Compact Objects and Binaries in Dense Star Clusters
Proceedings IAU Symposium No. 398, 2026
H. M. Lee, J. Hong & R. Spurzem, eds.
doi:10.1017/S1743921325104274

Modelling black hole accretion through an α-disc in dwarf galaxies with a resolved interstellar medium

Eun-jin Shin[1,2], Debora Sijacki[1,2], Matthew C. Smith[3], Martin A. Bourne[1,2,4] and Sophie Koudmani[4,5]

[1]Institute of Astronomy, University of Cambridge, Madingley Road, Cambridge CB3 0HA, UK email: ejs237@cam.ac.uk

[2]Kavli Institute for Cosmology, University of Cambridge, Madingley Road, Cambridge CB3 0HA, UK

[3]Max-Planck-Institut für Astrophysik, Karl-Schwarzschild-Str. 1, D-85748, Garching, Germany

[4]Centre for Astrophysics Research, Department of Physics, Astronomy and Mathematics, University of Hertfordshire, College Lane, Hatfield, AL10 9AB, UK

[5]St Catharine's College, University of Cambridge, Trumpington Street, Cambridge CB2 1RL, UK

Abstract. We perform high-resolution simulations of a $10^{10}\,M_\odot$ dwarf galaxy hosting a $10^4\,M_\odot$ intermediate-mass black hole (IMBH), reaching $\lesssim 0.01$ pc resolution. Our model resolves a multiphase ISM with star formation, radiative feedback, and individual supernovae, while BH accretion is captured using an α-disc model that includes Lense-Thirring torques and hence follows spin evolution self-consistently. We find that a nuclear star cluster (NSC) efficiently captures inflowing gas and promotes the formation of a dense circumnuclear disc (CND) on ~ 6 pc scales. Gravitational torques from the NSC drain angular momentum, circularizing the gas onto the accretion disc and enabling BH growth together with spin-up. The CND undergoes in-situ star formation, which regulates BH accretion through feedback. Our results highlight the interplay between BH accretion, star formation, and feedback in the multiphase ISM, emphasize the role of NSCs in mediating inflows, and point to future cosmological applications. Details are presented in Shin et al. (2025).

Keywords. accretion, accretion discs, black hole physics, methods: numerical, galaxies: dwarf, galaxies: star formation, galaxies: nuclei

1. Introduction

Intermediate-mass black holes (IMBHs; $10^2 - 10^6\,M_\odot$) are regarded as the missing link between stellar-mass and supermassive BHs (SMBHs), and unveiling their origin and growth is crucial to understanding the assembly of SMBHs across cosmic time (e.g., Volonteri 2010). Despite their intrinsically low luminosities and limited dynamical influence, which make them difficult to detect, the number of IMBH candidates in both local and high-redshift galaxies is steadily increasing (e.g., Askar et al. 2023). Among the various environments, nuclear star clusters (NSCs) are considered particularly promising sites for hosting IMBHs (e.g., Greene et al. 2020). Their high densities enable the formation of very massive stars through runaway stellar collisions, which may then collapse directly into BHs. In addition, NSCs offer conditions of mass segregation and dynamical friction

© The Author(s), 2026. Published by Cambridge University Press on behalf of The International Astronomical Union. This is an Open Access article, distributed under the terms of the Creative Commons Attribution licence (https://creativecommons.org/licenses/by/4.0/), which permits unrestricted re-use, distribution and reproduction, provided the original article is properly cited.

https://doi.org/10.1017/S1743921325104274 Published online by Cambridge University Press

that enable hierarchical BH mergers; owing to their high escape velocity, BHs can remain bound even after gravitational-wave recoil kicks, and NSCs further supply fuel through tidal disruption events (e.g., Fujii et al. 2024; Rantala et al. 2024). These properties make NSCs one of the most favourable environments to study the formation and growth of IMBHs. Once BHs enter the IMBH regime, gas accretion becomes a major growth channel. To understand the coupled feeding and feedback of BHs and galaxies, simulations must bridge scales from kpc inflows to sub-0.01 pc accretion discs. To this end, we present the *MandelZoom* framework (Shin et al. 2025), a suite of multi-scale simulations that follow gas inflows from a resolved ISM to the α-disc, enabling a self-consistent model of BH, NSC, and galaxy co-evolution.

