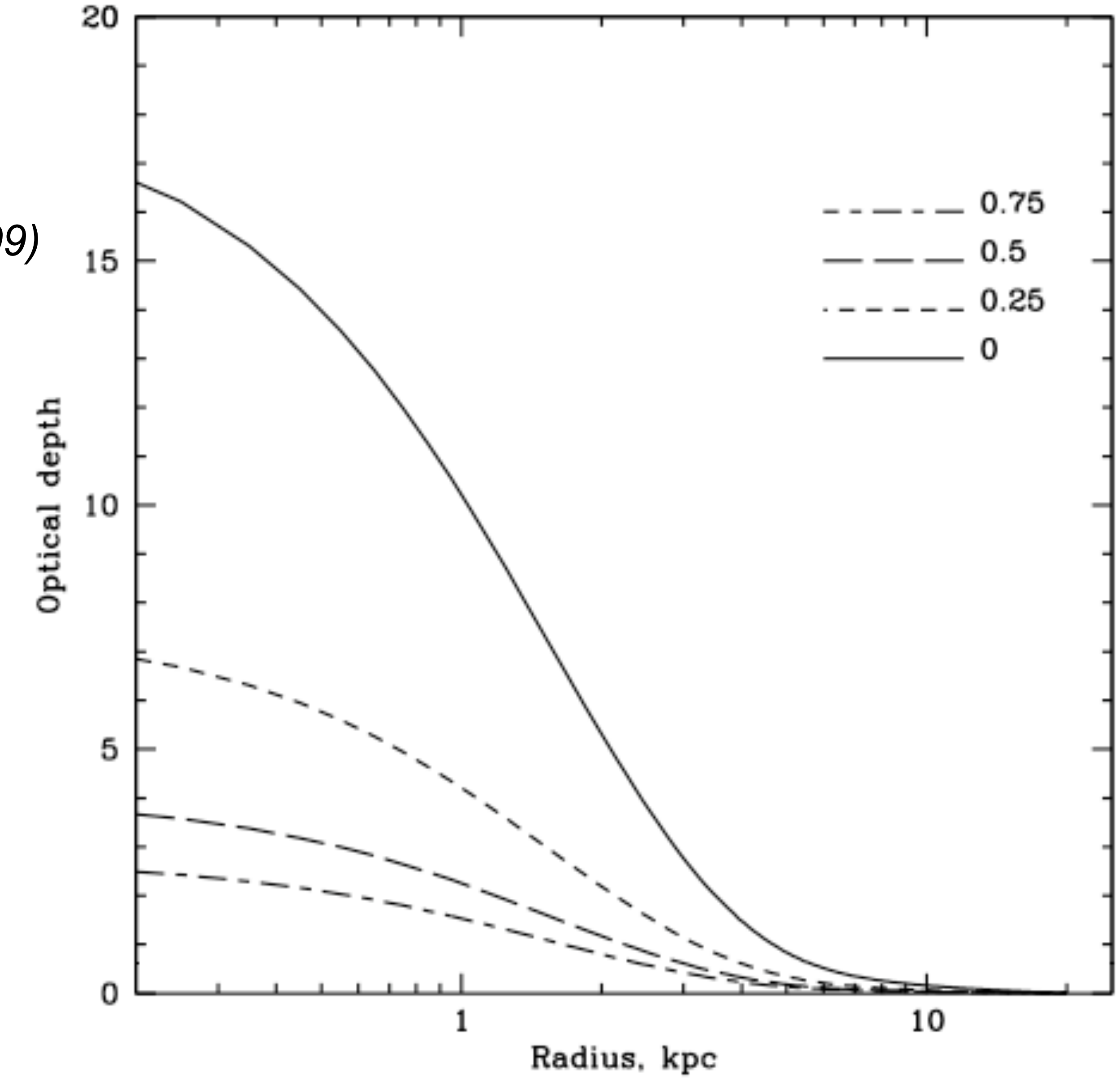

Figure 7. Optical depth of the 15.01 Å line calculated from the given radius to infinity, for isotropic turbulent velocities corresponding to Mach numbers 0.0, 0.25, 0.5, and 0.75. A centrally peaked Fe abundance distribution is assumed.

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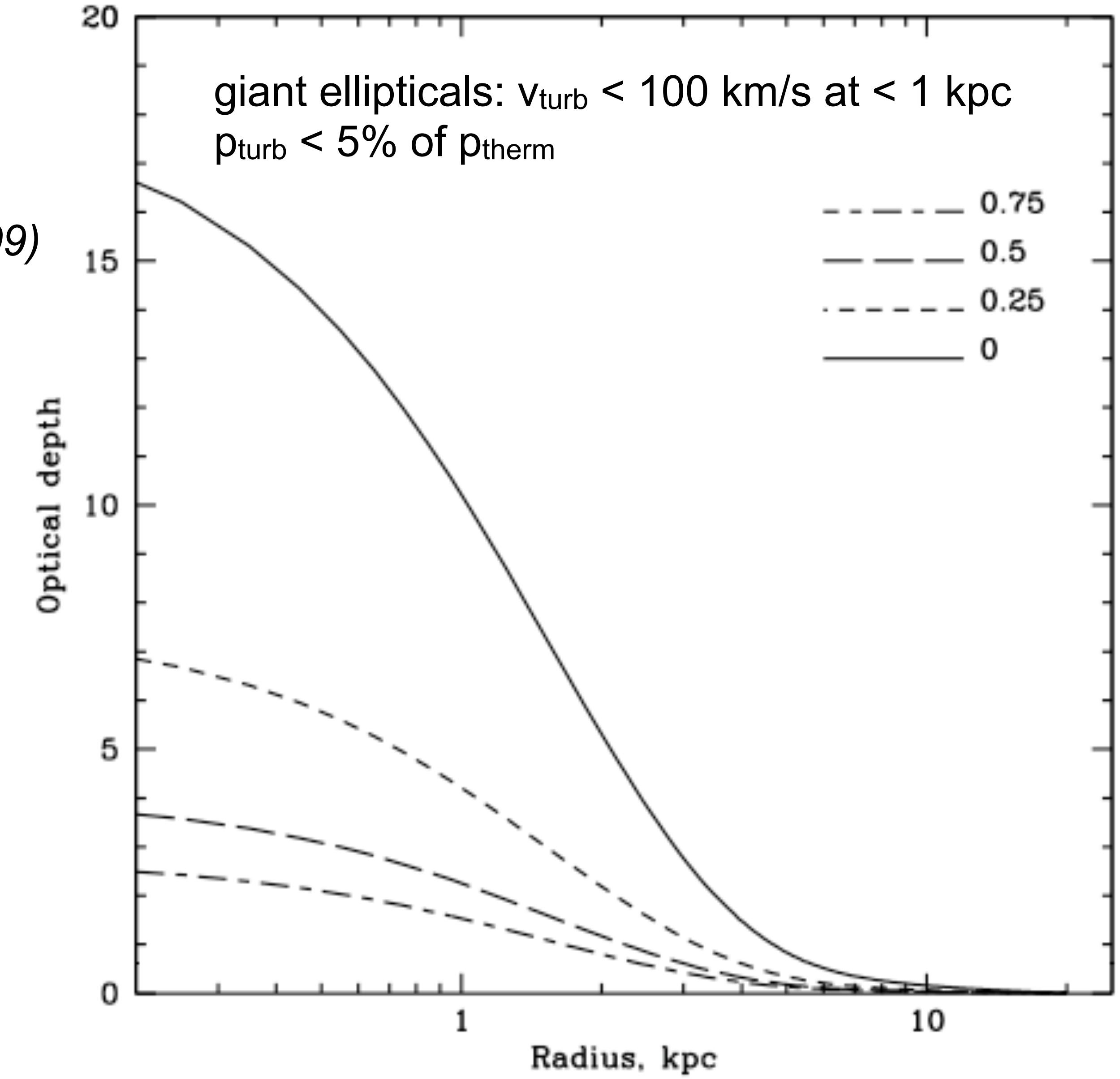

