Understanding the impact of feedback and cosmology on star formation and the distribution of gas within haloes

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1 Overview

I visited the Centre for Computational Astrophysics (CCA) at the Flatiron Institute in New York from 1st to 5th May 2023, funded by the Cosmology and Astroparticle Student and Postdoc Exchange Network (**CASPEN**). My host was **Rachel Somerville**.

The main purpose of the visit was to initiate collaborations with the Galaxy Formation and Cosmology X Data Science groups at the Centre for Computational Astrophysics (CCA) on projects of mutual interests. The discussions began in the context of the Simba Collaboration Workshop, which took place at the CCA from 1st to 4th May 2023. The workshop brought together both local and international scientists working on research related to the Simba suite of cosmological hydrodynamic simulations [1] and on the CAMELS project [8].

During the workshop, I presented recent [6] and ongoing work on the impact of stellar/AGN feedback processes on the distribution and physical state of baryonic matter in the Universe. I also presented the `Pygad` code [4, 5], which is a tool to generate synthetic absorption spectra from numerical simulations. Given that I previously adapted this code for the Simba simulation, I presented it to the audience at the workshop.

Other participants also showcased of their ongoing research, and there was plenty of time to brainstorm on new ideas. This setting served as a starting point for several individual meetings that I held both with CCA members and other participants to the workshop on 5th and 6th May.

This report summarises the main outcomes of my visit. In § 2 I will briefly describe my current lines of research, which I sought to expand through collaborations with CCA scientists. In § 3 I will summarise the main points emerged in the discussions that I held during my visit, and the subsequent plan for collaborations. I will then summarise the main outcomes of my visit in § 4.

2 Scientific background

My research interests span galaxy formation, cosmology and large-scale structure. Currently, I am working on two main lines of investigation.

2.1 The impact of baryon-driven astrophysics on galaxy formation

A major challenge for a theory of galaxy formation in a cosmological context is represented by the modelling of baryon-driven astrophysics. Indeed, simulations show that mechanisms such as stellar winds or jets ejected by active galactic nuclei (AGN) are effective at heating and expelling gas from galaxies, thereby counteracting star formation. Such "feedback processes" are often implemented as sub-grid prescriptions that can vary from code to code, potentially limiting the predictive power of cosmological simulations and hindering the physical interpretation of observations. It is thus crucial to study the effect of different feedback prescriptions in hydrodynamic cosmological simulations on the distribution and physical properties of baryonic matter in the Universe.

In a recent work, I used five variants of the Simba cosmological simulations, each with different feedback implementations [6]. I then analysed the distribution of different baryonic phases (e.g., cold/hot gas, stars, etc.) within and outside haloes of different masses, and at different cosmic epochs.

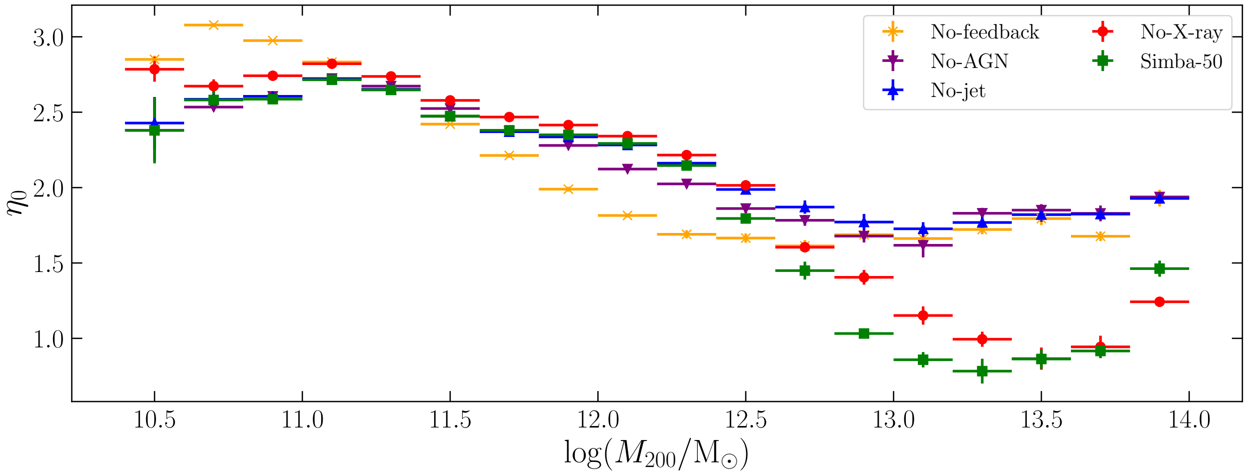

Figure 1: Slope of the gas density profile at redshift $z = 0$ in different Simba runs, as reported in the legend. Including AGN-jets makes the slope less steep (preliminary).

