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Simulating feedback from active galactic nuclei in galaxy clusters with pre-existing turbulence

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Outline

Introduction

Cooling-flow problem, turbulent heating, observation and simulation

Methodology

Simulation setting, how to stir the galaxy cluster

Results

Entropy, shocks & sound waves, velocity dispersion

Conclusion

Turbulent heating is not enough to balance cooling

Cooling Flow Problem

- Radiative cooling rate: $L_x \propto n^2$
- Cool-core clusters : $t_{cool} << t_{Hubble}$
- Massive gas inflows and high SFR
  → absent in the observation
- AGN feedback, thermal conduction, cosmic rays, and turbulence etc.

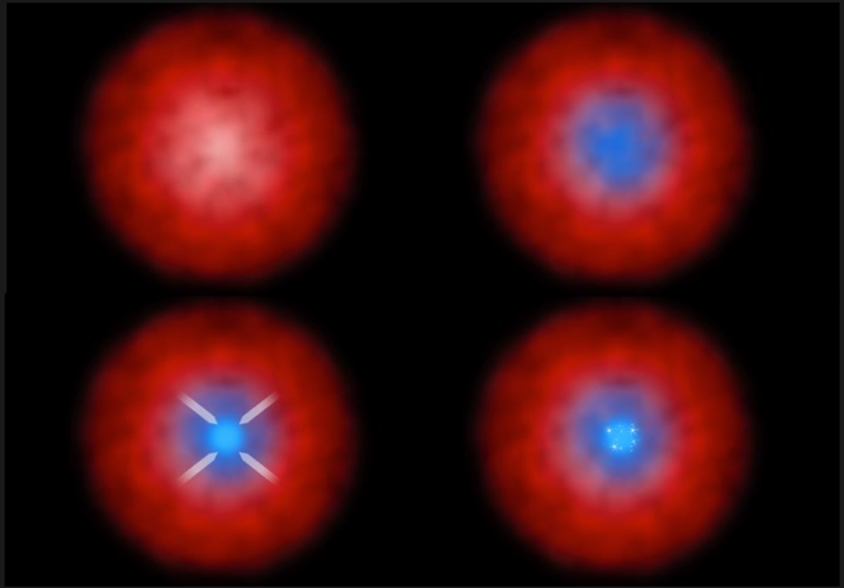
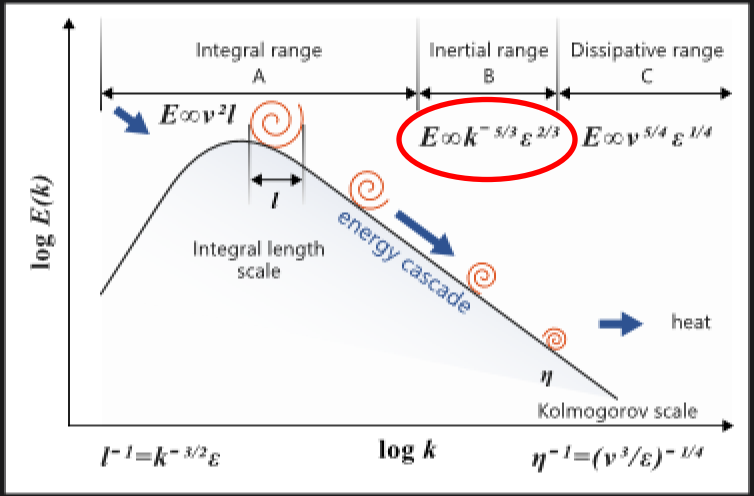


Illustration: NASA/CXC/M.Weiss

Turbulent Heating

- Hydrodynamic instabilities resulting from merger events and AGN feedback etc. $\longrightarrow$ cascade decay $\longrightarrow$ dissipating energy into heat
- Turbulent heating rate: $Q_{turb} \sim \rho {\sigma_l}^3 / l$
- The heating rate is sensitive to the velocity dispersion
- Turbulence driving scale is one of the main sources of uncertainty