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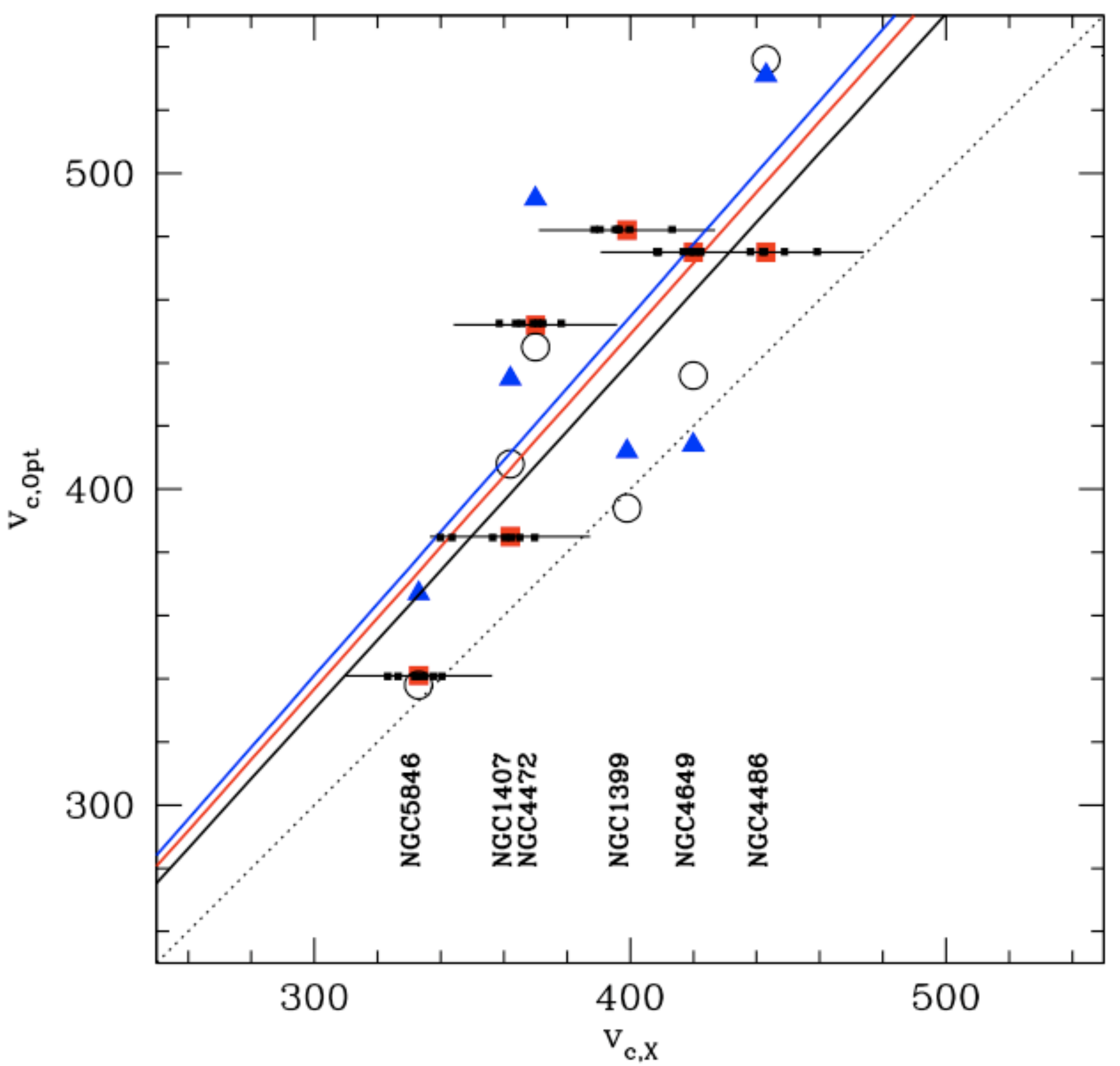

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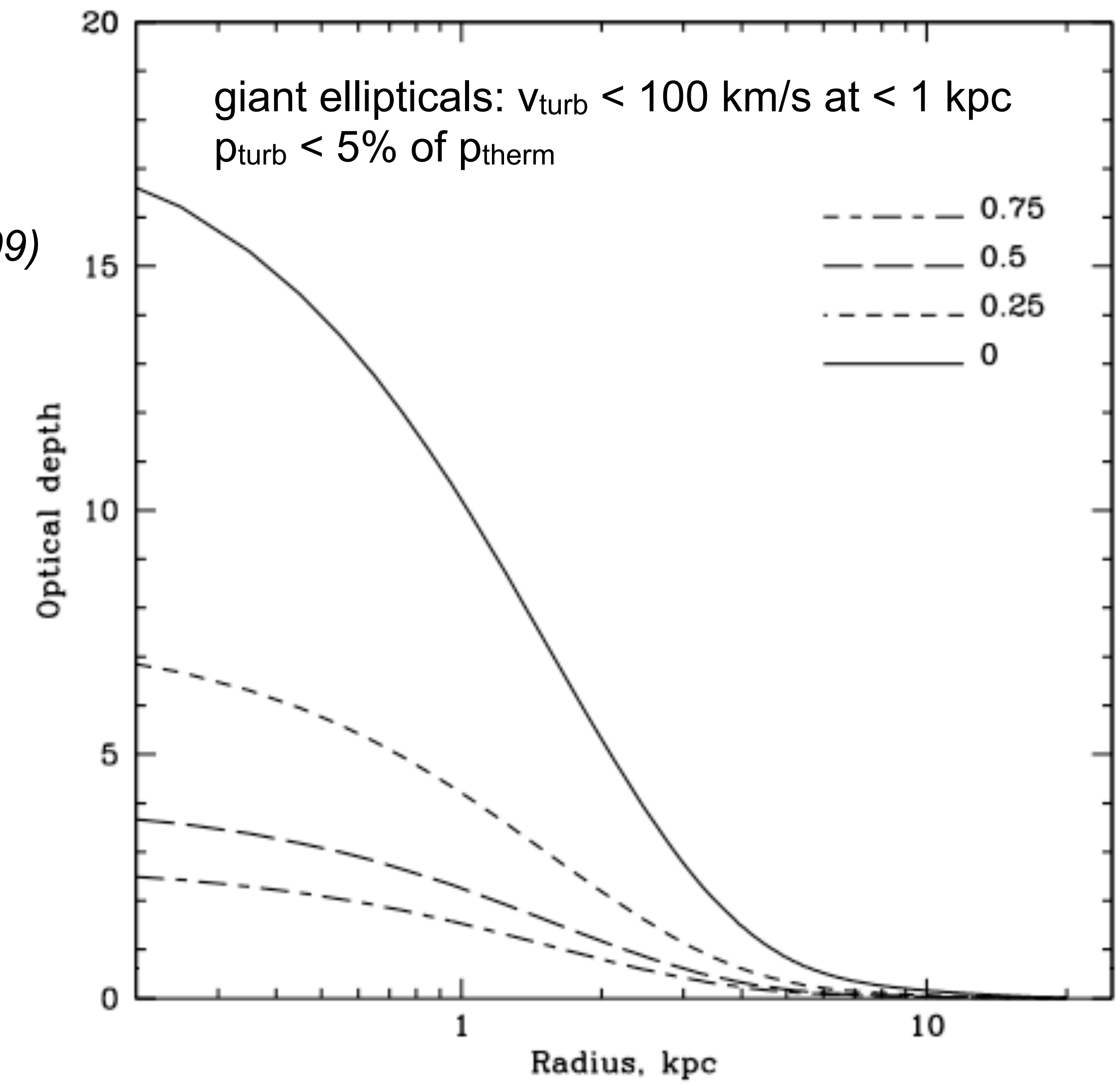

