Energy Partition of AGN-ICM Interaction

Sebastian Lacayo[1*], Brian O'Shea[2], & Deovrat Prasad[2,]

1. Florida International University , Miami, Florida 33199, USA
2. Michigan State University , East Lansing , Michigan 48824, USA

Introduction

- Hot diffuse plasma [also known as intra-cluster medium (ICM)] undergoes radiative cooling that leads to the precipitation of cold gas from the ICM into the cluster core.
- The cold gas accretes onto the supermassive black hole (SMBH) located in the cluster's central galaxy, fueling outbursts of powerful jets known as active galactic nuclei (AGN).
- The AGN outbursts compensates for the radiative cooling losses of the ICM by transferring the energy back into the ICM through shocks, turbulence, and cavities.

Objectives

- Understand how the active galactic nuclei (AGN) and supermassive black hole (SMBH) at the center of a galaxy cluster reheat the surrounding medium.
- Calculate what percentage of AGN energy is located in cavities, shocks, and turbulence using yt.

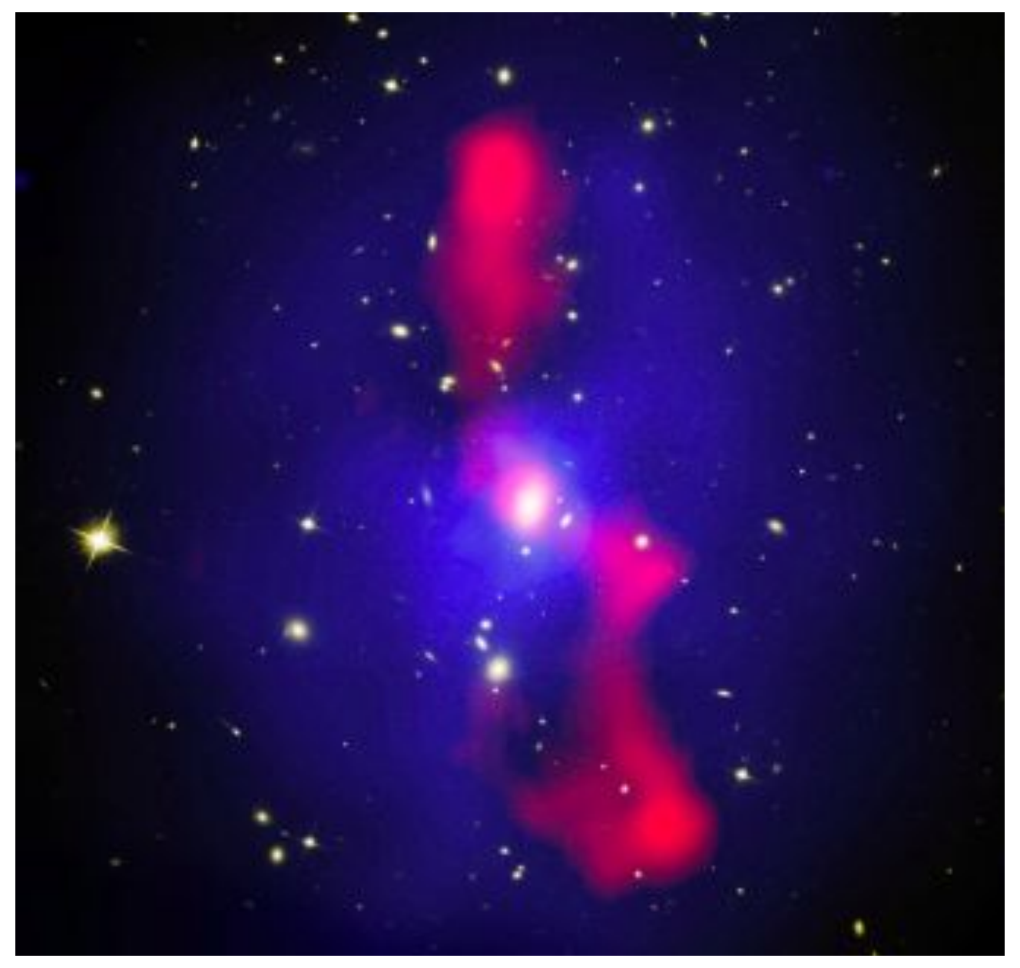


Figure 1: The above image shows an overlayed x-ray, radio, and observational image of AGN jets and the surrounding ICM in the MS0735.6+7421 cluster.