2. Numerical Setup

We simulate an isolated dwarf galaxy of total mass $10^{10}\,\mathrm{M}_\odot$, consisting of a dark matter halo, exponential stellar and gaseous discs, and a circumgalactic medium. At its centre, we place a $10^4\,\mathrm{M}_\odot$ BH and embed an NSC with a total mass of $3\times10^5\,\mathrm{M}_\odot$. The NSCs are modelled with collisionless stellar particles representing old stars that interact only gravitationally. The simulations are performed with the Arepo code (Springel 2010; Pakmor et al. 2016). Radiative cooling and UV background heating are included via the Grackle library (Smith et al. 2017). Star formation and feedback follow the model of Smith et al. (2021), where individual stars are explicitly sampled from the Kroupa (2001) IMF, and feedback channels include photo-ionization, photoelectric heating, and supernovae (SNe). This approach captures the clustered nature of feedback and its regulation of the multiphase ISM.

To capture galactic inflows to the BH accretion scale, we employ the super-Lagrangian refinement scheme (Curtis & Sijacki 2015). Gas cells are progressively refined according to their distance from the BH, reaching a minimum cell size of $\lesssim 0.01$ pc in its vicinity. This resolution is sufficient to resolve the self-gravity radius of the accretion disc ($r_{\mathrm{SG}}\sim 0.1-0.2$ pc in our BH system) with thousands of cells, enabling tracking of gas inflows from the ISM to the accretion disc. Following Fiacconi et al. (2018), we adopt an α-disc model (Shakura & Sunyaev 1973). At r_{SG}, we measure the inflow of mass and angular momentum, ensuring that only circularized gas contributes to accretion. The disc evolves by accreting this material and exchanging angular momentum with the BH through both the gas supply and the Lense-Thirring effect (Bardeen & Petterson 1975), enabling a self-consistent model of BH-disc co-evolution in a galactic environment.

3. From kpc to sub-0.01pc: circumnuclear disc evolution and angular momentum transport by nuclear star clusters

Our simulations reproduce a thermally and dynamically complex multiphase interstellar medium (ISM; see Fig. 1). Cold, dense clumps and filaments form, along which stars are born and emit FUV radiation that ionizes and heats the surrounding gas. As massive stars reach the end of their lifetimes, SN explosions drive shocks and generate large low-density cavities. Thus, the morphology of the ISM is shaped by the continuous interplay between cold star-forming gas and the radiative and mechanical feedback from stellar populations (Smith et al. 2021). The gravitational potential of the NSC induces frequent orbit crossings and shocks, dissipating energy and removing angular momentum from the gas, thereby promoting the formation of a dense CND with a radius of ~ 7 pc. Once circularized, the gas loses further angular momentum due to the NSC and is transported onto the α-disc, where it delivers mass and angular momentum that drive the evolution of the BH mass and spin through the Lense-Thirring effect. The CND undergoes episodic *in-situ* star formation. Massive stars emit ionizing radiation and FUV photons and heat the CND before exploding as SNe, whose shocks compress the gas toward the centre. This

https://doi.org/10.1017/S1743921325104274 Published online by Cambridge University Press

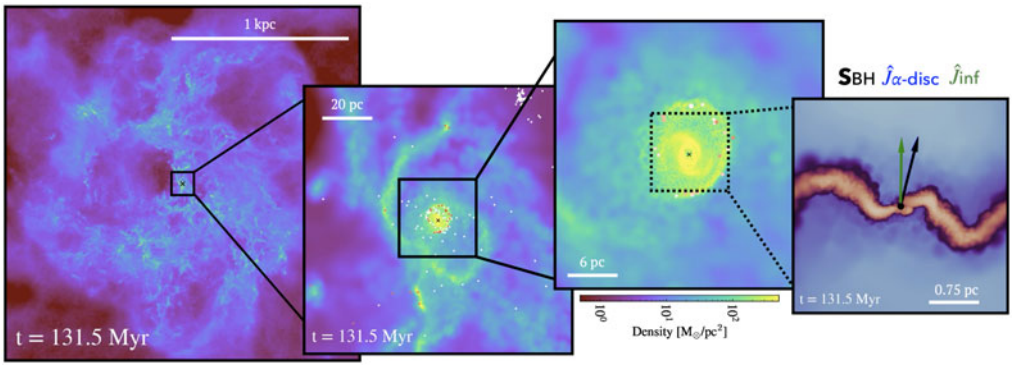


Figure 1. Gas surface density maps, zooming from kpc to sub-pc scales. A dense CND forms around the BH and channels gas toward the α-disc. The rightmost panel shows a 3 pc slice with the orientations of the BH spin ($\mathbf{S}_{\rm BH}$; *black*), the α-disc angular momentum ($\hat{J}_{\alpha\text{-disc}}$; *blue*), and the inflowing gas ($\hat{J}_{\rm inf}$; *green*).