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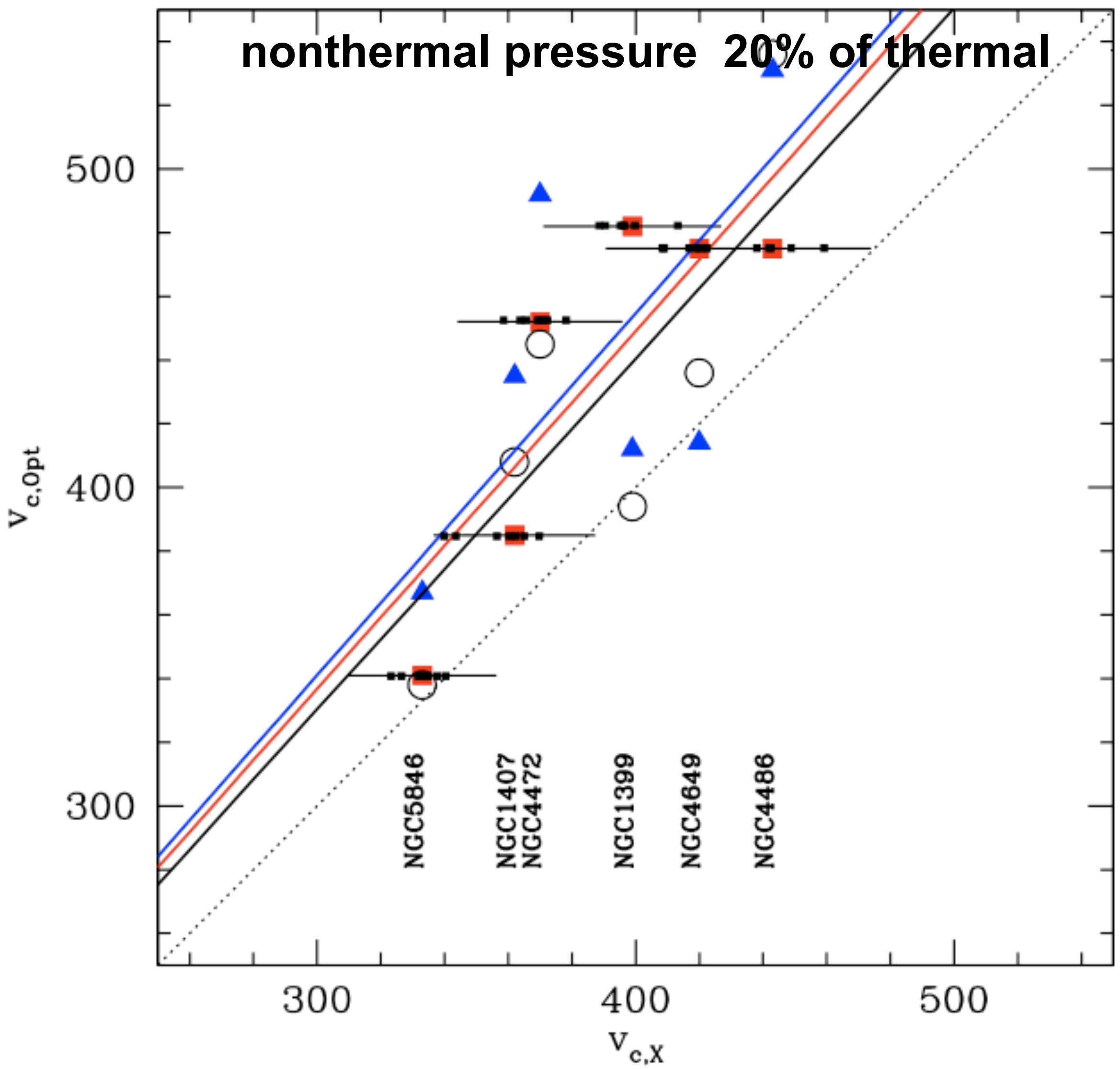
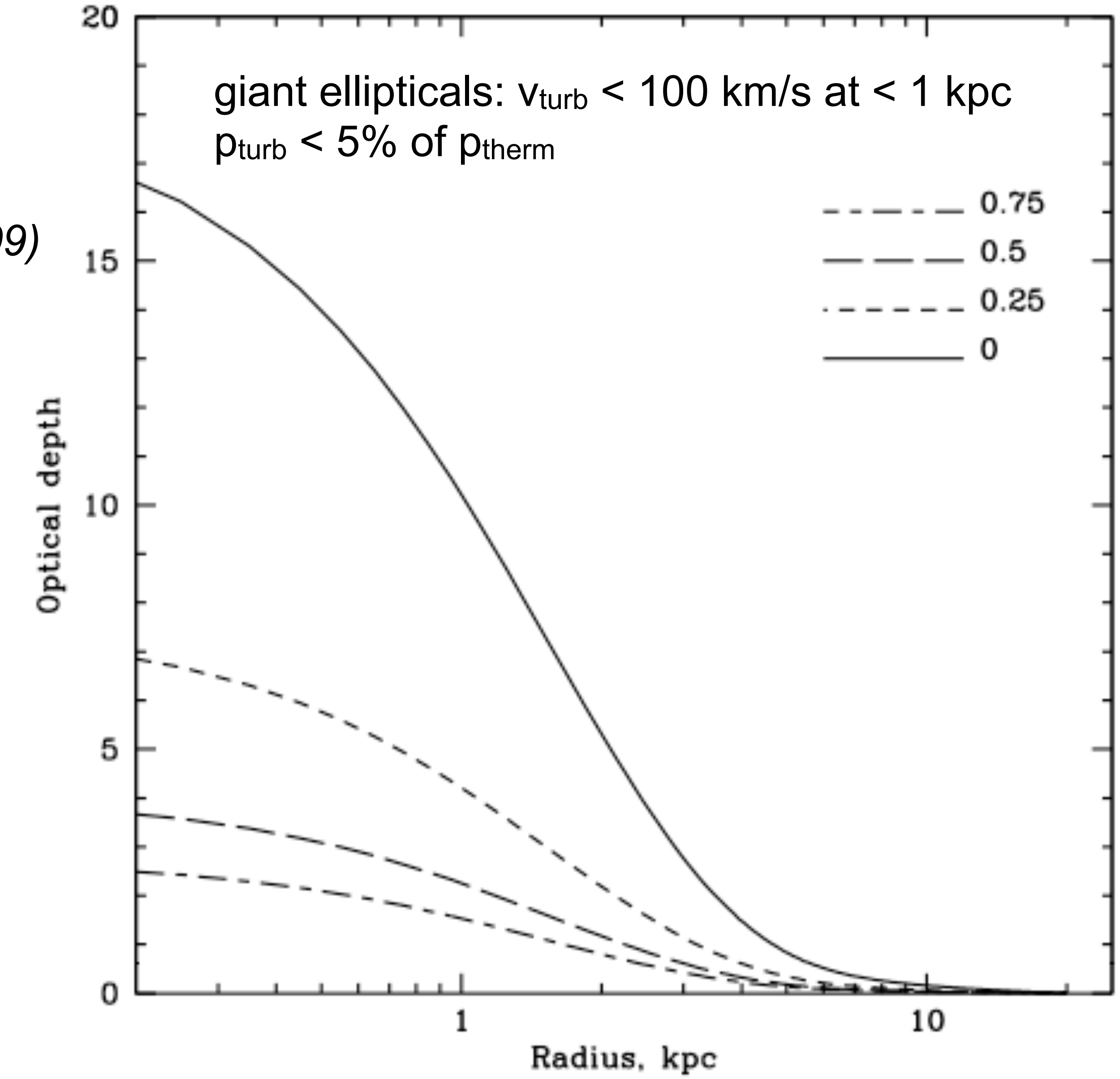


Churazov et al. (2010)

giant ellipticals: v_{turb} < 100 km/s at < 1 kpc
p_{turb} < 5% of p_{therm}



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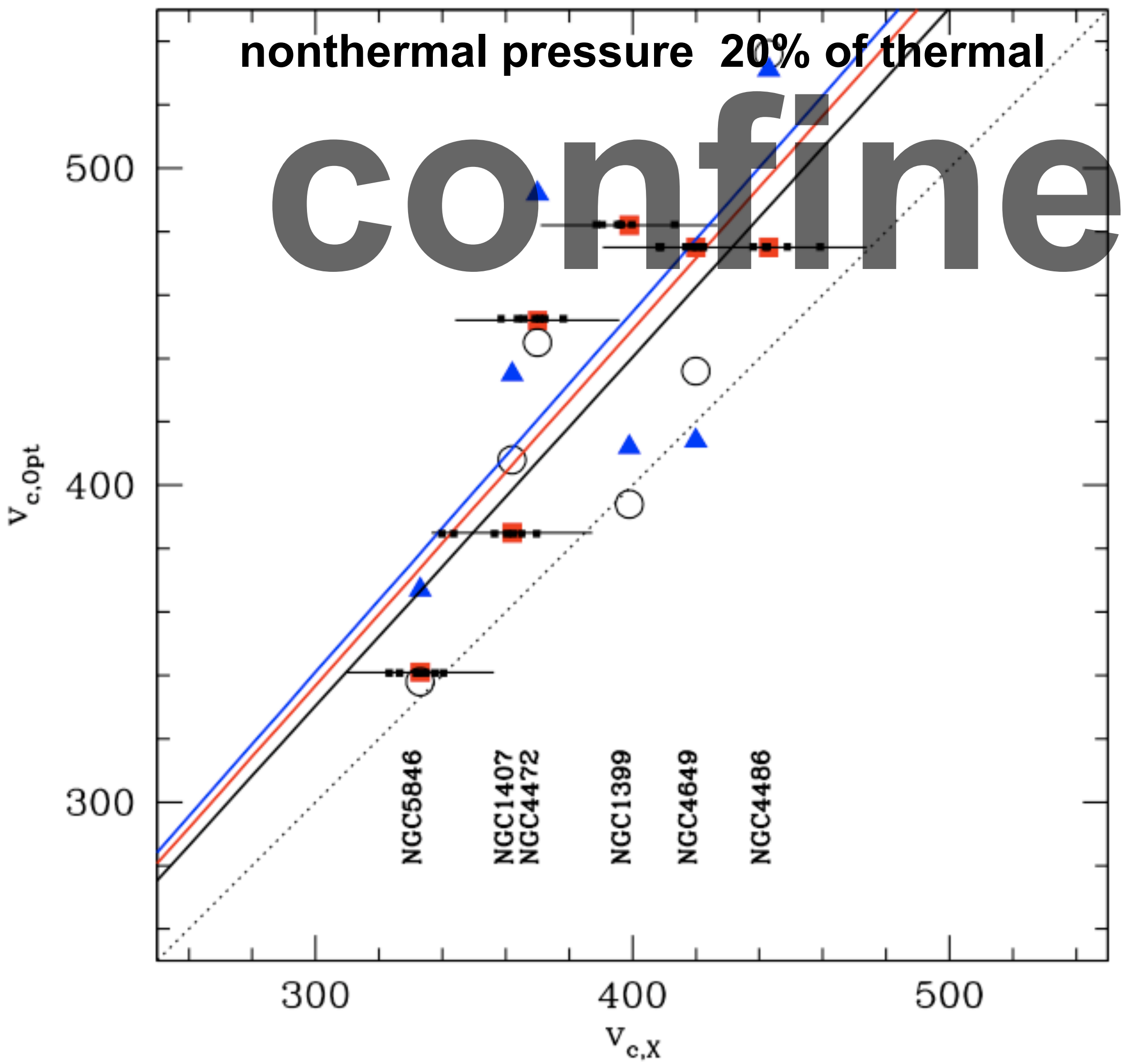

