Inter-University Centre for Astronomy and Astrophysics
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December 1, 2024

Search Committee
Department of Astronomy
The Ohio State University
Columbus, OH, USA

Dear Members of the Search Committee,

I am writing to express my interest in the Buckeye Postdoctoral position at The Ohio State University. My research bridges galactic astrophysics and cosmology, leveraging full hydrodynamic cosmological simulations such as IllustrisTNG, EAGLE, and CAMELS to investigate how astrophysical processes in galaxies impact the nature and evolution of dark matter haloes. In addition to performing and analyzing such cosmological simulations, I develop controlled numerical experiments to study the formation of galaxies and their interaction with their host dark matter haloes. These efforts have equipped me with the expertise and independence necessary to design and lead innovative research projects that align with Ohio State's vibrant academic environment. I have also formulated a well-defined research plan to construct a physical description of the response of dark matter haloes to galactic astrophysics, aiming to significantly enhance our inferences about cosmology and dark matter physics from observations.

Currently, I am a Senior Research Scholar at IUCAA, where I have submitted my PhD thesis under the supervision of Prof. Aseem Paranjape. My thesis explores the astrophysical effects of galaxy formation and evolution on dark matter haloes, with a particular focus on their radial density profiles, which are directly relevant to observations such as rotation curves. While this primarily involves analyzing state-of-the-art cosmological simulations that produce realistic galaxies, I also develop tractable semi-numerical experiments to study galaxy-halo interactions in a more controlled manner. Additionally, I am engaged in a data science collaboration utilizing advanced statistical techniques, such as machine learning, to extract insights from the wealth of data produced by cosmological surveys.

Building on this foundation, my proposed research aims to establish a cohesive model for galaxy-halo interactions over cosmic time. A key goal is to quantitatively connect astrophysical feedback, particularly AGN-driven outflows, to the relaxation and structural evolution of dark matter haloes. Leveraging my time-correlated framework and Ohio State's computational resources and collaborations, I plan to advance this effort significantly. This aligns with your department's strengths in cosmology, large-scale structure, and galaxy formation. My prior experience with cosmological inferences using galaxy surveys, such as eBOSS and mock DESI data in collaboration with Prof. Hector Marin, further motivates me to contribute to Ohio State's strong ties with DESI.

Ohio State's extensive observational and computational resources, including its ties to DESI and the Ohio Supercomputing Center, are uniquely suited to support my proposed work. The department's collaborative research environment, particularly the interdisciplinary opportunities provided by CCAPP, would also enrich my development as an independent researcher. I am particularly excited about contributing to the department's legacy of leadership in both theoretical and observational

cosmology.

Beyond research, I am passionate about fostering a diverse and inclusive academic environment, mentoring students in astrophysics and actively participating in outreach activities aimed at making science accessible to broader audiences. As part of the Ohio State community, I look forward to engaging in these efforts and mentoring early-career researchers.

Thank you for considering my application. I have included my CV, publication list, and a detailed description of my past and proposed research. I look forward to the opportunity to contribute to the department's research endeavors and would welcome the chance to discuss my plans in more detail.

Sincerely,
Premvijay Velmani,
Senior Research Scholar,
IUCAA Pune, India

References

Prof.Dr. Aseem Paranjape
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Prof.Dr. Nishikanta Khandai
National Institute of Science Education and Research (NISER) Bhubaneswar, India
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Prof.Dr. Subhabrata Majumdar
Tata Institute of Fundamental Research (TIFR) Mumbai, India
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Research

Cosmology and Large Scale Structure - Dark matter haloes, their evolution and distribution in the cosmic web - Galaxy formation, feedbacks and their impacts on host haloes - Cosmological (hydrodynamical) simulations, Analytical halo formation models and numerical experiments - Self-similar haloes and galaxies.

I primarily work on an interface between cosmology and astrophysics of galaxies, trying to understand and build a physical model of the impacts of galactic astrophysical processes on the dark matter haloes. This will not only make it easier to study cosmology and dark matter physics with haloes but also helps build a consistent picture of galaxy formation and evolution.

