TITLE : Formation Pathways and Dynamics of Supermassive Black Holes in Hierarchical Galaxy Formation

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ABSTRACT:

Supermassive black holes are fundamental constituents of massive galaxies. This notion has been accepted since the late 1960s, when it was realised that supermassive black holes might power quasar emissions. Yet, several outstanding questions about the mutual relations between supermassive black holes and galaxies remain after several decades of research. This Thesis addresses some specific aspects of the formation and dynamical evolution of supermassive black holes in the broader context of hierarchical galaxy formation. We use cosmological and idealised hydrodynamical simulations, as well as analytical techniques, to probe:
- the formation and morphological evolution of high redshift galaxies;
- the formation of massive black hole seeds within the direct collapse scenario;
- the evolution of supermassive black hole pairs in gas-rich environments.

In detail:

Chapter 2: We study the morphological evolution of 22 galaxies down to z = 3 (with stellar masses ~1e8-1e11 Msol) in the Argo cosmological zoom-in simulation. Argo traces the assembly of a group-size halo with ~ 2e13 Msol at z = 0 in a slightly over-dense region, i.e. a common and representative environment. The high resolution allows us to quantitatively study the structure of the galaxies by means of several indicators, such as profile decomposition, B/T ratios, and angular momentum content. We recover a diversity of morphologies, including late-type/irregular disc galaxies with flat rotation curves, spheroid dominated early-type discs, and a massive elliptical galaxy, already established at z~3. We identify major mergers as the main trigger for the formation of bulges. Minor mergers and stellar bars can also drive the bulge growth in some cases. We conclude that morphological transformations of high-redshift galaxies of intermediate mass are likely triggered by processes similar to those at low redshift and result in an early build-up of the Hubble sequence.

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Chapter 3: Some flavours of the direct collapse scenario postulate the existence of quasi-stars -- massive gaseous envelopes sustained by the accretion power of a central embryo black hole -- as the final stage of supermassive stars. In the quasi-star scenario, the embryo black hole experiences an initial super-Eddington growth, that in less than a million years may leaves a 1e4-1e5 Msol black hole seed. Super-Eddington accretion, however, may also induce vigorous mass-loss that can limit the amount of mass able to reach the black hole. We study the properties of super-Eddington, radiation continuum-driven winds launched from the surface of massive objects and we apply them to quasi-stars. We find that: (i) photon-tiring effects are not present, since the wind is ultimately accelerated by the gas-radiation enthalpy; (ii) mass outflows can severely limit the black hole growth to ~1e4 Msol by blowing the envelope away; and (iii) massive quasi-stars are bright and blue, therefore possible targets for the James Webb Space Telescope. We also apply a model of steady-state rotation to quasi-stars.
We study the amount of angular momentum close to the accretion region. We find that quasi-stars with mass >1e5 Msol would not be able to form a central accretion disc. On the other hand, smaller quasi-stars can form an accretion disc, but mass outflows would be so strong to quickly halt the black hole growth. We foresee a bimodal outcome from quasi-stars: (i) when the original supermassive star is >1e5 Msol, the quasi-star cannot form and most of the mass collapses into a black hole seed ~1e4-1e5 Msol; (ii) in the opposite case, the quasi-star can form, but the feedback from the black hole quickly evaporates the envelope, leaving a ~1e2-1e3 Msol seed.

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Chapter 4: Massive black hole pairs below kpc separations are a natural prediction of hierarchical structure formation. When their separation shrinks enough, e.g. by interacting with the surrounding gas, they coalesce with a burst of gravitational waves. We study how a clumpy and inhomogeneous gas environment may influence the pair dynamics. First, we simulate pairs at initial separation of $\sim$100 pc embedded in isolated circumnuclear discs. We find that gravitational interactions with massive clumps and scattering off spiral arms erratically perturbs the orbital decay, either accelerating or decelerating it. Gravitational slingshots can occasionally kick a black hole out of the disc plane. Then, the black hole mostly orbits in the less dense stellar background, resulting in a longer orbital timescale. The stochasticity mainly emerges when there are clumps more massive than the black hole, with decay timescales ranging from $\sim$1 up to 100 Myr. Then, we confirm these results with a binary merger simulation at pc resolution, where a multi-phase interstellar medium develops from star formation, supernova feedback, and radiative cooling.

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