Interplay of galaxy formation and the evolution of dark matter haloes in the cosmic web

Premvijay Velmani

Inter-University Centre for Astronomy and Astrophysics (IUCAA), India

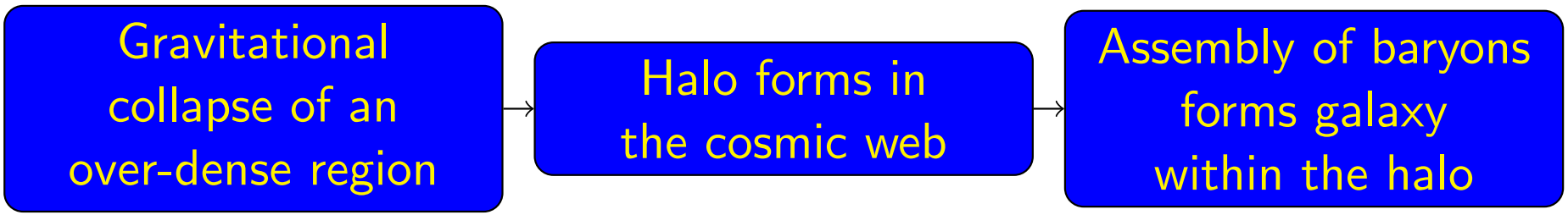


This work done with Prof. Aseem Paranjape



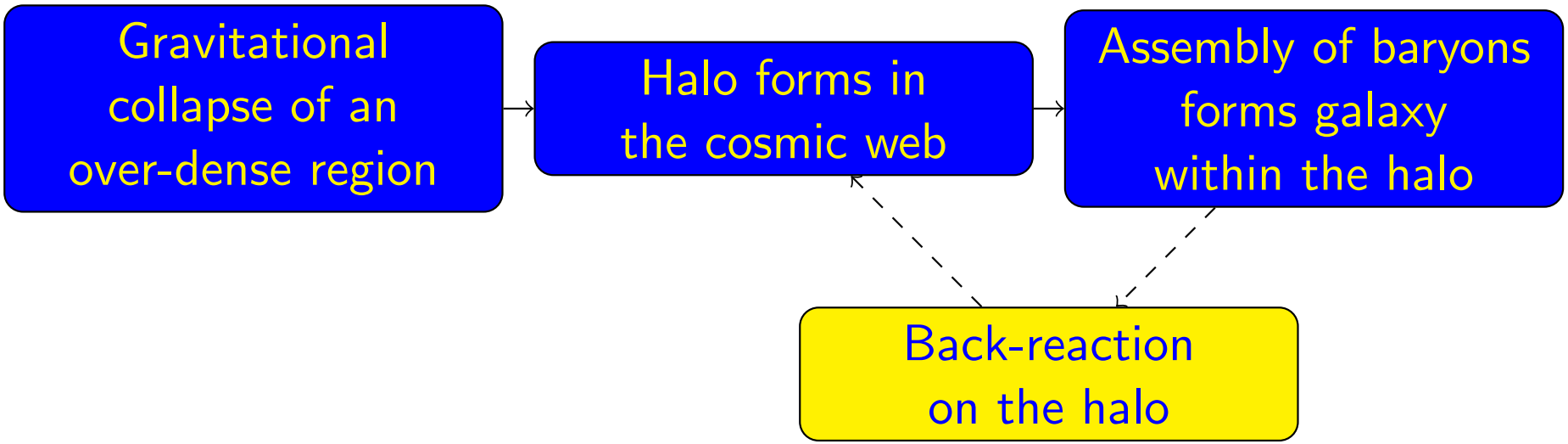
Introduction

- As matter clumps over overdensities due to gravity, the baryons cool and condense to form galaxies, leaving extended objects of dark matter haloes in the common paradigm of cosmology.
- These haloes are crucial in studying cosmology and dark matter particle physics, and are often modelled without any baryonic astrophysics using techniques like cosmological N-body simulations.
- Modeling galaxy formation does depend upon these haloes using for example semi-analytical techniques.