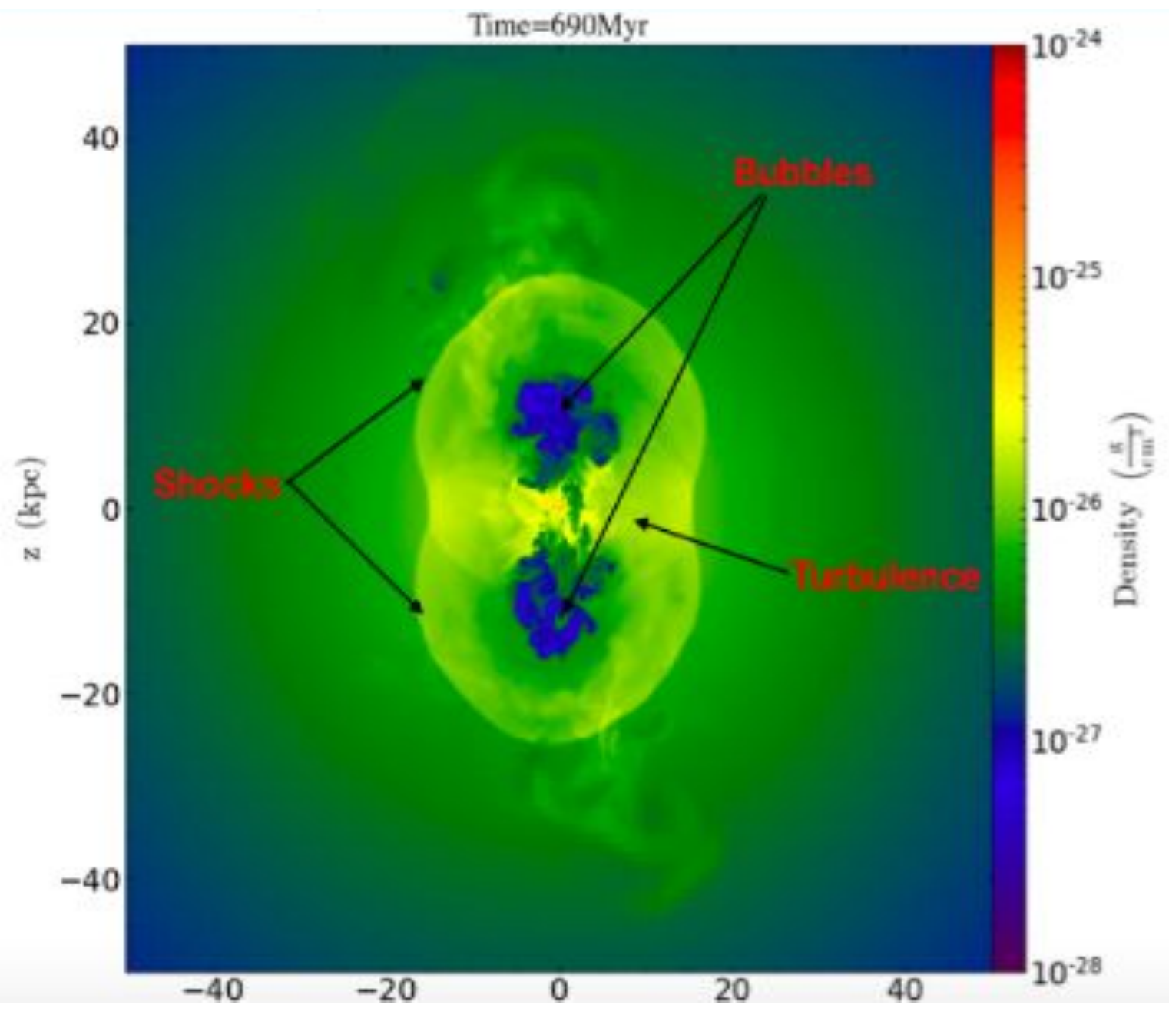
