# MODEST-24: Exploring Dense Stellar Systems Across Cosmic Time

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Nicolaus Copernicus Astronomical Center, Warsaw, Poland

# Book of Abstracts

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## Formation and evolution of star clusters in galactic environments

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Star clusters do not form in isolation, but enshrouded in hierarchical gaseous filaments embedded in a galactic tidal field. To understand the role of radiation, stellar winds and supernovae of massive stars in regulating the multiphase interstellar medium we must decipher how the young host clusters form, evolve and interact with their surrounding galactic environment. In this talk, I present novel hydrodynamical N-body simulations of the formation and evolution of resolved star clusters in low-metallicity dwarf galaxies where stellar dynamical interactions around massive stars are solved with an algorithmically regularized integrator. Gravitational interactions in the rest of the simulation employ gravitational softening and a tree-algorithm. The simulations include evolution tracks for radiation and element-by-element stellar winds and supernovae of individual stars, utilizing the initial stellar mass function that is realized down to 0.08 solar masses during star formation. Our simulations now capture mass segregation, dynamical binary formation and mass-loss of entire populations of star clusters as they form and evolve in a galactic environment. The clusters form initially compact, expanding rapidly after the embedded phase to match the typical effective radii of observed young star clusters (<100 Myr) in dwarf galaxies. In agreement with previous studies that used simplified treatment of runaway and walkaway stars, the reduced clustering of supernovae through the removal of massive stars from clusters has only a small impact on the galaxy-wide properties. These simulations pave the way toward detailed chemodynamical modelling of the formation of globular clusters where stellar interactions and mergers may play a significant role in the growth and feedback of very massive stars and intermediate mass black holes.

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## The GigaEris Simulation: Stellar clusters in MW-sized galaxies at z>4

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The GigaEris simulation is a cosmological, N-body hydrodynamical “zoom-in” simulation of the formation of a Milky Way-sized galaxy with the unprecedented resolution of better than a thousand solar masses, encompassing of order a billion particles within the refined region. The simulation employs a modern implementation of smoothed-particle hydrodynamics, including metal-line cooling and thermal diffusion. In this talk, we will use our ability to resolve star clusters to show some very good candidates for blue proto-Globular clusters (GC) that have properties consistent with those of Globular Clusters of massive present-day spiral galaxies. These proto-GC are born near dark matter halos, with the exception of the oldest object, which appears to be the perfect GC at first but is actually a stripped compact dwarf galaxy that has interacted with the main halo and has lost its entire dark matter content due to tidal mass loss. Furthermore, we investigate nuclear star cluster formation in the progenitor of a Milky Way-sized galaxy for the first time using a cosmological simulation, as well as its relation to the assembly and evolution of the galactic nuclear region as.

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## Long Term Evolution and Dissolution of Star-Forming Regions

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Stars will typically spend the first few million years of their lives in their natal star-forming regions. The initial densities in these regions often mean young stars are much more likely to experience the effects of close encounters, massive star stellar winds and potentially even nearby supernovae. Therefore, understanding the dynamical evolution of star-forming regions is key to understanding star (and planet) formation and it tells us much about the stars' early lives. However, the dissolution of star-forming regions into the Galactic disc is much less well understood. Does the dissolution rate depend more on the initial mass, density or virial state of the star-forming region? Using N-body simulations of the first 100Myr of a star-forming region, we aim to understand the effects of various factors on star cluster dissolution. In particular, we focus on the effects of an external tidal field on star-forming regions of varying radii, mass, density and initial degree of spatial and kinematic substructure. In this talk I will present the results from a suite of simulations, and discuss the implications of these regions' evolution on star formation, and the young planetary systems that form simultaneously with the stars.

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## Impact of Radiation Feedback on the Formation of Globular Cluster Candidates during Cloud-Cloud Collisions

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To understand the impact of radiation feedback during the formation of a globular cluster (GC), we simulate a head-on collision of two turbulent giant molecular clouds (GMCs). A series of idealized radiation-hydrodynamic simulations is performed, with and without stellar radiation or Type II supernovae. We find that a gravitationally bound, compact star cluster of mass $M_{GC} \sim 10^5 M_\odot$ forms within ≈ 3 Myr when two GMCs with mass $M_{GMC} = 3.6 \times 10^5 M_\odot$ collide. The GC candidate does not form during a single collapsing event but emerges due to the mergers of local dense gas clumps and gas accretion. The momentum transfer due to the absorption of the ionizing radiation is the dominant feedback process that suppresses the gas collapse, and photoionization becomes efficient once a sufficient number of stars form. The cluster mass is larger by a factor of ~2 when the radiation feedback is neglected, and the difference is slightly more pronounced (16%) when extreme Ly$\alpha$ feedback is considered in the fiducial run. In the simulations with radiation feedback, supernovae explode after the star-forming clouds are dispersed, and their metal ejecta are not instantaneously recycled to form stars.

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**Formation of dense stellar systems across cosmic time / 68**

## Multiple Stellar Populations Speculations on Cluster Migration and Gas Re-Accretion

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The formation of multiple populations of stars in globular clusters and their further evolution is still the subject of much debate and awaiting resolution. Many scenarios have been proposed to explain their formation. One of the most commonly proposed is the AGB scenario, in which chemically reprocessed gas from the envelopes of AGB stars mixes back with primary gas flowing into the center of the cluster.
Based on this scenario, about two hundred MOCCA code simulations of cluster evolution have been carried out, considering additional physical processes mainly related to the external environment in which globular clusters live. These processes are related to taking into account: the time shift of the formation of the second population of stars, their different concentrations, initial mass functions, deviations from virial equilibrium, migration of globular clusters and the influence of dynamical chamming on the orbit of clusters. Analysis of the simulation results showed that the observed parameters of multiple stellar populations and the global parameters of clusters associated with the Milky Way are well reproduced, in particular, it seems that the lack of visible multiple populations for young star clusters can be explained. I will summarize the conclusion resulting from these simulations in the form of a speculative scenario.

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**Formation of dense stellar systems across cosmic time / 60**

## The original composition of the gas forming first-population stars in globular clusters

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Globular clusters (GCs) are among the most fascinating objects in the Universe, but their formation and evolution remain a key challenge in astrophysics. These dense and compact agglomerates of stars are believed to have formed from the dense cores of super-giant molecular clouds during the earliest stages of galaxy formation. However, the environment in which GCs originated is still quite unexplored, as only a small amount of intra-cluster medium (ICM) has been observed in present-day GCs. Furthermore, such ICM would not accurately reflect the chemical composition of the proto-cluster gas, as it is contaminated by the material expelled by GC stars during their post-main-sequence evolution.

To address this challenge, we have developed a new method for identifying GC stars formed from pristine material, known as first-population (1P) stars, and determining the chemical composition of the environment from which proto-GCs originated. Our approach relies on the 'Chromosome Map' (ChM), which is a pseudo-two-color diagram that enables the detection of star-to-star variations in chemical composition with an unprecedented precision of ~ 0.01 dex in [Fe/H]. By analyzing ChMs across a large sample of 55 Galactic GCs, we have determined the chemical composition of the gas from which Milky Way clusters formed approximately ~ 11-13 Gyr ago.

In this talk, I will describe how 1P stars can be used to investigate the chemical composition of GC natal clouds, focusing on our latest observational results. Additionally, I will discuss the impact of these new findings on the formation scenarios of multiple stellar populations in GCs.

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**Formation of dense stellar systems across cosmic time / 139**

## Clumpy Star Clusters: Rethinking IMF Limits

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Star clusters (SCs) are not born in spherical symmetry, contrary to the idealized initial conditions used in the vast majority of $N$-body simulations performed so far. Observations suggest that the initial conditions for star formation are highly structured and clumpy, both in the distribution of

molecular gas from which stars form (Williams 1999 and references therein) and in the distribution of newly-formed stars (Bate et al. 1998; Gladwin et al. 1999, Goodwin & Whitworth 2003).

Additionally, in most studies involving simulations of SCs and isolated binaries, the assumed upper limit of the Initial Mass Function (IMF) has gradually increased up to ~150 $M_{\odot}$, primarily to account for the massive Black Holes detected by the Ligo-Virgo collaboration. However, while we observe massive stars up to ~300 $M_{\odot}$ in young SCs and in star-forming regions such as R136 (Crowther et al. 2010), it remains uncertain whether stars can form with such high mass or if they are the product of collisions.

In this talk, I will present the results of a suite of direct N-body simulations of clumpy SCs with varying upper limits of the IMF. Our simulations demonstrate that it is not necessary to assume an IMF upper limit as large as 150 $M_{\odot}$ to form the observed massive stars. Instead, these massive stars form from stellar collisions in the very early evolutionary stages of the SC, facilitated by the initial high density of the clumps.

Finally, we discuss the implications of a reduced upper limit of the IMF on the mass spectrum of compact objects in different environments and its impact on the formation of gravitational wave sources.

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**Formation of dense stellar systems across cosmic time / 30**

## Realistic initial conditions for young stellar clusters

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Initial conditions of stellar cluster simulations generally consist of a monolithic structure. However, both theoretical and observational studies suggest that stellar clusters form hierarchically and therefore host subclusters that could trigger stronger stellar interactions. Hence, it is fundamental to include more detailed initial conditions when studying the evolution of stellar clusters and especially stellar dynamics within them. In this talk, I will describe the development of a set of realistic initial conditions for young stellar clusters starting from hydrodynamic simulations of molecular clouds. I will then discuss how to exploit them to perform more realistic $N$-body simulations and show the impact of these new conditions in the context of compact object formation and merger.

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**Formation of dense stellar systems across cosmic time / 15**

## Can we verify the Dissolving Star Cluster Model as formation channel for dSph galaxies?

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We have proposed a formation scenario for dSph galaxies which does not include any interaction with other galaxies, called the Dissolving Star Cluster Model. In this model the gas, accumulating inside the dark matter halo of the dwarf forms stars in form of small star clusters and associations which orbit the central region of the dark matter halo. These small entities do not survive for long and spread their stars along their trajectories, thereby forming the luminous component of the dSph galaxy as we see today. Our numerical simulations have shown that the resulting objects resemble all observables of dSph galaxies very well and let to the prediction of stellar streams inside the dwarfs which should survive until the present day.
Using observational data from Leo I we are now able to test the predictions from our model with real data. Using a special software to detect stellar streams from the radial velocity measurements of stars inside Leo I we are able to detect more streams than what simple noise would predict. The projected angular momentum directions of those streams are in concordance with our model and seem to rule out the destroyed dwarf disc scenario.

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**Nuclear star clusters and the Galactic nucleus** / **57**

## Formation and evolution of the Nuclear Star Cluster in the Milky Way and other spiral galaxies on the cosmological time scale.

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According to the standard LCDM model, the globular clusters (GCs) of the Milky Way (MW) are the first gravitationally bound stellar systems to form in the early Universe, with a typical age of about 10-12 billion years. GCs are quite common in the Galaxy. In early 2020, 150 of them were found in the MW, in 2022 - 160, and more than 10 stellar systems are candidates for GCs. In the past few years, we have been getting more and more direct evidence for the existence of a supermassive black hole (SMBH) at the center of the MW and other galaxies. In addition to the SMBH, the Nuclear Star Cluster (NSC) is also located in the center of the Galaxy. Several mechanisms have been proposed for the formation of such NSCs. Two main ones are distinguished: (i) the migration of gas into the center of the Galaxy and the subsequent formation of the stellar content of the NSCs, and (ii) the migration of GCs into the center of the Galaxy and their subsequent destruction and total or partial merging with the compact central NSCs. The goal of our study is to numerically model the formation of NSCs by the dynamical interaction of GCs with the central region of the MW and other spiral galaxies (e.g., Andromeda), including the strong interaction with the central SMBHs. Based on the numerical calculations performed, qualitative estimates of the probabilities of complete and partial absorption of individual GCs in different orbits will be given.

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**Nuclear star clusters and the Galactic nucleus / 141**

## Modelling the Milky Way nuclear star cluster

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The Galactic center region has a mass of ~10^9 M_sun. It consists of the nuclear stellar disk (NSD), a flat, rotating stellar structure, and the nuclear star cluster (NSC), the densest concentration of stars in the Galaxy.
The NSC and NSD are distinct structures of the Milky Way, but also connected to the larger Milky Way structures, e.g. via the inflow and outflow of gas, and the infall of star clusters. Our knowledge of the larger Milky Way structures, Galactic disc, bulge and halo, has expanded in recent years through surveys and dedicated missions. Hidden behind large amounts of interstellar dust, the Galactic centre structures, NSC and NSD, are inaccessible for these surveys, and they miss an important piece for our understanding of the Milky Way's formation and evolution, leaving us with many unanswered questions, such as:
How did the NSC assemble within the NSD and the other larger structures of the MW? What is NSC's history of mass accretion and star formation, can we identify distinct events?

In this talk I will present spectroscopic observations of the NSC and inner NSD, resulting in >2,500 stellar spectra, and measurements of their line-of-sight velocity and overall metallicity. These data can constrain dynamical models of the Galactic centre, which inform us about the mass distribution, dynamical structure and evolution of the NSC.

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**Nuclear star clusters and the Galactic nucleus / 21**

## Dynamical models of the Milky Way nuclear star cluster

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The nuclear star cluster (NSC) of the Milky Way has been extensively studied in the last decades, using ground-based astrometry and spectroscopy of ~10000 stars in the inner 10 pc.

The Galactic centre is unique in that we have a direct measurement of the mass of the supermassive black hole (SMBH) from the motion of S-stars, which can be tracked for a significant fraction of the orbital period. However, the remaining vast majority of stars in the NSC are essentially a single kinematic snapshot, and fall within the realm of classical methods for inferring the gravitational potential from the assumption of dynamical equilibrium.
I present a new twist in this analysis based on the iterative self-consistent modelling method with action-space distribution functions. I discuss the constraints on the NSC properties and the intrinsic degeneracies and limitations of this inference procedure, which are relevant more generally for dynamical modelling of extragalactic nuclear clusters.

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**Nuclear star clusters and the Galactic nucleus / 107**

## The extended mass distribution in the Galactic center

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Since 2017, the GRAVITY interferometer at ESO's Very Large Telescope has allowed us to obtain astrometric data with unprecedented accuracy of the S-stars orbiting around Sagittarius A*, turning them into a powerful tool to investigate the gravitational potential around the supermassive black hole at the center of our Galaxy.
In particular, for the star S2, we have been able to detect the in-plane, prograde Schwarzschild precession of the orbit's pericenter angle, as predicted by General Relativity.

In this talk, I will discuss the effect of an extended distribution of mass around Sagittarius A*, which is expected to be composed mainly of a dynamically relaxed cusp of old stars and stellar remnants. Assuming the distribution follows a smooth, spherically symmetric density profile, it would add a retrograde precession of the stellar orbits, counteracting the prograde relativistic precession. I will present the upper limits that we obtain with S-stars data on the amount of extended mass that could lie within the orbit of S2, roughly in the central 10 milliparsecs of our Galaxy, and I will show that it is in slight tension with the theoretical predictions.

Then I will discuss the effect of the granularity of this mass distribution, which is actually composed of a finite number of bodies. This can cause deviations in the orbital motion of stars compared to a smooth density distribution, due to the breaking of spherical symmetry and the presence of scattering events. Most notably, it leads to a precession of the orbital plane. The question I aim to answer through numerical simulations is whether these deviations could be observable with the current astrometric accuracy of GRAVITY and whether they could perturb our measurement of the Schwarzschild precession of S2 and, potentially, of the spin and quadrupole moment of Sagittarius A*.

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**Nuclear star clusters and the Galactic nucleus / 116**

## Orbital Evolution of S Stars Due to Resonant Relaxation

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Recently the precession rate of S2 around the SMBH at the Galactic Center is reported (Abuter et al., 2020). At the same time, other astronomical and physical values, such as orbital elements of S2, mass of the central SMBH, the distance to it, parameters for GR effect and so on, are estimated.

From a theoretical point of view, Rauch & Tremaine (1996) predicted the precession of stars around an SMBH due to resonant relaxation (RR) which is a relaxation in the angular momentum space. Though RR may take place around the SMBH at the GC, the estimation in above report did not include this effect.

We performed a series of $N$-body simulations (w/wo General Relativistic effect) of a star cluster model of the GC.

We found that:

(1) RR takes place in the GC.

(2) S2's periapsis can move up to $10^{-4}$ rad. per period.

(3) The largeness of the movement of periapsis is not negligible compared to that due to GR effect.

Thus the effect of RR may affect the values estimated in Abuter et al., 2020.

We also found that the largeness of movement of periapsis of S2 depends on the mass $M$ and the number of stellar/compact objects $N$ of the star cluster as $\sim MN^{-1/2}$.

How large the periapsis moves due to RR is determined probabilistically for the statistical nature of RR. It is, therefore, difficult to say something about the mass and composition of the GC cluster from only the observation of S2. However, if future observations provide us not only precession data of S2 but also those of other S stars, it will be a clue to make clear the mass and components of the central region of the Galaxy.

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**Nuclear star clusters and the Galactic nucleus / 24**

## Statistical Mechanics in the Galactic Center: Anisotropic Mass segregation and Phase Transition

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Galactic nuclei, the densest stellar environments in the Universe, exhibit a complex geometrical structure. The stars orbiting the central supermassive black hole follow a mass segregated distribution both in the radial distance from the center and in the inclination angle of the orbital planes. This distribution may represent the equilibrium state of vector resonant relaxation (VRR).
In this talk, I present simple statistical physics models to understand the equilibrium distribution found previously in numerical simulations. Using the method of maximising the total entropy and the quadrupole mean-field approximation, we determine the equilibrium distribution of axisymmetric two-component gravitating systems with two distinct masses, semimajor axes, and eccentricities. We explore the parameter space of energy and angular momentum and find evidence of vertical mass segregation.
I will also discuss disk-isotropic transitions in the statistical mechanical models. When one component dominates, the transition from a spherical disordered state to a flattened ordered state is continuous as a function of stellar mass, semimajor axis, eccentricity, and net angular momentum. This can help to determine the features of these massive perturbers from the observations of the stellar orbits. We identify the system parameters where a discontinuous phase transition occurs both in the canonical and in the microcanonical ensembles. We also study negative absolute temperature equilibria for which the more energetic states are relatively more populated.
Lastly, I will present the N-body VRR dynamical simulation results. Two-component systems are found to relax to the theoretical thermal equilibrium. This occurs even when the two components have small inter-component interaction energy, where a phase transition could occur. We demonstrate in the simulations that the change in one of the components can induce a (discontinuous) transition in the other component between a disk state and an isotropic state. Additionally, the simulations reproduce the negative absolute temperature states.