Experiences

PhD Research Fellow at IUCAA — *Pune, India*

PI: Prof. Aseem Paranjape — *2020-present*

- I have run N-body and hydrodynamics simulations of cosmological volumes using GADGET4 and SWIFT codes including some of the baryon astrophysics.
- Using structure finding codes such as ROCKSTAR and VELOCIraptor, I have made halo catolgues and merger trees.
- I have studied cosmological information such as matter power spectrum and various halo and galaxy properties in simulations.
- Besides my own simulations, I have also worked on simulations produced by large collaborations such as IllustrisTNG and EAGLE.
- I also worked on Self-similar models of halo formation and evolution along with galaxy formation.
- I also worked with semi-analytical models of dark matter haloes and galaxies and did numerical experiments with such models.
- In a mini project done with Prof. Hector marin, I have inferred cosmological parameters from eBOSS and mock DESI data.
- I am currently working in a data science collaboration focused on using machine learning techniques in cosmological data compression and inference.
- In another collobaration, I am working on the effect of supermassive black holes on the nature and the evolution of overall dark matter in the haloes.

MS Thesis at IISER Bhopal — *Bhopal, India*

PI: Prof. Sukanta Panda — *2018-2019*

- I worked on cosmological perturbations in an anisotropic Bianchi type-I background and its evolution in a Bouncing model.

Publications

The quasi-adiabatic relaxation of haloes in the IllustrisTNG and EAGLE cosmological simulations — *https://doi.org/10.1093/mnras/stad297*

Premvijay Velmani, Aseem Paranjape

Properties beyond mass for unresolved haloes across redshift and cosmology using correlations with local halo environment — *https://doi.org/10.1093/mnras/stac2605*

Sujatha Ramakrishnan, Premvijay Velmani

A self-similar model of galaxy formation and dark halo relaxation — *https://doi.org/10.1088/1475-7516/2024/05/080*

Premvijay Velmani, Aseem Paranjape

Dynamics of the response of dark matter halo to galaxy evolution in IllustrisTNG — *https://doi.org/10.48550/arXiv.2407.08030*

Premvijay Velmani, Aseem Paranjape

The evolving role of astrophysical modelling in dark matter halo relaxation response — *https://doi.org//10.48550/arXiv.2408.04864*

Premvijay Velmani, Aseem Paranjape

Conferences and Events

The Abdus Salam International Centre for Theoretical Physics — *Trieste, Italy*

Summer School on Cosmology 2022 — *July 2022*

- Presented a talk on "Impact Of Galaxy Formation On The Dark Matter Haloes In The Cosmic Web" at ICTP, an UNESCO organisation.

International Centre for Theoretical Sciences — *Bengaluru, India*

Largest Cosmological Surveys and Big Data Science 2023 — *April 2023*

- Worked on a mini project analysing redshift space distortion information from mock DESI data
- Presented a talk on "Impact Of Galaxy Formation On The Dark Matter Haloes In The Cosmic Web" at ICTP, an UNESCO organisation.

Inter-University Centre for Astronomy and Astrophysics — *Pune, India*

Pune-Mumbai Cosmology and Astro-Particle Meeting - 2 — *February 2024*

- Presented a talk on "Interplay of baryonic galaxies and their host dark haloes - Insights from self-similar analysis"

Tata Institute of Fundamental Research — *Mumbai, India*

Pune-Mumbai Cosmology and Astro-Particle Meeting - 3 — *September 2024*

- Discussion focussed meeting

Korea Institute for advanced Study(KIAS) — *Hilton yeongju, South Korea*

11th KIAS Workshop on Cosmology and Structure Formation — *October 2024*

- Presented a talk and a poster on "Interplay of galaxy formation and the evolution of dark matter haloes in the cosmic web - Dynamics of Relaxation".

Other talks

Indian Institute of Science Education and Research, Pune — *Pune, India*

Last Friday Talk — *Jan 2024*

- Presented a talk on "A self-similar model of galaxy formation and dark halo relaxation".

Inter-University Centre for Astronomy and Astrophysics — *Pune, India*

Last Friday Talk — *November 2023*

- Presented a talk on "Impact Of Galaxy Formation On The Dark Matter Haloes In The Cosmic Web".

Inter-University Centre for Astronomy and Astrophysics — *Pune, India*

Last Friday Talk — *March 2024*

- Presented a talk on "A self-similar model of galaxy formation and dark halo relaxation".

