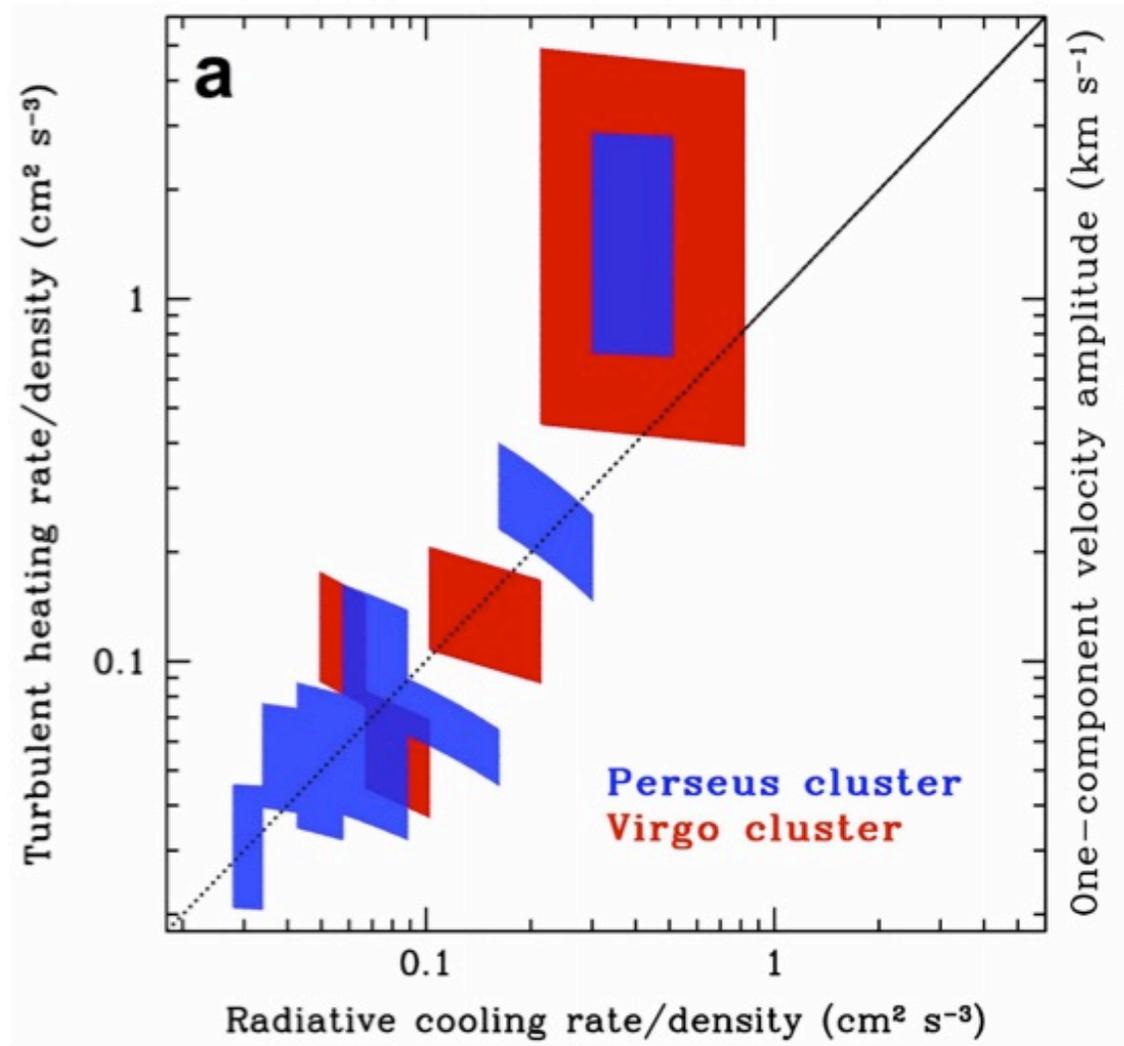


OUTLINE

- Turbulence and ICM heating
- Can one heat the ICM by AGN-induced turbulence?
- Need for physics beyond pure hydro
(spoiler: it has yoooooge impact on the evolution of ICM & central AGN)
 - dissipation of weak shocks and sound waves
 - B-fields & cosmic rays

