On the Evolution of Dark Matter Halo Properties after Major and Minor Mergers

SIP SCIENCE INTERNSHIP PROGRAM

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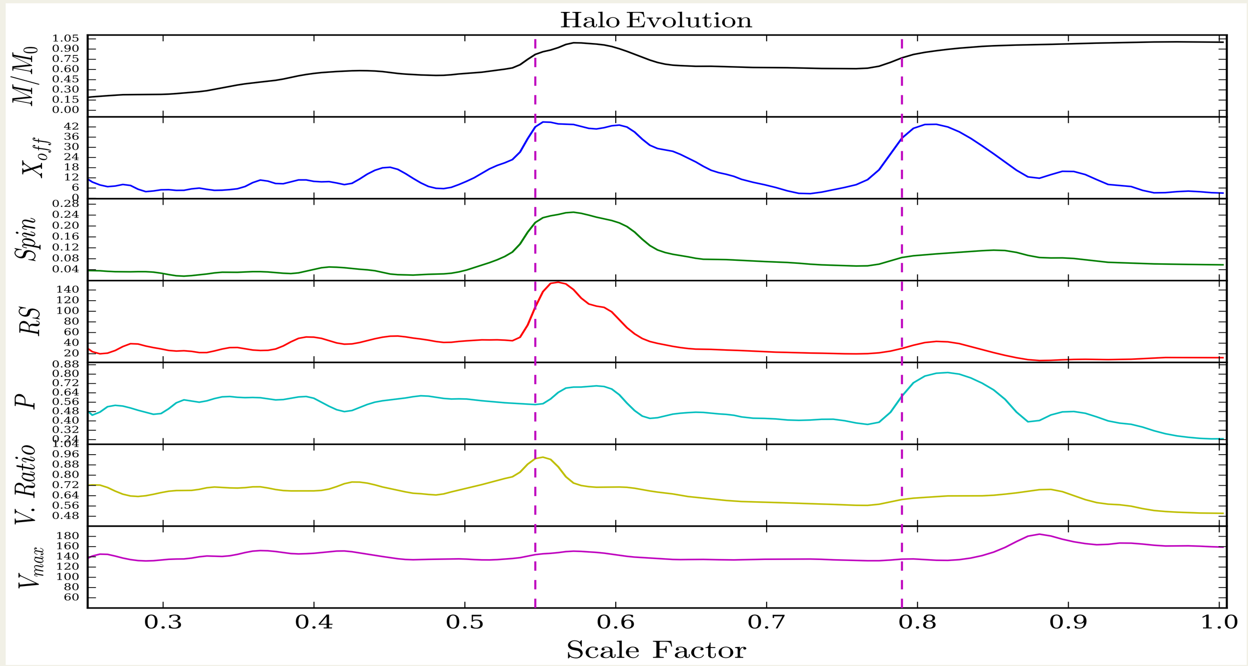
Introduction

In the standard Lambda-CDM model of our Universe, it is said that galaxies form and evolve within dark matter halos. Although it is expected that halos mass typically grow over time, it was recently discovered that there are times where halos experience “relaxation”, in which they actually lose mass for a period of time. Studies have detailed its cause to come from major mergers, i.e., where the merging halos have a mass ratio of $m/M > 0.3$. To investigate the effects of these major mergers, our project analyzed outputs produced by ROCKSTAR on the Bolshoi-Planck simulation to evaluate properties (centering, spin, prolateness, scale radius, and virial ratio) at distinct scale factors. In order to characterize these merger events, we applyied a Gaussian filter to the property evolutions and characterized peak distributions, frequencies, and variabilities. However, there were also halos that experienced relaxation without the presence of major mergers. We hypothesized that this was due to minor mergers. By using property peaks to create a novel merger detection algorithm, we found minor mergers and matched them to the unaccounted halos. Studying both major and minor mergers together, we aim to gain a more complete view of dark matter halo growth histories.

Methodology

By mapping halos by their roots and recording their properties chronologically, we plotted the evolution of properties for each individual halo. A sample halo’s evolution is provided below:



- M is the mass in units of $M_\odot/h$
- X_{off} is the offset of the halo center from the center of mass within the radius
- *Spin* is the dimensionless measure of amount of rotation
- *RS* is the scale radius in kpc/h where the logarithmic slope of the density profile equals -2
- *P* is the prolateness measure of halo shape from 0 (spherical) to 1 (needle shaped)
- *V. Ratio* is the virial ratio; ratio of halo kinetic to potential energy (0.5 for relaxed halos).
- V_{max} is the maximum circular velocity in km/s.