The main conclusion was that stellar feedback is the most important agent in shaping the distribution and physical state of baryons in the Universe at redshift $z > 2$ in low-mass haloes, while feedback due to AGN-driven jets is dominant at $z < 2$ in high-mass haloes. As a follow-up work, I am now investigating the impact of the different feedback prescriptions on the slope of the gas density profiles within haloes. My preliminary results, which I showed during the Simba Collaboration Workshop, suggest that AGN jets cause high-mass haloes to be characterised by slowly declining gas density profiles, whilst in the absence of AGN jets the density profiles are steeper (Fig. 1).

2.2 The impact of fundamental cosmological parameters on cosmic star formation

While the impact of astrophysical processes such as stellar and AGN feedback on cosmic star formation history has been extensively studied, the role played by the cosmological parameters has received less attention in the literature. I am therefore analysing how changing the cosmological constant Λ would impact the global star formation efficiency over the entire history of the universe. I do this via an analytic model for cosmic star formation that I recently published [7]. As a byproduct of this work, I also developed an analytic model for the baryon mass fraction in haloes across different masses and redshifts.

My preliminary results suggest that for large values of Λ cosmic star formation history is suppressed because the cutoff of the halo mass function moves towards lower masses. For smaller values of Λ, the efficiency of star formation is suppressed for astrophysical rather than cosmological reasons. For a fixed halo mass, the virial radius increases as Λ decreases, hence the typical gas density within the halo also decreases, thereby suppressing the cooling rate and consequently slowing down star formation.

3 Outcomes

In this section, I will summarise the main outcomes of my meetings with CCA scientists and attendants of the Simba Collaboration Workshop.

Rachel Somerville An obvious connection between our research interests is the modelling of the distribution of different baryonic phases within haloes from first principles. Together with Viraj Pandya, Rachel worked on semi-analytic modelling of matter and energy flows within haloes [2, 3]. While the physics is modelled analytically from first principles, the value of the slope of the gas density profile needed to be assumed. For this reason, my preliminary results on the dependence of the slope on feedback processes in the Simba simulation could inform further extensions of their semi-analytic modelling. We agreed to get back in touch after my work is finalised to discuss further collaborations.

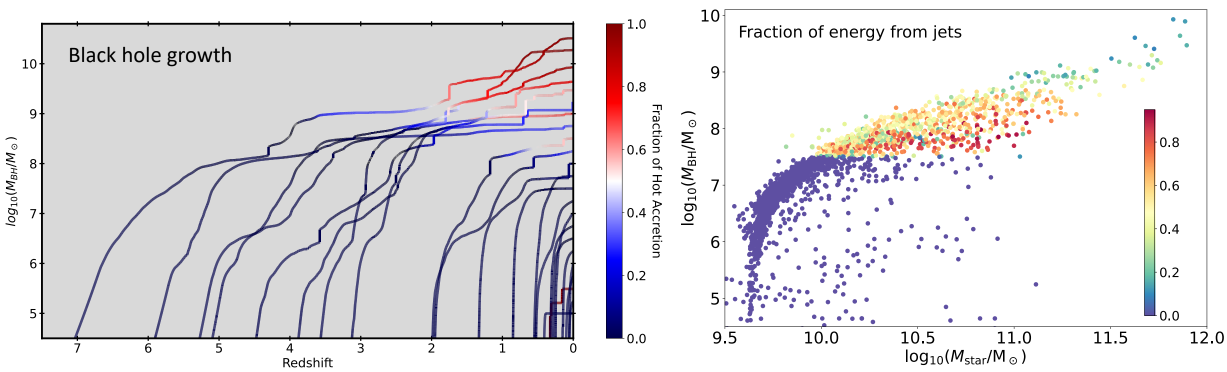

Figure 2: *Left panel*: Evolution of the black hole mass for the most massive black holes in the Simba simulation. Each line represents a black hole, and is colour-coded according to the fraction of the accretion rate due to hot accretion (i.e., Bondi). *Right panel*: Black hole mass – stellar mass relationship for all black holes residing in galaxies for the Simba simulation. Each point represents a black hole and is colour coded according to the fraction of ejected energy that is due to the AGN-jets mode. Both figures are preliminary results, courtesy of Daniel Anglés-Alcázar.