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**Flash Poster Presentations (in-person) / 69**

## Massive triples on the edge of stability

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Star systems containing three stars are common in the universe, with the triple fraction increasing with the mass of the star. Approximately 10% of solar-type stars reside in triples, while this fraction goes up to 60% for 10 stars of 10 solar masses. To fully understand the evolution of massive stars, triple evolution should be taken into account. One of the evolutionary pathways for triples is dynamical instability, in which stellar winds or mass transfer can destabilize the orbits, resulting in disintegration of the triple. In this talk I will present the results of n-body simulations of massive, unstable triples. I will show how these systems can produce collisions between massive stars, or high-velocity massive runaways. I will present the estimated rates for these events, and discuss it in the context of potential observational counterparts.

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**Flash Poster Presentations (in-person) / 101**

## Trumpler 5 - Cluster Properties and Exotic Populations

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Star clusters are ideal test beds for studying the formation and evolution of stars in diverse environments. Open clusters, being relatively sparse systems and located at a closer distance, as compared to the globular clusters, allow a more detailed analysis of their individual single and multiple stellar members. Trumpler 5 is a populous, intermediate-age (~3.4 Gyr), metal-poor ([Fe/H] ~ -0.3) open cluster, located approximately at 3000 pc. The cluster is well-known in the literature for its broadened main-sequence and large population of blue straggler stars (BSS). We have identified 3150 cluster members (membership probabilities, P > 0.6) using a machine learning-based algorithm, ML-MOC. In addition to a broadened main-sequence, we notice a distinct gap in the color-magnitude diagram, right below the main-sequence turn-off. We identified 29 high-probability BSS, of which 12 have a counterpart in one or more of the UVIT/AstroSat far-UV filters F148W, F154W, or F169M. Additionally, we identify 8 blue-lurker candidates based on their bright fluxes in the far-UV and their location on the main-sequence in the optical color-magnitude diagram. We present a detailed analysis of the cluster properties, including differential reddening, the kinematics, and the dynamical properties of the cluster. Moreover, we present the properties of the BSS and blue lurker candidates and their unresolved hot companions based on the multi-wavelength spectral energy distributions covering data from far-UV to mid-IR.

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**Flash Poster Presentations (in-person) / 106**

## GlobULeS-V. UVIT/AstroSat studies of stellar populations in NGC 362: Detection of Blue Lurkers and extremely low-mass white dwarf in a Globular Cluster

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We report the discovery of four blue lurkers with low- and extremely low-mass white dwarf (ELM WDs) companions in the Galactic globular cluster NGC 362 using AstroSat's Ultra Violet Imaging Telescope (UVIT). We analyzed the multi-wavelength spectral energy distribution (SED) of FUV-bright MS stars using data from the UVIT, UVOT, GAIA EDR3, and 2.2m ESO/MPI telescopes. Two each of low-mass WDs and ELM WDs are found as companions for the four blue lurkers by the fitting of two-component SED models. The effective temperatures, radii, luminosities, and masses of two low-mass WDs are (35000, 23000) K, (0.04, 0.05) $R_{\odot}$, (1.45, 0.22) $L_{\odot}$, and (0.2, 0.2) $M_{\odot}$, while the two ELM WDs are (14750, 14750) K, (0.09, 0.10) $R_{\odot}$, (0.34, 0.40) $L_{\odot}$, and (0.18, 0.18) $M_{\odot}$. The position of blue lurkers within the cluster shows that they originated via the Case A/B mass-transfer mechanism in a low-density environment. This is the first detection of blue lurkers with low-mass WDs and ELM WDs as companions in a globular cluster. The companion's cooling age is less than 4 Myr, which suggests that they were just recently formed. These binary systems might have originated due to the cluster's recent core collapse.

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**Flash Poster Presentations (in-person) / 89**

## Limitations of aperture photometry for star cluster studies

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Recent studies have shown, that inconsistencies in the integrated colour indices (CIs) between real star clusters and theoretical models arise due to projection of bright stars inside the apertures. Thus, in this study we determined achievable accuracy and applicability limits of the aperture photometry approach for star cluster studies. We modelled a large grid of artificial 3D star clusters covering the parameter space of the M 31 clusters. Images were simulated by projecting each model onto 2D plane from 100 directions. Cluster images were generated in six passbands, matching Panchromatic Hubble Andromeda Treasury (PHAT) survey. To investigate the accuracy limits of aperture photometry, we measured artificial cluster images and performed parameter determination tests. We have shown that star clusters with and without post-main sequence stars exhibit considerable differences. We have demonstrated that CIs measured using an aperture with radius smaller than cluster's half-light radius lead to unreliable determination of cluster parameters. Additionally, we recommend to use colour-magnitude diagram fitting methods to derive parameters of young (<30 Myr) clusters, as aperture photometry-based parameter determination of such objects is troublesome regardless of the aperture size. Furthermore, we have shown that the randomness of cluster projection angle introduces uncertainty of CIs reaching up to 0.1 mag, depending on cluster parameters and aperture size. Also, we have demonstrated that due to stochastic effects structural parameters of low mass (<1000 $M_{\odot}$) and younger than ~100 Myr star clusters are rather unconstrained and show large uncertainties. We anticipate that the results of this study will be helpful in data analysis and interpretation of present/future star cluster surveys in the Local Universe (<10 Mpc).

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**Flash Poster Presentations (in-person) / 70**

## A multi-wavelength perspective of millisecond pulsars in NGC 362

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It is well established that the frequent stellar dynamical interactions in the high-density globular cluster (GC) cores make them efficient factories of exotic objects, including **millisecond pulsars (MSPs)**. In fact, the number of MSPs per unit mass in the Galactic GC population is some $10^3$ times larger than in the Galactic field.
As part of a large project that aims at exploiting the **synergy** between the last generation of high-resolution instruments for the identification and characterization of MSP in GCs, I will present recent results obtained for the old GC **NGC362**.
One of the key innovative points of this analysis is the adoption of a **multi-instrument** and **multi-wavelength** approach that makes use of multi-epoch optical and UV **Hubble Space Telescope** ACS and WFC3 data, NIR **Gemini Multi-conjugate Adaptive Optics** system images and information provided by **X-ray observations**.
With such a huge and complex database, we were able to identify more than **50 optical counterparts** to X-ray sources, revealing a rich and diverse population of interactive binaries in this cluster. Interestingly, **more than 10%** of these sources show positions in the color-magnitude diagram and peculiar light curves compatible with the typical signatures of MSP companions known in the literature. In particular, one counterpart exhibits a typical variability and period expected for a **Black Widow system**.
These potential counterparts will be used to feed an ongoing radio **MeerKAT** data analysis to help constrain the parameters, such as the position, of interesting radio sources.
The results of this work demonstrate the importance of the adoption of a multi-instrument and multi-band approach for a comprehensive characterization of MSPs. In turn, this kind of analysis will pave the way for future scientific applications allowing the selection of the most promising targets for the **next generation telescopes**, such as ELT and SKA.

**Affliation**:

Università di Bologna - INAF OAS

**Current Position**:

PhD Student

**Flash Poster Presentations (in-person) / 144**

## Gravitational Wave Phase Shifts in Eccentric Black Hole Mergers as a Probe of Dynamical Formation Environments

**Authors:** Johan Samsing[1]; Kai Hendriks[1]

**Co-authors:** Bin Liu [2]; Daniel D'Orazio [1]; Lorenz Zwick [1]

[1] *Niels Bohr Institute*

[2] *Zheijang University*

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We quantify for the first time the gravitational wave (GW) phase shift appearing in the waveform of eccentric binary black hole (BBH) mergers formed dynamically in three-body systems. For this, we have developed a novel numerical method where we construct a reference binary, by evolving the
post-Newtonian (PN ) evolution equations backwards from a point near merger without the inclusion of the third object, that can be compared to the real binary that evolves under the influence from the third BH. From this we quantify how the interplay between dynamical tides, PN -effects, and the time-dependent Doppler shift of the eccentric GW source results in unique observable GW phase shifts
that can be mapped to the gravitational dynamics taking place at formation. We further find a new analytical expression for the GW phase shift, which surprisingly has a universal functional form that only depends on the time-evolving BBH eccentricity. The normalization scales with the BH masses and initial separation, which can be linked to the underlying astrophysical environment. GW phase shifts from a chaotic 3-body BH scattering taking place in a cluster, and from a BBH inspiraling in a disk migration trap near a super-massive BH, are also shown for illustration. When current and future GW detectors start to observe eccentric GW sources with high enough signal-to-noise-ratio, we
propose this to be among the only ways of directly probing the dynamical origin of individual BBH mergers using GWs alone.

**Affliation**:

Niels Bohr Institute

**Current Position**:

PhD Student

**Flash Poster Presentations (in-person) / 91**

## Clues on the formation of massive star clusters from stellar rotation

**Author:** Sebastian Kamann[1]

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Using MUSE spectroscopy, we have recently revealed the existence of distinct populations of slowly and fast rotating stars in young (<2 Gyr) massive (10^5 solar masses) star clusters in the Magellanic Clouds. The differences in the stellar angular momenta naturally explain peculiar features observed in the colour-magnitude diagrams of the clusters, such as split main sequences or extended main-sequence turn-offs, without requiring that the clusters experienced extended periods of star formation. However, the origin of the bimodal stellar spin distribution is being still debated, and competing scenarios have been proposed. In this poster, I will present our results and explain their implication for our understanding of the formation of massive star clusters.

**Affliation**:

Liverpool John Moores University

**Current Position**:

Senior Scientist or Faculty

**Flash Poster Presentations (in-person) / 10**

# Star Clusters in the Disk of Andromeda

**Author:** Eimantas Kriščiūnas[1]

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Star clusters play a pivotal role in understanding galaxy formation processes and evolution. However, investigations of star clusters within the disk of our Galaxy are limited due to interstellar extinction. Therefore, to understand evolution of star cluster systems in galaxy disks observations of nearby galaxies are needed. The best object for this purpose is the Andromeda (M31) galaxy, where ample of discovered star clusters enables us to study their impact on the evolution of stellar populations from the centre to the galaxy disk outskirts.

In this presentation, we aim to explore the connections between star clusters and the star formation history of the M31 galaxy disk using the Panchromatic Hubble Andromeda Treasury (PHAT) survey data. Based on the determined individual cluster parameters –age, mass, extinction, and metallicity –we investigated radial and azimuthal distributions of star clusters, providing the clues to the recent evolution of the M31 disk.

**Affliation**:

Center for Physical Sciences and Technology, Vilnius, Lithuania

**Current Position**:

PhD Student

**Flash Poster Presentations (in-person) / 39**

# Binary black hole mergers in Population III star clusters

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Population III (Pop III) stars are ideal candidates for the formation of intermediate-mass black holes (IMBHs) because of their small mass loss and top-heavy initial mass function. If such stars were to form in star clusters, their IMBH remnants would have a higher probability of creating binary systems and eventually merge, leaving behind black holes (BHs) massive enough to be seeds of the super-massive black holes we observe now.
In my talk, I will present novel simulations of binary black hole (BBH) formation in Pop III star clusters run with the semi-analytic code `FASTCLUSTER`. I will focus on two extreme cases: the first, in which all first-generation BBHs in the cluster are derived from the evolution of primordial binaries; and the second, in which BBHs are instead formed dynamically because of three-body encounters (hereafter, dynamical BBHs). Either way, we find a large number of BBH mergers with primary masses above the mass gap ($m_1 > 230\,M_\odot$), contrary to what is expected in the case of Pop III isolated binaries, which show a primary mass distribution peaking at $m_1 \sim 30\,M_\odot$ and few or no mergers in the IMBH mass range. Notably, we observe that in our simulations the primary BH mass has a peak at $m_1 \geq 500 M_\odot$ when the BBHs are dynamical and sampled with a distribution that

favors high-mass BHs. Depending on both their final relativistic kick, and on dynamical interactions, a number of remnant BHs will be able to form a chain of mergers. I will show that in our simulated clusters we form supermassive black hole seeds of $10^3\,\mathrm{M}_\odot$ via hierarchical BBH mergers by $z = 10$.

**Affliation**:

Gran Sasso Science Institute

**Current Position**:

PhD Student

**Flash Poster Presentations (in-person) / 61**

## Probing the Gaia atmospheric parameters of stars in globular clusters

**Author:** Sergen Özdemir[None]

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Numerous stellar surveys have been or will provide photometric, astrometric, and spectroscopic data for a large number of stars in the Milky Way and neighbouring galaxies. Modern data processing tools and analysis methods are needed to deal with these data sets and obtain accurate and precise results. In this context, we are developing a new spectroscopic analysis pipeline based on the differential analysis method that is also assisted by machine learning techniques. This pipeline, called CHESS (CHEmical Survey analysis System), aims to automate the steps needed to obtain high-quality stellar parameters and abundances from large samples of spectra. Precise chemical abundances for as many elements as possible are key to the study of Galactic archaeology. For initial tests of CHESS, we are focussing on a reanalysis of high-resolution archival UVES spectra of stars in clusters. Here, we concentrate on a discussion of about 1000 stars that are members of globular clusters and have been observed with UVES. To automatically identify the spectra of similar stars that are suitable for a differential analysis, CHESS first performs what we call a similarity analysis by directly using the observed spectra. This step of the analysis uses unsupervised machine learning algorithms (such as clustering and dimensionality reduction methods). To validate the findings, we used atmospheric parameters from several catalogues (in particular those available in Gaia DR3). Alternatively, such a similarity analysis also serves as a consistency check of the atmospheric parameters in these catalogues. The stars that CHESS identifies as very similar should have almost the same values of effective temperature, surface gravity, and metallicity. In this talk, we present our method to find similar stars and discuss some limitations of its use in the case of globular clusters (related to abundance correlations among the stars).

**Affliation**:

Nicolaus Copernicus Astronomical Center

**Current Position**:

PhD Student

**Flash Poster Presentations (in-person) / 43**

## Detailed study of the stability of a planetary system captured by a massive stellar remnant

**Authors:** Matyas Fuksa[1]; Vaclav Pavlik[2]; Vladimir Karas[2]; Steven N. Shore[3]

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To date, several planetary systems around pulsars are known. While those systems could be relics, another formation channel has recently been proposed. Massive stellar remnants (i.e., neutron stars and black holes) likely receive a natal supernova velocity kick due to the asymmetry of their birth event, propelling them through space at high speed. We study the hypothetical encounters between planetary systems and such remnants to explore the possible formation of planetary systems around massive remnants through capture. We also investigate their long-term dynamical stability on the time scale of Gyrs.

We use a suite of N-body models (integrated with IAS15 from REBOUND) of the Solar system where a massive object was launched towards it (varying its mass, incident angle, velocity, and impact parameter). Here, we focus on one of these simulated encounters between the Solar system and a 10-solar-mass interloper (10 km/s heliocentric velocity, 60° incidence angle from the ecliptic, 2 au impact parameter) which results in the capture of all planets. The initially chaotic system gradually stabilises during the first 500 Myr by ejecting planets via close planetary encounters until only Mercury, Earth and Jupiter remain. A late ejection of Mercury around 3 Gyr then leaves a stable three-body system, supporting the hypothesis of capture events being viable formation scenarios for planetary systems around stellar remnants.

**Affliation**:

Astronomical Institute, Charles University, Prague, Czech Republic

**Current Position**:

Masters or undergraduate student

**Flash Poster Presentations (in-person) / 63**

# A fast evolution code for star clusters with stellar-mass black holes.

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Stellar-mass black holes play a crucial role in the dynamical evolution of globular clusters. In this work we discuss a fast method to evolve star clusters with varying initial black hole contents. We use the fast model clusterBH to reproduce the evolution of globular clusters in the database of Cluster Monte Carlo (CMC) models. In particular, we reproduce the evolution of the total stellar mass, the cluster half-mast radius and the total mass of the black hole population. We reproduce these time-dependent quantities within 30% for a range of initial cluster masses, cluster radii and Galactocentric radii. This fast model runs «1 sec and has powerful applications, such as fitting initial conditions of observed clusters and forward models of gravitational wave production.

**Affliation**:

ICCUB

**Current Position**:

PhD Student

**Flash Poster Presentations (in-person) / 79**

## Binary-single scattering with unequal masses: implications for gravitational waves

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Binary black hole inspirals in globular clusters occur when the binary's eccentricity surpasses a critical value, denoted as $e_{\mathrm{GW}}$. This $e_{\mathrm{GW}}$ depends mainly on the binary's masses and semi-major axis. We perform $10^7$ binary-single scattering experiments with unequal masses to identify the different channels that produce high eccentricity binaries. We determine how the cross section for resonant encounters and gravitational wave inspiral depend on mass. Applying the results to globular cluster conditions, we find that half of the inspirals are due to resonant interactions. The other half comes from flybys that excite the eccentricity of binaries that initially were just below the eccentricity threshold. This mechanism is not included in fast models for dynamical production of binary black hole inspiral. Including it roughly doubles the number of in-cluster inspirals, increasing the agreement between fast models and more accurate $N$-body simulations.

**Affliation**:

ICCUB

**Current Position**:

PhD Student

**Flash Poster Presentations (in-person) / 124**

## Investigating Dynamical Ages of Open Clusters using Blue Straggler Stars

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Blue straggler stars (BSS) are rejuvenated core hydrogen-burning stars that are bluer and brighter than the main-sequence turnoff stars of star clusters. They are believed to have formed via binary evolution and multiple stellar interactions. BSS are among the most massive populations of star clusters and therefore experience significant gravitational drag compared to other cluster populations and sink in the cluster center faster than any other cluster population. This observational signature has been used to assess the dynamical ages of globular clusters. We estimate the relative sedimentation level of the BSS population of 23 old open clusters (ages > 1 Gyr), utilizing various methods

such as normalized BSS radial distributions, and estimation of the area enclosed between cumulative radial distributions of BSS and reference populations, $A^+$. Upon comparing the theoretical parameters related to clusters' dynamical states and the observed values of $A^+$, we learn that they follow the same broad correlation as found in the globular clusters.

**Affliation**:

Institute of Astronomy, National Central University, Taiwan.