Education

Inter University Centre for Astronomy and Astrophysics (IUCAA affiliated to JNU) — *Pune, Maharashtra*

Doctor of Philosophy — *July 2019 - July 2024*

- Thesis title: Interplay of galaxy formation and the evolution of dark matter haloes in the cosmic web
- Thesis advisor: Prof. Aseem Paranjape

Indian Institute of Science Education and Research (IISER) Bhopal — *Bhopal, Madhya Pradesh*

Bachelor of Science and Master of Science (BS-MS) Dual Degree — *August 2014 - May 2019*

- Obtained a CPI/CGPA of 9.4 with major in Physics and a minor in Mathematics.
- MS thesis: "Evolution of anisotropic perturbations in bouncing cosmology" under the guidance of Prof. Sukanta Panda.

Tamil Nadu Board of Secondary Education — *Chennai, Tamil Nadu*

Class 12 - plus two — *Graduated March 2014*

- **94.58** %, Obtained **96.25** % excluding language subjects.

Tamil Nadu Board of Secondary Education — *Chennai, Tamil Nadu*

Class 10 - SSLC — *Graduated April 2012*

- **93.6** %, Obtained **99.33** % excluding language subjects and 100 % in science.

Awards and fellowships

Aug.2021	**Senior Research Fellowship**, Inter-University Centre for Astronomy and Astrophysics	*Pune, India*
Aug.2019	**Junior Research Fellowship**, Inter-University Centre for Astronomy and Astrophysics	*Pune, India*
Jan.2019	**Junior Research Fellowship**, Council of Scientific & Industrial Research	*New Delhi, India*
Aug.2014	**INSPIRE Scholarship**, IISER, Department of Science & Technology	*Bhopal, India*
June.2014	**Cash Prize Award**, Second rank in 12th board exam	*Chennai, India*
April.2012	**SSLC cash prize award**, Centum in 10th board exam	*Chennai, India*

Professional Skills

Computer skills

Programming	Python, Bash, C, C++, IDL, Fortran, R, Wolfram, Matlab/Octave
Python libraries	Includes numpy, scipy, pandas, astropy, cobaya, camb, colossus, casa, h5py, sklearn, matplotlib, seaborn, getdist, pyqtgraph, vispy, vpython, pyopengl, pyopencl, pycuda, conda, mpi4py and PyQt5
Simulation tools	GADGET4, SWIFT, ROCKSTAR, VELOCIraptor, MUSIC2-monofonIC
Analytical tools	Mathematica (packages xTensor, xCoba, xPert, xPand), Maple, Python sympy
Operating system	Linux system administration, Bash, distros including Arch Linux, Ubuntu, Fedora, RHEL, SUSE, Centos; Windows administration, Visual Studio, Powershell, Windows Subsystem for Linux; Remote adinistration, SSH, HPC clusters with PBS jobs scheduler and NFS storage.
Markup Languages	LaTeX, HTML, CSS, Markdown, MS Office/ Libreoffice
Media creation	Adobe Creative Cloud apps, DaVinci Resolve, Blender, Poser, Audacity

Teaching skills

Physics Cosmology, Astrophysics, General relativity, Mathematical and Computational methods

Academic Achievements

May 2022	**Summer School on Cosmology 2022**, Invited with funds by ICTP, UNESCO	*Trieste, Italy*
Jun 2018	**CSIR UGC NET - Physics**, Qualified JRF with a score of 115 and all India rank of 116	*India*
Aril 2014	**JEE MAIN / AIEEE**, Qualified with a score 190	*India*
May 2014	**NEET UG / AIPMT**, Qualified with a score of 350.	*India*
June 2014	**JEE ADVANCED**, Qualified with a rank of **4056** within OBC category.	*India*
June 2016	**SOLOLEARN - Python**, Completed with certification	

Hobbies & Interests

I do a variety of things but usually they are connected to my strong curiousity, striving to understand each and every thing as I encounter in everyday life. This not only allows me to enjoy the beauty of nature from newer dimensions, I think this is necessary to develop myself and our civilisation as a whole. As a challenge seeking person I also enjoy this process of cracking the puzzles of nature.

