

Research Overview and Future Directions

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Introduction

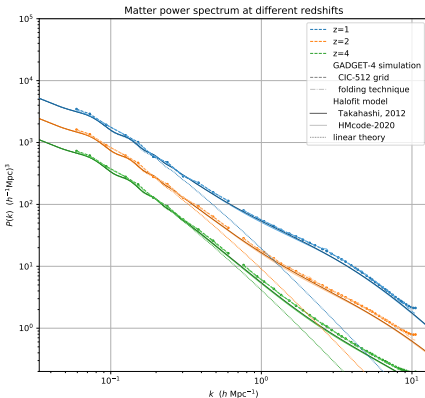
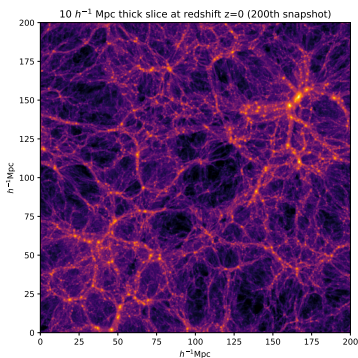
- My research at IUCAA, Pune, mainly involves performing and analysing cosmological simulations with and without galactic astrophysics.
- Along with simulations, I do more controlled numerical experiments with a focus on physical modelling which can then be compared with observations.
- I have several research plans based on my past research that will directly benefit from the expertise of KIAS and the available simulation data such as HR5.
- I am also excited with the kind of research done at KIAS and hence open to collaborate in those projects.

Background

- Completed Master of Science (MS) from IISER in 2019 with major in Physics and 1 year thesis work in theoretical cosmology.
- Joined IUCAA Pune for PhD in August 2019 and did one year gradschool training in modern astrophysics research.
- Started working with Prof. Aseem in 2020. I did comprehensive exploration with cosmological simulations for 1 year and proposed my thesis work.
- Worked on my thesis "Interplay of galaxy formation and the evolution of dark matter haloes" for 3 years from 2021 to 2024. Now approved for defence in next month.
- As I got another year at IUCAA till July 2025, I continued my research after thesis submission and came up with well-defined long-term research plans.
- Recent KIAS Cosmology workshop, got me know more about the interesting research works over there. I am confident that KIAS has sufficient resources and expertise to get interesting results with these research plans.

Exploring large scale structure in cosmological simulations

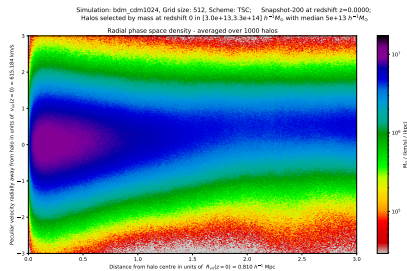
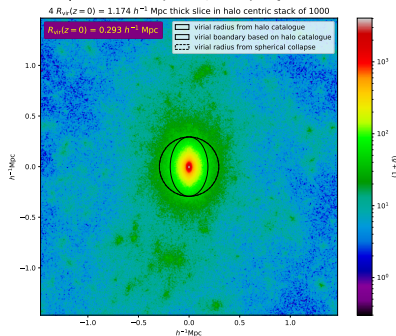
- I started by performing cosmo simulations with GADGET and GADGET based codes.
- Generated transfer function with CAMB and used 2LPT codes to generate initial conditions for cosmo simulations.
- Sample figures from initial exploration with cosmological simulations.



Exploring haloes in galactic and cluster scales

- Found halo substructures with FoF, SUBFIND, ROCKSTAR, VELOCIRAPTOR and built merger trees.
- Sample figures from initial exploration with cosmological simulations.

Simulation: bdm_cdm1024, Grid size: 512, Scheme: TSC; Snapshot-200 at redshift $z=0.0000$; Halos selected by mass at redshift 0 in $[2.87e+12, 3.13e+12] h^{-1}M_{\odot}$ with median $2.99e+12 h^{-1}M_{\odot}$



Past Research: Overview

- Focused on dark matter halo dynamics in cosmological simulations.
- Studied halo relaxation responses using **IllustrisTNG, EAGLE, and CAMELS**.
- Developed self-similar models for galaxy formation and tested against simulations.
- Analyzed astrophysical feedback processes, especially **AGN feedback impacts** on halo structure.

