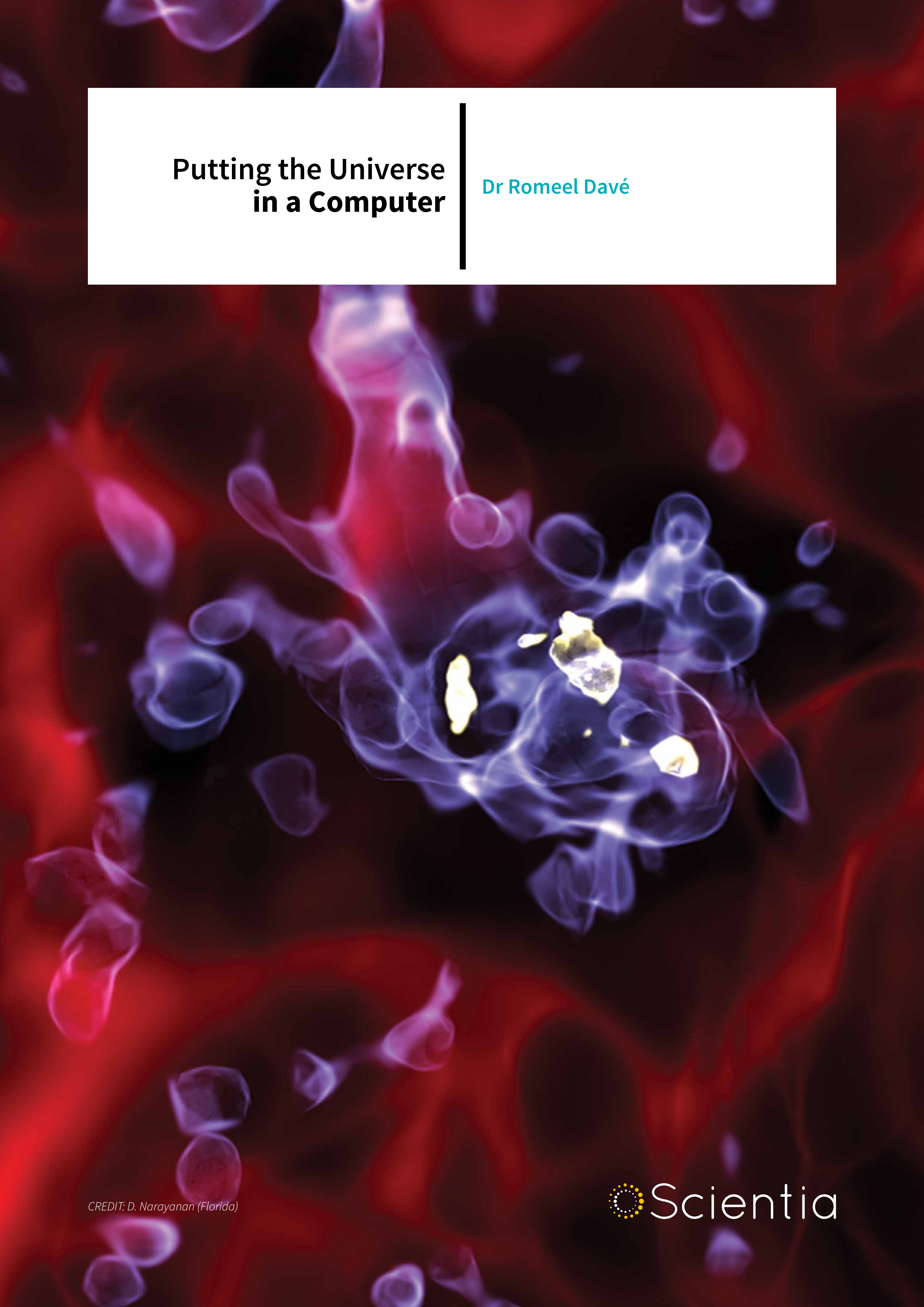
Putting the Universe in a Computer

Dr Romeel Davé



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Scientia

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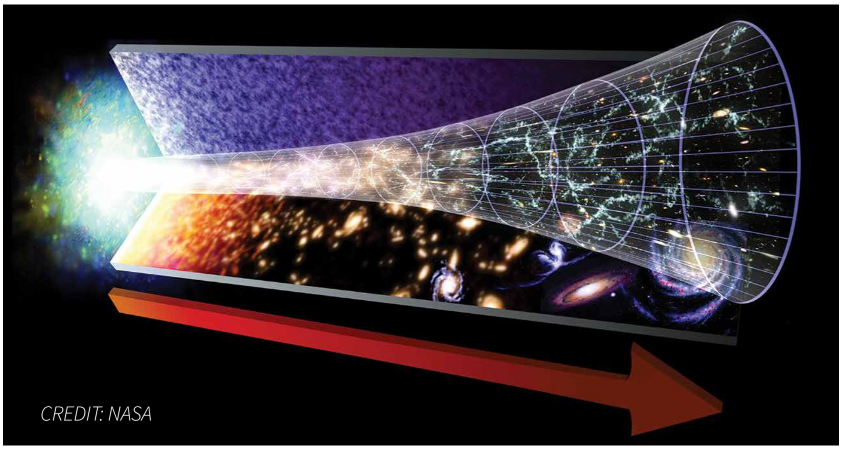
Galaxy formation theorist **Dr Romeel Davé** and his team at the University of the Western Cape use high-performance supercomputer simulations to answer basic questions about the evolution of galaxies and our visible Universe.



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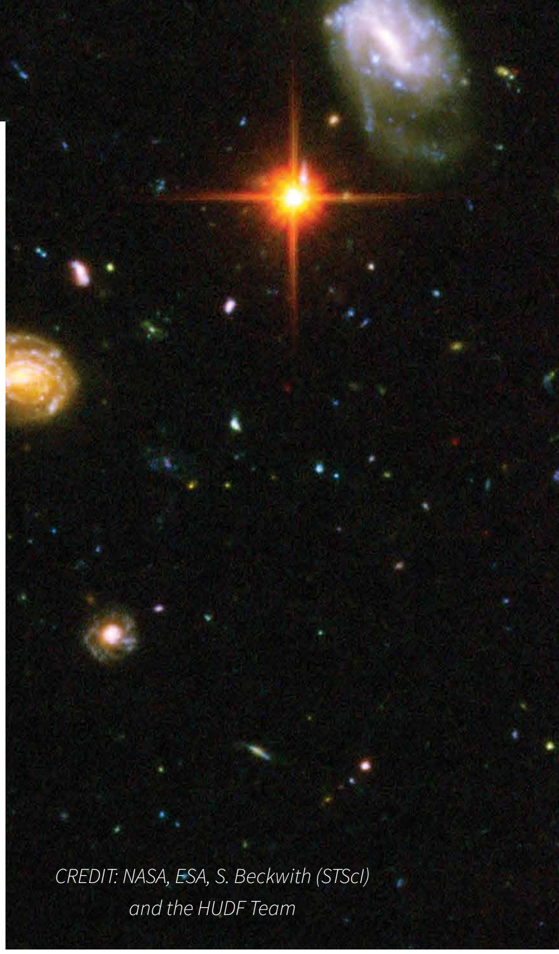

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Humans have always been mesmerised by the night skies, and strived to understand our place in this vast Universe. Our current understanding suggests the beginning of our observable Universe occurred in a Big Bang – an unimaginably hot and dense state that expanded rapidly, creating matter out of nothing but tiny quantum fluctuations. Over the nearly 14 billion years that followed, the inexorable pull of gravity grew these fluctuations into the hundreds of billions of galaxies that we can observe today. Our most sophisticated telescopes such as the Hubble Space Telescope can see galaxies far out in space and commensurately back in time, back even into the first billion years of existence. Stunning images show a fascinatingly complex and rich population of galaxies, including majestic spirals like our Milky Way, formless ellipticals, and chaotic irregulars. To scientists like Dr Davé at the University of the Western Cape, this prompts the fundamental question: How did all this come to be?

As powerful as they are, telescopes merely take snapshots at an instant in time – human lifetimes are too short to directly watch the Universe evolve. This is where Dr Davé and his colleagues step in. Dr Davé's team builds sophisticated computer programs that aim to simulate the Universe from the Big Bang until today. The goal is to reproduce the dizzying range of observations seen with advancing optical, radio, X-ray, and other telescopes, armed with nothing but the laws of physics and powerful supercomputers. Ultimately, this would allow us to make a movie of how our Universe evolved from the Big Bang until today, connecting humans to the beginnings of time within a single cosmic origins story.