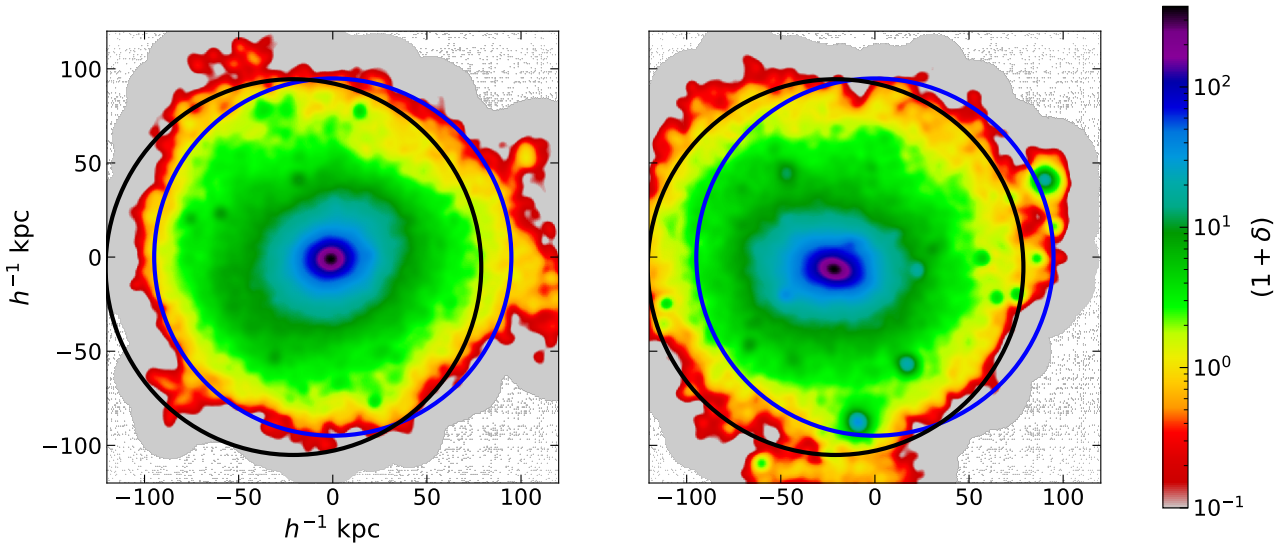
Introduction: Hydrodynamical simulations with galaxies

- Realistic galaxies are produced by modern hydrodynamical simulations of cosmological volumes with various subgrid baryonic prescriptions for the unresolved baryonic astrophysics such as in EAGLE, IllustrisTNG, Horizon, SIMBA, etc.
- In these simulations, the phase-space distribution of dark matter within the haloes have also been found to be significantly different and diverse indicating strong response to galaxies they host.



Dark matter halo response to galaxies

A halo from EAGLE simulation in the presence of galaxy (right image) can be seen more compact, spherical and even their centres shifted.



In particular, the change in the halo-centric distances affects radial mass profiles of haloes that influence key observables such as the rotation curves and radial acceleration relations.