Daniel Anglés-Alcázar Daniel showed unpublished results that demonstrate that after $z = 2$ the growth of black holes in Simba starts being dominated by Bondi accretion (i.e., hot accretion - see Fig. 2, left panel). Given that I notice that after $z = 2$ AGN jets have the dominant effect on gas within and outside haloes, we discussed possible correlations between our findings. Indeed, the speed of AGN jets is tied to the mass and accretion rate of black holes. Furthermore, Daniel showed that in the most massive haloes AGN feedback surprisingly reverts from radiative mode to jets mode (Fig. 2, right panel). The former injects considerably fewer energy in the surrounding gas, and this would explain why I am currently seeing that the slope of the gas density profile becomes less steep when AGN jets are active (and thus push more gas towards the outskirts of the halo) in group-size haloes, but become again steeper in cluster-sized haloes (where the AGN radiative mode has a weaker effect on the displacement of gas outwards).

Shy Genel Shy was very interested in my results described in § 2.1. He suggested that the reason why $z = 2$ seems to act as a “watershed” between an epoch of where stellar feedback dominates on AGN feedback and vice versa might have to do with the growth history of black holes, which would impact when jets are active. I informed him of my discussion with Daniel Anglés-Alcázar, and he suggested that it would be informative to further analyse the connections between black hole history and impact of AGN feedback on the distribution and temperature of the gas in the Universe within the CAMELS suite of simulations. Indeed, CAMELS allows for a more fine-grained exploration of the parameter space.

Fred Jennings Fred took part in the Simba collaboration workshop, and showed his work on X-ray mock observations of clusters. In particular, he showed the gas density, temperature and pressure profiles in group-size and cluster-size haloes in Simba. His work is therefore very close to my research on the impact of feedback on the slope of the gas density profile of haloes. He agreed to produce similar plots for all of the Simba feedback variants. I committed to repeat my analysis by separating the haloes in bins of M_{500} rather than M_{200}, and to extract 2D instead of 3D gas density profiles. These changes will enable the creation of mock observations for future X-ray facilities (such as Athena) and make predictions as to whether forthcoming measurements will be able to discriminate among the predictions of cosmological simulations with different feedback models.

Francisco Villaescusa-Navarro Francisco and I mainly discussed about his recent publication where he showed that with a machine-learning algorithm applied on the CAMELS suite of simulations, it was possible to predict the matter density of the Universe (i.e., the cosmological parameter $\Omega_{\rm m}$) from the star formation properties of only one galaxy. The impact of $\Omega_{\rm m}$ on the star formation history of the galaxy appears to be orthogonal to the effect of other astrophysical parameters. I showed him how my previous and ongoing work described in § 2.2 can explain why Ω_m seems to be so impactful. However, he pointed out that in my case I am fixing the astrophysical parameters, so it would be useful to see if also in my analytic model Ω_m has a prominent role in the star formation history even when reasonable variations of the astrophysical parameters are taken into account. I agreed to look into that. I proposed that the CAMELS suite fo simulations could be extended to include also extreme counter-factual cosmologies (such as with very high values of the cosmological constant), as a 'stress-test' of galaxy formation models in unusual regimes. Francisco said that it is an interesting question, but it would be useful to perform an exploratory analytical study first before committing considerable computational resources. I agreed and I will contact him again after addressing the questions that he raised.

4 Conclusions

My visit at the CCA has been incredibly productive. I laid out a path forward for collaborations with several scientists from the CCA and other institutes, defining concrete projects for the future. Therefore, the primary aim of my visit has been achieved beyond expectations. Thanks to my discussions with other researchers, I also understood the origin of certain behaviour of the simulations that I considered in my work. This further enriched the scientific value of my visit.

Acknolwedgements

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