Turbulent dissipation and ICM heating





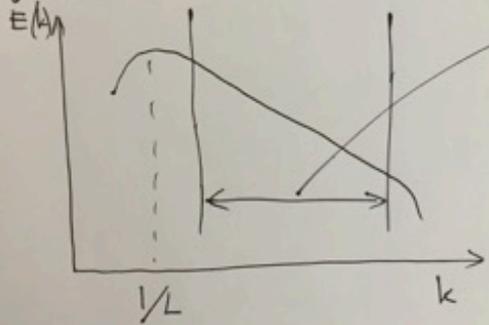
(1)

$$Q_{\text{turb}} \sim \rho v^2 \frac{1}{\frac{L}{v}} \sim \frac{\rho v^3}{L}$$

$$L = \left(\begin{array}{c} \text{energy-containing} \\ \text{scale} \end{array} \right)$$

not easy to determine observationally

energy spectrum



in the turbulent cascade, the energy flux in the inertial range = const
(scale-independent, i.e., the energy just trickles down to smaller scales w/o loss)

$$E(k) \sim C_k \epsilon^{2/3} k^{-5/3} ; \text{ modulo factors of } 2\pi$$

$$C_k \approx 1.65 \approx \mathcal{O}(1)$$

$$\epsilon = \left(\begin{array}{c} \text{density-normalized} \\ \text{dissipation rate} \end{array} \right) = \frac{Q_{\text{turb}}}{\rho}$$

$$k E(k) \sim \frac{3 V_k^2}{2}$$

$$\frac{v_k^2}{k} \sim \epsilon^{2/3} k^{-3/3} \quad ; \quad \text{nodal factors } \mathcal{O}(1) \quad (2)$$

$$\epsilon^{2/3} \sim v_k^2 k^{2/3}$$

$$\boxed{P_{\text{kin}} = \rho_0 \epsilon \sim \rho_0 k v_k^3} \quad \text{High power}$$

How to measure v_k ? Link it to $\frac{\delta p}{\rho}$ (observable)
(via $\delta b_x / L_x$)

$$\ddot{z} \sim -\omega_{BV}^2 z \quad , \quad \omega_{BV}^2 = \frac{g}{\gamma} \frac{dk}{dz} = \frac{g}{\gamma} \frac{1}{H_k}$$

$$\ddot{z} \sim -\frac{1}{\rho} \frac{dP}{dz} \frac{1}{\gamma} \frac{1}{H_k} z$$

$$\sim \frac{1}{\rho} P \frac{1}{H_p} \frac{1}{\gamma} \frac{1}{H_k} z \sim \frac{1}{\gamma^2} c_s^2 \frac{1}{H_p H_k} z$$

$$\left(\text{Specific energy of the oscillator} \right) = E \sim v_k^2 \sim \ddot{z} \cdot z$$

restoring force is driven by δK , and so displacement z ~~is~~ can be linked to δK

(3)

$$\frac{\delta K}{K} \sim \frac{\frac{dK}{dz} z}{K} = \frac{z}{H_K}, \quad z \sim H_K \frac{\delta K}{K}$$

$$\sigma_K^2 \sim \frac{1}{\gamma^2} c_s^2 \frac{1}{H_p H_K} \left(H_K \frac{\delta K}{K} \right)^2$$

$$\frac{\sigma_K}{c_s} \sim \left(\frac{H_K}{H_p} \right)^{1/2} \frac{\delta K}{K} \sim \mathcal{O}(1) \frac{\delta K}{K} = \mu$$

For low Mach number, fluctuations will be subsonic.

