

# Research Overview and Future Directions

## Discussion with Prof. Raul Angulo

Premvijay Velmani  
premv@iucaa.in

Inter-University Centre for Astronomy and Astrophysics (IUCAA), Pune  
PhD Supervisor : Prof. Aseem Paranjape

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# Introduction

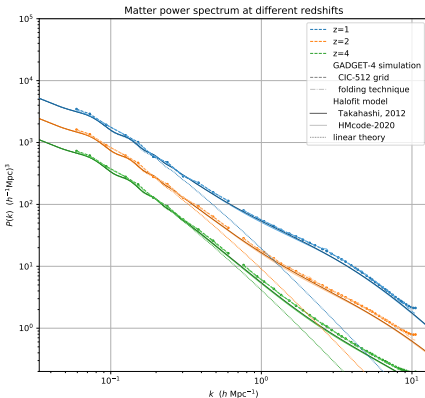
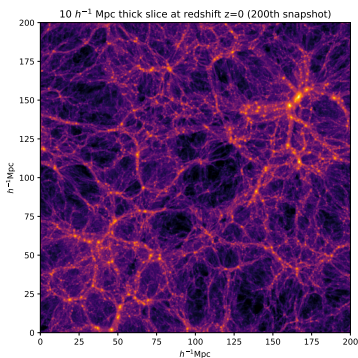
- My research at IUCAA, Pune, with Prof. Aseem Paranjape focus on the interface between cosmology and Astrophysics.
- Primarily I perform and analyse cosmological simulations with and without galactic astrophysics.
- Along with simulations, I do more controlled numerical experiments with a focus on physical modelling which can then be compared with observations.
- Particularly interested in your recent research with FLAMINGO simulations and several of your works related to baryonification.
- I also have several research plans based on my past research that will directly benefit from your expertise.
- I have also worked on a mini project with Prof. Hector Gil-marin to infer cosmological parameters from eBOSS and mock DESI data, so I am open to collaborate in similar observations.

# Background

- Completed Master of Science (MS) in Physics in 2019 and 1 year thesis work in theoretical cosmology (with linear cosmological perturbations).
- Joined IUCAA Pune for PhD in August 2019 and did one year gradschool comprehensive training in broader ongoing research in astrophysics.
- Started working with Prof. Aseem in 2020 and got into computational cosmology, I did comprehensive exploration with cosmological simulations for a 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. Awaiting defence in next month.
- As I got another year at IUCAA till July 2025, I continued my research after thesis submission and also developed well-defined long-term research plans.

# Exploring large scale structure in cosmological simulations

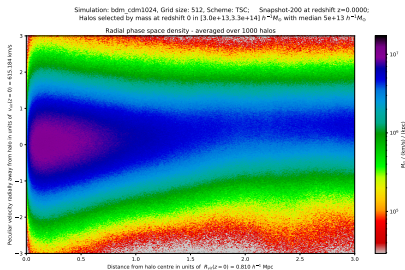
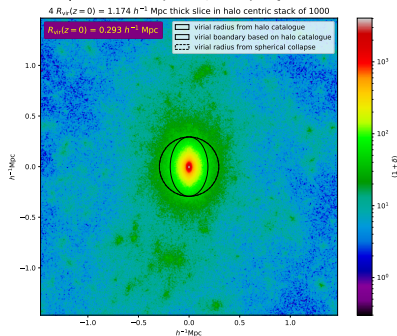
- I started by performing cosmo simulations with GADGET and GADGET based codes.
- Generated transfer function with CAMB and used 2LPT codes to generate initial conditions for cosmo simulations.
- Sample figures from initial exploration with cosmological simulations.