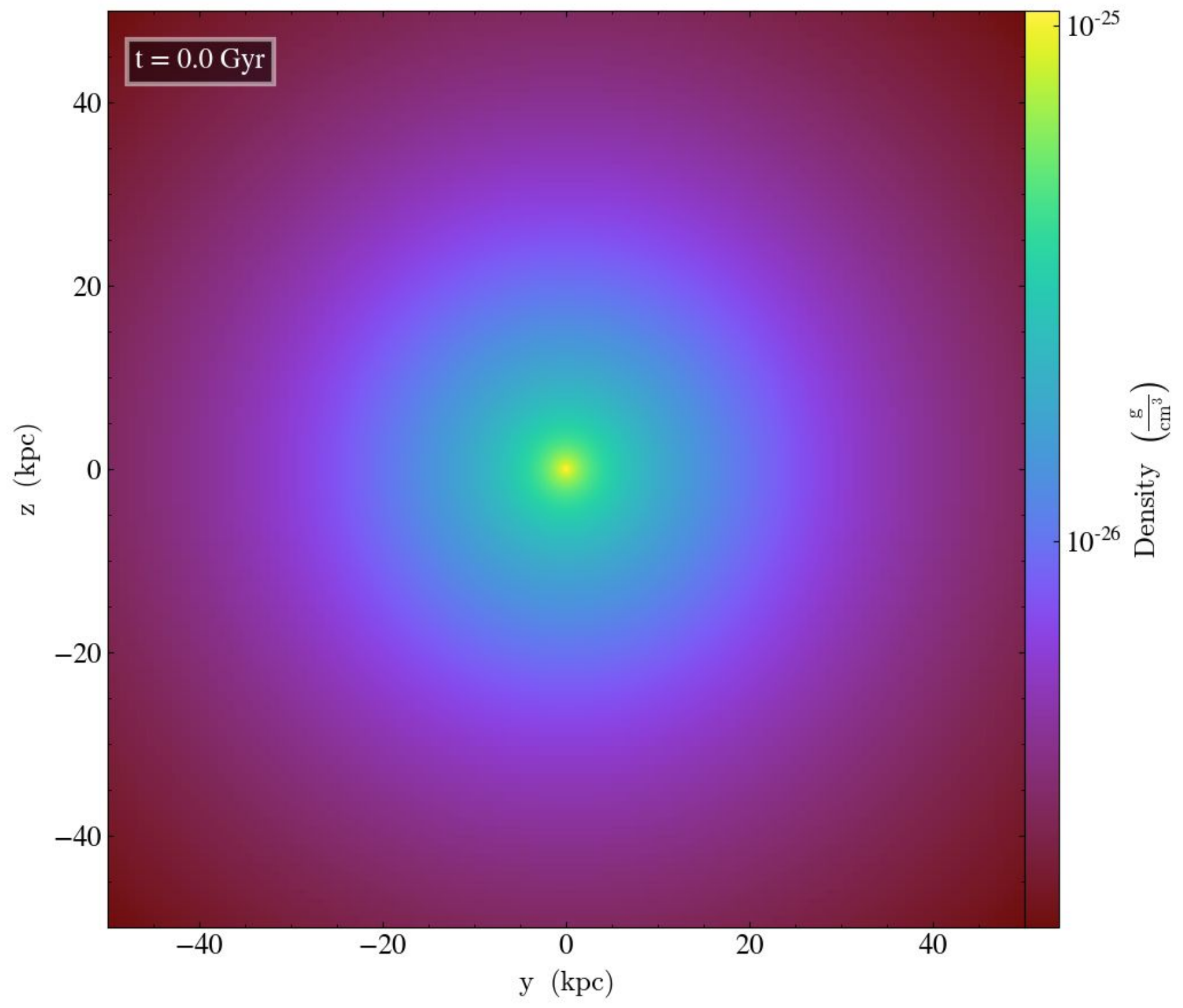


