# Multi-Messenger Astrophysics Using Computer Simulations of Nuclear Star Clusters

*(John von Neumann Excellence Project 2024/2)*

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## 1. Supermassive Black Holes (SMBH)

Galaxies like our own Milky Way harbor a supermassive central black hole (few million to few billion solar masses) in their centers. There is evidence for the presence of such central massive or supermassive black holes from the earliest times in our universe, shortly after the formation of first stars and galaxies. This has been confirmed by both deep astrophysical observations e.g. with the recent James Webb Space telescope (JWST) as well as from theoretical grounds (computer models of structure and galaxy formation in the universe). How do the massive black holes in galactic centers grow to their observed sizes, and from what mass range are their progenitors drawn? We are examining this in our project, by following the formation and the growth of stellar-mass seed black holes through direct N-body simulations of nuclear star clusters. The black holes grow through direct hyperbolic encounters with stars (tidal disruption or direct capture) or through relativistic energy loss in strongly bound binaries. Our computer models consist of a generally Newtonian N-body simulation for a large number of stars (up to few million, which is the record particle number for this type of numerical models of dense, gravothermal star clusters); this is complemented by a detailed account of how the stars in our models evolve, changing their mass and radius with time, finally becoming a compact remnant (white dwarf, neutron star, stellar mass black hole); relativistic dynamics (in high order Post-Newtonian form) is used to follow the evolution of binaries of compact obects and their final coalescence under gravitational wave emission. We predict gravitational wave signals from these mergers, which would be measured by LIGO/Virgo/KAGRA. Our model simulations also show a possible pathway for intermediate mass black hole (IMBH) formation, a subject of hot debate whether they exist in our nearby universe.

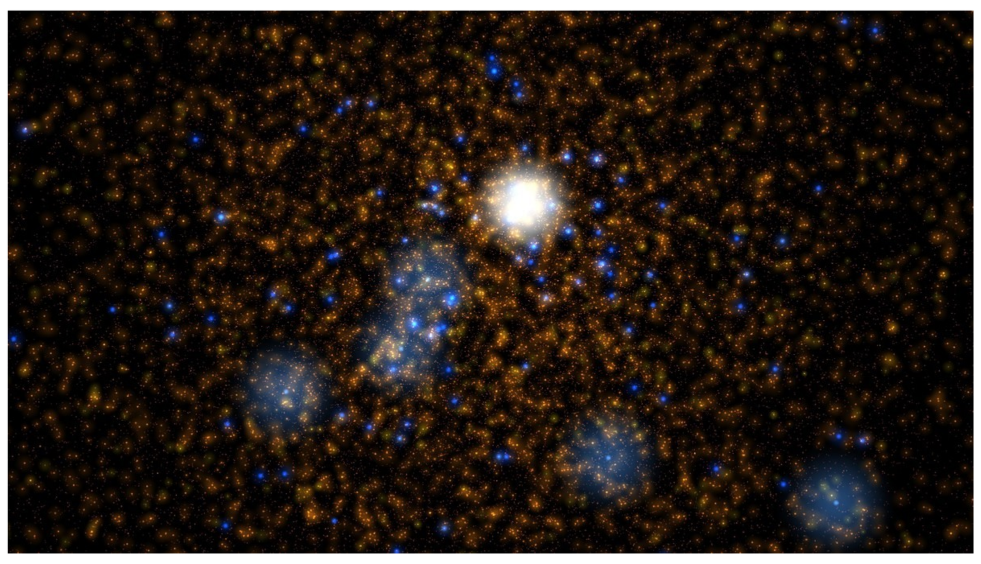

Fig. 1: *A simulated star cluster from the DRAGON-II simulations. Orange and yellow dots are stars similar to our sun; blue dots are massive stars with 20 to 300 times the mass of the sun; the big white object in the middle respresents a star with a mass of about 350 solar masses. During the next steps in the simulation it will collapse and form an intermediate mass black hole. A youtube movie of this is available (see link below).*


https://www.youtube.com/watch?v=8_74BRTI11Y&authuser=0

The movie is a zoom-in/out of a single snapshot in the simulation in which a very massive star with mass larger than 350 solar masses forms, the big white spot is the VMS, the blue stars with a bright halo are those with mass > 100 $M_\odot$; the blue stars without halo have masses $20 < m/M_\odot < 100$; red and yellow stars are less massive than 20 $M_\odot$. The first author of our 2023/2024 publications (Manuel Arca Sedda) has been an Alexander-von-Humboldt fellow hosted by our Heidelberg team, who is now professor at the Gran Sasso Science Institute (GSSI) in L'Aquila near Rome.

