Finding Neutrino Wakes in an N-body Simulation

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This Project

This project uses data from the Quijote N-body simulation for massive neutrinos. Using the Pylians3 python module, the aim of this project is to reveal neutrino properties from a wake of neutrinos produced from moving dark matter halos.

What are neutrinos?

The standard model predicts that in the early universe neutrinos were produced in copious amounts through weak interactions. These neutrinos free stream through the universe today on a scale dependent on the neutrino mass. Above this scale neutrinos will cluster like cold dark matter (CDM) does, and below it they free stream and suppress the growth of large-scale structure[1].

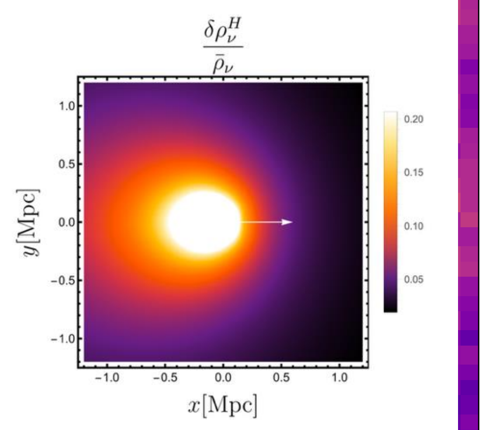

Figure 2Anistropic clustering of neutrinos behind a point mass halo.

Neutrino Wakes

As a dark matter halo moves through the free streaming neutrinos it experiences a phenomenon known as dynamical friction. This friction on the halo induces a displacement in the halo's position relative to the neutrino background. This displacement results in an anisotropic overdensity of neutrinos behind the halo i.e. a neutrino wake, as shown in figure 1. The magnitude of this wake is dependent on the sum of neutrino masses and so a neutrino wake can be used to constrain the neutrino mass[2].

Results

In figure 2 are the stacked and velocity aligned halo positions. A dipole feature in the neutrino overdensity is clearly visible and becomes more defined as the neutrino mass increase, due to the increased velocity dispersion. The CDM doesn't exhibit the same effect and is most likely due to its lower velocity dispersion. Noticeably the subtraction fields (on the right) don't show a neutrino wake.

Method

The data used in this project was provided by the Quijote N-body simulation for massive neutrinos. Density fields for the particles (CDM & neutrinos) were produced by using a 3D gird and averaging the contents of each cube. A slice was then taken and all cubes along the depth of that slice averaged to produce a 2D slice of the simulation box. The halos within a slice were individually centred and rotated such that their velocities aligned. Doing so allows the halos and their surroundings to be stacked on top of each other. This was done for every possible slice in the box and along the x, y and z directions to artificially increase the number of halos in the box. The produced CDM and neutrino overdensities around the stacked halos could then be subtracted from one another to reveal fine structure such as a neutrino wake. This is similar to the method found in [3].

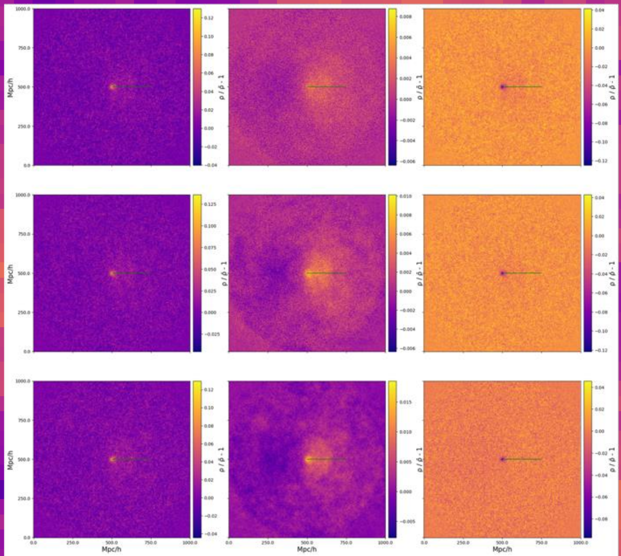

Figure 1 The stacked halo positions. The left column shows the CDM, the middle shows neutrinos and the right shows the difference between them. The top row shows the neutrino mass 0.1eV, the middle 0.2eV and the bottom 0.4eV.

Conclusion

Unfortunately no neutrino wakes were revealed in this project. This is likely due to the large scale dipole of the neutrinos dominating over any neutrino wake signal. Given that the dipole dominates in all three neutrino plots, the neutrino mass is irrelevant and the wake will always be too weak to be found. This has not been observed in other studies until now. It is possible that the neutrino wake will never be observed as the SNR for neutrino wakes is predicted to be very large[4] although improved modelling could allow its detection in simulation data.

Given that the dipole is clearly correlated with neutrino mass and to a significantly different strength than with the CDM, observational techniques such as gravitational lensing could be used to determine the mass of the neutrino by looking at the slight differences in the bending of light around a dark matter halo.

Future Work

Possible future work includes:

- Measuring the relative velocity field between the neutrinos and the CDM to reveal velocity dipole structure.
- Amplifying the CDM dipole feature to improve the subtraction of the dipole to reveal underlying structure such as a neutrino wake.

References

Figure one is from Caio Nascimento et al. (2023) [1] Julien Lesgourgues et al. (2014)
[2] Hong-Ming Zhu et al. (2016) [3] Derek Inman et al. (2015)
[3] Yan-Chuan et al. (2025)
[4] Caio B. de S. Nascimento et al. (2025)