Figure 2: The above graph shows a data file created using the Enzo code with annotated regions of AGN feedback which were generated via yt.

Simulation Initialization

- Simulations created from Enzo, a multi-physics hydrodynamic simulation code
- Initial parameters based on galaxy group NGC-5044
- Three components of gravity (Dark Matter, BGG, Supermassive black holes)
- Gas initialized in hydrostatic equilibrium



Plot shows the density slice of the x-z plane of the initial state of the intra-cluster medium (ICM). The ICM is initialized in hydrostatic equilibrium with radiative cooling and AGN feedback modules switched on.

Methodology

- We analyze our data using yt, an open source python package for analyzing volumetric/hydrodynamic data and extracting AMR data sets.
- Run a time series analysis through a Data set comprised of 2 Gyr worth of simulated data.

Energy Calculations

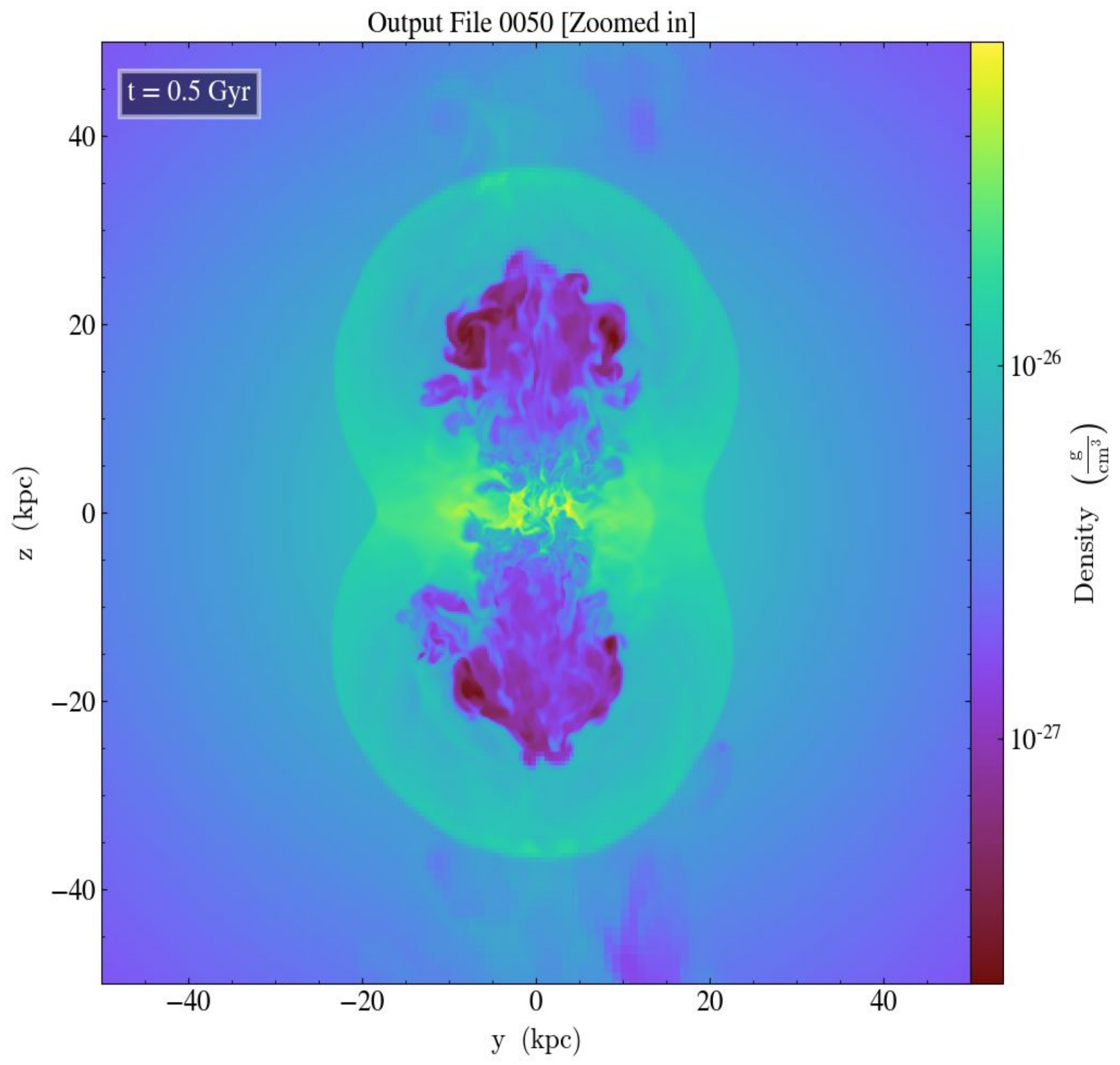


Figure 4: This graph is a slice of the x component at t = 0.5 Gyr of our data file '0050' scaled to show center 100 kpc.

- In order to extract proper information we need to create cuts and filter out unwanted data.
  - Generate a spherical data set of 50 kpc oriented at the center of our data set
  - Apply entropy criterion to the shock and cavity analysis
  - Added condition $\nabla \cdot \mathbf{V} < 0$, $\nabla T \cdot \nabla S > 0$ for shocks