**Current Position**:

Postdoc

**Flash Poster Presentations (in-person) / 146**

## Structure of Open Clusters

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**Co-authors:** Ernst Paunzen ; Tahereh Ramezani [2]

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We investigated the available Gaia catalogue data (DR3) of open clusters and studied cluster distances, sizes and membership distributions in the 3D space. The dependence of distance and size on the parallax-to-distance transformation was analysed. We argue that within two kpcs, the inverse-parallax method gives results comparable to the Bayesian approach based on the exponentially decreasing volume density. Both methods show similar dependence on the line-of-sight elongation of clusters. We also looked at a measure of elongations of the studied clusters and found that the most distant cluster contains about half of its members within a spherical fit located at about 1000 pc. These results show that the 3D structure of an open cluster cannot be studied appropriately beyond about 500 pc when using standard transformations of parallaxes to distances. Equally significant is our exploration of tidal tails. A star cluster elongates with time along its path and begins to lose members, primarily low-mass stars, forming two tidal tails along the cluster orbit. Our N-body simulations have revealed that for circular orbits, the length of the overdensities along the tidal tail from the cluster centre is solely dependent on the mass of the cluster and the strength of the tidal field. This length decreases monotonically with time. In the more general case of eccentric orbits, the orbital motion influences the length, leading to periodic compression and stretching of the tails, resulting in an oscillation with time. In the clusters'vicinity, tails are characterized as co-moving stars motion of the corresponding cluster. Simulations confirm that the tidal tails closely follow the orbit, showing only small drifts in the most remote parts of the tidal tails. Our presentation will shed light on our current understanding of the tidal tails of star clusters in our Milky Way, a significant contribution to the field.

**Affliation**:

Masaryk University

**Current Position**:

PhD Student

**Flash Poster Presentations (in-person) / 73**

## Estimating the Hubble constant from the mock GW data of Einstein Telescope

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The Hubble constant is a crucial cosmological parameter that is a measure of the rate of change of the cosmic scale factor per unit cosmic scale factor i.e. a_dot / a. There is a considerable discrepancy between the measurements of the Hubble constant from standard candle observations and those from cosmic microwave background (CMB) observations. Data from gravitational wave (GW) events can provide an independent constraint on the Hubble constant. Higher the number of events, the stronger is the constraint. A tight constraint is expected to be achieved in the era of the third generation detectors such as the Einstein Telescope (ET). Without relying on any electromagnetic observation, one can either use the double black hole (BH) merger or the double neutron star (NS) merger detections to break the mass-redshift degeneracy. We present a method of estimating the Hubble parameter using ET mock data for NS-NS events and discuss the challenges. We assume flat cosmology in our analysis.

**Affliation**:

University of Warsaw

**Current Position**:

PhD Student

**Flash Poster Presentations (in-person) / 126**

## White Dwarf - White Dwarf Gravitational Wave background in the LISA range as a tool to constrain binary evolution

**Author:** Sreeta Roy[1]

**Co-authors:** Tomasz Bulik [1]; Dorota Gondek-Rosinska [1]

[1] *Astronomical Observatory, University of Warsaw*

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Gravitational Waves have proven to be an excellent tool for understanding populations of binaries. In this work, we investigate the population of White Dwarf binaries in the Milky Way. We calculate the Gravitational Wave background from these sources in the LISA sensitivity range.

We use the COMPAS population synthesis code, and investigate the dependence of the background spectrum on the assumptions on binary analysis. We discuss the possibility of constraints on binary evolution that LISA Gravitational Wave observations may yield.

**Affliation**:

Astronomical Observatory, University of Warsaw

**Current Position**:

PhD Student

**Flash Poster Presentations (in-person) / 103**

# Zoom-in hydrodynamics simulations of binary mass transfer

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Most massive stars form in binary or even multiple systems. During their evolution, these binaries almost inevitably undergo a critical phase where the binary members exchange mass. It has been shown that this mass transfer plays a crucial role in shaping the evolution of both stars and is responsible for many fascinating astrophysical phenomena currently being observed, such as the formation of gravitational wave sources and the recently detected enigmatic quasi-periodic eruptions at galactic centers. Despite its importance, mass transfer remains one of the main uncertainties in binary stellar evolution and is typically modeled by simplified prescriptions. Although mass transfer is an intrinsically 3D phenomenon with possible nonlinear hydrodynamical effects, it has been predominantly studied analytically due to the high computational costs of numerical simulations for mass transfer. By adopting a novel approach enabling us to accurately simulate gas streams in 3D near the Lagrangian point with the hydrodynamics code Athena++, we investigate the properties of transferred mass over a wide range of mass ratios and overfilling factors. In this talk, I will present the results of the simulations and discuss astrophysical implications for the stability of mass transfer and the electromagnetic emission from transients involving mass transfer.

**Affliation**:

Max Planck Institute for Astrophysics

**Current Position**:

Postdoc

**Flash Poster Presentations (in-person) / 118**

# Survival of the planet-forming environment around three ejected runaway stars from the ONC

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During the early dynamical evolution of a dense stellar system, such as a young star-forming region, stars can be ejected as runaway stars following a close dynamical interaction. These stars are still extremely young at the time of ejection and might harbour a protoplanetary disc, which has been truncated or limited in size by the ejection encounter. Based on three runaway stars from the Orion Nebula Cluster that show tentative evidence of surviving disc material, we investigate their disc properties and likely evolution. We compare the properties of these runaway stars with those from N-body simulations of the ONC to determine the closeness of the encounters that have formed them. We then truncate discs of different initial sizes/masses based on these encounters and simulate their subsequent evolution to evaluate their planet-forming potential.

**Affliation**:

Imperial College London

**Current Position**:

Postdoc

**Flash Poster Presentations (in-person) / 47**

## Evolution of Disk-like Structures in the Galactic Centre

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In this work, we present an understanding of the complex mechanisms that govern the evolution of orbits in the Galactic Centre. Through N-body simulations, we have gained crucial insights into the evolution of disk-like structures in the Galactic Centre. We see that post-Newtonian corrections and perturbative effects are critical in stabilizing these structures. In their absence, these structures would disintegrate due to vector resonance relaxation. Additionally, our research has demonstrated how these disk-like structures can split and create multiple disks with different properties, which could explain both clockwise and counterclockwise disks, as well as the highly debated disk-like structures in the S-star cluster. Our findings shed light on the intricate interplay between gravitational forces from different bodies that shape the dynamics of stars, dusty sources, and compact stellar remnants in the Galactic Centre, providing an important theoretical contribution to the field.

**Affliation**:

Astronomical Institute, Charles University

**Current Position**:

PhD Student

**Flash Poster Presentations (in-person) / 36**

## Measuring energy equipartition in Globular Clusters with dynamical models

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**Co-authors:** Marco Merafina [2]; Oscar Straniero [3]

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**Introduction:** The gravitational encounters occurring in Globular Clusters (GCs) drive the system toward energy equipartition and trigger other dynamical processes, that still require a self-consistent theoretical description. Internal kinematics observations show a partial degree of equipartition (Libralato et al. 2018, 2019, 2022; Watkins et al. 2022), confirming N-body predictions (Trenti & Van Der Marel 2013; Bianchini et al. 2016; Webb & Vesperini 2017; Pavlik & Vesperini 2021, 2022)

**Method:** Through a multi-mass dynamical model we estimate the energy equipartition degree in eight GCs. We constrain model parameters fitting the velocity dispersion dependence on stellar mass from HST proper motion data by Watkins et al. 2022, comparing with the fitting function by Bianchini et al. 2016, found from N-body simulations. An higher equipartition degree is obtained for a more advanced dynamical state, identified by the parameter $\Phi_0$, a measure of the gravitational potential well. We discuss its relation with the equipartition mass $m_{\mathrm{eq}}$, in the Bianchini fitting function, as well as other structural properties. We also find that a constrain to $m_{\mathrm{eq}}$ obtained by fitting proper motion data suffers projection and shell selection effects, underestimating the level of equipartition. On the contrary, our equilibrium configuration predicts the equipartition degree at any radial coordinate, without suffering such effects.

**Conclusions:** With the help of our model, we plan to broad the analysis of the equipartition degree in GCs to obtain a more statistically significant sample for the structural parameters. Furthermore, we can perform N-body simulations setting initial conditions from our model, exploring an initial degree of equipartition (and mass segregation) as well as differences in the kinematical properties of Multiple Populations, an highly debated topic in the field. Indeed, their initial properties and their impact in the dynamical evolution of GCs are still widely unclear and require further investigation.

**Affliation**:

University of Campania "Luigi Vanvitelli" & INAF

**Current Position**:

PhD Student

**Flash Poster Presentations (in-person) / 153**

## Globular Clusters: The Cosmological Context from Coupled Simulations to Sub-grid Models

**Author:** Fred Thompson[1]

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Globular clusters (GCs) can be used to probe the Milky Way's accretion history, potential, and dark substructures. Additionally, GCs could provide formation pathways for nuclear star clusters and supermassive black hole seeds. A detailed understanding of GC formation and evolution is therefore necessary, so it is important to capture the relevant physics in cosmological simulations. Several high-performance codes can successfully model the collisional dynamics of GCs, which can then be coupled to collisionless galaxy formation codes; however, this approach is too expensive to carry out in explicit cosmological simulations, so either post-processing or sub-grid models are required. We are developing and testing sub-grid prescriptions for GC formation and evolution to be added to the RAMSES galaxy evolution code. In this poster, I will present our current progress in testing models for GC evolution using the AMUSE framework to carry out coupled GC–galaxy simulations. Our next steps will be to add this into RAMSES and begin testing models of GC formation using sink particles.

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**Current Position**:

PhD Student

**Flash Poster Presentations (in-person) / 14**

## The Origin of Young Stellar Populations in NGC 1783: Accretion of External Stars

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The presence of young stellar populations in Large Magellanic Cloud cluster NGC 1783 has caught significant attention, with suggestions ranging from it being a genuine secondary stellar generation to a population of blue straggler stars or simply contamination from background stars. Thanks to multi-epoch observations with the *Hubble Space Telescope*, proper motions for stars within the field of NGC 1783 have been derived, thus allowing accurate cluster membership determination. Here, we report that the younger stars within NGC 1783 indeed belong to the cluster, and their spatial distribution is more extended compared to the bulk of the older stellar population, consistent with previous studies. Through $N$-body simulations, we demonstrate that the observed characteristics of the younger stars cannot be explained solely by blue straggler stars in the context of the isolated dynamical evolution of NGC 1783. Instead, accretion of the external, low-mass stellar system can better account for both the inverse spatial concentration and the radial velocity isotropy of the younger stars. We propose that NGC 1783 may have accreted external stars from low-mass stellar systems, resulting in a mixture of external younger stars and blue straggler stars from the older bulk population, thereby accounting for the characteristics of the younger sequence.

**Affliation**:

School of Physics and Astronomy, Sun Yat-sen University

**Current Position**:

PhD Student

**Flash Poster Presentations (in-person) / 113**

## A Massive Star Photoionization Feedback Model Considering Density Inhomogeneity: Applicability to Star Cluster Formation Simulations and Larger Scale System Simulations

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Feedback mechanisms in massive stars are thought to have important implications for the evolutionary process of star clusters. Among them, photoionization feedback is the process by which ionized photons emitted by massive stars influence subsequent star formation in the surrounding environment.
In star cluster formation simulations, ionized regions can be correctly treated using a direct radiation hydrodynamics approach, but this requires very large computational resources. We aim to adopt a more simplified model for use in large-scale, high-resolution simulations to reduce computational costs.
In star cluster formation simulations by Fujii et al. (2021b) for galaxy simulations, an approximate strögren spherical model was used to evaluate the ionized region. However, due to the inhomogeneity of the density distribution in the actual star formation field, this mere approximation is usually considered inaccurate.
In this study, we introduce a model that independently evaluates the extent of the ionization structure in each direction of the icosahedron, incorporating the spatial inhomogeneity of the star-forming region in a simplified manner. This model is implemented and evaluated in the N-body/smoothed particle hydrodynamics code ASURA+BRIDGE (Saitoh et al. 2008, 2009; Fujii et al. 2021b). We conducted a series of comparative simulations using molecular clouds with an internal turbulence velocity field as initial conditions. Simulations using a spherical model based on the Strömgren sphere were also synchronized for comparison.
The simulations reproduced anisotropic ionized structures with corresponding anisotropic outflows during the evolution of star formation. In contrast, the spherical model exhibited only a purely spherical structure for the ionized region. Statistical results from multiple sets of simulations indicate that the purely spherical model exhibits a stronger suppression of star formation than the icosahedral model, which we attribute to its unidirectional energy accretion accelerating the termination of star formation.

**Affliation**:

Kobe University

**Current Position**:

PhD Student

**Observational properties of dense stellar systems in different environments / 72**

## Tracing massive star cluster formation: insights from the LISCA project

**Author:** Alessandro Della Croce[1]

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Clustered star formation is the dominant mode of star formation across cosmic time. Moreover, it plays a key role in many fundamental areas of astrophysics: from the early interplay between stellar and gas dynamics to the formation of gravitational wave sources and exotica, from the dynamical properties of young star clusters to galaxy assembly and evolution. Yet, the underlying physical processes governing massive star cluster formation are still poorly constrained. In particular, whether clusters form through a monolithic event or as a result of a hierarchical assembly process is still a matter of intense investigation.
Within this context, I will introduce the LISCA project. The project aims to characterize cluster formation and early evolution by performing the first comprehensive spectro-photometric and kinematic analysis of young clusters and associations using both Gaia DR3 and dedicated high-resolution spectroscopy secured through the SPA-TNG large program.

I will focus in particular on recent results obtained in the Perseus complex. We found that the region presents several young (< 30 Myr) star clusters organized in large hierarchical structures (at least three major structures) and embedded in a diffuse "stellar halo"exhibiting cluster-like features and out-of-equilibrium dynamics. These systems show properties in terms of 2D density structure, evidence of tidal interactions, mass segregation, and kinematics compatible with being at the early or at most intermediate stages of a massive cluster assembly process that could lead them to evolve as bound stellar clusters.
The results we obtained show that the formation of small stellar structures and their subsequent growth driven by dynamical interactions might have strongly contributed to shaping the observed properties of these hierarchical structures, thus possibly representing a viable process to form massive and long-lived stellar systems also in relatively low-density environments, like the Milky Way disk.

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**Observational properties of dense stellar systems in different environments / 81**

## Kinematics of Multiple Stellar Populations in Globular Clusters with JWST

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An intriguing phenomenon in globular clusters is the presence of multiple stellar populations with different light element compositions. The origin of this phenomenon is still unclear, but a key piece of information to solve this enigma resides in the structural and kinematic differences of the stellar populations. Globular clusters are, in general, very old stellar populations, but simulations indicate that while dynamical interaction in the clusters centers could have washed away information regarding the clusters'initial conditions, the outer regions can still preserve this information. In the context of multiple stellar populations, differences in kinematics can reveal aspects of the history of star formation of the cluster, constraining models for the formation of multiple populations. Data from previous studies regarding dynamics of multiple populations in globular clusters, due to instrumental limitations, were mainly focused on giant stars. In this work, we use NIRCam/JWST data to investigate the dynamics of first- and second-generation very low-mass stars in the globular cluster 47 Tucanae. We analyze, over large radial and mass ranges, differences in energy equipartition, anisotropy, and radial distribution for the multiple stellar populations in the cluster. Our results favor formation scenarios where a second generation of stars were formed more centrally concentrated in the clusters shortly after the first generation was formed.

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**Observational properties of dense stellar systems in different environments / 52**

## Metallicity variations among the primordial stellar population in Galactic globular clusters: A MUSE spectroscopic survey.

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Galactic globular clusters (GGCs) are known to have some degree of chemical complexity, indicating that they do not consist of a "single" stellar population. Instead, some stars have an atmospheric composition showing evidence of material processed by nuclear reactions. Recently, the issue has also been raised about how "mono-metallic" GGCs are. Intrinsic Fe dispersions among RGB stars of GGCs were found to be small but inconsistent with zero (Bailin 2019). The presence of Fe dispersion was also recently suggested as an explanation for the color spread (in F275W-F814W color) observed among the primordial population (P1), that with a normal chemistry, of RGB stars in GGCs. Iron abundance determinations for a handful of P1 stars in three GGCs indicated variations of about 0.1 dex (Marino et al, 2019,2023, Lardo et al. 2023).
In this work, I present metallicity measurements for P1 stars in 20 GGCs based on MUSE spectroscopy. Thanks to the observations conducted as part of the MUSE globular clusters survey, we derive metallicities for up to 250 P1 stars per cluster. In 17 of these clusters, we find a statistically significant correlation between the pseudo-color (Δ F275W-F814W) of the stars and their metallicity. This demonstrates the sensitivity of this filter combination to changes in metallicity. For the first time, we provide robust and homogeneous metallicity spreads, directly measured from spectroscopy, among the P1 stars of 17 GGCs and we find it to range between 0.03 and 0.2 dex. We also find a correlation between the metallicity spreads and the cluster's mass. This supports the idea of self-enrichment during the formation of globular clusters because a deeper gravitational potential well retains supernova ejecta more efficiently.

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**Current Position**:

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**Observational properties of dense stellar systems in different environments / 121**

## Unveiling the Heart of Darkness: Modeling the Central Kinematics of Omega Centauri and Its Elusive Black Hole

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Dense stellar systems, such as globular clusters and nuclear star clusters, represent natural laboratories for exploring the intricate interplay between gravitational interactions, stellar dynamics, and the formation of exotic objects like intermediate-mass black holes (IMBHs). Recent discoveries of massive black holes above 10^7 Msol in stripped nuclei within the Virgo and Fornax clusters have prompted a quest to understand the distribution of IMBHs in various galactic environments. But so far the expected population of black holes have not been found in the more abundant stripped nuclei expected at lower masses. The dense stellar systems within the Local Group's most massive clusters are the perfect place to hunt for the IMBHs, presenting significant implications for our understanding of globular cluster formation theories and the broader mechanisms governing black hole formation and growth in the early universe.
Omega Centauri (NGC 5139) stands out among globular clusters in the Milky Way for its massive size, complex stellar population, and the long-suspected presence of a central black hole. Likely the remnant nuclear star cluster of a galaxy accreted by the Milky Way, Omega Centauri's central kinematics present a complex puzzle. Our latest observations from MUSE obtained the highest-resolution spectroscopic data yet in the narrow field and the wide field modes. Our observations reveal a counter-rotating central kinematic structure within 20" relative to the bulk rotation of Omega Centauri. Furthermore, I will present the latest results of our Jeans'dynamical models, which aim to unravel the complexities of the central kinematics in this massive cluster. By integrating these observations and models, we aim to shed light on the elusive presence of an intermediate-mass black hole and its implications for our understanding of galactic nuclei dynamics and black hole demographics.