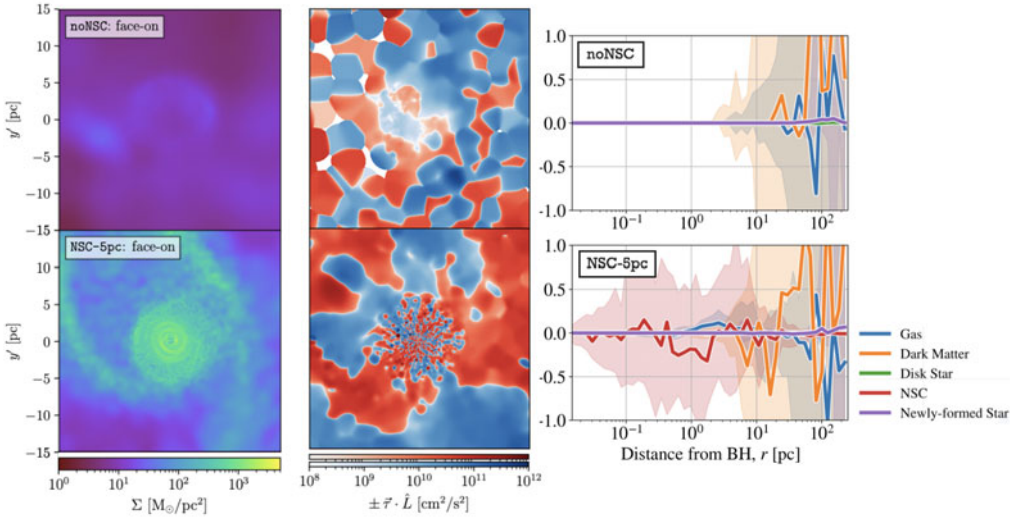


Figure 2. Gas surface density (*left*), torque maps (*middle*), and time-averaged radial torque profiles (*right*) for runs without (*top*) and with an NSC (*bottom*). The presence of the NSC leads to the formation of a dense CND and coherent negative torques that efficiently remove angular momentum from the gas, in contrast to the irregular torques in the `noNSC` run.

feedback feedback episode is short-lived but strongly boosts BH accretion. However, the cumulative effect of successive SNe can ultimately disrupt the CND entirely, quenching the BH accretion rate until fresh inflows form a new CND.

To identify the drivers of angular momentum loss, we compare simulations with and without NSCs (see Fig. 2). In the absence of an NSC, torques are irregular and dominated by stochastic interactions between gas and dark matter, producing no systematic inflow. By contrast, with an NSC, the torque maps reveal a structured torque pattern along the gas distribution. We found that the NSC extracts angular momentum from the CND, enabling the gas to spiral inward toward the BH. As the CND transfers angular momentum to the NSC, the cluster itself begins to spin up and its ellipticity increases.

https://doi.org/10.1017/S1743921325104274 Published online by Cambridge University Press

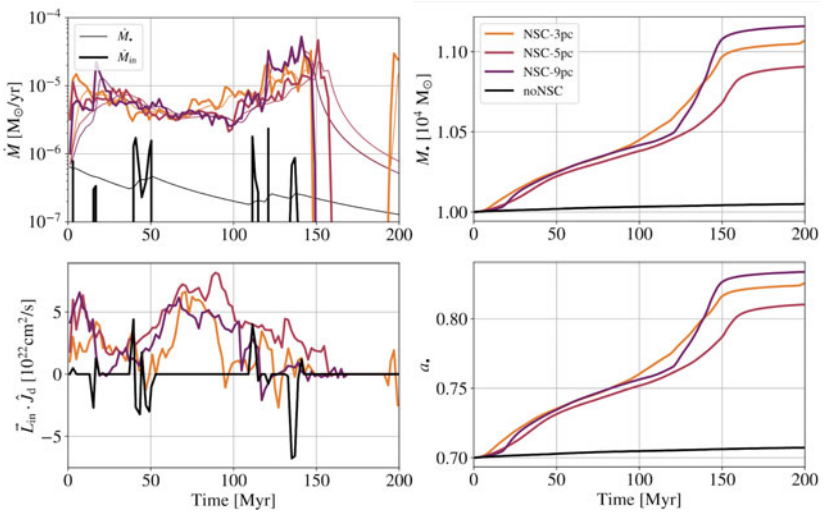


Figure 3. Time evolution of the BH accretion rate (*top left*), BH mass (*top right*), angular momentum inflow onto the accretion disc (*bottom left*), and BH spin (*bottom right*).