Relaxation response physics

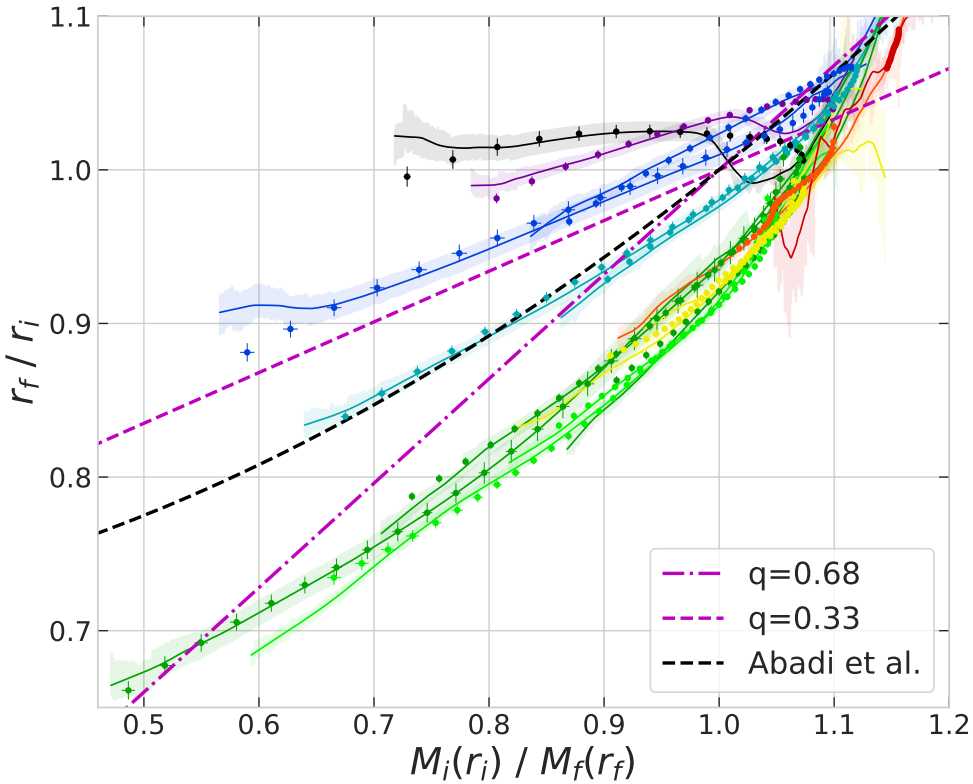
- Early works modeled this as adiabatic relaxation of dark matter in response to the **net** change in the gravitational potential due to galaxy formation.
- Consider a dark matter particle in circular orbit starting from radius r_i and adiabatically (conserving angular momentum) evolving to radius r_f caused by change in sphericalised total mass profile from $M_i(r)$ to $M_f(r)$ due to galaxy, then

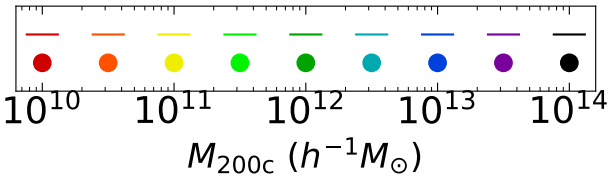
$$r_i\, M_i(r_i) = r_f\, M_f(r_f) \implies \frac{r_f}{r_i} = \frac{M_i(r_i)}{M_f(r_f)}\,.$$

- By assuming no shell crossing, these quantities can be calculated by the comparing total and dark matter mass profile in the presence and absence of galaxies using the relation $M_f^d(r_f) = M_i^d(r_i)$.
- Quasi-adiabatic relaxation models consider the relaxation ratio r_f/r_i as a function of the mass ratio M_i/M_f.

Relaxation in IllustrisTNG and EAGLE

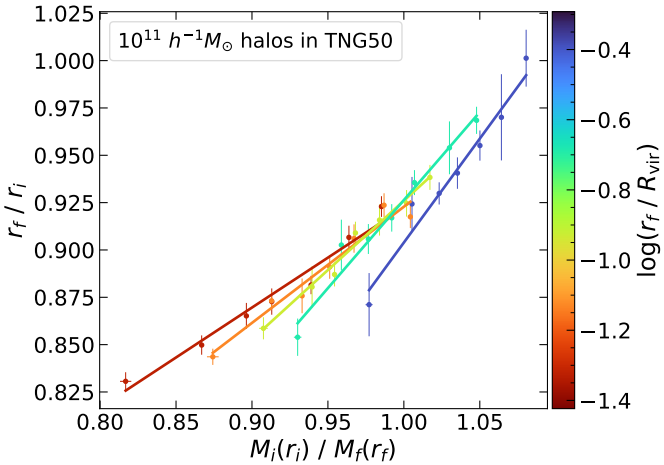
- We found that the relaxation relation (between r_f/r_i and M_i/M_f) varies widely between haloes of different mass scales in IllustrisTNG and EAGLE.
- Existing quasi-adiabatic framework failed to provide a simple description across all scales.

