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ABSTRACT
This is a simple template for authors to write new MNRAS papers. The abstract should briefly describe the aims, methods, and main results of the paper. It should be a single paragraph not more than 250 words (200 words for Letters). No references should appear in the abstract.

Key words: keyword1 – keyword2 – keyword3

1 INTRODUCTION

The study of dark matter and scalar fields around black holes, both supermassive and primordial and in binary systems, has been approached from relativistic analyses, ultralight dark matter solitons, Bose–Einstein condensates, relativistic accretion, axion stars, superfluidity and gravitational-wave effects.

1.1 Theoretical foundations: dark matter redistribution around black holes

The presence of a massive black hole redistributes the dark matter density profile in its vicinity; the adiabatic-growth method of (Gondolo & Silk 1999) starts from a model distribution function and grows the black hole holding adiabatic invariants fixed, while a fully relativistic treatment using the Schwarzschild geometry finds the density vanishes at $r = 2R_{\rm S}$ (not $4R_{\rm S}$) and produces much higher inner spikes (Sadeghian et al. 2013).

The mass–radius relation of self-gravitating Bose–Einstein condensates in a $-1/r$ external potential created by a central mass was characterised using a Gaussian ansatz, showing how a central mass modifies maximum masses and radii of axionic halos (Chavanis 2019).

1.2 Ultralight and fuzzy dark matter as black-hole environments

Recent dynamical measurements and Event Horizon Telescope imaging enable searches for ultralight-soliton cores near SMBHs; stellar-velocity and EHT constraints exclude naive soliton-halo extrapolations for particle masses 2×10^{-20}–8×10^{-19} eV (Sgr A*) and $\lesssim 4 \times 10^{-22}$ eV (M87*) and show SMBH dynamics can suppress soliton masses by orders of magnitude (Bar et al. 2019).

Numerical solutions of the Schrödinger–Poisson equations demonstrate a 'squeezing' of FDM soliton cores by central black holes (reduced core radius, increased central density), producing constraints on FDM masses (excluding $10^{-22.12}$–$10^{-22.06}$ eV under current assumptions) when applied to M87 and the Milky Way (Davies & Mocz 2020).

1.3 Scalar-field accretion and axion stars

Relativistic Bondi accretion of a gauge-singlet scalar onto a non-spinning black hole constrains scalar masses ($m \simeq 10^{-5}$ eV) and quartic couplings ($\lambda \lesssim 10^{-19}$), and yields a piecewise double-power-law inner spike profile ($\rho_0 \propto r^{-1.20}$ to $r^{-1.00}$) within the self-gravitating regime (Feng et al. 2022).

The density profile of superfluid dark matter around SMBHs exhibits distinct power-law behaviours depending on the equation of state, enabling distinction from collisionless predictions (De Luca & Khoury 2023).

Axion-star formation via gravitational Bose–Einstein condensation in virialised minihalos around primordial black holes is predicted in broad classes of axion models, with potentially large local populations and microlensing constraints from surveys such as EROS-2 (Hertzberg et al. 2020; Yin & Visinelli 2024).

1.4 Superradiant cloud formation in binary systems

Superradiant instability around rotating black holes populates bosonic bound states and, in binaries, leads to complex evolution when self-interactions and tidal effects are included; mode coupling can produce coexisting cloud families and dynamical instabilities (bosenova) that imprint on gravitational-wave phases (Takahashi et al. 2024).

1.5 Self-interactions and dephasing in binary black holes

Wave-like dark-matter overdensities between binary black holes can produce dephasing distinct from dynamical friction, maximising when the scalar Compton wavelength is comparable to the orbital separation ($2\pi/\mu \sim d$) (Aurrekoetxea et al. 2024b).

Numerical-relativity studies show that self-interactions modify cloud evolution: repulsive couplings saturate densities and reduce

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dephasing, while attractive couplings enhance growth and can trigger bosenova-like explosions that reduce local signal imprint; the resulting dephasing across coupling ranges has been quantified (Aurrekoetxea et al. 2024a).