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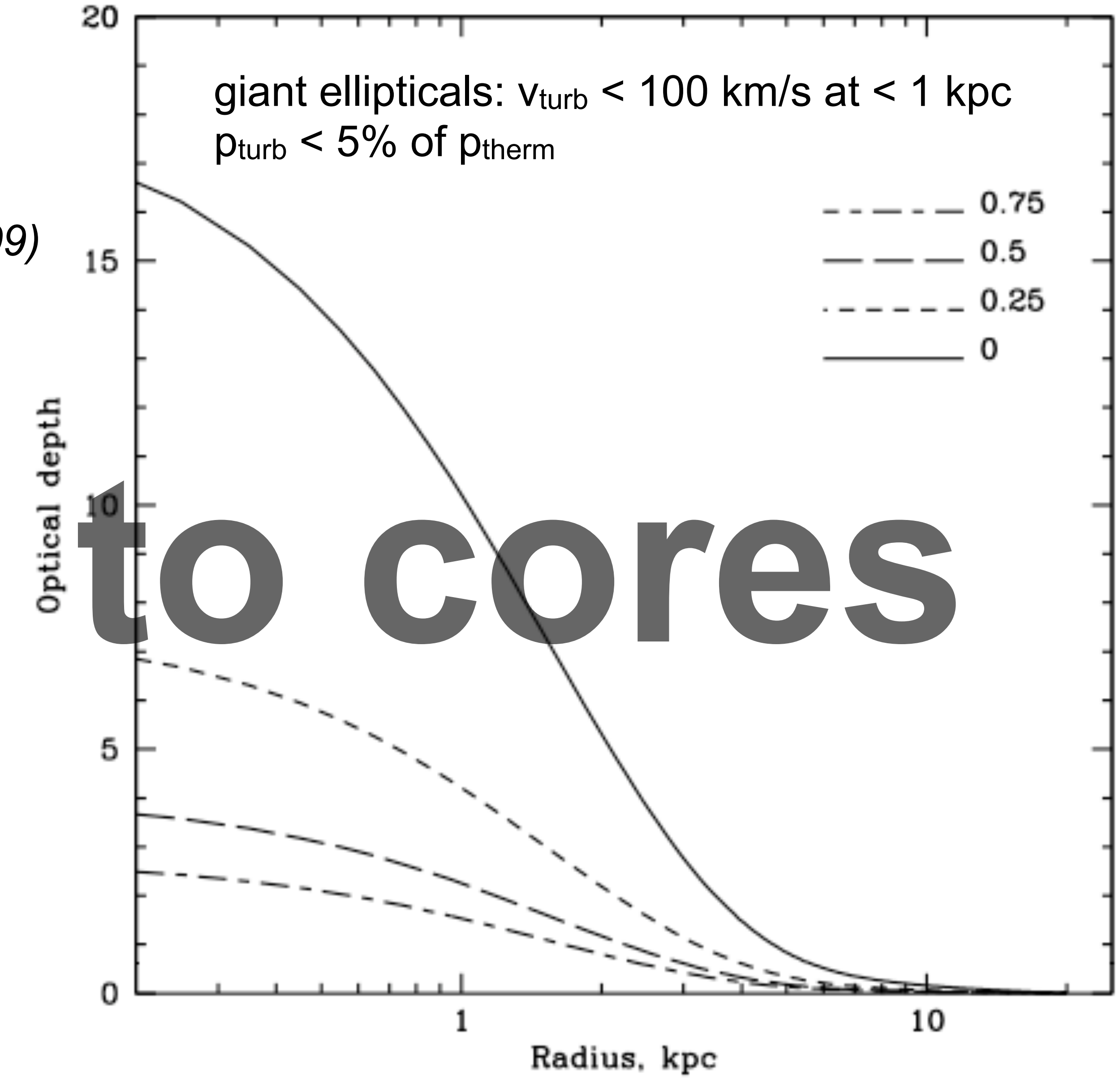

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Werner et al. (2010)

confined to cores

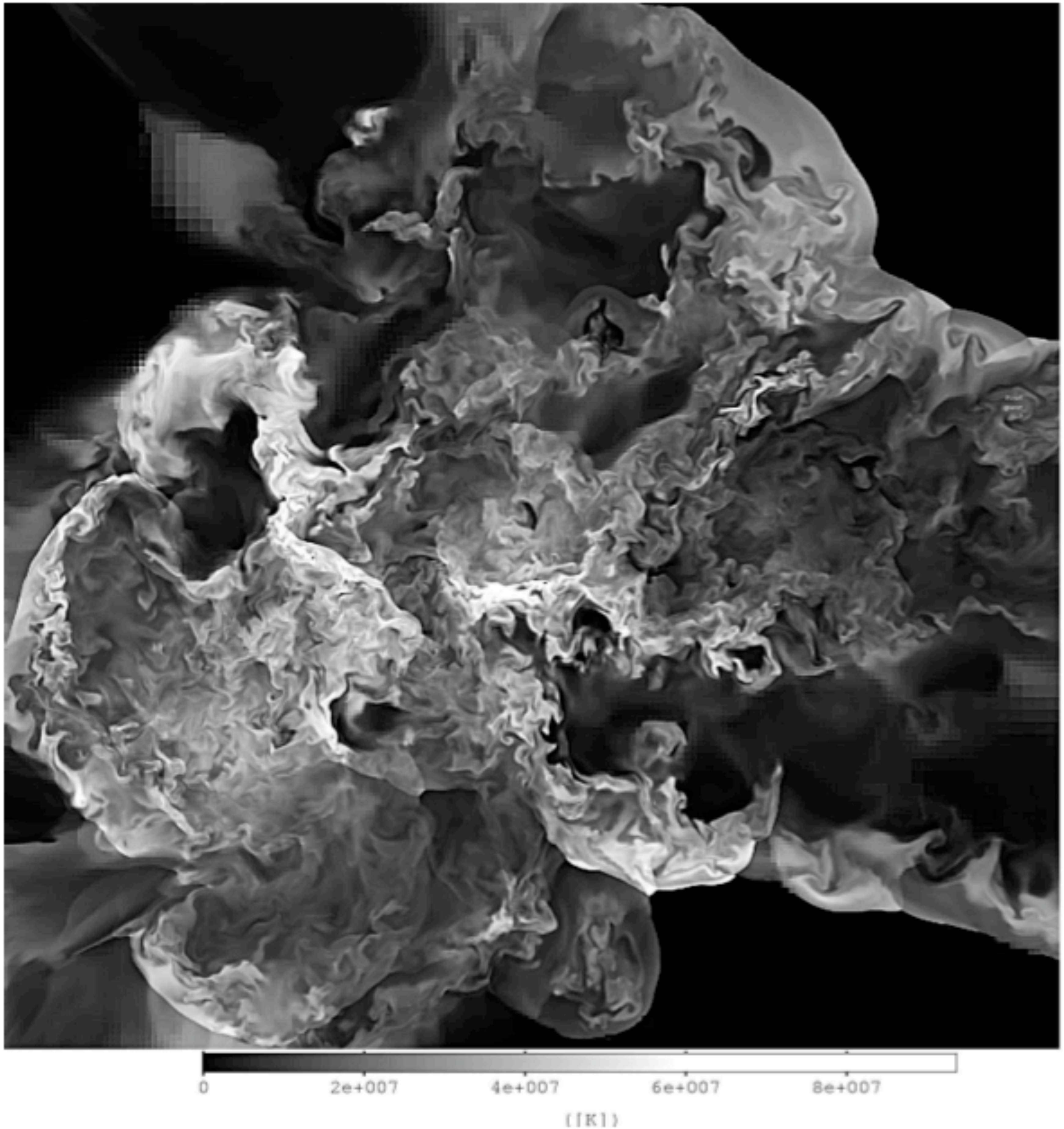


Fig. 1. 2-dimensional slice showing the gas temperature for the innermost region of galaxy cluster E1, during its main merger event ($z = 0.6$). The side of the slice is $8.8 Mpc/h$ and the depth along the line of sight is $25 kpc/h$.

Vazza et al. (2010)

Turbulence and B field generation

- Turbulence caused by shocks during LSS
- Turbulence amplifies B fields
- Turbulence is subsonic in clusters - supersonic in filaments