Making Models

Cosmologists currently estimate that about 70% of the Universe is made up of dark energy, a quarter is dark matter, and only about 5% is visible or so-called 'baryonic' matter. This baryonic matter includes everything we ordinarily think of as 'matter', or as Dr Davé explains, 'everything made up of elements in the periodic table.' While the nature of dark matter and dark energy remain fascinating mysteries, Dr Davé tells us that his work is focused more on questions regarding the evolution of the visible parts of the Universe. So, his work is primarily concerned with just 5% of the mass-energy in the Universe, but 'it's the interesting 5%, because it's the stuff that makes up galaxies, stars, planets, and us!'

Dr Davé was always interested in computer programming and numerical modelling. Although it is only in the past decade or so that computer simulations incorporating baryonic matter have emerged as a mature and valued approach, he has been developing and running such simulations since the 1990s, and pioneered some of the approaches still used today. 'I could see early on that computer modelling was going to grow into an important force in the field because of the complexity of the physical systems involved,' he says.

The underlying reason for this, Dr Davé argues, is that unlike Earth-bound lab scientists who can control their experiments, astronomers can't even reach their distant experimental subjects – galaxies, stars and planets – much less control them. 'It's a classic blind men and the elephant story,' explains Dr Davé. 'Telescopes can see different aspects of different objects at different times, but it takes computer models to synthesise all these disparate data into a single cohesive elephant.'

Early in his career, Dr Davé worked on aspects of cosmology such as dark matter and dark energy. While he maintains an interest in these areas, he finds studying baryonic matter to be a much richer endeavour. 'This is our story, the story of how we and everything we see got here,' he says. 'Virtually every culture or religion has its own origin myth. We astronomers are developing science's version of an origin myth – but unlike any that has come before, one that is testable, observationally verifiable, and grounded in the principles of physics.'

Simulating the Universe from the Start

Dr Davé likes to distil the aim of his research down to a basic question: 'Why does the Universe look the way it does?' To answer this question, he takes an empiricist's approach. He begins with the well-established initial conditions shortly after the Big Bang, adds in the laws of physics, sprinkles on some complicated physical processes such as the formation of stars and black holes, and throws this all into a computer. A single simulation can take months to run using thousands of CPU cores, but what comes out at the end is a rich and dynamic movie of the Universe and its evolution across all of time that can be tested against observations covering the full electromagnetic spectrum. For many observations, the simulations agree well with the empirical data, in which case Dr Davé says he 'dives into them to try and understand the fundamental physical processes that drive such agreement.' Often, though, his models disagree with observations. It is such disagreements that are most valuable, because this tells him that the model is missing some key component, or that a baseline assumption is incorrect. He must then come up with a new hypothesis, guided by physical intuition and observations, insert it into the model, and the process stars over. With each iteration, Dr Davé's simulations more closely reproduce observations of the real Universe, and become an ever more viable description of why the Universe looks the way it does.

Galaxy formation simulations must account for a Universe that includes a complex collection of physics such as star formation, black hole accretion, gas dynamics, and dark matter and dark energy that establish the galactic distribution within the Cosmic Web – the vast network of dark matter that houses all galaxies. To cover all these bases, Dr Davé's simulations include physics from classical dynamics, thermodynamics, chemistry, relativity, radiative processes and quantum mechanics, along with aspects of computer science such as hardware-optimised algorithm development and parallel computing. According to Dr Davé, the diversity of knowledge required is one of the most entertaining aspects of his work. 'To be a galaxy formation theorist, you have to be something of a physics dilettante, knowing a little bit about great many topics.' he says. 'I'm constantly having to learn about things I never thought I'd have to know, which is great fun.'

A major recent accomplishment of Dr Davé's group is the development of a suite of cosmological simulations they call MUFASA. 'MUFASA represents a re-think of how we play this game,' argues Dr Davé. 'It synthesises knowledge from simulations at multiple scales together with analytic modelling to yield among the closest agreement with data that any galaxy formation model has yet achieved.' Despite pushing the state of the art, Dr Davé admits that MUFASA remains far from reproducing all available observations, and even shows some vexing disagreements. 'We've made huge progress, but it's hard to overstate how far we have yet to go to build a fully successful model,' he says.

