# 177. An intermediate-mass BH in M4?

My two previous essays looked at how stellar mass black holes can leave an observable imprint on the morphology and kinematics of open clusters (essay 175) and stellar streams (essay 176).

Here, I look at Gaia's contribution in probing the existence of *intermediate-mass* black holes in globular clusters, and specifically in the globular cluster M4. At 6 kpc and age 12.2 Gyr (Caputo et al., 1985), M4 (NGC 6121) is the closest such system to the Sun.

Stellar mass black holes ($\lesssim 100 M_\odot$) are predicted to form in the late-evolutionary collapse of a single massive star, while supermassive black holes ($\gtrsim 10^5 M_\odot$) form in the high-density environment of galaxy centres. Intermediate-mass black holes, if they exist, sit between these two extremes: too massive to have formed by single star collapse, but lacking the environment necessary to form a supermassive black hole.

Unlike the observational situation for stellar mass or supermassive black holes, no intermediate-mass objects are definitively known. But interest in them lies in the fact that various secure mechanisms are expected to lead to their formation, e.g. via the merging of stellar mass black holes or other compact objects, or via the runaway collision of massive stars in dense globular star clusters. They may also exist as primordial objects formed in the Big Bang (e.g. Bernal et al., 2018).

The dense stellar environment of globular clusters, which are compact gravitationally-bound spheroidal systems comprising tens of thousands to many millions of stars, provide environments rich in many complex dynamical processes.

N-body simulations show, for example, less-massive stars migrating outwards with the core region becoming more crowded, complex interactions and orbital modifications due to the the dynamical heating of binary stars, effects of mass segregation, stellar escape through a variety of mechanisms (e.g. Weatherford et al., 2023) and, in some cases, 'core collapse' (e.g. Gürkan et al., 2004), all further influenced by the varying tidal field in their orbits around their host galaxy (e.g. Gnedin et al., 1999).

Alongside the formation of other 'exotic' objects such as black hole–luminous star binaries, Type Ia supernovae, blue stragglers, young neutron stars and fast radio bursts, one of the potential outcomes of dynamical processes within these dense environments are such intermediate-mass black holes (Miller & Hamilton, 2002; Portegies Zwart & McMillan, 2002; Portegies Zwart et al., 2004; Giersz et al., 2015; González et al., 2021).

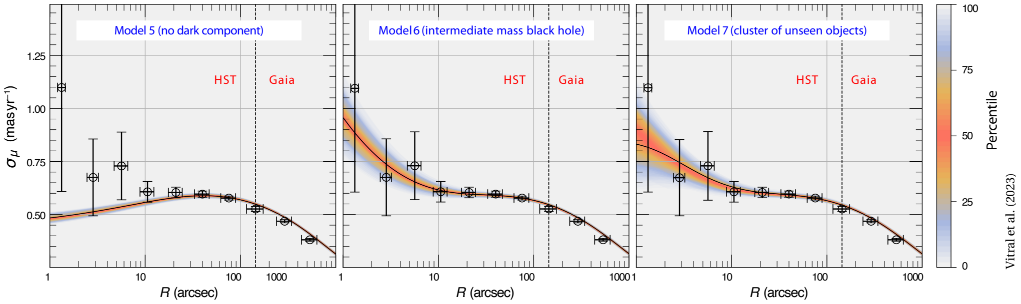
In the early N-body simulations of Miller & Hamilton (2002), for example, a massive black hole of $\sim 50 M_\odot$ is formed, either by a single massive star collapse or through collisions of a number of smaller mass objects. Importantly, such an object would be too massive to be ejected from the cluster by subsequent dynamical recoil. It then sinks to the centre of the cluster (in $\lesssim 10^6$ yr), where it continues to accrete lighter black holes to reach $\sim 1000 M_\odot$ over the $\sim 10^{10}$ yr cluster lifetime.

Predicted observable signatures (Giersz et al., 2015) include the spatial and kinematic structure of the host star cluster, possible radio, X-ray and gravitational wave emission due to dynamical collisions or mass transfer, and the creation of hypervelocity main-sequence escapers during strong dynamical interactions between binaries and such an intermediate-mass black hole.

There are numerous intermediate-mass black hole *candidates*. Chilingarian et al. (2018) identified 305 objects of mass $3 \times 10^4 - 2 \times 10^5 M_\odot$ in a sample of SDSS active galaxies, with X-ray emission inferred to originate from their accretion disks in 10 of them.