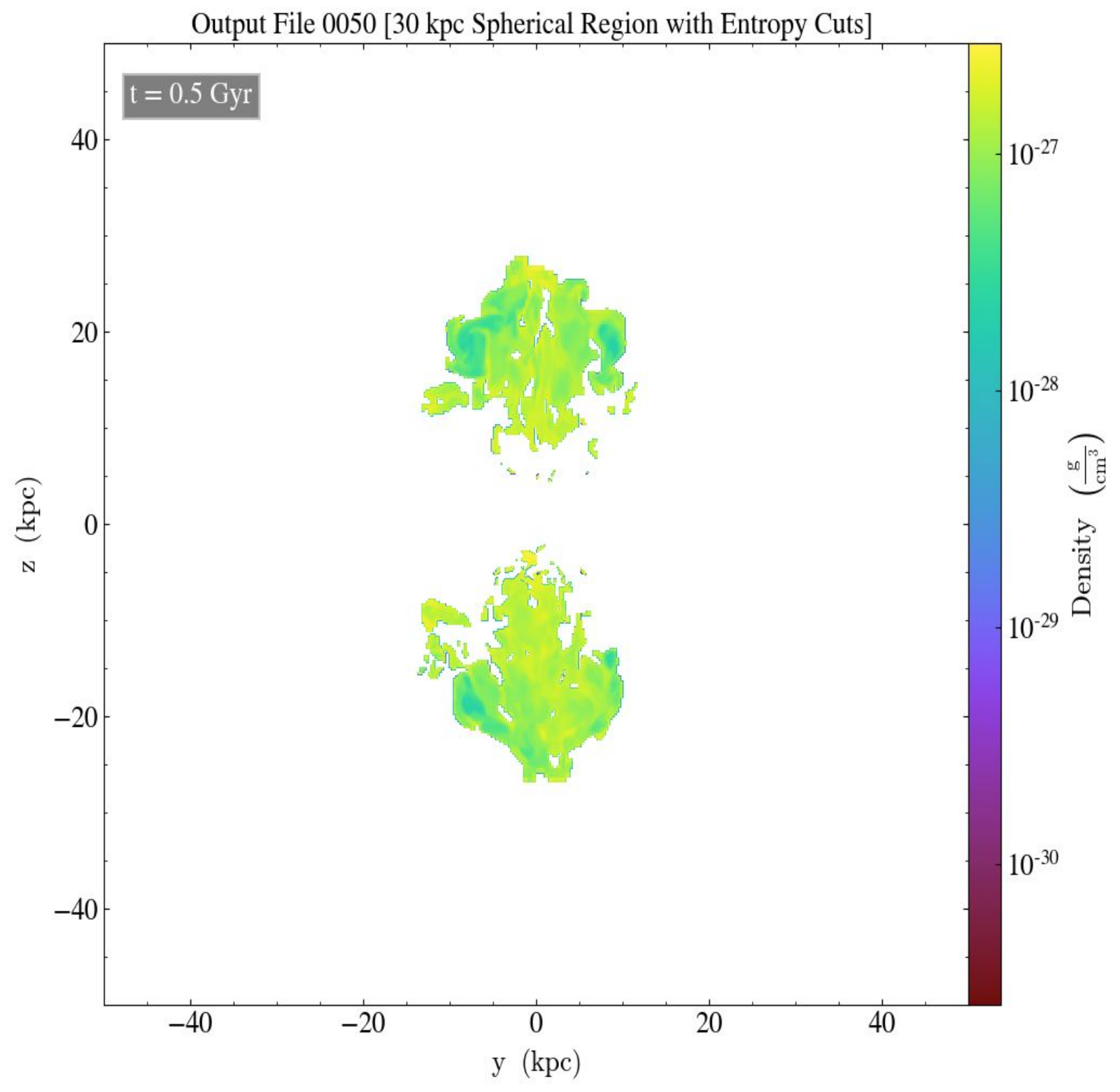


Figure 5: This graph is identical to figure 4 but has the entropy criterion cut regions to emphasize the cells where cavity bubbles are located.

