CASPEN Exit Report: BFExSymphony LMC Collaboration

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Abstract

Report on CASPEN visit to CCA, 9/21-10/5

1 Motivation

Evidence from tailored simulations [GCBL+19] and observations [CNGC+21] indicate the the Large Magellanic Cloud (LMC) – a massive satellite galaxy in the process disrupting in the Milky Way's dark matter halo – is likely on first infall [BKH+07] and is inducing a significant wake in the Milky Way's dark matter halo [GCBL+19, CGCD+20, CNGC+21]. Characterizing the size and strength of this wake in simulations will provide important predictions and theoretical underpinnings for observational results. However, so far, most of the studies of dark makes wakes have been restricted to tailored simulations with a smooth Milky Way dark matter halo and a single subhalo (the LMC). In this setup, anisotropies in the host halo are entirely induced by the infall of the LMC. This is not the case in a realistic cosmological halo, which will have undergone a number of mergers ranging in size and mass over the course of its assembly history. These mergers will each have left their own impact on the shape of the dark matter halo making it difficult to disentangle the impact of the LMC from the impact of other smaller or older mergers.

The Symphony Milky Way-est suite is a set of 20 Milky Way mass, high-resolution, dark-matter-only, zoom-in simulations constrained to have an identified LMC analog at a distance between $30 < r < 70$ kpc at the final snapshot [Buch et al., in prep]. This makes it ideal for studying the impact of varying cosmological histories and orbital parameters on the strength of the induced LMC dark matter wake and the overall shape of the halo. Additionally, for all subhalos above the resolution limit, individual particles are tracked using the method developed by [MDFW+23]. This allows us to separately examine the impact of the LMC infall on the smoothly accreted component of the Milky Way's dark matter halo as well as the full halo including undisrupted or partially disrupted substructure.

2 Methodology

The basis-function expansion (BFE) algorithm uses empirically chosen basis functions to expand the potential field of an ensemble of particles [PWK22]. The BFE algorithm can be applied across simulation snapshots resulting in a simplified representation of the density and potential of an N-body simulation which can then be compared across time. This provides a more convenient mathematical basis for characterizing the size and shape of dark matter halos in simulations and has been previously applied to the study of LMC wakes [GCBL+21].

The goal of the two-week CASPEN exchange was to apply the BFE algorithm to multiple snapshots of a single test halo from the Symphony suite of simulations using the `pyEXP` code base [PWK22] in order to understand and formulate best practices for the application of the BFE algorithm to the full Symphony MWest suite of simulations.

3 Results

In order to test the BFE algorithm, we began by applying it to a halo which had not experienced a recent major merger. This gave us a good baseline for understanding how the algorithm performed in

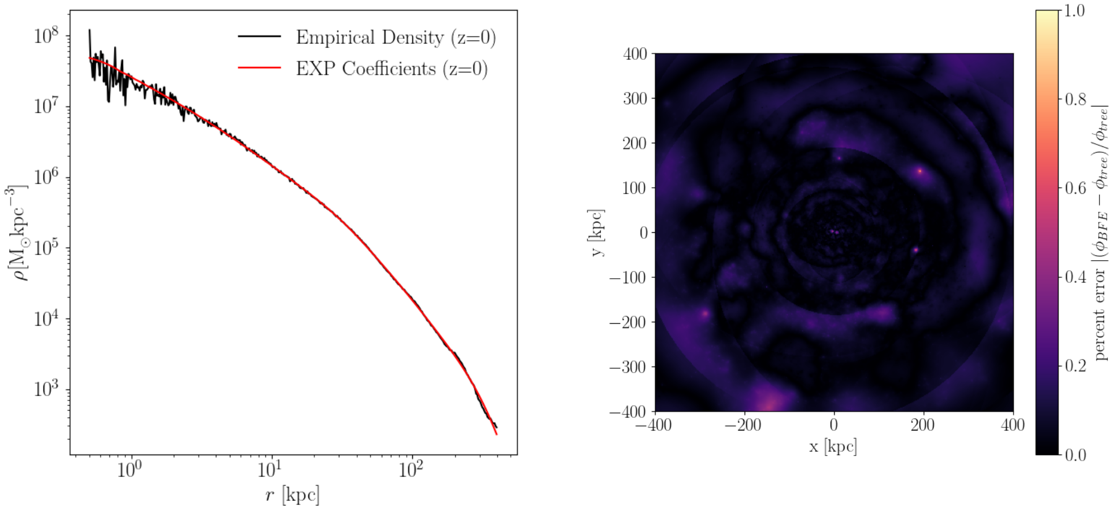

Figure 1: *left:* Comparison between empirical density profile from particle data (black) and density profile from BFE expansion (red). *right:* Percent error on potential reconstruction from BFE compared to tree-based potential calculation from particle data for potential slice at $z = 0$.

the case of a relatively well-behaved, spherically symmetric halo.

We found that the BFE was able to accurately approximate both the density and the potential (compared to a standard tree-based potential solver) with only ten radial ($n = 10$) and ten azimuthal ($l = 10$) modes (Figure 1.) We also found that approximating the particle density as an NFW density profile still produced a basis, which could accurately reconstruct the potential to within a few percent error and was less likely to result in a failure of the Sturm-Louiville Equation (SLE) solver than computing the basis based on the empirical particle density. Lastly, we found that the BFE was relatively insensitive to changes in the scale radius although very small choices of scale radii tended to result in non-orthogonal basis. We found that setting the scale length to the half-mass radius produced reasonable results.

In terms of the accuracy of the potential reconstruction, we found a trade-off between the maximum radius of the BFE and the likelihood of the expansion producing negative density values. Larger radii expansions produced more accurate approximations of the potential, but were much more likely to result in negative density values in the outer regions of the halo where the particle count from the simulations is low. We plan to investigate this trade-off further in future work.

Lastly, we applied the BFE algorithm to halo snapshots ranging from $z = 1$ to $z = 0$. Unsurprisingly, we ran into challenges when trying to find a basis which worked well for both the $z = 1$ and the $z = 0$ particle data, as on average, the halos at $z = 0$ are significantly larger than at $z = 1$. Investigating the best compromise basis to model the halo across its growth history will be another avenue of future analysis.

We plan to continue this analysis in the winter and spring with a paper expected in spring 2024.

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