Looking at Merger Distributions

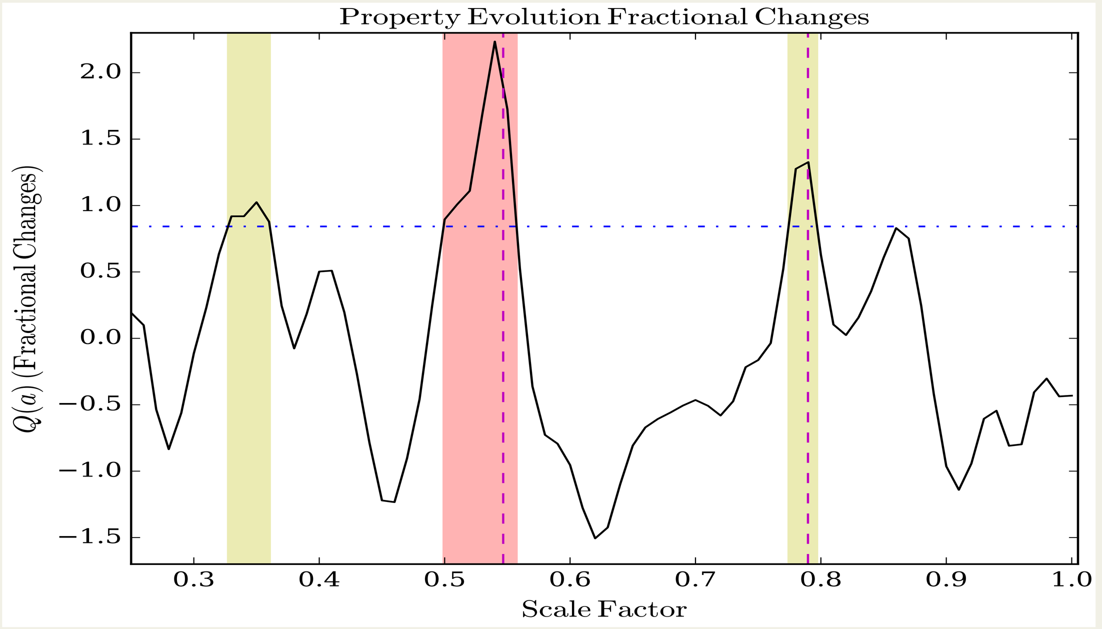
To characterize responses in the relaxation period, we first interpolated the evolution of the five properties onto an evenly spaced grid where the scale factors increment by 0.005 to set equal time intervals. We then applied a Gaussian filter at a standard deviation of $\sigma = 4.0$ (determined by various tests) to reduce noise. Examining the smoothed data, we tabulated the scale factor elapsed before recording a first, second, third, and fourth merger-induced peak. Finally, we reported the relative percentage of halos that peaked for each halo group.