Resonant interactions between binaries and solitons induce oscillatory gravitational-wave signatures that could be probed by future detectors such as LISA (Kim & Yang 2025).

1.6 Boson stars and exotic compact objects

Self-gravitating condensates (boson stars) composed of ULDM can host central black holes and exhibit configurations determined by hydrostatic equilibrium including the black-hole potential; their inspirals produce characteristic dephasing that can probe ULDM mass and coupling space (Banik et al. 2025).

Searches comparing LIGO/Virgo events to Proca-star simulations provide constraints and candidate interpretations for events such as GW190521 and GW200220, yielding boson-mass posteriors at $\sim 10^{-12}$–10^{-13} eV scales under the Proca hypothesis (Calderon Bustillo et al. 2023).

1.7 Superradiance and black-hole spin constraints

Analytical calculations of vector superradiant growth rates show spin-1 bound states can grow much faster than spin-0 states, enabling constraints on weakly-coupled spin-1 particle masses from rapidly spinning X-ray binaries (approximately 5×10^{-14}–2×10^{-11} eV) and lower-significance constraints from supermassive-BH spins at lighter masses (Baryakhtar et al. 2017).

Indirect and direct bounds derived from black-hole mass and spin measurements constrain dark-photon and axion-like masses over roughly 10^{-19}–10^{-11} eV, with superradiance probing roughly eight orders of magnitude in particle mass (Cardoso et al. 2018).

1.8 Gravitational-wave signals from scalar-field mergers

Numerical simulations of black-hole mergers in scalar overdensities show that binaries may merge earlier or later than in vacuum, with mass-dependent impacts on gravitational and scalar radiation across mass ratios $q = 1$ and $q = 1/2$ (Cheng et al. 2025).

Semi-analytic waveform models validated against numerical relativity enable Bayesian constraints on scalar environments in catalogues such as LIGO–Virgo–KAGRA and can yield tentative evidence for light-scalar environments in individual events (Roy et al. 2025).

Ultra-light vector-field environments induce oscillatory potentials that perturb binaries and imprint phase shifts computable within post-Newtonian stationary-phase approximations, with detectability forecasts for LISA-scale observations (Chase et al. 2025).

1.9 Compact-object mergers: from binary neutron stars to supermassive black holes

Light scalar fields minimally coupled to gravity can form lasting clouds around binary neutron stars, producing small dephasing and post-merger structure changes for sufficiently high densities, though effects remain small for astrophysical densities (Srikanth et al. 2025).

ULDM solitonic cores accelerate SMBH binary decay and can alleviate the final-parsec stalling; detailed simulations demonstrate more rapid decay and provide lower bounds on ULDM particle and SMBH masses consistent with observations (Boey et al. 2025; Koo et al. 2024).

1.10 The final parsec problem and ULDM solutions

When galaxies merge they can form SMBHBs that stall at parsec scales; ULDM haloes can generate waves via dynamical friction and gravitational cooling that carry away orbital energy and drive rapid decay, offering a viable route past the final-parsec barrier (Koo et al. 2024).

2 CONCLUSIONS

The last numbered section should briefly summarise what has been done, and describe the final conclusions which the authors draw from their work.

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The Acknowledgements section is not numbered. Here you can thank helpful colleagues, acknowledge funding agencies, telescopes and facilities used etc. Try to keep it short.

DATA AVAILABILITY

The inclusion of a Data Availability Statement is a requirement for articles published in MNRAS. Data Availability Statements provide a standardised format for readers to understand the availability of data underlying the research results described in the article. The statement may refer to original data generated in the course of the study or to third-party data analysed in the article. The statement should describe and provide means of access, where possible, by linking to the data or providing the required accession numbers for the relevant databases or DOIs.

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APPENDIX A: SOME EXTRA MATERIAL

If you want to present additional material which would interrupt the flow of the main paper, it can be placed in an Appendix which appears after the list of references.