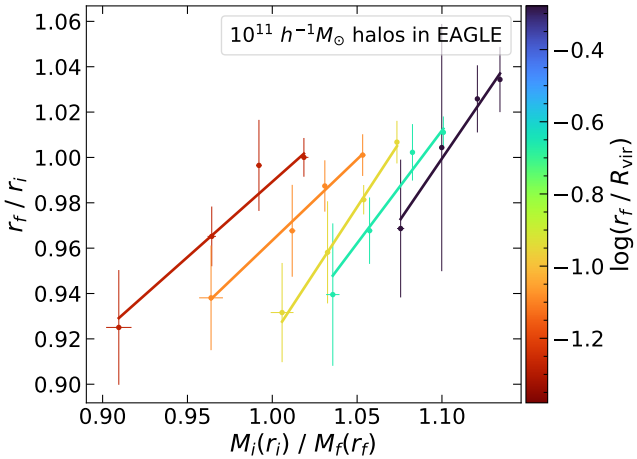


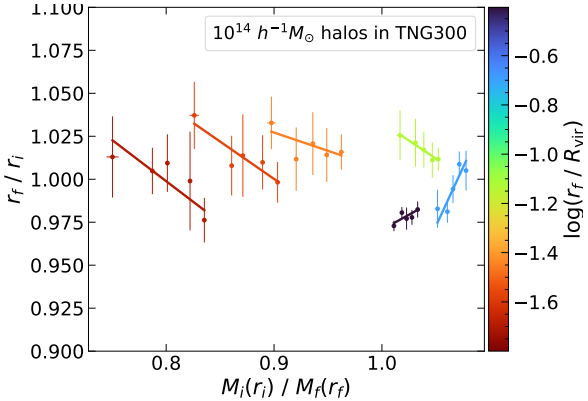


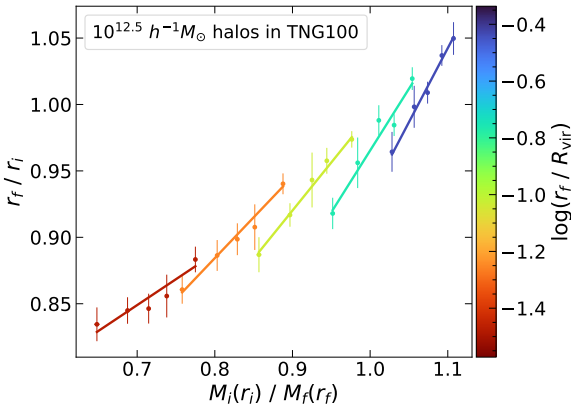
Dependence on halo centric distance

- A simple linear relation can accurately describe the relaxation, provided we assume an additional explicit dependence on the halo-centric distance.
- Notice that the exact nature of the relation is very different at different halo-centric distances (indicated by colorbar) for some halo masses, but they are all strongly linear.