$$K \propto \frac{T}{\rho^{2/3}} \propto \frac{p}{\rho^{5/3}} \propto \rho^{-5/3}; \quad \frac{\delta K}{K} \sim \frac{\delta \rho}{\rho}$$

$$\boxed{\frac{\sigma_K}{c_s} \sim \frac{\delta \rho}{\rho}}$$

When conduction operates, more specifically when it is fast, i.e., $t_{\text{cond}} \ll t_{\text{sound crossing}}$, then the restoring force is controlled by ∇T rather than ∇K . (4)

This happens when $\frac{L^2}{K} \ll \frac{L}{c_s}$, $k \sim \sigma_e \lambda_e$

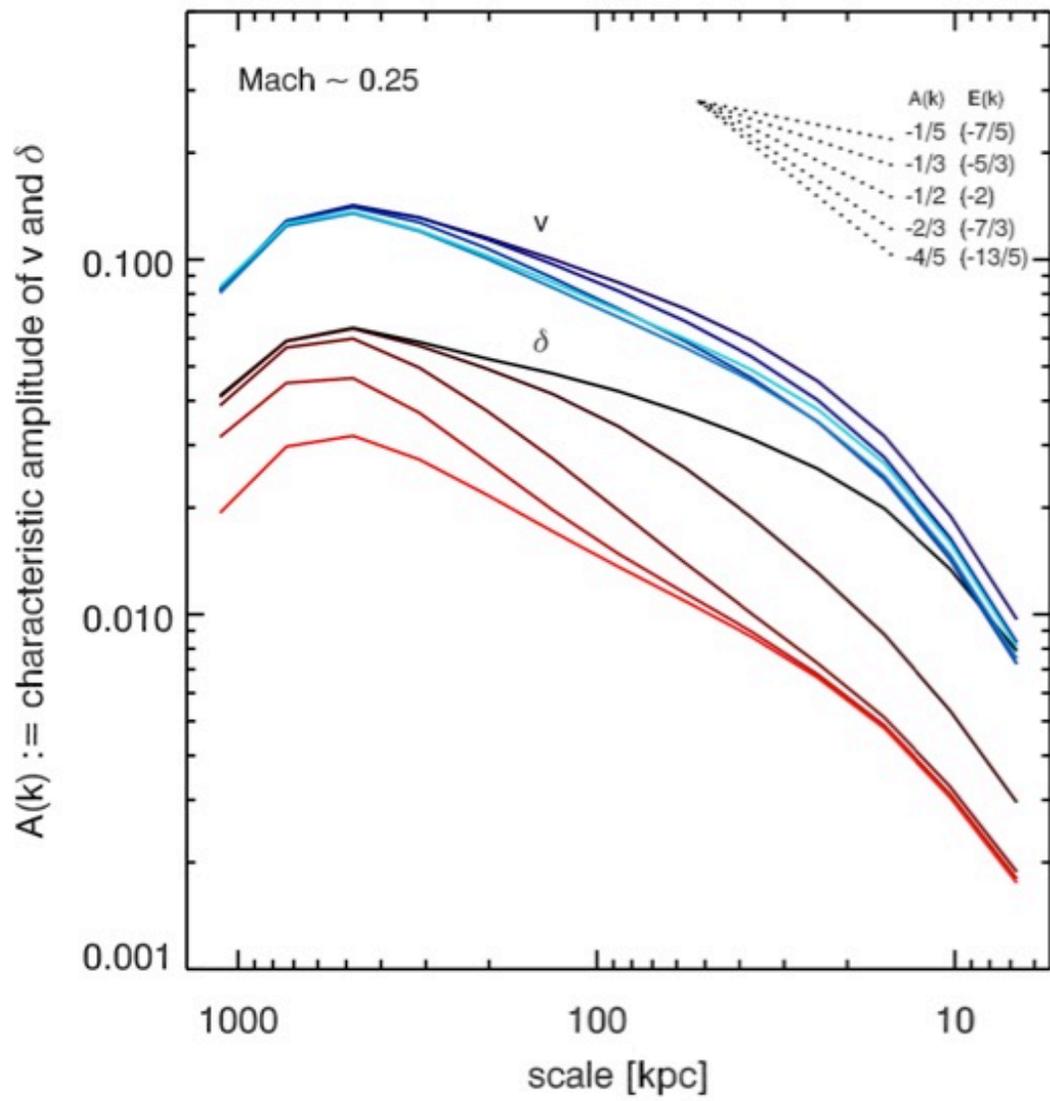
$$L \ll \sigma_e \lambda_e \frac{1}{c_s} \sim \underbrace{\left(\frac{m_p}{m_e}\right)^{1/2}}_{\sim 40} \cdot \underbrace{\lambda_e}_{\sim 20 T_8^2 n_{-3}^{-1} \text{ kpc}}$$