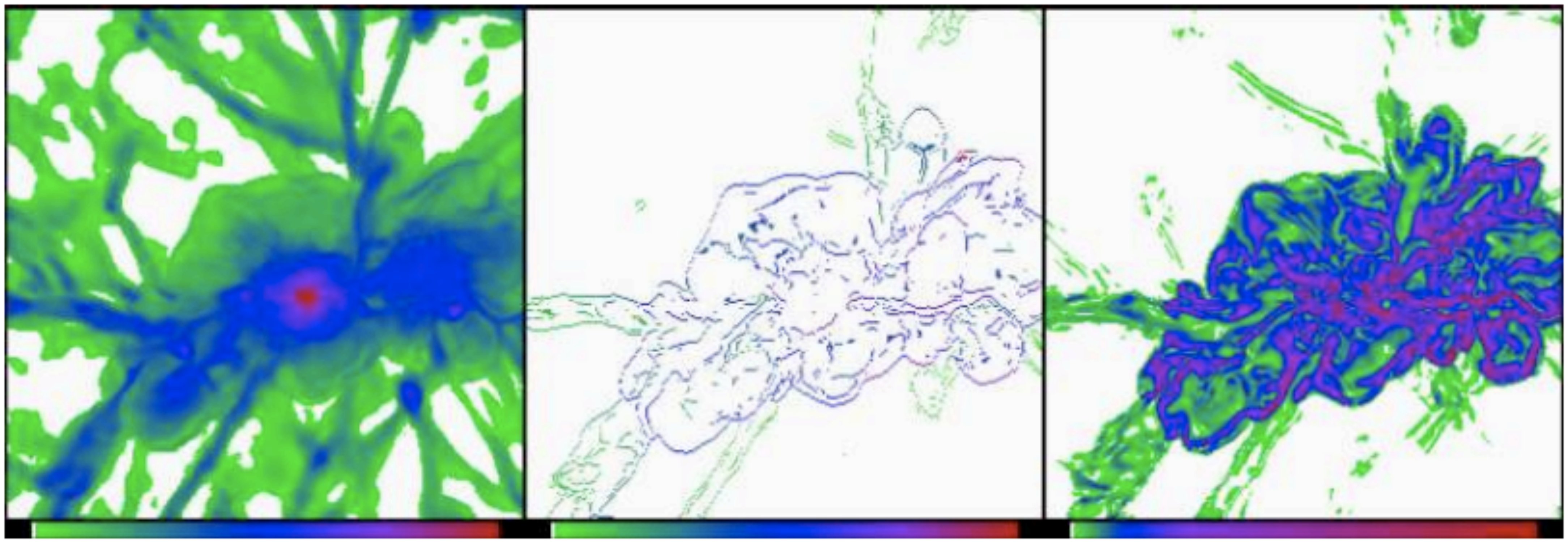
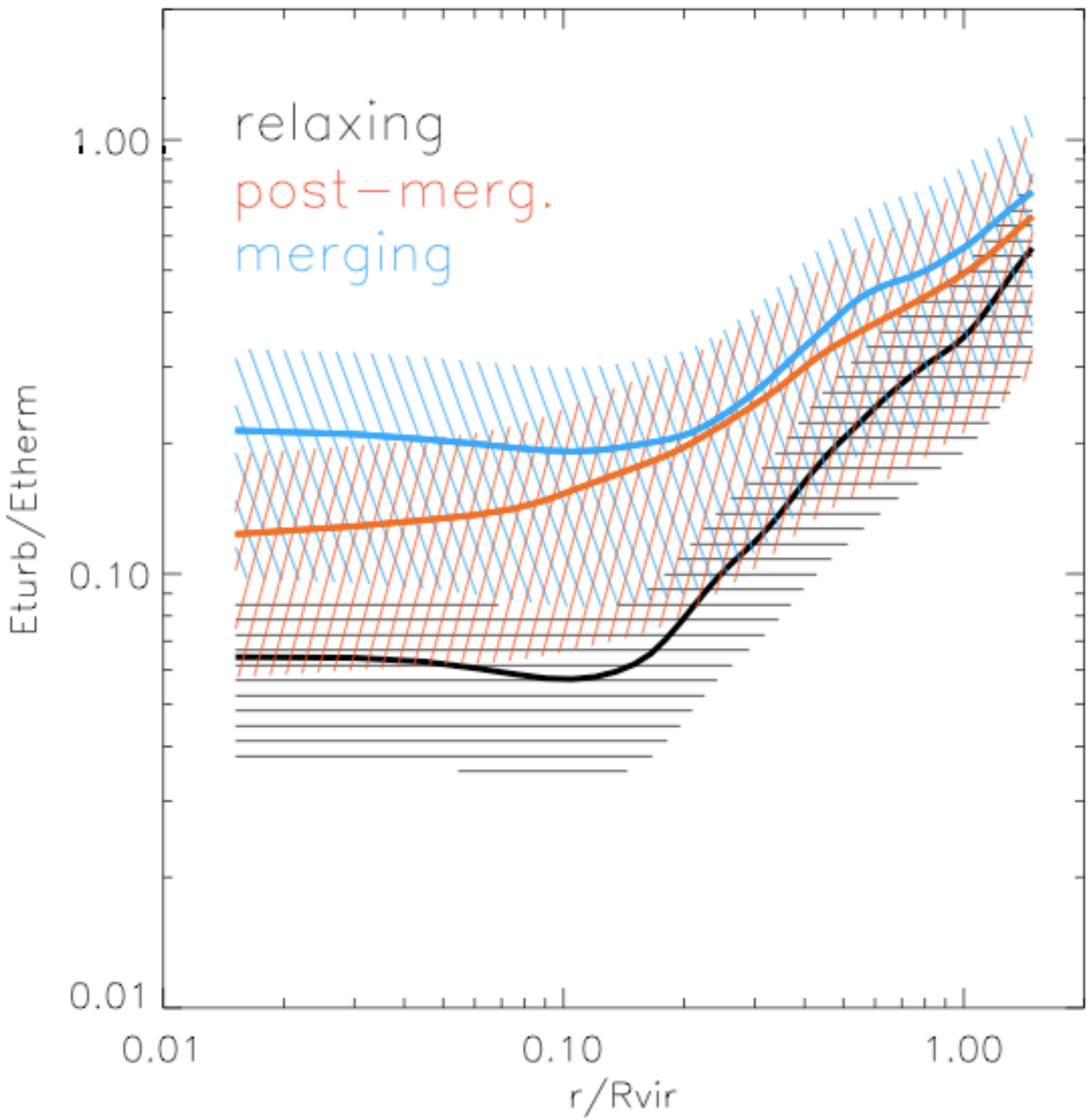


Fig. 1. Two-dimensional images showing gas density ρ in a logarithmic scale (left), locations of shocks with color-coded shock speed $v_{\rm shock}$ (middle), and magnitude of vorticity $\omega t_{\rm age}$ (right), around a cluster complex of $(25\ h^{-1}{\rm Mpc})^2$ area at present ($z = 0$). Here, h is the Hubble constant in units of 100 $\rm km\,s^{-1}Mpc^{-1}$. The complex includes a cluster of x-ray emission-weighted temperature $T_x \approx 3.3$ keV. Color codes for each panel are (left) $\rho/\langle\rho\rangle$ from 10^{-1} (green) to 10^4 (red); (middle) $v_{\rm shock}$ from 15 (green) to 1,800 $\rm km\,s^{-1}$ (red); and (right) $\omega t_{\rm age}$ from 0.5 (green) to 100 (red).

Ryu et al. (2008)



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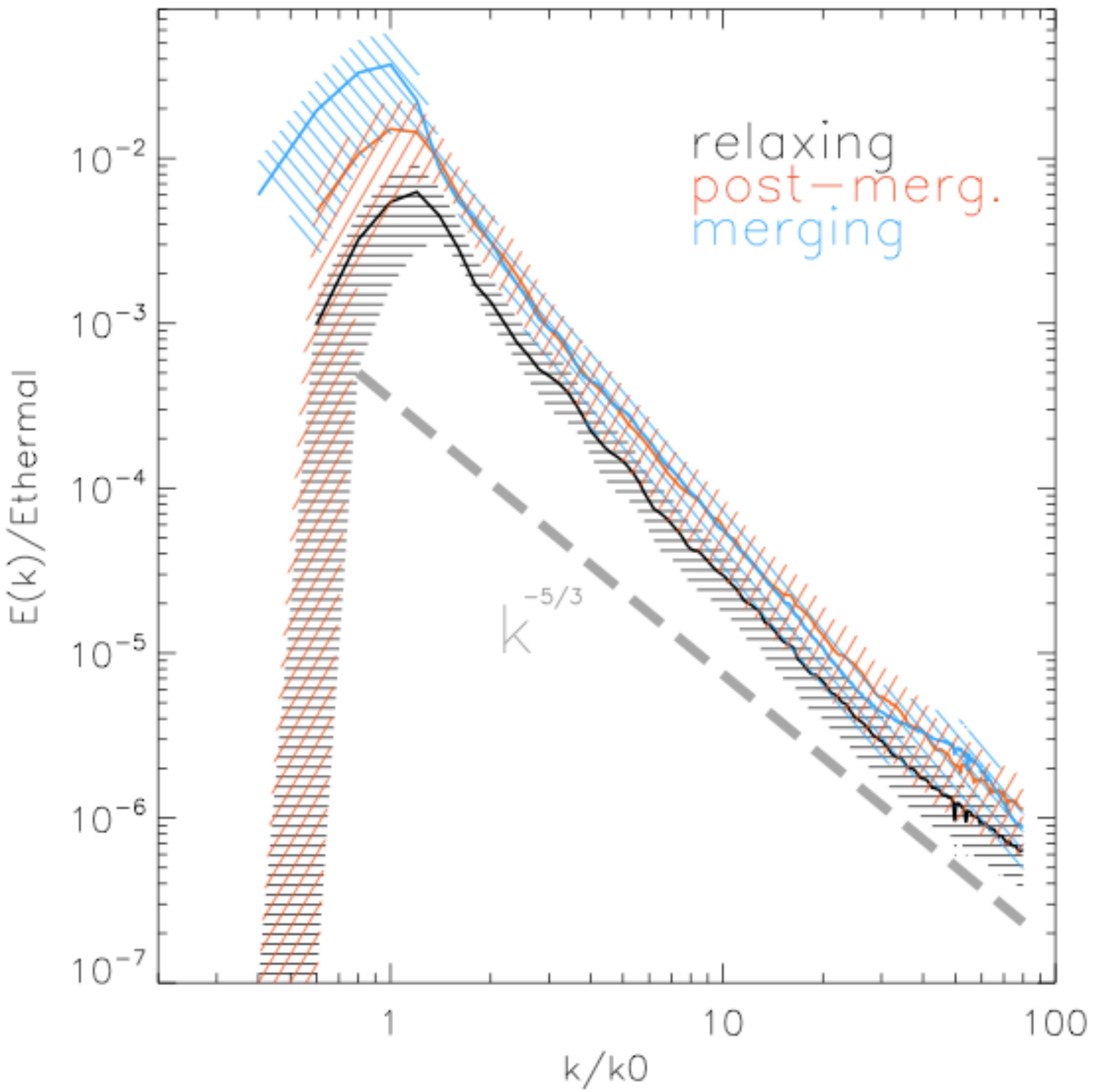


Fig. 7. Average power spectra of the 3–D velocity field for the different classes of galaxy clusters in our sample, at $z = 0$.