By synthesising this knowledge and applying his computer skills, Dr Davé says he is attempting to answer some of the most basic questions about our visible Universe: Why do galaxies exist in the multiple shapes, colours, and sizes we see? What regulates the growth of galaxies and their black holes? When were the first stars and galaxies formed and what did they look like? What lies between

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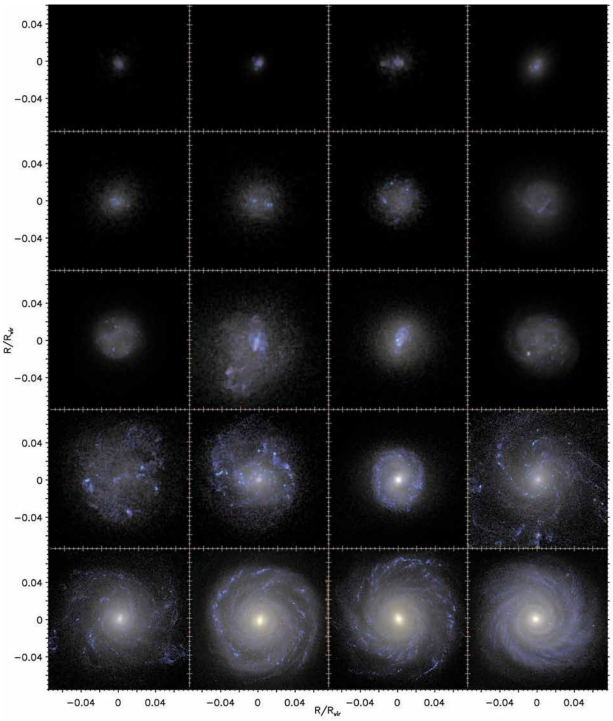

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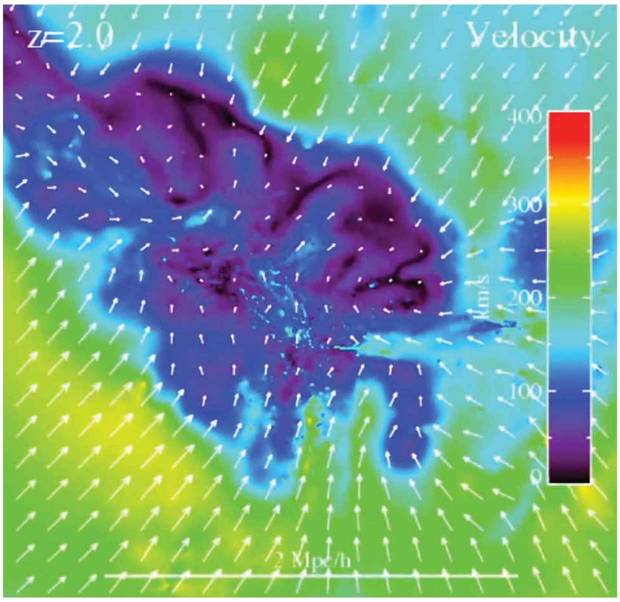

CREDIT: B. Oppenheimer (Colorado)

galaxies in the Cosmic Web? To him and many of his colleagues, these are some of the most fundamental questions in modern astrophysics, questions that are driving billions of dollars in investments into future astronomical facilities such as the James Webb Space Telescope.

The Universe as a Living System

Despite only recently coming to the fore as a major tool in understanding our Universe, computer simulations like those of Dr Davé's group have already been transformative in our basic picture of how galaxies form and grow. 'Before simulations,' Dr Davé explains, 'galaxies were thought of as island universes, solitary and set apart, having little interaction with their surroundings.'

Simulations changed all this. Generically, simulations forwarded a new paradigm that Dr Davé and fellow Professor Andrew Baker (Rutgers) dubbed 'the baryon cycle'. In his view, Dr Davé likens galaxies to living beings in ecosystems on Earth. Galaxies obtain fuel from their surroundings, some of which is transformed into visible stars, and some of it is ejected back out of the galaxy, later to be recycled back in. This is the cycle of baryonic matter in and out of galaxies. A galaxy's properties are then influenced not only by the nature of its birth location, but also by the way in which this cosmic ecosystem nurtures their growth. As with many biological systems, the relative importance of nature versus nurture remains an open question in galaxy evolution.

This new baryon cycle paradigm of galaxy evolution is the primary focus of Dr Davé's work. 'Even though a galaxy might look serene, it is in fact a roiling pot of energy that continually spews mass and energy into its surroundings, while at the same time pulling in fresh material owing to its gravity,' he explains. Dr Davé's view is that understanding how the baryon cycle operates is tantamount to understanding galaxy evolution, and by extension, the visible Universe.