Reading I use the world wide web to explore various topics in both natural science and others such as history, politics, technology and sustainable development, with a rational viewpoint.

Exploration I love to ocassionally go for trekking and also travel to experience various cultures and cuisines.

Sports I love to ocassionally take part in football, badminton, table tennis and swimming.

Other personality In my free time, I enjoy doing lots of home experiments driven by my own curiosity. And I can relate with prof. R Feynman that "Nearly everything is really interesting if you go into it deeply enough". I like challenges and I don't like doing simple things repetitively, so I keep exploring various new things. Trying to comprehend the logic behind complex things is my pleasure. I also love being more self-reliant not because I don't trusts others but simply I am eager to engage in every activity myself.

Extracurricular Activity

IUCAA open science day — *Pune, India*

Presented a poster on basics of cosmology — *Feb 2023*

IUCAA open science day — *Pune, India*

Created a video explaining probes of cosmology — *Feb 2021*

IUCAA open science day — *Pune, India*

Demonstrated creation of gravitational waves — *Feb 2019*

Singularity-15, IISER Bhopal — *Bhopal, India*

Bad Ad Hoc Hypothesis on gravity at the cosmic horizon — *April 2015*

Singularity-16, IISER Bhopal — *Bhopal, India*

Science Exhibition demonstration of a mega domino effect system — *September 2016*

IISER Science Council — *Bhopal, India*

Head of Artificial Intelligence and ML club; member of Physics, Mathematics and Astronomy Club — *Aug 2014 - May 2019*

Astronomy and Space Technology Awareness Camp — *Bhopal, India*

Workshop by spAts of IIT Kgp — *April 2015*

Mimamsa 2015 by IISER Pune — *Mumbai, India*

National Science Quiz — *January 2015*

Mimamsa 2016 by IISER Pune — *Bhopal, India*

National Science Quiz — *January 2016*

School level — *Chennai, India*

Competitions

- Winner in Science quiz intra school. Got selected in science talent exam conducted by The Hindu Educational Plus.
- Winner in debate about Education System.

References

Prof.Dr. Aseem Paranjape — *Pune, India*

Inter-University Centre for Astronomy and Astrophysics (IUCAA) — *aseem@iucaa.in*

Prof.Dr. Nishikanta Khandai — *Bhubaneswar, India*

National Institute of Science Education and Research (NISER) — *nkhandai@niser.ac.in*

Prof.Dr. Subhabrata Majumdar — *Mumbai, India*

Tata Institute of Fundamental Research (TIFR) — *subha@tifr.res.in*

Research Statement

Premvijay Velmani

November, 2024

1 Overview

1.1 Current Research

My research focuses on cosmology and large-scale structure to galactic astrophysics through both **cosmological simulations with full galaxy formation** prescription and more tractable numerical experiments of **dark matter haloes with galaxies**. Primarily, *I study the dynamics and evolution of dark matter haloes within the cosmic web focusing on how these structures interact with the astrophysical processes associated with galaxy formation and evolution.* In the ongoing research in cosmology and dark matter physics, the response of dark matter haloes to galaxies is frequently neglected or, at best, considered as nuisance parameters, modelled empirically based on specific simulations. My current work helps build a **comprehensive physical model of this halo response to galaxies** that is one of the key ingredients in ab initio modelling of the dark matter haloes. Additionally, by bridging galactic astrophysics with cosmology, this will also contribute to a better understanding of the formation and evolution of galaxies, including their dynamical interaction with their host dark matter haloes. In this regard, I have also obtained self-similar solutions to galaxy formation, interacting with its host dark matter halo.

1.2 Proposal statement

My primary research plan is to further understand and model the relaxation response of dark matter radial distribution to galaxies. Given that some of the key features have already been identified in my recent works [1, 3, 4], I expect to obtain a simple and realistic model of this with a few more measurements from cosmological simulations with galaxies. Further, by generalising the more tractable halo-galaxy systems [2], I expect to reproduce this relaxation response behaviour ab initio and provide a clear physical description for this model.

After establishing a simple, physical and accurate model for the response in the radial distribution, I would then try to also model response in the angular distribution (determining halo shapes) and velocity distribution, by following this approach of using a combination of simulations and other numerical experiments.