Kolmogorov energy spectrum

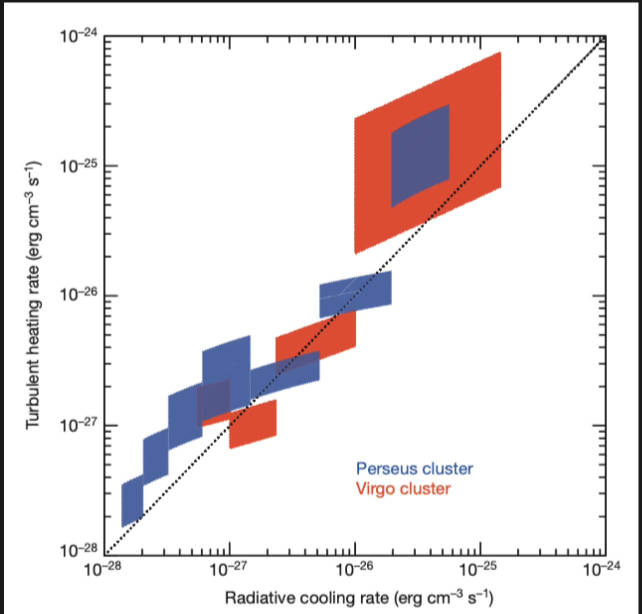


Observation vs. Simulation

Zhuravleva et al. (2014)

- Chandra X-ray surface brightness fluctuations
- Assuming a one-to-one conversion between density fluctuations and velocity fluctuations

⟶ Turbulent dissipation can balance radiative cooling



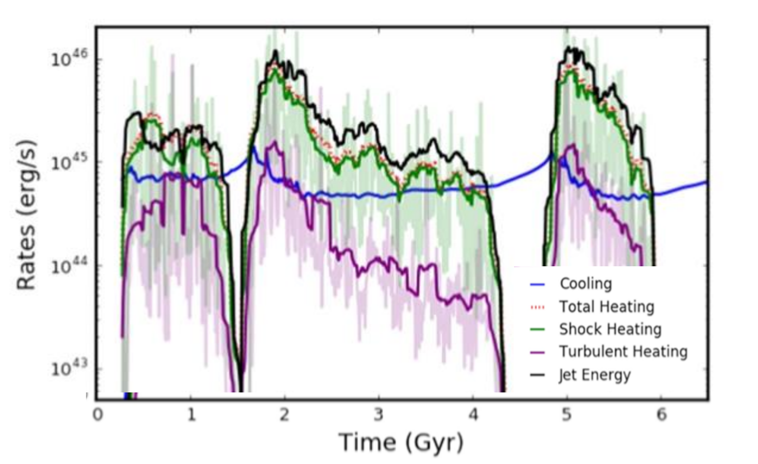
Zhuravleva et al. (2014)

Observation vs. Simulation

Simulation

- By simulating self-regulated AGN feedback, turbulent heating alone is insufficient to balance the radiative cooling is demonstrated

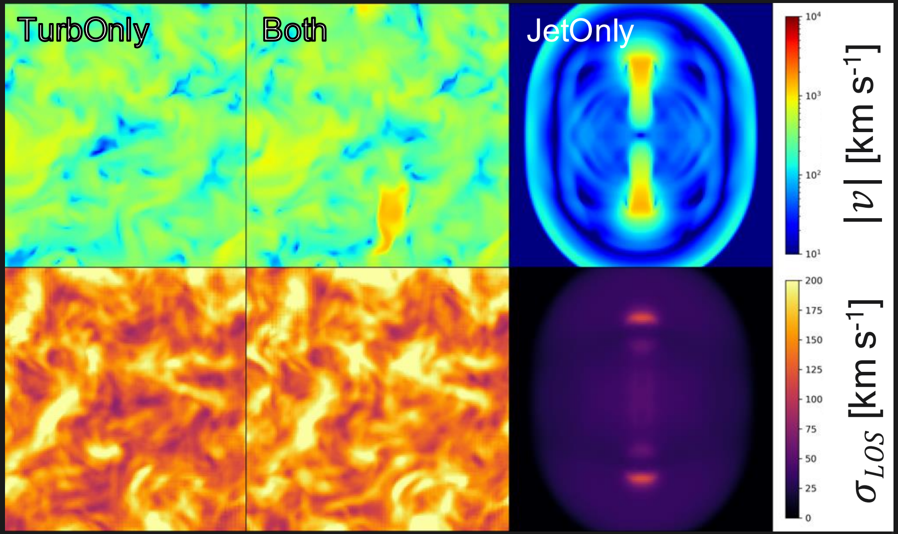
⟶ **Why there is the discrepancy between observations and simulations?**