The most pressing current questions surround how galaxies manage to eject huge amounts of matter back into surrounding space. Immense energy is required to do this, which might come from exploding supernovae, black holes, winds from massive stars, or cosmic rays, but exactly which of these are at work and how they operate remains unclear. Dr Davé and his colleagues aim to develop, as he puts it, 'new technologies, techniques, and telescopes to directly detect and measure the baryon cycle as it happens.' By combining such measurements with advancing simulations such as MUFASA, the team hopes to better understand the diversity of galaxies arising in various environments, much like biologists aim to understand the diversity of life on Earth arising in various habitats.

Moving on While Looking Back

Dr Davé's life is evolving forward much like his simulations, as he is in the process of moving to the University of Edinburgh to take up the Chair of Physics. There, he intends to put together a world-class group of scientists working in numerical simulations of galaxy formation and related issues in cosmology. 'At the Royal Observatory in Edinburgh there are already experts in simulations of the first stars and black holes on small scales, and cosmology on large-scales,' he explains. The latter refers to Professor John Peacock, who literally wrote the book on Cosmology – the standard textbook Cosmological Physics. Dr Davé expects that his galaxy formation models will help bridge the gap between small and large scale phenomena. He envisions Edinburgh to be a 'one-stop-shop for all astrophysical simulations of galaxies, from the smallest first objects to massive clusters today.'
Dr Davé's main research will be based on the MUFASA simulation project that he assembled over his years in South Africa. 'I have had a wonderful and rich experience in Cape Town over the last few years helping South Africa to emerge as an important player on the international astronomy scene.' South African astronomers are currently building the world's greatest radio telescope – the Square Kilometre Array. Dr Davé says he plans to continue to be heavily involved in South Africa's growth and emergence, but at the same time he is excited to join one of the UK's preeminent astronomical centres at the Institute for Astronomy in Edinburgh. With computers becoming ever more powerful and incredible new telescopes on the way, Dr Davé is enthusiastic about the prospect of discovering fascinating new insights into how galaxies, black holes, and intergalactic gas evolve over time, and doing his part to piece together the story our cosmic origins.

Meet the researcher

Dr Romeel Davé
SARChI Chair in Cosmology with Multi-Wavelength Surveys
Department of Physics and Astronomy
University of the Western Cape
Cape Town
South Africa

Dr Romeel Davé received his Bachelor's degree in Physics from the University of California at Berkeley and a Master's degree in Physics from the California Institute of Technology. He then pursued graduate work at the University of California in Santa Cruz, obtaining his PhD in Astronomy & Astrophysics in 1998. Following this, he was awarded a Lyman J. Spitzer Fellowship at the Princeton Department of Astrophysics, and subsequently a Hubble Fellowship at the Steward Observatory, before securing a faculty position in Astronomy at the University of Arizona in 2003. In 2013, Dr Davé joined the Department of Physics of the University of the Western Cape, where he is now the South African Research Chair in Cosmology with Multi-Wavelength Data. Dr Davé's research interests include numerical studies of galactic evolution, the intergalactic medium, large-scale galactic structure, reionisation, and general cosmology. His career highlights include writing the world's first parallel hydrodynamics code for galaxy formation, developing the first cohesive model connecting the evolution of galaxies and the intergalactic medium, and investigating the nature of the Universe's so-called 'missing baryons'. Dr Davé has authored or co-authored over 170 articles published in peer-reviewed journals garnering over 18,000 citations, and is regularly invited to give keynote or plenary talks at international conferences. With his wife Dr. Jarita Holbrook, he has co-produced prize-winning documentaries 'Hubble's Diverse Universe' (2009) and 'Black Suns: An Astrophysics Adventure' (2017).

CONTACT

T: (+27) 79 628 1440
E: romeeld@gmail.com
W: https://www.cetcapetown.org/romeel-dav

KEY COLLABORATORS

Rachel Somerville, Rutgers University
Desika Narayanan, University of Florida
Thorsten Naab, Max Planck Institute for Astrophysics
Neal Katz, University of Massachusetts, Amherst
Kristian Finlator, New Mexico State University

FUNDING

NSF
NASA
South African National Research Foundation
UK Royal Society