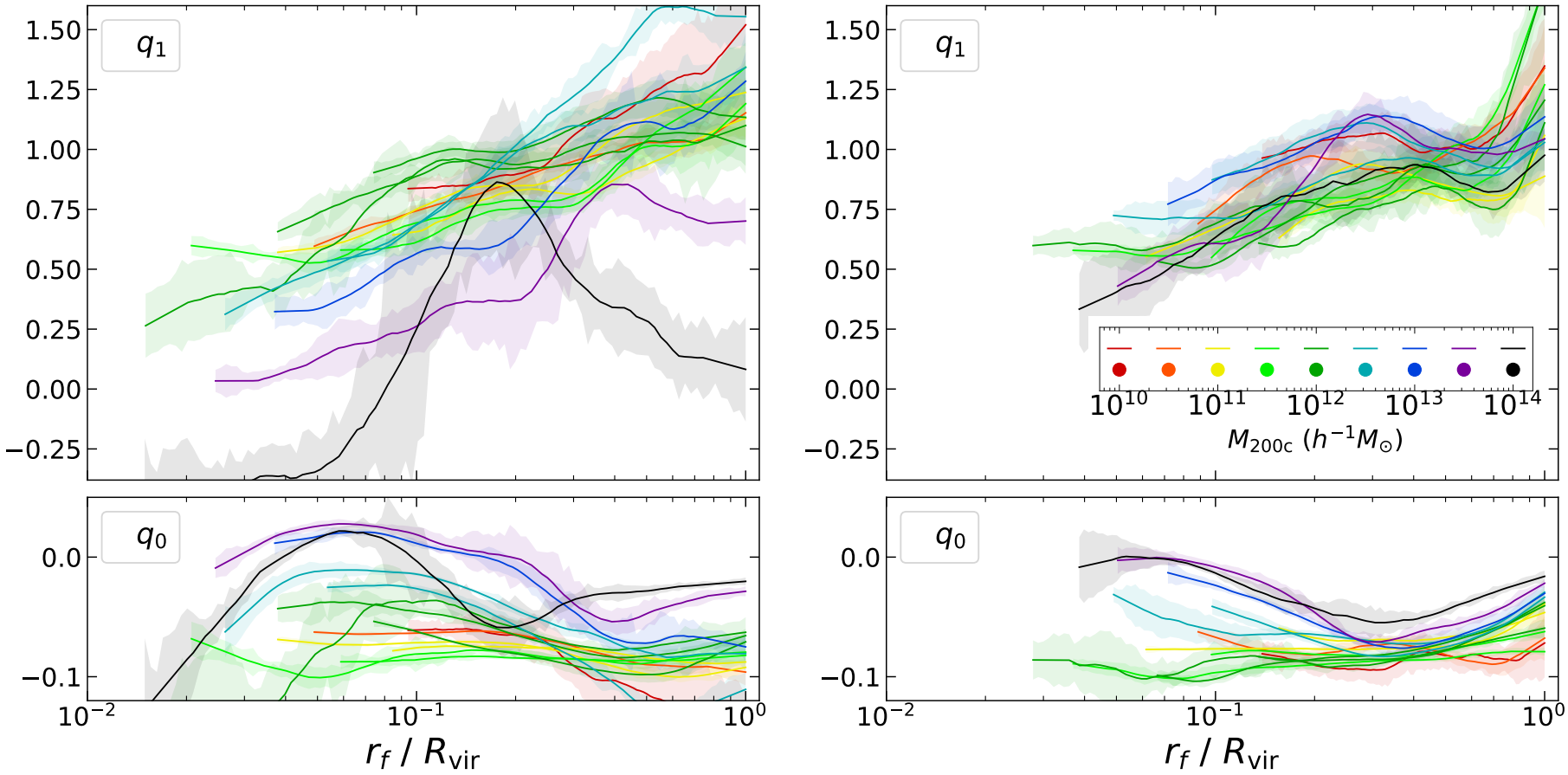






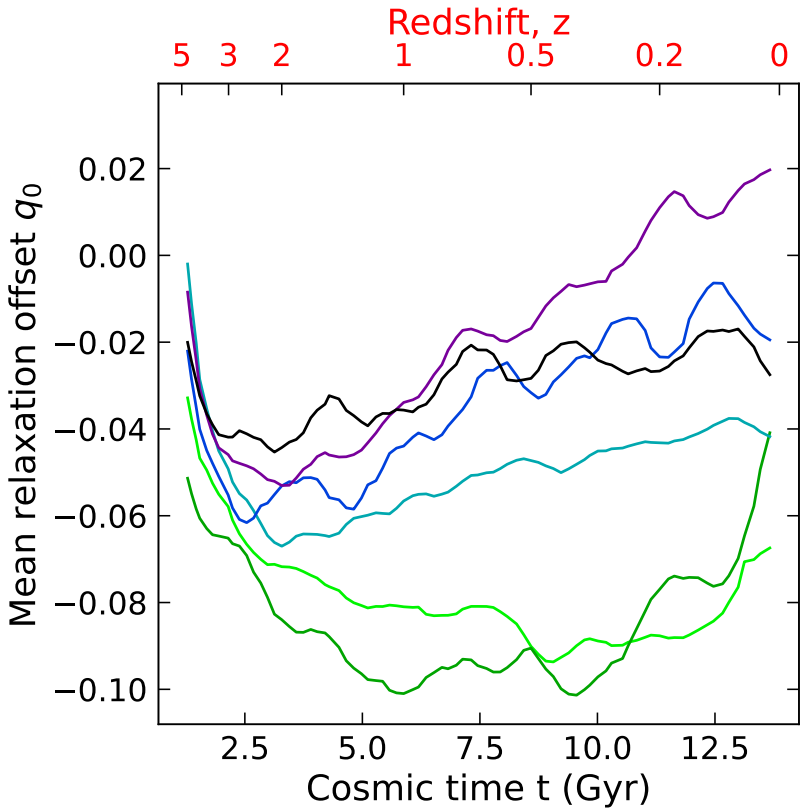
Universal description of Halo Relaxation Response

The radially dependent slope $q_1(r_f)$ and intercept $q_0(r_f)$ of this linear fit, is more universal across a wide range of halo masses up to $10^{13}h^{-1}M_\odot$ at $z = 0$ (left) and up to $10^{14}h^{-1}M_\odot$ at earlier redshift, $z = 1$ (right).