I also look forward to collaborate in exploring various other interesting questions about the dark matter haloes, galaxies and other objects that build the large-scale structure of the Universe.

1.3 Research Expertise

> *With strong expertise in cosmological simulations with and without galaxy formation, I primarily look forward to doing both inference-based simulations to build better theoretical understanding and simulations-based inference in estimating interesting quantities from large-scale surveys.*

During the course of my PhD research, I have performed cosmological simulations, including hydrodynamical ones that include some of the baryonic astrophysical processes such as cooling and star formation. I have primarily worked with various large simulation particle data such as IllustrisTNG, EAGLE, and CAMELS. I have also used structure finding codes to generate halo catalogues with merger trees and developed a kdtree-based algorithm to match them between different simulations of the same initial cosmological volumes. I have also developed codes to generate field information from simulation particle data, for both visualizing and computing cosmological quantities such as the matter power spectrum and halo/galaxy properties such as mass profiles and shapes. I have performed various statistical techniques, such as computing the correlation functions in multiple dimensions.

I have obtained novel self-similar solutions of interacting dark matter halo and the formation and evolution of galaxy pseudo-disk. Extending the

iterative mean field techniques employed in this approach, I also perform other numerical experiments in a more general case that can be directly compared against corresponding simulations. In a mini project done with Prof. Hector marin, I have inferred cosmological parameters from eBOSS and mock DESI data. I am currently working in a data science collaboration focused on using machine learning techniques in cosmological data compression and inference. In another collobaration, I am working on the effect of supermassive black holes on the nature and the evolution of overall dark matter in the haloes.

2 Key Contributions of My PhD Research

In my PhD thesis titled, "Interplay of galaxy formation and dark matter halo evolution in the cosmic web", I have done the following research with Prof. Aseem Paranjape.

- **Halo Relaxation Response in the cosmic web:** Through statistical analysis of a large number of haloes in cosmological simulations IllustrisTNG and EAGLE, we have developed models of quasi-adiabatic relaxation that accurately predicts the change in the dark matter radial distribution in response to the galaxy formation and evolution. These results also revealed the significance of feedback-related effects on the relaxation response and explicit dependence on halo-centric distance. This model provides an accurate fit to the relaxation responses observed in simulations of dark matter haloes and assists in the physical interpretation of the relaxation across a variety of haloes.

- **Role of Astrophysical processes and epoch:** Through an extensive collection of CAMELS simulations, we identified that not all but some of the simulation parameters controlling the feedback had a strong effect on the halo relaxation, and this is also significantly different at different redshifts.

- **Dynamics of the Relaxation:** We have studied the evolutionary history of the relaxation of haloes across cosmic time along with its correlation with evolving halo and galaxy properties. This revealed that the relaxation response on the halo manifests immediately in the inner halo regions and with a time delay of around 2–3 Gyr in the outer halo regions, followed by periods of star formation activity. This explains the emergence of the dependence on the halo-centric distance at a given cosmic time.

- **Self-Similar Model for Halo-Galaxy Interplay:** We have obtained spherical self-similar solutions of mutually interacting dark matter halo and gas that radiatively cools and forms a pseudo galaxy disk with an artificial viscosity. With this more tractable approach to experiment and understand the relaxation mechanism, we also obtained relaxation response relations consistent with full simulations.

3 Research Proposal

Building on my expertise in the astrophysical impacts on dark matter haloes, I plan to pursue several key avenues of research in a postdoctoral position:

1. **Time-Correlation Analysis of Galaxy-Halo Interactions:** My primary research plan is to explore the dynamics of the relaxation response further and extend the time-correlation analyses to examine how specific galaxy properties, such as those associated with AGN feedback, impact the relaxation of dark matter haloes. Through this work, I aim to capture the immediate and long-term effects of feedback processes, exploring how changes in galaxy mass distribution, star formation rates, and energy feedbacks affect the relaxation response of the dark matter halo at different halo-centric distances.