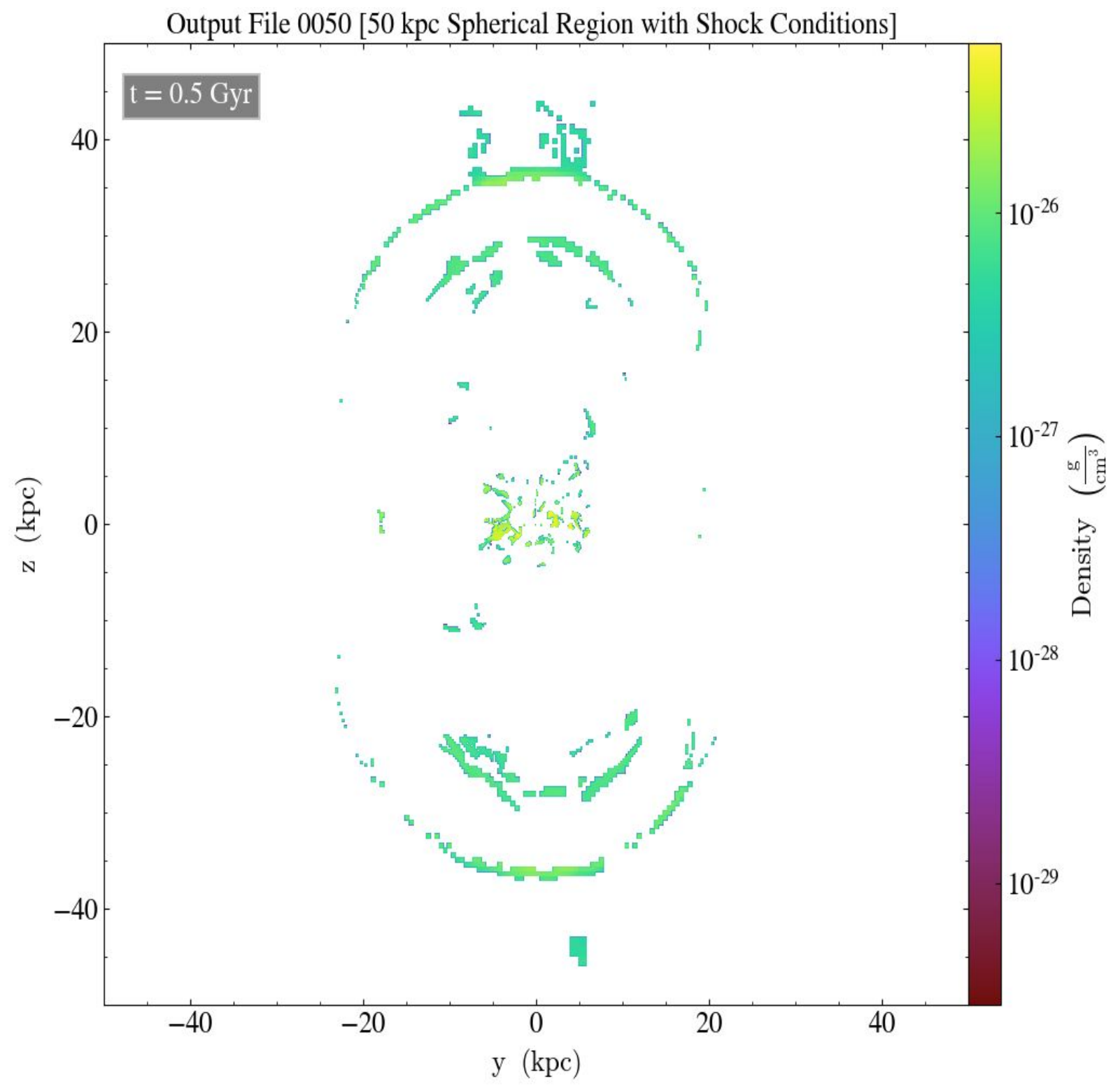


Figure 6: This graph is identical to figure 4 but has the shock conditions implemented to highlight cells where shocks are located.

- Following the data filtering process, we were able to calculate the cavity and shock energy for the simulation in separate time series.
- For every step in the time series we calculated the energy for every cell and added it up to get the total energies.