Relaxation Dynamics

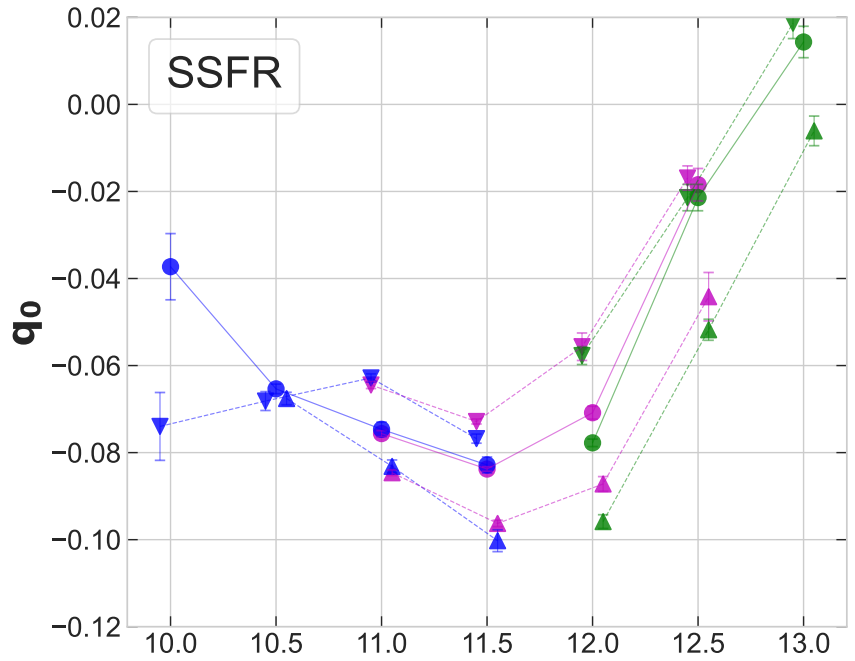
- Focusing on the intercept offset q_0, which describes the amount of relaxation $r_f/r_i - 1$ for dark matter shells with no net change in the total enclosed mass $M_i/M_f = 1$.
- It starts at zero, becomes more negative initially, but then apparently revert slowly back to zero.



Connection with star formation rate?

Astrophysical connection

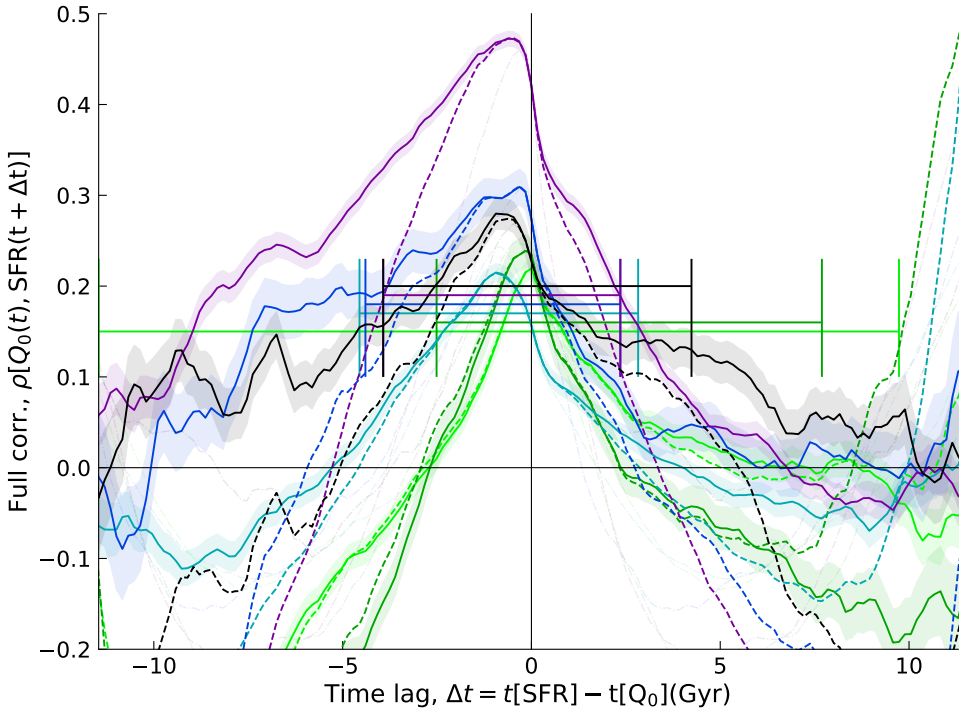
- Focusing on the intercept offset q_0, which describes the amount of relaxation $r_f/r_i - 1$ for dark matter shells with no net change in the total enclosed mass $M_i/M_f = 1$.
- The value of q_0 today was found to be more negative among haloes hosting galaxies with higher specific star formation rate (SSFR).



