Superresolution of Dark Matter Halos

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Refined Problem Statement

Schaurecker et al. [9] apply superresolution to cosmological structure in a dark matter only simulation called Illustris [6]. Rather than an *Eulerian* mesh, Illustris is based on a *Lagrangian* unstructured mesh (aka moving mesh) code called Arepo [10]. However, the Illustris code is not open source, just the data from it, so there is still a reason for researchers to use Eulerian mesh simulators. It would benefit them if the same superresolution techniques worked on traditional simulators as well. For this course project, I want to reproduce the results in Schaurecker et al. on data from an Eulerian simulator.

Astrophysical Simulation Codes

These are my criteria for choosing an astrophysical simulation code:

- The code should model self-gravity.
- The code should implement an Eulerian mesh without adaptive refinement.
- The project should have an extensive user manual.
- The project should have ready-to-run examples of cosmological-scale simulations with dark matter and hydrodynamics.

I went through the list of simulation codes on the course website and evaluated them according to my criteria:

- **PLUTO**: The code does not model self-gravity [5].
- **GADGET-4**: The code is particle-based simulation [11].
- **ZEUS**: The documentation is too sparse; no comprehensive user manual on the project page [13].
- **FLASH**: I was unable to find examples of cosmological simulations in [3] and [4].
- **Athena**: I was unable to find examples of cosmological simulations in [12] and [1].
- **Athena++**: I was unable to find examples of cosmological simulations in [2].
- **Enzo**: Enzo models self-gravity [7], is mesh-based [7], has extensive documentation [14], and examples of cosmological simluation [8]!

Run name	Illustris-Dark-2	Illustris-Dark-3
Volume [Mpc^3]	106.5^3	106.5^3
Box size [Mpc/h]	75	75
Dark matter particles	910^2	455^2

Figure 1: *Parameters used in Illustris*

Parameters

Schaurecker et al. [9] use Illustris-Dark-2 and Illustris-Dark-3 defined in [6], which I have copied in in fig. 1.

Once I have that, I will adapt Schaurecker's code[1] to read the output files from Enzo and execute training.

Analyses

Following Schaurecker et al. [9], I will compare three quantities between each dataset: power spectrum, galaxy two-point correlation, Halo mass distribution, and halo two-point correlation. The power spectrum is given by running a fast fourier transform over a cloud-in-cell interpolated density mesh. The two-point correlation function can be found by iterating over every pair of galaxies and accumulating a histogram of their distance. These can be compared between the original Illustris-2, Illustris-3, the low-resolution sampling of Illustris-3, the high-resolution sampling of Illustris-2, and the generated output of the neural net as in figure fig. 2.

References

[1] *Athena Documentation: User Guide*.

[2] *Athena++: User Guide*.

[3] *FLASH Center for Computational Science*. URL: https://flash.rochester.edu/site/gallery/.

[4] *FLASH User's Guide*. Oct. 2019. URL: https://flash.rochester.edu/site/flashcode/user_support/flash4_ug_4p62/.

[5] A. Mignone et al. "PLUTO: A Numerical Code for Computational Astrophysics". In: *The Astrophysical Journal Supplement Series* 170.1 (May 2007), pp. 228–242. DOI: 10.1086/513316. arXiv: astro-ph/0701854 [astro-ph].

