Bridging the Black-Hole Mass Gap: N-body Simulations of IMBH Formation in Globular Clusters

Science justification for Gadi allocation

Abstract

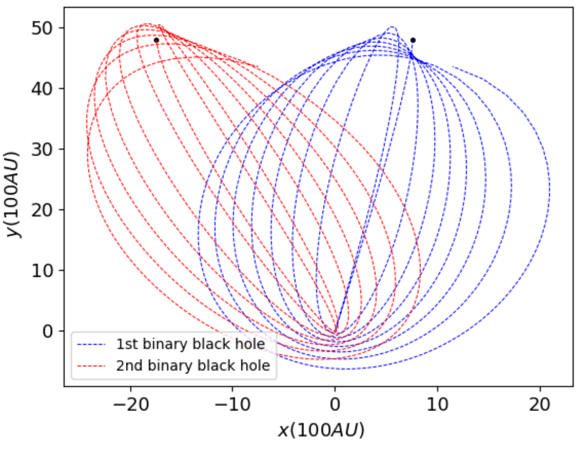
Intermediate-mass black holes (IMBHs; $10^{2-5}\,M_\odot$) bridge the gap between stellar-mass and supermassive black holes, yet their birth channel is hotly debated. We run star-by-star N-body simulations of 10^{4-6} stars in globular-cluster potentials, coupling GPU-accelerated NBODY6++GPU with 2.5-Post-Newtonian (PN) terms to track binaries. Varying cluster density, initial black-hole retention and metallicity, we follow 10 Gyr of dynamical evolution and record hierarchical mergers that climb past the pair-instability mass gap. The project yields merger trees, IMBH occupation fractions, and synthetic observables, providing first-principles predictions for forthcoming LISA and ELT surveys.

Motivation & Objectives

Observations hint at $\sim 10^3\,M_\odot$ dark objects in 47 Tucanae (Gultekin, 2017; Kiziltan et al., 2017) and M15 (Huang et al., 2025), while realistic theoretical studies of their formation channel are only possible recently, thanks to optimized algorithms for N-body systems. Direct N-body and Monte-Carlo studies point to two growth paths: (1) runaway stellar collisions that build a very-massive star (Fujii et al., 2024); (2) hierarchical mergers of dynamically formed black-hole (BH) binaries (Torniamenti, 2024), or a combination of the two(Barber & Antonini, 2025). However, the merger rate and the mass of IMBH from the latter channel are not well estimated, because the previous simulations rely on sub-grid models in Post-Newtonian (PN) regimes. Recent million-body runs with PeTar that merge very-massive collision products *and* subsequent BH–BH binaries can reach $\gtrsim 10^3\,M_\odot$, but their final masses are uncertain because the code omits relativistic recoil kicks, leading to an over-production of massive remnants (Barber & Antonini, 2025).

We aim to probe whether globular-cluster dynamics, followed with PN precision for a full 10 Gyr, can bridge that recoil barrier and grow IMBHs via direct BH–BH mergers. In particular, we can answer: **Q1** Can globular-cluster (GC) dynamics alone assemble IMBHs despite the gravitational-wave recoil barrier—that is, the 50–200 km s^{-1} kicks that often eject merger remnants once they exceed the cluster escape speed? **Q2** Which birth conditions (mass, concentration, metallicity, BH retention) maximize IMBH yield? **Q3** Which present-day observables (velocity-dispersion cusps, runaway stars) flag IMBH-hosting clusters?

Methodology



(a) Example binary over 1 Myr. Black dots mark the initial positions; coloured lines trace the orbits.

Parameter	Baseline	Range
$N_\star$	1×10^5	10^4–10^6
King W_0	7	5–9
Half-mass radius r_h	2.5 pc	1.5–6 pc
Metallicity Z	0.0002	0.0002–0.02
BH retention	50%	10–80%

(b) Baseline parameters and exploration grid. With this parameter space, we can explore typical massive Milky-Way GCs and track fallback & kick mechanisms of BH mergers.

We propose to use PN N-body code to test the black hole direct merging channel of IMBH formation. When a binary is in PN regime, we shorten the timestep and explicitly keep track of it. In this way, we calculate all the binary black holes and black hole-star binaries in a time scale of 10 Gyr (for example see Fig 1a). Then we can know whether and how these binaries would end up with IMBHs and how they interact with their environment.

We adopt the-state-of-art N-body simulation code NBODY6++GPU[1] (Beijing branch), which is already production-tested on supercomputers and including spin-dependent recoil kicks and 2.5-PN correction (Wang, 2015). Stars follow a Chabrier Chabrier (2003) IMF and evolve via the built-in evolution prescriptions (see Table 1b for detailed parameters).

Innovation & Feasibility

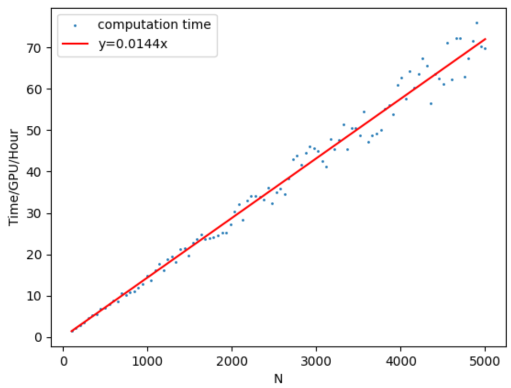


Figure 2: The relation of GPU time with number of particles N, which scales with $\sim O(N)$. This optimization test is done on an A100 GPU.

PN precision lets us follow binaries and determine their merging outcomes accurately; **large parameter coverage** maps IMBH yields across the full GC population; and **synthetic observables** bridge theory to LISA, JWST and ELT. We utilize our team's expertise on PN N-body code and experience on binaries within star clusters, which is the most important step for black hole mergering.

To achieve PN precision with our wide parameter space, it is necessary to compute evolution of many binaries in parallel with muti-GPU processing. Thus this work can only be done in supercomputers like Gadi. Benchmarks on the NBODY6++GPU test suite demonstrate 97 % GPU utilization and excellent scaling to 4×A100 per run. A single 2×10^5-star run costs $\sim 4 \times 10^{14}$ FLOPs; on four A100 GPUs this equals $\sim$ 10 wall-clock days for 10 Gyr. Our optimization test shows the time cost scales as $\sim O(N)$(see Fig2) which implies reasonable calculation time of $\sim 10^4$ GPU-core-hours even for clusters with 10^6 stars. Our 720-run grid requires $\sim 7 \times 10^7$ GPU-core-hours—comfortably within a 2 MSU allocation and parallelizable across the Gadi GPU queue.

Expected Outcomes & Legacy

Our runs will yield (i) the IMBH occupation fraction mapped against cluster mass and metallicity, (ii) a public merger-tree catalogue tailored for LISA rate forecasts, and (iii) synthetic kinematic maps plus runaway-star statistics to guide ELT follow-up. All products will be archived on DataCentral, providing a durable community resource.

References

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[1] `https://github.com/nbody6ppgpu/Nbody6PPGPU-beijing`