This higher excess relaxation might be related to larger amount of recent feedback output.

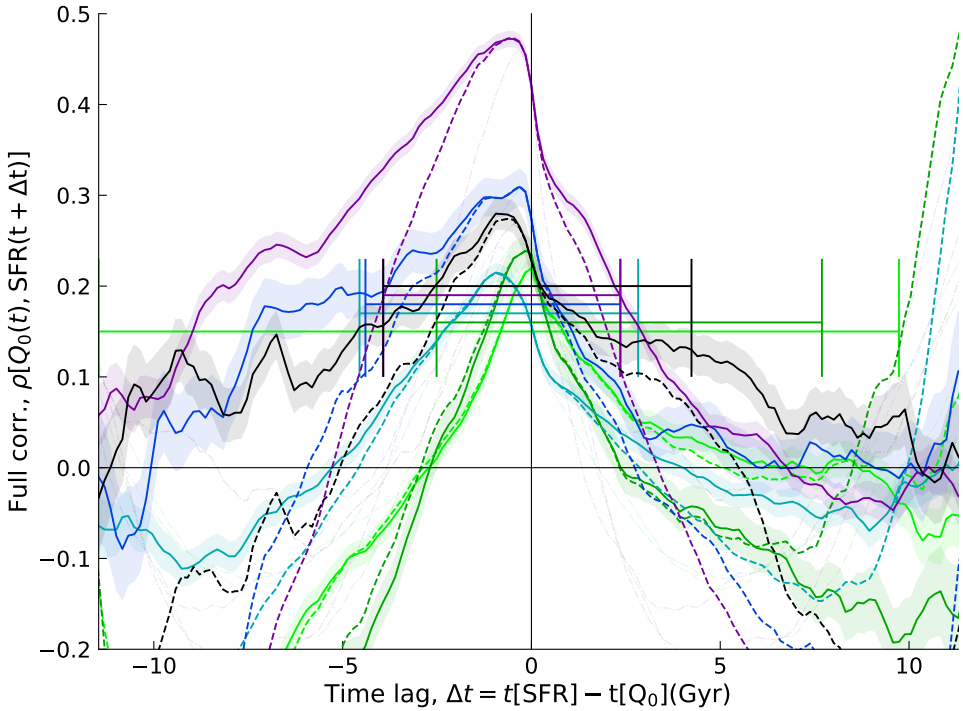
Temporal Connection with Astrophysics

Spearman-rank correlation between $Q_0 \equiv -q_0$ and mean SFR across a variety of haloes over long periods of time at different final halo masses suggests that the offset is typically stronger following periods of high star formation activity.