Li et al. (2017)

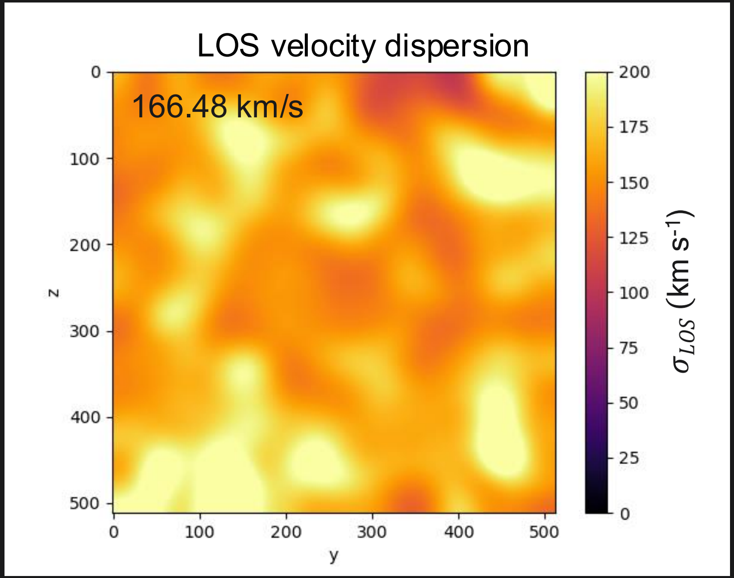
Methodology

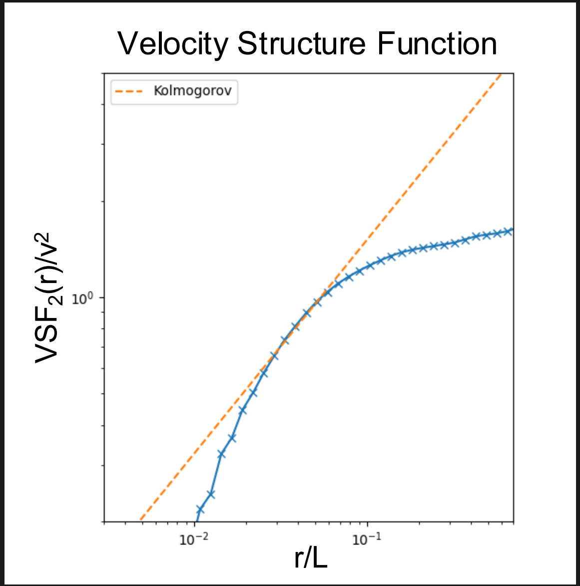
- 3D hydrodynamic simulation by using the FLASH code
- Perseus-like cluster
- Pre-existing turbulence: Ornstein-Uhlenbeck (OU) process
- Time-correlated acceleration field
- Single jet activity: bipolar, purely kinetic, duration time is 10Myr, jet power is 5×10^{45}erg/s



$$\sigma_{LOS} = \sqrt{\langle {v_{LOS}}^2 \rangle - \langle v_{LOS} \rangle^2}$$