The models, published by last year, are called DRAGON-II simulations, in recognition of a close collaboration with China; there are several other collaboration partners involved including MPA in Garching, MPIA in Heidelberg, the Nicolaus Copernicus Astronomical Center in Warsaw, and the Main Astronomical Observatory in Kyjiv, Ukraine. A press release of MPIA describes the results, which have been published last year:
https://www.mpia.de/aktuelles/wissenschaft/2023-13-imbh-dragon-ii.

## 2. Direct N-Body Code – scaling and facilities used

For simulations we use our massively parallel GPU accelerated direct N-body code Nbody6++GPU (Wang et al. 2015, Kamlah et al. 2022, Spurzem & Kamlah 2023). It is based on the legacy codes NBODYx, originally developed by S. Aarseth (e.g. Aarseth 1999, 2003) and contains all special astrophysical features developed over many years (4th order Hermite integrator with hierarchical block time steps; 2-body and few-body regularizations of binaries, triples, and higher multiples; Ahmad-Cohen neighbour scheme (AC scheme, Ahmad & Cohen 1973); stellar evolution of single and binary stars. It is maintained via a github repository[1].

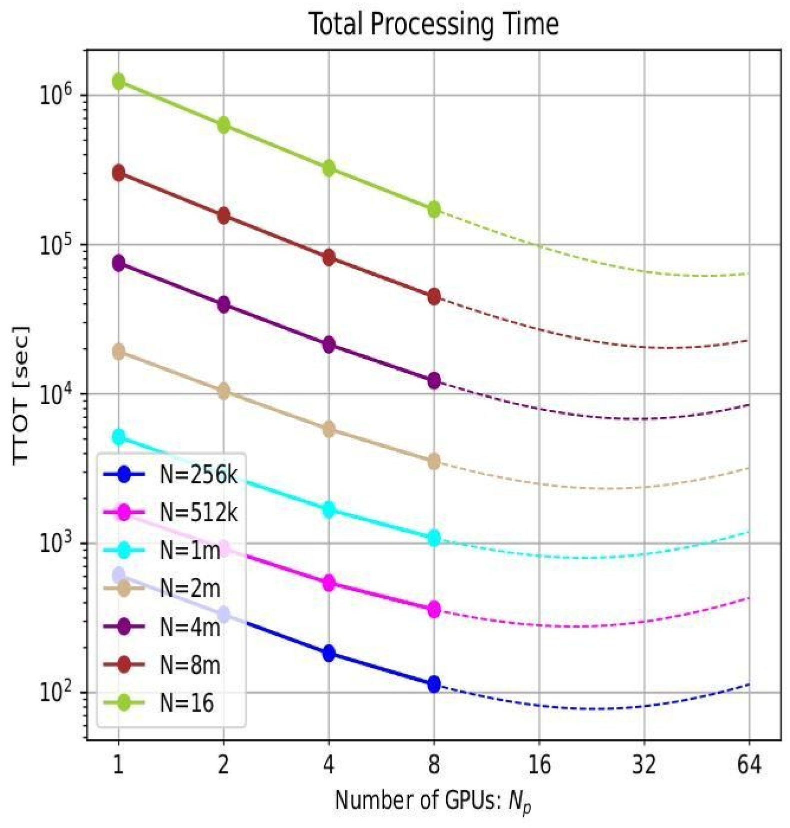


Fig. 2: *Strong Scaling of NBODY6++GPU with star-accreting supermassive black hole of 10% of the total cluster mass, here data from the raven cluster at MPCDF (juwels booster similar), total time for one NBODY model unit in secs (typical orbital time of a star in the system); different curves for particle numbers from 64k to 16m give an estimate of soft scaling behaviour.*

***Some References:***

- *Wang, L., Spurzem, R., Aarseth, S., Giersz, M., Askar, A., Berczik, P., Naab, T., Schadow, R., Kouwenhoven, M. B. N., The DRAGON simulations: globular cluster evolution with a million stars, 2016, MNRAS, 458, 1450*
- *Spurzem, R., Kamlah, A., Computational methods for collisional stellar systems, 2023, Living Reviews in Computational Astrophysics, 9, 3*
- *Arca Sedda, M., Kamlah, A. W. H., Spurzem, R., Rizzuto, F. P., Giersz, M., Naab, T., Berczik, P., The DRAGON-II simulations - III. Compact binary mergers in clusters with up to 1 million stars: mass, spin, eccentricity, merger rate, and pair instability supernovae rate, 2024, MNRAS, 528, 5140*
- *Arca Sedda, M., Kamlah, A. W. H., Spurzem, R., Giersz, M., Berczik, P., Rastello, S., Iorio, G., Mapelli, M., Gatto, M., Grebel, E. K., The DRAGON-II simulations - I. Evolution of single and binary compact objects in star clusters with up to 1 million stars, 2024, MNRAS, 528, 5119*
- *Arca Sedda, M., Kamlah, A. W. H., Spurzem, R., Rizzuto, F. P., Naab, T., Berczik, P., The DRAGON-II simulations - II. Formation mechanisms, mass, and spin of intermediate-mass black holes in star clusters with up to 1 million stars, 2023, MNRAS, 526, 429*
- *Li, S., Zhong, S., Berczik, P., Spurzem, R., Chen, X., Liu, F. K., Tracing the Evolution of SMBHs and Stellar Objects in Galaxy Mergers: A Multi-mass Direct N-body Model, 2023, ApJ, 944, 109*
- *Zhong, S., Li, S., Berczik, P., Spurzem, R., Revisit the Rate of Tidal Disruption Events: The Role of the Partial Tidal Disruption Event, 2022, ApJ, 933, 96*