Ultra-luminous X-ray sources in globular clusters may also signal their presence but lack dynamical confirmation, with examples being NGC 4472 in the Virgo cluster (Maccarone et al., 2007), and the X-ray/optical outburst source 3XMM J215022.4–055108 (Lin et al., 2020). Other globular cluster candidates include G1 in M31 (Baumgardt et al., 2003), and MGG 11 in M82 (Portegies Zwart et al., 2004).

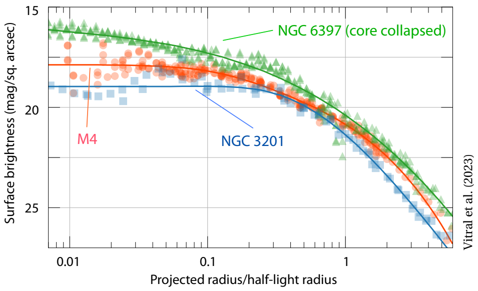
A very different candidate is the LIGO/Virgo gravitational wave event GW 190521 of 21 May 2019, in which the merger of two black holes ($85 M_\odot$ and $65 M_\odot$) probably led to a $142 M_\odot$ black hole (González et al., 2021).



The work that I will now describe also refers only to an intermediate-mass black hole *candidate*, one in the globular cluster M4, and resting on Hubble Space Telescope proper motion measurements as well as Gaia. But it demonstrates the value and fidelity of the Gaia results, and underlines the future prospects especially when the next data release, DR4, becomes available.

Previous to their work on M4, Vitral et al. (2022) used HST and Gaia EDR3 proper motions to model the internal kinematics of two other globular clusters: NGC 6397 (core-collapsed, as evidenced by the central luminosity profile) and NGC 3201 (non core-collapsed). In both clusters, they found velocities consistent with isotropy and evidence for a 'dark central mass' of $\sim 1000 M_\odot$. But their models did not suggest the existence of an intermediate-mass black hole in either.

Rather, for NGC 6397 they found a strong preference for an *extended* dark central mass of size 1% of the cluster's effective radius, and with the internal kinematics consistent with a population of hundreds of massive white dwarfs. For NGC 3201 they found a mild preference for an extended dark central mass, consistent with some 100 segregated stellar-mass black holes extending over a few per cent of the cluster's effective radius.



Similar modelling of M4 (NGC 6121) using HST and Gaia EDR3 data was then performed by Vitral et al. (2023), which in turn built on earlier work modelling the cluster's internal dynamics using both ground-based radial velocity data (e.g. Baumgardt & Hilker, 2018), N-body simulations (Hénault-Brunet et al., 2019), as well as Hubble Space Telescope imaging data to access the most crowded core region (e.g., Bedin et al., 2013; Malavolta et al., 2015; Baumgardt et al., 2022).

M4 is generally considered to be non core-collapsed, although possibly close to core-collapse (McLaughlin & van der Marel, 2005). A comparison of its surface brightness profile compared with those of NGC 6397 and NGC 3201 is shown in the figure opposite. The velocity data used by Vitral et al. (2023) provides coverage from the cluster's interior (the Hubble Space Telescope data extending from 149 arcsec down to 0.9 arcsec) out to its outermost radii, and comprises 4365 stars from HST, and 6158 stars (beyond 149 arcsec) from Gaia EDR3.

The median HST proper motion baseline is 10.6 yr, and the cluster's proximity yields high-precision motions with errors a factor 10 smaller than the cluster's velocity dispersion. This in turn provides a sufficient number of stars within ~1 arcsec from its centre to probe the possible presence of an inner dark mass.

As in Vitral et al. (2022), their fits used the `MAMPOSSt` code (Mamon et al., 2013), based on solving the Jeans equations to derive the global mass profile from the density and velocity dispersions of their tracer population (Cappellari, 2008; Watkins et al., 2013). Such models can include anisotropy and rotation (possible implications of a residual cluster rotation or non-sphericity are discussed), and can also allow for radially varying mass-to-light ratios as proxies for any differences in the spatial distributions of different mass populations.

They found isotropic motions in the core, with tangential motions in the outer parts. As shown above for their different models, the velocity dispersion in the outer parts is particularly well-defined by the Gaia data. They infer the existence of a dark central mass of some $800 \pm 300 M_\odot$, but were unable to distinguish between a point-like intermediate-mass black hole, and a dark population of stellar remnants extending out to 0.016 pc (or occupying a region a factor of two larger when removing one high-velocity star from the cluster centre).

They conclude that the dark central mass may be either an intermediate-mass black hole, or a very compact black hole population.

Future modelling should benefit from the data from Gaia DR4, or by making use of additional central objects from the dedicated 'Service Interface Function' scans already obtained for $\omega$ Cen, M4 and other high-surface density regions (Weingrill et al., 2023; see also essay 157).