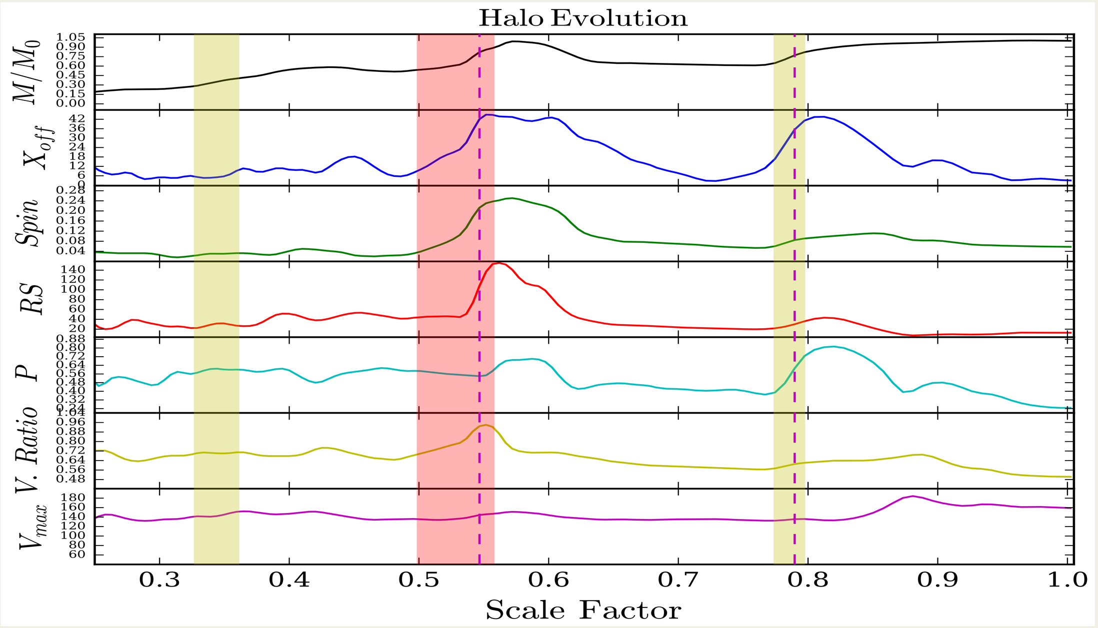
Algorithm for Detecting Minor Mergers

This algorithm centered around detecting common peaks among the different halo properties. For each property, we sought out fractional increases/decreases from one scale factor to the next using the interpolated 0.005 step-size array. Next, we had to calculate each property’s weighting to then create a combined fractional change:

$$w_{prop} = \frac{\bar{x}_{\delta_{prop},MM} - \bar{x}_{\delta_{prop},rand}}{\sigma_{\delta_{prop},rand}} \qquad \delta_{overall} = \sum\left(\frac{\delta_{prop} - \bar{x}_{\delta_{prop},rand}}{\sigma_{\delta_{prop},rand}} \times \frac{w_{prop}}{\sum w_{prop}}\right)$$

Optimizing a threshold to increase detection accuracy, we maximized agreement (% of recorded major mergers detected) and minimized disagreement (% of detections that are not recorded major mergers). Our final results: *Agreement*: 93.0%, *Disagreement*: 35.81%. To distinguish between major and minor mergers, we characterized each by the integral of their combined fractional change over the threshold. In the end, this is what our algorithm outputs:



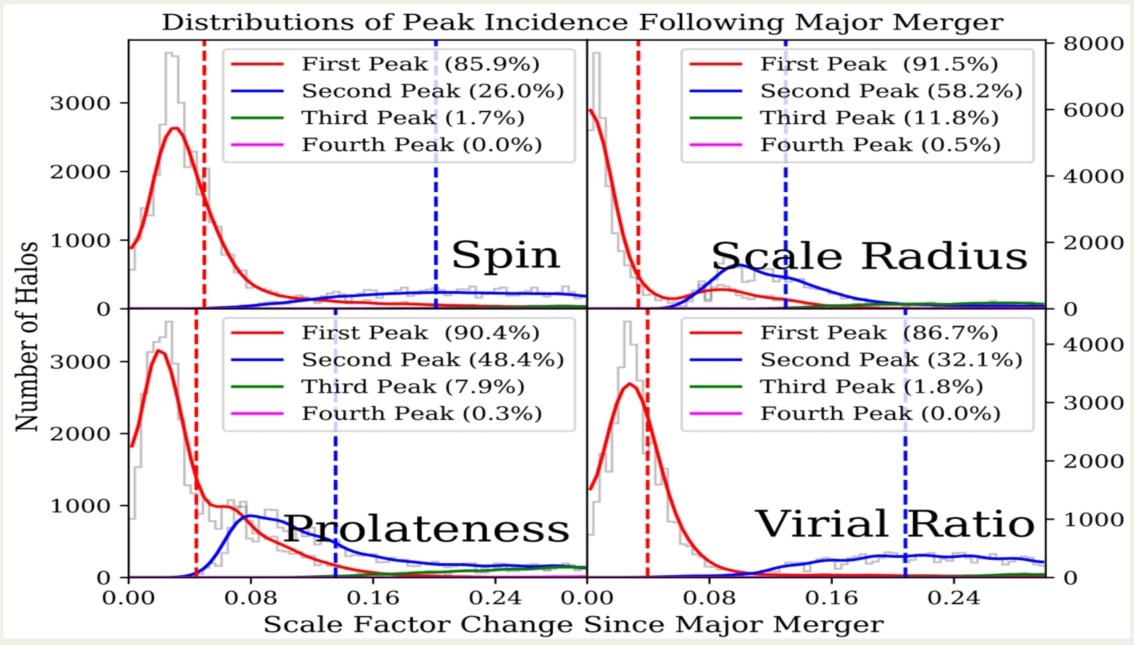


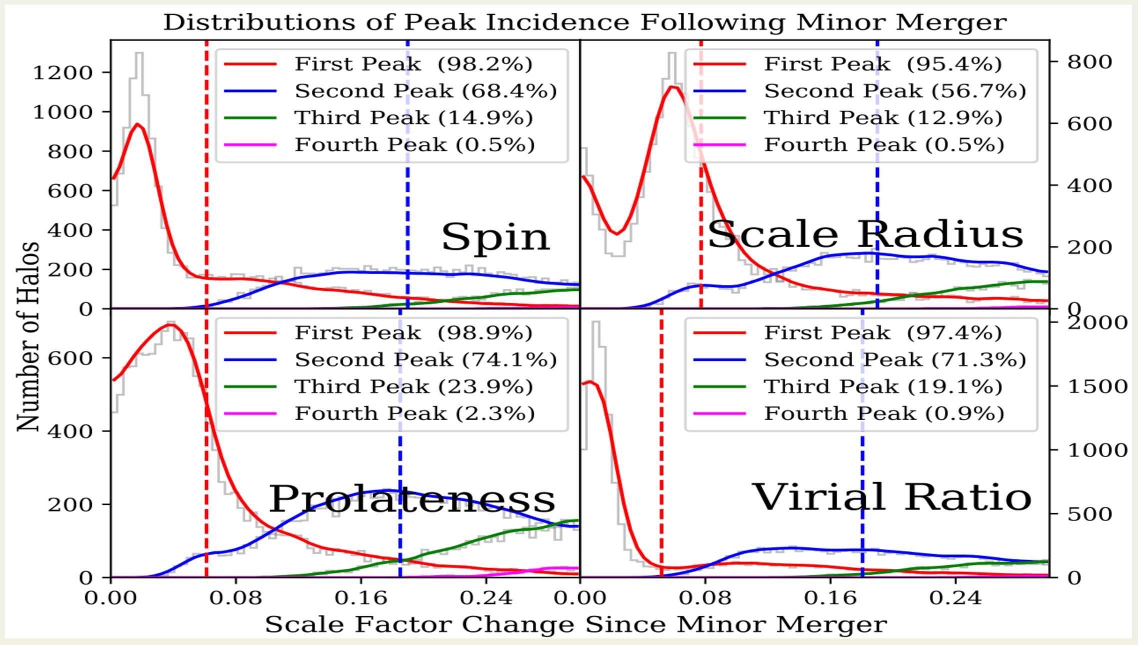
Red Major Merger

Yellow Minor Merger

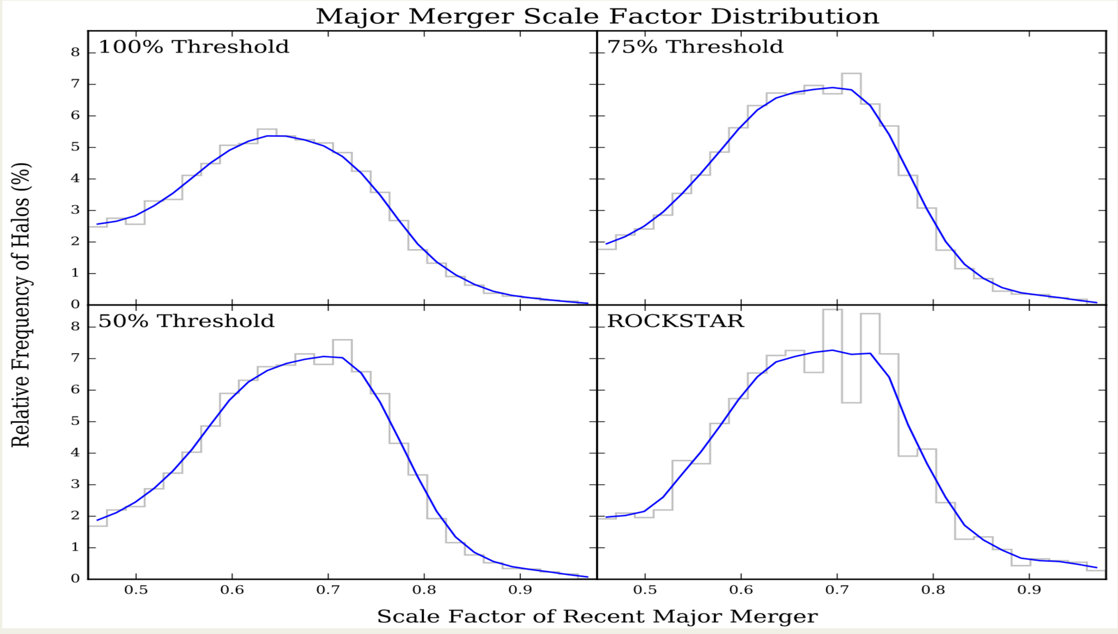
Results

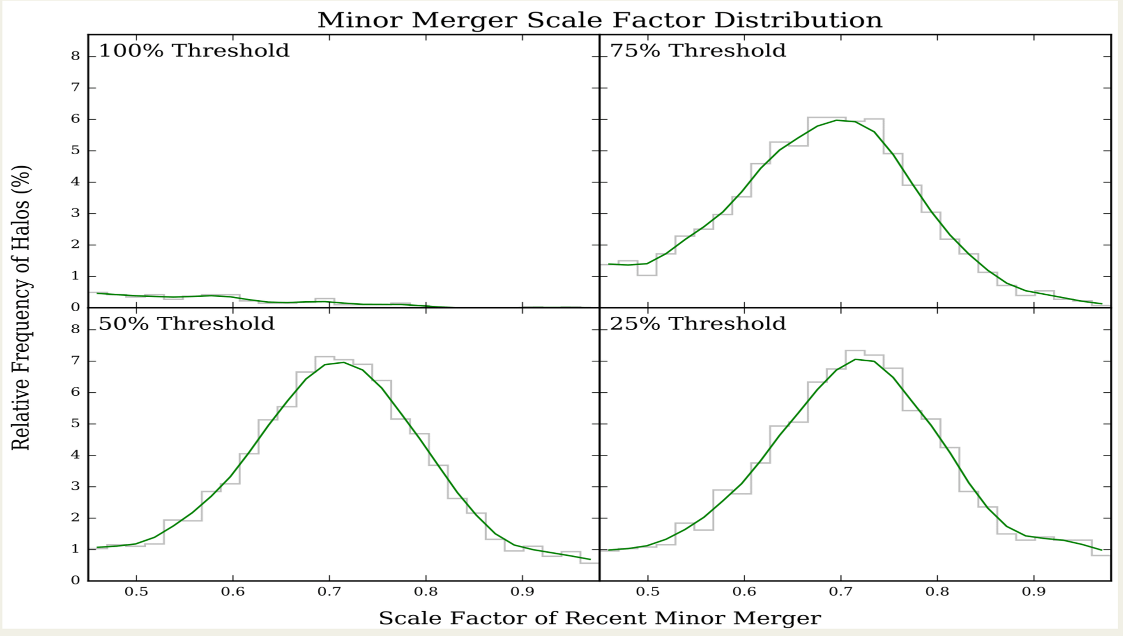
The two plots below display the distribution of peaks for four properties after following major and minor mergers. We see that a minor merger caused a peak in spin, scale radius, prolateness, and virial ratio following the merger. The spin and virial ratio for the first peak were the narrowest, while scale radius and prolateness had a delayed and broader range of peak times. The broad distributions of the second peak for Xoff, spin, and virial ratio suggests that this was generally not caused by the merger, a similar result observed from major merger responses.





We initially hypothesized that this unaccounted relaxation-based mass loss was due to minor mergers unrecorded by ROCKSTAR. With our algorithm, we first found a subset of halos that experienced > 5% mass loss without any recent major mergers. We then conducted our analysis in 4 groups of halos: 100%, 75%, 50%, and 25% of the original optimal threshold. Running through this data subset, we found a dominance of predicted minor mergers.





Discussion

When we compared the distribution of minor merger-driven mass loss from this subset with the distribution of major merger-driven mass loss from the entire dataset, we found striking similarities in shape, center, and spread. Just like major mergers, minor merger events around z = 0.4 will cause a relative minimum mass at z = 0. Hence, that is the reason why both distributions are centered around a = 0.7. Once again, we demonstrated that minor merger effects significantly affect dark matter halo evolutions and could be the causes for inexplicable property behaviors. These agreeable results between major and minor mergers may hint for a necessary re-evaluation of the 0.3 mass ratio merger classification. As a whole, our various distributions provided evidence that minor mergers act extremely similar to major mergers – both greatly influence property behaviors. Although they were “hidden” before, minor mergers can now be used to identify unexplainable property peaks. We emphasize that it is crucial to also account for minor merger effects in future dark matter halo studies.

Conclusion

In this study, we were able to characterize the distribution of responses for various dark matter halo properties following a major merger, including the degree to which some properties could peak multiple times. We also provided a new simple yet efficient algorithm that expanded upon ROCK- STAR’s halo finder and detected merger events through our work in property behaviors. This algorithm was the first of its kind to also record minor mergers, opening a new study of obscure minor merger events and giving it high potential to be employed in the future. Using the algorithm, we provided evidence that these minor mergers were actually driving factors behind unaccounted relaxation-based mass loss. In the end, our project’s analyses on halo properties following major and minor mergers should serve as vital parameters towards better understanding galaxy formation and evolution.