Key Contributions

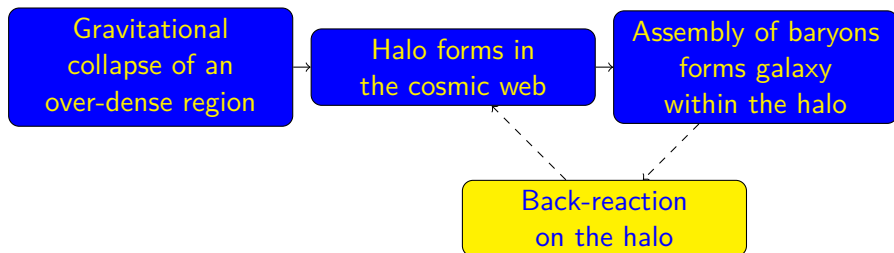
- Established connections between galaxy formation processes and halo relaxation timescales.
- Quantified the impact of baryonic physics on dark matter distribution.
- Improved time-correlation analysis techniques for astrophysical feedback processes.
- Collaborated on large-scale survey mock simulations for EUCLID and DESI.

Proposed Research Directions

- Enhance time-correlation methods to study baryonic feedback in dark matter haloes.
- Develop and implement **cosmological MHD simulations** for better theoretical modeling.
- Investigate galaxy-halo connections with a focus on AGN-driven relaxation processes.

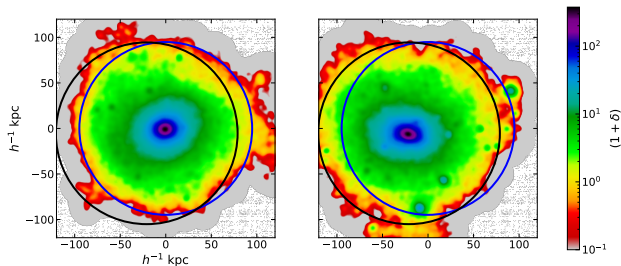
Hydrodynamical simulations with galaxies

- In 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

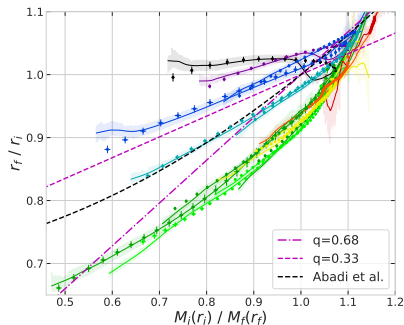
A halo from EAGLE simulation in the presence of galaxy (left image) can be seen more compact, spherical and even their centres shifted.



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.

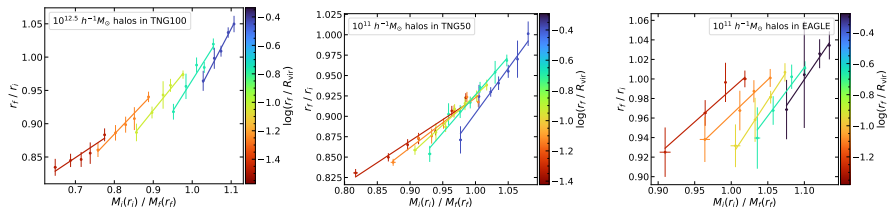
Relaxation response in IllustrisTNG and EAGLE

- Early works modeled this as adiabatic relaxation of dark matter in response to the net change in the gravitational potential due to galaxy formation.
- Quasi-adiabatic relaxation framework focus on modelling the relation between the relaxation ratio r_f/r_i as a function of the mass ratio M_i/M_f .
- 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 simulations like IllustrisTNG



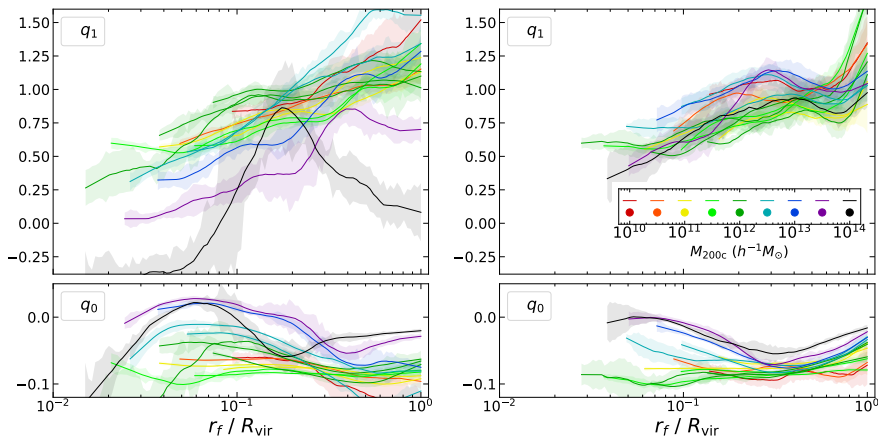
Dependence on halo centric distance

- A simple linear relation can accurately describe the relaxation, provided we assume an additional explicit dependence on the halo-centric distance (indicated by colorbar).