Turbulent Heating Rate

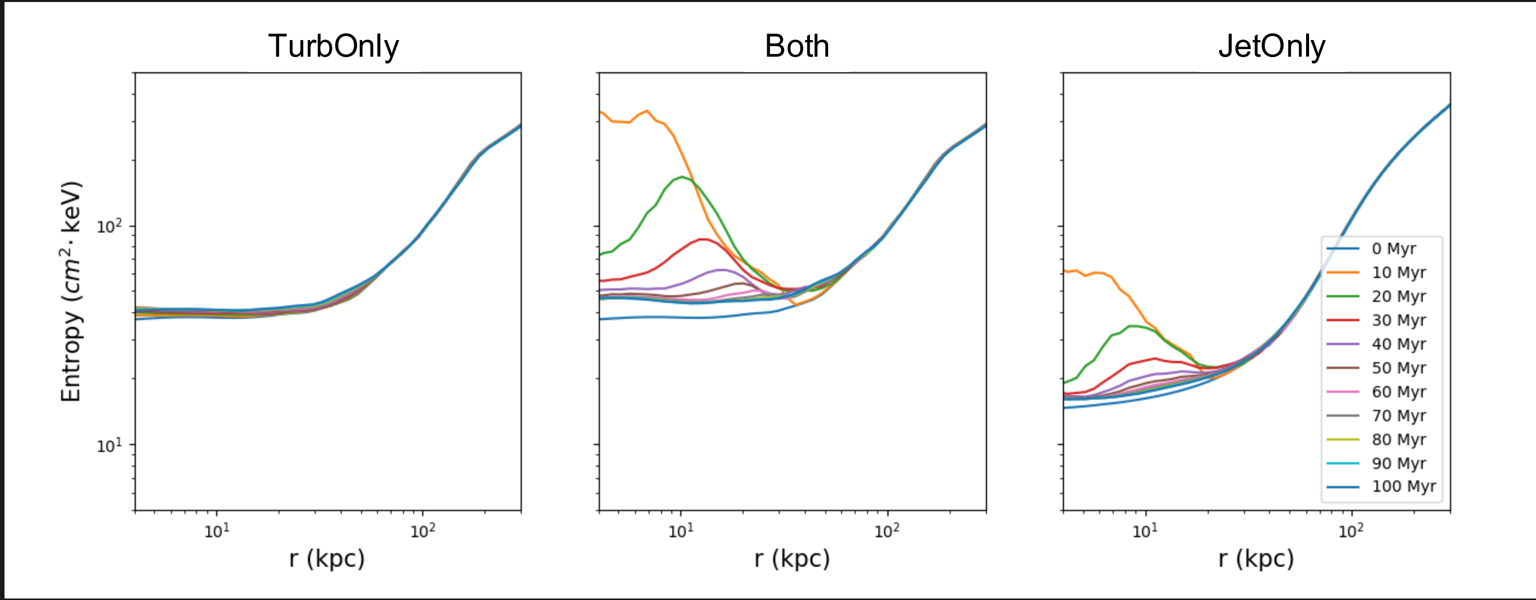




- We chose the setting where σ_{LOS} is comparable to the Hitomi observed level
- $VSF_p(r) = \langle |v(x + e_1 r, t) - v(x, t)|^p \rangle$, which can be used to quantify how velocity differences vary with spatial separation l
- Turbulent heating rate $Q_{turb} = \rho_0 C_Q V^3 / l$