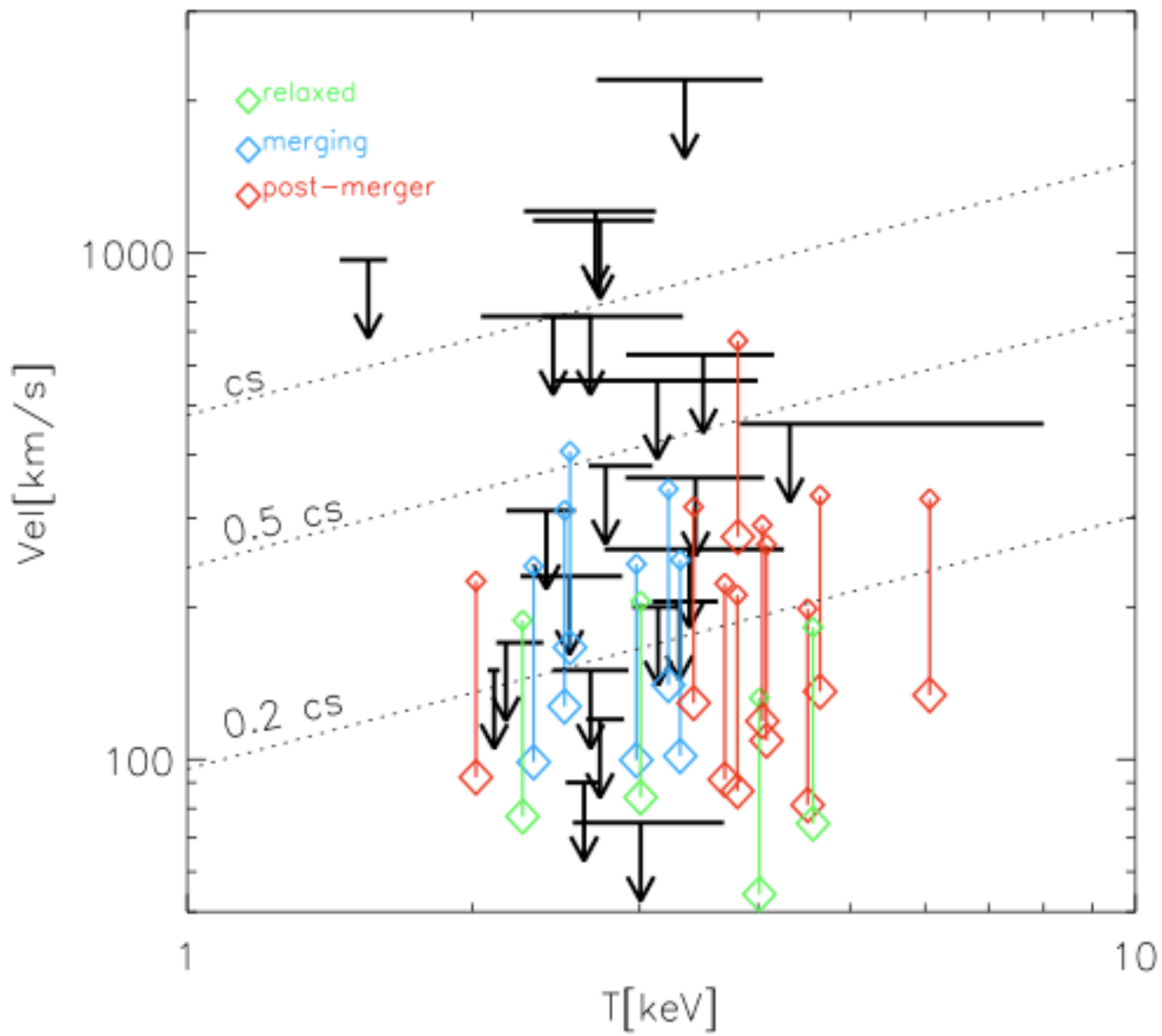
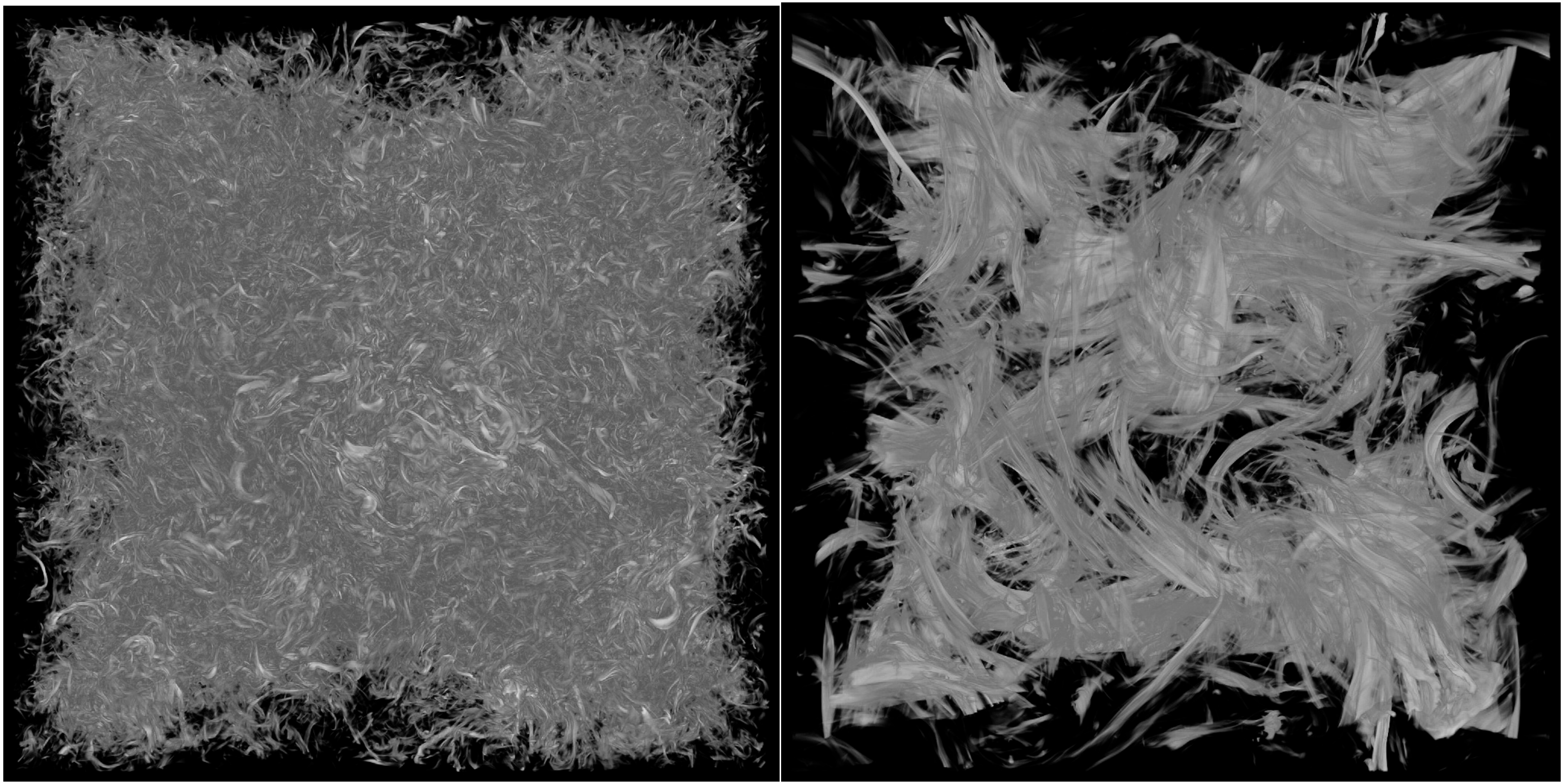


Fig. 10. Scaling between the average temperature and the mean velocity dispersion (small squares) for all clusters of the simulated sample (squares in colors) and for sample of the cluster observed with XMM-Newton by Sanders et al.(2010b). The additional dotted lines show the dependence of the ICM sound speed with the temperature. In order to compare with the observations, we filtered the velocity for the same spatial coherence scale of $l \approx 30$ kpc available to Sanders et al.(2010b); the data-point derived in this way are shown as connected thick squares.

Vazza et al. (2010)