**Affliation**:

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**Observational properties of dense stellar systems in different environments / 125**

## Galactic Archaeology with Globular Clusters - Europium is a Chemical Tag Between Globular and their Hosts Across All Metallicities

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Globular clusters (GCs) are among the most ancient objects in the local Universe, acting as tracers of galaxy formation across both space and time. With the recent JWST discovery of nitrogen-rich star formation in a redshift 11 galaxy, and the discovery that over 50% of the in-situ stars in the Milky Way (MW) likely formed in clusters, understanding the role of GCs in the context of galaxy evolution is becoming ever more important. The MW hosts a large (~150) and diverse population of GCs. Among these clusters, a fraction are thought to have formed in-situ, alongside the MW, while others were likely accreted alongside disrupted dwarf galaxies. Finding a chemical tag linking accreted GCs to their host galaxies is key to further unscrambling the MW halo. I will present results showing that the ratio of [Eu/Si] separates dwarf galaxy and MW stars at the same metallicities and

that this difference extends to the populations of accreted and in-situ GCs. While this difference has been seen before at high-metallicities, I will show that it extends to metallicities of [Fe/H] < -2 and that the difference cannot be explained by star formation efficiency alone. I will also show that this unique signature not only extends to Local Group dwarf galaxies and their globular clusters, but also to the halo of M31 - offering the opportunity to do Galactic Archaeology in an external galaxy.

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**Observational properties of dense stellar systems in different environments / 87**

## Binaries in massive clusters with MUSE: Omega Cen and NGC 1850

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Binary systems are important constituents of massive star clusters. They have been invoked to play an important role in the origin of phenomena observed in these environments, such as the extended main-sequence turn-offs, and to lead to the formation of exotic objects (blue straggler stars, low-mass X-ray binaries, Be stars etc).
A detailed characterization of the orbital properties of binary systems in clusters is crucial information for understanding the frequency of interactions or mergers between binary components, as well as for predicting how many binary interaction products are expected in individual clusters. However, such observational studies have become possible only recently, thanks to the advent of integral field spectrographs (e.g. MUSE/VLT) which have been able to monitor the innermost regions of clusters over time to identify these systems.
To study how the orbital properties of binaries evolve in clusters of different ages, as well as to search for binary interaction products, we are currently conducting a large spectroscopic campaign with MUSE.
We recently investigated NGC1850 (~100 Myr in Large Magellanic Cloud) and Omega Centauri (> 12 Gyr in our Galaxy). For both we have more than 15 epochs of MUSE observations, covering a temporal sampling of over 2 and 8 years, respectively. This allows us to identify their binary systems and constrain their orbits.
I will present the results of this study, discussing the orbital properties of the constrained systems in NGC1850 and Omega Centauri and the differences between these two clusters in terms of their binary population (e.g. orbital period distribution, binary mass function etc.)
Such studies are essential to provide important constraints to the modelling of massive star clusters, with the aim of obtaining more robust predictions in terms of their stellar and non-stellar population content, which so far is still very approximate in clusters of all ages.

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**Observational properties of dense stellar systems in different environments / 26**

## Rotation and expansion in open clusters using simulations and Gaia DR3

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Empirical constraints on the internal dynamics of open clusters are important for understanding their evolution and evaporation. High precision astrometry from Gaia DR3 are thus useful to observe aspects of the cluster dynamics. This work aims to identify dynamically peculiar clusters such as spinning and expanding clusters. We also quantify the spin frequency and expansion rate and compare them with N-body models to identify the origins of the peculiarities. We used the latest Gaia DR3 and archival spectroscopic surveys (APOGEE, GALAH, LAMOST etc.) to analyse the radial velocities and proper motions of the cluster members in 1428 open clusters. A systematic analysis of synthetic clusters is performed to demonstrate the observability of the cluster spin along with effects of observational uncertainties. N-body simulations were used to understand the evolution of cluster spin and expansion for initially non-rotating clusters. We identified spin signatures in 10 clusters (and 16 candidates). Additionally, we detected expansion in 18 clusters and contraction in 3 clusters. The expansion rate is compatible with previous theoretical estimates based on expulsion of residual gas. The orientation of the spin axis is independent of the orbital angular momentum. The spin frequencies are much larger than what is expected from simulated initially non-rotating clusters. This indicates that >1% of the clusters are born rotating and/or they have undergone strong interactions. Higher precision observations are required to increase the sample of such dynamically peculiar clusters and to characterise them.

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**Observational properties of dense stellar systems in different environments / 147**

## Bulk rotation in star cluster via N-Body simulations and observations

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N-Body simulations are adopted to understand the rotation in star clusters via the code N-Body6++GPU. The morphology of open clusters are significantly changed due to bulk rotation, especially at the early a few dozen million years. Binary systems also plays an important role in the dynamical evolution of rotating clusters. By comparing simulations to observation, we provide an example of a rotating cluster, Group X. We report the detection of bulk rotation signature in this nearby 400 Myr old star cluster Group X. Statistical analyses of the 3D velocity and residual motions of the member stars clearly indicate the presence of three-dimensional rotation in the cluster.

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**Current Position**:

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**Observational properties of dense stellar systems in different environments / 28**

## On the effects of unresolved binaries on the deduced total mass and stellar mass function of stellar clusters

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One of the most important quantities needed for understanding a stellar cluster's (SC's) formation and evolution is it's stellar mass and mass function (MF). However, the measurements of these quantities are complicated by the possible presence of unresolved binaries. This contribution explores the influence of unresolved binaries on the measured SC mass and MF. It also investigates the impact of unresolved binaries on the masses and MFs of the tidal tails of the SC. Depending on the measurement method, unresolved binaries can cause an overestimate of the SC mass of up to 42 % or an underestimate of up to 25 % in the investigated simulated SC. The power-law index of the MF is underestimated by up to 0.2 causing the observer to see a flatter MF. Additionally a positive correlation is found between the velocity dispersion and binary fraction within the tidal tails of a single SC. However, when comparing different SCs it is found that SCs producing tails with a large overall velocity dispersion have tails with a smaller binary fraction. This is important as a larger binary fraction leads to a flatter apparent MF.

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**Numerical approaches to modelling stellar systems and their constituents / 49**

## The emergence of angular momentum in globular clusters: insights from large N-body simulations

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The majority of Milky Way globular clusters (GCs) display a small, yet significant, amount of angular momentum, clearly detectable from line-of-sight and proper motion data sets. The origin of this angular momentum is still unknown, but its emergence may be linked to the primordial formation of GCs in the high-redshift universe.
In this talk, I will present 2 sets of direct N-body simulations run with NBODY6+++GPU:
1) ~25 large simulations with number of stars ranging from 250k to 1.5M, evolved in a tidal field and with stellar evolution, where different amounts of internal rotation are included in the initial

conditions;
2) ~20 simulations with 250k stars, with idealized clumped initial conditions, where no internal rotation is initialized.
The first set of simulations allows us to study the evolution of angular momentum through >10 Gyr time and constrain the typical amount of angular momentum needed at the formation stage to reproduce current observations. On the other hand, the set of initially non-rotating clumped simulations allow us to study the conditions under which rotation can naturally emerge in the early assembly stage of GCs. The ongoing analysis shows that >50% of these simulations acquire a significant amount of angular momentum in the first <100 Myr, as a result of the assembly and mergers of the clumps. These results are important in the perspective of linking the properties of the gas-dominated early phase of GC formation to the subsequent N-body dominated evolution.

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**Numerical approaches to modelling stellar systems and their constituents / 58**

## The strong impact of IMF in star cluster dynamics

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Massive stars have a significant impact on the dynamical evolution of star clusters. They play a crucial role during star formation, as their radiation can push surrounding gas away and inhibit further star formation. Additionally, strong mass loss from massive stars via strong winds can rapidly reduce the gravitational potential of star clusters and trigger their fast expansion. Once these massive stars evolve into black holes, they continue to drive the expansion of the cluster by forming binary black holes at the center. In this talk, we will discuss the impact of stochastic variations in star formation and the variation of initial mass function on the dissolution of star clusters. We will utilize numerical N-body simulations to explore the potential of combining these models with observations, such as Gaia and CSST data, to constrain the initial conditions of star clusters. Specifically, we will focus on investigating the dynamical effects of massive stars and black holes and their implications for the properties of initial mass functions.

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**Numerical approaches to modelling stellar systems and their constituents / 120**

## The Four-Body Problem in Newtonian Gravity

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Each outcome of the four-body problem can be regarded as some variation of the three-body problem. For example, when two single stars are produced (the 2 + 1 + 1 outcome), each ejection event is modeled as its own three-body interaction by assuming that the ejections are well separated in time. For each outcome, we derive, using the density-of-states formalism, analytical distribution functions that describe the properties of the products of chaotic four-body interactions. We perform a set of scattering simulations in the equal-mass point-particle limit to validate these results, and identify regions of parameter space that our model is not suited for. The agreement is strong, and highlights the importance of the initial semi-major axes. Binary-binary scatterings act to systematically destroy binaries. Instead they produce a binary and two ejected stars when the initial binary semi-major axes are similar, or a stable triple when the initial semi-major axes are very different. The 2 + 2 outcome produces the widest binaries, and the 2 + 1 + 1 outcome produces the most compact binaries. Hence, four-body interactions in clusters should act to systematically destroy binaries , independent of the initial orbital separation distribution.

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**Numerical approaches to modelling stellar systems and their constituents / 75**

## Isles of regularity in a sea of chaos amid the gravitational three-body problem

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The 3-body problem poses a longstanding challenge in physics and celestial mechanics. Despite the impossibility of obtaining general analytical solutions, statistical theories have been developed based on the ergodic principle. This assumption is justified by chaos, which is expected to fully mix the accessible phase space of the 3-body problem.
We probed the presence of regular (i.e. non chaotic) trajectories within the 3-body problem and assessed their impact on statistical escape theories.
Our analysis reveals that regular trajectories occupy up to 32% of the phase space, and their outcomes defy the predictions of statistical escape theories. Our findings underscore the challenges in applying statistical escape theories to astrophysical problems, as they may bias results by excluding the outcome of regular trajectories. This is particularly important in the context of formation scenarios of gravitational wave mergers, where biased estimates of binary eccentricity can significantly impact estimates of coalescence efficiency and detectable eccentricity.
Based on 2403.03247

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**Numerical approaches to modelling stellar systems and their constituents / 42**

## Relaxation and evolution towards inverse energy equipartition in star clusters

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Recent observations with HST and Gaia deepened our understanding of the internal kinematics of star clusters. Motivated by those findings, we aim to gain theoretical insights into how various kinematic properties influence the overall dynamical development of these stellar systems. Through N-body simulations, we explore the effects of different initial velocity distributions, ranging from tangentially to radially anisotropic. We reveal accelerated relaxation processes in the tangentially anisotropic models, leading to faster mass segregation in the inner regions and a more rapid evolution towards core collapse. Additionally, we observe distinct patterns in the evolution away from the initial equipartition of velocities, especially in the outer cluster regions. The radially anisotropic models evolve towards energy equipartition while the tangentially anisotropic and isotropic models show an "inverted" energy equipartition (where the high-mass stars have higher velocity dispersion than the low-mass stars). The duration and radial range of this inversion are influenced by the initial velocity distribution - increasing with the system's tangential anisotropy and decreasing with radial anisotropy.

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**Numerical approaches to modelling stellar systems and their constituents / 142**

## Updates on AMUSE

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AMUSE, the Astrophysical Multipurpose Software Environment, has been around since 2009, and it has been used in many different projects. AMUSE offers users the ability to combine different specialised simulation codes in a single simulation, which makes it possible to simulate complex systems that require interaction between different physical aspects and/or scales. Topics AMUSE has been used for include star formation, stellar winds, multiple stellar systems, and protoplanetary disks. In this talk I will showcase some recent projects, and provide updates on the status of AMUSE development.

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**Numerical approaches to modelling stellar systems and their constituents / 114**

## Dynamical mixing of multiple populations in globular clusters.

**Author:** Francisco I. Aros[1]

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Globular clusters (GCs) have multiple populations identified through abundance variations in a number of light elements. These populations also show, in some cases, differences in some dynamical properties such as their concentration, systemic rotation, and velocity anisotropy, differences that might still preserve partial memory of the initial configuration of the stellar populations. In this work, we analyse the degree of dynamical mixing of the multiple stellar populations in GCs, following the dynamical evolution of simulated GCs with multiple populations and tracing the mixing of the populations in the phase-space of energy and angular momentum. We connect the intrinsic phase-space mixing with the differences in the projected angular momentum and the velocity anisotropy of each stellar population. We also explore the signatures of dynamical mixing on the degree of energy equipartition of the stellar populations. Finally, we show the prospects for observing the signatures in angular momentum, velocity anisotropy, and energy equipartition in Galactic GCs.

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**Numerical approaches to modelling stellar systems and their constituents / 129**

## Gas and multiple evolution in young star clusters and other gas-rich environments

**Author:** Aleksey Generozov[1]

**Co-authors:** Hagai Perets [1]; Stella Offner [2]; Kaitlin Kratter [3]

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I will discuss how gas affects the evolution of multiple star systems in young star clusters and other gas-rich environments. In particular, gas can shrink and circularize wide binaries, potentially explaining observed changes in binary properties with star cluster age. Additionally, gas can trigger instabilities in multiple systems. Finally, gas may trigger the formation of binaries and higher-order multiples from initially unbound stars. I will present results from both semi-analytic calculations and hydrodynamic simulations.

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**Numerical approaches to modelling stellar systems and their constituents / 88**

## The dynamics of planet-like objects in star clusters

**Author:** Francesco Maria Flammini Dotti[1]

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The dynamical evolution of planet-like objects in star clusters is not easy observable in star clusters, and it still not possible in dense star clusters such as globular clusters. I will first introduce previous works that looked into the motion of these objects, and then I will numerically explore the dynamical evolution of such objects, varying the number density of the hosting star cluster. As a final point, I will try to confute if the relative large abundance of free-floating planets in our galaxy is due to their ejected free-floating planets. I will use NBODY6++GPU-ML (a N-body code which performs simulations with a large number of particles and massless particles, i.e., star clusters with free-floating planets). The results pinpoint how the planet-like objects are not particularly affected by mass segregation, but only by the central gravitational evolution of the core of the star cluster, suggesting that those particles, in relatively dense star clusters, are ejected only at much larger timescales.

**Affliation**:

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**Current Position**:

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**Virtual Poster Presentations / 13**

## Mass loss of the Milky Way globular clusters on cosmological timescale: interaction with the Galactic center

**Author:** Maryna Ishchenko[None]

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Our recent investigation (Ishchenko et al. 2023) was found the 10 Milky Way globular clusters which can potentially to interact with the nuclear star cluster during their lifetime. For the dynamical orbital integration of GCs, including the effects of stellar evolution, we employed a high-order parallel N-body code φ−GPU, which is based on the fourth-order Hermite integration scheme with hierarchical individual block time steps. The current version of the code also incorporates the up-to-date stellar evolution models. We select for subsequent full N-body modelling six GCs. First of all, we have chosen: HP1, NGC 6981, NGC 6401, NGC 6642, Palomar 6 and NGC 6681. We will present

the detailed dynamical and stellar mass loss of our set of GCsб including global evolution in a context with the interaction with the Galactic center. Also we present the dynamical evolution of the high mass remnants. The analysis will be carried out drying the whole 8 billion years of the GC's evolution in time variable potential.

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**Virtual Poster Presentations / 110**

## Long-Term Dynamical Evolution of Rotating Multiple-Population Globular Clusters

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We present the results of a set of N-body simulations aimed at investigating the long-term kinematic and spatial evolution of rotating multiple-stellar populations in globular clusters.
Our simulations start with a compact, rapidly rotating, and flattened second-generation (SG) subsystem embedded in the central regions of a more diffuse, and slow rotating first-generation (FG) cluster.
We explore the effects of internal dynamical processes and those driven by the external tidal field. Our investigation provides new insights into the evolution of rotation velocity, anisotropy, and angular momentum evolution of multiple populations in globular clusters and the dependence of these kinematic properties on the stellar mass. Finally, we present the results of the study of the evolution and mixing of the FG and SG spatial properties and discuss how the spatial mixing relates to the stellar kinematics and the kinematic mixing.

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**Virtual Poster Presentations / 95**

## Exploring the internal kinematics of Galactic Globular Cluster cores

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Globular clusters (GCs) are among the longest-studied stellar systems. Despite extensive study, their formation mechanisms, evolutionary history, and interplay with the host galaxy are still unknown. A key to solving these questions lies in the analysis of their internal kinematics, which can provide invaluable insights into their dynamical evolution. However, the study of GC kinematics presents significant challenges due to observational limitations, especially in crowded regions.
In the context of the Multi-Instrument Kinematic Survey (MIKiS), I have investigated the kinematic properties of a sample of massive and dense Galactic GCs, by using large samples of line-of-sight (LOS) velocities of individual stars located over the entire cluster extension. In particular, the talk will focus on the kinematic characterization of the high-density core regions, which are of particular interest because they are most affected by dynamical processes and are notoriously difficult to study due to extreme crowding. Using state-of-the-art integral field spectrographs assisted with adaptive optics (e.g. MUSE) we were able to probe these central regions and extract valuable kinematic information.
We present the derived velocity dispersion profile of each cluster surveyed and the detected rotation signals in most of them. Notably, our analysis excludes the presence of an intermediate-mass black hole in NGC 1904, contrary to previous findings, and reveals an intriguing core rotation in NGC 6440. We then discuss the comprehensive analysis of NGC 1904; for this cluster, we derived the rotation curve both in the LOS direction and in the plane of the sky, and compared our results with those of theoretical models to estimate the dynamical stage of the system. Overall, our results provide strong evidence that GCs are more complex systems than previously thought, and that their kinematic properties are powerful indicators of their dynamical evolution.

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**Virtual Poster Presentations / 102**

# Formation of globular clusters with intermediate-mass black holes

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The formation process of star clusters has not been fully understood yet. Recent numerical simulations of star-cluster formation are reaching the mass of globular clusters (1e6 Msun). However, in hydrodynamics simulation with N-body, the stars have been treated as super particles, representing several stars as one particle. We have developed a new N-body/smoothed-particle hydrodynamics (SPH) code, ASURA+BRIDGE, and have performed N-body/SPH simulations of forming star clusters with almost 1e6 Msun by resolving individual stars. Our code can integrate the orbits of stars without gravitational softening using a direct-tree hybrid N-body code, PeTar (Wang et al. 2020), combined with our N-body/SPH simulation code, ASURA+BRIGE (Fujii et al. 2021). In our simulations, runaway collisions of stars occurred in the forming globular clusters, and the mass of the very massive stars (VMSs) formed via runaway collisions reached a maximum of 1e4 Msun. According to a stellar evolution model, they can collapse to IMBHs with a mass of a few thousand Msun. Our results suggest that some globular clusters may host an IMBH more massive than 1000 Msun. In addition, such VMSs quickly lose their mass via stellar wind and pollute the surrounding gas. In our simulations, so-called second population stars are also formed from the polluted gas. They typically have more than 0.1% of the mass originating from the VMS.