$$L \ll \sim 800 \text{ kpc } T_8^2 n_{-3}^{-1}$$

Then, the relationship between μ & thermodynamical fluctuations becomes

$$\frac{v_k}{c_s} \sim \left(\frac{H_T}{H_p}\right)^{1/2} \frac{\delta T}{T}, \quad \text{since } H_T^{-1} = \frac{d \ln T}{dz}$$

Since $\frac{\delta T}{T} \ll \frac{\delta \rho}{\rho}$, as ~~the~~ δT is washed out by conduction, large $\delta \rho / \rho$ fluctuations do NOT imply large velocity fluctuations



Aurora (direct velocity measurements)

Motions can be decomposed into

$$\bar{\nabla} \cdot \bar{u} \neq 0 \quad (\text{compressible})$$

$$\bar{\nabla} \times \bar{u} \neq 0 \quad (\text{incompressible})$$

For $n \ll 1$, $\bar{\nabla} \cdot \bar{u} \approx 0$ & g-waves are characterized by $\bar{\nabla} \times \bar{u} \equiv \bar{\omega} \neq 0$.

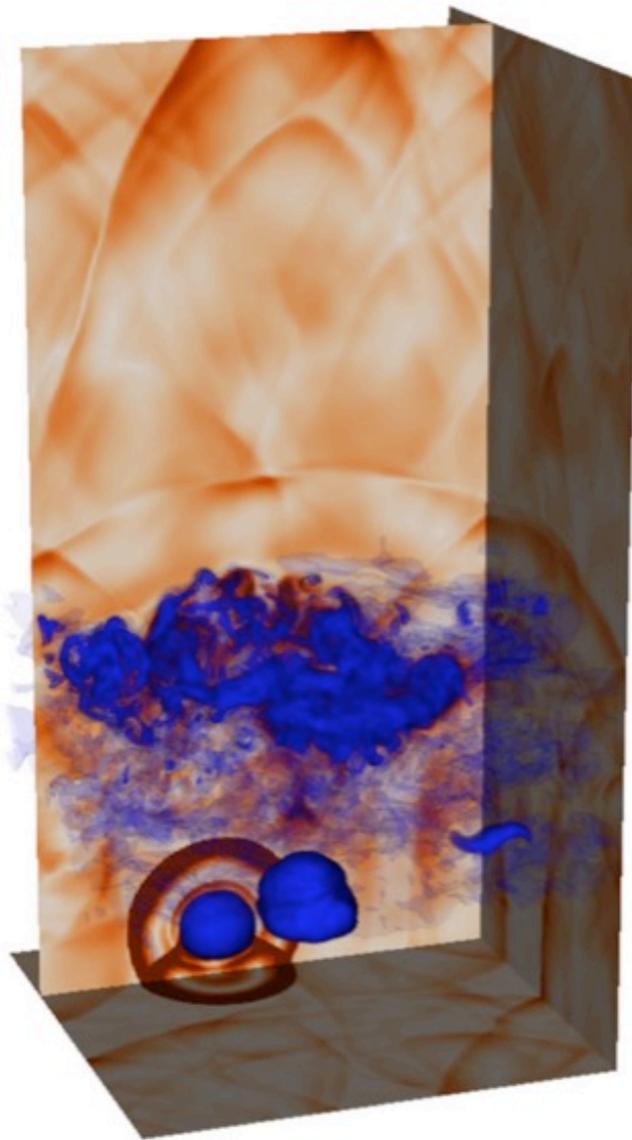
Evolution of vorticity $\bar{\omega}$ is:

$$\frac{D\bar{\omega}}{Dt} = \frac{1}{g^2} \bar{\nabla}_\rho \times \bar{\nabla} p$$