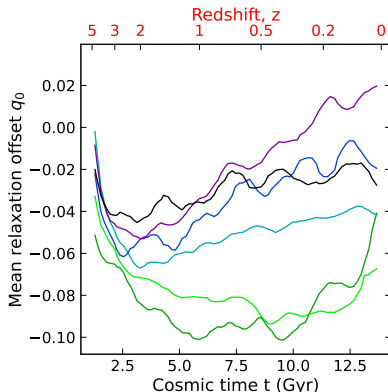
Universal description of Halo Relaxation Response

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

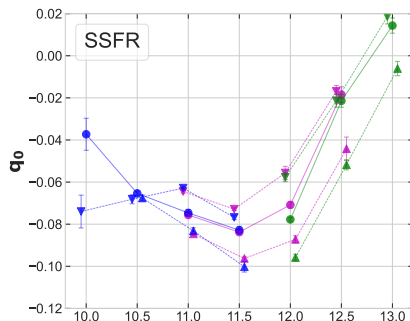
- Focusing on the intercept offset q_0 , which describes the amount of relaxation $r_f/r_i - 1$ for dark matter shells with no net change in the total enclosed mass $M_i/M_f = 1$.
- It starts at zero, becomes more negative initially, but then apparently revert slowly back to zero.



Connection with star formation rate?

Astrophysical connection

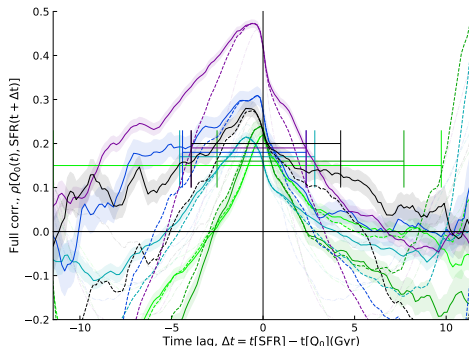
- Focusing on the intercept offset q_0 , which describes the amount of relaxation $r_f/r_i - 1$ for dark matter shells with no net change in the total enclosed mass $M_i/M_f = 1$.
- The value of q_0 today was found to be more negative among haloes hosting galaxies with higher specific star formation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



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

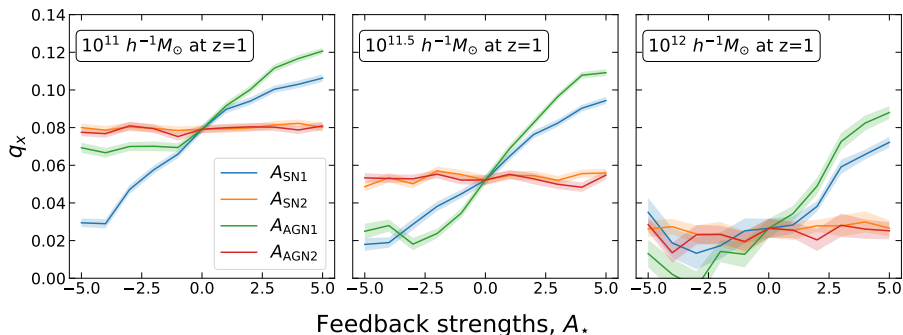
Temporal Connection with Astrophysics

- Correlation between relaxation response parameter is more strongly correlated to SFR and feedback at earlier times usually.
- And this response time lag is progressively larger as we go towards the outer halo.



Role of Astrophysical Feedback

We found that the relaxation response parameter (q_x shown), indeed strongly depends on the overall feedback flux from the galaxies, but not the burstiness in CAMELS simulations.



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.

Summary

- Extensive experience in cosmological simulations and astrophysical modeling.
- Strong focus on understanding baryonic impacts on dark matter dynamics.
- Excited to contribute to KIAS's research goals while pursuing innovative directions.
- Looking forward to discussing my research and ideas further.

List of Publications

- PremVijay Velmani, Aseem Paranjape, 2023, “The quasi-adiabatic relaxation of haloes in the IllustrisTNG and EAGLE cosmological simulations”, *Published in MNRAS*.
- PremVijay Velmani, Aseem Paranjape, 2024, “Dynamics of the response of dark matter halo to galaxy evolution in IllustrisTNG”, submitted to JCAP, *Accepted for publication in JCAP*.
- PremVijay Velmani, Aseem Paranjape, 2024, “Role of astrophysical modeling on dark matter halo relaxation response at redshifts $z = 0$ and $z = 1$ ”, *submitted response to editor in JCAP*.
- PremVijay Velmani, Aseem Paranjape, 2024, “A self-similar model of galaxy formation and dark halo relaxation”, *Published in JCAP*.
- Sujatha Ramakrishnan, PremVijay Velmani, 2022, “Properties beyond mass for unresolved haloes across redshift and cosmology using correlations with local halo environment.”, *published in MNRAS*.