**Affliation**:

The University of Tokyo

**Current Position**:

Senior Scientist or Faculty

**Virtual Poster Presentations / 31**

## Black Hole Accretion and Spin-up through Stellar Collisions in Dense Star Clusters

**Author:** Fulya Kiroglu[1]

[1] *Northwestern University*

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Despite the rising number of binary black hole (BH) mergers detected as gravitational wave (GW) sources by LIGO/Virgo, the evolutionary origin of these events remains a mystery. A growing body of evidence suggests that many of these events originated in dense stellar environments like globular clusters (GCs). Dense environments can produce qualitatively different properties of binary BH mergers compared to systems that merge in isolation, allowing us to disentangle the origins of GW sources. In this talk, I will present insights from N-body simulations of dense star clusters, emphasizing the frequency of collisions between BHs and massive stars. These interactions can lead to significant accretion of material tidally ripped away from stars, which can then spin up and/or grow the BHs significantly while also producing potentially observable transients. This would provide an alternative to stable mass transfer in binaries as a way of spinning up stellar BHs, assuming that they are born spinning slowly (as now considered very likely), with important implications for the interpretation of GW signals from merging BH binaries. Depending on the GC's properties, we find that as many as 50% of all binary BH mergers feature at least one BH component that was spun up through stellar collisions. Although mass accretion efficiency is highly uncertain, collisions with young massive stars may conceivably lead to highly spinning BHs which could be a key observable signature distinguishing them as dynamically-driven BH mergers. These findings hold particular significance as the upcoming observing run O4 for the LIGO-Virgo/Kagra collaboration promises to offer unprecedented constraints on the distribution of BH masses and spins in the coming years.

**Affliation**:

Northwestern University/CIERA

**Current Position**:

PhD Student

**Virtual Poster Presentations / 23**

## Global three dimensional MHD simulations of misaligned embedded mini disk in AGN disk: Nature vs Nurture

**Author:** Bhupendra Mishra[1]

[1] *CAMK*

**Corresponding Author:** mbhupe@camk.edu.pl

The LIGO/Virgo detections showed unexpected progenitor black hole masses (~66 solar mass). Such black holes with their mass falling in the pair instability mass-gap region seek a new formation

channel. We focus on the so-called AGN channel to understand such a puzzling progenitor mass. In this study, we numerically model 3D global MHD accretion flows of embedded black holes within a turbulent AGN disk. The turbulent AGN disk material starts to accrete into newly borned stellar mass black holes and forms randomly aligned accretion disk structures (circum-single disks). In this talk, I will show preliminary results of what causes such a misalignment and how this could affect the evolution of the accretion disk and eventually the spin parameter of the black hole.

**Affliation**:

Nicolaus Copernicus Astronomical Center

**Current Position**:

Postdoc

**Virtual Poster Presentations / 131**

## Gravitational Wave Signals from White Dwarf Binaries

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White Dwarf Binaries are abundant in Globular Clusters and are believed to contribute to the Gravitational Wave background. This background radiation should be visible by future space-based detectors such as LISA. We have taken a large number of WD binaries from GC simulations done in MOCCA and calculated their GW signal. This talk will present our thoughts behind this process and the results that we obtained.

**Affliation**:

CAMK

**Current Position**:

PhD Student

**Virtual Poster Presentations / 20**

## Hierarchical star cluster assembly boosts intermediate-mass black hole formation

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Observations and high-resolution hydrodynamical simulations indicate that massive star clusters assemble hierarchically from sub-clusters with a universal power-law cluster mass function. We study the consequences of such assembly for the formation of intermediate-mass black holes (IMBHs) at low metallicities ($Z = 0.01\ Z_{\odot}$) with our updated N-body code BIFROST based on the hierarchical fourth-order forward integrator. BIFROST integrates few-body systems using secular and regularized techniques including post-Newtonian equations of motion up to order PN3.5 and gravitational-wave recoil kicks for BHs. Single stellar evolution is treated using the fast population synthesis code SEVN. We evolve three cluster assembly regions with $N_{\mathrm{tot}} = 1.70$–$2.35 \times 10^6$ stars following a realistic IMF in ~1000 sub-clusters for $t = 50$ Myr. IMBHs with masses up to $m_{\bullet} \sim 2200\ M_{\odot}$ form

rapidly mainly via the collapse of very massive stars (VMSs) assembled through repeated collisions of massive stars followed by growth through tidal disruption events and BH mergers. No IMBHs originate from the stars in the initially most massive clusters. We explain this by suppression of hard massive star binary formation at high velocity dispersions and the competition between core collapse and massive star life-times. Later the IMBHs form subsystems resulting in gravitational-wave BH-BH, IMBH-BH and IMBH-IMBH mergers with a $m_\bullet \sim 1000\ M_\odot$ gravitational-wave detection being the observable prediction. Our simulations indicate that the hierarchical formation of massive star clusters in metal poor environments naturally results in formation of potential seeds for supermassive black holes.

**Affliation**:

Max Planck Institute for Astrophysics, Garching, Germany

**Current Position**:

Postdoc

**Virtual Poster Presentations / 6**

## Specks of light from AGNs as possible indicators of dynamical formation of binary black holes

**Author:** M. Paola Vaccaro[1]

**Co-author:** Michela Mapelli [2]

[1] *ITA-ZAH, Heidelberg University*

[2] *Institut für Theoretische Astrophysik - Universität Heidelberg*

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Gravitational wave detections of black holes (BHs) in the pair-instability mass gap have sparked interest in dynamical formation channels. In my work, I have explored the process of hierarchical BH mergers in active galactic nuclei (AGNs), which stand out with respect to other dynamical environments for three main reasons: enhanced binary formation due to migration traps, accelerated binary inspiral due to gas hardening and high merger remnant retention due to the deep gravitational potential of the AGN. In this talk, I will present the main results of my new semi-analytical model, which allows me to effectively explore the parameter space while capturing all the main physical processes involved. I will show that the interplay between gas torques and multi-body effects creates a population of binary BHs (BBHs) with unique and distinguishable characteristics: hierarchical mergers in this environment produce a strong correlation between masses and spins of BBH components, with some specimens having masses of thousands of solar masses with spins approaching the theoretical upper limit. Furthermore, I will show that some observed GW transients such as GW190521 are compatible with being produced from this channel. This hypothesis is further corroborated by the co-occurrence with the AGN flare ZTF19abanrhr, which is preferred over a random coincidence of the two transients with a log Bayes'factor of 8.6. I will also compare the AGN BBH population with other dynamical channels as well as the isolated evolution channel, evaluating their relative contributions to the third gravitational-wave transient catalog of the LIGO-Virgo-KAGRA collaboration.

**Affliation**:

Heidelberg University

**Current Position**:

PhD Student

**Special session dedicated to Prof. Rainer Spurzem and Prof. Roberto Capuzzo Dolcetta / 127**

## Simulating the evolution of star clusters: Risks and rewards

**Author:** Douglas Heggie[1]

[1] *University of Edinburgh*

I first quickly review the decades-long history of the development of the methods for simulating the dynamical evolution of star clusters, with additional discussion of N-body methods. Then I survey some things that can or could go wrong, with particular attention to the role played by the theory of two-body relaxation.

**Affliation**:

University of Edinburgh

**Current Position**:

Other

**Special session dedicated to Prof. Rainer Spurzem and Prof. Roberto Capuzzo Dolcetta / 151**

## The scientific journey of Prof. Roberto Capuzzo Dolcetta among stellar clusters and galactic nuclei

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**Special session dedicated to Prof. Rainer Spurzem and Prof. Roberto Capuzzo Dolcetta / 152**

## Rainer Spurzem: The history and art of direct N-body modelling around the globe

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**Special session dedicated to Prof. Rainer Spurzem and Prof. Roberto Capuzzo Dolcetta / 149**

## Are Dwarf Spheroidal and Ultra Faint Dwarf galaxies the most dark matter dominated stellar systems?

**Author:** Roberto Capuzzo Dolcetta[1]

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Dwarf Spheroidal galaxies and Ultra Faint Dwarf galaxies orbiting around the Milky Way are commonly considered as dynamically “hot” systems so that the high velocity dispersions measured could be compatible with a virial state just if their total mass is very large respect to the luminous mass. This led to the consideration that they are the most dark matter (DM) dominated stellar systems in the local Universe. If this is true, they would constitute interesting targets for “direct” observation of DM particles through their decay and/or annihilation, processes whose signature would be observable in gamma via, for instance, the Cherenkov Telescope Array (CTA) whose construction is in progress.
In this talk I would make a short review of data and discuss the compatibility of alternatives to the hypothesis of a huge quantity of DM with observed data.

**Affliation**:

Dep. of Physics, Sapienza, University of Roma, Italy

**Current Position**:

Senior Scientist or Faculty

**Special session dedicated to Prof. Rainer Spurzem and Prof. Roberto Capuzzo Dolcetta / 148**

## How it all started

**Author:** Rainer Spurzem[1]

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As a graduate student I had the privilege to learn from Daiichiro Sugimoto (then Visiting Gauss professor at Uni Goettingen) and Erich Bettwieser. A gaseous or moment model of star clusters was designed. Gravothermal oscillations were detected using this model, which inspired star cluster dynamics for many years, if not decades. I could contribute a little to the model by adjusting the heat conductivity for nuclear star clusters with supermassive central black hole and anisotropy. Douglas Heggie and Sverre Aarseth also visited my supervisor Erich Bettwieser in Goettingen during that time, so I could meet them and get the base of a future cooperation. Sverre Aarseth hosted me as a young graduate student and later postdoc in Cambridge many times, and Douglas Heggie in a project at Edinburgh University, both being always patient and extremely supportive. In Edinburgh I also met Mirek Giersz for the first time, starting a collaboration which lasts until today; with Douglas and Mirek we did quantitative comparisons between all different models, one plot of this work is in a standard textbook now (Binney/Tremaine). With Sverre I did a record 10k N-body simulation on a CRAY supercomputer, which was soon superseded by Jun Makino’s 64k particle model on a GRAPE special purpose computer. Building GRAPE had been pushed forward by Daiichiro Sugimoto and Jun Makino, our team was one of the first receiving a GRAPE board outside of Japan in a collaborative project. I am grateful to Gerhard Hensler in Kiel, and Roland Wielen in Heidelberg for supporting me in the next steps as assistant professor in Kiel and staff researcher and professor in Heidelberg, respectively. GPUs finally superseded GRAPE, but the software designed by the Japanese team made a very quick start possible using GPU. That then brought me to China, where a project to build a large GPU cluster was approved in 2010, and brought our team, including Peter Berczik, to Beijing. Some years full time, some years part time I have been working at NAOC and KIAA ever since. A very talented PhD student (Long Wang) came along and did the first honest and realistic million body simulation, the DRAGON simulation, using Nbody6++GPU (which he had significantly improved). That simulation had been the goal behind GRAPE construction, stated by Daiichiro Sugimoto in Nature (1990), and Douglas Heggie later announced a prize for the first such simulation, which went to Long Wang. I remember Douglas saying that he did not expect that this award would go to China… Recently modelling self-interacting dark matter has revived interest in gaseous or moment models again. I am lucky that I could benefit from all my teachers and collaborators, many more not mentioned in this short abstract and may be even not in the talk.

**Affliation**:

Univ. of Heidelberg (Germany); NAOC, CAS and KIAA, Peking University (China)

**Current Position**:

Senior Scientist or Faculty

**Numerical approaches to modelling stellar systems and their constituents / 134**

## Decoding binary evolution: insights from stripped stars

**Author:** Poojan Agrawal[1]

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Stripped stars, also known as naked helium stars, are the helium cores of stars that have lost their hydrogen-rich outer layer. The recent discoveries of stripped stars have provided valuable insights into massive star evolution, as well as the evolution of stellar binaries. In my talk, I will present results from the rapid stellar evolution code METISSE, used within the binary population synthesis code COSMIC. Specifically, I will discuss the impact of uncertainties in modelling stripped stars on the complex dynamics of mass transfer and the outcomes of common envelope evolution. I will compare the relative importance of these uncertainties with those of the hydrogen-rich massive stars in determining the population properties of binaries. This knowledge is crucial for the realistic modelling of diverse stellar systems such as star clusters, and can help us uncover the secrets of electromagnetic and gravitational-wave transients.

**Affliation**:

University of North Carolina at Chapel Hill

**Current Position**:

Postdoc

**Numerical approaches to modelling stellar systems and their constituents / 8**

## The cosmic rate of pair-instability supernovae

**Author:** Francesco Gabrielli[1]

[1] *SISSA*

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Pair-instability supernovae (PISNe) are explosions developing in the core of massive stars due to a thermonuclear, runaway process, ultimately leading to the total disruption of the progenitor.
They are expected to be the endpoint of the evolution of low-metallicity stars in the mass range between ~ 140 and 260 solar masses, and responsible for the existence of the upper mass gap in the black hole mass spectrum.
Despite the robust theoretical understanding of the pair-production mechanism, and their crucial implications for many astrophysical observations, PISNe have never been confidently observed. However, they are expected to be up to two orders of magnitude more luminous than typical core-collapse

supernovae (CCSNe), for which we have hundreds of observations. This leads to naturally wonder what could be the reason of their missed detection.

In this talk, I will present new results on the PISN rate as a function of redshift, obtained by combining up-to-date stellar evolution tracks from the PARSEC code, implemented in the population synthesis code SEVN, with an up-to-date empirical determination of the galaxy star formation rate and metallicity evolution throughout cosmic history. The goal is to provide a robust theoretical framework to understand where PISNe are across cosmic time, and study their detectability with instruments like JWST.
I will show how the PISN rate is affected by various assumptions in the theoretical models, including the criterion adopted to identify stars unstable against pair production, the maximum stellar metallicity to have PISNe, the upper limit of the stellar initial mass function, and the dispersion of the galaxy metallicity distribution in redshift.
Finally, I will discuss the expected PISN rate contribution coming from isolated binary evolution and star clusters, and how possible (or lack of) future PISN observations can help us constrain stellar and galaxy evolution models.

**Affliation**:

SISSA

**Current Position**:

PhD Student

**Numerical approaches to modelling stellar systems and their constituents / 71**

## Very massive stars do not expand: the uneventful life at the massive end of the IMF

**Author:** Amedeo Romagnolo[None]

**Co-author:** Alex Gormaz-Matamala [1]

[1] *CAMK*

**Corresponding Author:** aromagnolo@camk.edu.pl

Canonical stellar evolution models from both population synthesis and detailed evolutionary codes may predict Very Massive Stars (VMS, defined as $M_{\rm ZAMS}$ > 100 $M_\odot$) to become red supergiants and expand sometimes even more than 10,000 $R_\odot$. At those masses we now know that the luminosity levels are high enough for stellar envelopes to eject mass through winds at super-Eddington rates. This means that, already during the earliest evolutionary stages, VMSs behave like Wolf-Rayet stars and remain compact throughout their whole lifetime. We will show how this behavior has not only important consequences in isolated binary systems, where VMSs are consequently statistically incapable of initiating mass transfer events, but also in dense stellar systems, where the downsizing of VMSs up to three orders of magnitude can considerably affect the dynamical evolution of these environments. On top of that, having super-Eddington winds leads also to a drastically different picture in terms of the final black hole masses that VMSs can produce, which can further alter the structure of clusters.

**Affliation**:

Nicolaus Copernicus Astronomical Centre of the Polish Academy of Sciences

**Current Position**:

PhD Student

**Stellar multiplicity, exotica, and transients in star clusters / 105**

## Binaries in 47 Tuc: Confronting cluster simulations with observations

**Authors:** Johanna Mueller-Horn[None]; Stefan Dreizler[1]

**Co-authors:** Claier Ye ; Fabian Goettgens ; Sara Sarachino ; Sebastian Kamann ; Sven Martens

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Binaries are key objects in Globular Clusters and they influence their structure and dynamics. Especially interesting are pairs of stellar remnants as potential sources of gravitational wave events. Spectroscopic observations of binary stars in Globular Clusters allow to shed light on the poorly constrained period, eccentricity and mass ratio distributions, to develop an understanding of the formation of peculiar stellar objects and to probe the populations of dark stellar remnants. These results are then important benchmarks for cluster simulations. Using MUSE multi-epoch observations we monitored 11 wide-field-mode fields within the half-light radius of 47\,Tuc, one of the most massive Galactic Globular Clusters with a large population of blue stragglers and a predicted but as yet elusive population of up to hundreds of stellar-mass black holes. Over a period of 8 years, we obtained nearly 250000 radial velocity measurements for 22000 stars after applying quality cuts. In this talk, we present the results from this radial velocity monitoring. We derived the binary properties, namely the period distribution, the binary fraction of different stellar evolution stages, and the number of compact companions. Using dedicated state-of-the-art model Cluster Monte-Carlo simulations, we constructed mock observations with properties resembling the real observations. This enables to control the detection efficiency and allows a thorough comparison between models and observations, revealing an unexpected absence of short-period binaries and binaries with massive companions, highlighting the need to improve our understanding of stellar and dynamical evolution in binary systems. We discuss possible reasons for this discrepancy.

**Affliation**:

Georg-August-Universität Göttingen, Institut für Astrophysik und Geophysik

**Current Position**:

Senior Scientist or Faculty

**Stellar multiplicity, exotica, and transients in star clusters / 76**

## Runaway and Hyper-runaway Stars from Merging Star Clusters with Massive Black Holes

**Author:** Lazaros Souvaitzis[1]

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We investigate the impact of massive black holes (MBHs) in merging star clusters of $M_\star = 5.3 \cdot 10^4 M_\odot$ on the escaping population of high-velocity stars and compact objects (COs) incorporating relativistic effects (up to 3.5PN order) , utilizing the GPU-accelerated N-Body code BIFROST. If the merging clusters host central MBHs of $M_\bullet = 10^3 M_\odot$ , a fraction of $6.5\%$ of the stars, $42\%$ of the stellar black holes and $7\%$ of the white dwarfs escape the merger remnant after 100Myr, with velocities up to 650 $\mathrm{km\,s^{-1}}$. The ejection is driven by the formation and hardening of a MBH binary (MBHB) . Specifically the production of runaway stars (RSs) with $40 \leq \mathrm{v_{ej}} \leq 200\ \mathrm{km\ s^{-1}}$ and hyper-runaway stars (HRSs) with $\mathrm{v_{ej}} > 400\ \mathrm{km\ s^{-1}}$ is initiated when the binary semi-major axis

falls below the binary hard separation threshold after 3.2 Myr. With only one MBH the total number of RSs is reduced significantly and becomes even lower for HRSs, while in the absence of MBHs the number of RSs is very low and for the HRSs negligible. The MBHB also contributes to a wide spread of the ejection velocities distribution, in contrast to single or absence of MBHs in the remnant. We also investigate the impact of MBHs on the stellar densities, kinematics and structure of the remnants. Our simulations introduce an additional mechanism contributing to the generation of runaway, hyper-runaway and potentially hyper-velocity (HVS) stars and compact objects within galaxies, providing an alternative explanation for their origin. Finally, by varying the MBHB mass ratio, we study the hardening rate and coalescence timescale and its effect on the escaping population and discuss the implications for current (LVK) and future (LISA) observations of gravitational wave (GW) signals from such systems.