$$E_{cavity} = \sum 4 \cdot P_{cell} V_{cell}$$

$$E_{shocks} = \sum \tfrac{1}{2} \cdot \varrho_{cell} V_{cell} v^2_{cell}$$

Results

- Total energy of our AGN cavities and shocks, plotted with respect to time

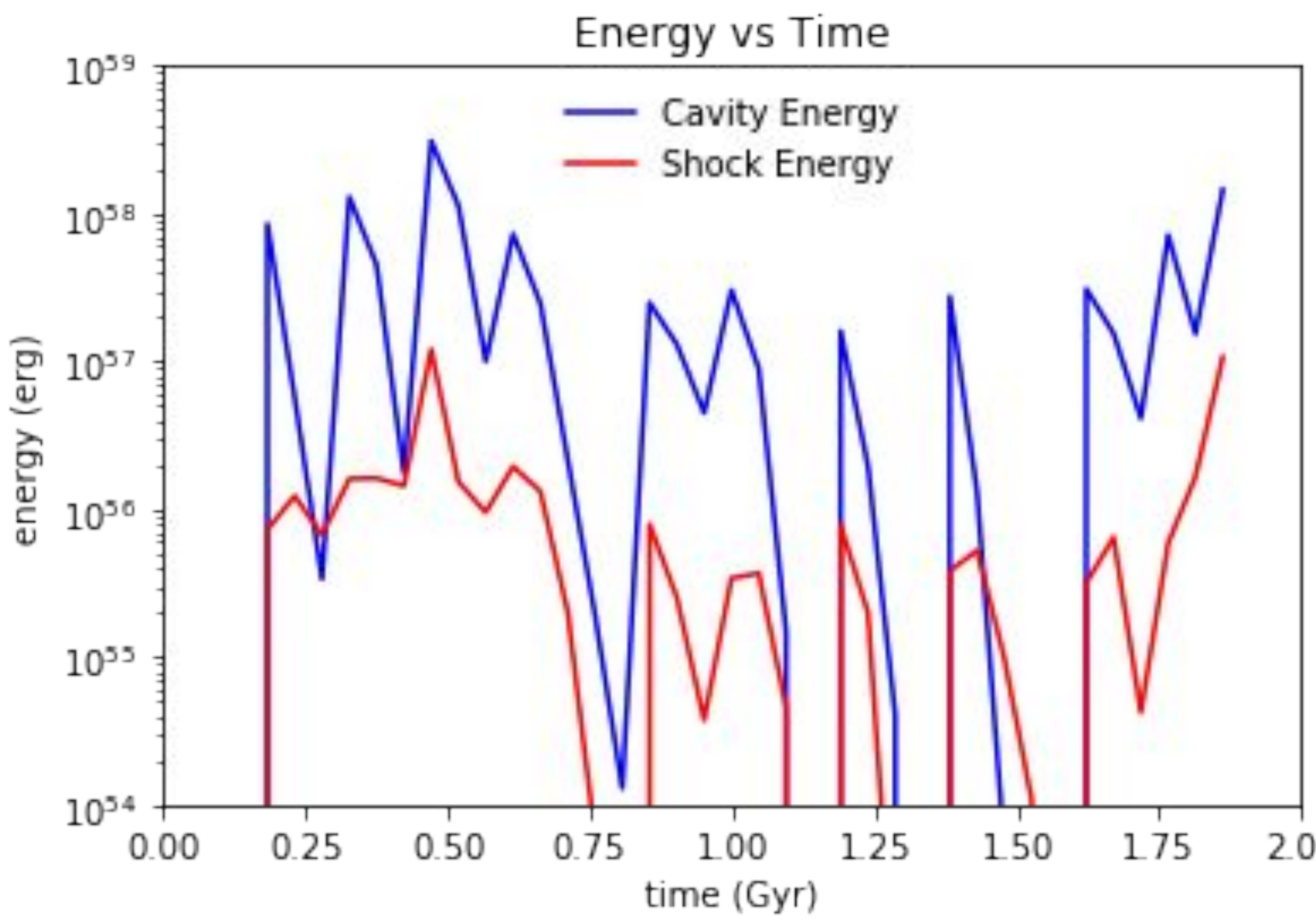


Figure 7: This graphs show our cavity and shock energy plotted vs time. We see that cavity energy is higher than our shock energy and as a result, cavity energy may play a bigger role in heating the ICM. Also, most of the shocks are weak shocks as they move out past 5 kpc.

Conclusion

- The results for our energy vs time graphs are appropriate given the cyclical nature of AGN feedback overtime
- We find that our cavity energy is two orders of magnitude larger than our shock energy
- We suspect our shock energy calculations are comprised of a max pollution percentage of around 10% due to turbulent ICM in the core
- Future work would comprise of using new physics and analysis tools to calculate turbulence energy

References

1. *Bryan, G.L.; et al. 2014, ApJS. 211:19. See enzo-project.org*
2. *Turk, Matthew J.; et al. 2011, ApJS. 192:1. See yt-project.org*
3. *"AGN Heating in Simulated Coo-Core Clusters," Li, Y., Ruszkowski, M., and Bryan, G. L., 2017, ApJ*
4. *"Heating Hot Atmospheres with Active Galactic Nuclei," McNamara, B. and Nulsen, P. J., 2007, ARAA*
5. *Figure 1: Credit: X-ray - NASA/CXC/Univ. Waterloo/B.Mcnamara Optical NASA/ESA/STScl/Univ. Waterloo/B.Mcnamara Radio: NRAO/Ohio Univ./L.Birzan et al*
6. *Figure 2: Credit: Deovrat Prasad, Michigan State University*

Acknowledgements

We appreciate helpful discussions with Aurora Coissairt, Carleen Markey and Dr. Grete. "This work was supported in part by Michigan State University through computational resources provided by the Institute for Cyber-Enabled Research."