2. **Numerical Experiments on Galaxy-Halo System Dynamics:** I am particularly interested in conducting controlled numerical experiments with simplified galaxy-halo-like systems to track the orbital evolution of dark matter test particles. By simulating responses to varying gravitational potentials that mimic galaxy formation processes, I aim to model timescales for halo relaxation and the dynamic response at different halo-centric distances. These findings can contribute to more physically motivated models for the relaxation dynamics of haloes, incorporating both spatial dependencies and feedback-related timescales.

3. **Hydrodynamical and Zoom Simulations for Galaxy-Halo Studies:** To support these goals, I also plan to run cosmological (zoom-in) simulations with full hydrodynamics and galaxy formation prescriptions. One of the interesting things to me is to perform simulations where the baryonic prescription is altered at specific timesteps during the course of the simulation and see how things respond to that change, especially the dark matter distribution in haloes.

3.1 Additional Areas of Interest

Beyond my primary research goals, I am eager to contribute to collaborative efforts that study other facets of dark matter distribution within simulations. This includes analyzing the power spectrum, halo-filament connectivity, and halo population statistics, especially as they relate to the distribution of galaxies in the cosmic web. I am also interested in roles that involve running mock simulations for current and upcoming large-scale surveys such as EUCLID and DESI, where insights from simulations can play a crucial role in interpreting observational data on galaxy clustering, gravitational lensing, and cosmic shear. I list below some of my long-term research plans.

1. Include halo shapes to physical model of relaxation: I aim to build a physical and accurate of response in halo shapes to the formation and evolution of galaxies

2. Investigating Halo Substructure Evolution: I will study how baryonic processes affect subhalo dynamics and tidal stripping within massive dark matter haloes, particularly in the context of satellite galaxy evolution.

3. Collaboration with Upcoming Surveys: I will work on integrating simulation results with upcoming surveys such as LSST and Euclid, helping to bridge the gap between observational data and theoretical predictions of dark matter distribution and galaxy formation.

4. Application to Baryonification Schemes: Incorporating the knowledge gained from detailed simulations into efficient baryonification schemes for fast cosmological predictions.

5. Exploring Alternative Dark Matter Models: I also intend to explore how alternative dark matter models, such as self-interacting dark matter (SIDM), alter the relaxation properties of haloes and how these can be distinguished from standard cold dark matter (CDM) in both simulations and observations.

4 Conclusion

By combining my experience with large-scale cosmological simulations and theoretical modelling, I aim to advance our understanding of the role different baryonic astrophysics play in mediating the response of dark matter haloes to galaxies. I am enthusiastic about the opportunity to advance our understanding of galaxy-halo interactions through the lens of both cosmology and astrophysics. My background in running and analyzing cosmological simulations, with and without galactic astrophysics, positions me to start contributing to projects that bridge astrophysics and cosmology immediately. I look forward to working within a collaborative environment where I can further develop my expertise in simulation-based cosmology and galactic astrophysics and contribute to our knowledge of the evolving universe.

References

[1] Premvijay Velmani and Aseem Paranjape. "The quasi-adiabatic relaxation of haloes in the IllustrisTNG and EAGLE cosmological simulations". In: MNRAS 520.2 (Apr. 2023), pp. 2867–2886. DOI: 10.1093/mnras/stad297. arXiv: 2206.07733 [astro-ph.GA].

[2] Premvijay Velmani and Aseem Paranjape. "A self-similar model of galaxy formation and dark halo relaxation". In: J. Cosmology Astropart. Phys. 2024.5, 080 (May 2024), p. 080. DOI: 10.1088/1475-7516/2024/05/080. arXiv: 2311.13952 [astro-ph.GA].

[3] Premvijay Velmani and Aseem Paranjape. "Dynamics of the response of dark matter halo to galaxy evolution in IllustrisTNG". In: *arXiv e-prints*, arXiv:2407.08030 (July 2024), arXiv:2407.08030. DOI: 10.48550/arXiv.2407.08030. arXiv: 2407.08030 [astro-ph.CO].

[4] Premvijay Velmani and Aseem Paranjape. "The evolving role of astrophysical modelling in dark matter halo relaxation response". In: *arXiv e-prints*, arXiv:2408.04864 (Aug. 2024), arXiv:2408.04864. DOI: 10.48550/arXiv.2408.04864. arXiv: 2408.04864 [astro-ph.CO].