**Affliation**:

Max Planck Institute for Astrophysics

**Current Position**:

PhD Student

**Stellar multiplicity, exotica, and transients in star clusters / 84**

## Stars and Black Holes in Young Star Clusters: Friends or Foes?

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In dense star clusters close encounters between stars and stellar mass black holes can have a wide variety of outcomes ranging from disruption of stars to the formation of bound quiescent binary systems as those recently discovered thanks to Gaia. The former are transients addressed as "micro-Tidal Disruption Events"(TDEs). To date, micro-TDEs have not yet been observed but they are promising multi-messenger sources predicted to be detected by next gravitational waves (GW) observatories.
In this contribution, I will discuss micro-TDEs originated in young star clusters from a dynamical perspective. I have performed a suite of numerical high-precision direct N-body simulations of massive collisional young star clusters (YSCs) with the state-of-the-art code PeTar. PeTar is an N-body code which is coupled with up-to-date stellar population synthesis codes, which are fundamental to treat star and BH progenitors. I will present some preliminary results about the population of micro-TDEs originated in YSCs through hyperbolic-parabolic encounters between single stars and BHs and, furthermore black hole binaries (BBHs). Then I will compare the properties of quiescent BH-star binaries formed in YSCs to those of Gaia BH3, the first halo dormant BH-star binary discovered in the MW.

**Affliation**:

University of Barcelona

**Current Position**:

Postdoc

**Stellar multiplicity, exotica, and transients in star clusters / 27**

## From Clustered Environments to Common Envelopes: The first systematic identification of white dwarf-main sequence post-common envelope binaries in star clusters

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Close binary systems are the progenitors to a variety of compact object mergers producing Type Ia supernovae and gravitational waves. While most short-period binaries are believed to have evolved through at least one common envelope (CE) phase, our understanding of CE evolution is limited due to the lack of observational benchmarks that connect the post-CE parameters with the pre-CE initial conditions. Identifying post-CE systems in star clusters can circumvent this issue by providing an independent constraint on the system's age, but only two white dwarf-main sequence (WD+MS) post-CE systems in a stellar cluster have ever been discovered. In this talk, I will describe our ongoing efforts to systematically identify the first population of WD+MS post-CE binary systems in Milky Way star clusters. First, I will describe our new catalogue of ~50 WD+MS binary candidates in ~30 open star clusters identified through multi-wavelength observations and supervised machine learning. Next, I'll detail the follow-up spectroscopy and monitoring of a subset of our systems that led to the characterization of new WD+MS post-CE systems in clusters. Our new sample will at least double the known population of post-CE systems in clusters, ultimately allowing for new observational constraints on one of the most uncertain yet important phases of binary evolution.

**Affliation**:

University of Toronto

**Current Position**:

PhD Student

**Stellar multiplicity, exotica, and transients in star clusters / 5**

## Binary Formation from Three Initially Unbound Bodies

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We explore three-body binary formation (3BBF), the formation of a bound system via gravitational scattering of three initially unbound bodies (3UB), using direct numerical integrations. For the first time, we consider systems with unequal masses, as well as finite-size and post-Newtonian effects. Our analytically derived encounter rates and numerical scattering results reproduce the 3BBF rate predicted by Goodman & Hut (1993) for hard binaries in dense star clusters. We find that 3BBF occurs overwhelmingly through nonresonant encounters and that the two most massive bodies are never the most likely to bind. Instead, 3BBF favors pairing the two least massive bodies (for wide binaries) or the most plus least massive bodies (for hard binaries). 3BBF overwhelmingly favors wide binary formation with super-thermal eccentricities, perhaps helping to explain the eccentric wide binaries observed by Gaia. Hard binaries form much more rarely, but with a thermal eccentricity distribution. The semimajor axis distribution scales cumulatively as a3 for hard and slightly wider binaries. Though mergers are rare between black holes when including relativistic effects, direct collisions occur frequently

between main-sequence stars—more often than hard 3BBF. Yet, these collisions do not significantly suppress hard 3BBF at the low velocity dispersions typical of open or globular clusters. Energy dissipation through gravitational radiation leads to a small probability of a bound, hierarchical triple system forming directly from 3UB.

**Affliation**:

Northwestern University

**Current Position**:

PhD Student

**Stellar multiplicity, exotica, and transients in star clusters / 119**

## Investigating Blue Straggler Stars of Open Clusters and Fields using UVIT/AstroSat

**Author:** Kaushar Vaidya[1]

**Co-authors:** Anju Panthi [1]; Vikrant Jadhav [2]; Annapurni Subramaniam [3]; Nagraj Vernekar [4]; Manan Agarwal [5]; Khushboo K. Rao [6]; Sindhu Pandey [7]; Sharmila Rani [3]; Sivarani Thirupathi [3]; Saketh Pinapati [1]

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Blue straggler stars (BSS) are anomalous core hydrogen-burning stars that have undergone a rejuvenation by acquiring mass either in a direct stellar collision or through mass transfer in binaries or mergers. We have been surveying the BSS of open clusters and Galactic fields using the Ultraviolet Imaging Telescope onboard the AstroSat telescope. Together in five open clusters (NGC 7789, NGC 2506, NGC 7142, NGC 6940, and NGC 2627) with ages ranging from ~1 Gyr to ~5 Gyr, we studied 33 BSS using the far-UV and near-UV observations from UVIT/AstroSat and GALEX, optical data from Gaia DR2/EDR3/DR3, and IR data from 2MASS, WISE, and Spitzer. Additionally, we studied 27 blue metal-poor stars, the field BSS candidates, using the observations from the above surveys. Based on the best-fit multi-wavelength spectral energy distributions, 15 out of the 33 BSS of the open clusters show more than 50% excess in the UV-flux and are successfully fitted with a double component. Among the field BSS candidates, 12 out of the 27 show UV excess and are successfully fitted with a double component. We present the properties of BSS, field BSS candidates, and their hot companions obtained from the spectral energy distributions. The majority of the ~45% binary BSS and binary field BSS have likely formed as a result of mass-transfer in a binary via Case-A/B or Case-C. In contrast, a few may have formed as a result of mergers or mass-transfer in hierarchical triple systems.

**Affliation**:

Department of Physics, Birla Institute of Technology and Science Pilani

**Current Position**:

Senior Scientist or Faculty

**Stellar multiplicity, exotica, and transients in star clusters / 86**

## Modelling Millisecond Pulsar Populations in Globular Clusters with NBODY6++GPU

**Author:** Yuzhe Song[1]

**Co-authors:** Debatri Chattopadhyay [2]; Rainer Spurzem [3]; Jarrod Hurley [1]; Simon Stevenson [1]

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Millisecond pulsars (MSPs) are neutron stars with rotational periods as low as a few milliseconds. They are formed via angular momentum transfer from accreted materials from a companion star. In the high density environment of globular clusters (GCs), MSPs are likely to form through dynamically formed interacting binaries. In fact, over 300 MSPs are detected in GCs, more than half of the known MSP population. In this work, we attempt to model the MSP populations in intermediate mass clusters using the state-of-the-art N-body simulation code, NBODY6++GPU. We update NBODY6++GPU to include a pulsar spin-down mechanism due to magnetic braking and pulsar spin-up from accretion. These results are compared with observed MSP populations in GCs with similar masses. We then correlate the number of observable MSPs to physical conditions of GCs, and also attempt to predict merger events involving neutron stars in GCs. Since the gamma-ray emission from GCs originates from MSPs, we use the results to imply the observed gamma-ray emission. Different gamma-ray emission mechanisms within GCs are discussed, including the direct superposition of MSP gamma-rays, and the inverse Compton scattering of various photon fields, such as cosmic microwave background, intra-cluster star light and galactic star light by relativistic particles in pulsar winds. The differences of MSP populations in GCs and in the Galactic field are discussed, with the field population modelled by COMPAS, a rapid binary population synthesis code. MSPs ejected from the clusters through dynamical interaction contribute towards the GeV Excess at the Galactic Centre, and this effect is also discussed in this work.

**Affliation**:

Swinburne University of Technology

**Current Position**:

Postdoc

**Stellar multiplicity, exotica, and transients in star clusters / 17**

## Probing Intracluster Dynamics and Evolution of Globular Clusters through Cataclysmic Variable Populations

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This study examines how the dynamical interactions in globular clusters (GCs) influence the formation and evolution of binary sources like cataclysmic variables (CVs), focusing on their X-ray luminosity distributions. Using the MOCCA simulation tool, we classify simulated GCs into three evolutionary stages (Classes I, II, and III) and observe significant differences in CV X-ray luminosities across these classes. Additionally, we analyze 179 CV candidates in 18 GCs using data from the Chandra X-ray Observatory, categorizing these GCs into three dynamical age Families (I, II, and III) based on a pre-existing classification. Both simulation and observational data indicate that CVs in more dynamically mature clusters show higher X-ray emissions, suggesting that CVs, like blue stragglers, can reveal a GC's dynamical history. These findings shed light on the relationship between GC dynamics and the evolution of compact binaries.

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**Current Position**:

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**Stellar multiplicity, exotica, and transients in star clusters / 132**

## MOCCA: Dynamical blue stragglers excess after core collapse

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In the talk I would like to show the results of MOCCA simulations of globular star clusters, which show clear signs of excess of number of blue stragglers stars (BSSs) due to core collapse. The excess of BSSs happens for the core collapses happening for different times (starting from 1-2 Gyr, and up to Hubble time) and for star clusters with different parameters. This feature seems to be common for various models, however it is more profound for core collapses taking place in the lower times.

During the talk I would like to show also that the excess of the number of BSSs is due to the excess of the dynamical ones. In turn, the evolutionary BSSs (not changed by the dynamical interactions) are basically not affected by the core collapse. Moreover, in the talk I would like to show some general conclusions how this excess of BSSs corresponds to global star cluster properties like half-mass relaxation times, total masses or half-mass radii.

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**Current Position**:

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**Stellar multiplicity, exotica, and transients in star clusters / 16**

## A systematic method to identify runaways from star clusters produced from single-binary interactions: A case study of M67

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Runaway stars are thought to have been ejected from star clusters with high velocities relative to the cluster centre-of-mass motion. There are two competing mechanisms for their production: supernova-based ejections in binaries, where one companion explodes leaving no remnant and launching the other companion at the instantaneous orbital velocity, and the disintegration of triples (or higher-order multiples) producing a recoiled runaway binary (RB) and a runaway star (RS).
After discussing the theoretical expectations for both mechanisms, we search for runaway star candidates using data from the Gaia DR3 survey, with a focus on triple disintegration in the old open cluster M67. We create a systematic methodology to look for candidate RS/RB runaway pairs produced from the disintegration of bound three-body systems formed from single-binary interactions, based on momentum conservation and causality. The method is general, and can be applied to any cluster having a 5D kinematic data set. We use our criteria to search for these pairs in a 150 pc circular field of view surrounding the open cluster M67, which we use as a benchmark cluster to test the robustness of our method. Our results reveal only one RS/RB pair that is consistent with all of our selection criteria, out of an initial sample size of $\sim 10^8$ pairs (i.e., $\sim 10^4$ objects).

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Masters or undergraduate student

**Stellar multiplicity, exotica, and transients in star clusters / 115**

# Inert compact binary formation in open clusters

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Gaia mission offers opportunities to search for compact binaries not involved in binary interactions (hereafter inert compact binaries), and results in the discoveries of binaries containing one black hole (BH) or one neutron star (NS), called "Gaia BHs" and "Gaia NSs", respectively. Tanikawa et al. (2024, MNRAS, 527, 4031) have first pointed out that Gaia BHs can be formed much more efficiently in open clusters than on isolated fields. Very recently, the presence of Gaia NS1 have been reported. We assess if Gaia BHs and NSs can be formed in open clusters through dynamical interactions. In order to obtain a large number of inert compact binaries similar to Gaia BHs and NSs, we have performed gravitational N-body simulations for a large number of open clusters whose total mass is 120 million solar masses. These clusters have various masses, metallicities, densities, and binary fractions. We have found that open clusters form Gaia BHs (1-10 per million solar masses) much more efficiently than Gaia NSs (at most 0.1 per million solar masses) for any cluster parameters. This is quite inconsistent with observational results, because the reported numbers of Gaia BHs and NSs are 2 and about 20, respectively. This is also true even if NS natal kicks are unrealistically small. We have concluded that Gaia BHs can be formed in open clusters, while Gaia NSs cannot.

**Affliation**:

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**Stellar multiplicity, exotica, and transients in star clusters / 99**

## Magnetic field amplification during stellar collisions and its implication for blue stragglers

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In dense stellar environments, stars can collide physically. Stellar collisions are known to play a key role in shaping the stellar population in the center of stellar clusters and galactic nuclei, as well as in creating exotic stars, such as blue stragglers, and electromagnetic transients. Previous studies on stellar collisions have mostly focused on the hydrodynamical effects on the properties of collision products. However, stars can be magnetized due to dynamo action in their convective regions or the inheritance of magnetic fields from the interstellar medium during their formation. Because magnetic fields can crucially affect the spin evolution and angular momentum transport inside stars, it is essential to understand possible magnetic field amplification during collisions and its impact on the long-term evolution of collision products. For instance, magnetic braking can provide a possible solution to the "angular momentum problem" for blue straggler formation, where excessive angular momentum inside collision products created by off-axis collisions would prevent them from settling into blue stragglers. To achieve this goal, we perform magnetohydrodynamics simulations of dynamical collisions between main-sequence stars in both globular and open clusters, using the state-of-the-art moving-mesh code AREPO. Our simulations suggest that magnetic fields can be amplified by more than ten orders of magnitude during collisions due to turbulent dynamo, resulting in strongly magnetized stars upon collision. We further investigate the long-term evolution of the magnetized collision products with magnetic braking using the 1D stellar evolution code MESA. I will discuss astrophysical implications of such significant magnetic field amplification in collisions for blue straggler formation and jetted tidal disruption events.

**Affliation**:

Max Planck Institute for Astrophysics

**Current Position**:

Postdoc

**Stellar multiplicity, exotica, and transients in star clusters / 77**

## A study of the exotic pulsars in the globular cluster NGC 1851

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The exceptionally high stellar densities in the cores of globular clusters (GCs) makes them remarkable hosts for an exotic pulsar population. In this talk, I will discuss the results from the radio timing

analysis of a couple of massive binary pulsars in the dense globular cluster NGC 1851, observed with the MeerKAT as a part of the TRAPUM (TRAnsients and Pulsars with MeerKAT) GC Survey. Both systems consist of millisecond pulsars in eccentric orbits with massive companions, suggesting they are the likely products of secondary exchange encounters.
The first binary is very fascinating as the total mass of the system exceeds the heaviest double neutron star known in our Galaxy. Additionally, it is also heavier than the most massive NS-NS merger candidate in LIGO/Virgo data. The derived companion mass places it as a compact object mass-gap candidate, with a mass larger than the largest precisely measured pulsars and smaller than the lightest known stellar-mass black holes (BHs). If the companion is identified as a massive neutron star, it would provide valuable insights into the equation of state of dense nuclear matter, leading to new constraints. On the other hand, if it is identified as a BH, it would signify the discovery of the first millisecond pulsar-BH system. This would offer a unique opportunity to test the properties and formation mechanisms of black holes.
The second one is an eccentric binary pulsar with a massive carbon-oxygen white dwarf companion, and we have obtained precise measurements of three spin frequency derivatives of the pulsar. The second derivative is too large to be accounted for by the cluster and suggests an ongoing encounter with a third mass around the binary. We discuss the nature of this nearby star and address the effects of the frequency derivatives on other timing parameters.

**Affliation**:

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**Current Position**:

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**Stellar multiplicity, exotica, and transients in star clusters / 44**

## Exploring the phenomenon of split main sequence in young star clusters via binary stars

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It is well-established that young stellar clusters in Magellanic Clouds (MCs) host stellar populations that are not simple. Features such as the split main sequence (MS) and the extended main sequence turn-off (eMSTO) are characteristics easily visible in all clusters younger than 2 Gyrs. Initially, these features were explained with prolonged or multiple star formation episodes, suggesting that they could be youthful counterparts of GCs.
The most supported interpretation is that all stars have the same ages but different rotation rates. Fast rotators are more prevalent on the red side (rMS), and slow rotators exhibit bluer colors (bMS). If rotation alone explains the eMSTO, this feature and the multiple populations in GCs are different phenomena.
Is it possible to form two stellar populations with different rotational velocities? A solution expects non-rotating MS stars to be initially rapidly rotators and later to be slowed down. This braking scenario could explain the extended eMSTO and the split MS phenomena without invoking an age difference.
According to this concept, interactions in binary star systems may be responsible for stellar braking, leading to a predominance of binaries among the blue MS.
I would present my investigation concerning the braking scenario based on tidal interactions, which play a fundamental role during the formation and evolution of cluster stars.
For the first time, I determine the frequency of binary stars among both blue and red MS stars in NGC1818, NGC1850, and NGC2164 using high-precision photometry data from the Hubble Space Telescope.
To achieve this, I employ a new method that compares multi-band photometry of binary systems with simulated diagrams of binary stars. This method allows me to infer information about the

dynamical history of binary systems in the target clusters, and my significant finding reveals insight into the formation of MS stars in young star clusters.

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**Current Position**:

PhD Student

**Stellar multiplicity, exotica, and transients in star clusters / 128**

## Whispering in the dark: X-ray faint black holes around OB stars

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Despite the potential of GAIA DR3 to reveal a large population of black holes (BHs), only a few BHs have been discovered to date in orbit with luminous stars without an X-ray counterpart. It has recently been shown that black holes in orbit with main sequence companions seldom form accretion disks, from where observable X-ray flux is conventionally thought to be produced. Yet, even without accretion disks, dissipative processes in the hot, dilute and magnetized plasma around the BH can lead to radiation. For instance, particles accelerated through magnetic reconnection can produce non-thermal emission through synchrotron. We study the X-ray luminosity from this large unidentified population of black holes using detailed binary evolution models computed with MESA, having initial donor masses from 10-90 Msun and orbital periods from 1-3162 d. A significant fraction (0.1% to 50%) of the gravitational potential energy can be converted into non-thermal radiation for realistic particle acceleration efficiency. A population synthesis analysis predicts at least 28 BH+OB star binaries in the Large Magellanic Cloud (LMC) to produce X-ray luminosity above 10**31 erg/s, observable through focused Chandra observations. We identify a population of observed SB1 systems in the LMC comprising O stars with unseen companions above 1.8 Msun that aligns well with our predictions of the orbital period and luminosity distribution of faint X-ray emitting BH+OB star binaries. The peak in the luminosity distribution of OB companions to these faint X-ray-emitting BHs lies around log(L/LSun) ~ 4.5-5. Finally, the X-ray luminosity from hot accretion flows around the faint BH can be ~one order of magnitude above the typical X-ray luminosity expected from embedded shocks in the stellar wind of the OB star companion.