Temporal Connection with Astrophysics

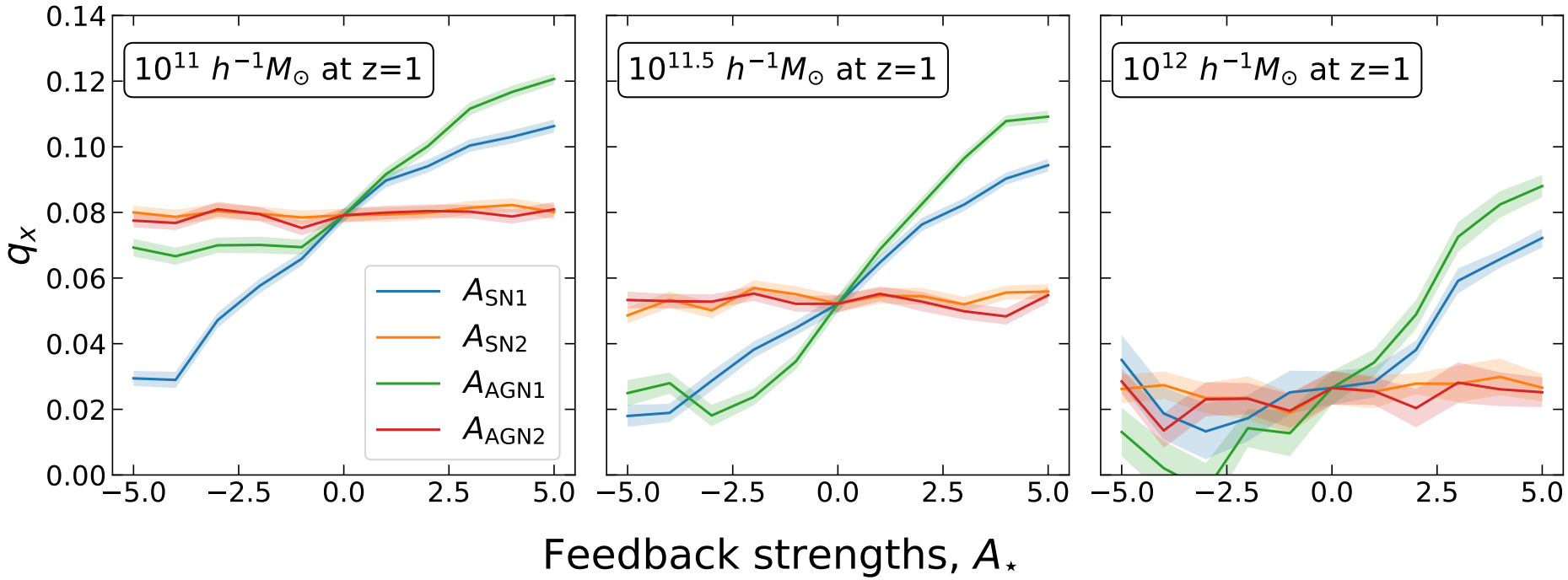
Spearman-rank correlation between $Q_0 \equiv -q_0$ and mean SFR across a variety of haloes over long periods of time at different final halo masses suggests that the offset is typically stronger following periods of high star formation activity.



Additionally, we also found that the offset in the inner region is immediately affected by high SFR, while the outer regions are affected after around 2-3 Gyr. This likely explains the explicit dependence on the halo-centric distance.

Role of Astrophysical Feedback

Using the suite of CAMELS simulations with variation in feedback strengths, we found that the offset parameter q_x, which is inversely related to q_0, indeed strongly depends on the overall feedback flux from the galaxies. However, the parameters controlling the feedback burstiness and the wind speed have negligible impact on the relaxation offset as shown below.



Future plans

- Use direct probe of feedback to understand the role of AGN and other feedback on the relaxation dynamics.
- Use analytical tools and semi-analytical experiments to build an entirely physical and accurate model of relaxation.
- Run galaxy forming cosmological simulations specially focussed on studying the dark matter halo relaxation response.
- Identify galaxy properties that keeps record of evolutionary history of galactic processes allowing accurate determination of dark halo response.

Future plans

- Use direct probe of feedback to understand the role of AGN and other feedback on the relaxation dynamics.
- Use analytical tools and semi-analytical experiments to build an entirely physical and accurate model of relaxation.
- Run galaxy forming cosmological simulations specially focussed on studying the dark matter halo relaxation response.
- Identify galaxy properties that keeps record of evolutionary history of galactic processes allowing accurate determination of dark halo response.

Thank You

For letting me share some of the correlations I made with the Universe, hope this increased your overall correlation with the elegant workings of the cosmos!