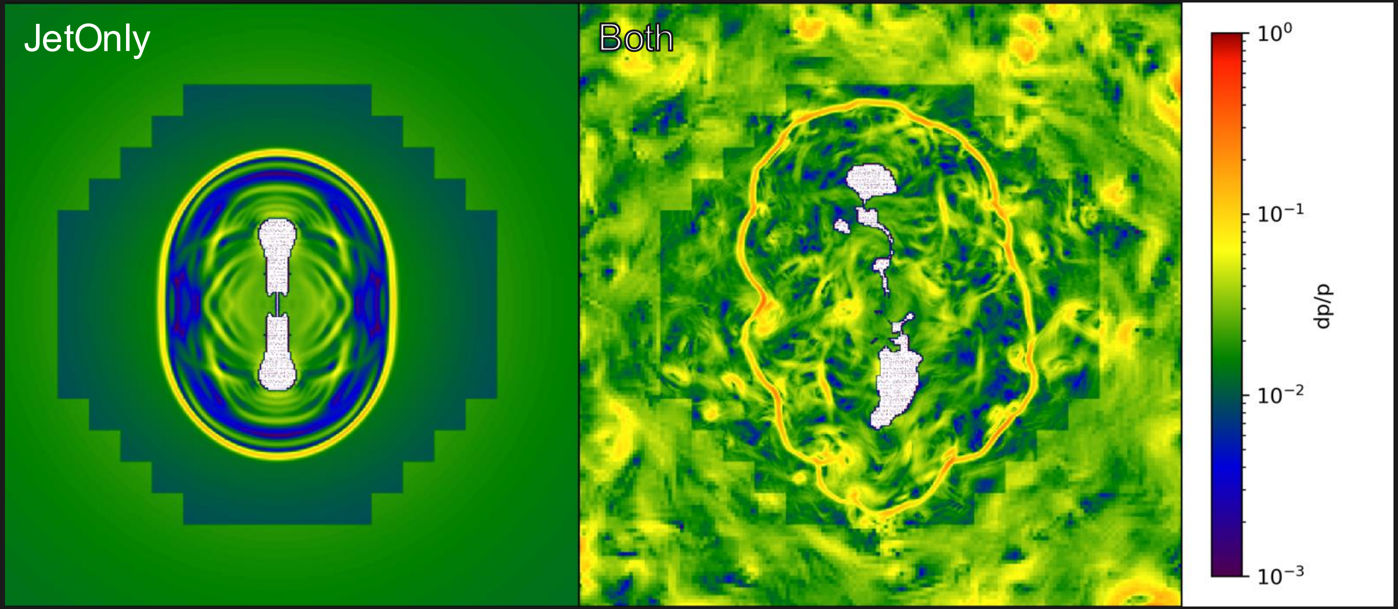
Results

Entropy Profile



- Entropy $K = k_B T / {n_e}^{2/3}$
- The entropy profiles of the Both run and JetOnly run are almost the same, which means that the turbulence does not affect heating significantly

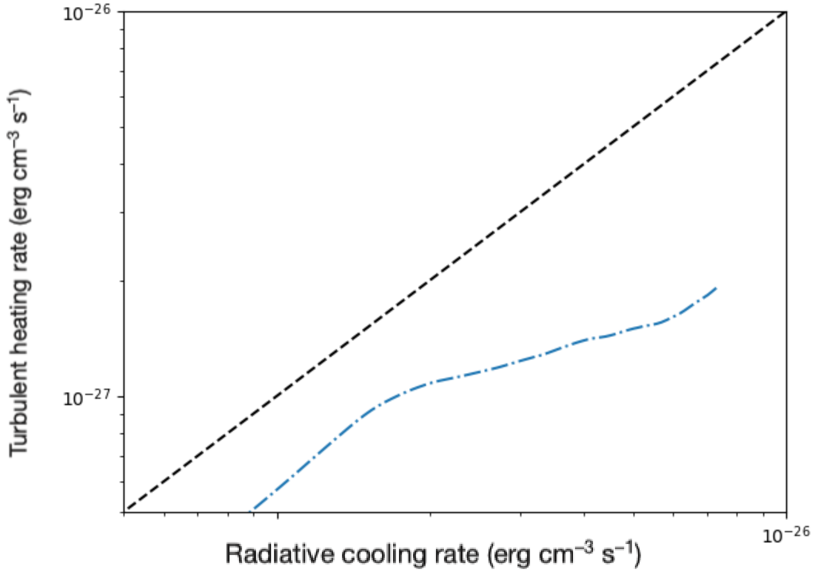
Shocks and Sound Waves (from Jet)



- Even though pre-existing turbulence dominates the velocity field, shocks and sound waves are still present from perturbation analysis

Preliminary Result - Turbulent Heating Rate

$$Q_{turb} = \rho_0 C_Q V^3 / l$$



- Our turbulent heating rate, calculated using the VSF, suggests that turbulent heating is not sufficient to balance cooling

Conclusion

- Velocity field is dominated by pre-existing turbulence
- However, our results show that jet heating remains dominant
- Our results suggest that turbulent heating may be subdominant, consistent with previous simulation studies