4. Accretion disc and BH mass and angular momentum evolution

To investigate how gas inflows shape BH growth, we examine the evolution of the accretion disc and the BH's mass and spin (see Fig. 3). The presence of an NSC sustains inflows to the α-disc, with short spikes triggered when stellar feedback compresses gas toward the centre. The BH grows steadily, and the feeding cycle is far more continuous with an NSC than without. Without an NSC, inflows are intermittent and misaligned, yielding negligible spin growth. By contrast, with an NSC, the rotationally supported CND produces structured inflows that keep the BH spin aligned with the disc via the Bardeen-Petterson effect, driving a gradual spin-up from $a = 0.7$ to ~ 0.85 over 200 Myr. These results highlight the critical role of NSCs in regulating both the mass and spin evolution of IMBHs.

5. Conclusions and Implications

We have presented results from the *MandelZoom* project (Shin et al. 2025), a new suite of multi-scale simulations that follow IMBH growth from a resolved multiphase ISM down to the α-accretion disc scale. Our simulations show that NSCs efficiently capture inflowing gas and promote the formation of dense CNDs on parsec scales. In the presence of NSCs, inflows remain coherent with the Lense-Thirring effect ensuring the stable spin growth, while *in-situ* star formation and feedback regulate both CND structure and BH accretion variability. This study establishes the first self-consistent framework linking galaxy-scale inflows to the joint mass and spin evolution of BHs through an α-disc model. Looking forward, extending this framework to incorporate AGN jet feedback (e.g., Bourne & Sijacki 2017; Talbot et al. 2021) will be a critical step toward capturing the full range of processes that regulate BH growth.

Acknowledgements. E.S., D.S., and M.A.B. acknowledge support from the Science and Technology Facilities Council (STFC; grant code ST/W000997/1). M.A.B. further acknowledges support from a UKRI Stephen Hawking Fellowship (EP/X04257X/1). S.K. acknowledges support from an 1851 Research Fellowship of the Royal Commission for the Exhibition of 1851 and a Junior Research Fellowship at St Catharine's College, Cambridge.

https://doi.org/10.1017/S1743921325104274 Published online by Cambridge University Press

References

Askar A., Baldassare V. F., Mezcua M., 2023, arXiv e-prints, p. arXiv:2311.12118
Bardeen J. M., Petterson J. A., 1975, ApJ, 195, L65
Bourne M. A., Sijacki D., 2017, MNRAS, 472, 4707
Curtis M., Sijacki D., 2015, MNRAS, 454, 3445
Fiacconi D., Sijacki D., Pringle J. E., 2018, MNRAS, 477, 3807
Fujii M. S., Wang L., Tanikawa A., Hirai Y., Saitoh T. R., 2024, Science, 384, 1488
Greene J. E., Strader J., Ho L. C., 2020, ARA&A, 58, 257
Kroupa P., 2001, MNRAS, 322, 231
Pakmor R., Springel V., Bauer A., Mocz P., Munoz D. J., Ohlmann S. T., Schaal K., Zhu C., 2016, MNRAS, 455, 1134
Rantala A., Naab T., Lahén N., 2024, MNRAS, 531, 3770
Shakura N. I., Sunyaev R. A., 1973, A&A, 24, 337
Shin E.-j., Sijacki D., Smith M. C., Bourne M. A., Koudmani S., 2025, arXiv e-prints, p. arXiv:2504.18384
Smith B. D., et al., 2017, MNRAS, 466, 2217
Smith M. C., Bryan G. L., Somerville R. S., Hu C.-Y., Teyssier R., Burkhart B., Hernquist L., 2021, MNRAS, 506, 3882
Springel V., 2010, MNRAS, 401, 791
Talbot R. Y., Bourne M. A., Sijacki D., 2021, MNRAS, 504, 3619
Volonteri M., 2010, A&ARv, 18, 279

https://doi.org/10.1017/S1743921325104274 Published online by Cambridge University Press