*Journal Abbreviations:*
*MNRAS = Monthly Notices of the Royal Astronomical Society*
*ApJ = The Astrophysical Journal*

[1] https://github.com/nbody6ppgpu

## 3. Tidal Disruption Events (TDE)

If a star is tidally disrupted by the SMBH on a parabolic orbit only half of its mass should be accreted while the other half has enough energy to escape from the SMBH (the classical model, Rees' conjecture, Rees 1988). TDEs, for decades just a theoretical idea, have been first observed by ROSAT (an X-ray observing space instrument) by Bade et al. (1996), Komossa & Bade (1999), see also Komossa (2015). Nowadays order 100 TDEs have been observed as transients from galactic nuclei across multi-wavebands from optical to X-rays and γ-rays (e.g. ZTF, nuSTAR, eROSITA, see review of Gezari 2021). It is expected that already in the next years several 100 TDEs per year will be detected by EinsteinProbe (Yuan et al. 2016) and ULTRASAT (Ben-Ami et al. 2022). In the further future instruments like LSST, ELT, GMT in the optical and SKA in radio wavebands will deliver tens of thousands of TDE detections per year (Bricman & Gomboc 2020, Szekerczes et al. 2024).

Tidal disruption events (TDE) in most previous papers, including our group's work (e.g. Hayasaki et al. 2018, Li et al. 2017, 2019), have been simulated using the assumption that the nuclear star cluster (NSC) surrounding the supermassive black hole (SMBH) consists of a single type of stars, of constant mass. There is just one well defined tidal radius according to the equation above, at which a star is tidally disrupted; and if it is tidally disrupted 100% of its mass are accreted to the growing SMBH.

We have improved this in three respects, and do large scale simuations using this in the current computing period:

1) Partial tidal disruptions are allowed in the sense that at a larger tidal radius the stellar envelope is removed (called a partial TDE or PTDE) – a remaining core of the star survives, has more encounters with the SMBH before it is finally accreted or ejected by the SMBH (Zhong et al. 2022).
2) Not all mass of the tidally disrupted star is accreted to the SMBH, it depends on the stellar orbit before disruption how much tidal debris is accreted (the standard Rees' 1984 conjecture says 50% for a parabolic orbit, in our case anything between 0 (for hyighly hyperbolic orbit) to 100% for a star strongly bound to the SMBH before disruption.
3) We follow every stellar type individually with regard to tidal disruption, starting with a realistic see details in Li et al. (2023) and the figure bellow. Initial stellar masses between 0.08 and 150 $M_\odot$; every star is evolving, so massive stars are being transformed into stellar mass black holes and neutron stars

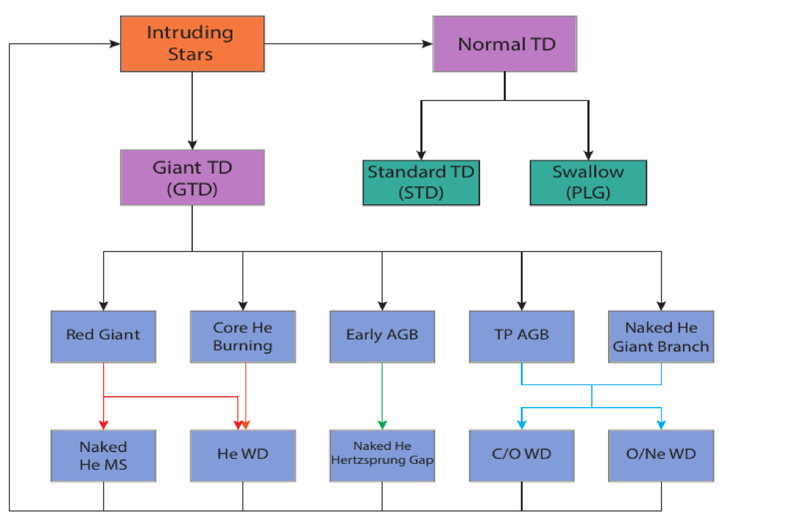


*Fig. 3: The fate of different types of stars after close encounters with SMBHs (from Li, Zhong, Berczik, Spurzem, et al. 2023)*

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