Magnetic energy density distributions

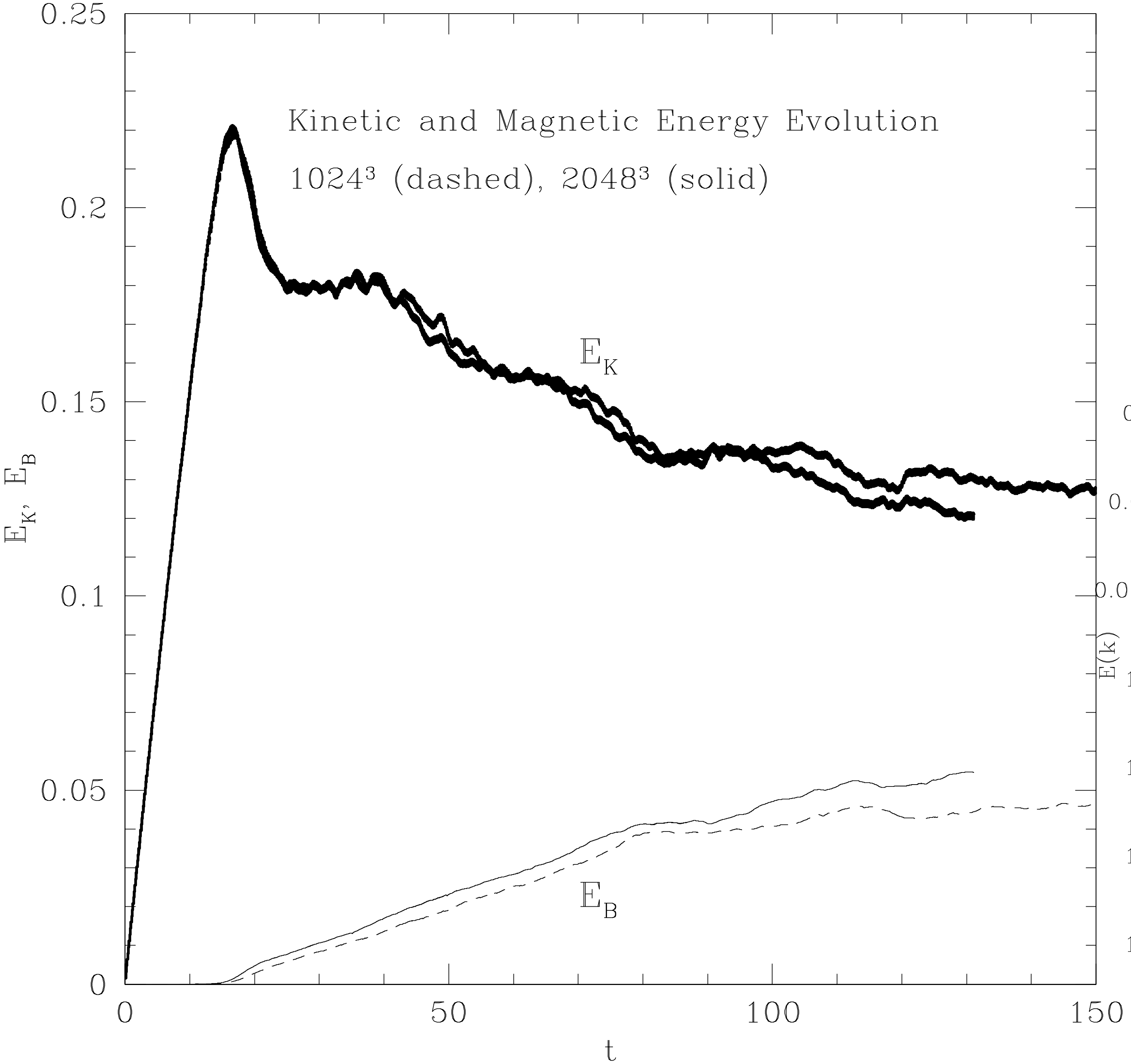


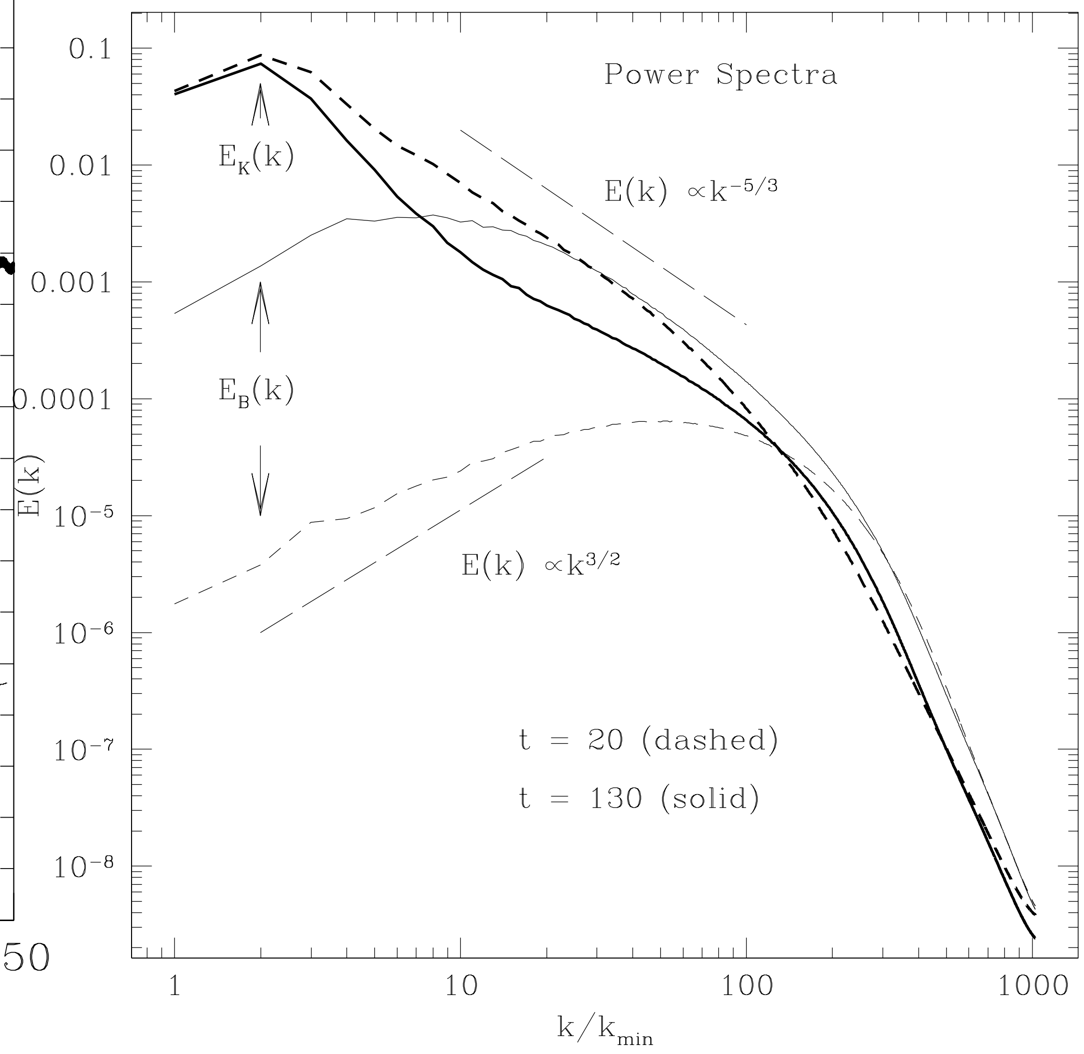
t=20

t=130

2048^3

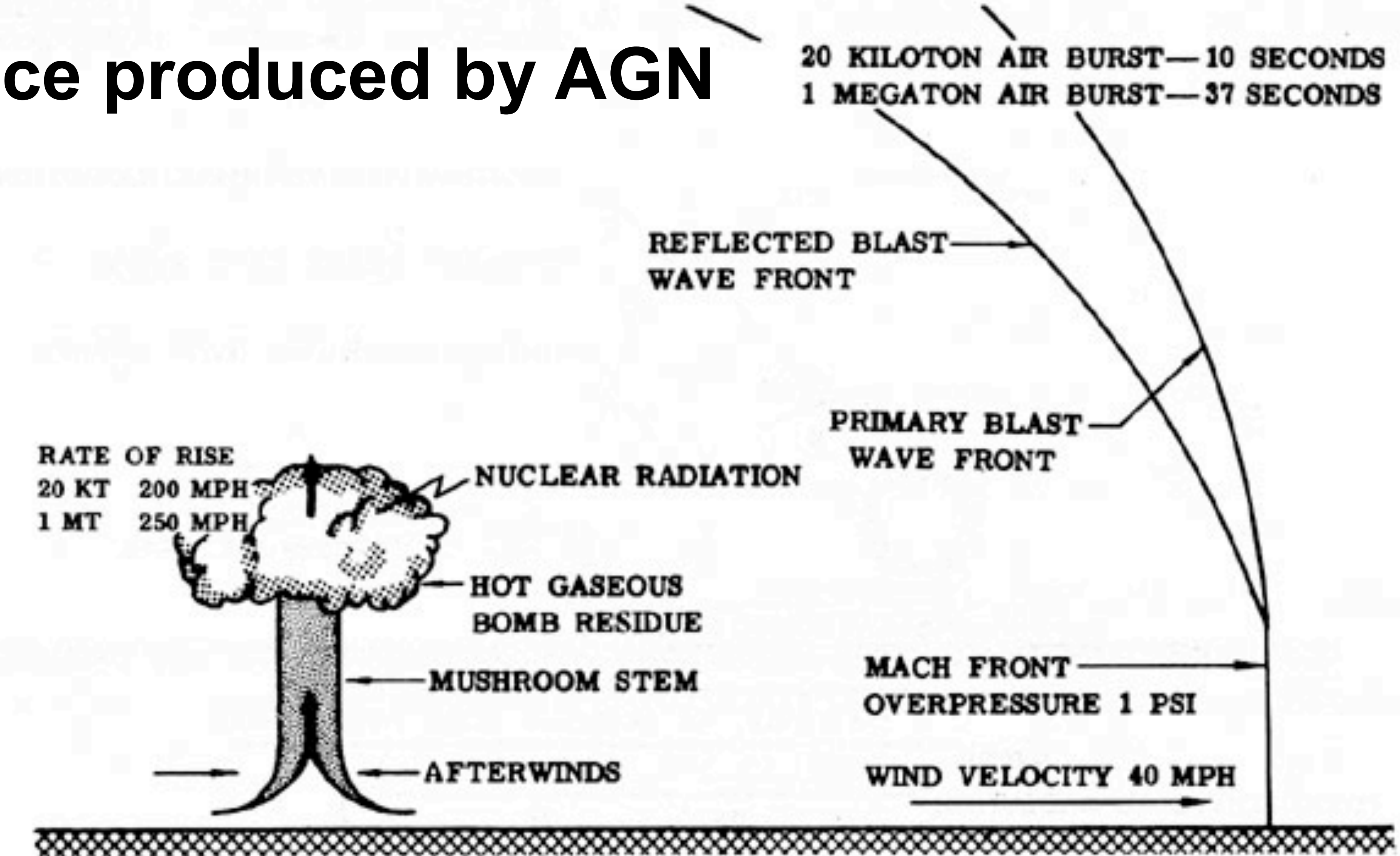
Jones et al. 2011

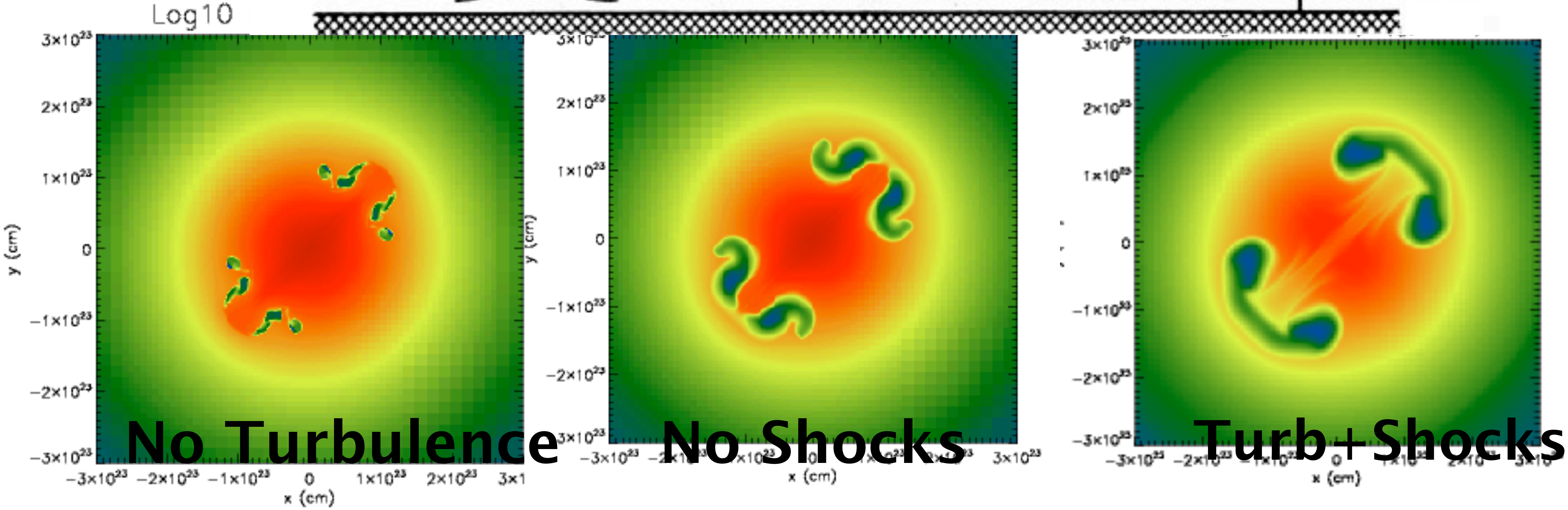




Jones et al. 2011

Turbulence produced by AGN





Scannapieco & Brüggen (2008)

Dimonte & Tipton ‘06 Turbulence Model

based on buoyancy-drag models for RT and RM instabilities: **self-similar, conserves energy, preserves Galilean invariance, works with shocks**

K = Turbulent KE , L= Turbulent Length Scale

$$\frac{\partial \bar{\rho} K}{\partial t} + \frac{\partial \bar{\rho} K \tilde{u}_j}{\partial x_j} = \frac{\partial}{\partial x_j}\left(\frac{\mu_t}{N_K}\frac{\partial K}{\partial x_j}\right) - R_{i,j}\frac{\partial \tilde{u}_i}{\partial x_j} + S_K$$

turb. diffusion — work associated with turbulent stress — source term with RM and RT contributions

$$\frac{\partial \bar{\rho} L}{\partial t} + \frac{\partial \bar{\rho} L \tilde{u}_j}{\partial x_j} = \frac{\partial}{\partial x_j}\left(\frac{\mu_t}{N_L}\frac{\partial L}{\partial x_j}\right) + \bar{\rho} V + C_C \bar{\rho} L \frac{\partial \tilde{u}_i}{\partial x_i},$$

turb. diffusion — growth of eddies through turb. motion — growth of eddies through motion in mean flow

$$S_K = \bar{\rho} V \left[C_B A_i g_i - C_D \frac{V^2}{2} \right], \qquad \mu_T = C_\mu \bar{\rho} L V, \qquad V \equiv \sqrt{2K}$$