$\bar{g} \parallel \bar{\nabla} p$, misalignments between $\bar{\nabla}_\rho$ & $\bar{\nabla} p$ lead
(to first order) to $\bar{\omega} \perp \bar{g}$, i.e. $\omega_z = 0$
 $\omega_x \neq 0$
 $\omega_y \neq 0$

to first order, i.e., before nonlinear effects kick in & turbulence develops

So $\omega_z \neq 0$ signifies the onset of turbulence.



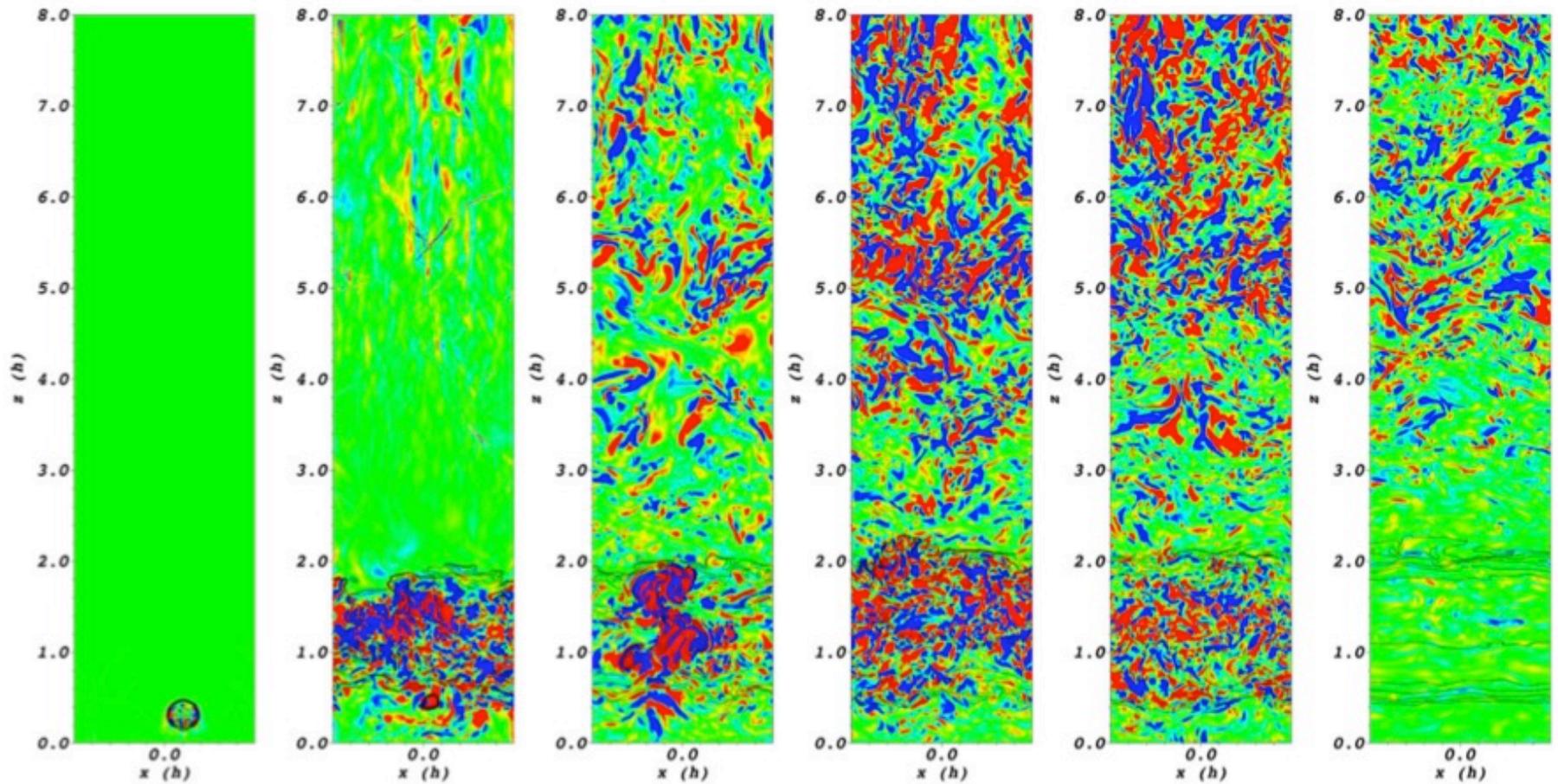
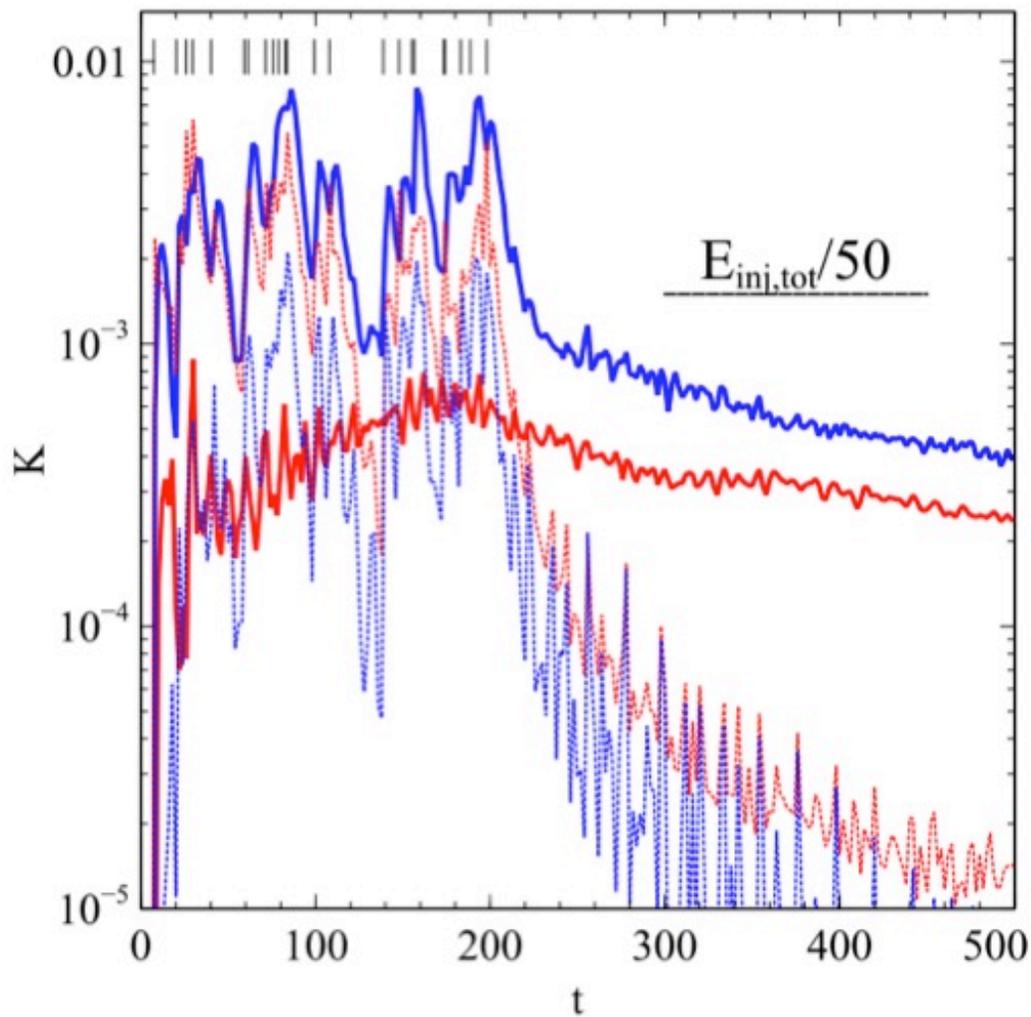


Figure 2. Magnitude of ω_z , the z -component of vorticity, in the $y = 0$ plane at times $t = 6, 84, 160, 180, 220,$ and $400h/c_{iso,0}$ (from left to right). The color table is set so that green is $\omega_z = 0$, and red/blue saturate at $\omega_z = \pm 0.2$.