**Affliation**:

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**Current Position**:

Postdoc

**Stellar multiplicity, exotica, and transients in star clusters / 137**

## The importance of dynamics in the cataclysmic variables in globular clusters

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For decades, it has been believed that globular clusters (GCs) are efficient environments for producing cataclysmic variables (CVs) due to the significant number of stellar interactions among their members. However, models in the last years have cast doubt on the validity of this scenario. In this study, I present the results of the first analysis of detectable CVs in core-collapsed and non-core-collapsed Galactic GCs to evaluate the influence of dynamics on their formation and evolution. I will also discuss how our findings compare to existing models. Our results, which combine information of systems observed in different wavelengths, challenge the relations between the number of detectable CVs and different cluster parameters reported in prior studies using only X-ray data. I will further explore the impact of observational biases on the current paradigm and discuss the implications of our findings for understanding the role of dynamics in the population of detectable CVs and other compact binaries within GCs.

**Affliation**:

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**Current Position**:

Senior Scientist or Faculty

**Stellar multiplicity, exotica, and transients in star clusters / 100**

## The disintegration process and orbital evolution of equal-mass hierarchical triple systems

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In collisional system simulations such as globular clusters, stable criteria for hierarchical triple systems are essential. SDAR (Wang et al. 2020) is a method capable of rapidly computing binaries, particularly hierarchical triple systems, but its efficiency depends on the accuracy of the stability criteria for these systems. Traditional criterion is expressed by the parameter $Q = q_{\mathrm{out}}/a_{\mathrm{in}}$, where $q_{\mathrm{out}}$ is pericenter distance of outer orbit and $a_{\mathrm{in}}$ is the semi-major axis of inner orbit. Previous stable criteria were determined based on the initial $Q$'s threshold. But it sometimes misjudges stable systems as unstable so that it suppresses the progress of simulation of the entire cluster.

In order to construct more precise criterion, we investigated the dynamical evolution of hierarchical triple systems and observed how they disintegrate by using $N$-body simulations.
We found that the processes of disruption differ between retrograde and prograde orbits. Retrograde orbits experience disruption through a single close encounter of inner and outer components, while prograde orbits are disrupted by the accumulation of random orbital element changes due to close encounters. This categorization holds even for cases with orbital inclination. These close encounters are more likely to occur when the apocenter of the inner and the pericenter of the outer happen to align coincidentally. Through the evolution of the system, the arrangement of particles gradually evolves into shapes conducive to frequent close encounters.

We also found that $Q$ oscillates during evolution and its amplitude correlates with system destabilization.
Based on these findings, we are constructing more accurate stable criteria for incorporation into $N$-body simulations. The prospects of this approach will be discussed.

**Affliation**:

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**Current Position**:

Masters or undergraduate student

**Stellar multiplicity, exotica, and transients in star clusters / 53**

## Synthetic Populations of Ultra-Luminous X-ray Sources in Globular Clusters

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Ultra-Luminous X-ray Sources (ULXs), which emit more X-rays than typical accreting black holes, remain enigmatic objects in astrophysics. With only around 20 ULXs potentially residing in Globular Clusters (GCs), they pose challenging targets for study. Previous research predominantly focused on ULXs in the field, yet in the dense environment of GCs, where stars are densely packed, dynamics become crucial in ULX formation.

Through Markov Chain Monte Carlo (MCMC) simulations, we investigate how dynamics influence ULX formation. Our findings reveal that dynamics can both facilitate and hinder ULX formation processes. They can tighten star pairs or exchange partners, aiding ULX formation, but they can also disrupt the process. This results in inherently different ULX populations formed in GCs compared to those in the field, where specific populations can be distinguished. Furthermore, we analyze the ejection process from GCs, where ULXs formed in these environments can contribute to the populations in the field.

Our work contributes to a deeper understanding of these high-energy sources, highlighting the crucial role of dynamics in shaping their populations.

**Affliation**:

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**Current Position**:

Postdoc

**Stellar multiplicity, exotica, and transients in star clusters / 117**

## The effect of dynamically formed binaries on young planetary systems

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Stars do not form in isolation but together with other stars, often in a clustered environment. During the dynamical evolution of these environments, stars will interact with each other. These encounters will affect any planetary systems that are in the process of forming around them. Many typical fly-by simulations focus on a single fly-by event's effect on a planetary system. However, during the early dynamical evolution of the birth cluster, dynamical binaries can form quickly from two single stars. The effect of dynamically formed binaries on any planetary systems that might have formed around their initially single stars is largely unexplored. In this talk, I will present results from young star cluster N-body simulations showing how dynamical binaries can be formed and destroyed again. I will then show isolated planet system simulations and present results focussing on the differences in the orbital parameters of planetary systems with close-in Super-Earths either in a dynamical or a primordial binary. I will show how dynamical binaries can accelerate the disruption of planetary systems and compare the differences in the resulting planetary architectures after several hundred Myr.

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**Stellar multiplicity, exotica, and transients in star clusters / 138**

## The ejection of hypervelocity stars from Milky Way globular clusters

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Discoveries of Milky Way stars with velocities in excess of the Galactic escape speed (~500 km/s at the Solar position) have been reported with increasing frequency in the era of large Galactic surveys. These 'hyper-velocity stars' serve as a fascinating probe of the extreme dynamical and astrophysical phenomena which produce them, such dynamical interactions with Sgr A* or supernovae within binaries. In this work we explore the possibility that three-body interactions between single stars and black hole binaries in dense Milky Way globular clusters eject stars well above the Galactic escape speed. Combining state-of-the-art cluster evolution simulations, dynamical interaction modelling, and mock observation techniques, we can predict the size and character of the globular cluster-ejected hyper-velocity star population which is (in principle) detectable in current and future surveys. We find that a significant population of these objects should lurk in the current data release from the Gaia space mission, and yet more should become detectable in future Gaia data release(s) and in the upcoming LSST survey.

In this talk I will outline our modelling approach, describe in further detail this population of very fast stars, and offer insight on effective observational strategies for identifying them.

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**Current Position**:

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**Chris Belczynski memorial session on compact objects and gravitational wave sources / 150**

## The life and work of Prof. Chris Belczyński

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**Affliation**:

**Current Position**:

**Chris Belczynski memorial session on compact objects and gravitational wave sources / 41**

## Stellar-mass binary black hole mergers and dormant black hole-star binaries from young massive and open star clusters

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In the first part of the presentation, I shall recapitulate my recent endeavours in investigating the role of dynamical interactions in moderate mass star clusters in producing stellar-mass binary black hole (BBH) mergers over cosmic time. Dynamical BBH mergers are obtained from long-term direct N-body evolutionary models of ~10^4 M_sun, pc-scale young massive clusters evolving into moderate-mass open clusters. These models consistently include recent stellar-origin black hole and neutron star masses and natal kicks, (pulsation) pair-instability supernova, black hole spins, post-Newtonian treatment, and general-relativistic recoil kicks. The resulting BBH merger rate and its cosmic evolution are compared with those from the LIGO-Virgo-KAGRA observations. I shall then demonstrate a new, in-progress model grid that incorporates the effect of external, galactic tidal field on clusters. This homogeneous grid spans over galactocentric distances 1.0-8.5 kpc. While strong tidal field dissolves the clusters much faster, it also accelerates their core collapse, favouring interactions among the clusters' BHs, so that the BBH merger production is not quenched. I shall demonstrate how various galactic star formation profiles potentially modify BBH-merger properties, e..g., their delay time distribution. In the second part, I shall focus on the dormant (or detached) BH-star binaries in the galactic field that these model clusters produce. Such binaries are of high current interest due to the recent discoveries of detached field BH-star binary candidates, namely, Gaia-BH1 and Gaia-BH2. The above star cluster models are particularly suitable for studying such binaries since the models are evolved at least until all BHs are practically depleted from them, making the clusters' contribution to the field BH-star binary population complete. These models produce field Gaia-BH1- and Gaia-BH2-like binaries at rates of ~ 10^-7 per M_sun. I shall compare these results with those from other recent studies.

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**Chris Belczynski memorial session on compact objects and gravitational wave sources / 123**

## Through the mantle of hydrogen: understanding mass transfer in black hole - star systems and the formation of binary black hole mergers

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One of the great challenges for gravitational-wave astrophysics is disentangling different formation channels of binary black-hole (BBH) mergers. Achieving this requires in-depth understanding of BBH formation pathways and robust predictions for observable channel characteristics. We tackle this challenge for binary evolution scenarios by systematically modeling mass transfer evolution in BH-star systems with MESA. We find that there is a limit to how close stable mass transfer (SMT) evolution can bring a star and a BH together without triggering them to merge as a result of a run-away mass-transfer instability. This limit is significantly more stringent than that imposed by the size of naked helium stars and it is independent of angular momentum loss during SMT. Instead, it results from the stellar structure and the flat entropy profile of the near-core layers in massive radiative donors. We show that this leads to a trend: the more evolved (expanded) the donor star, the more compact its core, and therefore the smaller orbital separation can be achieved. This trend is robust against modeling uncertainties and naturally produces an anticorrelation between effective spins and mass ratios of detectable BBH mergers. We demonstrate that the overall effectiveness of the SMT channel, on the other hand, is strongly tied to some of the key uncertainties in stellar evolution, such as internal chemical mixing, core-rejuvenation, and the extend of Main Sequence. I will discuss the significance of modern high-precision stellar astrophysics and surveys in narrowing down those long-standing unknowns to pave the way towards a robust model of BBH merger formation, in particular in the metal-poor regime that is also key for dynamical channels. Finally, we propose a new simple criteria for mass transfer stability for population synthesis that stems from the physical origin of instability in radiative donors and well approximates the behavior of detailed models.

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**Current Position**:

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**Chris Belczynski memorial session on compact objects and gravitational wave sources / 40**

## The ones that got away: formation and evolution of intermediate-mass black holes in massive star clusters

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Repeated stellar collisions and hierarchical mergers in dense and massive star clusters are among the most straightforward mechanisms to produce intermediate-mass black holes (IMBHs).

In my talk, I will investigate the formation channels of IMBHs in globular clusters up to $10^6$ $M_\odot$. To do this, I will rely on an extensive set of accurate N-body models run with the recently-developed `PeTar − MOBSE`, which is uniquely conceived to integrate both stellar interactions and long-term dynamical evolution in massive and long-lived stellar clusters. I will show how the initial central densities and masses of the cluster affect the probability to form and retain an IMBH. Finally, I will discuss the peculiar impact of hierarchical mergers on the growth of IMBHs and the expected mass spectra of binary black hole mergers.

**Affliation**:

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PhD Student

**Chris Belczynski memorial session on compact objects and gravitational wave sources / 108**

## Seeds to success: growing heavy black holes in dense star clusters.

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Intermediate mass black holes (IMBHs) serve as a crucial link between stellar-mass black holes, resulting from the death of massive stars, and supermassive black holes residing at the center of galaxies. Yet, we do not fully understand the necessary conditions for IMBH production, raising questions about whether they could constitute a completely distinct category of black holes.

Star clusters represent ideal laboratories to study the formation of IMBHs. In extremely dense clusters, stellar collisions can trigger the rapid assembly of a very massive star, ultimately collapsing to an IMBH. This initial 'seed' can then further grow via repeated mergers with stellar-mass black holes in the cluster.

Understanding the conditions under which IMBH growth proceeds unhindered is fundamental to identifying how IMBHs are produced and, potentially, to investigating their connection to supermassive black hole formation.

In my talk, I will discuss which structural parameters can help identify the optimal clusters for IMBH seeding. Then, I will compare these theoretical predictions with simulations performed with the new population synthesis code B-POP. Finally, I will present a peculiar set of clusters, obtained from our numerical models, nurturing the growth of IMBHs as massive as 10,000 to 100,000 solar masses.

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Gran Sasso Science Institute

**Current Position**:

PhD Student

**Chris Belczynski memorial session on compact objects and gravitational wave sources / 37**

## New evidence for an intermediate-mass black hole in ω Centauri

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The intermediate mass black hole (IMBH) regime is still poorly constrained with few detections between 150 and $10^5$ $M_{\odot}$.
An IMBH in ω Centauri, the Milky Way's most massive globular cluster, has been suspected for almost two decades, but all previous detections have been questioned due to their assumptions and the possible mass contribution of a central cluster of stellar mass black holes.
I will present a new astrometric catalog for the inner region of ω Centauri, containing 1.4 million proper motion measurements based on 20 years of Hubble Space Telescope observations.
Our catalog is supplemented with precise HST photometry in 7 filters, allowing the separation of its complex subpopulations. The catalog will be made publicly available, providing the largest kinematic dataset for any star cluster.
Our new catalog revealed 7 fast-moving stars in the innermost 3 arcseconds (0.08 pc) of ω Centauri. The inferred velocities of these stars are significantly higher than the expected central escape velocity of the star cluster, so their presence can only be explained by being bound to an IMBH. From the velocities we can infer a firm lower limit of the black hole mass of ~8,200 M . In addition, we compare the full distribution of stellar velocities to N-Body models that suggest the presence of an IMBH with M⊠50,000 M . These results confirm ω Centauri hosts an IMBH which makes this the nearest known massive black hole and, after the Milky Way center, only the second where we can track the orbits of multiple individual bound companions.

**Affliation**:

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**Current Position**:

PhD Student

**Chris Belczynski memorial session on compact objects and gravitational wave sources / 12**

## Do Intermediate-Mass Black Holes Exist in Galactic Globular Clusters? - Clues From X-ray Observations and Hydrodynamical Simulations

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Globular clusters (GCs) are thought to harbor the long-sought population of intermediate-mass black holes (IMBHs). We present a systematic search for a putative IMBH in 81 Milky Way GCs, based on archival {\it Chandra} X-ray observations. We find in only six GCs a significant X-ray source positionally coincident with the cluster center, which have 0.5–8 keV luminosities between $\sim 1 \times 10^{30}$ erg s$^{-1}$ to $\sim 4 \times 10^{33}$ erg s$^{-1}$. However, the spectral and temporal properties of these six sources can also be explained in terms of binary stars. The remaining 75 GCs do not have a detectable central source, most with $3\sigma$ upper limits ranging between $10^{29-32}$ erg s$^{-1}$ over 0.5–8 keV, which are significantly lower than predicted for canonical Bondi accretion. To help understand the feeble X-ray signature, we perform hydrodynamic simulations of stellar wind accretion onto a 1000 $M_\odot$ IMBH from the most-bound orbiting star, for stellar wind properties consistent with either a main-sequence (MS) star or an asymptotic giant branch (AGB) star. We find that the synthetic X-ray luminosity for the MS case ($\sim 10^{19}$ erg s$^{-1}$) is far below the current X-ray limits. The predicted X-ray luminosity for the AGB case ($\sim 10^{34}$ erg s$^{-1}$), on the other hand, is compatible with the detected central X-ray sources, in particular the ones in Terzan 5 and NGC 6652. However, the probability of having an AGB star as the most-bound star around the putative IMBH is very low. Our study strongly suggests that it is very challenging to detect the accretion-induced X-ray emission from IMBHs, even if they were prevalent in present-day GCs.

**Affliation**:

Nanjing Univeristy

**Current Position**:

PhD Student

**Chris Belczynski memorial session on compact objects and gravitational wave sources / 109**

## The case of an IMBH in the galactic centre: insights from N-body simulations

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We present the results of direct N-body simulations focusing on stellar discs interacting with a central supermassive black hole (SMBH) and an off-plane intermediate mass black hole (IMBH) embedded within a spherical star cluster. For models with a high-mass IMBH ($m_\bullet \simeq M_\mathrm{d}$) on a retrograde orbit with respect to the stellar disc, we find that the IMBH tends to anti-align with the radially overlapping disc stars' inclination angles, with a tendency to become orthogonal with respect to the outer region of the disc. The final state of the IMBH's inclination angle is governed by the relative magnitudes of the angular momentum vectors of the IMBH and the radially overlapping disc region. In contrast, when on prograde orbits, the IMBH and the disc always align with their total angular momentum vector. Lower mass IMBH models ($m_\bullet \ll M_\mathrm{d}$) on retrograde orbits exhibit roughly constant inclination angles over time. During the process of anti-alignment, a massive, retrograde IMBH disrupts the stellar disc. This disruption fragments the disc into 2–4 distinct sections, each characterised by overdensities of their angular momentum vectors. These sections are transient but become prominently observable between 5 to 6 Myrs. Their appearance coincides with the age of the young stars in the disc at the Galactic centre, offering a potential explanation for their observed distribution.

**Affliation**:

University of Oxford

**Current Position**:

Postdoc

**Chris Belczynski memorial session on compact objects and gravitational wave sources / 11**

# Star cluster properties from intermediate-mass black hole mergers

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Next-generation (XG) ground-based gravitational wave observatories are expected to be sensitive to mergers of intermediate-mass black holes (IMBHs) with a total source-frame mass in the hundreds out to a high redshift. Runaway tidal encounters lead to the formation of IMBHs in the cores of dense stellar clusters. I will discuss how single IMBH–IMBH merger events, occurring after the coalescence of clusters that sank into the center of their host galaxies, can be used to infer the properties of their progenitor star clusters. Implementing an astrophysically motivated analytic model and performing binary parameter estimation for our massive events in a network of three XG detectors, we find that inferring the structural properties of clusters through this channel is challenging due to model degeneracy. Nonetheless, the redshifts of cluster formation are better measured, and the cluster formation history may be inferred from an observed population of IMBH-IMBH mergers.