# Exploring haloes in galactic and cluster scales

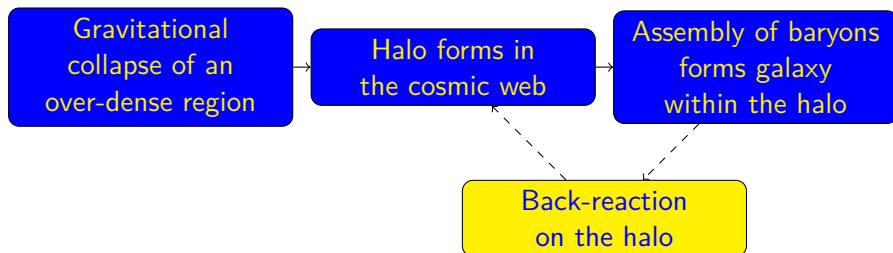
- Found halo substructures with FoF, SUBFIND, ROCKSTAR, VELOCIRAPTOR and built merger trees.
- Sample figures from initial exploration with cosmological simulations.

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  $2.99e+12 h^{-1}M_{\odot}$



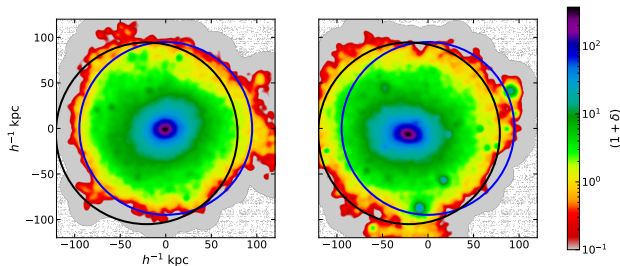
# Hydrodynamical simulations with galaxies

- 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

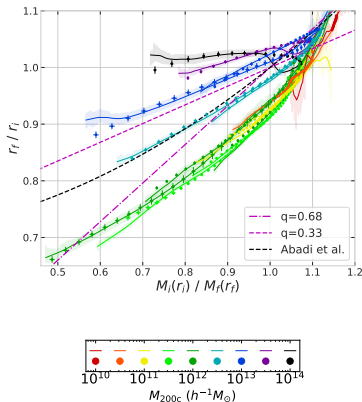
A halo from EAGLE simulation in the presence of galaxy (left image) can be seen more compact, spherical and even their centres shifted.



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

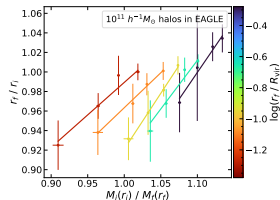
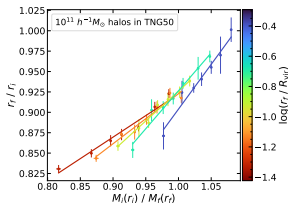
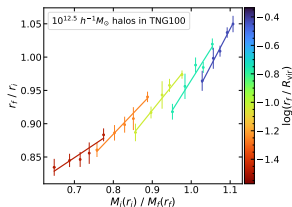
- Early works modeled this as adiabatic relaxation of dark matter in response to the net change in the gravitational potential due to galaxy formation.
- Quasi-adiabatic relaxation framework focus on modelling the relation between the relaxation ratio  $r_f/r_i$  as a function of the mass ratio  $M_i/M_f$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





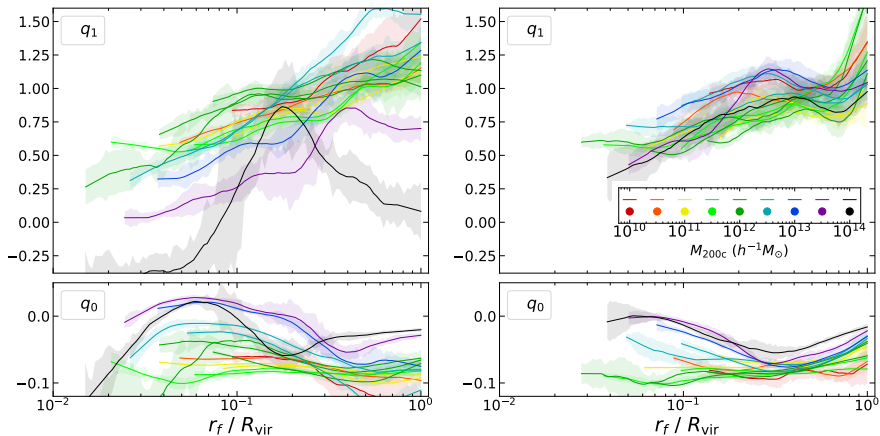
# Dependence on halo centric distance

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



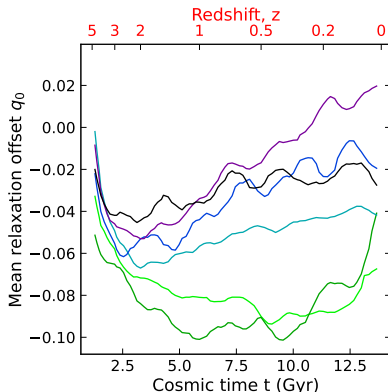
# Universal description of Halo Relaxation Response

