Abstract

The standard Lambda cold dark matter (ΛCDM) cosmological paradigm predicts that structure formation proceeds hierarchically, assembling the large-scale cosmic web. High-resolution computer simulations suggest that evolution of dark matter (DM) haloes is closely linked to this network of nodes, filaments, walls, and voids. Rather than serving as a passive backdrop, the cosmic web may exert an active dynamical influence on the structures residing within it. This dissertation explores how the cosmic web environment of the host DM halo is associated with the abundance, internal structure, and evolutionary history of its subhalo populations at present (redshift $z = 0$) and past (higher redshifts), and examines how these dependencies may propagate into the substructure boost factor of possible DM annihilation signatures.

Using COLOR N-body simulation and the `CaCTus` cosmic web classification framework, we analyze cumulative subhalo populations hosted by fixed-mass haloes residing in distinct cosmic web environments to help isolate environmental effects from simple halo mass scaling. Our results suggest that the cosmic web environment of the host imprints a systematic signal on its subhalo populations independently of the host mass. Subhaloes hosted by filament haloes tend to be 5 to 30% more abundant than the cosmic mean, while those hosted by void haloes show deficits of up to 50% at the high-mass end of the subhalo mass function. The total subhalo mass fraction varies by 2 to 20% between environments. Furthermore, subhaloes hosted by filament haloes appear 5 to 9% more concentrated than those hosted by void haloes, a trend most pronounced in the lowest-mass host systems.

For models where DM annihilates into gamma rays, we extend this analysis to the substructure boost factor of predicted DM annihilation. Since the annihilation rate scales with the square of the local density, environmental shifts in the properties of subhaloes hosted by haloes in different environments may alter the boost factor. By incorporating our environment-dependent host concentrations, subhalo mass functions, and internal density profiles into two semi-analytic frameworks, we find tentative indications that subhaloes hosted by void haloes exhibit boost factor suppressions of about 30% relative to the cosmic average, while those hosted by filament haloes display a mass-dependent transition, ranging from suppressions of $\sim$15% at low host masses to enhancements of $\sim$12% at high host masses. We also derive an empirical fitting prescription for this environment-conditioned boost factor as a potential basis for future implementation.

We investigate the physical origin of these signatures by tracing subhalo histories through cosmic time using merger trees. We compare subhalo populations across different environments at their present-day values and at their peak state, defined as the state in which they attain maximum mass or velocity in their merger history. Our results are consistent with a two-stage evolutionary picture. Part of the environmental dependence may be already established before the subhaloes fall into their host, which is also reflected in their peak properties. Afterward, subsequent evolution within the host further modifies these dependencies through environment-dependent tidal processing. Structural ratios suggest that the mass at the outskirts of subhaloes is substantially depleted, dropping to 25% to 60% of its peak value by the present day. Conversely, the inner structural potential appears more resilient, with the maximum circular velocity retaining 70% to 90% of its peak amplitude.

Tracing earlier time (simulation snapshots) suggests that this environmental ordering builds up progressively during major assembly phases. At redshift $z = 2.0$, the subhalo mass function shows an emerging differentiation for subhaloes hosted by proto-filament haloes, while the relation between maximum circular velocity and its corresponding radius exhibits a 30% to 40% environmental variation. These trends may be relevant for semi-empirical galaxy–halo modelling, as they are broadly consistent with the relative robustness of velocity-based proxies such as peak subhalo velocity compared to present-day bound mass, and may provide useful simulation-based baselines for future studies of environmental satellite evolution, lensing-related substructure statistics, and galaxy assembly bias.

The results of this thesis suggest that neglecting the cosmic web environment of the host halo when modelling subhalo statistics and DM annihilation signals at $z = 0$ and at higher redshifts may introduce systematic biases on the order of tens of percent. This indicates that the large-scale environment of the host warrants consideration as a potentially important component in future investigations of satellite galaxy populations, substructure demographics across cosmic time, gravitational lensing sensitivities, and indirect DM detection predictions.