**Affliation**:

Johns Hopkins University

**Current Position**:

PhD Student

**Chris Belczynski memorial session on compact objects and gravitational wave sources / 111**

# Formation of SMBH in galactic nuclei: LISA binaries & intermediate-mass ratio inspirals

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Supermassive black holes (SMBHs) are found to co-exist with a nuclear star cluster (NSC) in the nuclei of most galaxies. The work presented in this talk builds on the idea that the NSC forms before the SMBH through the merger of several stellar clusters that may contain intermediate-mass black holes (IMBHs). These IMBHs can subsequently grow in the NSC, and form an SMBH. To check the observable consequences of this proposed SMBH seeding mechanism, we created a mock population of galaxies and constructed their NSCs by aggregating stellar clusters. Each aggregating stellar cluster was assigned a probability for forming an IMBH based on its properties. If multiple IMBH are delivered to the NSC by stellar clusters than they may form a binary which can merge by gravitational wave emission. By looking at the NSCs in which we deliver two IMBHs to the NSC, we find that about 10% of these binary mergers maybe detectable with LISA and will have observed frequencies between 0.01 to 0.3 Hz. However, if we allow for the first IMBH to grow moderately (via gas accretion and/or tidal disruption of stars) before the delivery of the second IMBH, we find that more than 50% of the BH binaries will have properties at merger that may make them observable with LISA. In this case, many of the mergers will be intermediate-mass ratio (~0.001-0.01) inspirals with observable frequencies between 1E-4 to 0.3 Hz. The detection (or non-detection) of such binaries with LISA will provide insights and constraints on the seeding and growth mechanisms of SMBHs at the center of galaxies.

**Affliation**:

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**Current Position**:

Postdoc

**Chris Belczynski memorial session on compact objects and gravitational wave sources / 9**

## Eccentric Mergers in AGN Discs: Influence of the Supermassive Black-Hole on Three-body Interactions

**Author:** Gaia Fabj[1]

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There are indications that stellar-origin black holes (BHs) are efficiently paired up in binary black holes (BBHs) in Active Galactic Nuclei (AGN) disc environments, which can undergo interactions with single BHs in the disc. Such binary-single interactions can potentially lead to an exceptionally high fraction of gravitational-wave mergers with measurable eccentricity in LIGO/Virgo/KAGRA. We take the next important step in this line of studies, by performing post-Newtonian N-body simulations between migrating BBHs and single BHs set in an AGN disc-like configuration with a consistent inclusion of the central supermassive black hole (SMBH) in the equations of motion. With this setup, we study how the fraction of eccentric mergers varies in terms of the initial size of the BBH semi-major axis relative to the Hill sphere, as well as how it depends on the angle between the BBH and the incoming single BH. We find that the fraction of eccentric mergers is still relatively large, even when the interactions are notably influenced by the gravitational field of the nearby SMBH. However, the fraction as a
function of the BBH semi-major axis does not follow a smooth functional shape, but instead shows strongly varying features that originate from the underlying phase-space structure. The phase-space further reveals that many of the eccentric mergers are formed through prompt scatterings. Finally, we present the first analytical solution to how the presence of an SMBH in terms of its Hill sphere affects the probability for forming eccentric BBH mergers through chaotic three-body interactions.
We present the main results from https://arxiv.org/abs/2402.16948

**Affliation**:

Niels Bohr International Academy

**Current Position**:

Masters or undergraduate student

**Chris Belczynski memorial session on compact objects and gravitational wave sources / 29**

## SgrA* spin and mass estimates through the detection of an extremely large mass-ratio inspiral

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Estimating the spin of SgrA* is one of the current challenges we face in understanding the center of our Galaxy. In the present work, we show that detecting the gravitational waves (GWs) emitted by a brown dwarf inspiraling around SgrA* will allow us to measure the mass and the spin of SgrA* with unprecedented accuracy. Such systems are known as extremely large mass-ratio inspirals (XMRIs) and are expected to be abundant and loud sources in our galactic center. We consider XMRIs with a fixed orbital inclination and different spins of SgrA* (s) between 0.1 and 0.9. For both cases, we obtain the number of circular and eccentric XMRIs expected to be detected by space-borne GW detectors like LISA and TianQin. We find that if the orbit is eccentric, then we expect to always have several XMRIs in band while for almost circular XMRIs, we only expect to have one source in band if SgrA* is highly spinning. We later perform a Fisher matrix analysis to show that by detecting a single XMRI the mass of SgrA* can be determined with an accuracy of the order 10^{−2}M⊠, while the spin can be measured with an accuracy between 10^{−7} and 10^{−4} depending on the orbital parameters of the XMRI.

**Affliation**:

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**Current Position**:

Postdoc

**Chris Belczynski memorial session on compact objects and gravitational wave sources / 50**

## Unveiling the Dance of Off-Center Black Hole Duets: Insights from Jacobi Capture in Dwarf Galaxies

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It is well established that massive black holes reside in the central regions of virtually all types of known galaxies. Recent observational and numerical studies however challenge this picture, suggesting that intermediate-mass black holes in dwarf galaxies may be found on orbits far from the center. In this talk, I will present my recent work on the dynamics of off-center black holes in dwarf galaxies. I introduce a new scenario to describe off-center mergers of massive black holes, starting with a Jacobi capture. I find that these captures are a complex and chaotic phenomenon and I quantify how the likelihood of capture depends on the simulation parameters. I show that Jacobi captures in cored dwarf galaxies facilitate the formation of off-center black hole binaries. While this setup only allows for temporary captures, it has been shown that dissipative forces from stellar populations can stabilize the captures, motivating further investigation into their role in forming stable binary systems within stripped nuclei or globular clusters. My work shows that off-center mergers can have a major impact on the mass growth of black holes, and therefore they can play a fundamental role for the understanding of gravitational wave signals in the context of future observatories, such as LISA.

**Affliation**:

Observatoire Astronomique de Strasbourg

**Current Position**:

PhD Student

**Chris Belczynski memorial session on compact objects and gravitational wave sources / 67**

## Can the X-ray binaries in M83 be the progenitors of gravitational waves sources for LIGO/VIRGO/KAGRA?

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LIGO/VIRGO/KAGRA collaboration announced over 90 gravitational waves detections from double compact objects (DCOs) mergers, however, the origin and evolution scenario of their progenitors remains elusive.
One of the promising candidates for DCOs progenitors are the X-ray binaries (XRBs) where X-ray emission arises from the accretion of matter transferred from the companion star onto a black hole (BH) or a neutron star (NS).
To study the connection between XRBs and DCOs mergers we chose the spiral galaxy M83 which hosts 214 X-ray point sources identified as XRBs. Only 12 of them are found within stellar clusters while for the remaining 202 the formation site cannot be definitely indicated. Had they formed through the isolated binary evolution or the dynamical interactions in the stellar clusters remains an open question.
Regardless how they were formed, one can investigate what will be the final fate of the XRBs observed in M83. For that purpose we used the population synthesis calculations. We reproduced the number and X-ray luminosity of XRBs in M83 within isolated binary evolution model. We then followed the evolution of each XRB in the model population until the merging DCO was formed or the Hubble time was reached (if the merger didn't appear). Our results show that although all merging DCOs in our isolated binary evolution model go through the XRB phase only $\sim 1-2\%$ XRBs in M83 may evolve to form merging DCOs.

**Affliation**:

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**Current Position**:

Postdoc

**Chris Belczynski memorial session on compact objects and gravitational wave sources / 66**

## Dynamical formation of binary black holes in massive star clusters: a cosmological approach

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With nearly 200 hundred gravitational-wave detection candidates reported by the LIGO-Virgo-KAGRA Collaboration over the past decade, we are now entering an era where the statistical analysis of the properties of double compact objects provides us with a better understanding of the physical processes behind these extreme objects. However, the question of the astrophysical origin of merging binary black holes (BBHs) remains unsolved. The two main formation channels generally considered are the isolated evolution of binary stars and the dynamical assembly in dense star clusters.
Here we focus on the dynamical formation channel and on understanding the role played by the galactic environment in shaping the population of merging binary black holes. To this end, we apply a sub-grid model for cluster formation in giant molecular clouds to a series of zoom-in simulations of galaxies from the FIRE-2 project, and to individual galaxies in the cosmological volume simulation FIREbox. Combined with the code for star cluster evolution CMC, we are able to produce populations of star clusters and dynamically formed merging BBHs across cosmic time in a large sample of galaxies.

As massive star clusters preferentially form in the densest massive gas clouds, which are rarely found in low-mass galaxies, we expect these galaxies to make a limited contribution to the global production of dynamically formed merging BBHs. Furthermore, we find that massive clusters can host hierarchical BBH mergers: a massive second-generation BH, formed from an earlier BBH merger, pairing with a first-generation BH. These particular events are expected to have clear, identifiable physical properties. Identifying the formation channel of some of the observed BBH mergers could be the first step towards identifying their host galaxies, thus providing valuable information about their astrophysical origin.

**Affliation**:

Observatoire de la Côte d'Azur, Université Côte d'azur

**Current Position**:

PhD Student

**Chris Belczynski memorial session on compact objects and gravitational wave sources / 92**

## The Effect of Primordial Binaries and Cluster Dynamics on Binary Black Hole Mergers

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Dense stellar clusters are prime environments for the formation and evolution of bound binary black hole (BBH) systems, leading to eventual mergers. These BBHs can form through direct interactions among stellar objects or evolve from primordial binaries —binaries that originated within the cluster. Importantly, the dynamical interactions within these clusters have the potential to significantly influence BBH evolution by altering their orbital properties. This talk presents our recent research on how stellar cluster dynamics affect BBH populations and, consequently, the characteristics of their merger events. We employ N-body simulations, isolated stellar evolution models, and theoretical arguments to model stellar clusters with masses up to $M_{\rm cl} = 10^5\,{\rm M}_\odot$, both with and without primordial binaries. Our findings reveal that including a primordial binary population results in these BBHs dominating the merger numbers. Furthermore, in clusters with an initial mass of $M_{\rm cl} \leq 10^5\,{\rm M}_\odot$, approximately $50\%$ of all the BBH mergers are influenced by dynamical interactions that either directly formed these systems or significantly altered the merger times of BBHs from primordial binaries. Despite this, we find that clusters born with a high primordial binary fraction still exhibit a merger efficiency consistent with isolated binary population models.

**Affliation**:

Cardiff University

**Current Position**:

PhD Student

**Chris Belczynski memorial session on compact objects and gravitational wave sources / 64**

## The role of massive star binarity in the creation of upper mass-gap and intermediate-mass black holes in dense star clusters

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Isolated evolution of massive stars is expected to leave a "gap" in the mass spectrum of black holes (BHs) at birth between ~40-120 Msun due to (pulsational) pair-instability supernovae ((P)PISN). Recent detections of gravitational waves (GWs) from mergers of BHs with pre-merger source-frame individual masses in this so-called upper mass-gap, have created immense interest in a detailed understanding of their astrophysical formation environments and pathway(s). It has been previously shown that inside dense star clusters, mass-gap BHs and even intermediate-mass BHs (IMBHs) may form via dynamical channels- through repeated mergers of BHs or through BHs formed from massive stars with unusual core to envelope mass ratios formed via past collisions. Using a controlled set of detailed star-by-star multi-physics simulations, we investigate the role of massive-star binarity, defined as the fraction of massive (> 15 Msun) stars present in the star cluster existing in binary systems as opposed to singles, in the formation of massive BHs. For this purpose, we simulate star clusters with identical individual stellar population, but with a varying fraction of massive stars in binaries. We find that the number of massive BHs as well as the mass of the most massive BH that form via stellar collapse of stellar collision products are sensitive to the massive-star binarity of the star cluster. However, BH-BH mergers dominate the production of massive BHs over the cluster's lifetime. The massive BHs formed via BH-BH mergers are independent of the massive-star binarity. However, the demographics of the population of BH-BH mergers is again sensitive to the massive-star binarity. I will present our key results from this study.

**Affliation**:

Tata Institute of Fundamental Research, Mumbai

**Current Position**:

PhD Student

**Chris Belczynski memorial session on compact objects and gravitational wave sources / 97**

# Constraining the features of the BBH mass distribution through population synthesis simulation

**Authors:** Cristiano Ugolini[1]; Mario Spera[1]

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The first direct detection of gravitational waves (GWs), back in 2015, marked the beginning of a new era for the study of compact objects, and the upcoming next-generation detectors, such as Einstein Telescope (ET), are expected to add hundreds of thousands of compact binary coalescences to the list. We discovered up to 90 GW signals, from which we were able to put some constrains on the phenomenon leading to the formation, the evolution and the eventual merger of binary systems.
However, the processes occurring during the evolution of such systems exhibit degeneracies, making it challenging to obtain individual constraints.
In this talk, I will show the result we obtained when we tried to disentangle such degeneracies, performing population synthesis simulations under various assumptions and trying to reproduce the distribution we observe from the data collected by LVK.

**Affliation**:

SISSA

**Current Position**:

PhD Student

**Observational properties of dense stellar systems in different environments / 122**

## Determining the dynamics and mass function at the earliest stages of star cluster formation

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Although great progress has been made the last years on the shape of the Stellar Mass Function and the dynamics of stellar clusters in more evolved clusters, less is known on the earliest stages of star formation. Here we present recent JWST observations in conjunction with previous HST and VLT observations of a still forming star cluster, identified by a large molecular infall. The sensitivity of JWST allows determining the IMF deep into the brown dwarf region and the long baseline available in combination with previous HST observations allows determination of the velocity dispersion down to a km/s. We discuss the clustering, the velocity dispersion, and the Mass Function to low masses in the cluster and the implications for massive star formation and cluster formation.

**Affliation**:

European Southern Observatory

**Current Position**:

Senior Scientist or Faculty

**Flash Poster Presentations (in-person) / 80**

## Dynamical Friction of Black Holes Embedded in Turbulent AGN Disks

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Supermassive black holes in galactic nuclei are expected to accumulate a cusp of stellar-mass black holes around them. If the galactic nucleus evolves into an active galactic nucleus (AGN), these black holes will cross the AGN's gaseous disk twice per orbit, each time experiencing a gaseous dynamical friction force. This dynamical friction will induce alignment and circularization of the black holes within the AGN disk, potentially enhancing their interaction rate in the so-called AGN channel for gravitational wave formation. Consequently, many studies assume that black holes ultimately settle into perfectly circular and aligned orbits within the AGN disk.
However, accretion in AGN disks is fueled by turbulent motions within the gas. We demonstrate that turbulence counteracts dynamical friction, preventing the complete alignment and circularization of embedded black holes. We illustrate how to correlate local disk properties (density, sound speed, alpha viscosity) to the minimum values of eccentricity and inclination that embedded black holes can reach.

**Affliation**:

Niels Bohr Institute

**Current Position**:

Postdoc

**Observational properties of dense stellar systems in different environments / 135**

## Central kinematics of globular clusters: evidence for a massive black hole?

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A number of different hypotheses about the origin of Supermassive black holes (SMBHs) in the galactic centres was proposed. One formation channel that we investigate in our project is the gravitational runaway scenario, that suggests an SMBH seed to form by runaway collisions in dense star systems like globular clusters (GCs). We focused on two promising candidates that can host such a massive black hole: the second-brightest GC in the Milky Way 47 Tuc and NGC 1916 observed in the Large Magellanic Cloud (LMC). The central part of 47 Tuc was recently investigated in the ultra-deep radio survey, and a central point source that consistent with the location and emission strength expected from an ~1000 Msun black hole was detected. NGC 1916 was proposed to be a Nuclear Star Cluster (NSC) of the LMC, that makes it a great spot to search for a massive BH.
In this work, we analyse the kinematics of 47 Tuc with a combined MUSE Radial Velocities (RVs) and HST Proper Motions (PMs) sample that contains ~21 thousand stars with PMs and more than 7 thousand stars with RVs within the central 1 arcmin. The available three-dimensional velocity information makes it possible to identify high velocity stars in the cluster, that could be potential escapers, binary interaction products, or companions to an intermediate-mass black hole. We also compare our results with a Monte Carlo model that has a prediction about the black holes' population, and perform Jeans dynamical modelling to study the kinematics of the cluster to reveal its rotation or unseen mass distribution. For NGC 1916 we have the HST photometric data and MUSE RVs and metallicities for more than a thousand stars, that allows us to perform a chemical and kinematic analysis for the central part of the cluster.

**Affliation**:

LJMU

**Current Position**:

PhD Student

**Stellar multiplicity, exotica, and transients in star clusters / 83**

## Pulsar-black hole binaries in the dynamical environment of star clusters

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Over a third of all observed millisecond pulsars appear in Galactic globular clusters, which collectively account for less than 0.05% of the total number of stars in the Milky Way. Recently, there have been radio observations (with MeerKAT) of a possible millisecond pulsar-black hole (mass gap) eccentric binary in the globular cluster NGC 1851. On the other hand, the current generation of gravitational wave detectors (LIGO-Virgo-KAGRA, LVK) has been discovering neutron star-black hole binaries.

Using detailed pulsar evolution (through massive binary evolution) in massive globular clusters modeling (using the code PeTar), I will show the formation mechanism behind such pulsar-black hole binaries, aiming to decouple the contributions of angular momentum gain through mass transfer and tidal encounters in spinning up a neutron star. Accounting for radio selection effects, I will specifically highlight the MeerKAT-observed NGC 1851 millisecond pulsar binary and elaborate on the mass, mass ratio, spin, and eccentricity of such binaries. Furthermore, I will link such neutron star-black hole systems to those being observed by the LVK. I will also provide predictions for the near future, including ongoing high sensitivity radio telescopes like the SKA and MeerKAT, upcoming LVK observing runs, as well as future gravitational wave missions like the Laser Interferometer Space Antenna (LISA) and the Cosmic Explorer (CE).

**Affliation**:

Cardiff University

**Current Position**:

Postdoc

**Flash Poster Presentations (in-person) / 34**

## Massive black hole growth by full and partial tidal disruption events

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Tidal disruptions of stars by massive black holes (MBHs) in dense stellar clusters may be an important channel for MBH growth. While full tidal disruption events (FTDEs) have been studied extensively, recently the focus has shifted to understanding the impact of partial tidal disruption events (PTDEs). We study MBH growth in dense star clusters through full and partial tidal disruption events via direct N-body simulations using the novel hierarchical forth-order forward integrator code BIFROST. The code is GPU accelerated, making simulations of $10^6$ stars feasible, and can simulate arbitrary binary fractions due to efficiently parallelized secular and regularized integration techniques for binaries, fly-bys, triples and multiple subsystems. Post-Newtonian (PN) terms are included in the equations of motion of subsystem particles up to order PN3.5. We present first results on the growth of $10^3 M_\odot$ MBHs in a suite of simulations of compact star clusters up to $10^6$ stars. We compare MBH growth rates in models with FTDEs only and FTDEs+PTDEs and show how PTDEs influence massive BH growth. We compute FTDE and PTDE rates and compare our results to previous numerical predictions and current observational estimates. We also discuss how well the black hole growth can be represented by simple analytic fitting formulae which could have a wide range of applications for high-resolution cosmological simulations.

**Affliation**:

Max Planck Institute for Astrophysics

**Current Position**:

PhD Student