Reynolds, Balbus, Schekochihin 2015



Ambient ICM (incompressible) $< 0.01 E_{injected}$

Ambient ICM (compressible)

Reynolds, Balbus, Schekochihin 2015

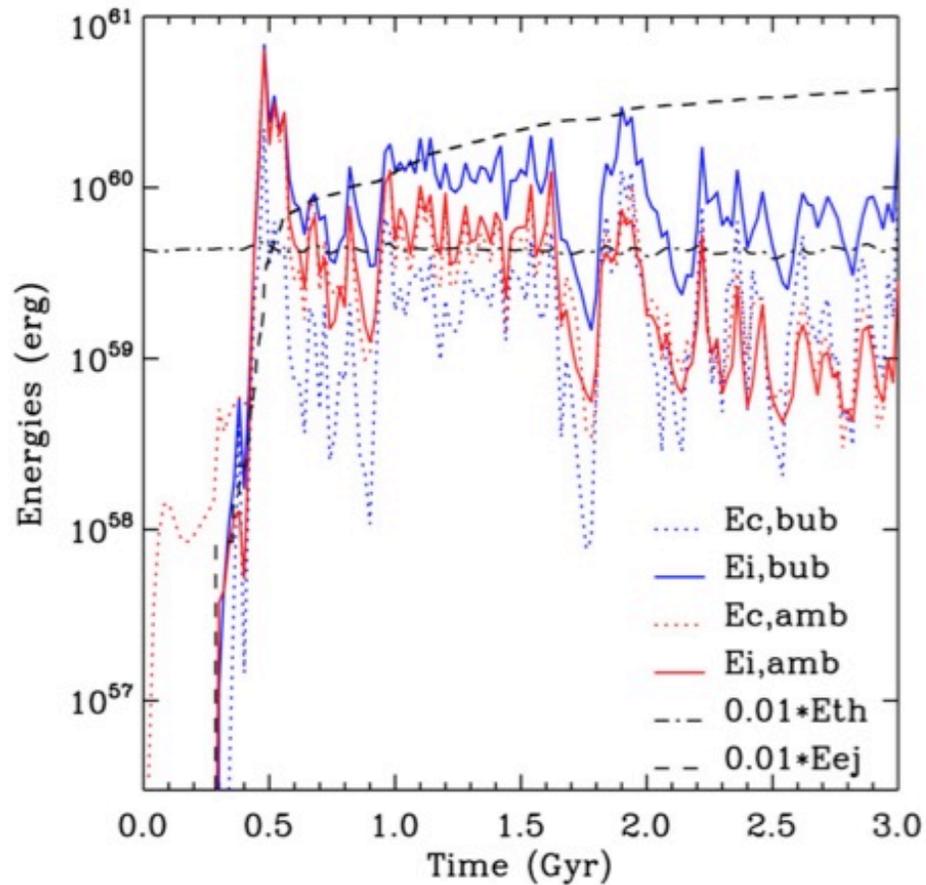


Figure 12. Evolution of the kinetic energies of the compressible (dotted) and incompressible (solid) velocity fields, which are further separated by regions containing the bubbles ($f_{\text{jet}} \geq 0.01$; blue) and excluding the bubbles ($f_{\text{jet}} < 0.01$; red). Dashed and dashed-dotted lines show 1% of the injected energy from the AGN and the total gas thermal energy within 100 kpc, respectively.

BEYOND IDEAL HYDRODYNAMICS