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

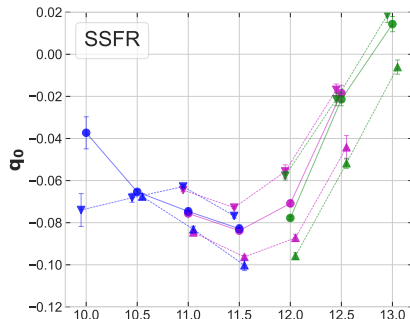
- Focusing on the intercept offset  $q_0$ , which describes the amount of relaxation  $r_f/r_i - 1$  for dark matter shells with no net change in the total enclosed mass  $M_i/M_f = 1$ .
- It starts at zero, becomes more negative initially, but then slowly reverts back to zero.



Connection with star formation rate?

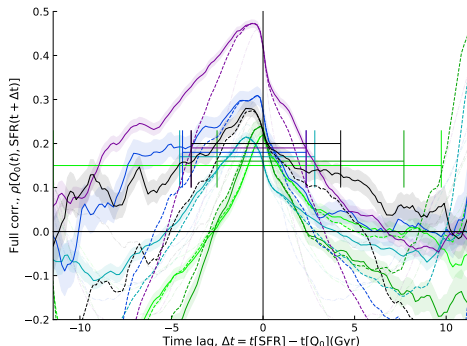
# Astrophysical connection

- An excess of relaxation relation quantified by  $q_0$  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.



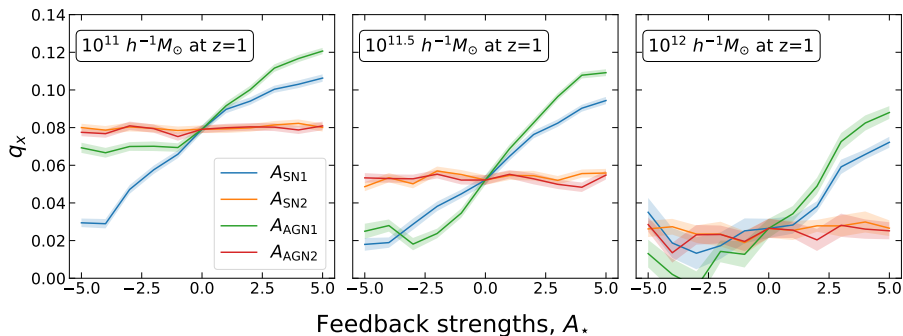
# Temporal Connection with Astrophysics

- 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 analytical tools and semi-analytical experiments to build an entirely physical and accurate model of relaxation.
- Develop galaxy forming cosmological simulations and perform simulations to answer specific questions regarding the dark matter halo relaxation response.
- Use direct probe of feedback to understand the role of AGN and other feedback on the relaxation dynamics.
- Identify gas properties such as metallicity that keeps record of evolutionary history of gas in galaxy allowing accurate modelling of dark matter in haloes and large-scale structure.
- Interested to collaborate in several of your current works especially in exploring the effect of galaxy on the large scale gas distribution.

# 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, *Published 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*.



# Summary

- Extensive experience in performing and analysing cosmological simulations with astrophysics.
- Primary research involves understanding baryonic astrophysical impacts on dark matter halo structure and evolution giving me the expertise to immediately join with in your research projects.
- I also have clear long-term research plans that strongly align with your expertise and benefit from the available resources.
- Looking forward to collaborate in exploring galaxies, haloes and large-scale structure through cosmological simulations.
- Excited to discuss potential research ideas with you.

Thanks for your interest!