Time-correlated acceleration field

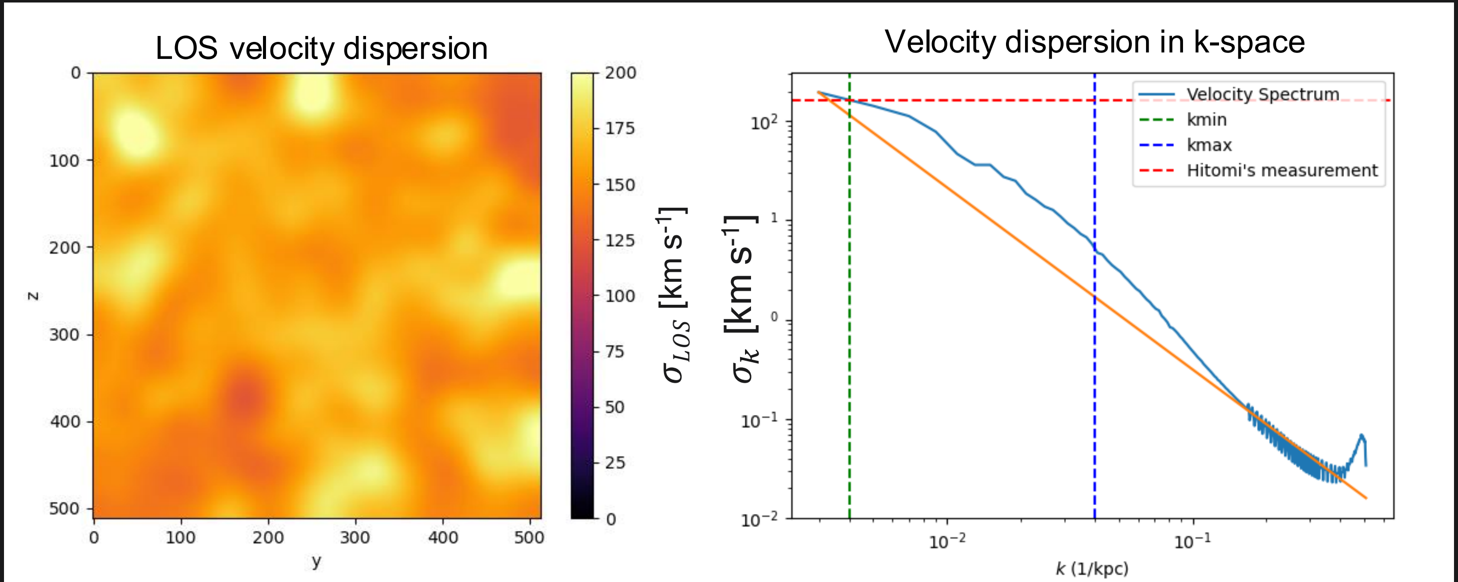
- Time-correlated means the value is related to its recent past (autocorrelation time) and beyond that time, the correlation decays, and the values behave more independently
- Ornstein-Uhlenbeck (OU) process:

$$\mathrm{d}\widehat{\vec{f}}(\vec{k},t) = f_0\,(\vec{k})\;\underline{\mathcal{P}}^{\zeta}(\vec{k})\;\mathrm{d}\vec{\mathcal{W}}(t)\;-\;\widehat{\vec{f}}(\vec{k},t)\,\frac{\mathrm{d}t}{T}\;.$$

Time-correlated acceleration field

Variable	Type	Default	Description
`ndim`	integer	3	The dimensionality of the simulation (1, 2, or 3)
`xmin, xmax`	real	−0.5, 0.5	Domain boundary coordinates in x direction
`ymin, ymax`	real	−0.5, 0.5	Domain boundary coordinates in y direction
`zmin, zmax`	real	−0.5, 0.5	Domain boundary coordinates in z direction
`st_spectform`	integer	1	Spectral shape (0: band, 1: paraboloid)
`st_decay`	real	0.5	Autocorrelation time of the OU process, $T = L_{\mathrm{peak}}/V$
`st_energy`	real	2e-3	Determines the driving amplitude
`st_stirmin`	real	6.283	Minimum wavenumber stirred (e.g., $k_{\mathrm{min}} \lesssim 2\pi/L_{\mathrm{box}}$)
`st_stirmax`	real	18.95	Maximum wavenumber stirred (e.g., $k_{\mathrm{max}} \gtrsim 6\pi/L_{\mathrm{box}}$)
`st_solweight`	real	1.0	Mode mixture $\zeta = [0,1]$ in Eq. (17.32). Typical values are 1.0: solenoidal; 0.0: compressive; 0.5: natural mixture.
`st_seed`	integer	140281	Random seed for stirring sequence
`end_time`	real	5.0	Final time in stirring sequence
`nsteps`	integer	100	Number of realizations between $t = 0$ and `end_time`
`outfilename`	string	"forcingfile.dat"	Output name (input file `st_infilename` for FLASH)

Velocity Dispersion



- When σ_{LOS} is comparable to the Hitomi observed level, but σ_k is significantly lower than it
- This could be a potential explanation for the persistent inconsistency between observations and simulations