buoyancy — drag — turb. viscosity — turb. velocity

Modified fluid equations

leading order in expansion around mean velocity: mean quantities are modified by presence of

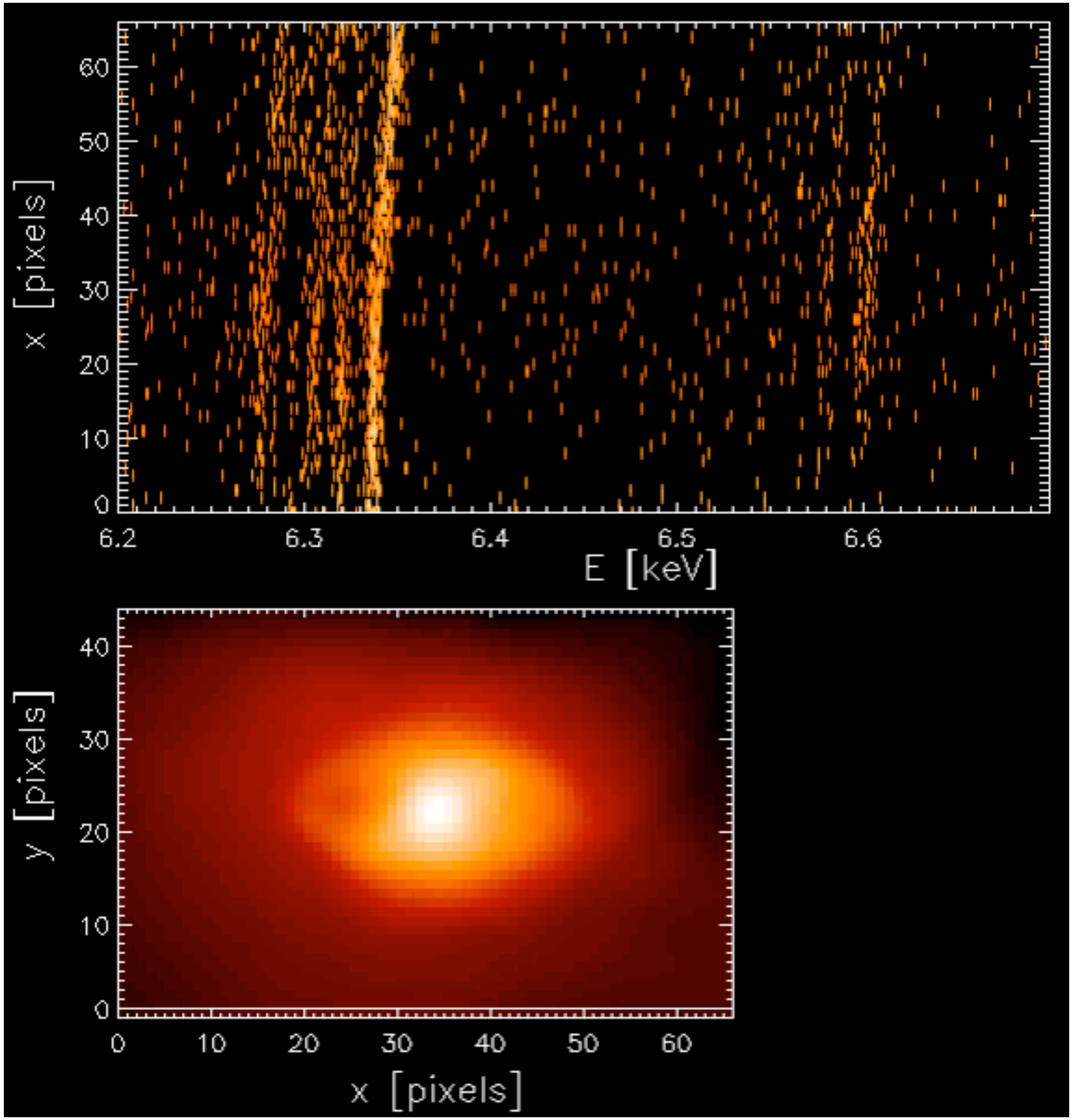
1. Reynolds stress R
2. Turbulent viscosity, mu
3. Source term S_K

$$\frac{\partial \rho u_i}{\partial t} + \frac{\partial \rho u_i u_j}{\partial x_j} = -\frac{\partial P}{\partial x_i} - \frac{\partial R_{i,j}}{\partial x_j}$$

$$\frac{\partial \rho E}{\partial t} + \frac{\partial \rho E u_j}{\partial x_j} = \frac{\partial}{\partial x_j}\left(\frac{\mu_t}{N_E}\frac{\partial E}{\partial x_j}\right) - \frac{\partial P u_j}{\partial x_j} - S_K$$

How can we measure turbulent motions?

simulated
IXO
spectra



Heinz, Brüggen & Morsony 2010

also see Rebusco et al. (2008), Inamov et al. (2005)

Here is a list of topics that are on our mind:

1. measurements of turbulence, turbulent spectra (how to measure it in stratified environments)?

2. Transport processes in turbulent media

3. Follow-up to discussion during BB lunch talk by Bodenschatz: applicability of Navier-Stokes equations to supersonic turbulence. Importance of higher-order terms?

4. MHD turbulence, turbulent dynamos

5. subgrid models of turbulence

6. particle acceleration in turbulent plasmas (Fermi-I)