[1] Available at https://github.com/dschaurecker/dl_halo

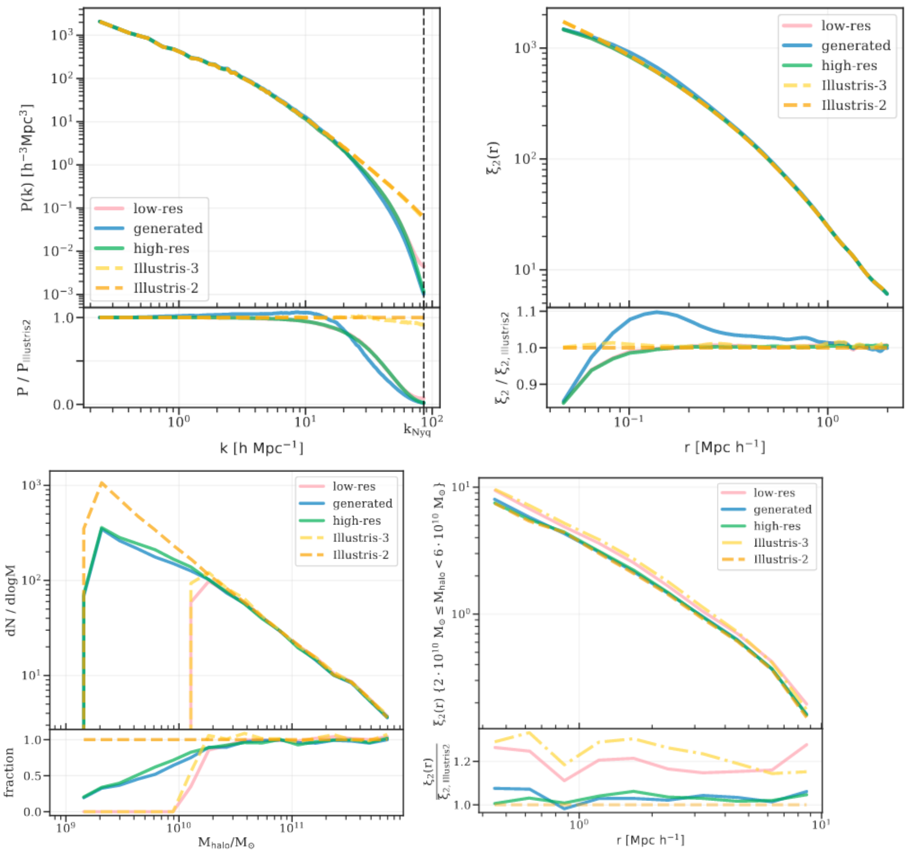

Figure 2: *These are figure 4, 5, and 6 from [9]. I will try to replicate it with Enzo in place of Illustris*

[6] D. Nelson et al. “The Illustris simulation: Public data release”. In: *Astronomy and Computing* 13 (Sept. 2015), pp. 12–37. ISSN: 2213-1337. DOI: https://doi.org/10.1016/j.ascom.2015.09.003. URL: https://www.sciencedirect.com/science/article/pii/S2213133715000864.

[7] Brian W. O'Shea et al. “Introducing Enzo, an AMR Cosmology Application”. In: *arXiv e-prints*, astro-ph/0403044 (Mar. 2004), astro–ph/0403044. arXiv: astro-ph/0403044 [astro-ph].

[8] *Sample inits and Enzo parameter files*. URL: https://enzo.readthedocs.io/en/enzo-2.4/tutorials/SampleParameterFiles.html.

[9] David Schaurecker et al. *Super-resolving Dark Matter Halos using Generative Deep Learning*. 2021. eprint: arXiv:2111.06393.

[10] Volker Springel. "Moving-mesh hydrodynamics with the AREPO code". In: *Proceedings of the International Astronomical Union* 6.S270 (2010), pp. 203–206. DOI: 10.1017/S1743921311000378.

[11] Volker Springel. "The cosmological simulation code GADGET-2". In: *Monthly Notices of the Royal Astronomical Society* 364.4 (Dec. 2005), pp. 1105–1134. DOI: 10.1111/j.1365-2966.2005.09655.x. arXiv: astro-ph/0505010 [astro-ph].

[12] James M Stone. *Athena Applications Page*. URL: https://www.astro.princeton.edu/~jstone/Athena/athena-apps/index.html.

[13] James M Stone. *Stone's Zeus Code Home Page*. URL: https://www.astro.princeton.edu/~jstone/zeus.html.

[14] *Welcome to Enzo's documentation!* URL: https://enzo.readthedocs.io/en/enzo-2.4/index.html.